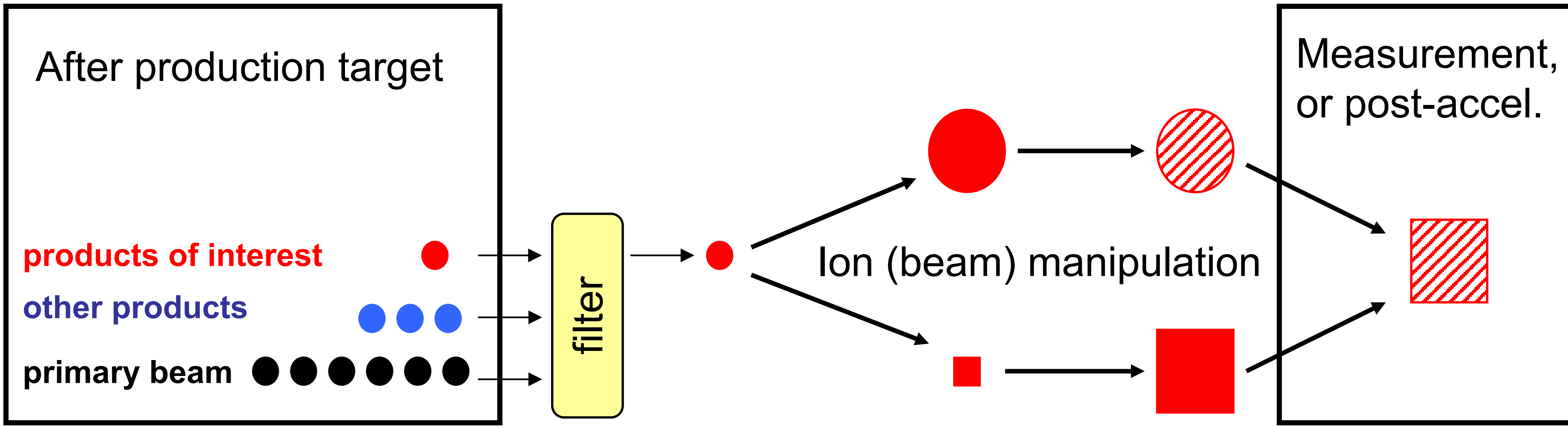
Techniques and challenges of ion beam preparation

A. Jokinen
Department of Physics, P.O.Box 35 (YFL)
FIN-40014 University of Jyväskylä



Beam preparation = **Purification** + **Manipulation**

Sub-Task 1 / **Sub-Tasks 2 and 3**

EURISOL-DS; Task 9, Beam preparation:
The objective of this task is to study the feasibility of a new generation of devices with orders of magnitude greater capacity and throughput in order to accumulate, cool, bunch and purify the high intensity radioactive ion beams of EURISOL.
(+ Construction of the prototype for beta-beams)

Manipulation of radioactive ions

Ion group (beam,cloud) properties

energy	*energy degrading* *stopping, trapping* *acceleration*
• energy spread	*cooling, trapping*
• emittance	*cooling*
• size	*cooling, trapping*
• time structure	*pulsing* *bunching*

"ion beam cooler"
(gas-filled RF quadrupole)
Sub-Task 2

Ion properties

• charge state	*ionization*
• ionic/atomic state	*optical pumping*
• spin direction	*alignment* *polarization*

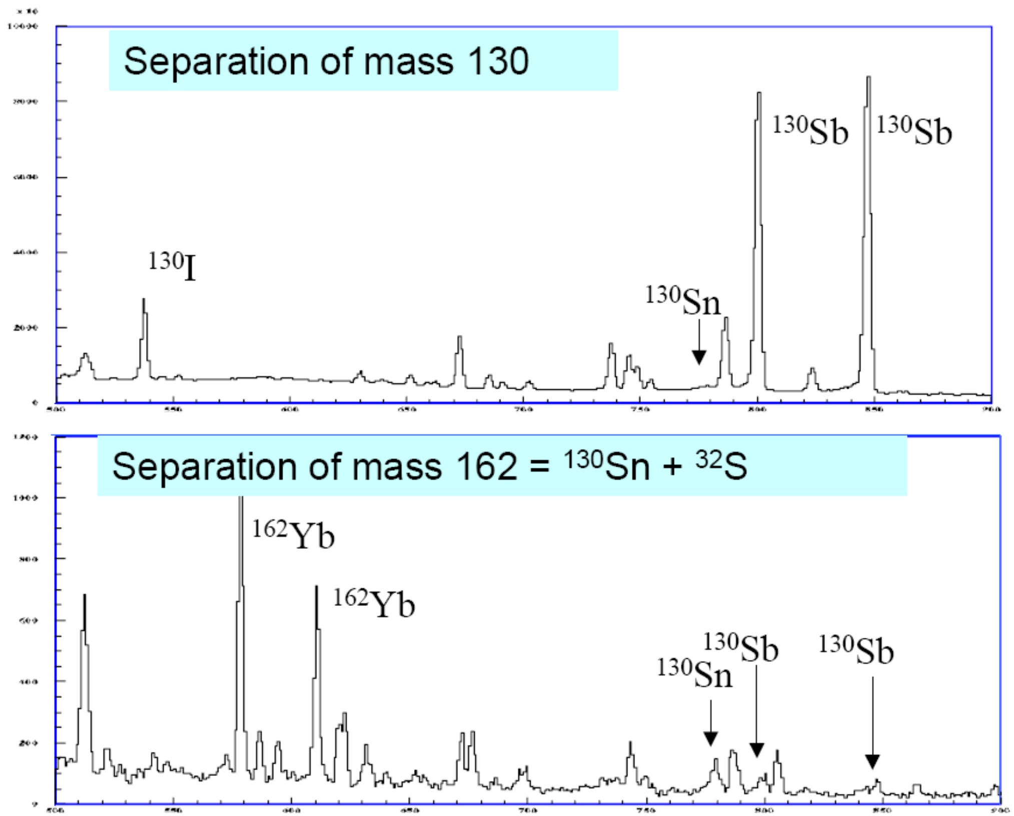
"charge breeder"
(ECRIS & EBIS)
Sub-Task 3

Target and ion source tricks

- Neutron converter → removal of spallation products
  - Absolute yield lower
  - Compensated by the selectivity (purity)
- Molecular sidebands → reduction of contaminants
  - Transfers products to new clean mass region
  - No laser ionization
- Ion guide approach (IGISOL) → access to refractory elements
  - No chemical selectivity
  - Fast
  - Overall efficiency low
- Laser ionization → chemical selectivity (Z)
  - Enhancement of chemical selectivity
  - Isomeric selectivity
- Laser ion source trap (LIST)
  - Reduction of contaminants → enhanced selectivity

Molecular sidebands

SnS$^+$ separation



Higher Z isobars dominant!

A=132 0.4% of Sn

Sb only as decay daughter of Sn

(+background from previous measurement)

A. Joinet, PhD thesis, Université de Paris, 2003

Another example: Spectrscopy of n-def. Sr isotopes produced from Nb-target and extracted as SrF molecule
→ No target-produced background (especially Rb !)

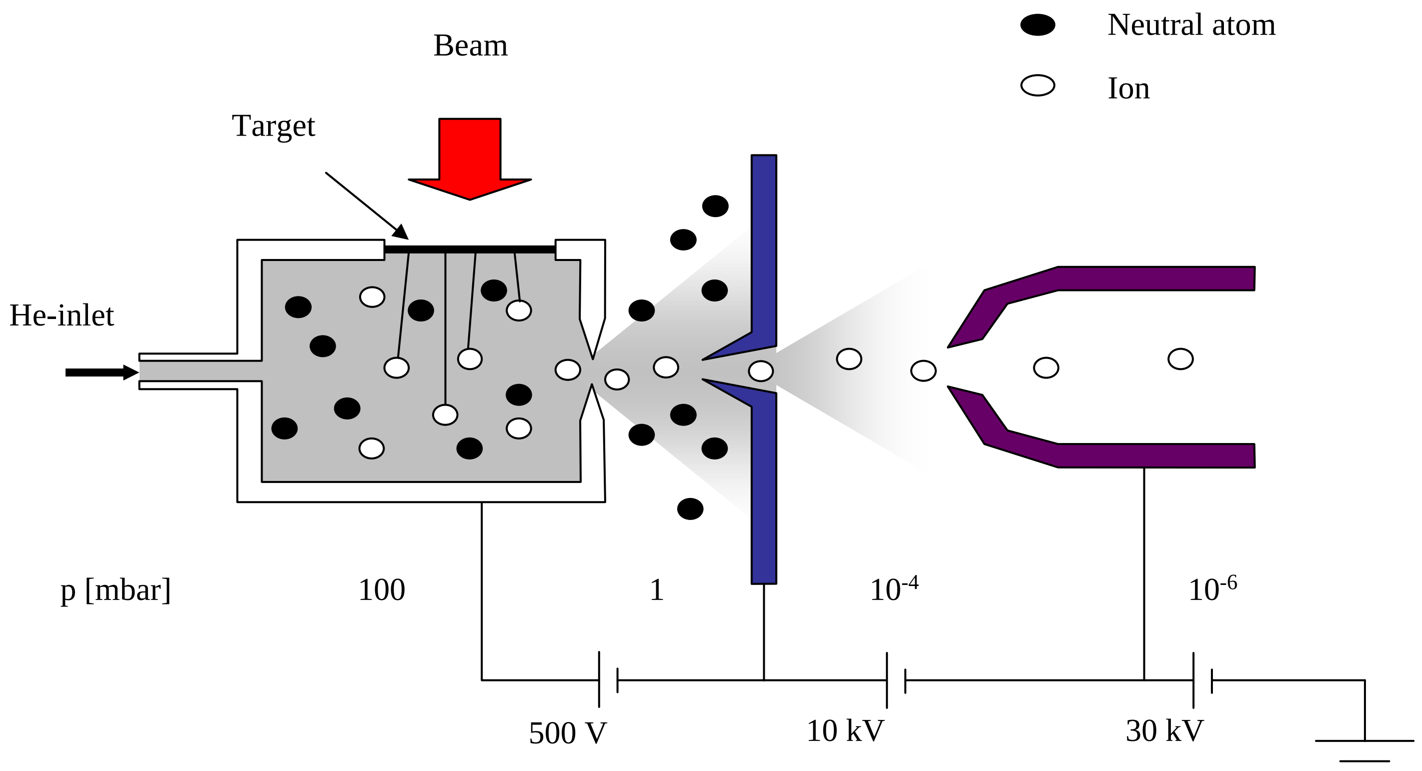
Target and ion source tricks

- Neutron converter → removal of spallation products
  - Absolute yield lower
  - Compensated by the selectivity (purity)
- Molecular sidebands → reduction of contaminants
  - Transfers products to new clean mass region
  - No laser ionization
- Ion guide approach (IGISOL) → access to refractory elements
  - No chemical selectivity
  - Fast
  - Overall efficiency low
- Laser ionization → chemical selectivity (Z)
  - Enhancement of chemical selectivity
  - Isomeric selectivity
- Laser ion source trap (LIST)
  - Reduction of contaminants → enhanced selectivity

IGISOL at JYFL

Thin target approach for refractory isotopes:

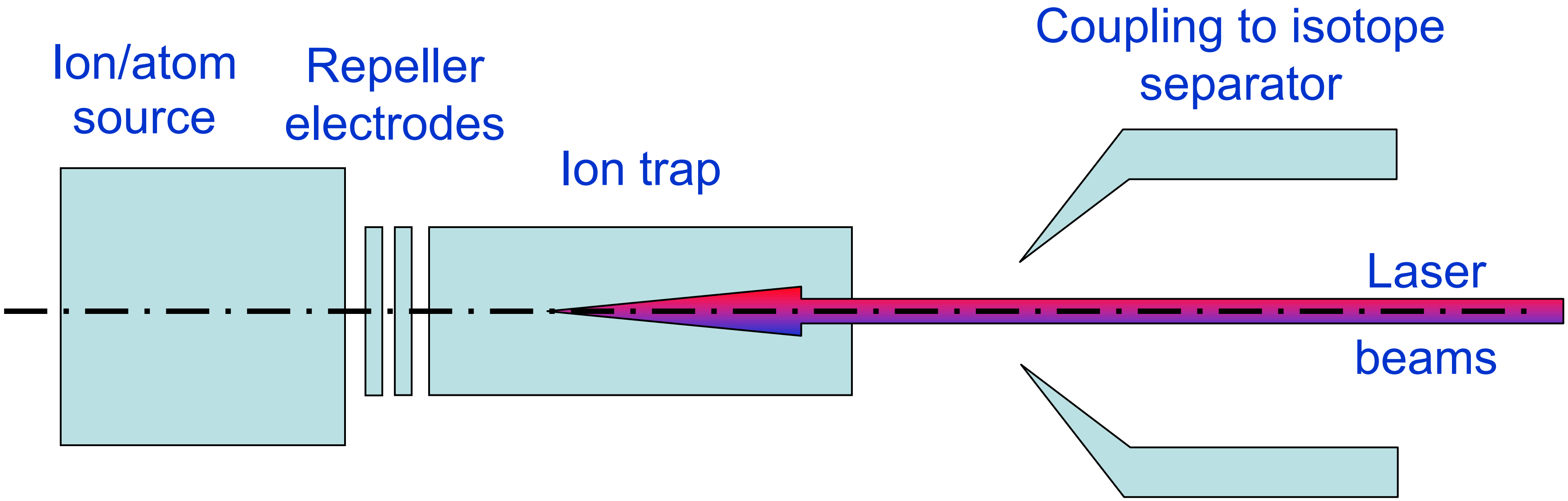
IGISOL (Ion Guide Isotope Separator On-Line)



Target and ion source tricks

- Neutron converter → removal of spallation products
  - Absolute yield lower
  - Compensated by the selectivity (purity)
- Molecular sidebands → reduction of contaminants
  - Transfers products to new clean mass region
  - No laser ionization
- Ion guide approach (IGISOL) → access to refractory elements
  - No chemical selectivity
  - Fast
  - Overall efficiency low
- Laser ionization → chemical selectivity (Z)
  - Enhancement of chemical selectivity
  - Isomeric selectivity
- Laser ion source trap (LIST)
  - Reduction of contaminants → enhanced selectivity

LIST (Laser ion source trap)

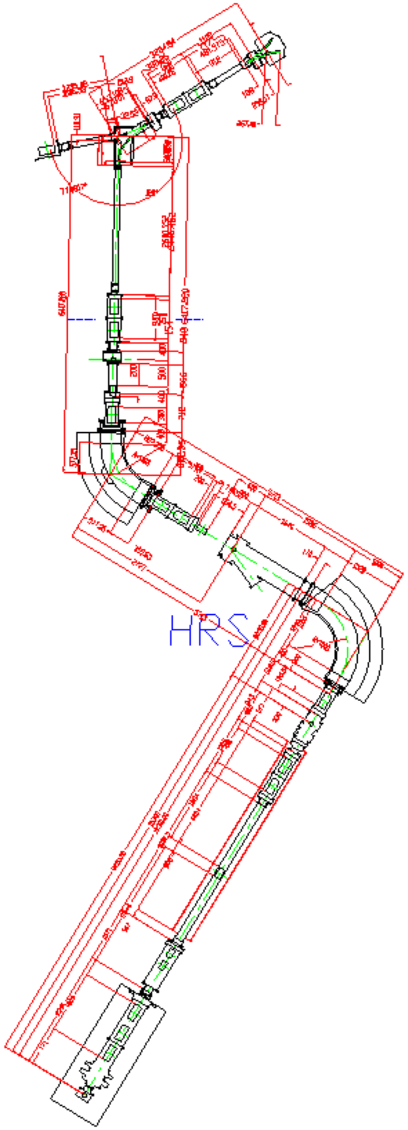


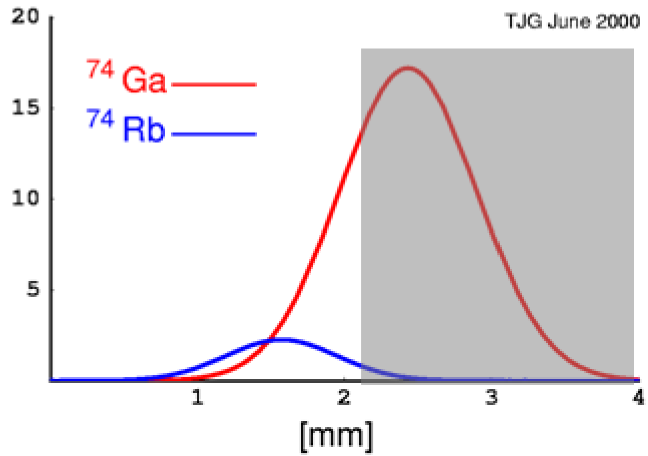
- Atoms exiting the source are selectively ionised by the lasers
- Ions produced in the source repelled back - >selectivity boost
- Laser-atom interaction length = v_{atom}/laser rep. rate
- Radial overlap over the interaction length critical for efficiency

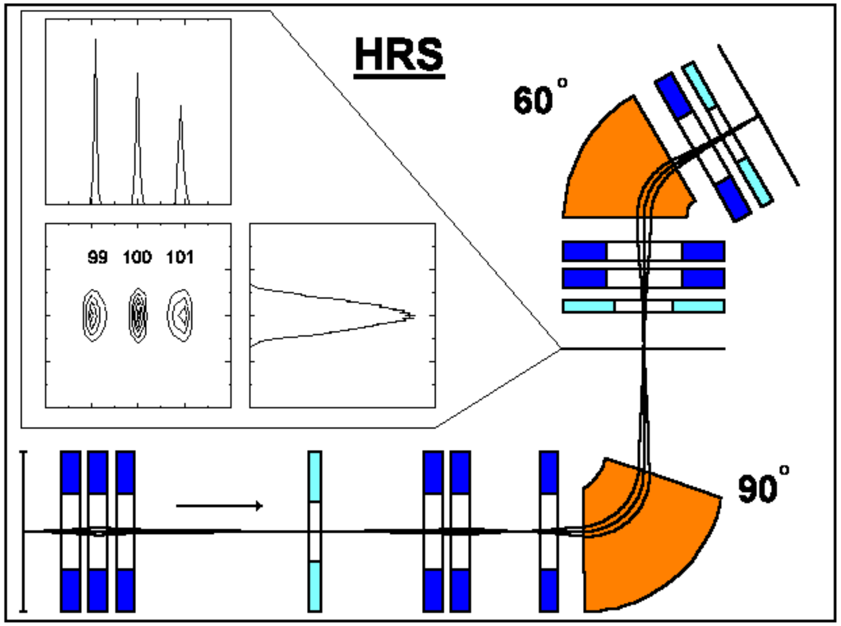
K. Blaum *et al.*,
Nucl. Instr. and Meth. B204, 331 (2003)

ISOLDE: diffusion/effusion of neutrals out from the source IGISOL: gas jet transport of neutrals out from the gas cell

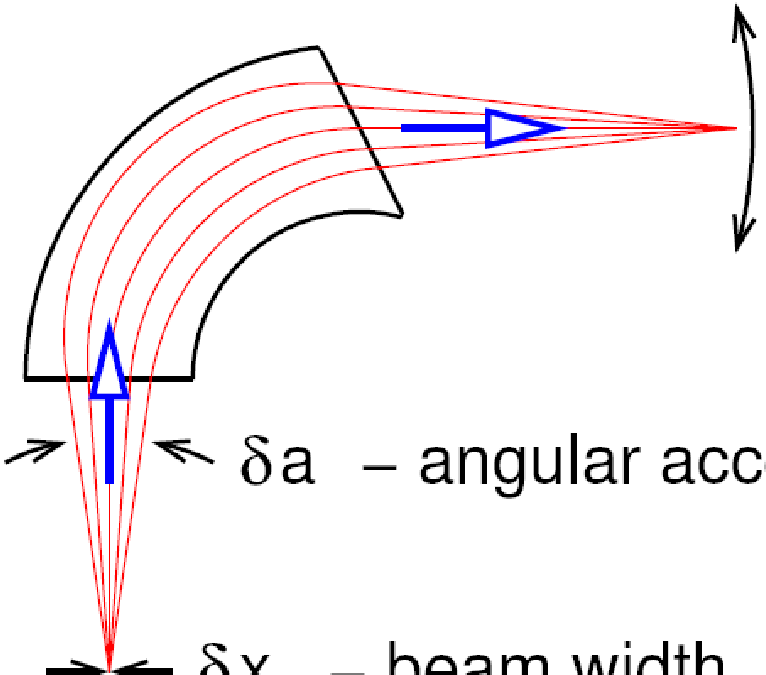
Magnetic separation (HRS at ISOLDE)







Basics of magnetic separation



D – Dispersion: (geometry)

$$\frac{\Delta m}{m} = \frac{\Delta x}{D}$$

δa – angular acceptance

Emittance:

$$\varepsilon = \frac{\pi}{4}\,\delta x \,.\, \delta a$$

δx – beam width

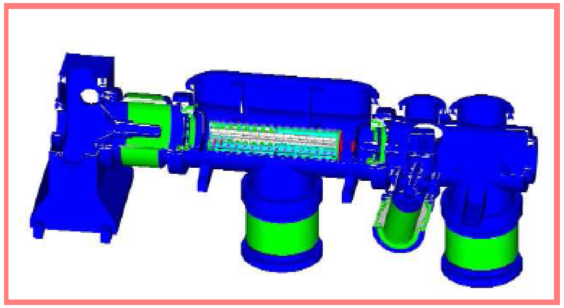
$$R = \frac{m}{\Delta m} = \frac{\pi}{4}\,\frac{D \,.\, \delta a}{\varepsilon}$$

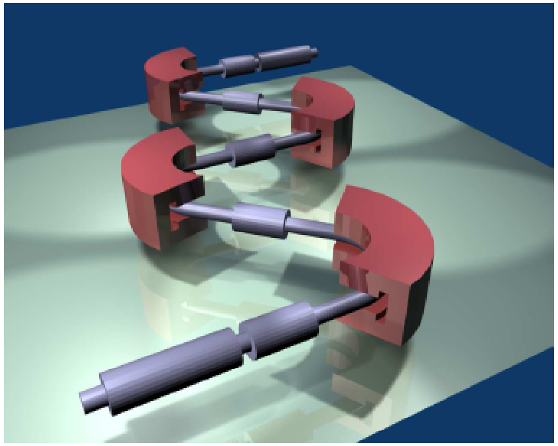
– in the ideal case (no distortions!)

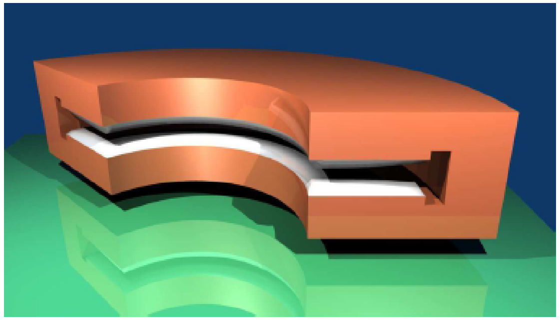
Optimization of mass purification

High resolution requires:

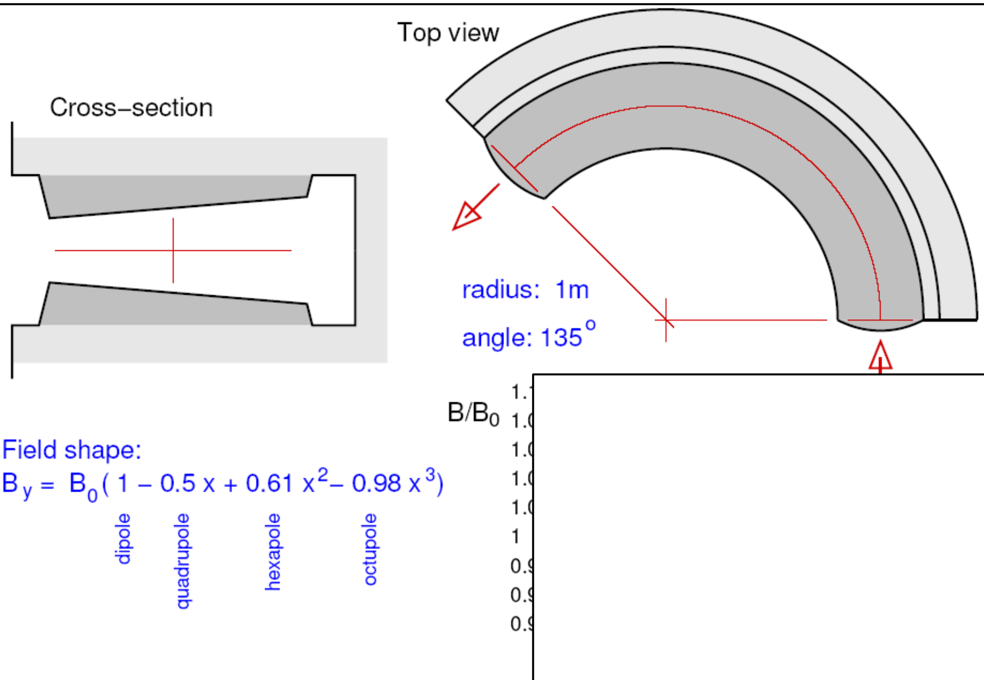
- Low emittance
  - Beam cooler
    - Pre–separator
- Large dispersion
  - Large / multiple magnets
- Correction of distortions
  - Multipolar magnetic field







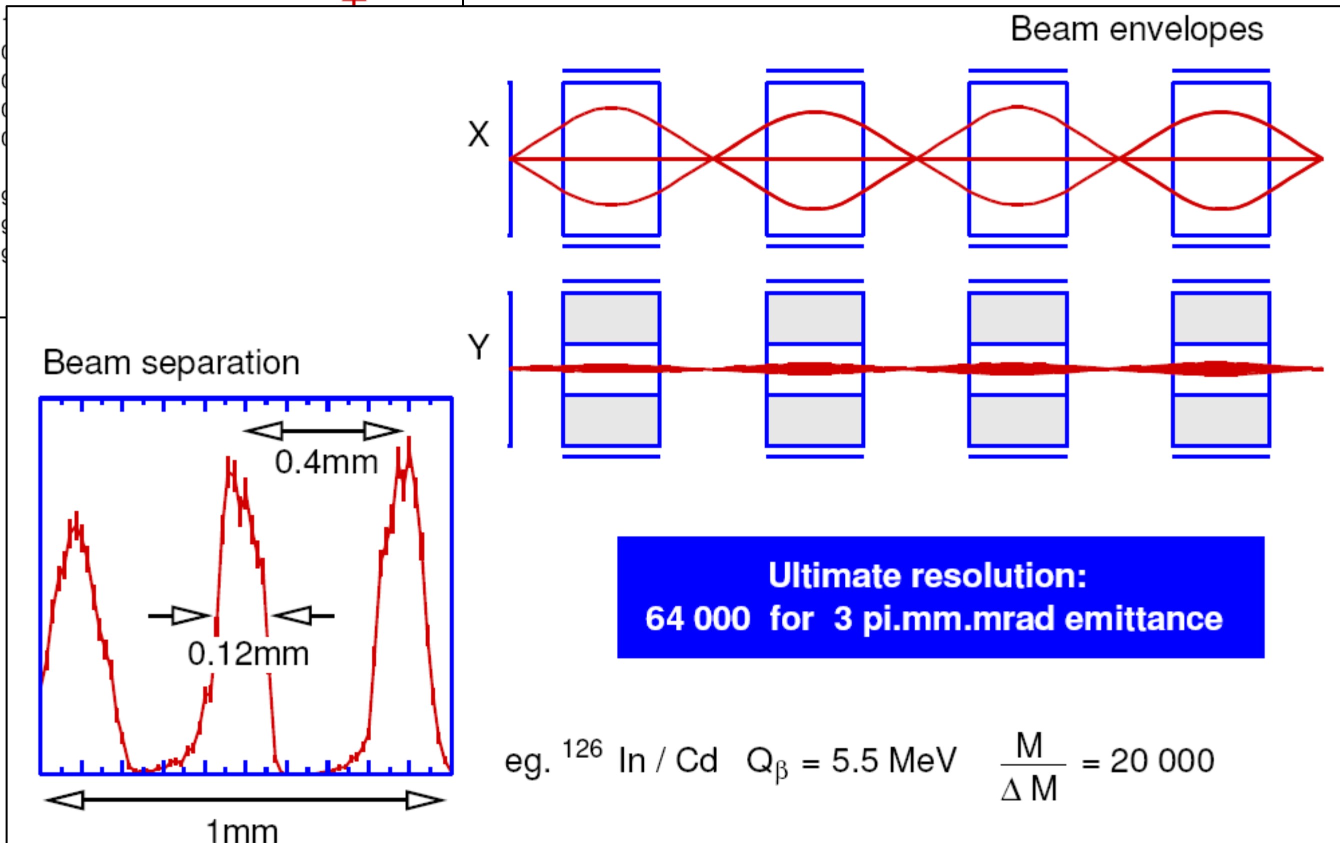
Sub-1: EURISOL-HRS



Multiple multipolar dipoles

Large dispersion

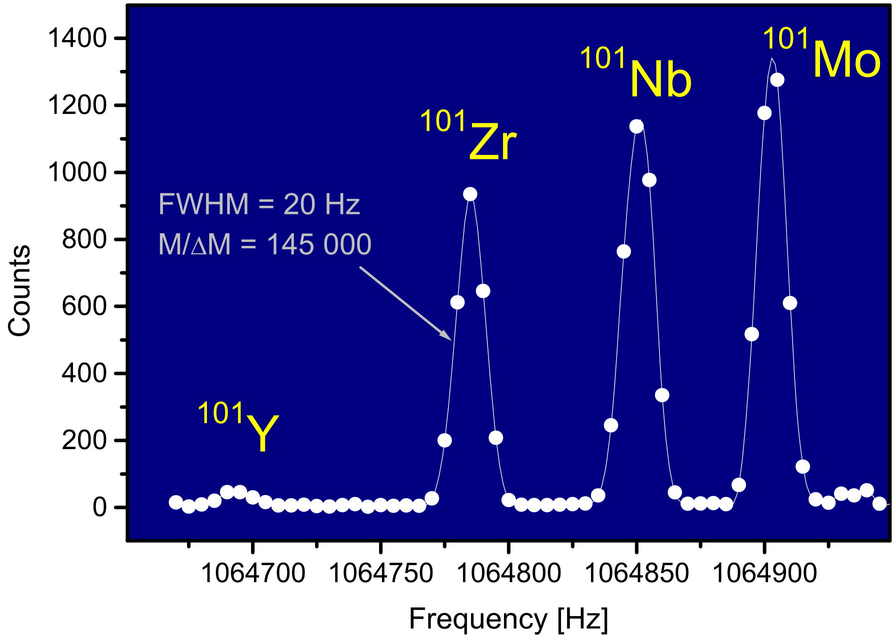
Corrections



(T. Giles, CERN)

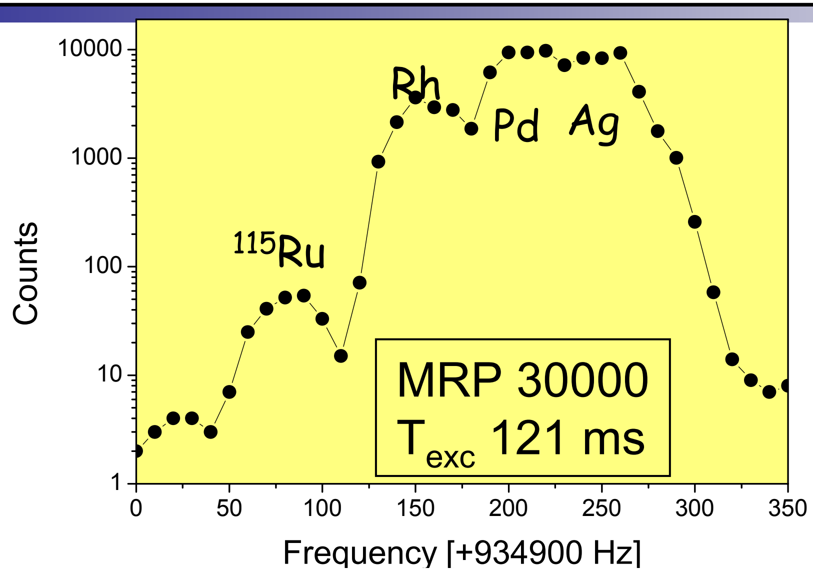
Purification in the Penning trap

Recipe:
Dipole excitation to blow up the radial motion of **all** ions
Mass-selective centering of wanted ions by resonance quadrupole excitation

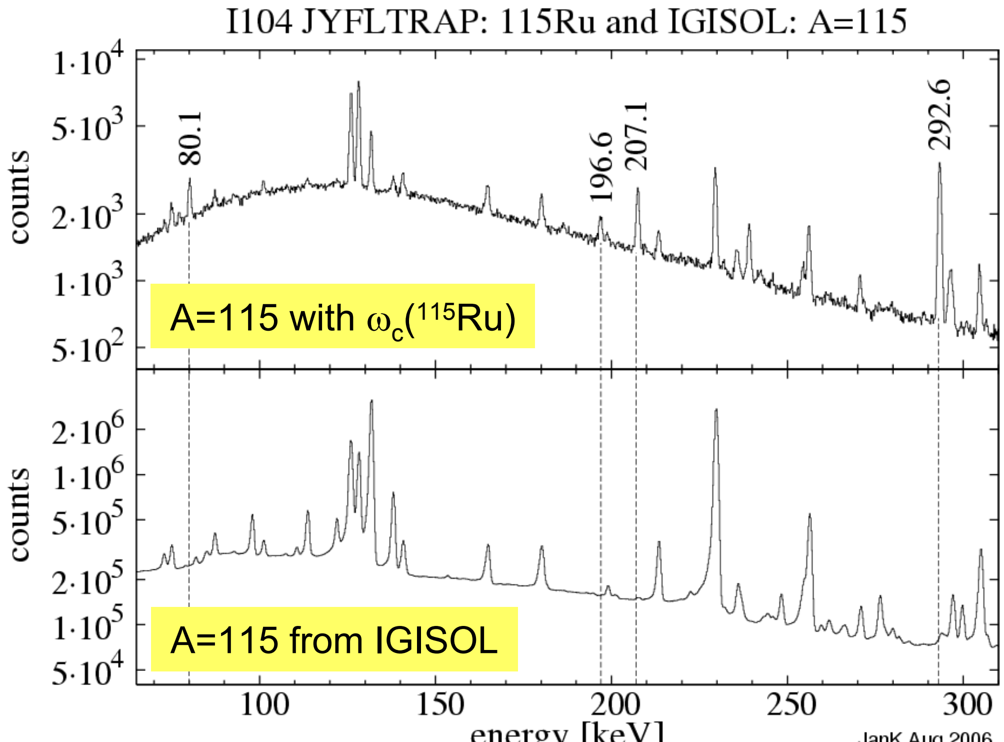


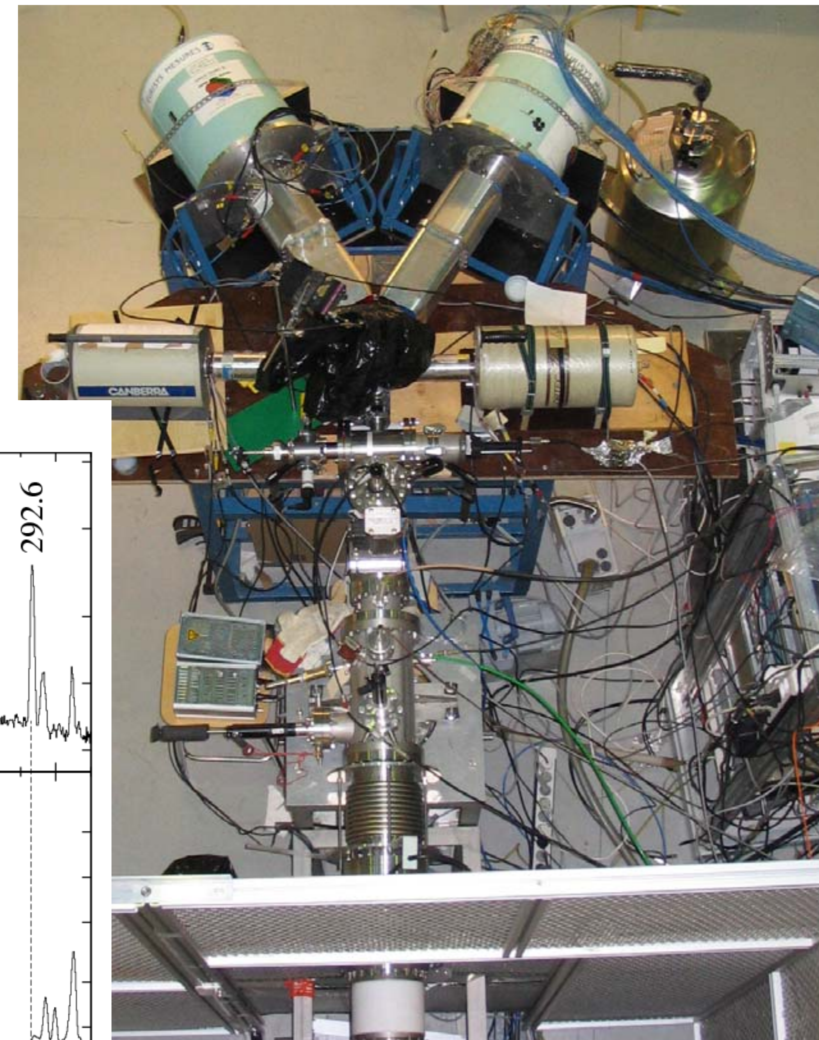
- FWHM ~ 20 Hz
- m/δm = 145000 possible (above spectrum m/δm ~ 53000) V. Kolhinen et al., NIM A528 (2004) 776
- sufficient for mass spectroscopy S. Rinta-Antila, PRC 70 (2004) 011301(R)
- ”Experimental approach”,
- RIB-facility use demonstrated at REX-ISOLDE

Trap-assisted spectroscopy



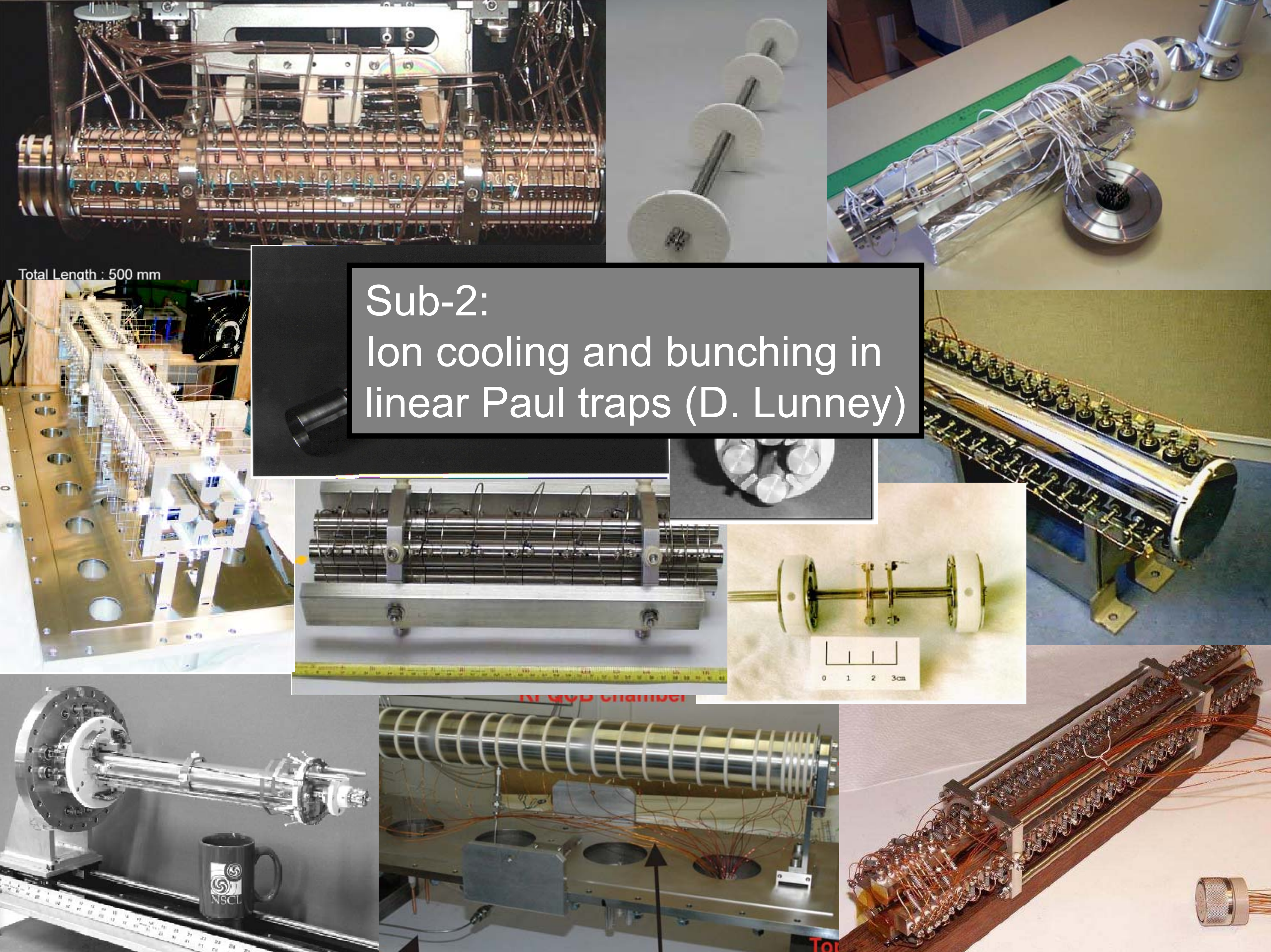
The first new decay scheme observed: ^{115}Ru





J. Kurpeta et al. EPJ A 31 (2007) 263

EURISOL Design Study


Sub-2:
Ion cooling and bunching in linear Paul traps (D. Lunney)
Total Length : 500 mm
0 1 2 3cm
NSCL

Ion beam cooler: principle

- reducing beam size, emittance, energy spread
- storing
- bunching (not chopping !)

the output does not depend on the input !

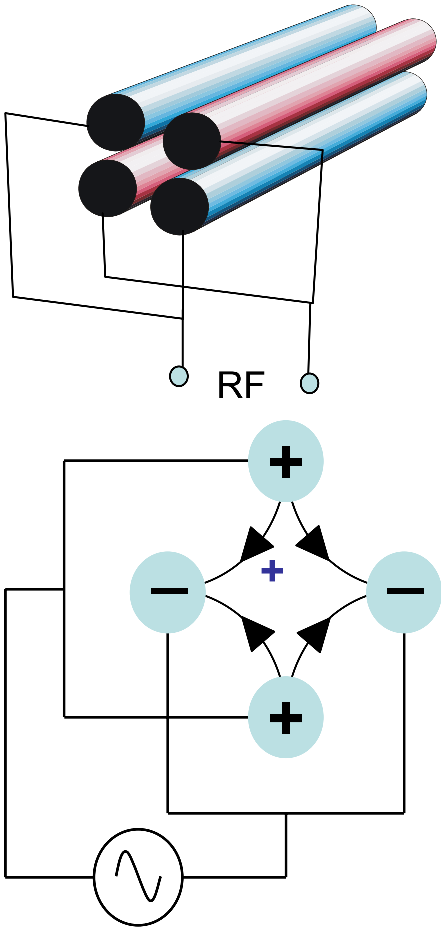
principle

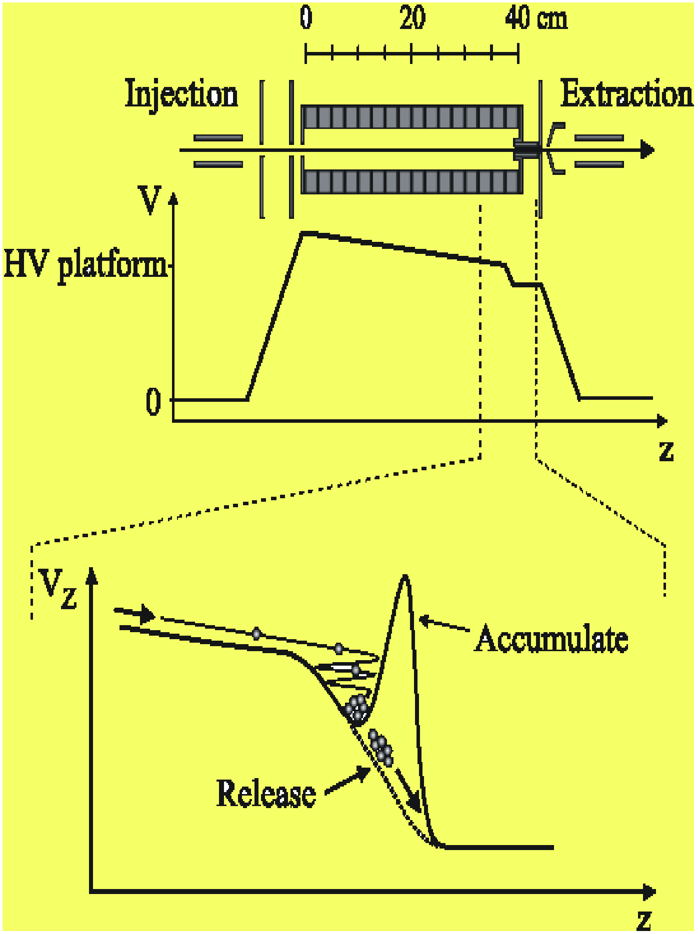
reducing energy spread:

thermalization in (He) gas

confinement by E-fields

- RF multipole
- Axial electrodes





Present RFQ-devices

Name	Input Beam	Input Emittance	Cooler Length	R_0	RF Voltage, Freq, DC	Mass Range	Axial Voltage	Pressure	Output Beam Qualities
Colette	60 keV ISOLDE beam decelerated to ≤ 10 eV	~ 30 π-mm-mrad	504 mm (15 segments, electrically isolated)	7 mm	Freq : 450 – 700 kHz	--	0.25 V/cm	0.01 mbar He	Reaccelerated to up to 59.99 keV with long. energy spread ~10 eV
LPC Cooler	SPIRAL type beams	Up to ~ 100 π-mm-mrad	468 mm (26 segments, electrically isolated)	15 mm	RF : up to 250 Vp, Freq : 500 kHz – 2.2 MHz	--	--	up to 0.1 mbar	--
SHIPTRAP Cooler	SHIP type beams 20-500 keV/A	--	1140 mm (29 segments, electrically	3.9 mm	RF: 30-200 Vpp, Freq: 800 kHz – 1.2 MHz	up to 260 amu	Variable: 0.25 – 1 V/cm	~ 5×10-3 mbar He	--
JYFL Cooler	IGISOL								y spread < 4
MAFF Cooler	30 decele								, Emittance -mm-mrad to mrad
ORNL Cooler	20-60 RIBs (								~2 eV
LEBIT Cooler	5 ke								
ISCOOL	60 keV								
ISOLTRAP Cooler	60 keV								ns ≈ 10p mm
TITAN RFCT	continuous 30–60 keV ISAC beam	--	--	--	RF: 1000 Vpp, Freq: 300 kHz - 3 MHz	--	--	--	6 π-mm-mrad at 5 keV extraction energy
TRIMP Cooler	TRIMP beams	--	660 mm (segmented)	5 mm	RF= 100 Vp, Freq.: up to 1.5 MHz	6 < A < 250	--	up to 0.1 mbar	--
SPIG Leuven cooler	IGISOL Beams	--	124 mm (sextupole rod structure)	1.5 mm	RF= 0-150 Vpp, Freq.: 4.7 MHz	--	--	~50 kPa He	Mass Resolving Power (MRP)= 1450
Argonne CPT cooer	--	--	--	--	--	--	--	--	--
SLOWRI cooler	--	--	600 mm (segmented sextupole rod structure)	8 mm	RF= 400 Vpp, Freq.: 3.6 MHz	--	--	~10 mbar He	--

- Plenty of devices prototyped
- Similar devices in size and operation parameters
- Different solutions for the electrode structures to provide transverse and axial confinement
- Perform very well : $\delta E < 1$ eV, dt ~ few μs, e ~ few π mm mrad, on-line efficiencies 80 %
- Not optimized for high intensities ! (EURISOL-DS)

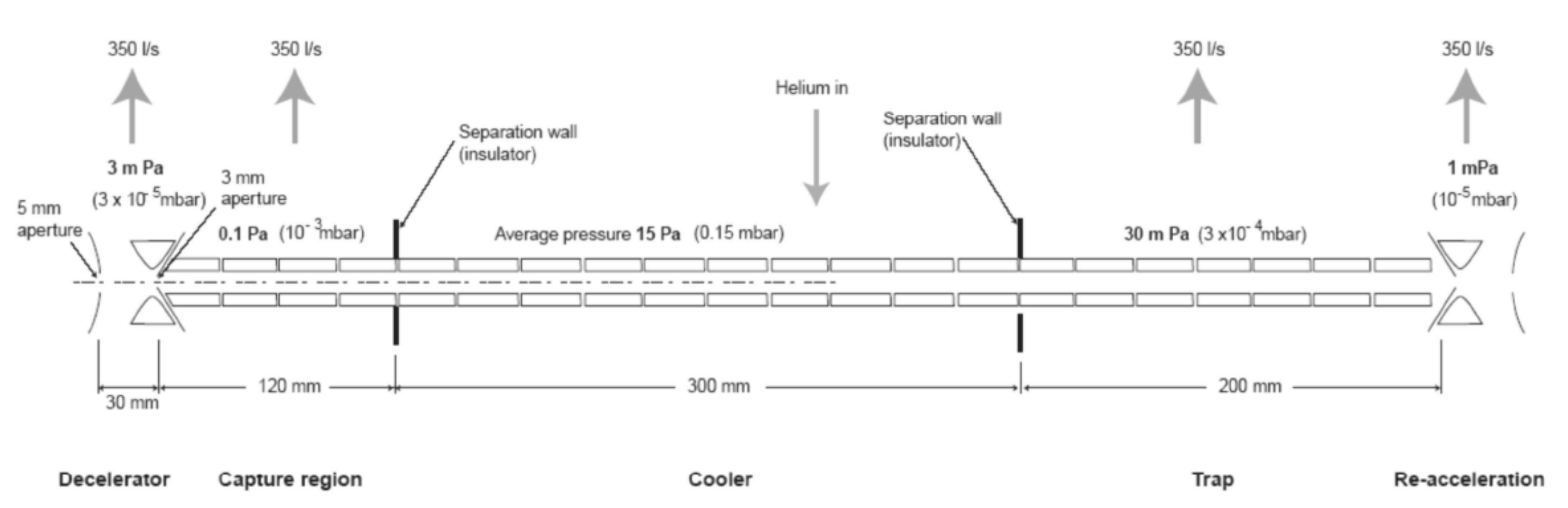
Next-generation RFQ for EURISOL

(in terms of an ion beam/cloud capacity)

$$D = \frac{eV^2}{4mr_0^2\omega_{RF}^2} = \frac{q_{Mathieu}V}{8}$$

e.g. A=40; 2x0=7 mm
@ 2 MHz; V(q=0.4) = 80 V; D = 8 eV
@ 20 MHz; V(q=0.4) = 8000 V; D = 800 eV

10-100-fold increase in the capacity based on the increasing of the pseudopotential depth D

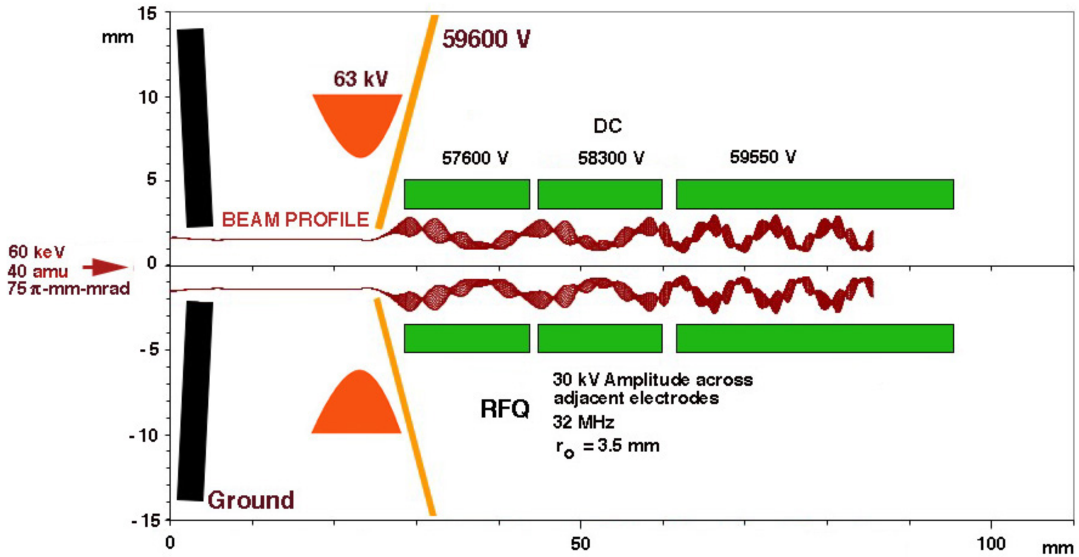


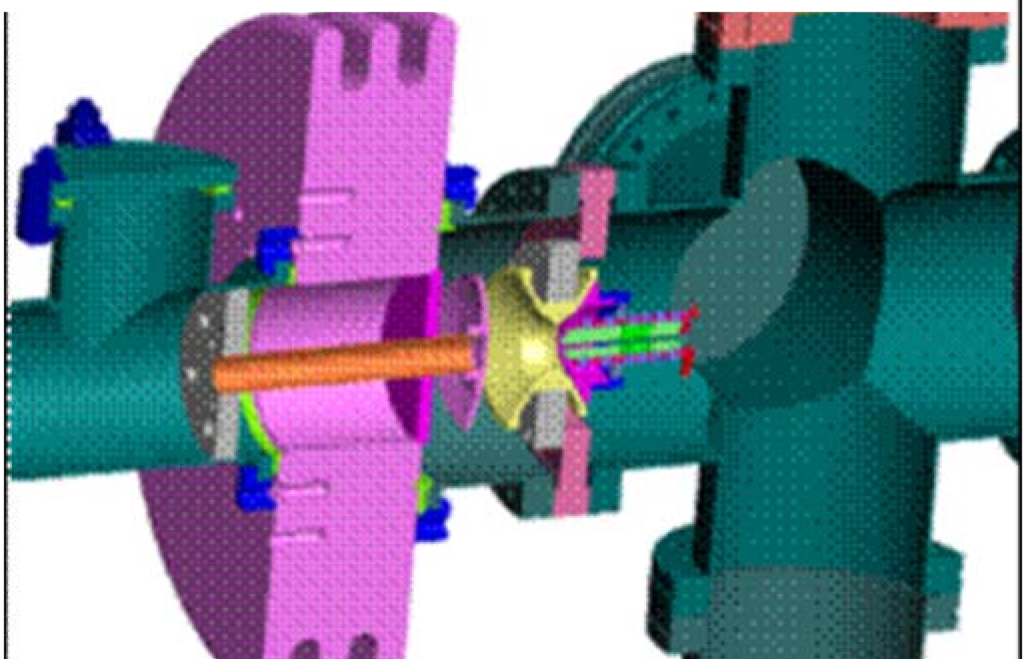
Technical proposalr by O. Gianfrancesco

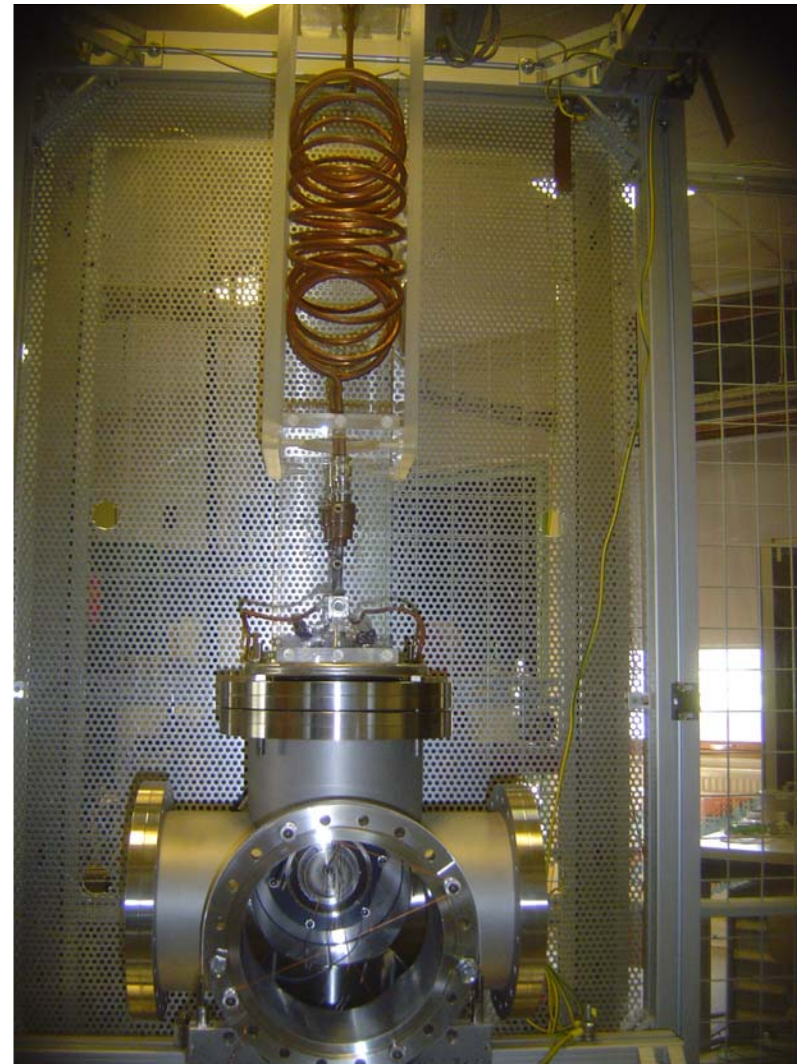
Technical challenge to be solved: 20-30 MHz at 10 kV !
➔10 μA beam or cooled bunches of 6×10^9 ions at 100 Hz rate

(D. Lunney, Orsay)

Radiofrequency: 10 kV beyond 10 MHz

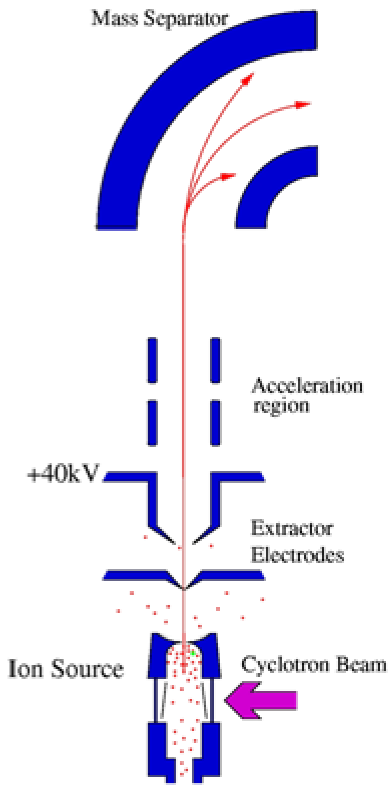


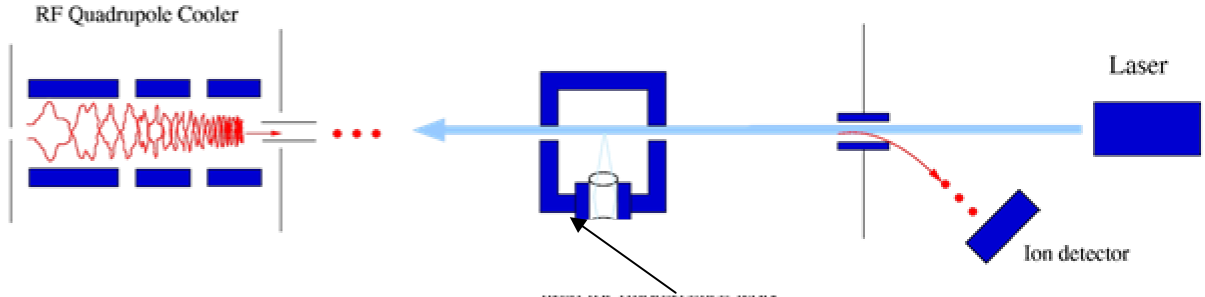




O. Gianfrancesco, Ph.D. thesis, McGill University (2005)

Cooling and bunching for collinear laser spectroscopy





Collinear Beams Laser Spectroscopy

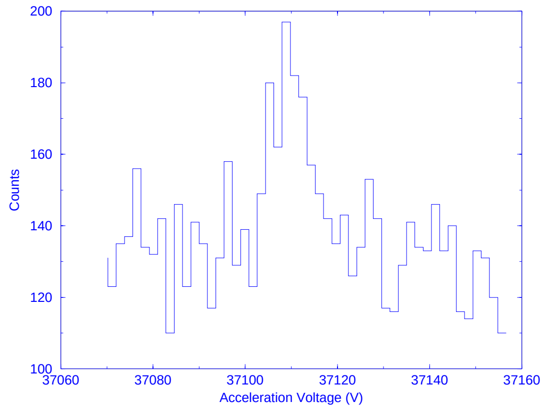
- **Reduces energy spread of ion beam (100eV → 1eV)**
- **Improves emittance of ion beam**
- **Trap and accumulates ions – typically 100 - 500 ms**
- **Releases ions in a 10 μs bunch**

A. Nieminen et al., Phys. Rev. Lett. 88 (2002) 094801

Collinear laser spectroscopy with bunched beams

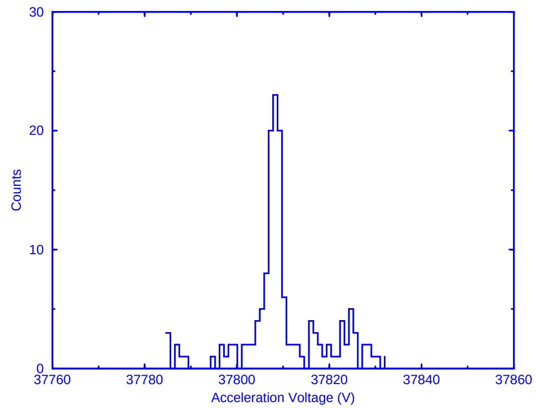
MANCHESTER 1824
The University of Manchester

Impact on the sensitivity of collinear laser spectroscopy of Zr



Before

5.25 hours @ ~8000 ^{88}Zr per sec (327nm)

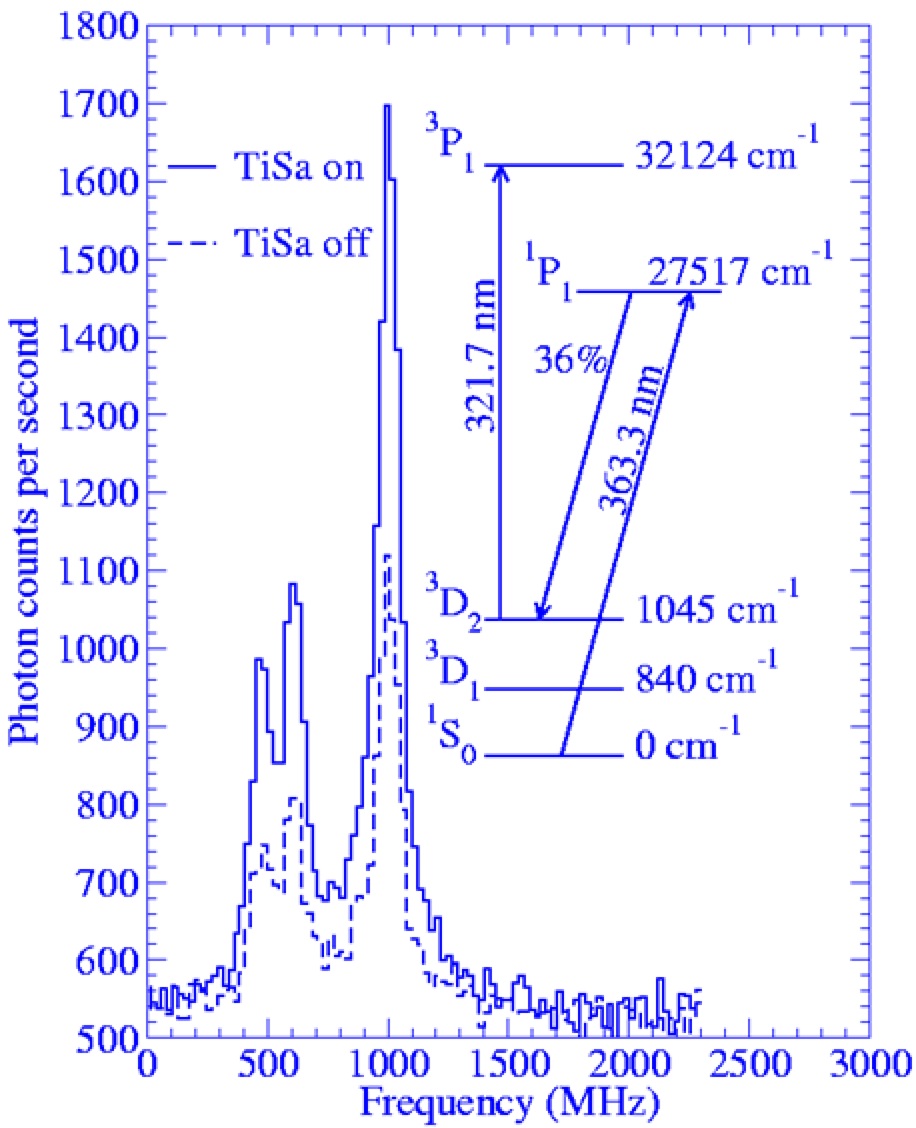


After

48 mins @ ~2000 ^{88}Zr per sec (310nm)

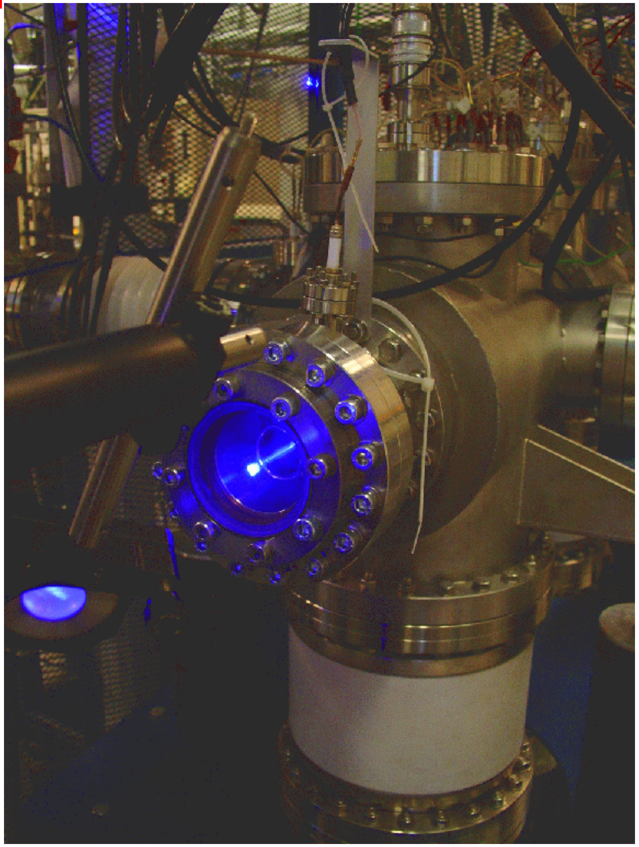
A. Nieminen et al., Nucl. Instr. Meth. A 469 (2001) 244
A. Nieminen et al., Phys. Rev. Lett. 88 (2002) 094801
J. Äystö and A. Jokinen, J. of Phys. B 36; At. Mol. and Opt. Phys. (2003) 573

Optical pumping in the ion cooler



Preparation for collinear laser spectroscopy: Optical transition with more components or stronger transition

Road to polarization in the cooler



Charge state breeding: basics

What ?

from singly charged to multiply charged ions

" $1^+ \rightarrow n^+$ "

Why ?

Low-E experiments with n^+
Cost effective post-acceleration

$E = q\,V$ $\left(\text{cyclotron: } E = K \frac{q^2}{A}\right)$

In principle

electron impact stepwise ionization

requirements

1) high enough electron energy

2) suitable combination of:
   - ionization time ($\rightarrow$ confinement)
   - high electron density
   - good vacuum

In practice

ECRIS
electron cyclotron resonance ion source

EBIS
electron beam ion source

EURISOL: Comparison EBIS v. ECRIS

	ECRIS	EBIS/T
Single charge state breeding efficiencies	< 20%	<30% <70% in principle
Beam purity	Support gas and rest gas In between peaks ~0.5-10 nA	Rest gas peaks 10-100 pA; In between peaks <<<1 pA (not detectable)
Beam particle rate limitations	> 1e12/s	<1e9/s with pre-bunching <1e11/s with continuous injection
Breeding times	50 ms	10 ms
Typical A/q	A/Q >5-6	A/Q > 2.6
Breakup of molecules	Possible	Possible
Energy spread of ions	negligible	Up to 0.5% for high current devices
Operation mode	Continuous	Pulsed
Ion beam acceptance	Large	Small

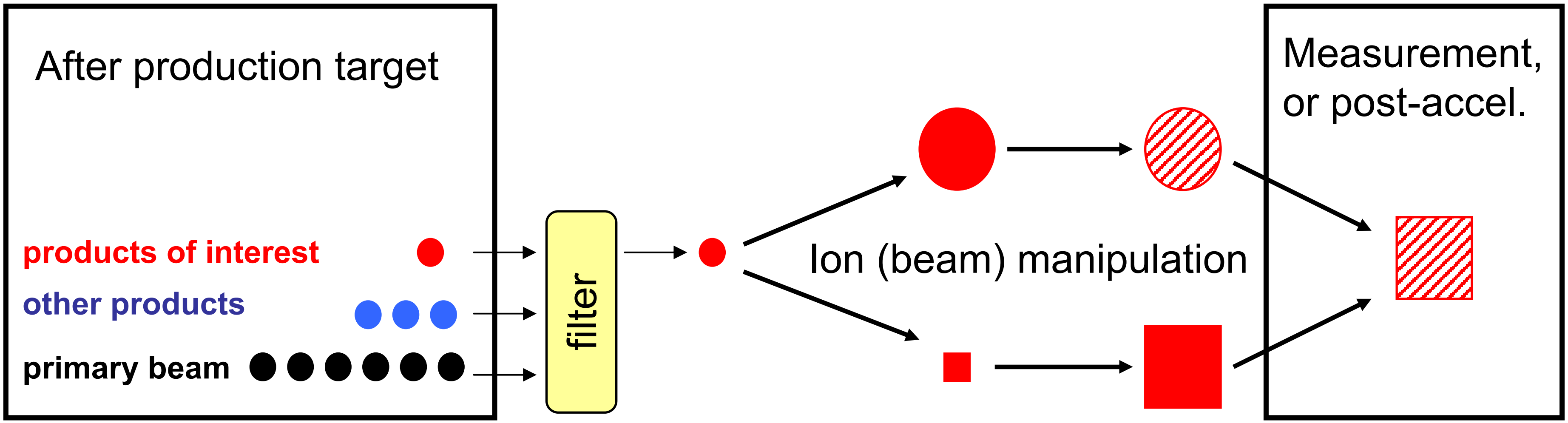
O. Kester, GSI
P. Delahaye, CERN

Complementary devices !!

Summary

- **Motivation for beam manipulation:**
  - Request from experimentalists ←→ Ion beam produced
  - Cost-effectiveness of post-acceleration
- **Parameters to be optimized:**
  - Composition of the beam (contaminansts, isobaric/isomeric purity)
  - Time structure (DC vs pulsed/bunched, width of the bunch)
  - Energy spread
  - Transverse emittance
  - Ionic properties (charge state, polarization, atomic state)
- **Progress during recent years:**
  - Innovation of ion coolers and bunchers → success story
  - Progress in charge breeding both in ECR and EBIS
  - EXOTRAPS, NIPNET, LASER, TRAPSPEC, CHARGE BREEDING, …
- **Challenges:**
  - High intensities → radiation problems, space charge problems, radiation safety problems
  - Effciency, (losses):
    - Low-energy nbeam transport and high-resolution separation, in practise 100 %
    - Ion coolers and bunchers: 80 % reachable, reduced efficiency for light masses (← H buffer gas ?)
    - Single charge state efficiencu still low, except for some favorable cases
    - Delay time losses for very short-lived isotopes

Thank you for your attention !



Beam preparation = **Purification** + **Manipulation**

Sub-Task 1 | **Sub-Tasks 2 and 3**