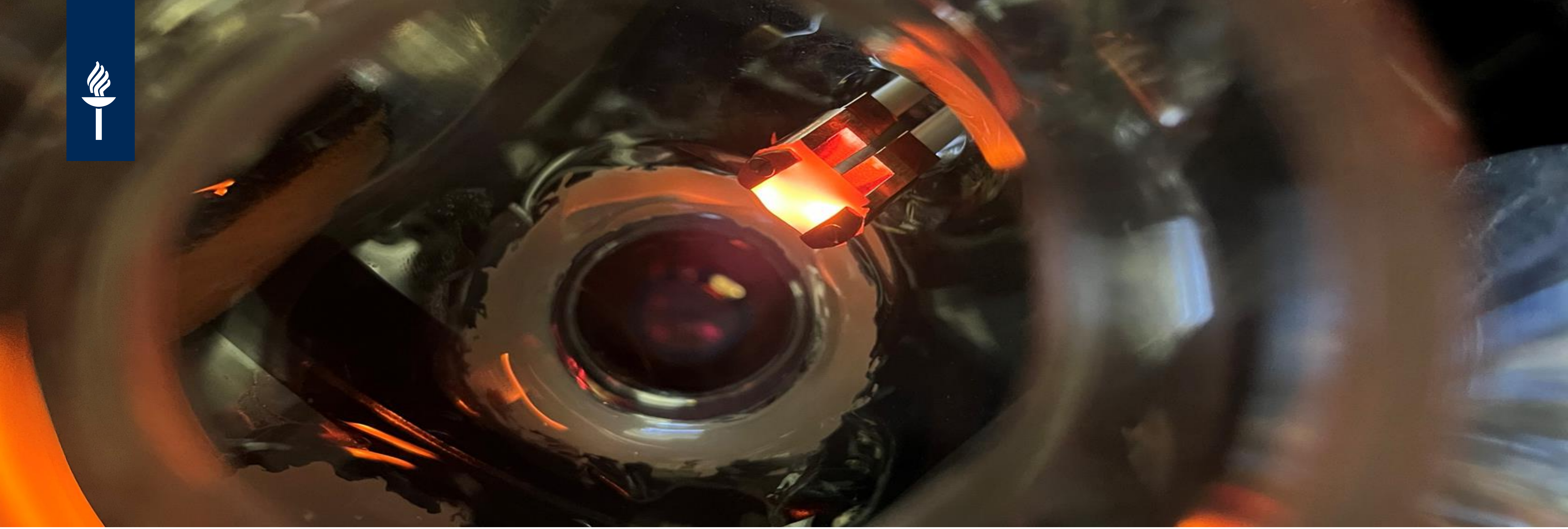

Ultra-Cold Caesium Trap

for magnetic octupole moment studies and coherent gamma generation

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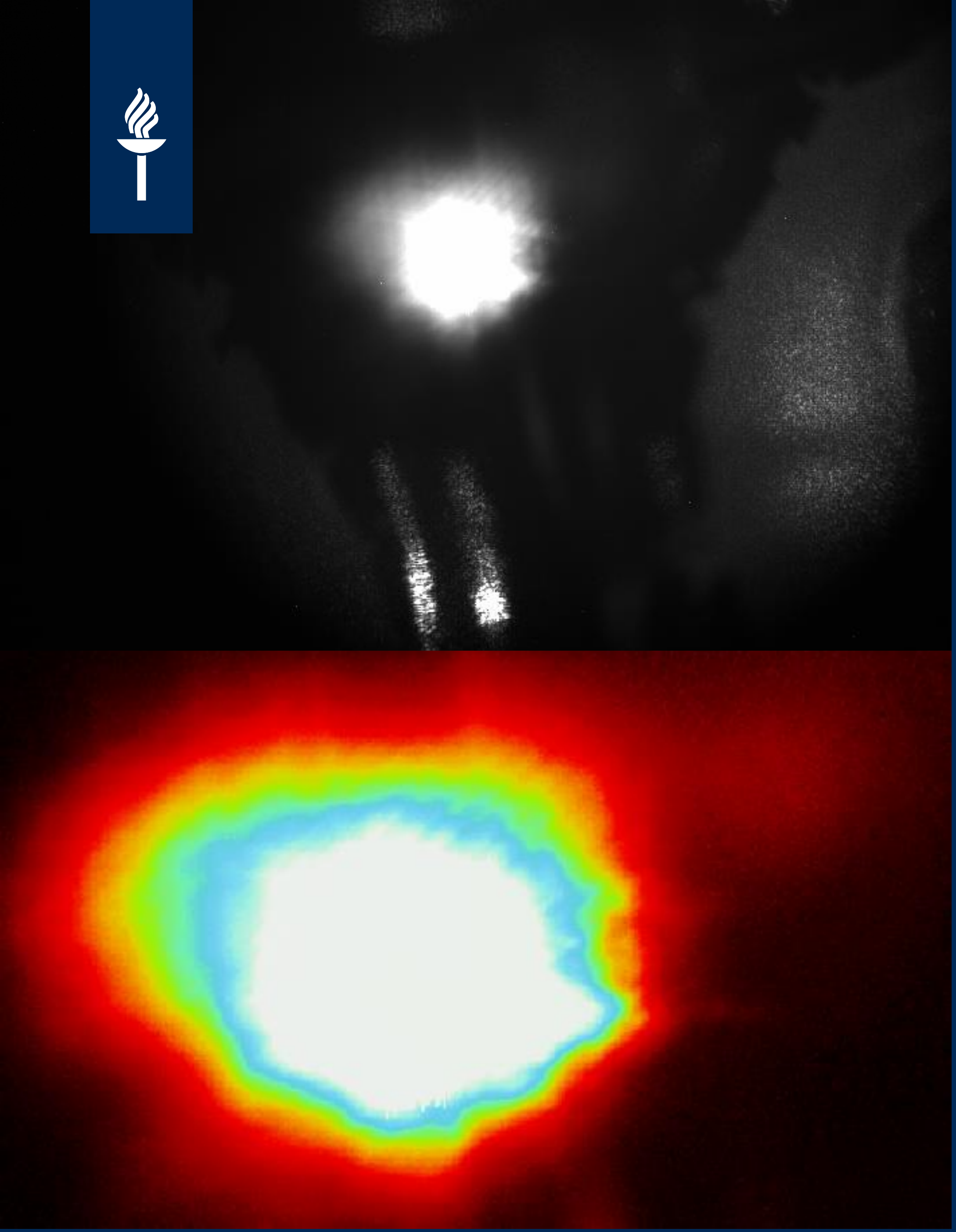
PLATAN 2024, University of Jyväskylä



Overview

- Motivations: going beyond ultra-cold ^{133}Cs
- Experiment at IGISOL facility
- Progress: offline and online test with ^{137}Cs
- Summary and future of IGISOL Cs atom trap

← ^{133}Cs vapour cooled and trapped in a magneto-optical trap (MOT) as observed via fluorescence imaging

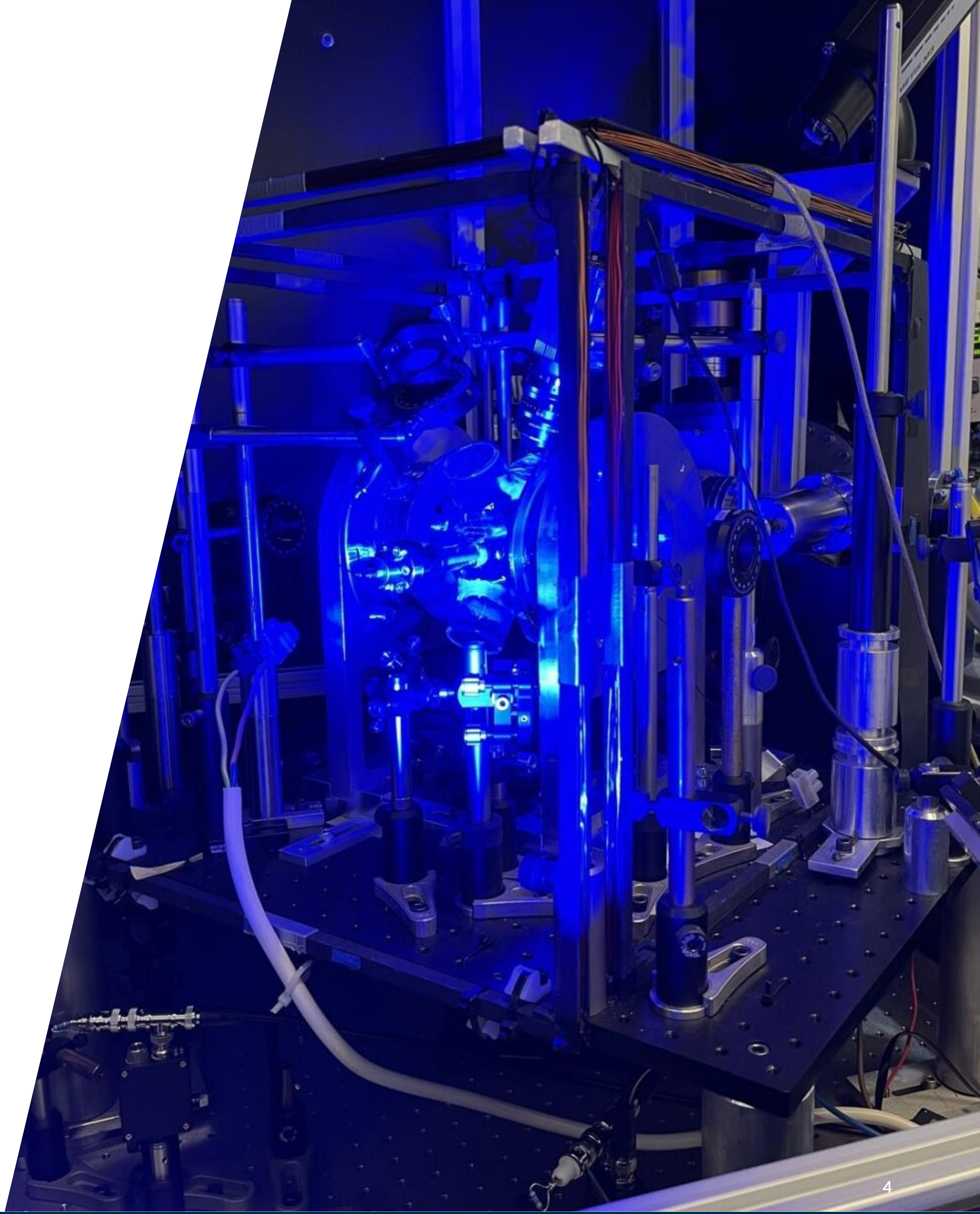
Welcome to the coldest place in Jyväskylä…

Beyond ultra-cold ^{133}Cs

- For bosonic gases,

$$n\lambda_{dB}^3 \geq 2.612 \dots$$

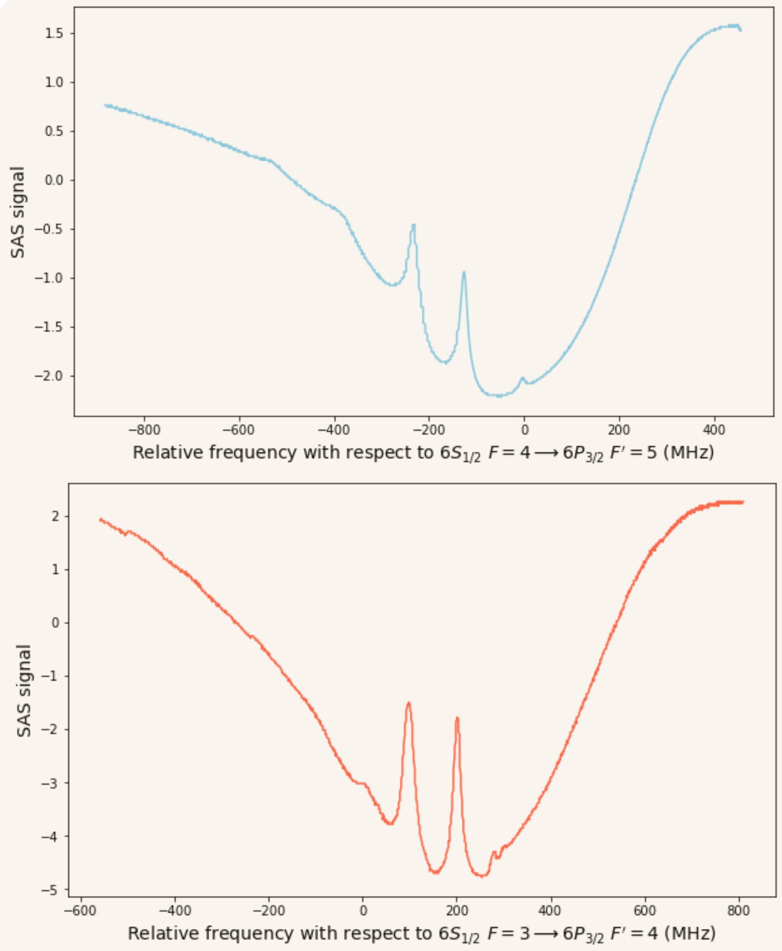
  the Bose-Einstein condensate (BEC) starts to form.
- The BEC and ultra-cold ^{133}Cs offer
  - Metrology and high-precision measurements with long interrogation times and suppressed shifts
  - Tunability of interactions in a controllable system with the knowledge of Feshbach resonances
  - Ideal platform with reduced fluctuations for tackling quantum few/many-body physics, quantum simulations and quantum information processing
- Going *beyond* cooling and trapping of stable ^{133}Cs
  - Unexplored scattering properties, tunability and isotope-dependent conditions towards the BEC of ultra-cold exotic Cs species
  - Ultra-cold inter-species system of radioactive Cs
  - A systematic study of nuclear properties of Cs isotopes with great precision
  - Gamma coherent radiation from the BEC of ^{135m}Cs



[1] C. L. Hung, PhD thesis, University of Chicago, 2011.
[2] T. Weber et al., Science **299**, (2003) 232-234.
[3] L. Marmugi, P.M. Walker, F. Renzoni, Phys. Lett. B **777** (2018) 281–285.

The nuclear magnetic octupole moment of Cs

- Probing the higher-order terms of the nuclear electromagnetic moments requires a high-precision measurement of the hyperfine structure.
- The interesting case: a large deviation of the measured magnetic octupole moment (Ω) of ^{133}Cs from the shell model theory
- If precisely measured,
  - refine the current nuclear models
  - access to nuclear structure and nucleon-nucleon interaction
- High-precision spectroscopy with the ultra-cold ensemble of Cs isotopes
  - Ultra-cold temperature helps reduce fluctuations and Doppler broadening.
  - A chain of isotopes allows removal of systematic effects, aids atomic calculations, and compares the effect across the neutron magic number and the magnetisation distribution of the last neutron.
  - Probing $6P_{3/2}$ HFS as it is likely to be the most sensitive
  - To see the entire splitting, require both cooling and repump manifolds from the $6S_{1/2}$ -> $6P_{3/2}$ (D2) transition.

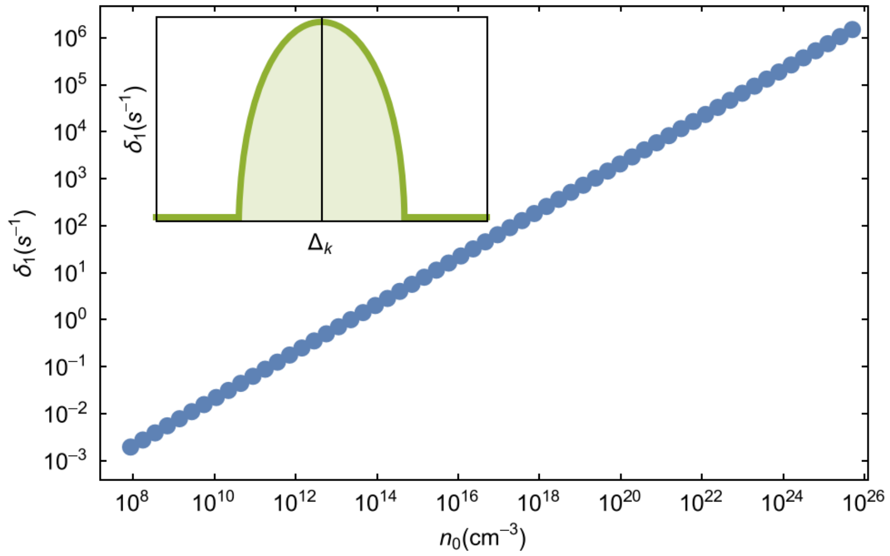


Combined $6P_{3/2}$ manifold from a room-temperature saturated absorption spectroscopy (SAS) signal of ^{133}Cs

[1] R.P. de Groote et al., Phys. Lett. B **827**, 136930 (2022).
[2] J. S. Grossman et al., Phys. Rev. Lett. **83**, 935 (1999).

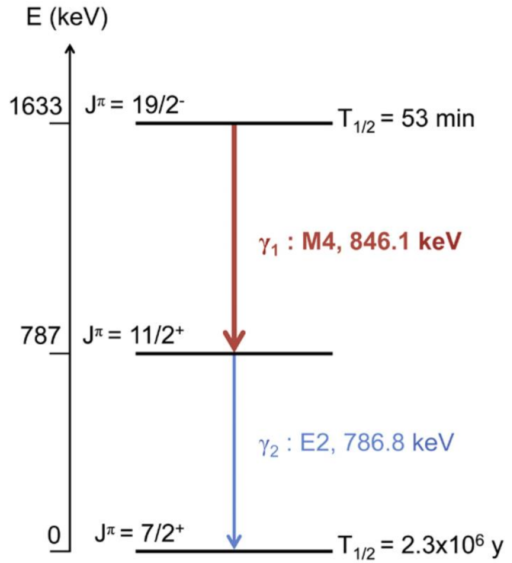
The GRASER from ^{135m}Cs BEC

- The BEC of ^{135m}Cs is proposed as a coherent gamma-ray source or a pulse *graser* via the M4 transition of 846.1 keV from the $t_{1/2}$ ~ 53 min isomeric state.
- Overcome the challenges of high pump energy, nuclear recoil and maintained population inversion



The critical parameter as a function of the emitter density and (inset) emission frequency interval, which spans a wide range of usual condensate densities and is non-zero.

L. Marmugi, P.M. Walker, F. Renzoni, Phys. Lett. B **777** (2018) 281–285.

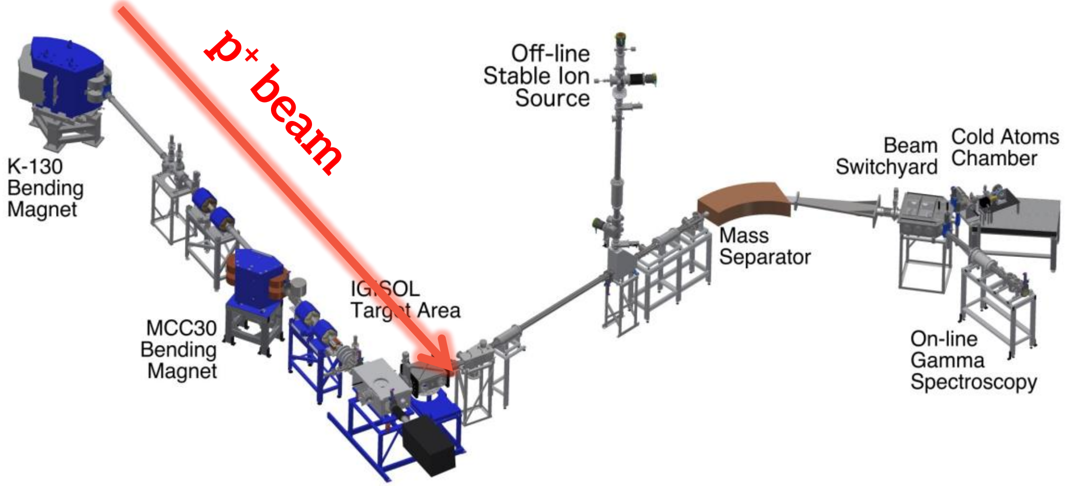


The scheme for coherent radiation: M4 and subsequent E2 transitions of ^{135m}Cs condensate

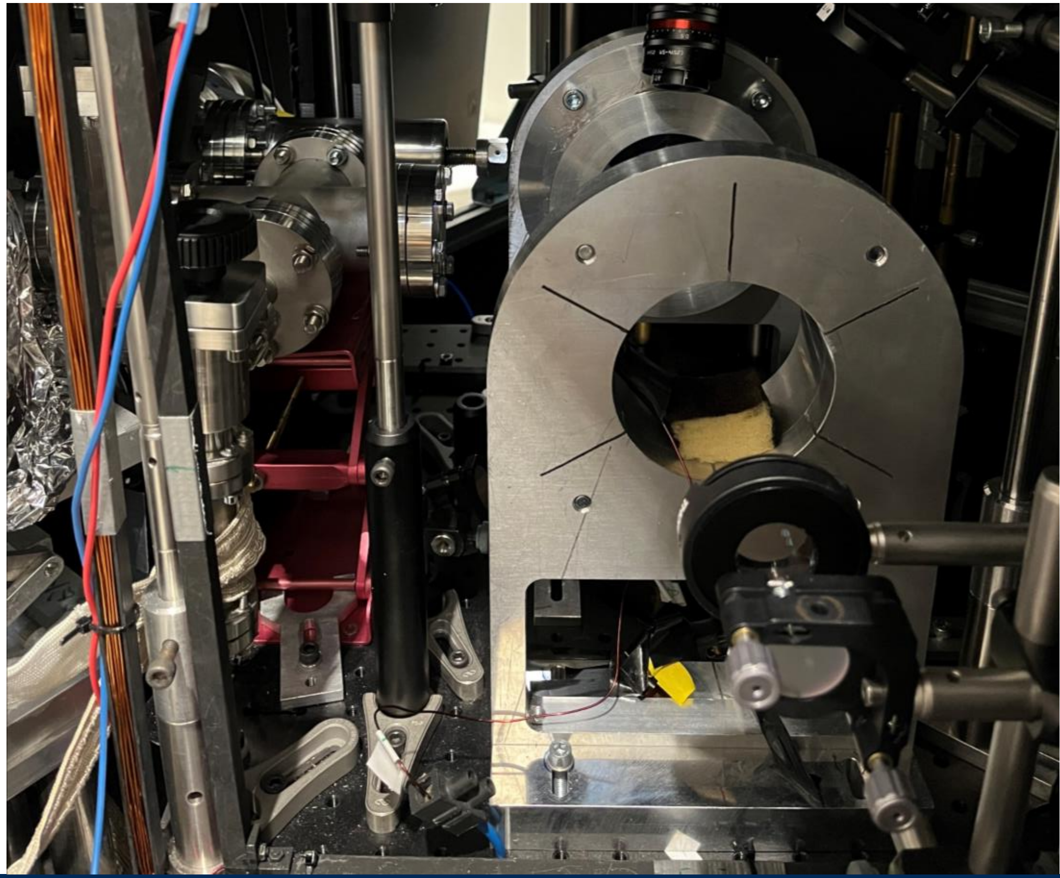
- Idea: the isomeric state is produced directly and isolated
  - Laser trapping selectivity
  - Linewidth suppression at the temperature of BEC
- The onset is triggered by the condensate's absolute instability
  - A spontaneous decay of one isomer triggers the decay of the whole emitters
  - Coherence of the BEC is transferred to the coupled photon field
- Non-zero criticality indicates that low emitter densities are possible, with the level of traditionally obtained condensates.

COOL‼ So how can we do that?

Cs atom trap at IGISOL

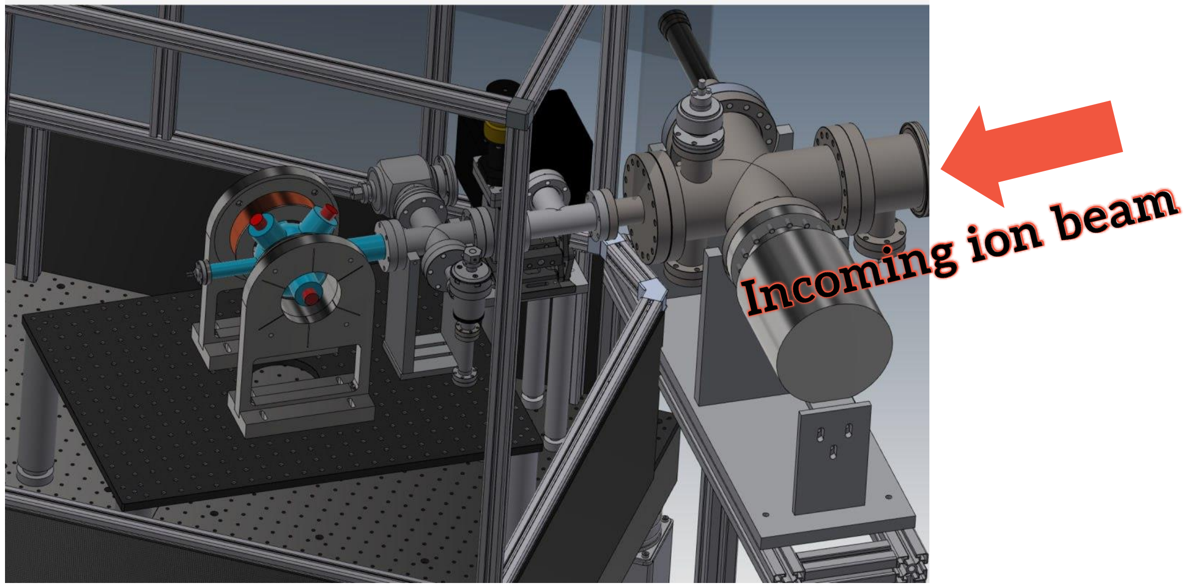


- Bridging the radioactive ion beam (RIB) production and cooling and trapping techniques for neutral atoms
- RIB part
  - Online production of Cs isotopes and isomers via proton-induced fission in a ^{nat}U target
  - Offline beam via the upstairs surface ionisation source (^{133}Cs) and the spark source (CsCl) at the front end are used for beam testing and efficiency calculation.
- Atomic cooling and trapping part
  - Ideally follow a common route for ^{133}Cs
  - Transition frequencies are shifted via an offset lock system with an additional reference laser.
  - Note that amongst the stable alkalis, the BEC of ^{133}Cs is already the most difficult to achieve*

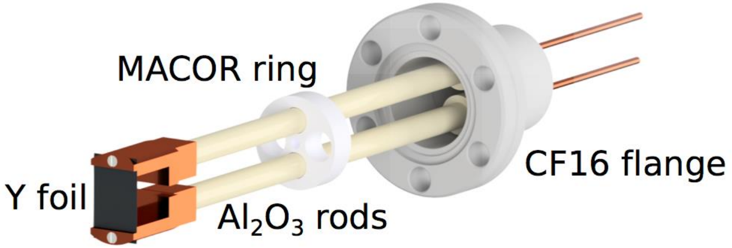


Neutralisation for atomic cooling and trapping

- Ion beam is stopped and neutralised by a Y foil mounted on an electrical feedthrough.
  - Neutralised atoms diffuse out via resistive heating up to 1000 K.
  - Special PDMS coating is required on the inner surface of the glass chamber
  - Hot atoms bounce and thermalise until reaching the trapping velocity of the first laser cooling stage.



The Cs atom trap beam line: the coated glass chamber is connected to the UHV cross, joining a vapour ampoule source with the beam line from the switchyard



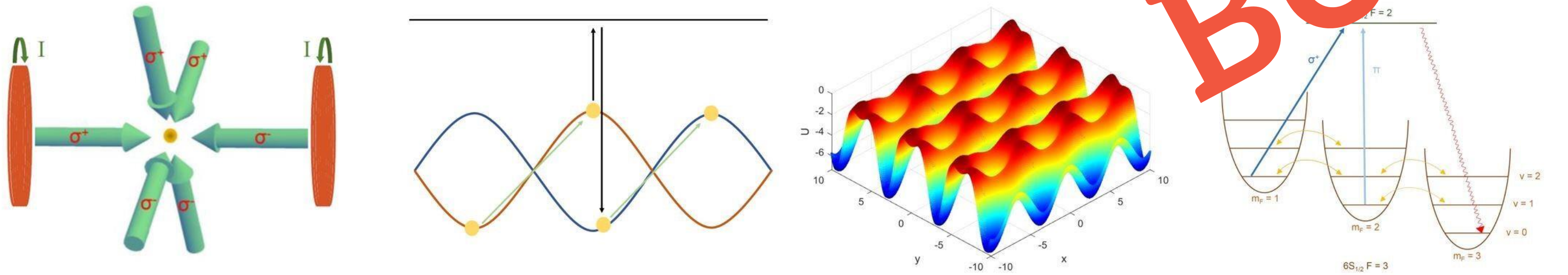
The neutraliser consists of the Y foil fixed on the Cu mount connected to the electrical feedthrough.

- Beam diagnostics are placed upstream including a Faraday cup and a MagneTOF, but the most important detector is the foil itself.
- A ^{133}Cs ampoule is also installed next to the chamber for day-to-day cooling and trapping optimisations.
- The current setup was built for the first stage of the atomic cooling and trapping process: a magneto optical trap (MOT).

Cooling and trapping for neutral Cs

- The starting point simply follows standard laser cooling techniques except the lack of Zeeman slower (or equivalent others) but the goal is to use a double-chamber LVIS configuration
- The tricky part: the magnetically trappable state of Cs is inelastic-scattering dominant
- Important stage for Cs: degenerate Raman sideband cooling to spin-polarise Cs to the lowest inelastic 2-body scattering suppressed state
- Then the final stage which no longer involves radiation pressure: evaporation in a dipole trap

BUT…

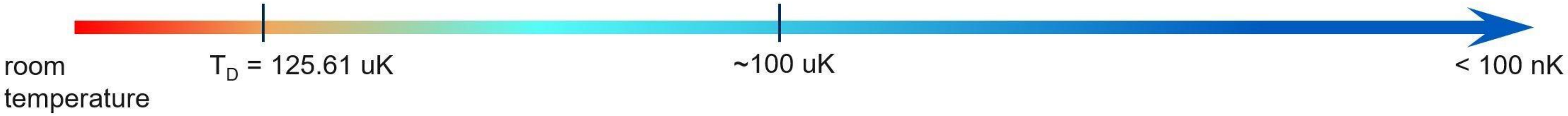


Magneto optical trap

CMOT and optical molasses

Raman lattice

degenerate Raman sideband cooling



Challenges: towards the BEC and ultra-cold spectroscopy

BEC-ing ^{133}Cs is already a tricky business

- 3-body inelastic scattering at a later high-density stage prevents efficient evaporative cooling.
- The knowledge of scattering properties helps tune away the recombination resonances.
- Good background + start high → afford to lose!

No idea what is going on with other Cs isotopes and isomers

- Need Feshbach resonance spectroscopy, photo-association scheme and further low-energy scattering information
- For ^{133}Cs, BEC only works with a narrow window at low magnetic field. Others may not be as lucky.

Challenges: towards the BEC and ultra-cold spectroscopy

(Too many) problems with the ion beam

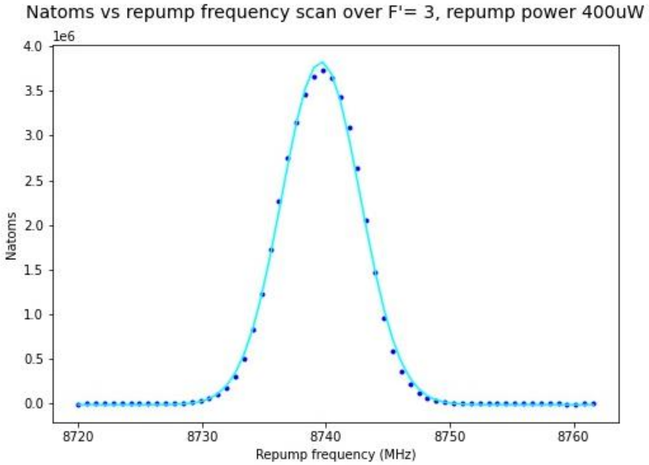
- Low production yield
- Hugh losses from ion optics imperfections
- The lack of beam diagnostics at the Y foil position
- The PDMS coating keeps degrading.

What is the best way to probe the very state featured in the cooling cycle?

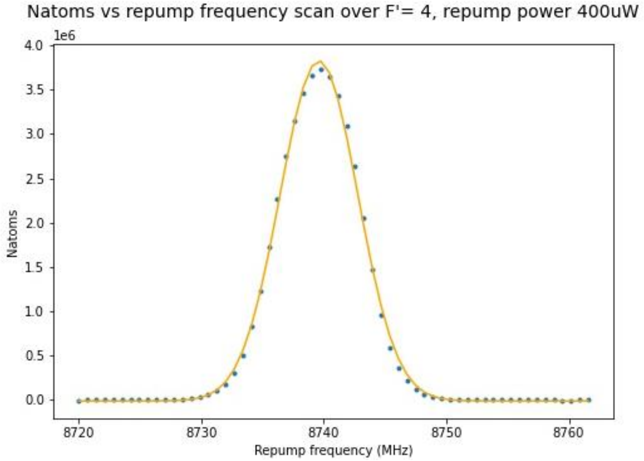
- Scanning transition cannot be filtered out from the cooling transition.
- MOT depletion and other population transfer methods cannot be applied.
- Ultimately, MF-free and trapping-free conditions are required for a very high precision result.
- The magic-wavelength dipole trap?

Progress

- Offset locking system has been tested with ^{133}Cs.
  - Stable and reliable over the course of a typical MOT procedure from the Y foil
  - Frequency jumps up to ~ 9GHz, good enough for most of the interesting isotopes, with the final limitation of the lasers' mode-hop-free range.
  - No other stable isotopes available – cannot experimentally verify the offset scheme.
- Preliminary tests with the spectroscopy of repump transition of ^{133}Cs vapour
  - Population change induced by scanning F' = 3 and 4 of the repump manifold
  - The linewidth can be reduced to ~Γ as the repump beam is well below the saturation but is traded with the population fluctuations.
  - The splitting is 1 MHz shifted from the current literature value, but note that no calibration of the RF scan nor further shift calculation is done at this point.
  - This demonstrates a simple way to obtain the F = 3 , 4 splitting of the $6P_{3/2}$ state for radioactive species planned for future tests.

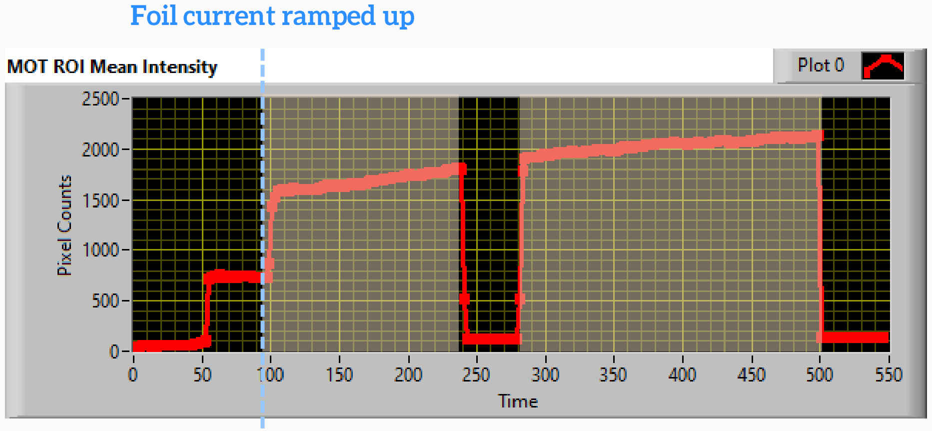


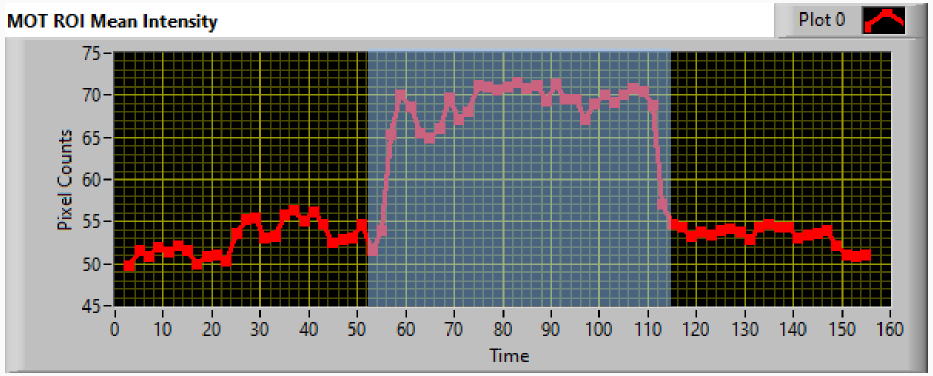
Natoms vs repump frequency scan over F'= 3, repump power 400uW



Natoms vs repump frequency scan over F'= 4, repump power 400uW

Progress





(above) Result from pre-implantation of 130pA with ~1 min exposure: the dash line indicates the increase in foil temperature while the shaded area represents the magnetic-field on periods.
(below) Result from live-loading mode: the increase in MOT signal is seen as the ion beam is unblocked. Time is in seconds.

- Coating test with the ^{133}Cs offline beam
  - The coating was reapplied and tested.
  - A clear increase in MOT signal is seen from both the pre-implantation and live-loading modes.
  - Unable to determine the total efficiency or the beam-to-MOT, neutralisation-coating efficiency due to the coating degradation, imaging problems and ion beam fluctuations
- Primary tests with online beams of ^{135}Cs and ^{137}Cs have been carried out with MOT.
  - Due to the lack of a proper frequency offset locking, unable to verify the preliminary signal of ^{135}Cs (pre-covid experiment).
  - ~3 beam days of ^{137}Cs with the offset-locking system. No ^{137}Cs is found from the MOT signal nor from the post-experiment gamma-ray detection with the Y foil.

Summary and future of IGISOL Cs atom trap

- Primary tests with a stable offline beam and online beams of ^{135}Cs and ^{137}Cs have been carried out with MOT. The lasers are stabilised and locked to the relevant transitions by means of the optical phase offset lock system. No clear evidence of Cs radioisotope trapping has been found so far.
- Lots of developments are needed!

Ion-beam production and diagnostics

- ○ Increase the production yield (with a hot cavity?)
- ○ Beam diagnostics at the position of beam implantation

↓

new implantation setup

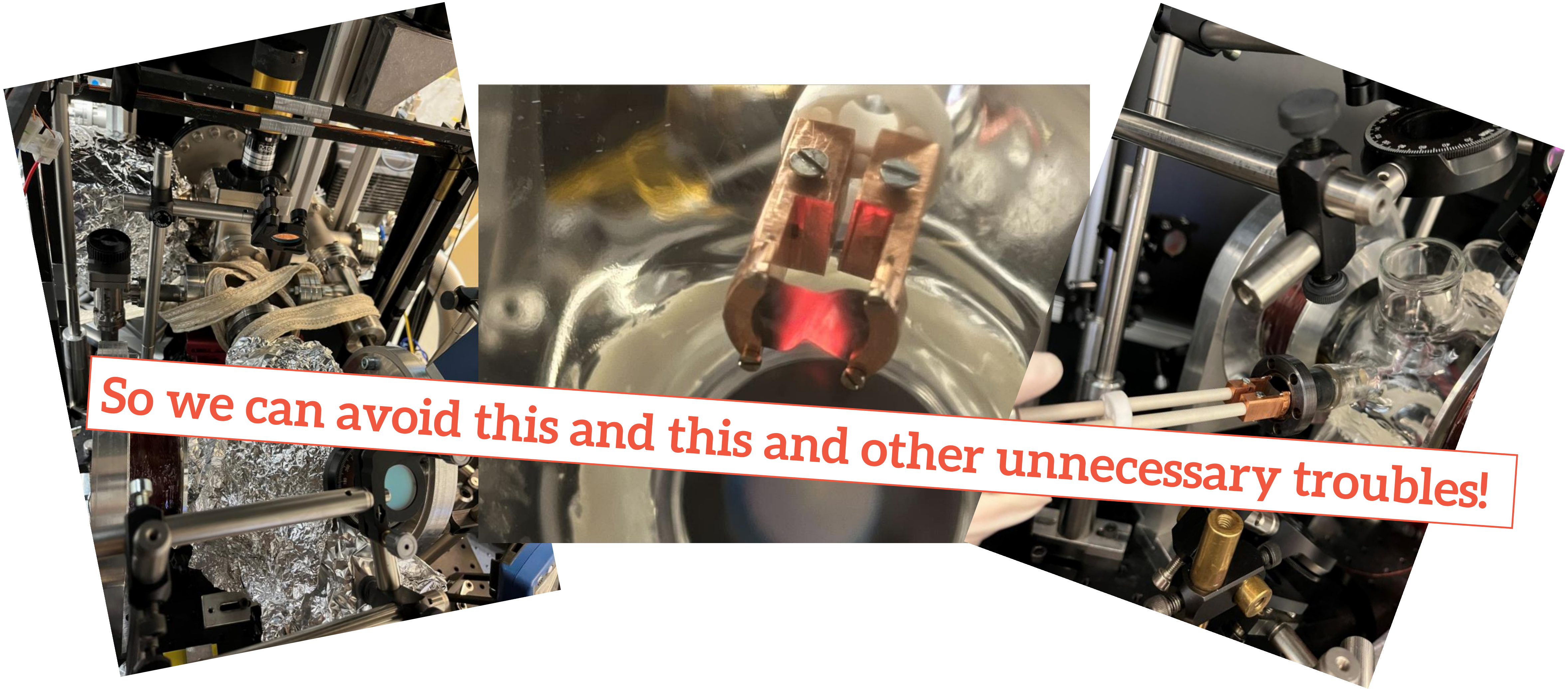
Chamber and neutralisation

- ○ Rebuild the current setup
- ○ separate implantation and cooling chamber to avoid degrading the coating and allow for installation of any necessary beam diagnostics in a steel implantation chamber
- ○ Well-designed mounting system for the foil to prolong the life cycle time

Cooling and trapping process for spectroscopy and BEC

- ○ Scanning of $6P_{3/2}$ with MOT, all fields off. Scanning time ~100μs (or even faster!)
- ○ Dipole trap with a magic wavelength as a future scheme
- ○ Scattering properties needed
- ○ BEC via runaway evaporation in a dipole trap following the development of Chin's group of the University of Chicago

IGISOL Cs Atom Trap 2.0 is coming…stay tuned!



So we can avoid this and this and other unnecessary troubles!