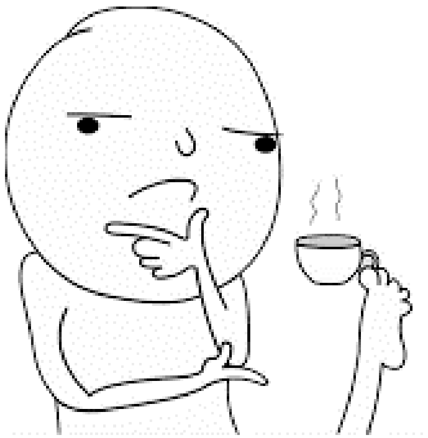

CAUTION
Theory will take
you only so far

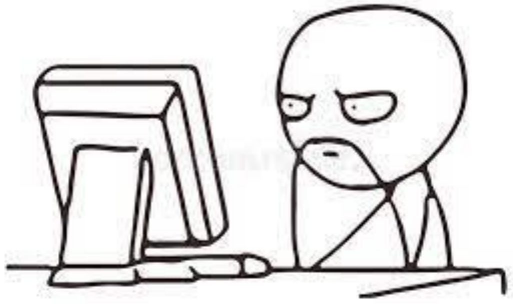
Laboratoire Kastler Brossel
Physique quantique et applications

Dude, how do you build a Magneto - Optical Trap?

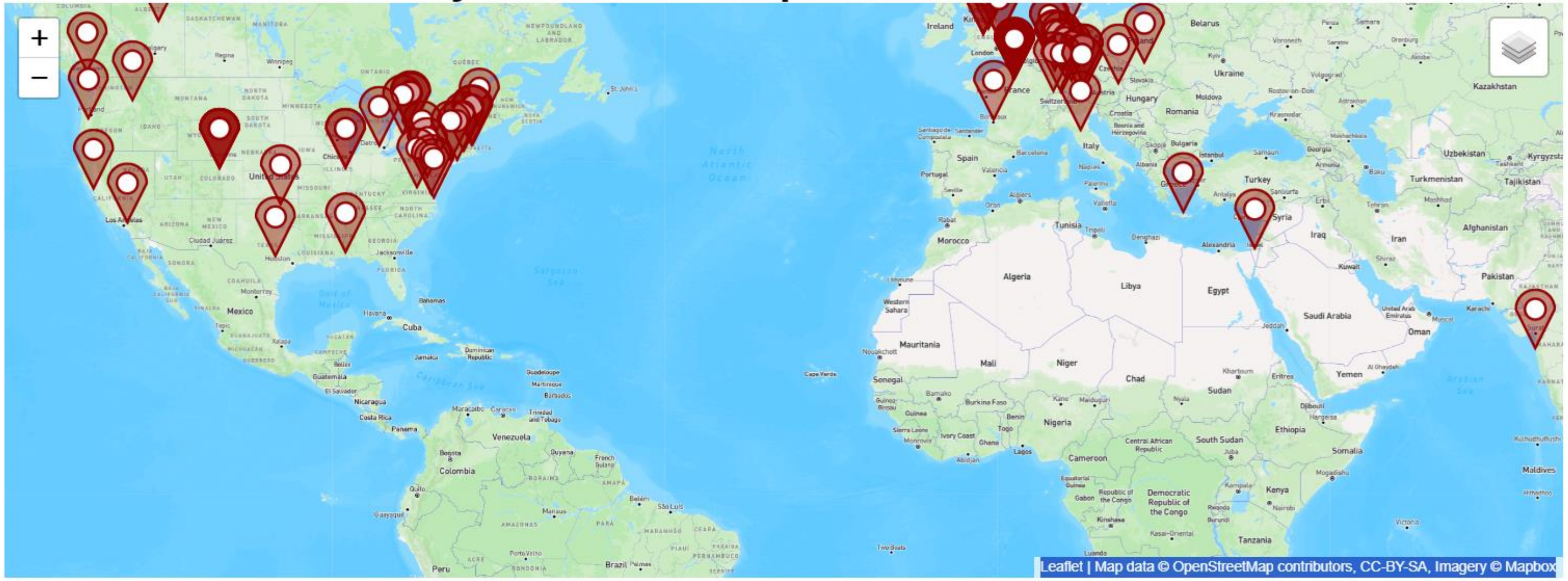


Workshop May 06, 2024

Sukhman K. S.



Every Cold Atoms Experiment in the World



Legend and Filter

Exp | Theory | Exp/Theory

H | He | Li | Na | K | Rb | Cs | Ca | Sr | Ba | Cr | Cd | Ar | Kr | Dy | Ho | Er | Yb | Th

Include unknowns | Include theory

Select all atoms | Select all | Select none

Hide/Show periodic table

Hide/Show table

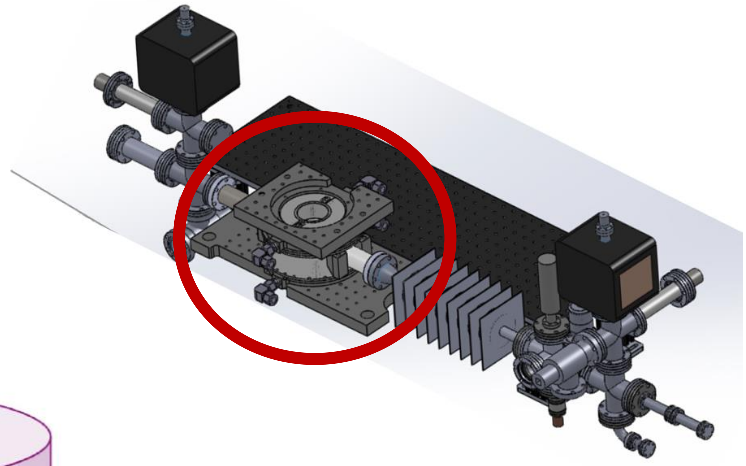
Group	Institution	Country	Exp/Theory	Atoms	Description	People	Comment

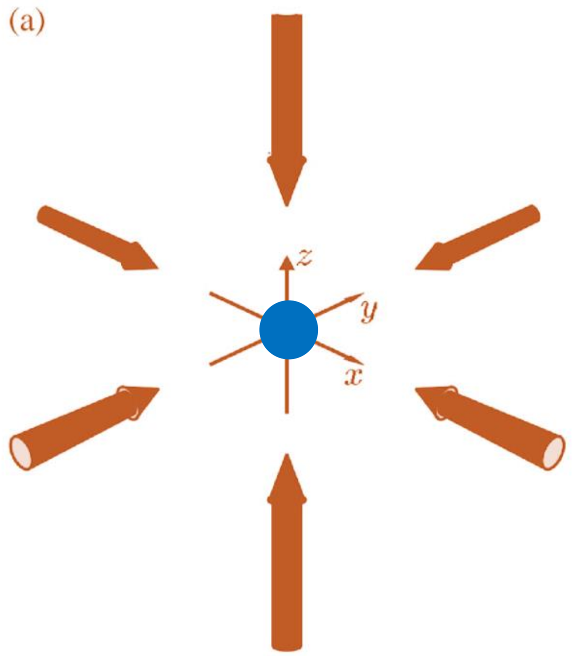
https://everycoldatom.com/

Outline

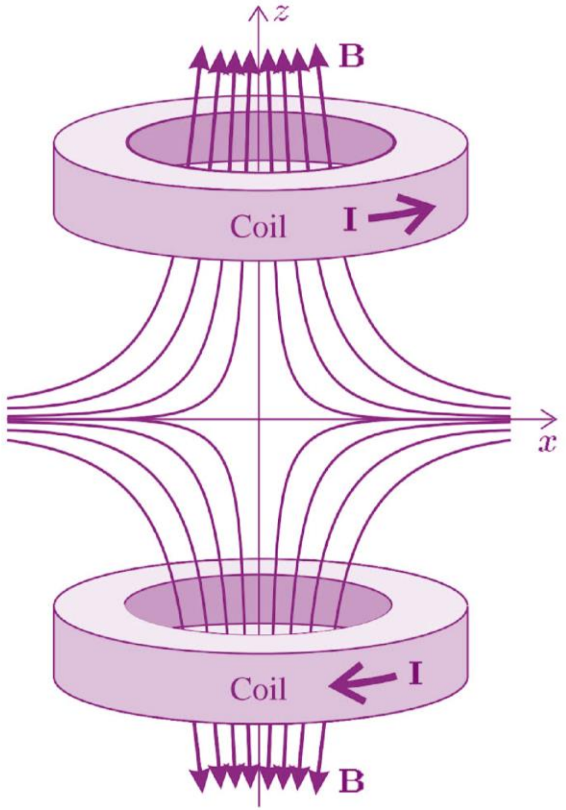
- Cooling and Trapping: MOT beams – Optical Molasses
- Vacuum System
- Generating Quadrupole Magnetic Field
- Limitations of MOT: Temperature, Density
- Characterization and Optimization of MOTs: Thermometry, Imaging System

MOT: Magneto-Optical Trap





3 retro-reflected beams



2 coils generating magnetic field

Atomic Physics, C. J. Foot (2005).

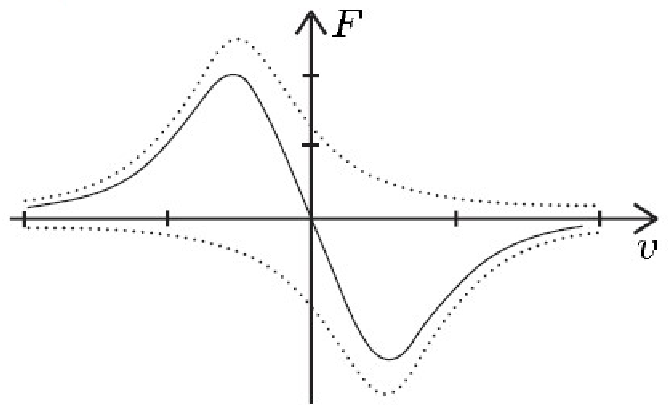
Cooling & Trapping forces

- Radiation Pressure Force

$$\boldsymbol{F}_{MOT} = -\alpha(\delta)\boldsymbol{v} - \frac{\alpha(\delta)}{k}\frac{g\mu_B}{\hbar}\ \boldsymbol{r}\,\nabla|\boldsymbol{B}|$$

Frictional force

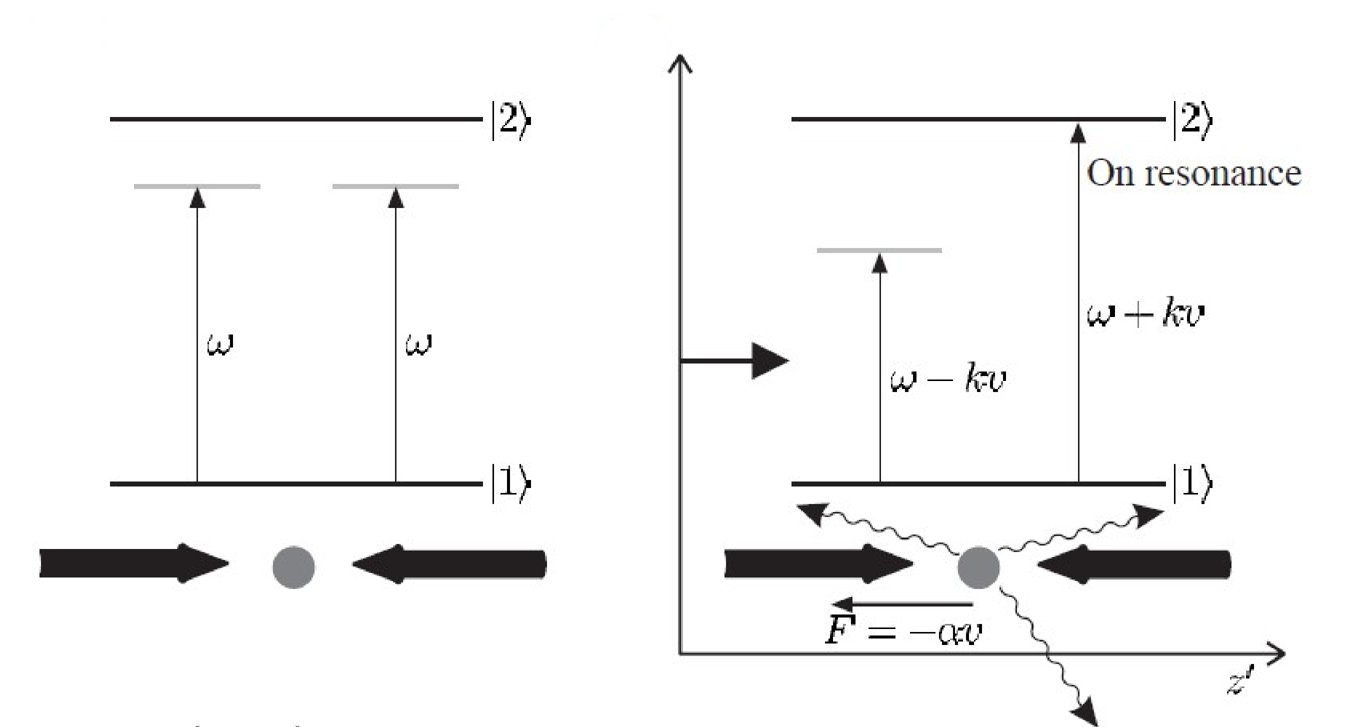
Trapping force



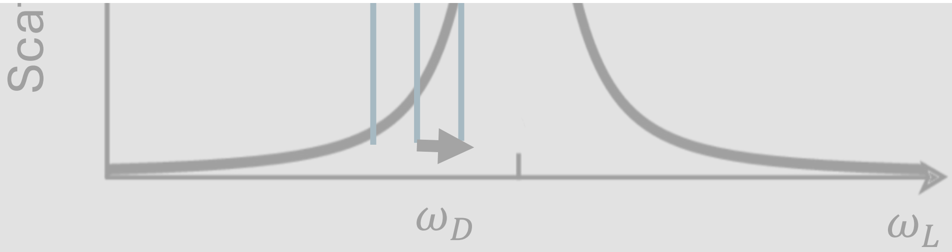
Doppler Cooling

Photon rec

Mirror

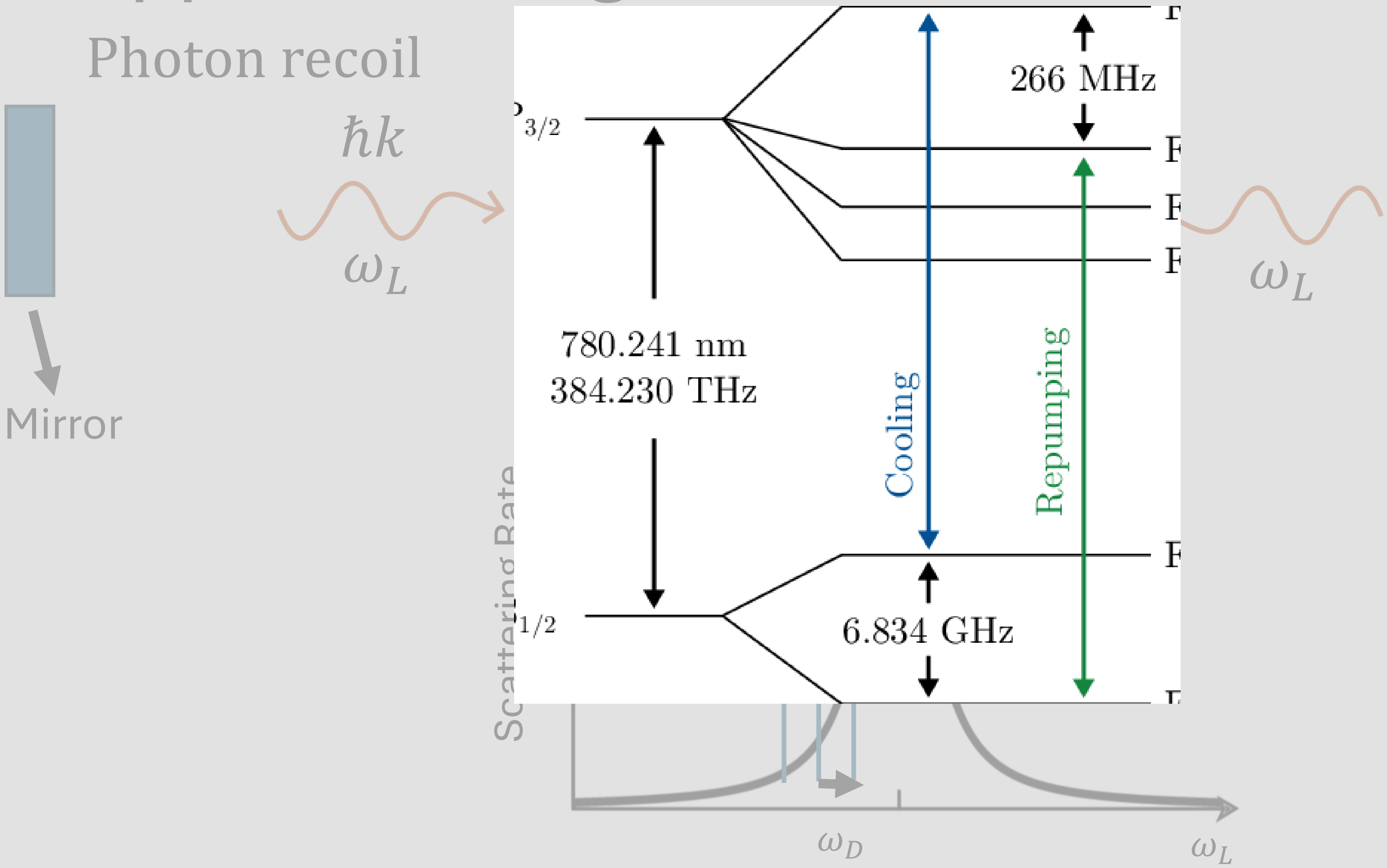


C. Foot (2005)



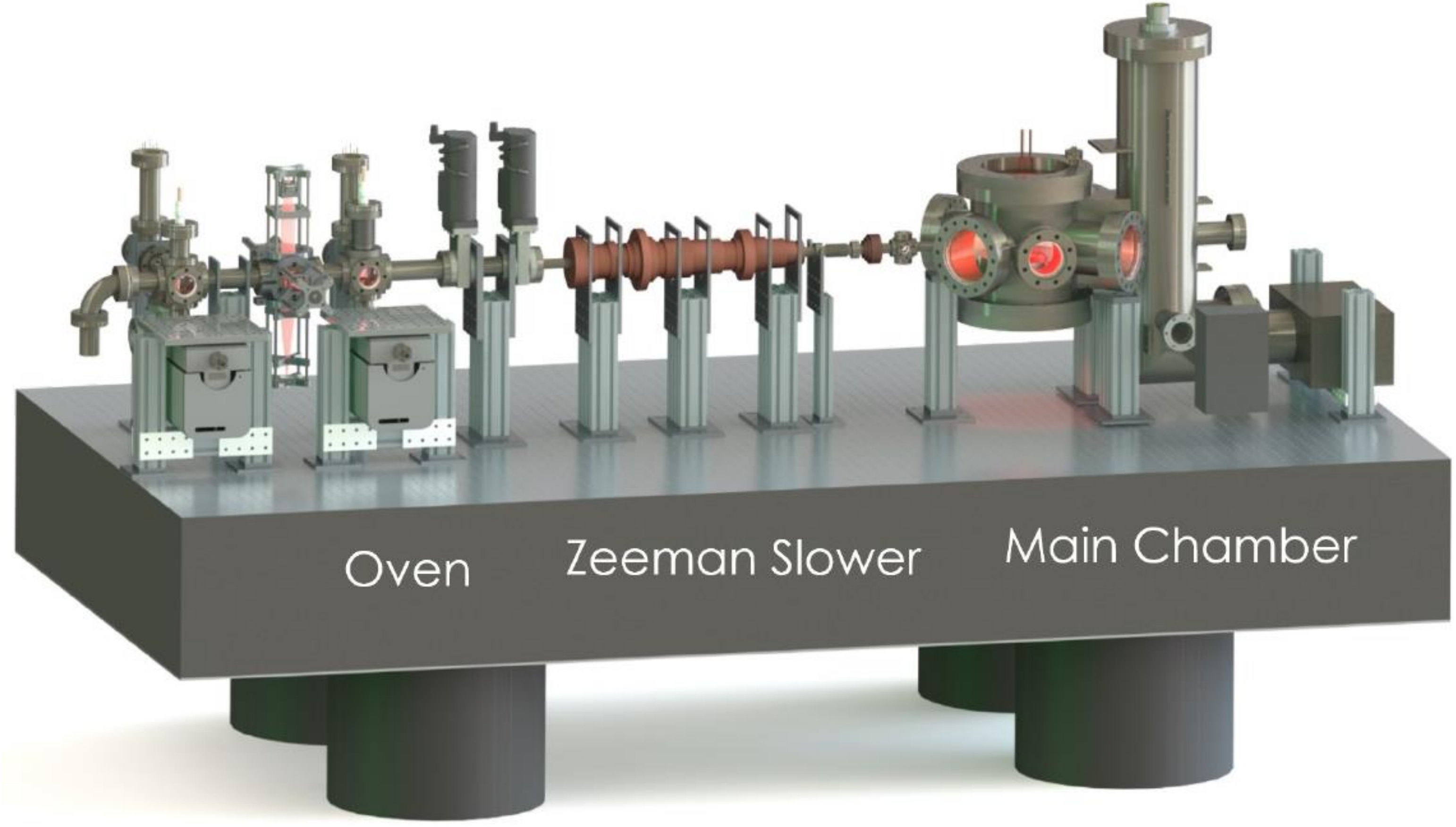
Doppler Cooling

Photon recoil



Vacuum

Typical Experimental Apparatus



Ultracold Lithium University of California, Santa Barbara;
PhD Thesis, C. Fujiwara (2019)

Molecular Flow regime

Mean free path $\lambda_{\text{mean}} \cong \frac{1}{n_0}\frac{1}{\sigma}$

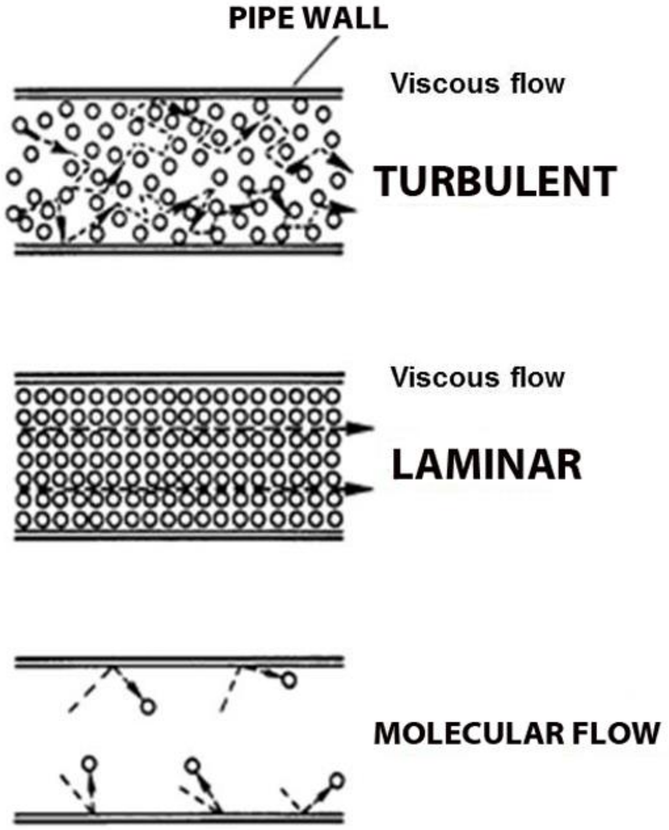
- **Mean free path**, for various pressure regimes:
  - $\lambda_{\text{mean}}(1\ \text{Torr}) \cong 30\ \mu m$
  - $\lambda_{\text{mean}}(10^{-6}\ \text{Torr}) \cong 30\ m$
  - $\lambda_{\text{mean}}(10^{-9}\ \text{Torr}) \cong 30\ km$

- **Throughput** $d/dt(PV) = Q$

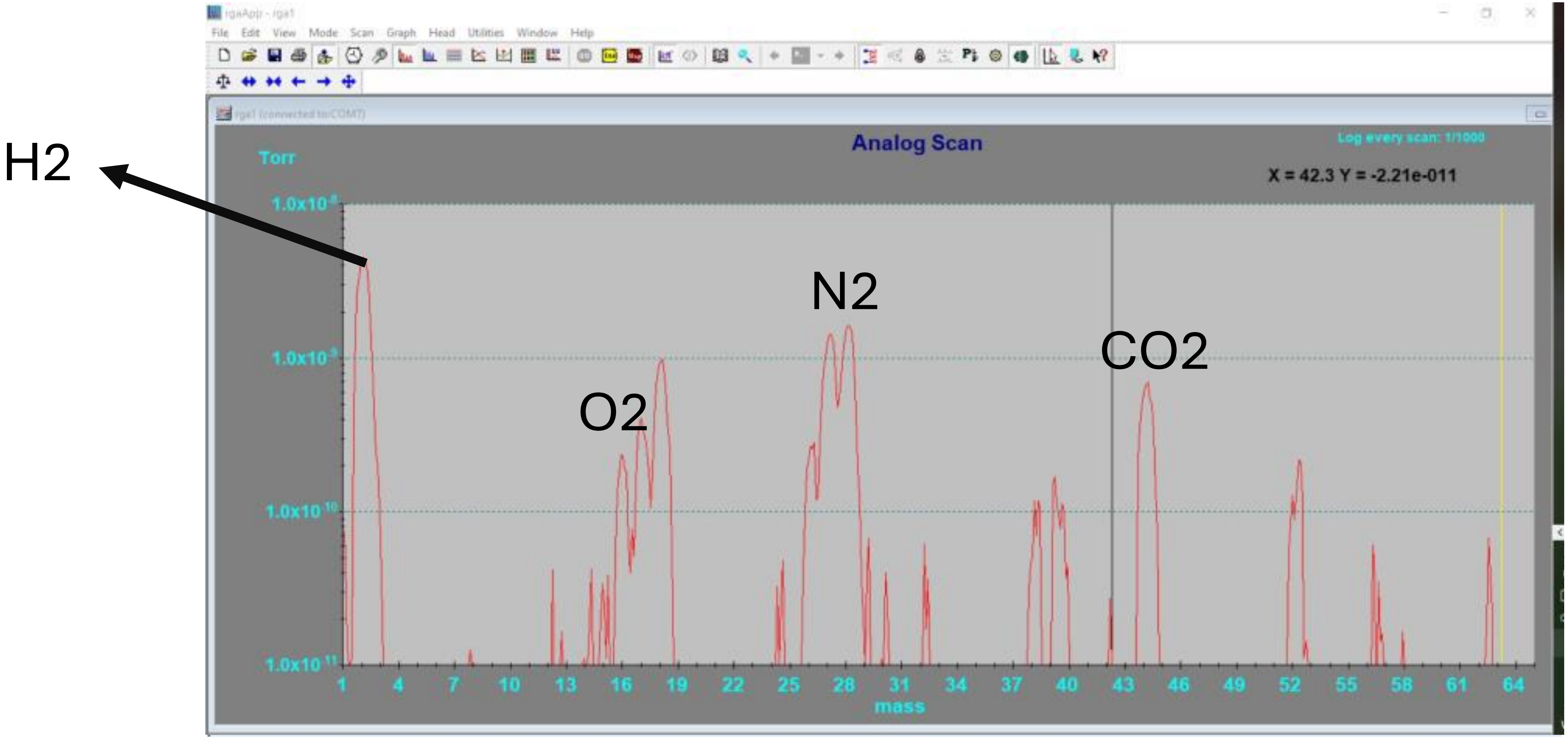
- **Conductance** $C = \frac{Q}{\text{P}_2 - P_1}$ and $C = \alpha\ C_a$

  - Aperture: $C = 9.3\ D^2$ *Litre/s* where diameter D in *cm*

  - Cylindrical tubes: $C = 12.4\frac{D^3}{L}$ L/s where length L in *cm*



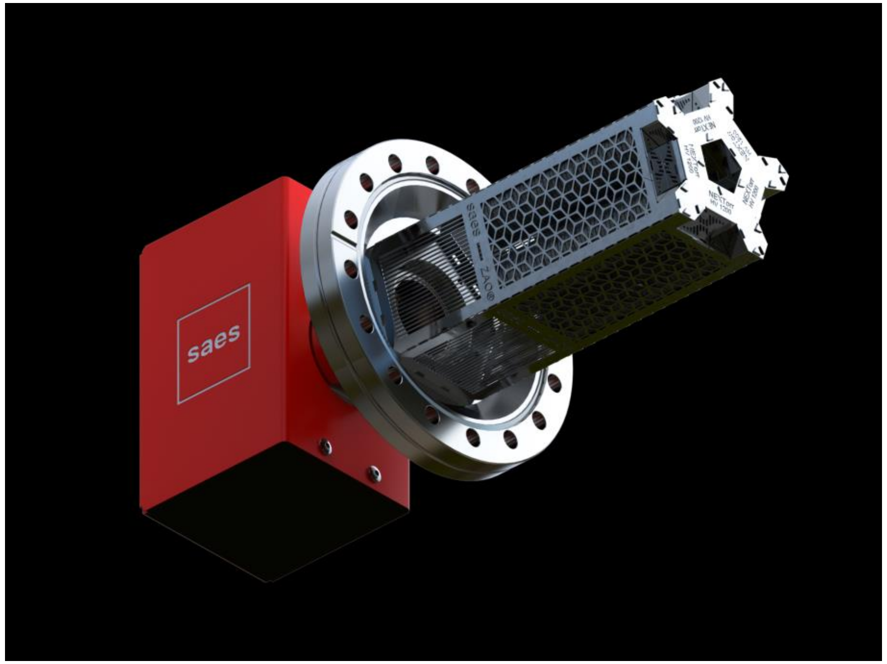
Leaks? Residual Gas Analyzer (RGA)



Vacuum System: Pumps

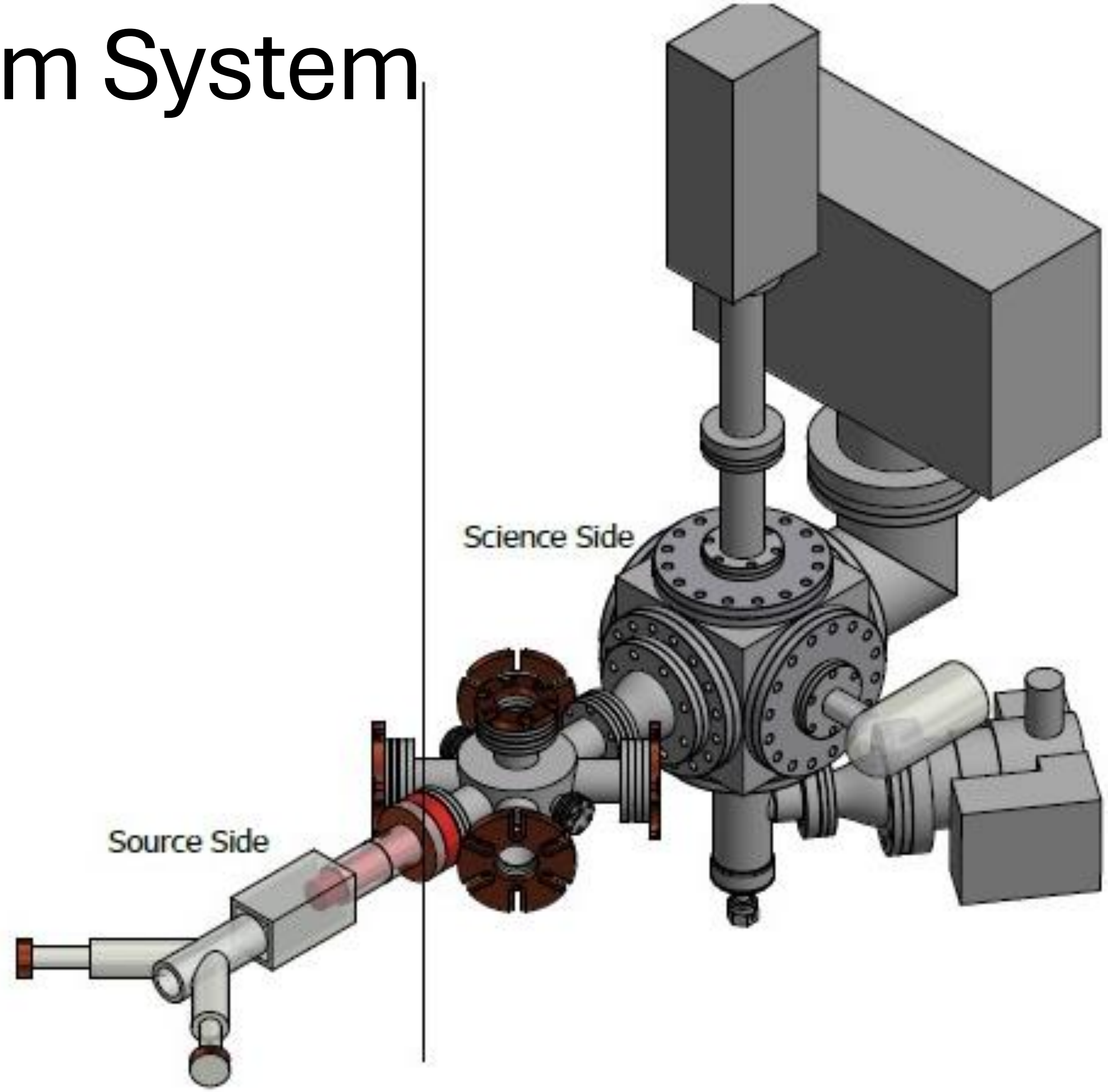
- **Roughing pump** (best 0.01 Torr) → **Turbo Pump** (10^{-6}-10^{-10} Torr)
- **Ion Pump**: Main pump removes the noble gases, primarily Ar (6 L/s) and CH_4 (15 L/s)

- **Non-evaporative Getter (NEG)**: e.g. Ti-Sub
  - to boost H2 pumping (byproduct: H2O, CO2, O2 and N2.)
  - Getters do not pump noble gases as they are not chemically reactive.



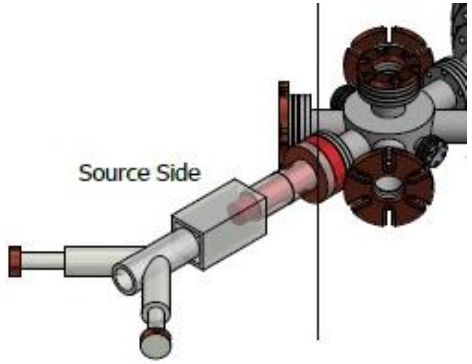
SAES

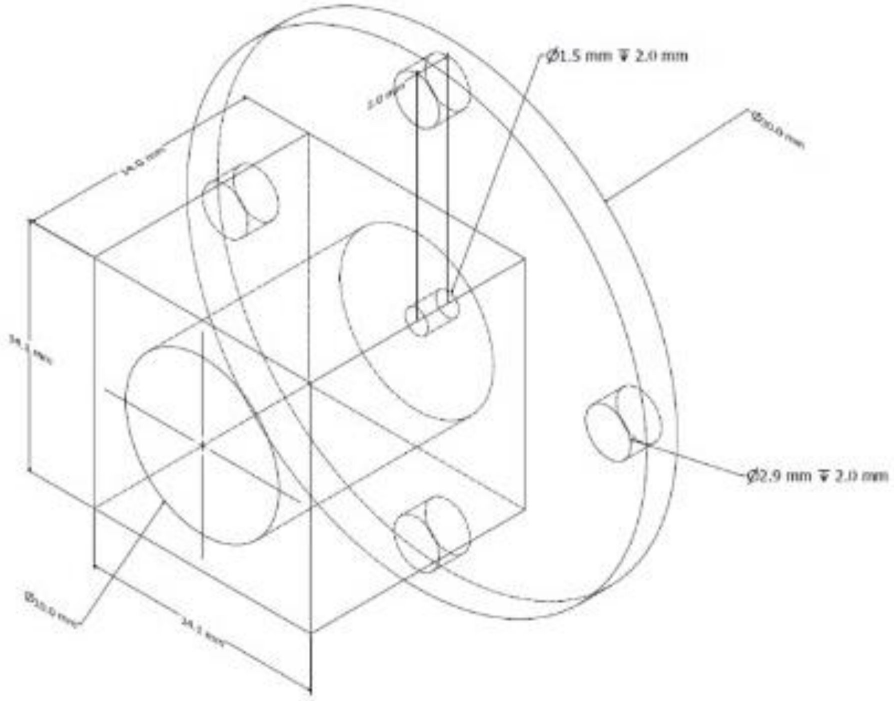
Sample Vacuum System



B. Hsu, Thywissen Lab internal report

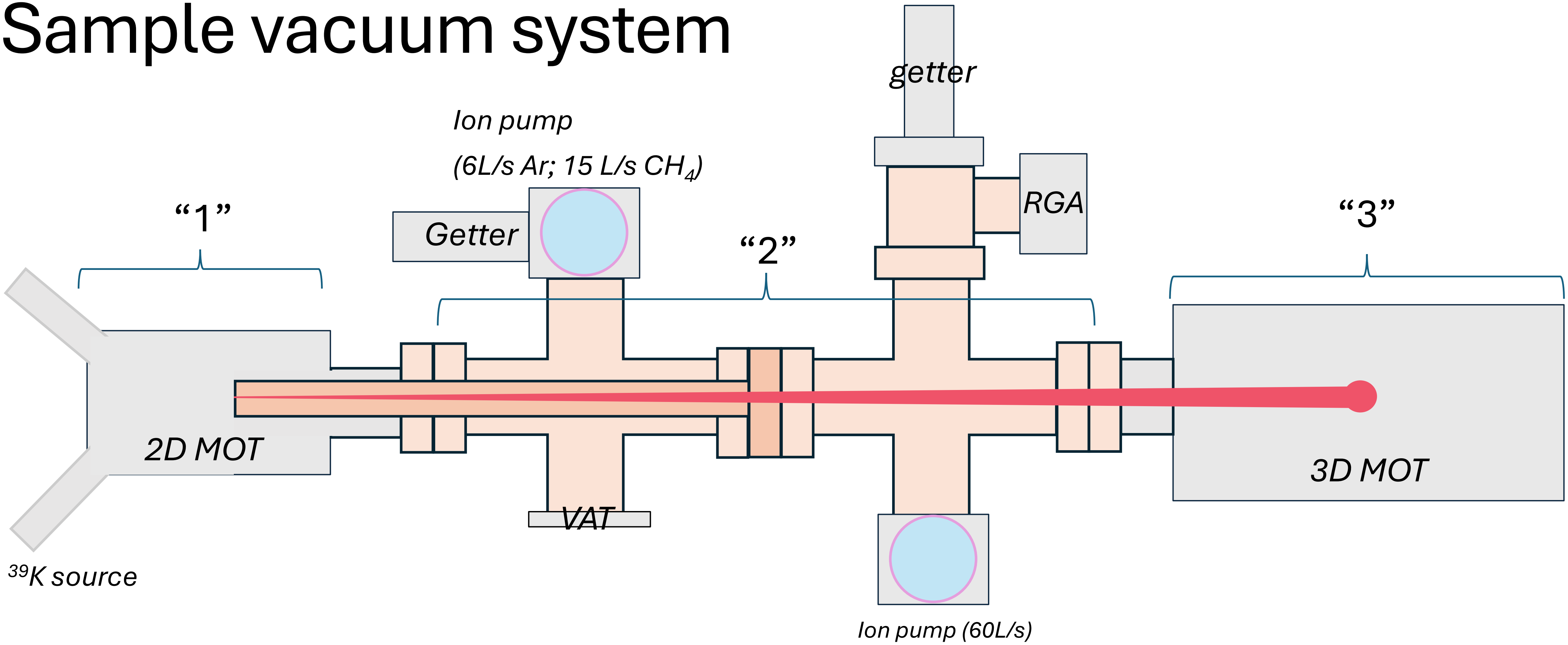
Differential Pumping Stage





Current differential pumping tube with a 1.5mm opening

Sample vacuum system



1. Isolation: C_{12}, C_{23} 'small' → $P_3 \sim 10^{-3} P_2 \sim 10^{-3} P_1$

2. Adequate pumping of 2, 3: $C_{P2,\,2}$, $C_{P3,\,3}$ 'large'
   i.e. low pressure & high pumping speed

3. High solid angle of 3D MOT

4. Optical access

Magneto-Optical Trap

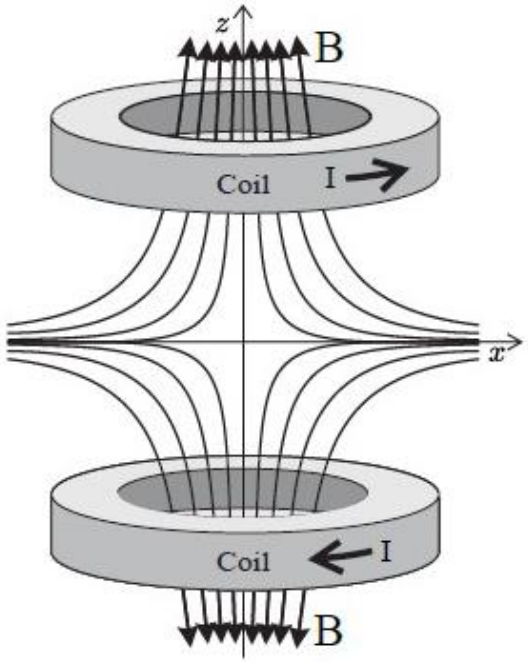
Magnetic Field

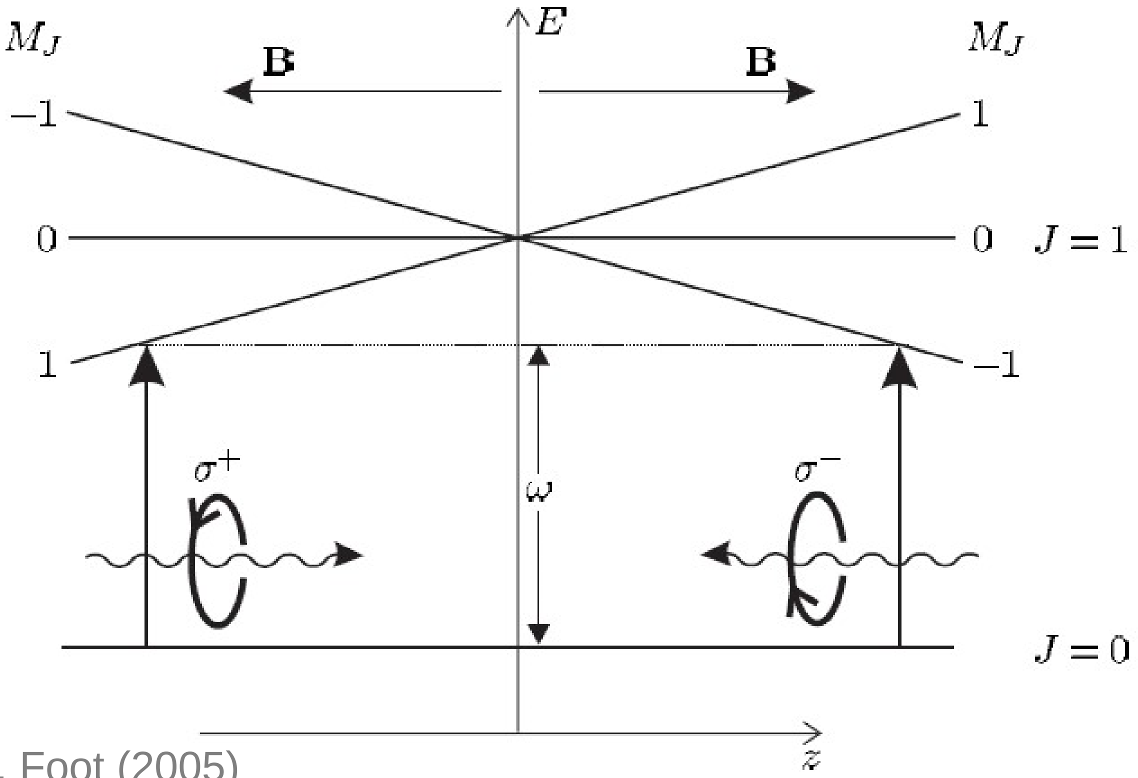
B-field gradient

Bias field

- Quadroupole field

$$\mathbf{B}(\mathrm{x},\mathrm{y},\mathrm{z}) = -\frac{\mathrm{b}}{2}\,x\,\hat{\boldsymbol{x}} - \frac{\mathrm{b}}{2}\,y\,\hat{\boldsymbol{y}} + (bz + B_0)\,\hat{\boldsymbol{z}}$$





- Zeeman shift at displacement z provided by the magnetic field is

$$U_Z = \frac{g\mu_B}{\hbar}\frac{dB}{dz}\,z$$

C. Foot (2005)

Magnetic Field – Design Considerations

1. Uniformity
2. Dynamic response: Self- & Mutual-Inductance
3. Power Dissipation: depends on RT copper resistivity, wire cross-section, length

   - E.g. Total resistance of 77 $m\Omega$ requires 10 V power supply with 130 A
     → anticipated power-dissipation: $I^2R = 1.3\ kW$

4. Hydrodynamic conductivity: determined by length & no of windings (limitations on cooling)
5. Feshbach fields: high fractional stability $\delta\mathrm{B}/\mathrm{B}_0$
6. Geometry: Hollow-core VS EDM

Electromagnets: Hollow-core

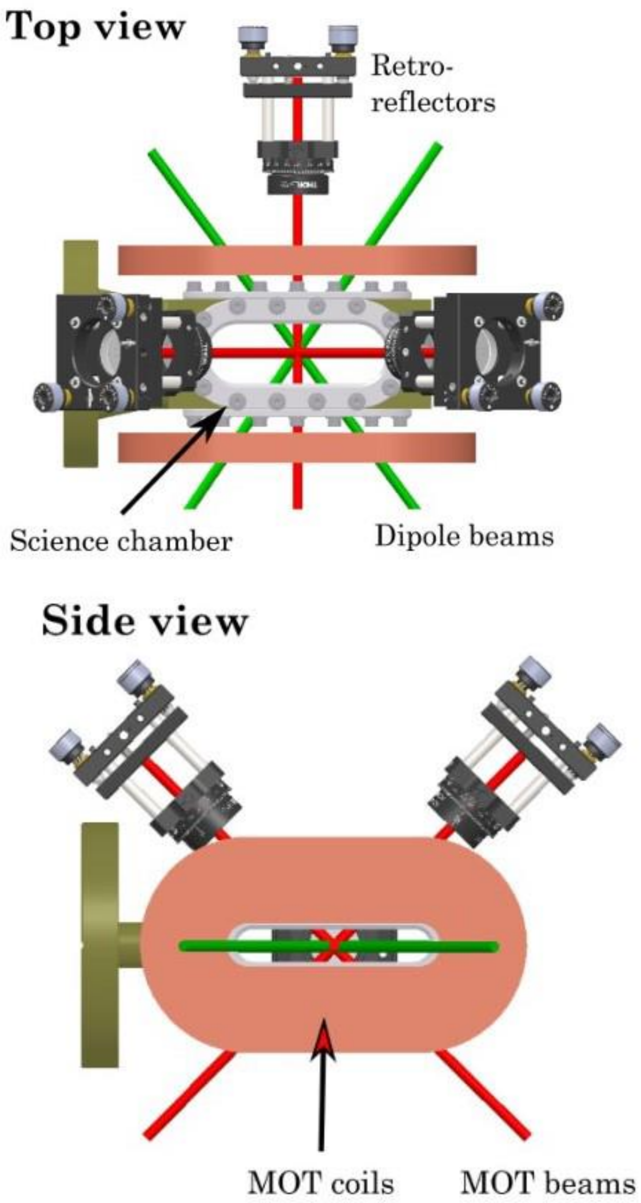
- Insulated copper wire with hollow-core
- Homogeneous field gradient upto distance r

$$r \leq \sqrt{3} r_{\text{eff}}$$

- Vacuum chamber constraint:
  - Separation distance d bw coils $\sim O(r_{\text{eff}})$

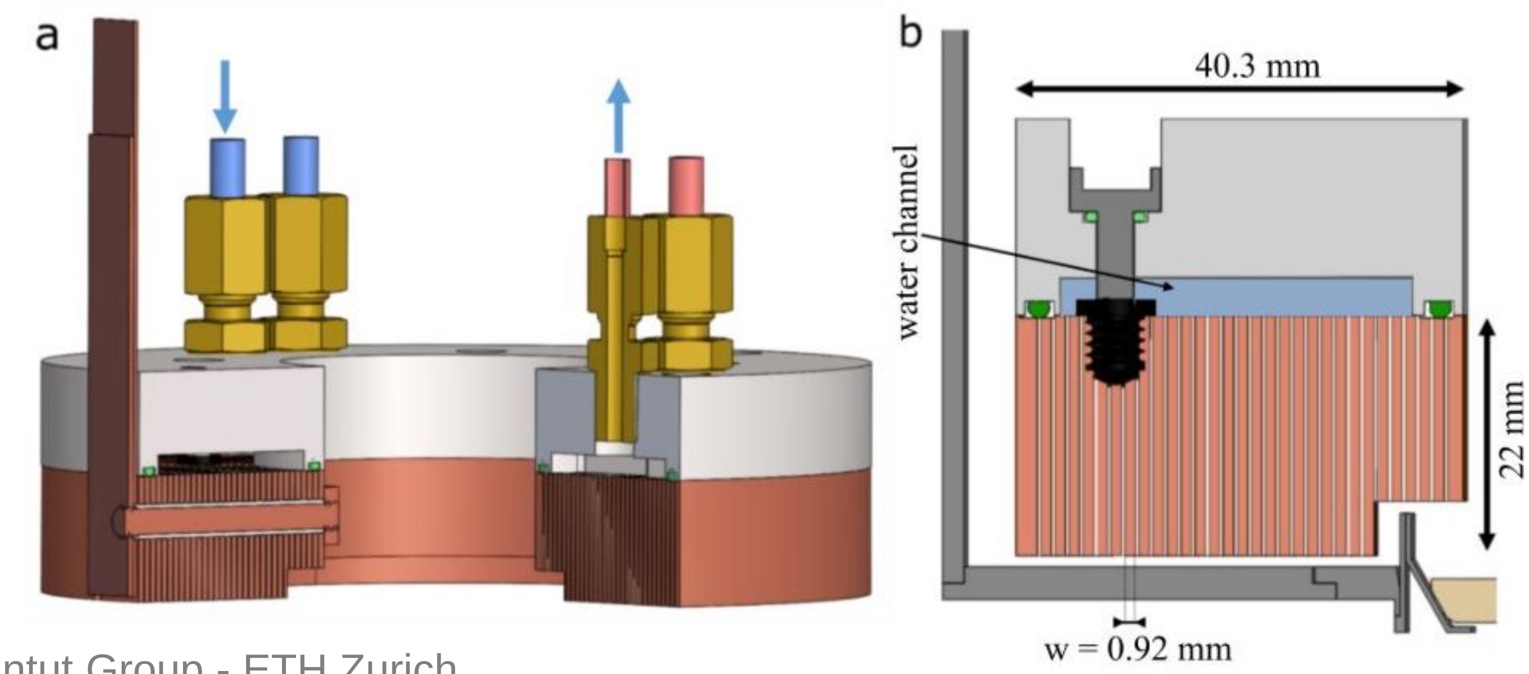
$$d \leq r_{\text{eff}}$$

- Issues: High water pressure, inefficient cooling, expansive, hard to recreate the same coils



Electromagnets

- Bulk-machined electromagnet (EDM 6Ethylene Propylene Diene Methylene rubber)



Brantut Group - ETH Zurich

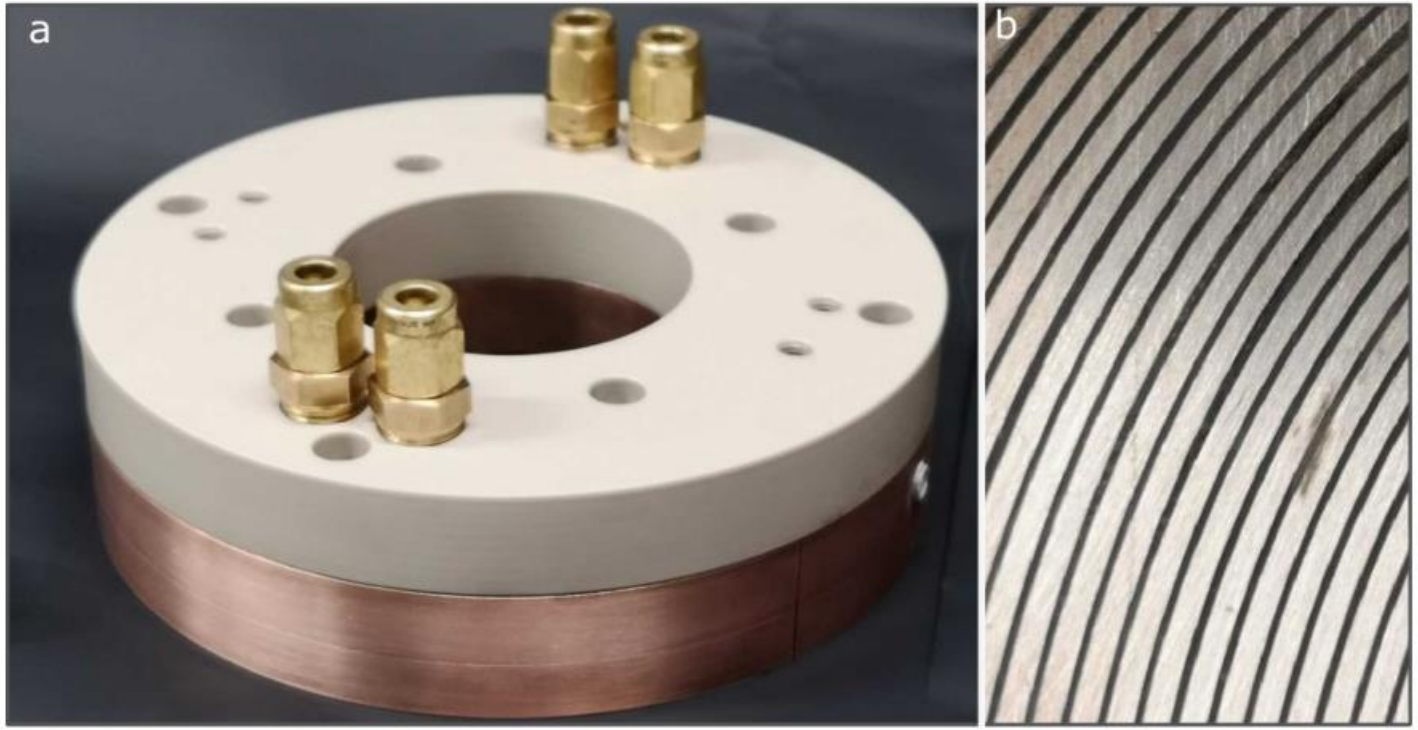


Figure 2: **a**: Photograph of the assembled electromagnet, showing the PEEK cap attached to the coil body, with coolant connections from the top. **b**: Close view of the top surface of the coil after glueing and machining on a standard lathe, showing the successive windings separated by the electrically insulating epoxy. The width of a copper winding is 0.92 mm.

K. Roux, t, SciPost Physics 6 (2019)

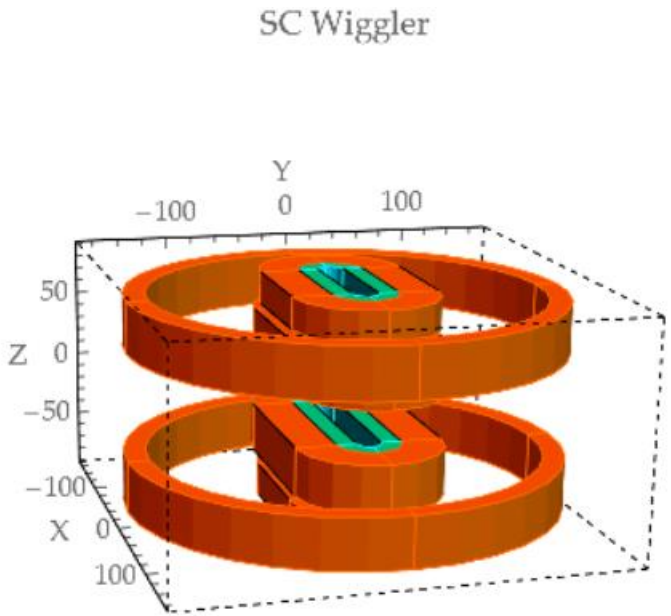
Radia: Quadroupole Magnet

Introduction & Theory

In this example, we model a simple iron-dominated quadrupole magnet. The pole-tips have hyperbolic faces with a flat chamfer at each end.

Field computations in the case of iron-dominated geometries present specific difficulties that usually make them less accurate t the case of structures dominated by coils or permanent magnets. Nevertheless, Radia includes special methods that enable one reasonable precision with a reasonable amount of computational effort—cpu time and memory usage.

Because this example bears some similarities to that of Example 5, all the remarks made there also apply here. We recommend t least review the introduction of that example before playing with this one. But, as a brief reminder for those in a hurry, the follo recommendations will help you achieve an acceptable level of precision within a reasonable time frame:

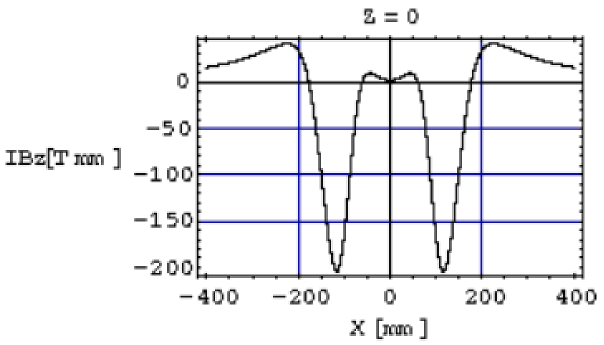


Credits: github.com/ochubar/Radia

Radia

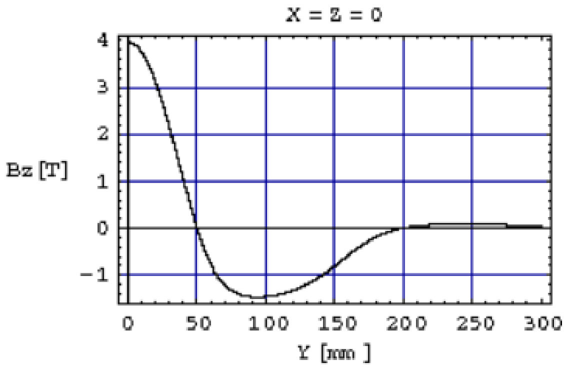
Plot the Field Integrals

```
Plot[radFldInt[Grp,"inf","ibz",{x,-300,0},{x,300,0}]
,{x,-400,400}
,FrameLabel->{"X [mm]","IBz [T mm]","Z = 0",""}];
```



Plot the Magnetic Field

```
RadPlotOptions[];
Plot[radFld[Grp,"Bz",{0,y,0}],{y,0,300}
,AxesOrigin->{0,0}
,FrameLabel->{"Y [mm]","Bz [T]","X = Z = 0",""}];
```



Credits: github.com/ochubar/Radia

Limitations: n, T

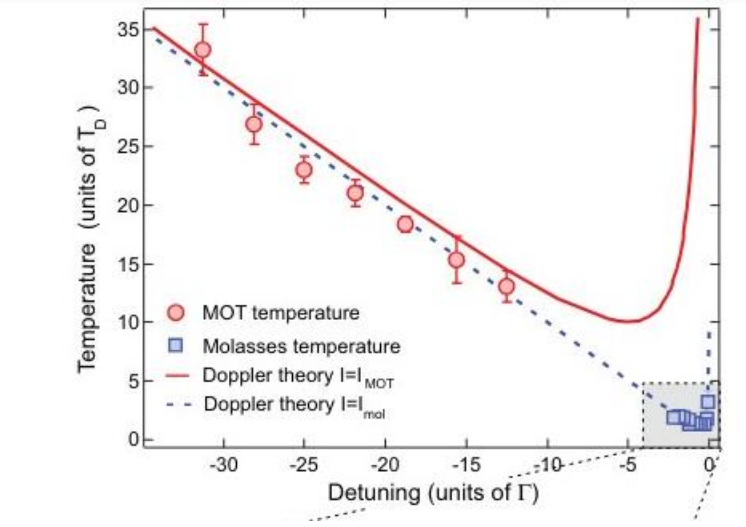
Limitations of a MOT: Temperature, T

- Temperature:
  - Doppler Limit (Foot)

$$T_D = \frac{\hbar\Gamma}{2\,k_B}$$

(alkali T_D ~100μK) T_D = 146 μK

  - Recoil limit (alkali T_{rec} ~1μK) T_{rec} = 362 nK → $v_{rec} \cong$ 6mm/s (typically 0.3-10cm/s)



R. Chang *et al.* (2014)

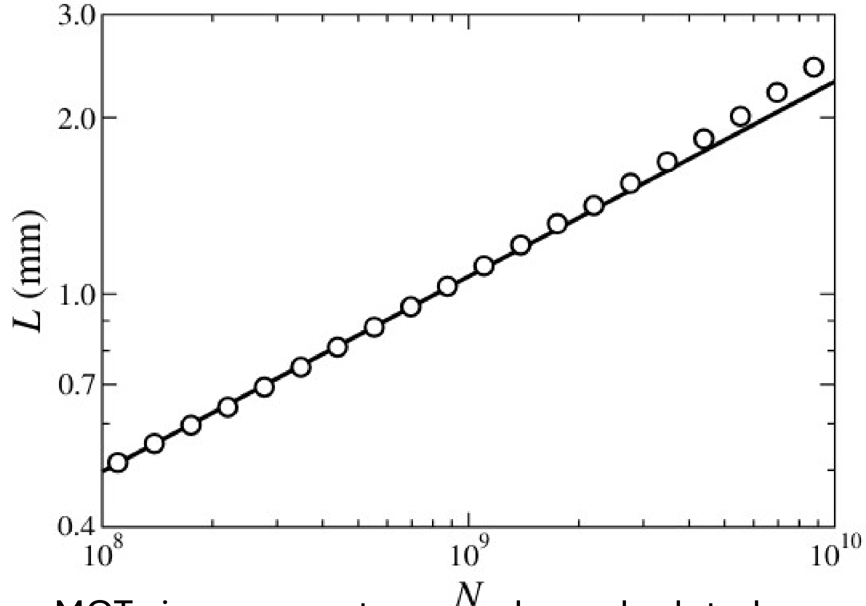
Limitations of a MOT: Density, n

- $n \approx 10^{10}$– $10^{11} cm^{-3}$

- MOT size (L) scaling $L \propto N^{1/3}$

Standard MOT parameters

MOT detuning	$\delta_{\mathrm{MOT}} = -2.5\Gamma$
MOT intensity per beam	$I_{\mathrm{MOT}} \approx 1.2 \mathrm{mW\,cm^{-2}}$
MOT beam waist	$w_{\mathrm{MOT}} \approx 2.4\,\mathrm{cm}$
Repumper detuning	$\delta_{\mathrm{rep}} = 0$
Repumper intensity per beam	$I_{\mathrm{rep}} \approx 0.5\,\mathrm{mW\,cm^{-2}}$
Repumper beam diameter	$L_{\mathrm{rep}} \approx 5\,\mathrm{cm}$ FWHM
Magnetic field gradient	$\nabla B = 10\,\mathrm{G\,cm^{-1}}$



MOT size versus atom number calculated (circles) compared to the $\mathrm{N} \sim L^{1/3}$ power law (solid line).

G. L. Gattobigio *et al.* (2010)

Measurement & Optimization:
n, temp

Imaging System: Absorption Imaging

- Absorption imaging

$$I_f = I_i e^{-OD} \qquad\qquad OD = n\sigma_0$$

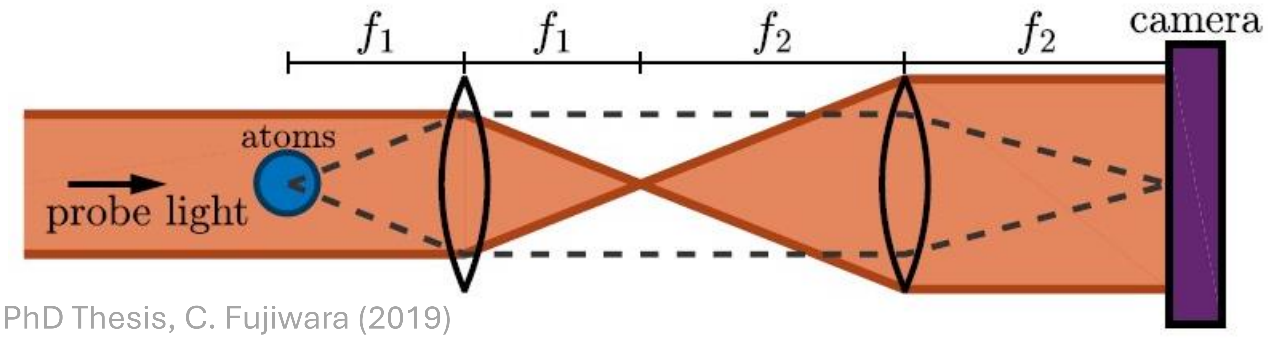
- Discretization of OD yields the number of atoms for a given pixel N_{px}

Physical area at location of atoms

$$N_{px} = \frac{A_{px}}{\sigma_0}\,\mathrm{OD} = \frac{A_{px}}{\sigma_0}\ln\left(\frac{\mathrm{I}_{i,\mathrm{px}} - \mathrm{I}_{d,\mathrm{px}}}{\mathrm{I}_{f,\mathrm{px}} - \mathrm{I}_{d,\mathrm{px}}}\right)$$

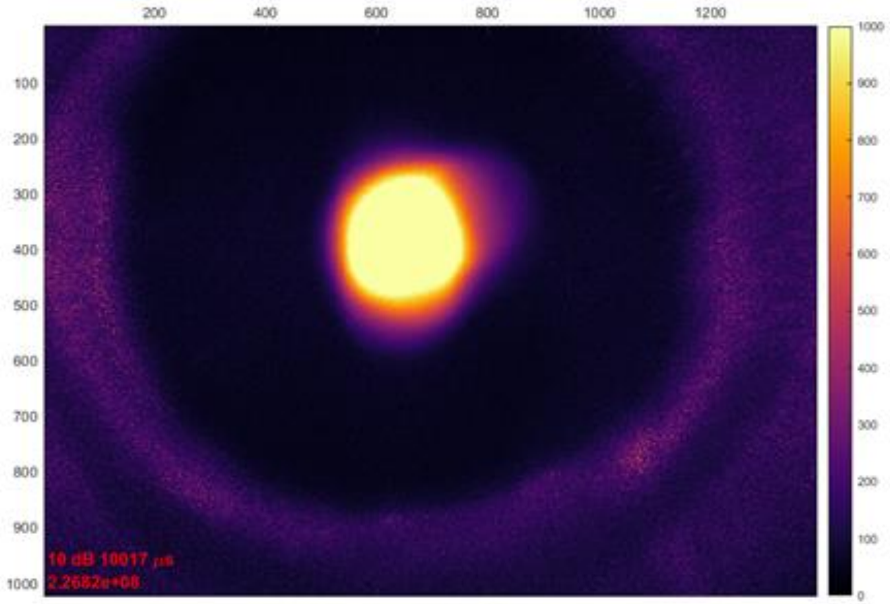
Measured bg pixel intensity per pixel (common mode noise)

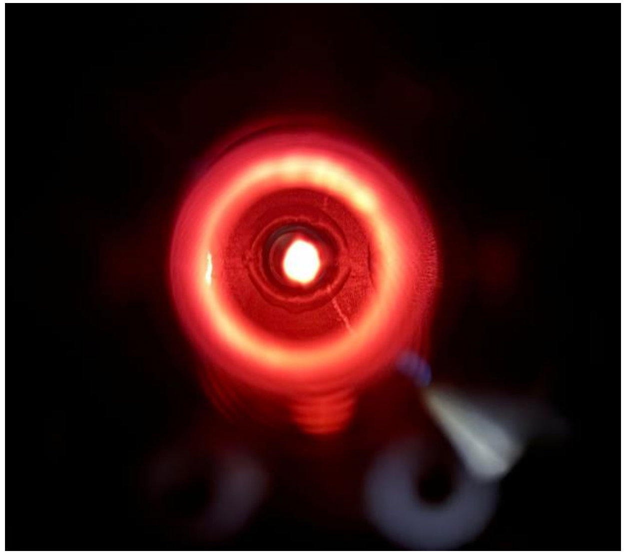
- Map atomic spatial distribution: 4F imaging system



PhD Thesis, C. Fujiwara (2019)

Fluorescence Image





The number of atoms N within the MOT is obtained by

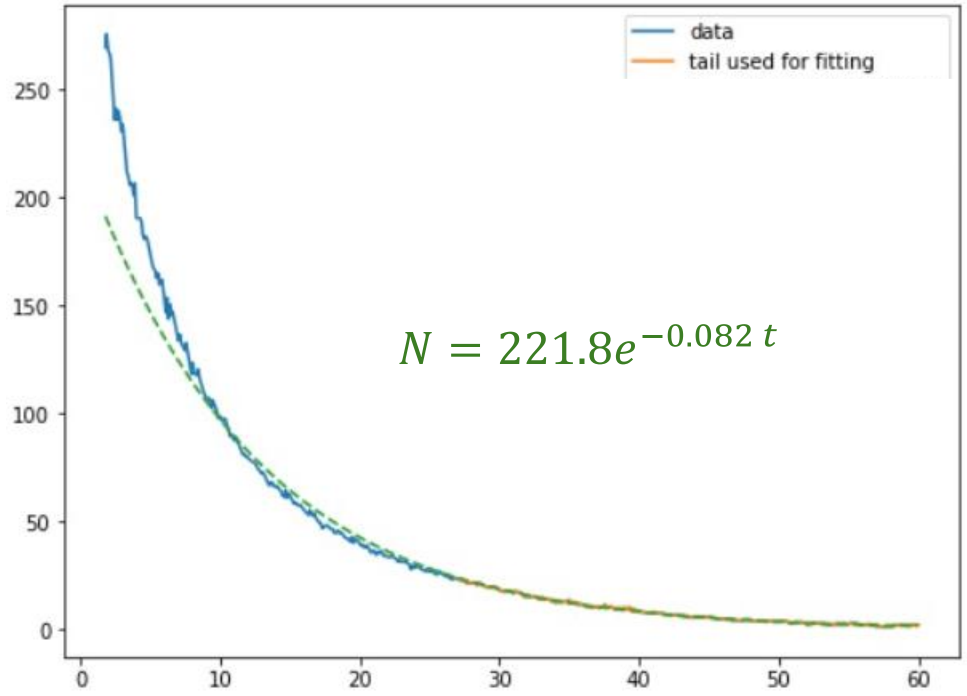
$$N\gamma_{sc} = \frac{4\pi}{\Omega}\,\mathrm{P}_{\mathrm{optical}}$$

Characterization – Trap Dynamics:

$$\frac{dN}{dt} = R - \gamma N - \beta \int n^2(\mathbf{r},t)d^3\mathbf{r}$$

After blocking 2D MOT beams

Avg Intensity in ROI

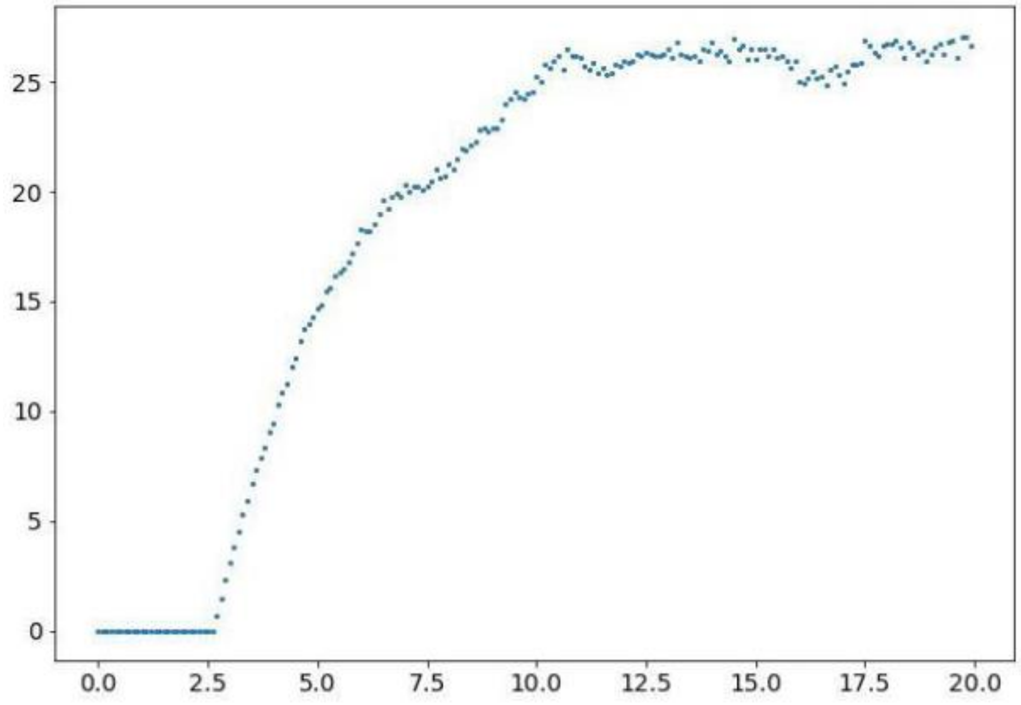


Time (s)

Lifetime

After unblocking 3D MOT beams

Avg Intensity in ROI



Time (s)

Loadtime

Ballistic Time-of-flight (TOF) thermometry: $insitu\ x$ and p distribution

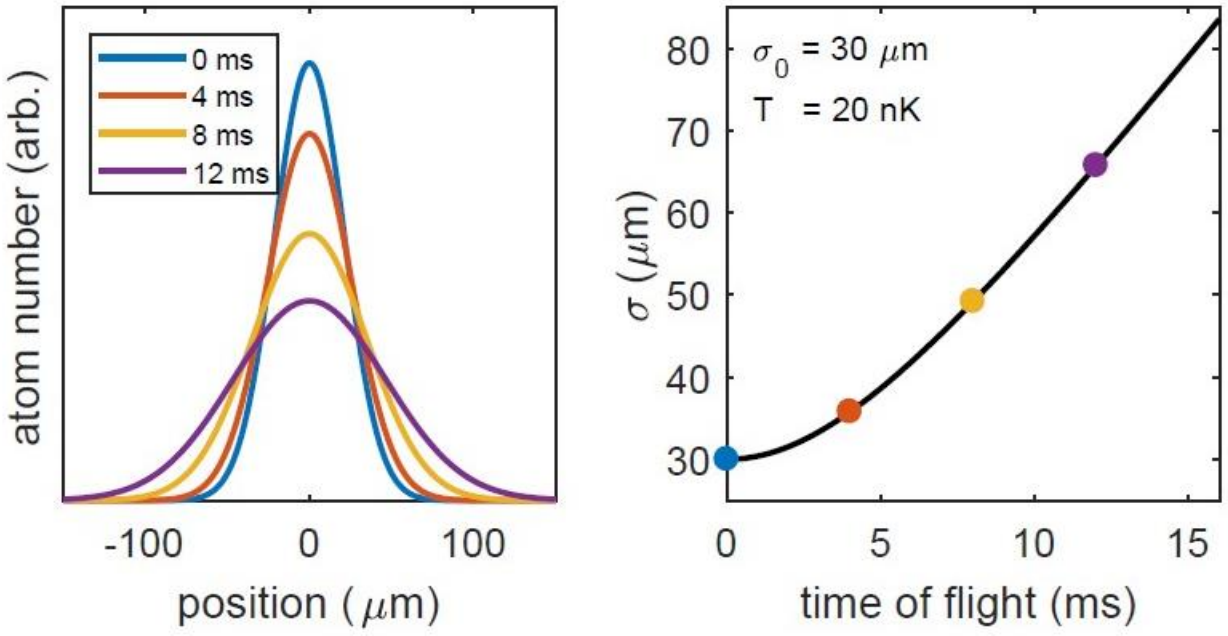
- Temperature of initial cloud σ_x is related to the cloud size

Cloud size

$$\sigma(t) = \sqrt{\left(\frac{k_B T}{m}\right) t^2 + \sigma_x^2}$$

Gaussian radius of momentum distribution $\sigma_p \propto$ T (eqp thm)

Gaussian radius of probability distribution for positions σ_x



PhD Thesis, C. Fujiwara (2019)

scientific visualizations. Let's proceed with this idea.

Here is the artistic representation of rubidium atoms at a few hundred microkelvin. The image features an ethereal cloud of atoms inside a vacuum chamber, highlighted with blue and violet hues to suggest extreme coldness. You can view the image above.