UNIVERSITY OF JYVÄSKYLÄ
DEPARTMENT OF PHYSICS

JYFL

RAPTOR

Resonance ionization spectroscopy And Purification Traps for Optimized spectRoscopy

A NOVEL APPROACH FOR RESONANCE IONIZATION SPECTROSCOPY

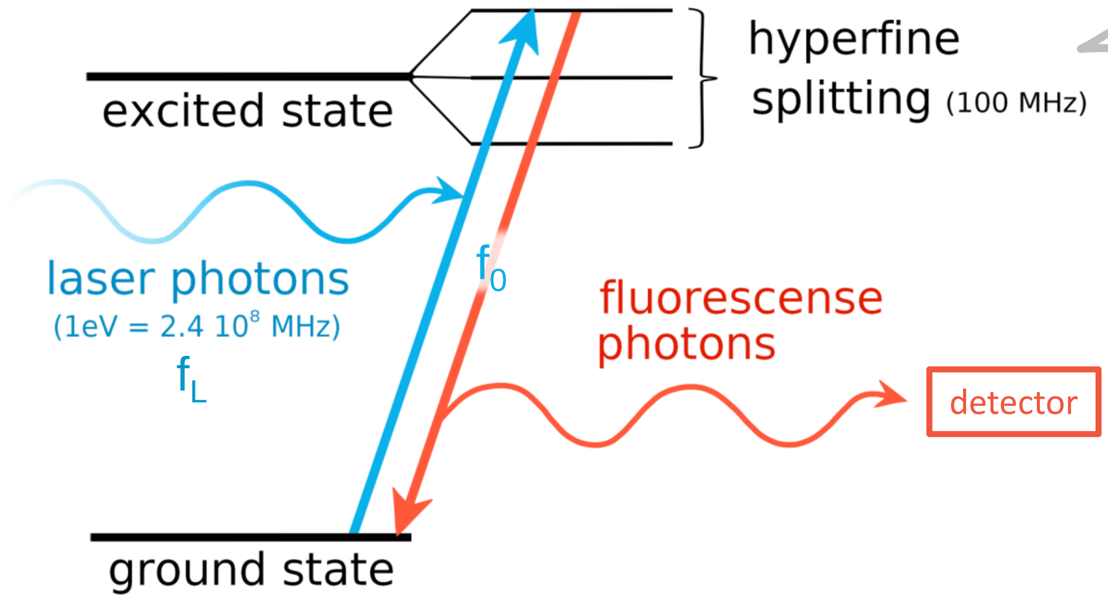
Sonja Kujanpää (sopikuja@jyu.fi)
A. Raggio, M. Reponen, W. Gins, I. D. Moore, R. P. de Groote

Contents

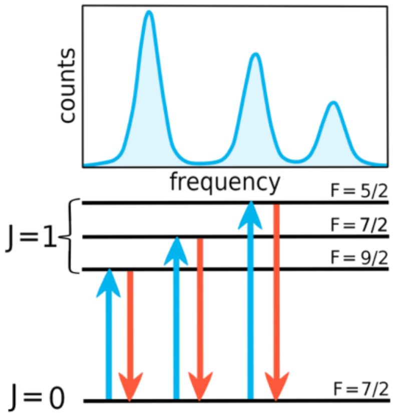
- Background → CRIS → RAPTOR → IGISOL
- Technical details
  - → Beamline schematic
- Current status: commissioning
  - → Stable Cu test
  - → Coming: stable Ag test
- Future: benchmarking experiment
  - → Radioactive Bi

Introduction to optical spectroscopy

- One routinely used technique in RIB-facilities is collinear laser spectroscopy (CLS)
  - / Laser beam is overlapped with fast ion beam, 30-60 keV
  - / When laser frequency f_L matches the transition frequency of the electronic transition f_0 = resonance!
    - → Then photon absorption cross section $\sigma \approx \lambda^2/2\pi$ is huge -> effective technique



FUN FACT: hyperfine structure effects are **6 orders of magnitude** smaller than laser frequency itself!

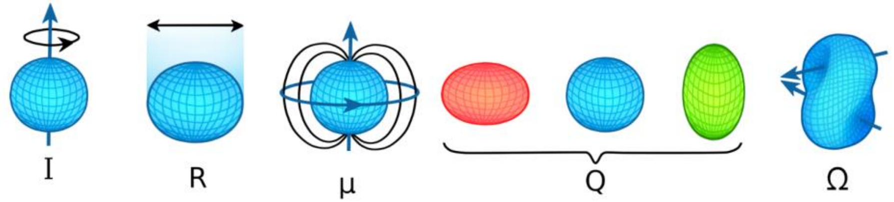


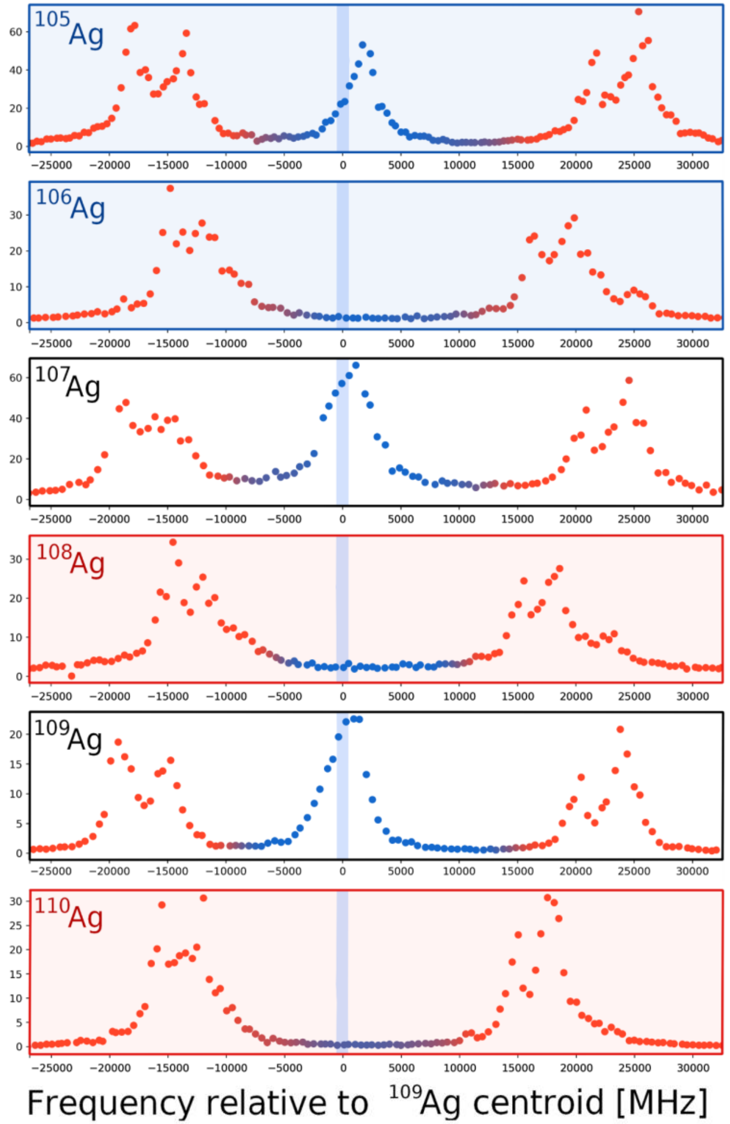
- Results in a HF spectrum arising from the coupling of nuclear and atomic spins (I = 0, no HFS, only FS peak)
  - / The hyperfine splitting and isotope shifts can be extracted
  - / Possible to gain information about the nuclear properties

Nuclear properties from HFS measurements

- In optical spectroscopy resonance counts are detected and form a HF spectrum
  - Counts as a function of laser frequency
    - → Number of peaks/relative intensities is determined by nuclear and atomic spins
    - → Location of peaks is determined by size of nuclear moments
  - From HF spectrum fit: nuclear electromagnetic moments
    - → magnetic dipole moment μ, electric quadrupole moment Q, (magnetic octupole moment Ω)

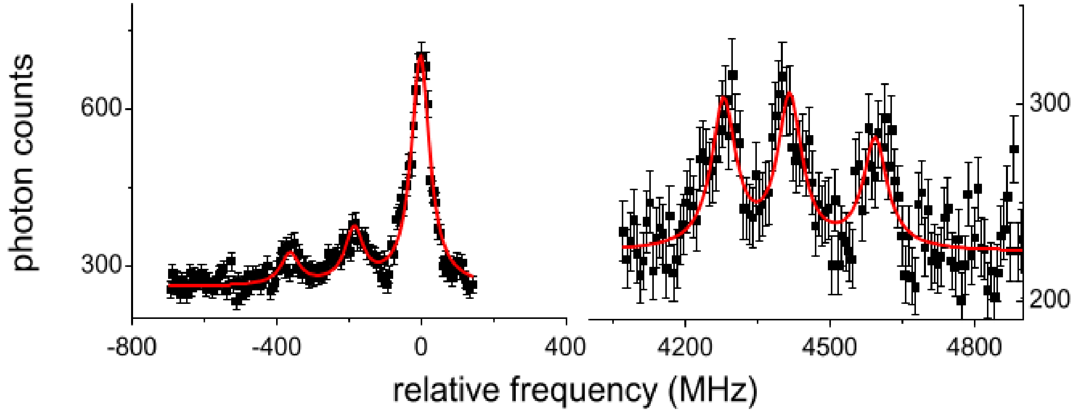
- Shifts in the atomic transition frequencies (isotope shifts) are seen as a function of neutron number
    - → Access to nuclear charge-radius ($\delta\langle R^2\rangle$) once atomic factors are known from e.g. a King plot





Comparing spectroscopy techniques

COLLINEAR SPECTROSCOPY



- High resolution (nat. linewidth ~30 MHz)
- Scanning voltage, not frequency (more reliable)
- Detecting photons (with PMT)
  - / Disadvantage: solid angle, quantum efficiency
- 1 CW laser
- Needs beams of 10^3 ion/s

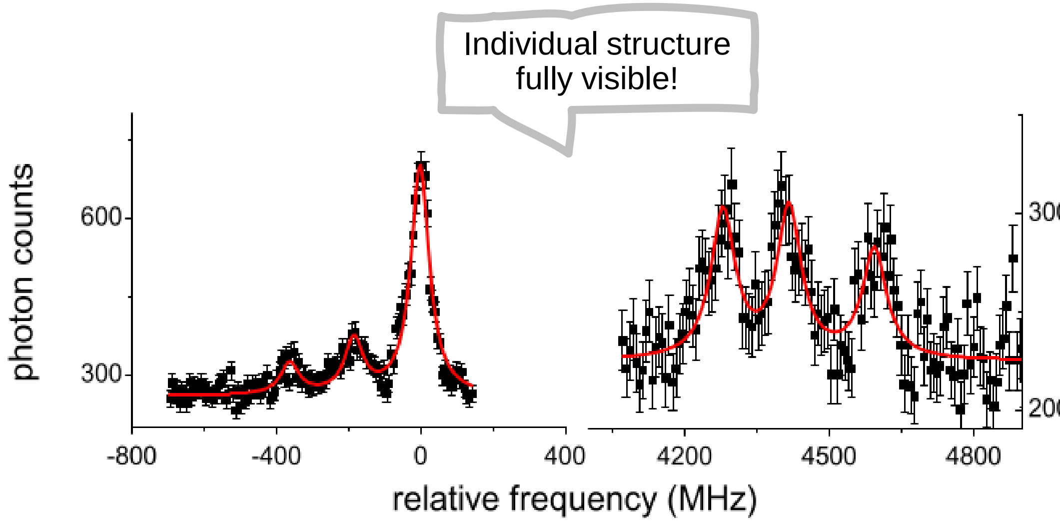
IN-SOURCE RESONANCE IONIZATION SPECTROSCOPY (RIS)

- Poorer resolution (100-1000 < CLS)
- Detecting ions, selective process
- High detection efficiency
- > 2 pulsed lasers
- Good for short lifetimes, low yields (< 1 ion/s)

Example spectra from K.T. Flanagan et al., Phys. Rev. Lett. 103 (2009) 142501

Comparing spectroscopy techniques

COLLINEAR SPECTROSCOPY



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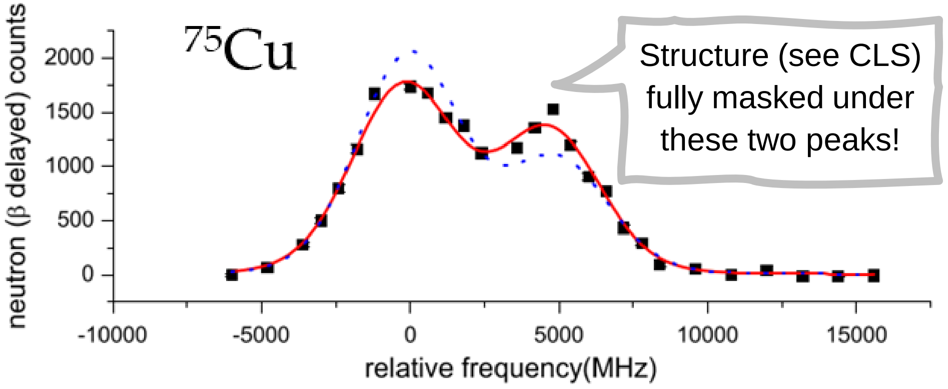
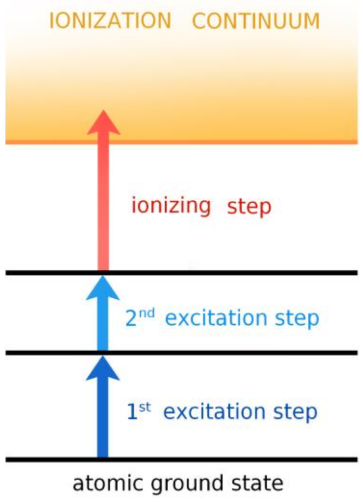




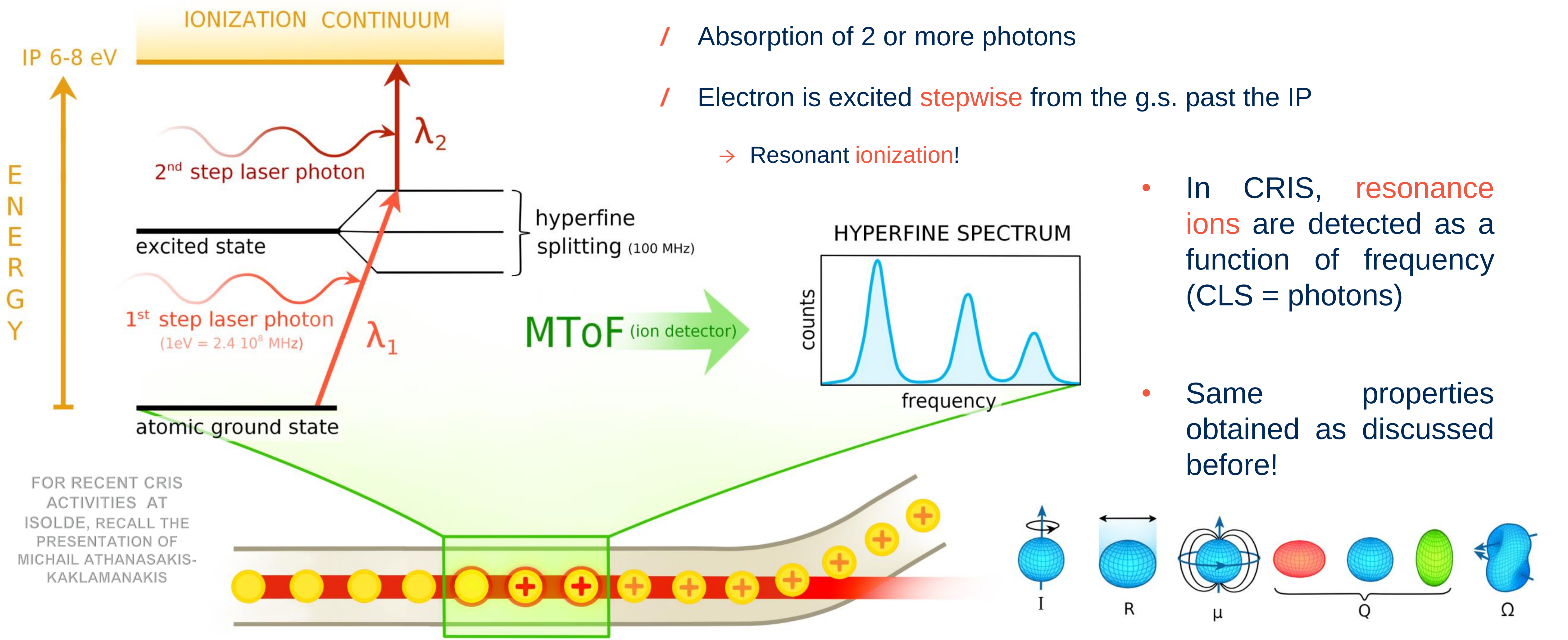
- Poorer resolution (100-1000 < CLS)
- Detecting ions, selective process
- High detection efficiency
- > 2 pulsed lasers
- Good for short lifetimes, low yields (< 1 ion/s)

What if we combine these techniques?

CLS + RIS = CRIS (Collinear Resonance Ionization Spectroscopy)

CRIS = medium to high resolution

- Atom beam is overlapped with 2 or more pulsed laser beams
  - Absorption of 2 or more photons
  - Electron is excited stepwise from the g.s. past the IP
    - → Resonant ionization!



- In CRIS, resonance ions are detected as a function of frequency (CLS = photons)
- Same properties obtained as discussed before!

FOR RECENT CRIS ACTIVITIES AT ISOLDE, RECALL THE PRESENTATION OF MICHAIL ATHANASAKIS-KAKLAMANAKIS

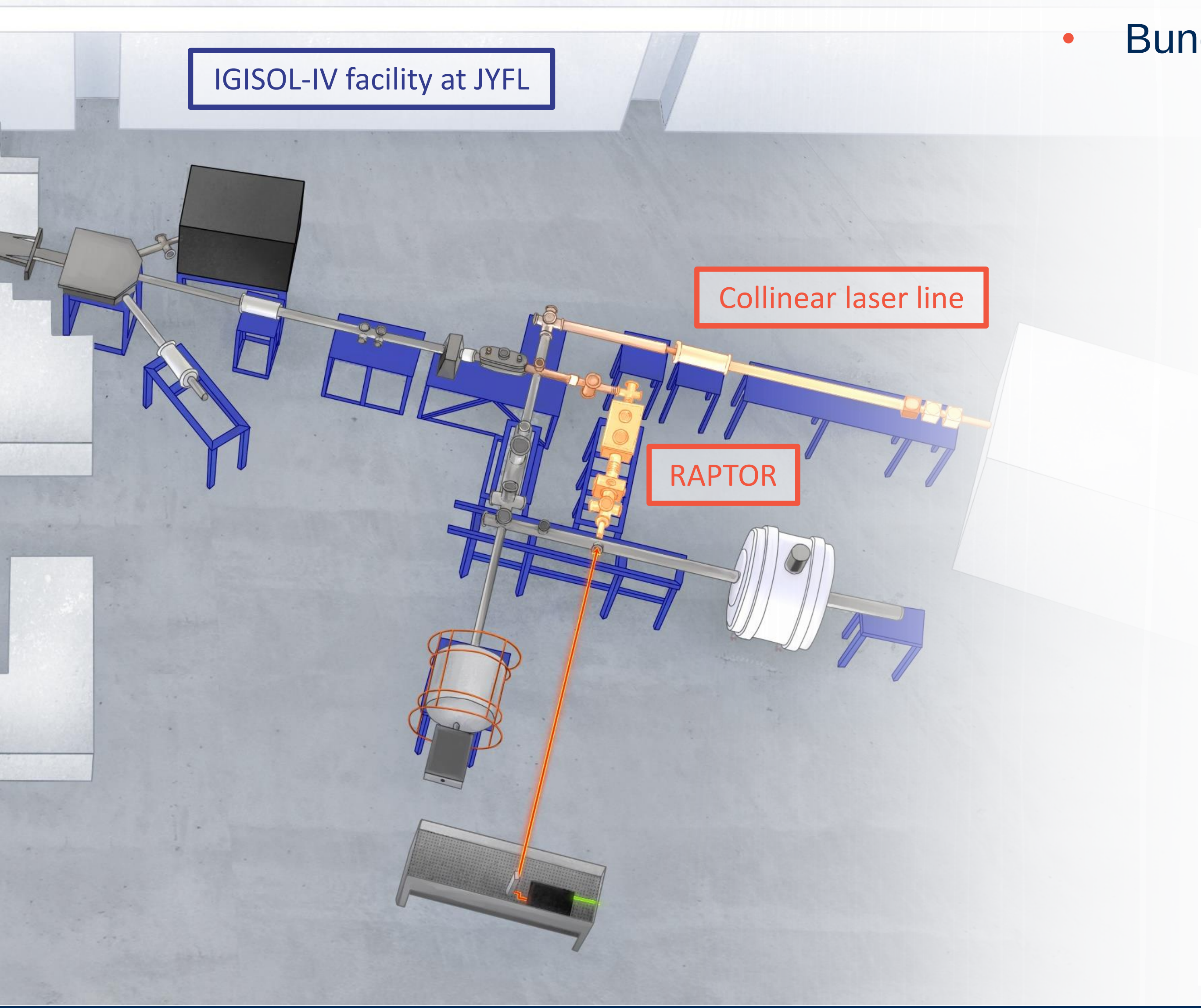
Motivation for RAPTOR

Resonance ionization spectroscopy **A**nd **P**urification **T**raps for **O**ptimized spect**R**oscopy

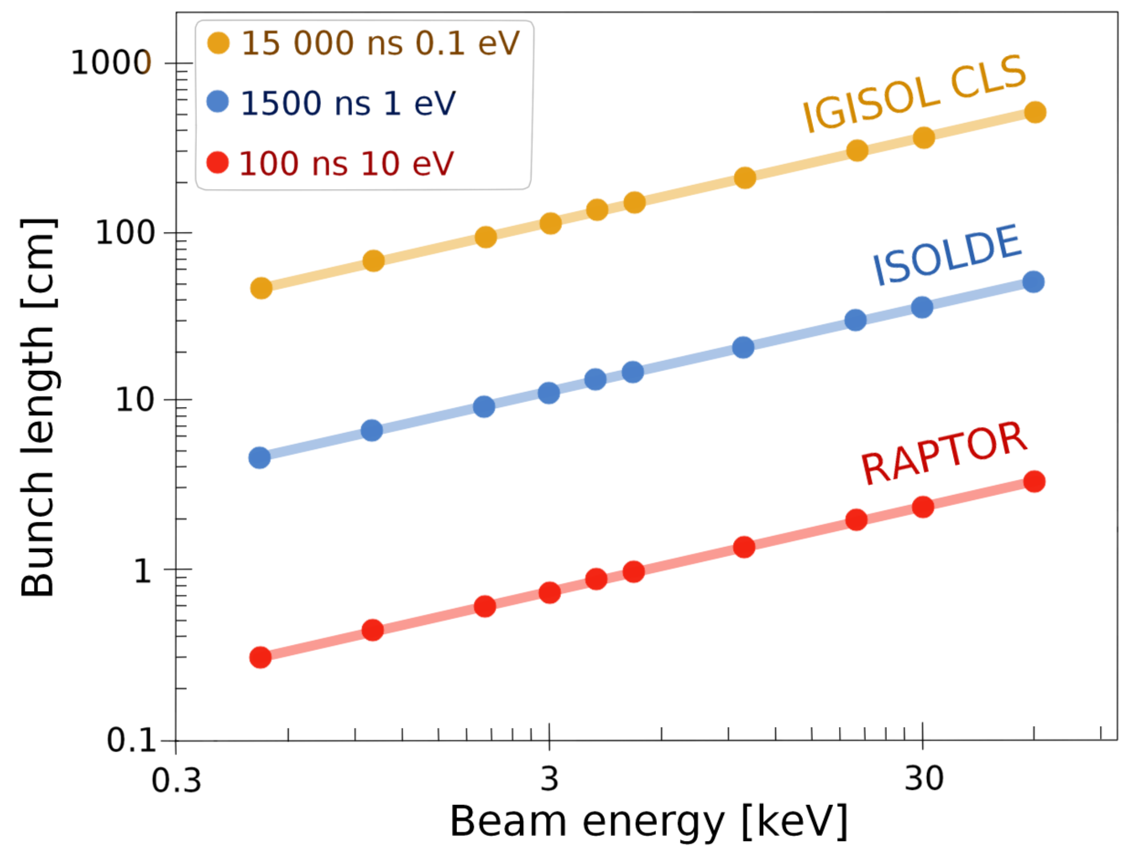
- Small footprint CRIS device (< 2 m) located at IGISOL (JYFL, Finland)
  - Allowed by a narrow (spatial) bunch of ~1 cm from the RFQ
  - Improved sensitivity (suppressed laser scatter)
  - Great selectivity between isomer/g.s due to HFS and charge radii

- Aiming to enable studies of isotopes not currently available anywhere else
  - Complex open d and f shell atomic systems
  - Refractory isotopes
  - Larger HFS and isotope shifts

Motivation for RAPTOR

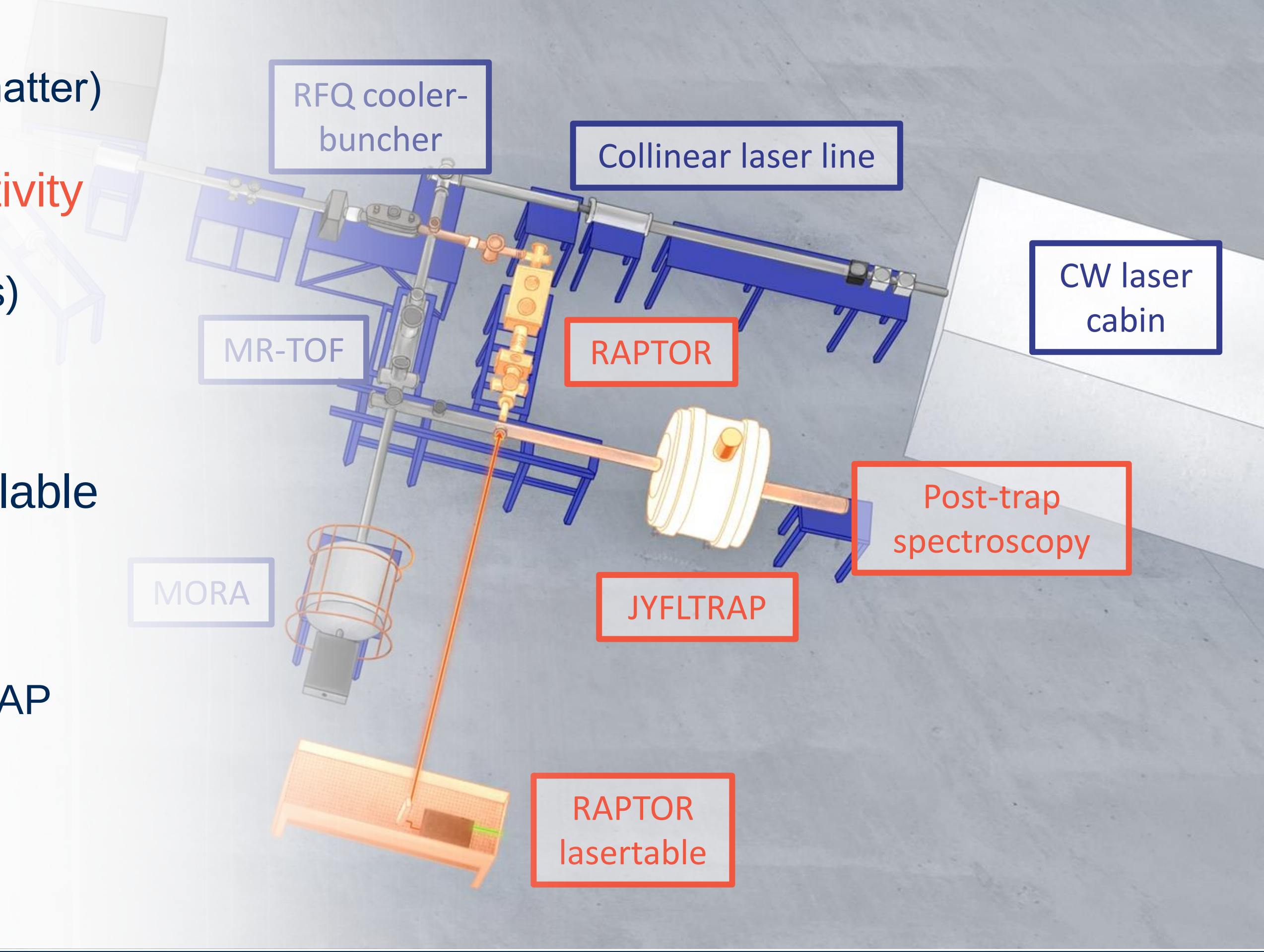


- Bunch length comparison between beamlines at 5 keV:
  - IGISOL collinear: 5 m
  - ISOLDE 0.5 m
  - RAPTOR 1 cm

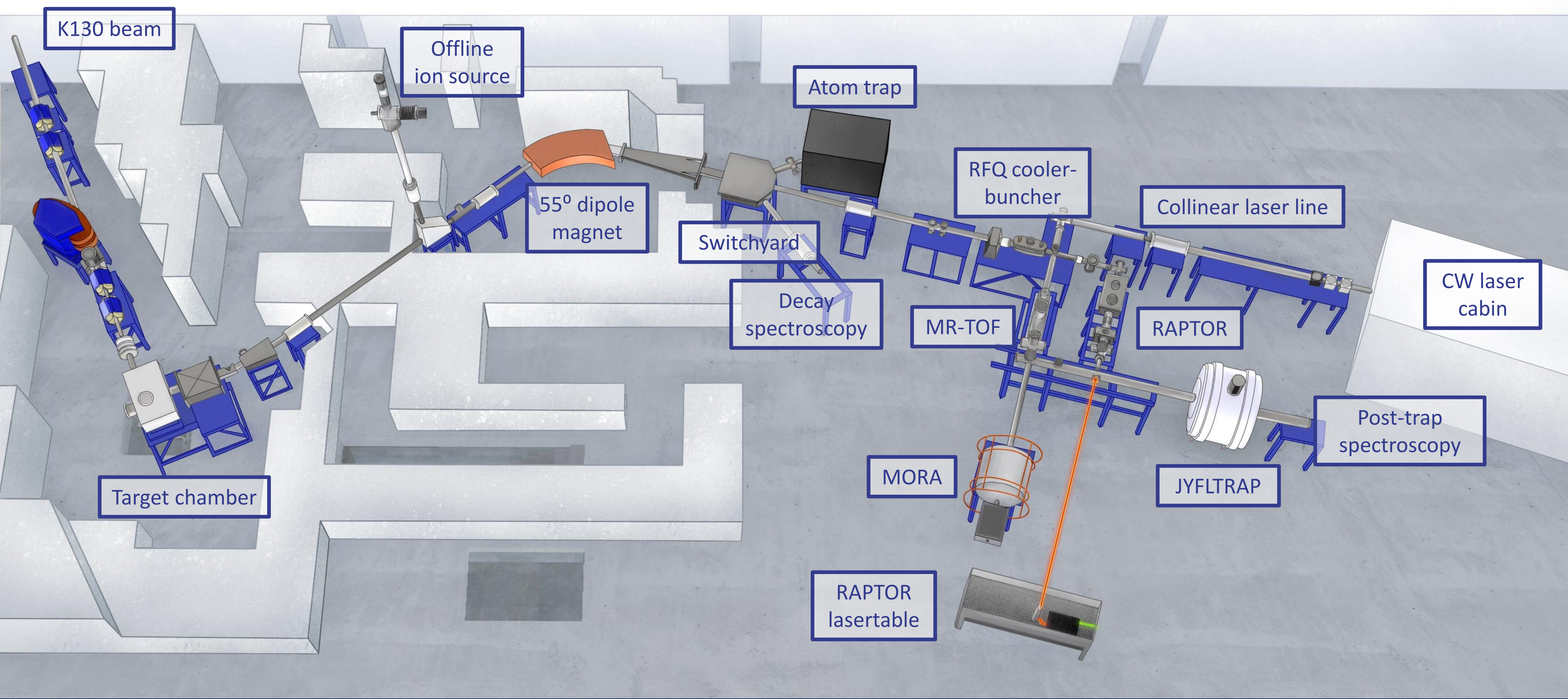


Motivation for RAPTOR

- Variable 2-10 keV beam energy instead of ‘conventional’ 30-60 kV
  - ~100 MHz linewidth using 1 cm bunch
  - Slightly worse resolution (for large HFS it doesn’t really matter)
- Lower beam energy increases charge-exchange selectivity
  - → A suitable neutralizer must be chosen (e.g. K, Na, Cs)
  - → Excited meta-stable states can be favoured
- High repetition rate (10 kHz) pulsed laser systems available
- Unique possibility to connect into a Penning trap
  - Can be used to isomerically clean the beams for JYFLTRAP
    - → Low-background measurements
    - → Laser-assisted post-trap decay spectroscopy

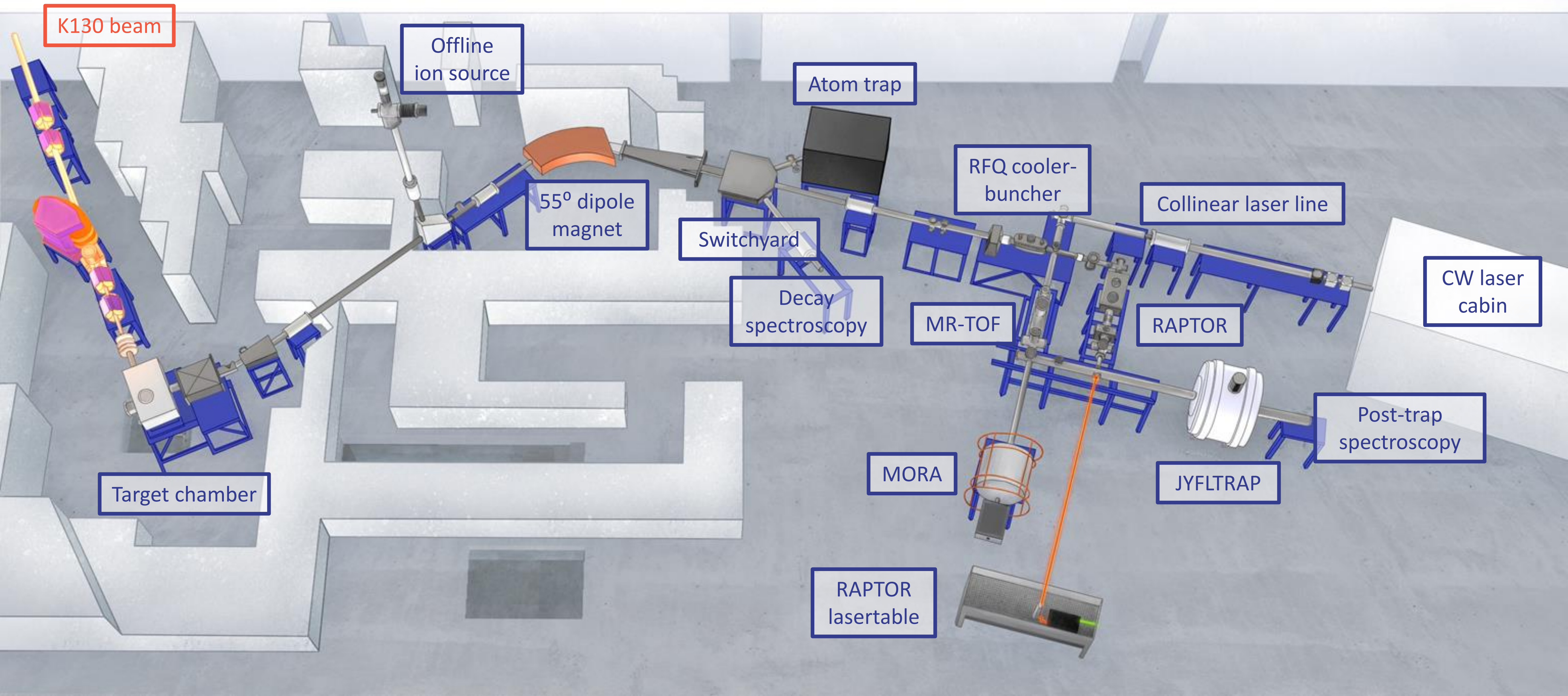


IGISOL-IV



K130 beam
Offline ion source
Atom trap
RFQ cooler-buncher
Collinear laser line
55° dipole magnet
Switchyard
Decay spectroscopy
MR-TOF
RAPTOR
CW laser cabin
Post-trap spectroscopy
MORA
JYFLTRAP
Target chamber
RAPTOR lasertable

IGISOL-IV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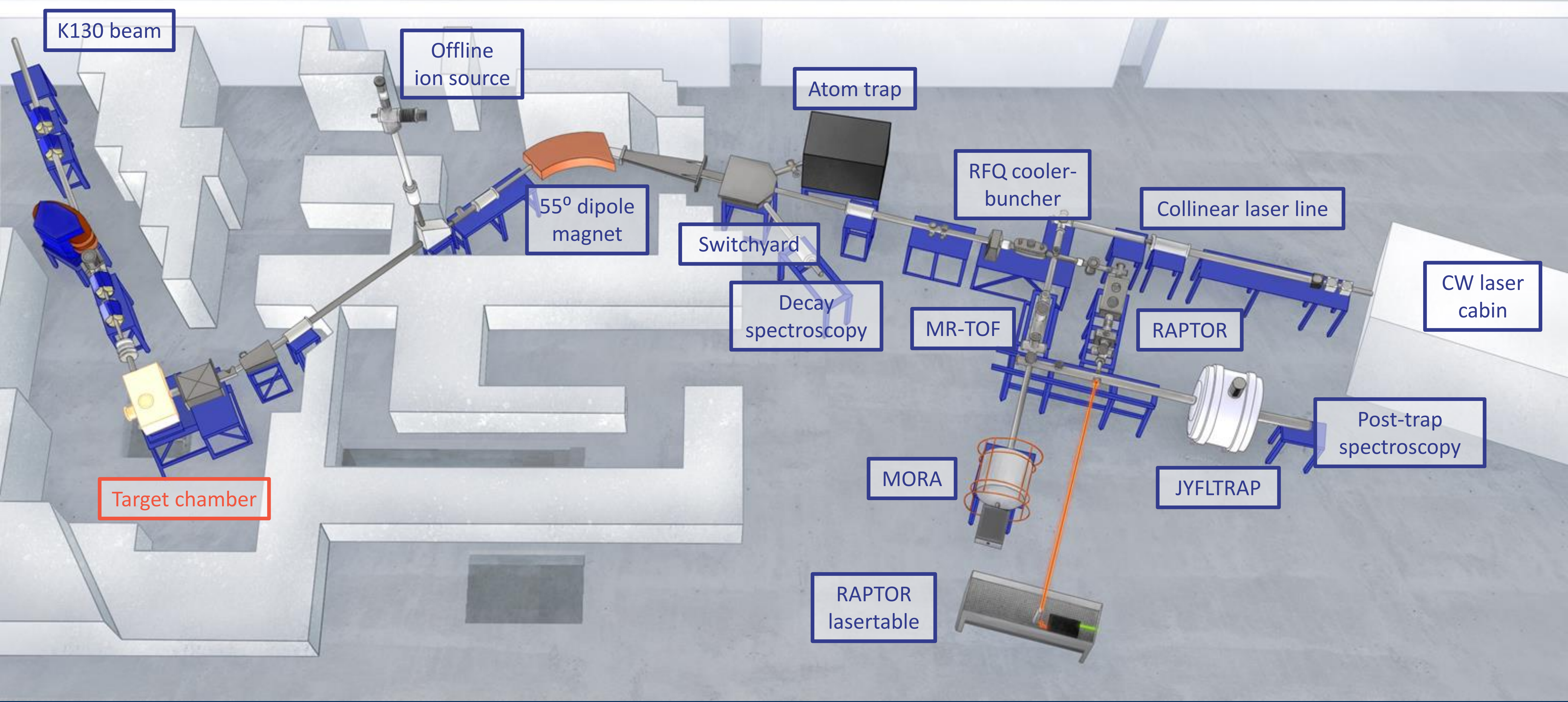

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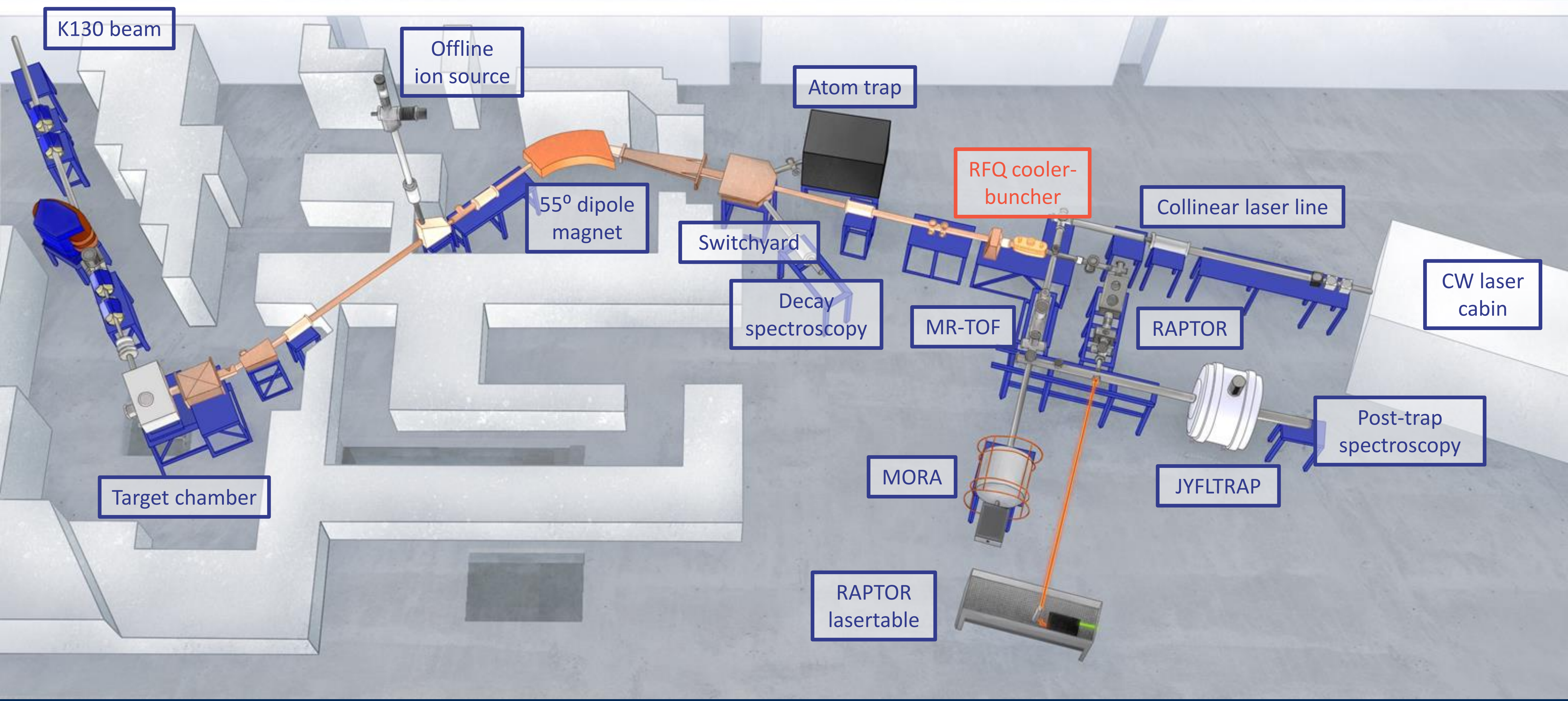
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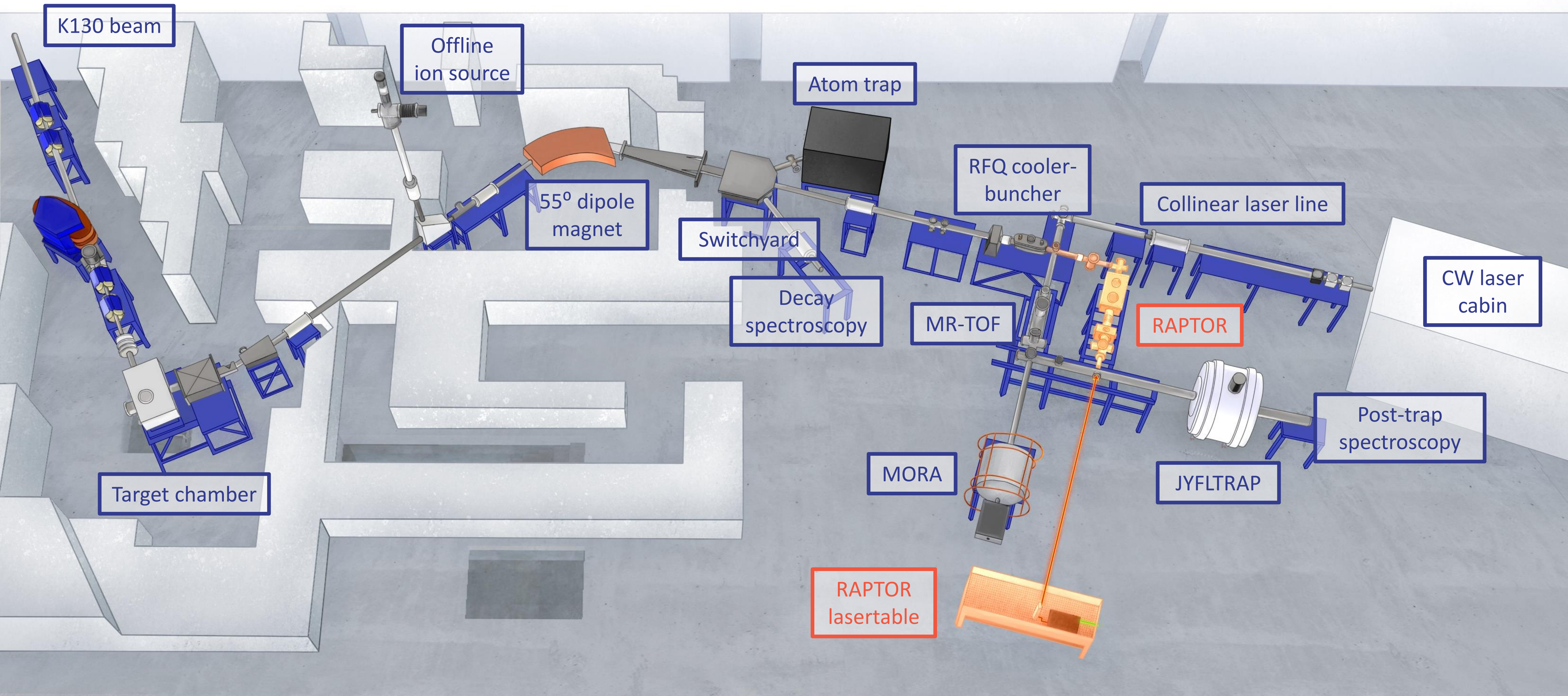
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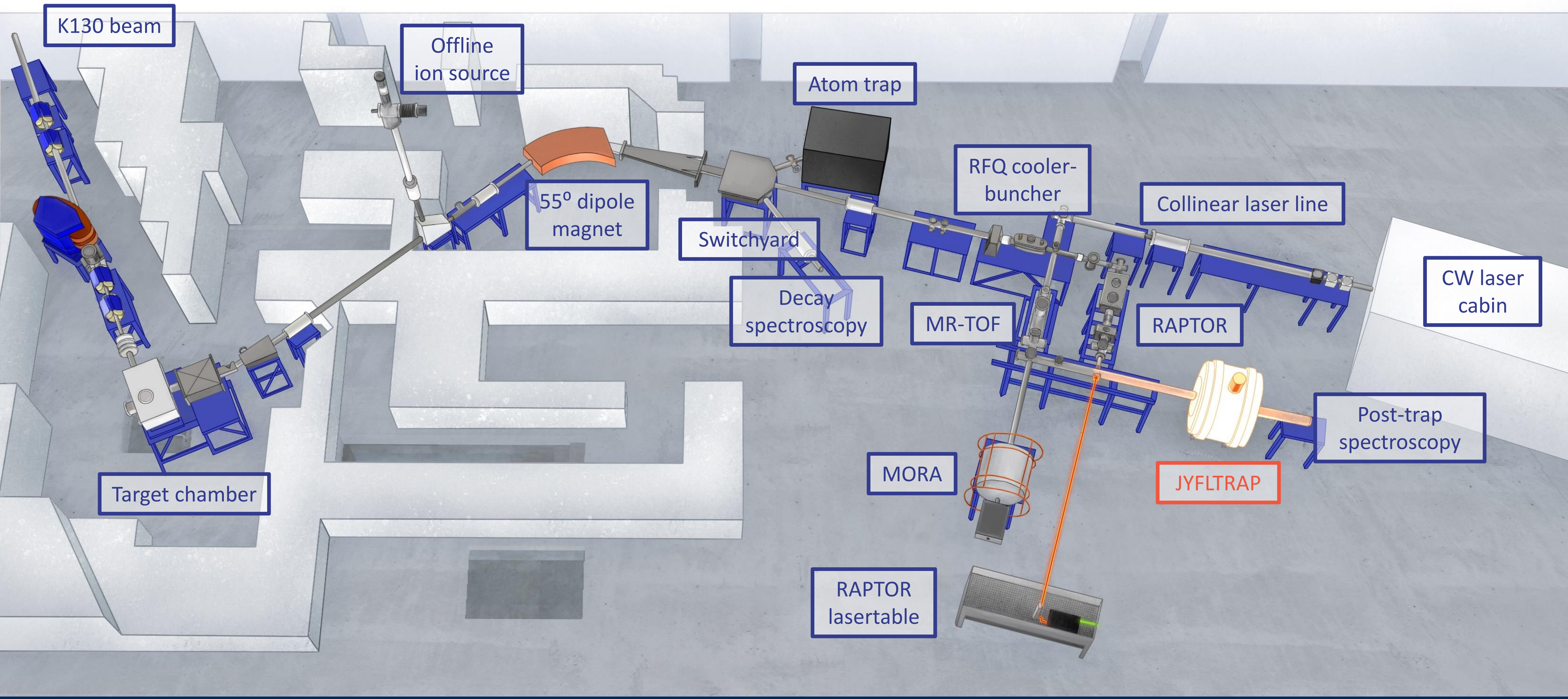

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CW laser cabin
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Target chamber
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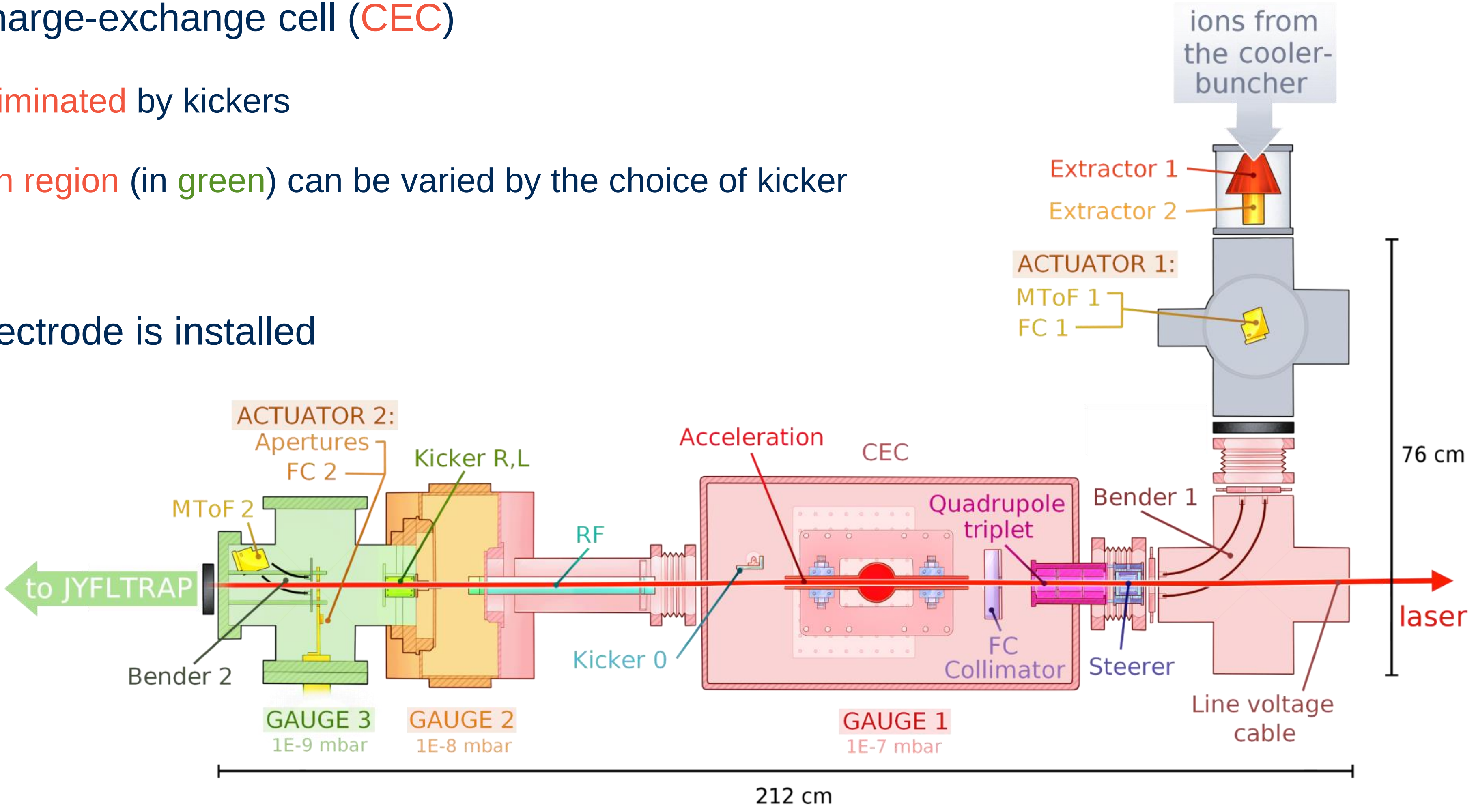
RAPTOR beamline

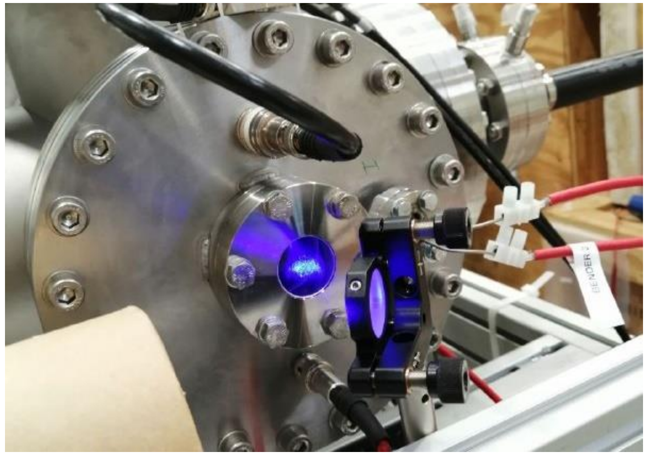
If you want to see ion beam simulations, ask for my extra slides!

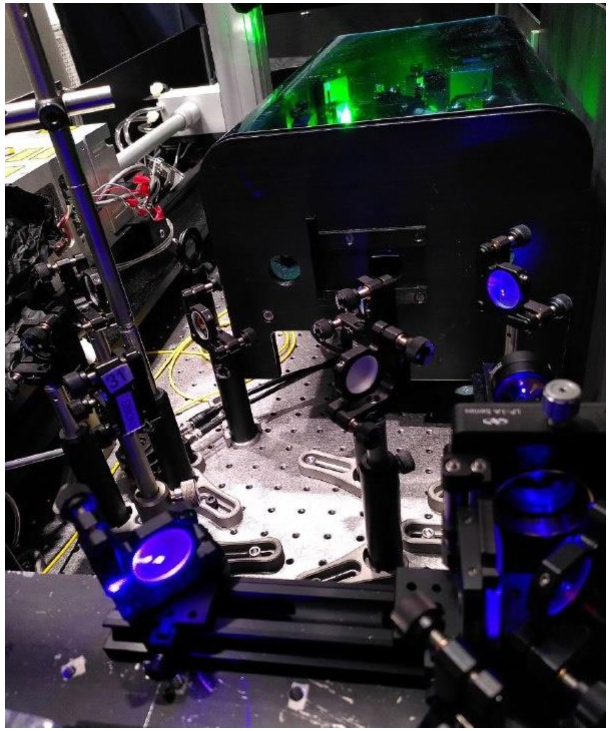
- Beam detection: Faraday cups (FC) and magnetof detectors (MToF)
- Neutralization happens in charge-exchange cell (CEC)
  - Non-neutralized beam is eliminated by kickers
  - The length of the interaction region (in green) can be varied by the choice of kicker electrodes
- For future: radiofrequency electrode is installed
  - To be used in laser-radiofrequency double-resonance method
  - A 3 orders of magnitude improvement to the experimental resolution!

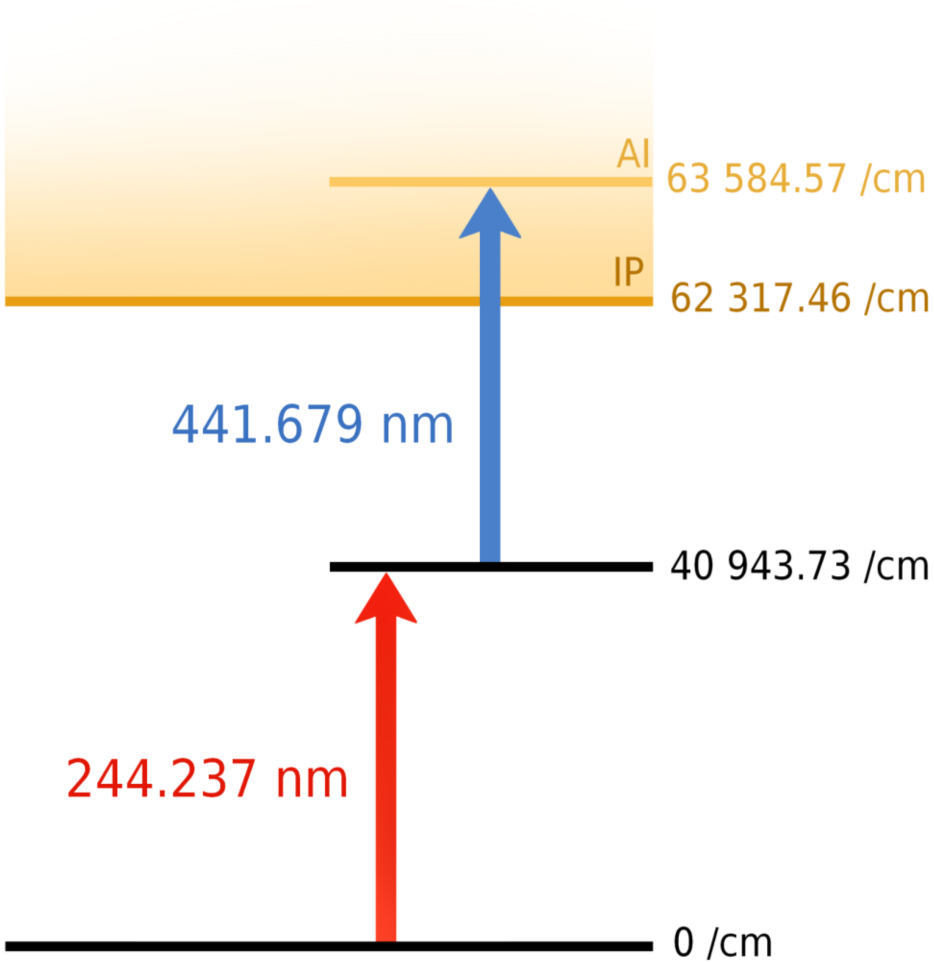


Commissioning

- Stable $^{63,65}Cu$ with using offline spark ion source
  - Bunched beam
- Lasers from RAPTOR laser table and FURIOS upstairs (anti-collinear)
  - 2-step scheme
  - Ti:Sa pulsed lasers

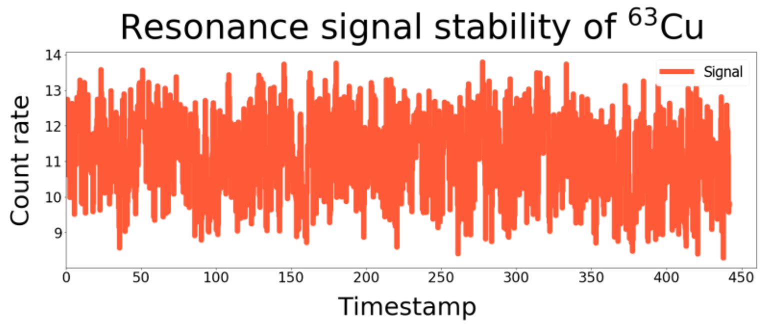


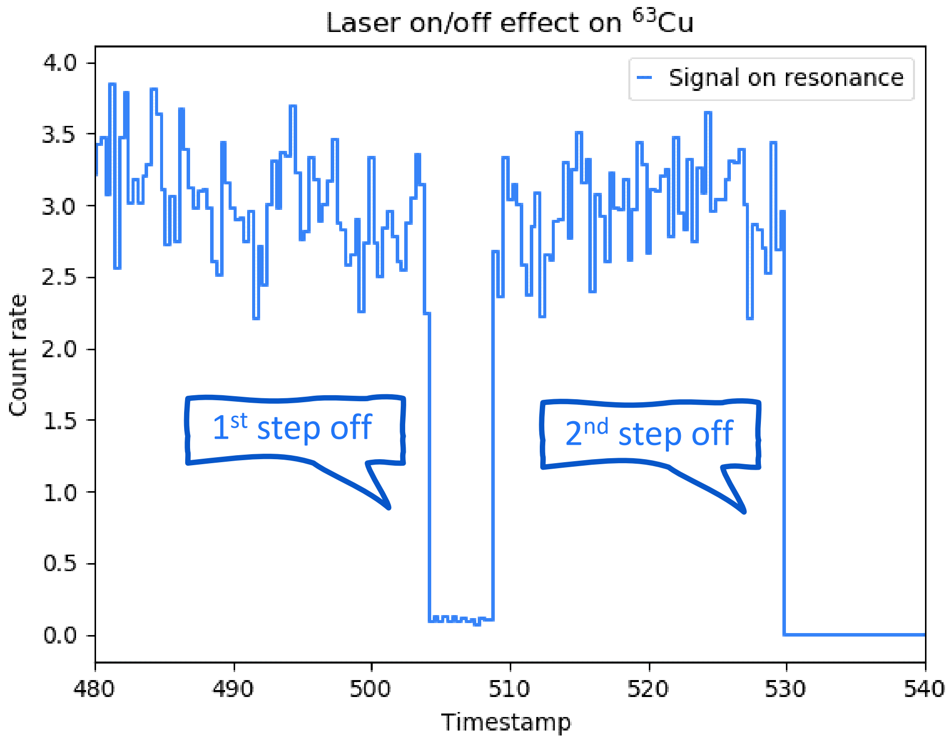


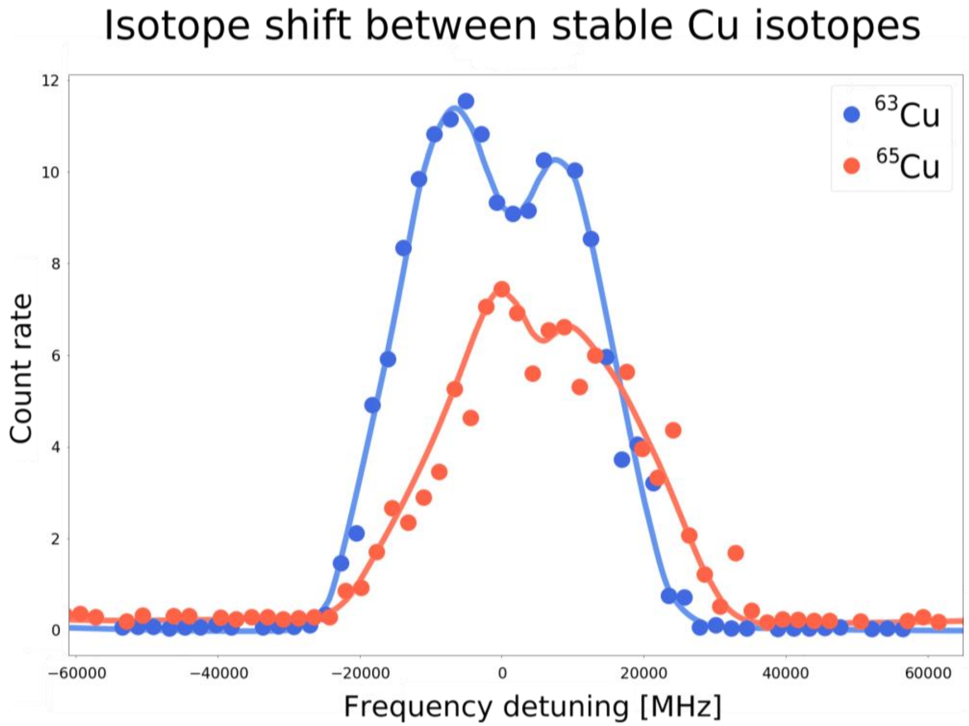


Commissioning results

- 20 GHz linewidth…
  - Dominated by laser bandwidth (broadband)
  - Tripled Ti:Sa for 1st step

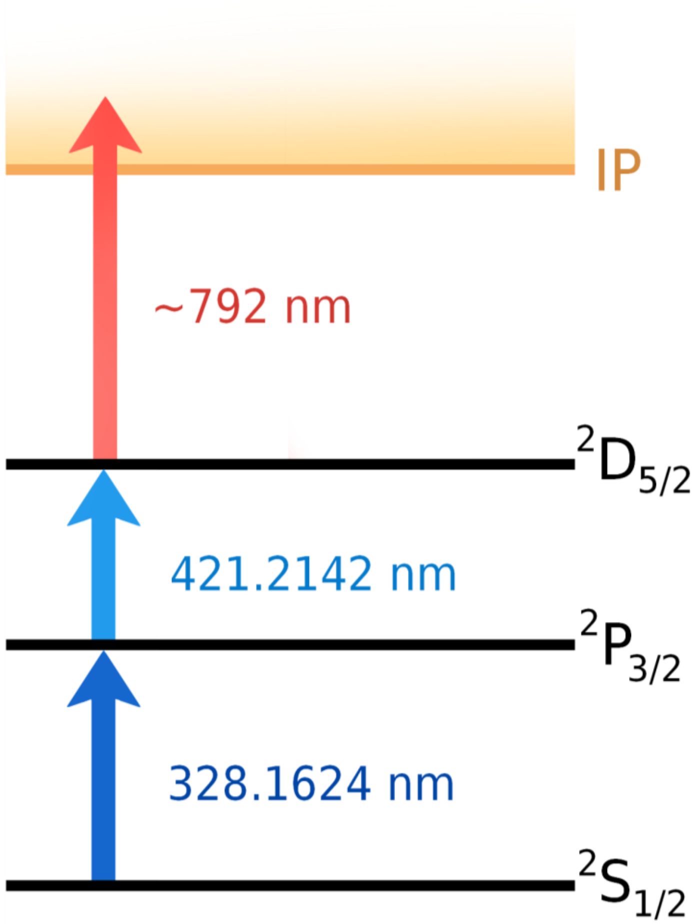






Commissioning, next step

- High-resolution stable Ag with a narrowband injection seeded laser
  - Ag neutralizes well with K (near 100%)
- Resolved HFS unlike in the Cu low-resolution test
  - Fitting to get nuclear moments
- Compare linewidths between ISOLDE/IGISOL/RAPTOR
  - Doppler contribution expected to be 50 MHz
  - If RAPTOR Ag test successful, Ag done at all 3 setups
    - → Easy to compare
    - → Important milestone allowing check of systematic uncertainties



Benchmarking with Bi

- Nuclear charge-radii of multi-quasiparticle states in $^{204\text{-}208}$Bi
  - / Measured at ISOLDE: ^{187,188,189,191}Bi *
  - / Short-lived isomers not yet studied ($t_{1/2}$ < 13 ms) as they won't come out of target ion-source in time *
- In several other elements the measurement of charge radii of multi-quasiparticle isomers has yielded surprising results **
  - / Quadrupole deformation larger in isomer v.s. g.s.
  - / Charge radii smaller in isomer v.s. g.s.
  - ➢ Quantitative explanation of this phenomenon still not available

Isotope	Spin	Lifetime	Cross section	Reaction	μ	Q	R
^{208}Bi	5^+	368 ky	270 mbarn	17 MeV, ^{nat}Pb(d,xn)^{208}Bi	✓	✓	✓
	10^-	2.58 ms			✓	X	X
^{207}Bi	$9/2^-$	31.20 y	500 mbarn	25 MeV, ^{nat}Pb(p,xn)^{208}Bi	✓	✓	✓
	$21/2^+$	182 μs			✓	✓	X
^{206}Bi	6^+	6.243 d	500 mbarn	25 MeV, ^{nat}Pb(p,xn)^{208}Bi	✓	✓	✓
	10^-	890 us			✓	✓	X
^{205}Bi	$9/2^-$	15.31 d	400 mbarn	25 MeV, ^{nat}Pb(p,xn)^{208}Bi	✓	✓	✓
^{204}Bi	6^+	11.22 h	400 mbarn	45 MeV, ^{nat}Pb(p,xn)^{208}Bi	✓	✓	✓
	10^-	13.0 ms			✓	✓	X
	17^+	1.07 ms			X	X	X

* A. Barzakh et al., Phys. Rev. Lett. 127 (2021) 192501

** M.L Bissell et al., PLB 645(4):330–334, 2007

Cross sections from TALYS calculations

Benchmarking with Bi

- Why Bi? → Close to doubly magic nucleus (minimal deformation)
  - For a system like this, any shape change in isomer should only increase nuclear radius
  - If a decrease is measured → may be explained by reduced pairing effects
- Once this new data on Bi isomers is obtained the role of different physical/nuclear structural effects may be isolated better
  - Combining with most recent nuclear theory
    - → May allow us to understand the reduction in nuclear charge radius of multi-quasiparticle isomers

Isotope	Spin	Lifetime	Cross section	Reaction	μ	Q	R
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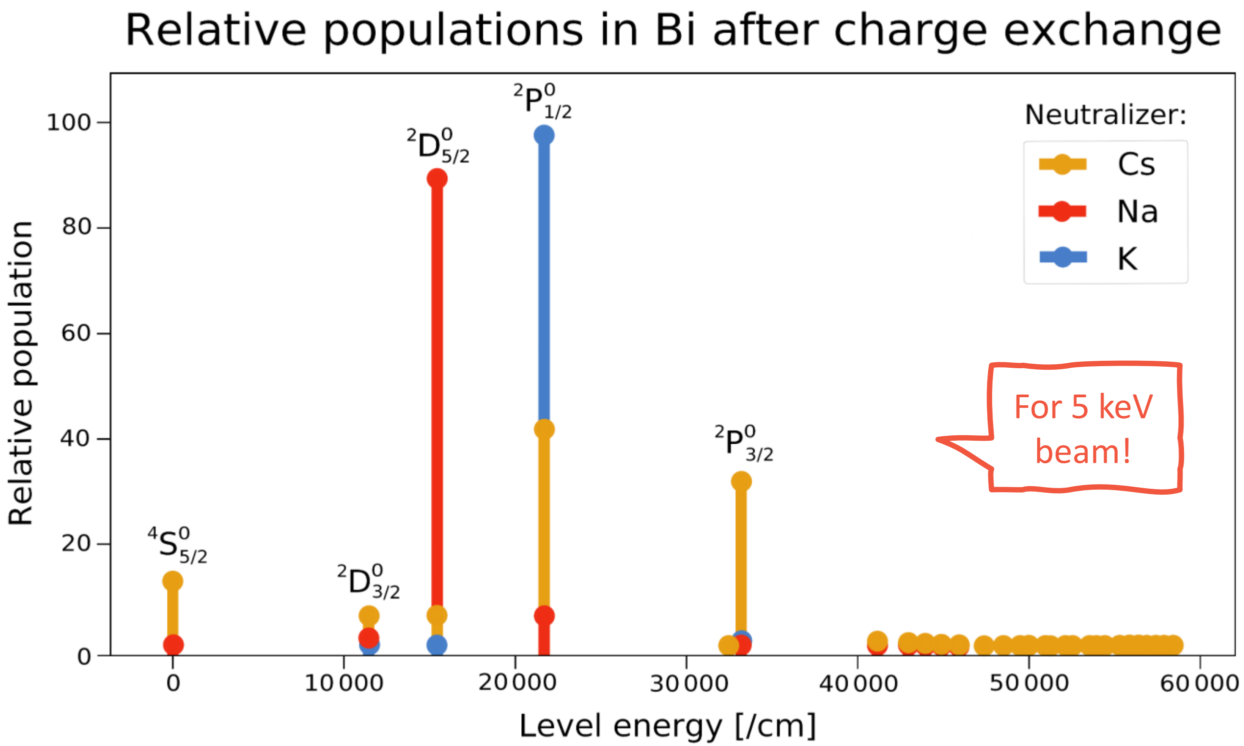
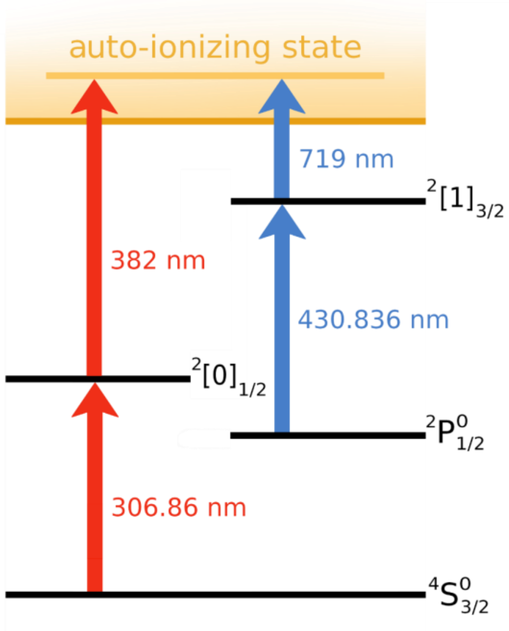
	10^-	13.0 ms			✓	✓	X
	17^+	1.07 ms			X	X	X

Cross sections from TALYS calculations

Benchmarking with Bi

- Variable beam energy in RAPTOR allows for more efficient charge-exchange
  - With a suitable neutralizer, almost 100% efficient population transfer into a state of interest is possible
    - → Experimental efficiency improves

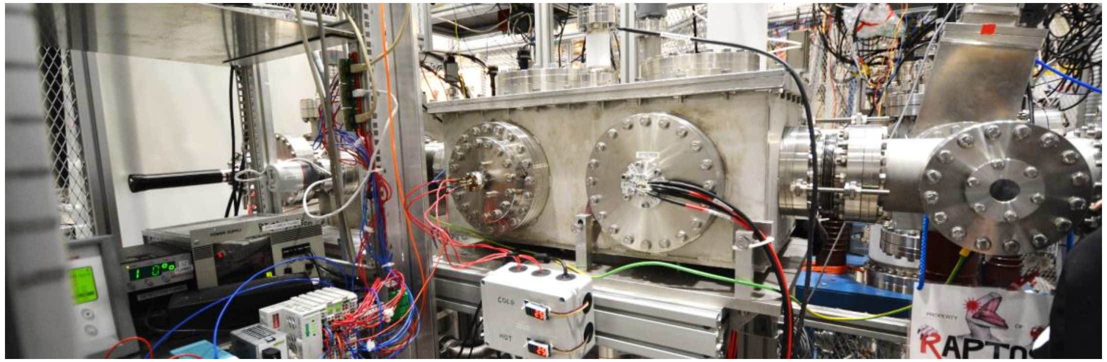


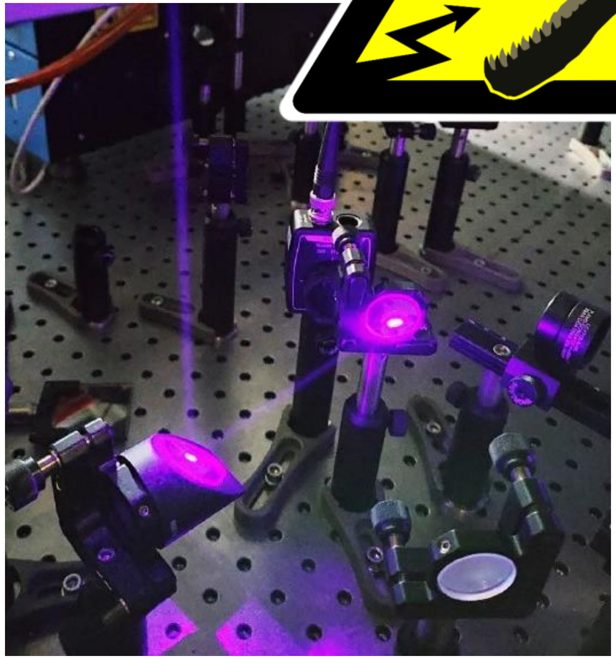


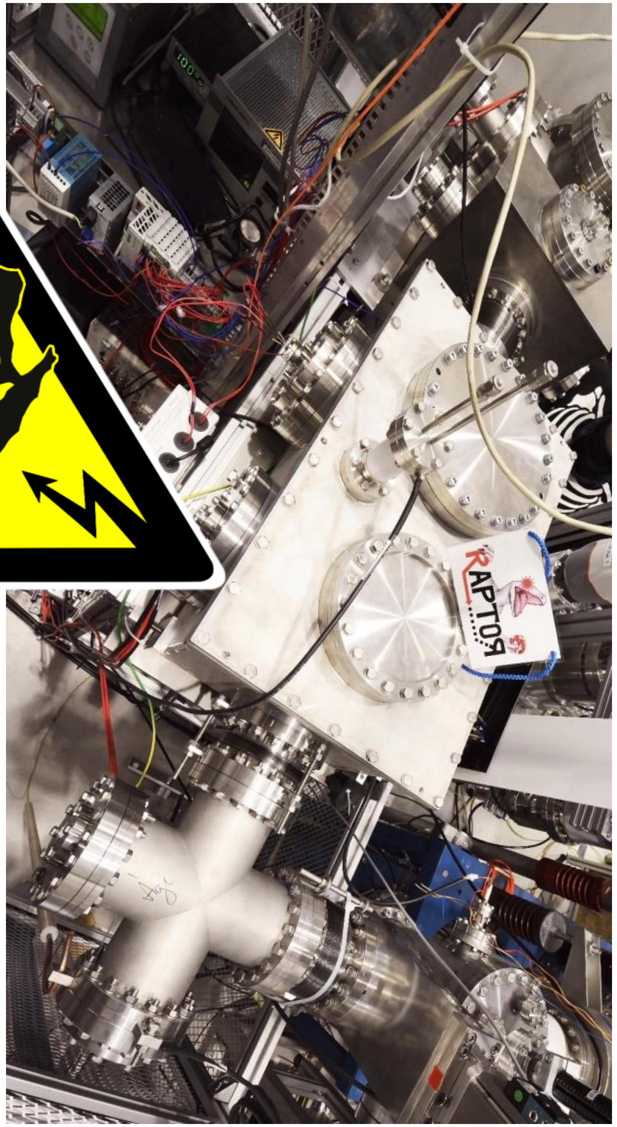
- Bi has 3 long-lived metastable atomic levels suitable for spectroscopy
  - Good sensitivity to mean-squared charge radii
  - Good ionization efficiency
  - Dipole and quadrupole moments can be extracted based on existing literature

Summary

- RAPTOR is a new ‘tabletop’ CRIS setup at JYFL, Finland
  - Variable and low beam energy
  - Penning trap possibilities
- Commissioning is ongoing: first successful stable element test done!
  - Next up is high resolution test
- After commissioning the aim is for radioactive Bi *
  - Nuclear charge-radii of multi-quasiparticle states
  - Ideal test case for RAPTOR





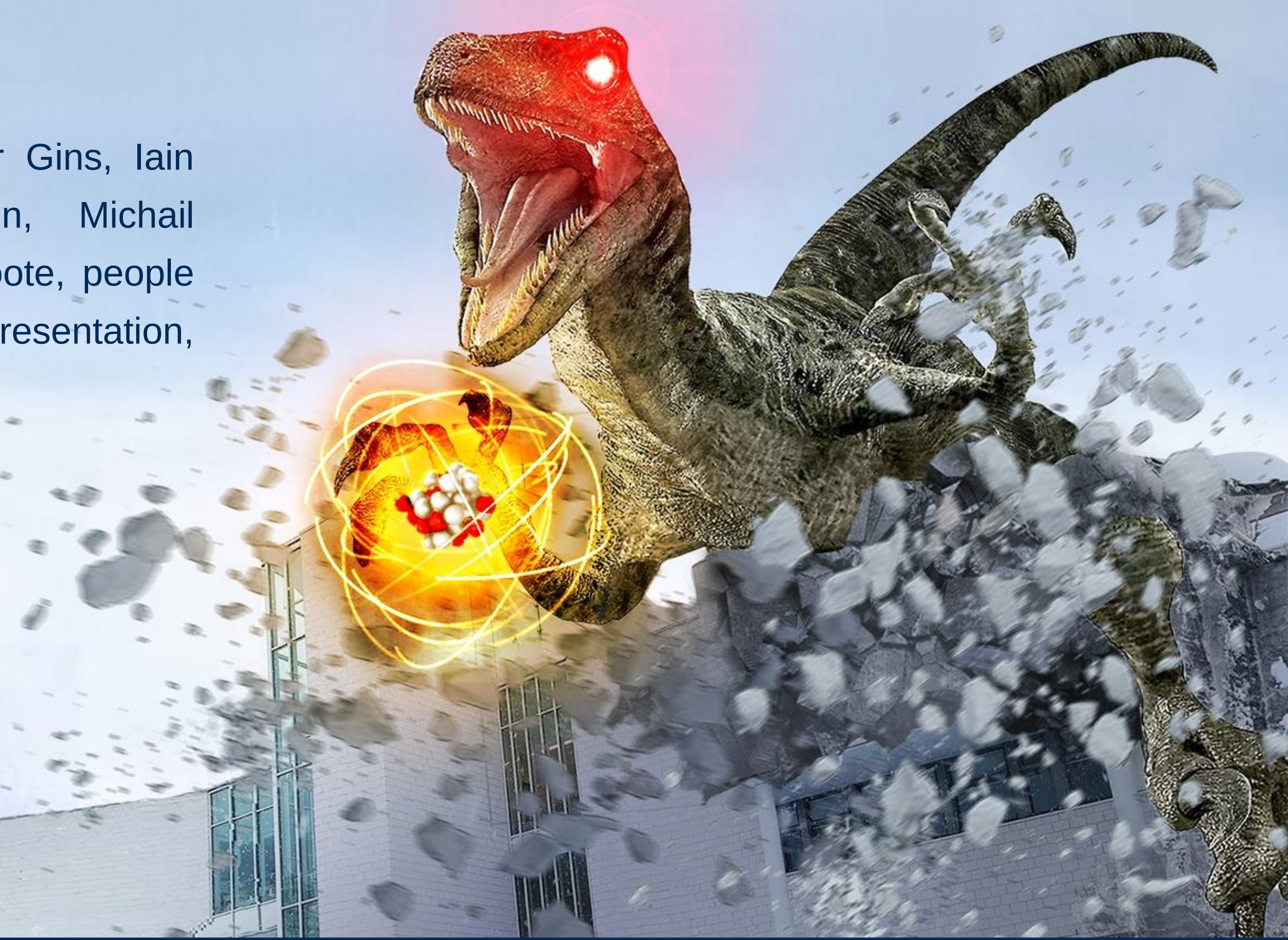


* Proposal accepted by JYFL-PAC, expected to run in 2023

Thank you for your attention!

Special thanks to:

Andrea Raggio, Mikael Reponen, Wouter Gins, Iain Moore, Jan Sarén, Ilkka Pohjalainen, Michail Athanasakis-Kaklamanakis, Ruben de Groote, people in the audience paying attention to this presentation, and of course the organizers!



volunteer here to do the Bi atomic theory:

sopikuja@jyu.fi

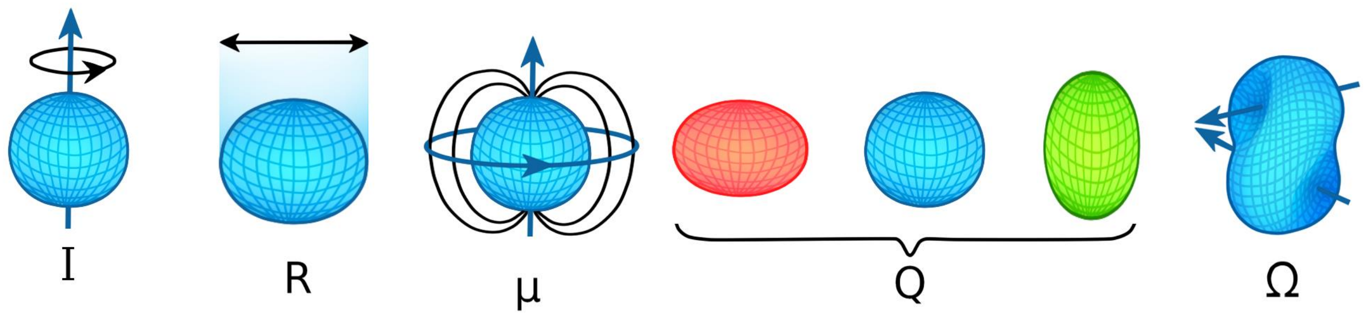
EXTRA: Nuclear properties from HFS

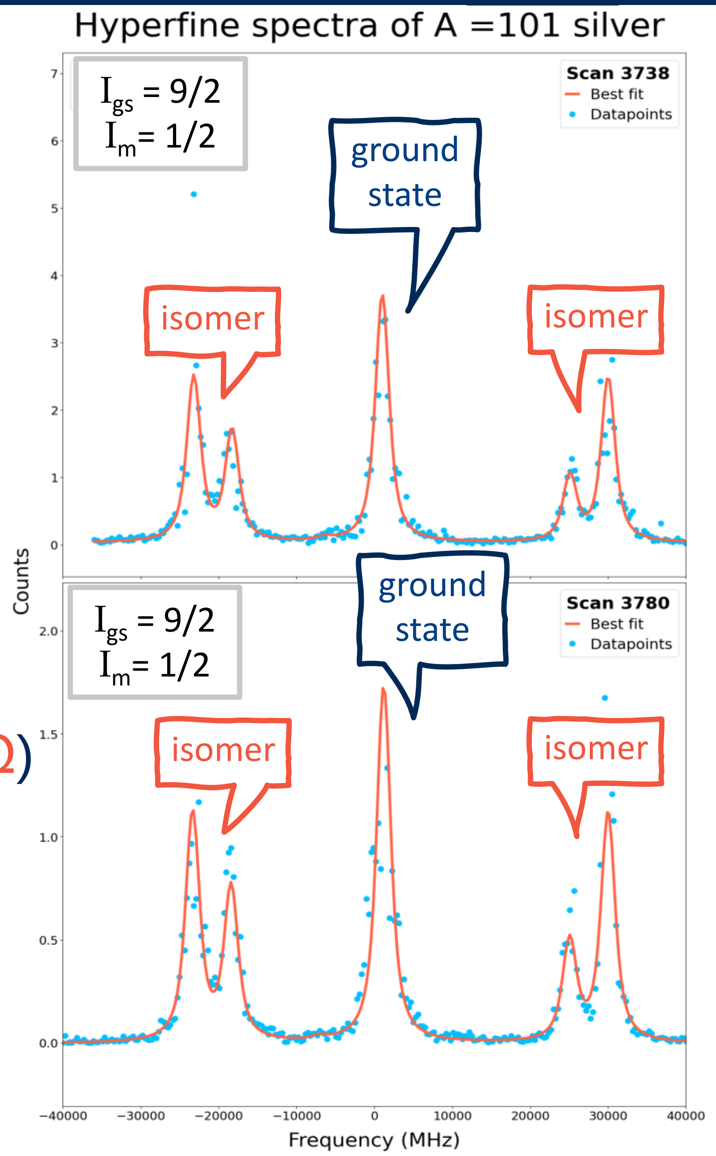
- Fit on HF spectra → obtain HF constants A,B,(C)
  - Combine with atomic calculations: corresponding nuclear electromagnetic moments

$$A = \frac{\mu_I}{IJ} \langle JJ| T_1^{(e)} |JJ\rangle$$

$$B = 2eQ \langle JJ| T_2^{(e)} |JJ\rangle \qquad C = -\Omega \langle JJ| T_3^{(e)} |JJ\rangle$$

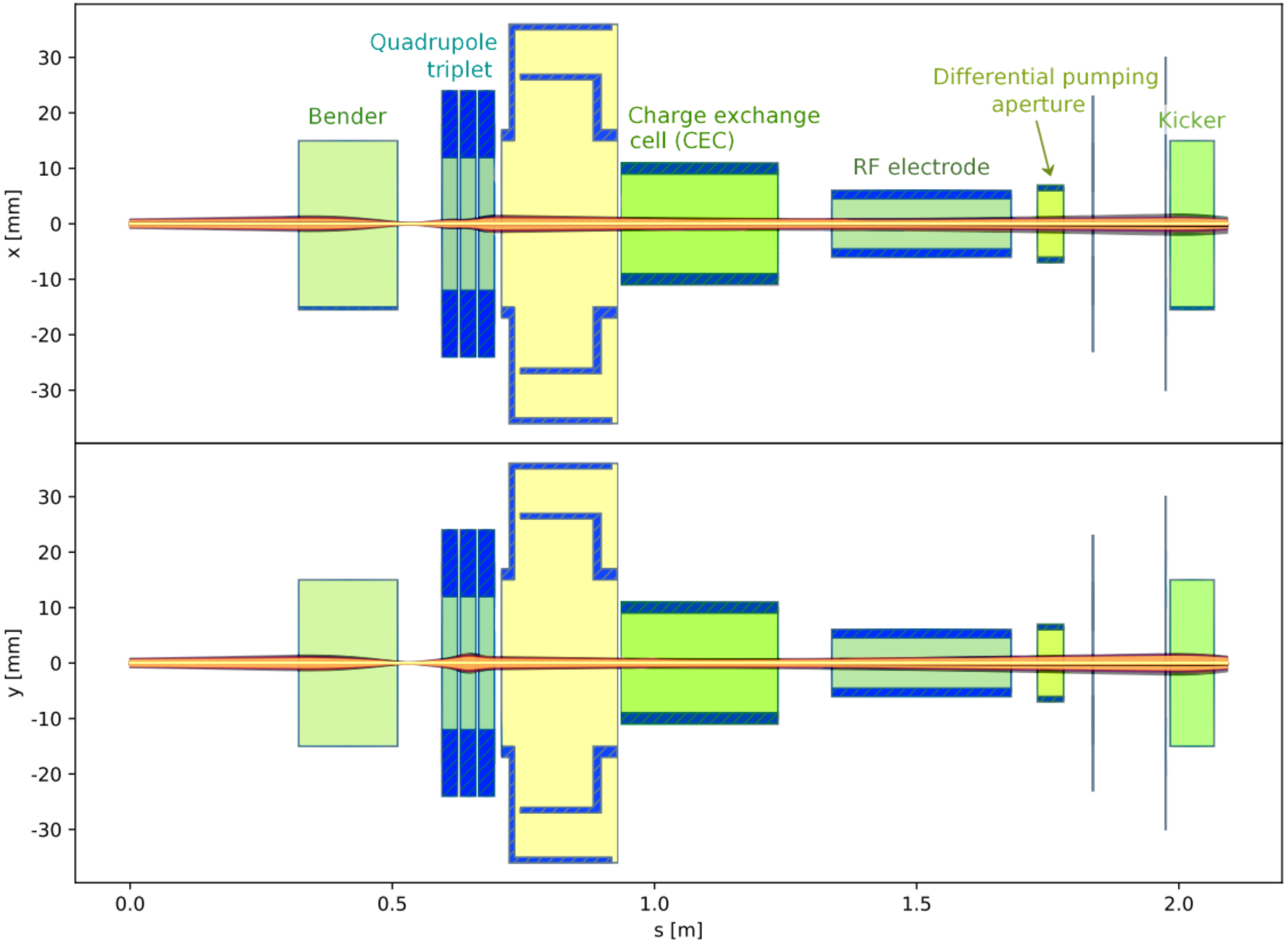
➢ Nuclear spin I, mean-squared charge radius δ<R²>, magnetic dipole moment μ, electric quadrupole moment Q, (magnetic octupole moment Ω)





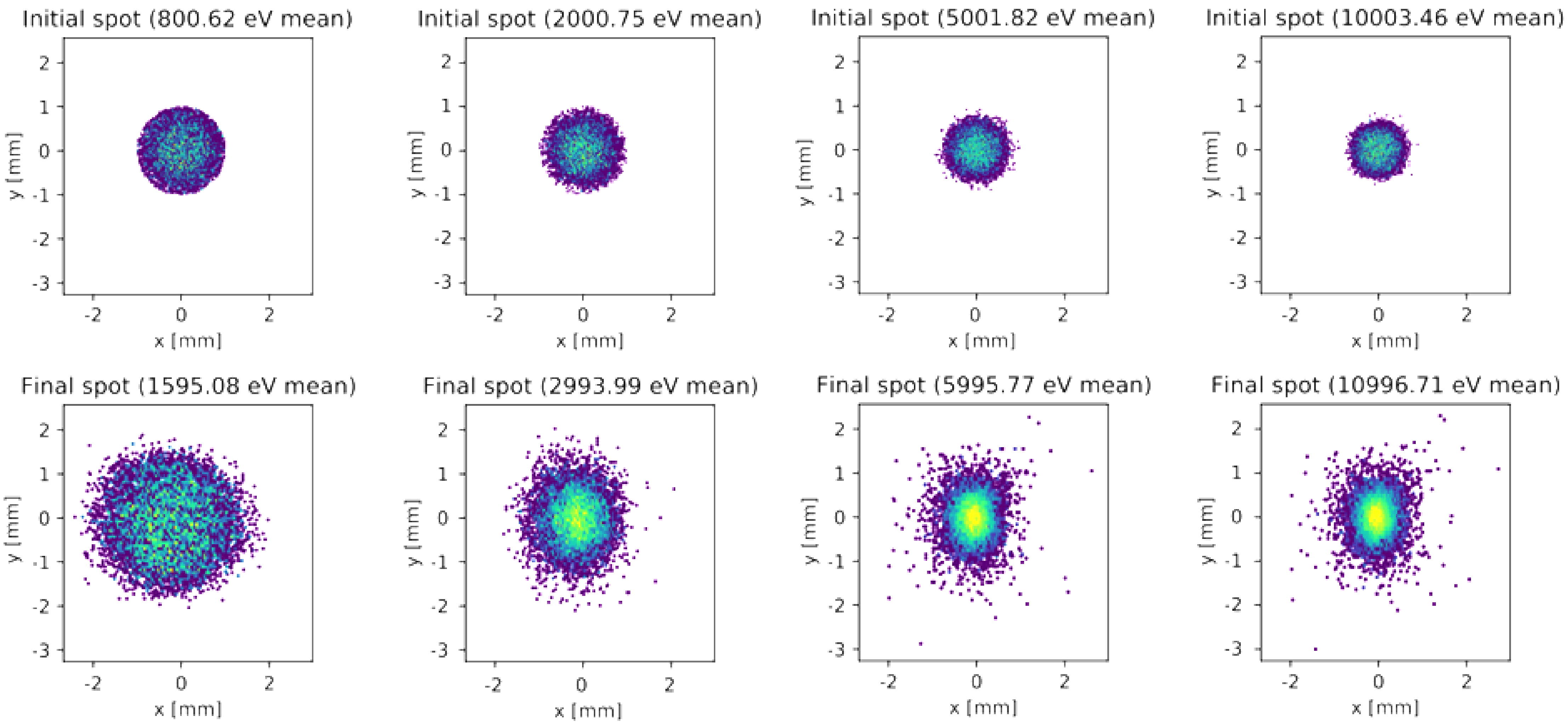
EXTRA: Ion beam simulations

- 95% envelope of beam in horizontal and vertical directions
- Different colors in beam represent different initial beam energies
- Starting conditions of the beam are results of simulations from RFQ through the RFQ chamber and extractor with some settings
- Even for a few keV energy good transport efficiency is expected
  - Downside is the bigger beam spot size



EXTRA: Ion beam simulations

- Beamspot sizes with different initial energies



Figures edited from simulations done by W. Gins in SIMION

EXTRA: Voltage simulations

- Electromagnetic field simulations for 5 keV beam