Probing the nuclear magnetic octupole moment of trapped Sr ions

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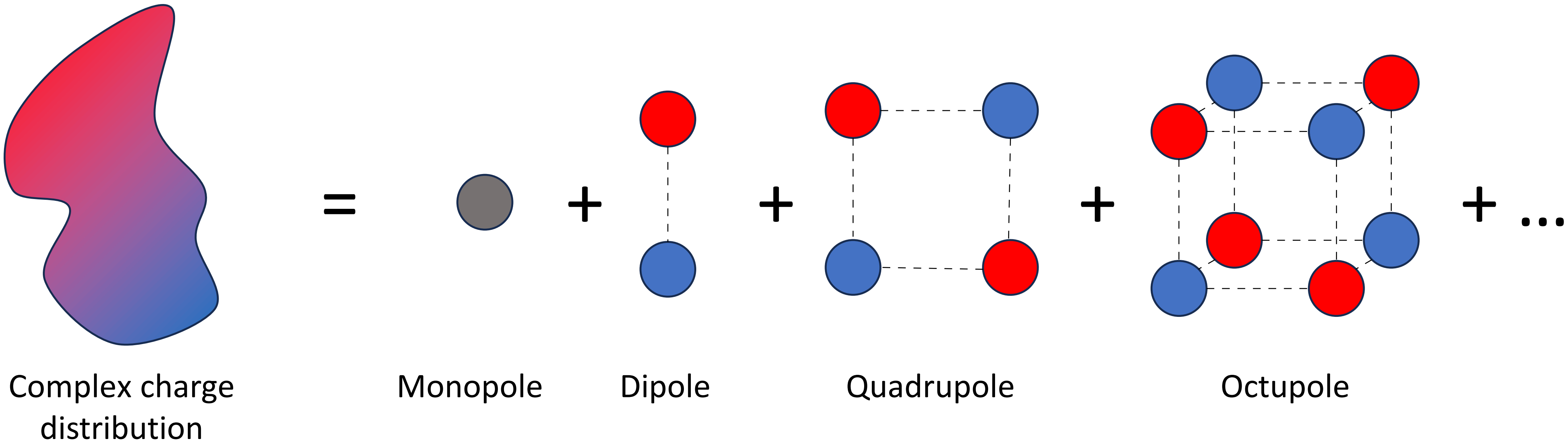
KU LEUVEN

III[rd] EARLY CAREER CONFERENCE in TRAPPED IONS

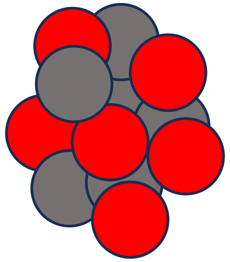
Nuclear magnetic octupole moment

Multipole expansion

Exemple of electric field :

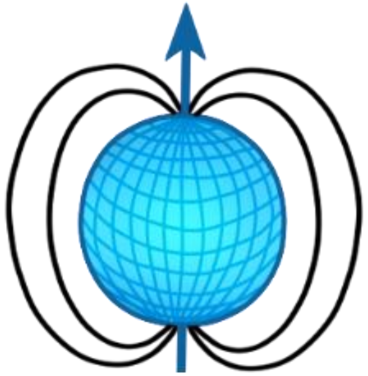


Electromagnetic multipole moments



Nucleus electromagnetic properties

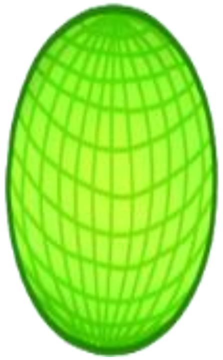
=



Magnetic Dipole

μ

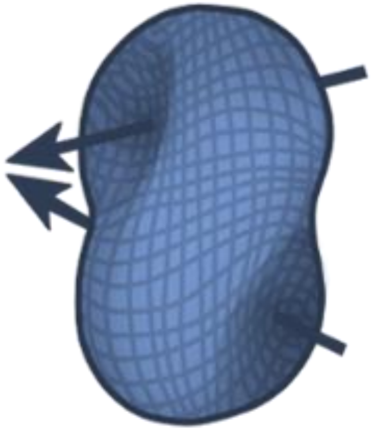
+



Electric Quadrupole

Q

+



Magnetic Octupole

Ω

+...

Magnetic moment operators

g_L, g_S : gyromagnetic ratios
Y_j^0 : spherical harmonic of rank j
g_L neutron = 0
g_L proton = 1

Operator

$$\mu = \widehat{M_1} = \sum_{j=1}^{A} \frac{\mu_N}{\hbar}\left(g_L^{(j)}\widehat{L_Z} + g_S^{(j)}\widehat{S_Z}\right)$$

$$\mathrm{Q} = \widehat{Q_2} = \sum_{j=1}^{A} g_L^{(j)} r_j^2 P_j(\theta_j)$$ No $g_S^{(j)}$, Proton only

$$\Omega = \widehat{M_3} = \sum_{j=1}^{A} \frac{\mu_N}{\hbar}\left(\frac{1}{2} g_L^{(j)}\widehat{L_Z} + g_S^{(j)}\widehat{S_Z}\right) \cdot \vec{\nabla}\left(r_j^3 \sqrt{\frac{7}{4\pi}} Y_3^0(\theta_j, \varphi_j)\right)$$

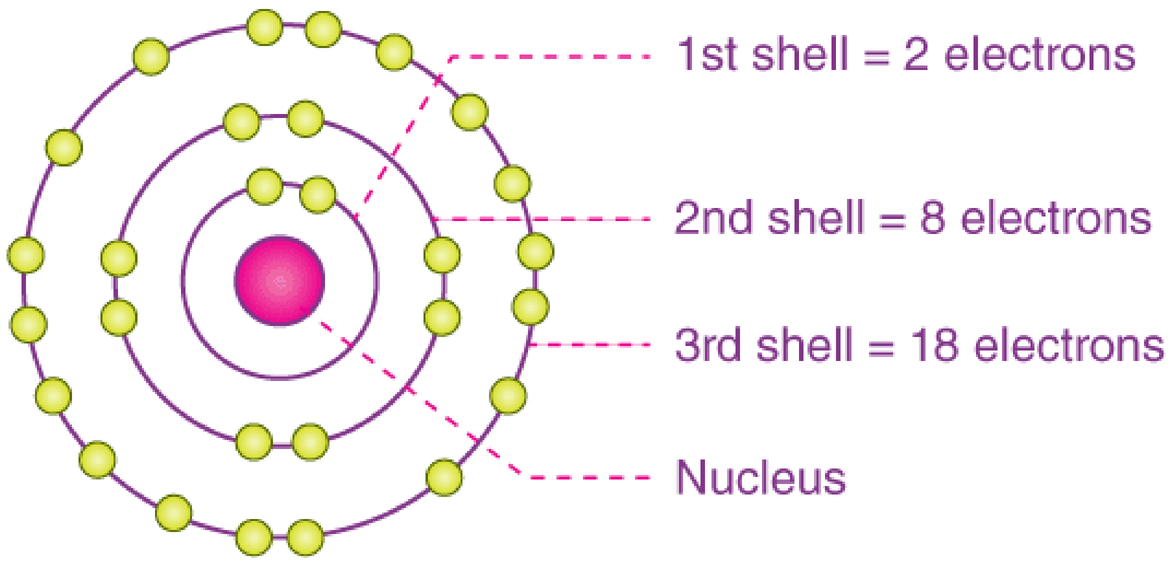
Same g-factors!

Spatial wf information

Blin-Stoyle, R. J. Theories of Nuclear Moments. Rev. Mod. Phys. ***28****, 75–101 (1956).*

Shell model

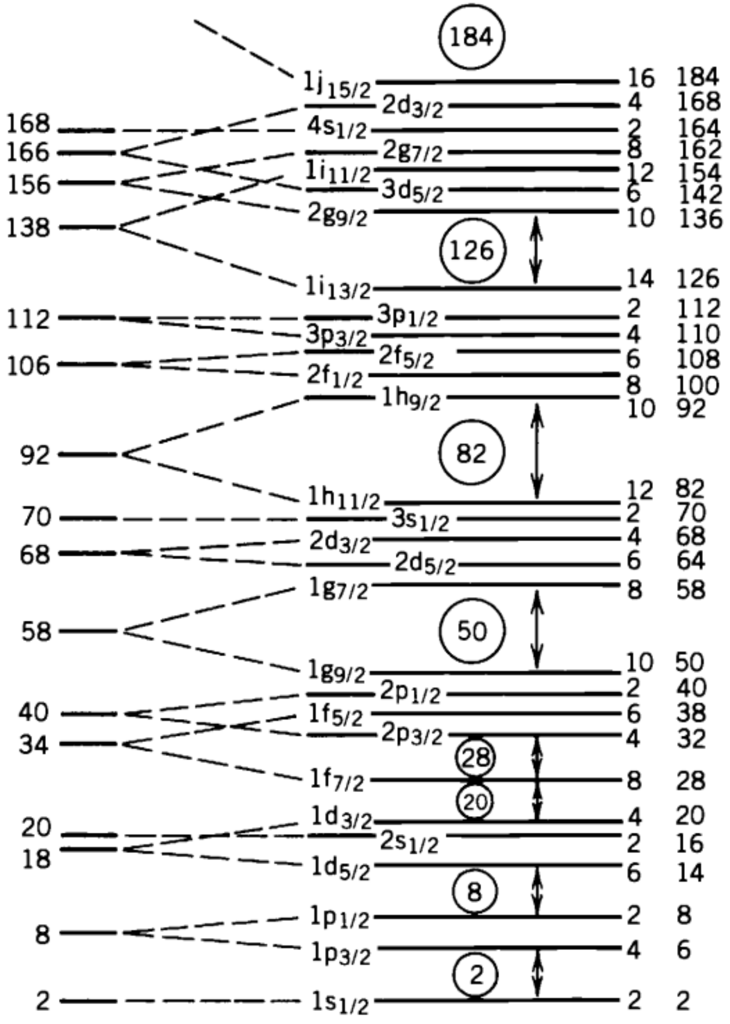
Atomic Shell Model



https://byjus.com/physics/shell-model/

Magic quantum numbers of nucleons (**2, 8, 20, 28, 50, 82…**) that are more tightly bound.

Nuclear Shell Model



Krane, Kenneth S. *Introductory nuclear physics*. Rev. ed. of *Introductory nuclear physics*/David Halliday. 2nd. ed. 1955.

Nuclear magic numbers: new features far from stability

O. Sorlin[1], M.-G. Porquet[2]

[1]Grand Accélérateur National d'Ions Lours (GANIL),
CEA/DSM - CNRS/IN2P3, B.P. 55027, F-14076 Caen Cedex 5, France
[2]Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse (CSNSM),
CNRS/IN2P3 - Université Paris-Sud, Bât 104-108, F-91405 Orsay, France

May 19, 2008

Nuclear magic numbers: new features f...

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May 19, 2008

Evidence for prevalent Z = 6 magic number in neutron-rich carbon isotopes

D.T. Tran[1,2], H.J. Ong[1], G. Hagen[3,4], T.D. Morris[3,4], N. Aoi[1], T. Suzuki[5,6], Y. Kanada-En'yo[7], L.S. Geng[8], S. Terashima[8], I. Tanihata[1,8], T.T. Nguyen[9,10,27], Y. Ayyad[1], P.Y. Chan[1], M. Fukuda[11], H. Geissel[12,13], M.N. Harakeh[12,14], T. Hashimoto[15], T.H. Hoang[1,2], E. Ideguchi[1], A. Inoue[1], G.R. Jansen[3,16], R. Kanungo[17], T. Kawabata[7], L.H. Khiem[2], W.P. Lin[18], K. Matsuta[11], M. Mihara[11], S. Momota[19], D. Nagae[20], N.D. Nguyen[21], D. Nishimura[22], T. Otsuka[23], A. Ozawa[24], P.P. Ren[18], H. Sakaguchi[1], C. Scheidenberger[12,13], J. Tanaka[1], M. Takechi[25], R. Wada[18,26] & T. Yamamoto[1]

Nuclear magic numbers: new features fa...

O. Sorlin[1], M.-G. Porquet[2]
[1]Grand Accélérateur National d'Ions L...
CEA/DSM - CNRS/IN2P3, B.P. ...
[2]Centre de Spect...
CNRS/IN2P3 - ...

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... [3,16], R. Kanungo[17],

^{78}Ni revealed as a doubly magic stronghold against nuclear deformation

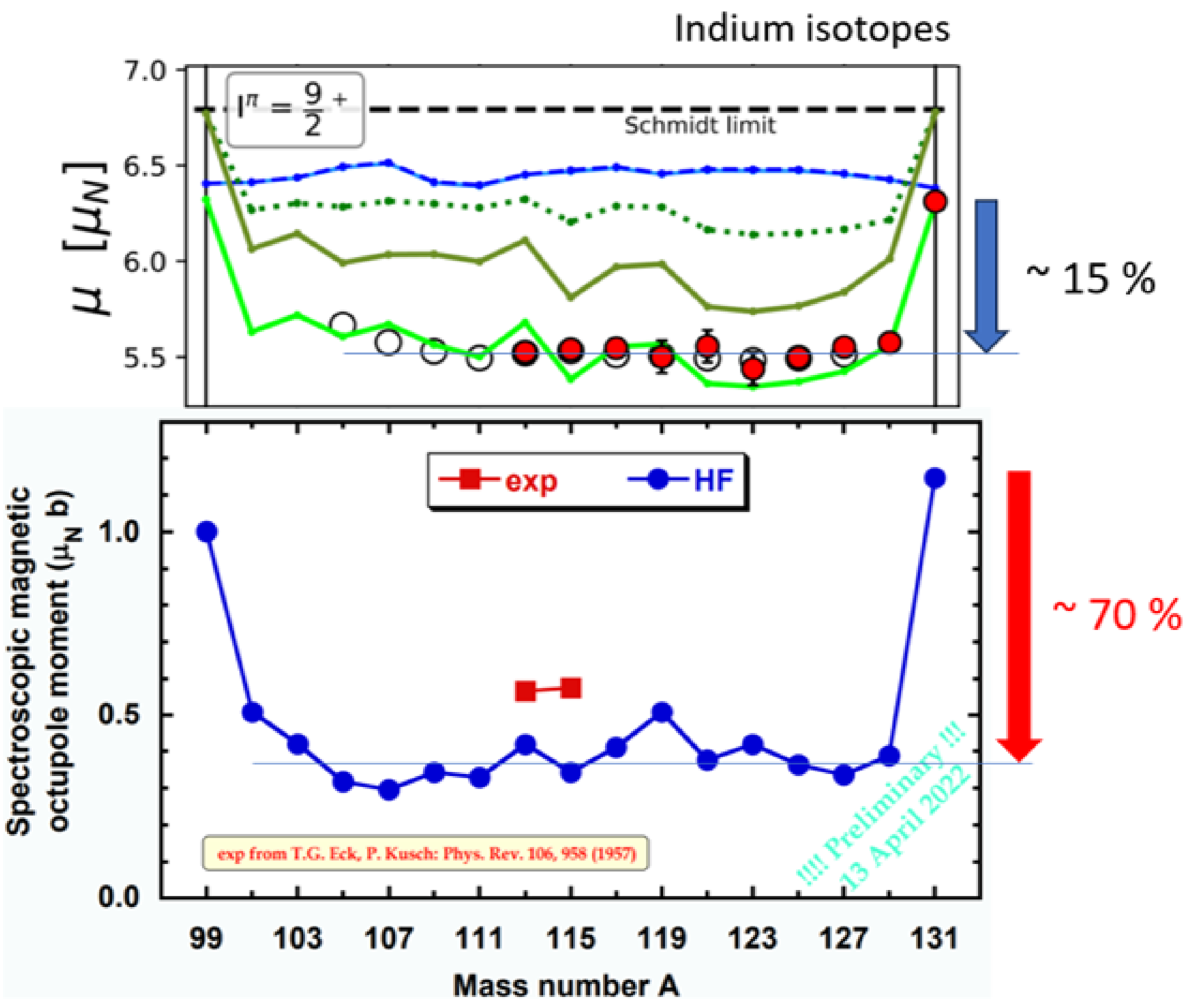
R. Taniuchi,[1,2] C. Santamaria,[3,2] P. Doornenbal,[2,*] A. Obertelli,[3,2,4] K. Yoneda,[2] G. Authelet,[3] H. Baba,[2] D. Calvet,[3] F. Château,[3] A. Corsi,[3] A. Delbart,[3] J.-M. Gheller,[3] A. Gillibert,[3] J.D. Holt,[5] T. Isobe,[2] V. Lapoux,[3] M. Matsushita,[6] J. Menéndez,[6] S. Momiyama,[1,2] T. Motobayashi,[2] M. Niikura,[1] F. Nowacki,[7] K. Ogata,[8,9] H. Otsu,[2] T. Otsuka,[6,1,2] C. Péron,[3] S. Péru,[10] A. Peyaud,[3] E.C. Pollacco,[3] A. Poves,[11] J.-Y. Roussé,[3] H. Sakurai,[1,2] A. Schwenk,[4,12,13] Y. Shiga,[2,14] J. Simonis,[15,4,12] S.R. Stroberg,[5,16] S. Takeuchi,[2] Y. Tsunoda,[6] T. Uesaka,[2] H. Wang,[2] F. Browne,[17] L.X. Chung,[18] Zs. Dombradi,[19] S. Franchoo,[20] F. Giacoppo,[21] A. Gottardo,[20] K. Hadyńska-Klęk,[21] Z. Korkulu,[19] S. Koyama,[1,2] Y. Kubota,[2,6] J. Lee,[22] M. Lettmann,[4] C. Louchart,[4] R. Lozeva,[7,23] K. Matsui,[1,2] T. Miyazaki,[1,2] S. Nishimura,[2] L. Olivier,[20] S. Ota,[6] Z. Patel,[24] E. Şahin,[21] C. Shand,[24] P.-A. Söderström,[2] I. Stefan,[20] D. Steppenbeck,[6] T. Sumikama,[25] D. Suzuki,[20] Zs. Vajta,[19] V. Werner,[4] J. Wu,[2,26] and Z.Y. Xu[22]

Key points

Magnetic Octupole moment give information about **Nuclear shape** and **Nucleons distribution**

Magic quantum numbers of nucleons (**2, 8, 20, 28, 50, 82…**) that are more tightly bound.

Magnetic octupole moments: sensitive probe

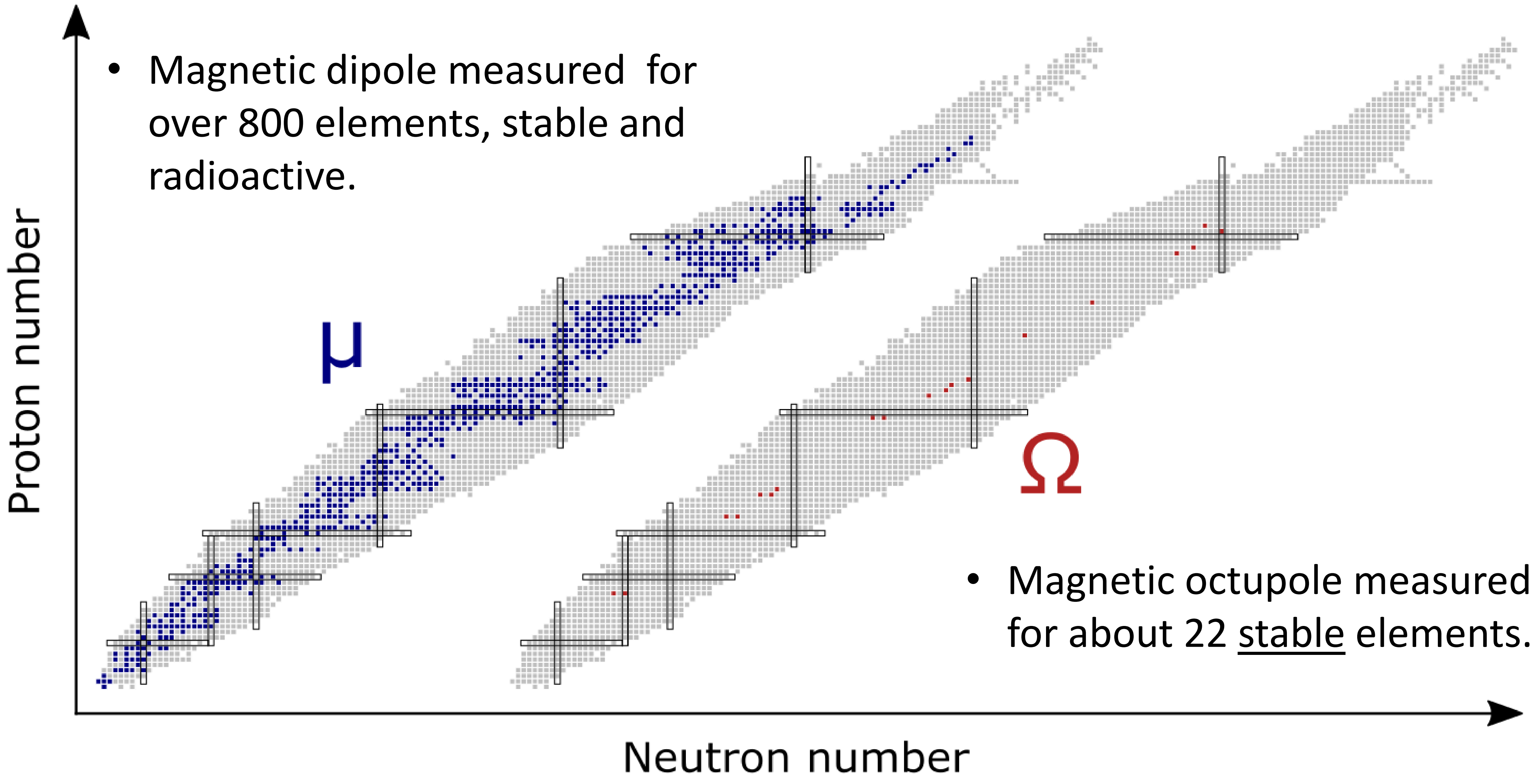


DFT calculations for In isotopic chain between N=50-82 [*J. Dobacewski*]

- Theoretical work based on density functional theory (DFT) calculations, for the Indium (Z=49) isotopic chain
- μ only drops 15% away from the closed N=82 (^{131}In) shell, Ω drops by 70%

Vernon, A. R. *et al.* Nuclear moments of indium isotopes reveal abrupt change at magic number 82. *Nature* **607**(2022).

- Magnetic dipole measured for over 800 elements, stable and radioactive.



- Magnetic octupole measured only for about 22 stable elements.

Objective

Measure the magnetic octupole moment of $^{83\text{-}93}Sr$. In doing so, probing the nuclear wavefunctions and magnetization of single-nucleon systems at the neutron shell N=50 (Sr).

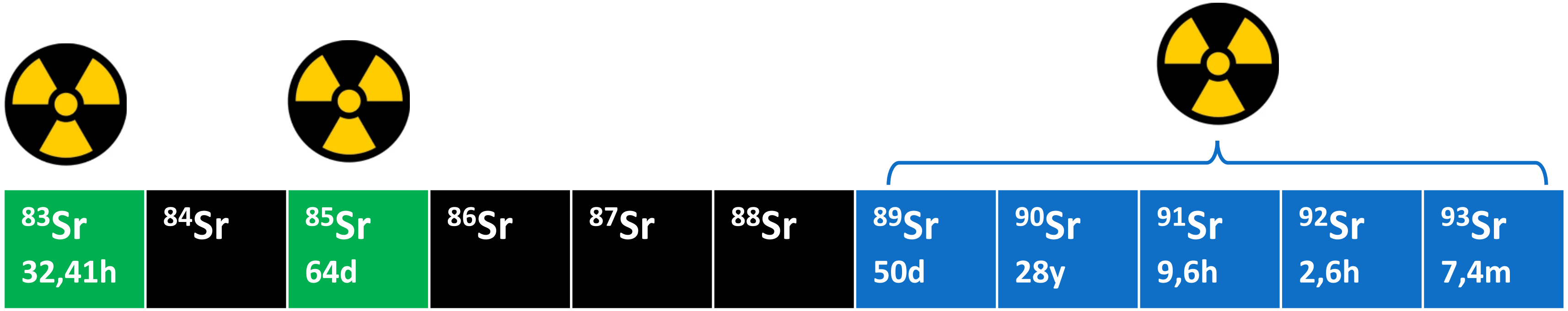
^{83}Sr	^{84}Sr	^{85}Sr	^{86}Sr	^{87}Sr	^{88}Sr	^{89}Sr	^{90}Sr	^{91}Sr	^{92}Sr	^{93}Sr
32,41h		64d				50d	28y	9,6h	2,6h	7,4m

Objective

Measure the magnetic octupole moment of $^{83\text{-}93}$Sr. In doing so, probing the nuclear wavefunctions and magnetization of single-nucleon systems at the neutron shell N=50 (Sr).

First Setup : Measurement on neutral Sr

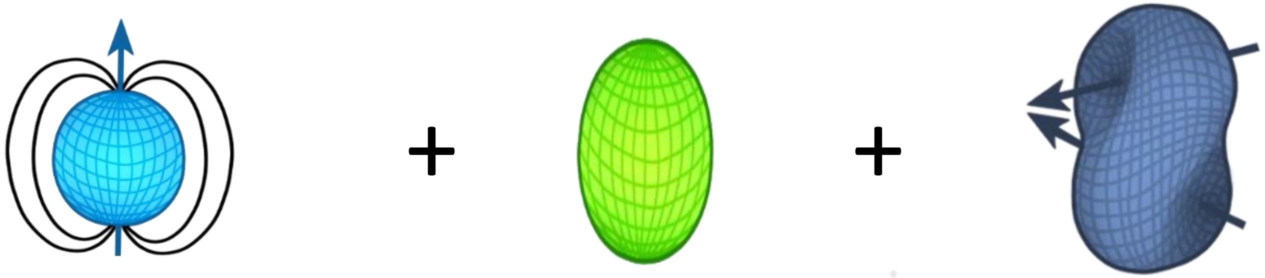
Second Setup: Measurement on radioactive Sr



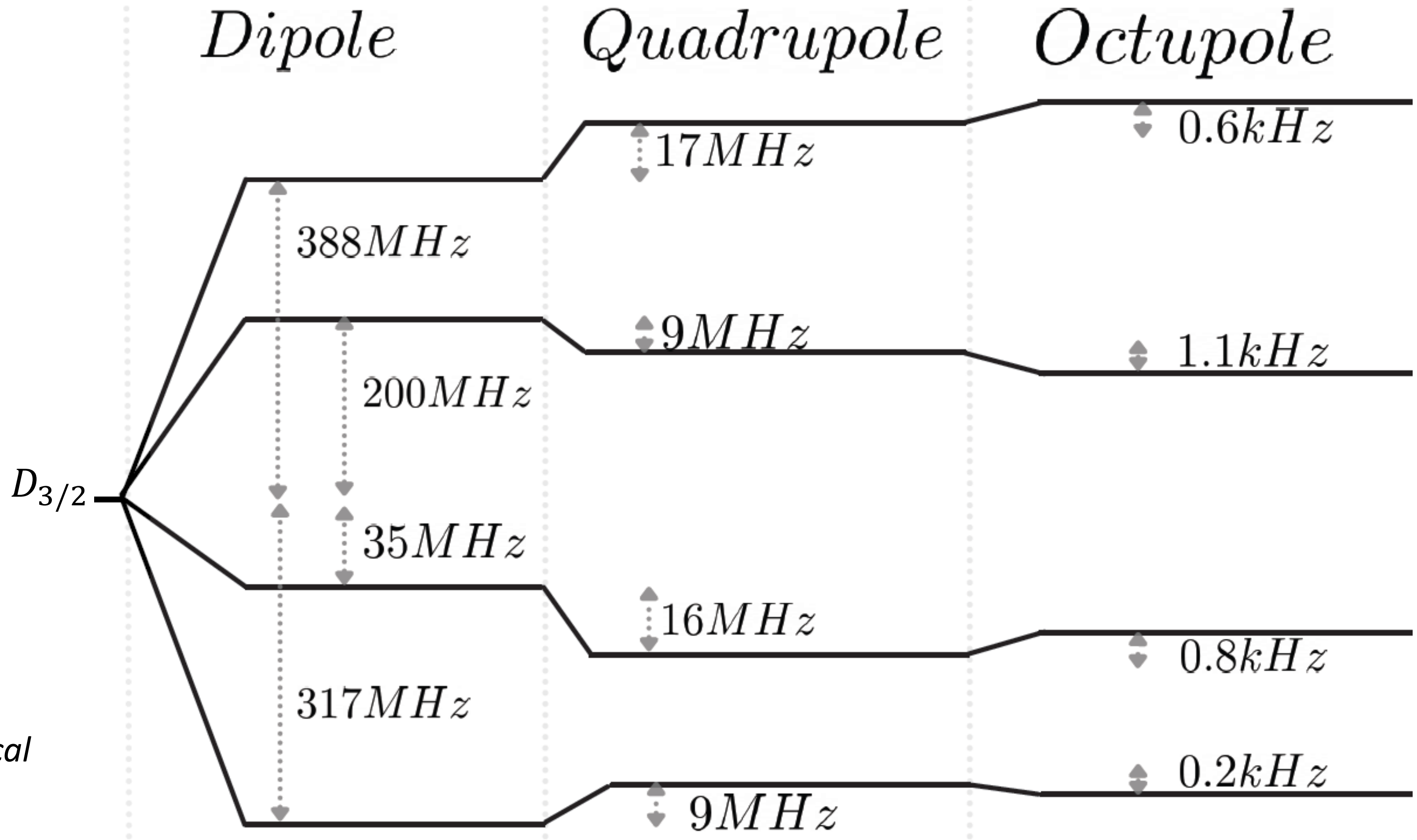
How to access it ?

How ? : Spectroscopy

$$\Delta E_{HFS} =$$



Schwartz, C. Theory of Hyperfine Structure. *Phys. Rev.* **97**, 380–395 (1955).

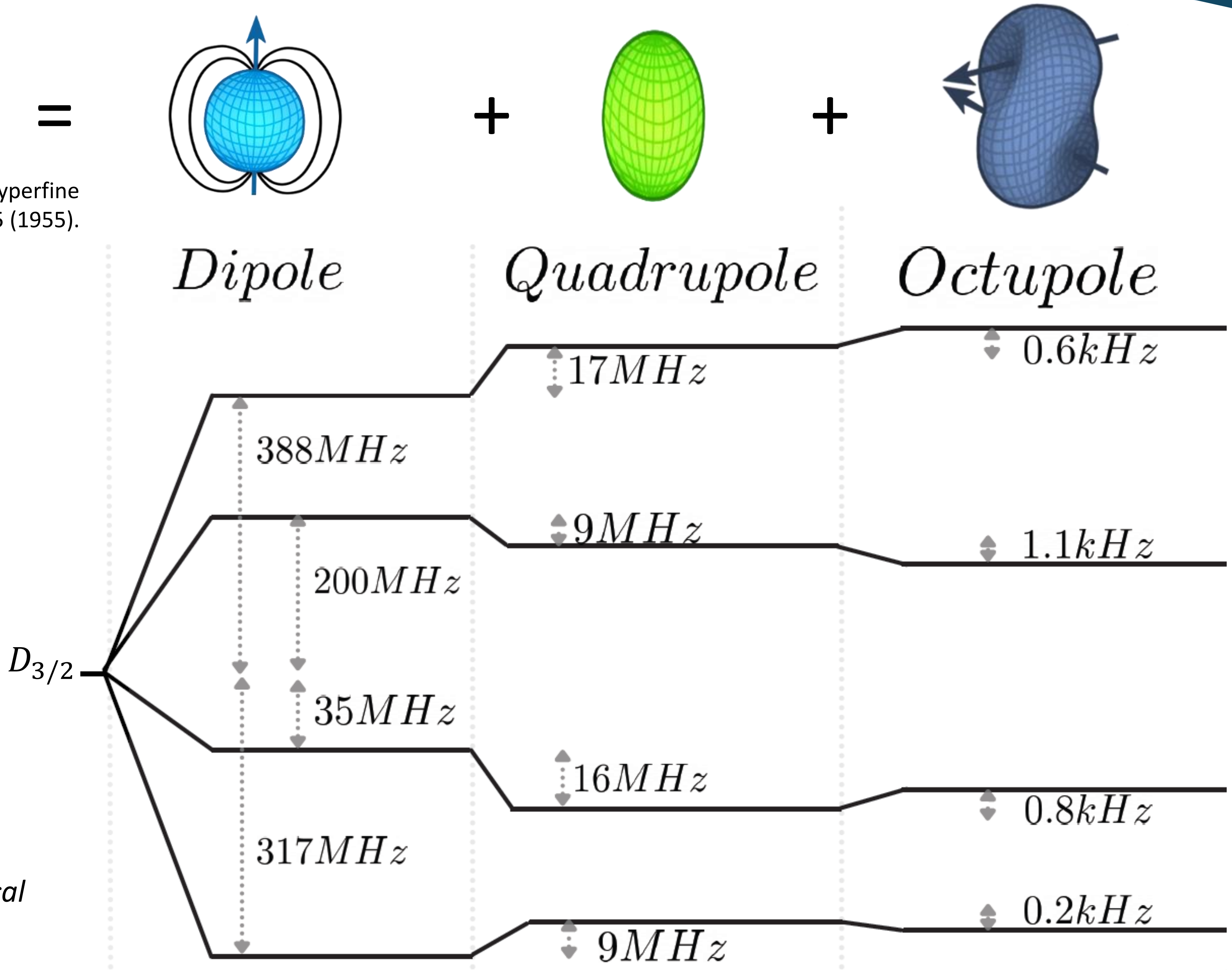


- Nuclear moments lead to shift and splitting of fine structure levels (*hyper*fine structure)
- Contribution of higher-order magnetic octupole moment is three or more orders of magnitude smaller

Example: $D_{3/2}$ state in 87Sr^{+}. Theoretical [*B.K. Sahoo*].

How ? : Spectroscopy

$$\Delta E_{HFS} =$$

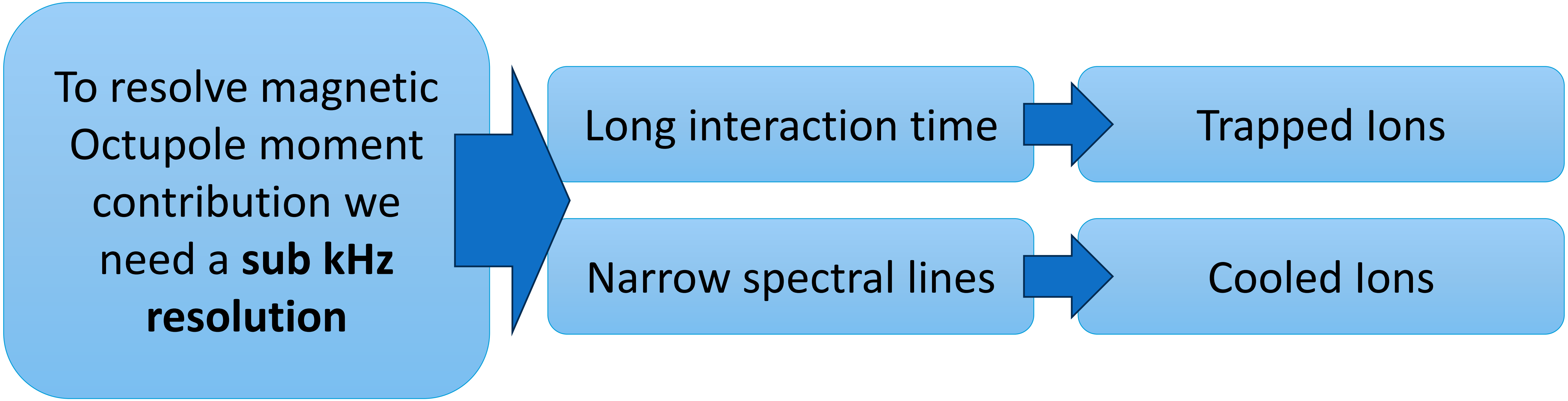


Schwartz, C. Theory of Hyperfine Structure. *Phys. Rev.* **97**, 380–395 (1955).

To resolve magnetic Octupole moment contribution we need a **sub kHz resolution**

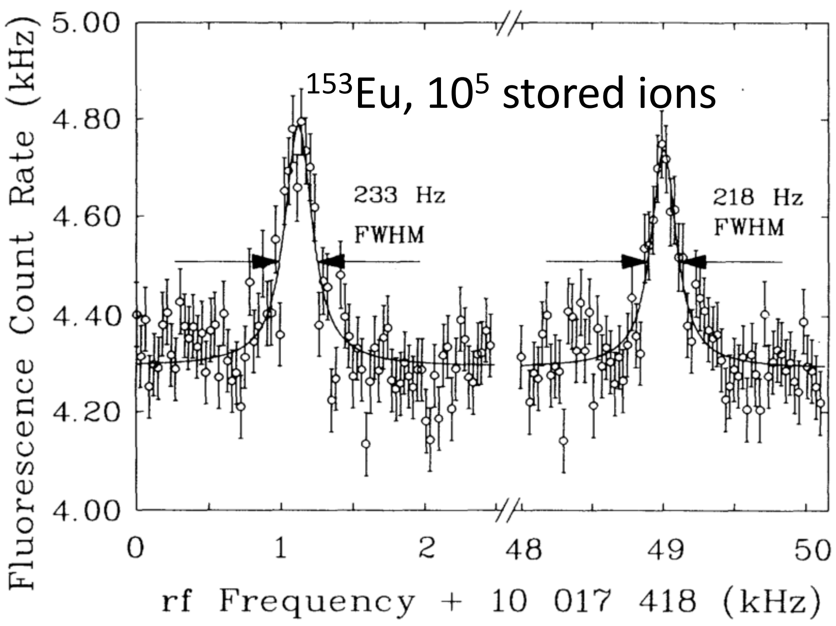
Example: $D_{3/2}$ state in 87Sr^{+}. Theoretical [*B.K. Sahoo*].

Where ? : In a trap

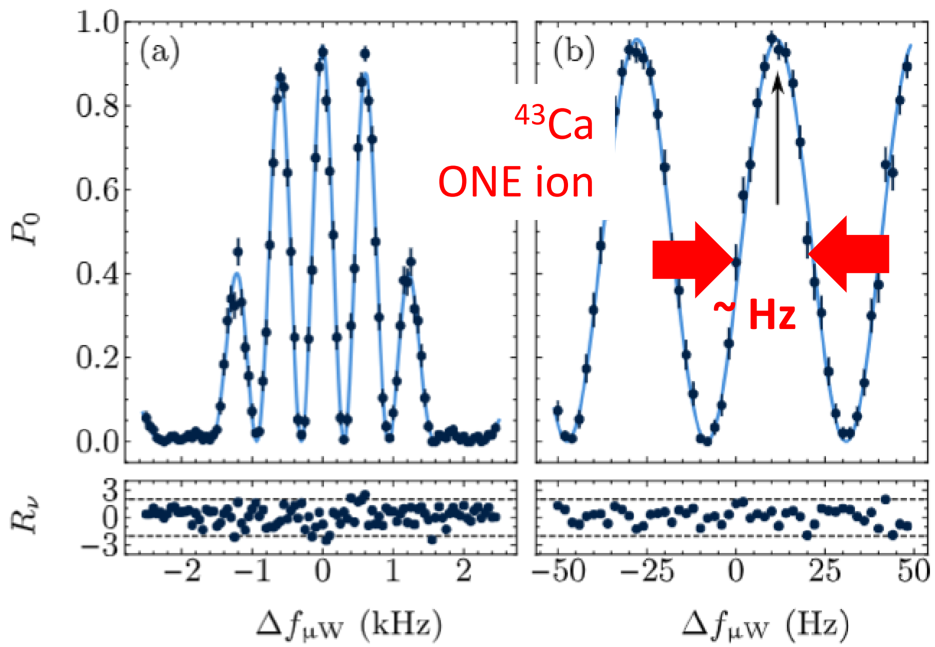


Spectroscopy of trapped ions

- Placing ions inside of a trap naturally yields longer interaction times (compared to Beamlines)
  - << kHz linewidths!
  - Eu: nontrivial atomic structure!
  - ^{43}Ca **g-factor!** (@ ~ 150 gauss) – g and A at ppm level in one experiment!



O. Becker et al, PRA 48, 5 1993

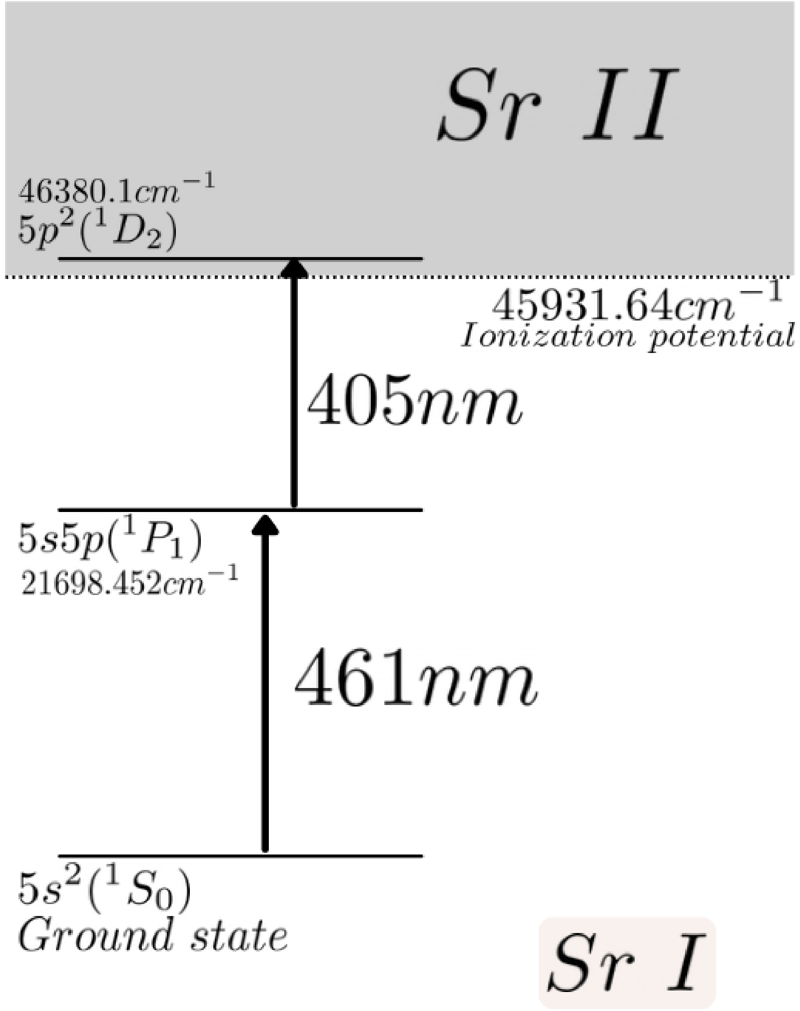


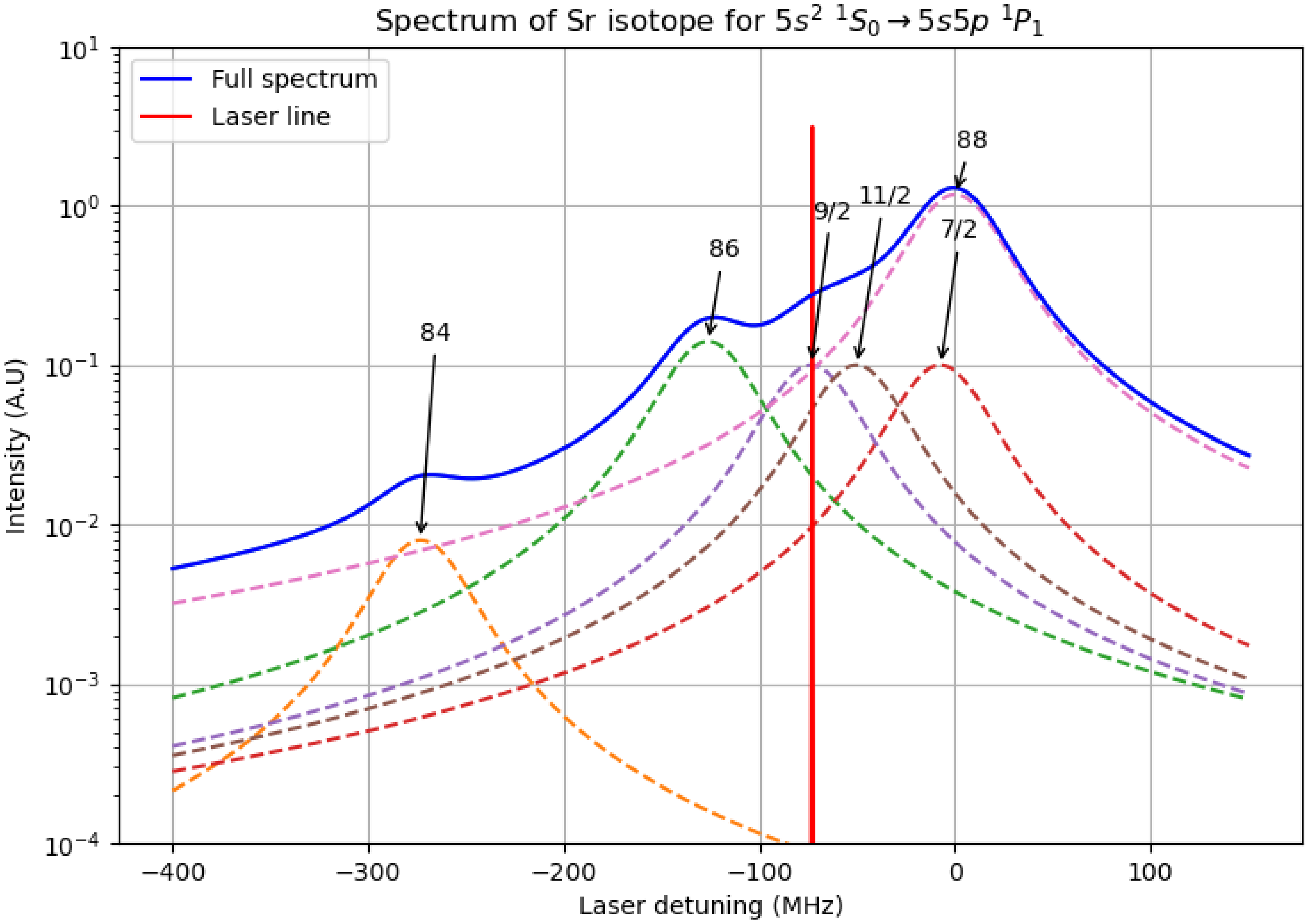
R. K. Hanley, PRA 104, 052804 (2021)

Measurement scheme

Laser Scheme

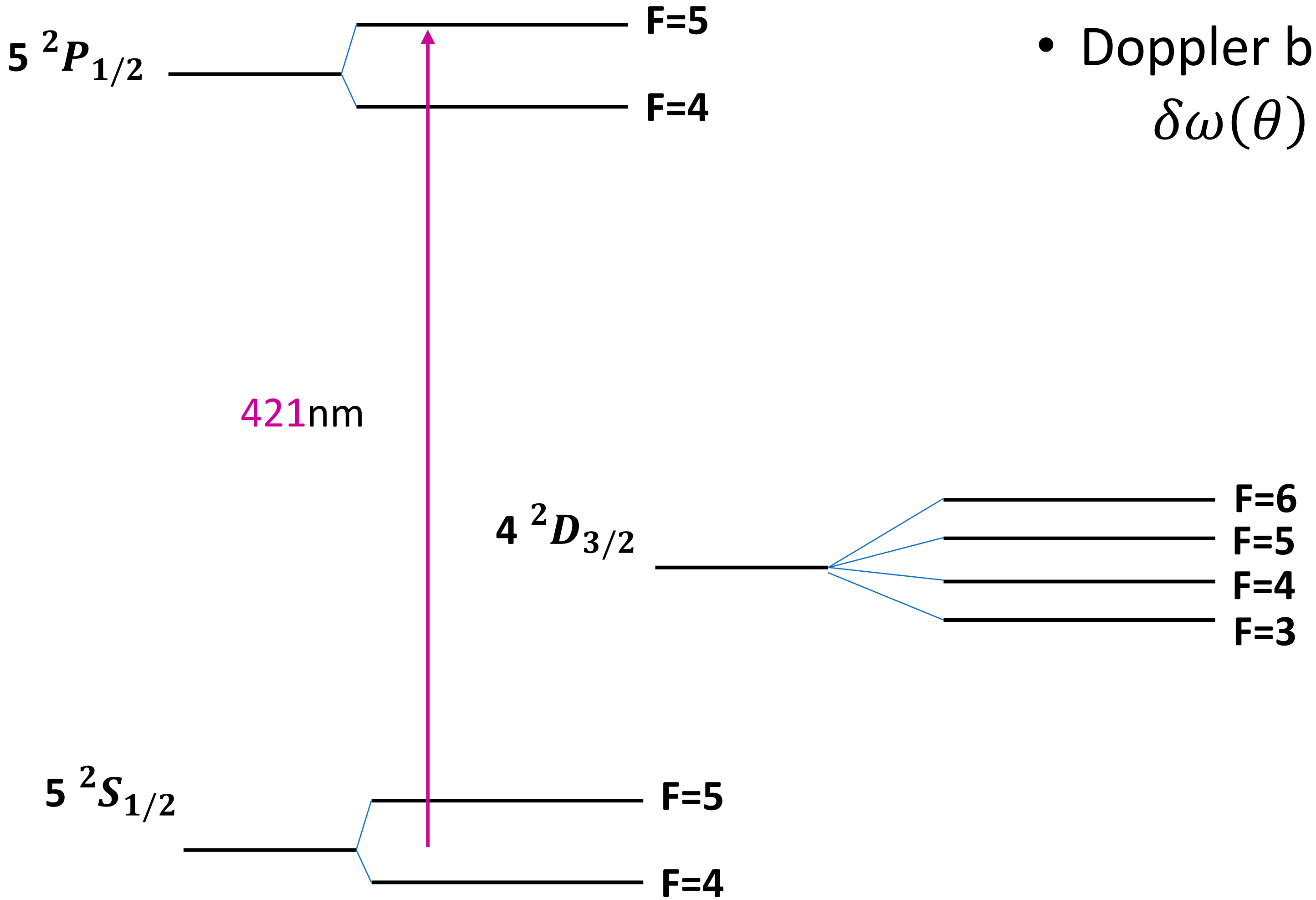
Step 1 : Ionisation





Laser Scheme

Step 2 : Cooling



$^{87}Sr^{+}$ hyperfine structure

- Recoil temperature: $T_{min} = \frac{\hbar\Gamma}{2k_B}$
- Doppler broadening:
  $$\delta\omega(\theta) = k\sqrt{2(1-\cos\theta)k_B T/M}$$

<u>Cooled Ions</u>

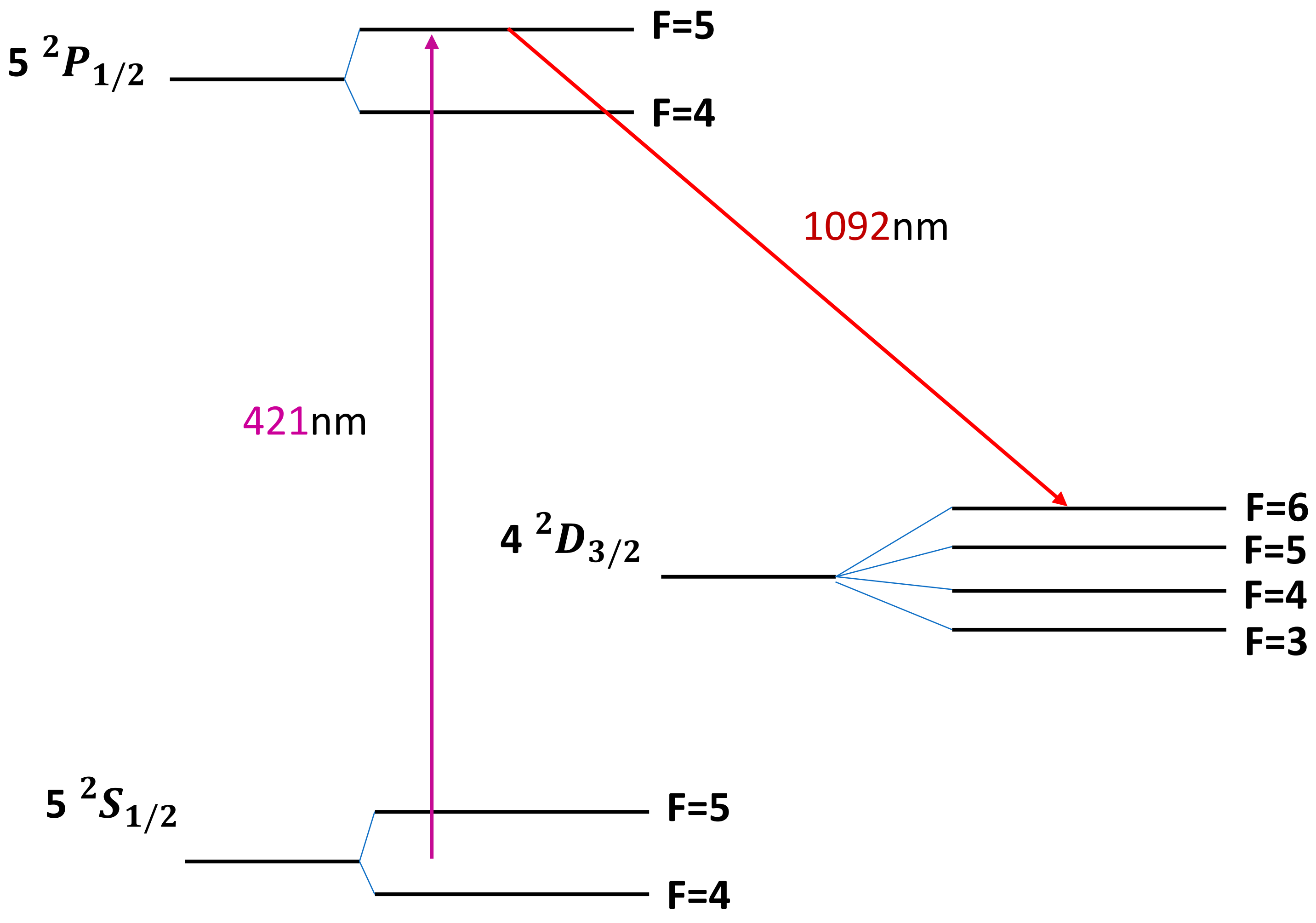
E= 4,3 e-8 eV

T~513μK

$\delta\omega(\theta)$=4,5 MHz

Laser Scheme

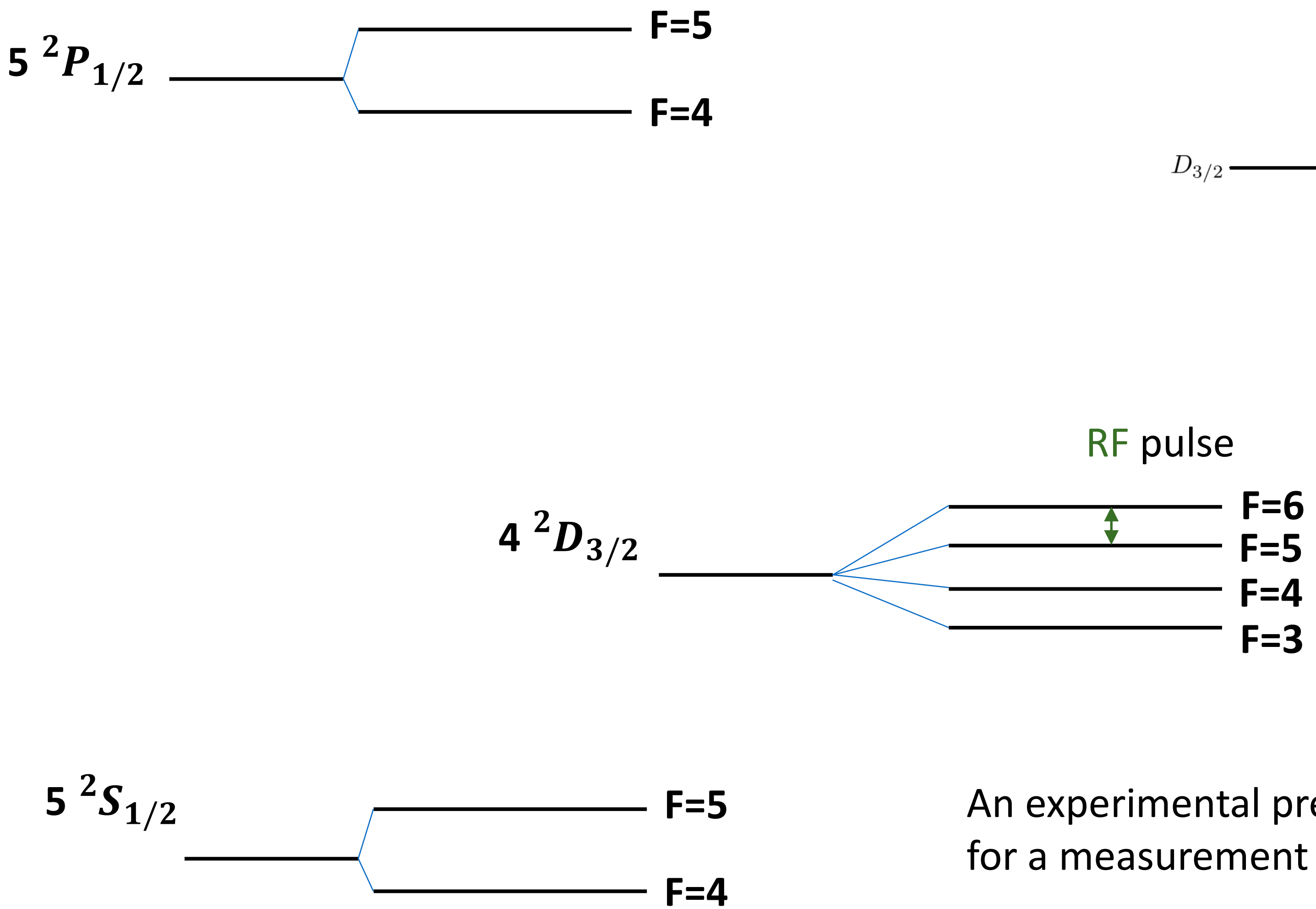
Step 3 : Preparation



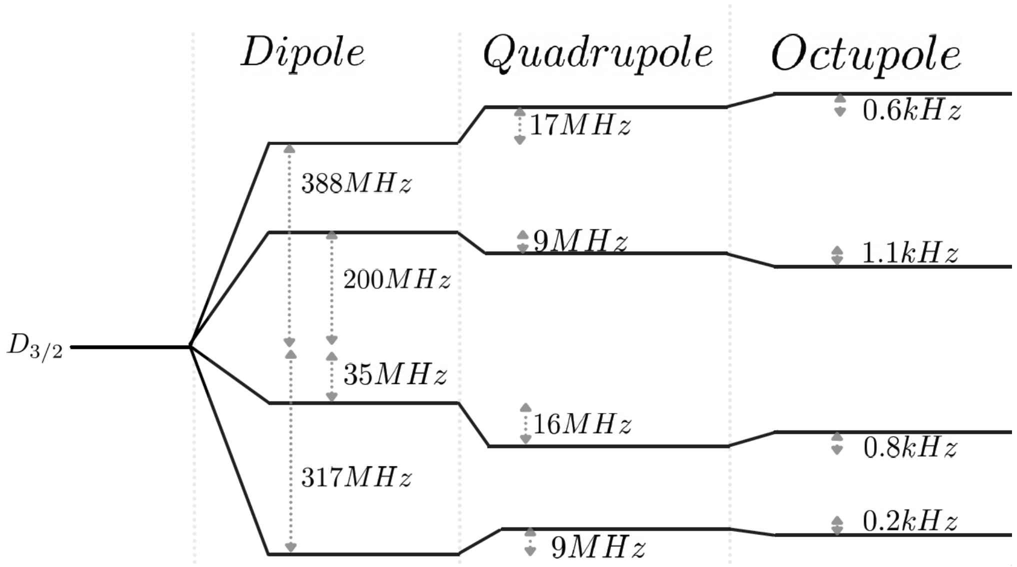
$^{87}Sr^{+}$ hyperfine structure

Laser Scheme

Step 4: Shelving



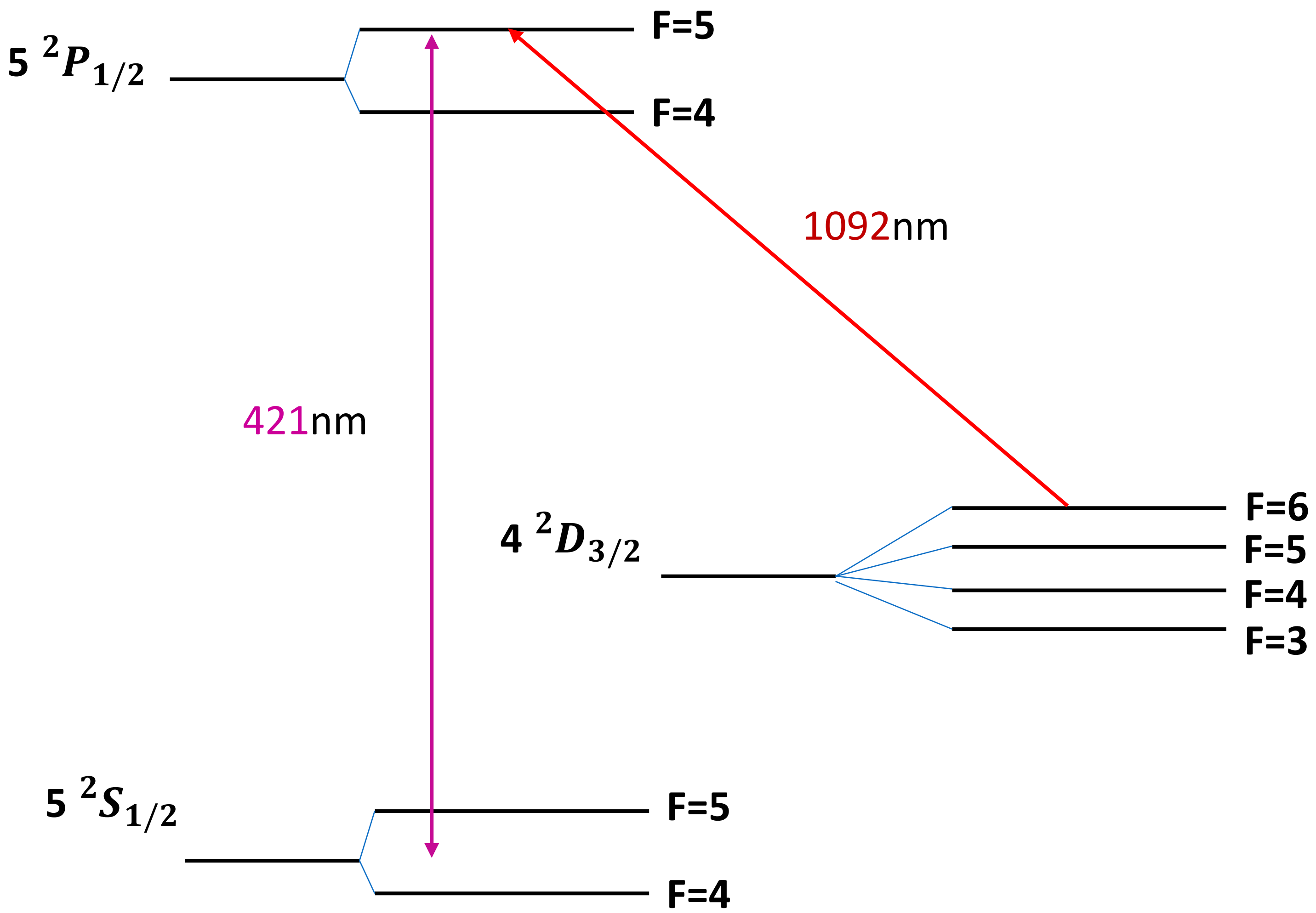
$^{87}Sr^{+}$ hyperfine structure



An experimental precision of the order of 1-10 Hz is sufficient for a measurement of Ω with an experimental precision of 10%.

Laser Scheme

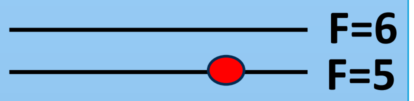
Step 5 : Detection



$^{87}Sr^+$ hyperfine structure

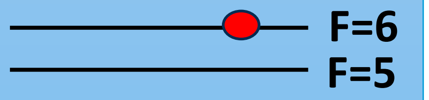
Detection on 421nm light

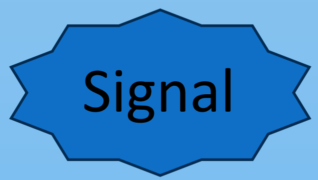
- If shelved :



No signal

- If not :





Key points

Magnetic Octupole moment give information about **Nuclear shape** and **Nucleus distribution**

Sub kHz resolution spectroscopy of Hyperfine structure to resolve it

Ideal measurement platform : **Laser cooled** ions in a **linear Paul trap**

Experimental setup

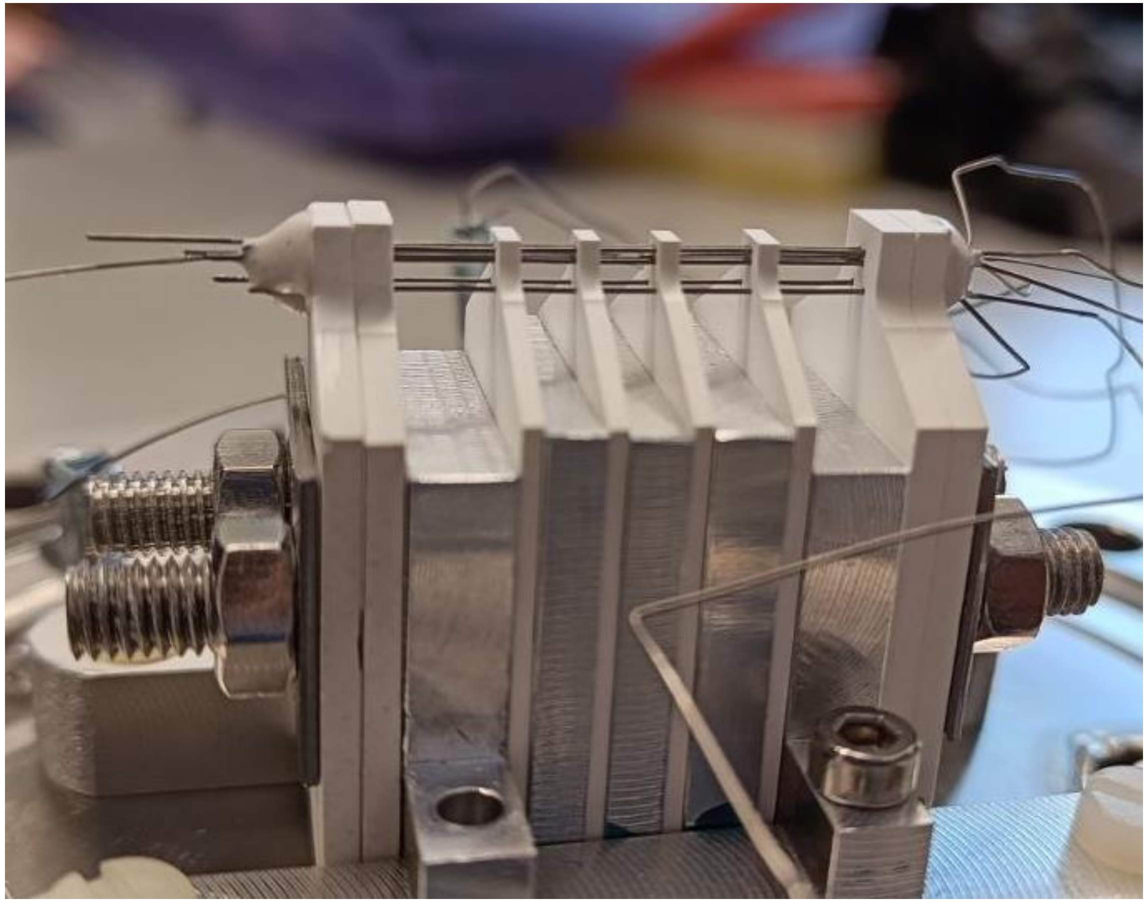
Experimental setup

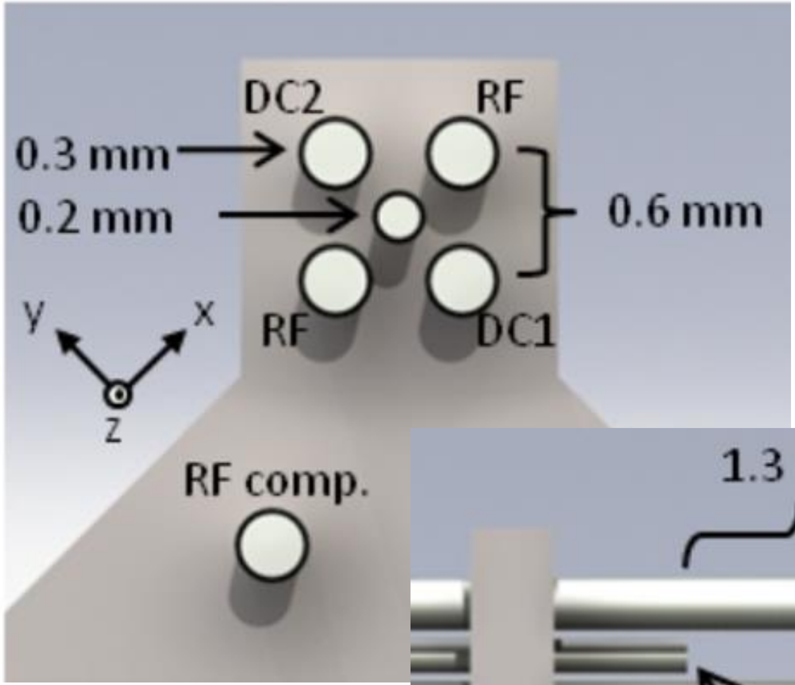
DISCLAMER : Early Stage

Neutral Sr Trap

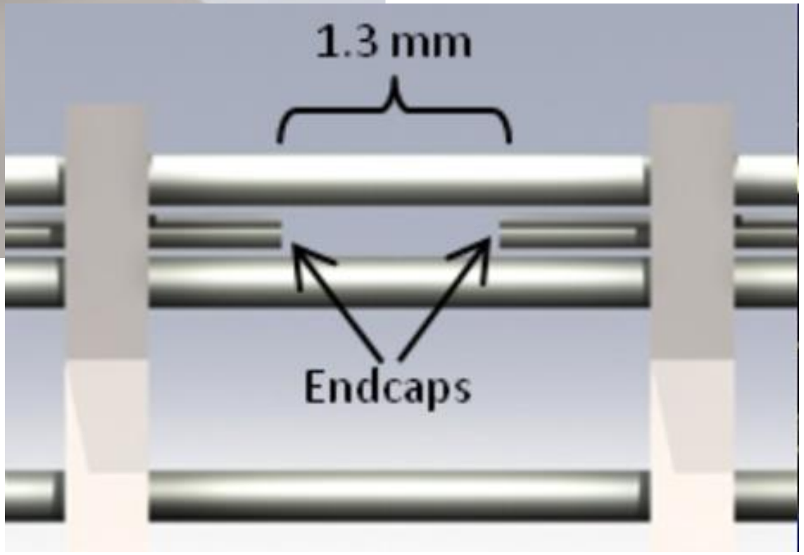
Linear Paul trap

- Testbench for spectroscopy methodology **with stable atoms**
- Design from quantum group @Weizman Institute





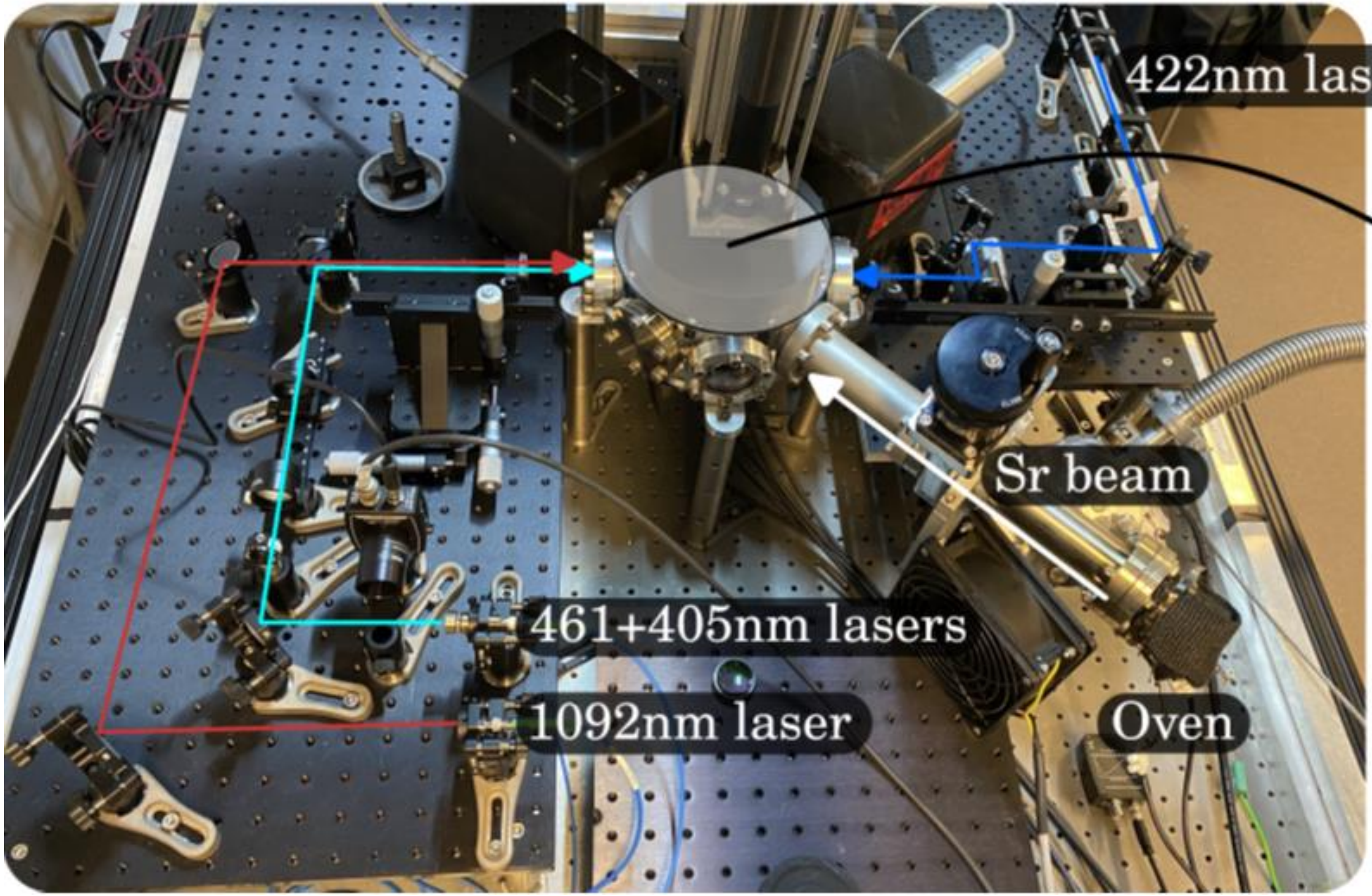
Akerman, N. Trapped ions and free photons. (Weizmann Institute of Science, 2012).

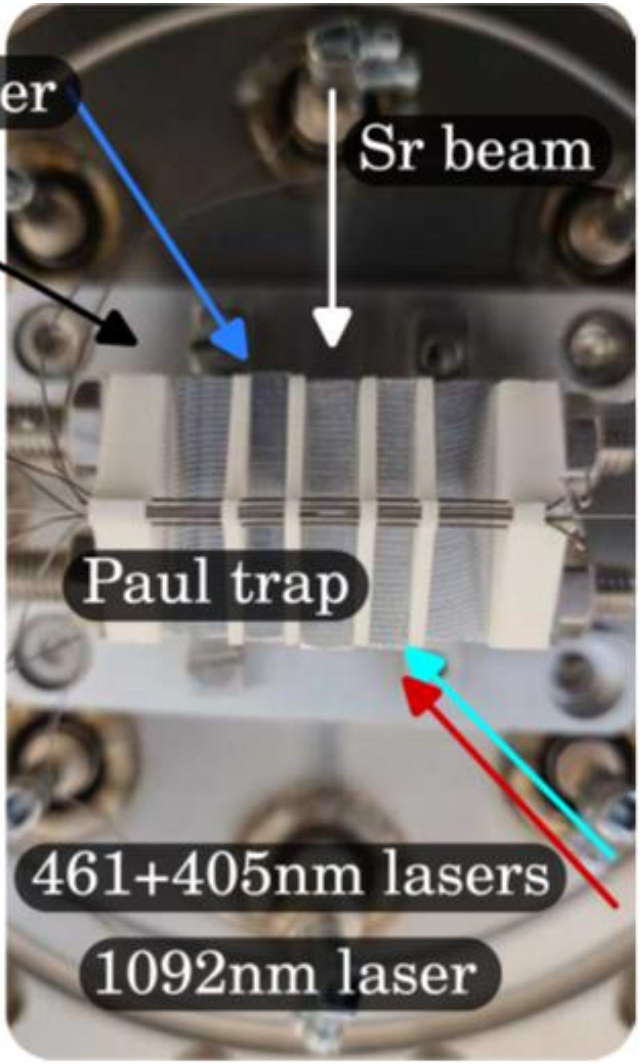


Precision trap @KUL

Laser systems

Vacuum chamber + imaging system





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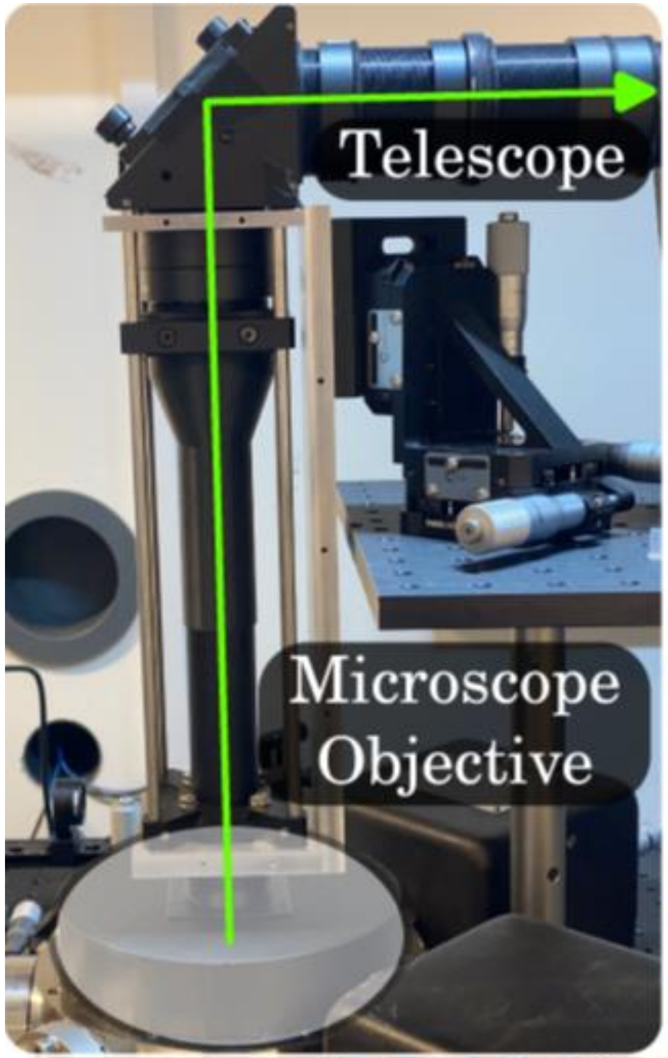
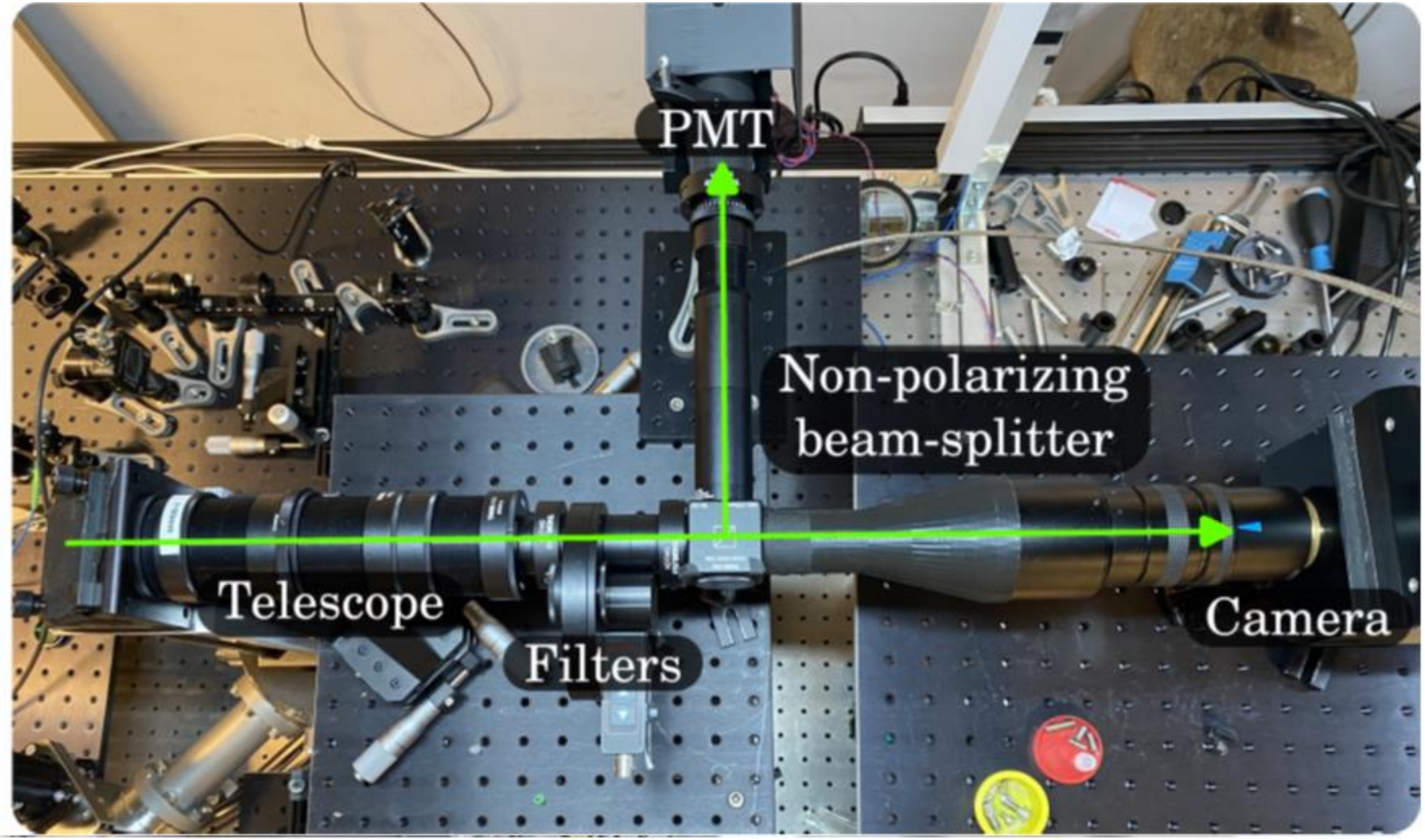
Laser systems



Vacuum chamber + imaging system



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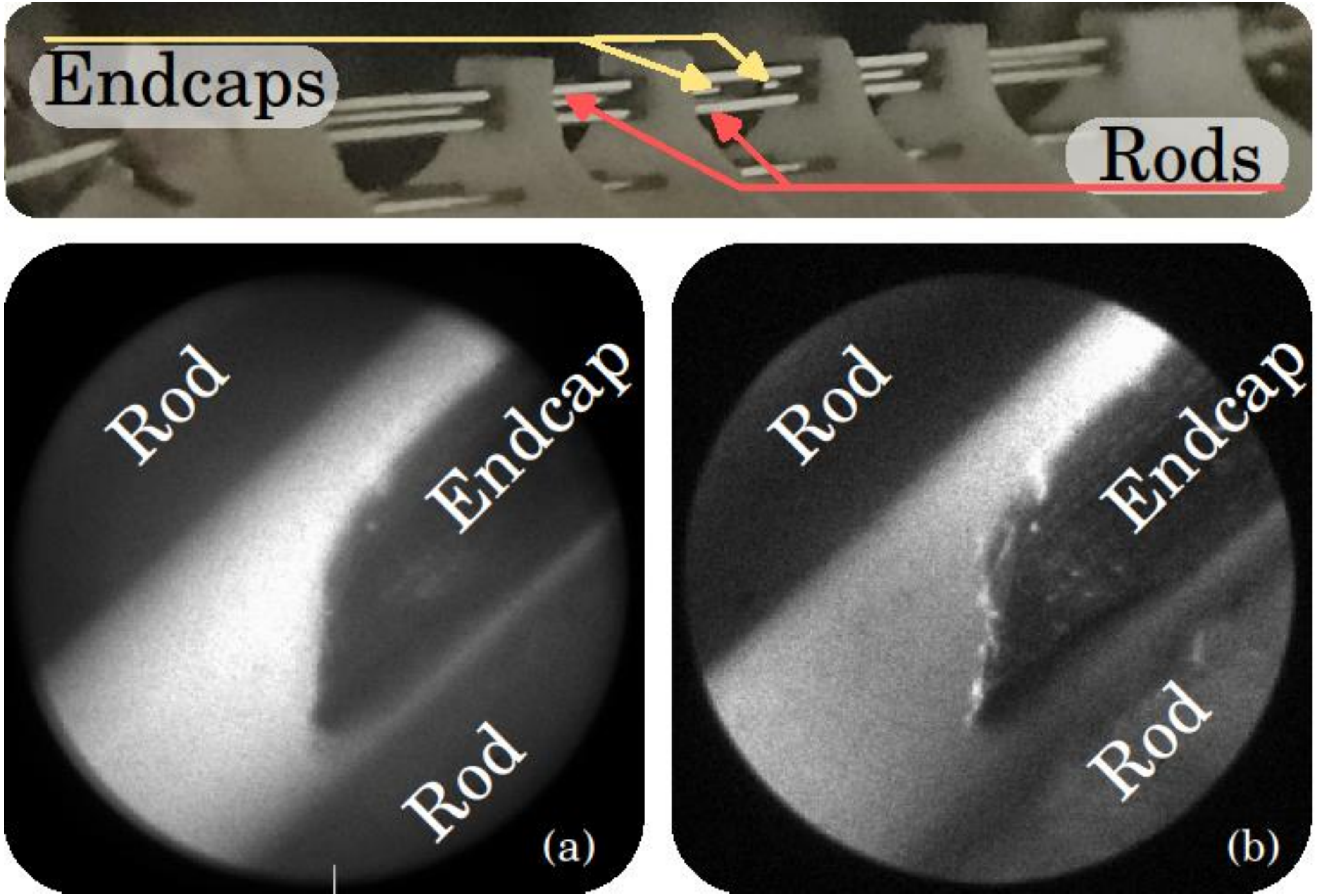
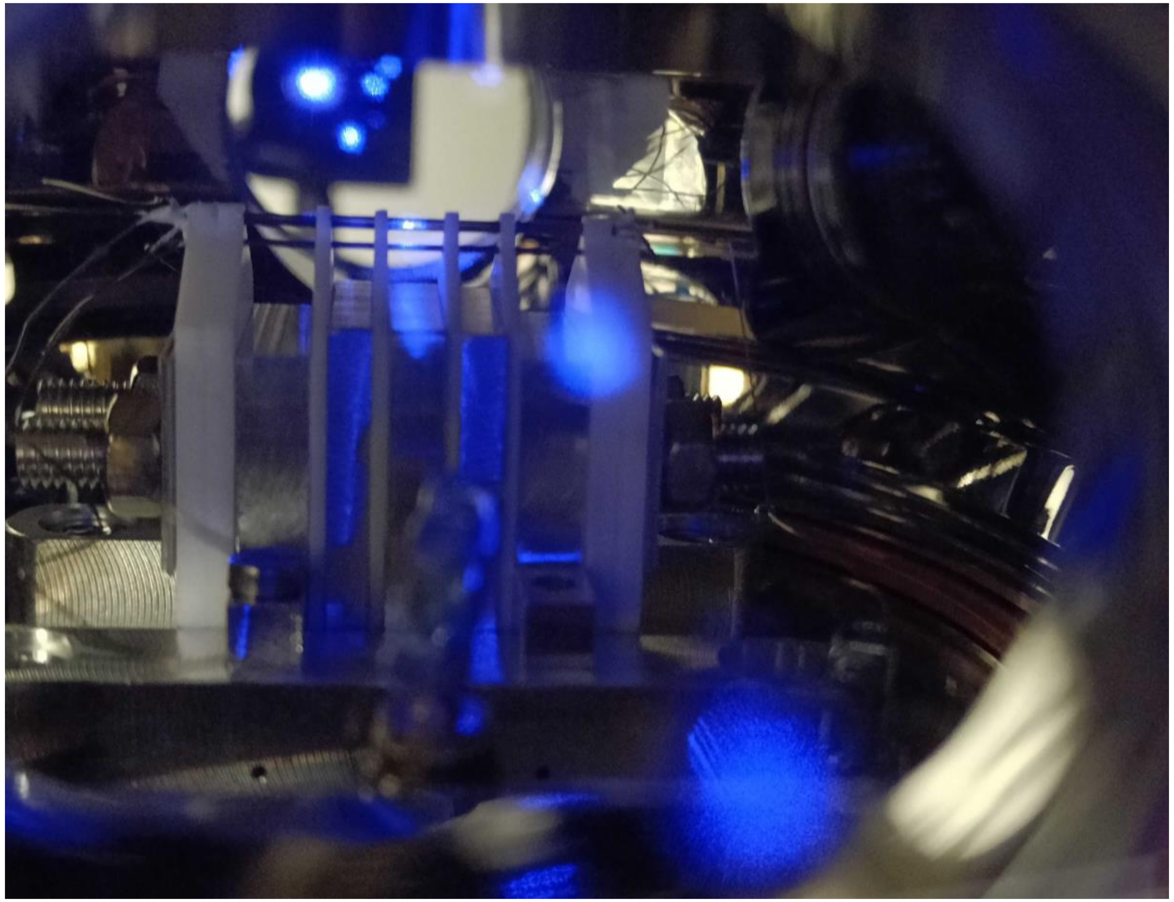
Laser systems

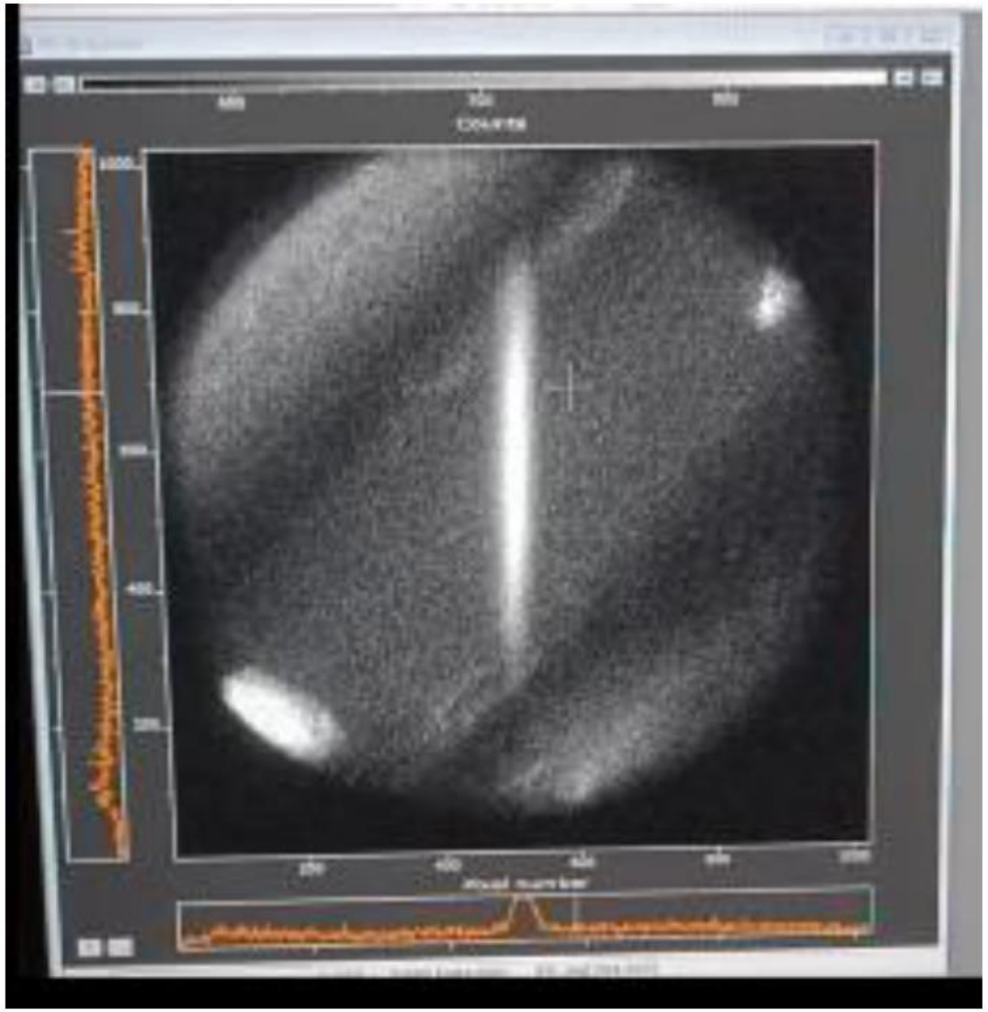
Vacuum chamber + imaging system



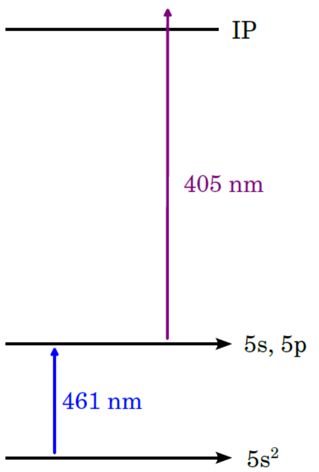
Precision trap @KUL

Fluorescence of **atoms** (not yet ions)
= test of atom source, lasers, detection and realtime imaging setup

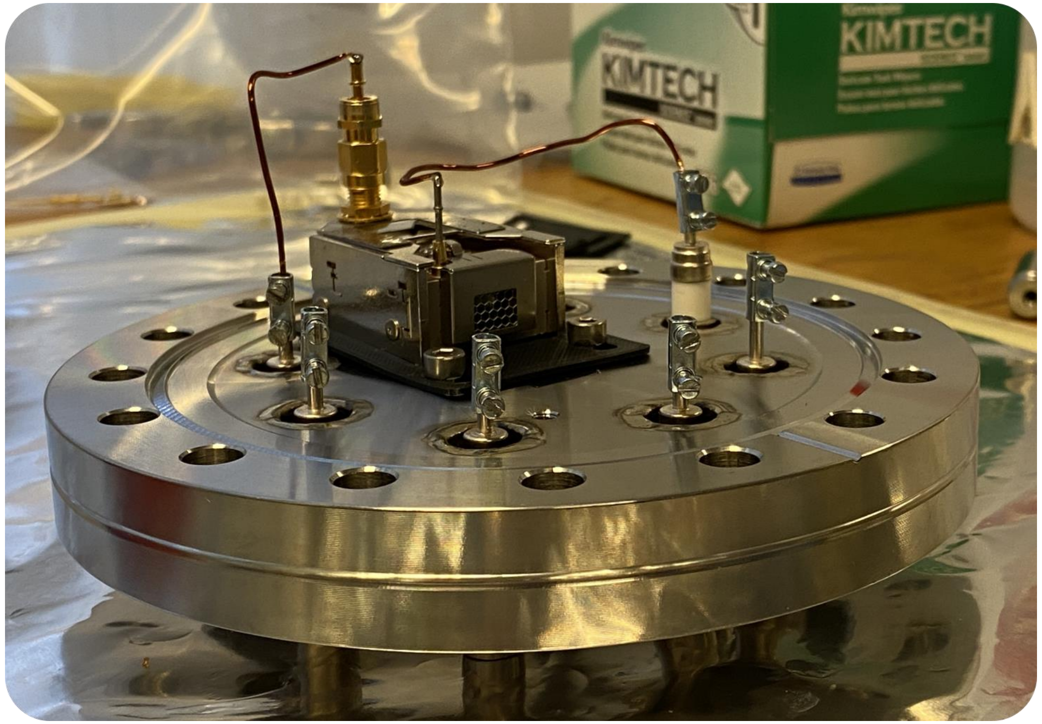


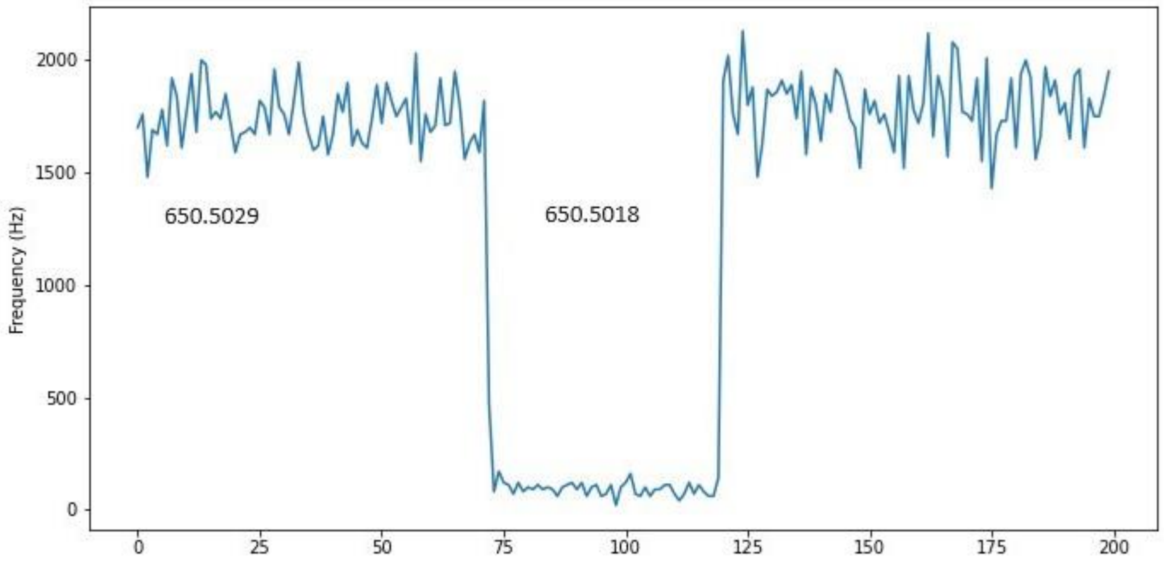


Precision trap @KUL



The ionizing laser set is tested to ensure we make ion to trap. For this we put an ion detector (magneTOF) inside the vacuum chamber

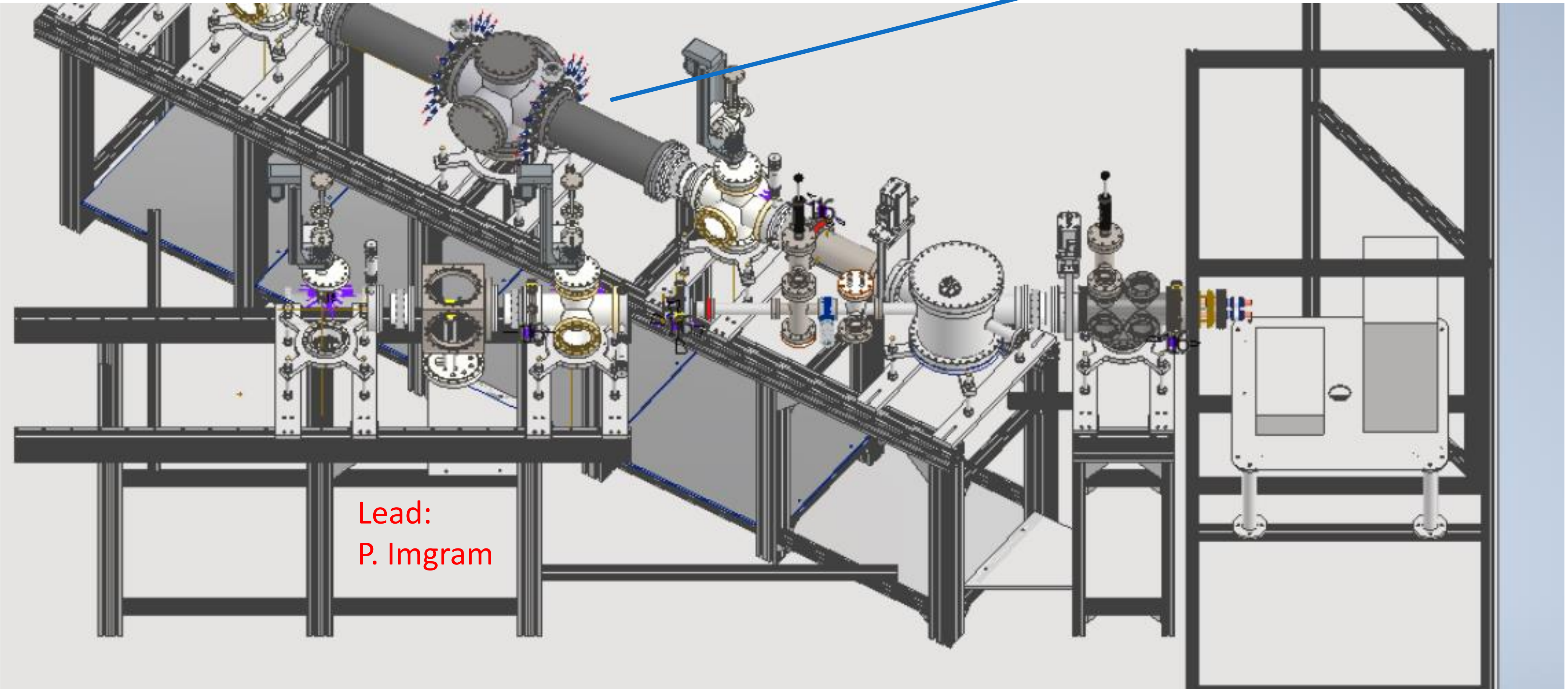




Fast-ions trap

Catching and cooling ~10 keV ions @ KUL

MR-TOF + REBEL (PI: Agi Koszorus)



Beamline construction

Empty Beamline

Beamline construction

Empty Beamline

Lead:
P. Imgram→

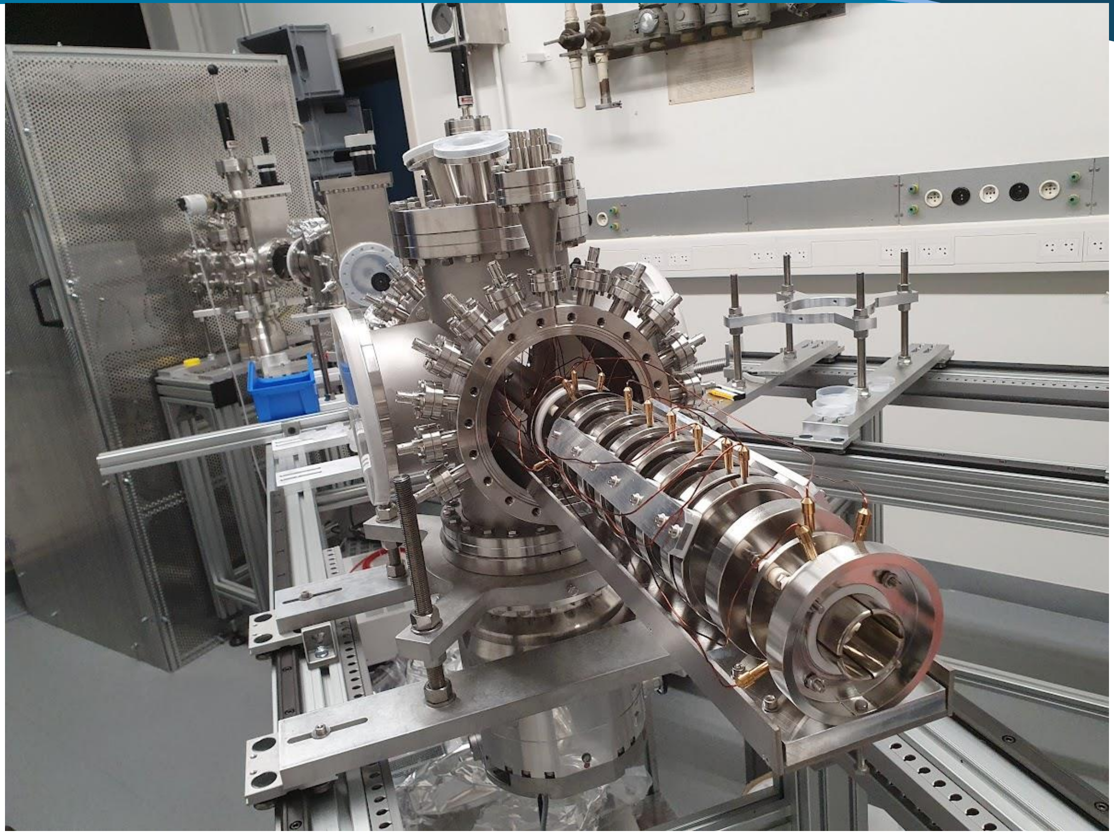
Beamline construction

Faraday cup

Lead:
P. Imgram→

Beamline construction

Faraday cup



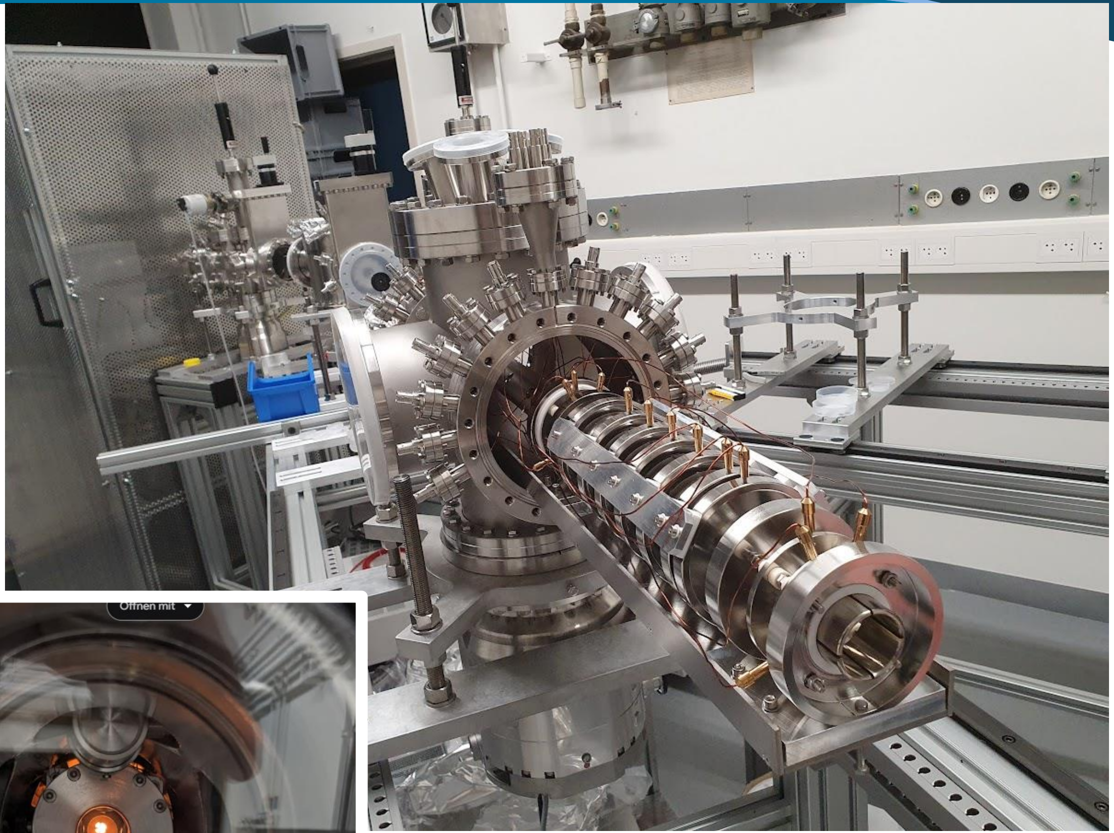
MR-ToF

Lead:
P. Imgram→

Beamline construction


Empty Beamline


Faraday cup


MR-ToF

Ion Source

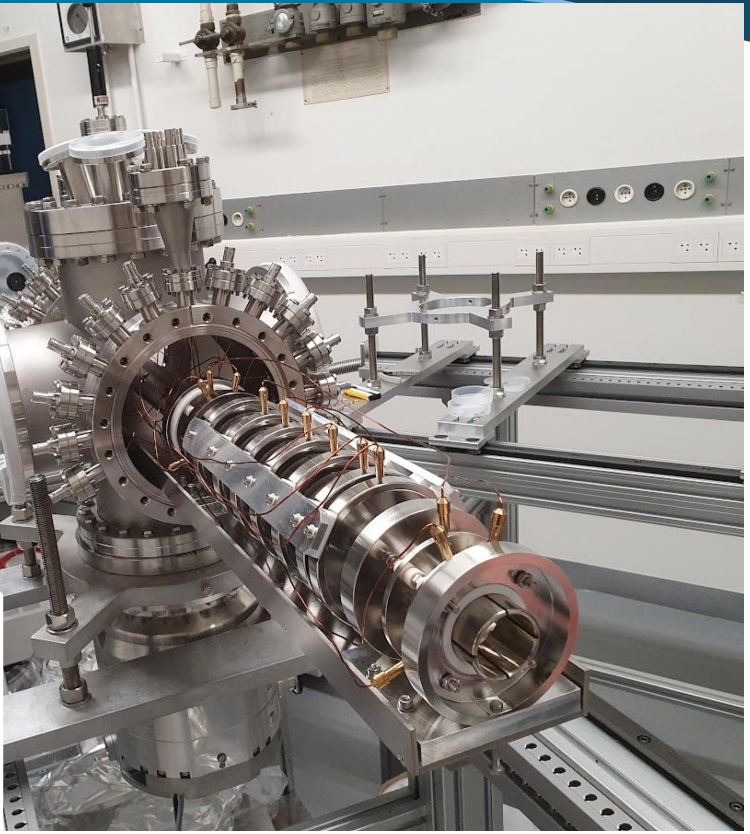
Lead:
P. Imgram→

Beamline construction

~~Empty~~ Beamline

Ion Source

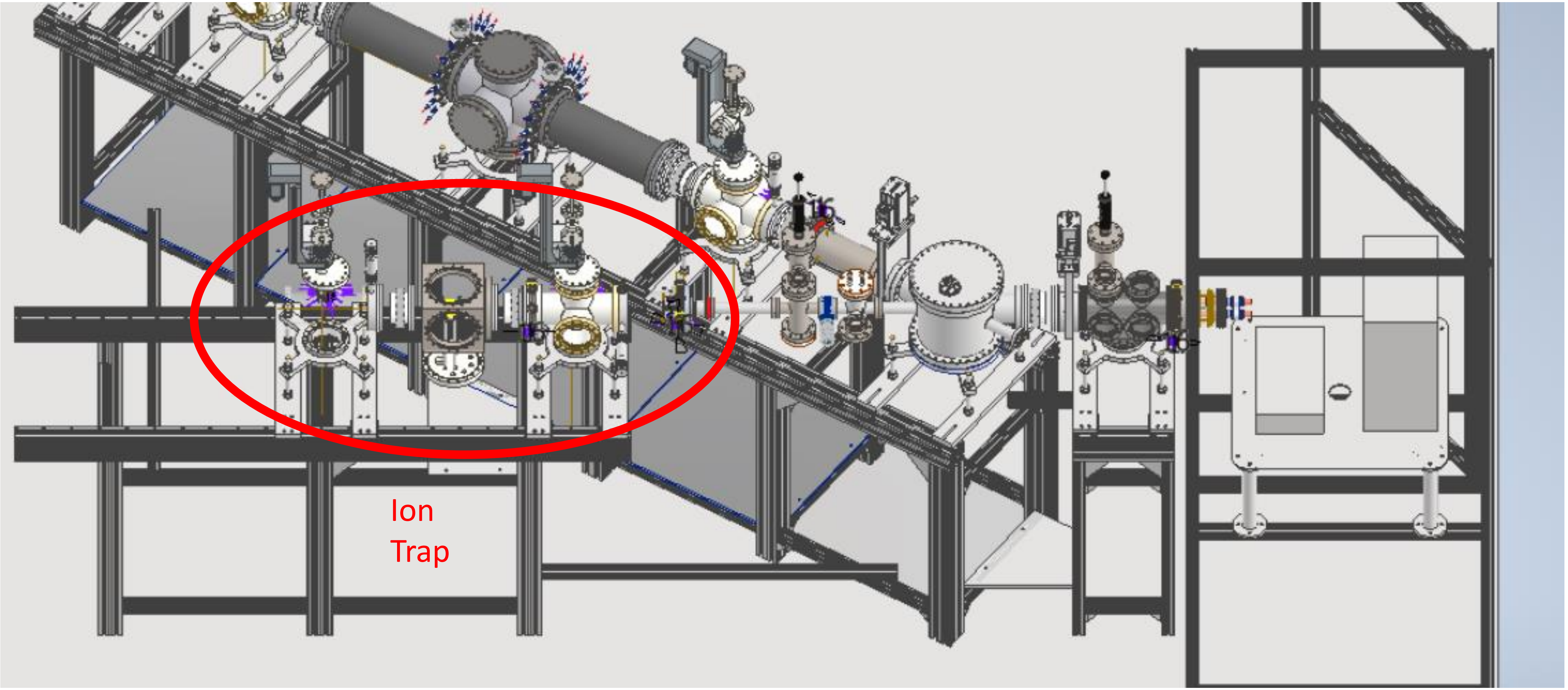
Faraday cup



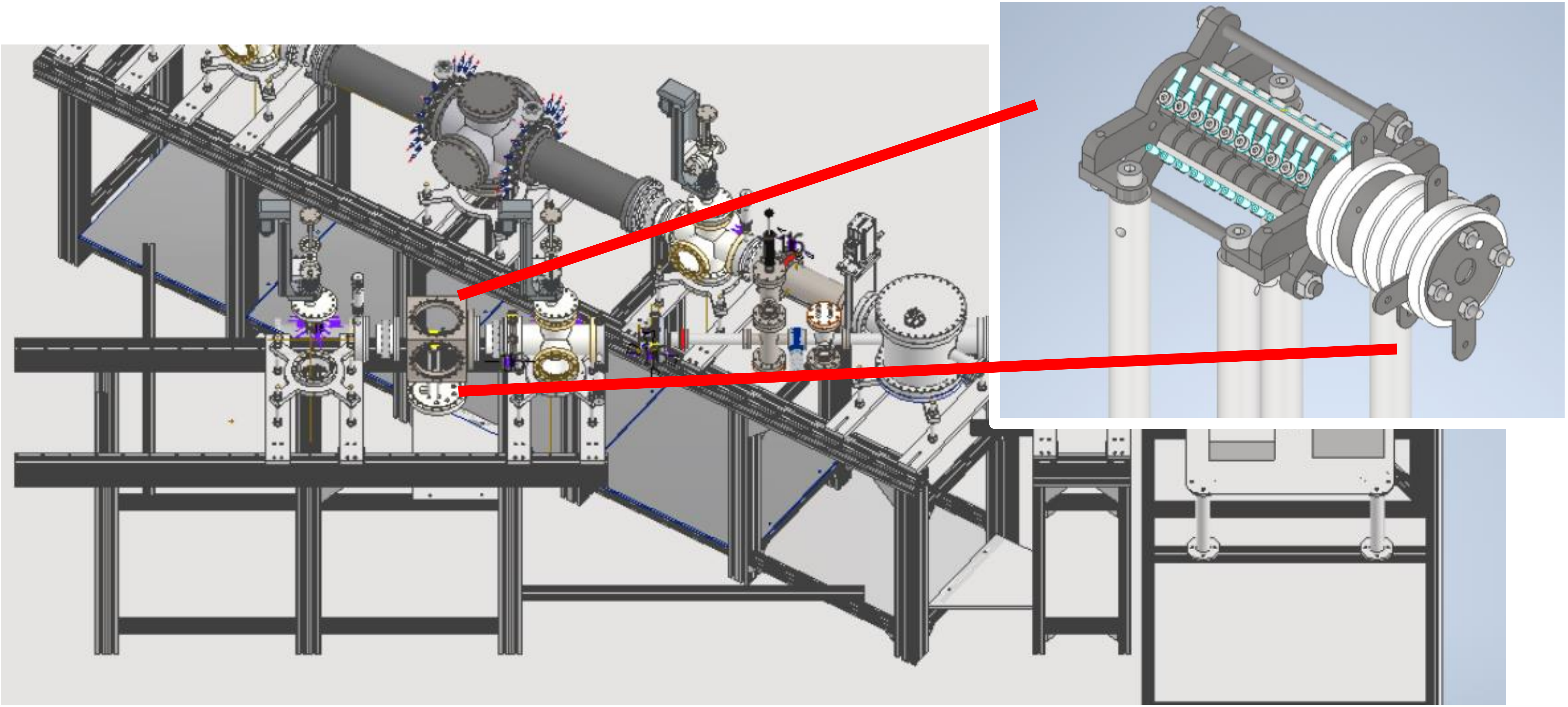
MR-ToF

Lead:
P. Imgram→

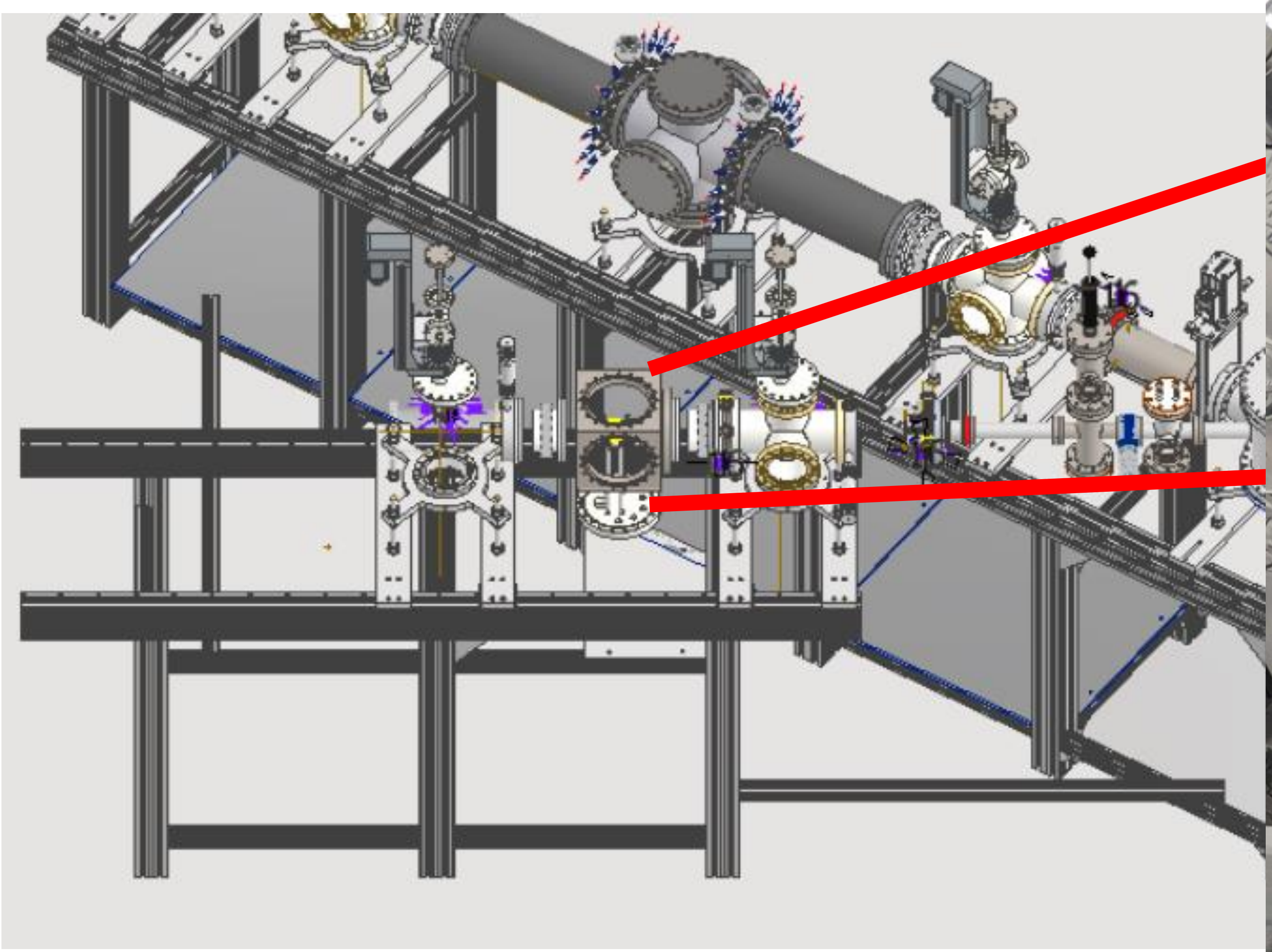
Catching and cooling ~10 keV ions @ KUL

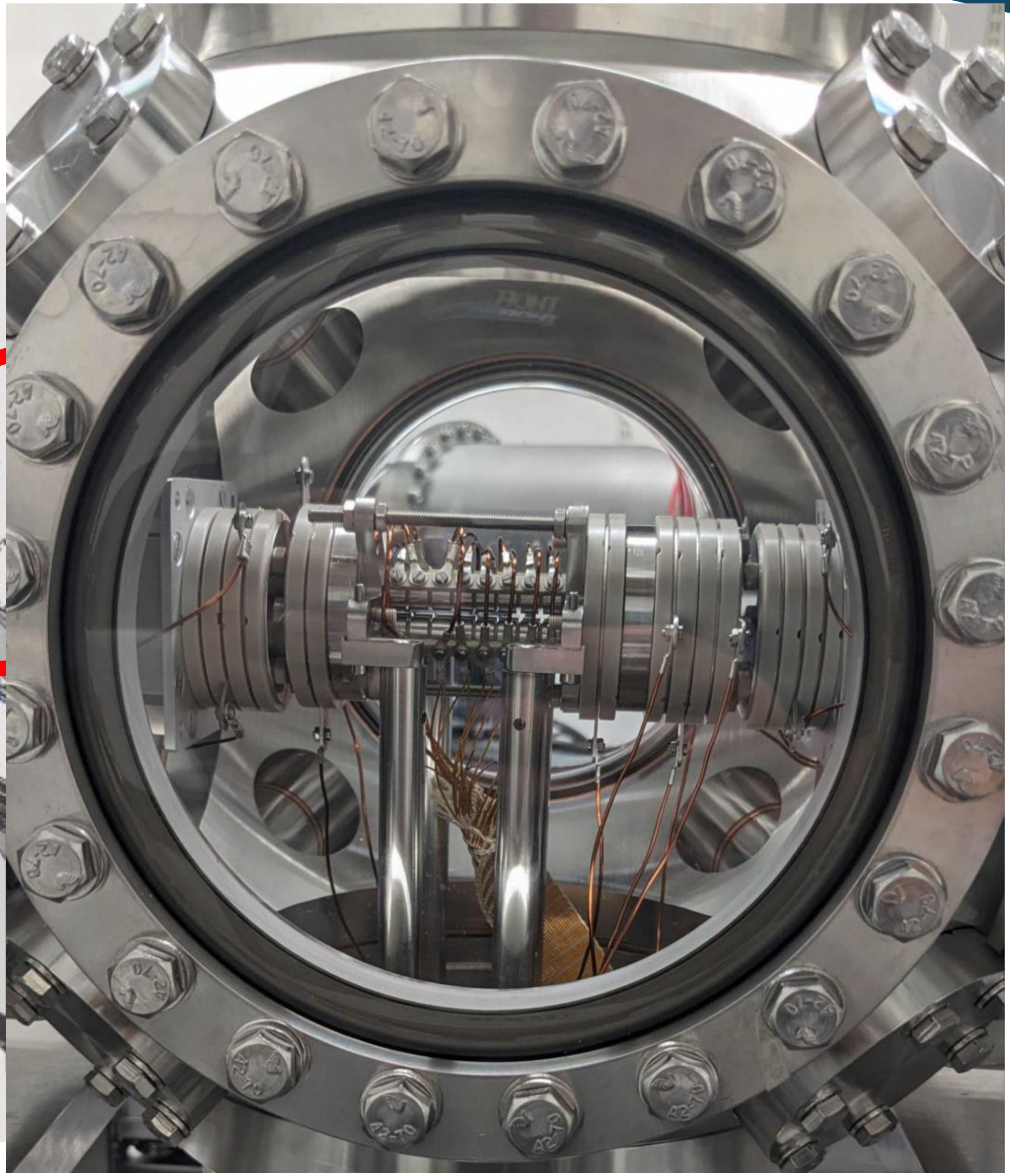


Catching and cooling ~10 keV ions @ KUL



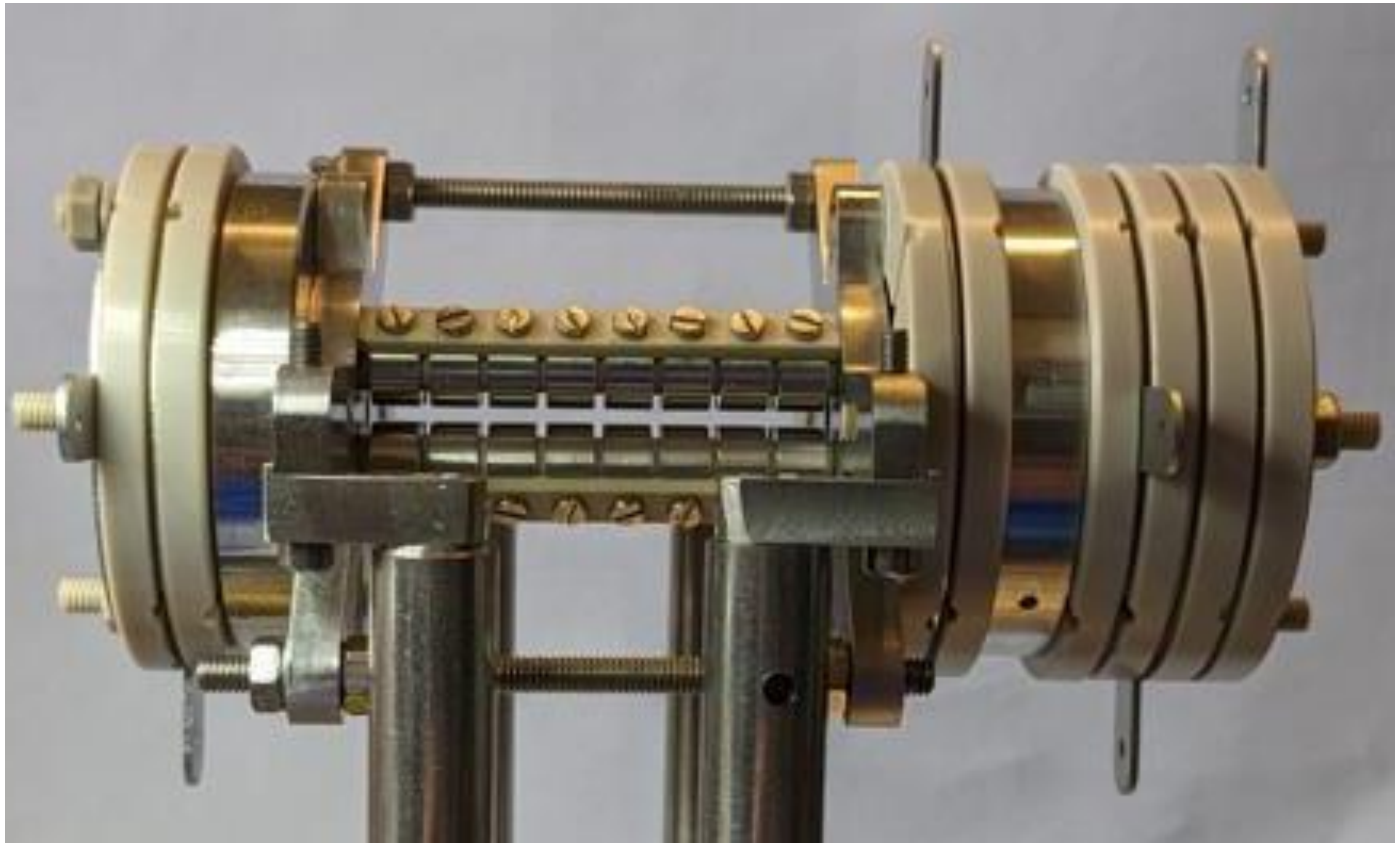
Catching and cooling ~10 keV ions @ KUL





Segmented trap

PhD Student :
S. Pelonis



Final design of the Decelerator and Trap :

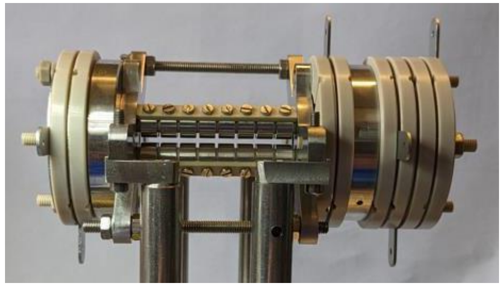
•2 injection deceleration segments

•An Einzel lens for additional focusing

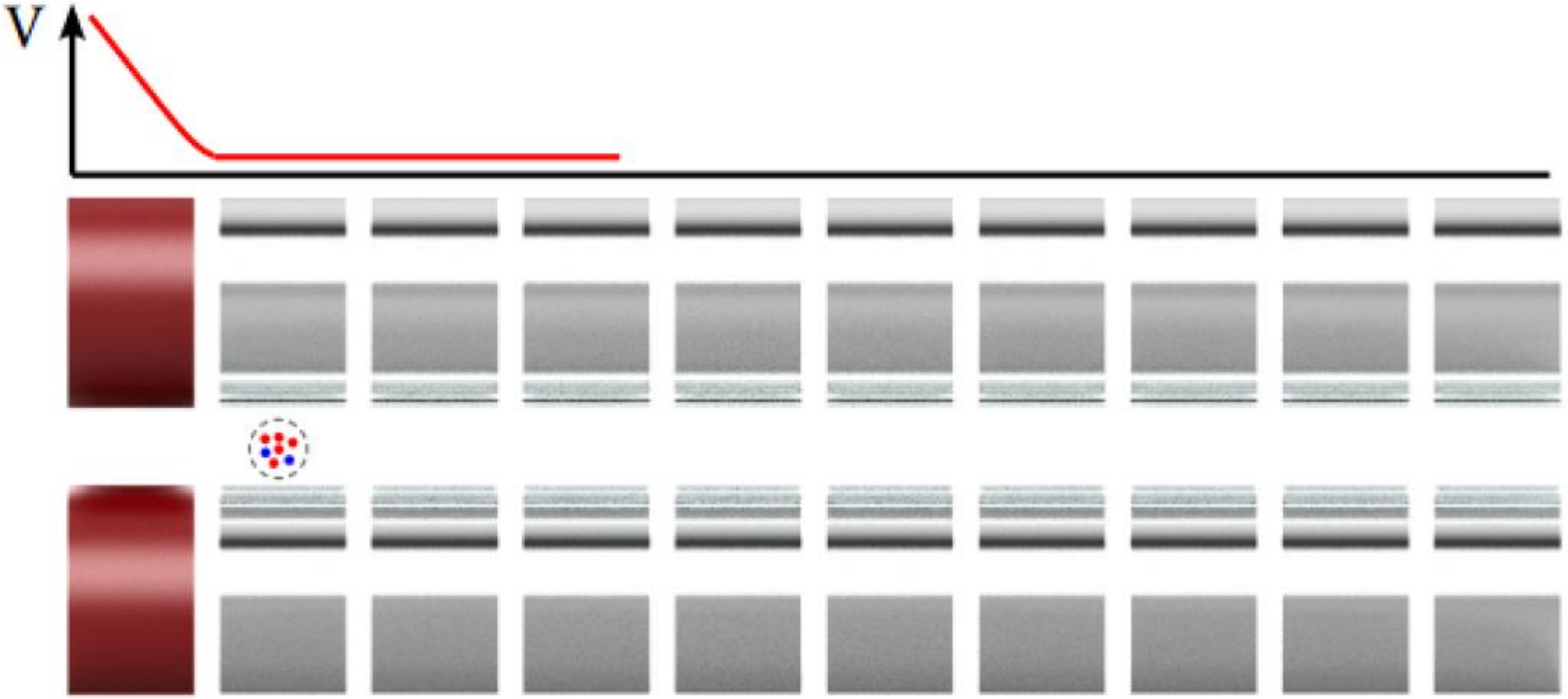
•The trap made of 8 pairs of segmented electrodes

•A set of extraction optics

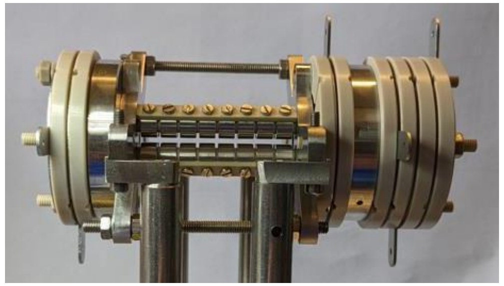
Segmented linear Paul trap with an increasing DC field along its z-axis



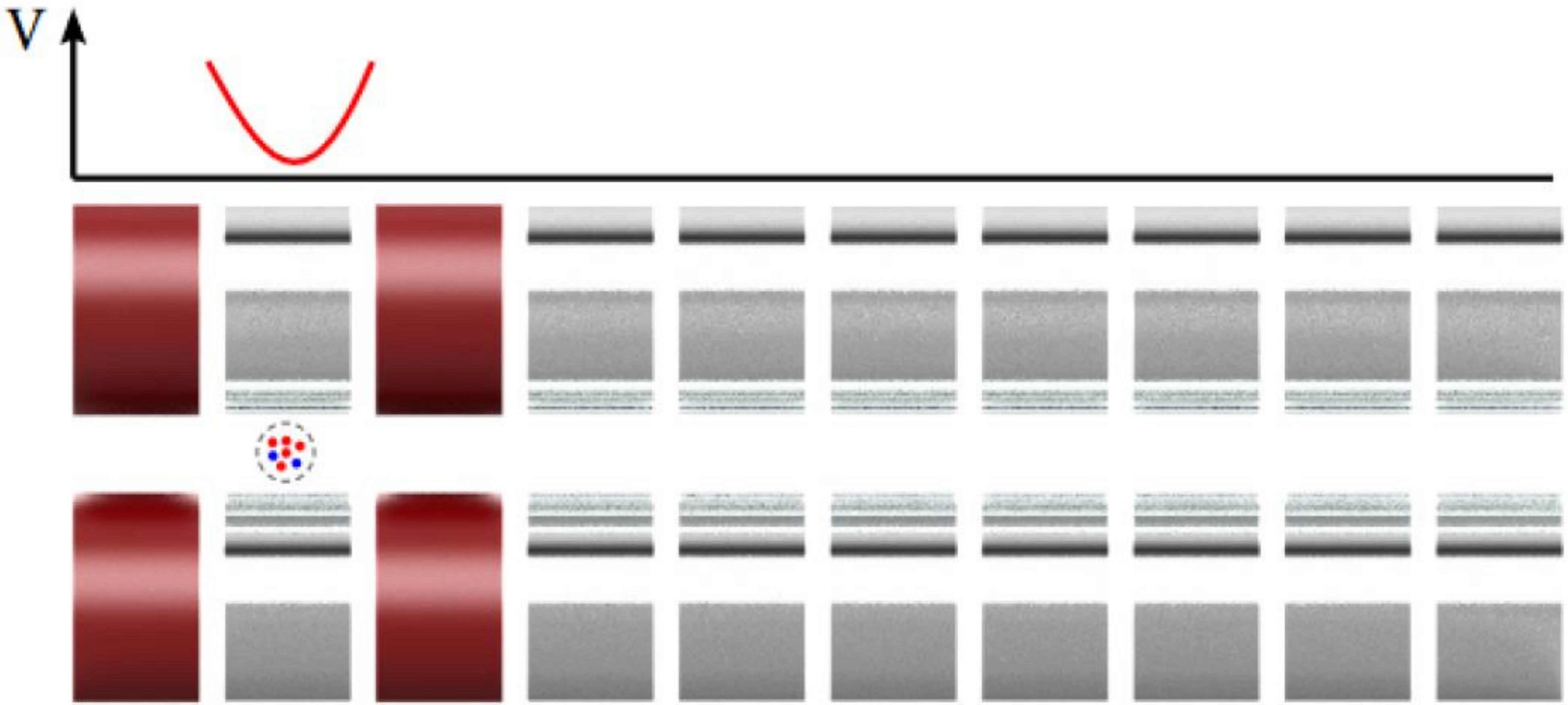
Final design of the Trap



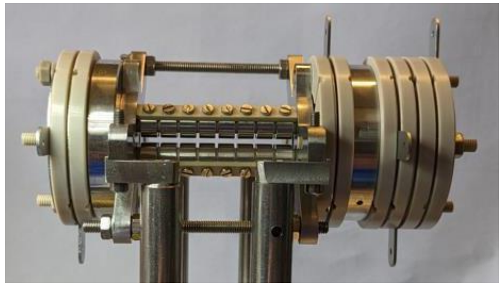
Segmented linear Paul trap with an increasing DC field along its z-axis



Final design of the Trap

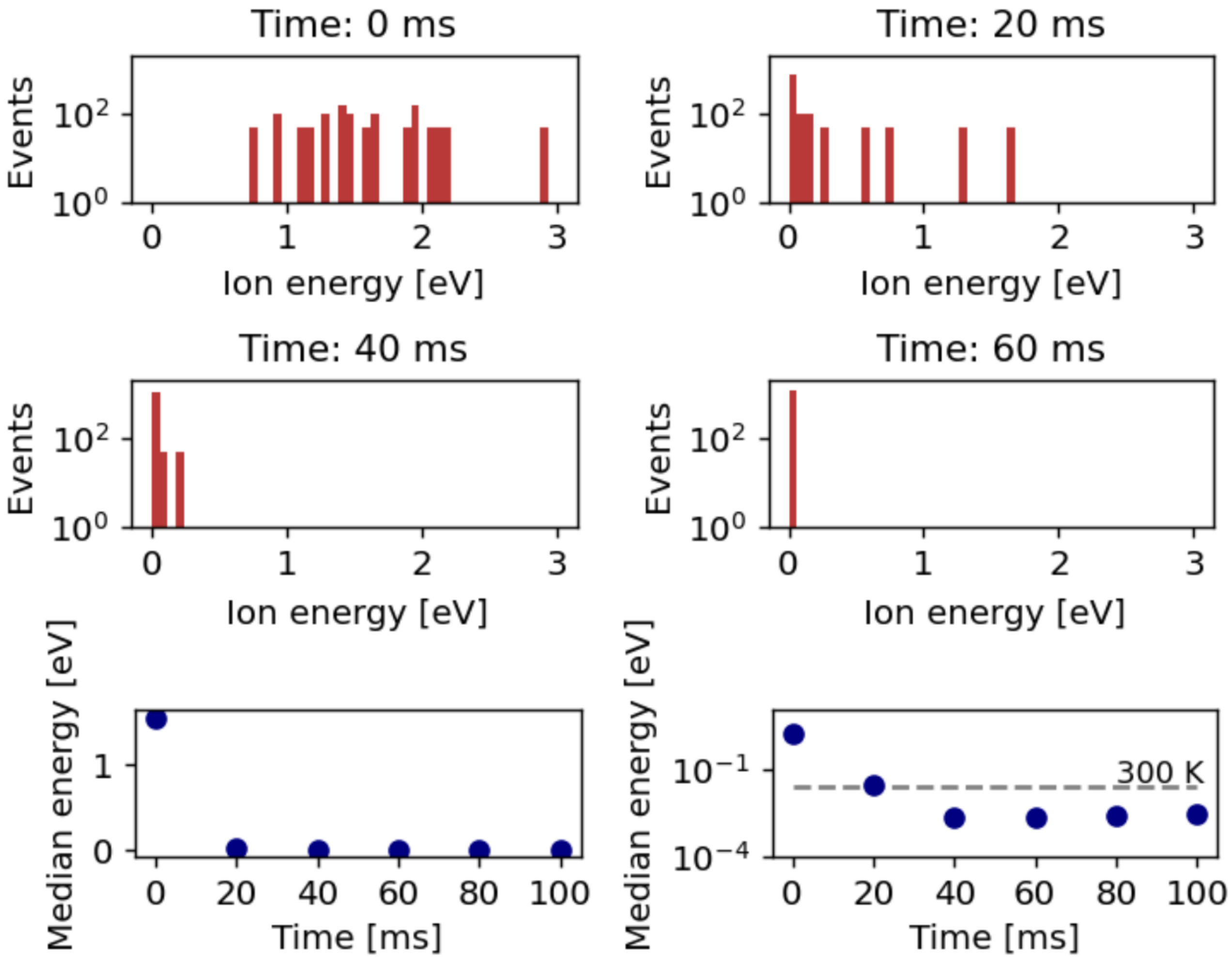


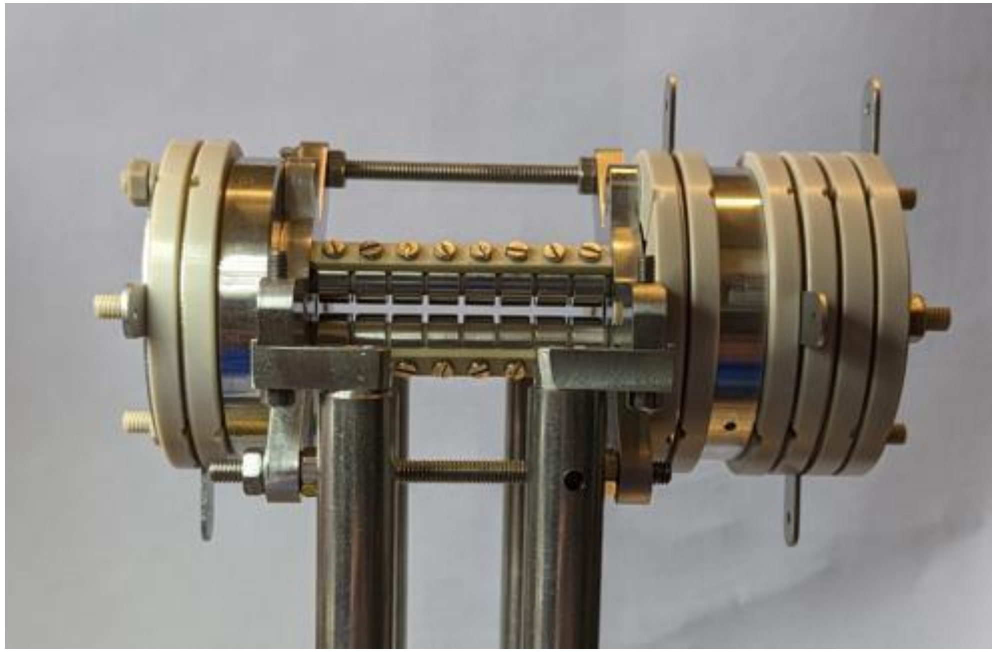
Segmented linear Paul trap with an increasing DC field along its z-axis



Final design of the Trap

Simulation: laser cooling in <100 ms with 10 kV initial beam energy





^{83}Sr	^{84}Sr	^{85}Sr	^{86}Sr	^{87}Sr	^{88}Sr	^{89}Sr	^{90}Sr	^{91}Sr	^{92}Sr	^{93}Sr
32,41h		64d				50d	28y	9,6h	2,6h	7,4m

Conclusion

- Objective is to provide data on unexplored properties of radioactive isotopes, to probe the **distribution of neutrons** within the nucleus, to study fundamental **properties of nucleons** within the nuclear medium, and their internucleon forces.
- New methodology which relies on the **measurement of magnetic octupole** moments, never measured before for any radioactive species
- Experimental setups are in construction and progressing fast

Acknowledgement

Thank you

A. Candiello

J.Grondin

S. Pelonis

P. Imgram

R. De Groote

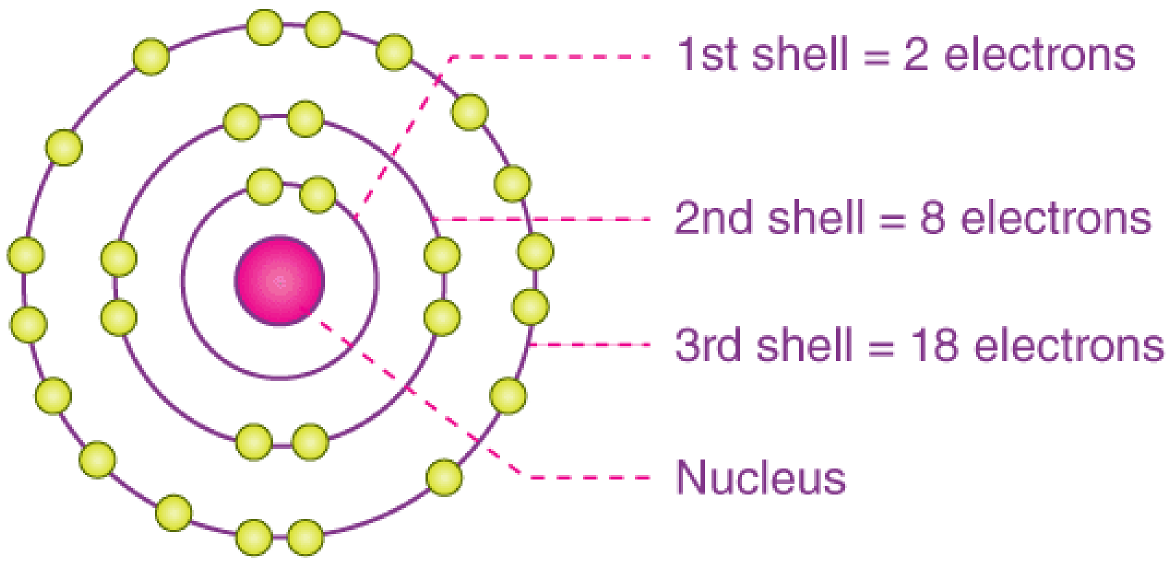
KU LEUVEN

Questions ?

Supp material

Shell model

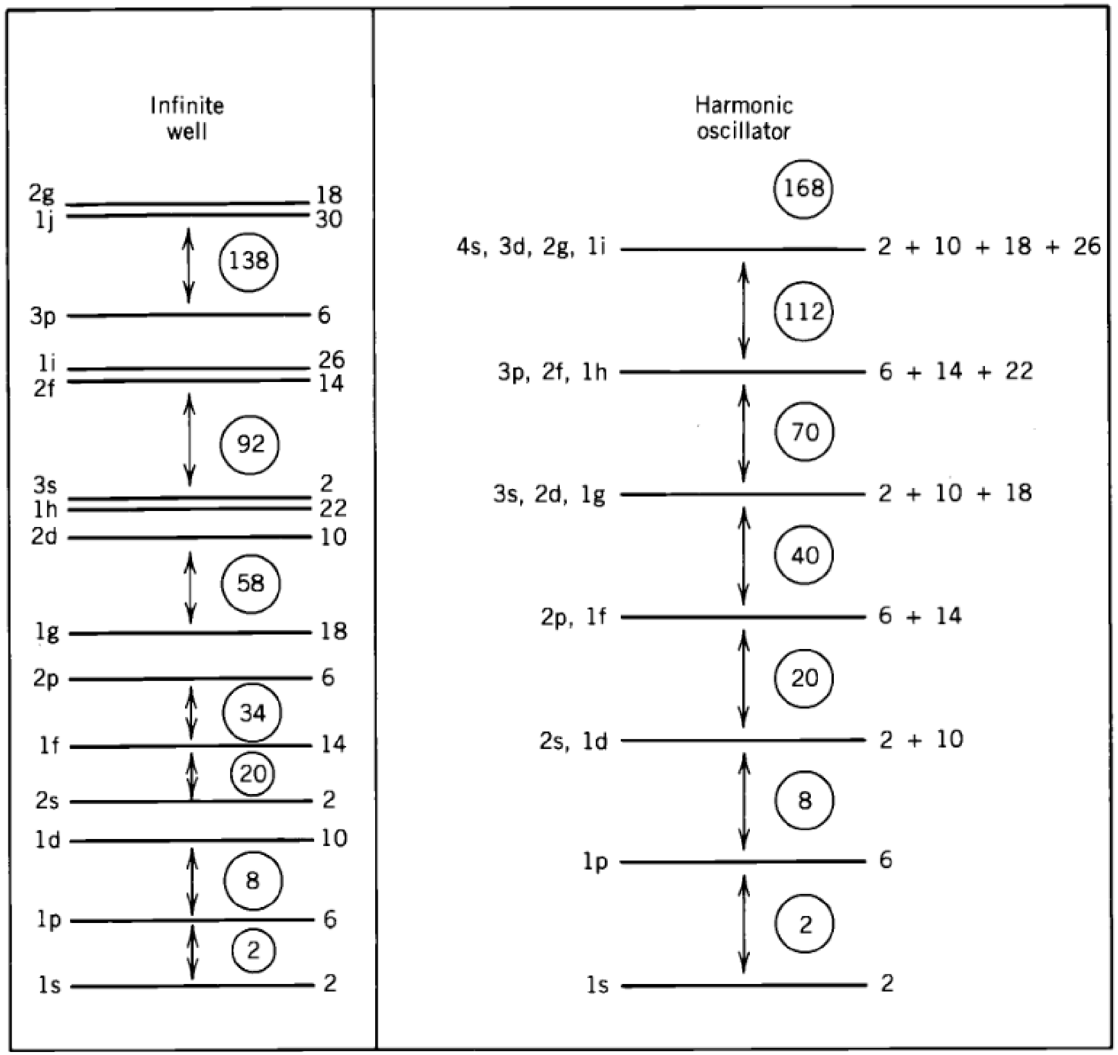
Atomic Shell Model



https://byjus.com/physics/shell-model/

magic quantum numbers of nucleons (**2, 8, 20, 28, 50, 82, and 126**) that are more tightly bound.

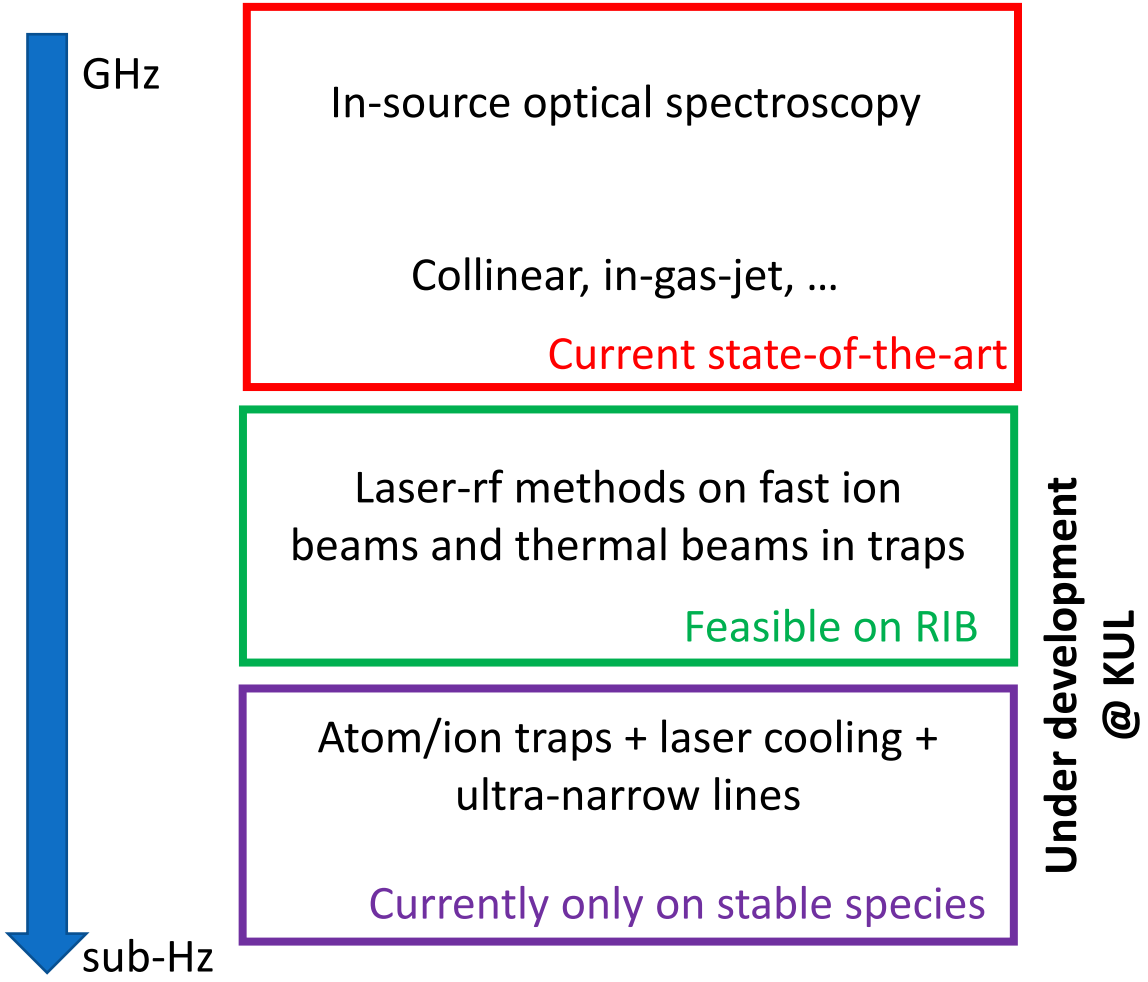
Nuclear Shell Model



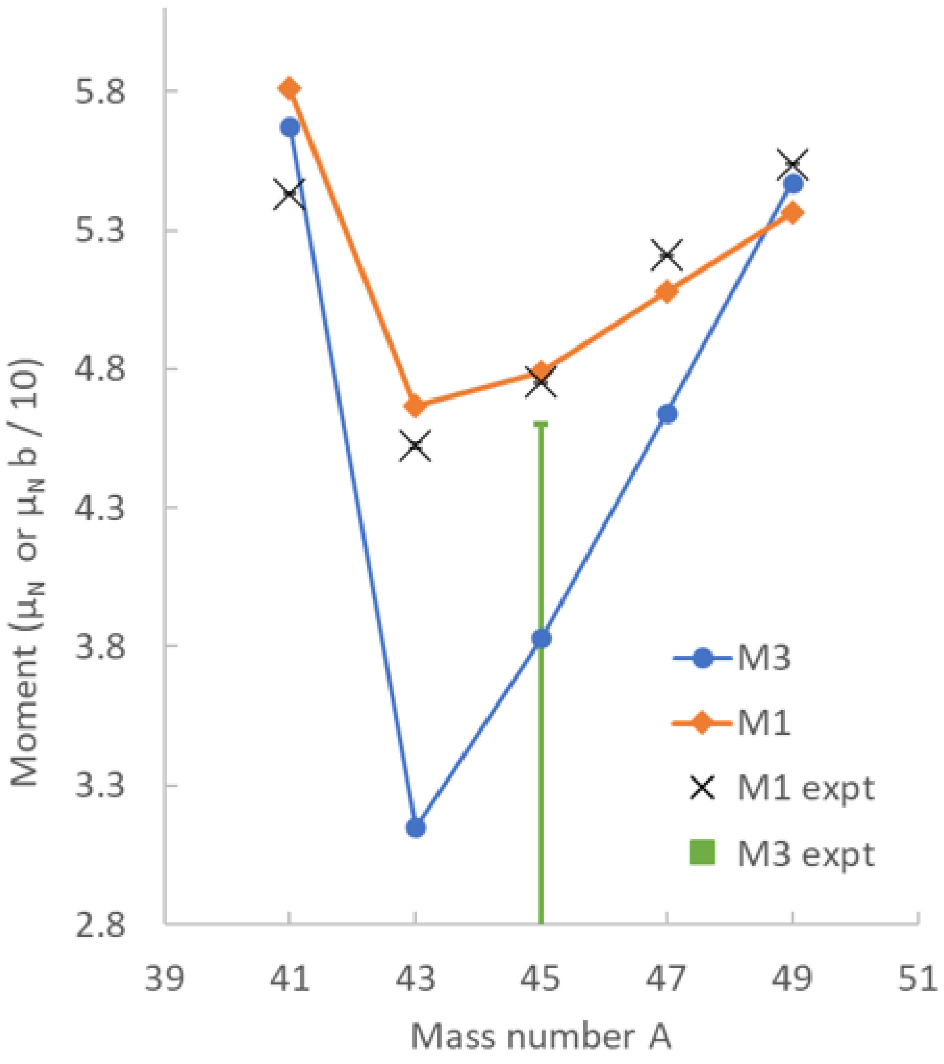
Krane, Kenneth S. *Introductory nuclear physics*. Rev. ed. of *Introductory nuclear physics*/David Halliday. 2nd. ed. 1955.

Precision frontier in RIB studies

- Magnetic dipole moments
- Electrical quadrupole moments and charge radii
  - provides a measure of the deformation and shape of the proton distribution of the nucleus
- Hyperfine anomaly
  - Relates to the distribution of magnetization inside nuclear volume
- Higher-order moments
  - **<u>Magnetic octupole</u>**, electric hexadecapole, …



Magnetic octupole moments: sensitive probe



Shell model calculations for Sc isotopic chain between *N*=20-28 [*C. Yuan*]

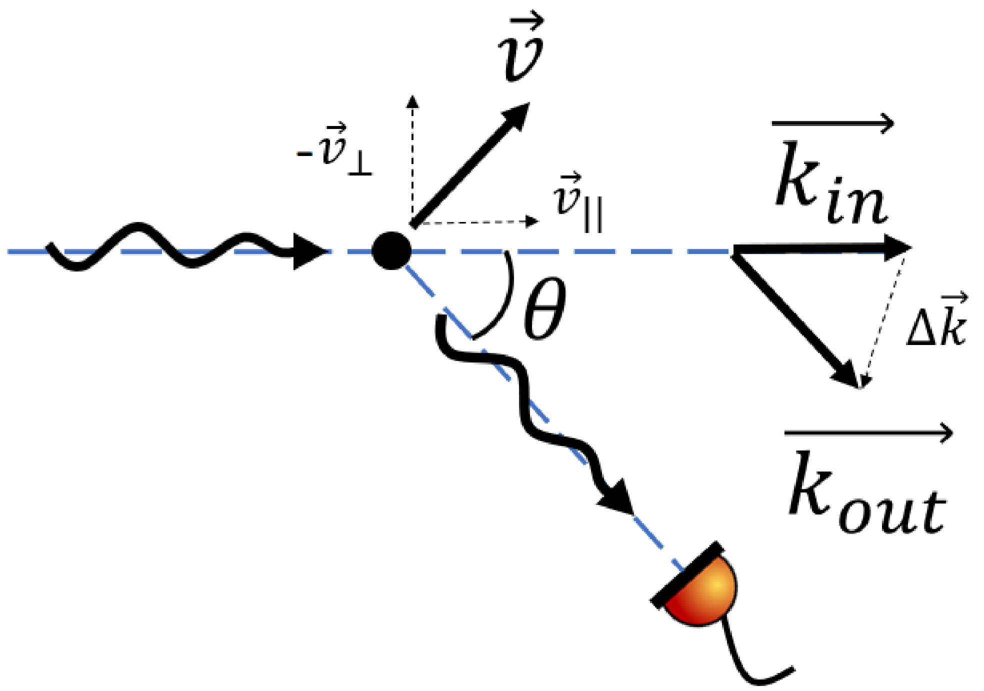
- Magnetic octupole moments display strong shell effects, stronger the dipole moments. calculated in Scandium (Z=21)

- The predicted value of $\Omega(^{43}Sc)$ is only about 50% of $\Omega(^{41,49}Sc)$, in contrast to a drop of only 20% for μ

Laser cooling

- Recoil temperature: $T_{min} = \frac{\hbar\Gamma}{2k_B}$
- Doppler broadening:

$$\delta\omega(\theta) = k\sqrt{2(1-\cos\theta)k_B T/M}$$



Objective

Measure the magnetic octupole moment of $^{83-93}$Sr. In doing so, probing the nuclear wavefunctions and magnetization of single-nucleon systems at the neutron shell N=50 (Sr).

Short term : Measurement on neutral Sr

Long term : Measurement on radioactive Sr

No Hyperfine structure

Why Strontium ?

Table 1: Transition characteristics for cooling for several Alkaline-earth ions (and Yb+)

Characteristics	Ca+	Sr+	Ba+	Yb+	Ra+
	$4S_{1/2} \rightarrow 4P_{1/2}$	$5S_{1/2} \rightarrow 5P_{1/2}$	$6S_{1/2} \rightarrow 6P_{1/2}$	$6S_{1/2} \rightarrow 6P_{1/2}$	$7S_{1/2} \rightarrow 7P_{1/2}$
Wavelenght λ (nm)	397	422	493,545	369,5	468,224
Excited state lifetime τ (ns)	6,9	7,39	7,855	8,1	9,4
Natural linewidth $\Gamma = \frac{1}{\tau}$ (MHz)	144	135	127	123	106,1
Doppler temperature T_{Dop}(μK)	547	513	482	467	403
Maximum deceleration $a_{max}(m \cdot s^{-2})$	$1,8 \cdot 10^6$	$7,2 \cdot 10^5$	$3,7 \cdot 10^5$	$3,82 \cdot 10^5$	$1,99 \cdot 10^5$
Optimum cooling velocity $v_c(m \cdot s^{-1})$	189	120	86	87,40	63,08
Saturation intensity I_{sat} (mW.cm^{-2})	47,6	37,2	21,9	50,6	21,5

Table 2: Transition wavelenght for repumping for several Alkaline-earth ions (and Yb+) previously cooled in an ion trap

Characteristics	Ca+	Sr+	Ba+	Yb+	Ra+
	$3D_{3/2} \rightarrow 4P_{1/2}$	$4D_{3/2} \rightarrow 5P_{1/2}$	$5D_{3/2} \rightarrow 6P_{1/2}$	$5D_{3/2} \rightarrow {}^3D[3/2]_{1/2}$	$6D_{3/2} \rightarrow 7P_{1/2}$
Wavelenght λ (nm)	866,214	1092	649,869	935	1078,796

Laser Scheme

Step 1 : Ionisation

Isotopic Abundance :

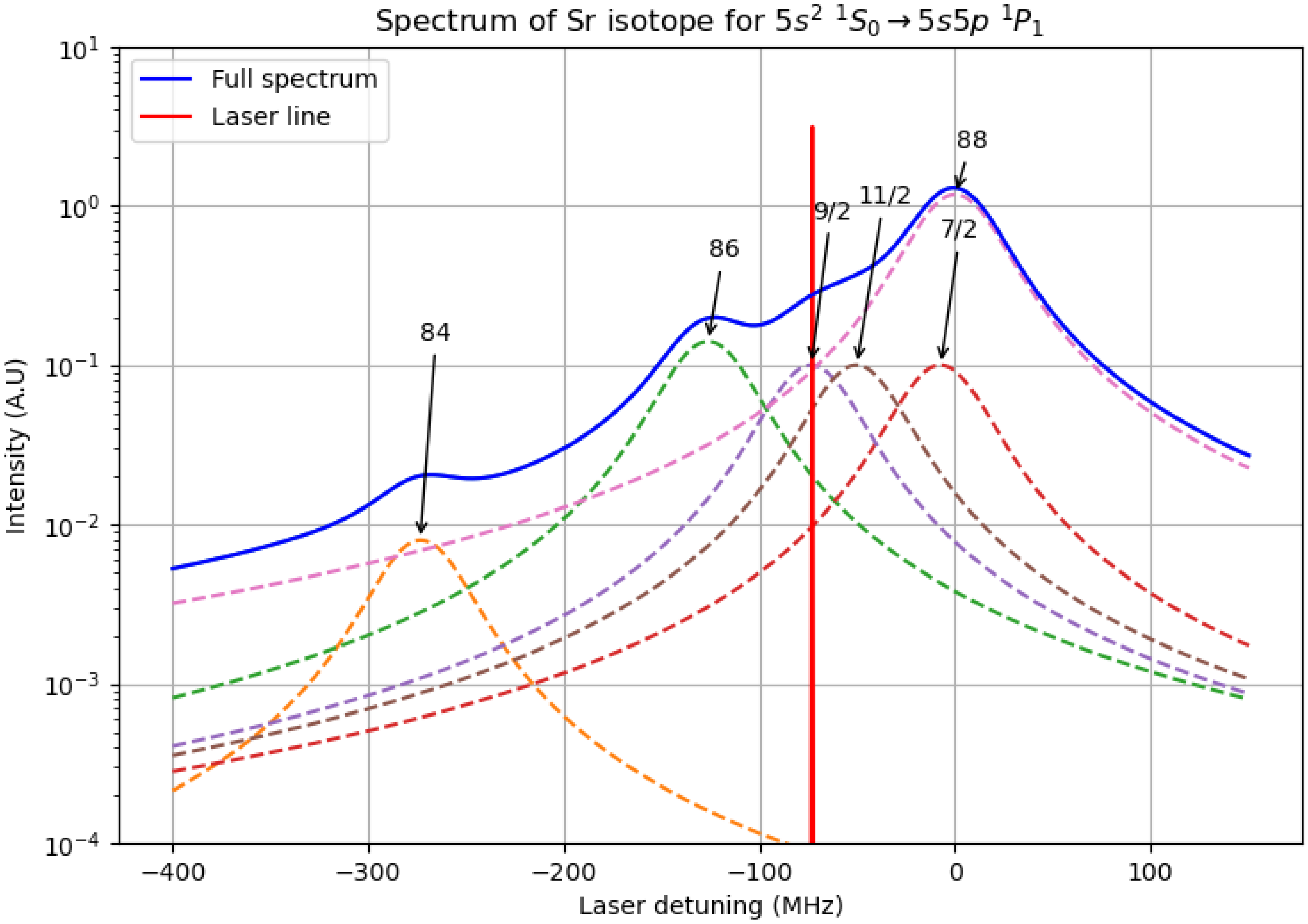
^{88}Sr : 82,6%

^{87}Sr : 7%

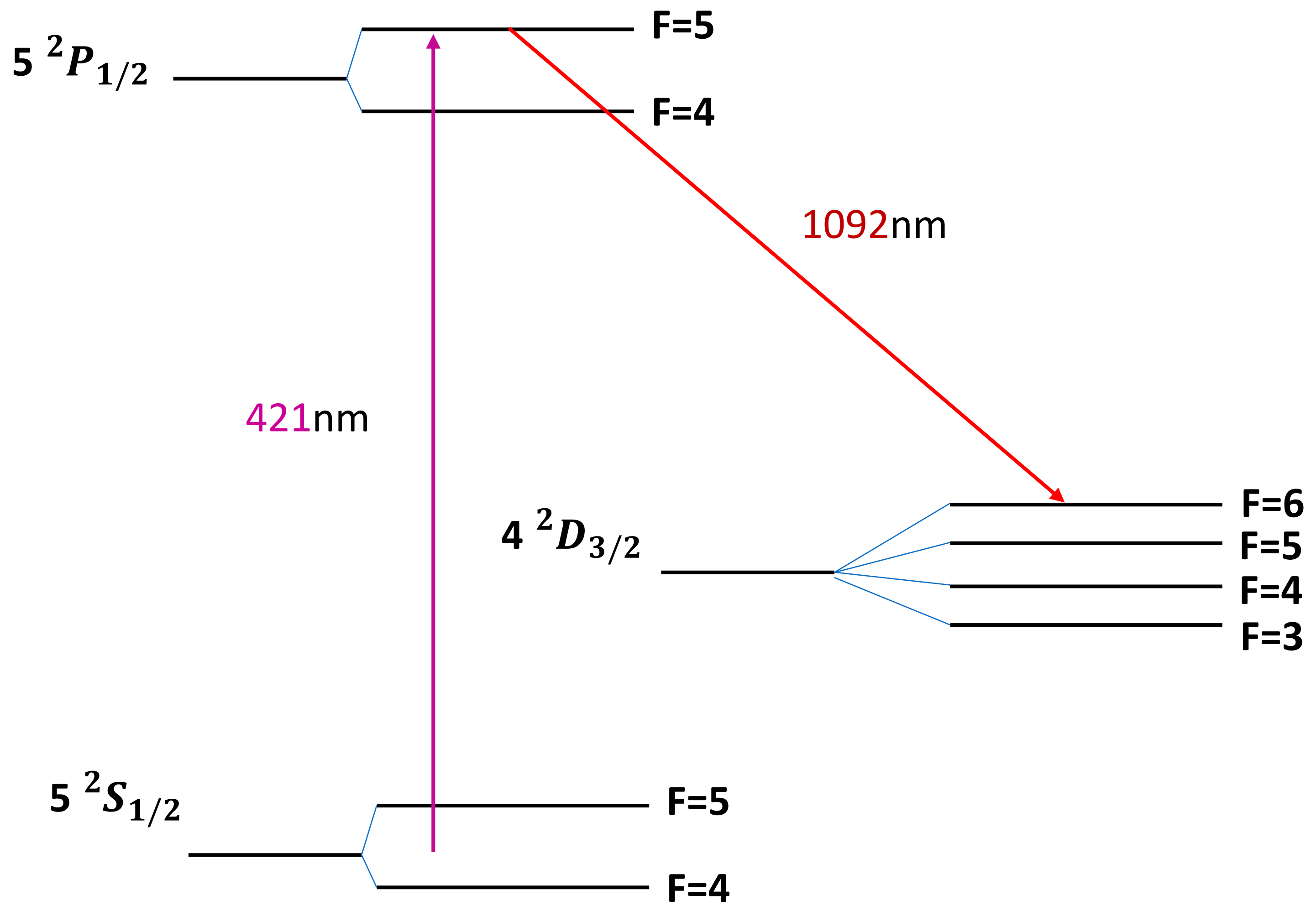
^{86}Sr : 9,6%

^{84}Sr : 0,57%

Best chance of getting ^{87}Sr for a shift of Δf=-72.97 MHz with a 59% probability to excite 87SR () for a laser of 300 kHz width.

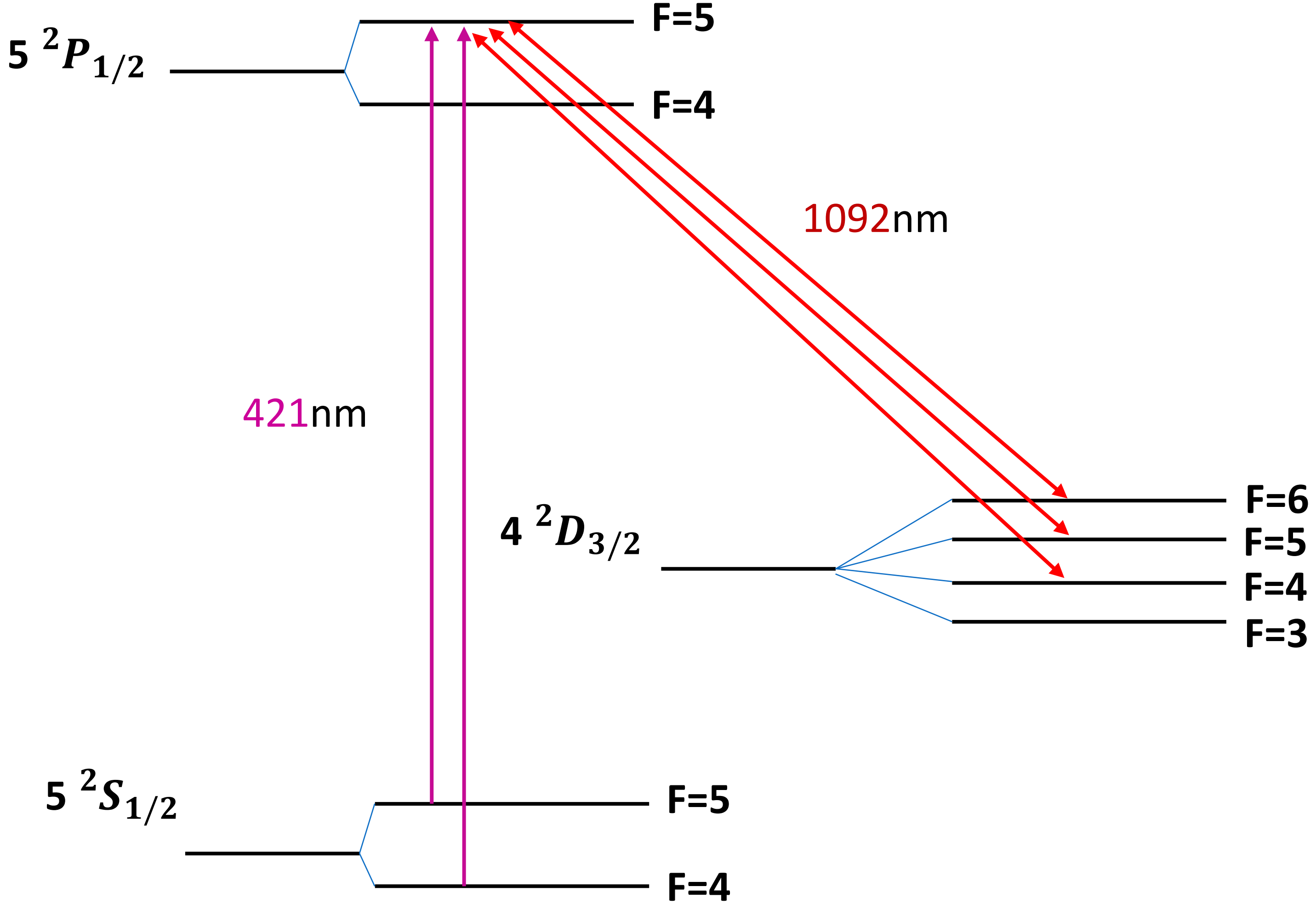


Laser Scheme



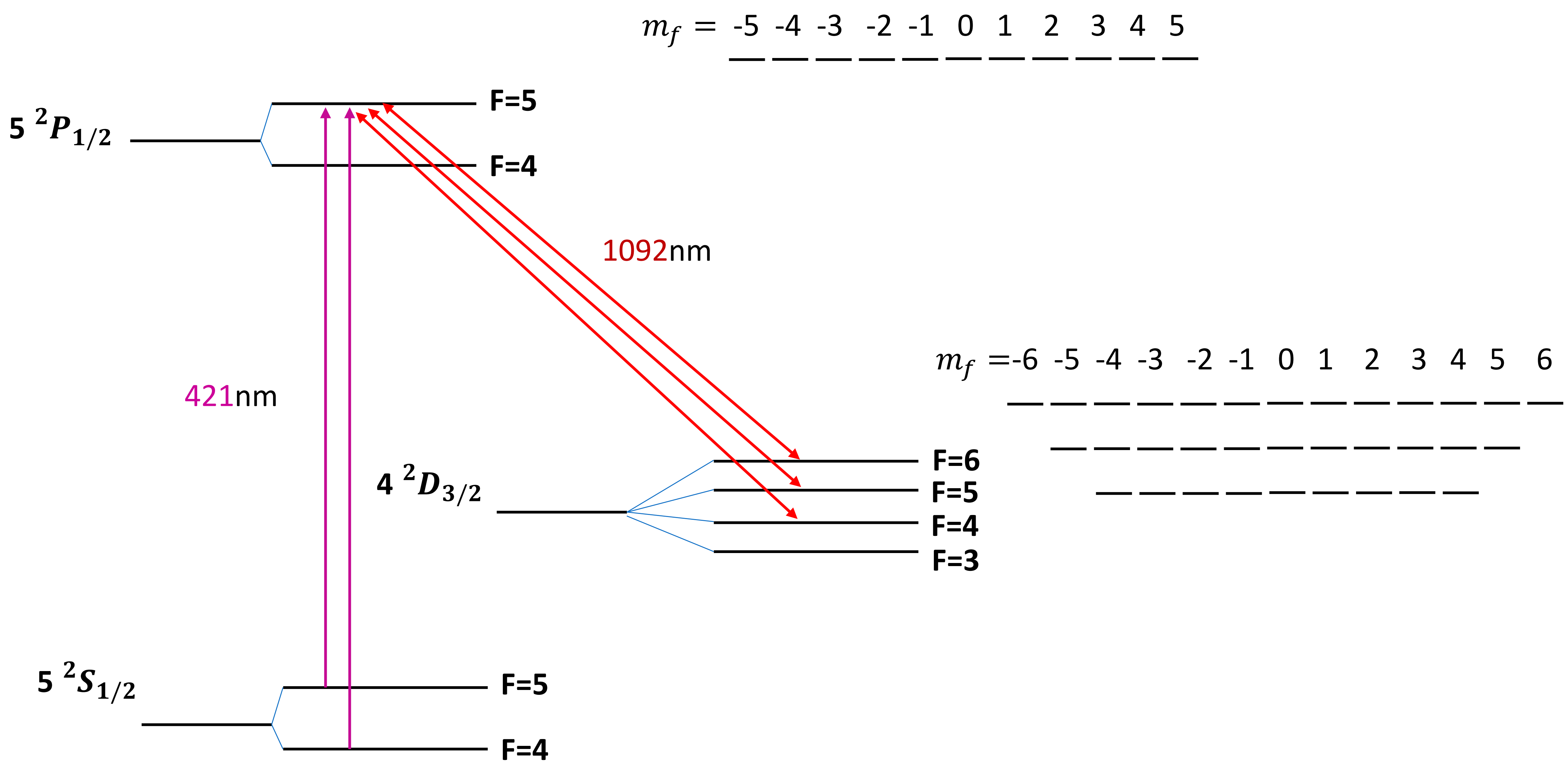
$^{87}Sr^{+}$ hyperfine structure

Laser Scheme



$^{87}Sr^{+}$ hyperfine structure

Laser Scheme



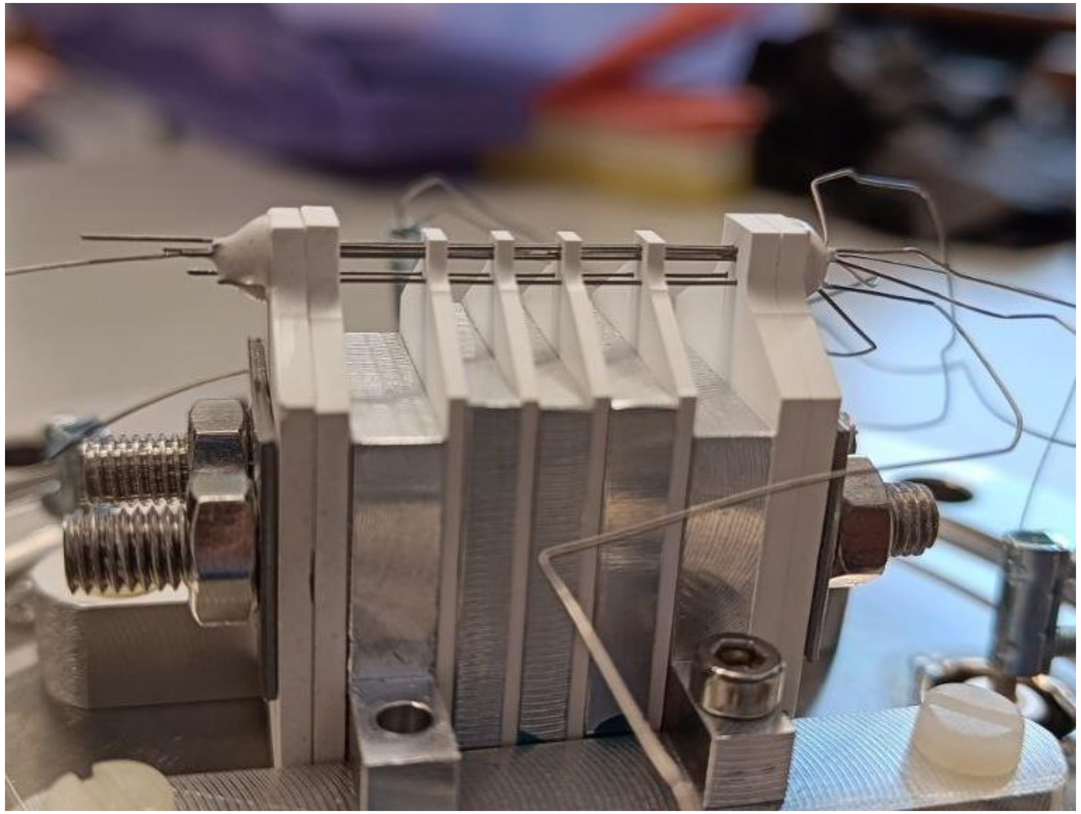
$^{87}Sr^+$ hyperfine structure

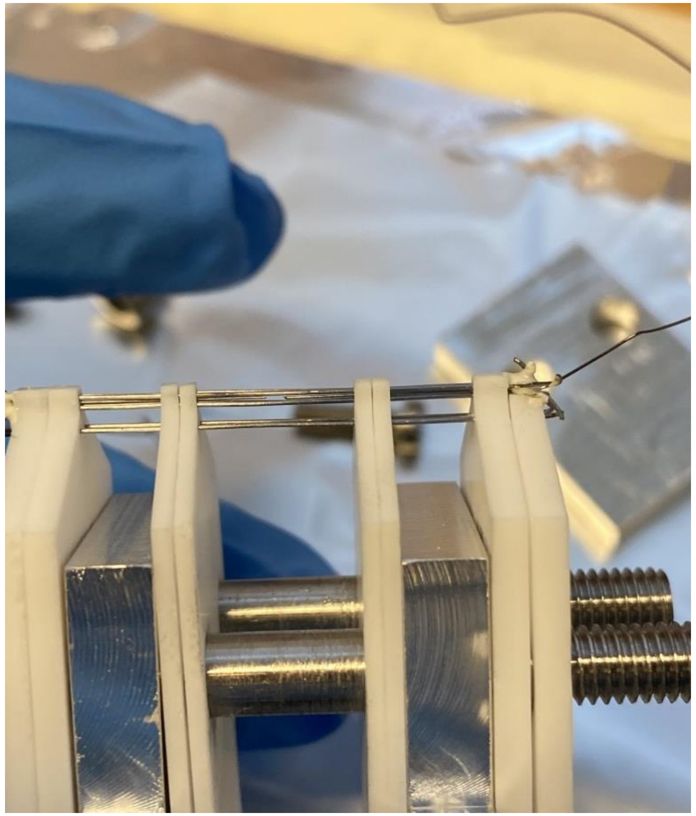
State detection using coherent Raman repumping and two-color Raman transfers

Boon Leng Chuah, Nick C. Lewty, and Murray D. Barrett
Center for Quantum Technologies and Department of Physics,
National University of Singapore, 3 Science Drive 2, 117543 Singapore
(Dated: October 27, 2018)

We demonstrate state detection based on coherent Raman repumping and a two-color Raman state transfer. The Raman coupling during detection selectively eliminates unwanted dark states in the fluorescence cycle without compromising the immunity of the desired dark state to off-resonant scattering. We demonstrate this technique using $^{137}Ba^+$ where a combination of Raman coupling and optical pumping leaves the $D_{3/2}\,|\,F''=3, m_F''=3\,\rangle$ metastable state optically dark and immune to off-resonant scattering. All other states are strongly coupled to the upper $P_{1/2}$ levels. We achieve a single shot state-detection efficiency of 89.6(3)% in a 1ms integration time, limited almost entirely by technical imperfections. Shelving to the $|\,F''=3, m_F''=3\,\rangle$ state before detection is performed via a two-color Raman transfer with a fidelity of 1.00(3).

Catching and cooling ~10 keV ions @ KUL





Precision trap @KUL