Production and Manipulation of Radioactive Ion Beams

Almost all activities to be discussed can naturally be adapted for EURISOL

Iain Moore

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Rare isotope beam preparation and manipulation

- Beam purity — *mass sep., chemical selectivity*
- Emittance — *cooling*
- Energy spread — *cooling & trapping*
- Temporal structure — *pulsing/bunching*
- Ionic/atomic state — *optical pumping*
- Charge state — *ionization/breeding*

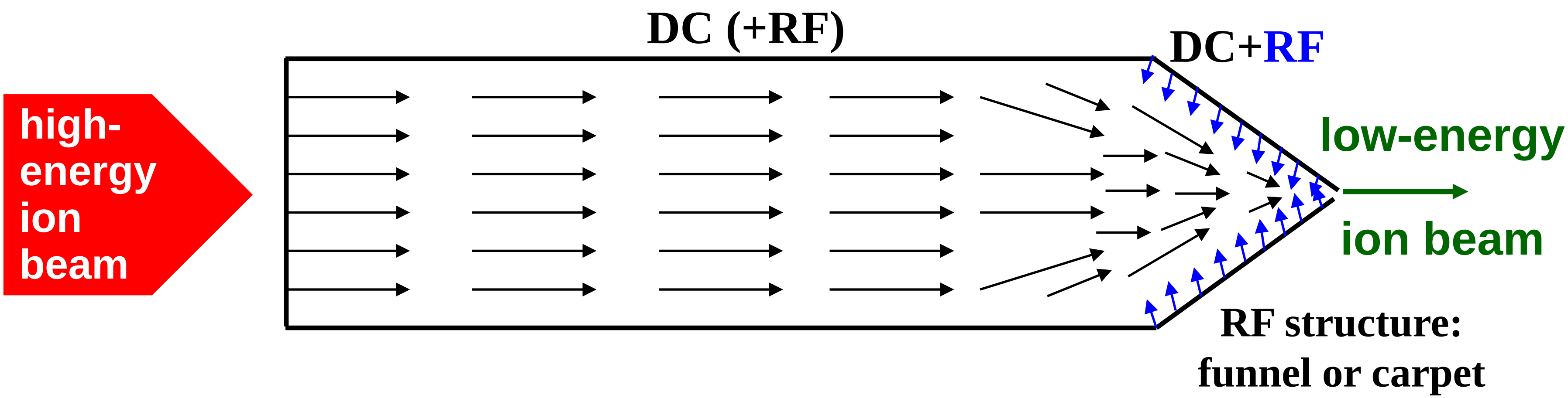
A personal viewpoint from recent developments!

RIBs: from high to low energy

Gas catchers: universal devices capable of extracting recoils from essentially all production mechanisms into a low-energy beam.

GOAL

High-precision experiments with exotic nuclei almost at rest (production by projectile fragmentation / fission)



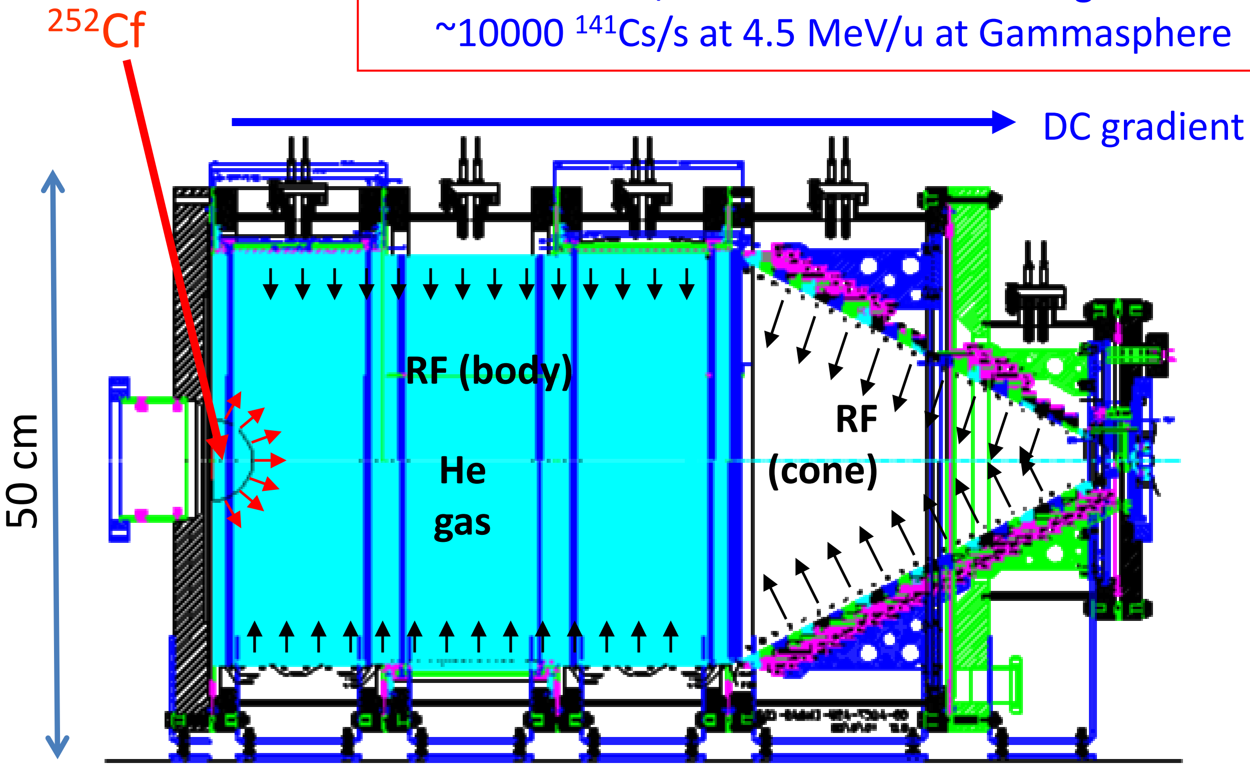
- universal (all but He) and fast production (~5-50 ms)
- high selectivity (inherent via in-flight separation)
- high efficiency (though element dependent)
- could be used in connection with EURISOL !

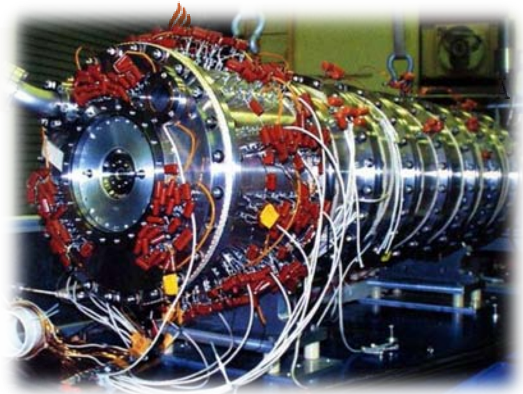
Novel high intensity gas catchers

CARIBU

Argonne NATIONAL LABORATORY

- low-energy and re-accelerated RIBs (masses, decay and laser spectroscopy)
- 80 mCi ^{252}Cf source, 70 isotopes for PAC expts.
- 340 mCi source (September 2012)
- Yield with new source 4-5× previous source: ~20000 ^{141}Cs/s at 27+ out of the charge breeder, ~10000 ^{141}Cs/s at 4.5 MeV/u at Gammasphere





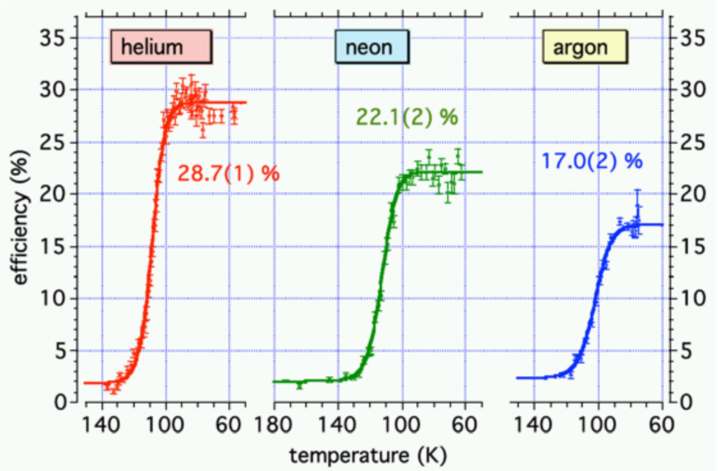
G. Savard et al., Int. J. of Mass. Spec. 251 (2006) 252
http://www.phy.anl.gov/atlas/caribu/ATLAS_Cf_upgrade.pdf

UHV cells to cryogenic catchers (~70K)

Max-Planck-Institut für Kernphysik

<u>Advantages</u>

- Ultra-pure helium
  - Ideal for ion survival
  - No formation of molecules/adducts
- 2+ charge state
  $\rightarrow$ shorter extraction times

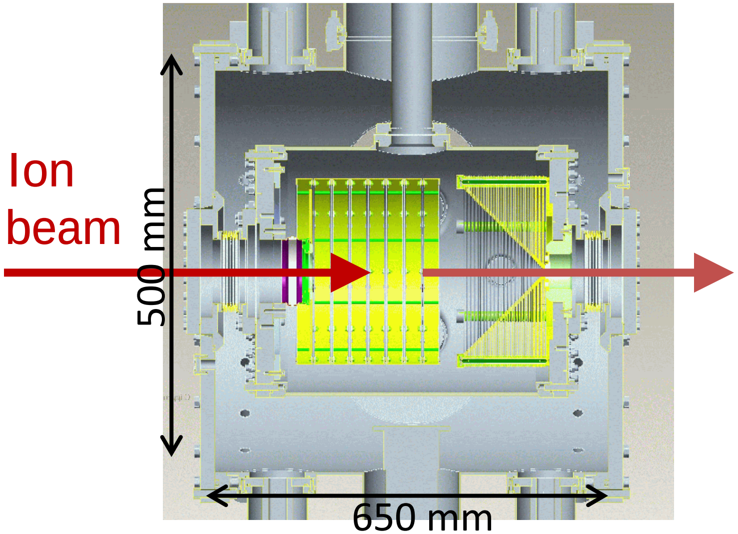


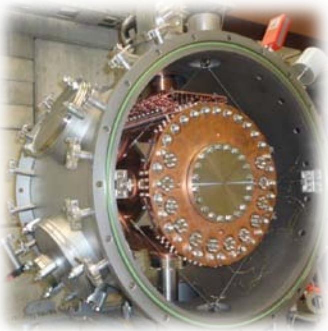
Transport efficiency of α-decay recoil ions in a closed chamber

P. Dendooven et al., NIMA 558 (2006) 580

A. Saastamoinen, I.M. et al., NIMA 685 (2012) 70

A cryogenic gas cell for SHIPTRAP





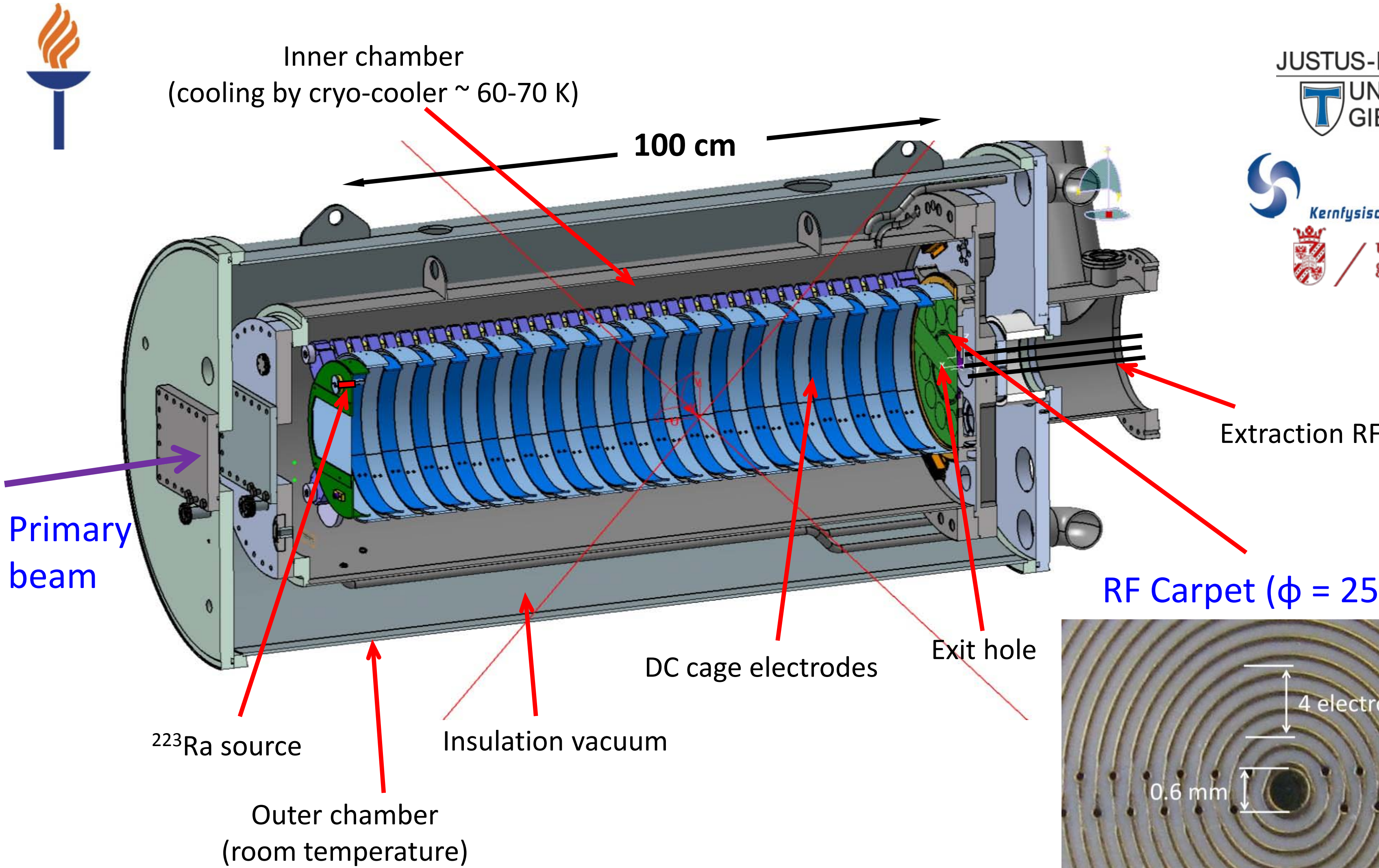
- Fully assembled, rf ready
- Cooled to 30K, at 50 mbar room temp equivalent
- ^{223}Ra recoil source tests
- Ready for on-line use

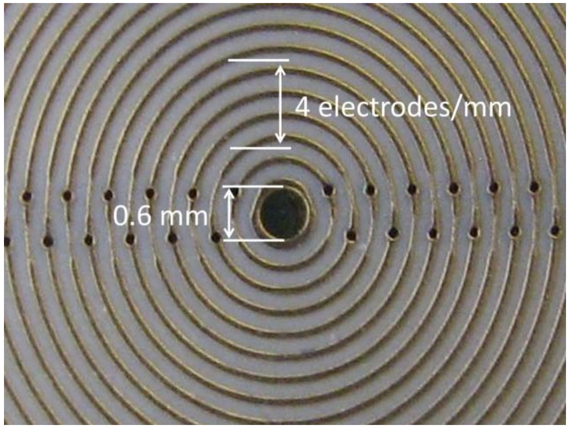
S. Eliseev, C Droese et al.

HELMHOLTZ ASSOCIATION

S. Eliseev et al., Nucl. Instr. and Meth. B 266 (2008) 4475–4477

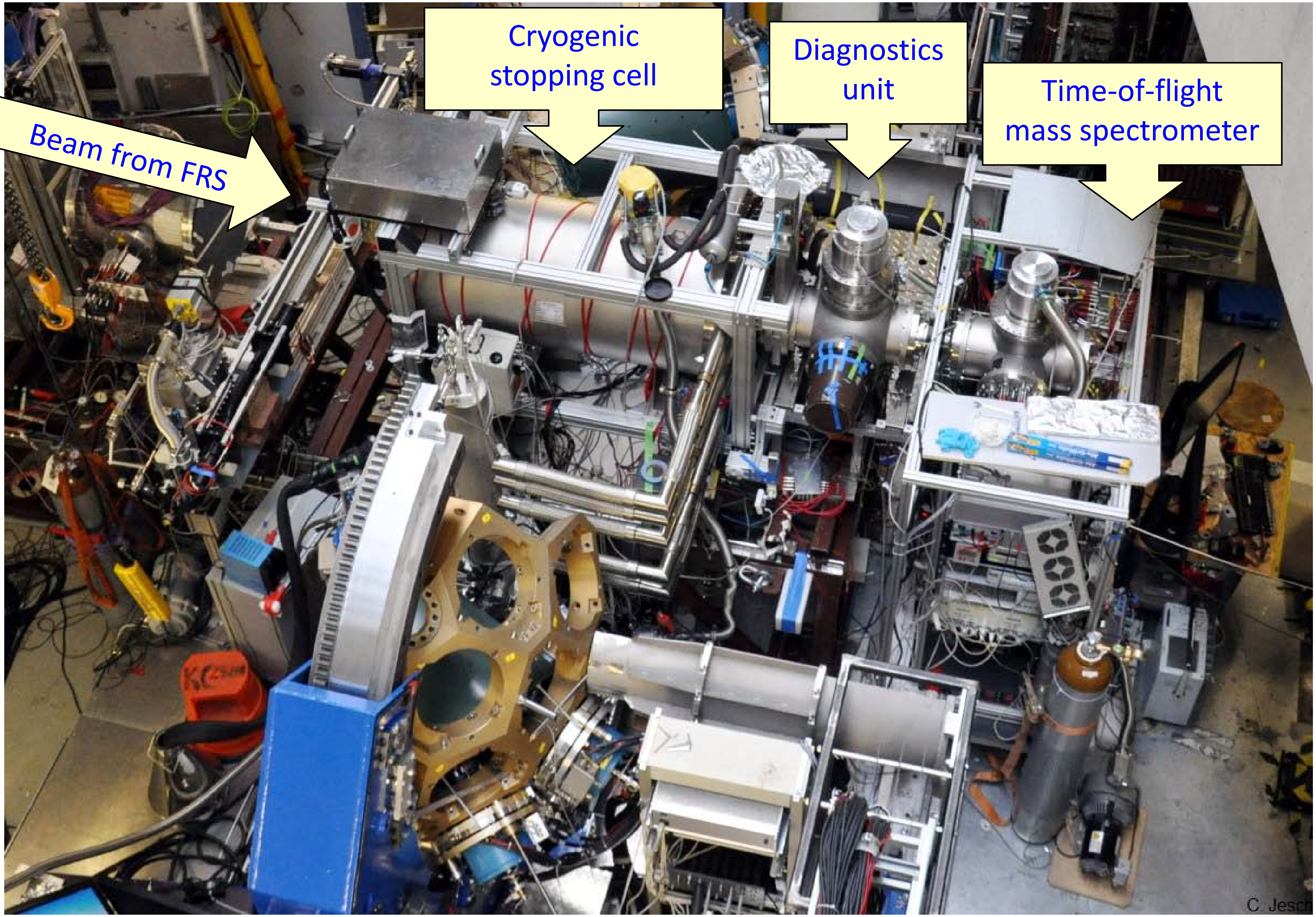
Cryogenic stopping cell design for S-FRS



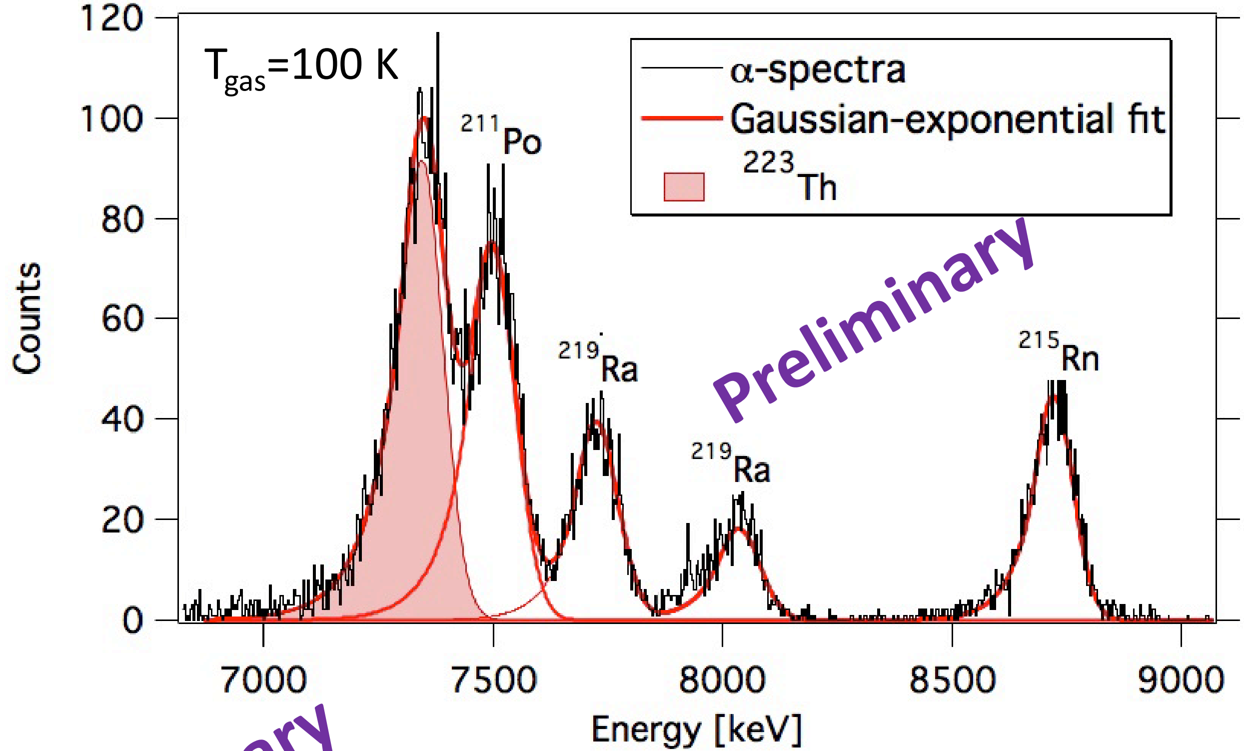


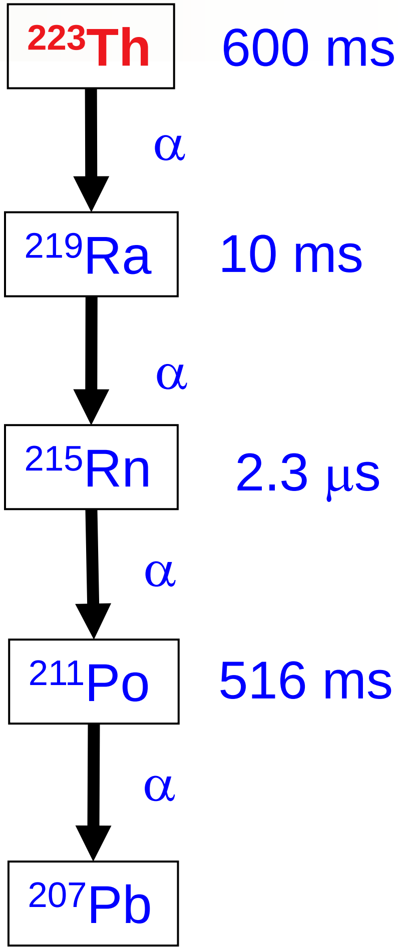
M. Ranjan et al., Europhys. Lett. 96 (2011) 52001
M.P. Reiter, Master Thesis, Justus-Liebig-Universität Gießen (2011)

On-line experiments: October 2011, July 2012



Stopping cell performance

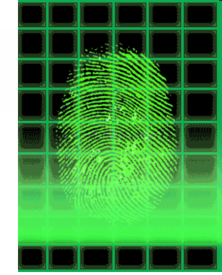


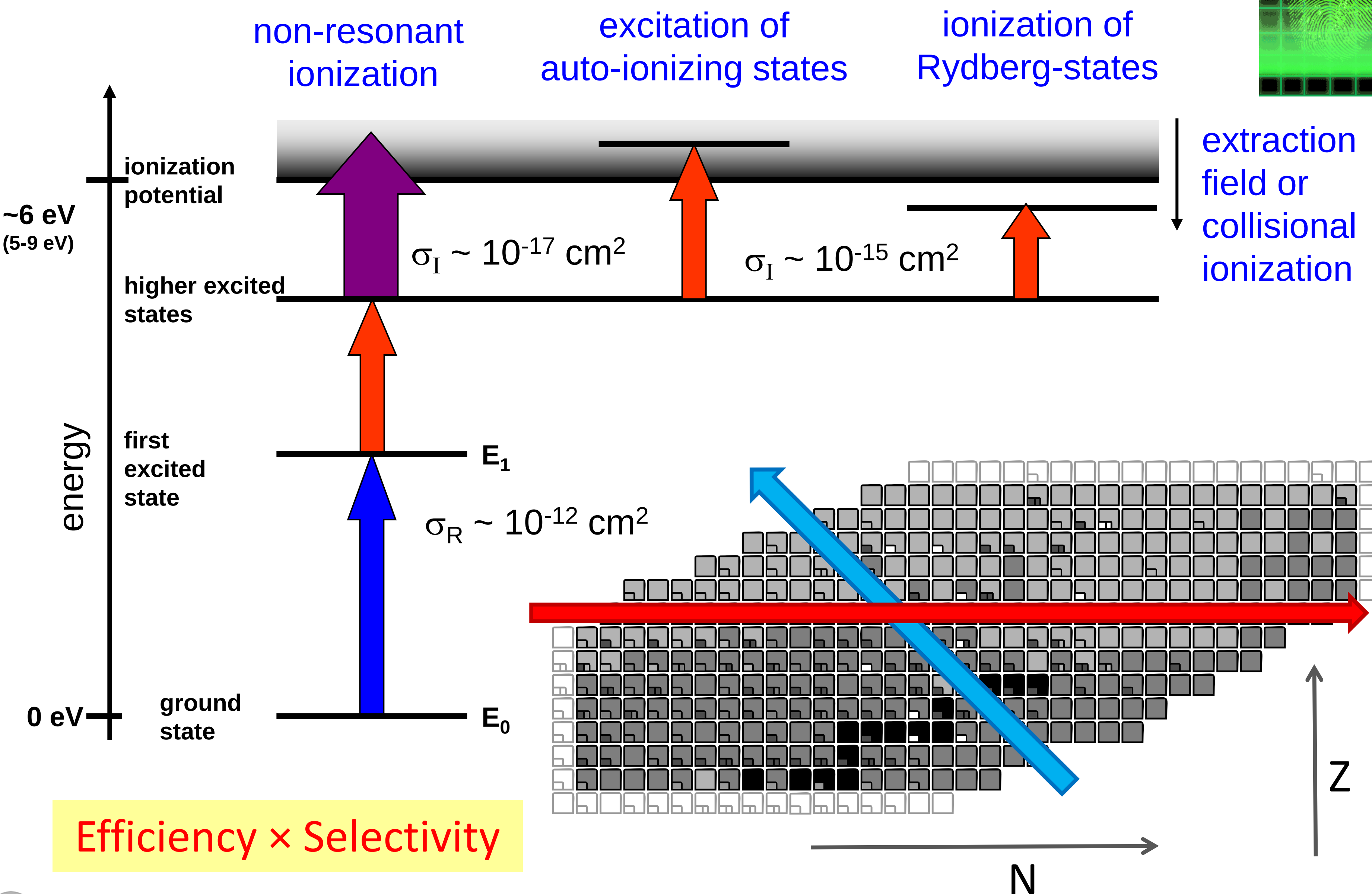


	^{223}Th
Stopping efficiency	(27 ± 3)%
Survival and extraction efficiency	(43 ± 9)%
Total efficiency	(12 ± 2)%

- Almost 2× > density than other rf- cells
- Mean extraction time from centre of cell ~25 ms
- Intensity limitation not expected for most Super-FRS beams

Selective resonant laser ionization

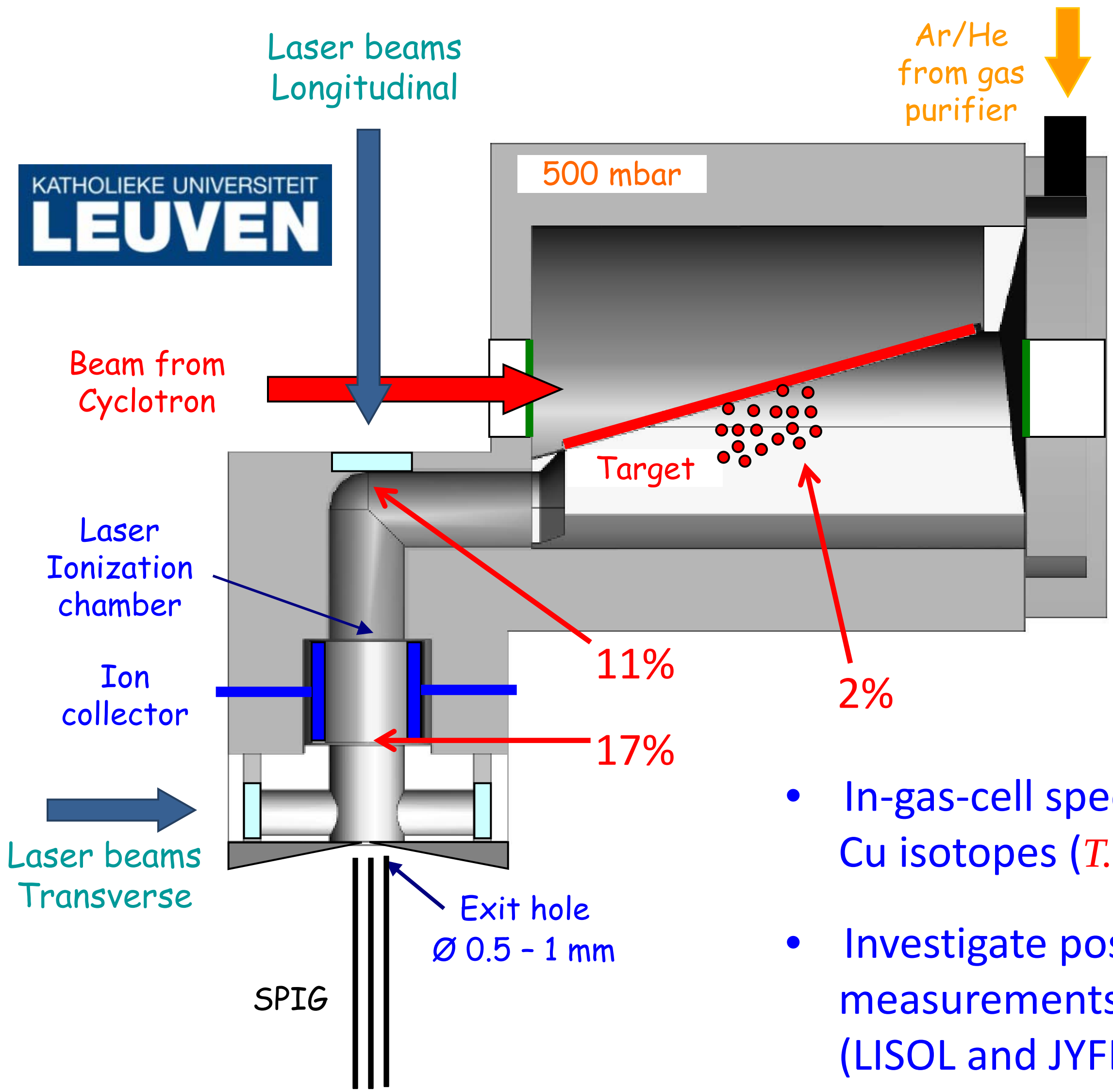




Efficiency × Selectivity

Gas cell selectivity and spectroscopy

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ



Separation of stopping and laser ionization volumes improves:

- laser ionization efficiency for high cyclotron beam current
- Ion selectivity

Production of ^{94}Rh
Selectivity:
[Laser(on)/Laser(off)]
Ion Collector OFF = 450
Ion Collector ON = 2200

- In-gas-cell spectroscopy of neutron deficient Cu isotopes (*T. Cocolios et al., PRL 103 (2009) 102501*)
- Investigate possibility of performing similar measurements near *N*=*Z* line around *A*=100 (LISOL and JYFL)

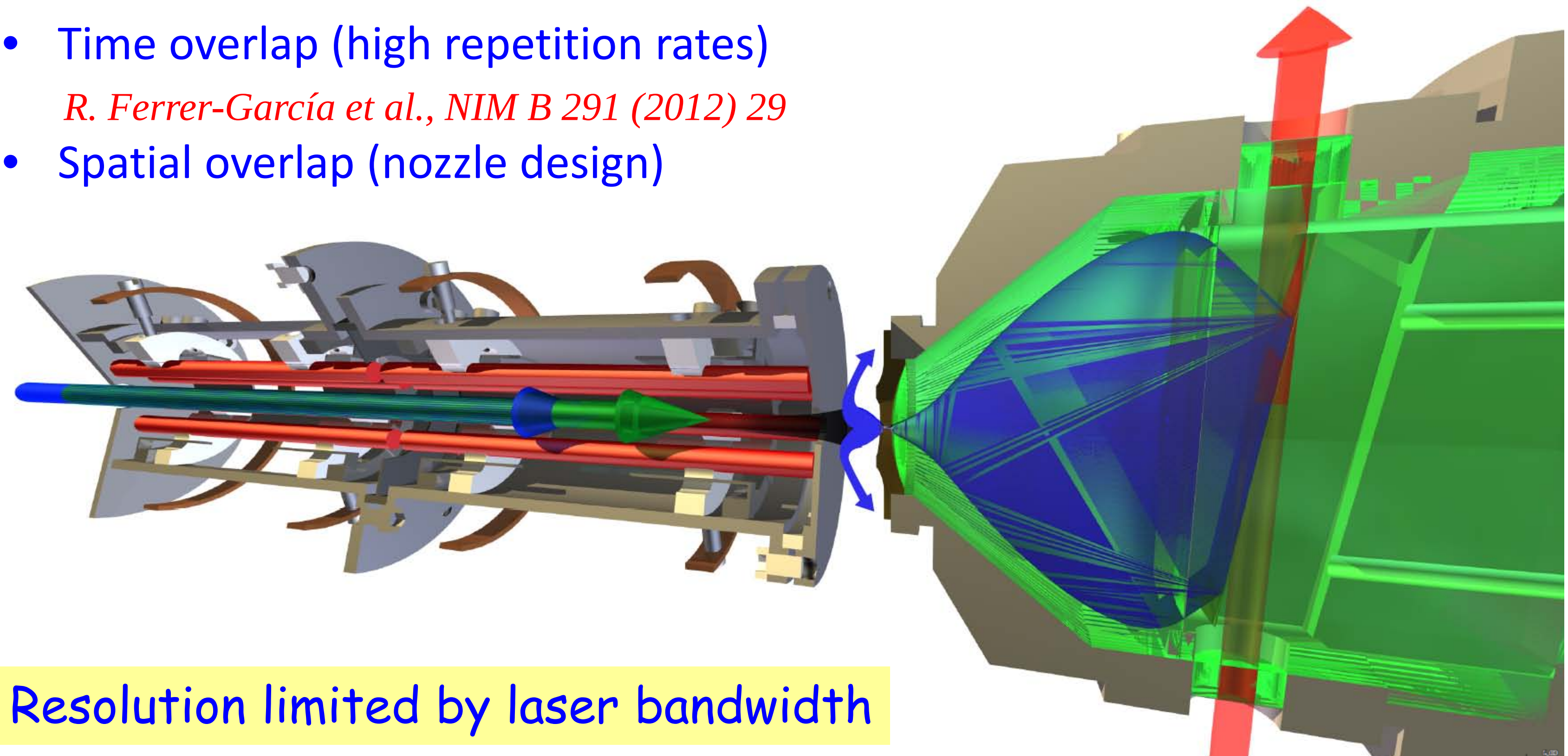
Yu. Kudryavtsev et al., NIM B 267 (2009) 2908   *M. Reponen, PhD thesis, JYFL (2012)*

JYFL

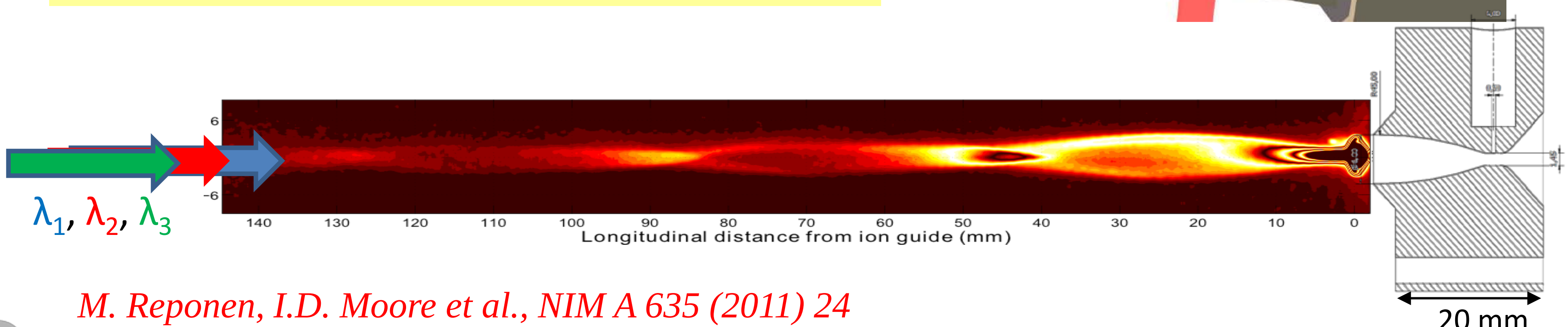
In-gas-jet laser resonance ionization spectroscopy

- Time overlap (high repetition rates)

  R. Ferrer-García et al., NIM B 291 (2012) 29
- Spatial overlap (nozzle design)



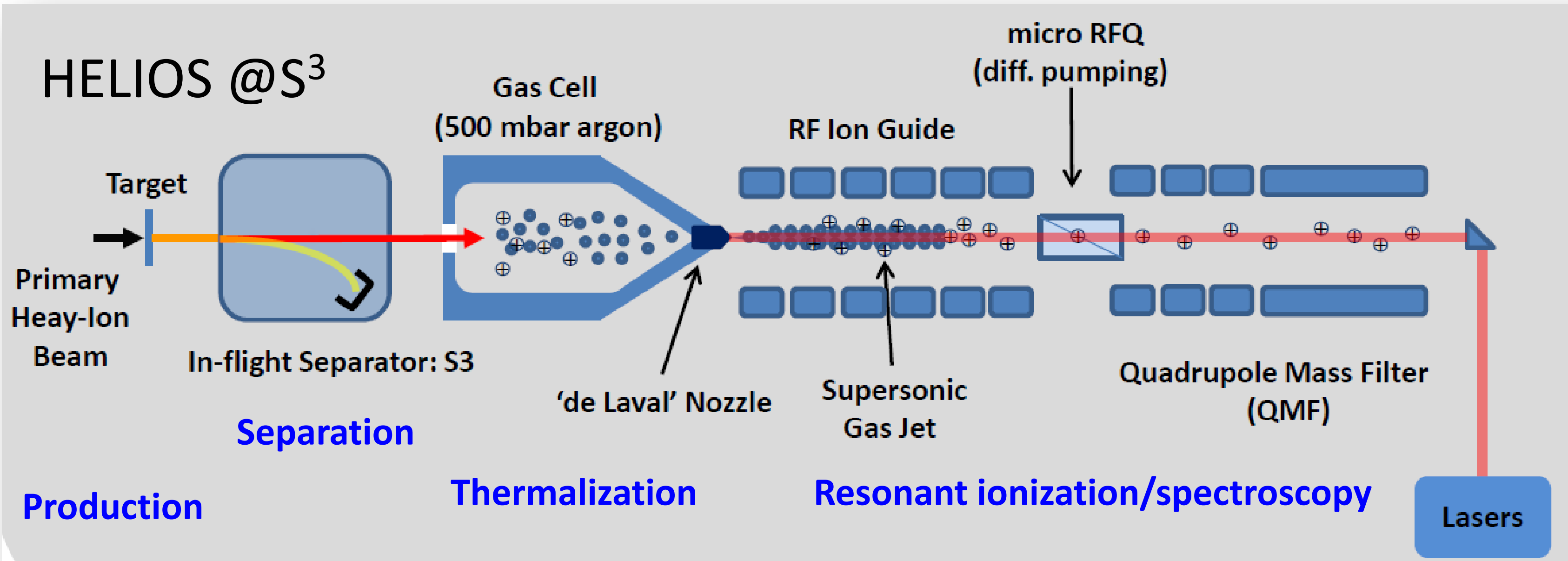
Resolution limited by laser bandwidth



M. Reponen, I.D. Moore et al., NIM A 635 (2011) 24

Heavy Element Laser IOnization Spectroscopy

An alternative approach towards laser spectroscopy of heavy elements



- Expected production rates:

  $^{208}Pb(^{48}Ca,2n)^{254}No$: ~150 pps (10 pμA primary beam intensity)

- Strategy

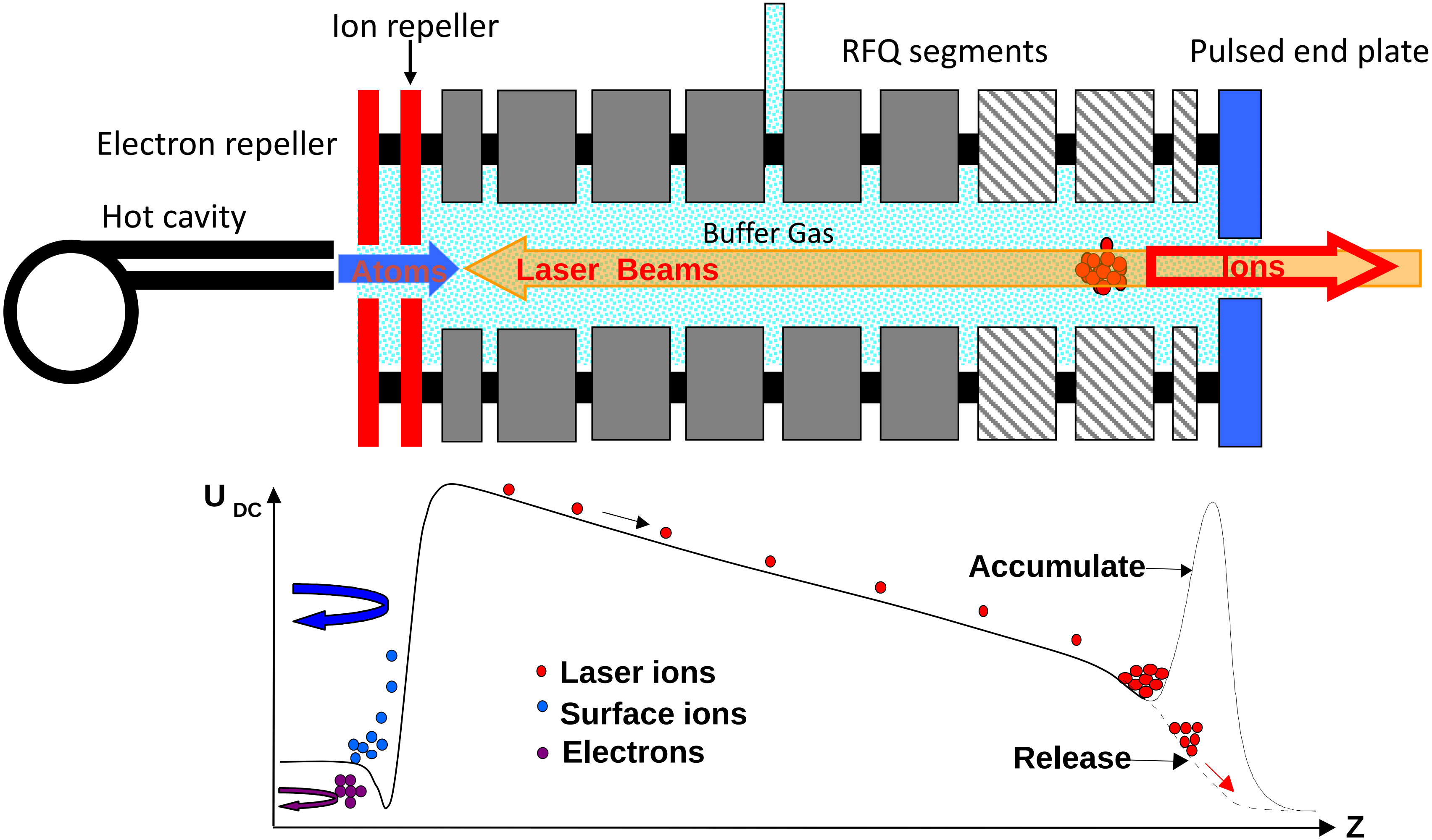
  In-gas cell laser ionization spectroscopy (broadband – 5 GHz):

  In-gas jet laser ionization spectroscopy (narrow band – 200 MHz)

Courtesy of Piet Van Duppen

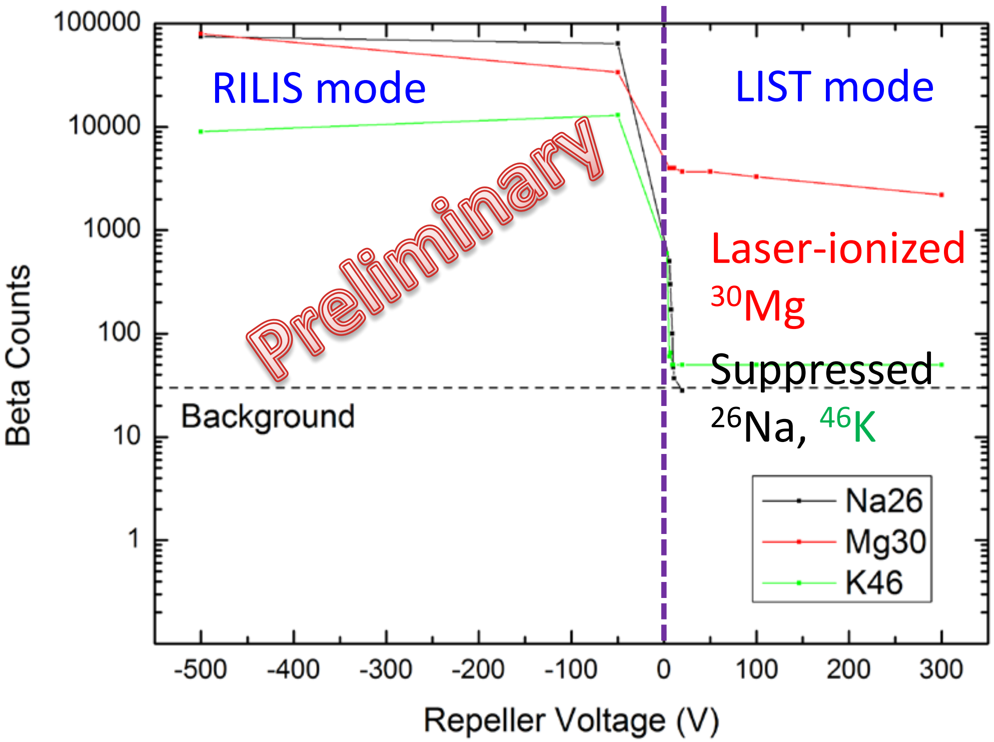
Hot cavity laser ion source trap

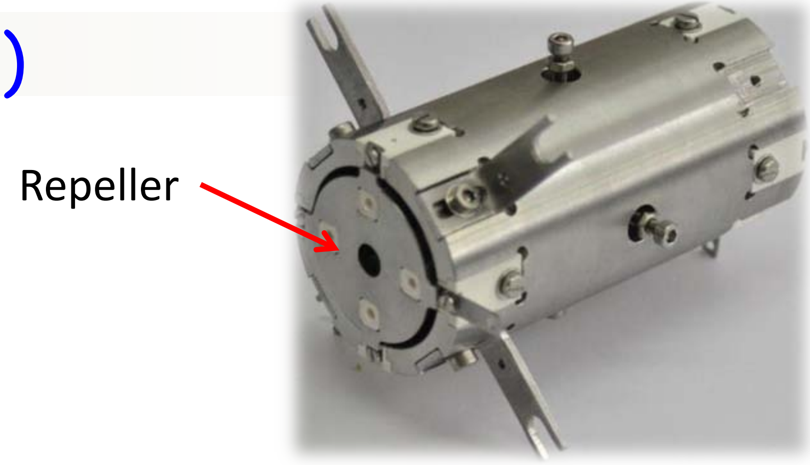
``To achieve the highest selectivity in RIB production"

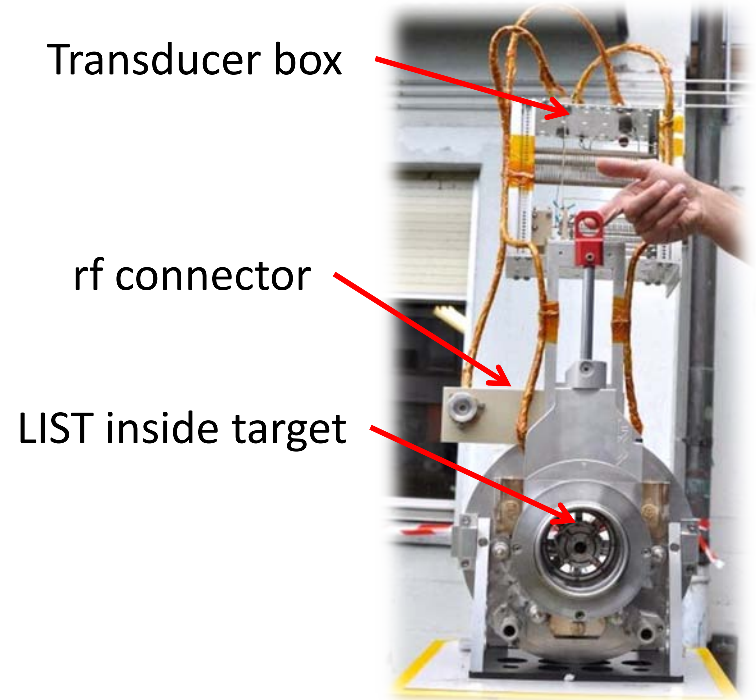


F. Schwellnus et al., Rev. Sci. Instrum. 81 (2010) 02A515.

LIST on-line at ISOLDE (2012)





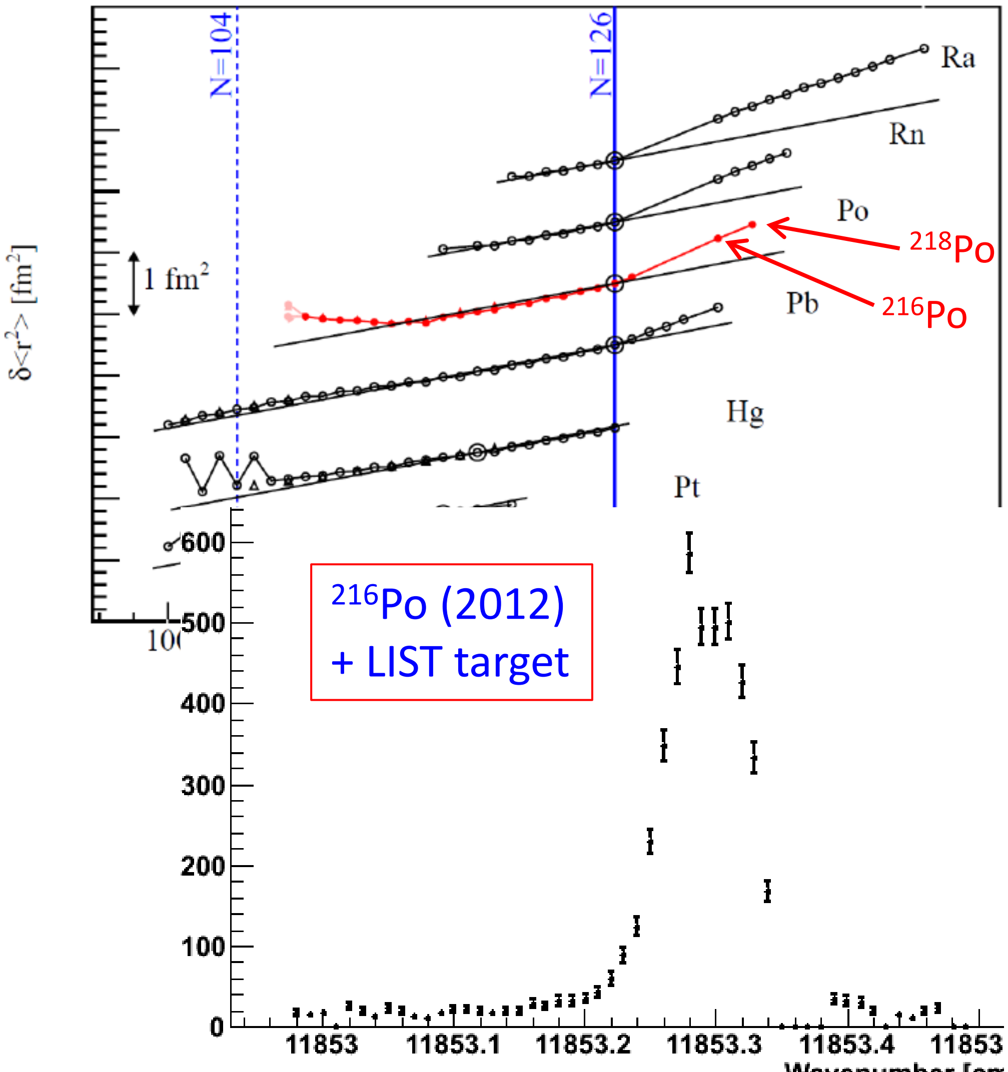


- LIST was successfully tested with UC_x target
  - -> No loss of performance over 5 days
- Suppression of Na-, Al-, K-, Fr-, U-isotopes studied
  - -> Suppression factors varied from 100 to 1000
- Laser ionization of radioactive Mg and Po in LIST mode

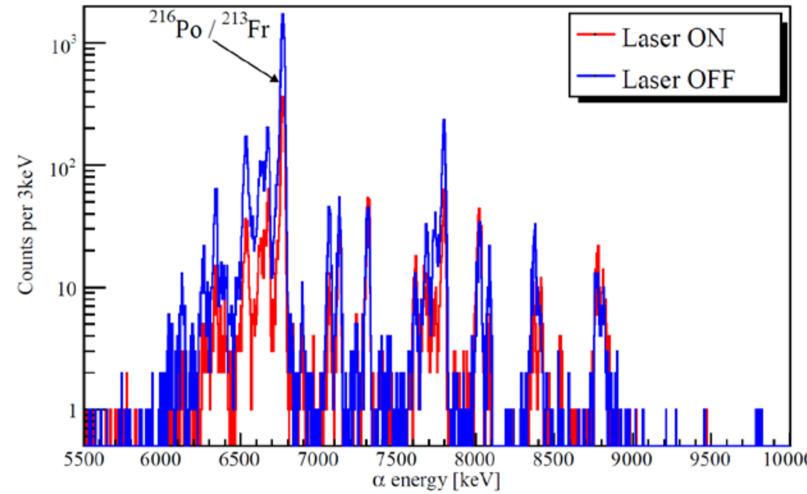
Courtesy of Daniel Fink

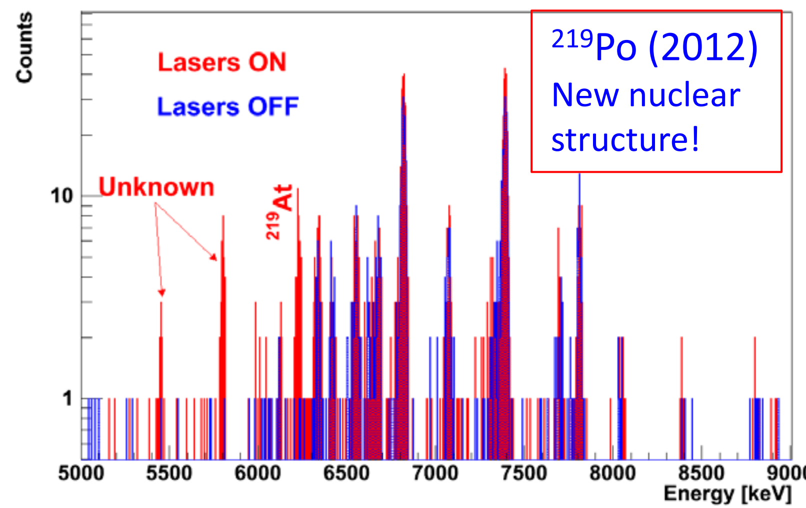
LIST: suppression of Fr; ionization of Po

In-source laser spectroscopy: a Po survey



^{216}Po, first attempt in 2007



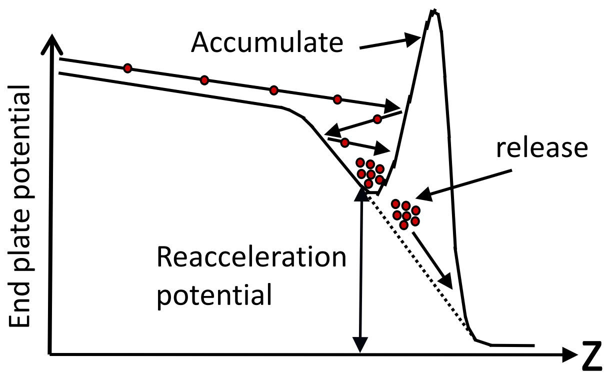


Courtesy of Thomas Cocolios & Daniel Fink

Low energy ion beam coolers

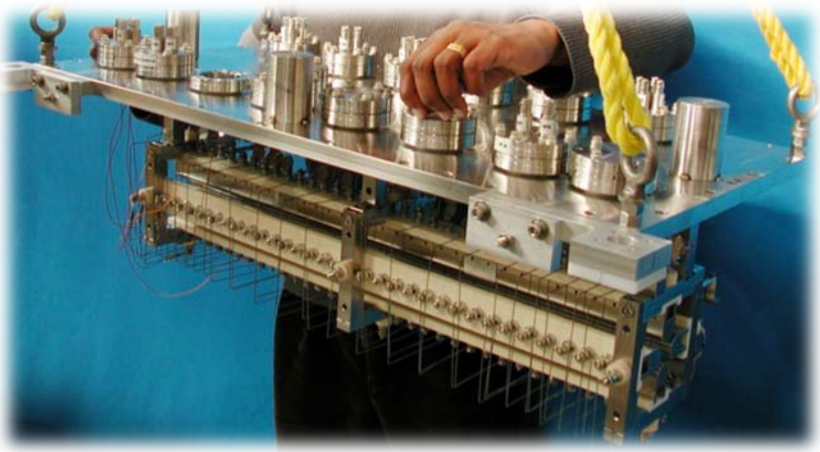
Rare isotopes often produced with non-ideal properties

- Duty cycle not matched to experiment (eg: ion traps)
- Energy spread too high (eg: laser spectroscopy)
- Transverse emittance too high (eg: RIB facilities)
- *``debuncher´´ for CW formation, P. Delahaye next talk !*

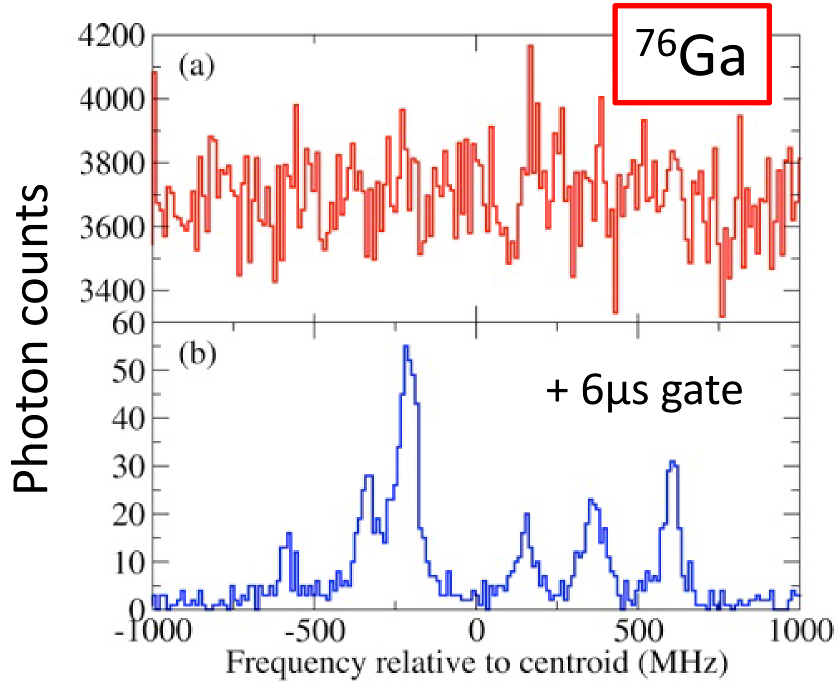


More than a dozen RFQ coolers in operation/construction

- Efficiency ~40-80% with beam deceleration
- Energy spread < 1eV
- Transverse emittance ~few π mm mrad
- Bunch widths ≤ few μs



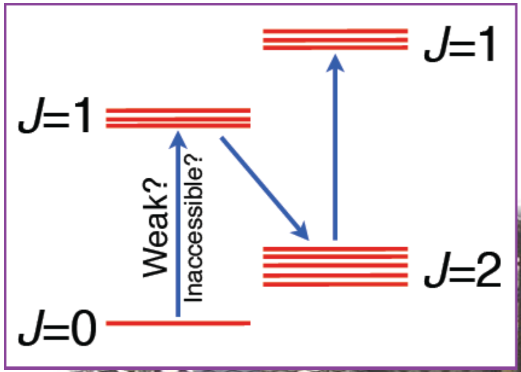
TITAN's RFQ buncher (TRIUMF)

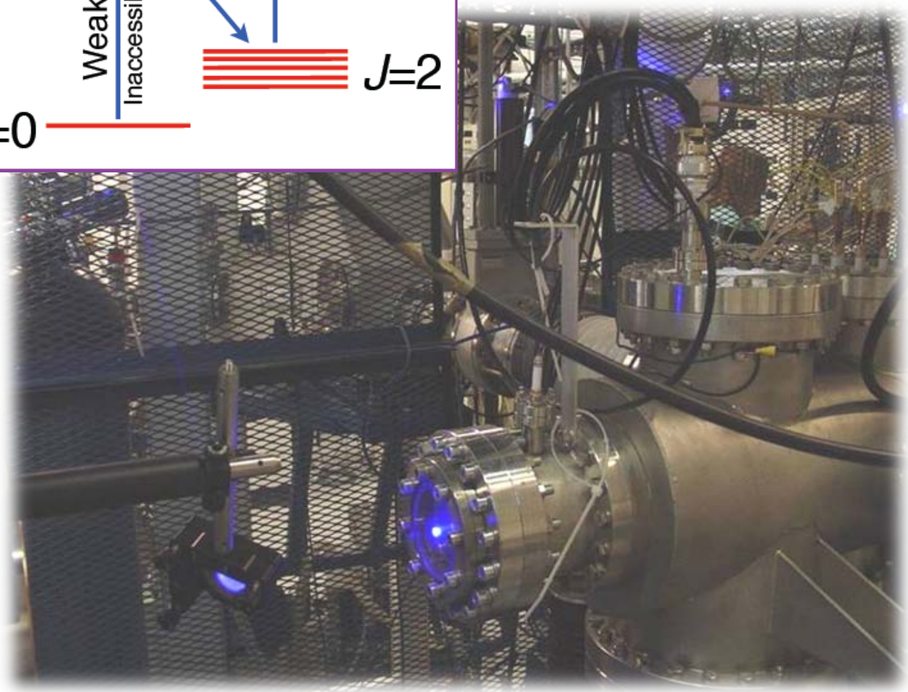


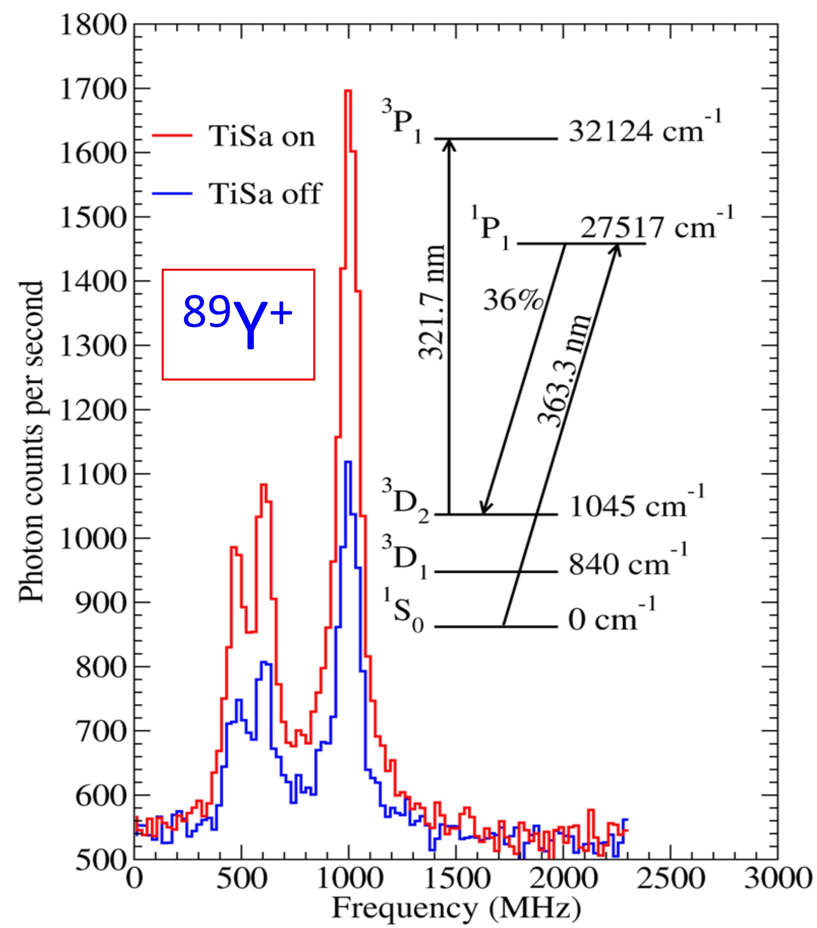
E. Mané et al., PRC 84 (2011) 024303

Optical manipulation of atomic states

- *J*=0 → *J*=1 gives *μ*, *Q*, δ<r²> but not *I*
- Access to more accessible/efficient transitions
- New elements to study (eg. transition metals)







F.C. Charwood et al., Phys. Lett. B ***674*** *(2009) 23*
B. Cheal et al., Phys. Rev. Lett. ***102*** *(2009) 222501*

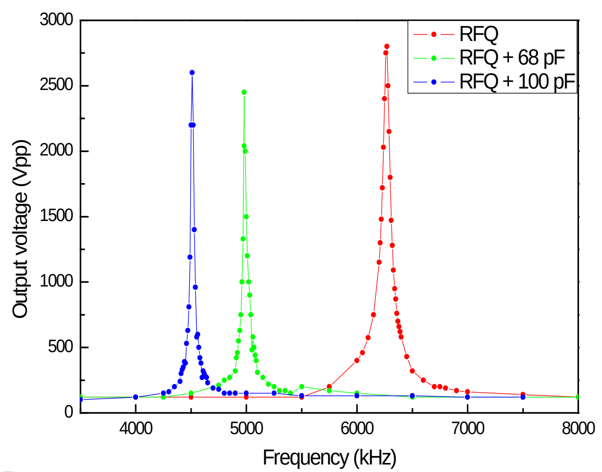
Future extension: polarization of beams

High intensity beam cooler - SHIRAC

Spiral II High Intensity Radiofrequency Cooler (SHIRAC)

- Designed to manipulate the high intensity RIBs from SPIRALII target to HRS

Requirements:
- Current up to 1 μA
- 60% transmission (*A*=132)
- Emittance 1π mm mrad
- Energy spread ~2eV
- No bunching, DC mode only



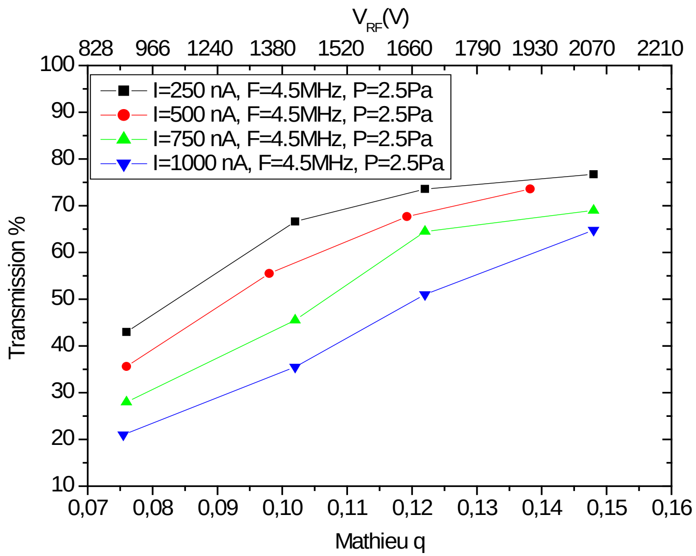
Special RF system designed for the high intensity

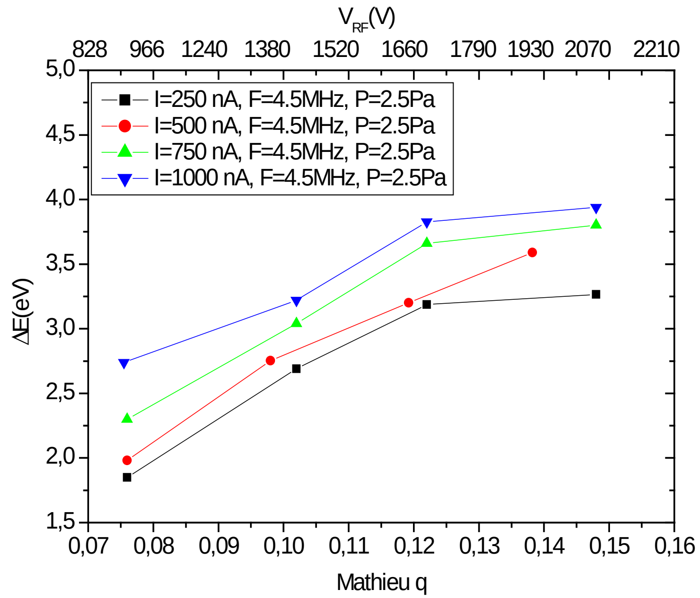
- 6.5 MHz at 8kV
- Tunable and harmonic

Courtesy of Gilles Ban

SHIRAC – current status

Surface ionization source: Cs^+ at 5 keV



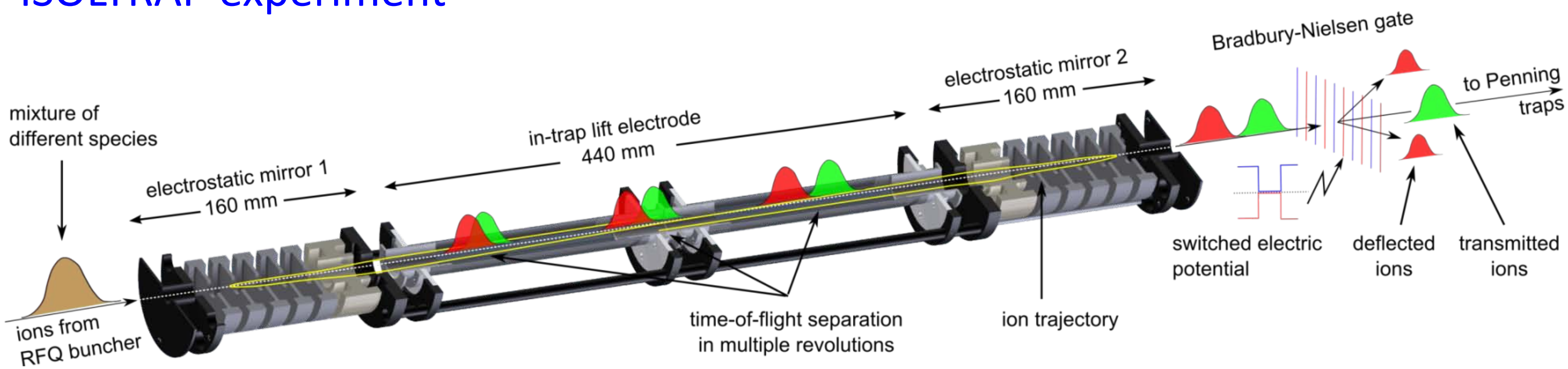


- Emittance ~1.5 π mm mrad for 1 μA
- Nuclear environment adaptation underway

Work of PhD student Ramzi Boussaid

MR-TOF Mass Spectrometry at ISOLTRAP

- Multi-reflection time-of-flight mass separator at the ISOLTRAP experiment



Support Penning-trap mass spectrometry

Mass measurements get access to beams with minute production rates, tens of ms half-lives and high suppression of contaminants due to:

- auxiliary isobaric purification
- fast purification
- accumulating of ion of interest

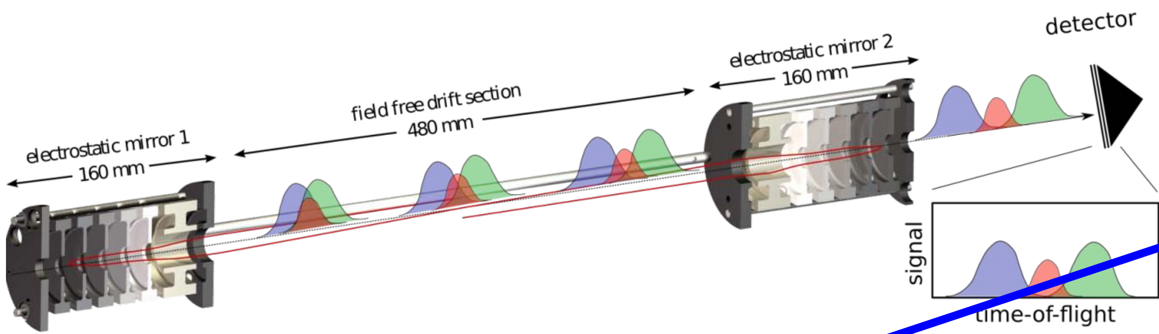
MR-TOF plus detector as stand-alone system

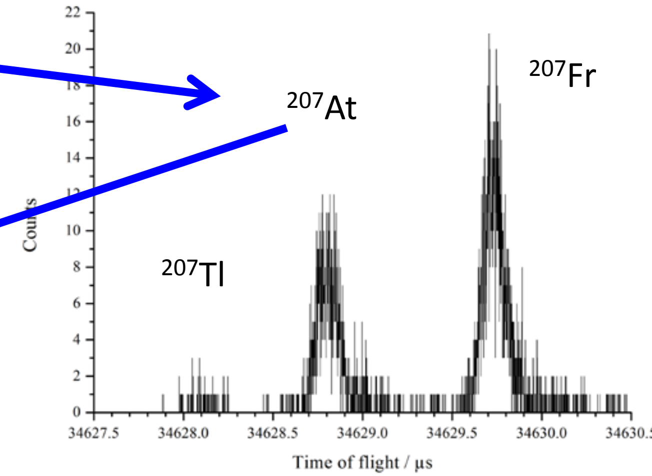
The MR-TOF offers a way to separate background for direct single-ion detection using MCP (time scale: tens of ms)

- direct mass measurements
- in-source spectroscopy

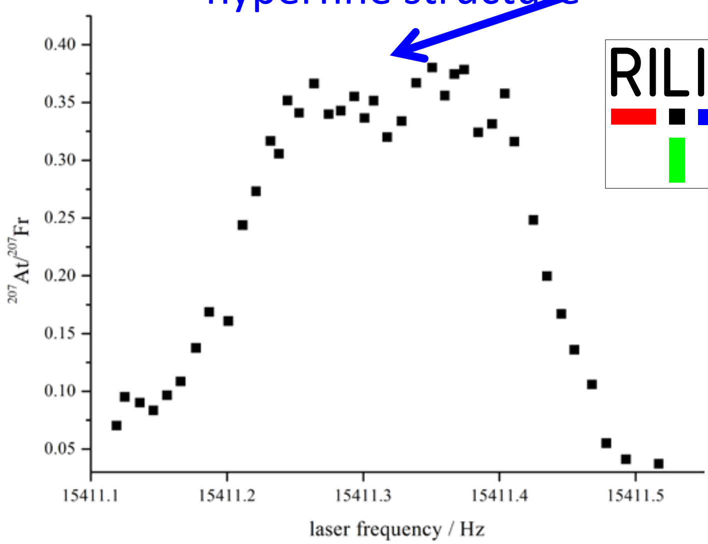
R. N. Wolf et al., Nucl. Instr. and Meth. A 686, 82-90 (2012)

Recent results at ISOLTRAP



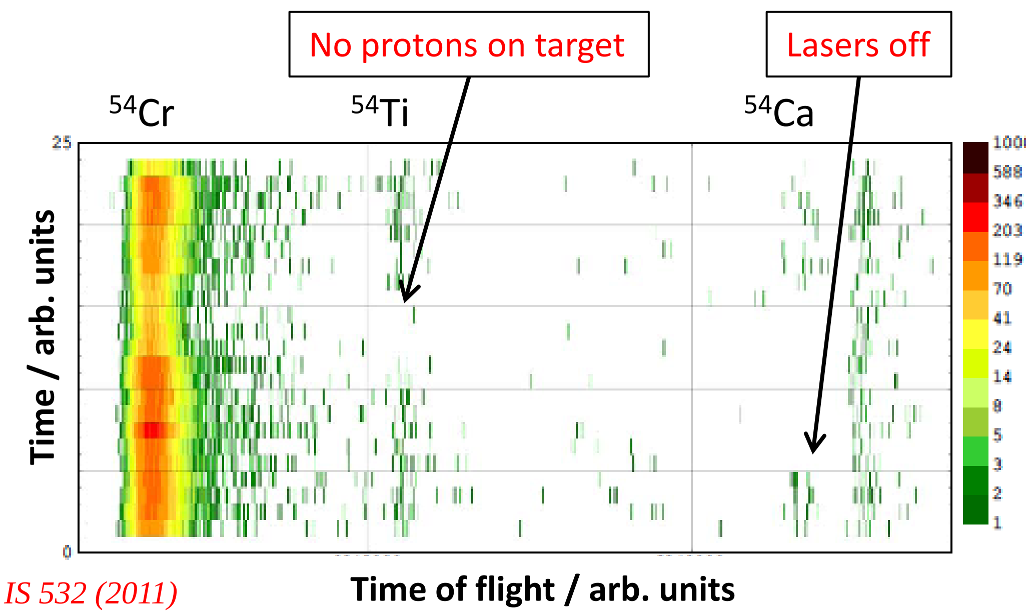


In-source spectroscopy for hyperfine structure



RILIS

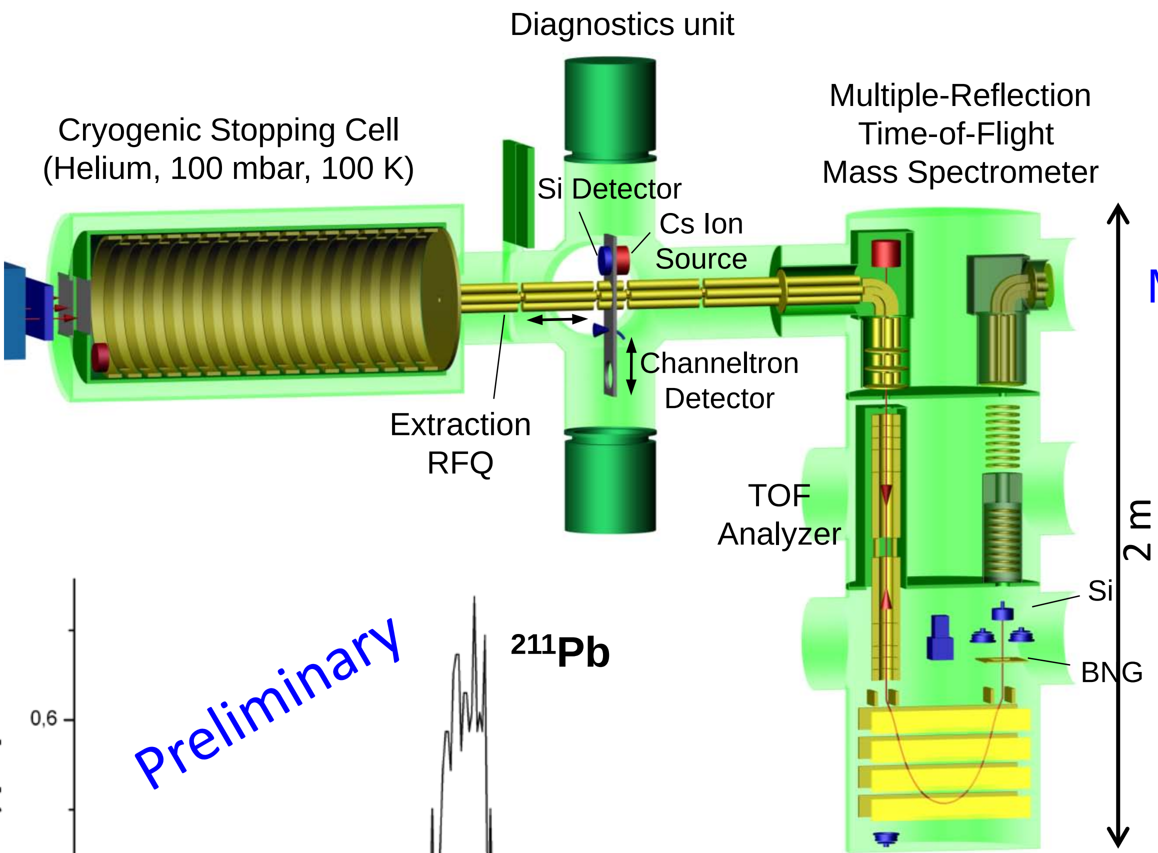
Direct mass measurements of $^{52-54}$Ca



See poster of S. Kreim (ISOLTRAP)

S. Kreim et al., INTC-P-299, IS 518 (2011) INTC-P-317, IS 532 (2011)

MR-TOF-MS and the ion catcher at GSI



Mass Resolving Power

600,000

Mass Measurement Accuracy

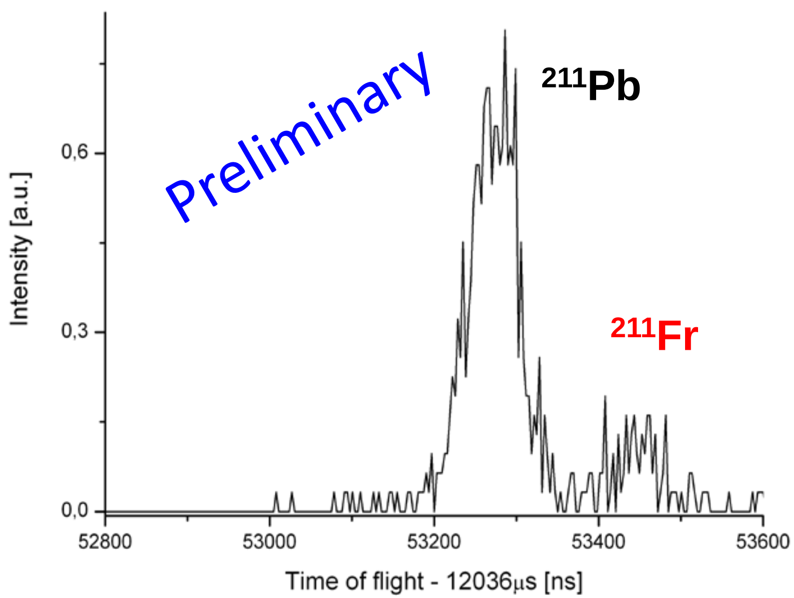
~10^{-7}

Measurement Duration

~10 ms

Transmission efficiency

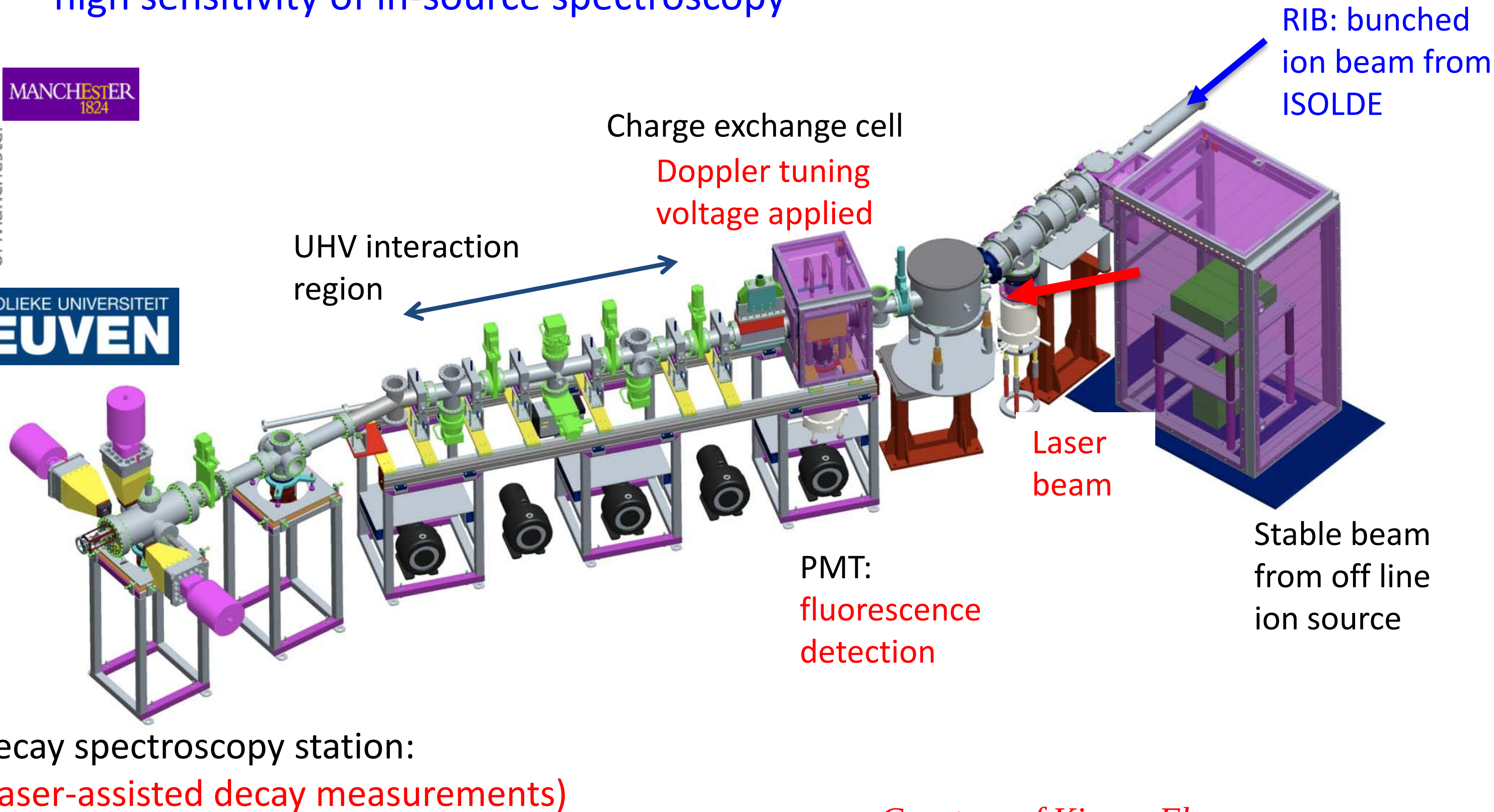
up to 70%



- Broadband mode for characterization of the cryogenic ion catcher (diagnostics tool)
- High resolution mode for mass measurement (^{213}Rn with half-life 19.5 ms)

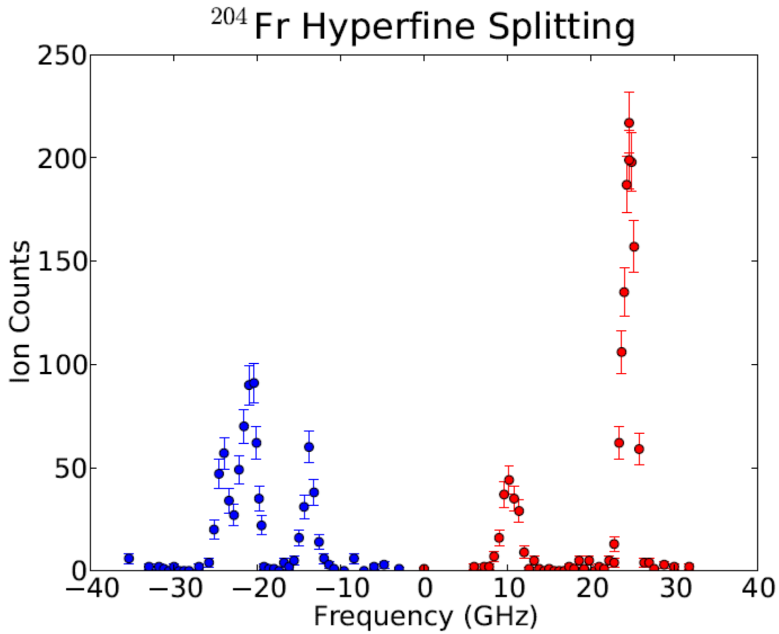
Collinear Resonance Ionization Spectroscopy

CRIS: ``Combining the high resolution nature of collinear beams with the high sensitivity of in-source spectroscopy´´



Courtesy of Kieran Flanagan

August/October 2012 - new data on francium

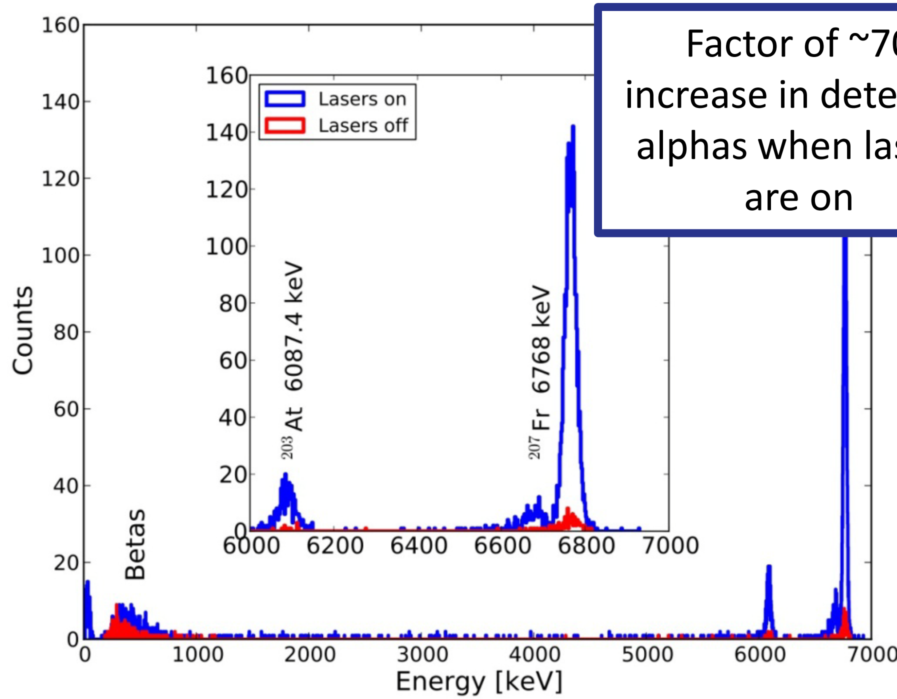


Key points:

- Efficiency achieved 1:60
- Background suppression ~1:500 000 (pressure limited, expect 1:1e6)
- $^{202-206,218,219,229,231}$Fr

Laser-assisted decay spectroscopy

- Using the HFS, decay spectroscopy can be made on pure isomeric (or ground state) beams
- Assisted α-, β-, and γ-decay spectroscopy



Factor of ~70 increase in detected alphas when lasers are on

Summary and outlook

- Important advancements continually made at all facilities to be able to handle the ever-increasing improvements in primary/secondary beam intensities:
  - *purity, energy spread, temporal structure, charge state, ionic/atomic state*....

- Gas catchers becoming more common and finding new applications:
  - *versatile, universal*

- Cooler-bunchers are standard laboratory equipment:
  - *High efficiency, universal*, easy to build
  - Next frontier approaches – *high intensity* devices

- Commissioning of MR-TOF-MS devices complements Penning trap techniques and can be used in a variety of modes (stand-alone devices, diagnostic tools etc)

- Novel in-source/in-jet spectroscopy demonstrated at both ISOL and gas cell-type facilities; plans for future facilities.

❖ Not discussed: application of storage rings, Penning traps and so on!!!

❖ Many of these techniques can be applied at a future EURISOL facility ☺