TEQ - Kick off Meeting

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Marta Marchese	QUB	Marta Marchese
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Southampton, June 22nd, 2018

Andrea Vinante

Preparing for the TEQ experiment at Southampton

University of Southampton, UK

Some questions about TEQ experiment

- What is the optimal size of the nanoparticle in order to do relevant (noninterferometric) tests of collapse models ?

- We want/need very low pressure (P<1E-10 mbar)
  & very low temperature (T<1 K)
  Can we ever cool a levitated nanoparticle in such conditions?

- Can we keep the particle cold when doing measurements?
  Could a stroboscopic measurement strategy work?

Continuous Spontaneous Localization (CSL)

Schrödinger equation + Stochastic term (collapse noise field)

$$d|\psi_t\rangle = \left[-\frac{i}{\hbar}H\,dt + \boxed{\sqrt{\lambda}\int d^3x(N(\mathbf{x}) - \langle N(\mathbf{x})\rangle_t)dW_t(\mathbf{x}) - \frac{\lambda}{2}\int d^3x(N(\mathbf{x}) - \langle N(\mathbf{x})\rangle_t)^2 dt}\right]|\psi_t\rangle$$

2 phenomenological constants (free parameters)

- Correlation Length r_C

  (N = number density of nucleons, “smeared” over r_C)

  conventional “literature value” $r_C = 10^{-7}$ m

- Collapse rate λ

  Lower bounds (to guarantee collapse at “macroscopic” or “mesoscopic” scale)

  $\lambda \sim 10^{-16}\ \mathrm{s}^{-1}$ @ $r_C = 10^{-7}$ m following Ghirardi, Rimini, Weber (GRW)

  $\lambda \sim 10^{-8}\ \mathrm{s}^{-1}$ @ $r_C = 10^{-7}$ m following Adler

Measurable effects

1) Collapse of massive quantum superpositions

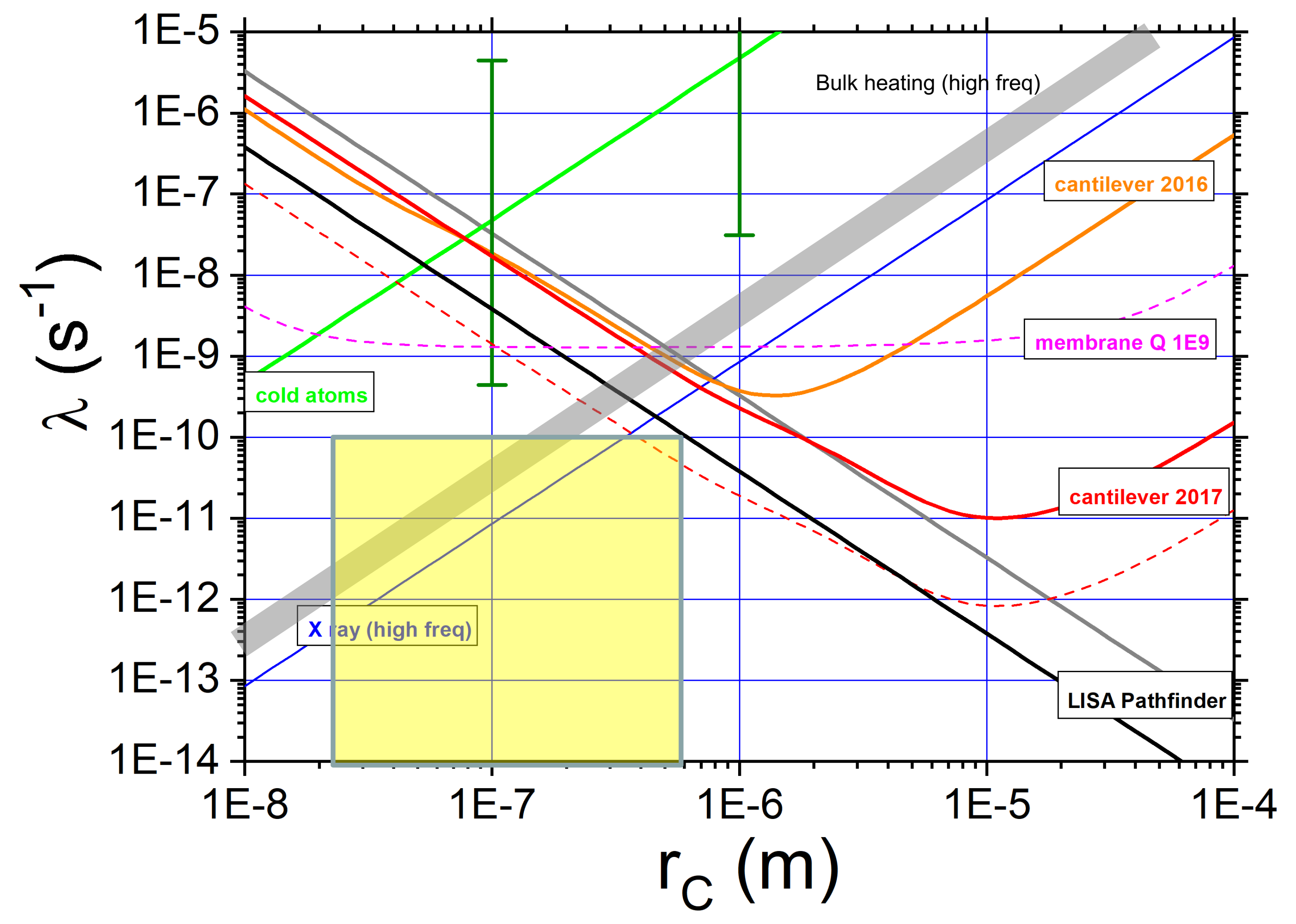
⇩

Matter wave interferometers

2) Indirect effects (non-interferometric)

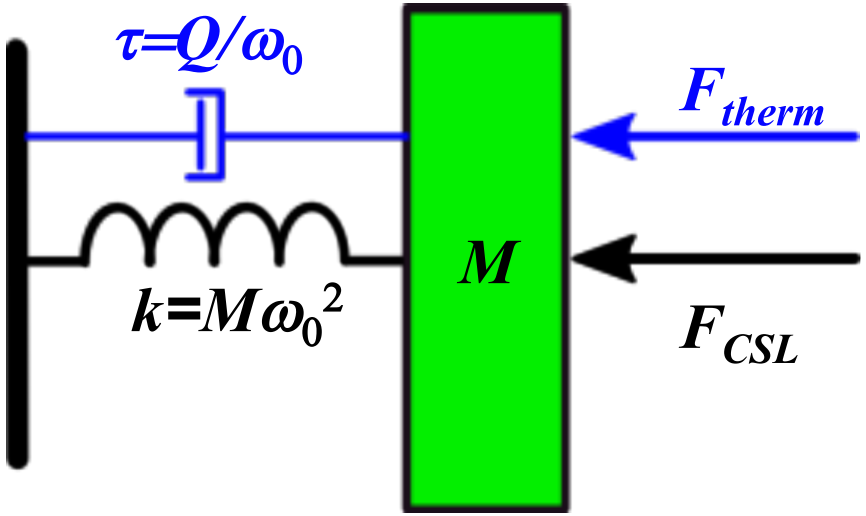
- X-ray spontaneous emission from free electrons
- Spontaneous heating of materials systems (i.e. solid matter)
- Spontaneous diffusion / force noise in mechanical systems/resonators

Current bounds on CSL parameter space



REGION OF INTEREST for NANOSPHERES !

Random Collapses → Momentum kicks → Stochastic driving force



$$\langle E \rangle = k_B \mathrm{T} + \Delta E_{CSL} = k_B(T + \Delta T_{CSL})$$

S. Nimmrichter et al, PRL 113 020045 (2014)
L. Diosi, PRL 114, 050403 (2015)
A. Vinante et al, PRL 116, 090402 (2016)

CSL-heating on a mechanical resonator

$$\langle E\rangle = k_B T + \boxed{\frac{\hbar^2 \eta Q}{2m\omega_0}}$$

$$S_{ff} = \frac{4k_B T m\omega}{Q} + \boxed{2\hbar^2\eta}$$

$$\begin{aligned}\eta &= \frac{2\lambda}{m_0^2}\iint \mathrm{d}^3\mathbf{r}\,\mathrm{d}^3\mathbf{r}'\,\exp\left(-\frac{|\mathbf{r}-\mathbf{r}'|^2}{4r_C^2}\right)\frac{\partial\rho(\mathbf{r})}{\partial z}\frac{\partial\rho(\mathbf{r}')}{\partial z'} \\ &= \frac{(4\pi)^{\frac{3}{2}}\lambda\, r_C^3}{m_0^2}\int\frac{\mathrm{d}^3\mathbf{k}}{(2\pi)^3}k_z^2\, e^{-\mathbf{k}^2 r_C^2}\,|\tilde{\rho}(\mathbf{k})|^2\end{aligned}$$

MAXIMIZATION of Signal to Noise (actually Noise to Noise):

High $\tau = \frac{Q}{\omega_0}$ ⇒ Low Frequency! (opposite as in quantum optomechanics)

Low T

Low $\frac{\eta}{m}$ →

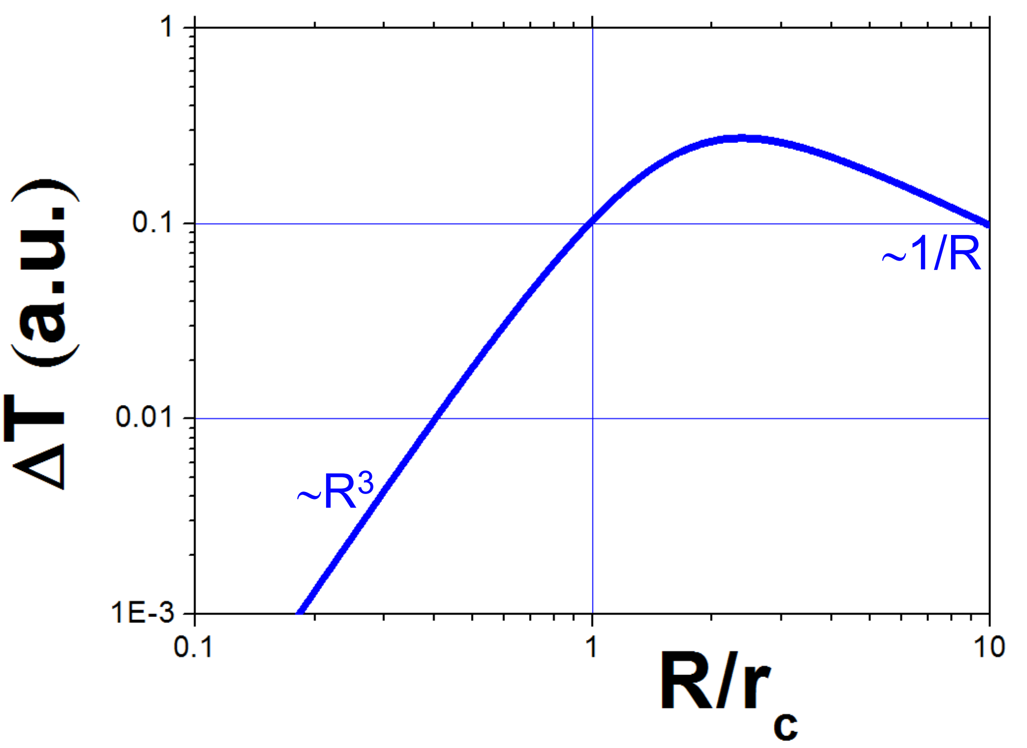
1) Size $\ll r_c$ (coherent) $\eta/m \propto m$

2) Thickness $L \gg r_c$ $\eta/m \propto \rho/L$ $\eta \propto \rho^2 A$

("surface" noise)

Example: CSL heating of a sphere

Exact solution for a sphere of radius R (at fixed ρ, Q and f_0)



$$\eta = \frac{(4\pi)^2 \lambda r_C^2 \rho^2 R^2}{3m_0^2}\left[1 - \frac{2r_C^2}{R^2} + e^{-\frac{r_C^2}{R^2}}\left(1 + \frac{2r_C^2}{R^2}\right)\right]$$

$$\Delta T = \frac{\hbar^2 \eta}{2k_B m}\tau$$

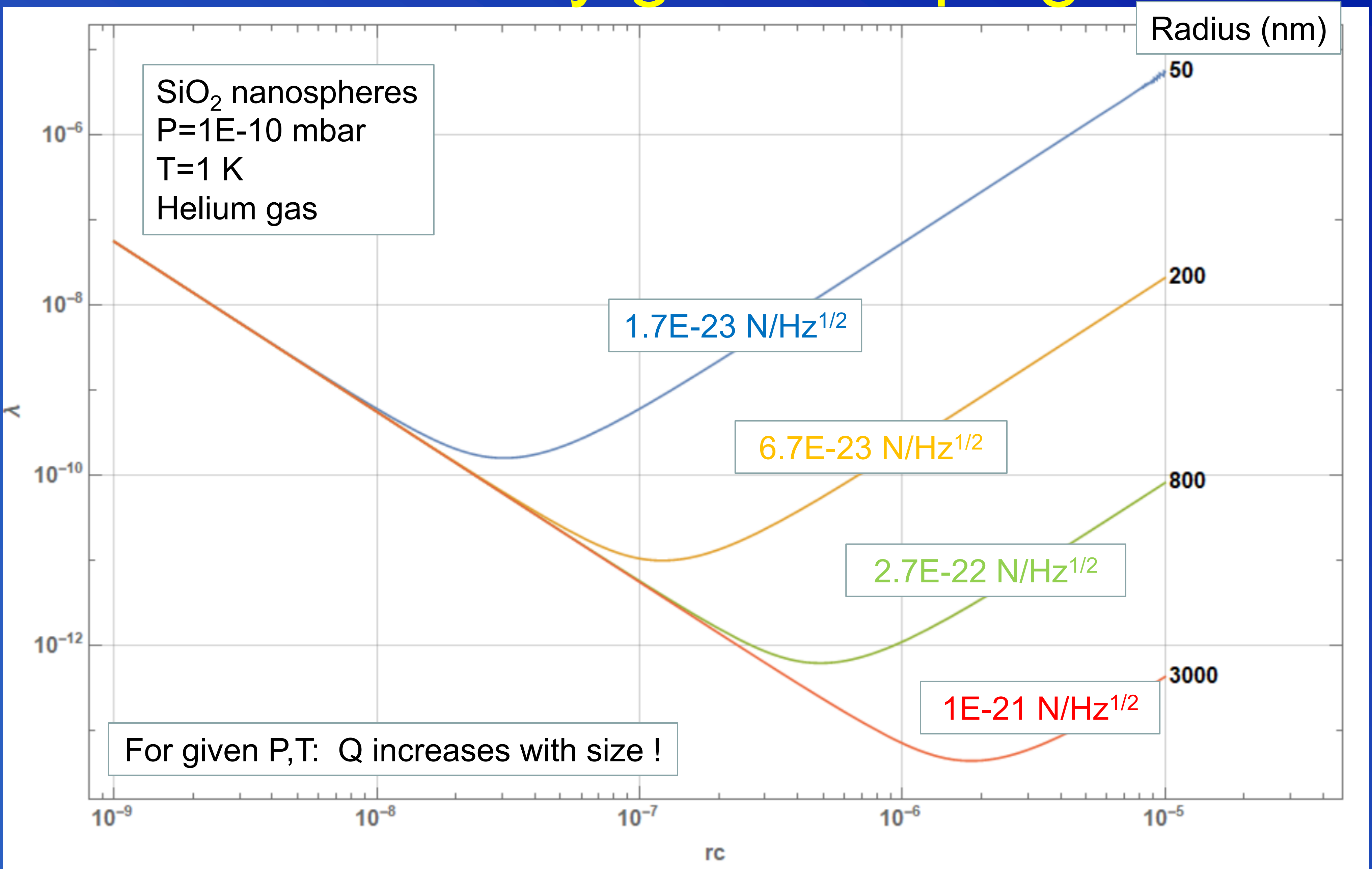
Maximum at $R \simeq 2r_C$

NOTE:

1) The density is important !

2) Sphere is not the best geometry. For given mass, cube is slightly better !

BUT: if only gas damping



SiO$_2$ nanospheres
P=1E-10 mbar
T=1 K
Helium gas

For given P,T: Q increases with size !

Conclusions

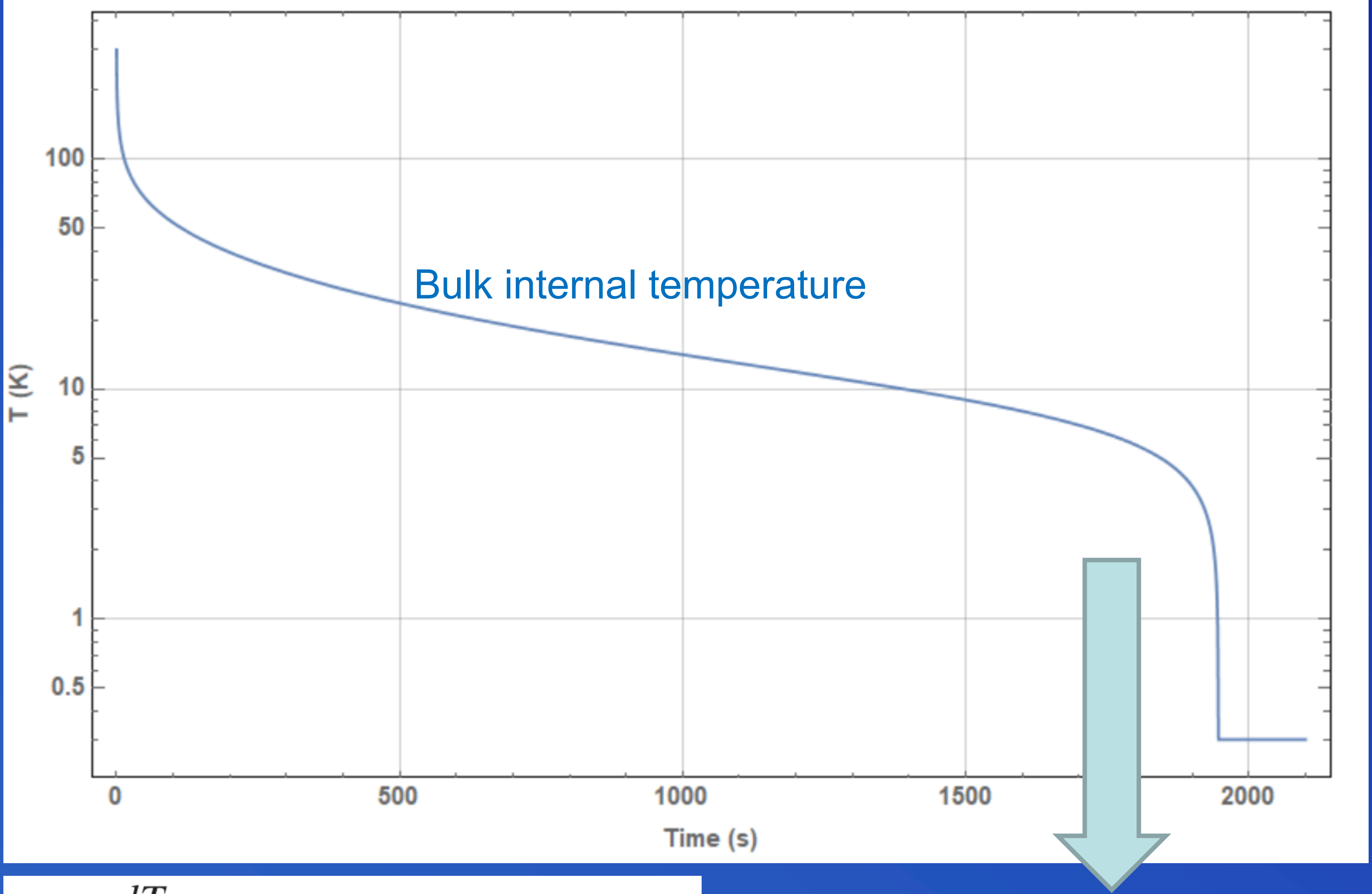
- Radius should not be smaller than 200 nm
  Materials with density higher than SiO_2 would help

- For radius >> 200 nm, bound @ $r_c=10^{-7}$ is almost independent of particle size for given P,T

Can we ever thermalize a micro/nanoparticle @ T<1K, P=1E-10 mbar ? (given for granted we can load & trap)

Yes, provided that external heating
(for trapping, measuring) is low enough …

Thermalization curve



SiO$_2$ nanosphere
R=200 nm

Gas: helium
P=1E-10 mbar
T0=0.3 K

T[0]=300 K

$$C(T)\frac{dT}{dt} = -\dot{Q}_{gas}(T) - \dot{Q}_{bb}(T) + \dot{Q}_{in}$$

Debye model

Heat flow to gas

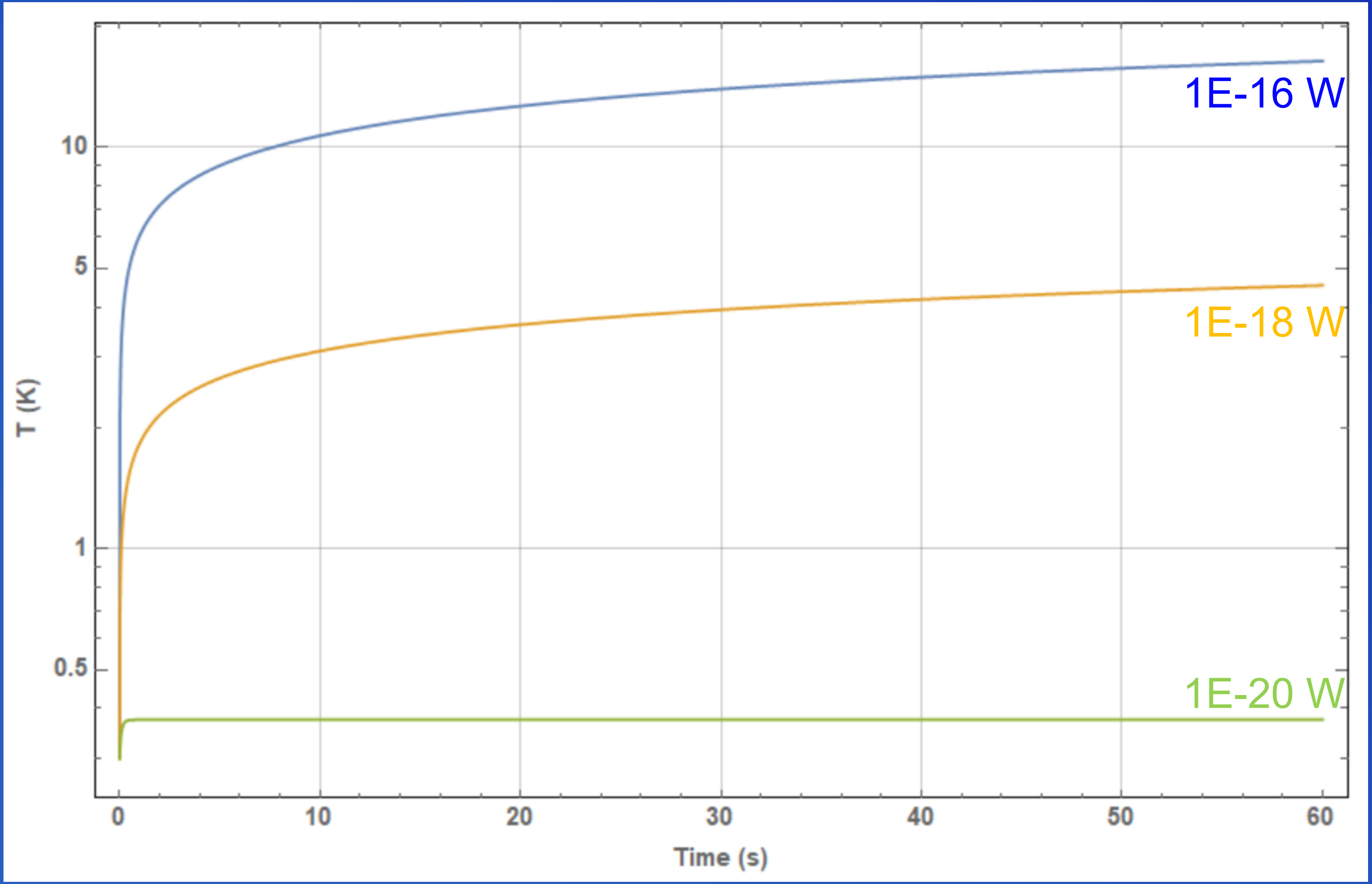
Blackbody emission

External Heat input

No need for Buffer Cooling

Key assumption: No input power !

Add a continuous power (levitating fields , measurement beam, uncontrolled heat leaks)



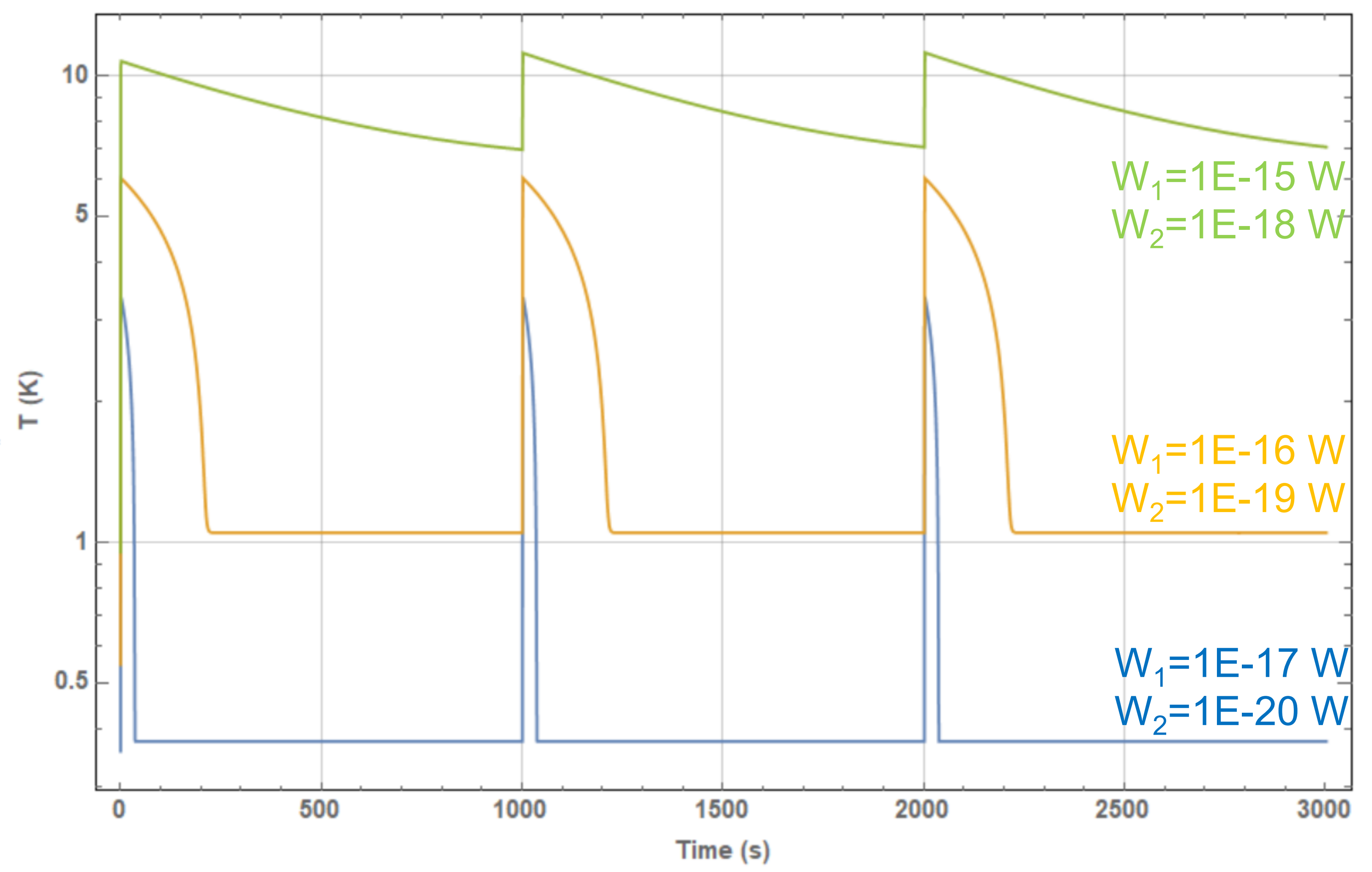
SiO_2 nanosphere
R=200 nm

Gas: helium
P=1E-10 mbar
T0=0.3 K

T[0]=0.3 mK

Pulsed input power (stroboscopic measurement)

W_1 (high) for 1 s – W_2 (low) for 1000 s



SiO_2 nanosphere
R=200 nm

Gas: helium
P=1E-10 mbar
T0=0.3 K

T[0]=0.3 K

The TEQ He-3 cryostat

Initial Idea: Dry Dilution Refrigerator

Good: T >10 mK
No need for liquid helium (lower running cost)
Continuous operation
Bad: Large vibrations from precooler compressor
Expensive

Final: Wet He3-sorption Refrigerator

Bad: T >300 mK
Needs liquid helium (higher running cost)
Single shot operation (t>60 hours, rechargeable)
Good: Ultralow vibration operation mode
Cheaper (in the short term…)

The tender

Mandatory Requirements

- T < 300 mK
- Single shot hold-time > 60 hours
- Experimental space: Diameter x Length = 15 x 25 cm
- UHV compatible vacuum chamber (P<1E-10 mbar)
- Ultralow vibration mode

Outcome

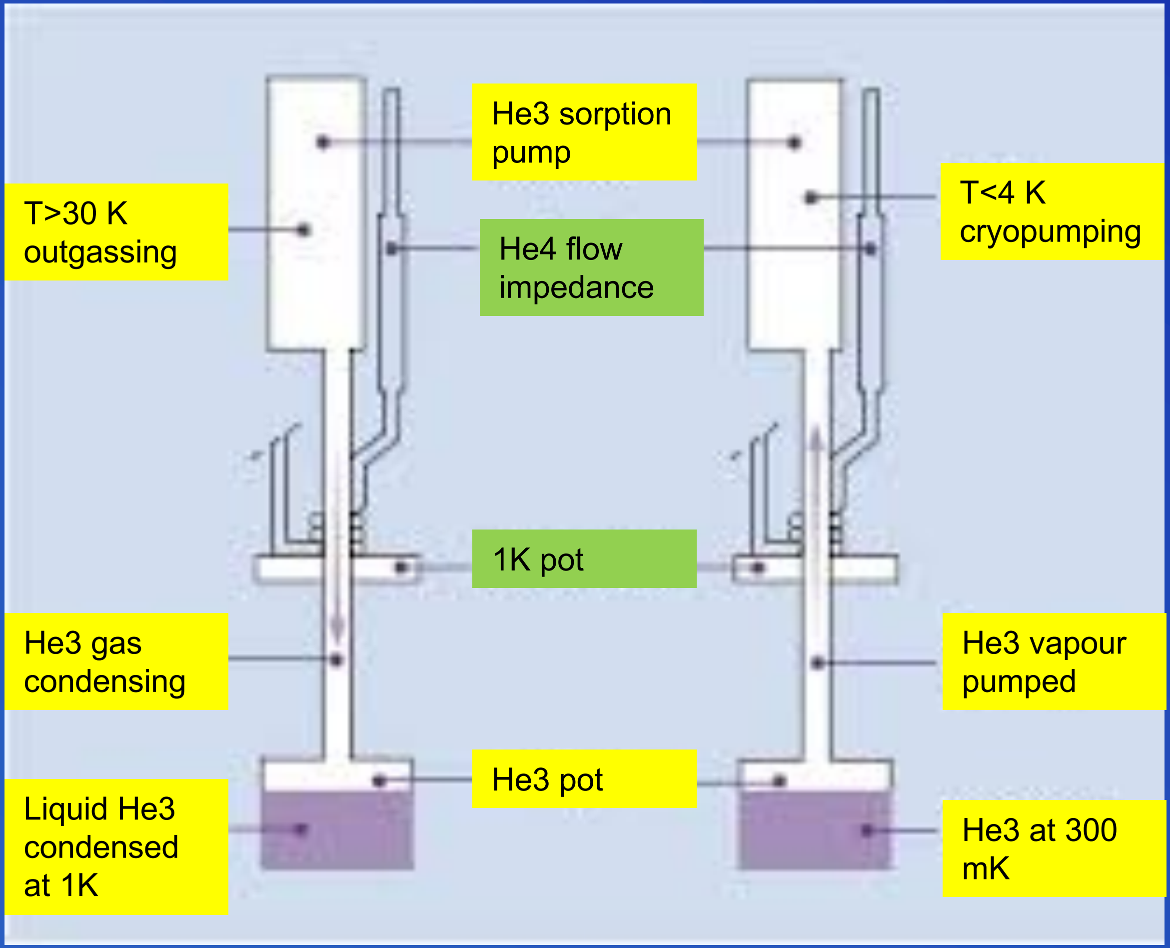
- Four companies initially interested
- Two companies completed the bidding process

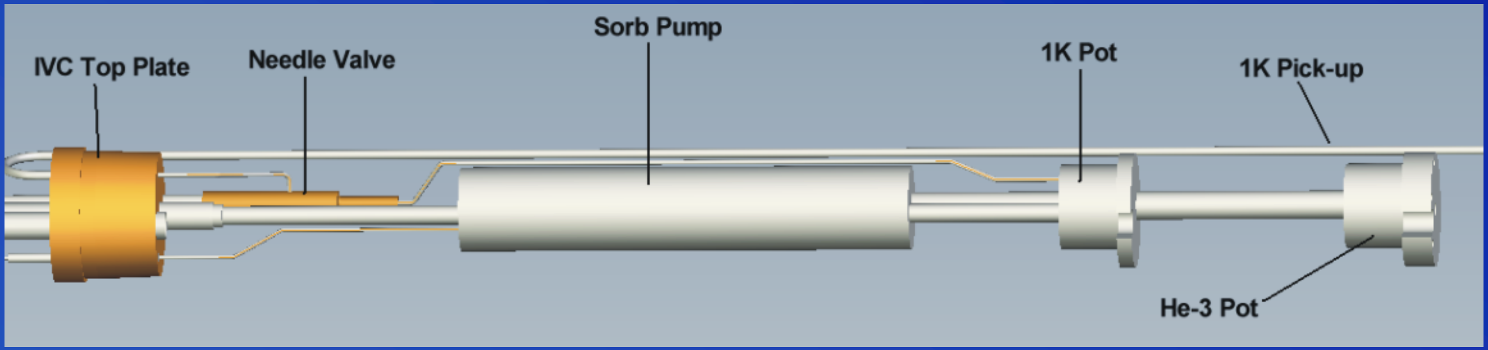
Winner: ICE Oxford (UK)

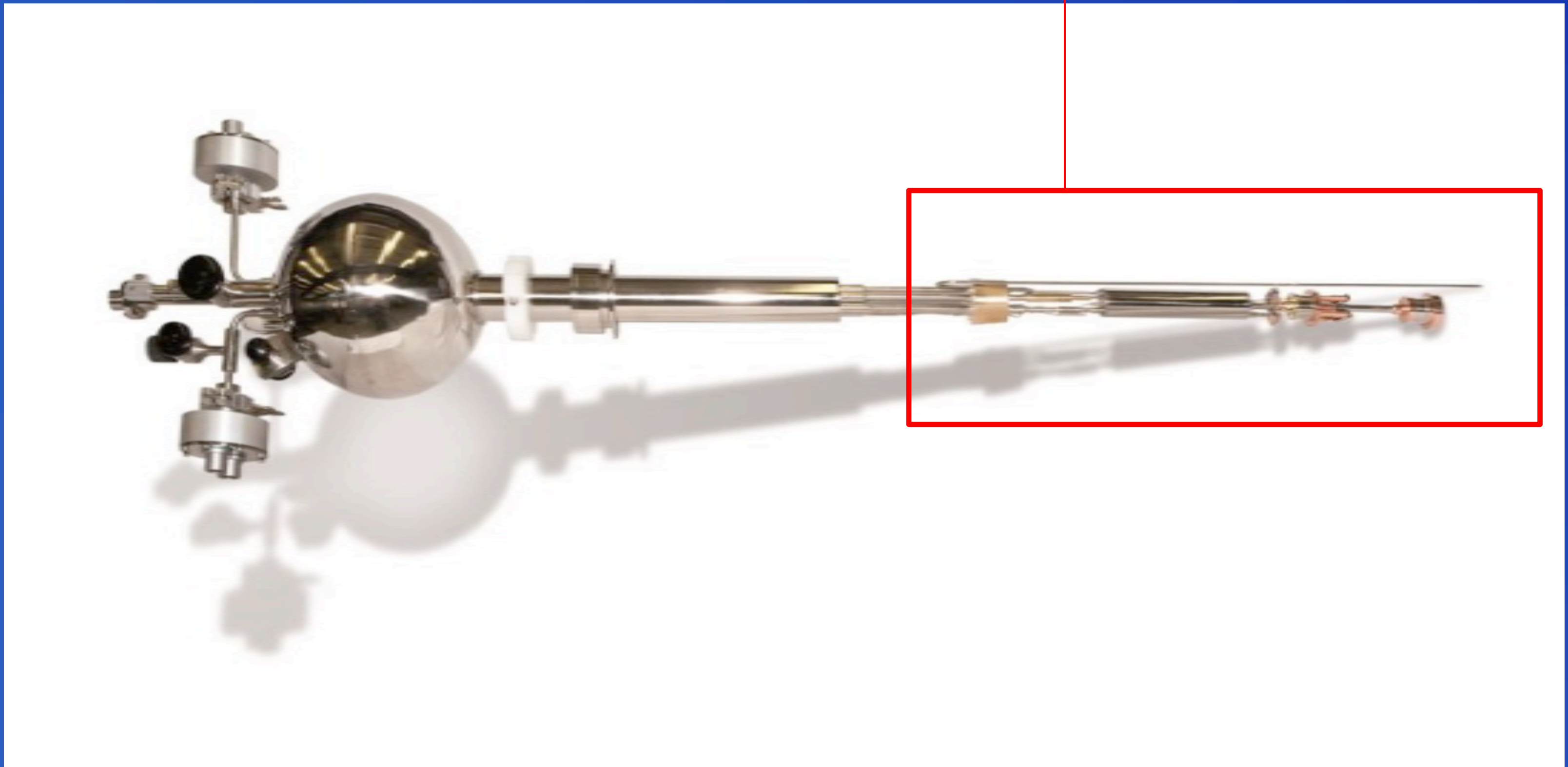
How it works

1 Condensation
(Regeneration phase ~ 1-2 hours)

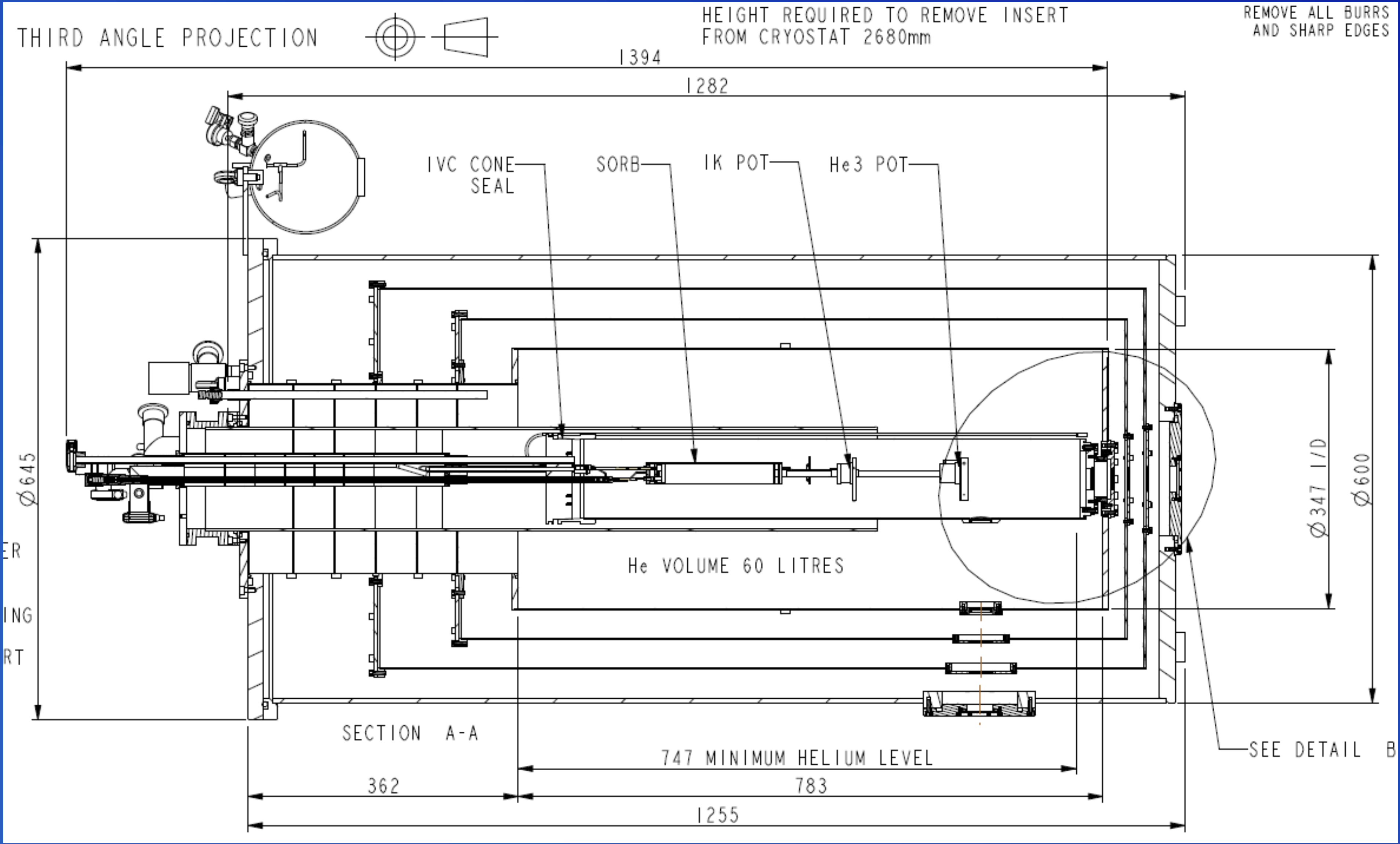
2 Evaporation
(Cooling phase t>60 hours)




IVC Top Plate
Needle Valve
Sorb Pump
1K Pot
1K Pick-up
He-3 Pot



A similar ICE system (Paris optomech.)



Additional features

UHV

- Low outgassing rate materials
- UHV flanges
- Residual gas pressure < 1E-10 mbar at the experiment (?)

Optical access

- Optical windows
- Optical fibers (?)

Preinstalled wiring

- 10 flexible coaxial lines
- 12 twisted pairs in one bundle

External mechanical isolation

Wiring (current design)

Coaxial lines: meant for ac signals, e.g. Paul trap “rf bias”

- Stainless steel flexible line
- Cryogenic section: switch to NbTi/CuNi matrix shielded twisted (superconducting to minimize Joule + conduction heating)
- Voltage rating 600 V
- SMA connectors on top flange
- 10x , IS IT ENOUGH ?

Twisted pairs: meant for dc or low freq signals, e.g. Paul trap “dc bias”

- Constantan, cryogenic section switch to NbTi/CuNi
- Voltage rating should be up to 200 V
- Single bundle / Single Fischer connector on top flange
- 12x, IS IT ENOUGH ?

Heat load due to Paul trap bias

1) Ohmic losses:
Heavily suppressed by superconducting wiring

2) Heat conduction through wiring
Heavily suppressed by superconducting wiring

3) Dielectric loss heating in the wiring insulation: Dominant mechanism

$$W \simeq \frac{1}{2}\delta_L \omega C V_{rf}^2$$

$$\delta_L \simeq 10^{-4}$$

For N=10 lines, C≈20 pF

$\omega/2\pi$ (kHz)	V_{rf} (V)	W (μW)
10	100	6
20	200	50
100	1000	6000

For this cryostat W<100 μW advisable

Mechanical Isolation

Key idea: No vibrations produced inside the cryostat
(except helium boiling noise but no mechanical pumps)

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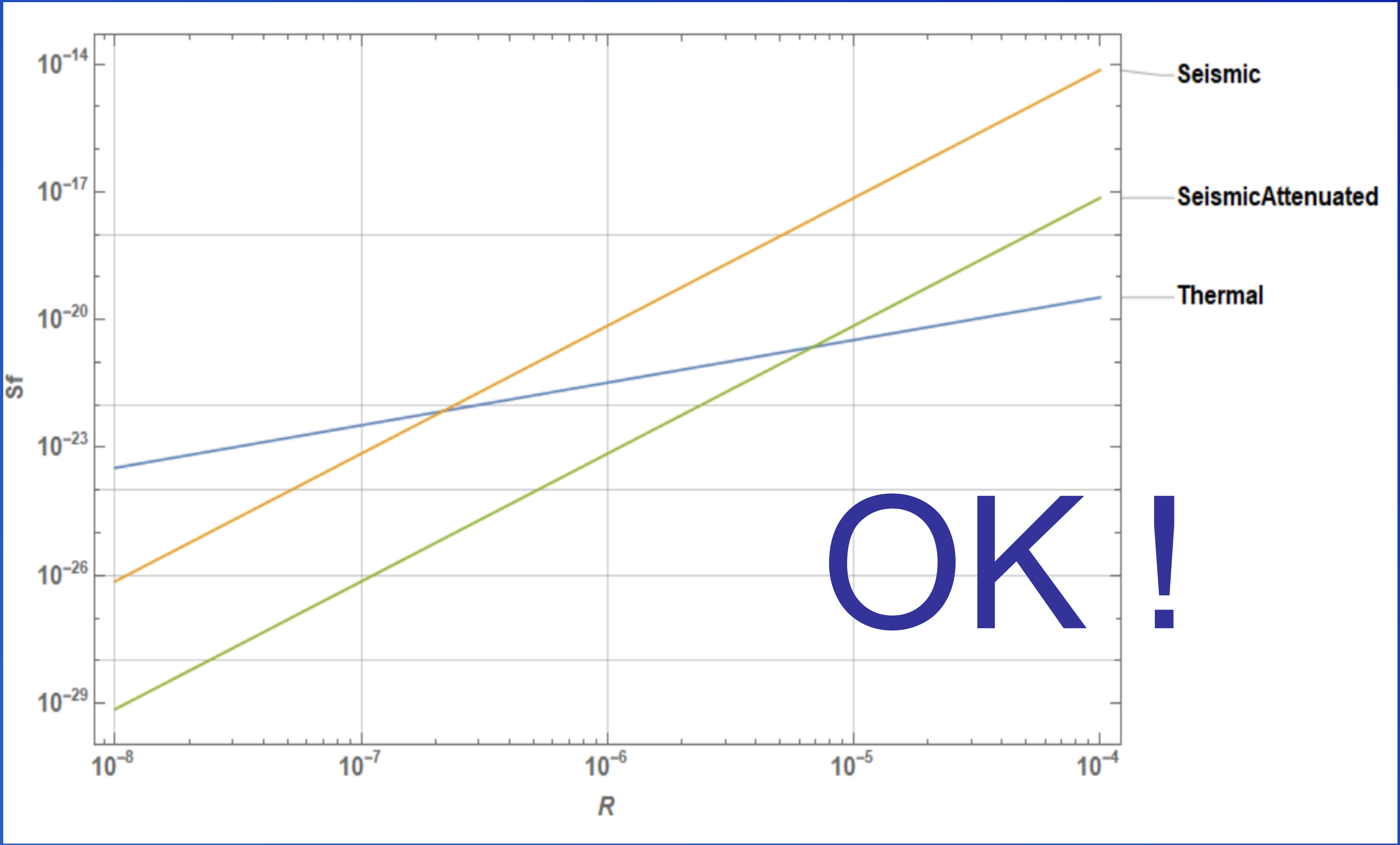
Only external noise relevant

The all cryostat will be suspended
on a pneumatic mechanical isolator (Newport)
Attenuation > 60 dB @ 30 Hz

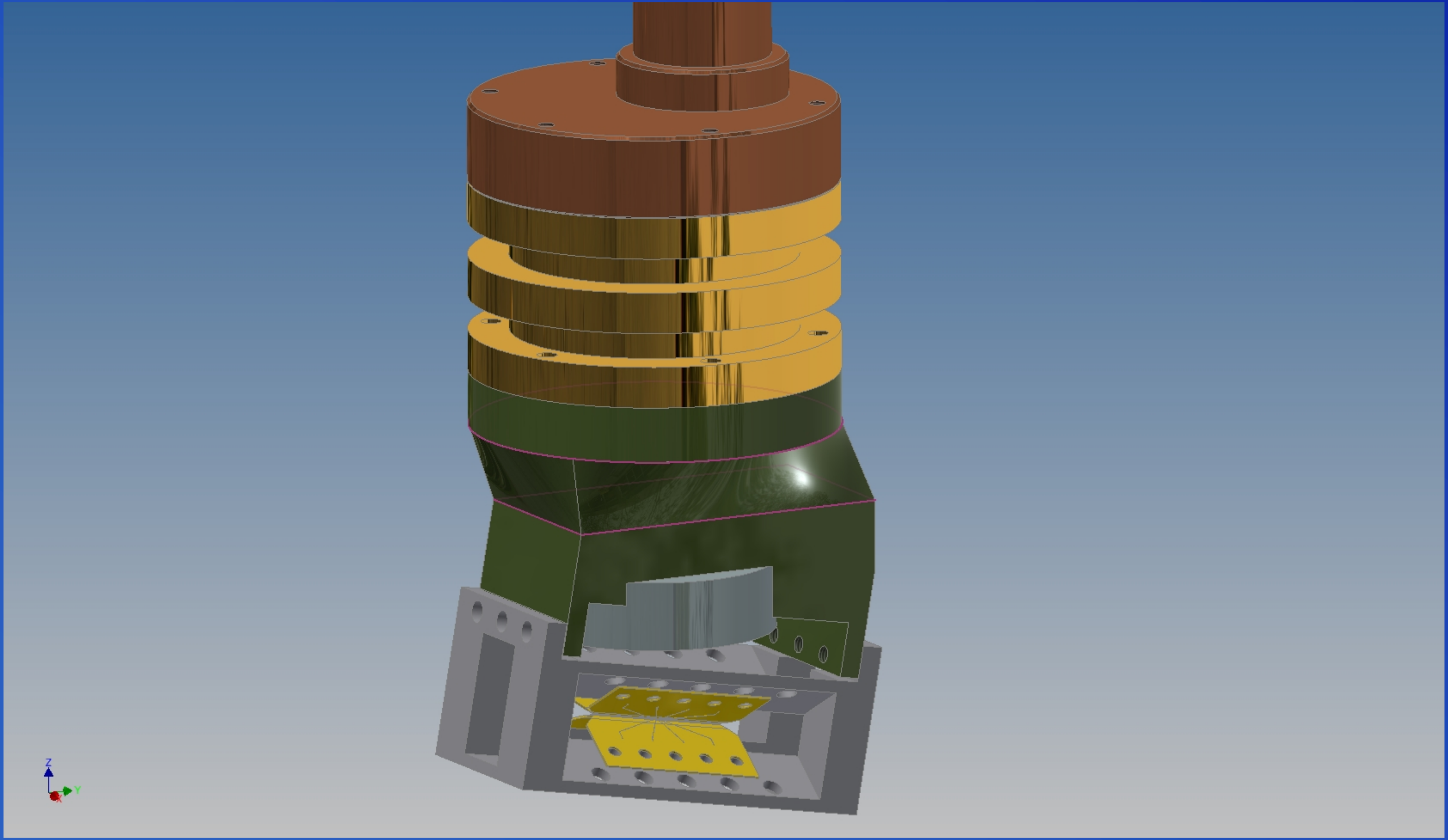
IS IT ENOUGH?

Seismic noise (using standard figures)

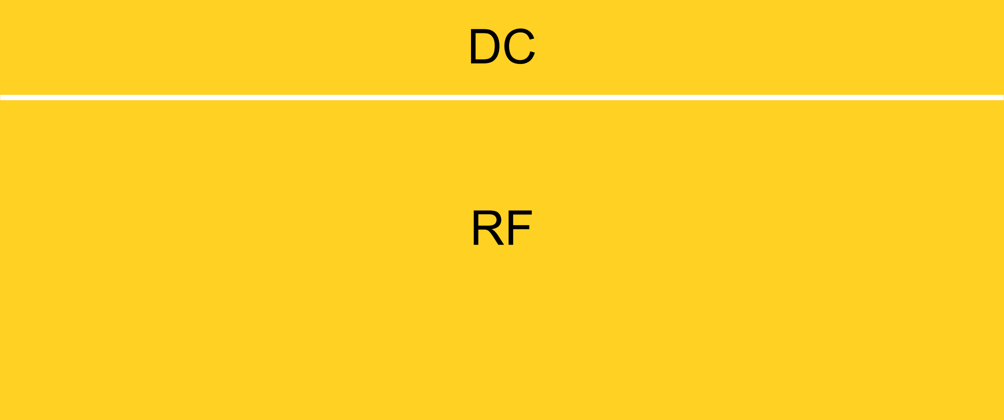


OK !

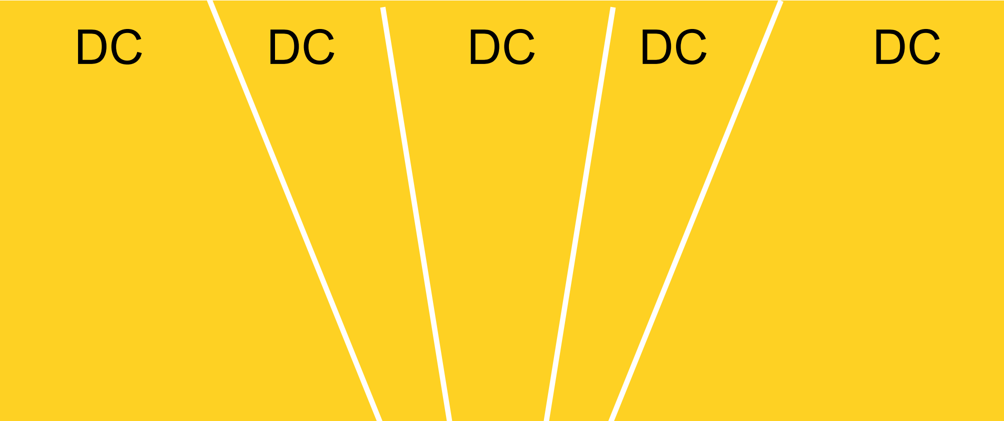
possible Paul trap assembly (parabolic mirror + optical windows)



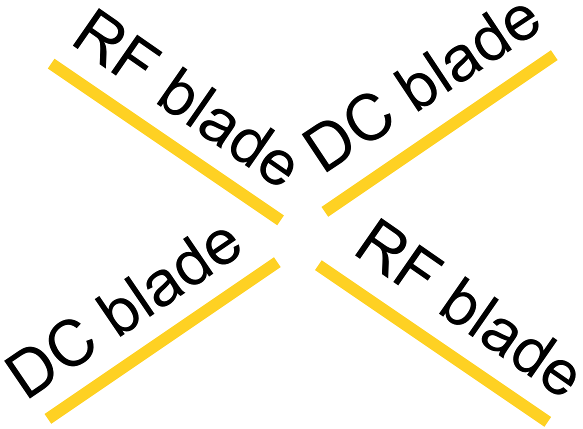
RF blade electrode



DC blade electrode



Mounted electrodes
in a end view:

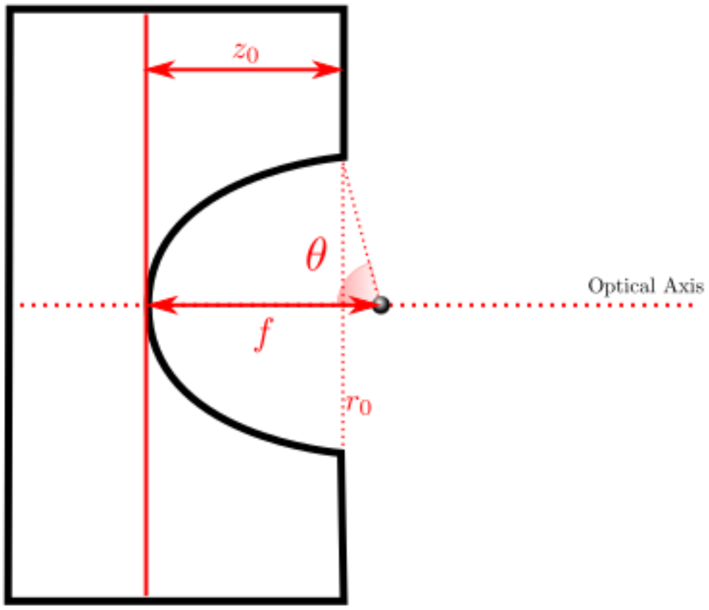


Price: 450 £/blade

Detection

with
Paraboloidal Mirror

Intro to Paraboloidal Mirror



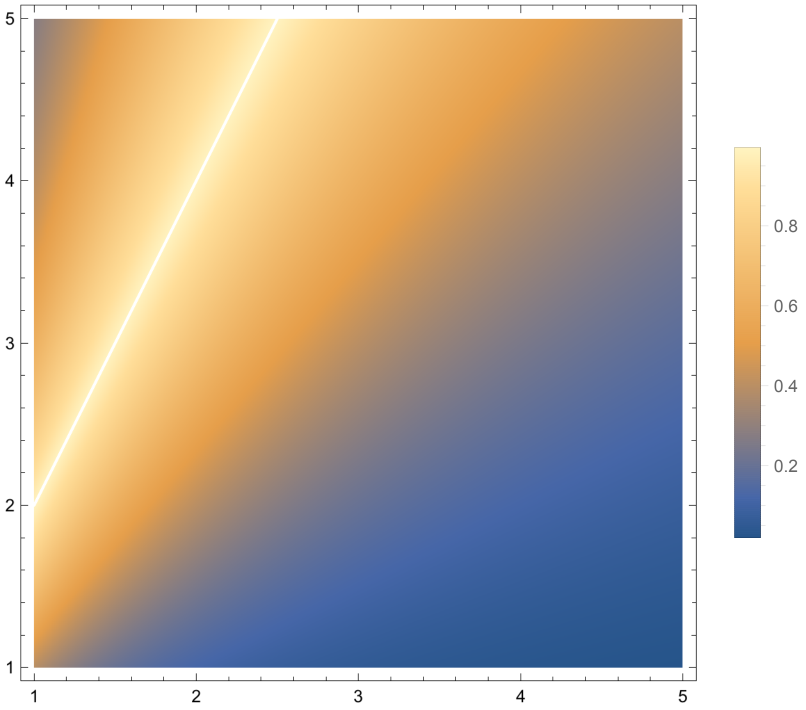
Here r_0 is the radius of curvature, z_0 depth of mirror to the apex, and f is the focal length. The numerical aperture for a lens is defined as:

$$\text{NA} = \int_0^{\theta} \sin(\theta')\, d\theta' = 1 - \cos(\theta)$$
$$= 1 - \cos\left(\tan^{-1}\left(\frac{r_0}{f - \frac{r_0^2}{4 f}}\right)\right)$$

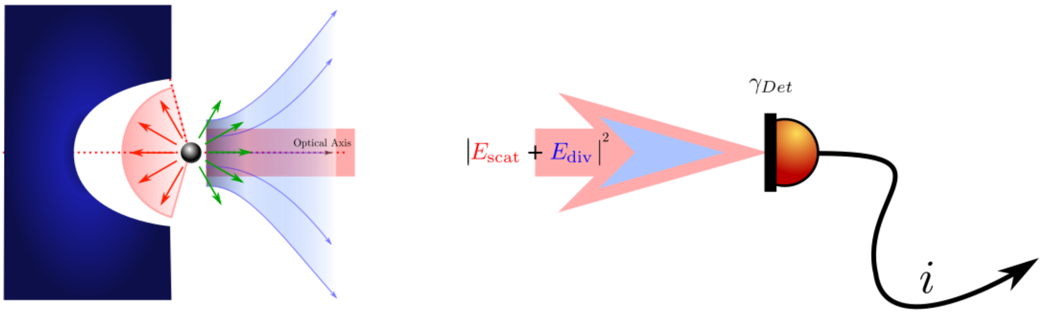
```
NApara[f_, r0_] := 1 - Cos[ArcTan[r0/(f - r0^2/(4 f))]];
```

It is worth noting that the maximum NA of 1 is achieved as $\cos(\theta) \to 0$, $\tan\theta \to \frac{\pi}{2}$, $r_0 \to 2 f$

```
DensityPlot[NApara [f, r0], {f, 1 , 5 },
 {r0, 1, 5}, PlotPoints → 100, PlotLegends → Automatic]
```



Detection At the Detector



We can divide the problem into the following parts:

- How much power is scattered by the particle?
- How much power is collected and then detected at the detector?
- How much scattering force generated by the particle?
- And the limits of detection? i.e. What is the temperature sensitivity based on the position sensitivity?
- What is also the force sensitivity based on the above values?

1. How much power is scattered by the particle?

```
Cnst := {hbar → 1.05 × 10^-34, c → 3 × 10^8, n → 1.45,
  ϵ0 → 8.8 × 10^-12, kB → 1.38 × 10^-23, h → 6.626 × 10^-34}
OurPara := {λ → 1550 × 10^-9, Radius → 50 × 10^-9, Ω → 2 π 1 × 10^3,
  γ → 2 π 269 , f0 -> c / λ, ηc → 0.0005, ω0 → 2 π f0, NA → 0.997,
  ρ → 1800, m → ρ 4 π Radius^3 / 3, k → 2 π / λ, w0 → λ/(π NA), γc → Radius/w0}
NovotnyPara := {λ → 1064 × 10^-9, Ω → 2 π 150 × 10^3, γ → 2 π 269 ,
  f0 -> c / λ, ηc → 0.0005, ω0 → 2 π f0, Radius → 50 × 10^-9,
  NA → 0.9, P0 → 70 × 10^-3, k → ω0/c, m → 1.14 × 10^-18}
TEQpara := {λ → 1550 × 10^-9, Ω → 2 π 1 × 10^3, γ → 2 π 269 ,
  f0 -> c / λ, ηc → 0.0005, ω0 → 2 π f0, Radius → 50 × 10^-9,
  NA → 0.997, k → ω0 / c, m → ρ 4 π Radius^3 / 3, ρ → 1800,
  Γ → 0.619 ((9 π) / Sqrt[2]) ((ηair d^2) / (ρ kB T0)) (Pgas / Radius), Pgas → 100 × 10^-10,
  ηair → 18.2 × 10^-6, d → 0.375 × 10^-9, T0 → 300, w0 → λ/(π NA), γc → Radius/w0}
```

```
(* Polarizability [1]*)
α := 4 π ϵ0 Radius^3 (n^2 - 1) / (n^2 + 2)
(* Rayleigh Cross Section [1]*)
σscat := α^2 k^4/(6 π ϵ0^2)
(* Scatter Power
 The additional parameter γc,
is a ratio of the beam focal waist w0 and the particle radius.
*)
PScat := γc σscat I0
I0 := 2 P0 NA^2 π/λ^2
(* P0 k^2 NA^2/(2 π) *)
```

```
PScat //. Cnst //. TEQpara /. {P0 → 600 × 10^-3}
(*PScat//.Cnst//.NovotnyPara/.{P0→ 100 10^-3,γc→ 1}*)
PScat //. Cnst //. TEQpara /. {P0 → 0.5 × 10^-3}
```

```
4.02284 × 10^-7
```

```
3.35237 × 10^-10
```

Therefore, the trapped particle at the focal region will scatter **400 nW @ P_0 = 600 mW.** Whilst **@ 0.5 mW** of P_0 the scattering is 0.3 **nW**. For a 50 nm radius particle.

2. How much power is collected and then detected at the detector?

The photon scatter once collect reaches the detector through massive amounts of losses. These losses are:

- γ_{para}, collection of the paraboloidal mirror = NA/2
- $N_{\text{optElements}}$, Number of Optical mirrors = 4
- γ_{mirrors}, efficiency of optical silver mirrors = 0.96
- QE, detector quantum efficiency

From which we get the total detection efficiency (we add an additional loss parameter as not all the light is focussed on to the photodetector [2]):

```
QE := (S 1240) / λ (* The Quantum Effiency[3]*)
γTotal := γpara γmirrors^NElements QE (DetectorArea / MirrorDiameter) //.
  {γpara → NA / 2, γmirrors → 0.96 , NElements → 4, S → 1, λ → 1550 ,
   NA → 0.997, DetectorArea → 0.3 × 10^-3, MirrorDiameter → 3 × 10^-3}
(*Note: NEPmin refers to Minimum measured NEP,
Rmax is max responsivity, R is Gain output *)
NEP := (NEPmin Rmax ) / R //. {Rmax → 1, NEPmin → 1.55 × 10^-12, R → 10^5}
NEPAbs := NEP Sqrt[bandwidth] /. bandwidth → 4 × 10^6
OpticalInput := ((1 × 10^-3) / 50) (1 / R) /. R → 10^5

{"Detector Efficiency",
 γTotal //. Cnst //. TEQpara /. {P0 → 0.5 × 10^-3, Impedance → 50}}
{"Pdet", PScat γTotal //. Cnst //. TEQpara /. {P0 → 0.5 × 10^-3, Impedance → 50}}
{"Pscat", PScat //. Cnst //. TEQpara /. {P0 → 0.5 × 10^-3}}
{"OpticalInput with oscilloscope", OpticalInput // N}
{"NEP_bnd", NEPAbs // N}
{"Allowed S/N",
 AllowedSN = (PScat γTotal) / NEPAbs //. Cnst //. TEQpara /. {P0 → 0.5 × 10^-3, Impedance → 50}}
{"Predicted Temp@ 300 K", PredictedTemp = 300 / AllowedSN × 10^3 "mK"}
{"Predicted Temp@ 300 mK", PredictedTemp = 300 × 10^-3 / AllowedSN 10^6 "μK"}
```

```
{Detector Efficiency, 0.0338719}

{"Pdet", 1.3626138112109088`*^-10}

{Pscat, 4.02284 × 10^-9}

{OpticalInput with oscilloscope, 2. × 10^-10}

{NEP_bnd, 3.1 × 10^-14}

{Allowed S/N, 4395.53}
```

```
{Predicted Temp@ 300 K, 68.2512 mK}
```

```
{Predicted Temp@ 300 mK, 68.2512 μK}
```

The detection efficiency seems to be 0.03 compared to *Jain et al* [1] to be 0.0005.

For 500 μW of incident Power:

Detector NEP@λ = 0.015 fW/$\sqrt{\text{Hz}}$
Detector Signal = 0.1 nW
Scattered Signal = 4 nW
NEP@(λ, Bandwidth) = 31 fW

If at signal of 0.1 nW is 300 K then to reach gr bound state at 1 μK a signal drop of factor 10^8 needs to be accommodated. The available S/N is 10^4.

If starting temp is 300 K => 68 mK
if starting temp is 300 mK => 68 μK

$\text{NEP}\ 10^{15}$

```
0.0155
```

The question of how small a signal can our current detectors detect can be characterised by Noise Equivalent Power (NEP). For our case the NEP is 0.01**55 fW/$\sqrt{\text{Hz}}$.**

$3\times10^{-7}/\text{Sqrt}[4\times10^{6}]\ //\ \text{N}$

1.5×10^{-10}

$$\frac{300\times10^{-3}}{\frac{0.1\times10^{-9}}{31\times10^{-15}}}\ //\ \text{N}$$

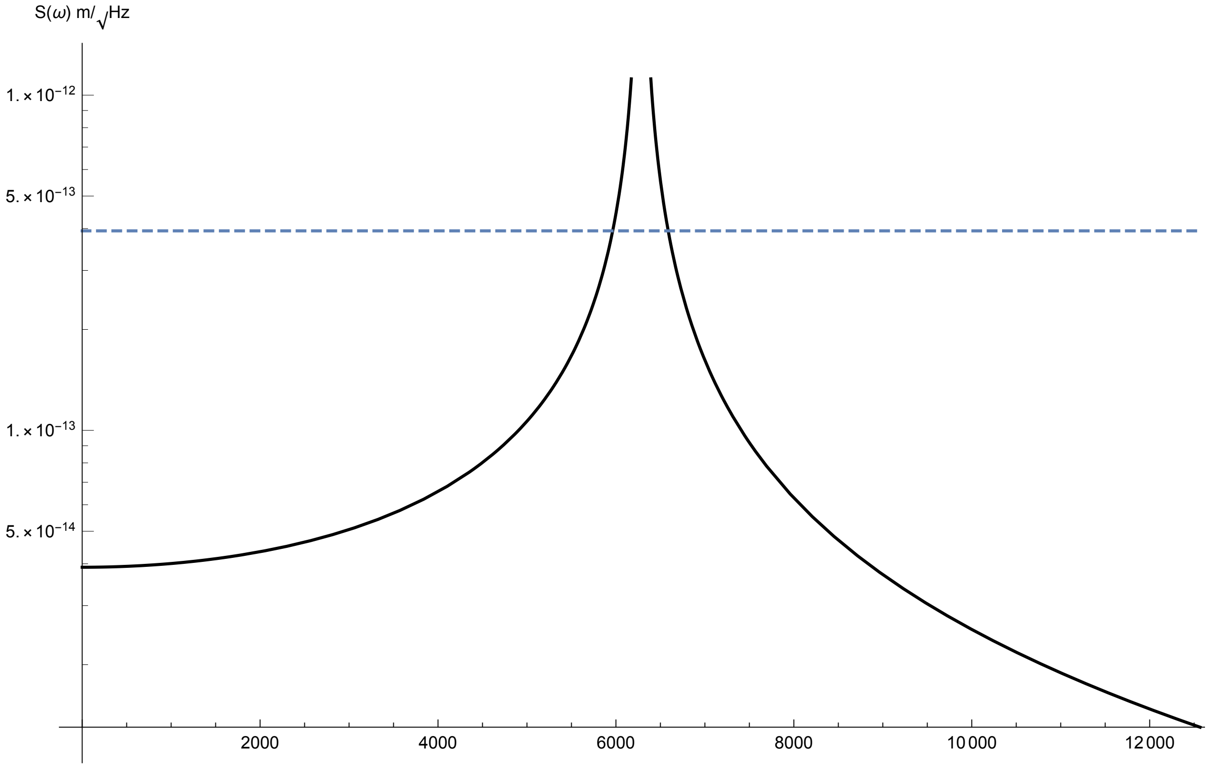
```
0.000093
```

3. Noise Power Spectral Density

```
TEQpara := {λ → 1550 × 10^-9, Ω → 2 π 1 × 10^3, γ → 2 π 1 × 10^-6 ,
   f0 -> c / λ, ηc → 0.0005, ω0 → 2 π f0, Radius → 50 × 10^-9, NA → 0.997,
   P0 → 0.5 × 10^-3, k → ω0 / c, m → ρ 4 π Radius^3 / 3, ρ → 1800,
   Γ → 0.619 ((9 π) / Sqrt[2]) ((ηair d^2) / (ρ kB T0)) (Pgas / Radius),
   Pgas → 100 × 10^-10, ηair → 18.2 × 10^-6, d → 0.375 × 10^-9, T0 → 300} //. Cnst
Γ / (2 π) //. TEQpara //. Cnst
```

```
1.35294 × 10^-7
```

```
Syzp := hbar / (2 π m γ Ω) //. Cnst //. TEQpara //. Cnst;
(* Zero Point Spectral Density *)
SOsci := ((2 kB T) / (π m)) (Γ / ((Ω^2 - ω^2)^2 + (ω Γ)^2)) //. Cnst //. TEQpara //. Cnst //.
   {T → 300 × 10^-3} ;(* Mechanical Motion *)
Sysn := NEP / (10^4)^2(* Detector Noise *)
SyOscN := 1 × 10^-12 / (10^4)^2(* Oscilloscope Noise *)
SyShotNoise :=
  (*Stotal:= SBrown + SOsci + Sthermal;*)
  ScaleFactor = 1;
PlotZP = LogPlot[Sqrt[Syzp] ScaleFactor, {ω, 0, 2 π .2 × 10^4}, PlotStyle → Red];
PlotOsc = LogPlot[Sqrt[SOsci] ScaleFactor, {ω, 0, 2 π .2 × 10^4}, PlotStyle → Black];
(* PlotTotal=
  LogPlot[Sqrt[Stotal]ScaleFactor,{ω,0,2 π 1 10^4}, PlotStyle→Dashed]; *)
PlotSN = LogPlot[Sqrt[Sysn] ScaleFactor, {ω, 0, 2 π .2 × 10^4}, PlotStyle → Dashed];
Show[PlotOsc, PlotZP, PlotSN,
 PlotRange → All,
 PlotPoints → 150, PlotStyle → Medium,
 AxesLabel → {"ω (Hz)", "S(ω) m/√Hz"}, PlotRange → All]
```



```
Sqrt[Sysn]
3.937 × 10^-13
```

```
Sqrt[SOsci //. Cnst //. TEQpara //. Cnst]
```

$$0.0154182 \sqrt{\frac{1}{7.22634\times 10^{-13}\,\omega^2 + \left(4\,000\,000\,\pi^2 - \omega^2\right)^2}}$$

```
(* PlotRange→
 {{2 π 50 10^3,2 π 150 10^3},{Log[Sqrt[1 10^-30]], Log[Sqrt[1 10^-15]]}},*)

 xvar = 1 × 10^-12;
Ekbt = 0.5 kB T //. Cnst //. SotonPara //. T → 300
Eke = 0.5 m Ω^2 xvar^2 //. Cnst //. SotonPara
Tmp = (m Ω^2)/kB xvar^2 //. Cnst //. SotonPara
xv = Sqrt[(kB T)/(m Ω^2)] //. Cnst //. SotonPara //. T → 3 × 10^-3
(*SBrown :=S0/ω^2 //.{gfactor→ 10^5,S0 → 10^-12/gfactor} ;(* Brownian Noise *)
*)(*Sthermal :=( 2 kB Tnoise Γ)/π //.{Tnoise→ 300}//.Cnst//.TEQpara ;
(* Thermal Noise *)*)
(*PlotBrown =
 LogPlot[Sqrt[SBrown ]ScaleFactor,{ω,0,2 π .2 10^4}, PlotStyle→Brown];
PlotThermal= LogPlot[Sqrt[Sthermal]ScaleFactor,
  {ω,0,2 π .2 10^4}, PlotStyle→Orange];*)
```

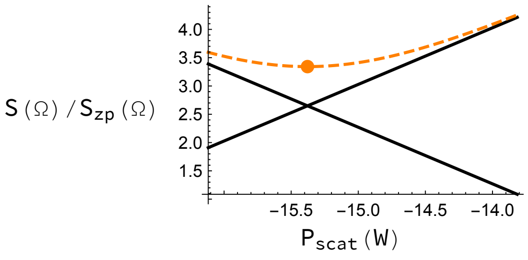
How much power at Backaction and Photon Recoil Limit?

The criteria required for the minimum amount of scattered power required to resolve the system (i.e. overcoming measurement noise/imprecision) whilst limiting the backaction is [1]:

```
Syzp := hbar / (2 π m γ Ω) (* Zero Point Spectral Density *)
Syimprecision := (Syzp / 2) (1 / ηc) ((m c^2 γ Ω) / (2 ω0 Pscat))
(* Measurement Imprecision *)
Sybackaction := (Syzp / 2) (2 / 5) ((2 ω0 Pscat) / (m c^2 γ Ω))
(* Measurement Backaction *)
Syy := Syimprecision + Sybackaction
PScatmin := Sqrt[5 / (8 ηc)] (Ω / ω0) m c^2 γ (*  *)

TEQpara := {λ → 1550 × 10^-9, Ω → 2 π 1 × 10^3, γ → 2 π 269 ,
  f0 -> c / λ, ηc → 0.0005, ω0 → 2 π f0, Radius → 100 × 10^-9,
  NA → 0.997, P0 → 0.5 × 10^-3, k → ω0 / c, m → ρ 4 π Radius^3 / 3, ρ → 1800}

TEQPointX = PScatmin //. TEQpara //. Cnst;
TEQPoint = Log[Syy / Syzp //. TEQpara //. Cnst /. {Pscat → TEQPointX}];
plotImp = LogLogPlot[Syimprecision / Syzp //. TEQpara //. Cnst,
   {Pscat, 1 × 10^-7, 1 × 10^-6}, PlotStyle → Black];
PlotBack = LogLogPlot[Sybackaction / Syzp //. TEQpara //. Cnst,
   {Pscat, 1 × 10^-7, 1 × 10^-6}, PlotStyle → Black];
PlotSyyTEQ = LogLogPlot[Syy / Syzp //. TEQpara //. Cnst,
   {Pscat, 1 × 10^-7, 1 × 10^-6}, PlotStyle → {Dashed, Orange}];
teqP = Graphics[{PointSize[Large], Orange, Point[{Log[TEQPointX], TEQPoint}]}];
Labeled[Show[plotImp, PlotBack, PlotSyyTEQ, teqP, PlotRange → All],
 {"Pscat (W)", "S(Ω)/Szp(Ω)"}, {Bottom, Left}]
```



Whilst noting that the scattering power is also dependant upon the incident laser power given by:

```
(*JainPointX = PScatmin//.NovotnyPara//.Cnst;
SotonPointX = PScatmin//.SotonPara//.Cnst;*)
(*JainPoint =Log[Syy/Syzp//.NovotnyPara//.Cnst/.{Pscat→ JainPointX}];
SotonPoint = Log[Syy/Syzp//.SotonPara//.Cnst/.{Pscat→ SotonPointX}];*)
(*PlotSyy=
 LogLogPlot[Syy/Syzp//.NovotnyPara//.Cnst, {Pscat,1 10^-7,1 10^-4},PlotStyle→Red];
PlotSyySoton=LogLogPlot[Syy/Syzp//.SotonPara//.Cnst,
   {Pscat,1 10^-7,1 10^-4},PlotStyle→Dashed];*)
(*PlotSyy=LogLogPlot[Syy/Syzp//.NovotnyPara//.Cnst,
   {Pscat,1 10^-7,1 10^-4},PlotStyle→Red];
g=Graphics[{PointSize[Large],Red,Point[{Log[JainPointX],JainPoint}]}];
s=Graphics[{PointSize[Large],Blue,Point[{Log[SotonPointX],SotonPoint}]}];*)
```

Power absorbed/Scattered

```
ϵ = 2;
(*(*ϵi*) = 2 ϵ ; (* for 1550nm *)*)
ϵi = 2 ϵ 2.5 × 10^-8; (*n=2+i 2.5 10^-8 *)
ϵr = ϵ - ⅈ ϵi;
```

$$\mathtt{I0} := \frac{\mathtt{P0}\, k^2\, \mathtt{NA}^2}{2\,\pi}$$

```
PScat := σscat I0
```

$$\sigma\mathtt{scat} := \frac{\alpha^2\, k^4}{6\,\pi\,\epsilon 0^2}$$

$$\alpha := \left(4\,\pi\,\epsilon 0\ \mathtt{Radius}^3 \left(n^2 - 1\right) \big/ \left(n^2 + 2\right)\right)$$

$$\mathtt{Pabs} := 12\,\pi\,\frac{\mathtt{I0}}{\lambda}\left(\frac{4\,\pi\,\mathtt{Radius}^3}{3}\right)\mathtt{Im}\left[\frac{\epsilon + ⅈ\,\epsilon i - 1}{\epsilon + ⅈ\,\epsilon i + 2}\right]$$

```
SotonPara :=
 {λ → 1550 × 10^-9, f0 -> c / λ, ω0 → 2 π f0, NA → 0.997, P0 → 0.1 × 10^-3, k → ω0 / c}
CavityPara := {λ → 1064 × 10^-9, f0 -> c / λ,
  ω0 → 2 π f0, NA → 0.997, P0 → 0.5 × 10^-3, k → ω0 / c}
PScat
Pabs
```

$$\frac{4\,k^6\left(-1 + n^2\right)^2 \mathtt{NA}^2\ \mathtt{P0}\ \mathtt{Radius}^6}{3\left(2 + n^2\right)^2}$$

$$\frac{4.71239 \times 10^{-7}\ k^2\ \mathtt{NA}^2\ \mathtt{P0}\ \mathtt{Radius}^3}{\lambda}$$

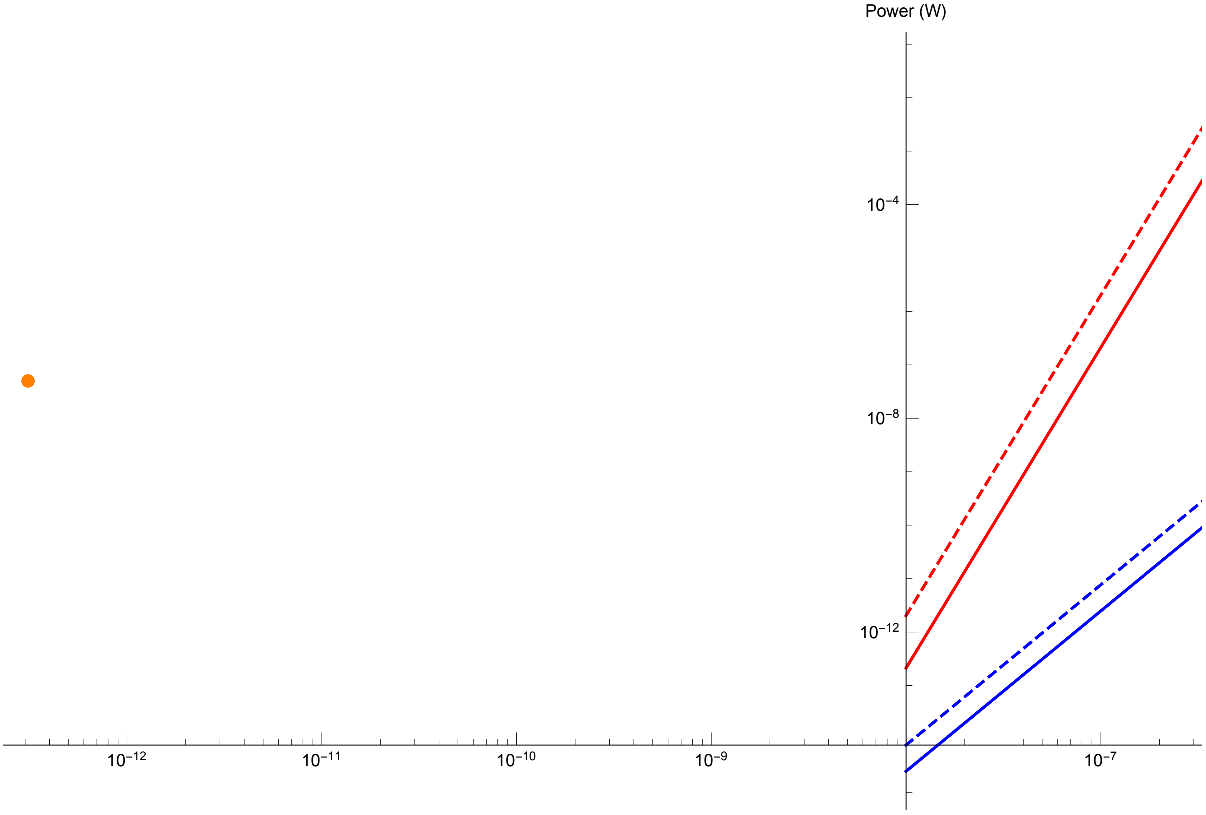
$$\frac{4\,k^6\left(-1 + n^2\right)^2 \mathtt{NA}^2\ \mathtt{P0}\ \mathtt{Radius}^6}{3\left(2 + n^2\right)^2}$$

$$\frac{4\,k^6\left(-1 + n^2\right)^2 \mathtt{NA}^2\ \mathtt{P0}\ \mathtt{Radius}^6}{3\left(2 + n^2\right)^2}$$

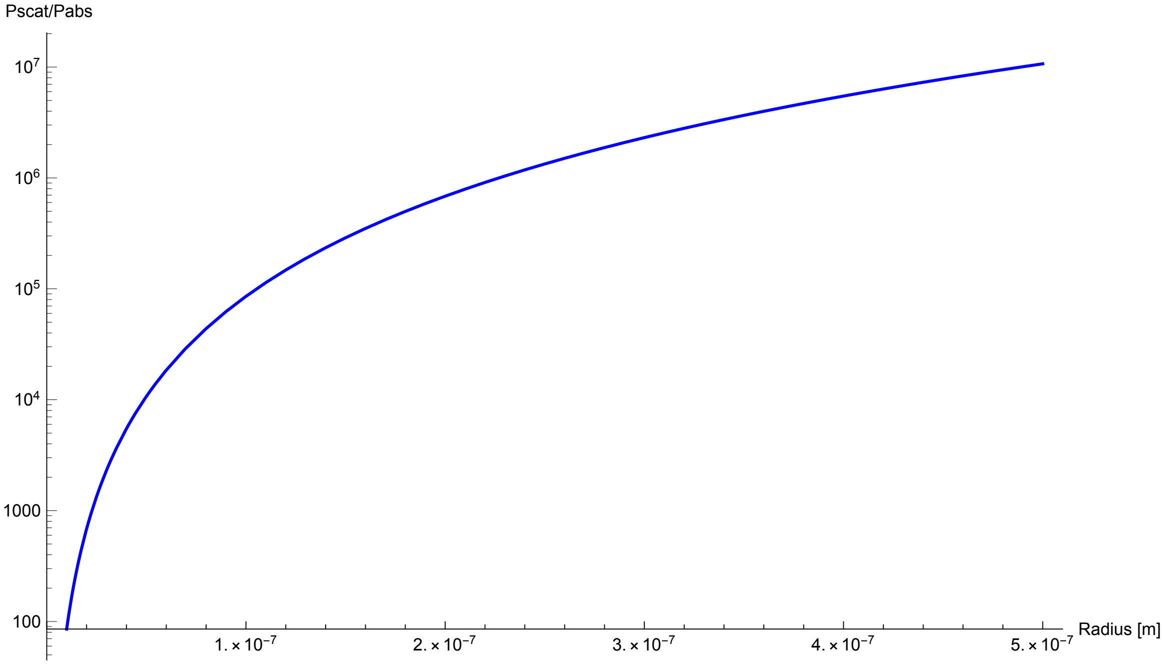
```
Pabs //. Cnst //. SotonPara /. {Radius → 50 × 10^-9}
```

$$6.20735 \times 10^{-14}$$

```
CavityAbs = LogLogPlot[Pabs //. Cnst //. CavityPara,
   {Radius, 10 × 10^-9, 500 × 10^-9}, PlotStyle → {Dashed, Blue}];
CavityScat = LogLogPlot[PScat //. Cnst //. CavityPara,
   {Radius, 10 × 10^-9, 500 × 10^-9}, PlotStyle → {Dashed, Red}];
ParaAbs = LogLogPlot[Pabs //. Cnst //. SotonPara,
   {Radius, 10 × 10^-9, 500 × 10^-9}, PlotStyle → {Blue}];
ParaScat = LogLogPlot[PScat //. Cnst //. SotonPara,
   {Radius, 10 × 10^-9, 500 × 10^-9}, PlotStyle → {Red}];
teqP = Graphics[{PointSize[Large], Orange, Point[
     {Log[Pabs //. Cnst //. SotonPara /. {Radius → 50 × 10^-9}], Log[50 × 10^-9]}]}];
Show[CavityAbs, CavityScat, ParaAbs, ParaScat, teqP, PlotRange → All,
 AxesLabel → {"Radius (m)", "Power (W)"}, PlotStyle → Large]
```



```
LogPlot[PScat/Pabs /. Cnst //. SotonPara, {Radius, 10 × 10^-9, 500 × 10^-9},
 PlotStyle → {Blue}, AxesLabel → {"Radius [m]", " Pscat/Pabs"}]
```



Thermal Force Noise

```
Fnoise := Sqrt[(4 kB T m Ω)/Q]
```

```
TEQpara := {λ → 1550 × 10^-9, Ω → 2 π 1 × 10^3, f0 -> c / λ, ηc → 0.0005, ω0 → 2 π f0,
    Radius → 50 × 10^-9, NA → 0.997, k → ω0 / c, m → ρ 4 π Radius^3 / 3,
    ρ → 1800, Γ → 0.619 ((9 π) / Sqrt[2]) ((ηair d^2) / (ρ kB T0)) (Pgas / Radius),
    Pgas → 100 × 10^-10, ηair → 18.2 × 10^-6, d → 0.375 × 10^-9,
    T0 → 300, w0 → λ/(π NA), γc → Radius/w0} //. Cnst
```

```
Fnoise //. {T → 300 × 10^-3, Q → Ω/Γ} //. TEQpara //. Cnst
```

```
3.64246 × 10^-24
```

Incident Power

The σ_{scat} is the scattering cross - section due to Rayleigh scatter and I_0 the incident laser intensity determined by P_0 the incident laser power and numerical aperture (NA).

The equation that tells us the detection laser power required to satisfy the condition of being able to reach ground state can be described by:

$$P_{\text{inc}} = \left(\left(3 \times \sqrt{10}\, \pi\, \gamma\, m\, c^2\, \epsilon_0{}^2\right) / \left(k^6\, \text{NA}^2\, \alpha^2\right)\right) \frac{\Omega}{\omega 0} \sqrt{\frac{1}{\eta_c}}$$

where α is the polarizability of the particle, Ω the oscillator frequency and $\omega 0$ the frequency of light, and η_c is the detector efficiency. γ is the total damping due to feedback + radiation pressure + gas collision.

Key Parameters

```
Cnst := {hbar → 1.05 × 10^-34, c → 3 × 10^8, n → 1.45, ϵ0 → 8.8 × 10^-12, kB → 1.38 × 10^-23}
NovotnyPara := {λ → 1064 × 10^-9, Ω → 2 π 150 × 10^3, γ → 2 π 269 , f0 -> c / λ, ηc → 1,
  ω0 → 2 π f0, Radius → 50 × 10^-9, NA → 0.9, P0 → 70 × 10^-3, k → ω0/c, m → 1.14 × 10^-18}
OurPara := {λ → 1550 × 10^-9, Radius → 100 × 10^-9, Ω → 2 π 1 × 10^3,
  γ → 2 π 269 , f0 -> c / λ, ηc → 0.0005, ω0 → 2 π f0,
  NA → 0.997, ρ → 1800, m → ρ 4 π Radius^3 / 3, k → ω0 / c}
```

Pinc :=
$$\frac{3\sqrt{\frac{5}{2}}\,c^2\,m\,\left(2+n^2\right)^2\,\gamma\,\sqrt{\frac{1}{\eta c}}\,\Omega}{8\,k^6\,\left(-1+n^2\right)^2\,NA^2\,Radius^6\,\omega 0}$$

```
Pinc 1 × 10^3 mW //. NovotnyPara //. Cnst
Pinc 1 × 10^3 mW //. OurPara //. Cnst
```

```
1.41123 mW
```

```
0.493314 mW
```

From the above it is apparent that for Novotny’s case he requires roughly 70 mW to reach this regime, whilst changing the NA and wavelength of light allows you to use greater power of 117 mW of laser power.

Ratio of Scatter Force and Photon Recoil

If you have a particle in a trap that scatters a certain amount of power, evidently the incident light will impart a Photon pressure on the particle. What is the strength of this force acting on the particle.

$$\texttt{OpticalParameters} := \left\{\texttt{w0} \to \frac{\lambda}{\pi\,\texttt{NA}},\ \texttt{zR} \to \frac{\pi\,\texttt{w0}^2}{\lambda},\ \texttt{I0} \to \frac{2\,\texttt{P0}}{\pi\,\texttt{w0}^2}\right\}$$

$$\texttt{w[z\_]} := \texttt{w0}\ \texttt{Sqrt}\left[1 + \left(\frac{\texttt{z}}{\texttt{zR}}\right)^2\right]$$

$$\texttt{R[z\_]} := \texttt{z}\ \left[1 + \left(\frac{\texttt{zR}}{\texttt{z}}\right)^2\right]$$

$$\texttt{Intensity} := \texttt{I0}\left(\frac{\texttt{w0}}{\texttt{w[z]}}\right)^2 \texttt{Exp}\left[\frac{-2\,\texttt{r}^2}{\texttt{w[z]}^2}\right]$$

```
(*The use of n2 is dependant on the material. Change
 this if you change the particle or the wavelenth of light*)
```

$$\texttt{Fscat} := \frac{128\,\pi^5\,\texttt{n1}\,\texttt{a}^6}{3\,\texttt{c}\,\lambda^4}\left(\frac{\texttt{m}^2-1}{\texttt{m}^2+2}\right)^2 \texttt{Intensity //. \{z} \to \texttt{0, r} \to \texttt{0, a} \to \texttt{Radius, n1} \to \texttt{1\} //. OpticalParameters //. Cnst}$$

The final form of the scattering force can be written as:
$F_{\text{scat}} = 2.7 \times 10^{-4}\, n_1 \frac{(m^2-1)^2}{(m^2+1)^2} \frac{\text{NA}^2 P_0}{\lambda^6} \text{Radius}^6$
where $m = \frac{n_2}{n_1}$with n_1 and n_2 are the refractive indices of the environment (air) and the particle (silica). NA is the numerical aperture, λ is the wavelength of light and $P_0$is the incident power.

In this case, if we consider the incident $P_0 = P_{\text{inc}}$then we can work out the scattering force imparted on the particle:

$10\text{x}10^{-9}$ nm	$25\text{x}10^{-9}$ nm	$50\text{x}10^{-9}$ nm	$100\text{x}10^{-9}$ nm	$200\text{x}10^{-9}$ nm
0 4.90046×10^{-6} fN 0.000490046 fN 0.00245023 fN	0 0.0011964 fN 0.11964 fN 0.598201 fN	0 0.0765697 fN 7.65697 fN 38.2848 fN	0 4.90046 fN 490.046 fN 2450.23 fN	0 313.629 fN 31 362.9 fN 156 815. fN

The rows refer to the power P_0 at 0, 1 mW, 100 mW, 500 mW and the numbers in the table refer to

```
TEQpara := {λ → 1550 × 10^-9, Ω → 2 π 1 × 10^3, γ → 2 π 269 ,
  f0 -> c / λ, ηc → 0.0005, ω0 → 2 π f0, Radius → 50 × 10^-9, NA → 0.997,
  P0 → 0.5 × 10^-3, k → ω0 / c, m → ρ 4 π Radius^3 / 3, ρ → 1800,
  Γ → 0.619 ((9 π) / Sqrt[2]) ((ηair d^2) / (ρ kB T0)) (Pgas / Radius),
  Pgas → 100 × 10^-10, ηair → 18.2 × 10^-6, d → 0.375 × 10^-9, T0 → 300}
```

```
Grid[Table[Fscat 1 × 10^15 fN //. TEQpara,
  {P0, {1 × 10^-6, 500 × 10^-6, 1 × 10^-3}}, {Radius, {50 × 10^-9, 200 × 10^-9}}], Frame → All]
```

0.0000765697 fN	0.313629 fN
0.0382848 fN	156.815 fN
0.0765697 fN	313.629 fN

```
Insert[ReplacePart[Grid[{{0.0000765697 fN, 0.313629 fN},
    {0.0382848 fN, 156.815 fN}, {0.0765697 fN, 313.629 fN}}, Frame → All],
  1 → Prepend[First[Grid[{{"1 μW", 0.0000765697 fN, 0.313629 fN},
       {"500 μW", 0.0382848 fN, 156.815 fN}, {"1 mW", 0.0765697 fN, 313.629 fN}},
      Frame → All]], {"P0", "50 nm", "200 nm"}]],
 {Background → {None, {GrayLevel[0.7], {White}}},
  Dividers → {Black, {2 → Black}}, Frame → True,
  Spacings → {2, {2, {0.7}, 2}}}, 2]
```

P_0	50 nm	200 nm
1 μW	0.0000765697 fN	0.313629 fN
500 μW	0.0382848 fN	156.815 fN
1 mW	0.0765697 fN	313.629 fN

Paul Trap

The **Paul trap** potential can be given by the following equation:

$U_{\mathrm{ion}} = \frac{1}{2} m\, \omega_{\mathrm{ion}}^2\, r_e^2$

where m is the mass of the particle, ω_{ion} the angular frequency of oscillation, r_e the distance between the electrodes. Alternatively the force for a quadrupole ion trap is given by:

$F_{\mathrm{ion}} = -\frac{2e}{d_0}\left(V_{\mathrm{dc}} + V_{\mathrm{rf}} \operatorname{Cos}(\omega_{\mathrm{ion}}\, t)\right) x$

where e, is the electric charge, d_0 a size parameter constant, V_{dc} and $V_{\mathrm{rf}}$are the voltages of the applied DC and RF fields, whilst $\omega_{\mathrm{ion}}$is the driving frequency of the RF applied along the x direction of the system.

```
IonPara := {re → 500 × 10^-6, ωion → 2 π 1 × 10^3}
U := 1/2 m ωion^2 re^2
Fion := - (2 e)/d0 (Vdc + Vrf Cos[ωIon t])
U / kB T //. IonPara //. OurPara //. Cnst /. T → 300 // N
3.41238 × 10^8
```

References

[1] Jain, V., Gieseler, J., Moritz, C., Dellago, C., Quidant, R.and Novotny, L., 2016. Direct measurement of photon recoil from a levitated nanoparticle.Physical review letters, 116 (24), p .243601.
[2] PDB450C(-AC) https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=5201
[3] https://www.hamamatsu.com/resources/pdf/ssd/ingaas_kird0005e.pdf

Status of the LNF activities on electronics

TEQ MEETING

Southampton, June 22 2018

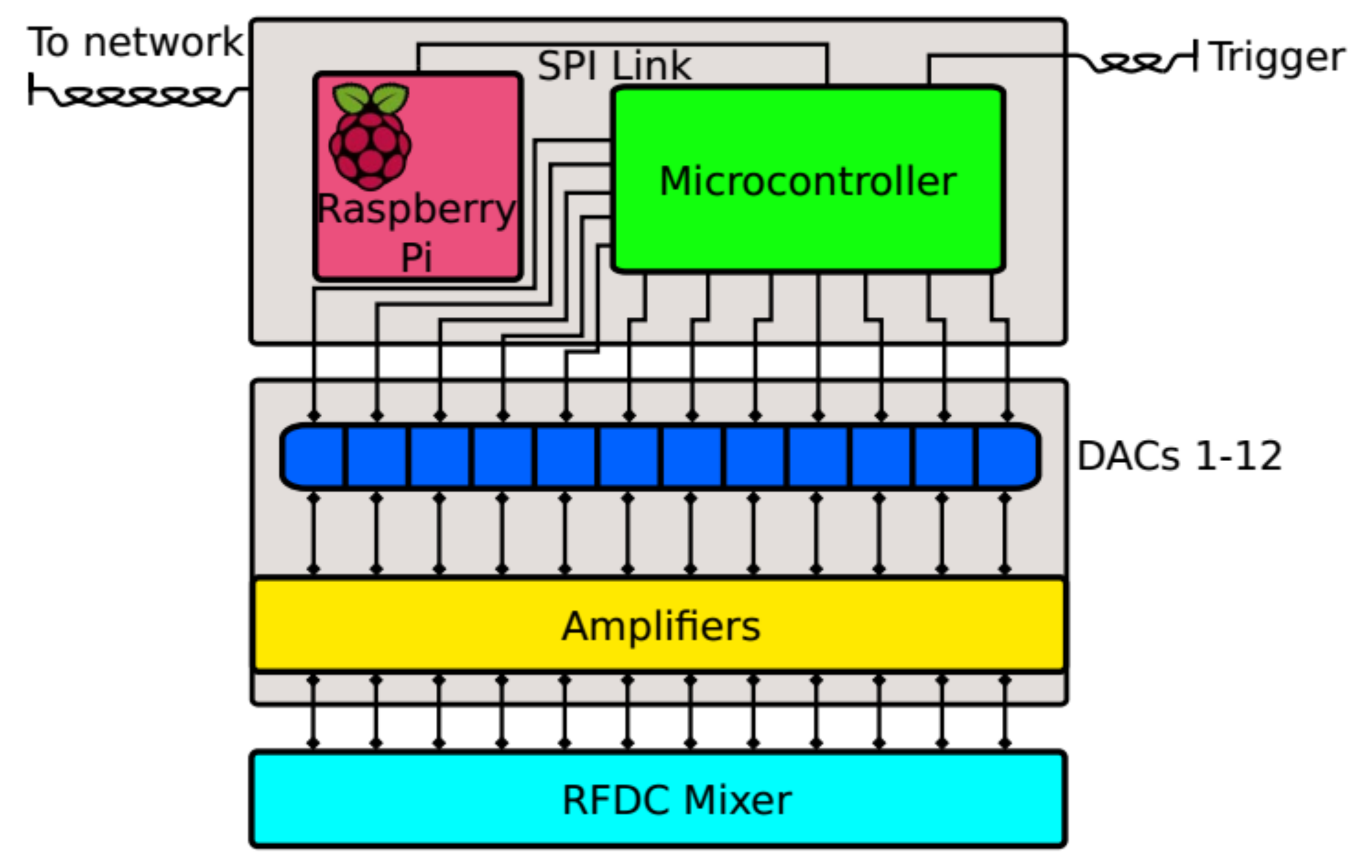
Power Supply Requirements

Due to its ambitious finality, the Particle Trap Power Supply must respond to the following specifics:

- Max amplitude 50V
- Typical Bandwidth 10kHz
- Maximum output Noise 22nV/√Hz

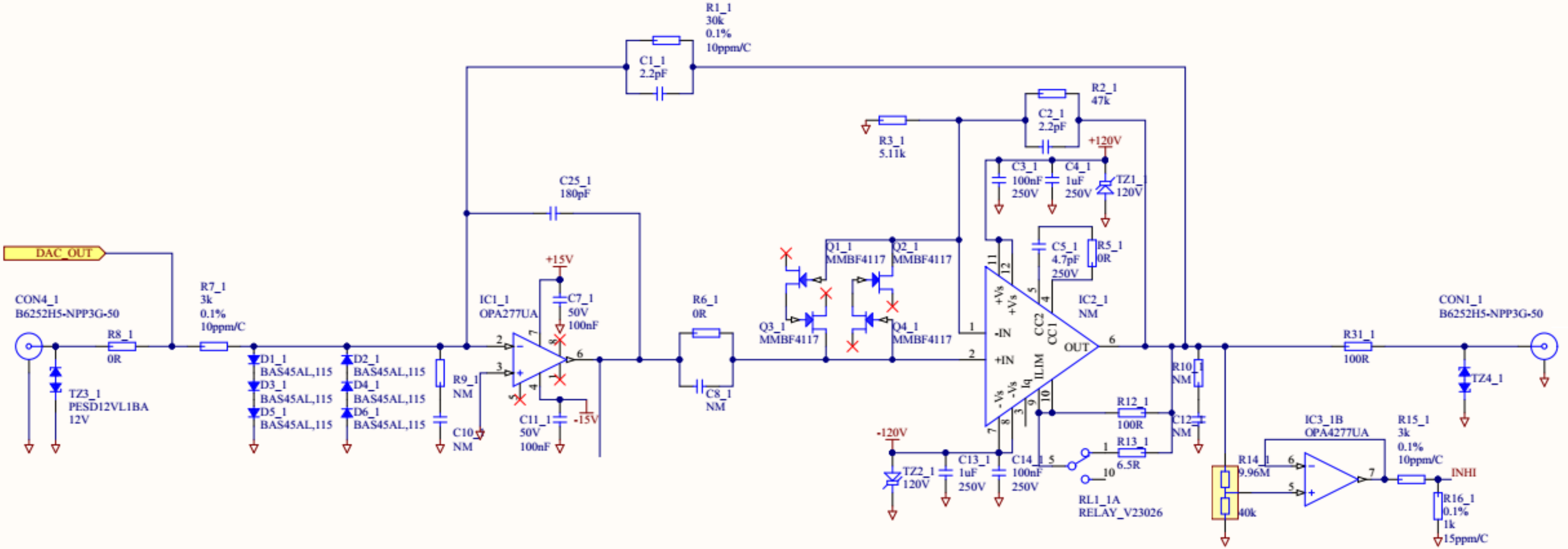
Ⓥ $\boxed{S_V^{DC}(\omega) \lesssim 5 \cdot 10^{-16} \; V^2/Hz \quad @^{\omega = 100 - 1000 Hz} \text{ AND } V_{DC} = 50V}$

Current Power Supply Apparatus



- Raspberry π *microcontroller*
- AD5791 DAC
- Custom HV amplifier
- RF DC Mixer

Amplifier Schematic



Power Supply Requirements

Current design has been thoroughly reviewed to check if specifics were respected.

DC GAIN = 10 OK

Bandwidth = 300kHz OK

NOISE…

Among all specifics, noise is indeed the most critical.

Amplifier NOISE analysis

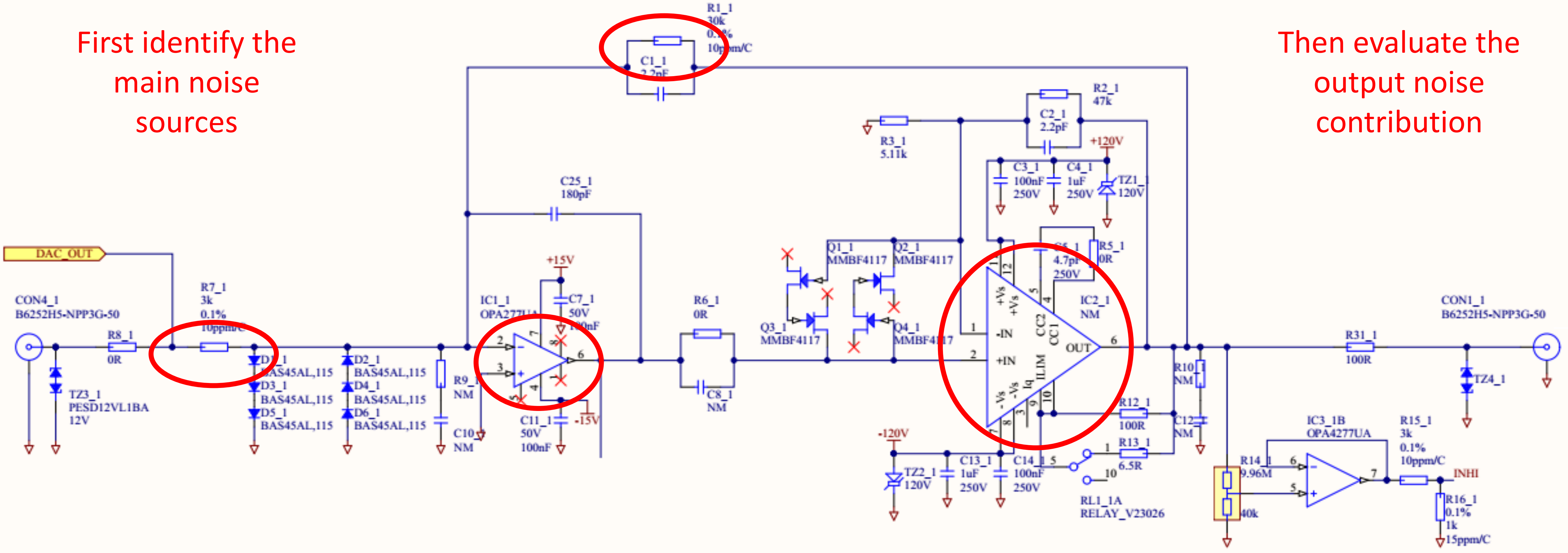
NOISE analysis include:

- Identify the main sources of noise
- Calculate Noise GAIN for each source
- Output Noise Estimation for each source
- Quadratic Sum of all Noise contibution

Amplifier NOISE analysis

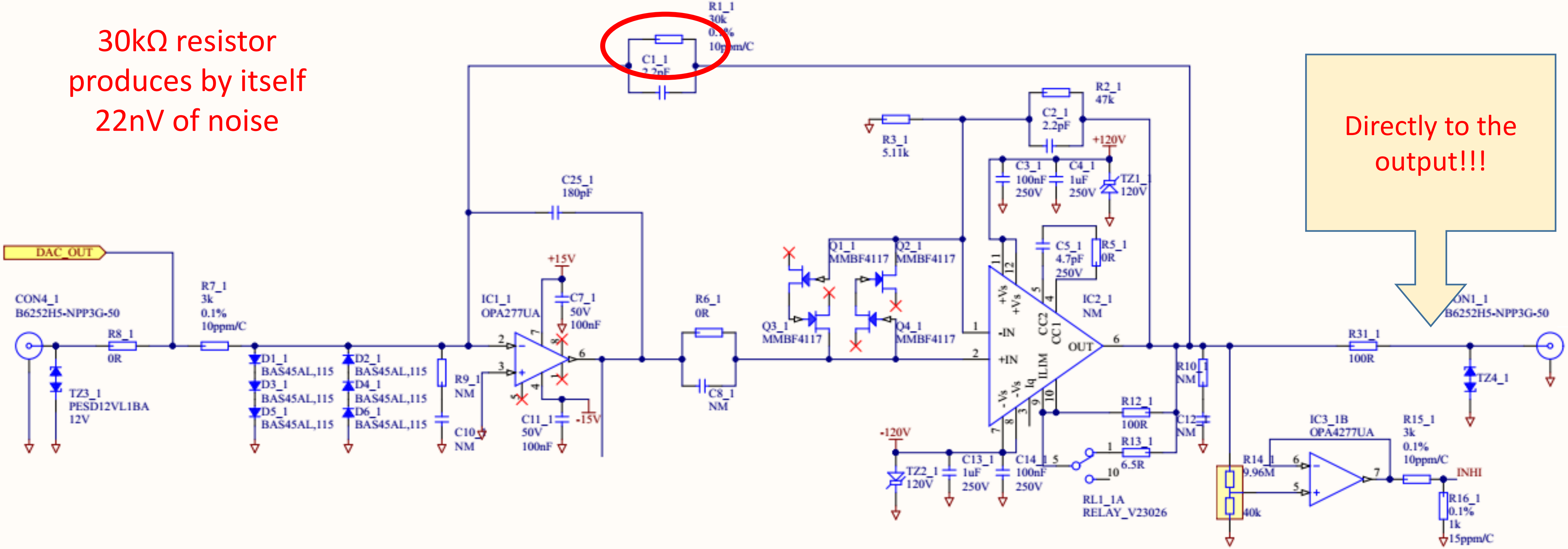
First identify the main noise sources

Then evaluate the output noise contribution



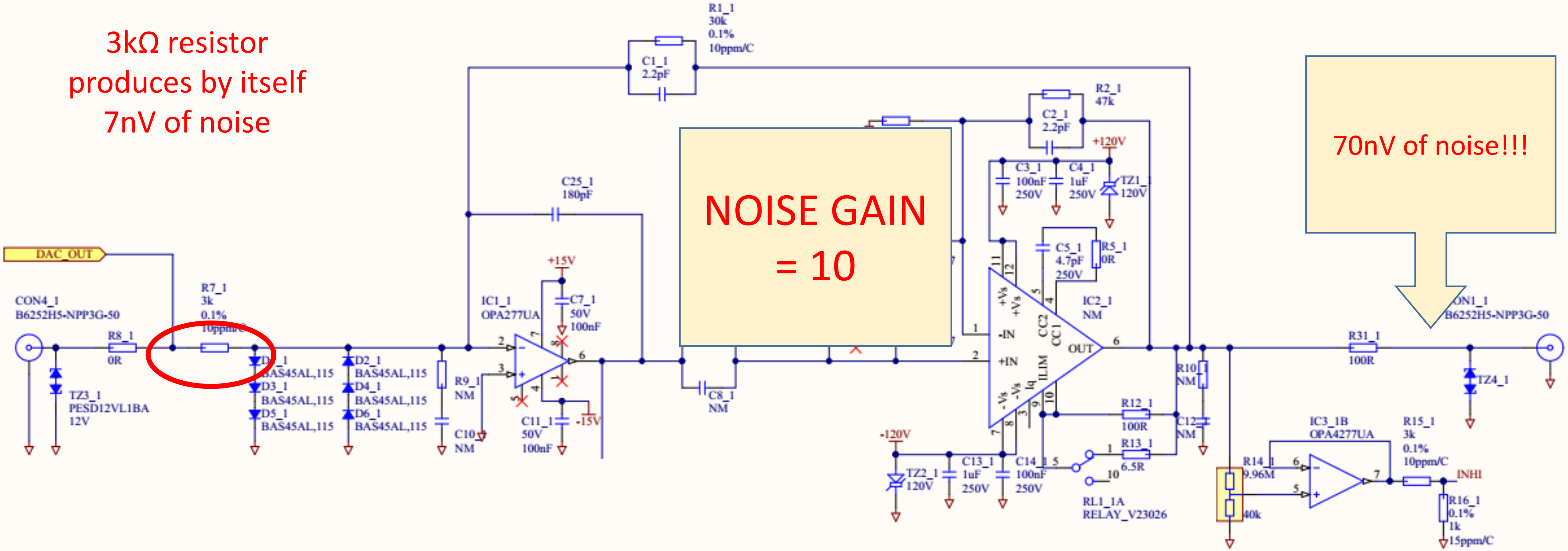
Amplifier NOISE analysis

30kΩ resistor produces by itself 22nV of noise



Directly to the output!!!

Amplifier NOISE analysis

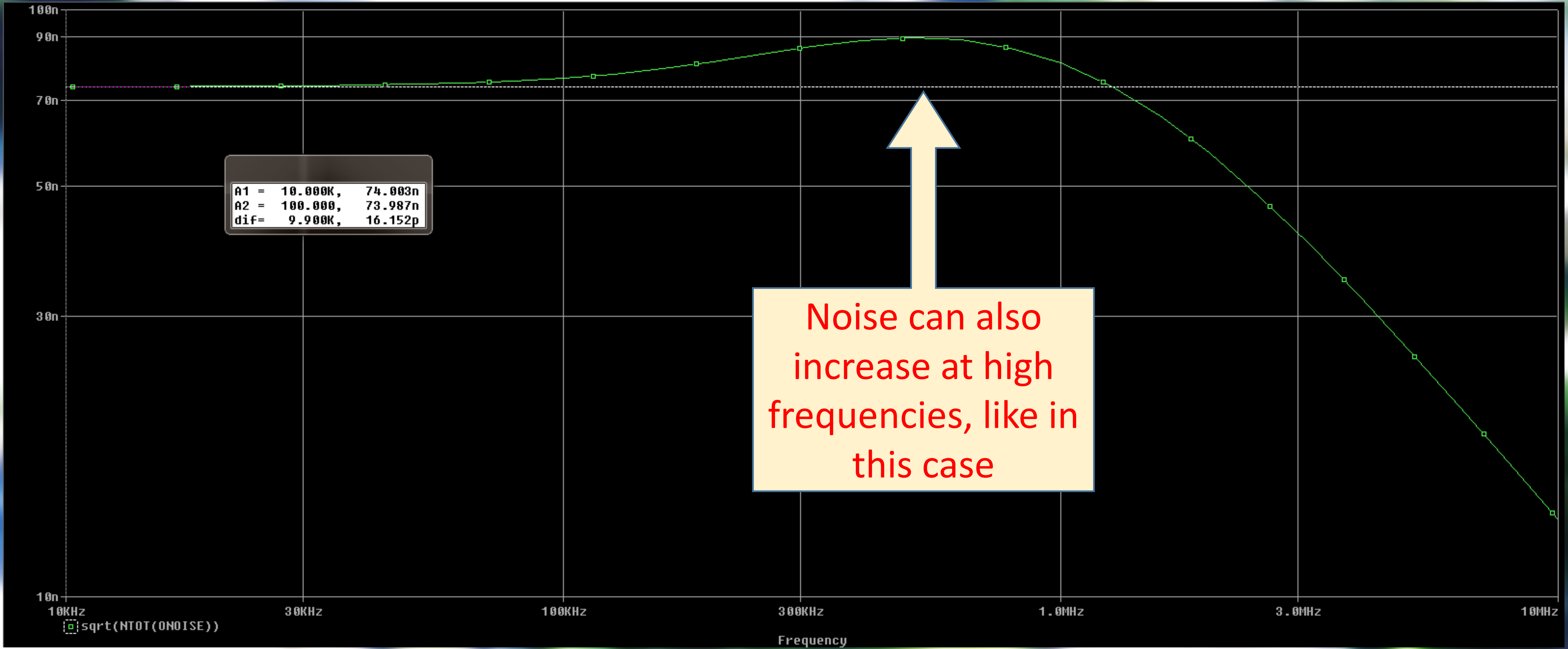


3kΩ resistor
produces by itself
7nV of noise

NOISE GAIN
= 10

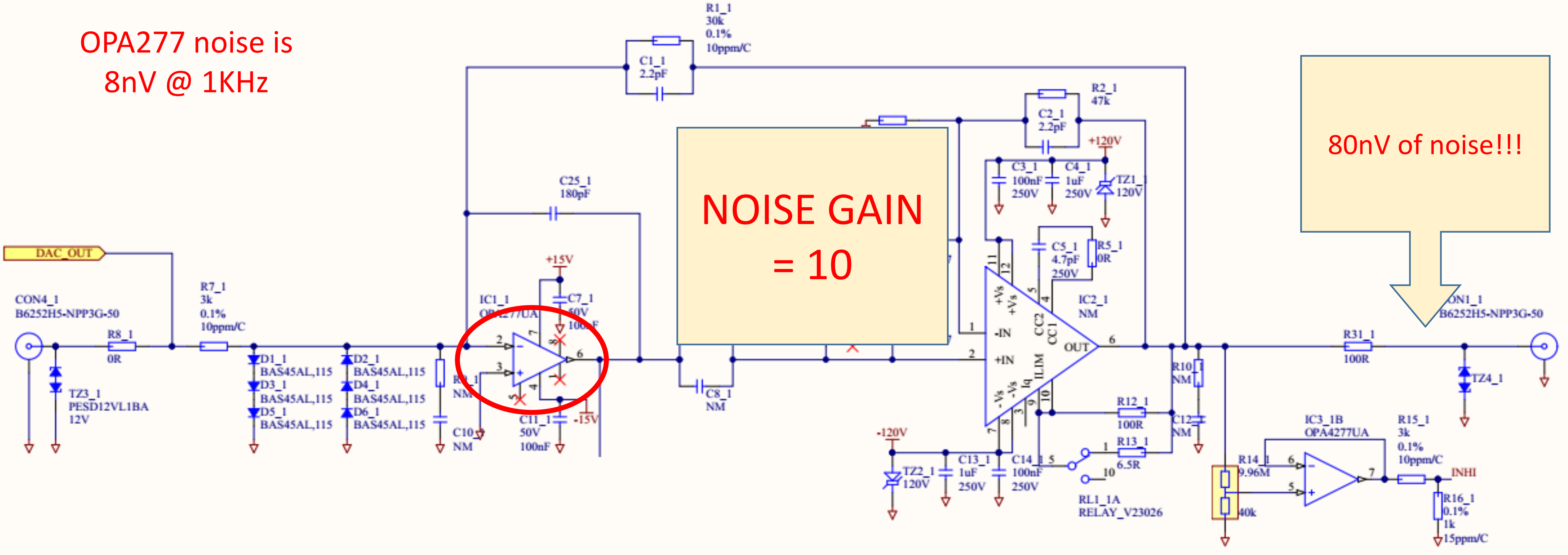
70nV of noise!!!

Amplifier NOISE analysis



Noise can also increase at high frequencies, like in this case

Amplifier NOISE analysis

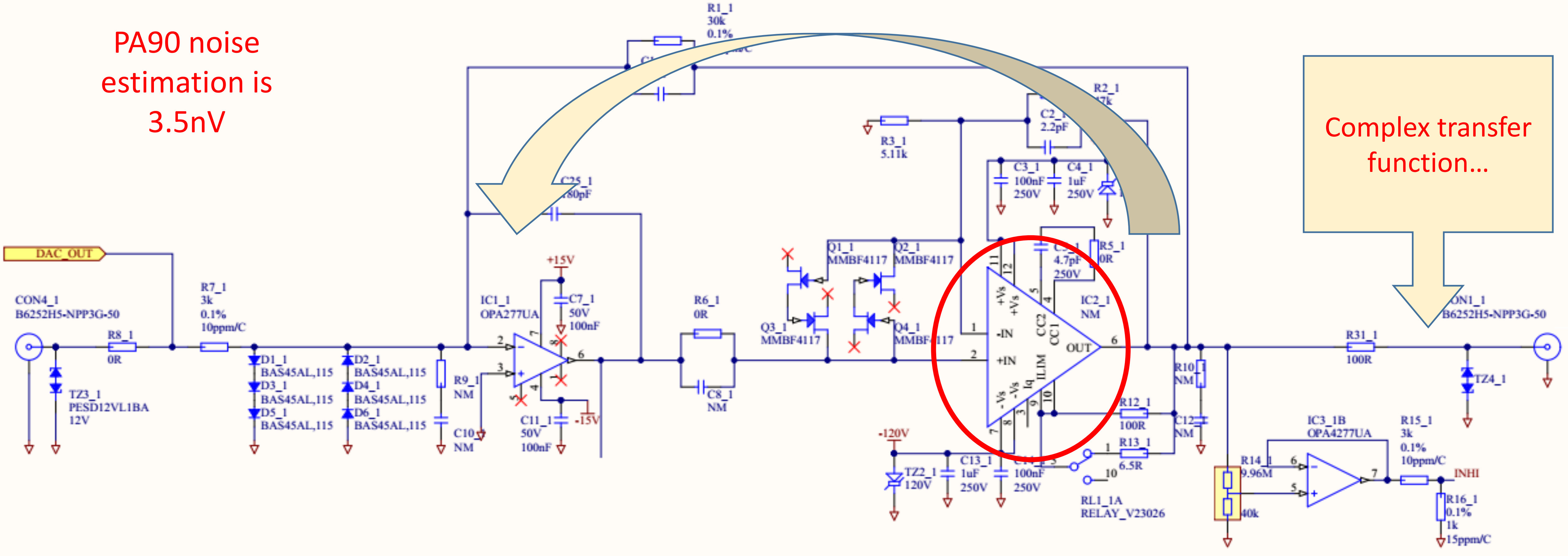


OPA277 noise is
8nV @ 1KHz

NOISE GAIN
= 10

80nV of noise!!!

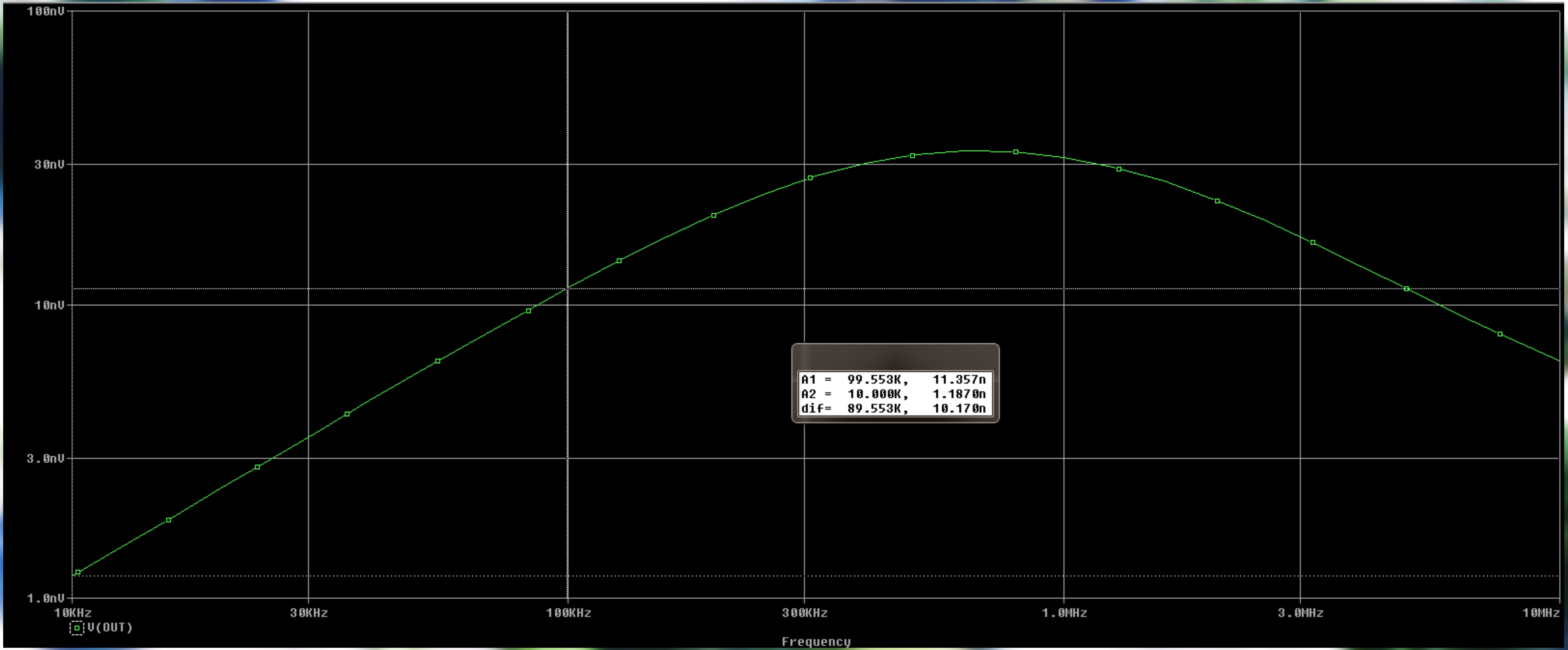
Amplifier NOISE analysis



PA90 noise estimation is 3.5nV

Complex transfer function…

Amplifier NOISE analysis



```
A1 =   99.553K,    11.357n
A2 =   10.000K,    1.1870n
dif=   89.553K,    10.170n
```

Power Supply Requirements

Current design has been thoroughly reviewed to check if specifics were respected.

DC GAIN = 10	OK
Bandwidth = 300kHz	OK
TOTAL NOISE	MORE THAN 100nV/√Hz!

BUT WE CAN SOLVE!

Power Supply Adjustements

Current design can be salvaged with a few expedients:

- Reduce resistor values, maintaining DC Gain
- Increase capacitor values, maintaining time constants
- Replace OPA277 with a low noise amplifier
- Place on the output an additional Low Pass Filter at desired BW

Power Supply Adjustements

Possible solution is to replace:

- R1=1K R7=100R R2=10K R2=1K C1=68pF C2=10pF
- OPA277 with LT6018 (same package, 1nV of noise)
- Add 100kHz low pass filter

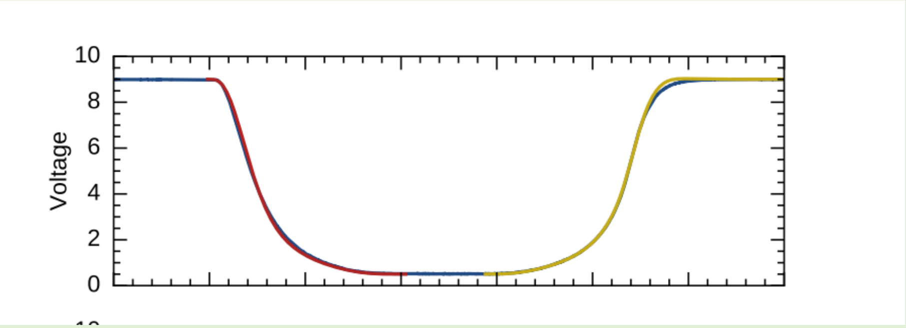
Result is…

15nV/√Hz of noise!

But still we are not considering the signal source…

SIGNAL SOURCE (DAC)

In the current application a "bath curve" dynamics is required



- Signal source is AD5791 DAC
- From datasheet its noise is 7.5nV/√Hz
- By using this source the output noise would be 75nV/√H at least!
- The maximum source noise allowed is 1.5nV/√H

SIGNAL SOURCE (DAC)

Signal generator must be replaced for noise and other issues.

A better candidate is AD9106 waveform generator.

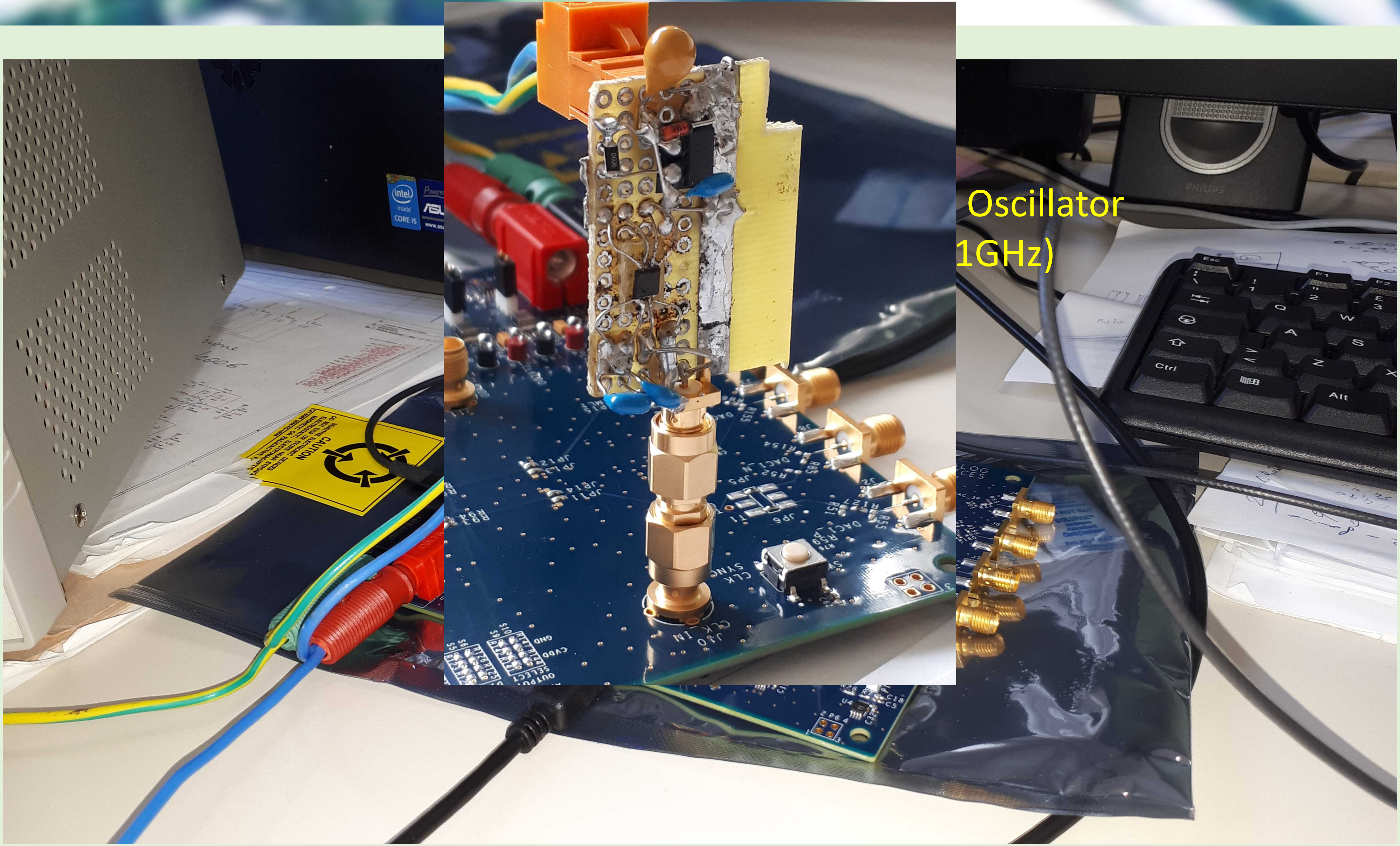
- Current mode DAC
- High accuracy and stability
- From datasheet noise is 0,999nV/√Hz
- SPI Programmable device
- 4 channels
- Low cost (20€ per chip)
- Evaluation board with labview interface
- USB connection

SIGNAL SOURCE (DAC)

Evaluation board has already been purchased and currently under test.

DRAWBACKS:

- Evaluation board costy (500€)
- External Clock reference (1Ghz typ.)
- Labview interface not user friendly!
- No manual included!



Oscillator

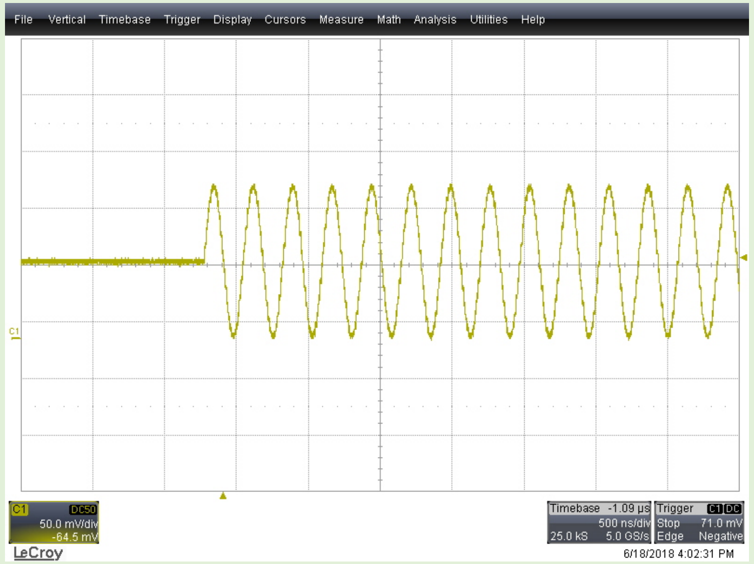
1GHz)

SIGNAL SOURCE (DAC)

NEXT STEPS ARE:

- Signal pattern generation
- Noise tests
- Output filter design
- Integration in current set-up
  - Using current board
  - Developing new layout with specific features

WAVEFORM SAMPLES

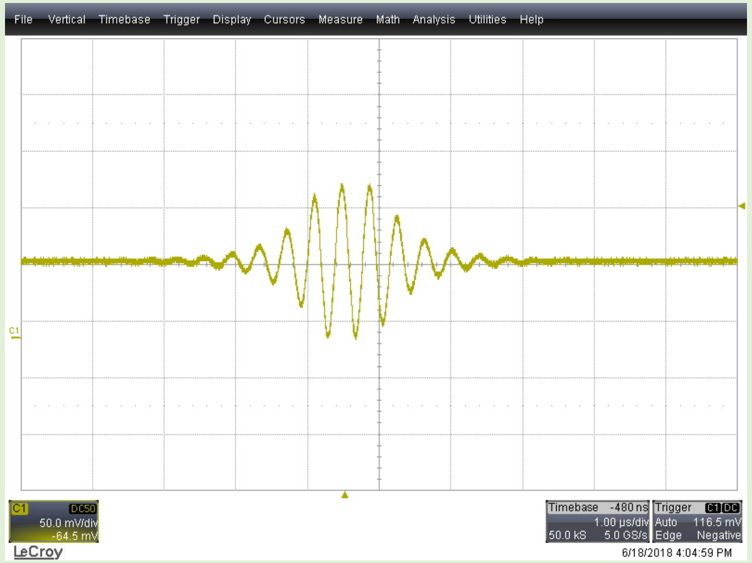


C1 DC50
50.0 mV/div
-64.5 mV

Timebase -1.09 µs
500 ns/div
25.0 kS 5.0 GS/s

Trigger C1 DC
Stop 71.0 mV
Edge Negative

6/18/2018 4:02:31 PM

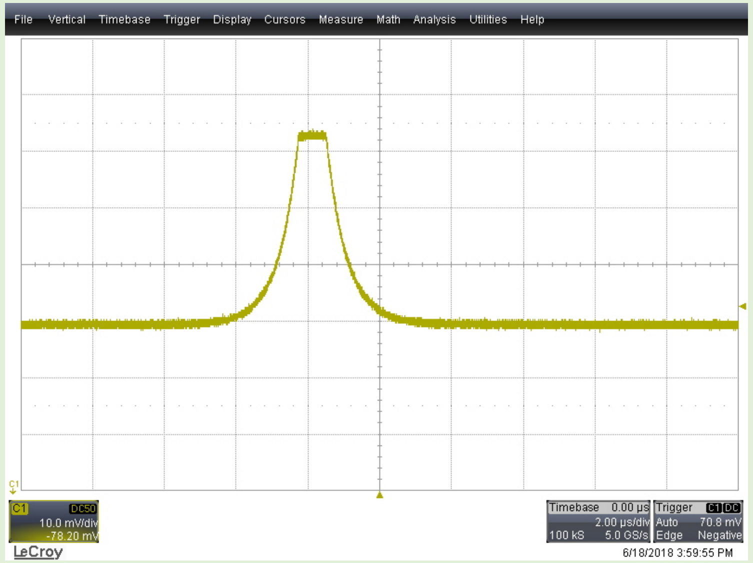


C1 DC50
50.0 mV/div
-64.5 mV

Timebase -480 ns
1.00 µs/div
50.0 kS 5.0 GS/s

Trigger C1 DC
Auto 116.5 mV
Edge Negative

6/18/2018 4:04:59 PM



C1 DC50
10.0 mV/div
-78.20 mV

Timebase 0.00 µs
2.00 µs/div
100 kS 5.0 GS/s

Trigger C1 DC
Auto 70.8 mV
Edge Negative

6/18/2018 3:59:55 PM

C1 DC50
10.0 mV/div
-78.20 mV

C2 DC50
1.00 V/div
0 mV offset

Timebase -17.4 ns
5.00 ns/div
250 S 5.0 GS/s

Trigger C1 DC
Stop 82.0 mV
Edge Negative

6/18/2018 3:57:03 PM


Status of the LNF activities on electronics

Grazie per l'attenzione!

TEQ MEETING

Southampton, June 22 2018

Testing the Large-Scale Limit of Quantum Mechanics (TEQ)

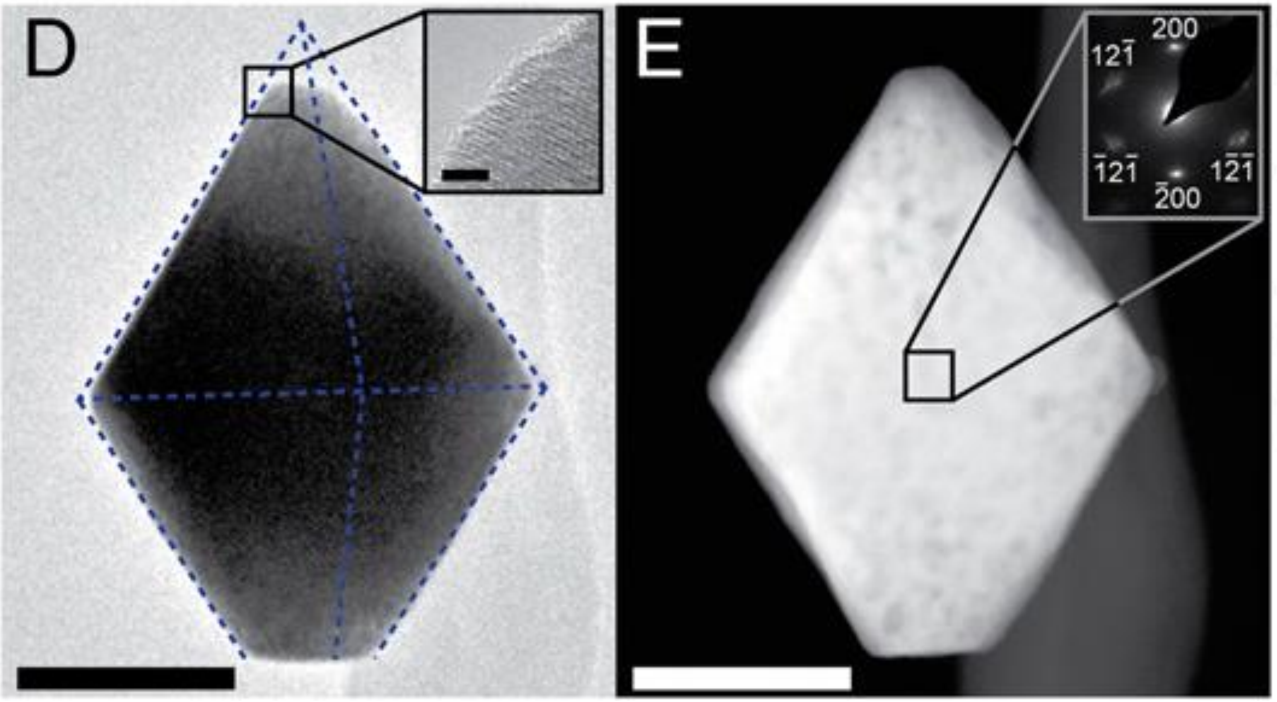
Synthesis of **Yb-doped $LiYF_4$** Colloidal Nanocrystals

Liberato Manna
Luca De Trizio
Francesco De Donato

Southampton – 22nd of June

Work Progress: 2nd of February 2018

Reference synthesis protocol: Solvothermal Approach



200nm

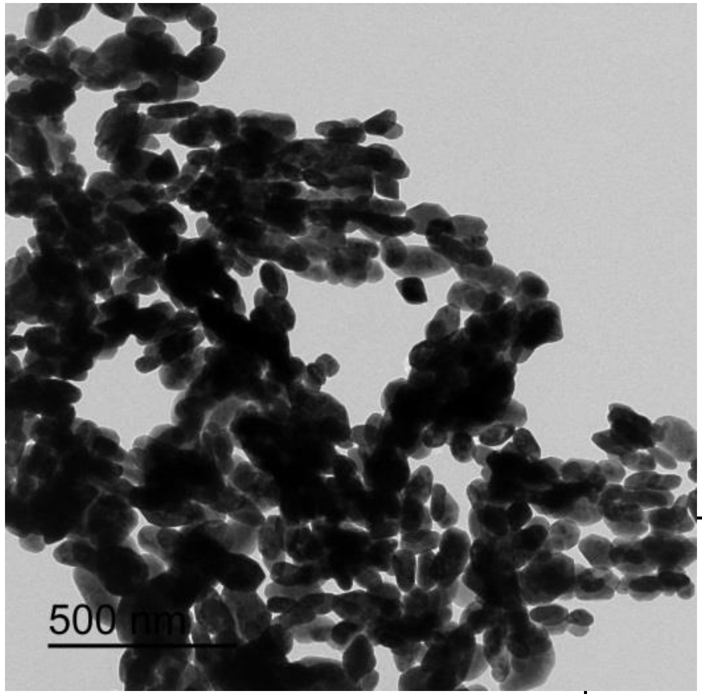
$2\%\ Er^{3+}, 10\% Yb^{3+}:LiYF_4$

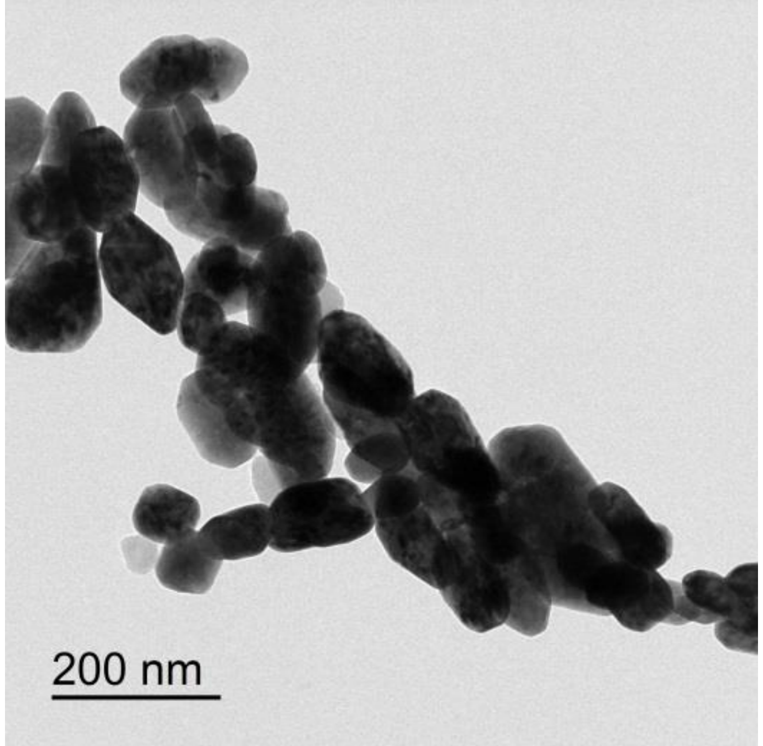
$10\%\ Yb^{3+}:LiYF_4$

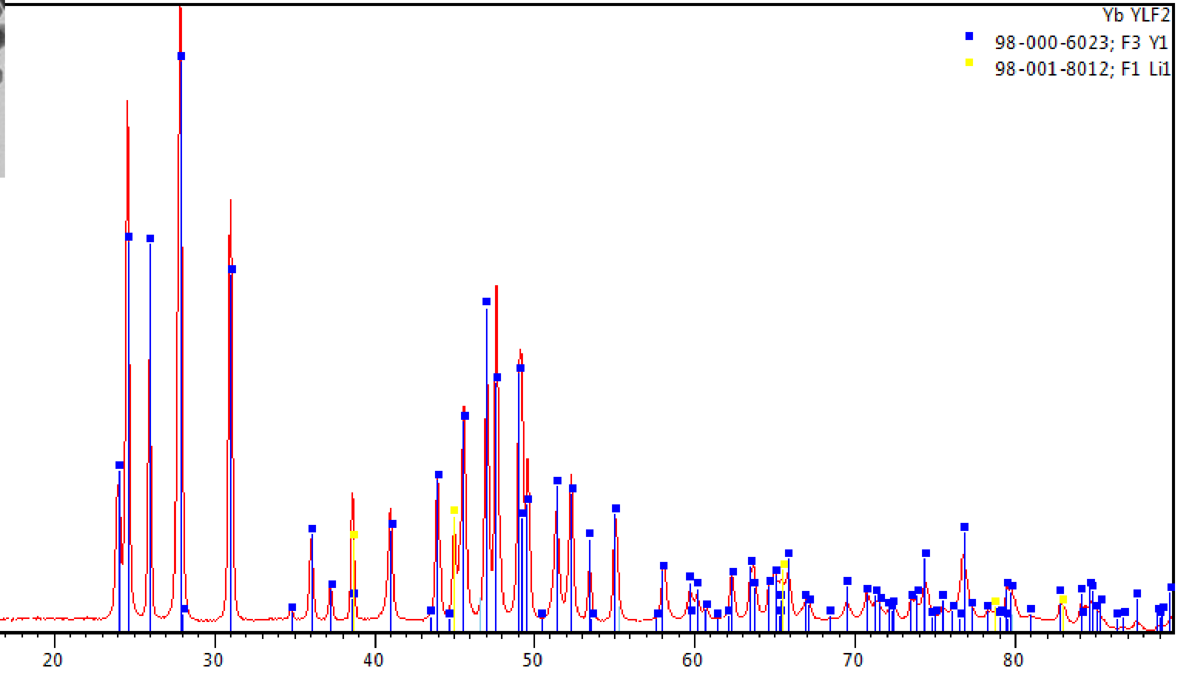
Reference paper: Roder et al. *PNAS* **2015**, 112 (49) 15024-15029

Work Progress: 2nd of February 2018

Our Results: Solvothermal Approach



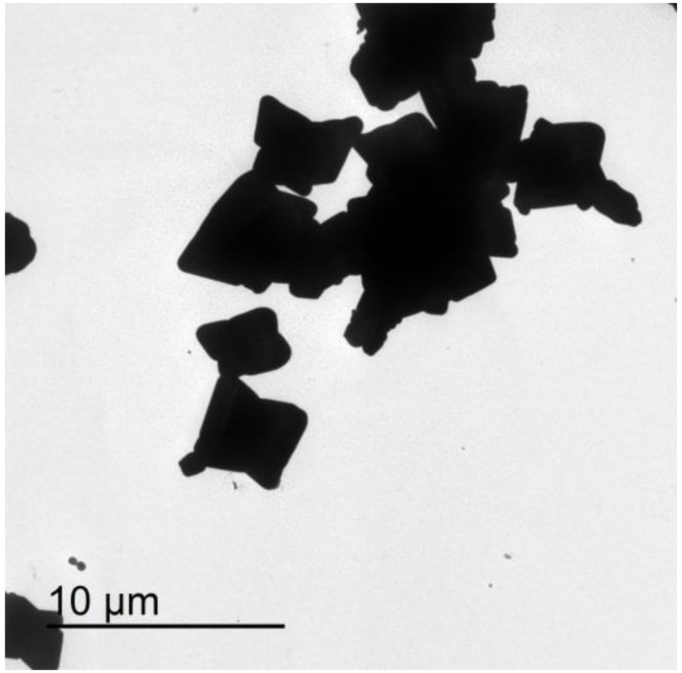




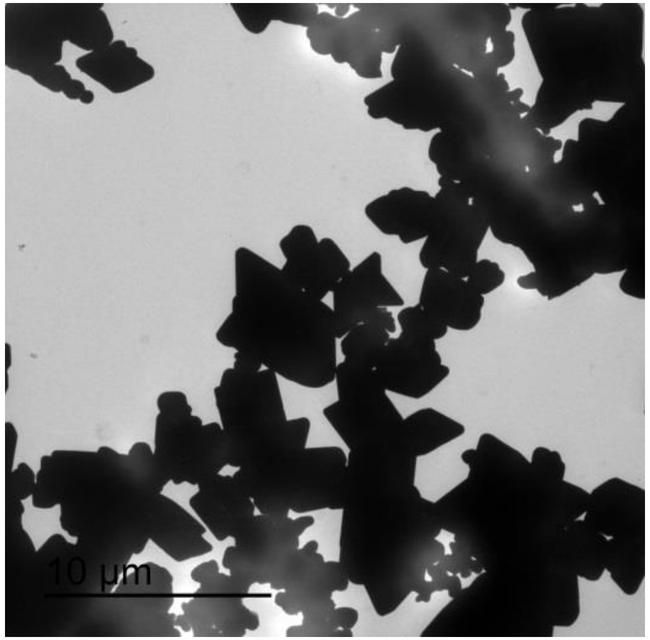
Yb:YLF Sample 2

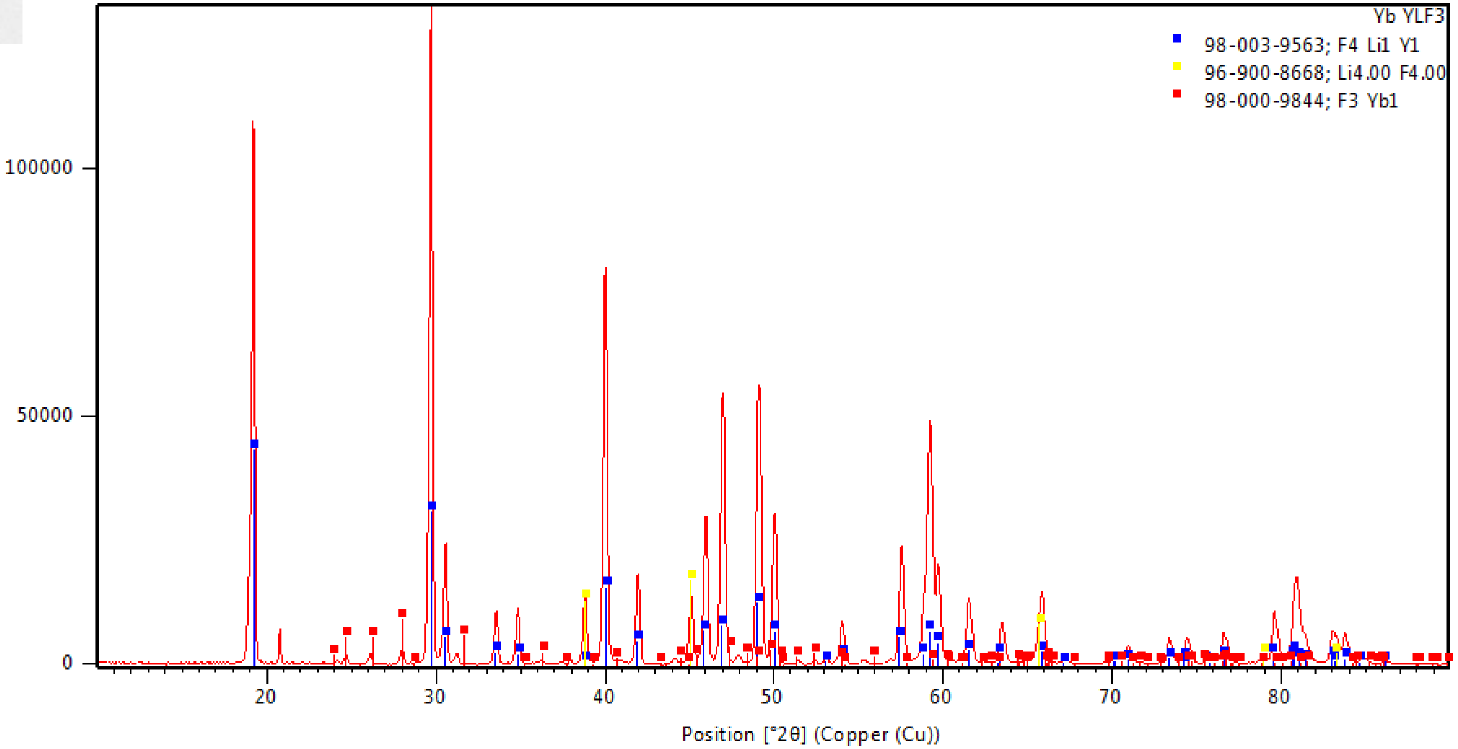
Our Results

Solvothermal Approach

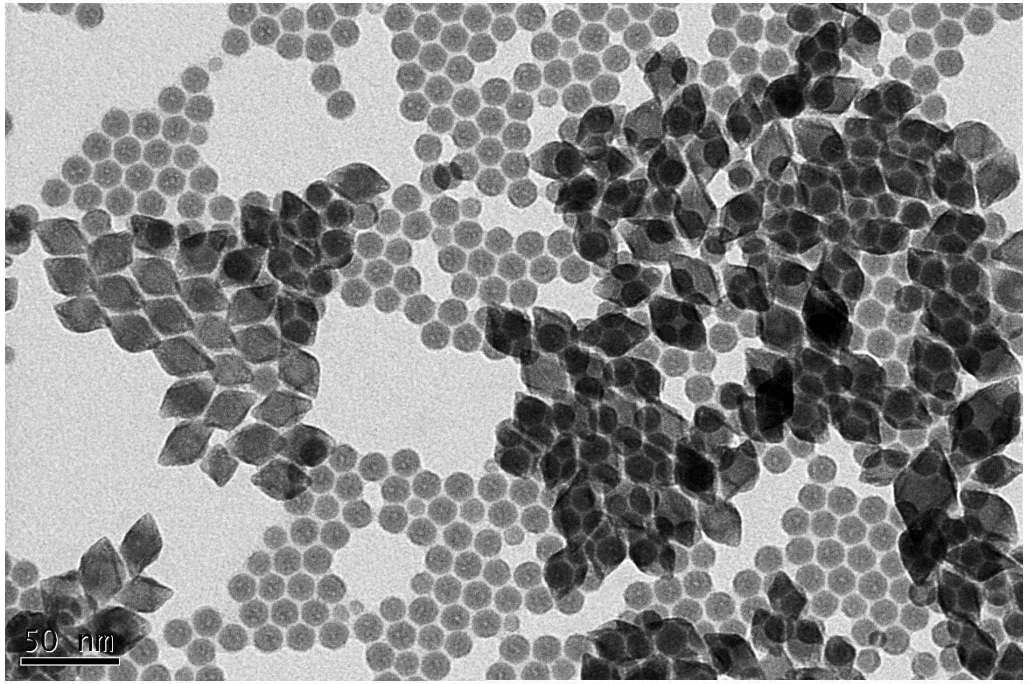


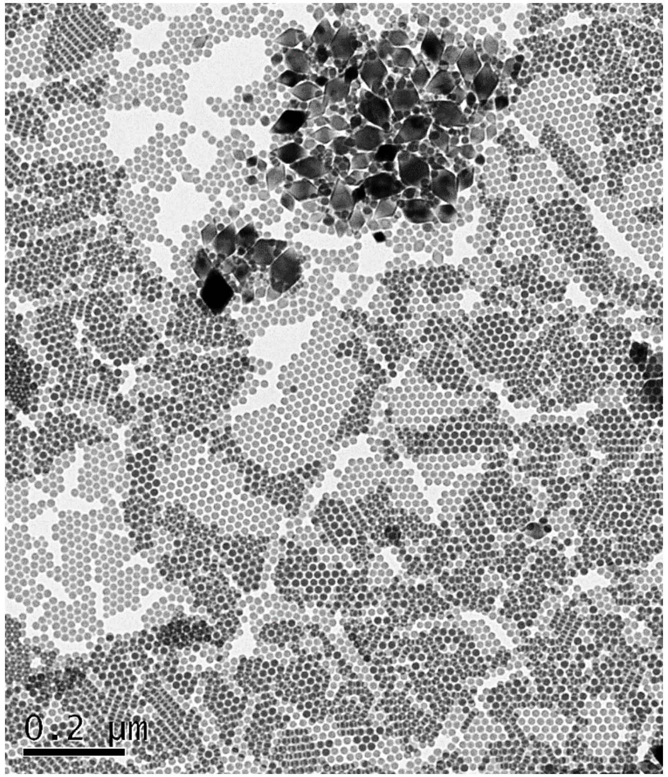
Yb:YLF Sample 3



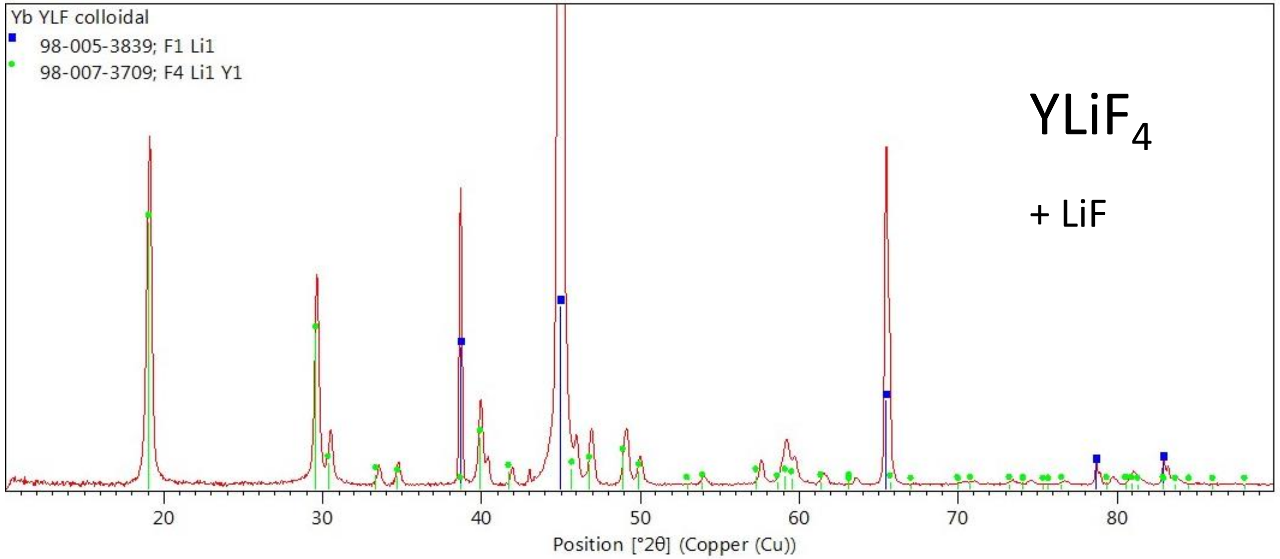


Work Progress: 2nd of February 2018





Colloidal Approach



$YLiF_4$

+ LiF

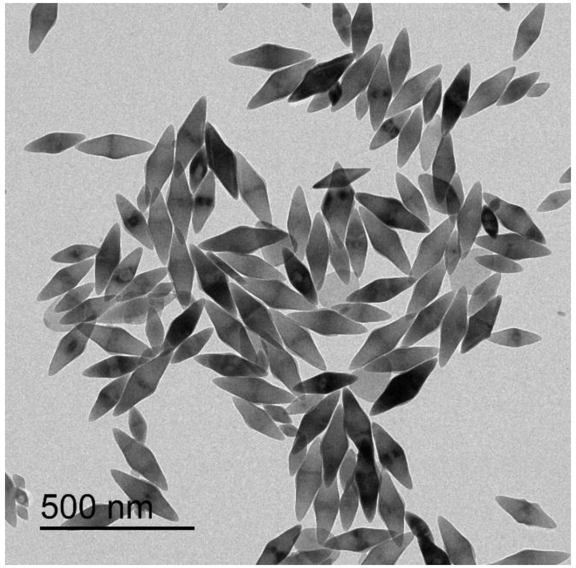
Roberts et al. *J. Am. Chem. Soc.* , **1961**, 83 (5), pp 1087–1088
Du et al. *Dalton Trans.*, **2009**,0, 8574-8581

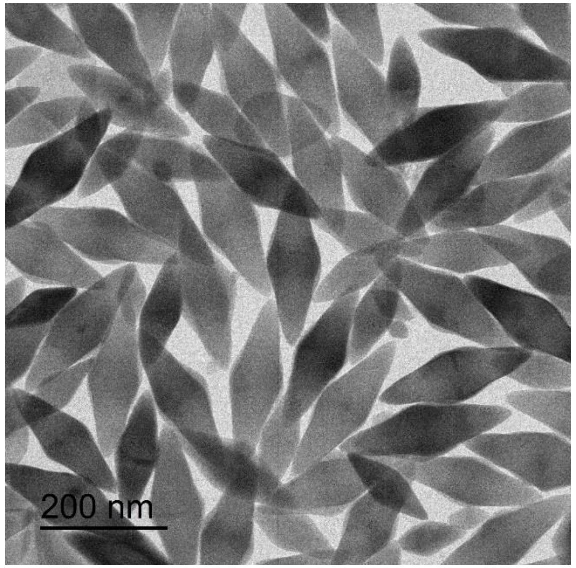
Work Progress: Today

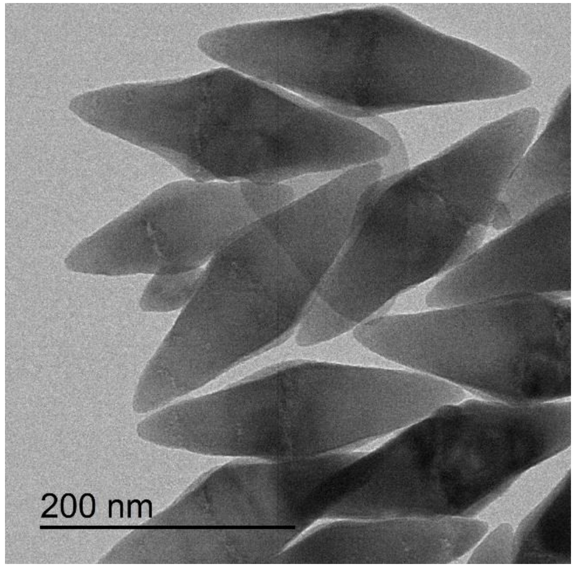
«non doped» $LiYF_4$ NCs

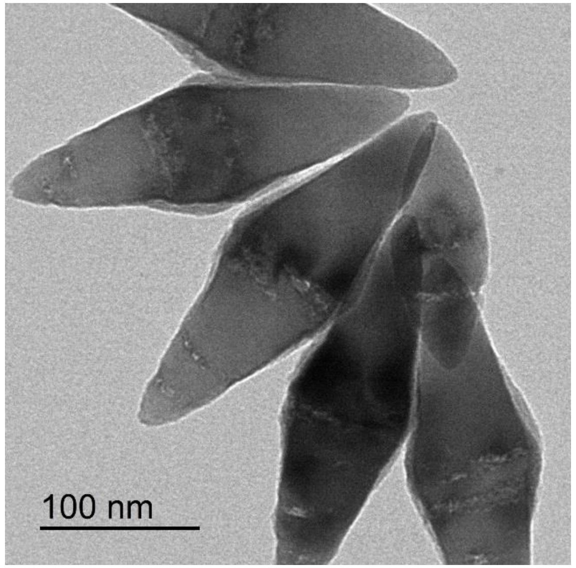
$LiCO_3$	1 mmol
Y_2O_3	1 mmol
TFA	5 mL
H_2O	5 mL

- The acqueous solution was heated up to 100°C under N_2 flow to get a clear solution
- The solution was dried under vacuum to remove the excess of TFA and water
- The resulting powder was solubilized in 12 mL of a mixture of Oleic Acid and Octadecene and degassing at 120°C for 1 hour
- 330 °C (10°C/min) – Growth 15 min



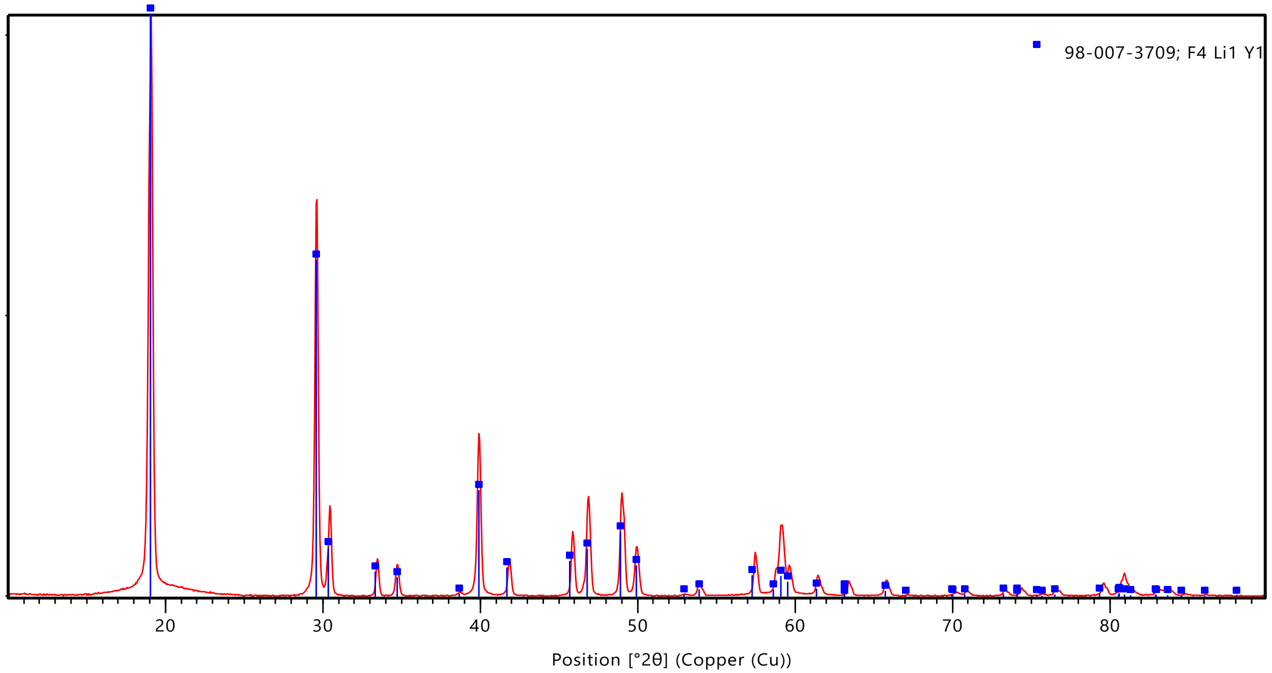






«non doped» LiYF$_4$ NCs

XRD analysis

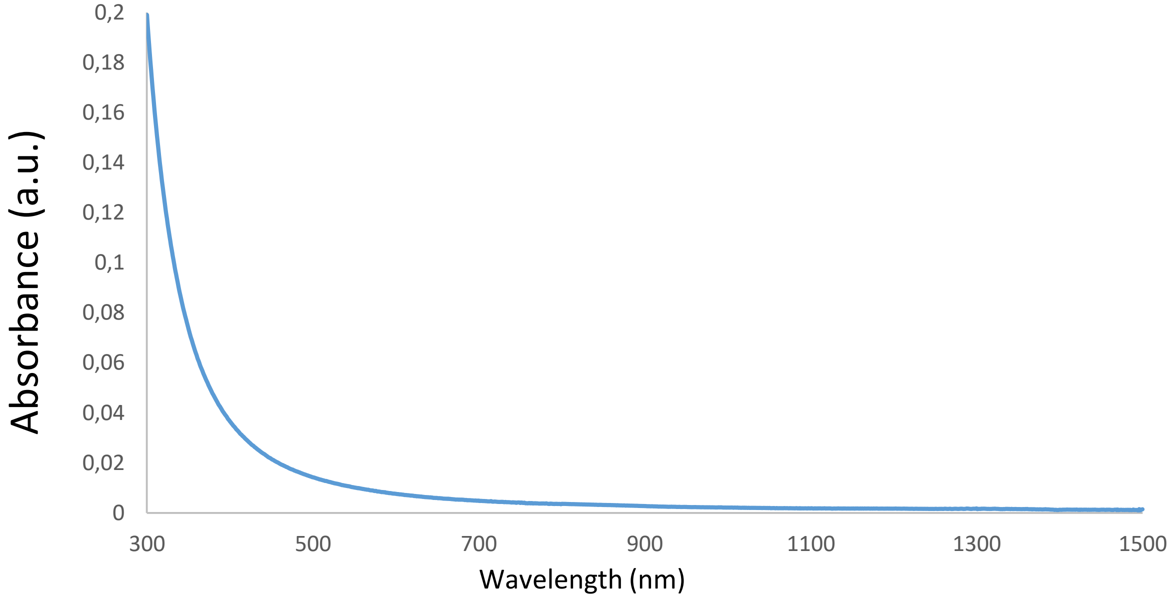


Lithium yttrium fluoride

Tetragonal structure

Optical Properties

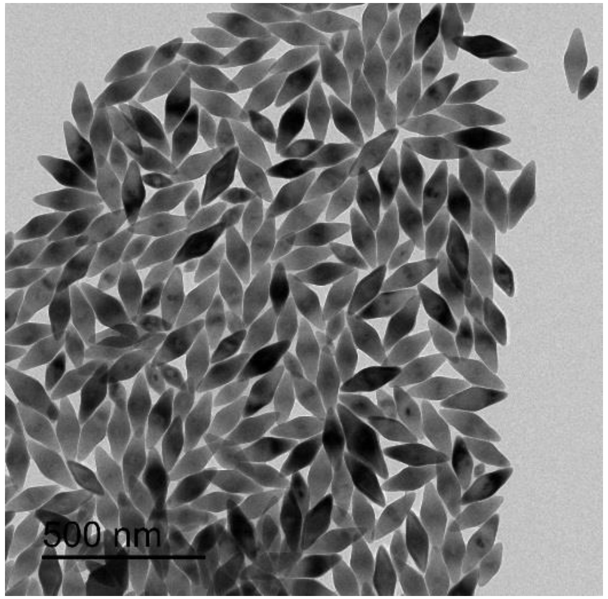
dispersion of nanocrystals in tetrachloroethylene (TCE)

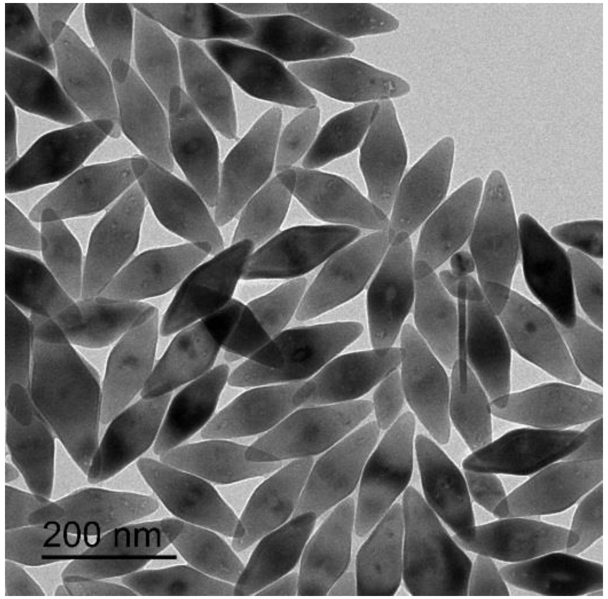


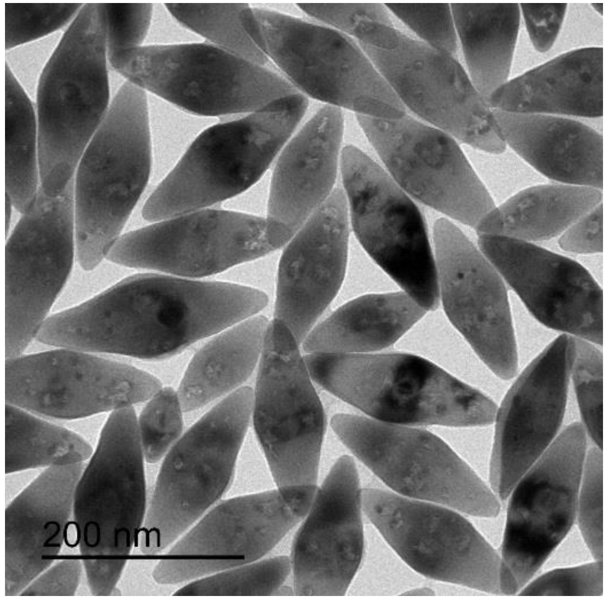
Yb-doped $LiYF_4$ NCs

Different $Yb:LiYF_4$ NC samples were synthesized following the same protocol, adding also Yb_2O_3, as Yb precursor, from the very beginning.

30% $Yb:LiYF_4$ NCs

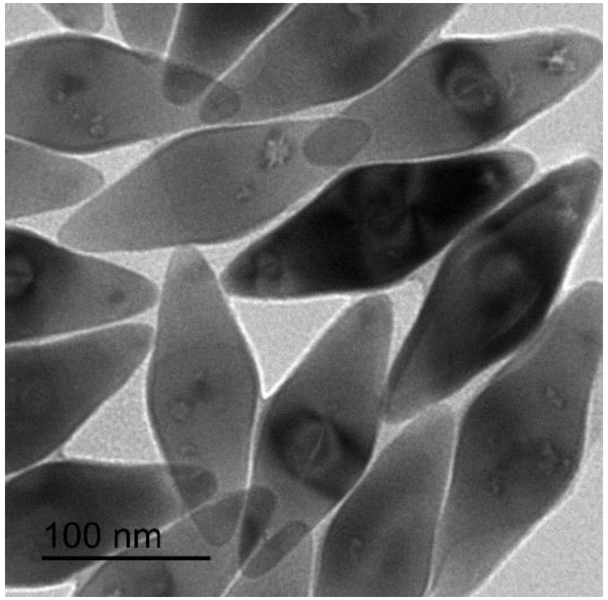






ICP elemental analysis

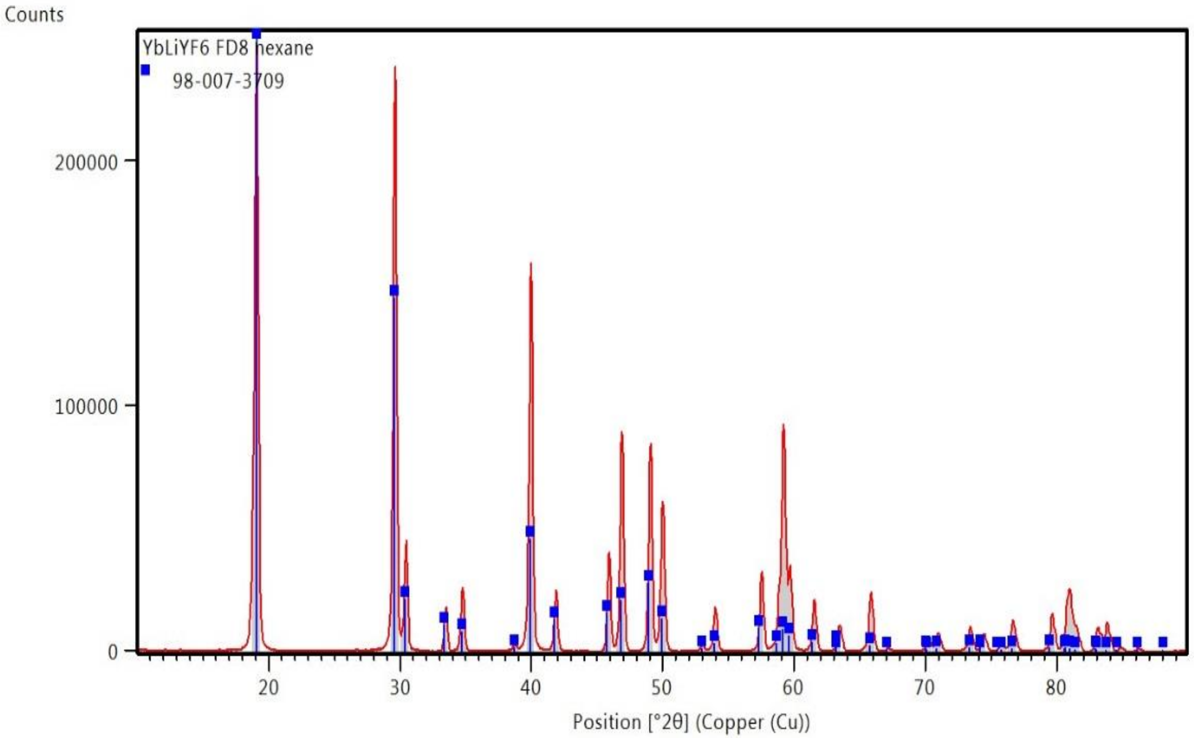
Yb/Y=0.30



Yb-doped LiYF$_4$ NCs

30% Yb:LiYF$_4$ NCs

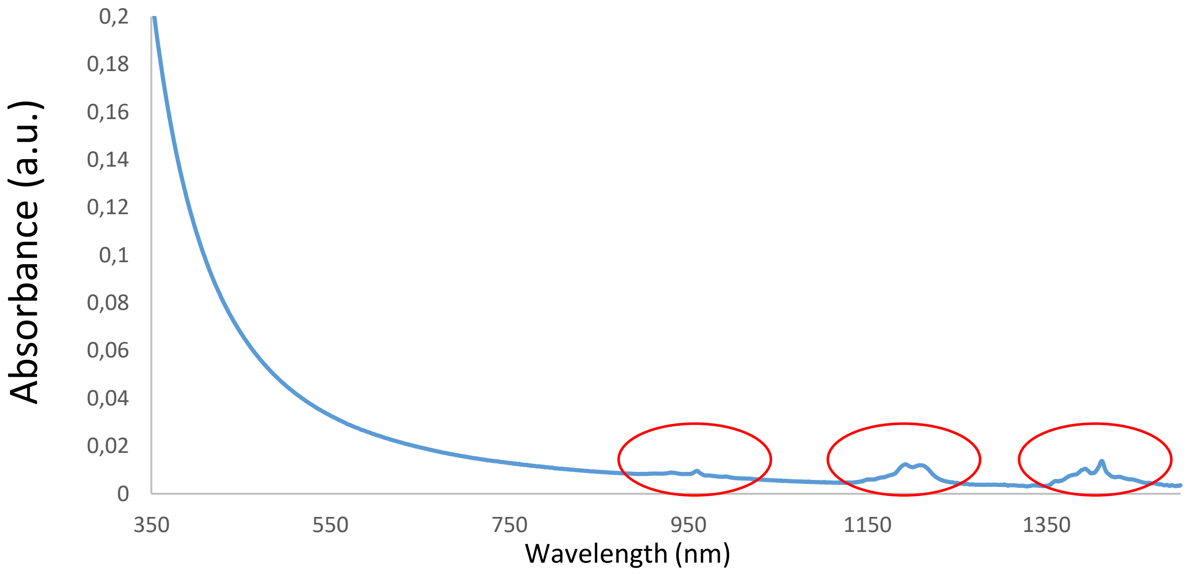
XRD analysis



Lithium yttrium fluoride

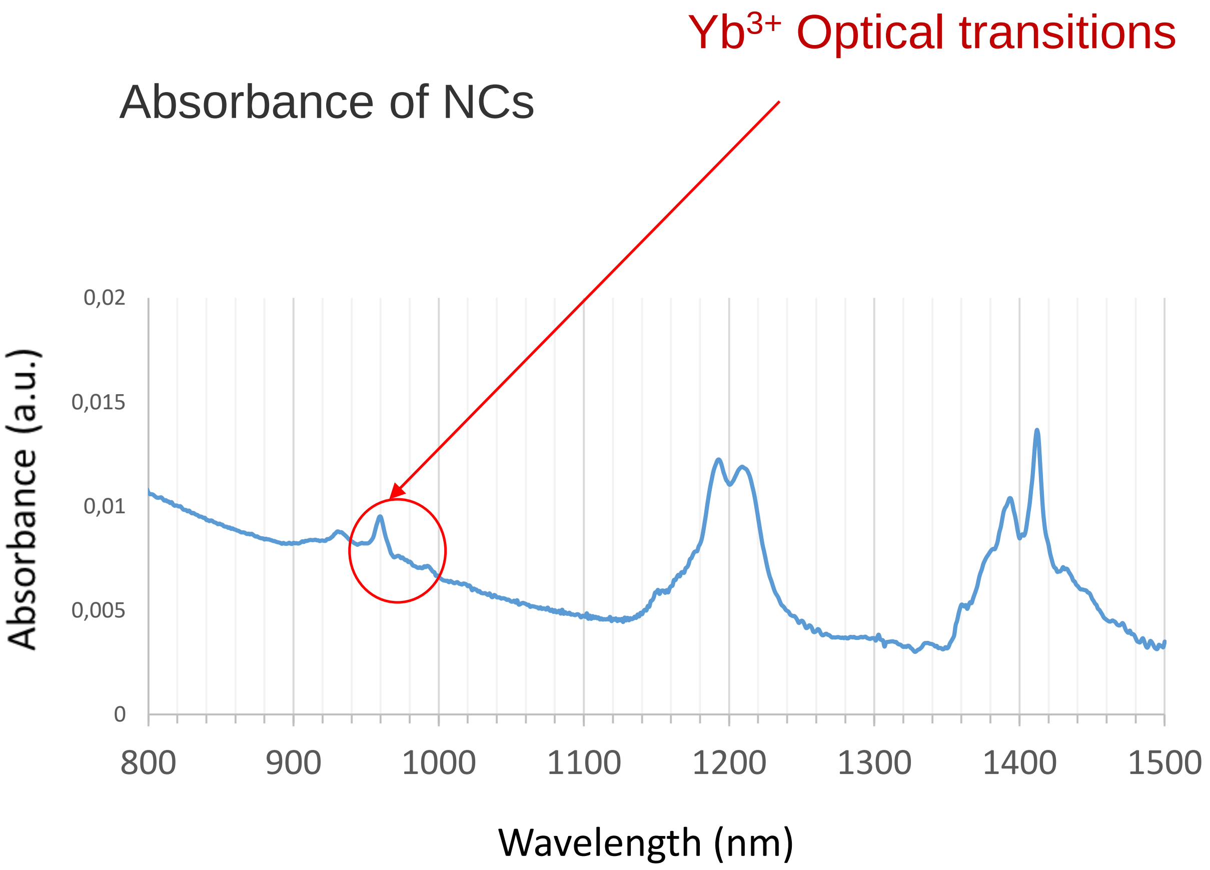
Tetragonal structure

Optical Properties

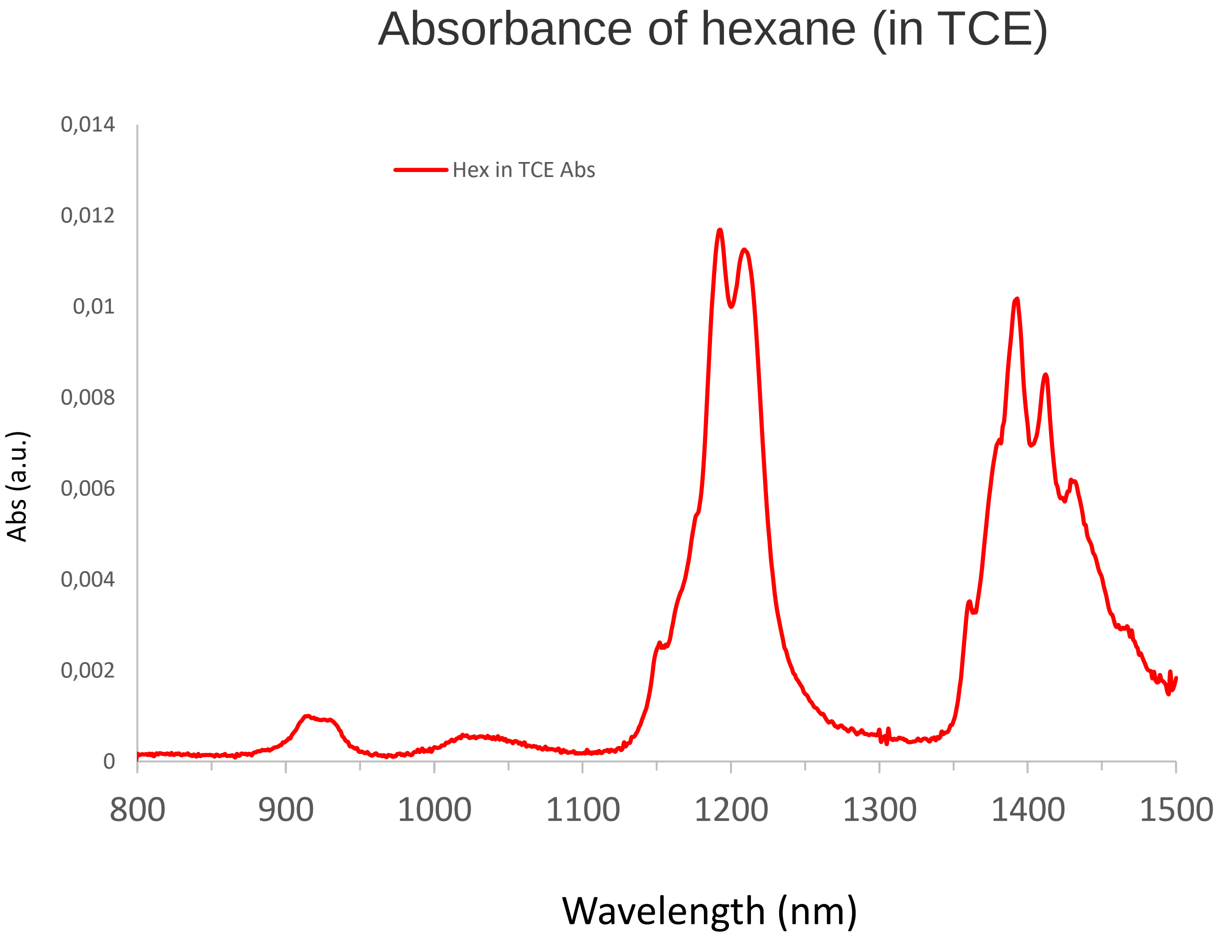


Yb-doped $LiYF_4$ NCs

30% $Yb:LiYF_4$ NCs

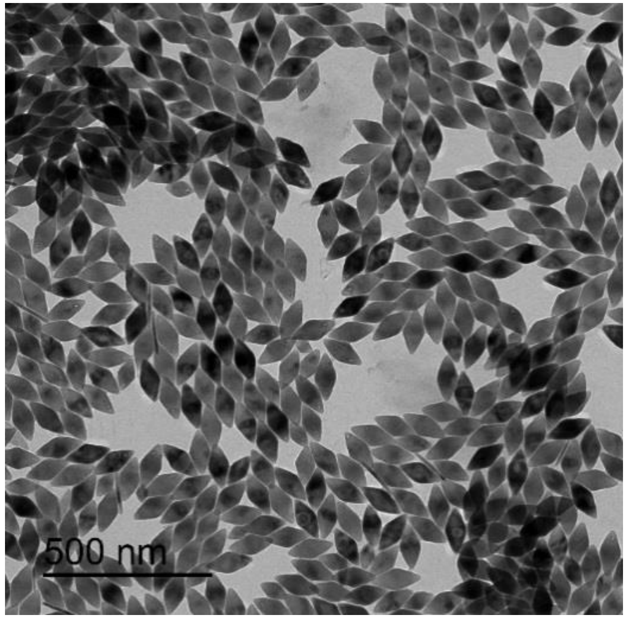

Absorbance of NCs

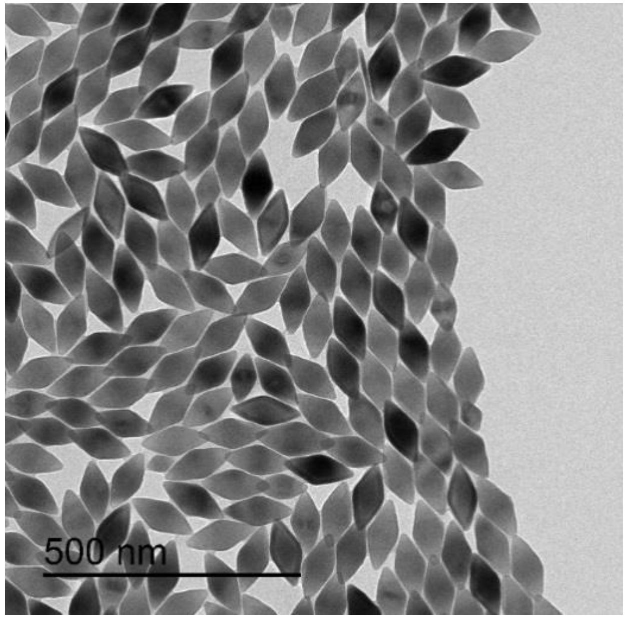
Yb^{3+} Optical transitions

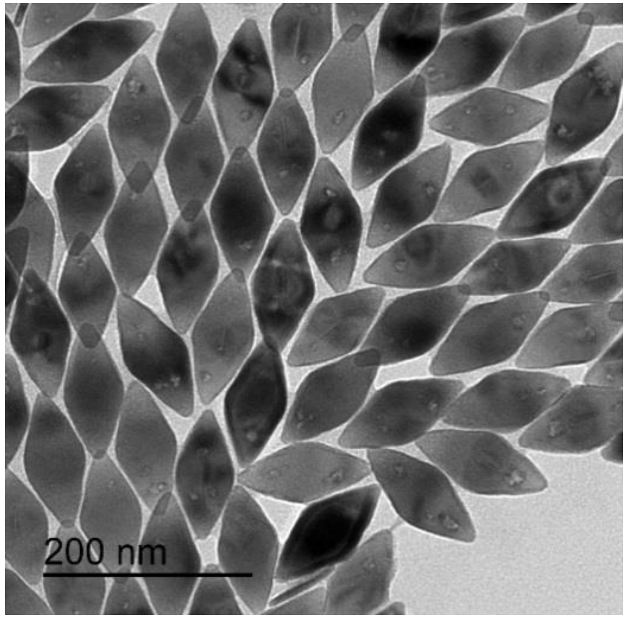

Absorbance of hexane (in TCE)

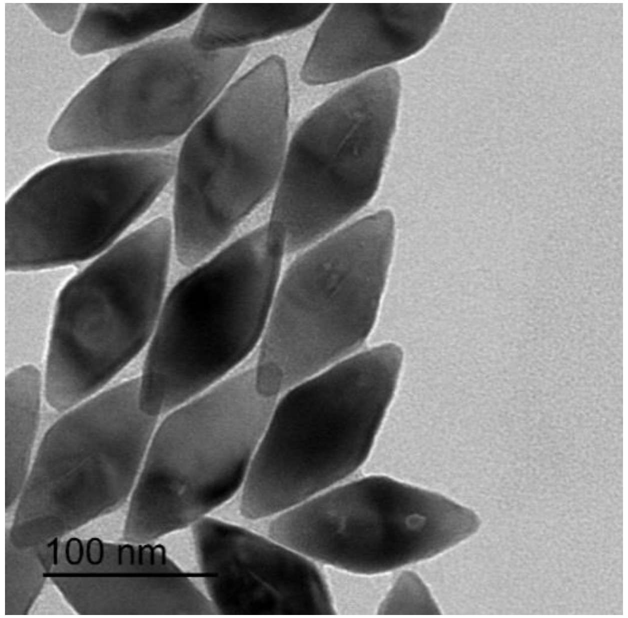
Yb-doped $LiYF_4$ NCs

38% Yb:$LiYF_4$ NCs









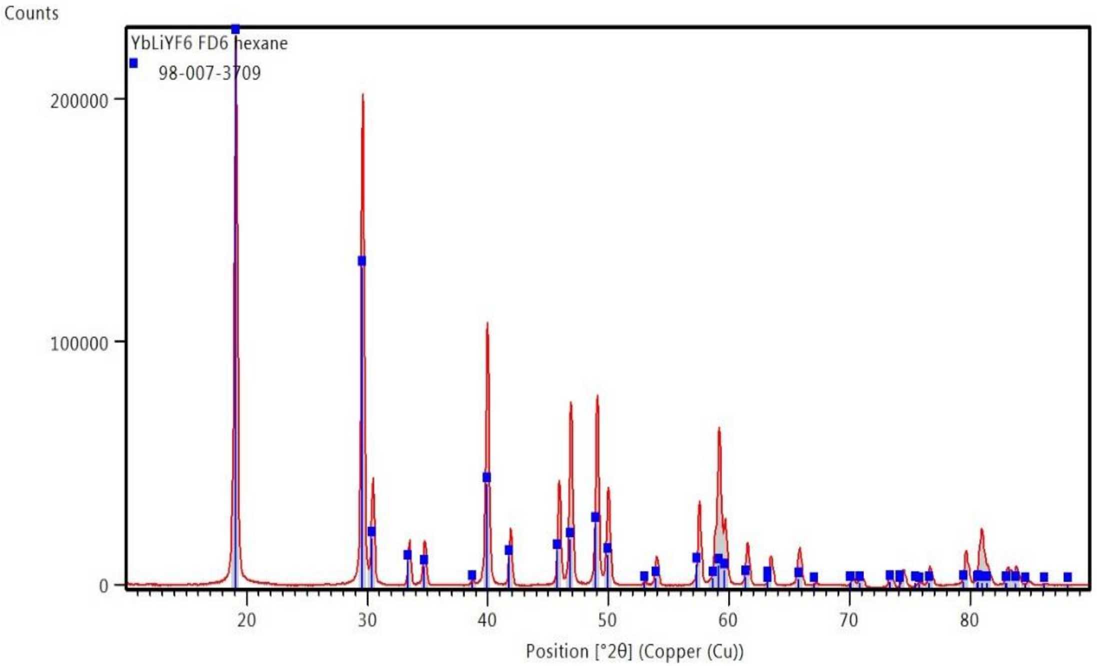
ICP elemental analysis

Yb/Y=0.38

Yb-doped $LiYF_4$ NCs

38% $Yb:LiYF_4$ NCs

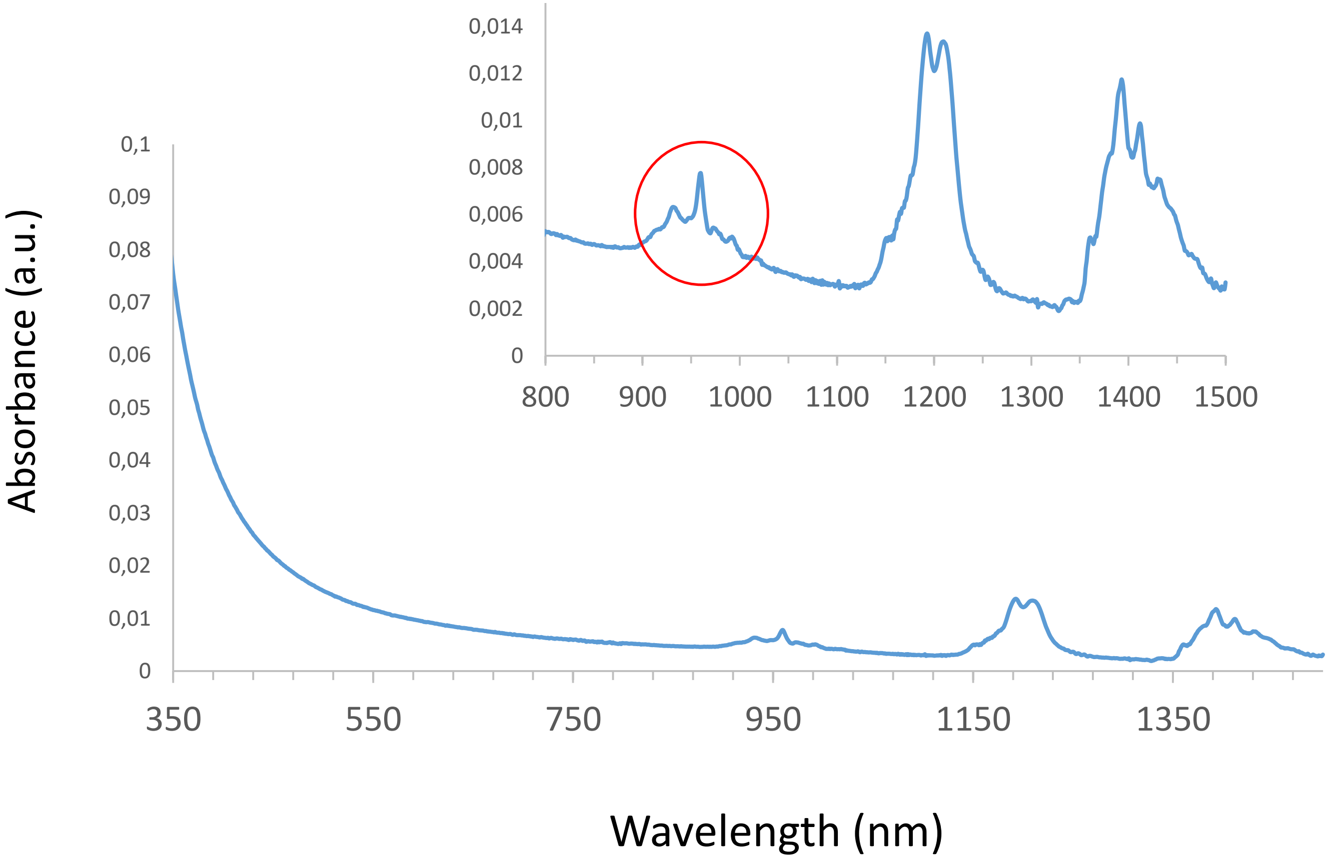
XRD analysis



Lithium yttrium fluoride

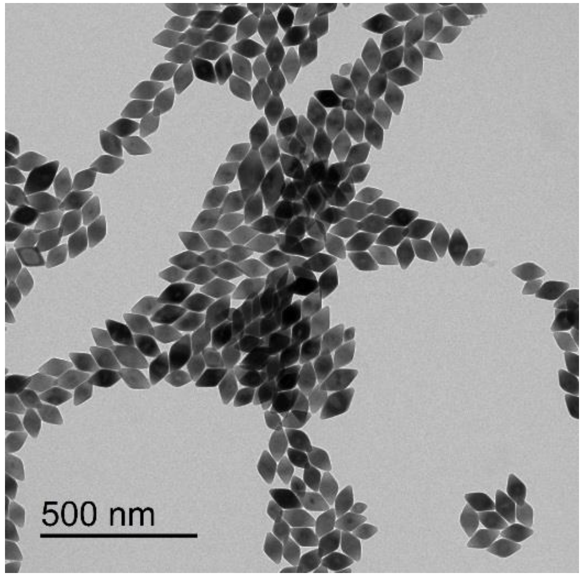
Tetragonal structure

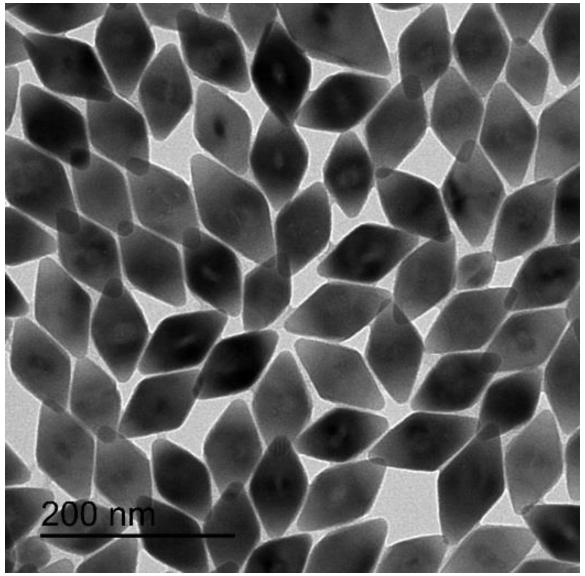
Optical Properties

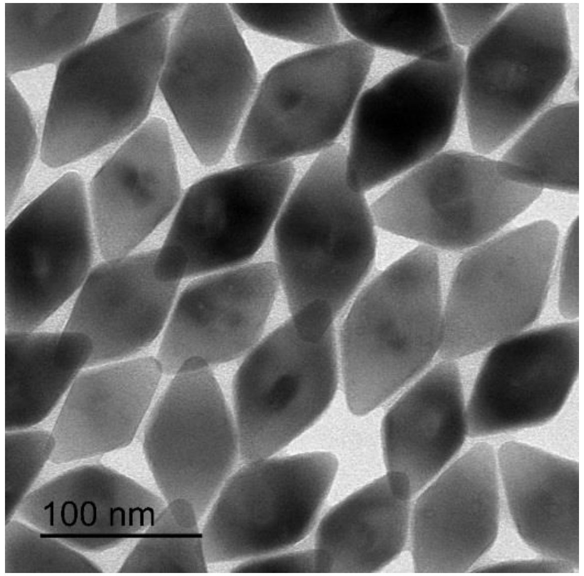


Yb-doped $LiYF_4$ NCs

127% Yb:$LiYF_4$ NCs

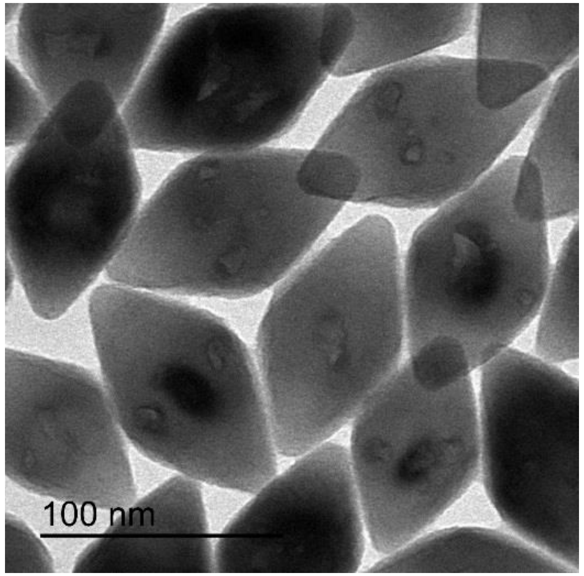






ICP elemental analysis

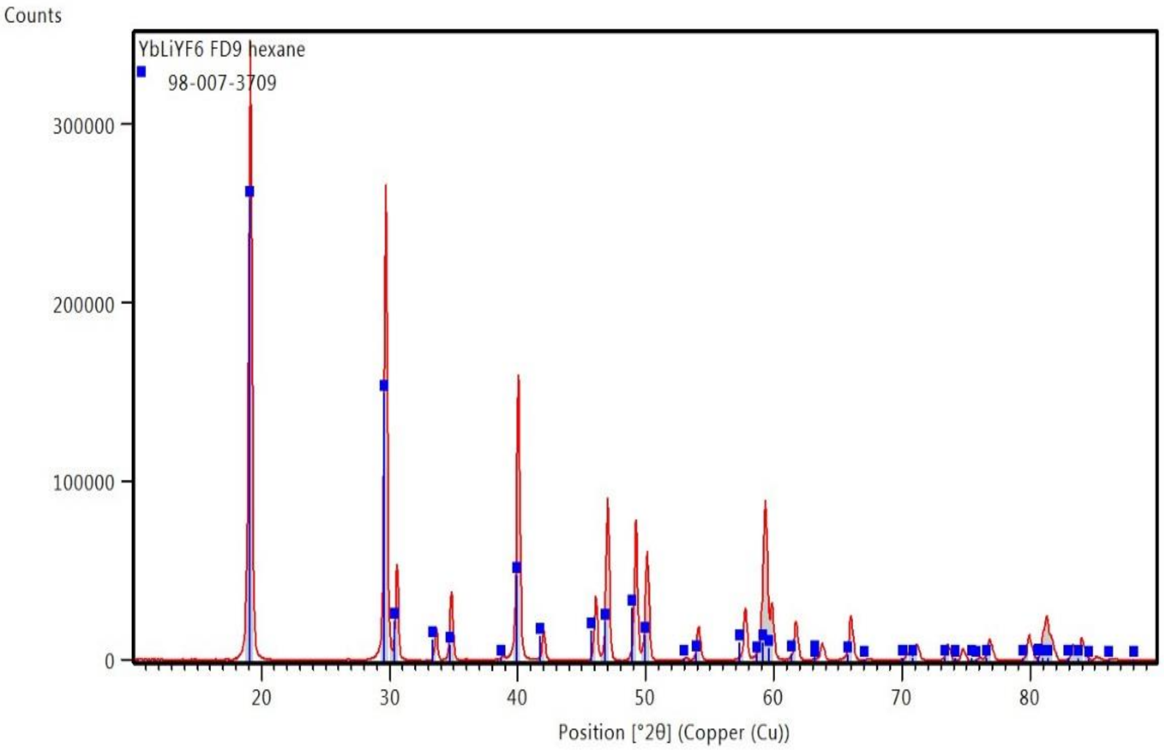
Yb/Y=1.27



Yb-doped $LiYF_4$ NCs

127% Yb:$LiYF_4$ NCs

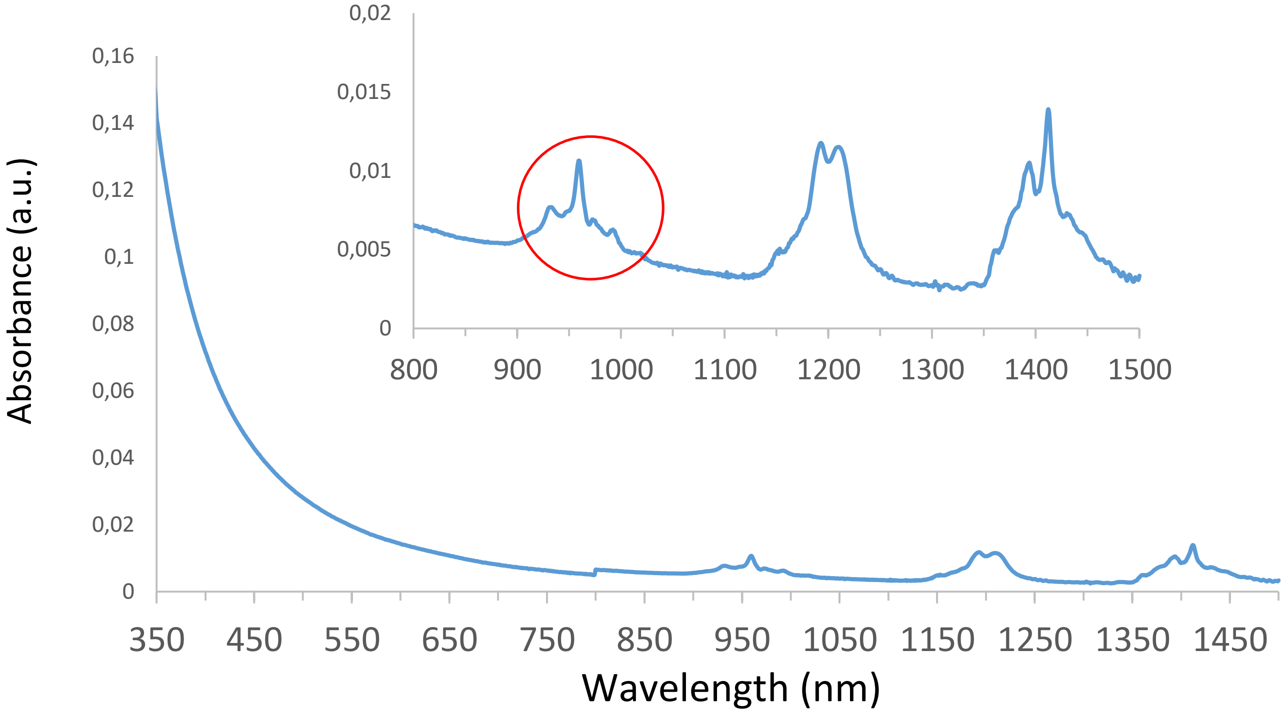
XRD analysis



Lithium yttrium fluoride

Tetragonal structure

Optical Properties



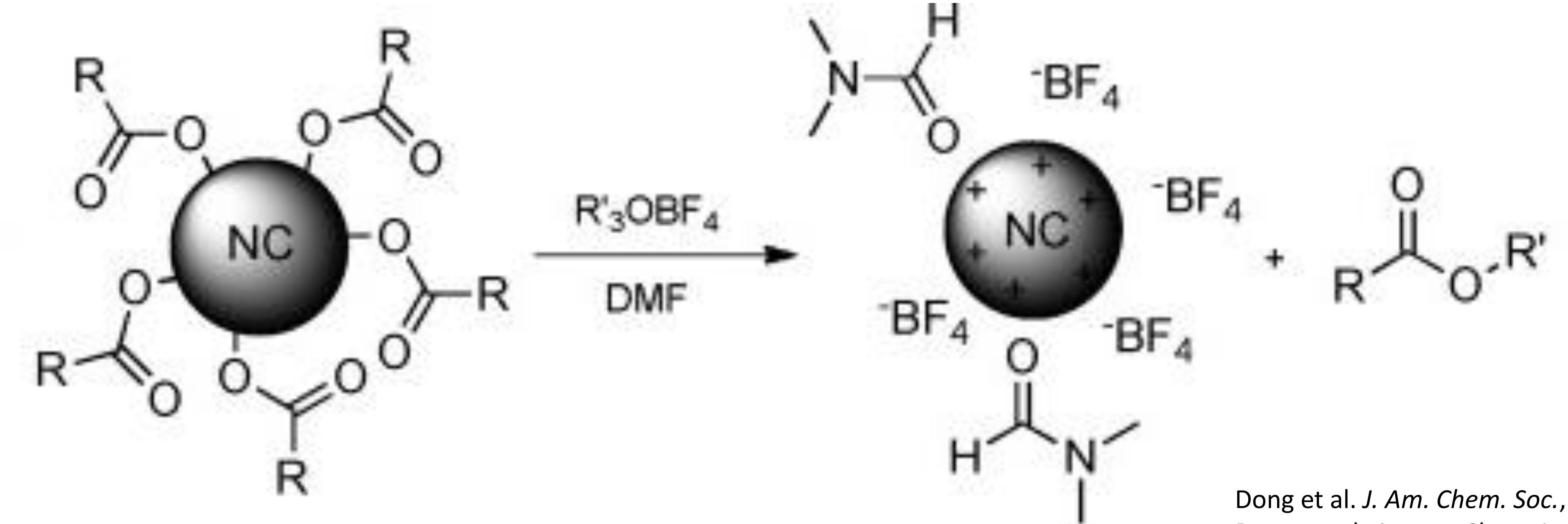
Ligand Stripping

Making the NCs dispersible in Methanol

In order to remove the ligands from the surface of NCs we employed:

-Triethyloxonium tetrafluoroborate ($NOBF_4$)

-Triethyloxonium tetrafluoroborate (Et_3OBF_4)

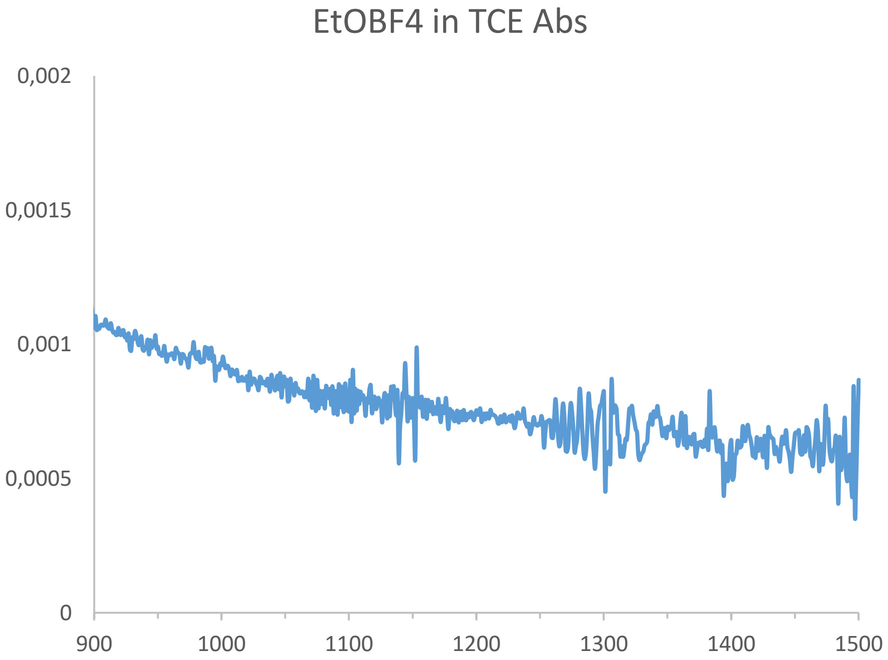


Dong et al. *J. Am. Chem. Soc.*, **2011**, *133* (4), pp 998–1006
Rosen et al. *Angew. Chem. Int. Ed.* **2012**, 51, 684 –689

Ligand Stripping

Both reagents yielded good results:

the size, shape, composition and crystal structure were not altered upon the ligand removal procedure



Thanks for Your Attention

Current status of the TEQ trap design

Michael Drewsen
Department of Physics and Astronomy
Aarhus University
Denmark

TEQ Meeting, June 21, 2018
University of Southampton, UK

Outline

I) Physical layout

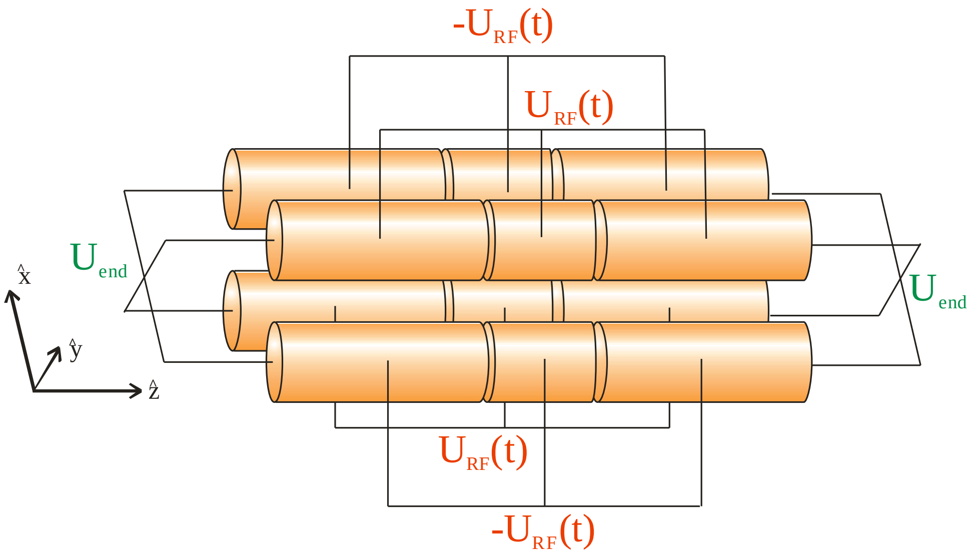
I) Requirements related to the electronics and heating

I) Passive NC cooling

I) Still unresolved issues

I) Physical layout

The linear Paul trap



Sinusoidal RF potential: $U_{RF}(t)=U_{RF}\sin(\Omega t)$

Effective oscillation freq.'s:

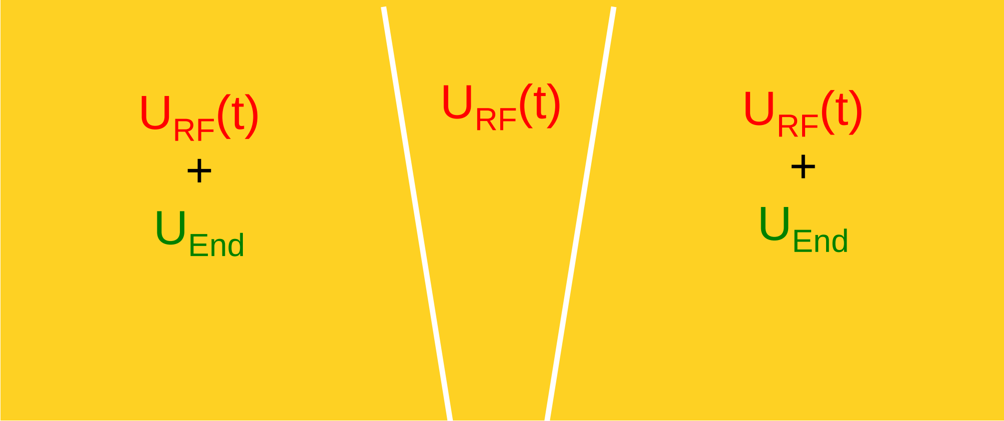
$\omega_r=1/2\,\beta\,\Omega\,,\quad \beta=(1/2\,q^2+a)^{1/2}$

$\omega_z=(-1/2\,a)^{1/2}\Omega$

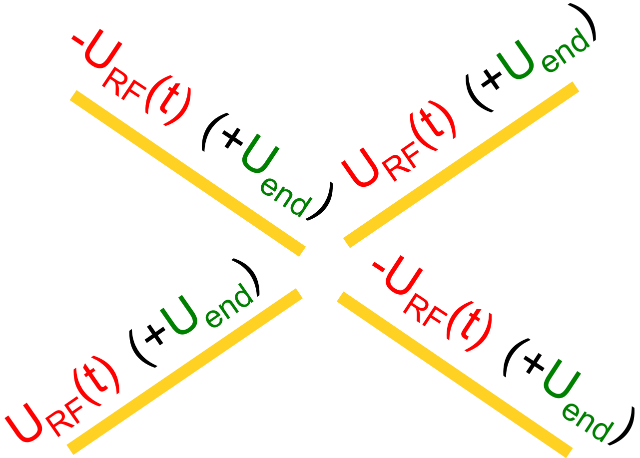
$$q=\frac{4QU_{RF}}{m\Omega^2 r_0^{\ 2}}\qquad a=-\frac{\alpha Q U_{end}}{m\Omega^2 r_0^{\ 2}}$$

Blade electrode trap I

Blade electrode structure



Mounted electrodes in an end view:

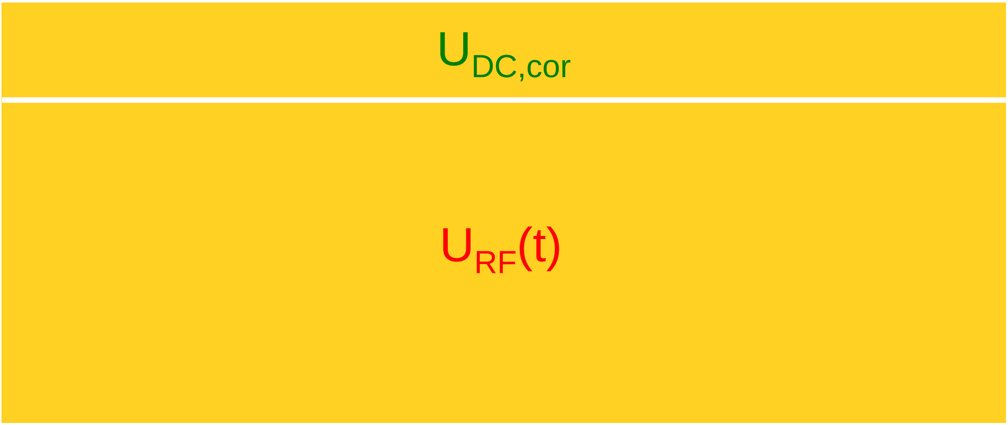


Note:

$U_{RF}(t)$ and U_{end} has to be mixed together.

Blade electrode trap II

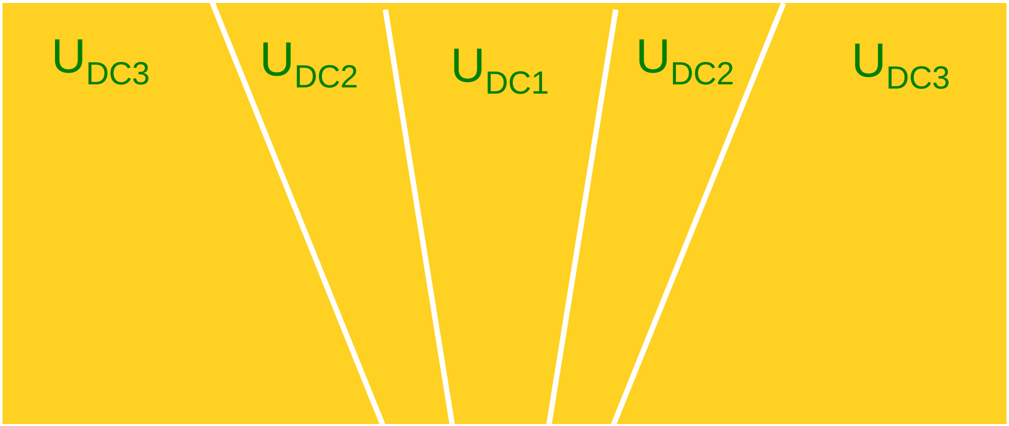
RF blade electrode



$U_{DC,cor}$

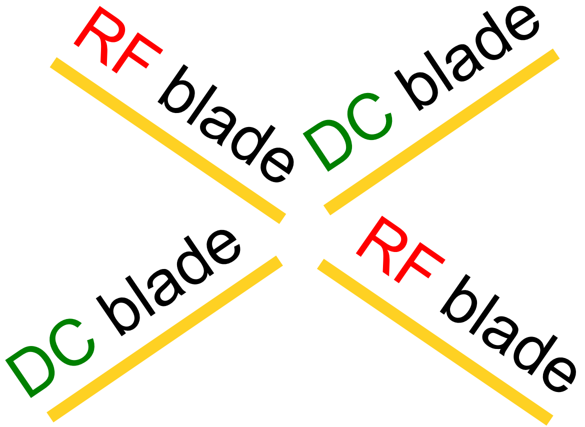
$U_{RF}(t)$

DC blade electrode



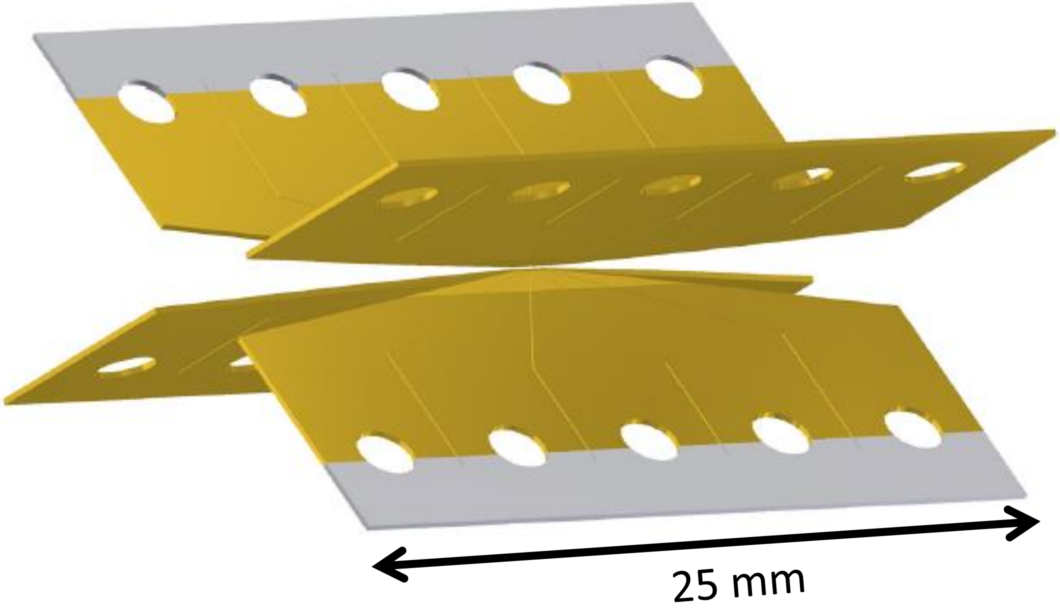
U_{DC3} U_{DC2} U_{DC1} U_{DC2} U_{DC3}

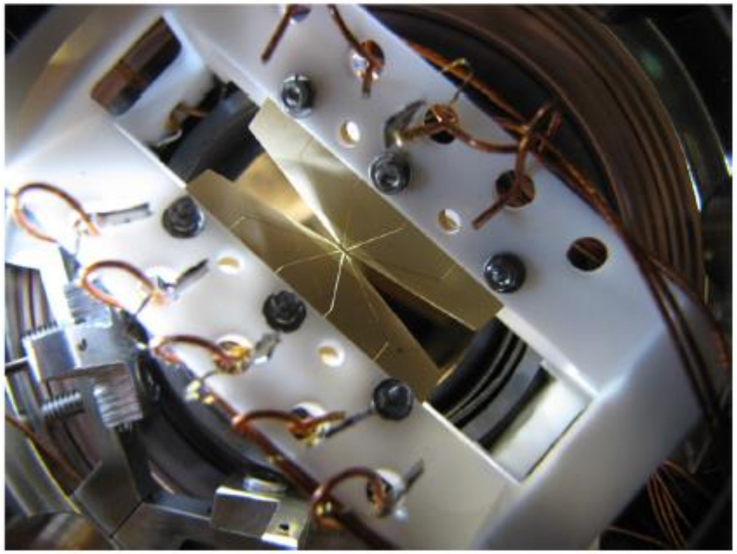
Mounted electrodes
in an end view:



No mixing of $U_{RF}(t)$
and U_{end} needed!

Linear rf trap
designed by Chris Monroe’s Group

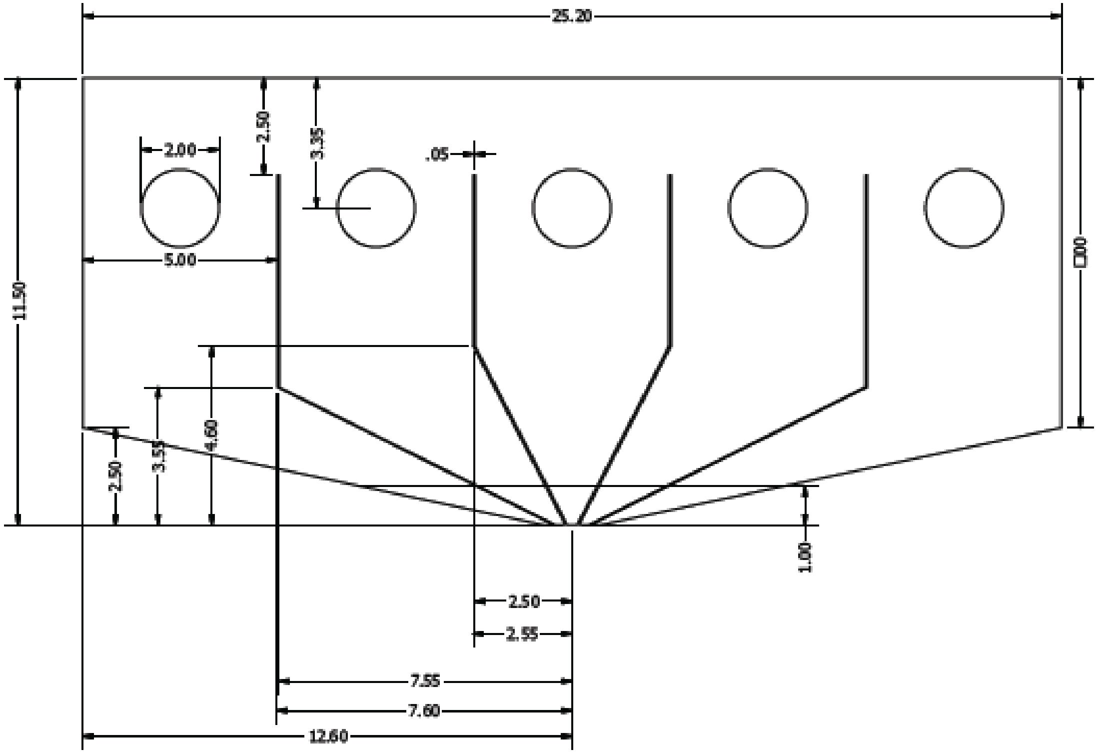


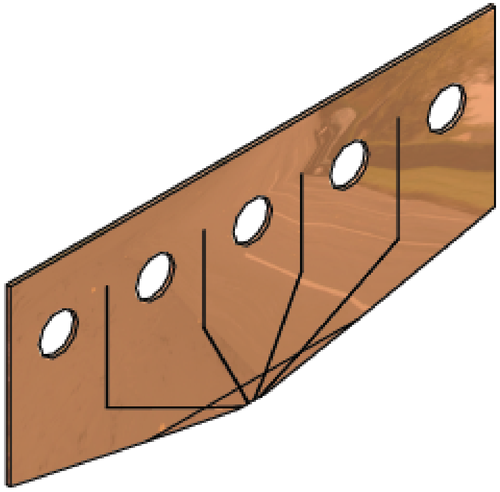


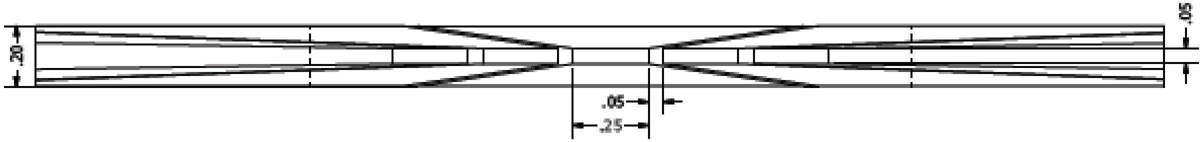
<u>Blade mat.:</u>
Gold on
Alumina

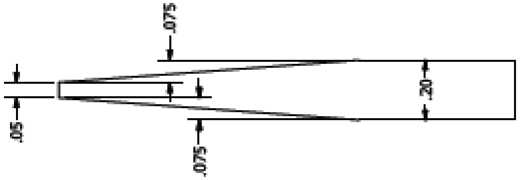
From PhD thesis of David Hucul

TEQ linear rf trap
Design by Chris Monroe's Group

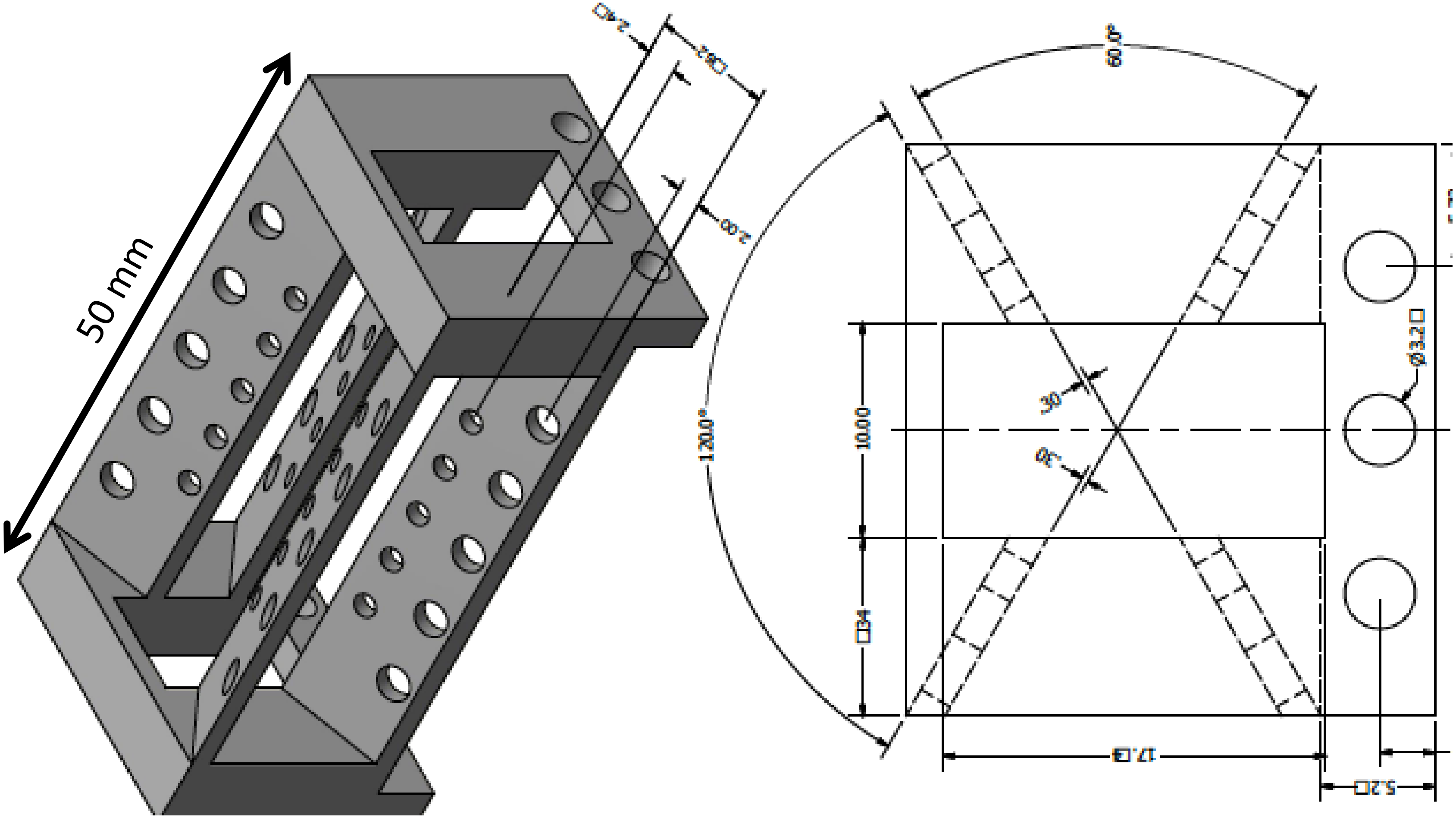




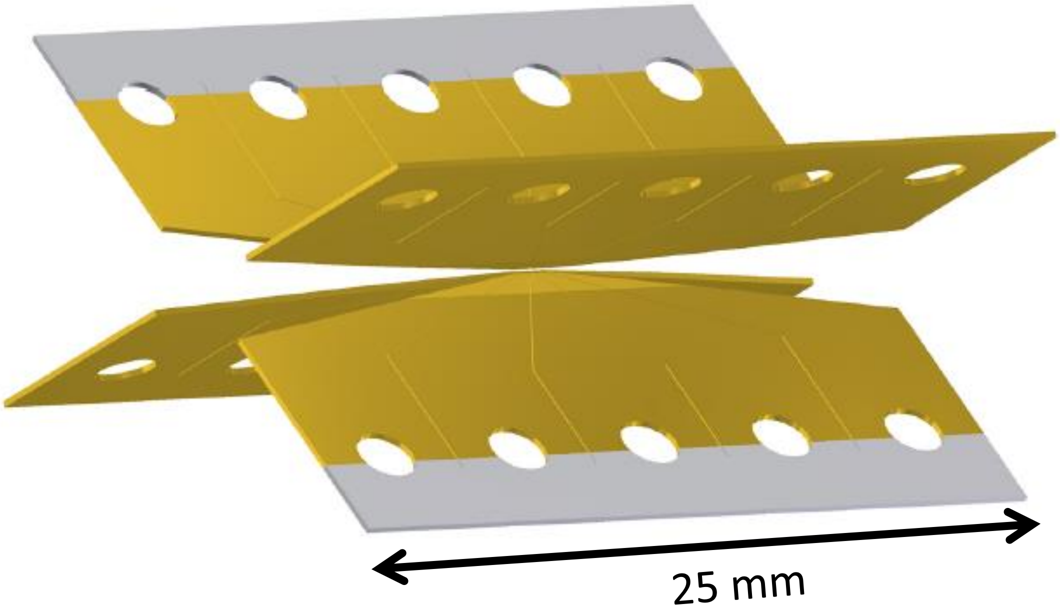


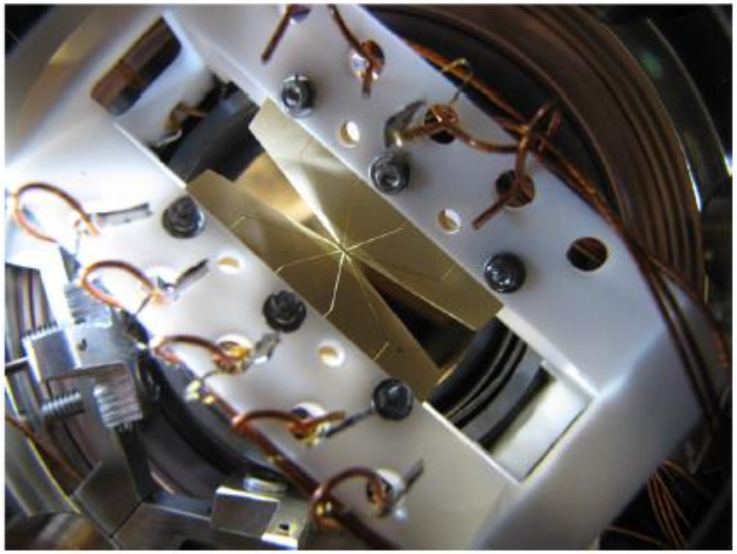


Linear rf trap
designed by Chris Monroe's Group



Linear rf trap designed by Chris Monroe’s Group



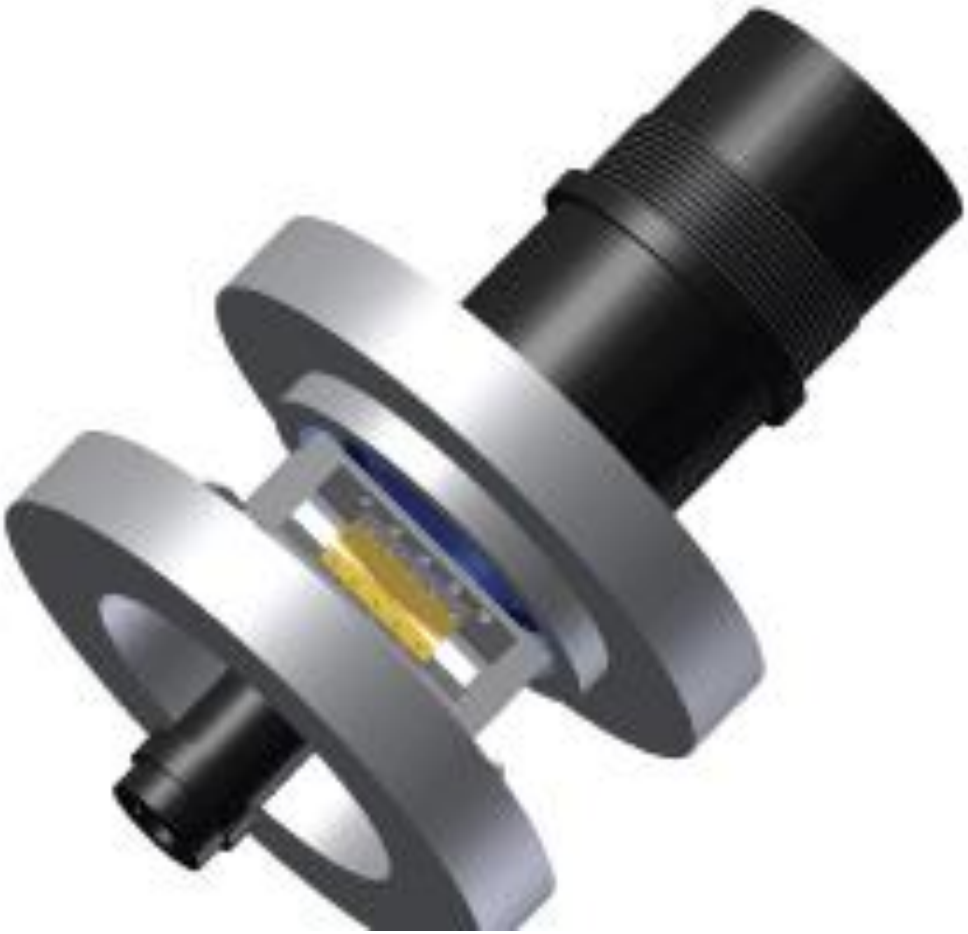


Blade mat.:
Gold on
Alumina

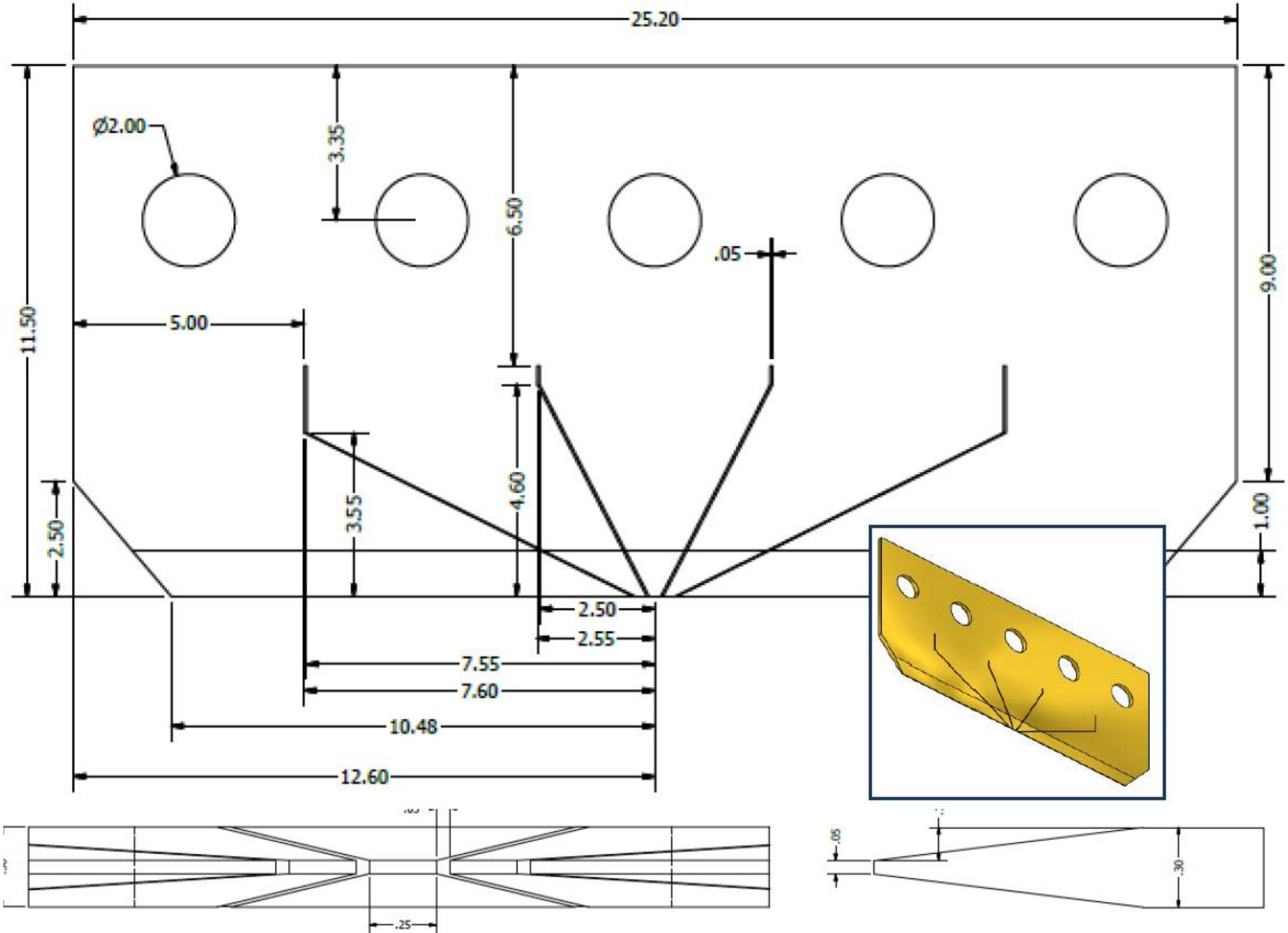
From PhD thesis of David Hucul

Linear rf trap
designed by Chris Monroe's Group

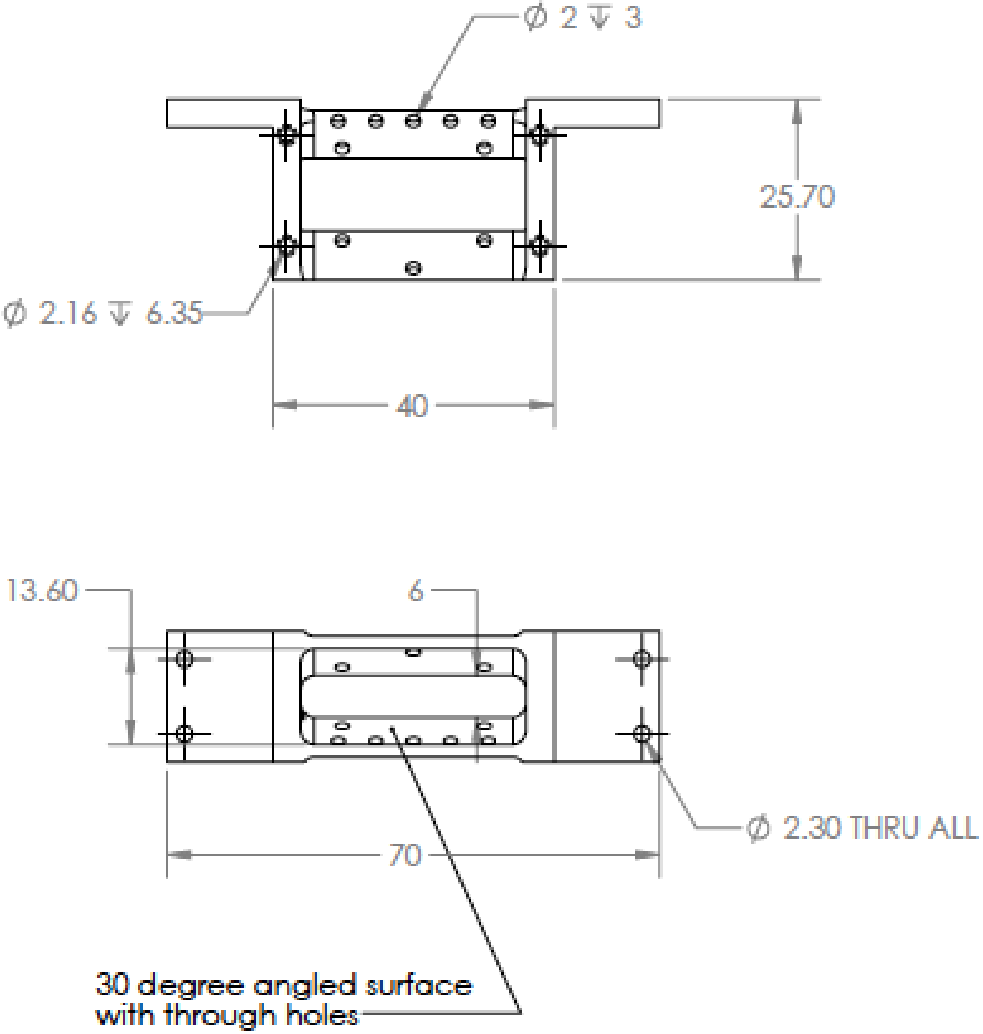
Imaging setup

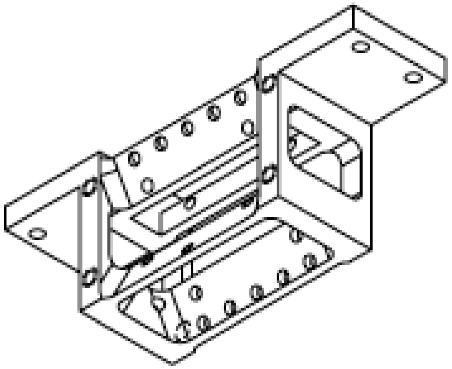


TEQ linear rf (ac) trap?
Design by Chris Monroe’s Group



TEQ linear rf (ac) trap?
Design by Chris Monroe’s Group

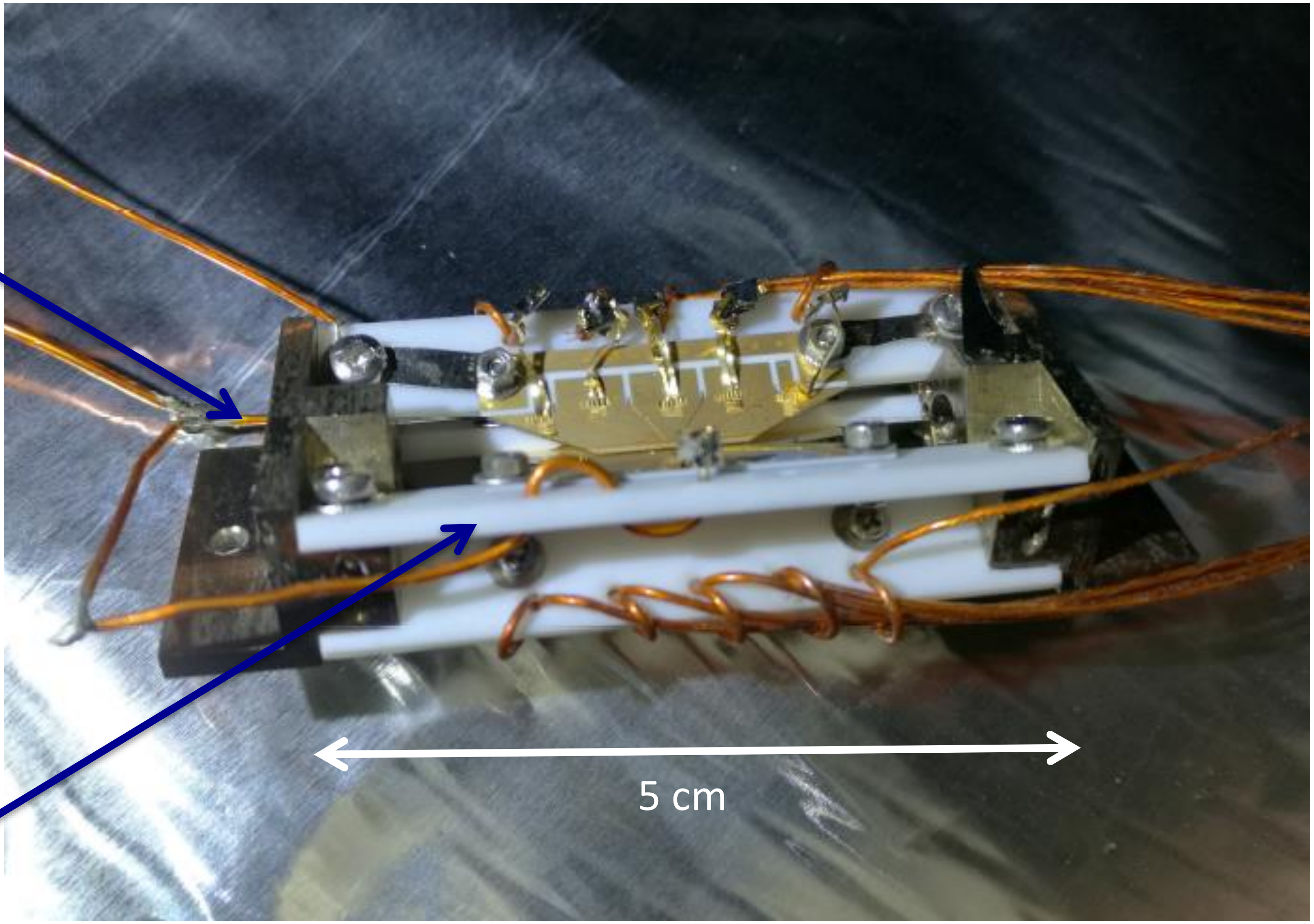




Blade Trap Holder
Drawn By: P.W. Hess
Material: Sapphire or Alumina
Notes:

- All Units in mm
- Tolerances on angled surfaces < 1 mil (0.025 mm)

Another option for blade support constructed by Shuoming An, Tsinghua Uni.

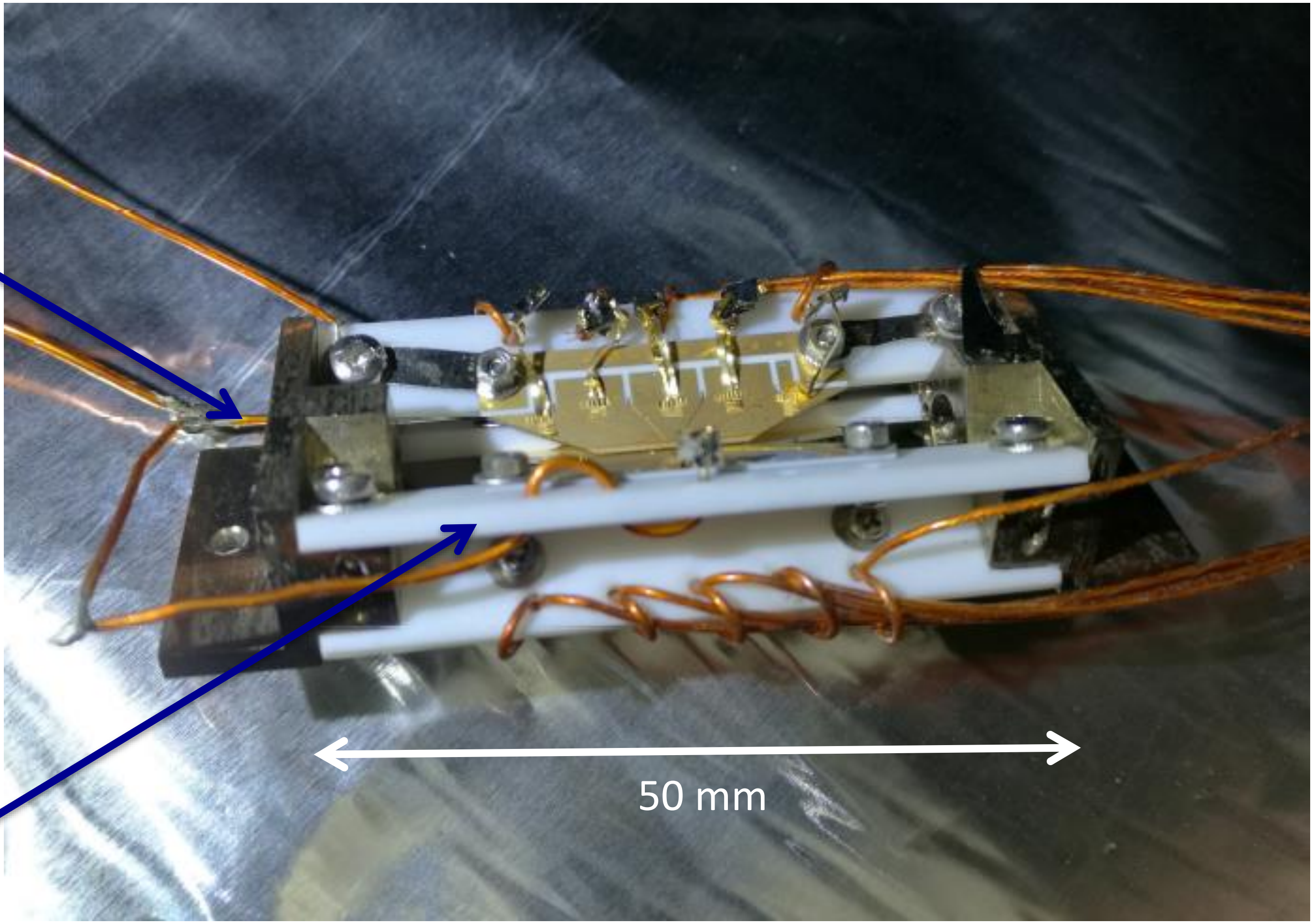


Stainless steel

Macor®

5 cm

Another option for blade support constructed by Shuoming An, Tsinghua Uni.



Copper

Shapal^{TM}

50 mm

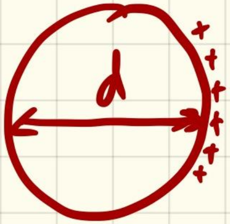
Monolitic blade electrode holder best for precise alignment

II) Requirements related to the electronics and heating

ISSUES REGARDING THE TRAP DESIGN

PARAMETERS RELATED TO PARTICLES:

(1)



$d = 100\,\text{nm}$, $\rho = 5\,\text{g/cm}^3$ $\Rightarrow$

$$\boxed{\begin{array}{l} Q = 10 - 10^{4}\,e\ (!?) \\ m = 2.6 \cdot 10^{-18}\,\text{kg} \end{array}}$$

RADIAL FREQUENCY:

$$(*)\quad \omega_r^2 = \frac{q^2}{8}\Omega^2 - \frac{1}{2}\omega_z^2 \quad , \quad U_{RF}(t) = U_{RF}\cos(\Omega t)$$

$$(**)\quad q = \frac{2U_{RF}}{r_0^2\Omega^2} \times \frac{Q}{m}$$

STABLE MOTION: $q \in [0; 0.9]$

DC - SUPPLY

REQUIREMENT FROM EXCLUSION PLOT :

(1) FORCE NOISE POWER SPEZ. : $\sqrt{S_F(\omega)} \le 3 \cdot 10^{-22}\ \mathrm{N}/\sqrt{\mathrm{Hz}}$ @ $\omega = 2\pi \times (100-1000\,\mathrm{Hz})$

IN GENERAL, ONE CAN ESTABLISH A SIMPLE RELATION BETWEEN THE POWER SPECTRUM OF THE ELECTRIC FIELD NOISE $S_E(\omega)$ AND OF THE VOLTAGE APPLIED:

$$\text{(II)} \qquad \boxed{S_E(\omega) = A\,\frac{S_V(\omega)}{D^2}}$$

HERE, D DEPENDENT ON THE GEOMETRY AND SIZE OF THE TRAP ELECTRODES, AND A IS RELATED TO THE NUMBER OF ELECTRODES TO WHICH A VOLTAGE IS APPLIED.

FOR THAT CONSIDERED MAXIMAL VOLTAGES OF ~50V ARE NEEDED. HENCE,

REQUIREMENTS FOR DC-SUPPLIES:

(V) $$\boxed{S_V^{DC}(\omega) \lesssim 5\cdot 10^{-16}\ V^2/Hz \quad @^{\omega=100-1000\,Hz} \text{ AND } V_{DC}=50\,V}$$

THE REQUIREMENT TO THE AC-SUPPLY IS AT LEAST A FACTOR OF 10 SMALLER, DUE TO THE FACT THAT IT IS THE SAME SOURCE APPLIED TO THE VARIOUS ELECTRODES, THERE ARE FEWER ELECTRODES, AND IN PRINCIPLE THE NOISE WILL MAINLY ACT ON THE RADIAL MOTION. HENCE,

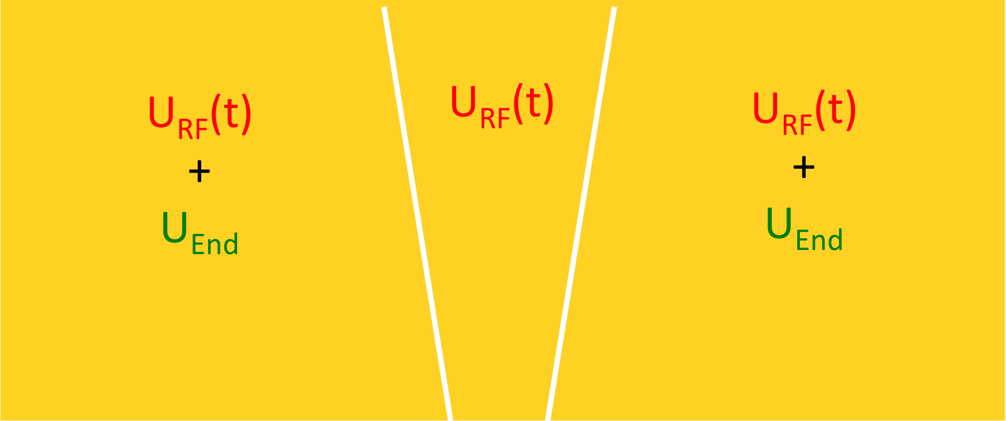
REQUIREMENTS FOR AC SUPPLY:

(VI) $$S_V^{AC}(\omega) \lesssim 5 \cdot 10^{-15}\ V^2/Hz \ @\ \omega = (100 - 1000\ Hz)\times 2\pi,\ V_{AC} = 30\ V, \text{ and } \omega_{AC} = 2\pi(1-10\ kHz)$$

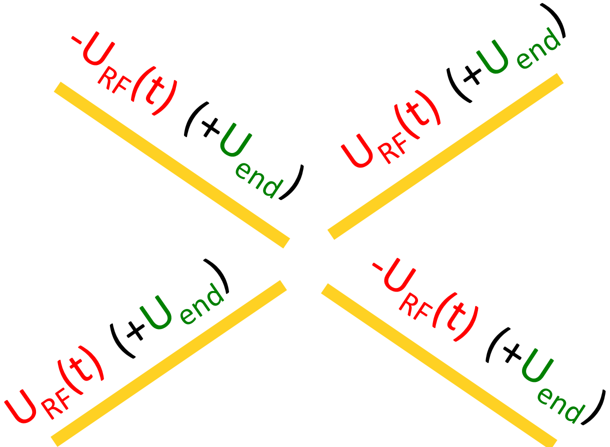
Can we meet these requirements in both potential trap configurations?

Blade electrode trap I

Blade electrode structure



Mounted electrodes
in an end view:

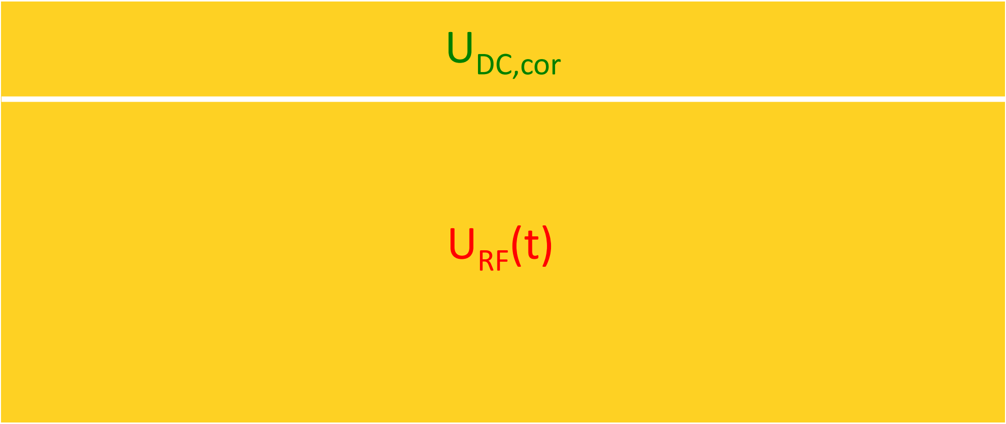


Note:

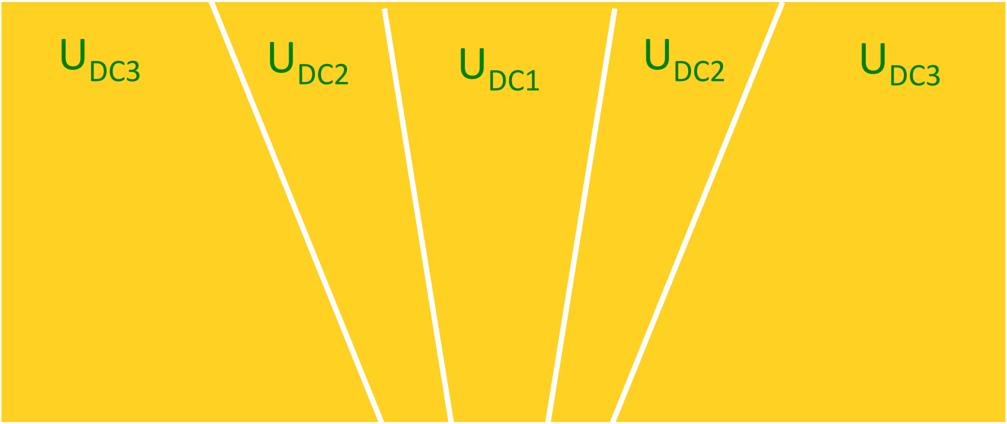
$U_{RF}(t)$ and U_{end} has to be mixed together.

Blade electrode trap II

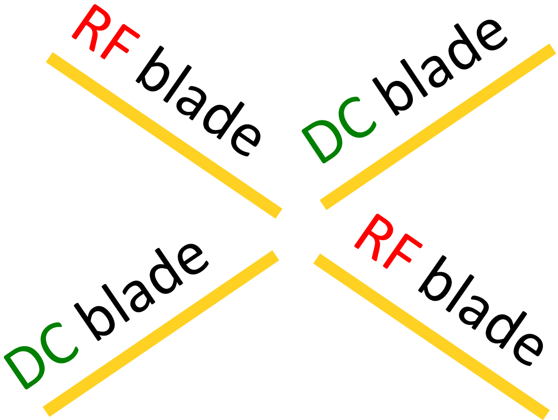
RF blade electrode



DC blade electrode



Mounted electrodes in an end view:



No mixing of $U_{RF}(t)$ and U_{end} needed!

WHAT ABOUT HEAT LOAD?

IF LEAD WIRES HAS A LENGTH OF $l = 20\,\text{cm} = 0.2\,\text{m}$

⇒ CU WIRING

$$R_{WIRE} = 6.7 \cdot 10^{-5}\,\Omega$$

$$R_{EXTERNAL} = 3 \cdot 10^{-5}\,\Omega$$

$l \sim 0.01\,\text{m}$

⇒ $$\boxed{R_{TOT} = 20 \times (R_{WIRE} + R_{EXT.}) \simeq 2\,\text{m}\Omega.} \quad (4)$$

THEN THE TOTAL MEAN ELECTRICAL POWER DISSIPATED IS

$$\overline{P_{TOT}} = R_{TOT} \cdot \overline{i^2(t)}$$

$$= \frac{1}{2} R_{TOT} \cdot C_{TOT}^2 \cdot \Omega^2 \cdot U_{RF}^2$$

FOR $\Omega = 2\pi \times 30\,\mathrm{kHz}$ AND $U_{RF} \hat{=} 300\,\mathrm{V}$, ONE GETS

(5) $$\boxed{\overline{P_{TOT}} = 1.3 \cdot 10^{-7}\,\mathrm{W} = 0.1\,\mu\mathrm{W} \ll P_{Ca40} \approx 50\,\mu\mathrm{W}}$$

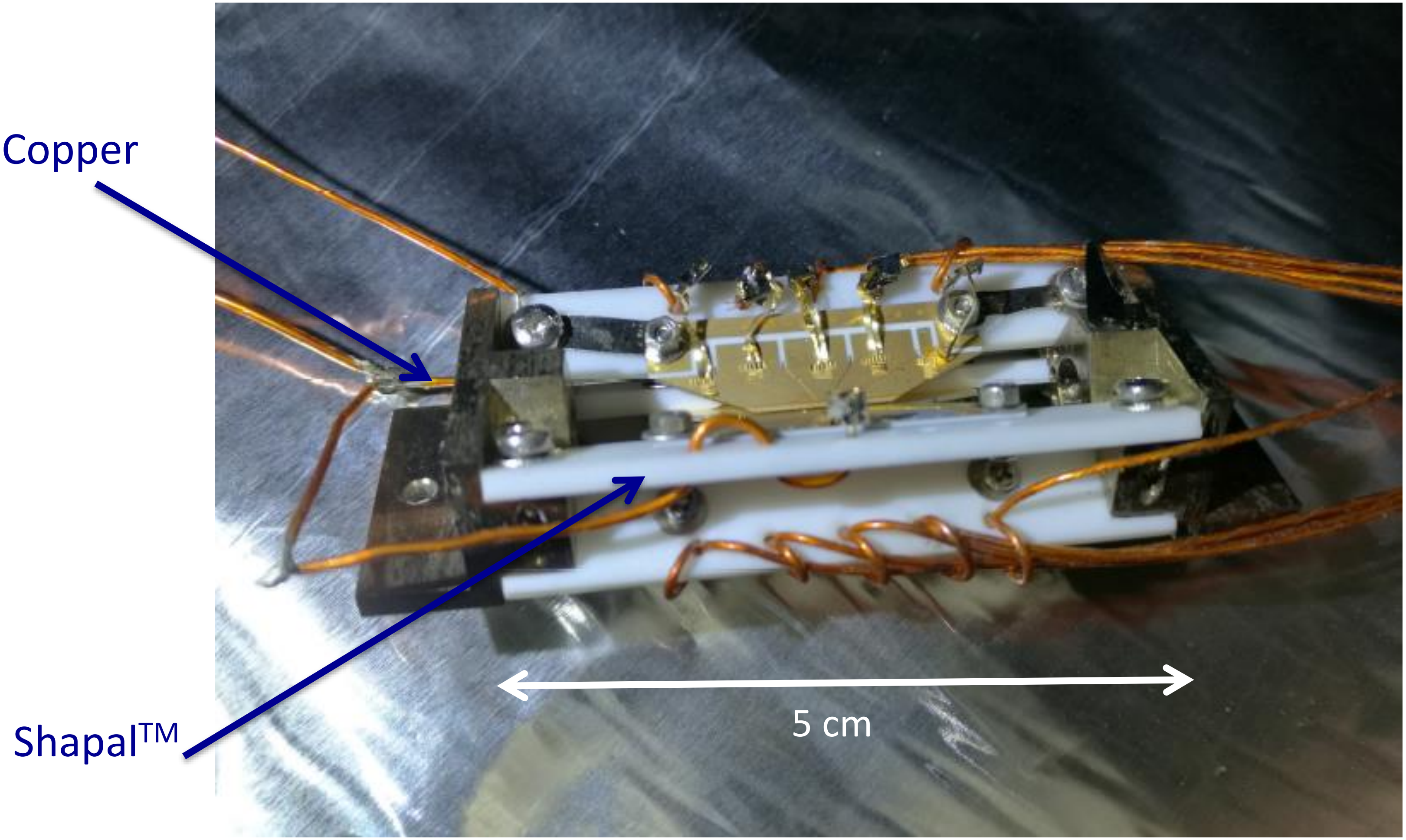
GREAT!

ESTIMATE OF TEMPERATURE DIFF. ΔT BETWEEN TRAP AND CRYO-HEAD:

ESTIMATE OF HEAT LOAD FROM WIRES

GOING FROM 4K → 20 mK

Another option for blade support constructed by Shuoming An, Tsinghua Uni.



III) Passive NC cooling

NOTES ON RADIATIVE AND BUFFER GAS COOLING

RADIATIVE COOLING:

$$\left\{\begin{array}{l} \dfrac{dE_{NC}}{dt} = -A\cdot\sigma\, T^4, \quad A = 4\pi\cdot r_{NC}^2 \ \text{AND} \\ \qquad\qquad \sigma = \text{STEFAN-BOLZMAN CONST} \\ \qquad\qquad\quad = 5.67\cdot 10^{-8}\, W\, m^{-2}\, K^{-4} \\ E_{NC} = C_{TOT}(T)\cdot T = \frac{4\pi}{3}\rho_{NC}\cdot r_{NC}^3\, C_m(T)\cdot T, \end{array}\right.$$

$C_m(T)$ = HEAT CAPACITY/kg

$\Downarrow$

$$\boxed{\begin{aligned} \frac{dT}{dt} &\equiv -\alpha_R(T)T^4, \\ \alpha_R(T) &= \frac{3\sigma}{C_m(T)\cdot\rho_{NC}\cdot r_{NC}} \end{aligned}} \quad (8)$$

ASSUME $\alpha_R = \text{CONST}$:

$$\frac{dT}{dt} = -\alpha_R T^4 \Rightarrow \frac{1}{T^4}\, dT = -\alpha_R\, dt$$

$$\Downarrow \quad \left[-\frac{1}{3}\frac{1}{T^3}\right]_{T_0}^{T} = -\alpha_R (t - t_0)$$

$$\Downarrow \quad \frac{1}{3}\left[\frac{1}{T_0^3} - \frac{1}{T^3}\right] = -\alpha_R t \qquad (t_0 \equiv 0)$$

$$\Downarrow$$

$$(9) \quad \boxed{T^3 = \frac{1}{\frac{1}{T_0^3} + 3\alpha_R t}}$$

ASSUME NOW $T_{\text{FINAL}} \ll T_0$ (EX: $T_0 \simeq 300\text{K}$, $T_{\text{FINAL}} = 300\text{mK}$)

THEN

$$(10) \quad \boxed{T \simeq \beta_R\, t^{-1/3}, \quad \beta_R \equiv \frac{1}{(3\alpha_R)^{1/3}}}$$

LET'S LOOK AT TYPICAL COOLING TIMES:

$$\left\{ \begin{array}{l} r_{nc} = 50\,nm, \quad \rho_{np} = 2200\,kg/m^3, \quad c_m = 700\,J/(kg \cdot K) \\[2ex] \alpha_R = \dfrac{3\sigma}{c_m \rho_{nc} \cdot r_{nc}} \end{array} \right.$$

$\Downarrow$

$$\alpha_R = 2.2 \cdot 10^{-6} \frac{1}{s\,K^3}$$

$$\beta_R = \frac{1}{(3\alpha_R)^{1/3}} \Rightarrow \beta_R = 53 \frac{K}{s^{-\frac{1}{3}}}$$

$$T \simeq \beta_R\, t^{-1/3} \quad \text{AND} \quad T_{FINAL} = 1K$$

$\Downarrow$

$$\boxed{t_{FINAL} \simeq 1.5 \cdot 10^5\,sec \sim 50\ \text{HOURS}!} \tag{11}$$

NB: EXTREMELY LONG TIME $\Rightarrow$ TRAPPING AT LOW TEMP FOR WEEKS NEEDED!

BUFFER GAS COOLING:

WE WILL ASSUME $m_{BG} \ll m_{NC}$, WHICH IS CLEARLY SATISFIED FOR A BUFFER GAS OF ^3He!

IN THIS SCENARIO A HEAD ON COLLISION WILL LEAD TO THEN FOLLOWING KINETIC APPROXIMATION

BEFORE COLLISION

AFTER COLLISION

HENCE:

$$E_{BG}^{f} = \frac{1}{2} m_{BG} \cdot v_{BG}^{f\,2}$$

$$= E_{BG}^{i} + \frac{1}{2} m_{BG} \cdot v_{NC}^{i\,2} \pm m_{BG} \cdot v_{BG} \cdot v_{NC}^{i}$$

THE SIGN OF THE LAST TERM DEPENDS ON THE DIRECTION OF $\vec{v}_{NC}$

SO IN AVERAGE IT WILL BE ZERO, AND THE AVERAGED GAINED ENERGY OF THE BUFFER GAS PARTICLE WILL BE

$$\Delta E_{BG} = \frac{1}{2} m_{BG} v_{WC}^{i\,2}$$

ENERGY CONSERVATION GIVES HENCE

$$\boxed{\begin{aligned}\Delta E_{WC} &= -\frac{1}{2} m_{BG} \cdot v_{WC}^{i\,2} \\ &= -\frac{1}{2} \frac{m_{BG}}{m_{WC}} \cdot k_B T ,\end{aligned}} \tag{12}$$

SINCE $\frac{1}{2} k_B T = \frac{1}{2} m_{WC} \cdot v_{WC}^{i\,2}$.

IF WE ASSUME A COLLISION RATE OF Γ_{coll} THEN WE CAN ESTABLISH THE FOLLOWING EQUATION

FOR THE INTERNAL ENERGY LOSS OF THE NC:

$$\frac{dE_{NC}}{dt} = -\Delta E_{NC}\cdot\Gamma_{coll}$$

$$\Downarrow$$

$$C_{tot}(T)\cdot\frac{dT}{dt} = -\frac{1}{2}\frac{m_{BG}}{m_{NC}}\cdot k_B\Gamma_{coll}\cdot T$$

$$\Downarrow$$

$$\boxed{\begin{aligned}\frac{dT}{dt} &\equiv -\alpha_{BG}\,T\,, \\ \alpha_{BG} &\equiv \frac{1}{2}\,\frac{m_{BG}}{m_{NC}}\,\frac{k_B\Gamma_{coll}}{C_{tot}(T)}\end{aligned}} \tag{13}$$

SINCE $m_{NC} = \frac{4\pi}{3}\rho_{NC}\cdot r_{NC}^3$, $C_{tot} = \frac{4\pi}{3}\rho_{NC}\cdot r_{NC}^3\cdot C_m$

AND $\Gamma_{coll} = \Phi_{BG}\cdot\underset{\pi\cdot r_{NC}^2}{\underset{\approx}{\sigma_{coll}}}$, WHERE Φ_{BG} = FLUX OF BG ATOMS

σ_{coll} = COLLISIONAL CROSS-SECTION

WE CAN REWRITE α_{BG} AS

$$\alpha_{BG} = \frac{9}{32\pi} \times \frac{m_{BG}\cdot k_B}{\rho_{wc}^2\cdot C_m} \times \frac{1}{r_{wc}^4} \times \underset{\| \; n_{BG}\cdot\bar{v}_{BG}}{\Phi_{BG}}$$

ASSUMING THE BG ATOMS IS AN IDEAL GAS, THEN

$$\begin{cases} n_{BG} = \dfrac{P_{BG}}{k_B T_{BG}} \\ \bar{v}_{BG} = \left(\dfrac{3k_B T_{BG}}{m_{BG}}\right)^{1/2} \end{cases}$$

$$\Downarrow$$

$$\Phi_{BG} = P_{BG}\cdot\left(\frac{3}{m_{BG}\cdot k_B\cdot T_{BG}}\right)^{1/2}$$

AND

$$\boxed{\alpha_{BG} = \frac{3^{\frac{5}{2}}}{32\pi} \times \frac{P_{BG}}{\rho_{wc}^2\cdot C_m} \times \left(\frac{m_{BG}\cdot k_B}{T_{BG}}\right)^{1/2} \times \frac{1}{r_{wc}^4}} \tag{14}$$

EXAMPLE:

$\rho_{WC} = 2200\,kg/m^3$ $\quad$ $r_{WC} = 50\,nm$

$c_m = 700\,J/(kg \cdot K)$

$T_{BG} = 1K$

$P_{BG} = 10^{-3}$ mbarr $= 0.1$ PASCAL

$m_{BG} = 3 \cdot 1.67 \cdot 10^{-27}\,kg = 5 \cdot 10^{-27}\,kg$

(14) $\Downarrow$

$\alpha_{BG} \approx 2 \cdot 10^{-7}\,s^{-1}$

$\Downarrow$

(15) $\tau_{BG} \equiv \frac{1}{\alpha_{BG}} = 5 \cdot 10^{6}\,s \approx 1000$ HOURS

≈ 40 DAYS

≈ 1 MONTH !

SOLUTION: SMALLER WC's OR $P_{BG} \approx 1$ mbarr $= 100$ PASCAL ?!

$P = 1\,\text{mbar} = 100\,\text{pascal}$ and $T_{BG} = 1\,K$

$\Downarrow$

$n_{BG} = 7 \cdot 10^{24}\, m^{-3}$ (solid He: $n \sim 10^{28}$)

so ok!

($\lambda_{\text{de Broglie}}$= 1.5 nm @ T=1K)

Same results would be achieved by assuming a lower T_{BG}

IV) Still unresolved issues

I) Integrating of optical elements (Imaging and cooling)

I) CNP loading

II) Resistive cooling (Circuitry at 4K or lower?)

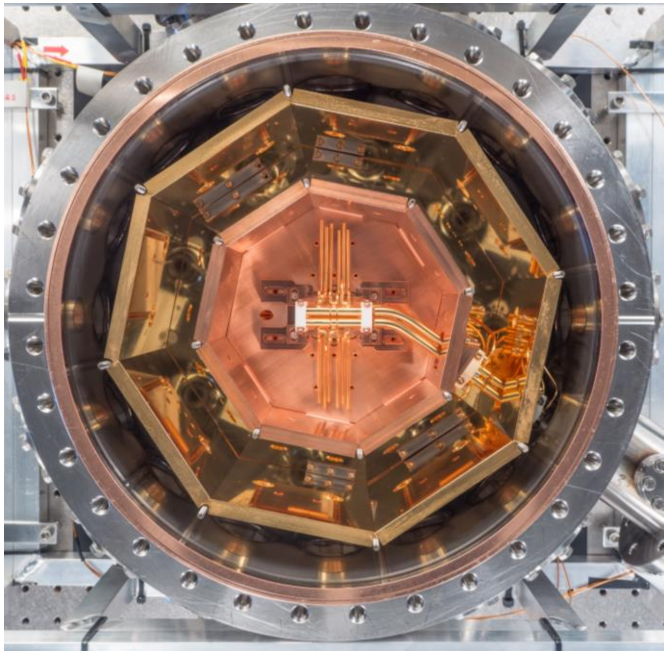
I) Effect of charge migration on the NCs during experiments

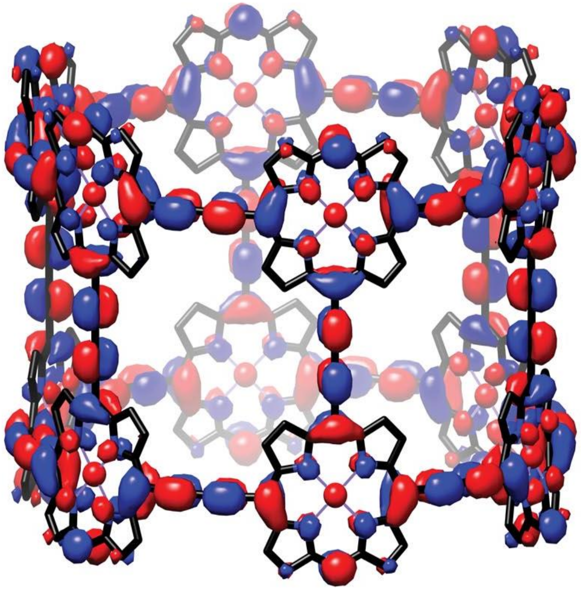
II) Changing in mass during an experiment due to adsorption

I) …

Potentially new AU TEQ contribution

Experiments med ground-state-cooled
highly-charged bio-molecule homologues
in a cryogenically cooled linear rf trap





Cryogenically cooled linear rf trap

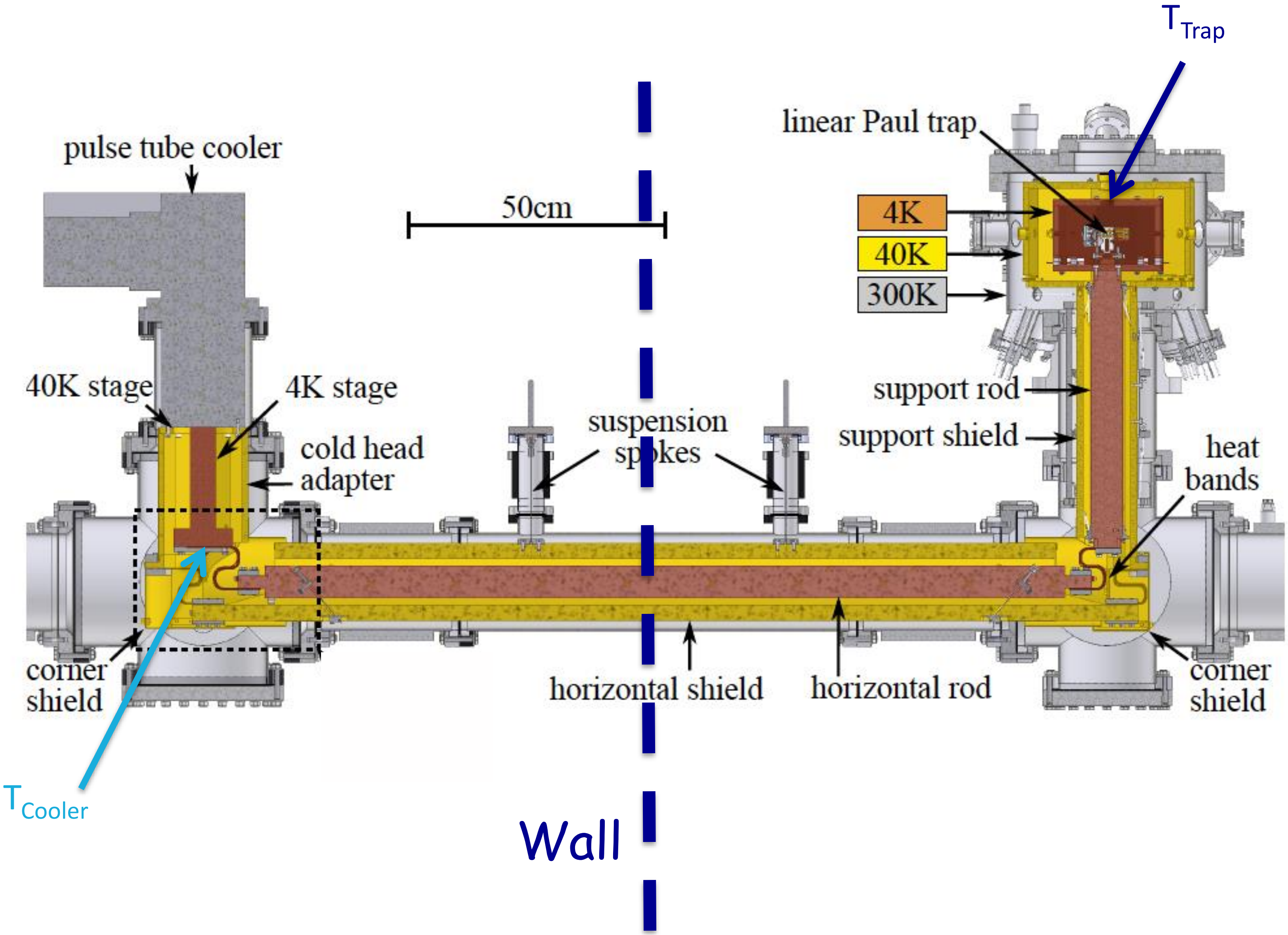
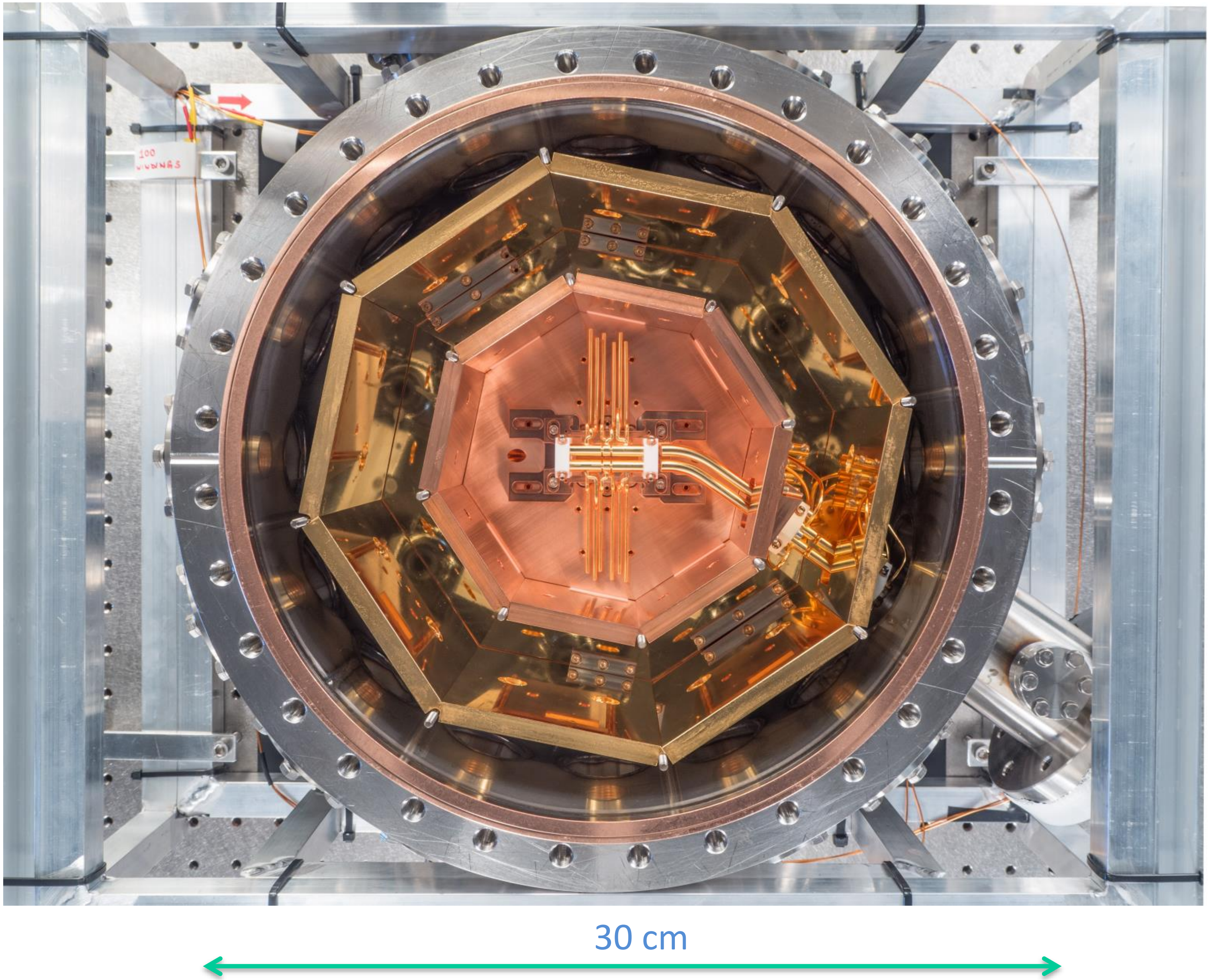
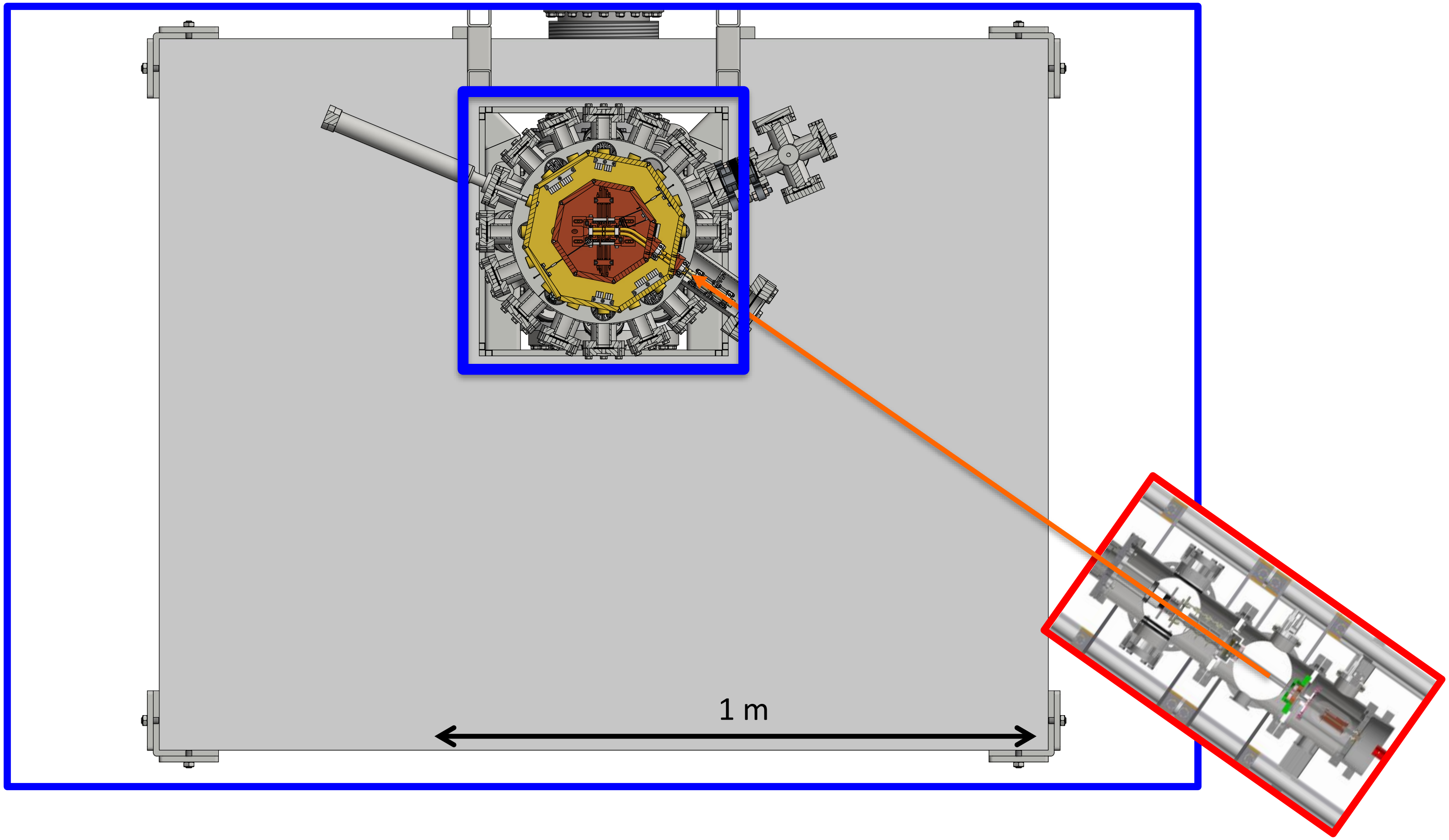


Photo of central trapping region



Idea:

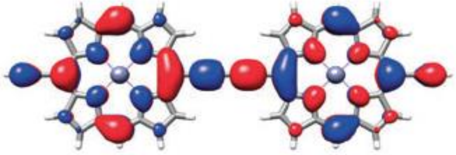
Work with *single*, charged molecular species injected from an electrospray source into a cryogenically cooled ion trap:



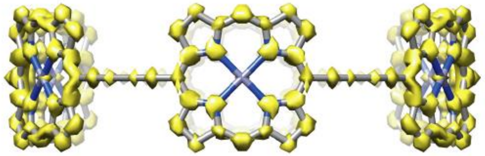
New collaborator

Prof. Harry L. Anderson
Dept. Chemistry
University of Oxford

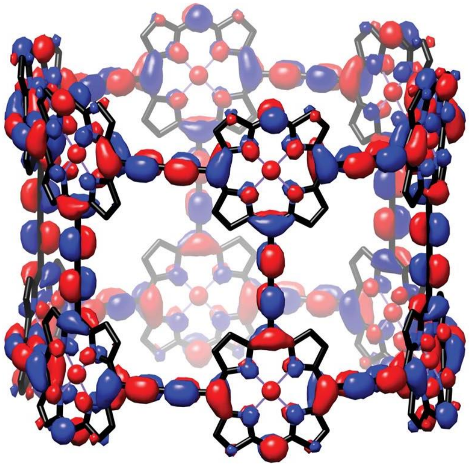
Molecular Engineering



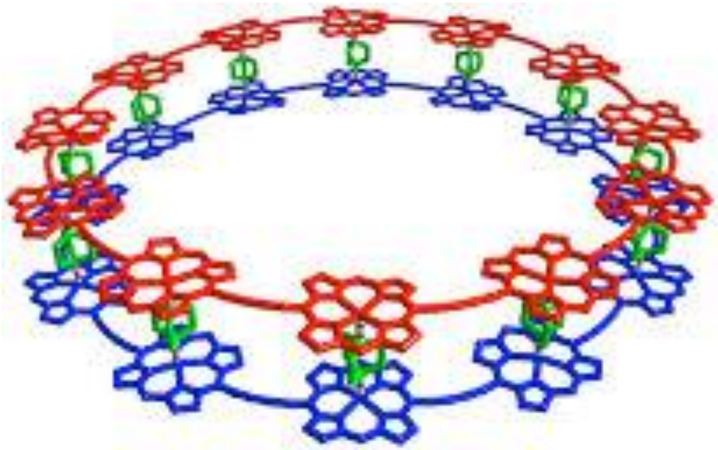
2-porphyrin



6-porphyrin

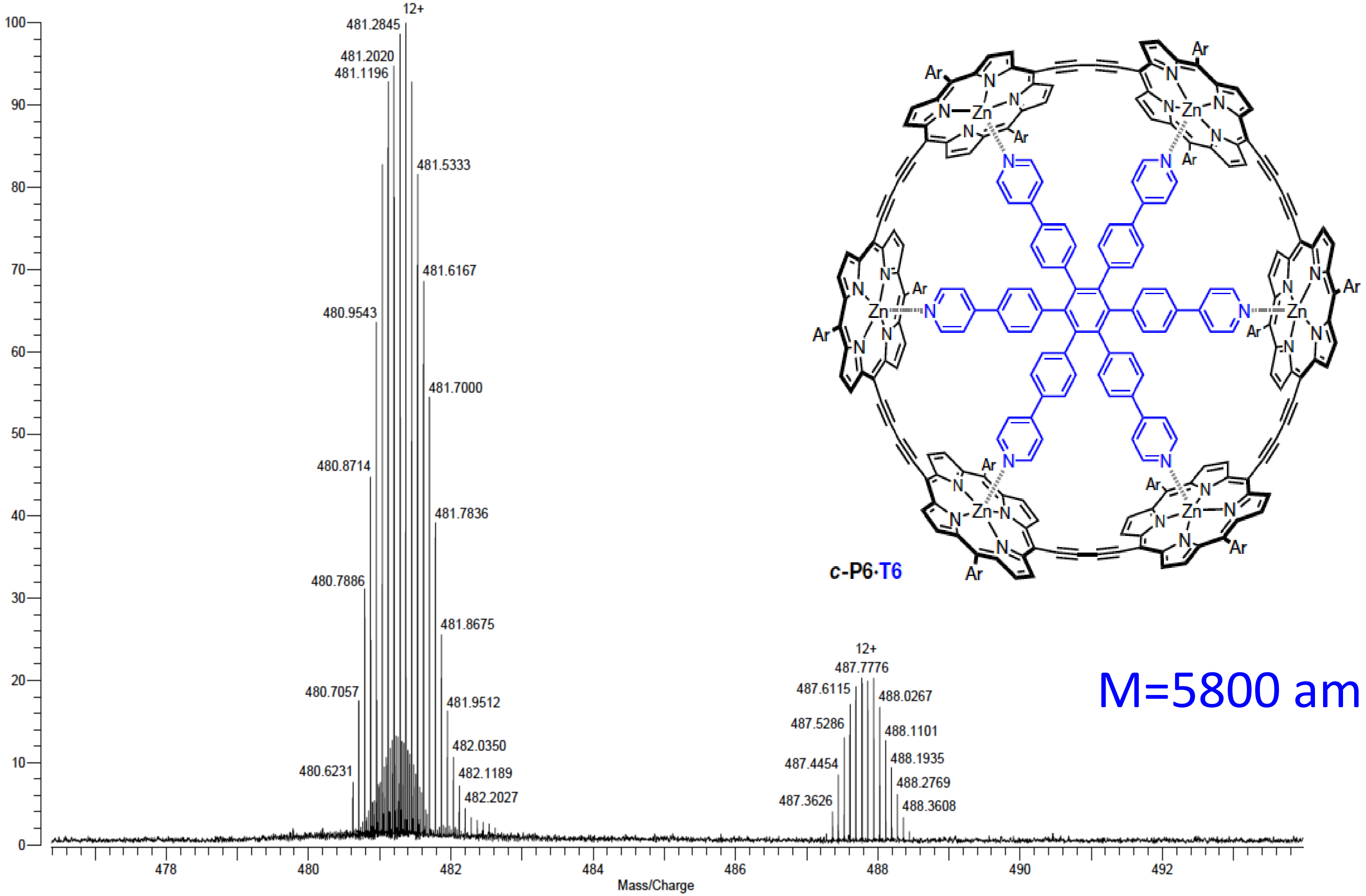


12-porphyrin



24-porphyrin

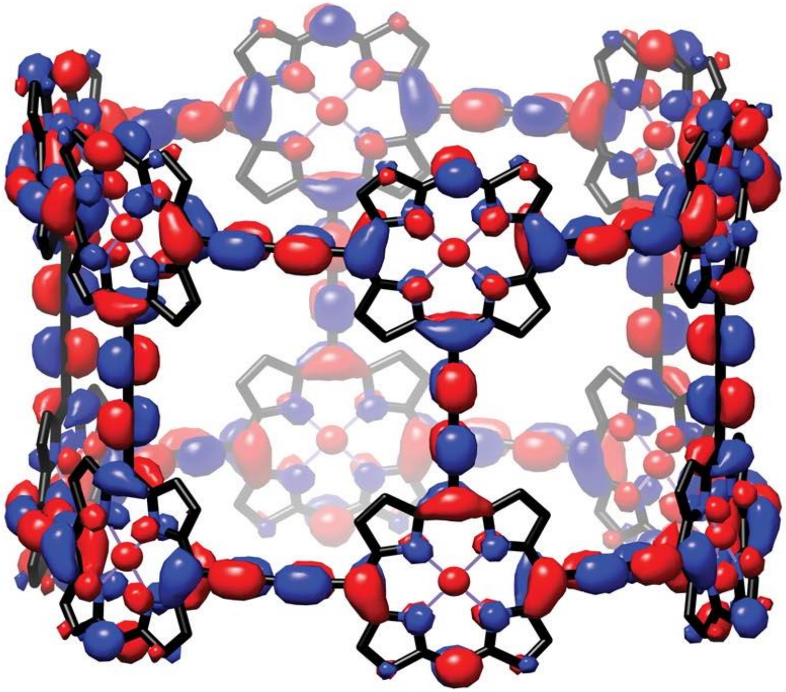
Electrospay mass spectra of highly charged c-P6•T6 porphyrine



c-P6·T6

M=5800 amu

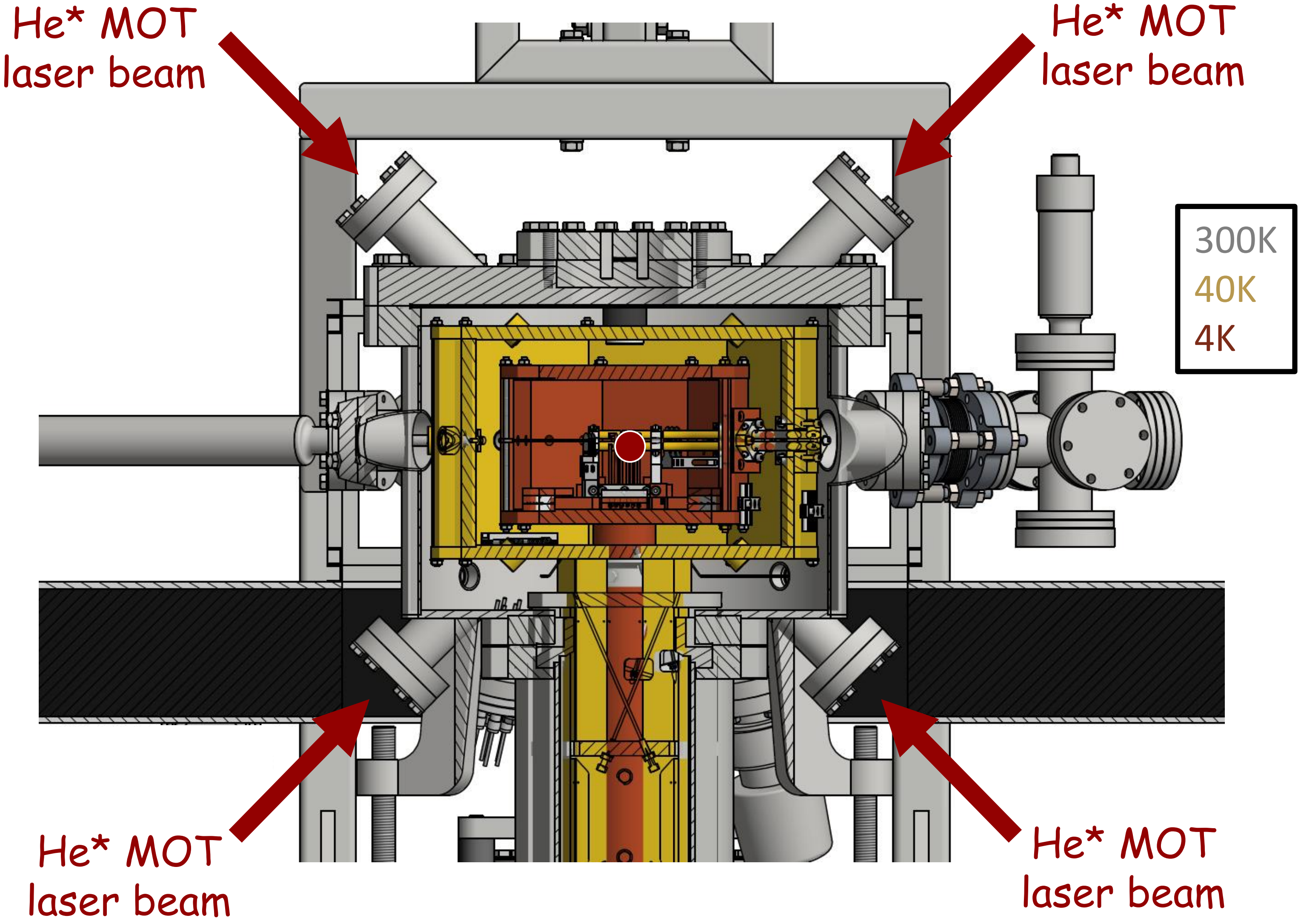
12-porphyrine



M>10^4 amu !

Next step:

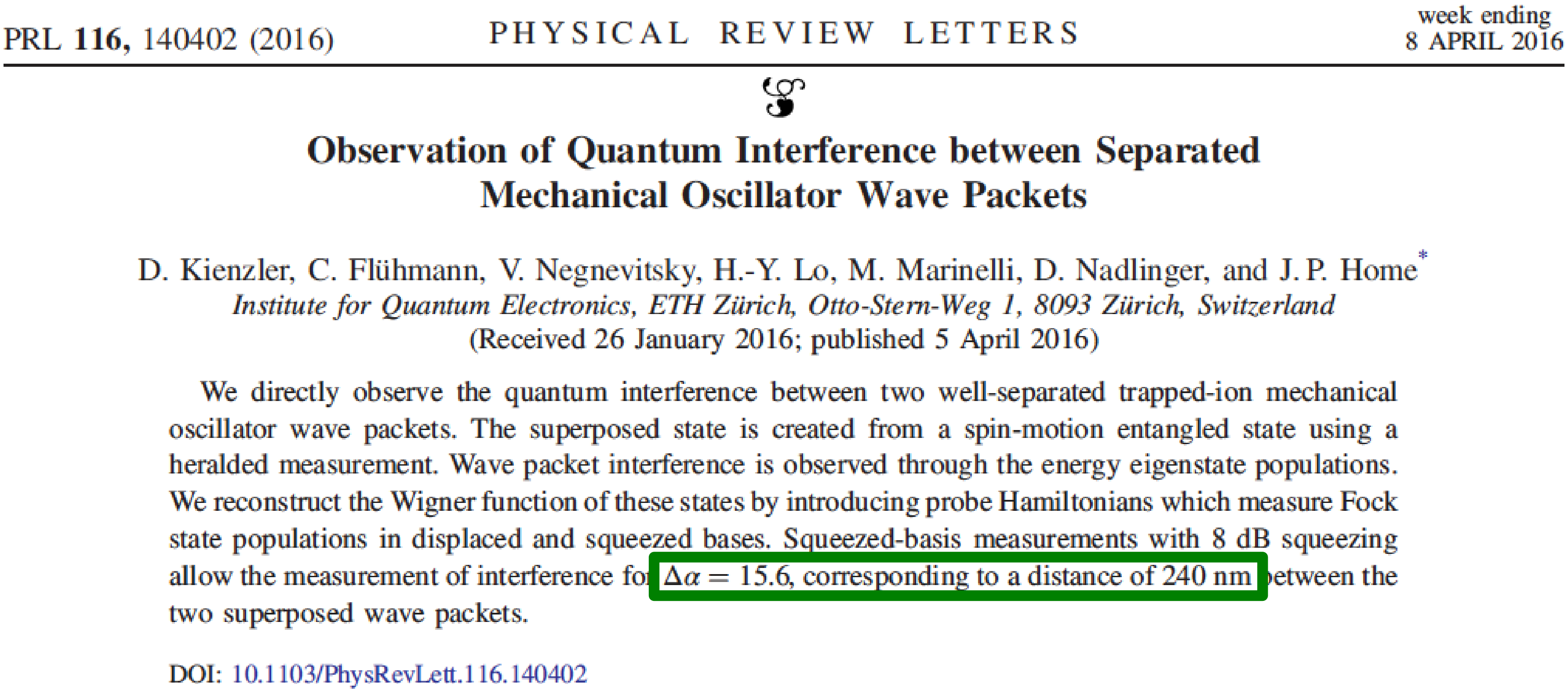
Buffer gas cooling with quenched He* MOT atoms



T_{He} ~ 1 mK => hopefully very cold molecular ions too!

Ways towards improved detection sensitivity?

I) Creation of Schrödinger’s Cat states



PRL **116,** 140402 (2016) PHYSICAL REVIEW LETTERS week ending 8 APRIL 2016

Observation of Quantum Interference between Separated Mechanical Oscillator Wave Packets

D. Kienzler, C. Flühmann, V. Negnevitsky, H.-Y. Lo, M. Marinelli, D. Nadlinger, and J. P. Home*
Institute for Quantum Electronics, ETH Zürich, Otto-Stern-Weg 1, 8093 Zürich, Switzerland

(Received 26 January 2016; published 5 April 2016)

We directly observe the quantum interference between two well-separated trapped-ion mechanical oscillator wave packets. The superposed state is created from a spin-motion entangled state using a heralded measurement. Wave packet interference is observed through the energy eigenstate populations. We reconstruct the Wigner function of these states by introducing probe Hamiltonians which measure Fock state populations in displaced and squeezed bases. Squeezed-basis measurements with 8 dB squeezing allow the measurement of interference for $\Delta\alpha = 15.6$, corresponding to a distance of 240 nm between the two superposed wave packets.

DOI: 10.1103/PhysRevLett.116.140402

$$|\psi_{\text{ent}}\rangle = \frac{1}{\sqrt{2}}(|+\rangle|\alpha\rangle + |-\rangle|-\alpha\rangle)$$

II) Quantum lock-in detection of change in motional state

Quantum Lock-in Force Sensing using Optical Clock Doppler Velocimetry

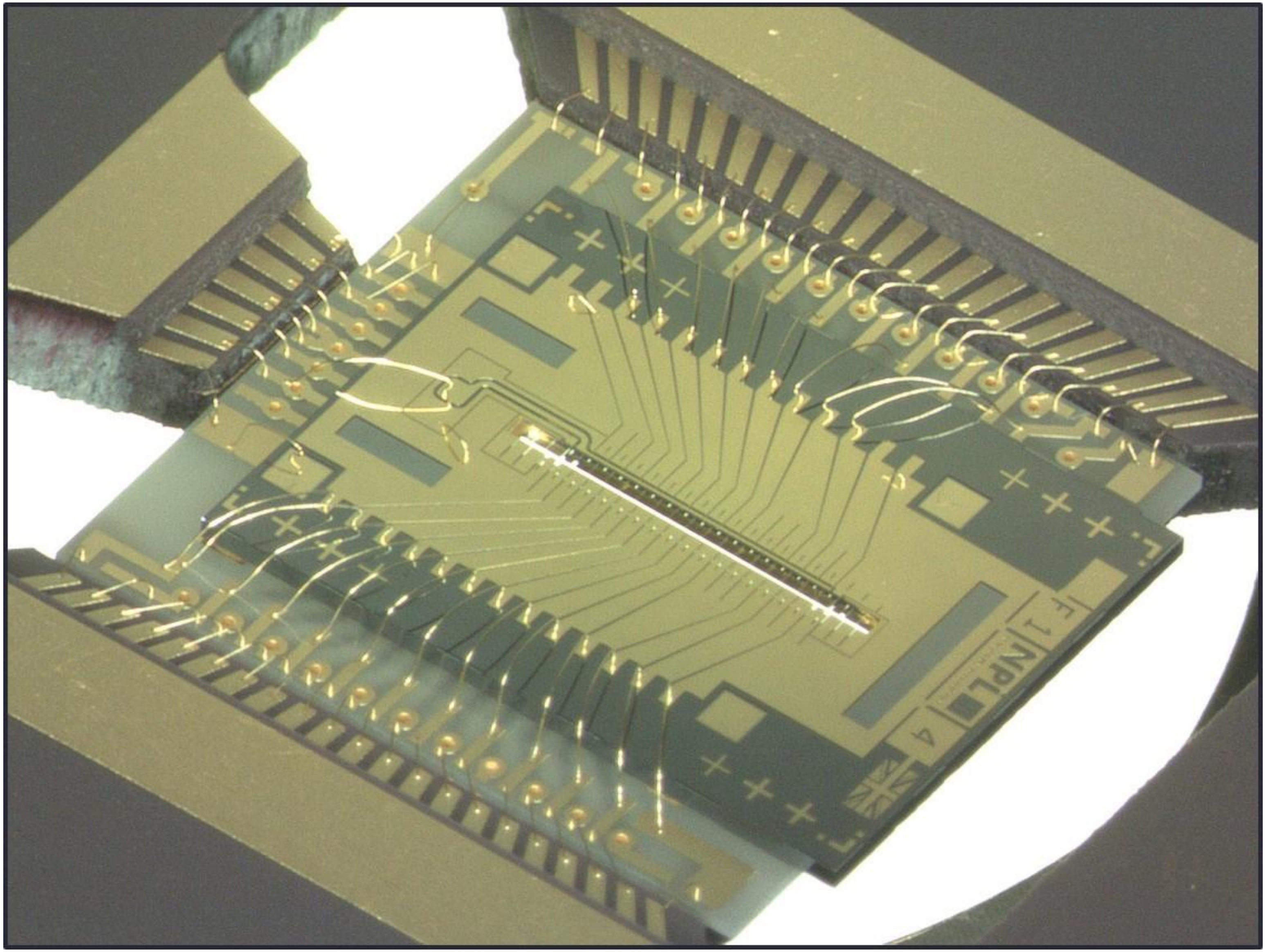
Ravid Shaniv[1] & Roee Ozeri[1]

March 1, 2016

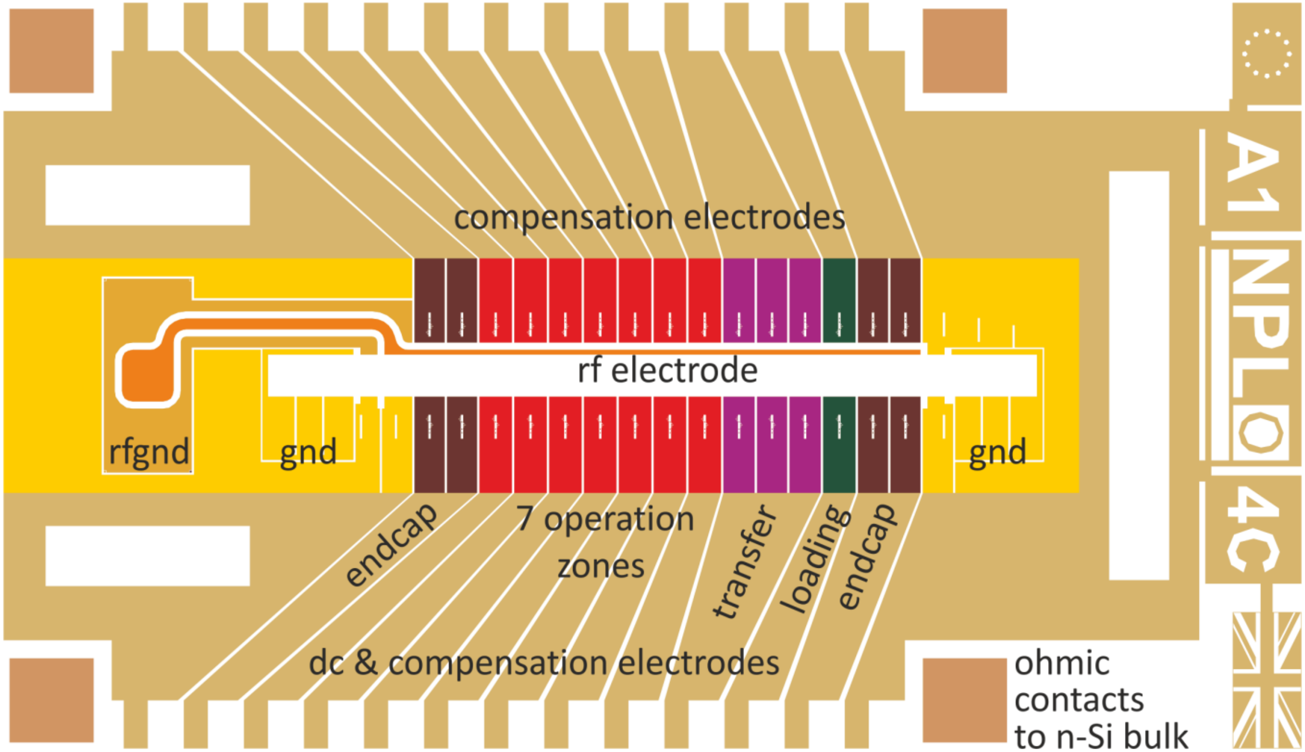
Abstract

Force sensors are at the heart of different technologies such as atomic force microscopy or inertial sensing [2, 1, 3]. These sensors often rely on the measurement of the displacement amplitude of mechanical oscillators under applied force. Examples for such mechanical oscillators include micro-fabricated cantilevers [3], carbon nanotubes [4] as well as single trapped ions [5, 6] . The best sensitivity is typically achieved when the force is alternating at the mechanical resonance frequency of the oscillator thus increasing its response by the mechanical quality factor. The measurement of low-frequency forces, that are below resonance, is a more difficult task as the resulting oscillation amplitudes are significantly lower. Here we use a single trapped $^{88}Sr^+$ ion as a force sensor. The ion is trapped in a linear harmonic trap, and is electrically driven at a frequency much lower than the trap resonance frequency. To be able to measure the small amplitude of motion we combine two powerful techniques. The force magnitude is determined by the measured periodic Doppler shift of an atomic optical clock transition and the Quantum Lock-in technique is used to coherently accumulate the phases acquired during different force half-cycles. We demonstrate force detection both when the oscillating force is phase-synchronized with the quantum lock-in sequence and when it is asynchronous and report frequency force detection sensitivity as low as $5.3 \times 10^{-19} \frac{\mathrm{N}}{\sqrt{\mathrm{Hz}}}$.

NPL monolithic trap

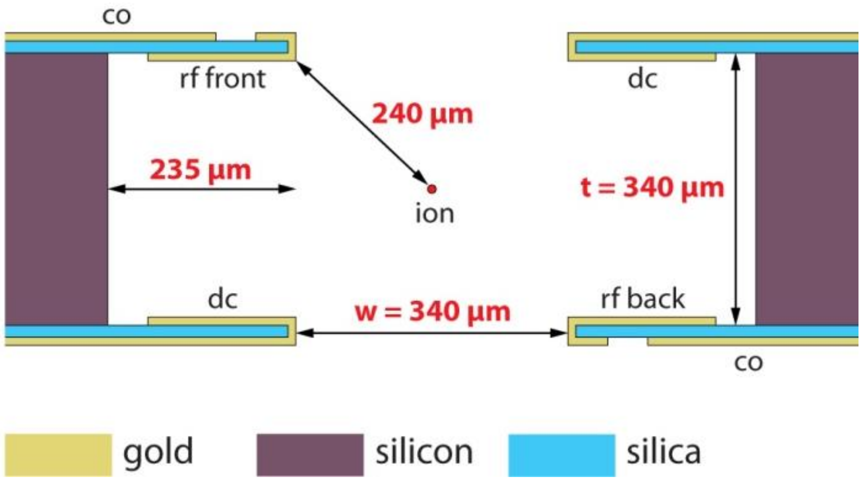


NPL monolithic trap



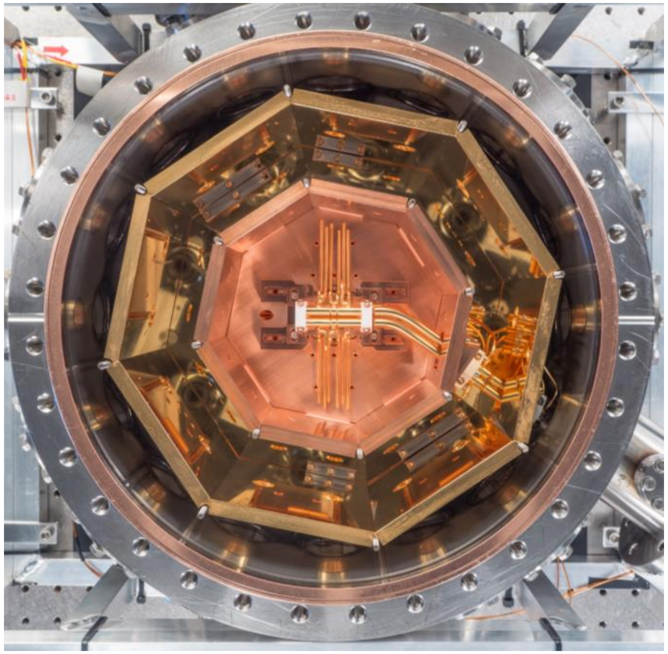
Electrode layout

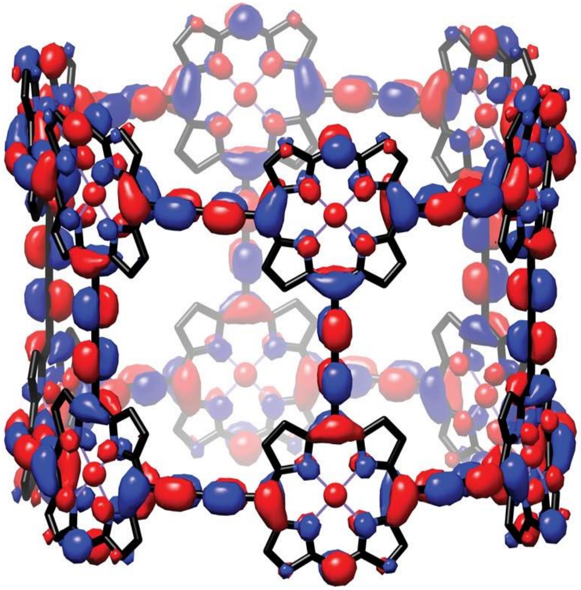
Cross-section



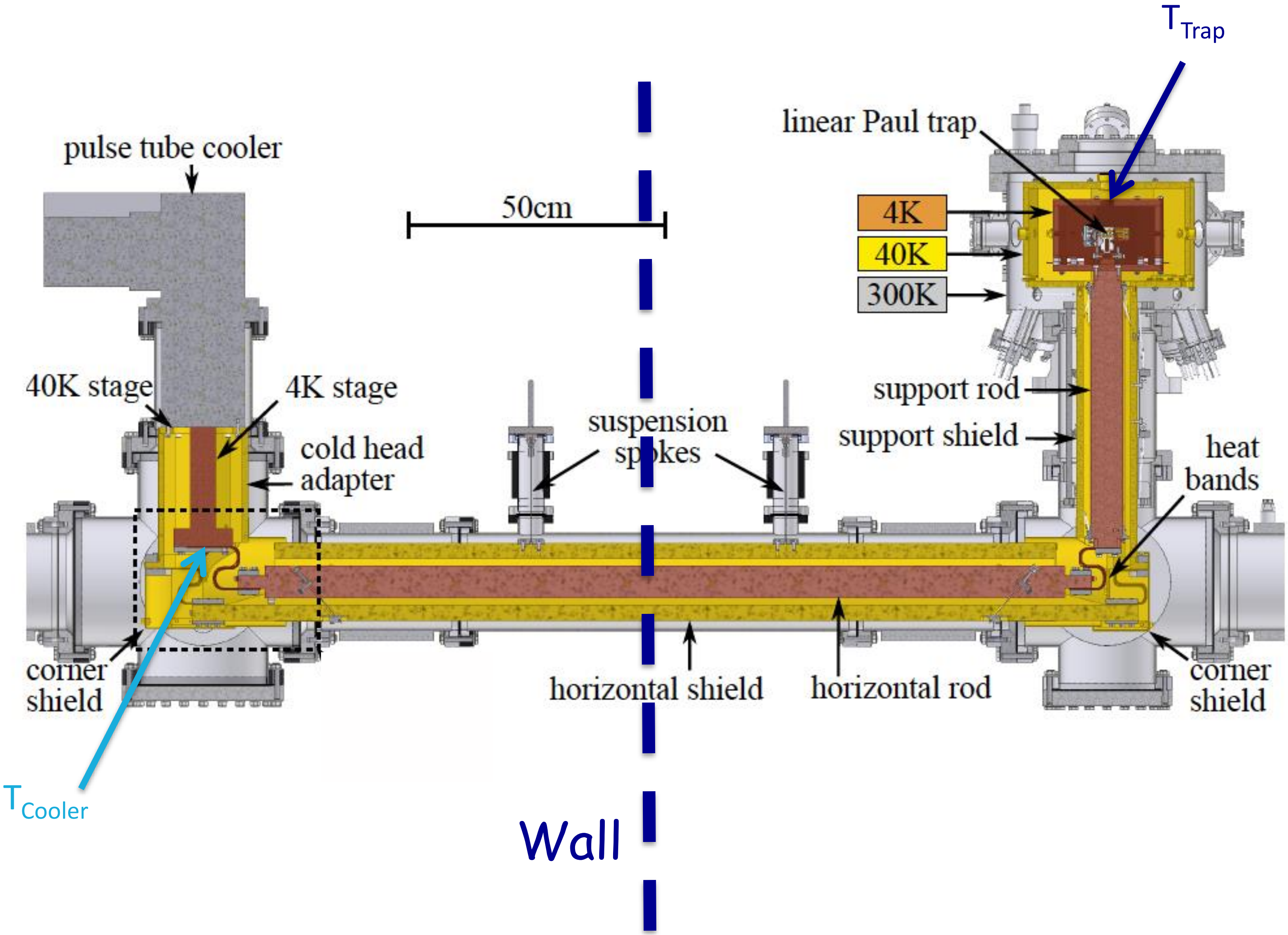
Potentially new AU TEQ contribution

Experiments med ground-state-cooled
highly-charged bio-molecule homologues
in a cryogenically cooled linear rf trap

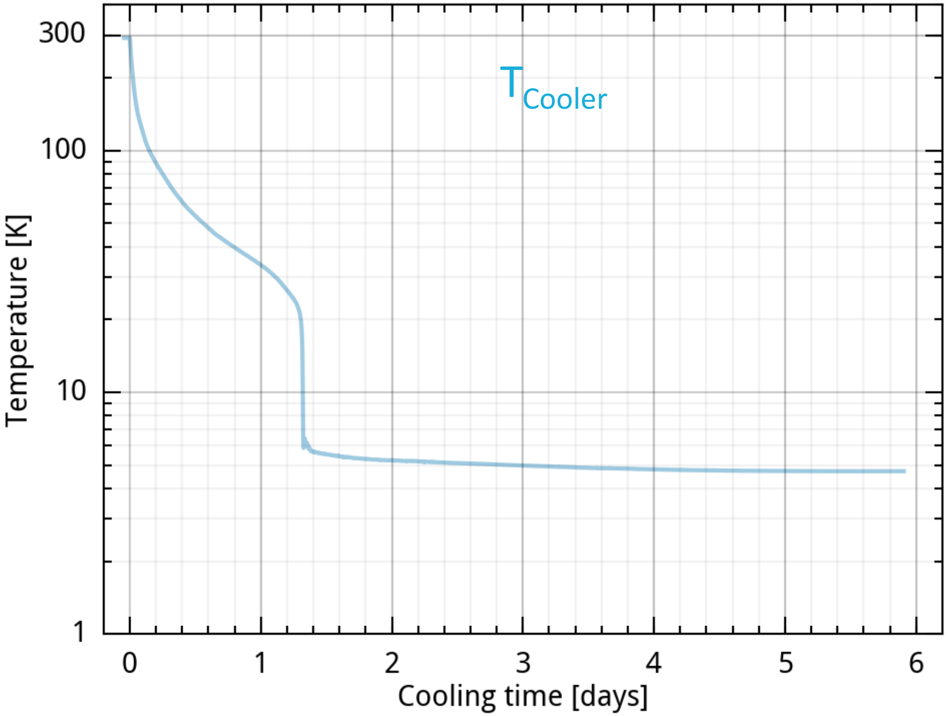


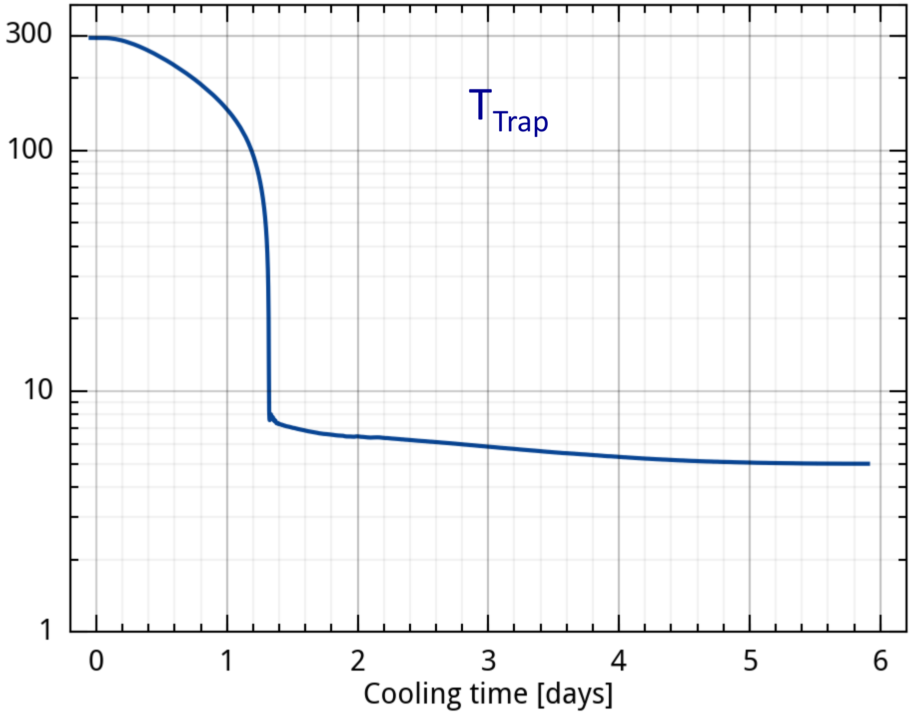


Cryogenically cooled linear rf trap

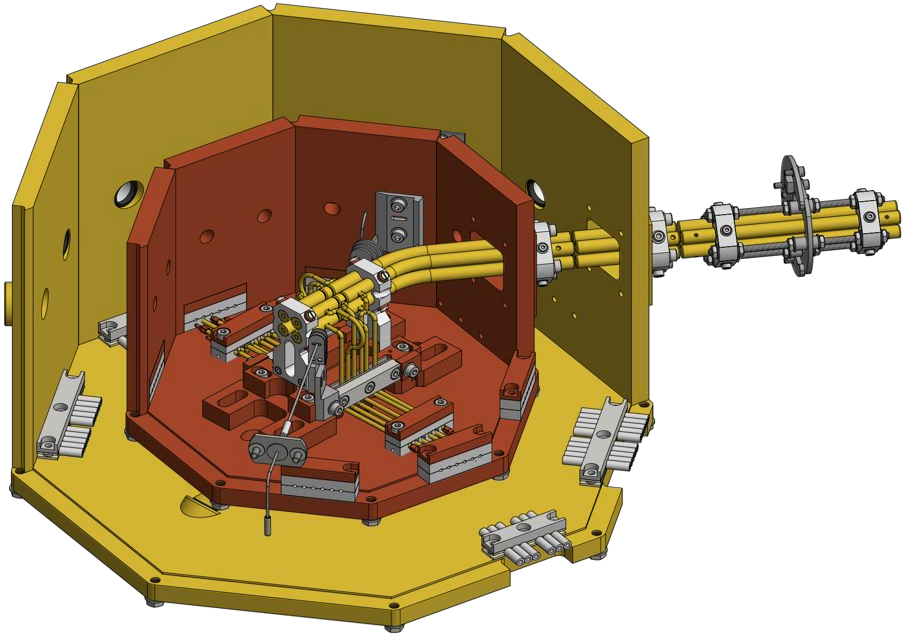


Cryogenically cooled linear rf trap





Trap details



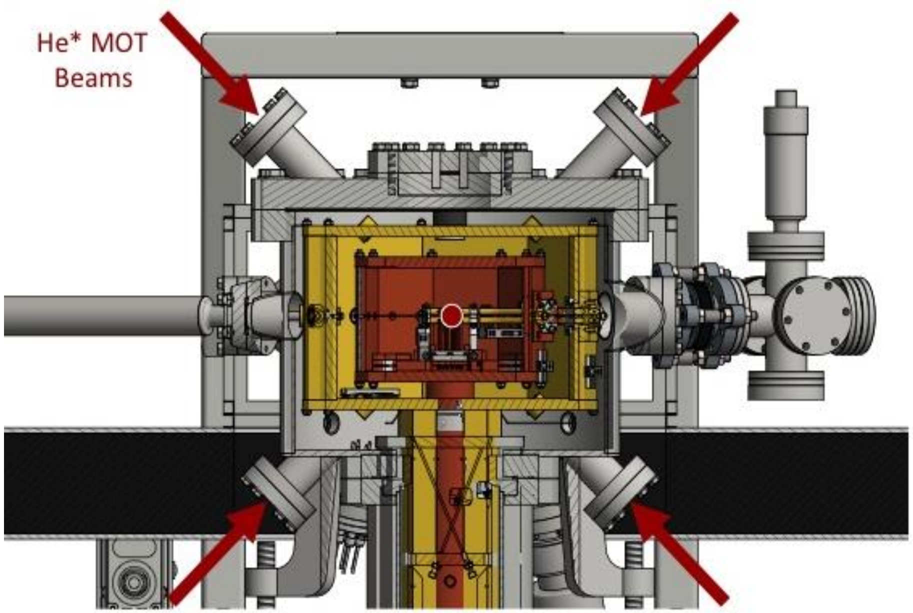
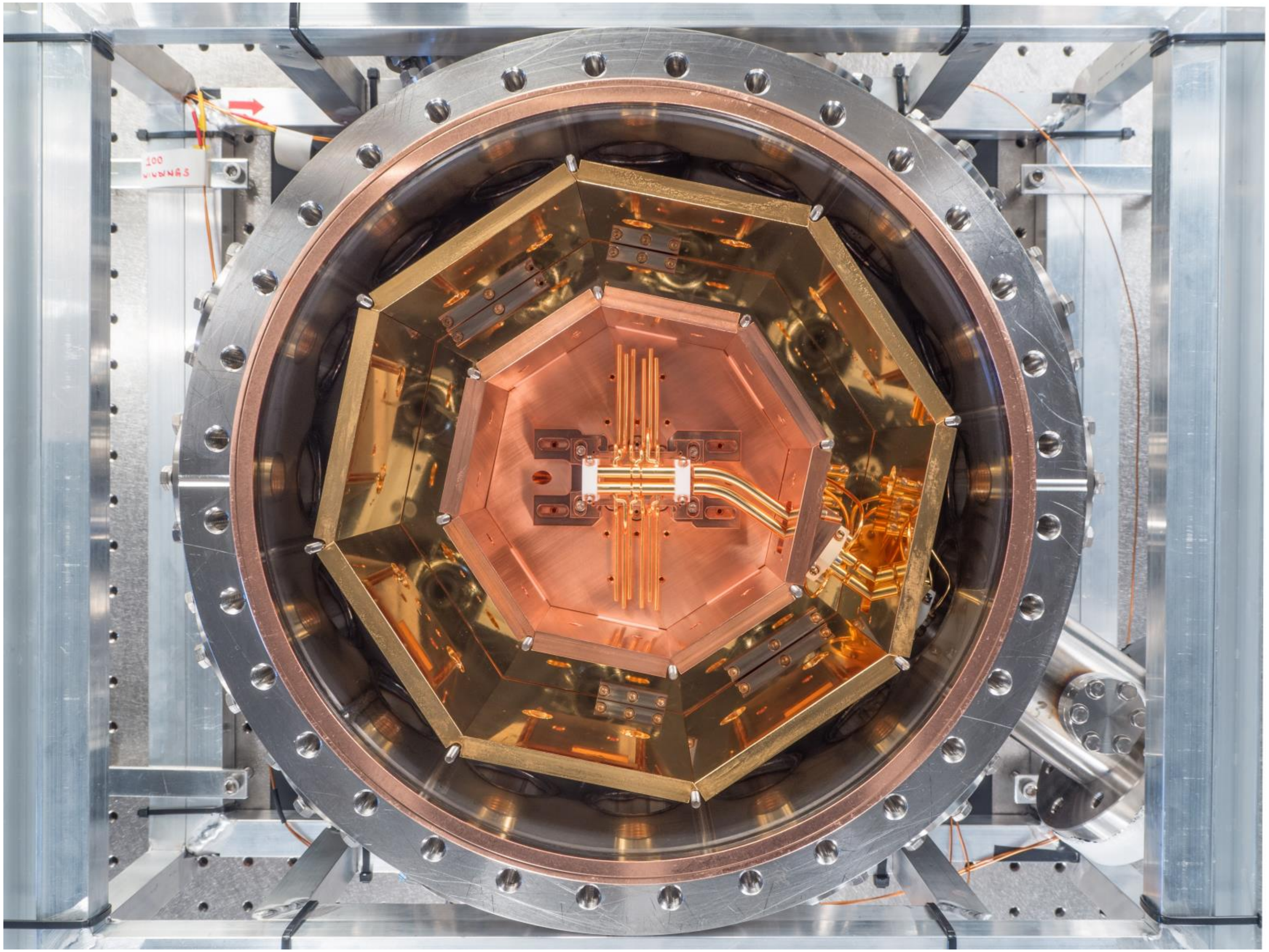


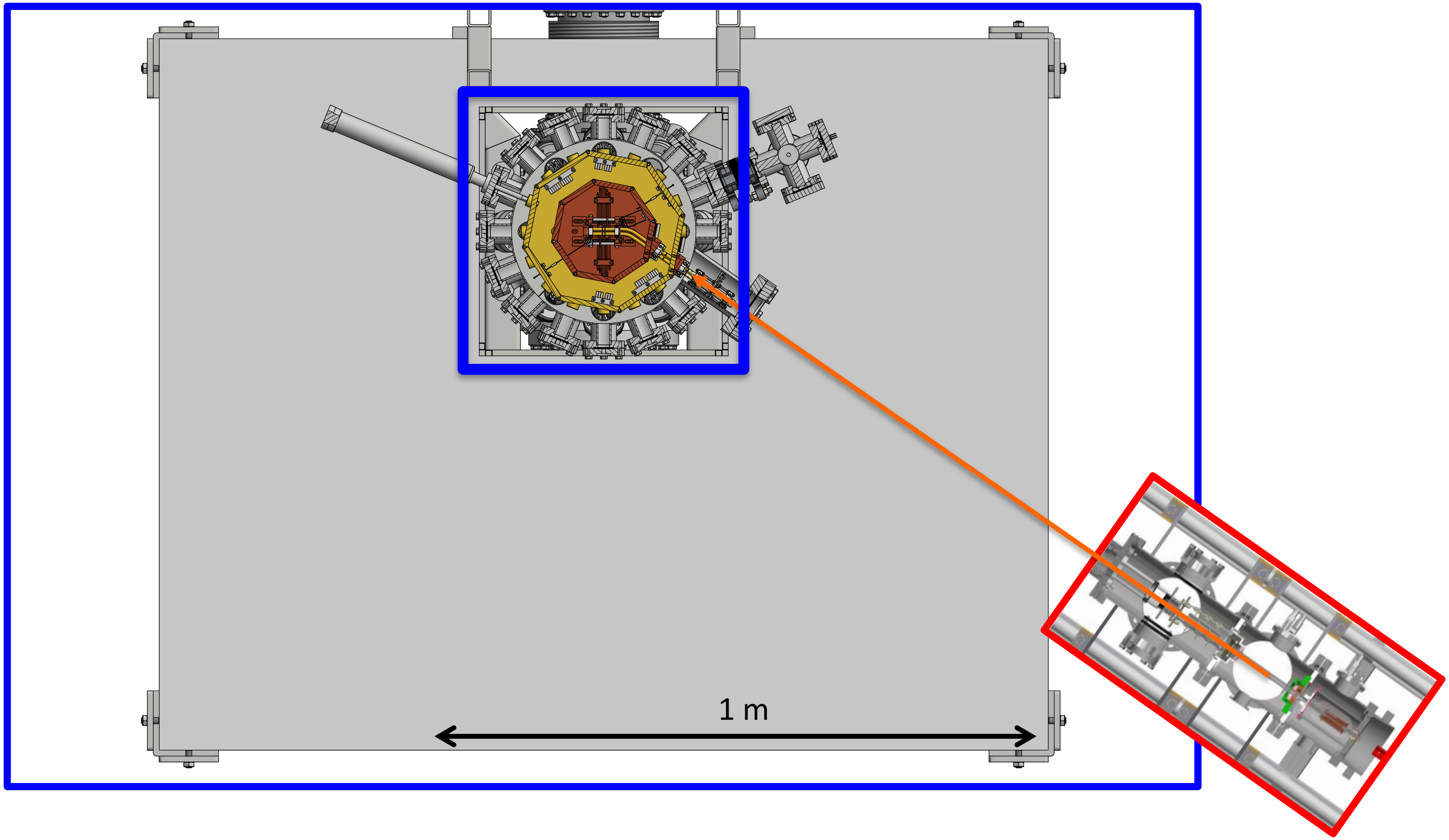
Photo of central trapping region



30 cm

Idea:

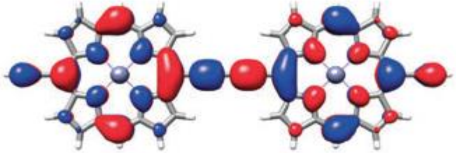
Work with *single*, charged molecular species injected from an electrospray source into a cryogenically cooled ion trap:



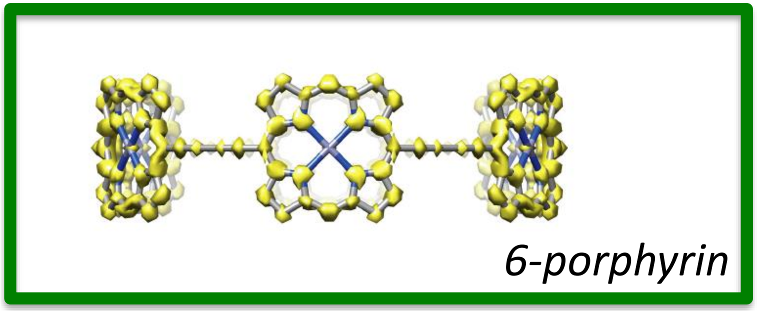
New collaborator

Prof. Harry L. Anderson
Dept. Chemistry
University of Oxford

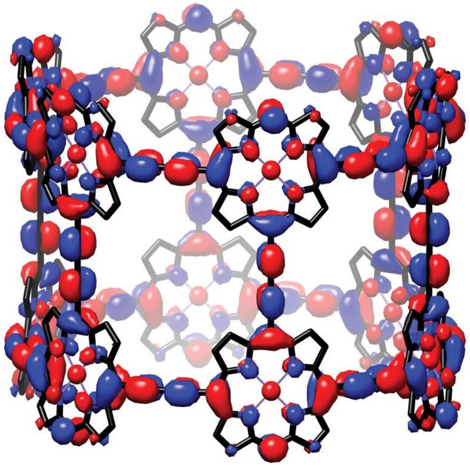
Molecular Engineering



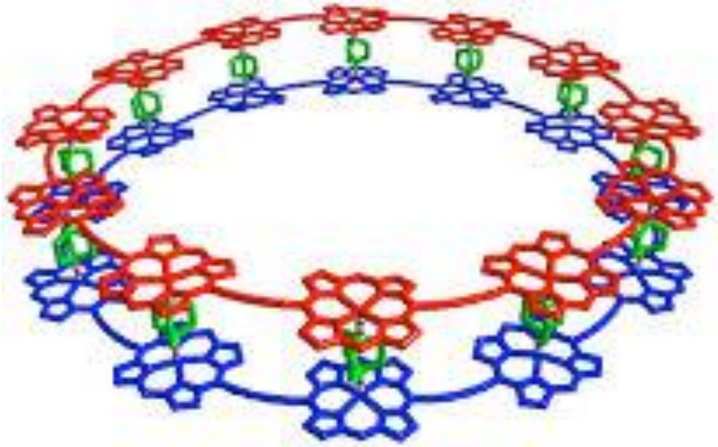
2-porphyrin



6-porphyrin

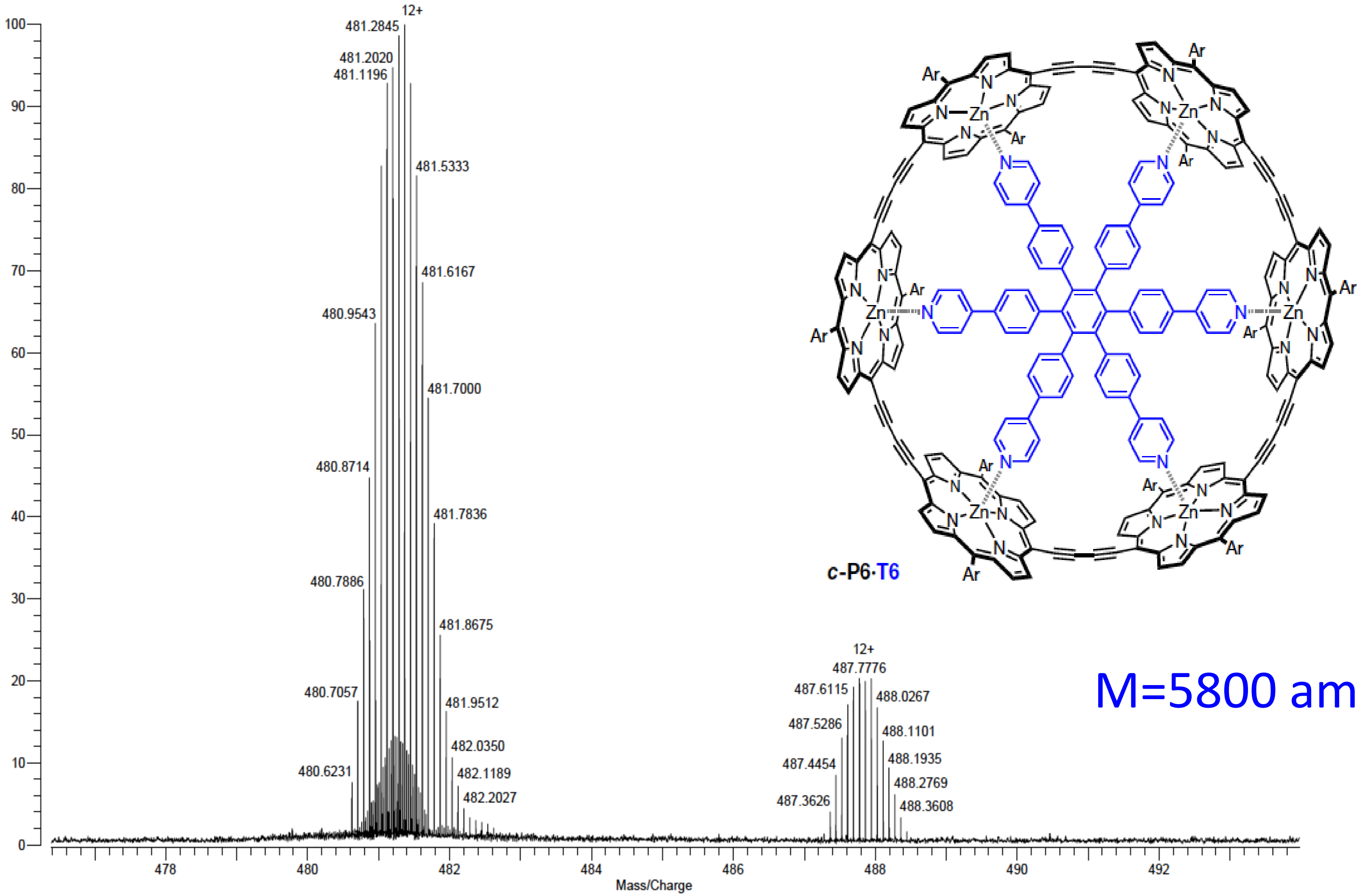


12-porphyrin



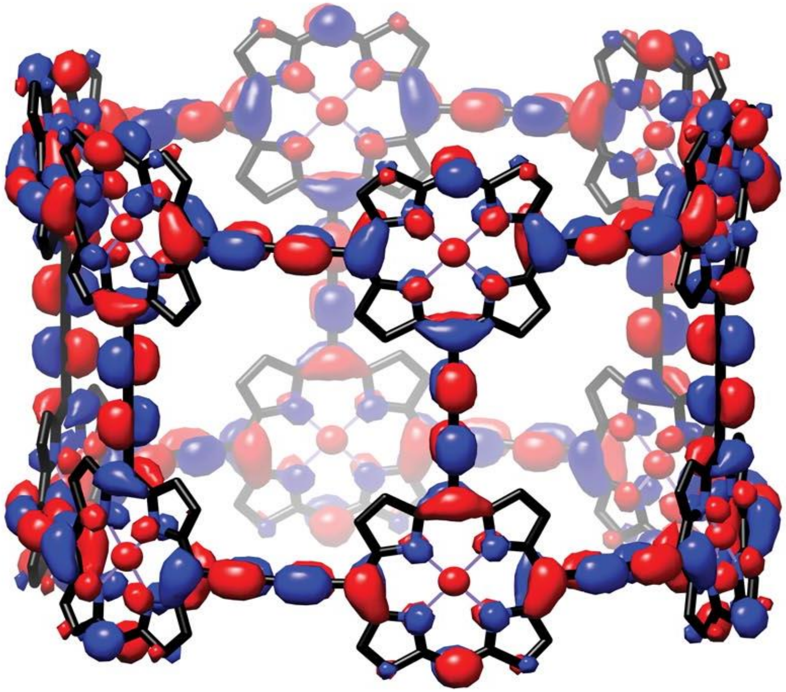
24-porphyrin

Electrospay mass spectra of highly charged c-P6•T6 porphyrine



M=5800 amu

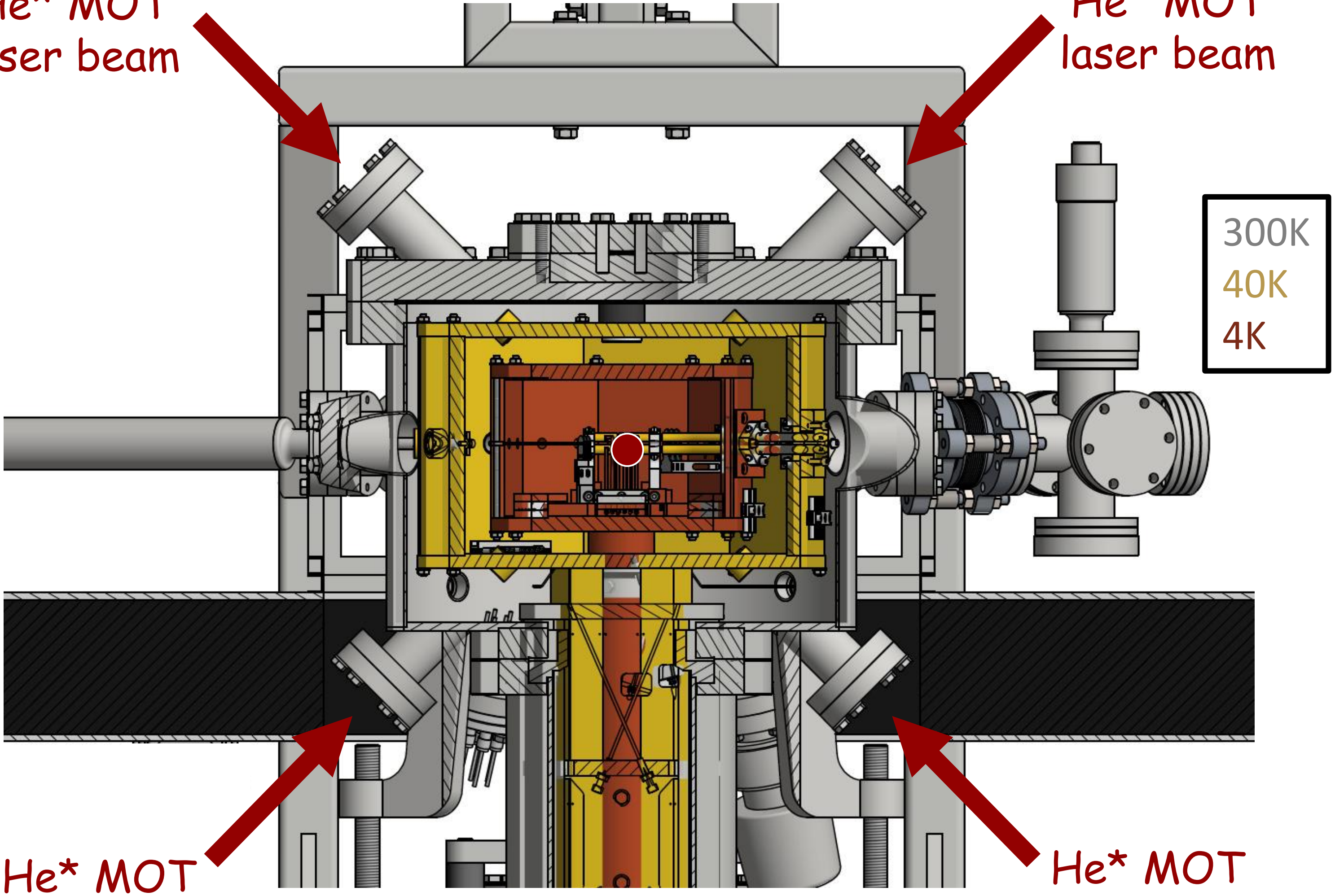
12-porphyrine



M>10^4 amu !

Next step:

Buffer gas cooling with quenched He* MOT atoms



He* MOT laser beam

He* MOT laser beam

300K
40K
4K

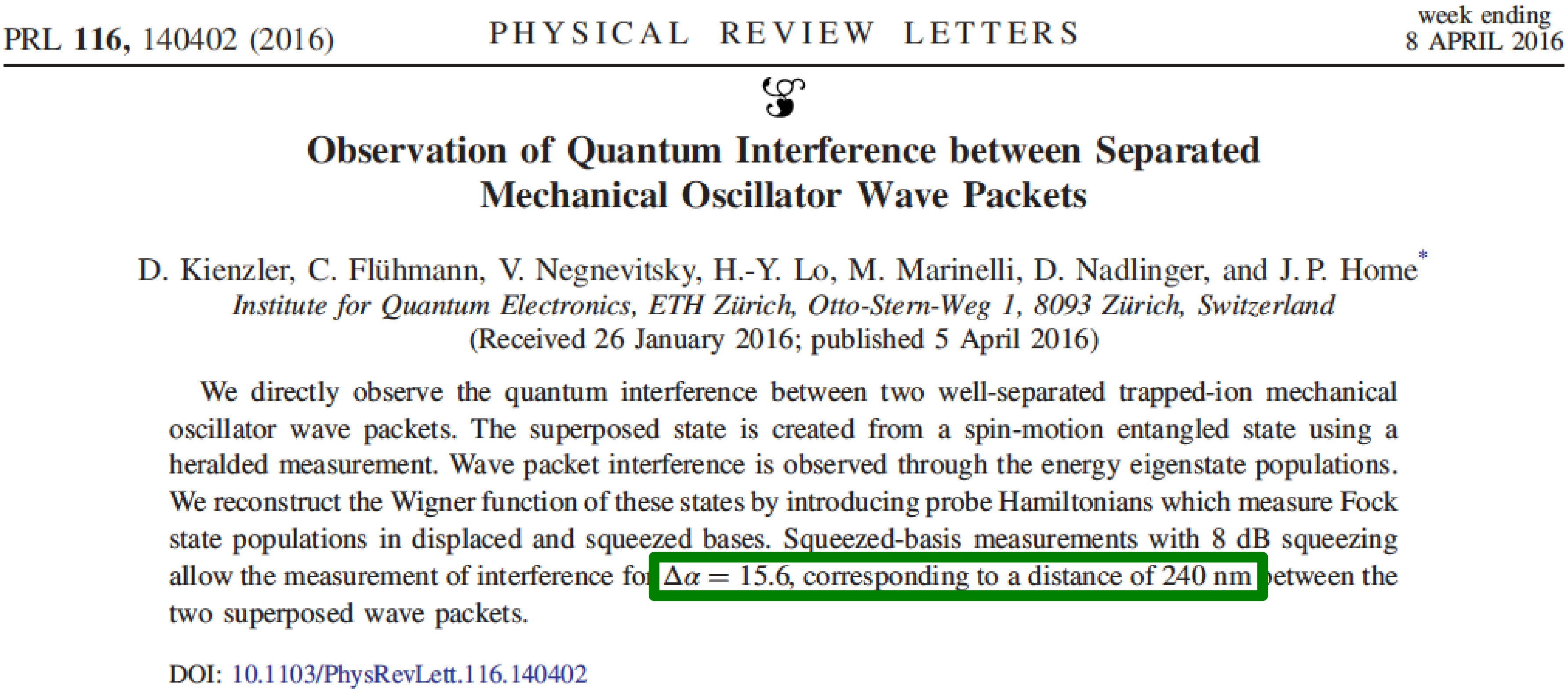
He* MOT laser beam

He* MOT laser beam

T_{He} ~ 1 mK => hopefully very cold molecular ions too!

Ways towards improved detection sensitivity?

I) Creation of Schrödinger’s Cat states



PRL **116,** 140402 (2016) PHYSICAL REVIEW LETTERS week ending 8 APRIL 2016

Observation of Quantum Interference between Separated Mechanical Oscillator Wave Packets

D. Kienzler, C. Flühmann, V. Negnevitsky, H.-Y. Lo, M. Marinelli, D. Nadlinger, and J. P. Home*
Institute for Quantum Electronics, ETH Zürich, Otto-Stern-Weg 1, 8093 Zürich, Switzerland
(Received 26 January 2016; published 5 April 2016)

We directly observe the quantum interference between two well-separated trapped-ion mechanical oscillator wave packets. The superposed state is created from a spin-motion entangled state using a heralded measurement. Wave packet interference is observed through the energy eigenstate populations. We reconstruct the Wigner function of these states by introducing probe Hamiltonians which measure Fock state populations in displaced and squeezed bases. Squeezed-basis measurements with 8 dB squeezing allow the measurement of interference for $\Delta\alpha = 15.6$, corresponding to a distance of 240 nm between the two superposed wave packets.

DOI: 10.1103/PhysRevLett.116.140402

$$|\psi_{\text{ent}}\rangle = \frac{1}{\sqrt{2}}(|+\rangle|\alpha\rangle + |-\rangle|-\alpha\rangle)$$

II) Quantum lock-in detection of change in motional state

Quantum Lock-in Force Sensing using Optical Clock Doppler Velocimetry

Ravid Shaniv[1] & Roee Ozeri[1]

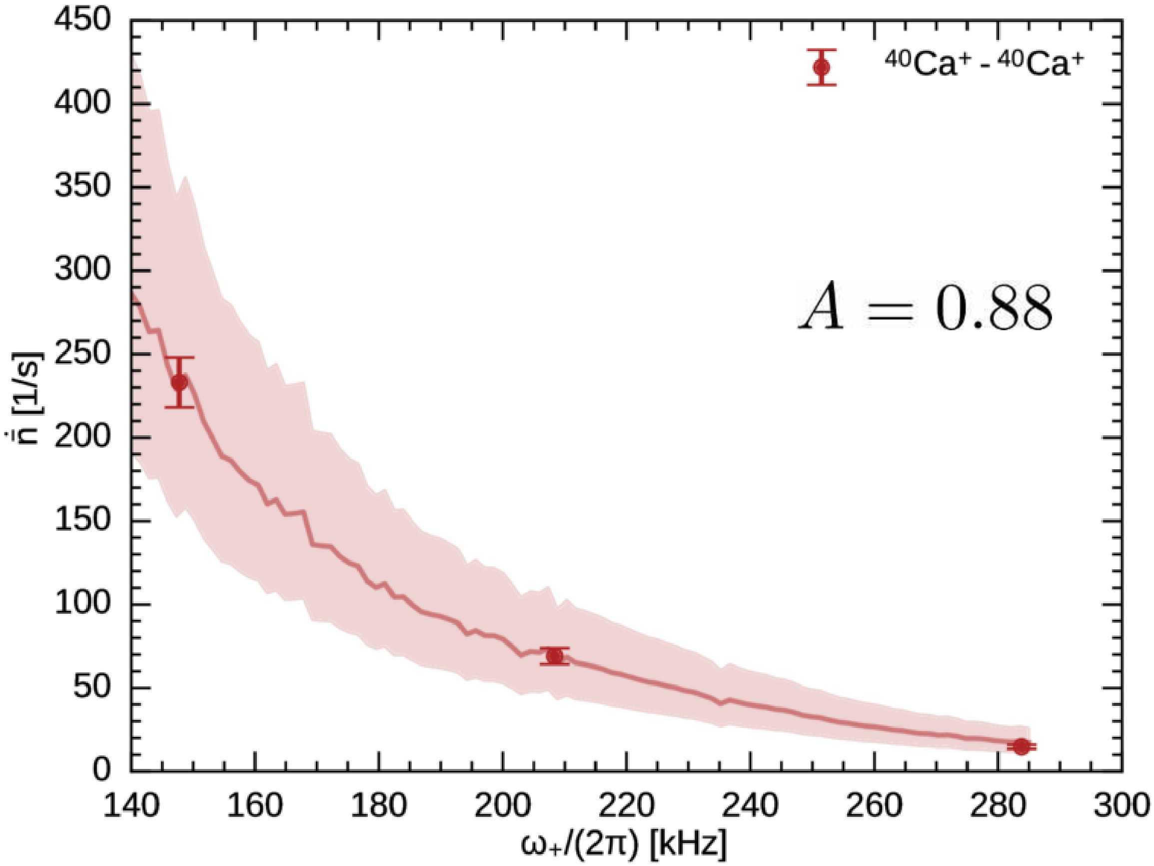
March 1, 2016

Abstract

Force sensors are at the heart of different technologies such as atomic force microscopy or inertial sensing [2, 1, 3]. These sensors often rely on the measurement of the displacement amplitude of mechanical oscillators under applied force. Examples for such mechanical oscillators include micro-fabricated cantilevers [3], carbon nanotubes [4] as well as single trapped ions [5, 6] . The best sensitivity is typically achieved when the force is alternating at the mechanical resonance frequency of the oscillator thus increasing its response by the mechanical quality factor. The measurement of low-frequency forces, that are below resonance, is a more difficult task as the resulting oscillation amplitudes are significantly lower. Here we use a single trapped $^{88}Sr^+$ ion as a force sensor. The ion is trapped in a linear harmonic trap, and is electrically driven at a frequency much lower than the trap resonance frequency. To be able to measure the small amplitude of motion we combine two powerful techniques. The force magnitude is determined by the measured periodic Doppler shift of an atomic optical clock transition and the Quantum Lock-in technique is used to coherently accumulate the phases acquired during different force half-cycles. We demonstrate force detection both when the oscillating force is phase-synchronized with the quantum lock-in sequence and when it is asynchronous and report frequency force detection sensitivity as low as $5.3 \times 10^{-19} \frac{\mathrm{N}}{\sqrt{\mathrm{Hz}}}$.

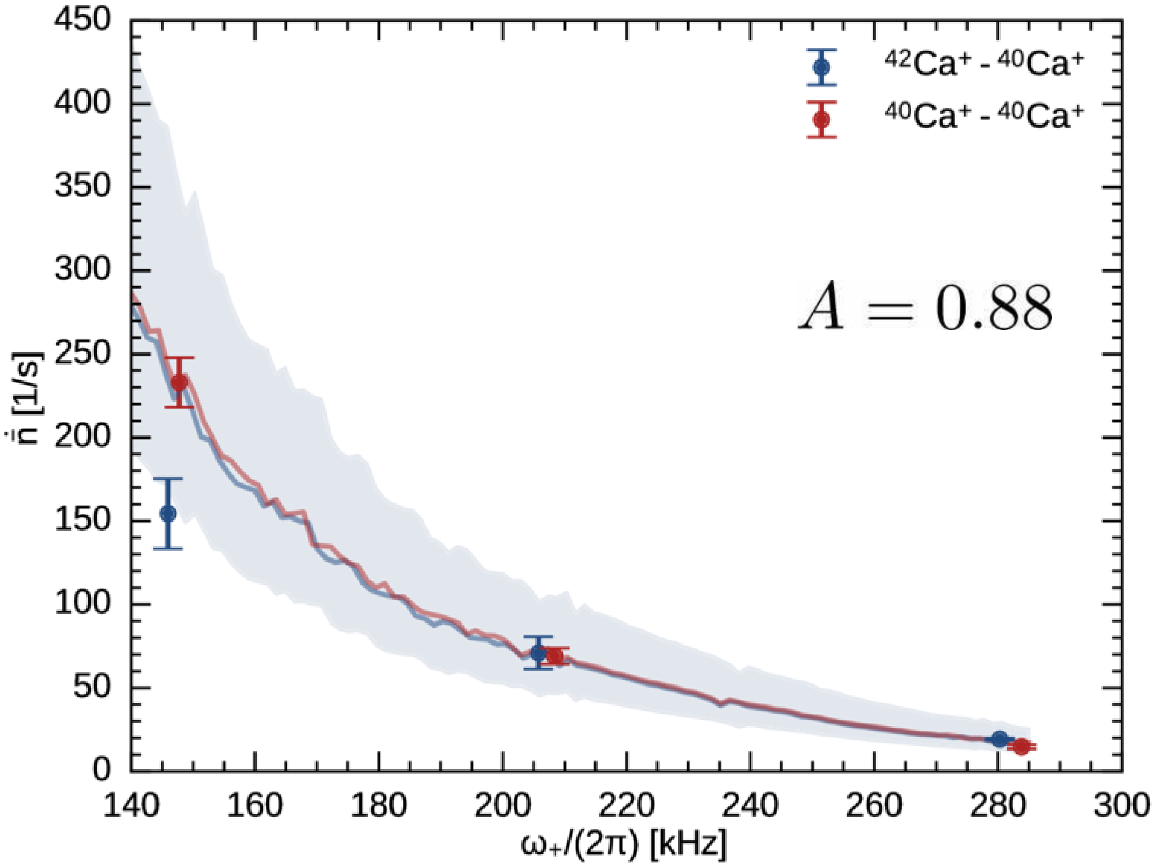
Heating of two ions

$$\dot{\bar{n}} \simeq A \times 8 \frac{e^2}{4 m_1 \hbar \omega_\pm} \frac{S_{V_{DC}}(\omega_\pm)}{D^2} \left(\beta_1^{\pm\prime} + \frac{\beta_2^{\pm\prime}}{\sqrt{\mu}} \right)^2$$



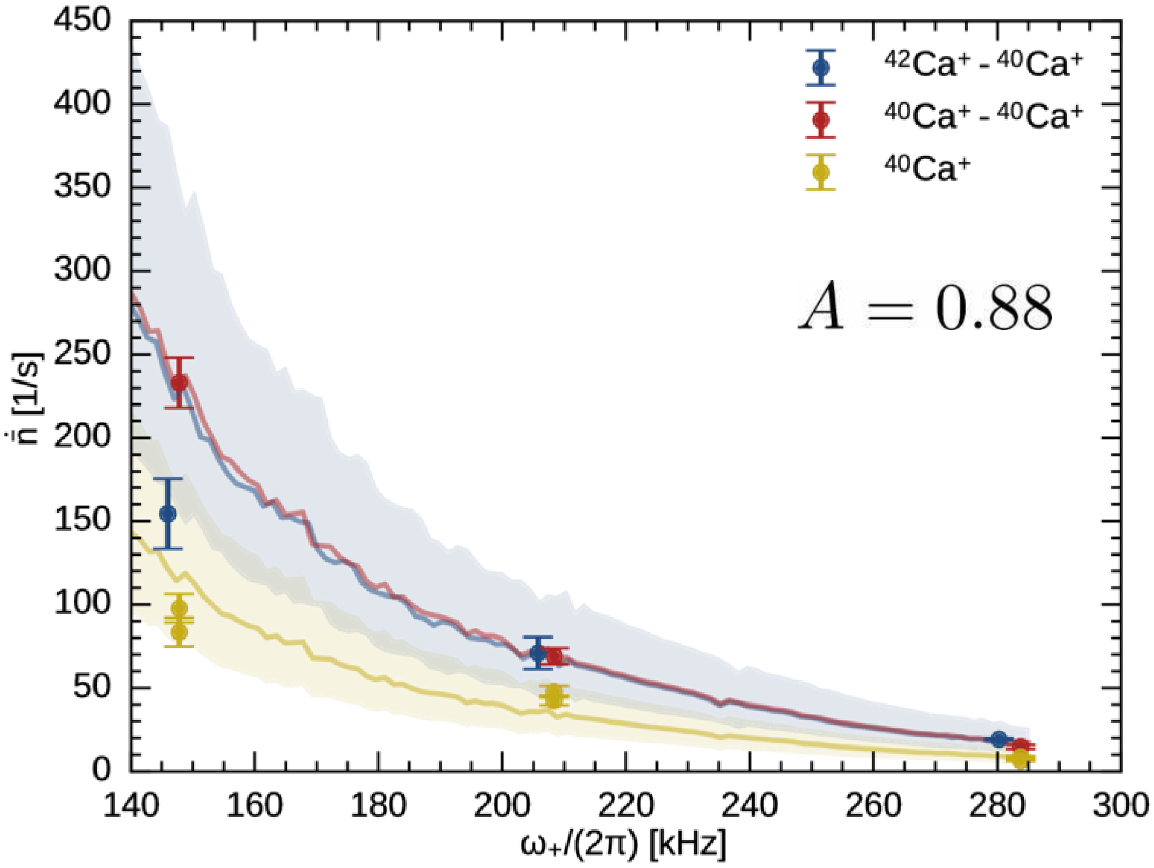
Heating of two ions

$$\dot{\bar{n}} \simeq A \times 8 \frac{e^2}{4 m_1 \hbar \omega_\pm} \frac{S_{V_{DC}}(\omega_\pm)}{D^2} \left(\beta_1^{\pm\prime} + \frac{\beta_2^{\pm\prime}}{\sqrt{\mu}} \right)^2$$



Heating of two ions

$$\dot{\bar{n}} \simeq A \times 8 \frac{e^2}{4 m_1 \hbar \omega_\pm} \frac{S_{V_{DC}}(\omega_\pm)}{D^2} \left(\beta_1^{\pm\prime} + \frac{\beta_2^{\pm\prime}}{\sqrt{\mu}} \right)^2$$



Shapal Hi-M Soft™

SHAPAL™Hi-M soft is based upon the first translucent aluminium nitride developed by Tokuyama Soda Co. Ltd. and is a composite sintered body of AlN and BN.

Shapal Hi-M Soft™

Thermophysical properties of sapphire, AlN and $MgAl_2O_4$ down to 70 K

St. Burghartz, B. Schulz

Kernforschungszentrum Karlsruhe, Institut für Materialforschung 1, P.O. Box 3640, 76021 Karlsruhe, Germany

SHAPAL at 100 K 2.1 W/cm K:

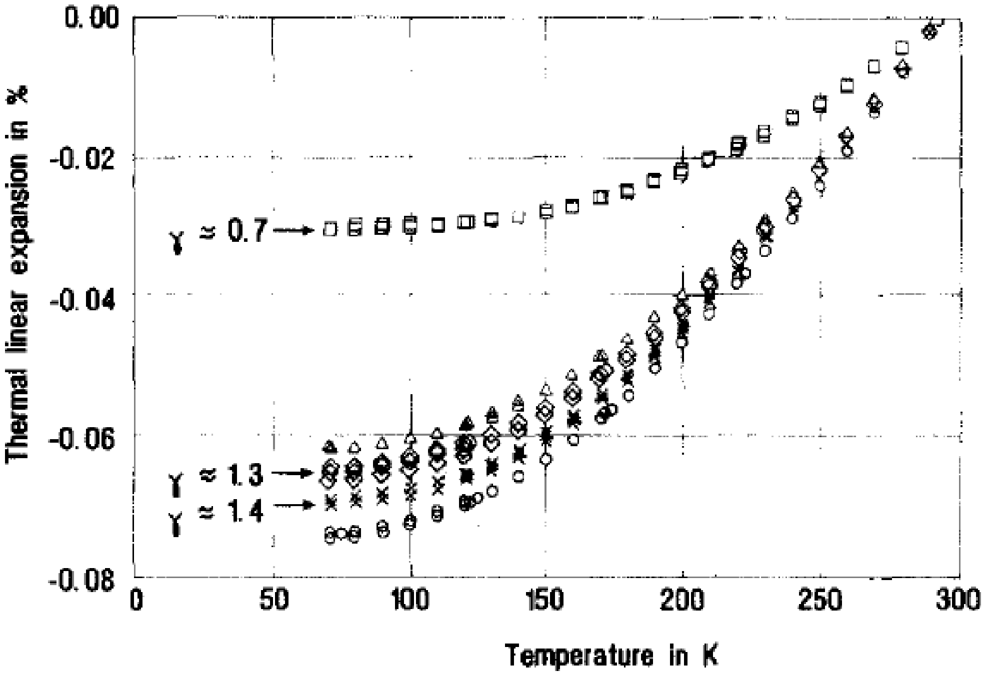
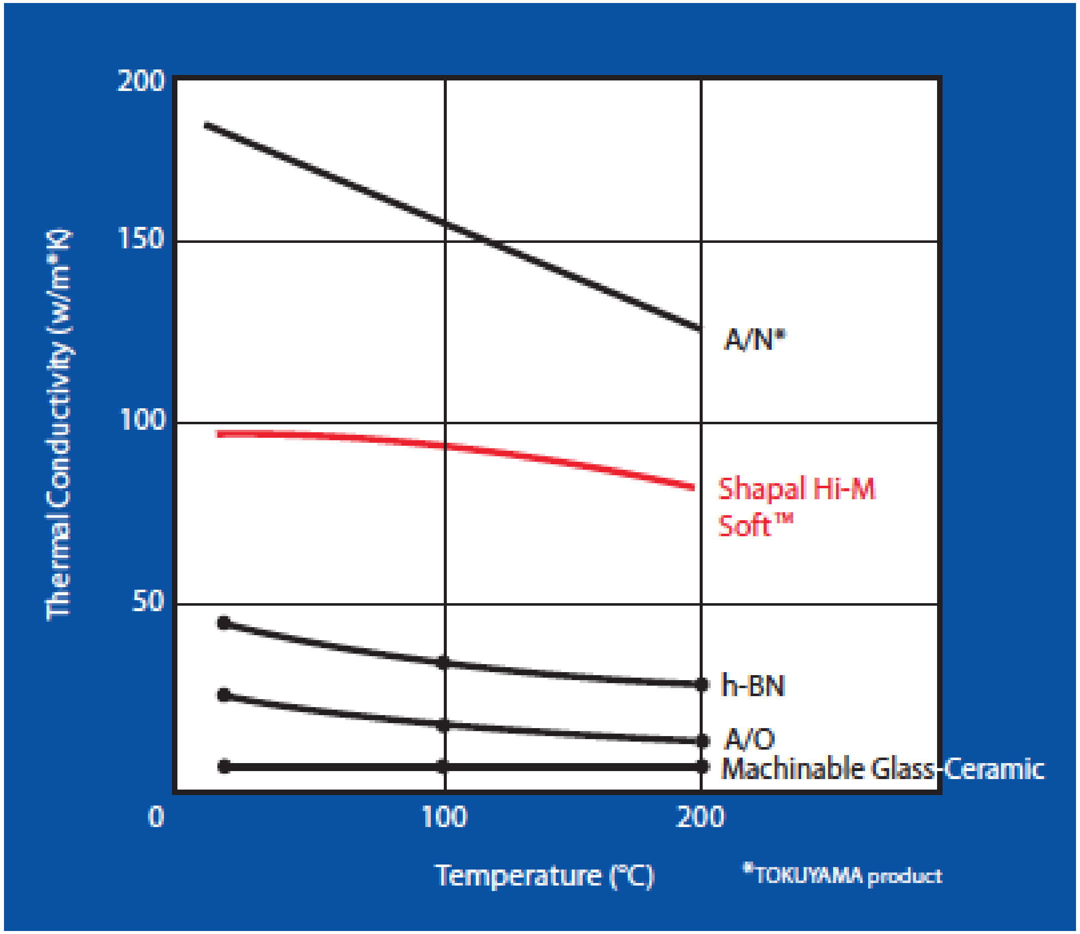


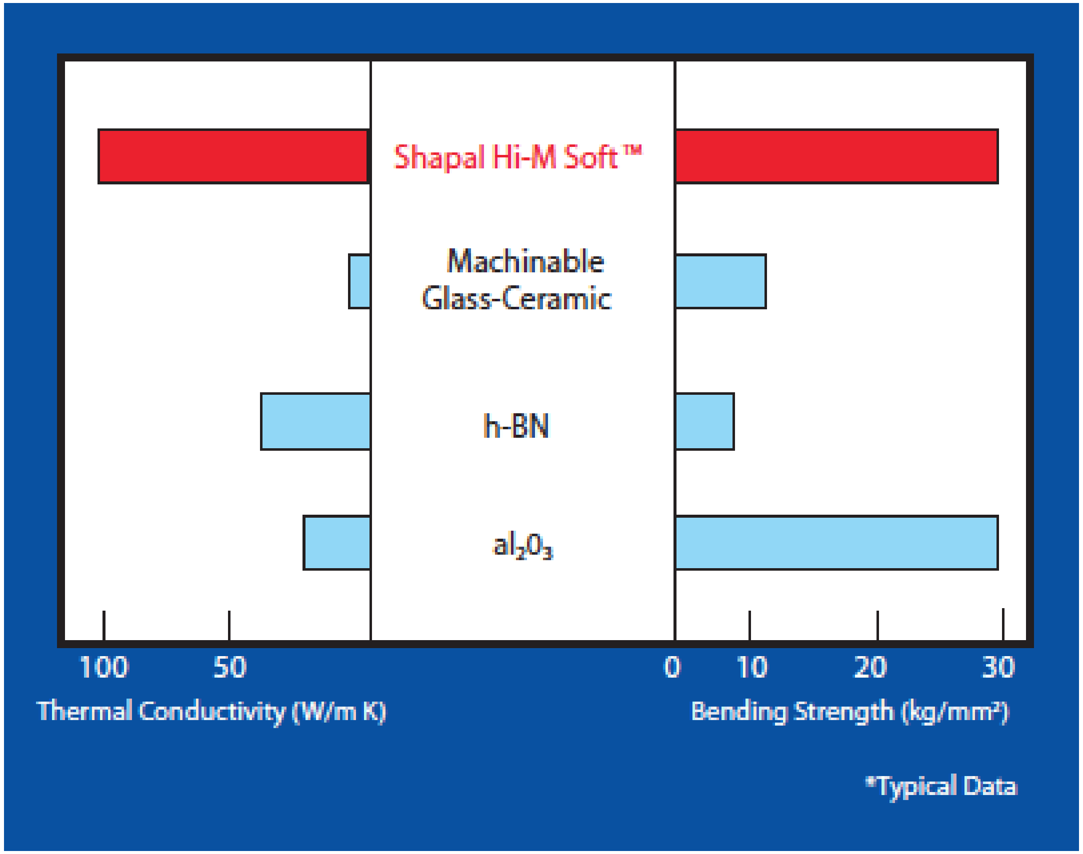
Fig. 2. Thermal linear expansion of sapphire ((○) ∥ c, (△) ⊥ c), α-Al_2O_3 (◇), AlN Shapal (□) and $MgAl_2O_4$ (×), γ is the Grüneisen constant.

Journal of Nuclear Materials 212–215 (1994) 1065–1068

Shapal Hi-M Soft™



Shapal Hi-M Soft™



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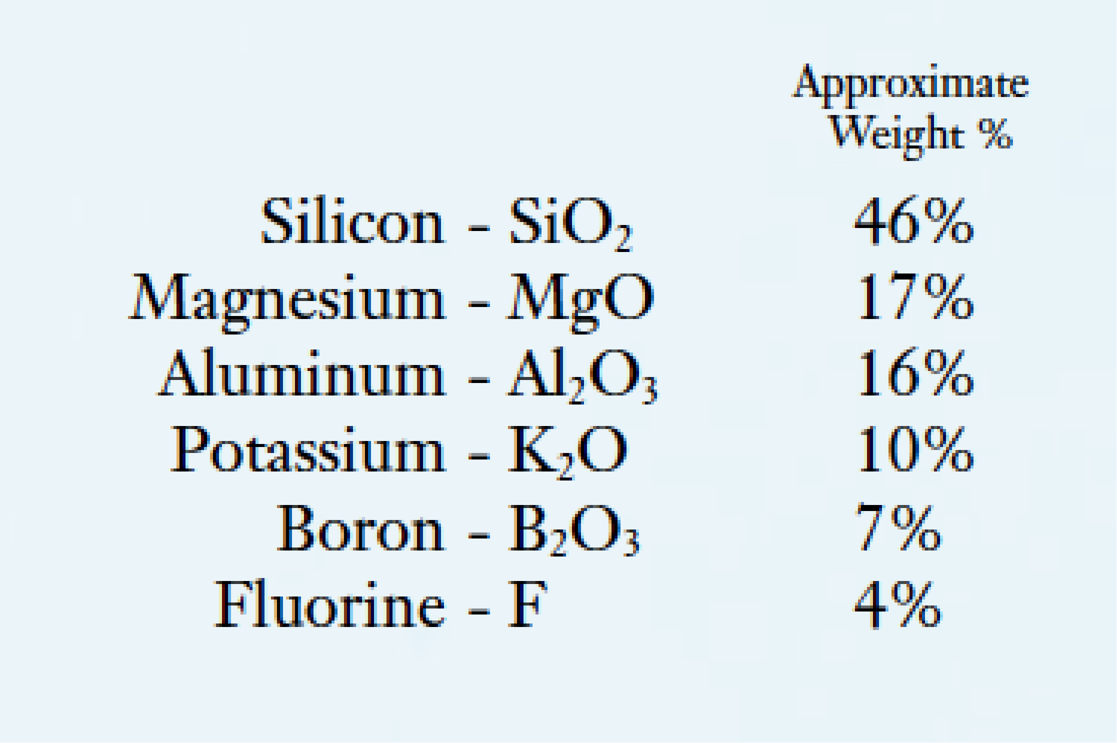
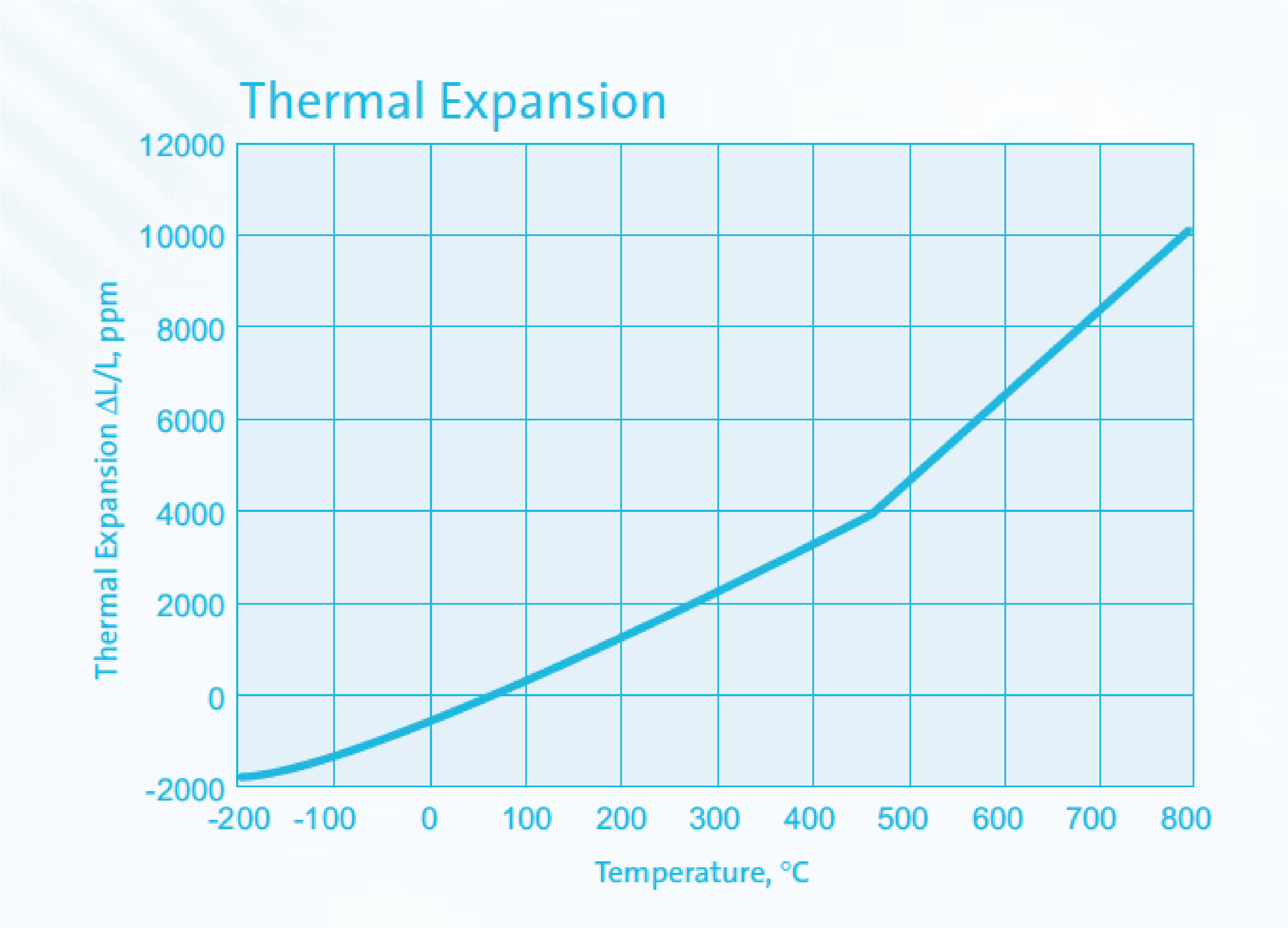
Machinable Glass Ceramic

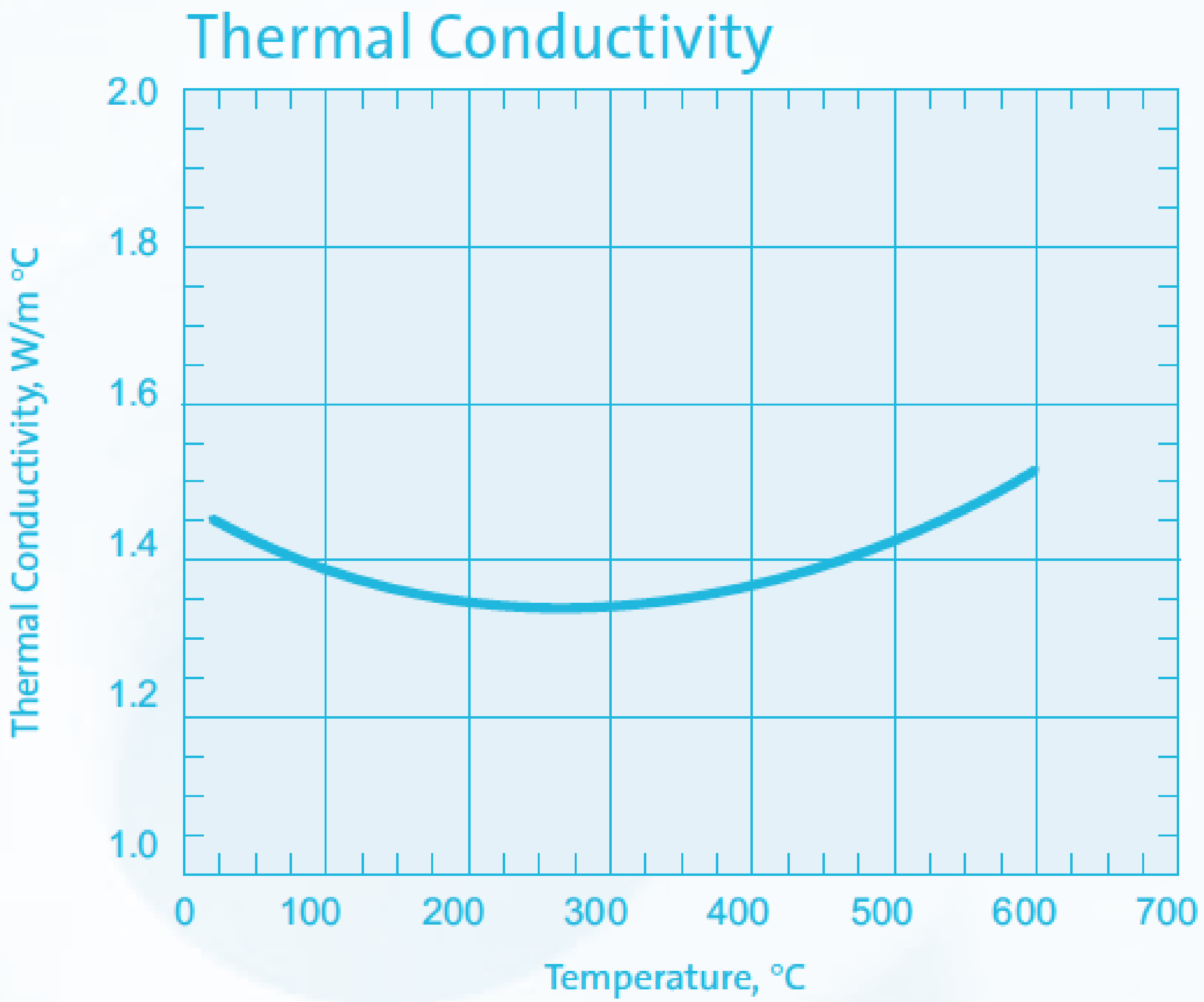


	Approximate Weight %
Silicon - SiO_2	46%
Magnesium - MgO	17%
Aluminum - Al_2O_3	16%
Potassium - K_2O	10%
Boron - B_2O_3	7%
Fluorine - F	4%

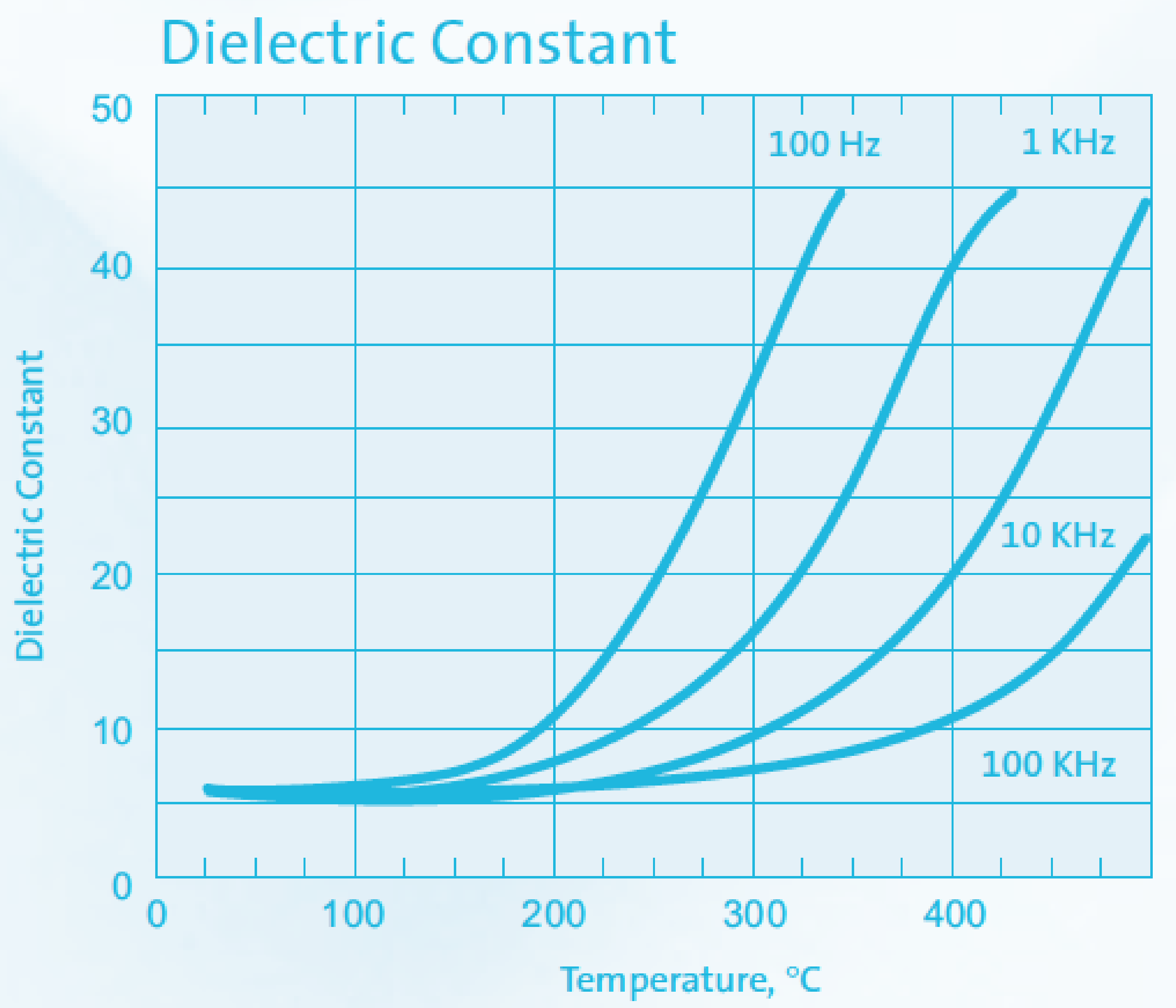
Macor®


Thermal Expansion
Thermal Expansion ΔL/L, ppm
12000
10000
8000
6000
4000
2000
0
-2000
-200
-100
0
100
200
300
400
500
600
700
800
Temperature, °C

Macor®

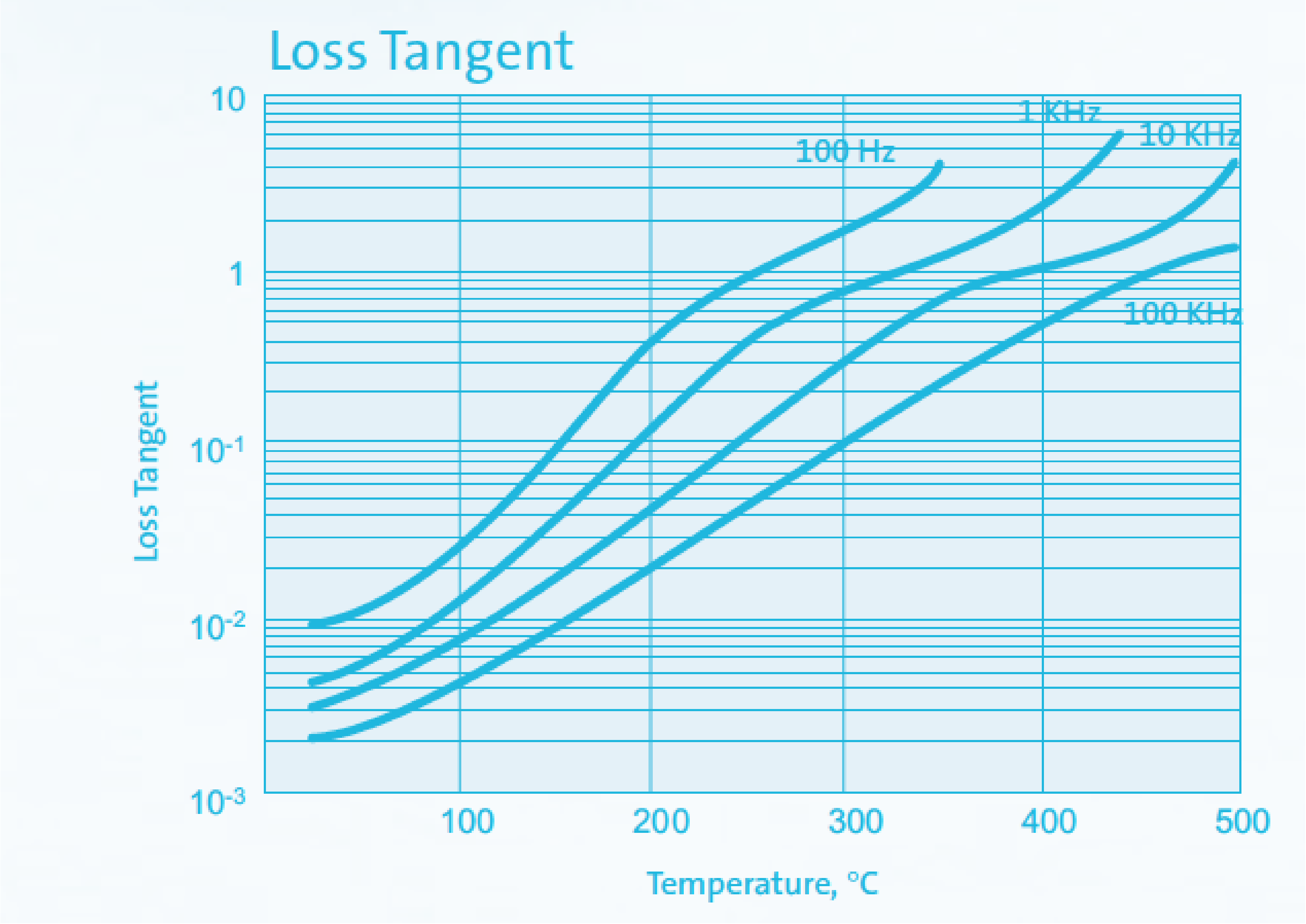

Thermal Conductivity
2.0
1.8
1.6
1.4
1.2
1.0
Thermal Conductivity, W/m °C
0
100
200
300
400
500
600
700
Temperature, °C

Macor®

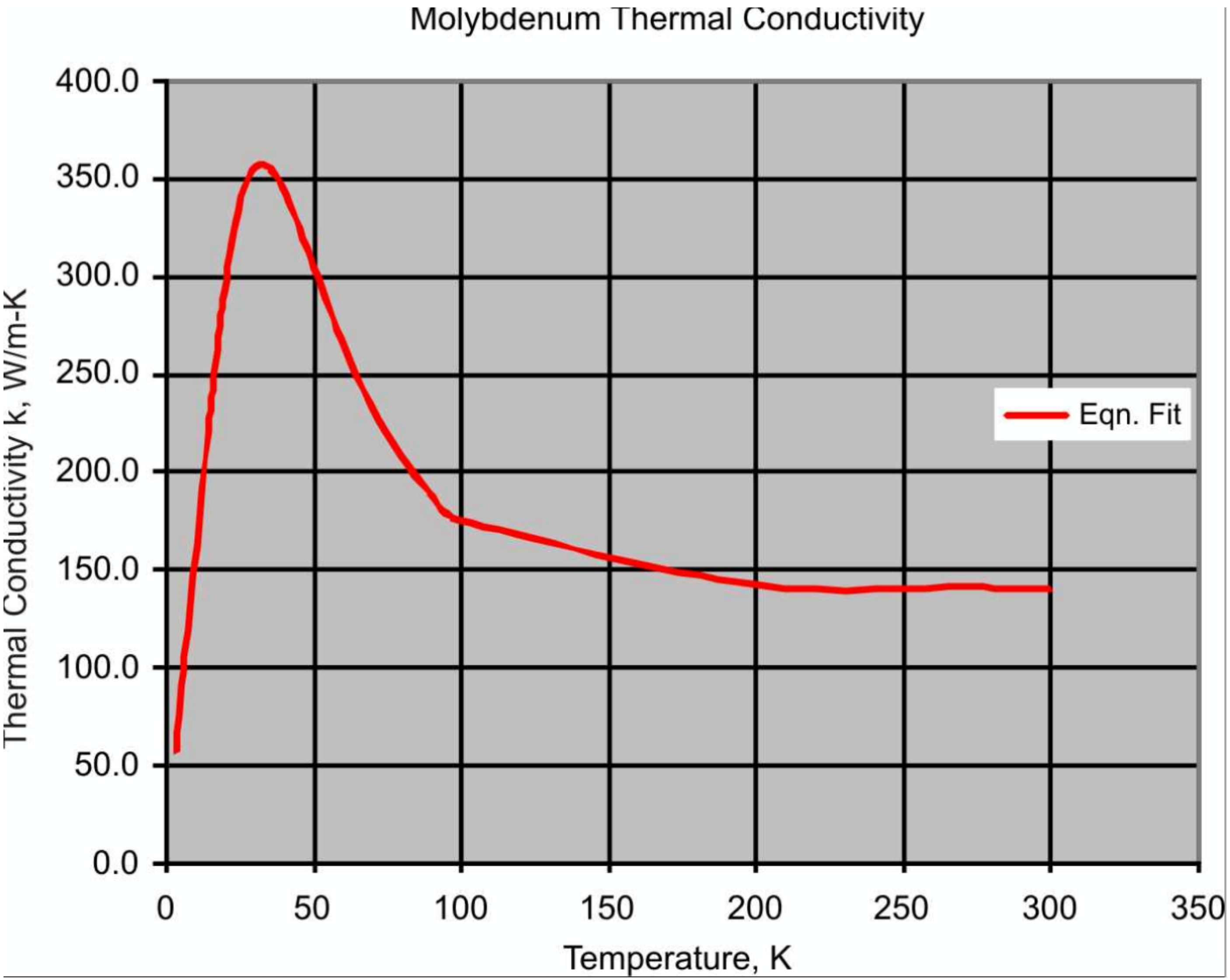


Dielectric Constant
Dielectric Constant
50
40
30
20
10
0
0
100
200
300
400
Temperature, °C
100 Hz
1 KHz
10 KHz
100 KHz

Macor®

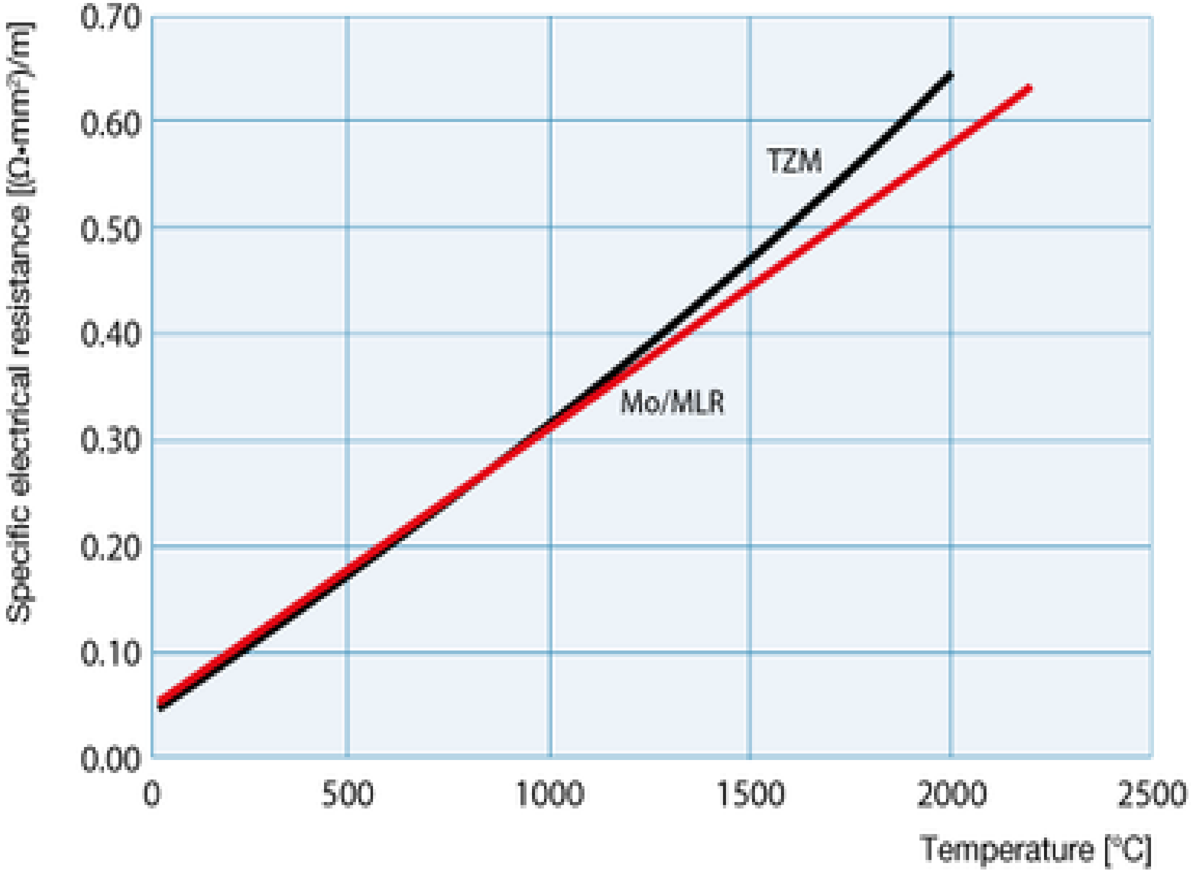

Loss Tangent
10
1
10-1
10-2
10-3
100 Hz
1 KHz
10 KHz
100 KHz
Loss Tangent
100
200
300
400
500
Temperature, °C

Molybdenum

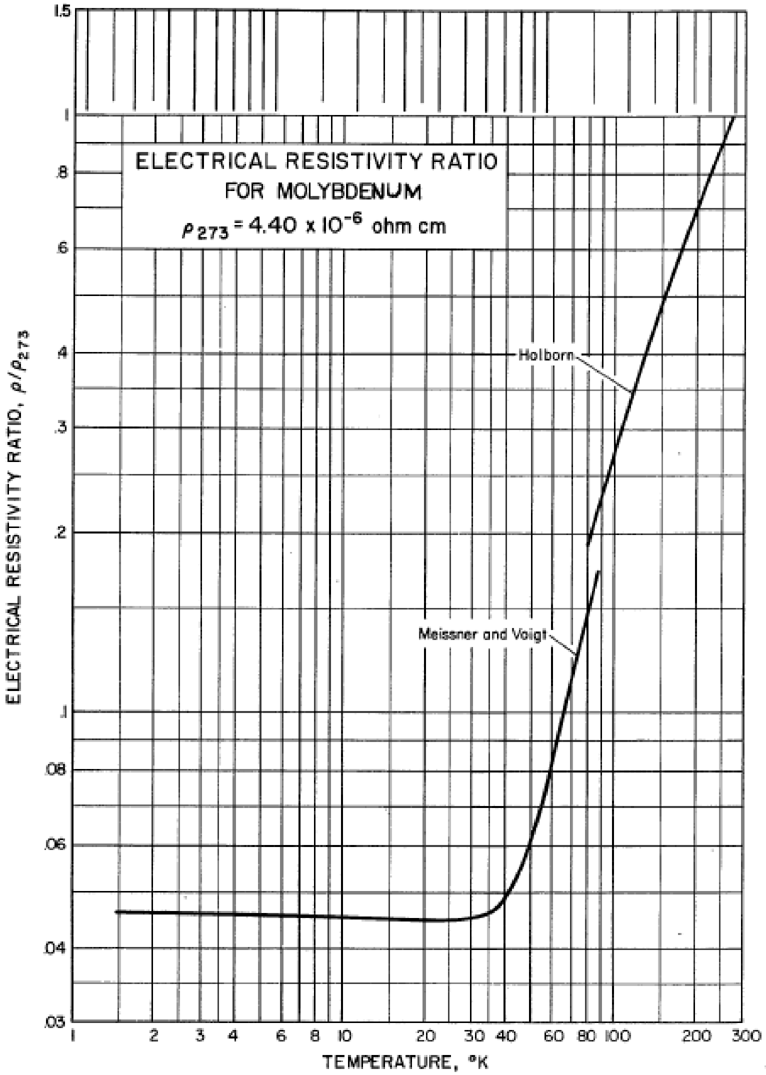


NIST, Cryogenic technologies group

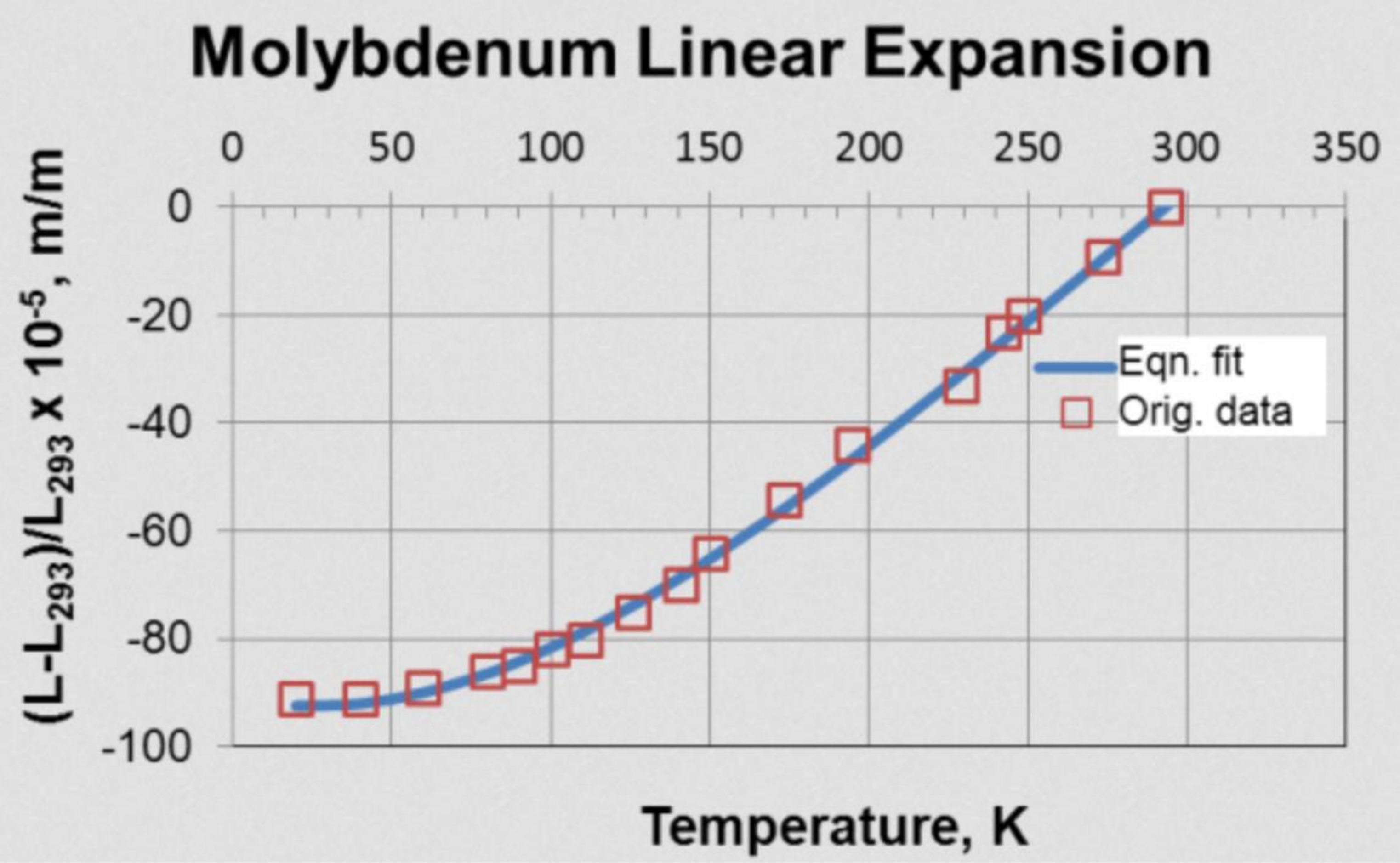
Molybdenum


Specific electrical resistance [(Ω·mm²)/m]
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0
500
1000
1500
2000
2500
Temperature [°C]
TZM
Mo/MLR

Molybdenum


ELECTRICAL RESISTIVITY RATIO
FOR MOLYBDENUM
$\rho_{273} = 4.40 \times 10^{-6}$ ohm cm
Holborn
Meissner and Voigt
ELECTRICAL RESISTIVITY RATIO, ρ/ρ_{273}
1.5
1
.8
.6
.4
.3
.2
.1
.08
.06
.04
.03
1
2
3
4
6
8
10
20
30
40
60
80
100
200
300
TEMPERATURE, °K

Molybdenum


Molybdenum Linear Expansion
0
50
100
150
200
250
300
350
0
-20
-40
-60
-80
-100
$(L-L_{293})/L_{293} \times 10^{-5}$, m/m
Temperature, K
Eqn. fit
Orig. data

Copper

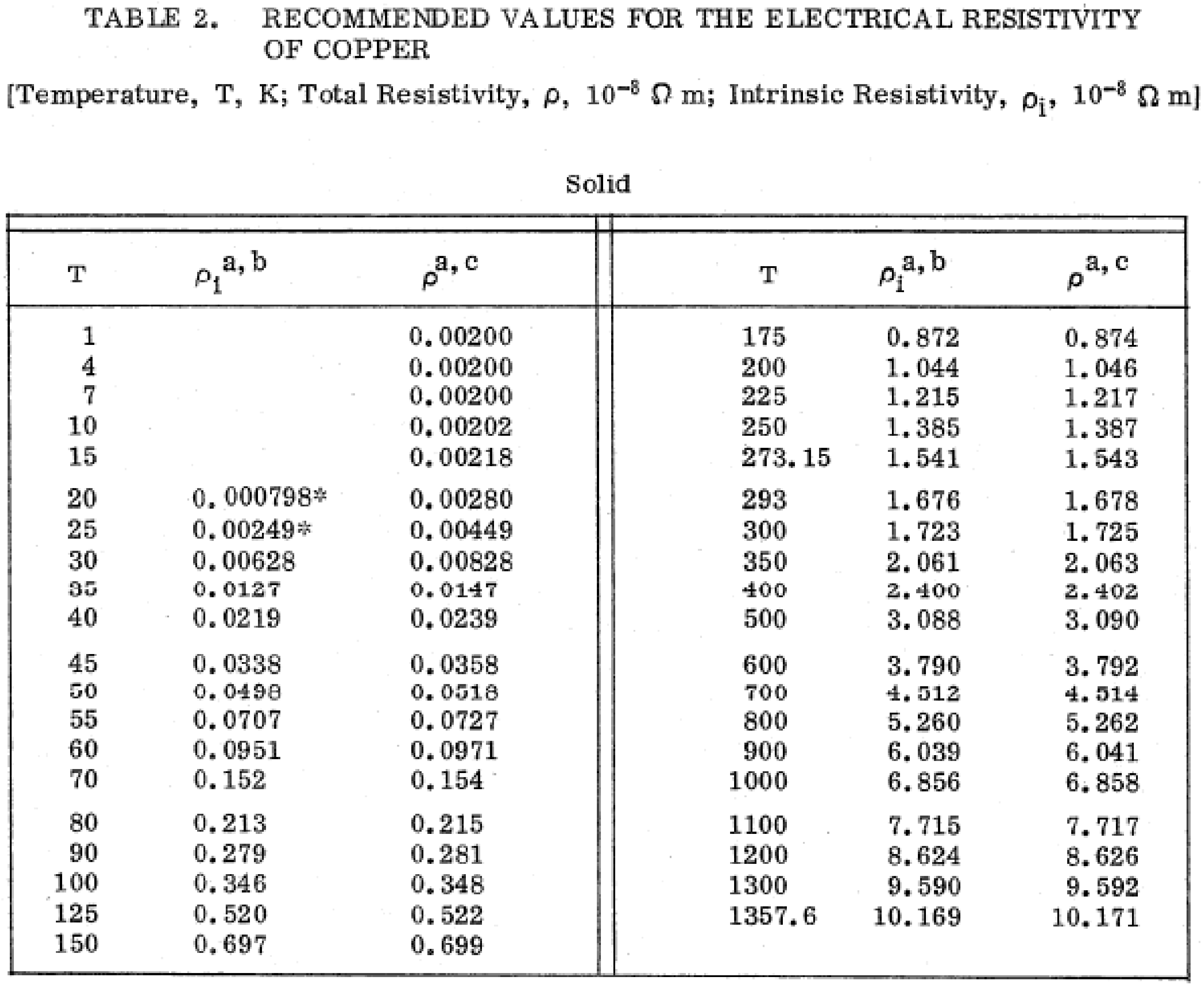
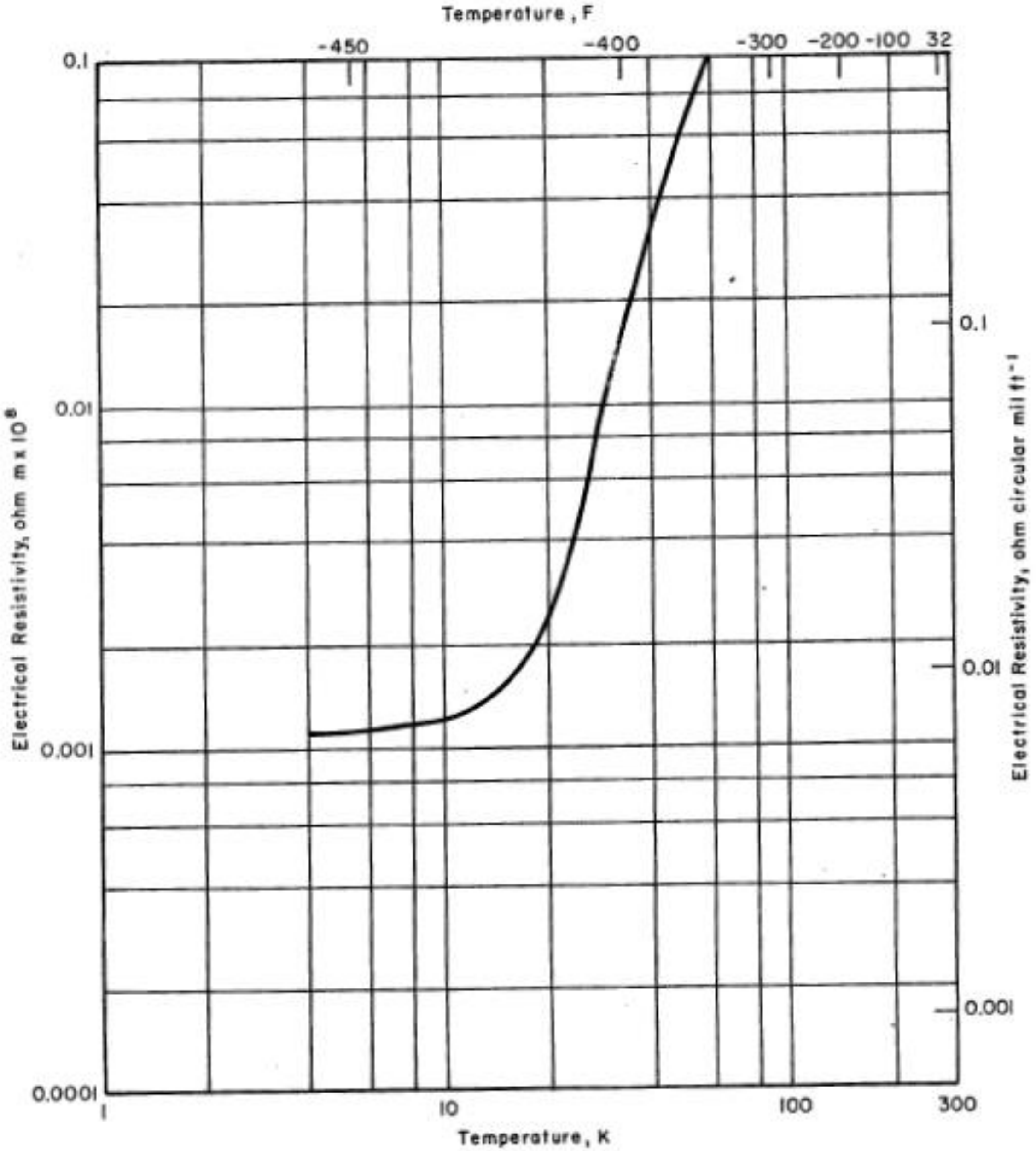


TABLE 2. RECOMMENDED VALUES FOR THE ELECTRICAL RESISTIVITY OF COPPER

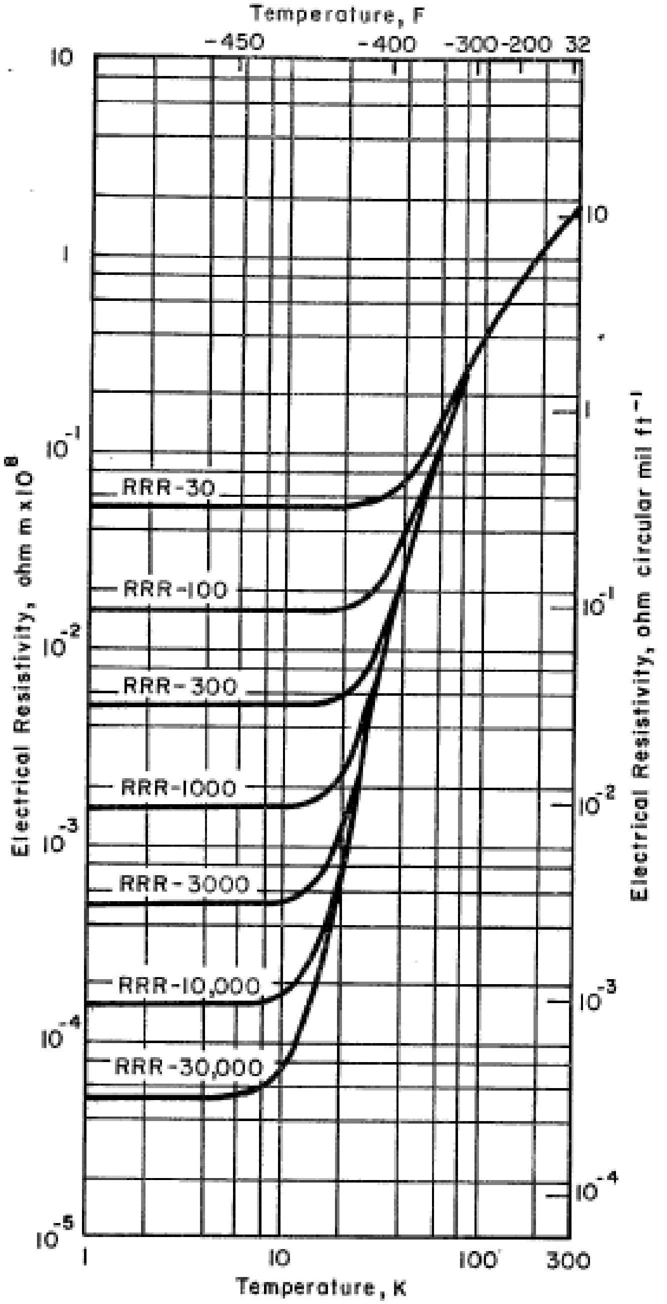
[Temperature, T, K; Total Resistivity, ρ, $10^{-8}\ \Omega$ m; Intrinsic Resistivity, ρ_i, $10^{-8}\ \Omega$ m]

Solid

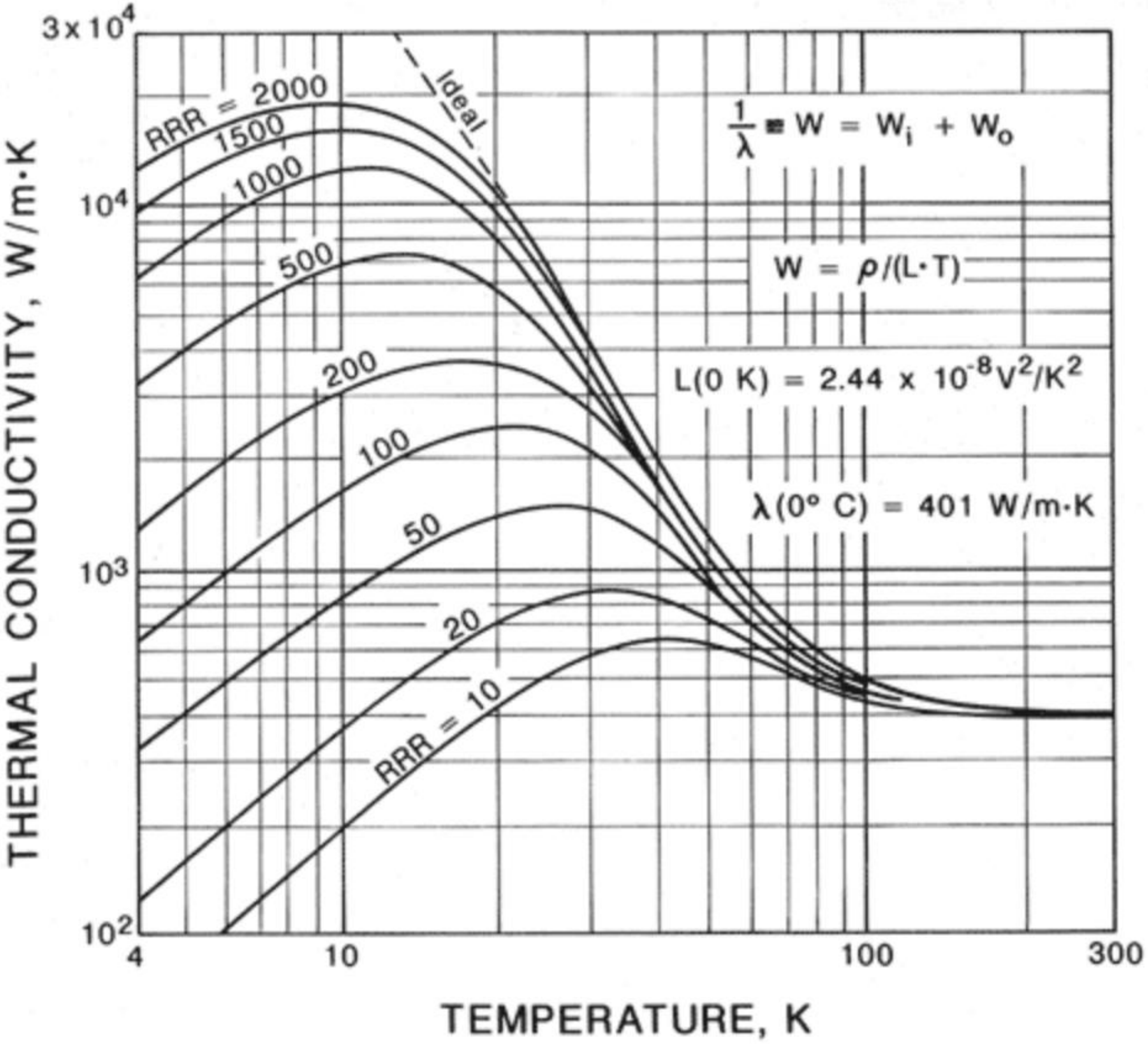
T	$\rho_i^{a,b}$	$\rho^{a,c}$
1		0.00200
4		0.00200
7		0.00200
10		0.00202
15		0.00218
20	0.000798*	0.00280
25	0.00249*	0.00449
30	0.00628	0.00828
35	0.0127	0.0147
40	0.0219	0.0239
45	0.0338	0.0358
50	0.0498	0.0518
55	0.0707	0.0727
60	0.0951	0.0971
70	0.152	0.154
80	0.213	0.215
90	0.279	0.281
100	0.346	0.348
125	0.520	0.522
150	0.697	0.699
175	0.872	0.874
200	1.044	1.046
225	1.215	1.217
250	1.385	1.387
273.15	1.541	1.543
293	1.676	1.678
300	1.723	1.725
350	2.061	2.063
400	2.400	2.402
500	3.088	3.090
600	3.790	3.792
700	4.512	4.514
800	5.260	5.262
900	6.039	6.041
1000	6.856	6.858
1100	7.715	7.717
1200	8.624	8.626
1300	9.590	9.592
1357.6	10.169	10.171



ELECTRICAL RESISTIVITY VERSUS TEMPERATURE FOR COPPER



ELECTRICAL RESISTIVITY VERSUS TEMPERATURE FOR COPPER


3 x 10^4
10^4
10^3
10^2
THERMAL CONDUCTIVITY, W/m·K
4
10
100
300
TEMPERATURE, K
RRR = 2000
1500
1000
500
200
100
50
20
RRR = 10
Ideal
1/λ ≡ W = W_i + W_o
W = ρ/(L·T)
L(0 K) = 2.44 x 10^-8 V^2/K^2
λ(0° C) = 401 W/m·K

Gold

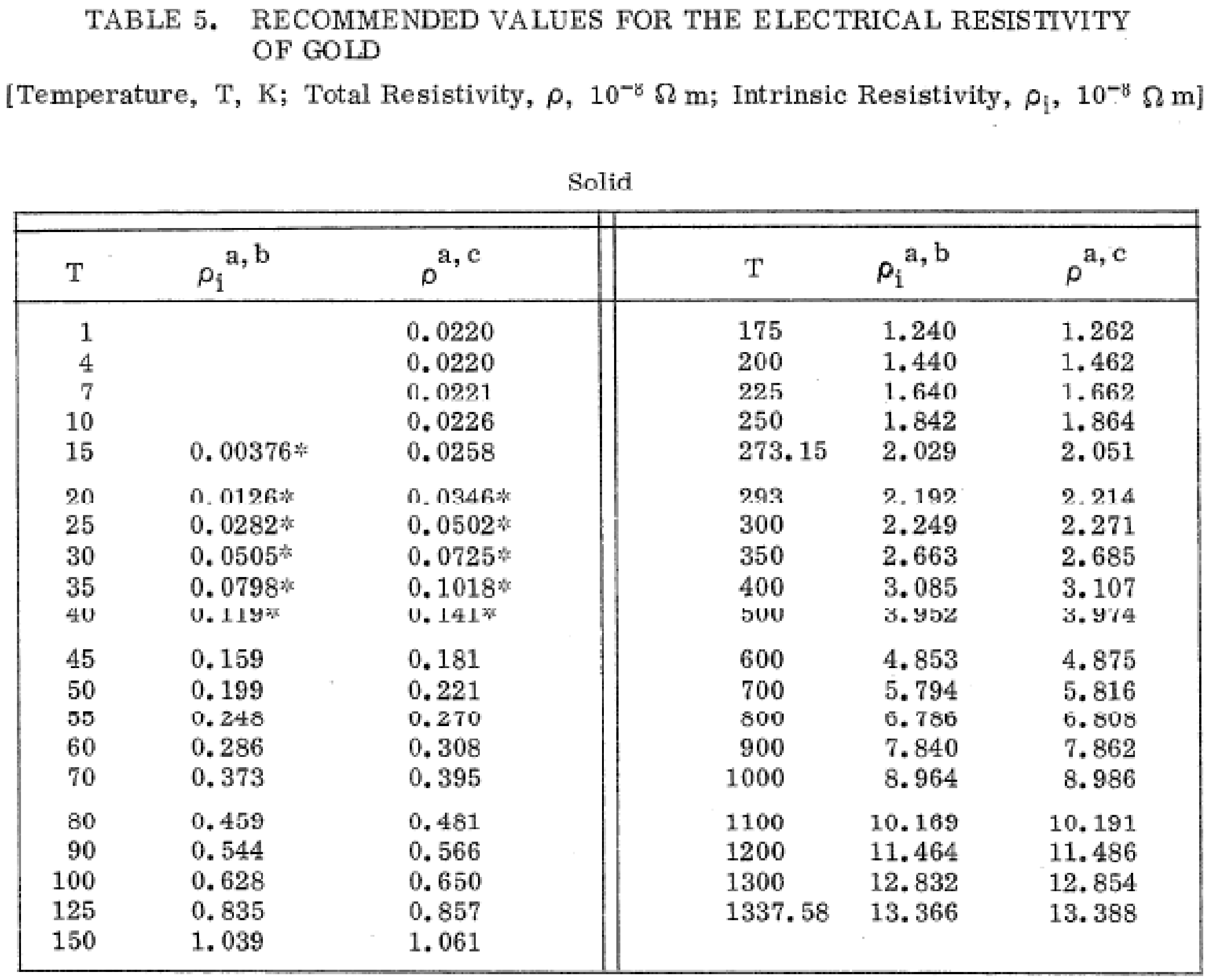
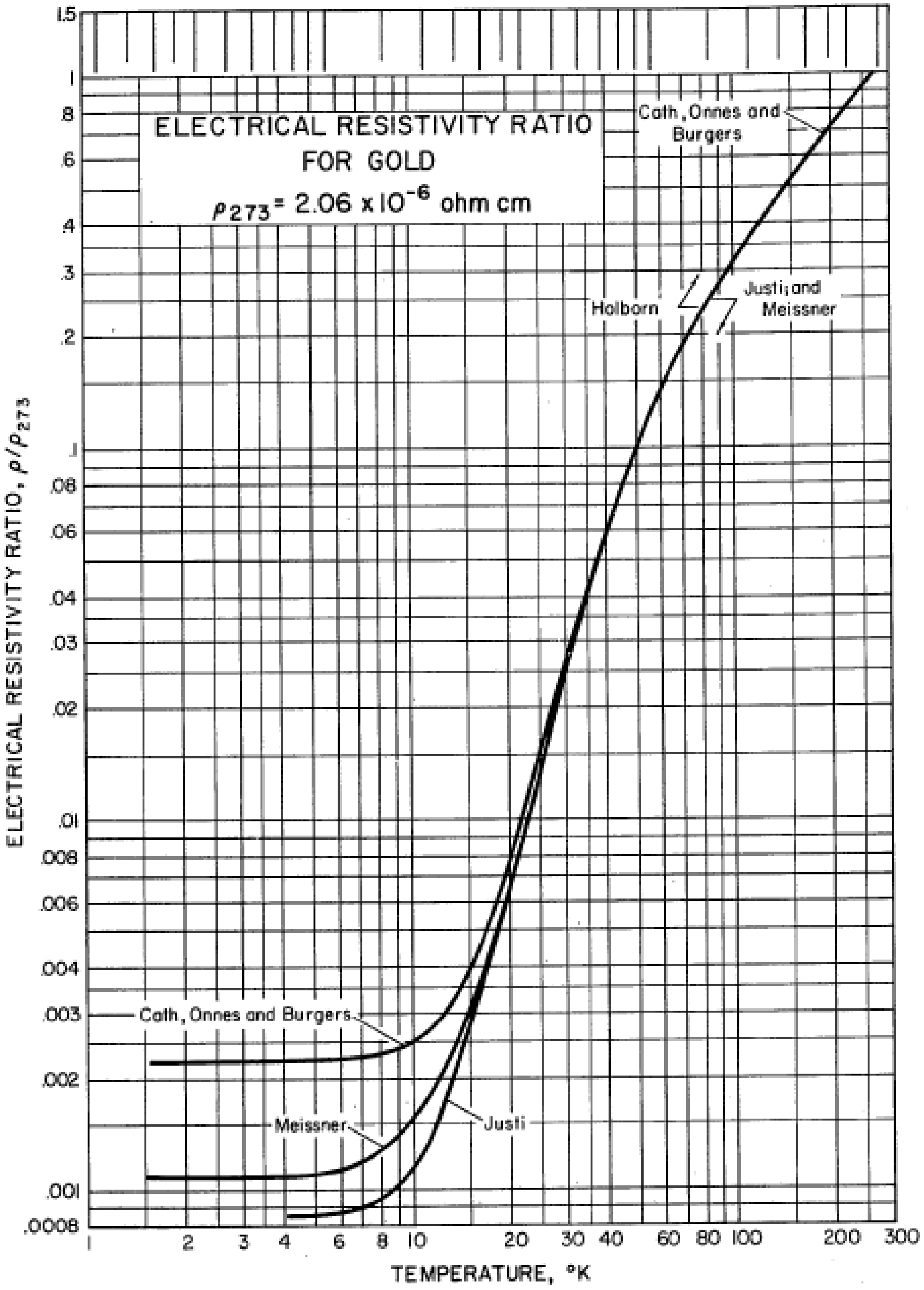


TABLE 5. RECOMMENDED VALUES FOR THE ELECTRICAL RESISTIVITY OF GOLD

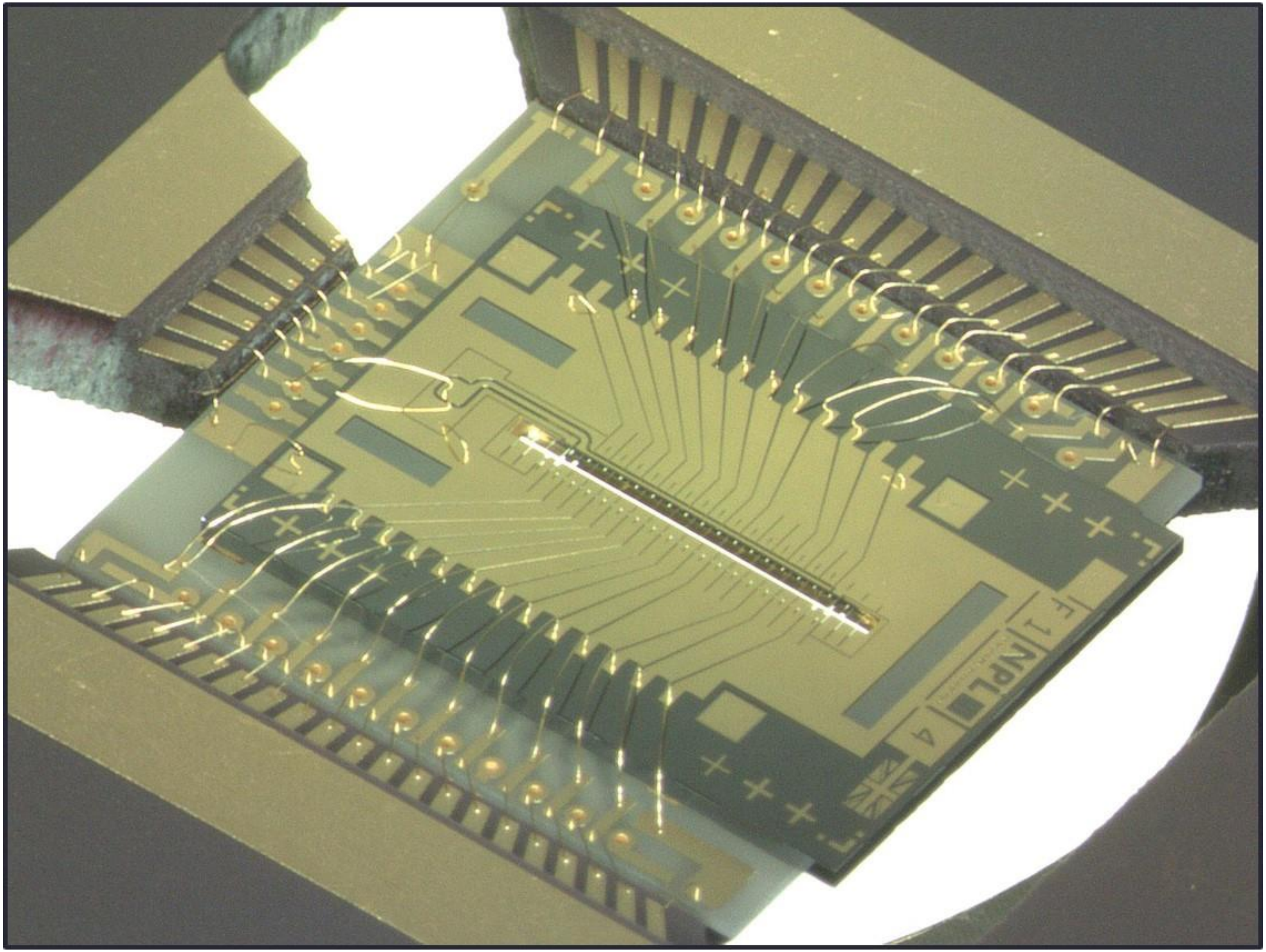
[Temperature, T, K; Total Resistivity, ρ, $10^{-8}\ \Omega\ \mathrm{m}$; Intrinsic Resistivity, ρ_i, $10^{-8}\ \Omega\ \mathrm{m}$]

Solid

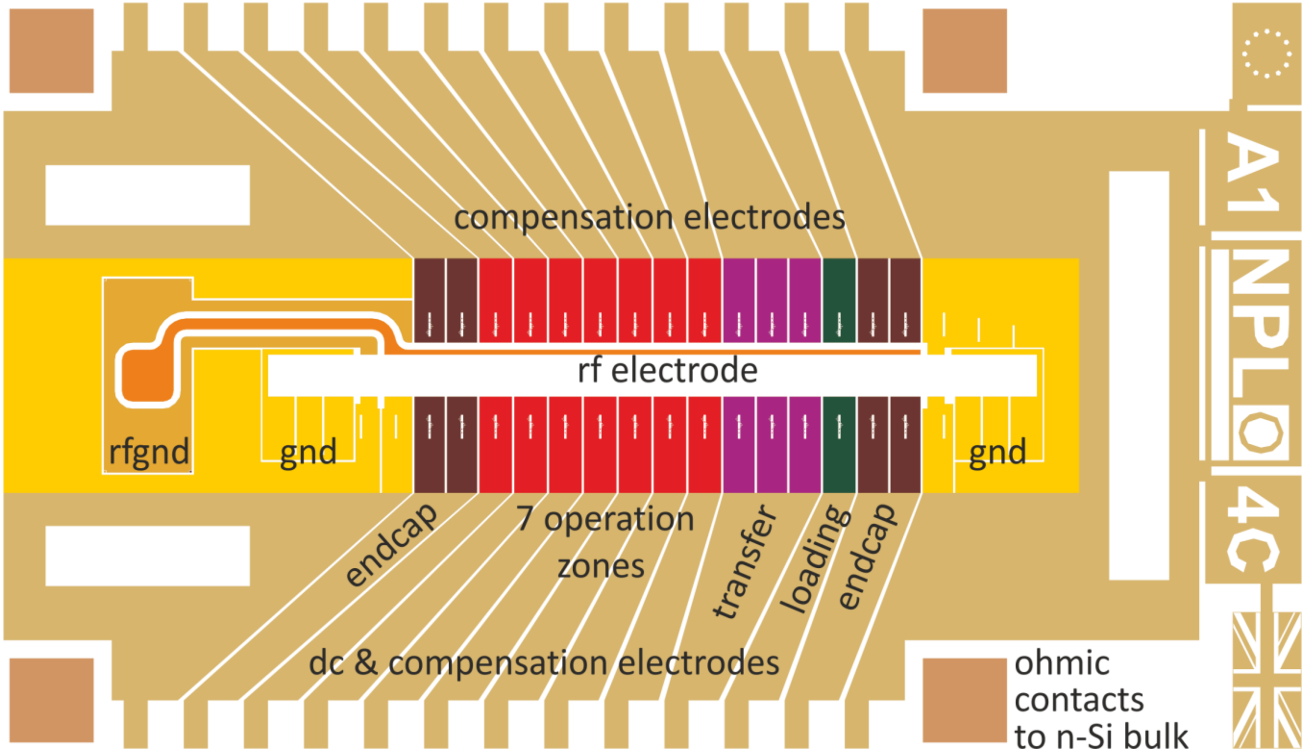
T	$\rho_i^{a,b}$	$\rho^{a,c}$	T	$\rho_i^{a,b}$	$\rho^{a,c}$
1		0.0220	175	1.240	1.262
4		0.0220	200	1.440	1.462
7		0.0221	225	1.640	1.662
10		0.0226	250	1.842	1.864
15	0.00376*	0.0258	273.15	2.029	2.051
20	0.0126*	0.0346*	293	2.192	2.214
25	0.0282*	0.0502*	300	2.249	2.271
30	0.0505*	0.0725*	350	2.663	2.685
35	0.0798*	0.1018*	400	3.085	3.107
40	0.119*	0.141*	500	3.952	3.974
45	0.159	0.181	600	4.853	4.875
50	0.199	0.221	700	5.794	5.816
55	0.248	0.270	800	6.786	6.808
60	0.286	0.308	900	7.840	7.862
70	0.373	0.395	1000	8.964	8.986
80	0.459	0.481	1100	10.169	10.191
90	0.544	0.566	1200	11.464	11.486
100	0.628	0.650	1300	12.832	12.854
125	0.835	0.857	1337.58	13.366	13.388
150	1.039	1.061			


ELECTRICAL RESISTIVITY RATIO
FOR GOLD
ρ_{273} = 2.06 x 10^{-6} ohm cm
Cath, Onnes and Burgers
Holborn
Justi, and Meissner
Cath, Onnes and Burgers
Meissner
Justi
ELECTRICAL RESISTIVITY RATIO, ρ/ρ_{273}
1.5
1
.8
.6
.4
.3
.2
.1
.08
.06
.04
.03
.02
.01
.008
.006
.004
.003
.002
.001
.0008
1
2
3
4
6
8
10
20
30
40
60
80
100
200
300
TEMPERATURE, °K

NPL monolithic trap

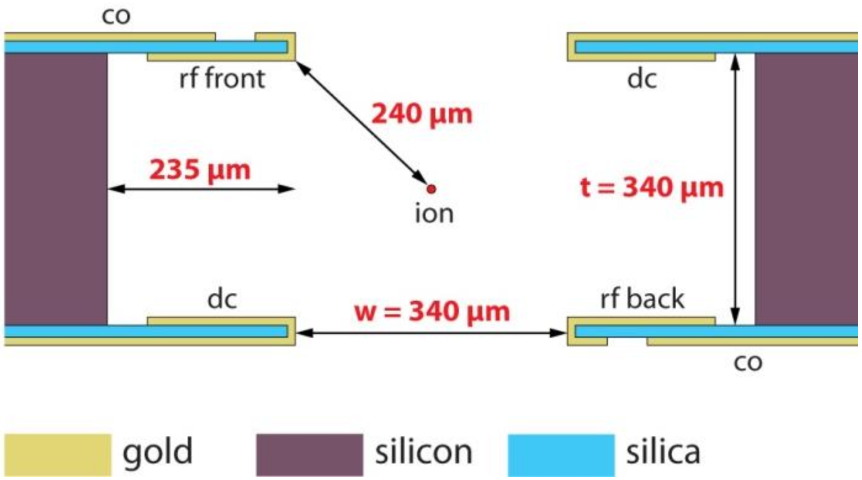


NPL monolithic trap

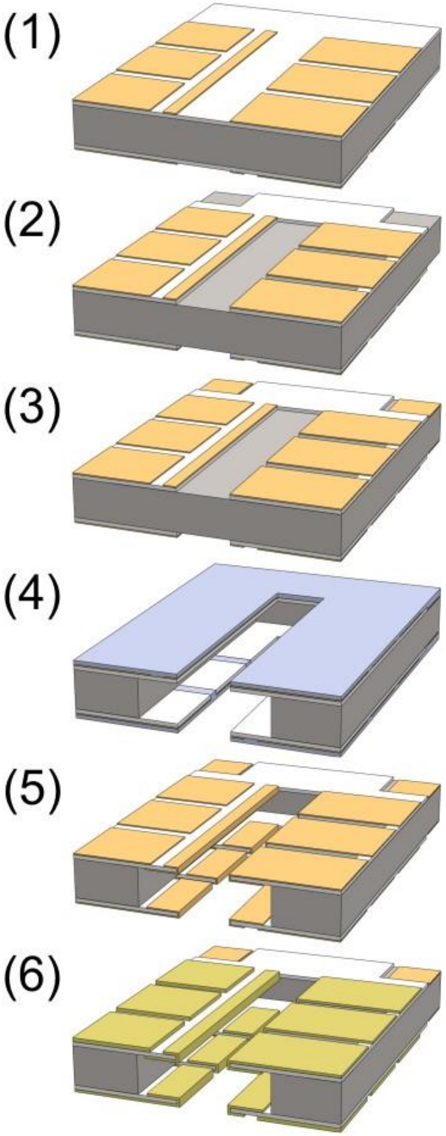


Electrode layout

Cross-section



Microfabrication

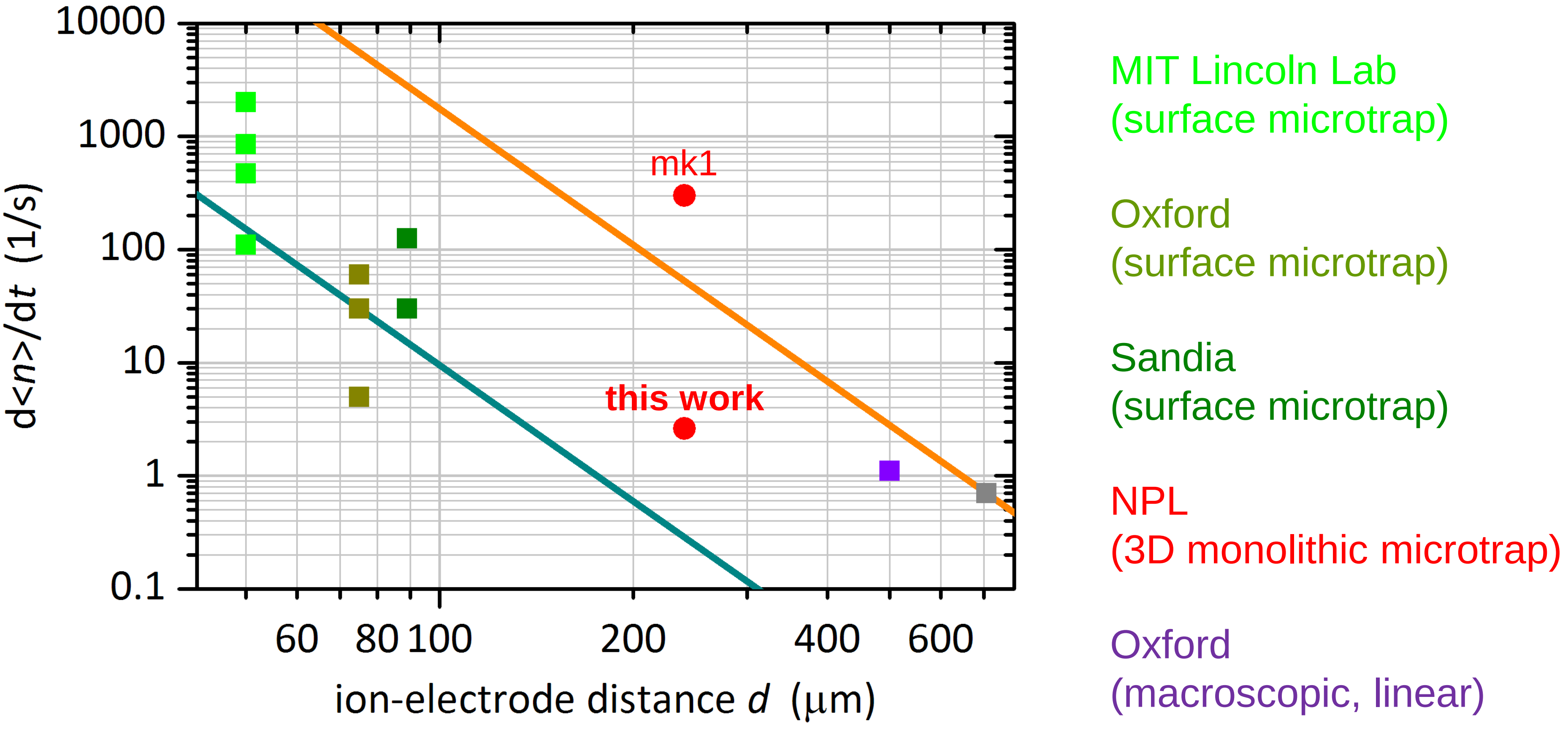


	NPL prototype	**Wafer batches 2&3**
metallisation	wafer	wafer
SiO_2 etch	wafer	wafer
ohmic metallisation	wafer	wafer
Si etch	die	**wafer**
internal metallisation	die	**wafer** with KELVIN NANOTECHNOLOGY
electroplate	die	die

Innovate UK

P. See, G. Wilpers, P. Gill, A. G. Sinclair, J. Microelectromech. Syst., **22** 1180 (2013).

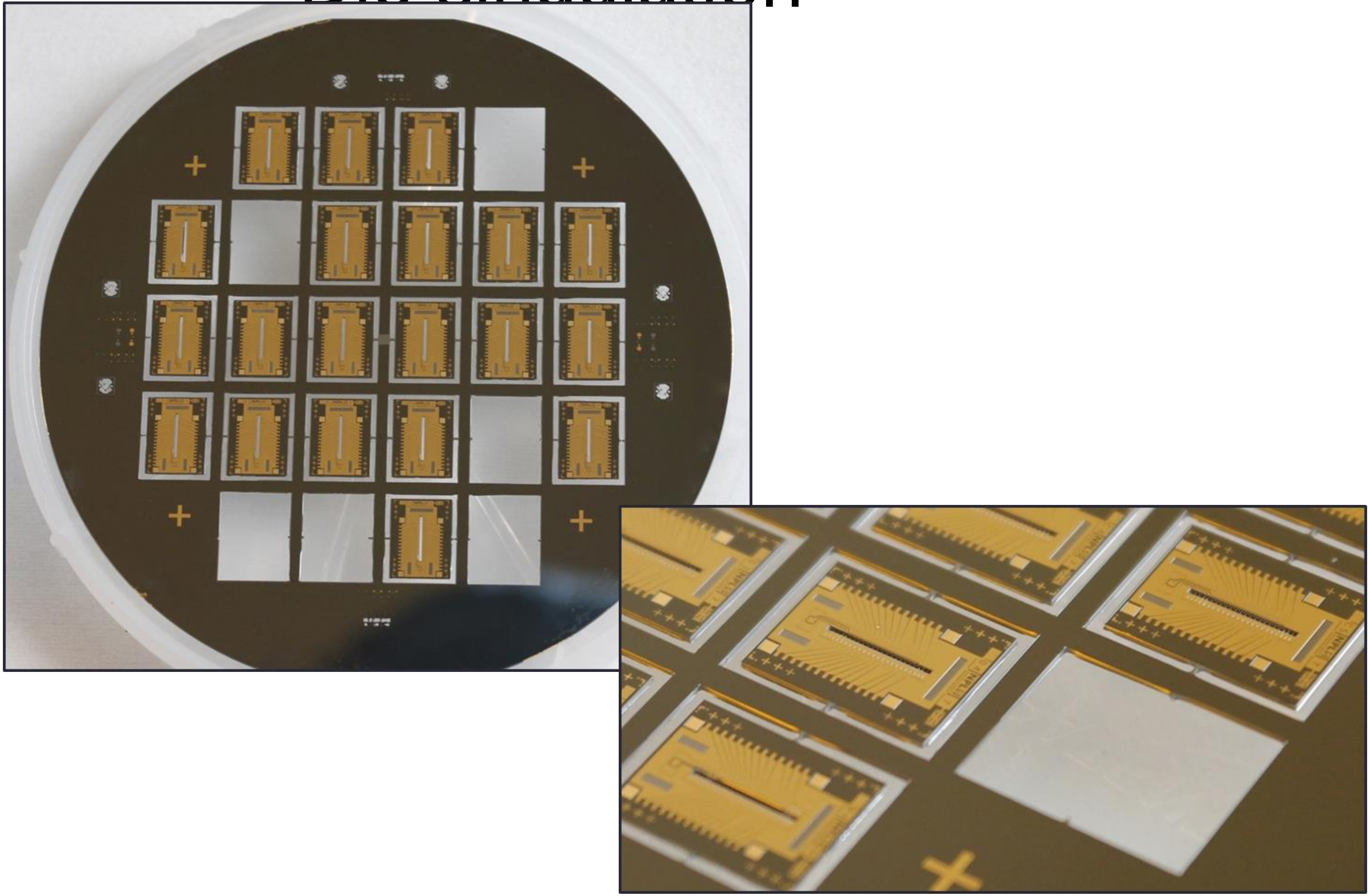
Recent heating rates (trap @ T_{ambient})



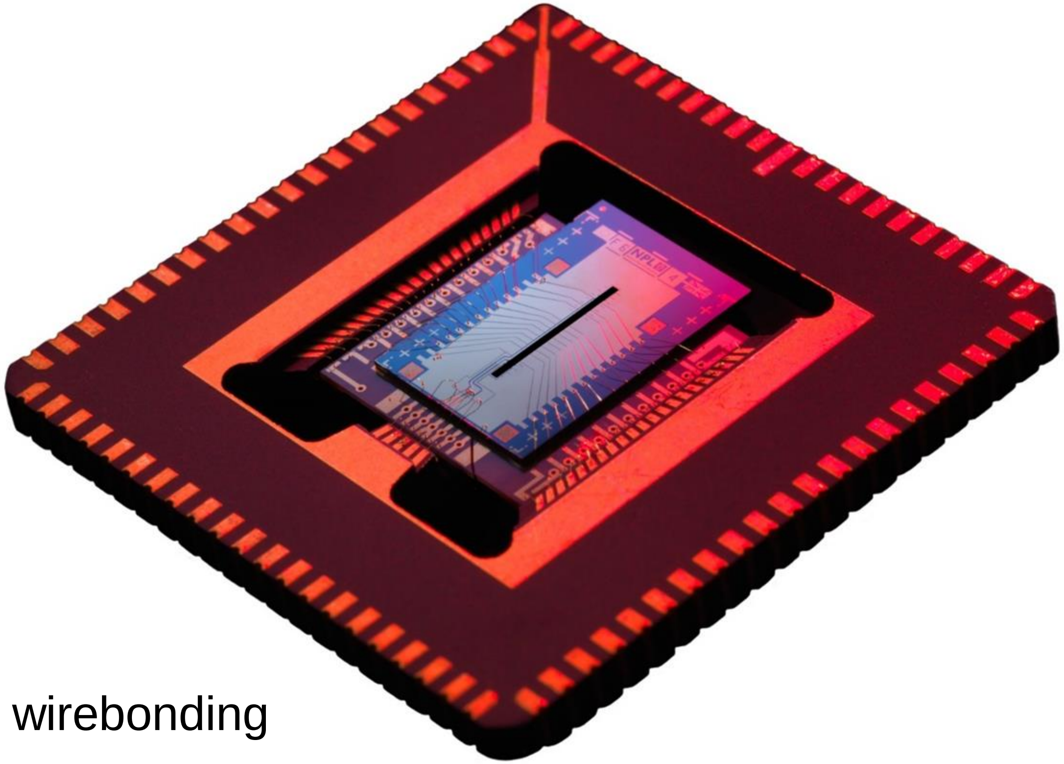
$$\dot{n} = \frac{e^2 S_E(\omega_z)}{4m\hbar\omega_z} \qquad S_E(\omega) \propto \frac{1}{d^4}$$

M D Hughes, *et al*, Contemp. Phys. 52, 505 (2011)
I. A. Boldin, *et al*, arXiv:1708.03147v1 (2017)

Die singulation



Automated electronic packaging



wirebonding

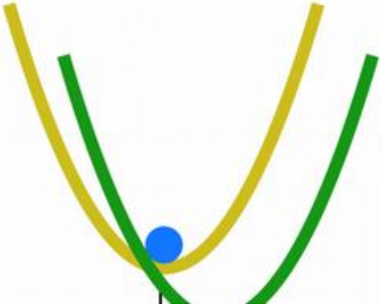
with optocap A company of ALTER TECHNOLOGY GROUP Innovate UK

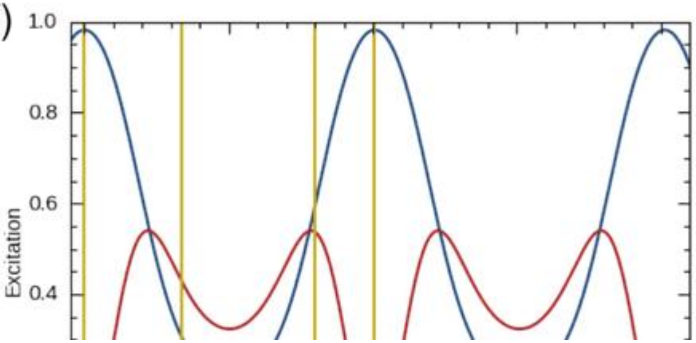
Molybdenum trap

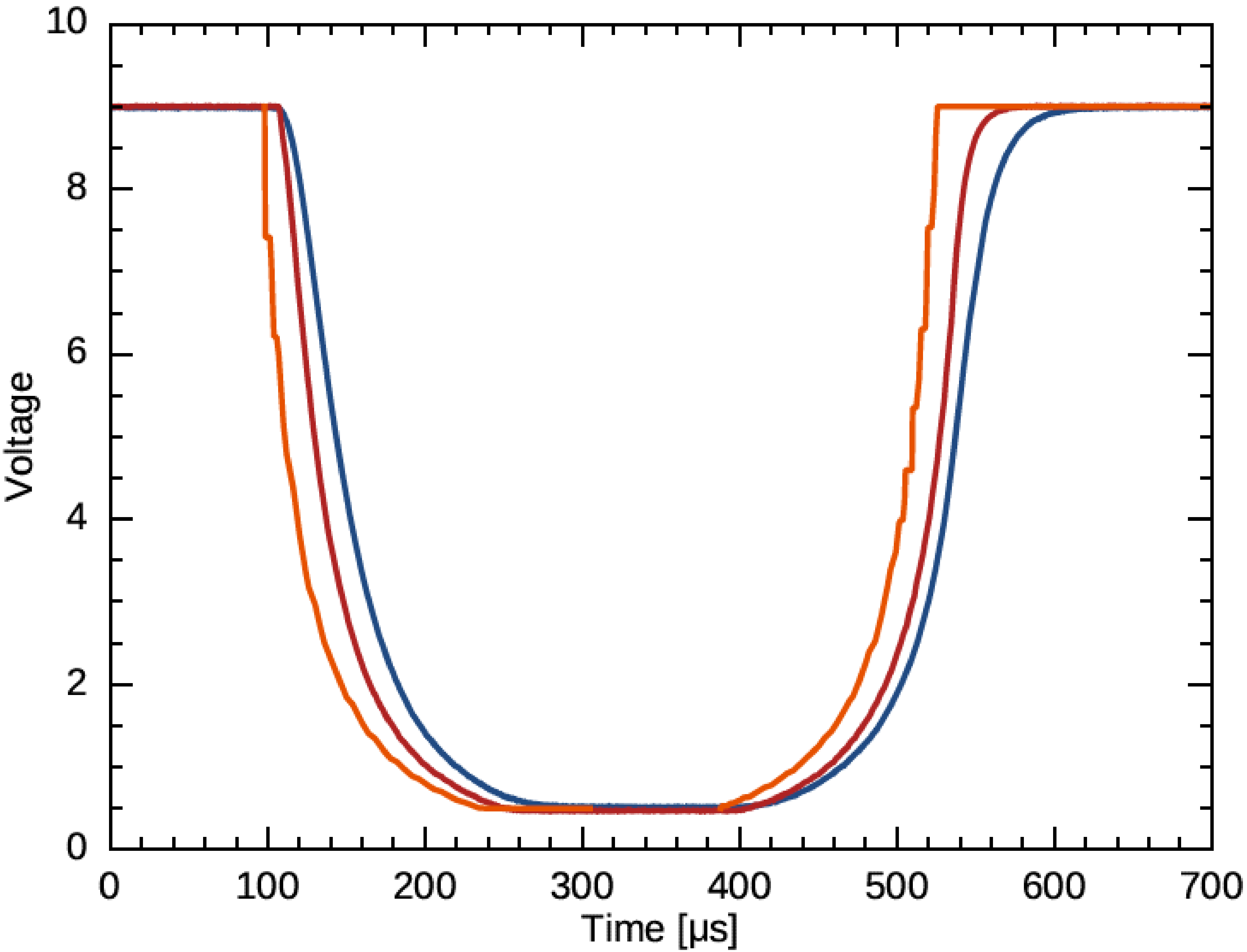
$\alpha = 0.96$
$\bar{n}_{th} = 0.06$

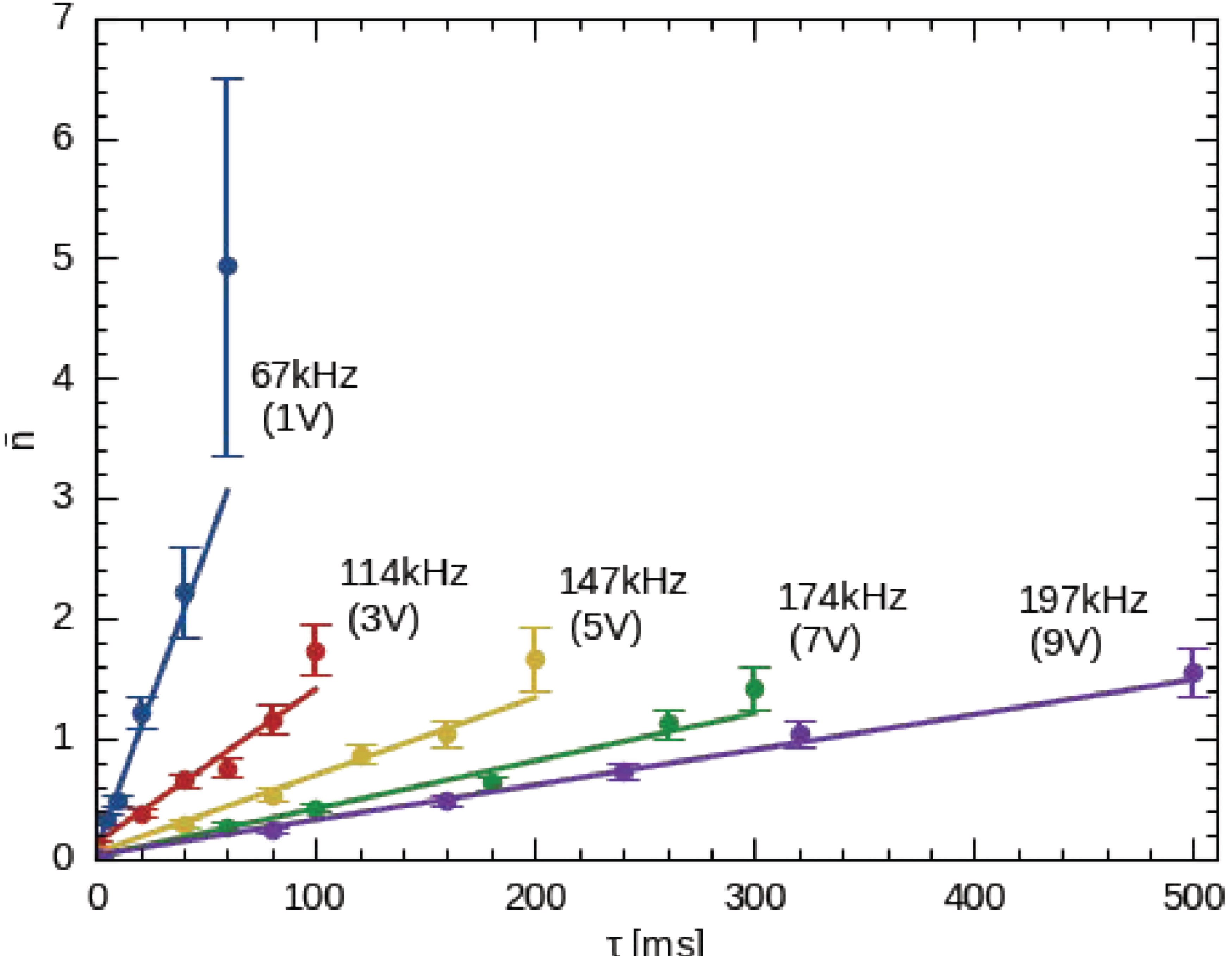
$\Delta z = 96$ nm → $\Delta V = 0.2$ mV
at $\omega_z/(2\pi) = 49.99$ kHz (0.5V)

$\Delta z = 49$ nm → $\Delta V = 1.8$ mV
at $\omega_z/(2\pi) = 197.7$ kHz (9V)

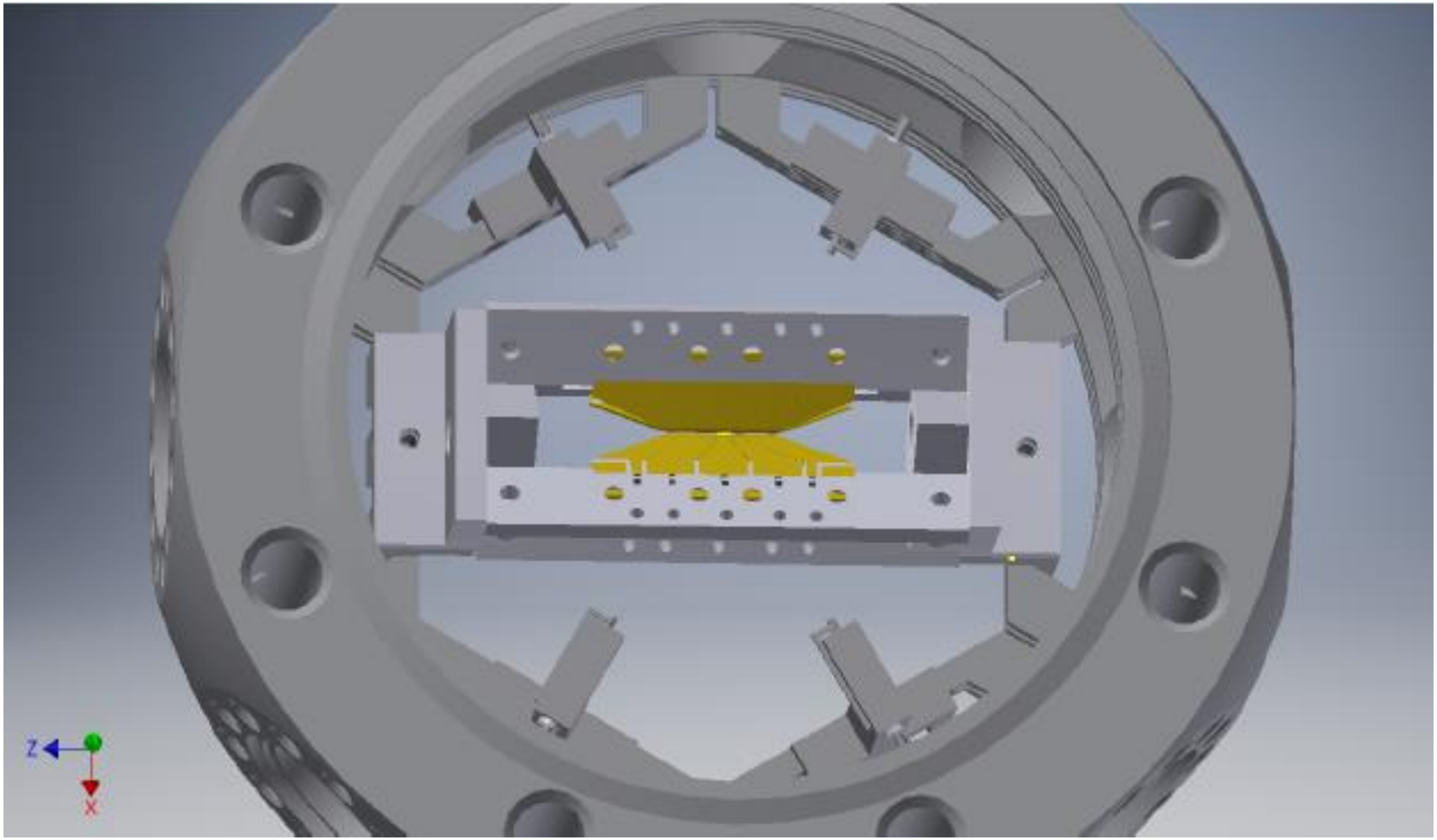


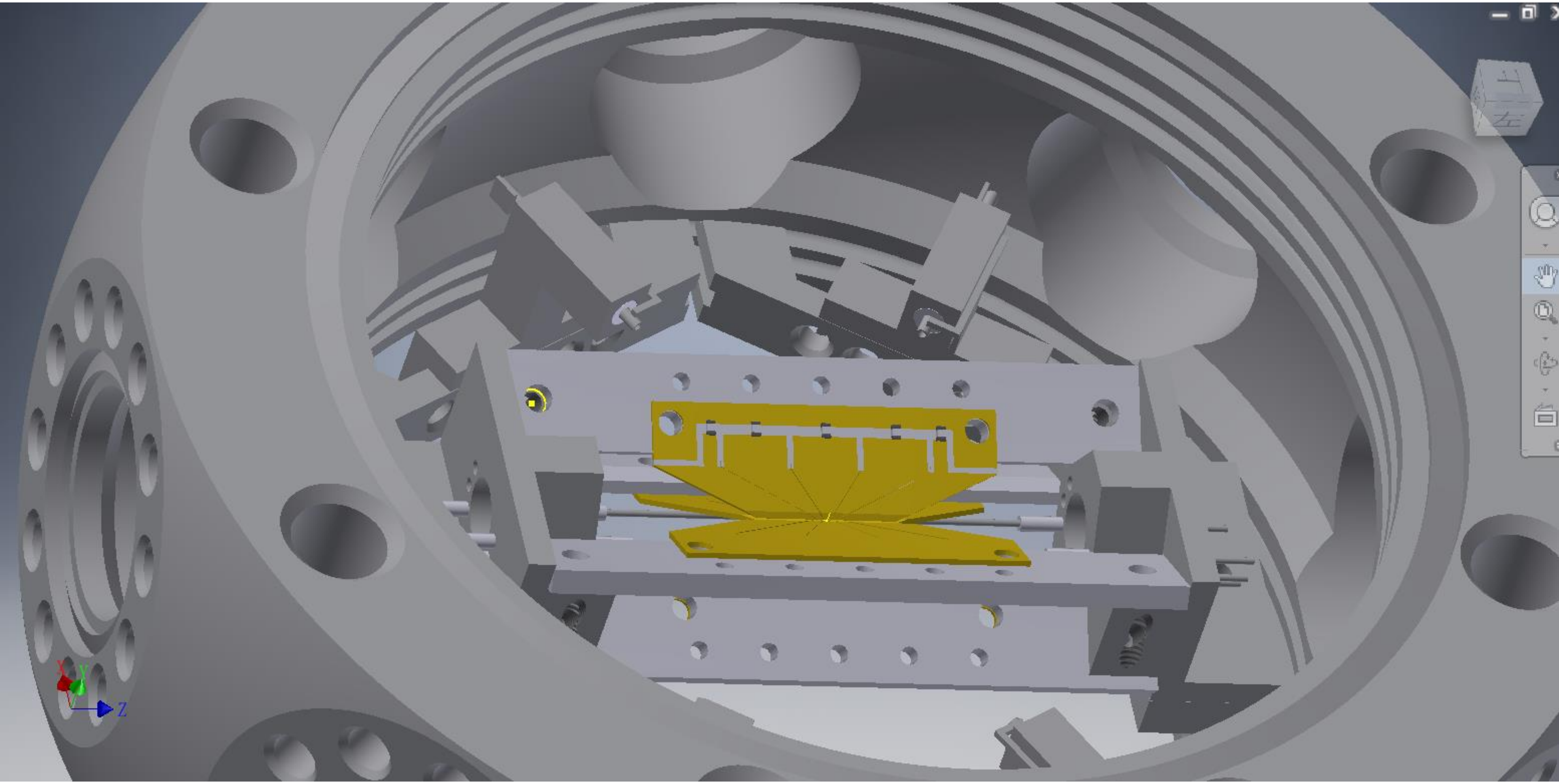


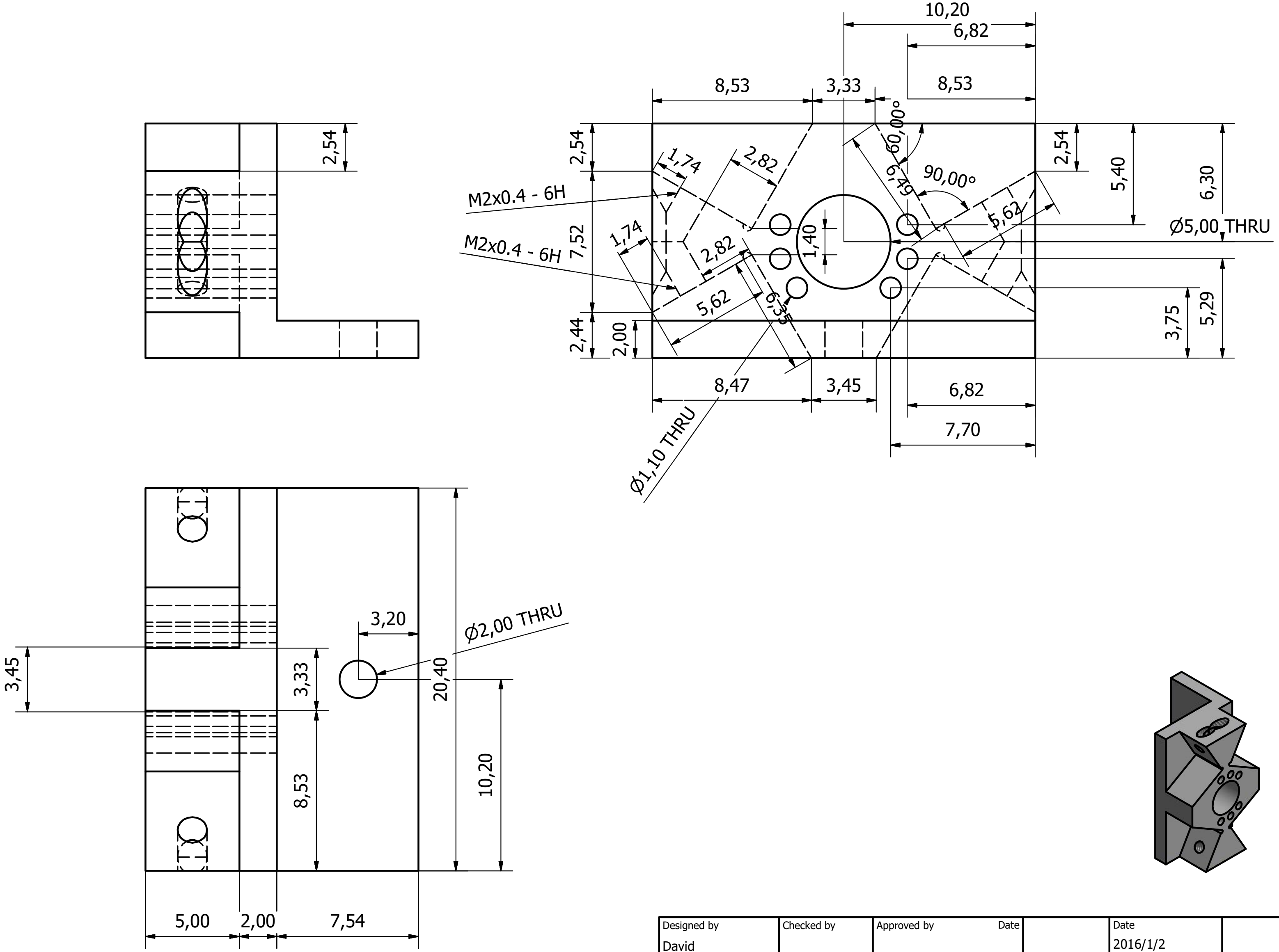

10
8
6
4
2
0
Voltage
0
100
200
300
400
500
600
700
Time [µs]



n̄
τ [ms]
0
100
200
300
400
500
0
1
2
3
4
5
6
7
67kHz
(1V)
114kHz
(3V)
147kHz
(5V)
174kHz
(7V)
197kHz
(9V)


Z
X


X
Y
Z

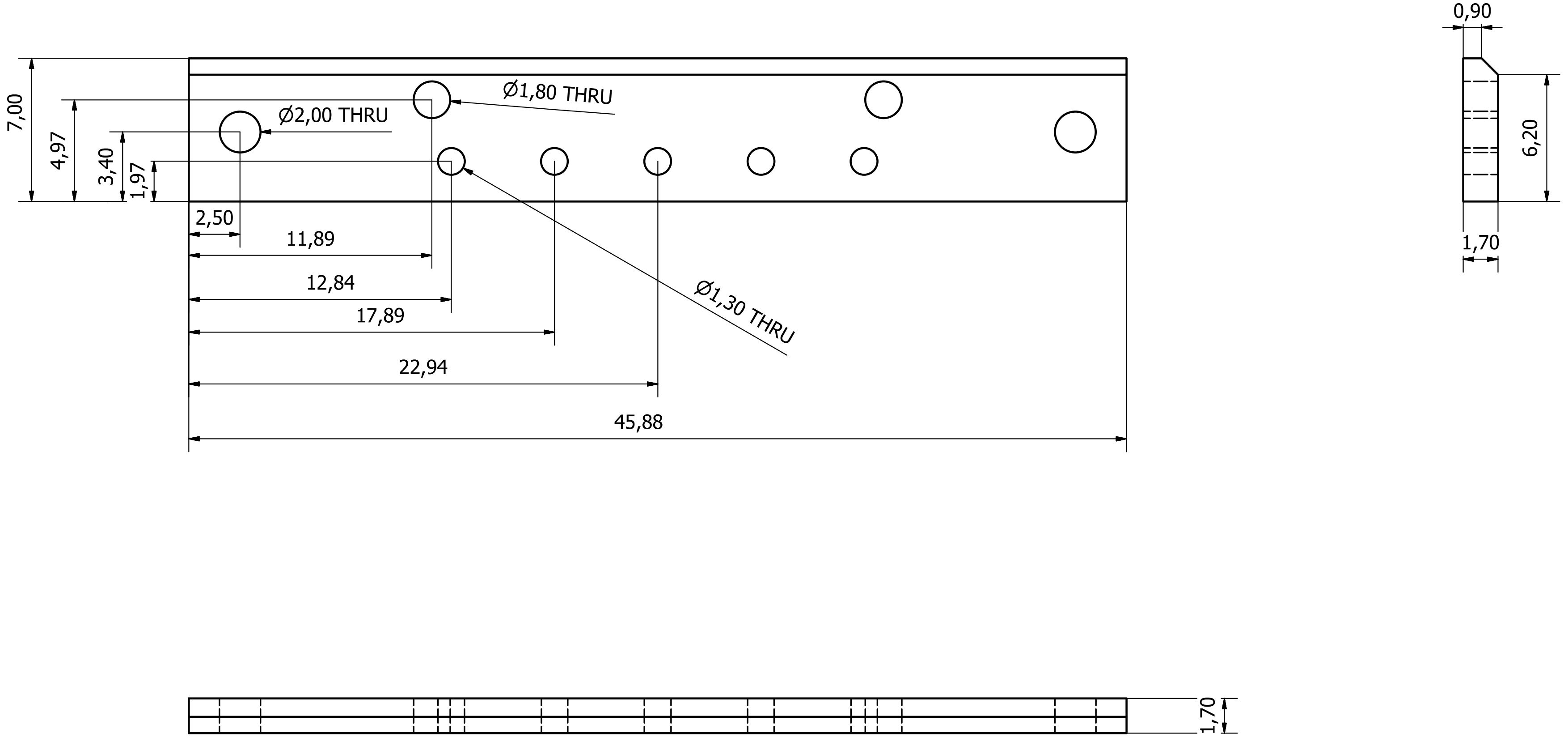


Designed by	Checked by	Approved by	Date		Date	
David					2016/1/2	

XHolder-R1

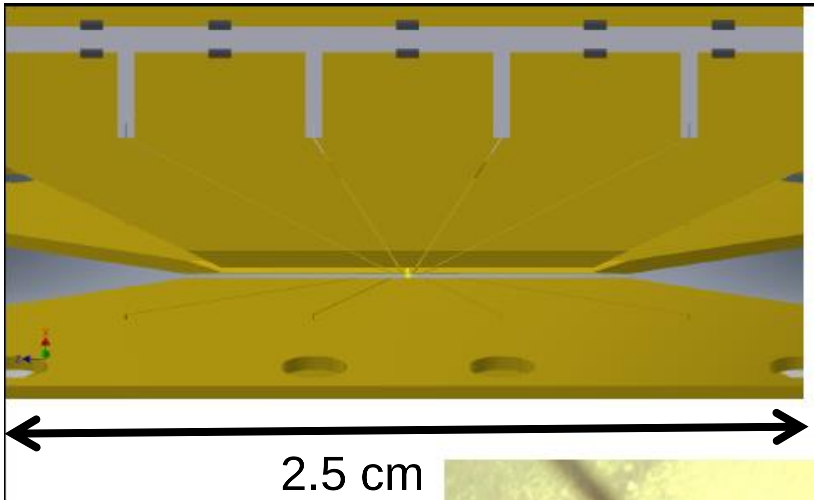
Edition

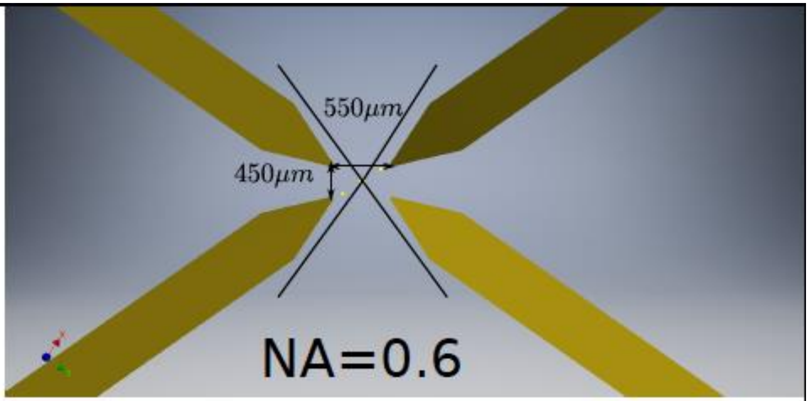
Sheet
1 / 1

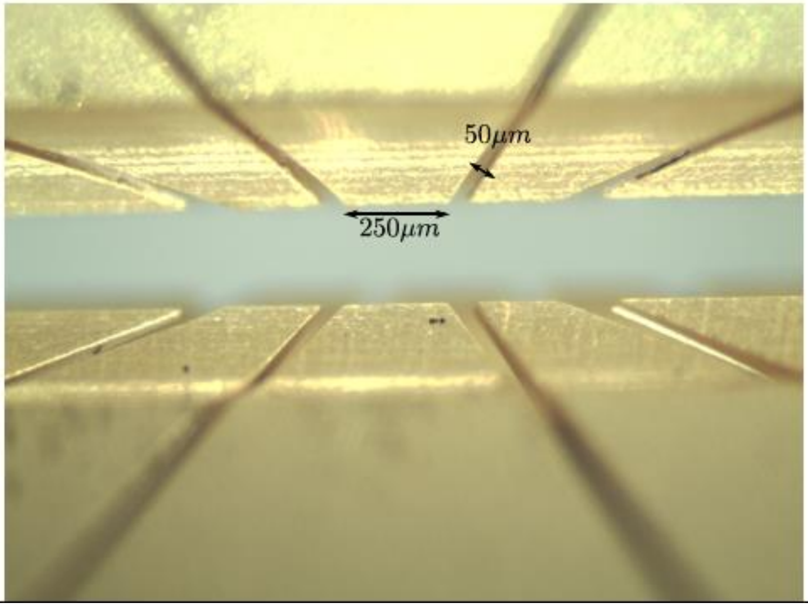


Designed by David	Checked by	Approved by	Date	Date 2016/1/20
XHolderArm-R			Edition	Sheet 1 / 1

TEQ linear rf (ac) trap
Design by Chris Monroe's Group



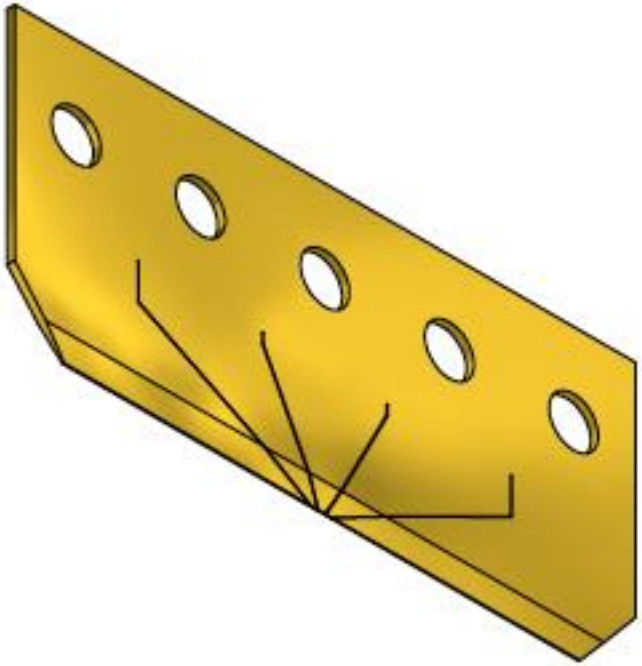


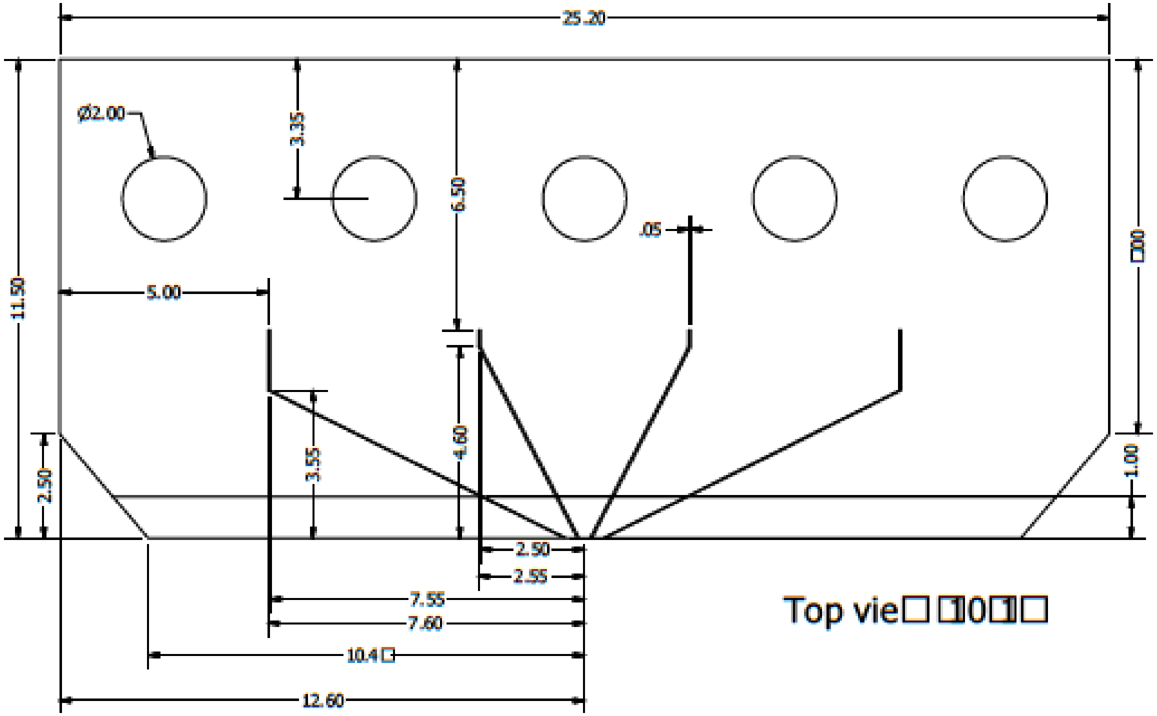


Mat.:
Gold on
Alumina

Design: Chris Monroe's grou

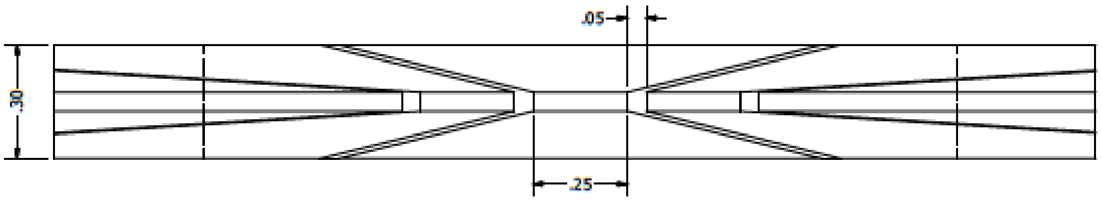
TEQ linear rf (ac) trap
Design by Chris Monroe’s Group



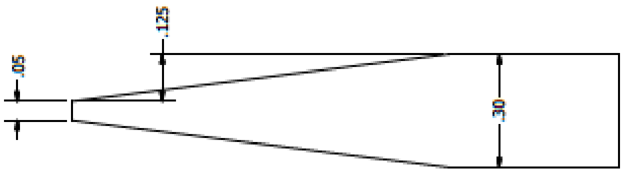


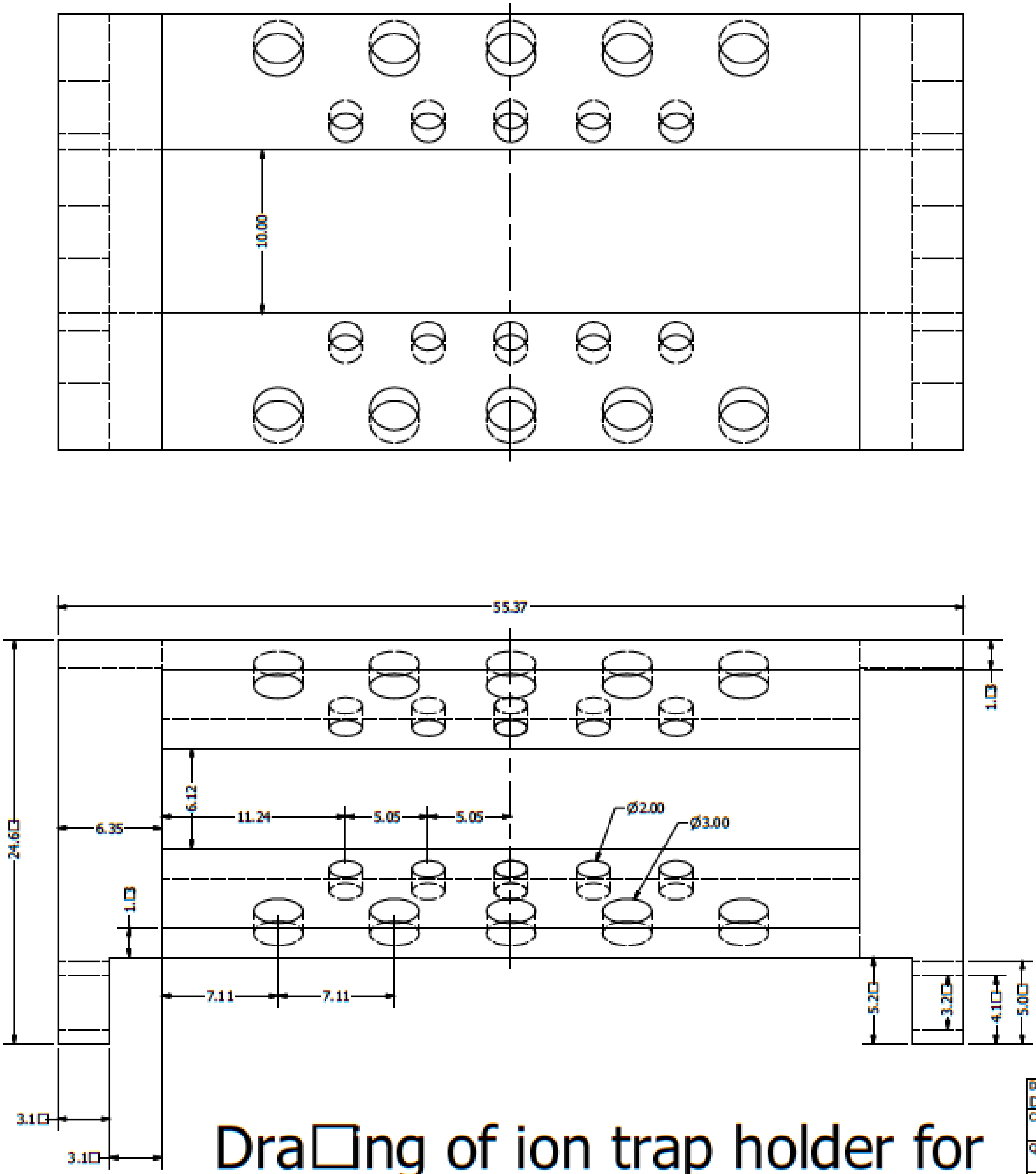
Top vie□ □10□1□

Front vie□ □100□1□



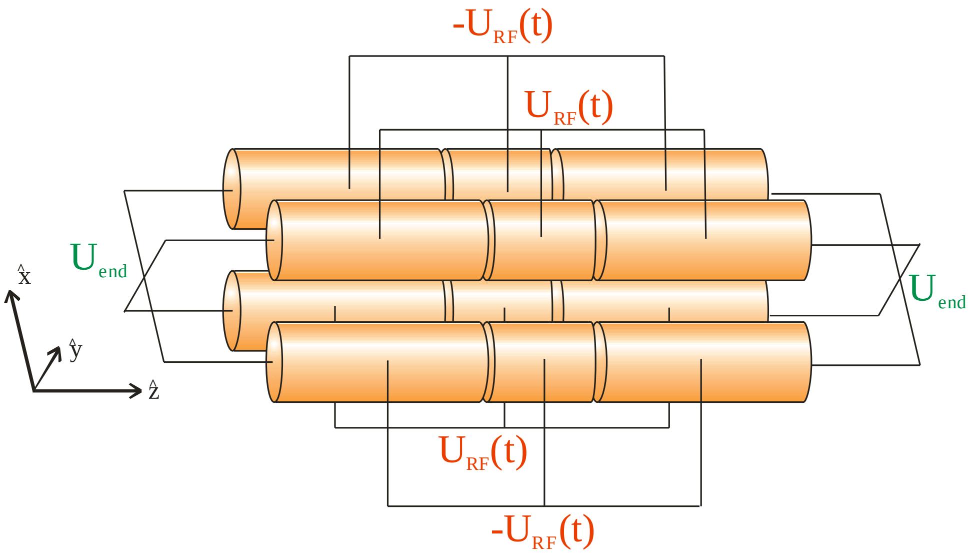
Side vie□ □100□1□





Drawing of ion trap holder for 0.3 mm thick blades

The linear Paul trap



Sinusoidal RF potential: $U_{RF}(t)=U_{RF}\sin(\Omega t)$

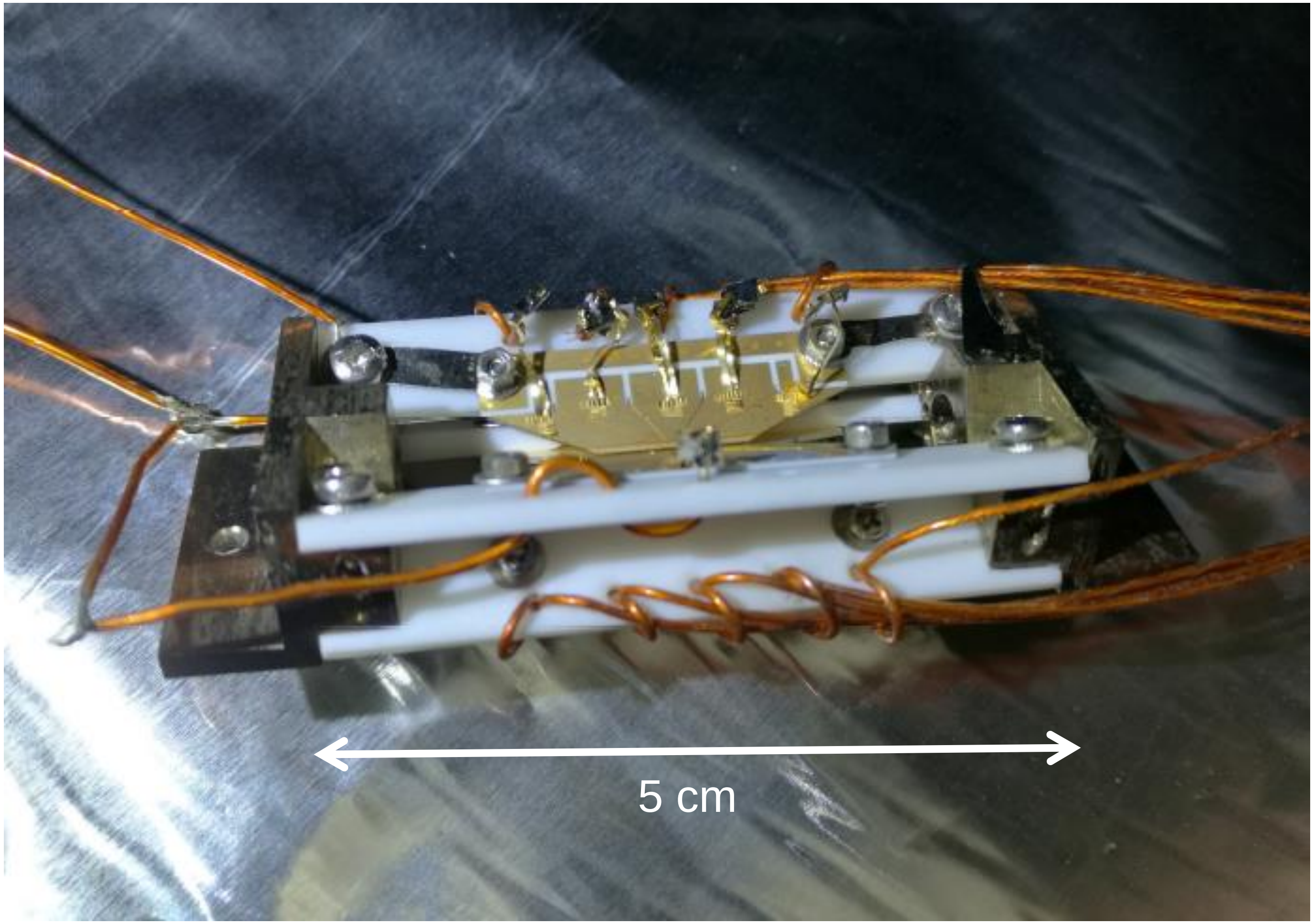
Effective oscillation freq.'s:

$\omega_r=1/2\,\beta\,\Omega\,, \quad \beta=(1/2\,q^2+a)^{1/2}$

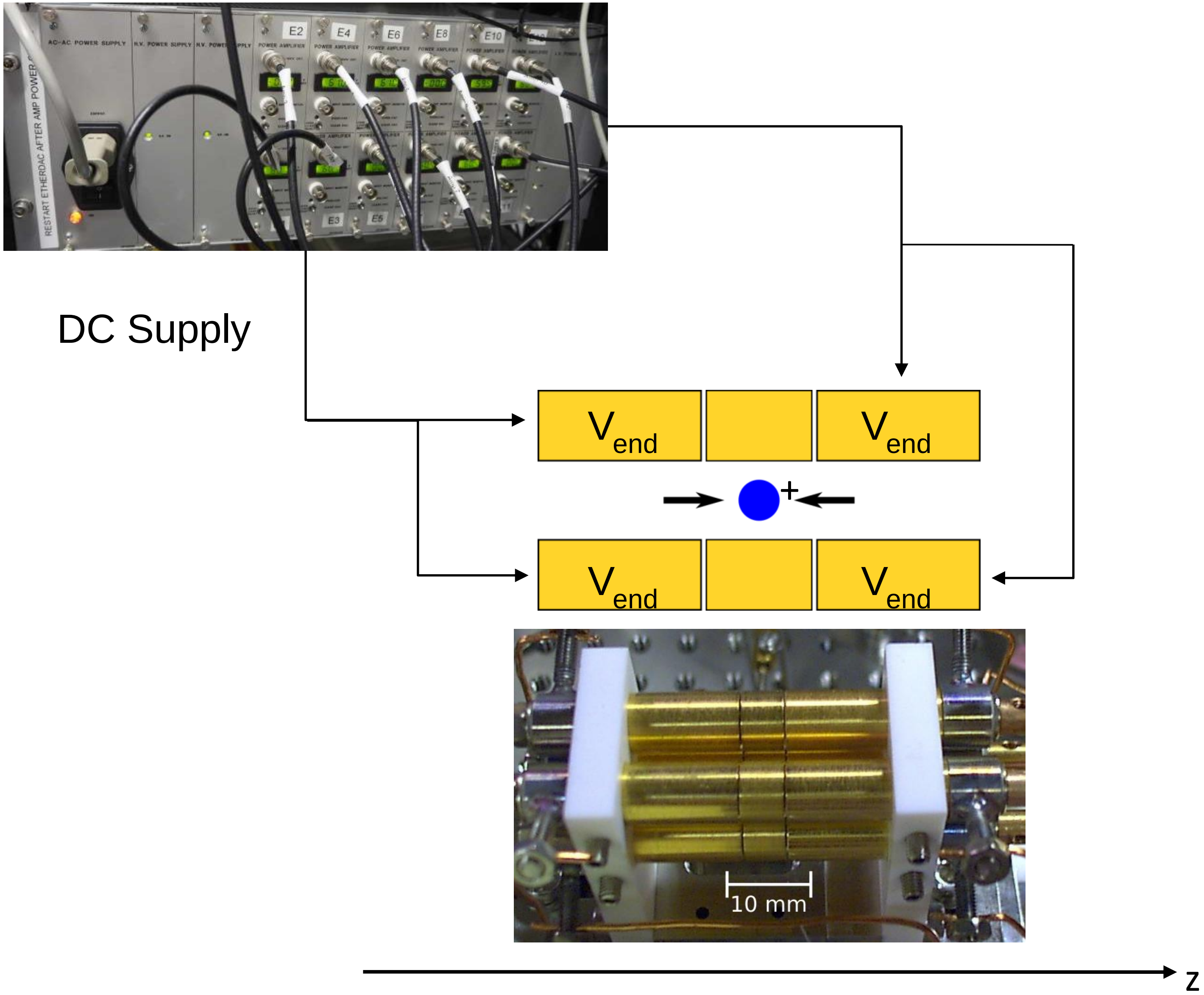
$\omega_z=(-1/2\,a)^{1/2}\Omega$

$$q=\frac{4QU_{RF}}{m\Omega^2 r_0^{\,2}} \qquad a=-\frac{\alpha Q U_{end}}{m\Omega^2 r_0^{\,2}}$$

TEQ linear rf (ac) trap
Design by Chris Monroe’s Group

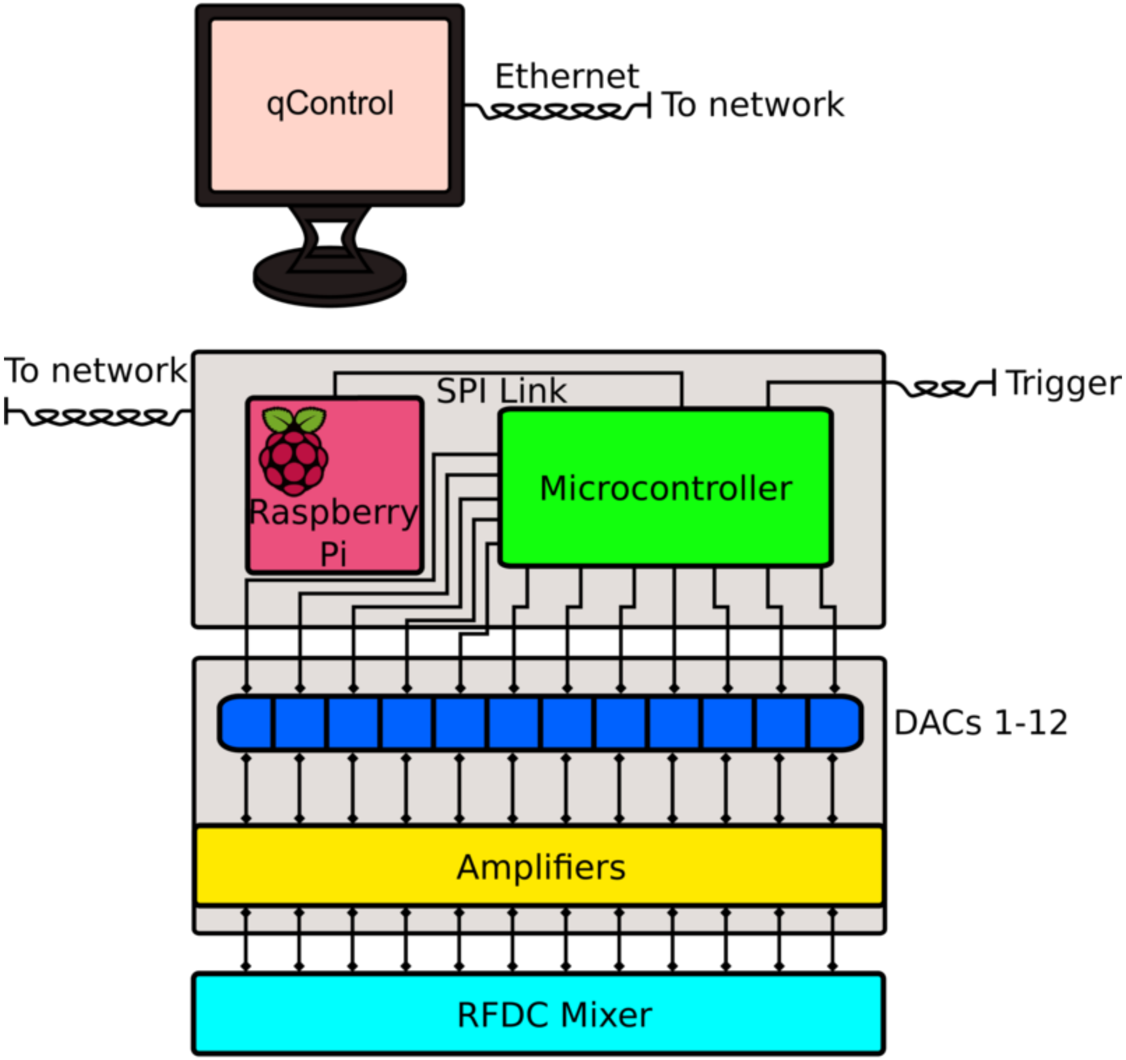


Past DC supply noise-tests



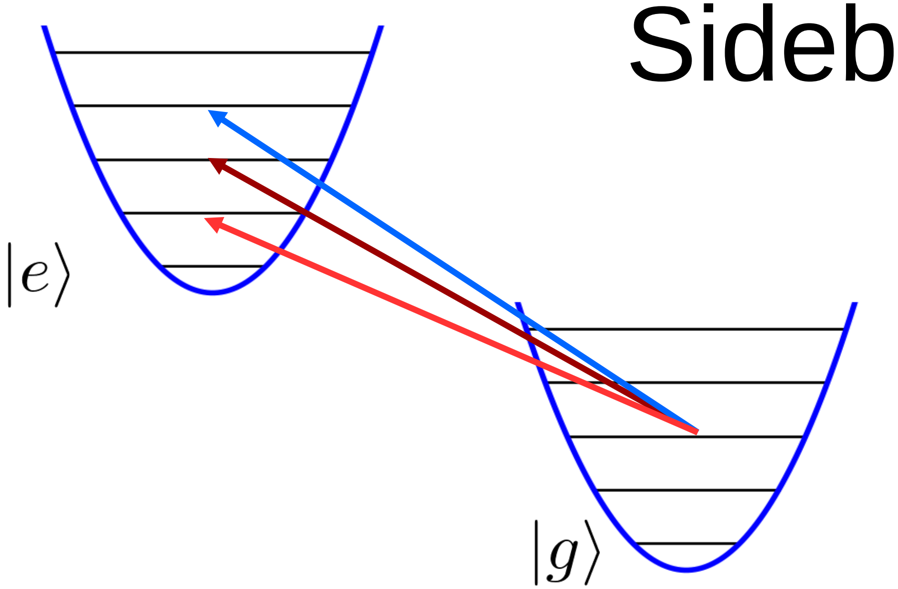
DC Supply

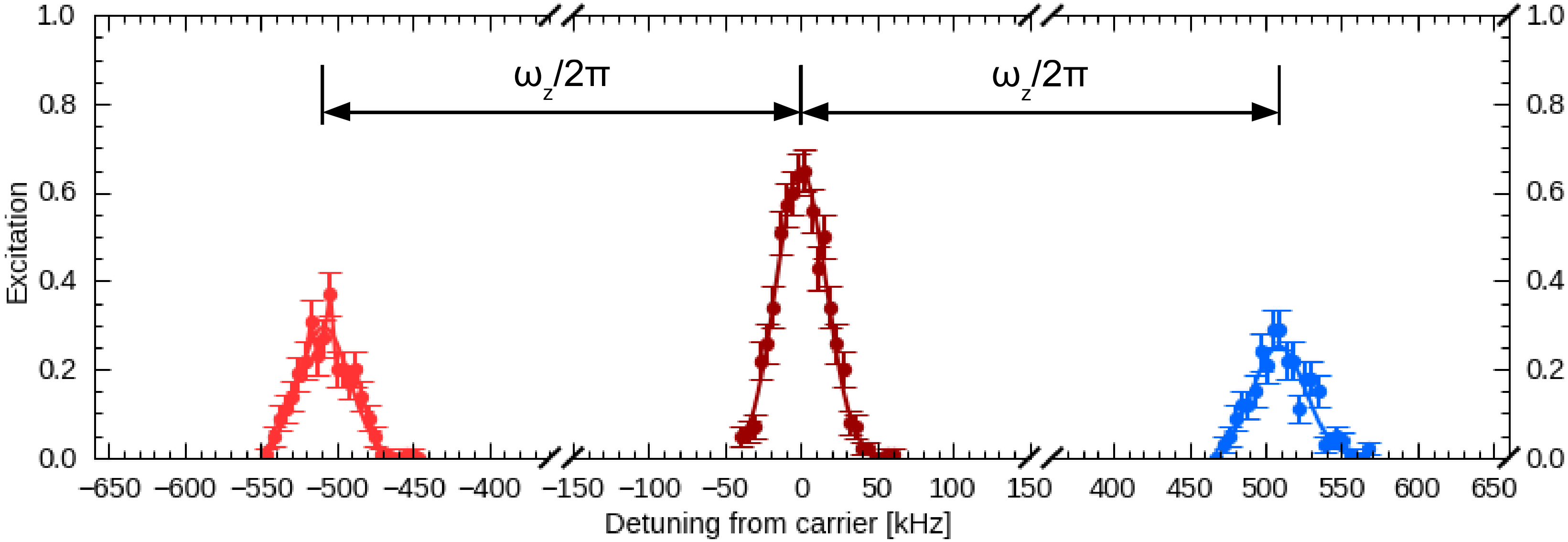
DC supply



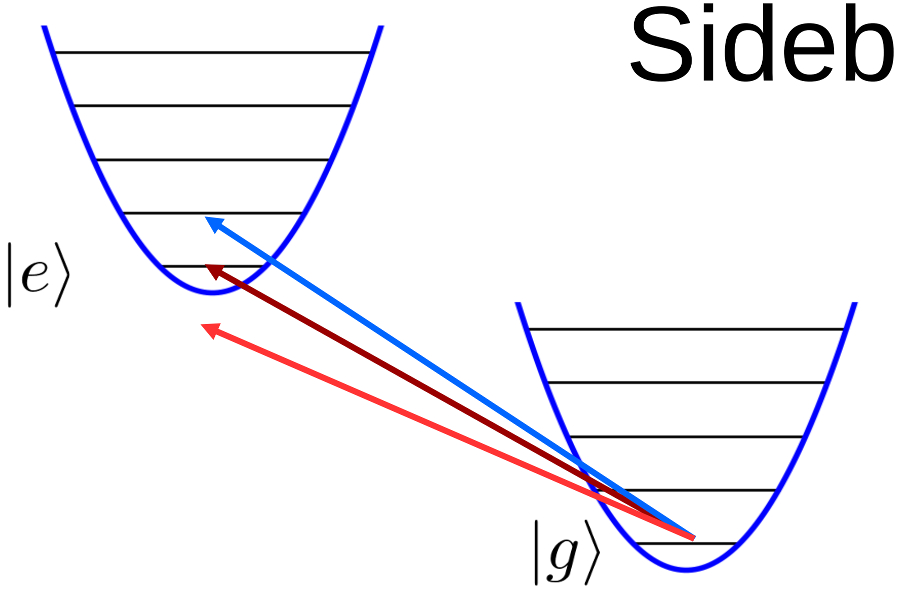
EtherDAC 2.1

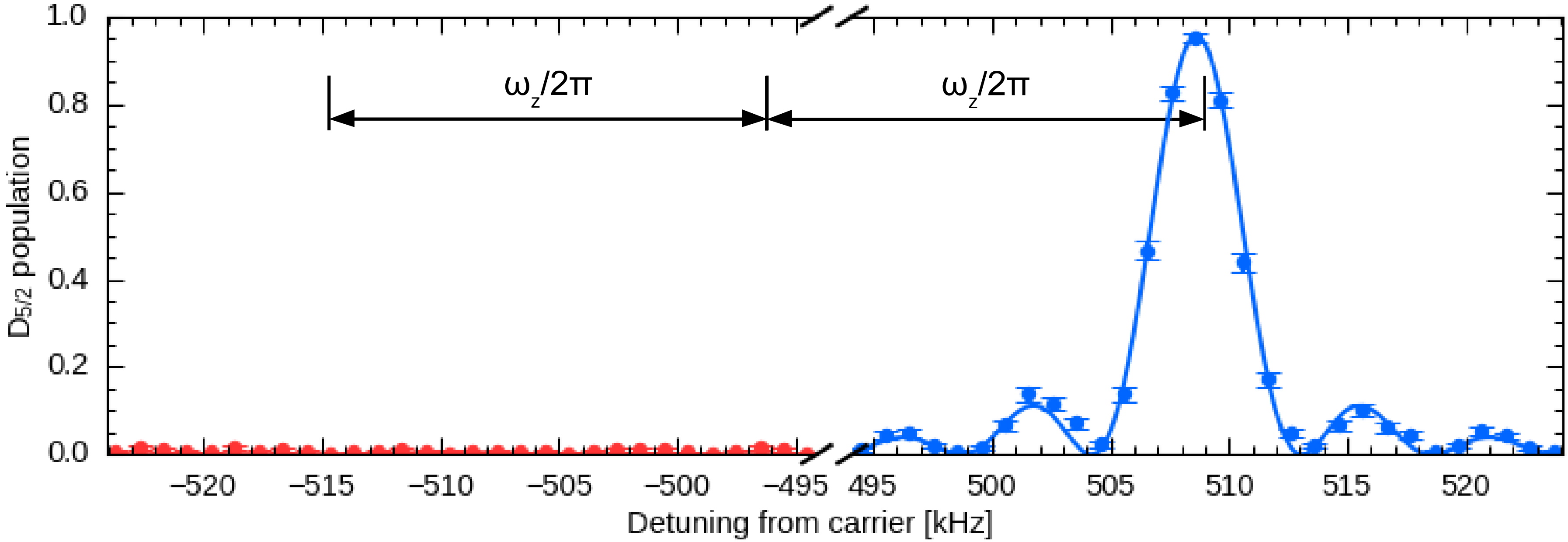
Sidebands


$|e\rangle$
$|g\rangle$

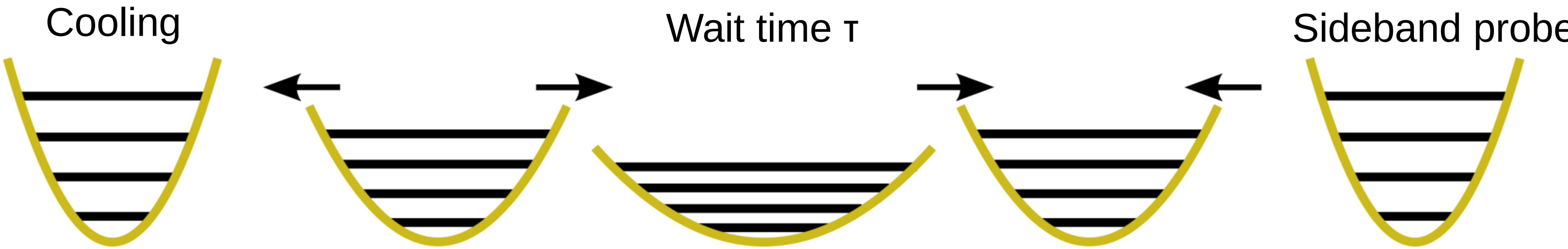

$\omega_z/2\pi$
$\omega_z/2\pi$
Excitation
0.0
0.2
0.4
0.6
0.8
1.0
−650
−600
−550
−500
−450
−400
−150
−100
−50
0
50
100
150
400
450
500
550
600
650
Detuning from carrier [kHz]

Sidebands


$|e\rangle$
$|g\rangle$


$\omega_z/2\pi$
$\omega_z/2\pi$
1.0
0.8
0.6
0.4
0.2
0.0
$D_{5/2}$ population
−520
−515
−510
−505
−500
−495
495
500
505
510
515
520
Detuning from carrier [kHz]

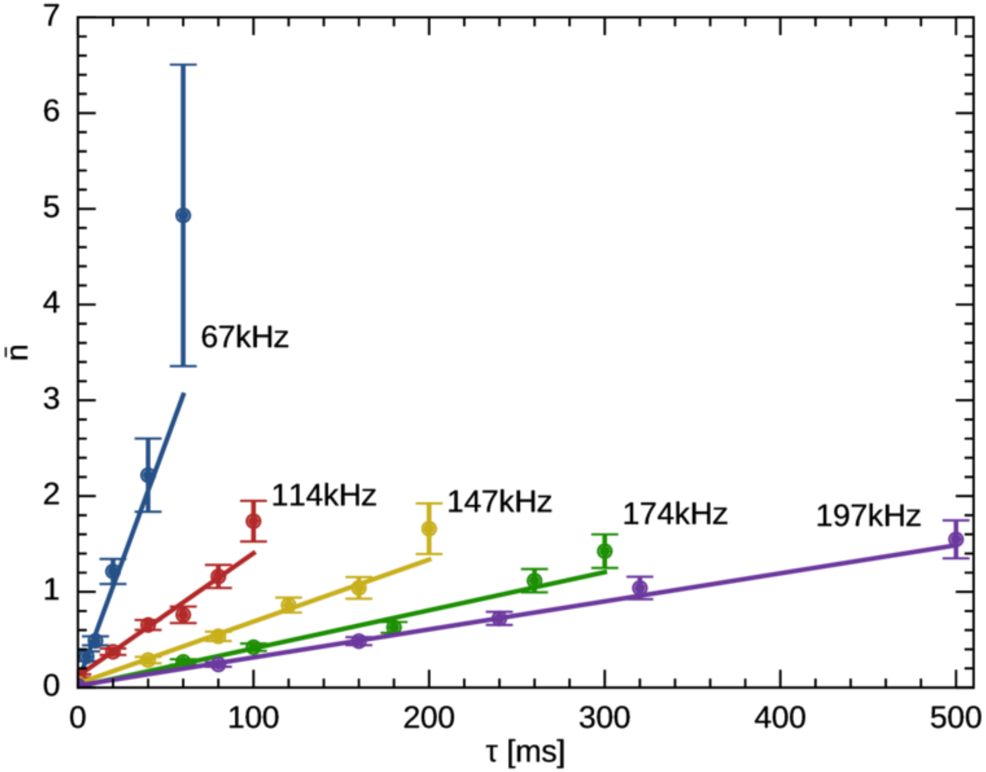
Heating rates



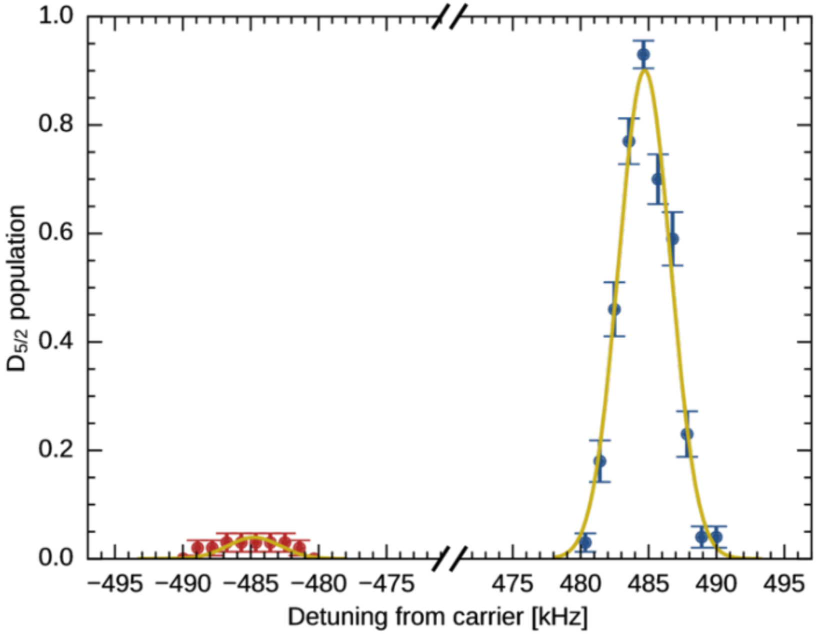
Cooling

Wait time τ

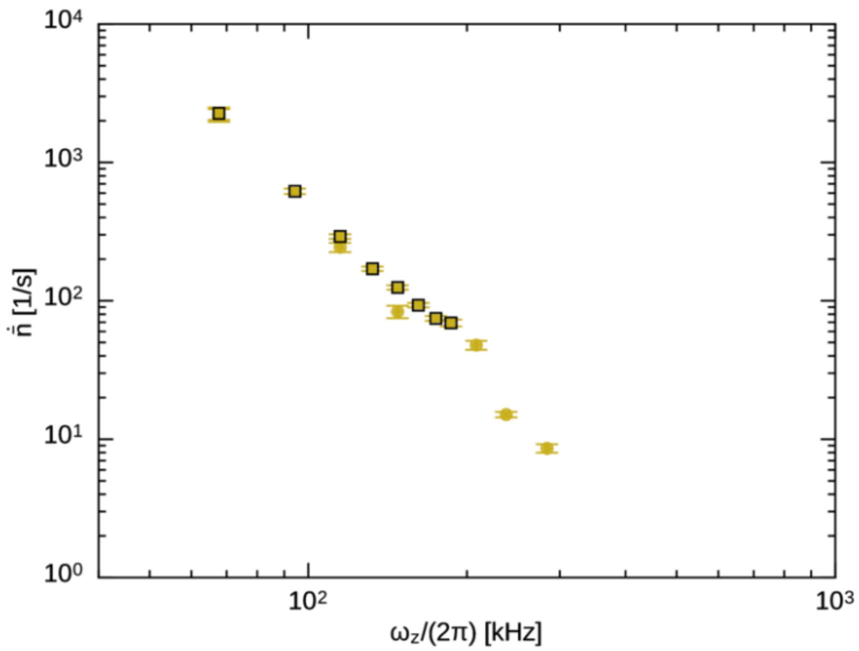
Sideband probe

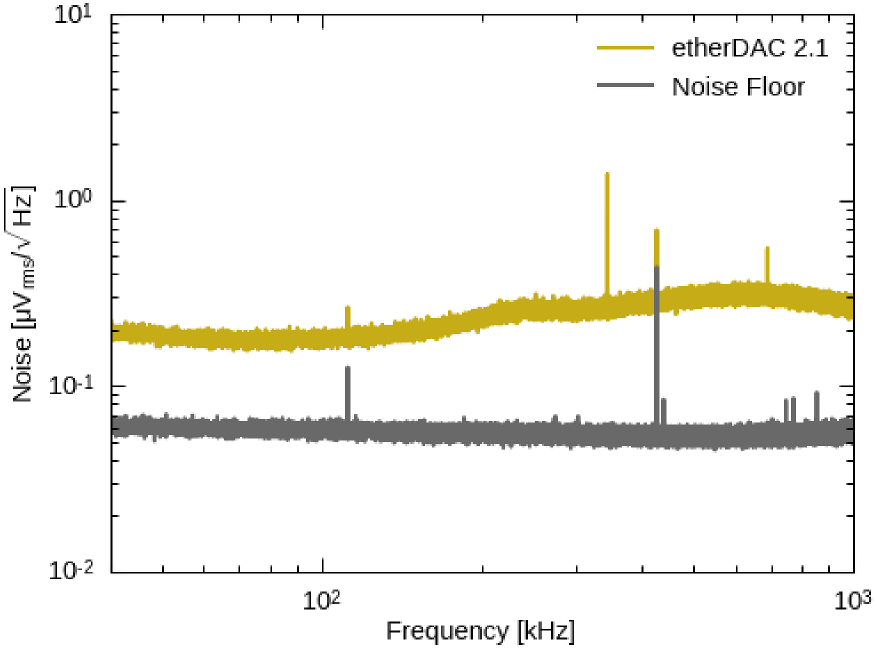


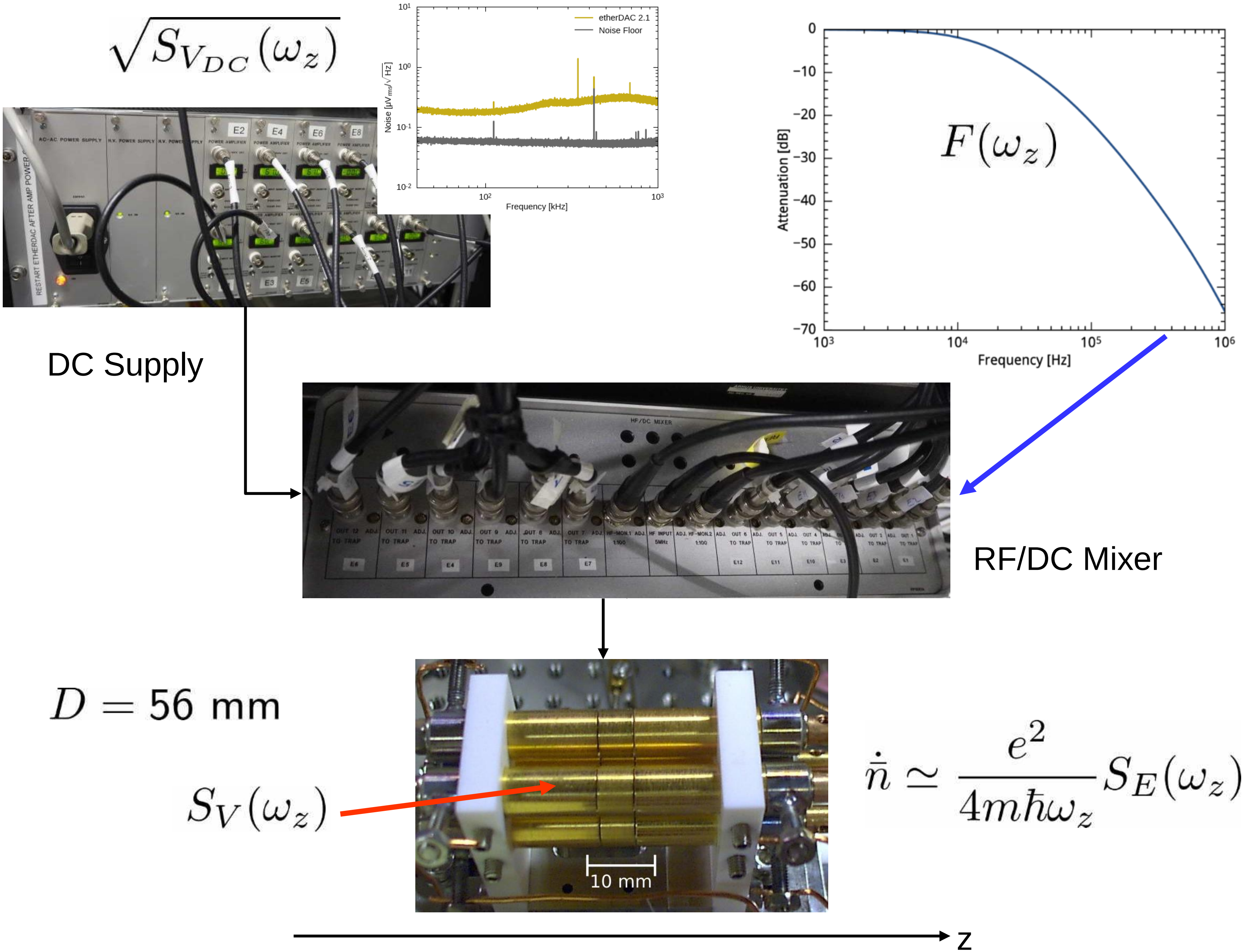
$$\bar{n} = \frac{h_{rsb}}{h_{bsb} - h_{rsb}}$$



Heating rates of a single $^{40}Ca^{+}$







$$\sqrt{S_{V_{DC}}(\omega_z)}$$

$$F(\omega_z)$$

DC Supply

RF/DC Mixer

$$D = 56\ \text{mm}$$

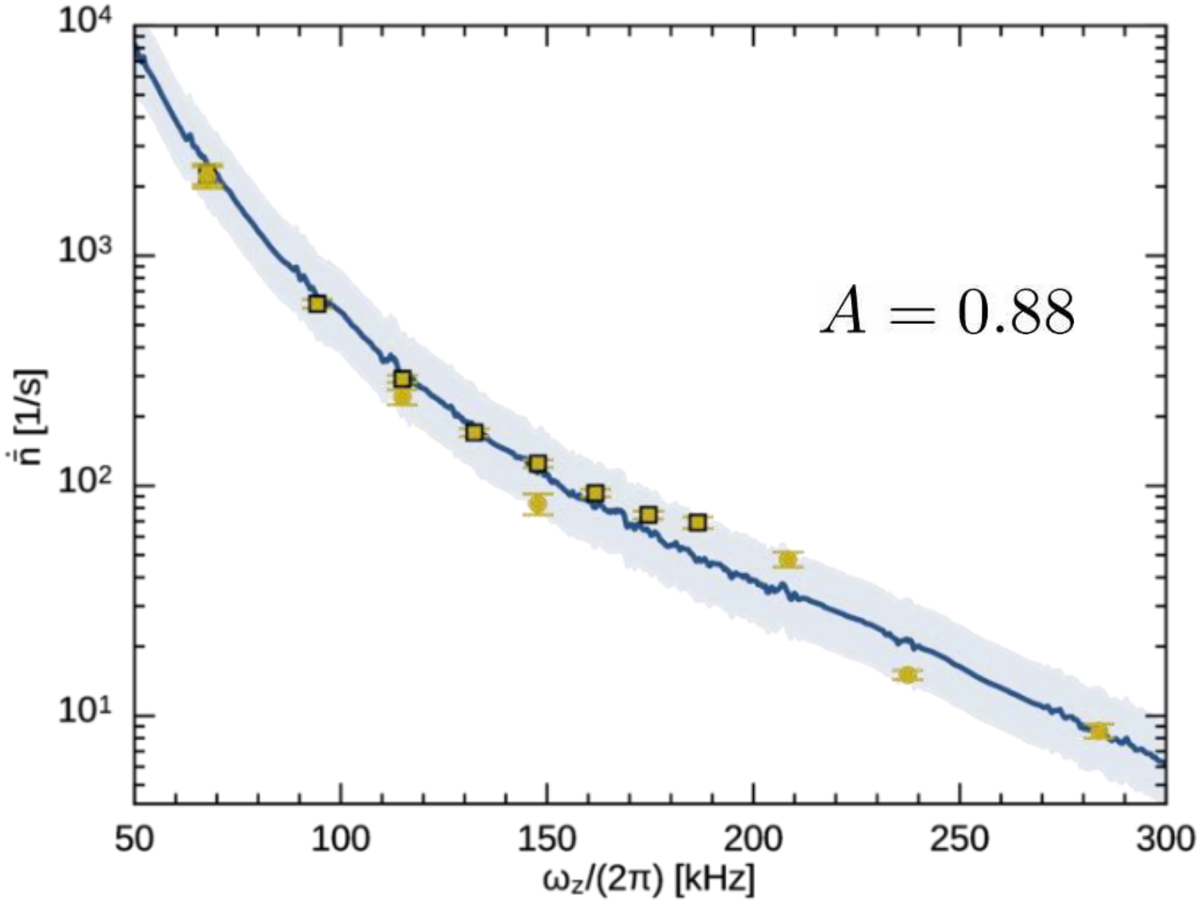
$$S_V(\omega_z)$$

$$\dot{n} \simeq \frac{e^2}{4m\hbar\omega_z} S_E(\omega_z)$$

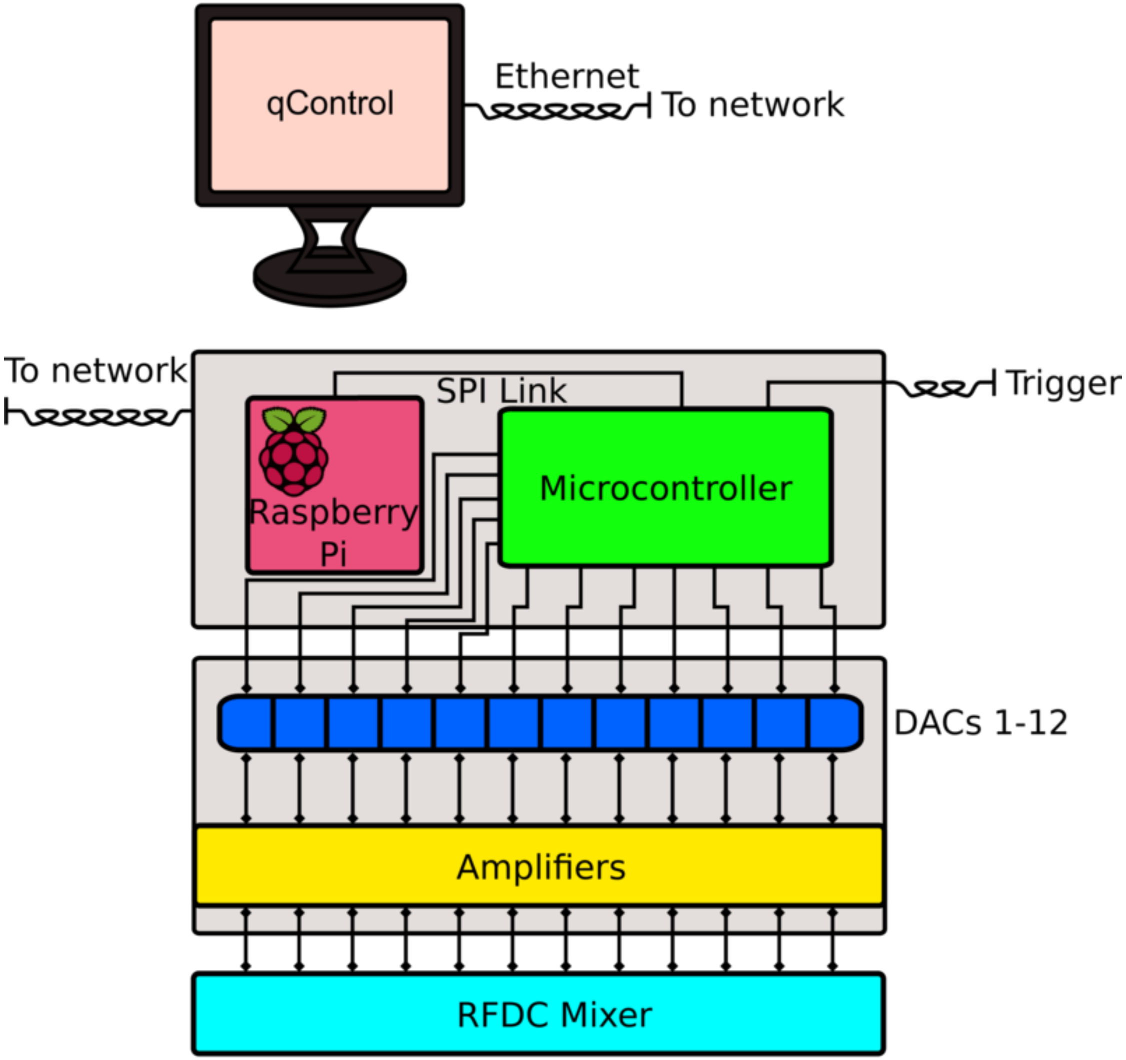
z

Heating rate model – single ion

$$\dot{\bar{n}} \simeq \qquad 8\frac{e^2}{4m\hbar\omega_z}F(\omega_z)^2\frac{S_{V_{DC}}(\omega_z)}{D^2}$$

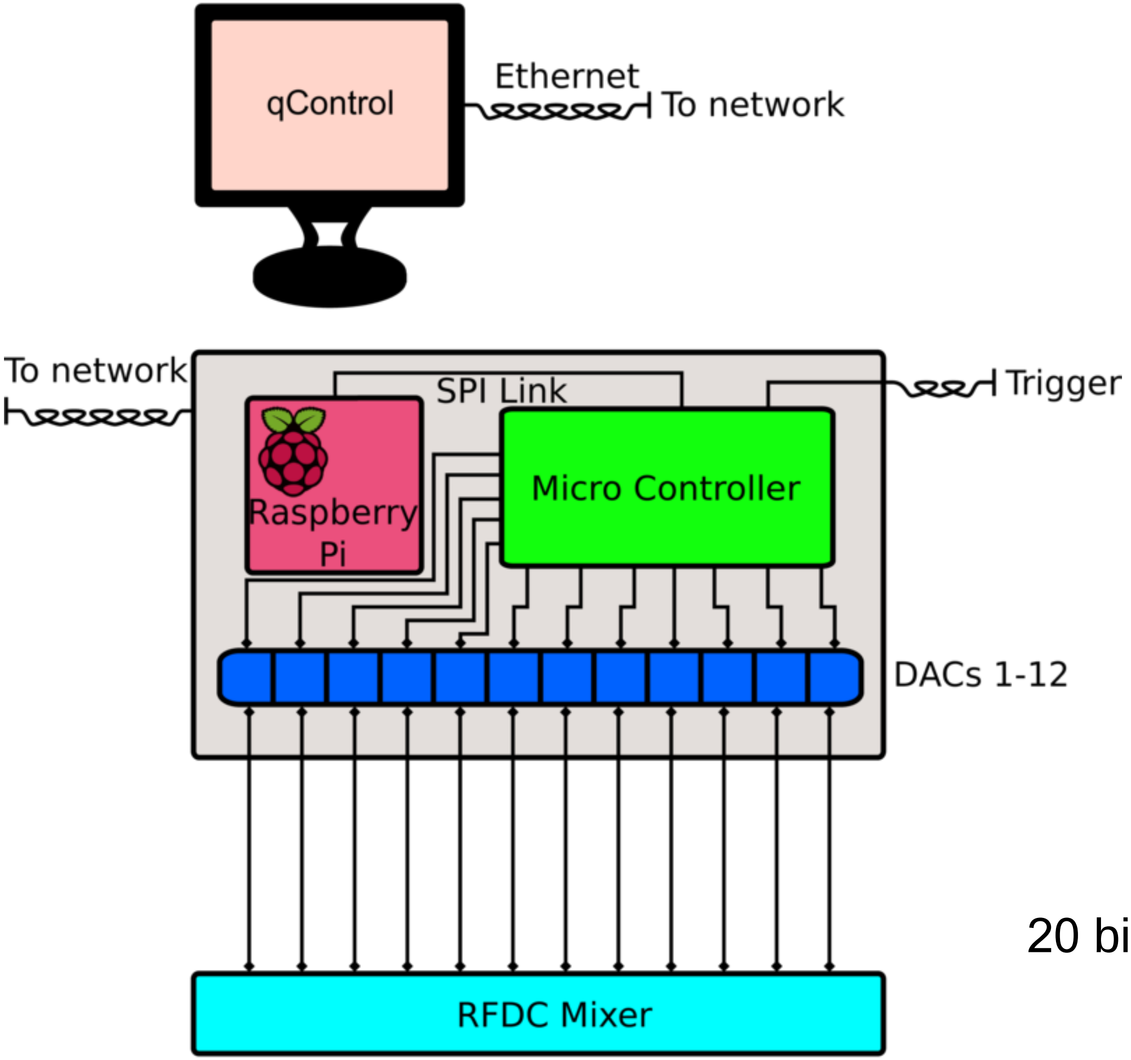


DC supply



EtherDAC
2.1

DC supply

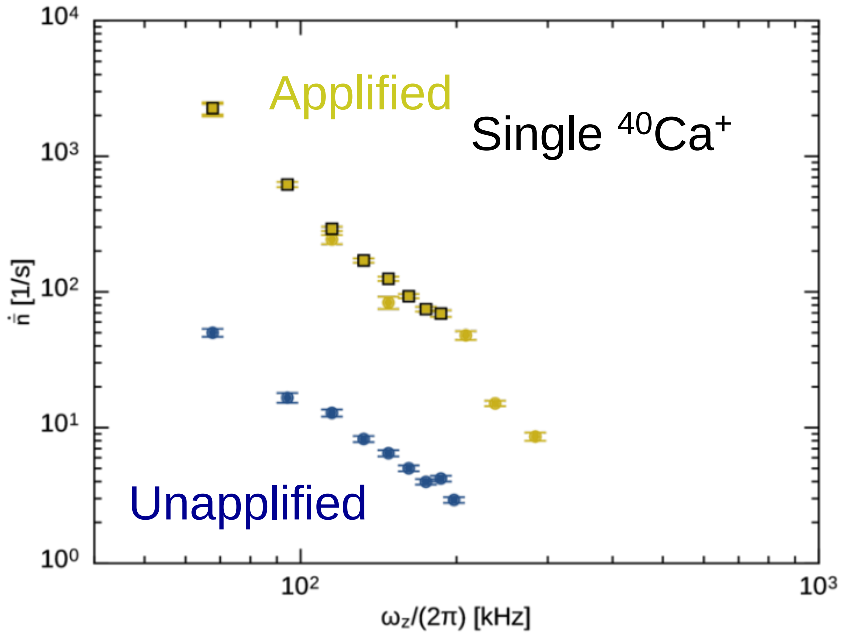


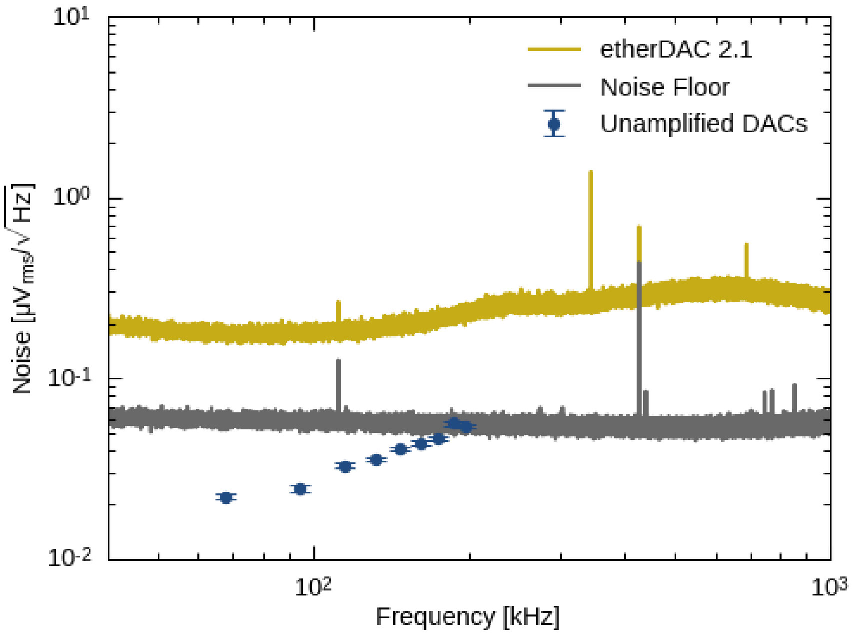
EtherDAC
1.0

20 bit DAC: These exp.: -1->10 V
Next step: -10 -> 10 V

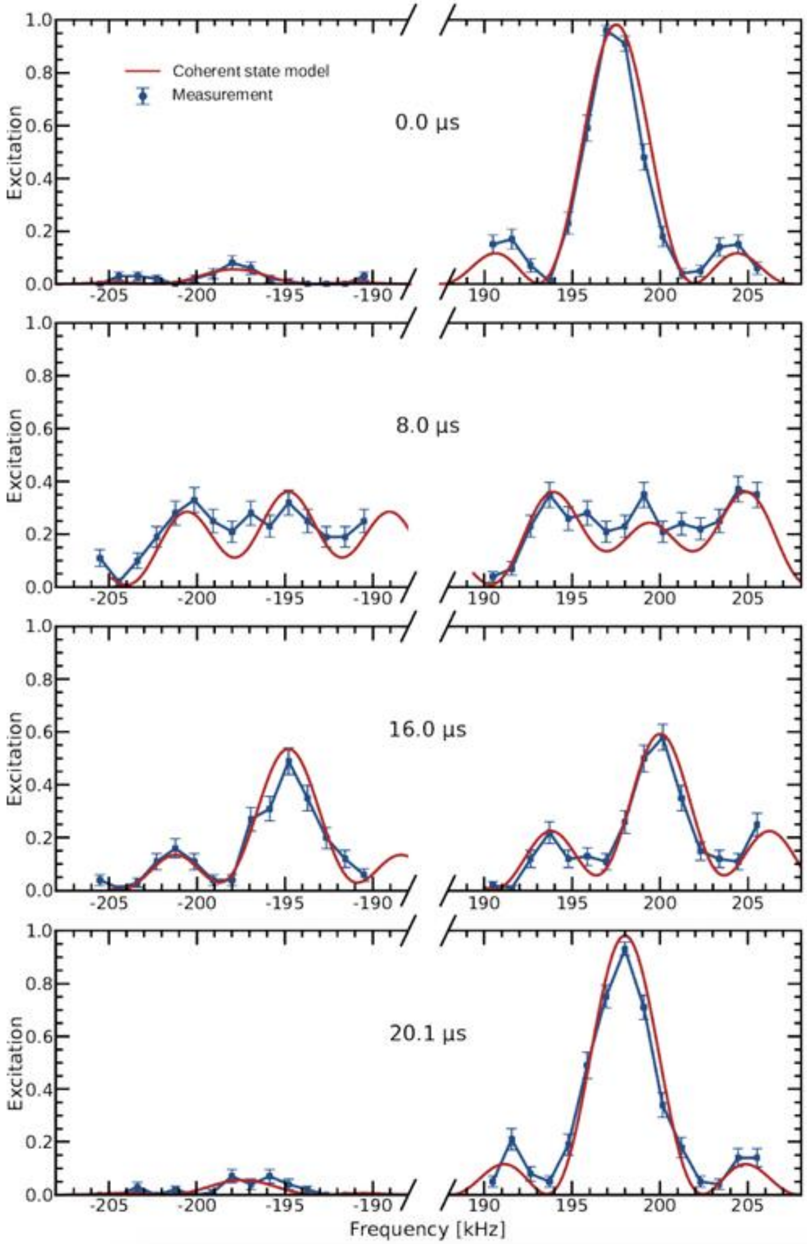
Heating rates with unamplified (DAC) supply

$$\dot{\bar{n}} \simeq A \times 8 \frac{e^2}{4m\hbar\omega_z} F(\omega_z)^2 \frac{S_{V_{DC}}(\omega_z)}{D^2}$$

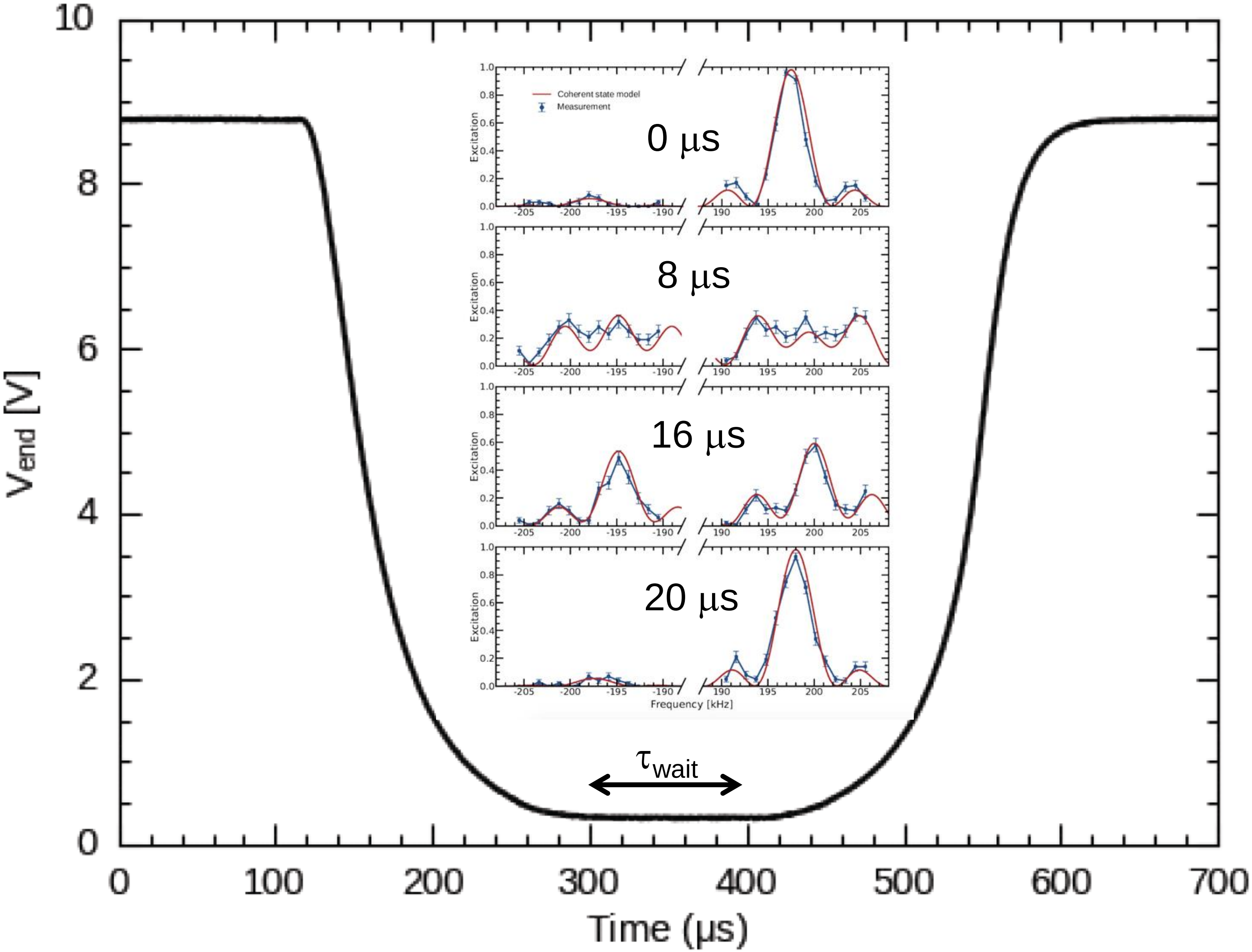




~20 times lower heating!


Coherent state model
Measurement
0.0 µs
8.0 µs
16.0 µs
20.1 µs
Excitation
0.0
0.2
0.4
0.6
0.8
1.0
-205
-200
-195
-190
190
195
200
205
Frequency [kHz]

Motional kicks due to ramping



‘Design and Realization of the TEQ experiment’ meeting

Part I – Project Management

Southampton – 22nd June 2018

MINUTES

1. Welcome to the participants by Angelo Bassi, Chair. The members present at the Meeting are:

   James Bain (M2)
   Peter Barker (UCL)
   Angelo Bassi (UniTs)
   Massimiliano Bazzi (INFN)
   Matteo Carlesso (UniTs)
   Catalina Curceanu (INFN)
   Luca De Trizio (TUD)
   Michael Drewsen (AU)
   Alessandro Ferraro (QUB)
   Giulio Gasbarri (UniTs)
   Oussama Houhou (QUB)
   Marta Marchese (QUB)
   Mauro Paternostro (QUB)
   Thomas Penny (UCL)
   Antonio Pontin (UCL)
   Anishur Rahman (UCL)
   Muddassar Rashid (UoS)
   Ashley Setter (Uos)
   Christopher Timberlake (UoS)
   Marko Toros (UoS)
   Hendrik Ulbricht (UoS)
   Andrea Vinante (UoS)

2. **Next Steering Committee Meeting**

The Chair, in agreement with the partner TUDelft, proposes to hold the Next Steering Committee Meeting on 8-9 November 2018 in Delft. The partners agree with date and place and confirm their presence.

The Chair presents the tentative agenda for the Next Steering Committee Meeting:

Tentative agenda

Management (1/2 day):

- Monitoring of milestones/deliverables
- Discussion of critical issues (if any)
- Preparation for the review meeting

Science: Theory and Experimental Discussion

Workshop: to be defined

The agenda will be finalized in the next months.

3. Review Meeting

The Steering Committee members present at the meeting discuss the date to propose to the PO for the first Review Meeting.
According to the latest message of the PO to the PI and to the project timing, the meeting has to take place in the second half of February 2019.
The proposed dates for the Review Meeting are: **February 26 or 27, 2019**. A decision will be made between the PO and the PI. The PI reminds what was discussed at the Kick-off Meeting:

"- The PI of every unit should be present.
- The day before the meeting a "rehearsal" will take place."
[From the minutes of the Kick-Off Meeting]

The Steering Committee members discuss the place to propose to the PO for the first Review Meeting.

According to the latest message of the PO to the PI, the SC "[…] could have the meeting at one of the partners sites in case there is experiment/equipment/physical results to be shown to the monitors to help them with their assessment on the work".

The SC members unanimously decide to propose to the PO to hold the Review Meeting in Brussels. Other venues will be taken into consideration for the other Review Meetings (M30 and M48).

The Steering Committee discuss the name of the monitors to propose to the PO for the first Review Meeting. The PO has asked for 9 names in three areas. The list of names which will be proposed to the PO includes:

a. Quantum mechanics/foundations:
Chiara Macchiavello (Pavia University, Italy)
Christiane Koch (Kassel, Germany)
Adrian Kent (Cambridge, UK)
Ward Struyve (KU Leuven, Belgium)

b. Optomechanics: Theory
Alexia Auffeves (Grenoble, France)
Radim Filip (Olomouc, Check Republic)
Vittorio Giovannetti (SNS Pisa, Italy)

c. Optomechanics: Experiments
Romain Quidant (ICFO Spain)
Lukas Novotny (ETH Zurich Switzerland)
Tracy Northrup (University of Innsbruck Austria)

The PI presents the tentative agenda for the Review Meeting, as per last message of the PO:

9:00 – 9:15	R. Borissov (chair)	Introduction, tour du table
9:15 – 9:45		Overview by the coordinator
9:45 – 10:30		WP 1
Coffee (10:30 to 11:00)		
11:00 – 11:45		WP 2
11:45 – 12:30		WP 3
Lunch (12:30 to 13:30)		
13:30 – 14:15		WP 4
14:15 – 14:30		WP 6 (management)
14:30 – 14:45		WP 7 (dissemination)
14:45 – 15:15		Financial data
15:15 – 15:45		Innovation potential discussion
15:45 – 16:15	*General discussion*	
16:15 – 16:45	*Assessment preparation by monitors and PO*	
16:45 – 17:00	R. Borissov	Closing

4. Closing

Angelo Bassi, Chair, wraps up the discussion on management issues and gives the word to the other speakers for the scientific discussion.