PRISMAP school on radionuclide production

Ion sources for ISOL

Mia Au

CERN SY-STI

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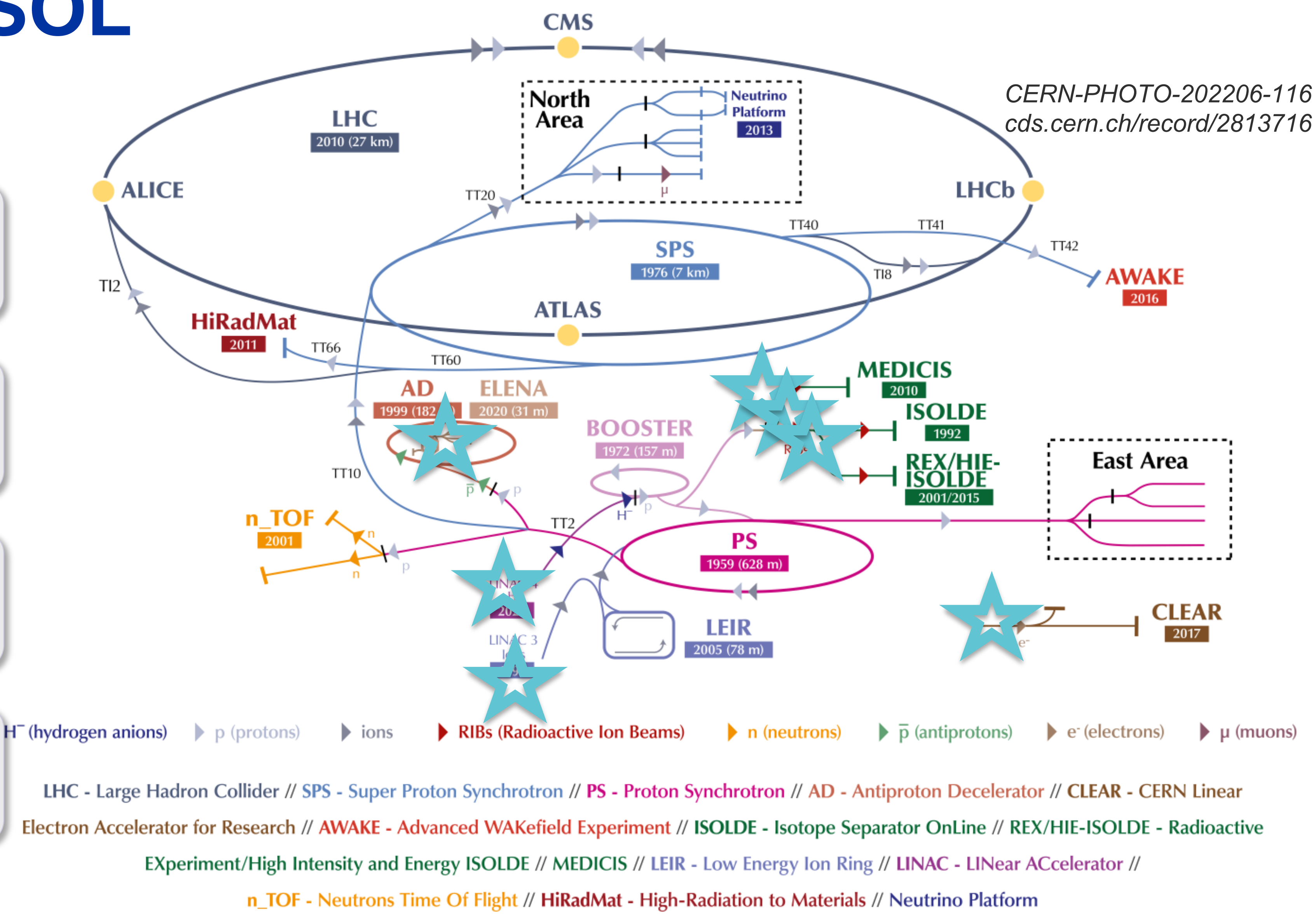
Ion sources for ISOL
Outline:

1 Introduction

2 Ionization phenomena

3 ISOL ion sources

4 Applications



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Ion sources for ISOL - Outline

What?

- Broadly: a device to create a beam of charged particles

Why?

- Charged particles respond to electric and magnetic fields, allowing the manipulation of particle beams
- Ion sources define important properties of the particle beam:
  - Type of particle
  - Intensity (number of particles)
  - Energy of the particles
  - Position and velocity (shape and emittance)
  - Number of charge units per particle (charge state)
  - Time structure of the particles

How?

- This lecture ☺

The Isotope Separation On-Line (ISOL) method

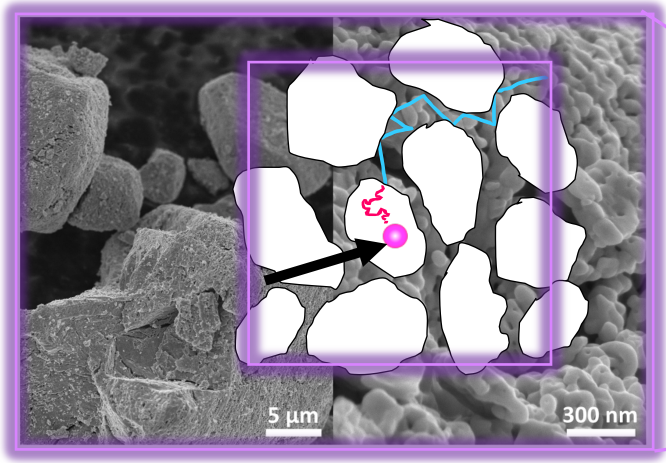
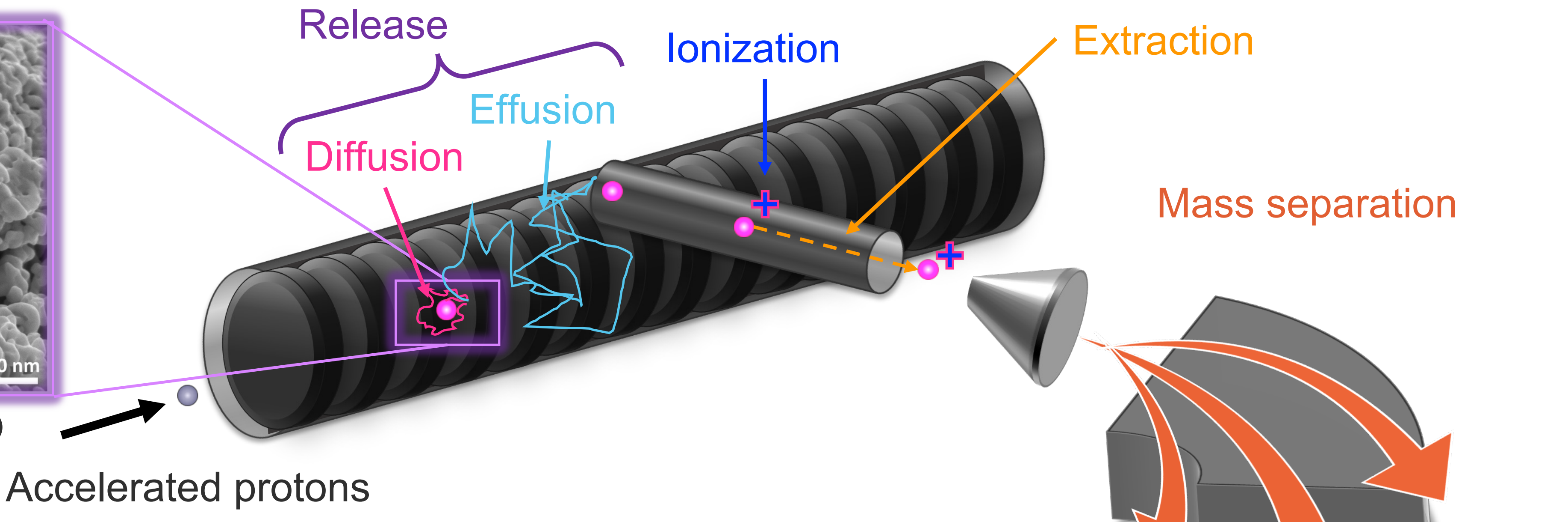


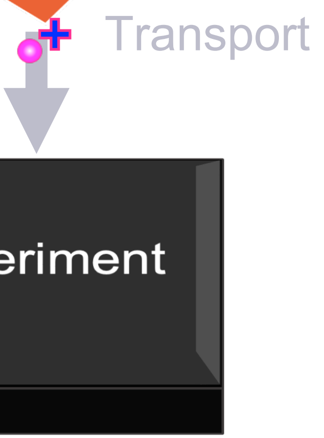
Figure published in Ramos *et al.*, (2020)
NIM B **463**, 201



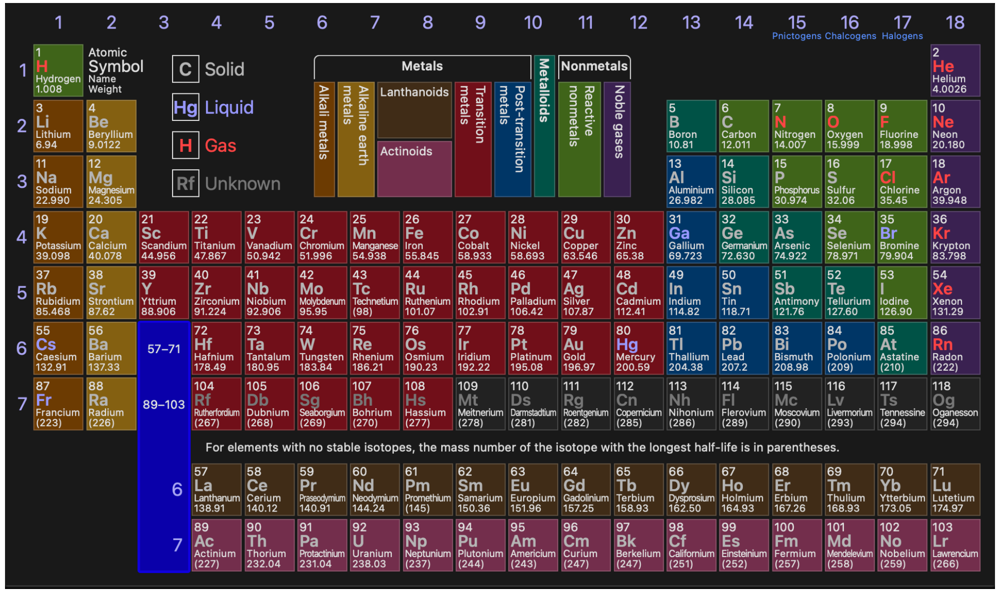
1. Production
2. Release
3. Ionization
4. Mass separation
5. Delivery to experiments

$$Beam\ Intensity = \sigma \cdot j \cdot N_t \cdot \varepsilon$$

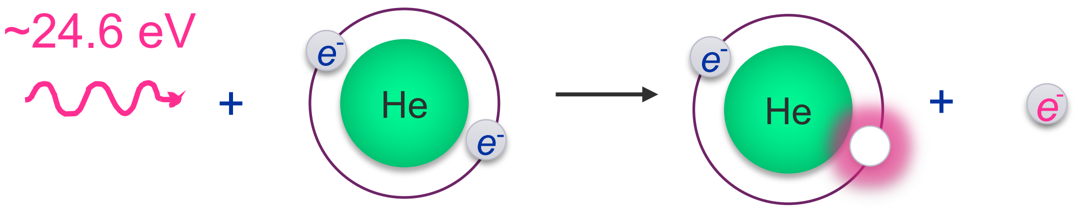
N_t – Number of target atoms
j – Proton flux [cm^{-2}]
σ – Cross section [mb]
ε – Efficiency [%]

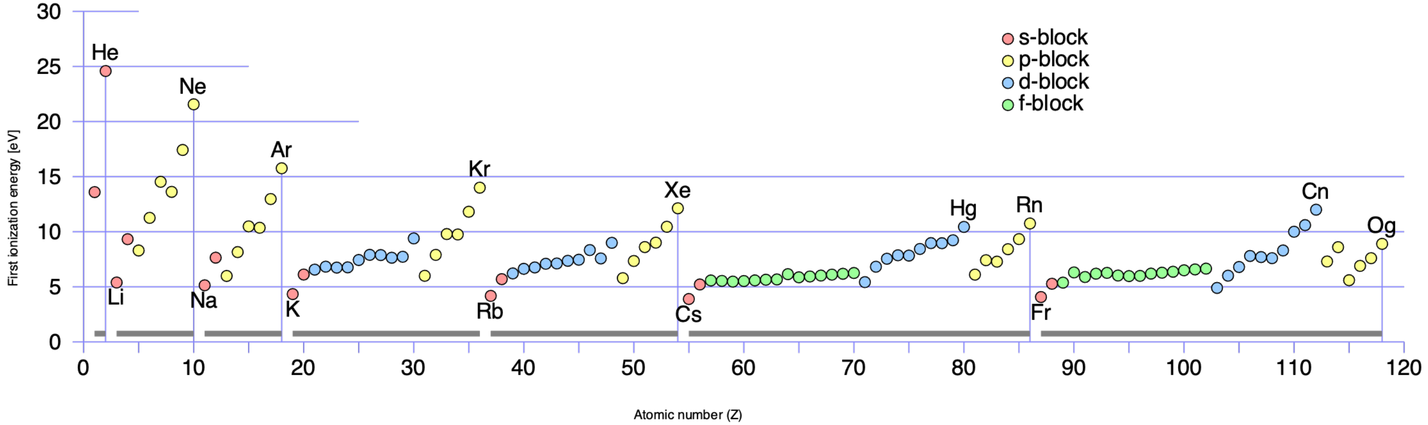


ISOL Step 3: Ionization



energy + He → He^+ + e^-



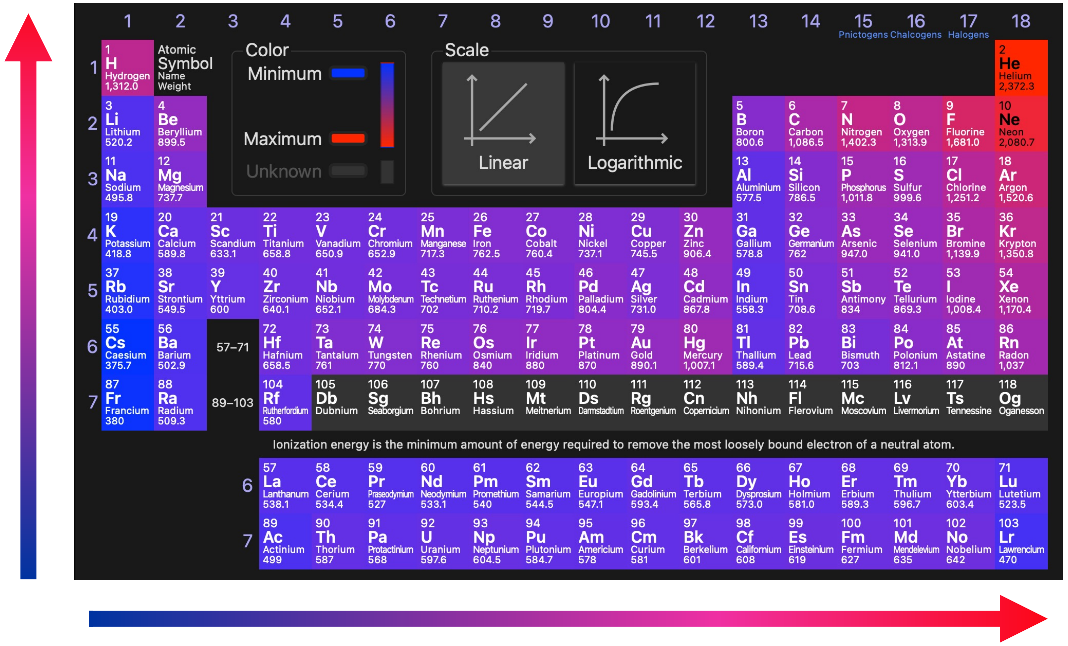


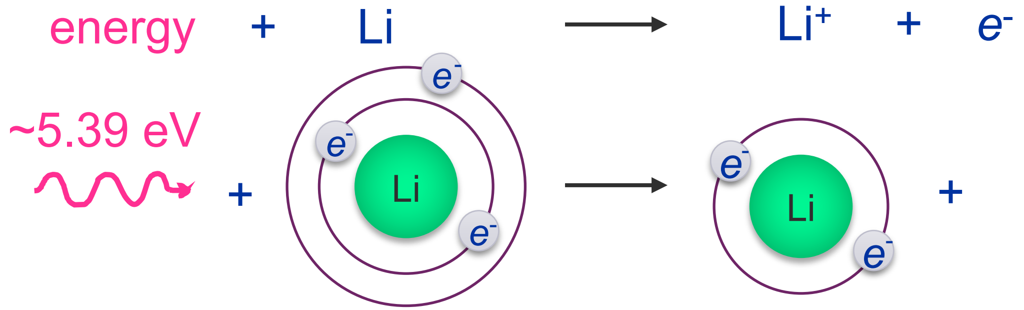
Ionization potential (IP) / ionization energy (IE)

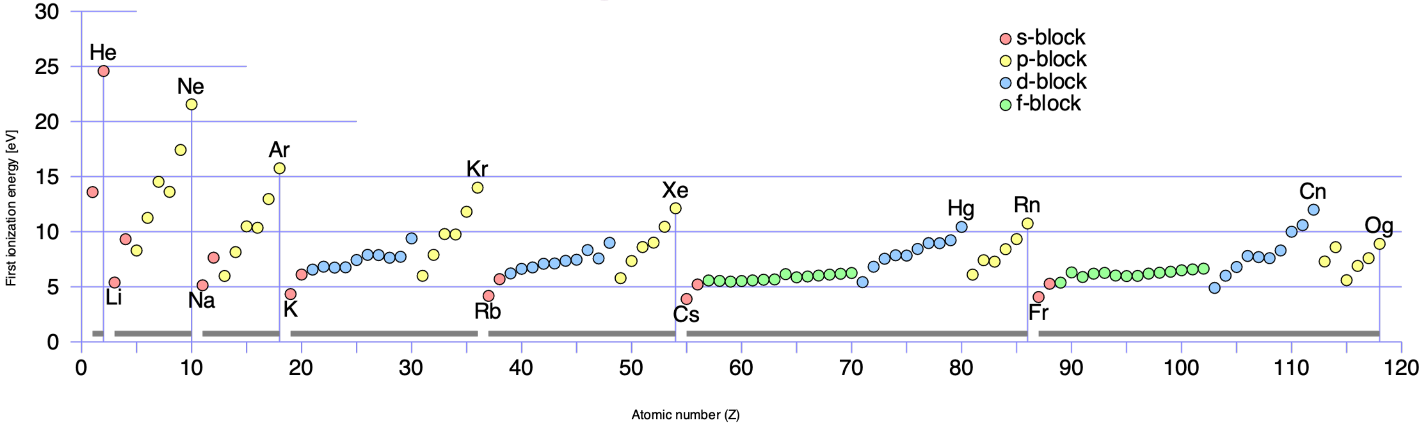
- the energy needed to remove an electron from an atom (or ion)
  - First IP: energy to ionize the neutral atom
- The IP depends on the electronic “shell structure” of the atom

[1] www.ptable.com
[2] Graph of first ionization energies in eV (https://commons.wikimedia.org/wiki/File:First_Ionization_Energy_blocks.svg)

ISOL Step 3: Ionization







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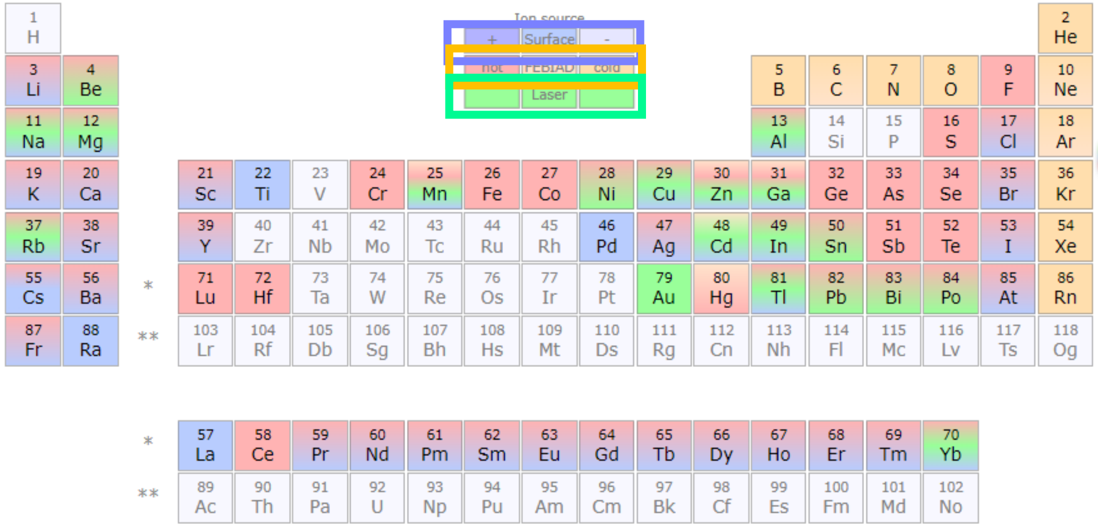
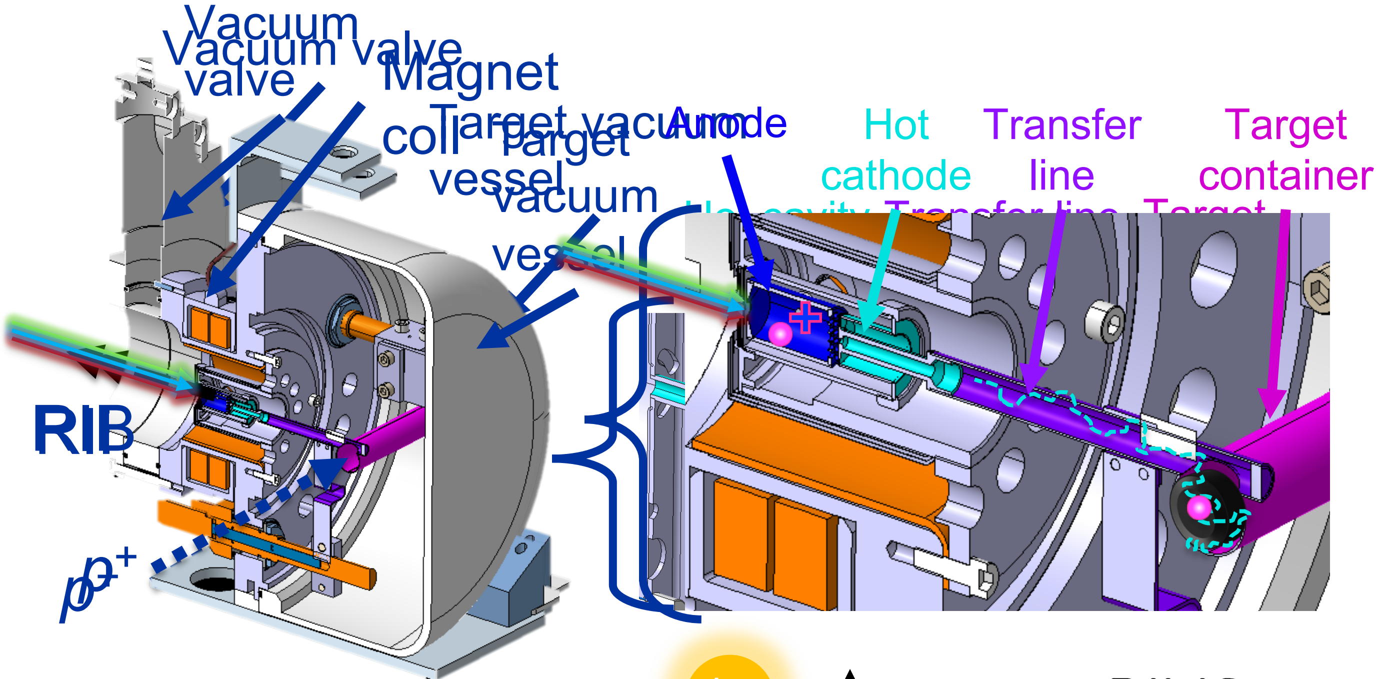
ISOL Step 3: Ionization

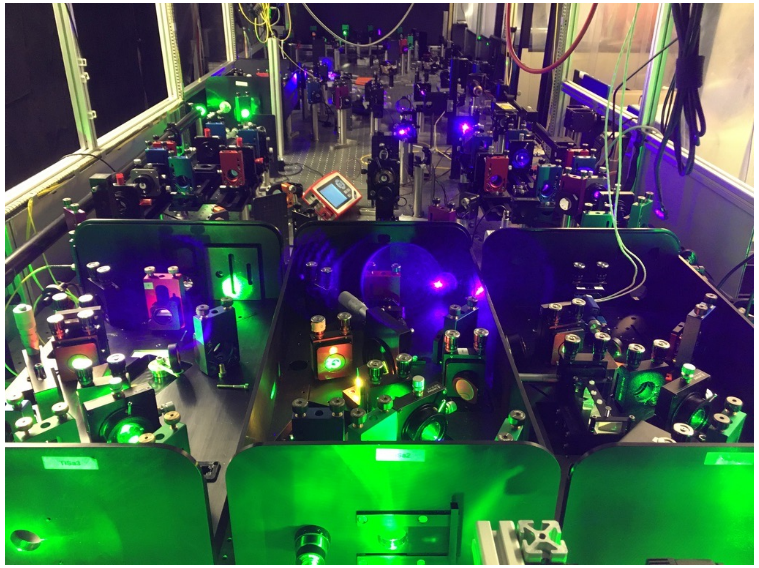


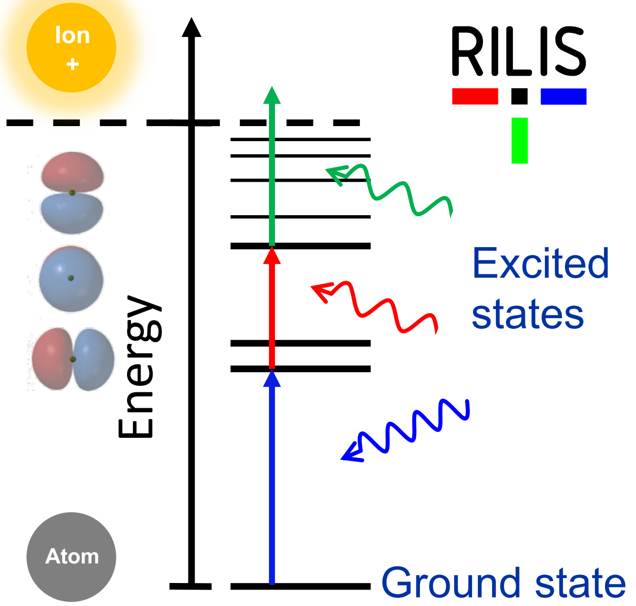
cern.ch/isolde-yields

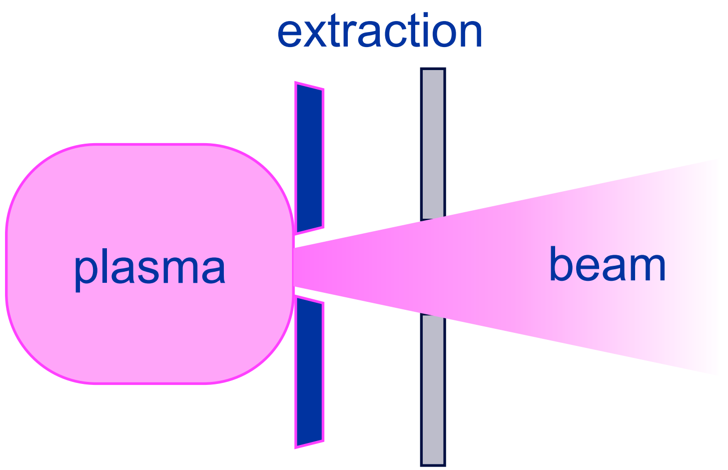


Ion sources

- Surface ionization
- Electron impact ionization
- Resonance laser ionization







Ionization

Mechanisms, processes and interactions

References and literature:

1. The Physics and Technology of Ion Sources 2nd edition Ian G. Brown (2004), WILEY-VCH
2. Handbook of Ion Sources, B. Wolf (1995)

1 Plasmas
2 Ionization mechanisms
3 Surface interactions
4 Beam formation and extraction

Plasmas and their parameters

Plasma: “fourth state of matter” – instead of molecules, composed of ions, electrons, and neutrals

Density

- electron density n_e, ion density n_i and neutral density n_n
- “charge neutrality” : $\sum q_i n_i = n_e$
- Ionization fraction: $\boldsymbol{\beta} = \frac{n_i}{n_i + n_n}$

Temperature

- Typical units of electron volts (eV)
  1 eV = 11 600 K
- In an isotropic plasma at thermal equilibrium, the Maxwell-Boltzmann distribution leads to:
  - $\bar{v_e} = 67\sqrt{T_e}\left[\frac{\text{cm}}{\mu\text{s}}\right]$ $\bar{v_i} = 1.57\sqrt{\frac{T_i}{A}}\left[\frac{\text{cm}}{\mu\text{s}}\right]$
- electrons, ions, and neutrals may have different temperatures: T_e, T_i, T_n

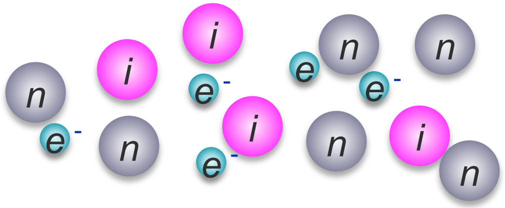
Collisions

- Kinetic theory of gases → plasmas
- Mean free path $\lambda = \frac{1}{n\sigma}$
- collision time τ (collision frequency $\upsilon = \frac{1}{\tau}$) $\tau = \frac{1}{n\sigma v}$
- Collision times ~ns to ms

Frequency

- Oscillations of electrons and ions in response to small deviations away from charge neutrality
  - $\omega_e^2 = \frac{e^2 n_e}{\varepsilon_0 m_e}$ $\omega_i^2 = \frac{q^2 e^2 n_i}{\varepsilon_0 m_i}$

Provides the supply of charged particles



Electron impact ionization

- collisions of electrons with atoms or molecules, where ionization to charge state i can happen for $E_e \geq \epsilon_i$
- Typical cross-section maximums around $E_e \approx 3.5\epsilon_i$

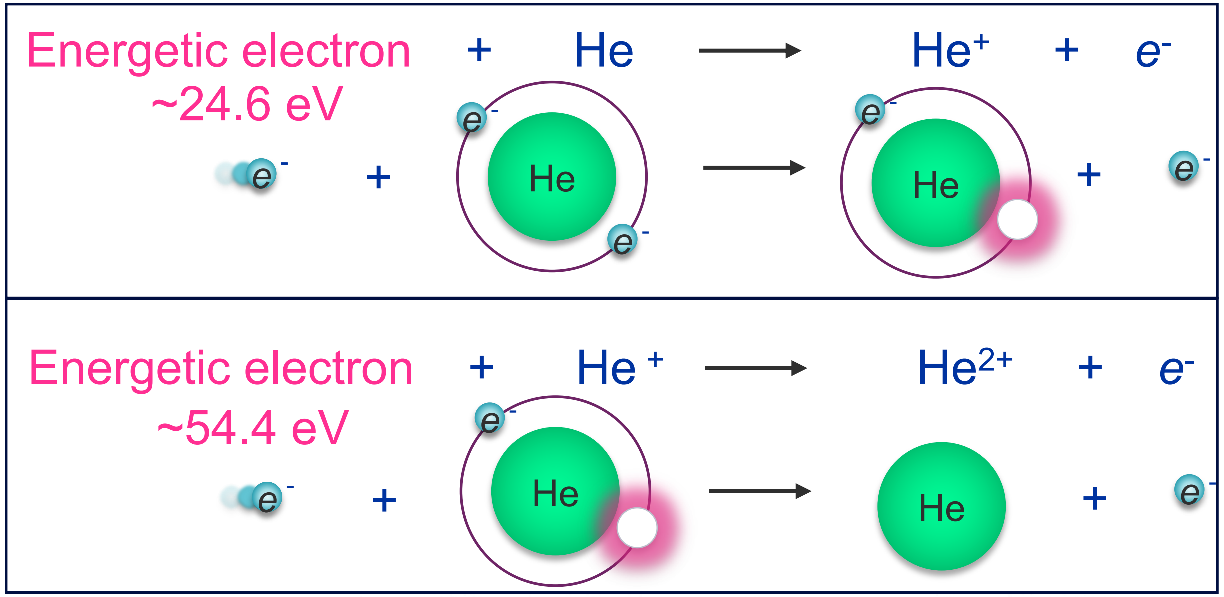
Multiple ionization

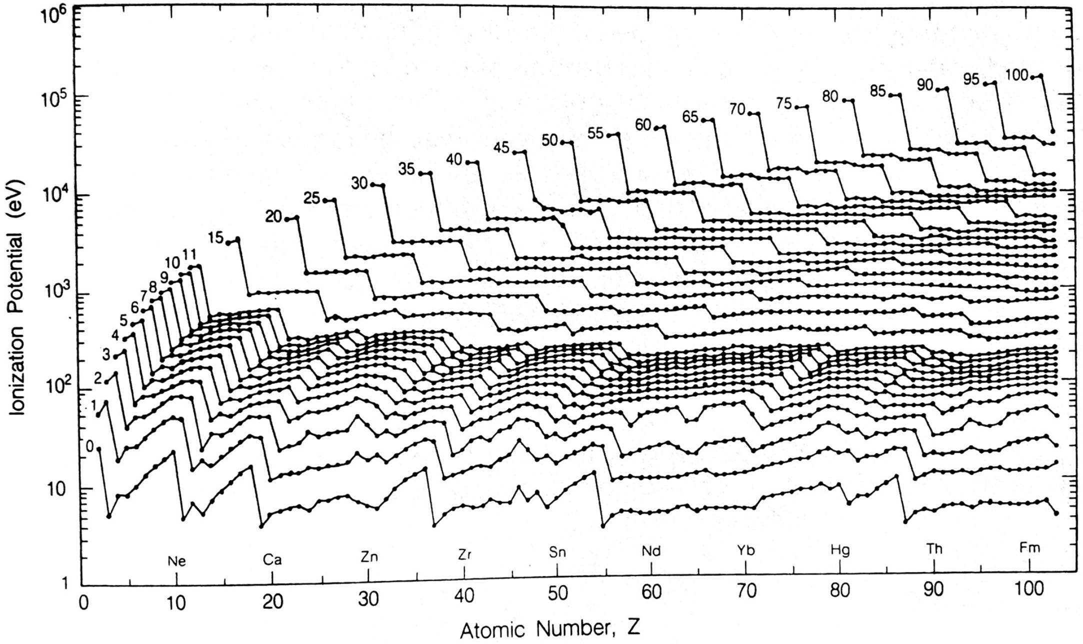
- Removal of multiple electrons: “multiply-ionized”, “multiply-charged”, “highly charged ions”
- Single or multiple (step-wise collisions)

Electron impact in plasmas

- Electron temperature T_e : $\overline{v_e} = \sqrt{\frac{8k_B T_e}{\pi m_e}}$ and $\overline{E_e} = \frac{3}{2}k_B T_e$
- Number of electron impact events:
  - Plasma electron density n_e or electron current $j_e = n_e v_e$
  - Required ion confinement time:

$$\tau_i(q) = \sum_{k=0}^{q-1} \frac{1}{n_e \langle \sigma_{k,k+1} v_e \rangle}$$

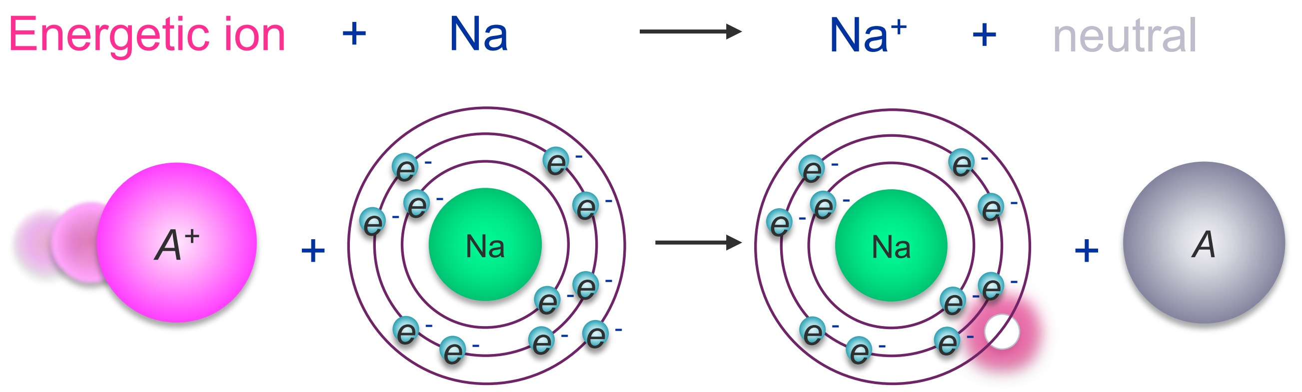




Ion impact ionization

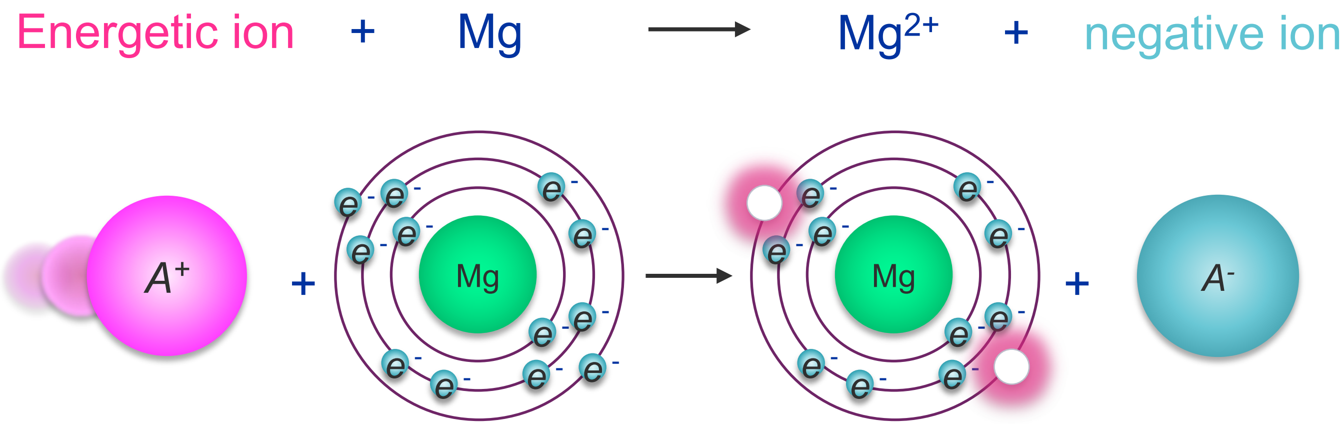
Charge exchange

- Collisions between ions and atoms where an electron is exchanged
- Maximum ionization cross-sections occur when the energetic particle has a similar speed to the orbital electron – requires high energy ions compared to electron impact



Double charge exchange

- Single step or stepwise exchange of multiple electrons
- negative ion production from positive ion beams
- Alkalis (Na, K, Rb, Cs) can do stepwise double charge exchange
- Alkali-earths (Mg, Ca, Sr, Ba) can do single-step double charge exchange



Chemical ionization

- “soft” ionization technique – produces ions with little excess energy, reduced fragmentation for molecules (M)
- Typically a gas-phase acid-base reaction using an ionized reagent gas to react with and ionize an analyte

Reagents

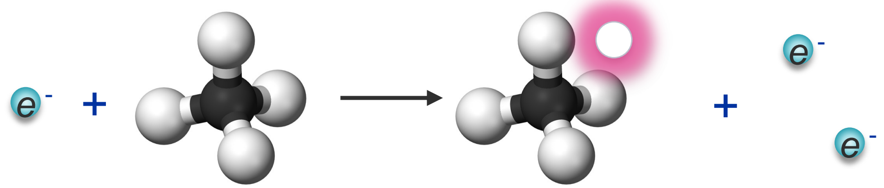
- Ex: Methane CH_4 (PA 5.7 eV) isobutane C_4H_{10} (PA 8.5 eV) ammonia NH_3 (PA 9.0 eV)

Reactions

- Proton transfer (“protonation”)
- Adduct formation
- H- transfer
- Charge exchange

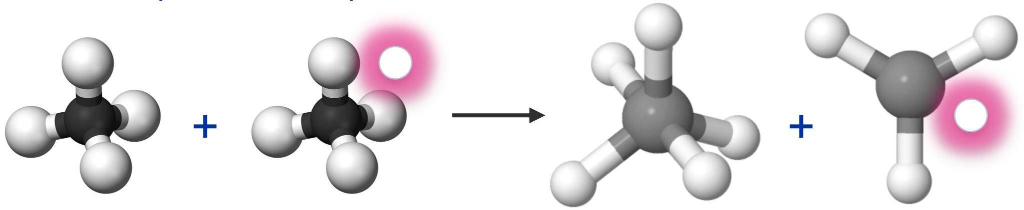
Ion formation

$$e^- + CH_4 \longrightarrow CH_4^{+\bullet} + 2e^-$$

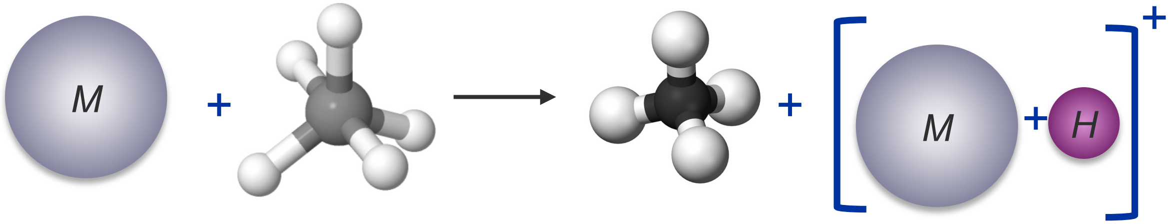


Formation of secondary reagents

$$CH_4 + CH_4^{+\bullet} \longrightarrow CH_5^+ + CH_3^\bullet$$



Protonation



[1] Harrison *Chemical Ionization Mass Spectrometry, 2nd Edition* (1992)

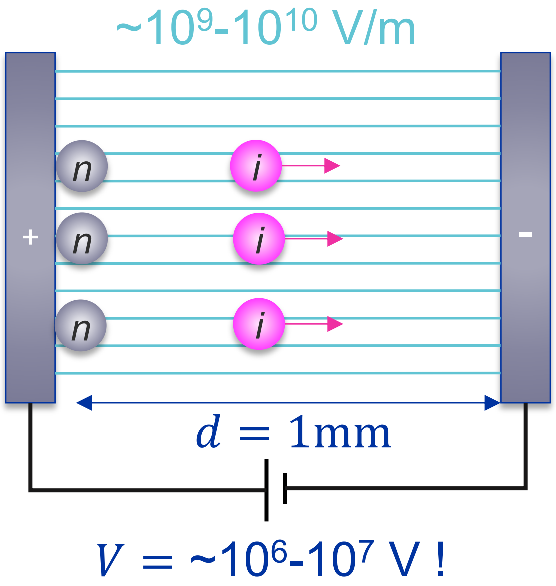
Field ionization

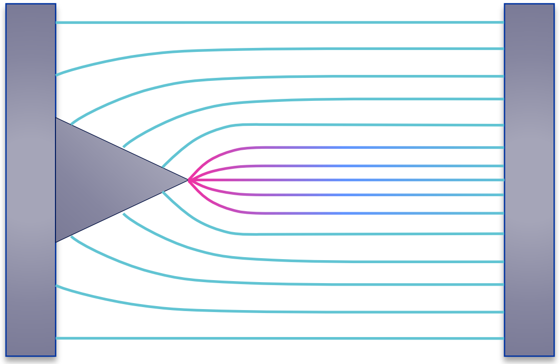
Field desorption

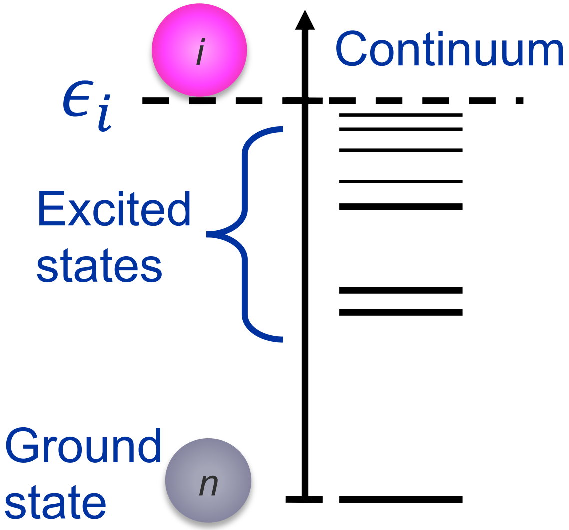
- electric fields can be used to ionize neutrals
  - Volatile species
- Sharp points enhance field intensity

Ionization from excited states

- ionization of highly excited atoms in a well-controlled static electric field
- Lower required fields







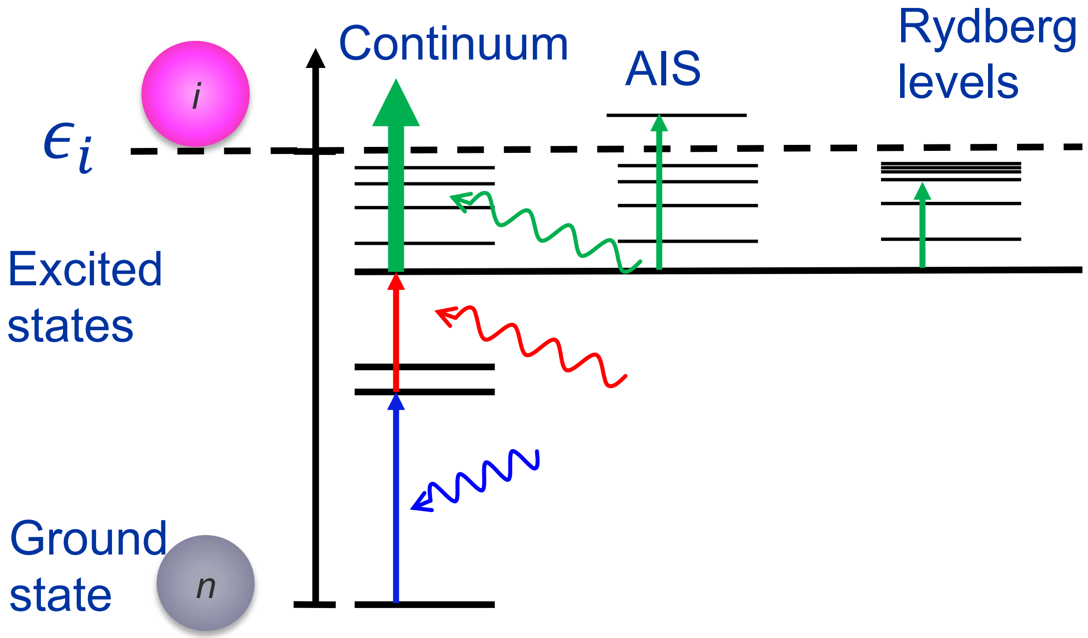
[1] *Beckey H.D. Field ionization mass spectrometry. Research/Development, 1969, 20(11), 26*

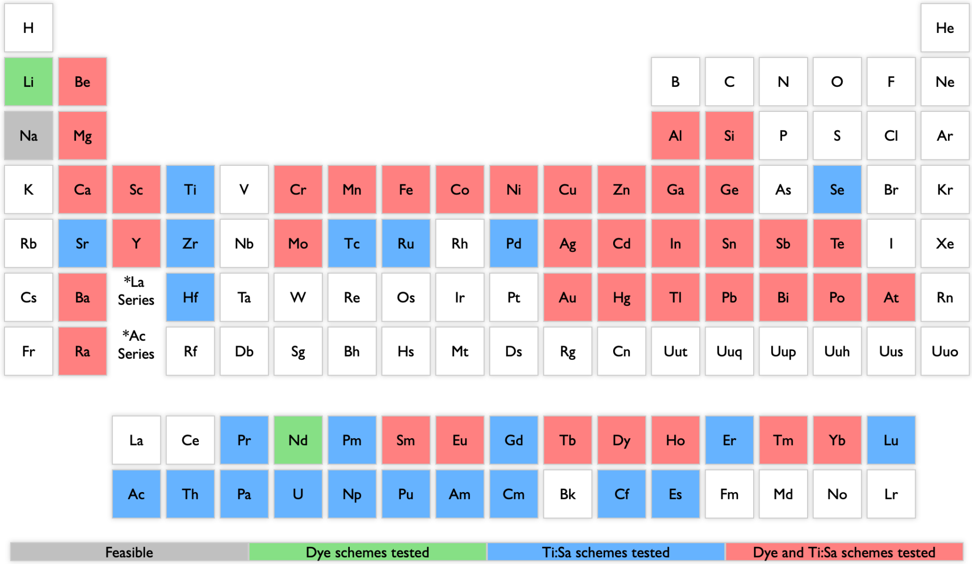
Photoionization

- Photons can eject electrons from atoms or ions if $E_\gamma \geq \epsilon_i$
  - $\lambda \approx 1\,200$ nm for E_γ =1 eV
  - Single-photon ionization: vacuum UV or soft X-rays

Stepwise photoionization

- Excitation of an electron through a series of electronic transitions that cumulatively give $E_{\gamma,total} \geq \epsilon_i$
- Non-resonant ionization to the continuum
- Auto-ionizing states (AIS)
- Rydberg levels





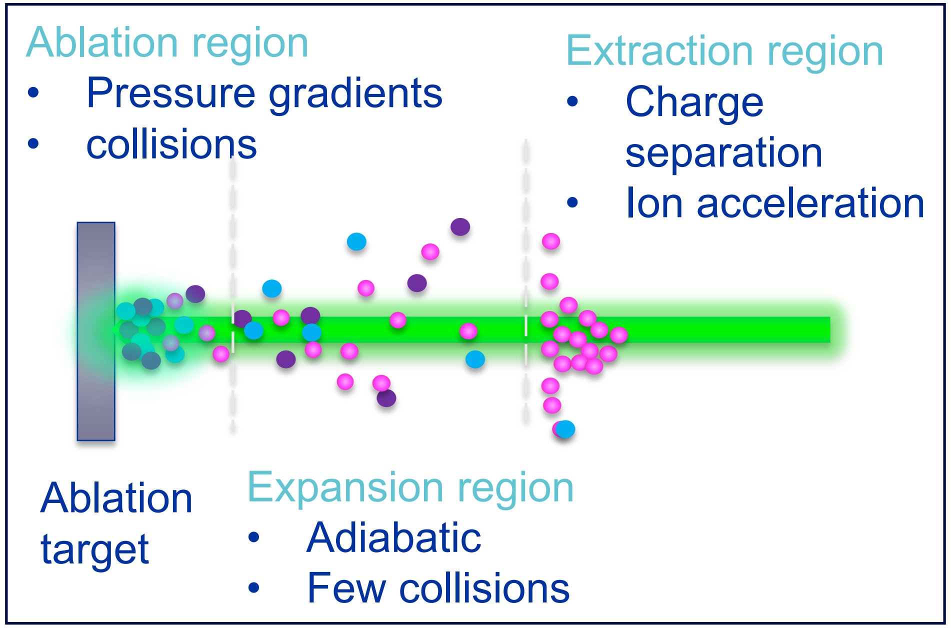
[1] Fedosseev et al., (2017) J. Phys. G Nucl. Part. Phys. 44 (2017) 084006
[2] RILIS Elements (2024), https://isolde-rilis2.web.cern.ch

Kinetic ejection

Ejection of particles from surfaces when solid material is bombarded with high enough energy

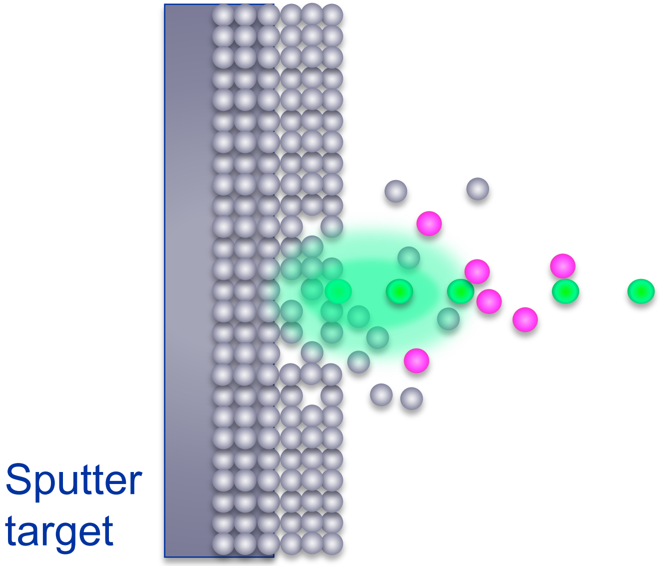
Laser ablation

- Photons in a laser beam impart energy to electron and lattice components of a solid – *not* photoionization
- Low flux: heated material at the surface evaporates or sublimates
- High flux: heated material is converted to a plasma: ion production
- Dependence on laser pulse-length



Sputtering

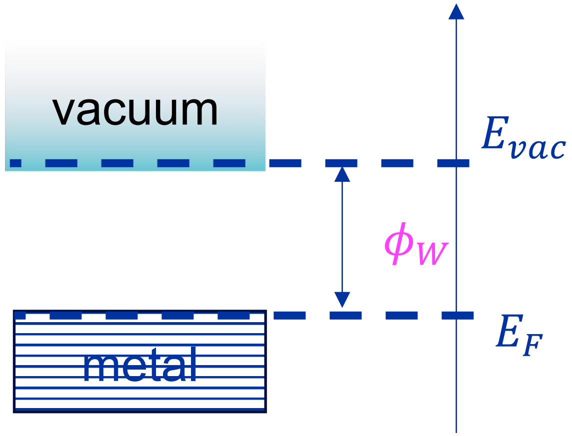
- Atoms from a solid target are released by bombardment with energetic ions
- Minimum energy required to remove an atom from the target



Electron sources

Work function ϕ_W

- Minimum energy required to eject an electron from the surface



Low work function materials

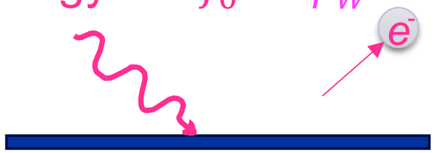
- Dispenser cathodes (ex. porous W with BaO, CaO)
- Coatings (ex. Cs, …)
- Single crystals (ex. LaB_6, CeB_6)

Photoemission

- Photocathodes for electron emission
- Sensitive to surface conditions and vacuum requirements

Photoelectric effect [1]

Energy $= hf_0 = \phi_W$



$$eff_{quantum} = \frac{n_{e-}}{n_\gamma}$$

[1] A. Einstein, Analen der Physik, 322 (1905) p 132 (in German)

Example: scanning electron microscope (SEM)

	Tungsten hairpin	CeB_6 crystal	Schottky FEG
Emission mechanism	Thermionic	Thermionic	Electron Tunnelling
Lifetime	100 h	1500 h	>10,000 h
Tip emitting diameter	100 µm	25 µm	100 nm
Resolution @30 kV	4 nm	3 nm	1 nm
Resolution @1 kV	50 nm	25 nm	5 nm
Low-kV imaging (<5 kV)	Yes	No	Yes
Vacuum	10^{-1} – 10^{-5} mbar	10^{-7} mbar	10^{-9} mbar
Cost of ownership	Lowest	Medium	Highest

Table 1: Comparison of electron source characteristics for SEM.

https://www.nanoscience.com/blogs/which-electron-source-is-best/

Thermionic emission

- Emission of charge carriers from a surface due to thermal energy

Electron emission from surfaces

- electron gas in a metal at a given temperature: Richardson-Dushman equation [1,2]

Electron current density

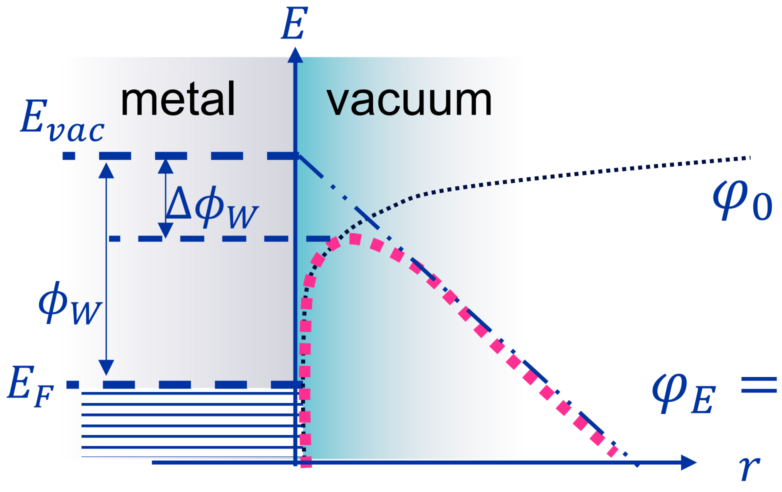
$$J = \underbrace{\frac{4\pi m_e q_e}{h^3} k_B{}^2}_{} T^2 e^{\frac{-\phi_W}{k_B T}} \left[\frac{\text{A}}{\text{m}^2}\right]$$

Richardson constant $C_R \approx 120$ [A cm^{-2} K^{-2}]

Emission in electric fields

- Schottky effect [3]: moderate electric fields E lower the potential barrier for electrons to escape the hot surface by an amount ΔW
- Field emission/Fowler-Nordheim tunnelling [4]: strong E-fields make the potential barrier thin enough for electrons to tunnel through

$$\phi_W{}^* = \phi_W - \Delta\phi_W = \phi_W - \sqrt{\frac{q_e^3 E}{4\pi\varepsilon_0}}$$



$$\varphi_0 = \frac{-q_e}{4\pi r \varepsilon_0}$$

$$\varphi_E = -q_e E r$$

[1] O.W. Richardson, Phil Mag Ser 6 28 (1914) p 633
[2] S. Dushman, Phys Rev 21 (1923) p 623
[3] W. Schottky, Z f Physik 14 (1923) p 63
[4] R.H. Fowler, L. Nordheim, Proc R soc London A 119 (1928) p 173

Ionization at surfaces

- Collisions of electrons and atoms can cause ionization

$$\alpha = \frac{n_1}{n_0} = \frac{g_1}{g_0} e^{-\frac{W-\epsilon_1}{k_B T}} \quad \beta = \frac{n_1}{n_1+n_0} = \frac{\alpha}{1+\alpha}$$

Langmuir equation [1]

- Ratio of ions to neutrals desorbing from a surface

Saha equation [2]

- derived for the degree of ionization in the sun
- equilibrium of an ionized gas at a given temperature

$$\frac{n_{i+1} n_e}{n_i} = \frac{2}{\Lambda^3} \frac{g_{i+1}}{g_i} e^{-\frac{\epsilon_{i+1}-\epsilon_i}{k_B T}}$$

n_i : density of ions in charge state *i*
n_e : density of electrons
Λ : Electron de Broglie wavelength $\Lambda = \sqrt{\frac{h^2}{2\pi m_e k_B T}}$
g_i : Degeneracy for charge state *i*
ϵ_i : Energy to remove *i* electrons from neutral species

Saha-Langmuir equation [3,4]

- $n_i \approx n_e$: quasi-neutrality
- P : pressure
- Plasma sheath formation shields wall potentials

$$\alpha = \frac{n_1}{n_0} = \frac{g_1}{g_0} A_0 T^2 \frac{1}{q_e n_1} \sqrt{\frac{2\pi m}{k_B T}} e^{\frac{-\epsilon_1}{k_B T}}$$

β : ionization coefficient $\quad \beta = \frac{n_1}{n_1+n_0} = \frac{\alpha}{1+\alpha}$

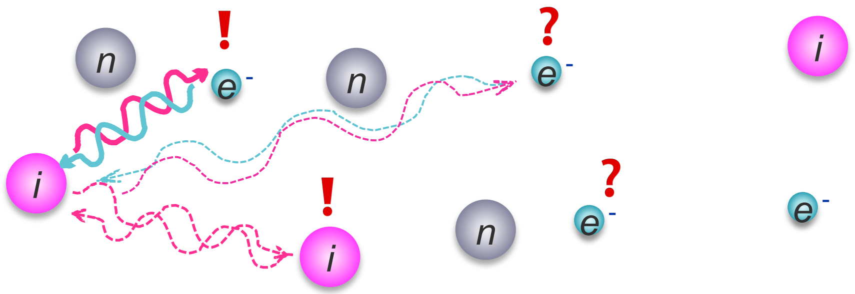
[1] I. Langmuir, Phys. Rev. 2 (1913) p 450
[2] M. N. Saha, Philosophical Magazine Series 6. 40 (238): 472 (1920)
[3] A. Latuszynski and V. I. Raiko, Nucl. Instr. and Meth. 125 (1975) 61.
[4] R. Kirchner and Piotrowski, NIM B 153 (1978) p 291

Plasma boundaries

$$|F| = \frac{|q_1 q_2|}{4\pi\varepsilon_0 r^2}$$

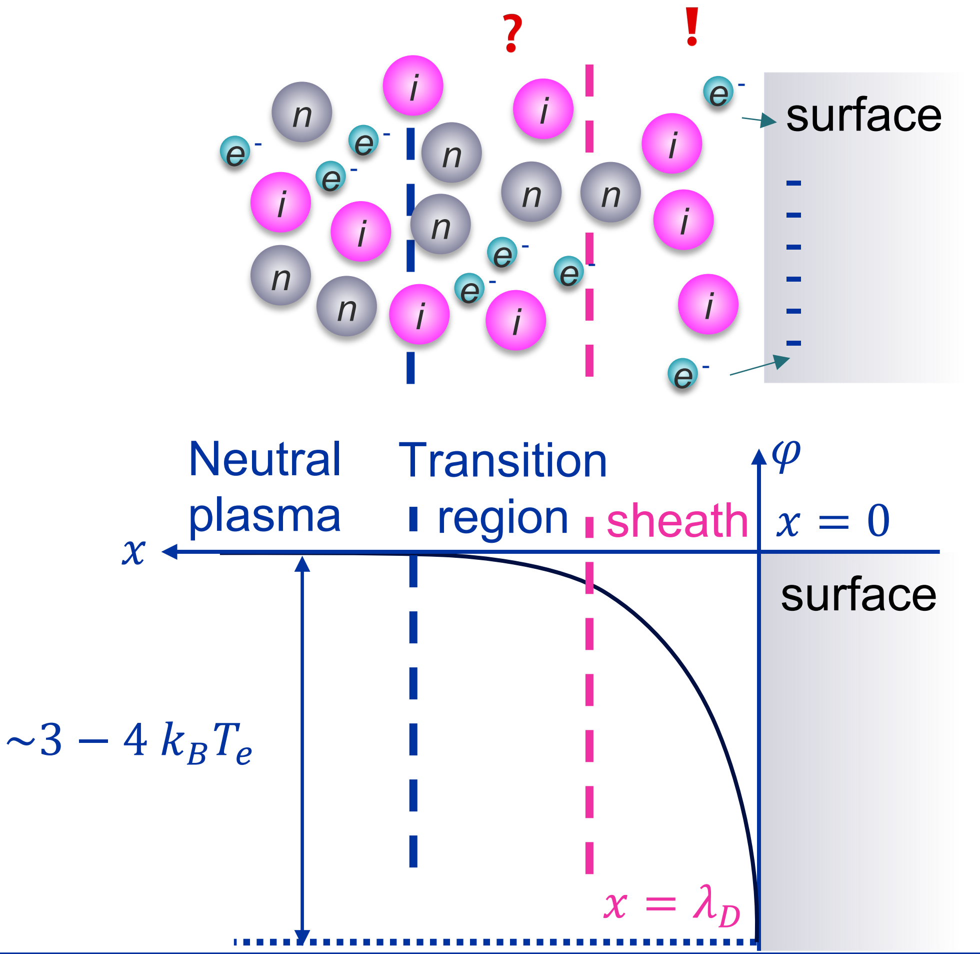
Screening effect

- Plasma particles interact by electromagnetic interactions



Plasma sheath

- Boundary layer formed at interfaces between plasmas and walls
- Wall acquires a charge
- Plasma acquires a potential respective to the wall—not locally charge neutral—and redistributes to cancel external fields
- Sheath thickness = shielding distance
  - Plasma only: Debye length $\lambda_D = \sqrt{\frac{\varepsilon_0 k_B T_e}{e^2 n_e}}$ [1]
  - With an applied potential: $d_{sheath} = \lambda_D \sqrt{\frac{V_{applied}}{k_B T_e}}$



[1] P. Debye, E. Hückel, (1923). Physikalische Zeitschrift. ***24*** *(9) p 185–206.*

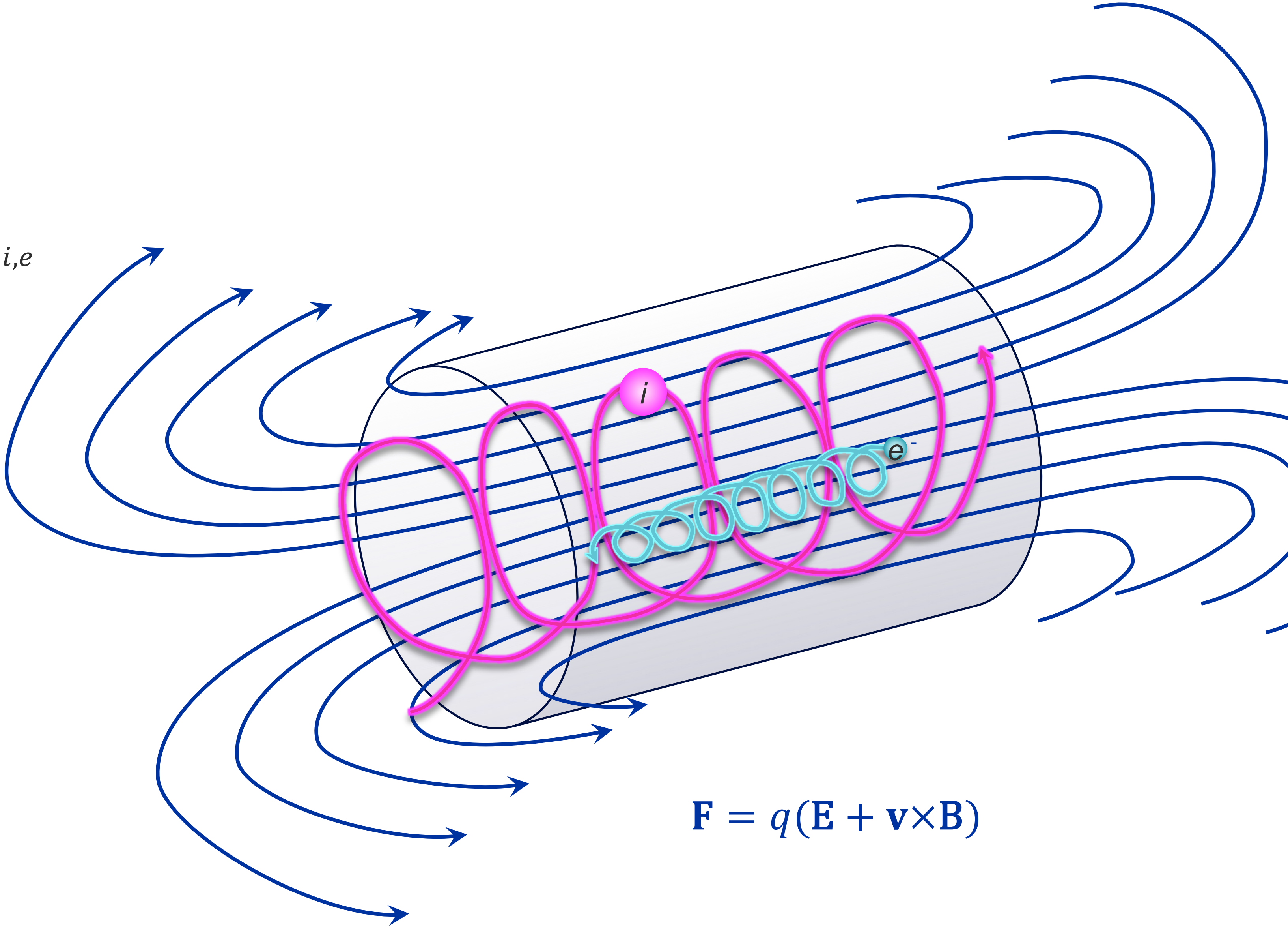
Magnetic effects

Gyro-frequencies

- Precession of ions and electrons
- Collision frequency $\nu_{i,e} \ll \omega_{cyclotron,i,e}$

Magnetic and plasma pressure

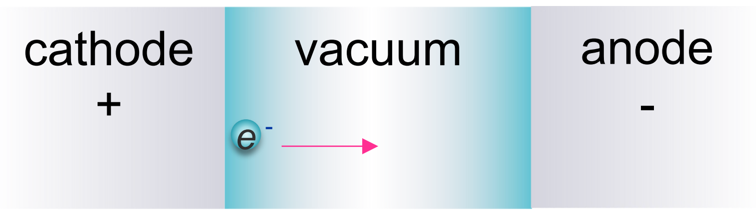
- $P_{mag} = \frac{B^2}{2\mu}$, $\mu = \frac{1}{2}\frac{m{v_\perp}^2}{B}$
- $P_{plasma} = n_e k_B T_e + n_i k_B T_i$
- $P_{plasma} \ll P_{mag}$
  - magnetic confinement



$\mathbf{F} = q(\mathbf{E} + \mathbf{v}\times\mathbf{B})$

Space charge

A collection of charged particles in a region of space, so that the extra charge is considered to be distributed across the region

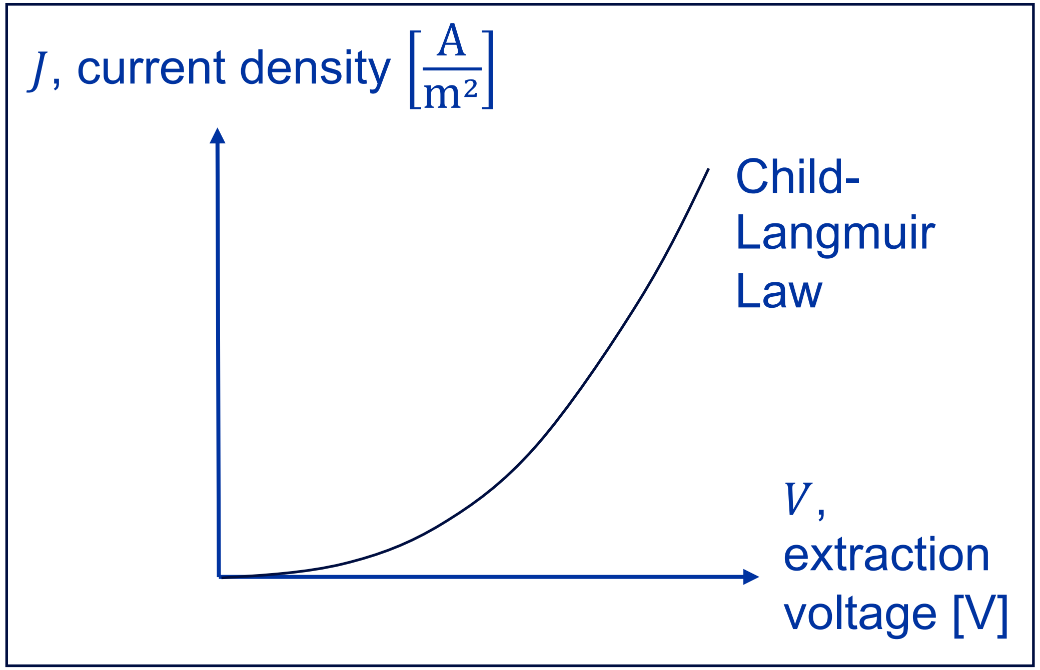


Space-charge-limited current

- Child's law, or "three-halves power law" [1]
- Usual assumption: particle velocity is 0 at the surface
  - Generalization for nonzero initial velocities [2]

Application to electron currents

- Cylindrical geometries [3] -> "Child-Langmuir Law"
- At some voltage, the operation may transition from the space-charge limited case into the emission limited case



Electron current density

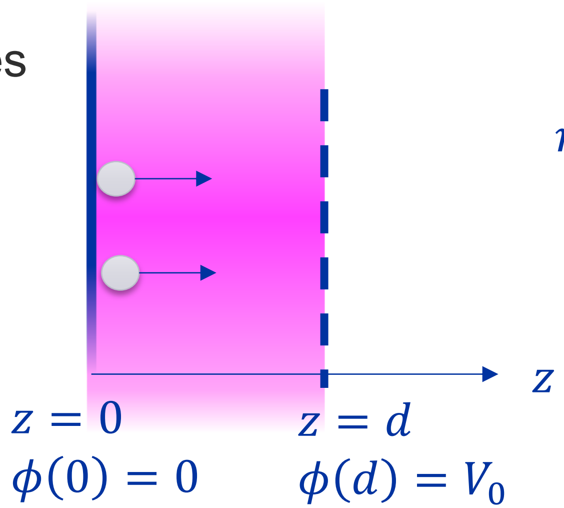
$$J = \frac{I}{S} = \frac{4\varepsilon_0}{9}\sqrt{\frac{2q_e}{m_e}}\frac{V^{3/2}}{d^2} \quad \left[\frac{\text{A}}{\text{m}^2}\right]$$

[1] C.D. Child, Phys Rev Lett 32 (1911) p 492
[2] B. Conley, Masters thesis MIT, Cambridge (1995) p 24
[3] I. Langmuir, Phys. Rev. 2 (1913) p 450

Beam formation

Particle emission

- Emission of charged particles into an acceleration gap



$$v_z(z)^2 = \frac{-2q\phi(z)}{m_0}$$

$$n(z) = \frac{J}{q v_z(z)}$$

$$\frac{d^2\phi}{dz^2} = \frac{-n(z)q}{\varepsilon_0} = \frac{-J}{\varepsilon_0\sqrt{\frac{-2q\phi(z)}{m_0}}}$$

$$\phi(z) = V_0\left(\frac{z}{d}\right)^{4/3}$$

$$J_0 = \frac{4\varepsilon_0}{9}\sqrt{\frac{2q}{m_0}} \times \frac{V_0{}^{3/2}}{d^2} \quad \left[\frac{\mathrm{A}}{\mathrm{m}^2}\right]$$

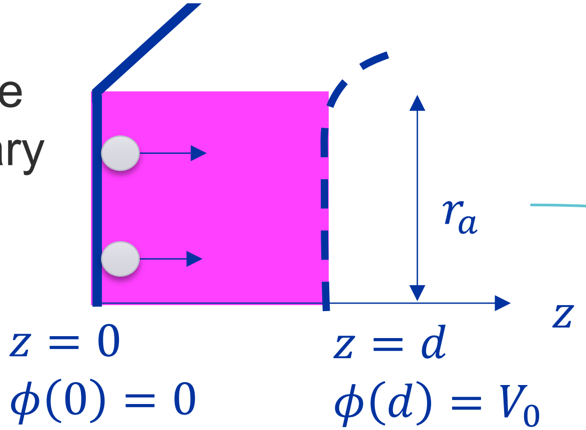
Maximum current density

Child's law [1]

- Infinite emission surface
- Non-relativistic

Pierce geometry [2]

- Finite-size emitter
- Electrodes shaped to form the potential at the beam boundary
- cylindrical

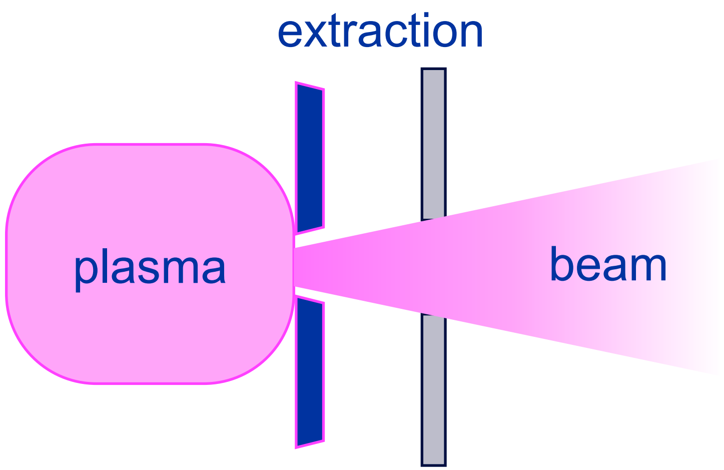


For $2r_a \ll d$

$$I_0 = \frac{4\varepsilon_0}{9}\sqrt{\frac{-2q}{m_0}} \times \frac{\pi r_a^2}{d^2} V_0{}^{3/2} \quad [\mathrm{A}]$$

Maximum current

[1] C.D. Child, Phys Rev Lett 32 (1911) p 492
[2] J.R. Pierce, J Appl Phys 11 (1940) p 548



Recap

Ionization mechanisms, processes and interactions

1	Plasmas
2	Ionization mechanisms
3	Surface interactions
4	Beam formation and extraction

References and literature:

1. The Physics and Technology of Ion Sources 2nd edition Ian G. Brown (2004), WILEY-VCH
2. Handbook of Ion Sources, B. Wolf (1995)

ISOL ion sources

A brief overview

References and literature:

1. R. Kirchner, Review of ISOL target—ion-source systems (2003) NIM B, 204, p. 179

1 Surface ion sources

2 Resonance laser ion sources

3 Electron bombardment ion sources

4 Negative ion sources

5 Other ion sources

Ion source properties for RIB production

Efficiency

- Radioactive isotopes in / radioactive ions out

Universality

- Variety of available ion beams

Selectivity

- Purity, contaminant suppression

Simplicity

- Operational complexity, free parameters

Reliability

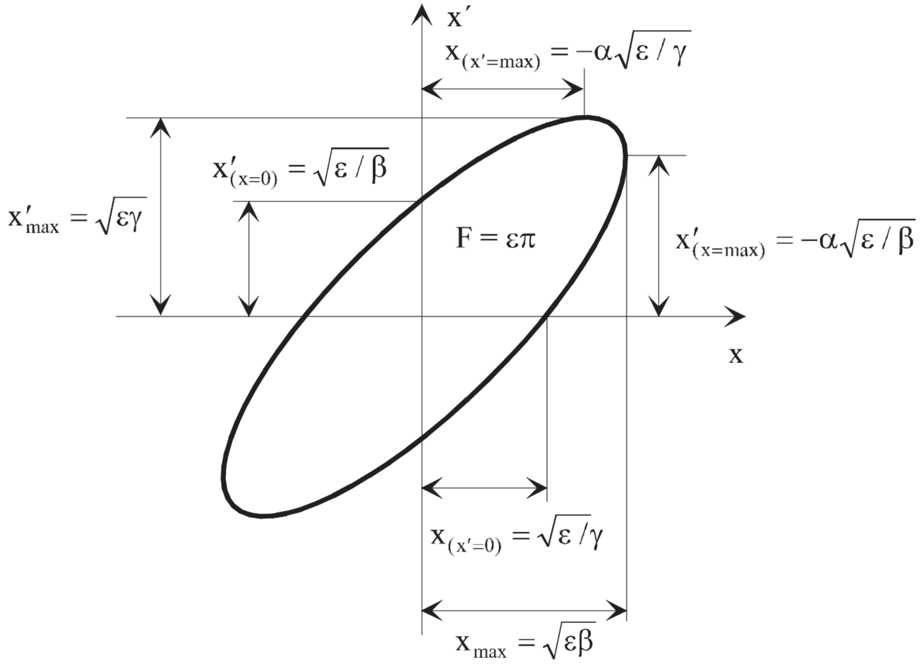
- Operation limits, failure modes

Maximum intensity

- "brightness"

Emittance and energy spread

- Beam size and shape, momentum distribution



Ion source properties for RIB production

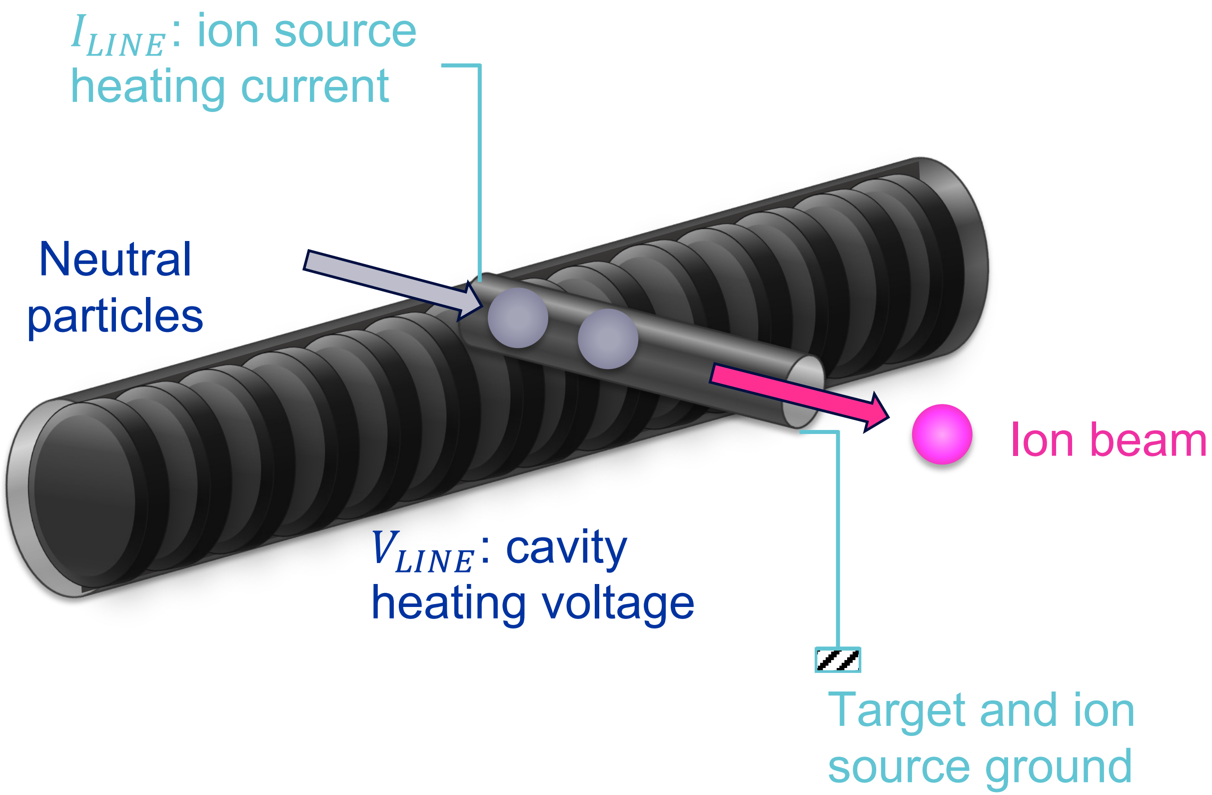
Considerations for RIBs

- Short half-lives – short residence times
- High radiation environments
- Operational periods – few weeks, facility dependent

Adapted from Y. Martinez-Palenzuela, K. Chrysalidis, B. Marsh et al., (201
Int. Conf. Ion. Sources presentation - Young Speaker Award

Surface ion sources

- Hot cavity ion sources have been used since the 1970s and are still being studied and developed
  - Simple and robust construction, short residence times – radioactive ion beams



[1] M. Turek et al, Rev. Sci. Instrum. 83, 023303 (2012)
[2] M. Huyse et al., NIM B 215 (1983) p 1-5
[3] R. Kirchner and Piotrowski, NIM B 153 (1978) p 291

Surface ion sources

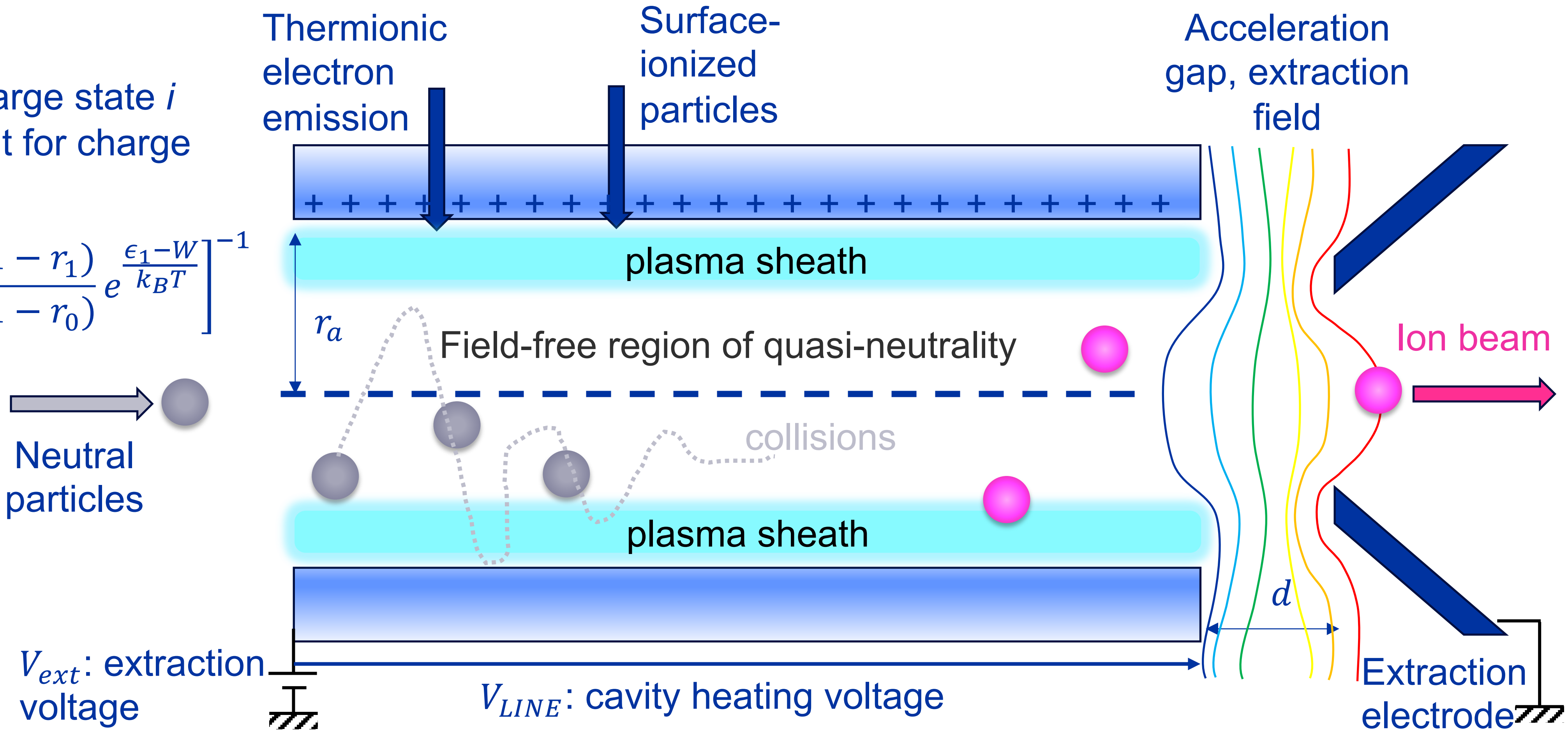
- Hot cavity ion sources have been used since the 1970s and are still being studied and developed
  - Simple and robust construction, short residence times – radioactive ion beams

Turek Model [1]:

g_i : degeneracy for charge state *i*

r_i : reflection coefficient for charge state *i*

$$\beta = \frac{n_1}{n_1 + n_0} = \left[1 + \frac{g_1(1-r_1)}{g_0(1-r_0)} e^{\frac{\epsilon_1 - W}{k_B T}}\right]^{-1}$$



[1] M. Turek et al, Rev. Sci. Instrum. 83, 023303 (2012)
[2] M. Huyse et al., NIM B 215 (1983) p 1-5
[3] R. Kirchner and Piotrowski, NIM B 153 (1978) p 291

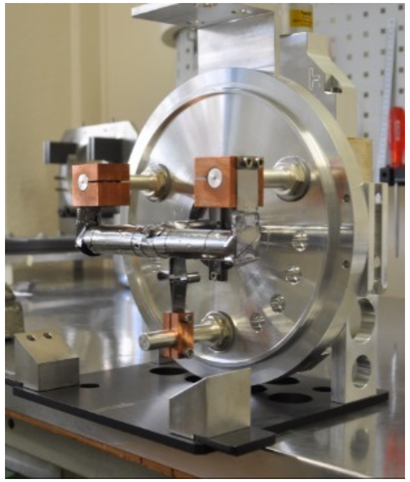
Developments in surface ion sources

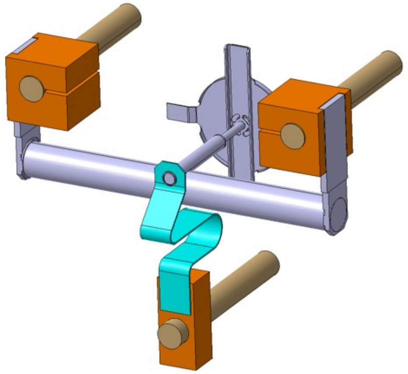
Temperature homogeneity

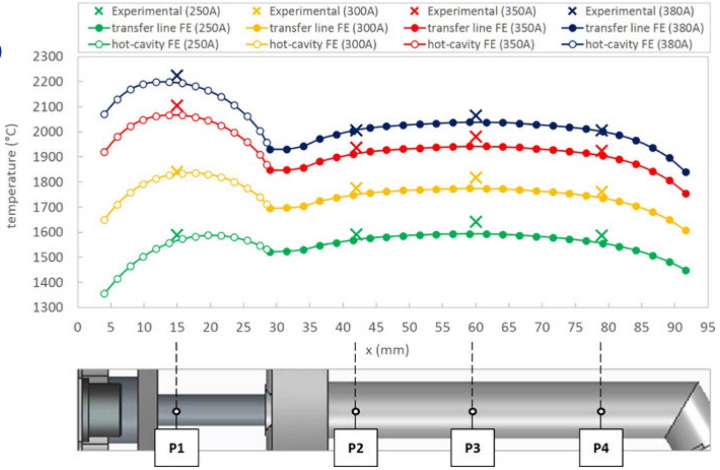
- Engineering heating to prevent condensation [1,2]

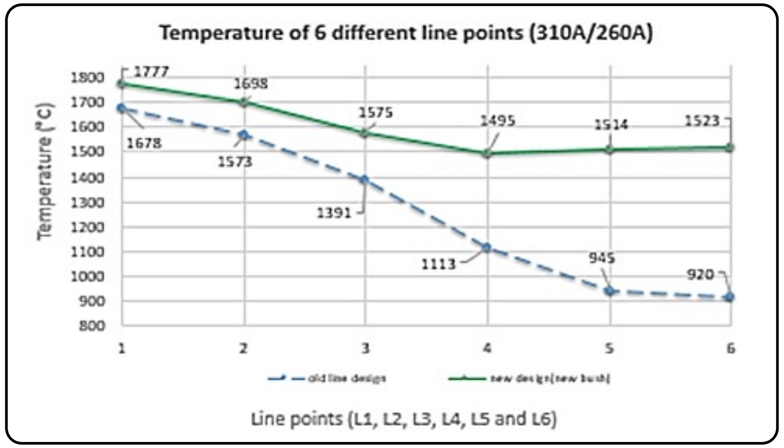
Contaminant suppression

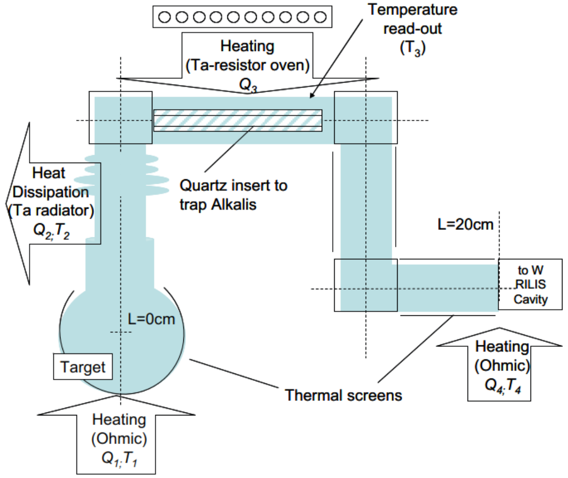
- Isothermal vacuum chromatography
  - Alkali suppression: quartz glass transfer line [3,4]

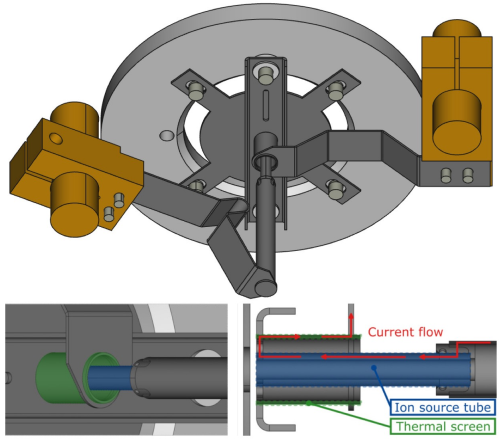












active thermal screen [2]

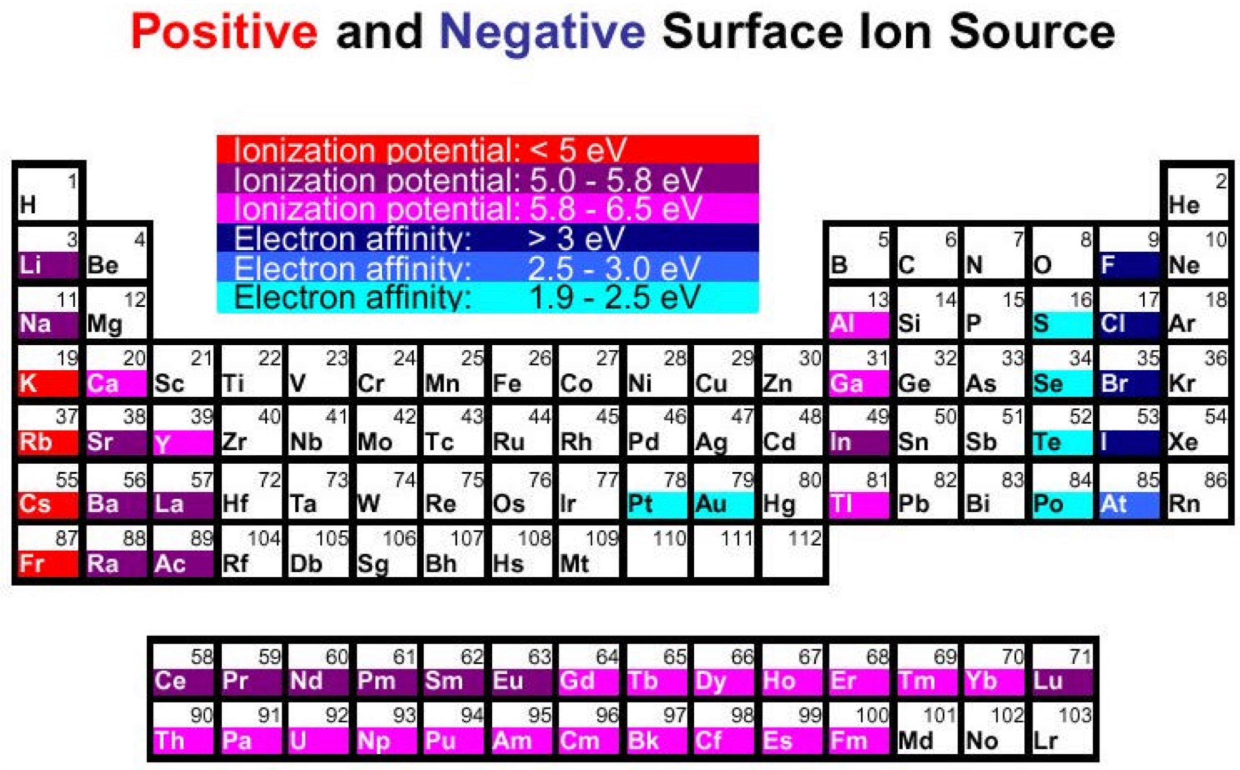
[1] M. Manzolaro et al., Rev. Sci. Instrum. 87, 02B502 (2016)
[2] S. Hurier et al., First ion source at ISOL@MYRRHA with an improved thermal profile - Theoretical considerations ICIS'23 (2023)
[3] U. Köster et al., NIMB, 266 (2008) p. 4229
[4] Bouquerel, E, et al. Eur. Phys. J. Spec. Top. 150, 277–280 (2007).

Surface ion sources

Properties

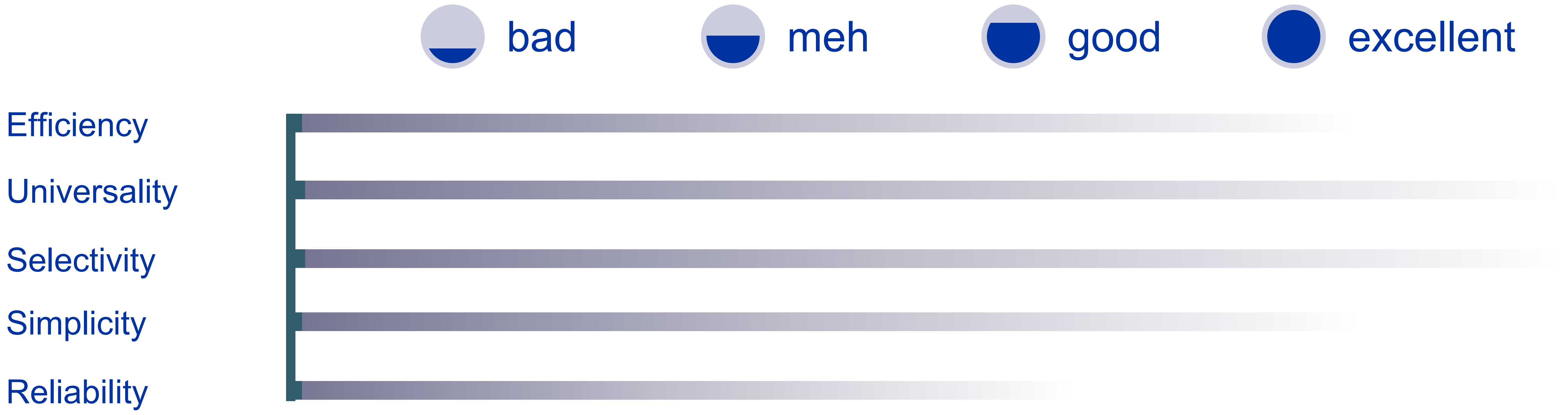
- Efficiency: 100% for $\epsilon_i \leq 5$ eV, few % for $\epsilon_i \leq 6.5$ eV
- Used for alkali and alkaline earths, rare earths
- molecules as BaF, SrF, RaF
- Short delay time (half-lives as short as 10 ms)

Source material	Work function [eV]
Molybdenum	4.15
Tantalum	4.12
LaB_6	2.5-2.7
GdB_6	1.5-2.7
$SrVO_3$	1.79 (predicted)



Surface ion sources – properties for ISOL

Questions about surface ion sources?

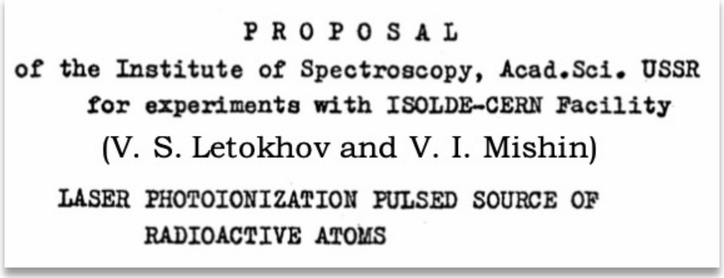


Resonance Ionization Laser Ion Source (RILIS)

Use of tunable wavelengths for resonance photoionization since 1984 [1]

RILIS [2-5]

- Step-wise resonant excitation
- Element-selective


PROPOSAL
of the Institute of Spectroscopy, Acad.Sci. USSR
for experiments with ISOLDE-CERN Facility
(V. S. Letokhov and V. I. Mishin)
LASER PHOTOIONIZATION PULSED SOURCE OF RADIOACTIVE ATOMS

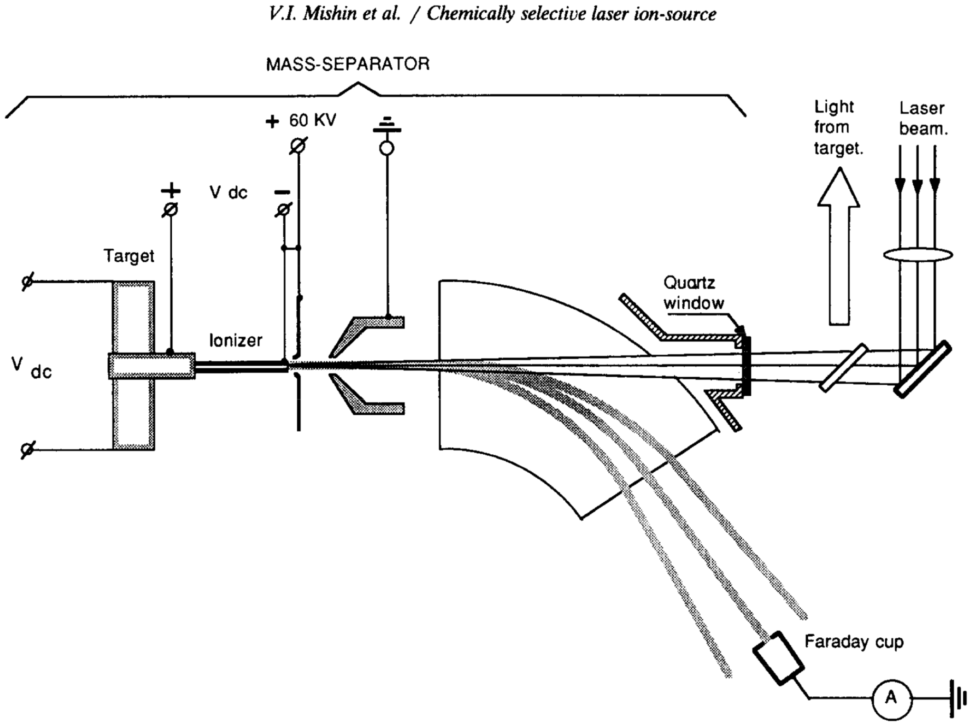
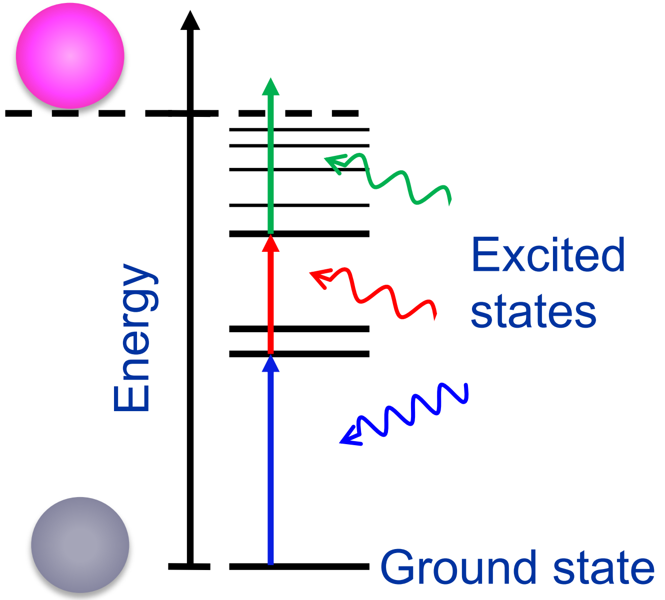
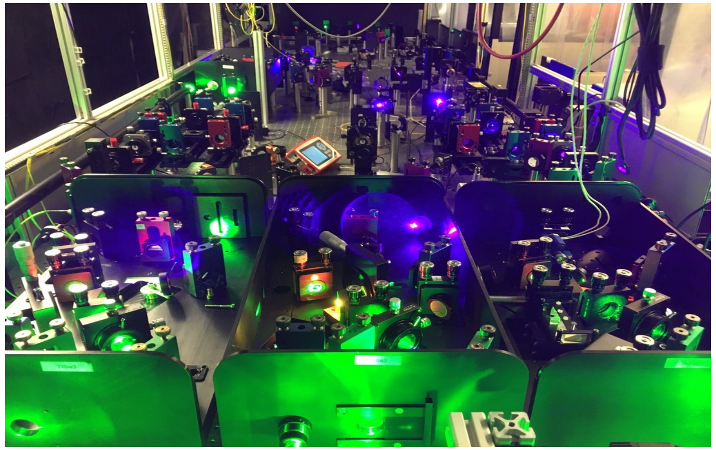


Fig. 1. Schematic representation of the mass-separator and laser ion-source.



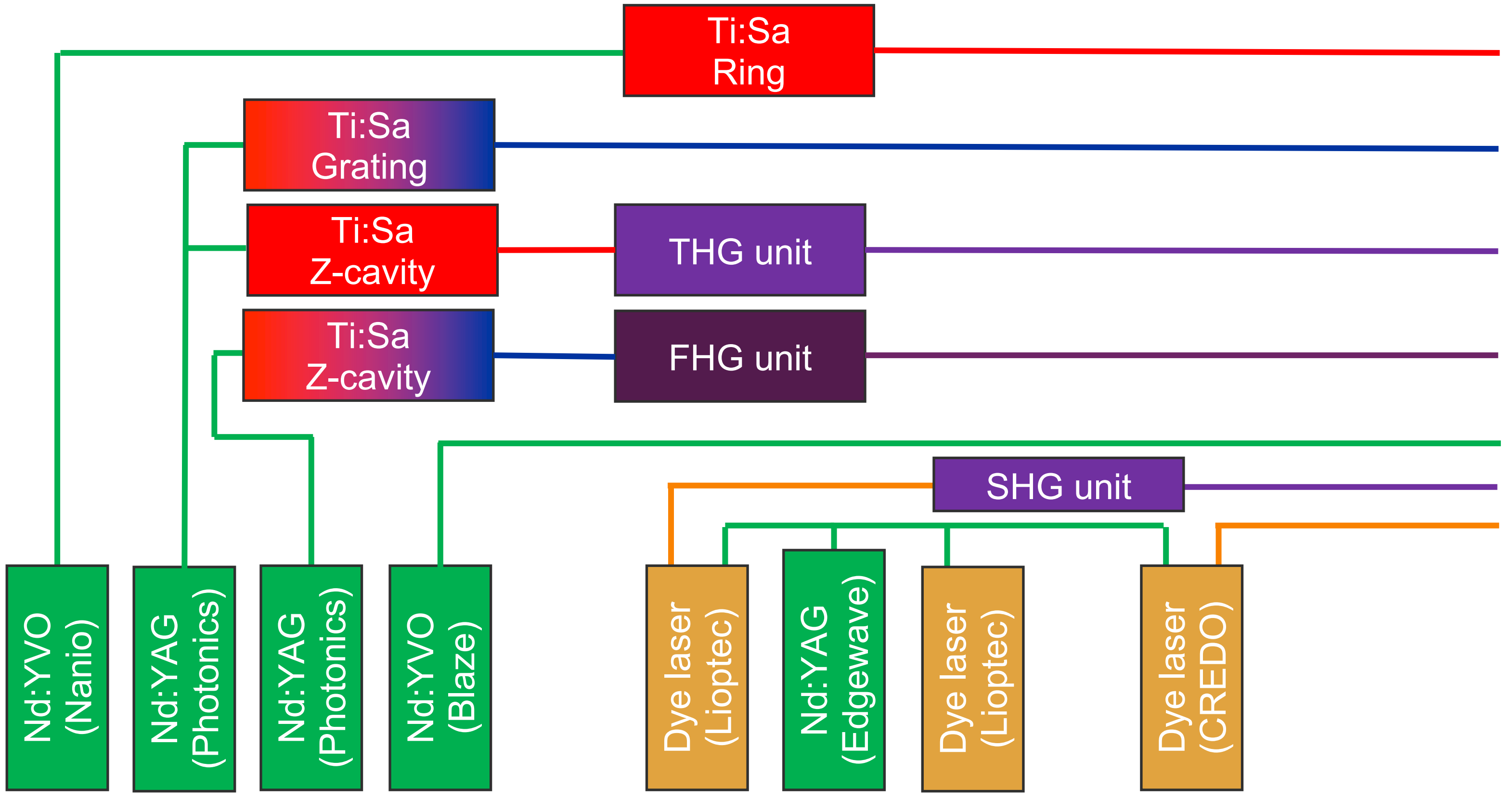


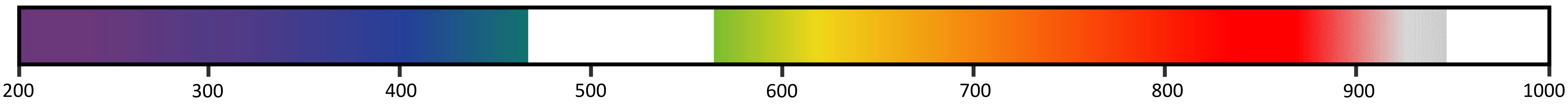
[1] Letokhov and Mishin (1984)
[2] Fedosseev et al., J. Phys. G Nucl. Part. Phys. 44 (2017) 084006
[3] Marsh et al., Rev. Sci. Instrum. 85, (2014) 02B923
[4] Mishin, Fedoseyev et al., NIM B 73 (1993) 550
[5] Alkhazov et al., NIM A 306 (1991) 400

RILIS lasers

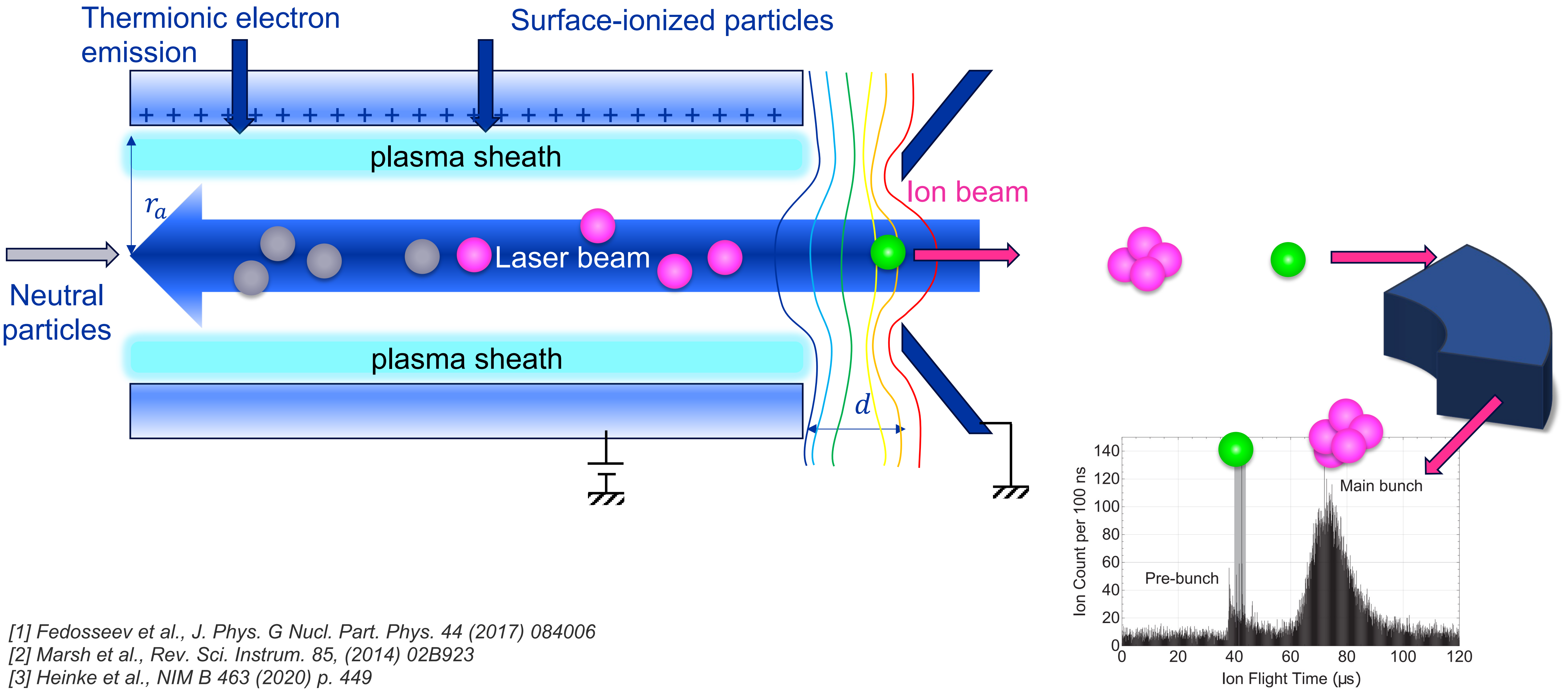
RILIS at CERN-ISOLDE

Slide courtesy of C. Bernerd (2023)
Introduction to RILIS: RILIS @CERN,
ISOLDE workshop 2023





Resonance laser ionization in hot cavities



[1] Fedosseev et al., J. Phys. G Nucl. Part. Phys. 44 (2017) 084006
[2] Marsh et al., Rev. Sci. Instrum. 85, (2014) 02B923
[3] Heinke et al., NIM B 463 (2020) p. 449

Developments in RILIS ion sources

[1] R. Mancheva, PhD thesis work, CERN
[2] Heinke *et al.* (2023) *NIM B.* **541** (8-12)
[3] Marsh *et al., Rev. Sci. Instrum. 85,* (2014) *02B923*

High throughput ion source [1]

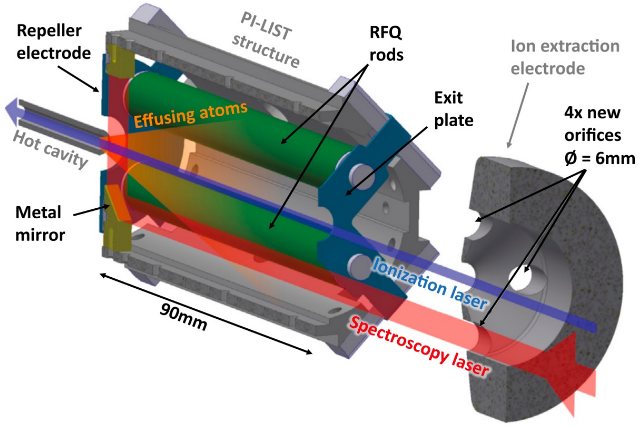
- High ion load → breakdown of confinement potential

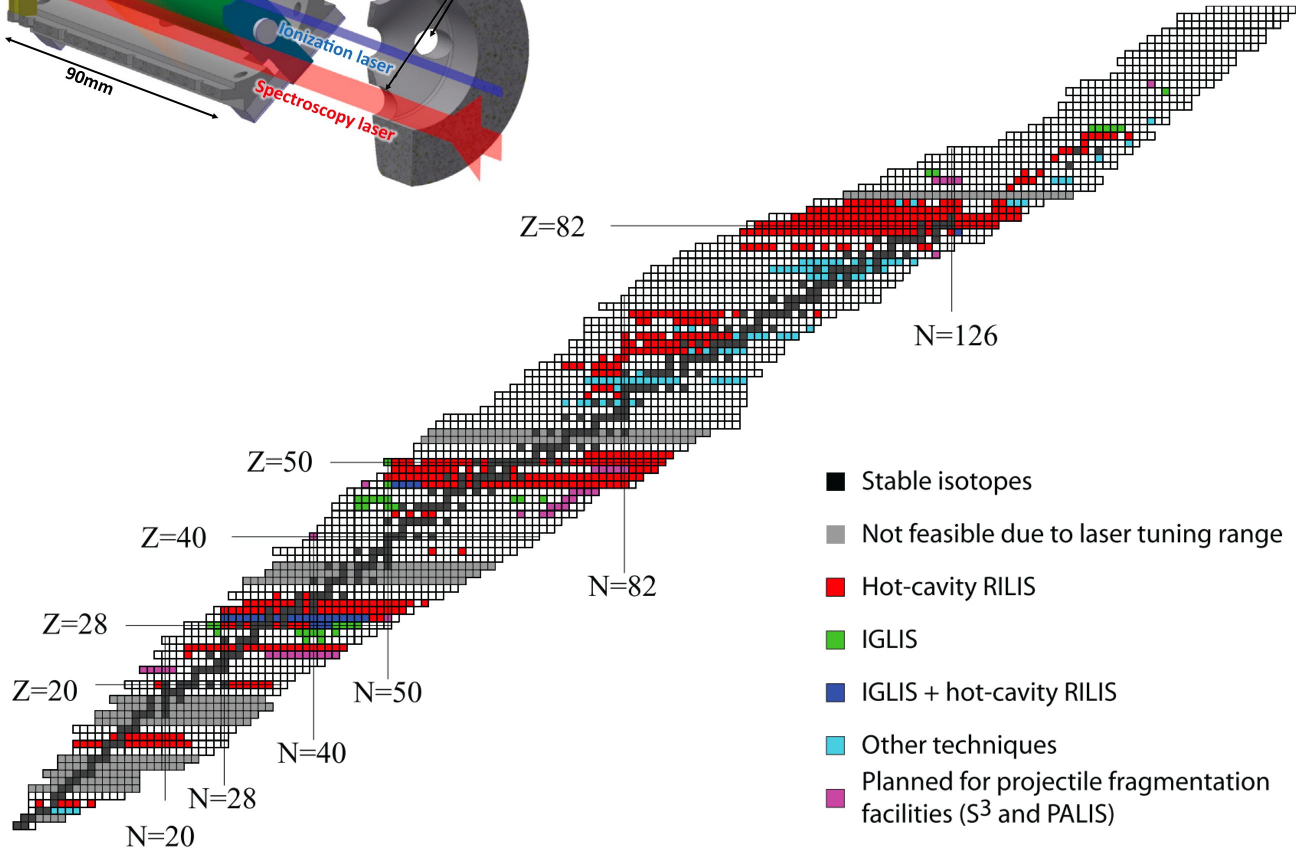
Laser Ion Source and Trap (LIST)

- Implementation at CERN-ISOLDE [2]
- Suppression of surface ions

Laser developments

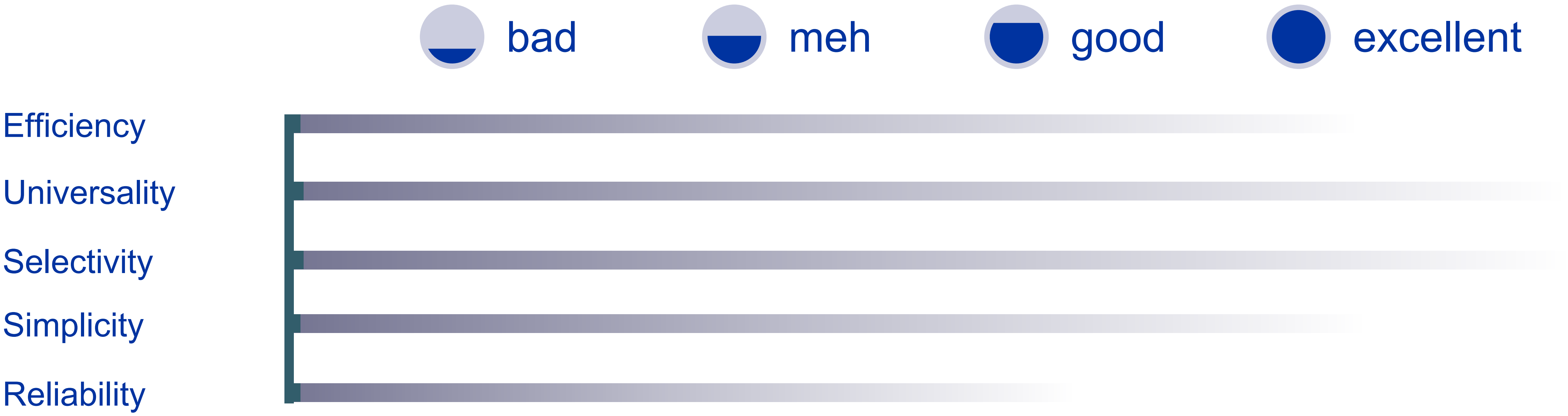
- Frequency range
- Tunability
- Power
- Stability
- Operational simplicity
- Not just for ion sources





RILIS-type ion sources – properties for ISOL

Questions about resonance ionization laser ion sources?



Electron bombardment ion sources

Nielsen-type ion source

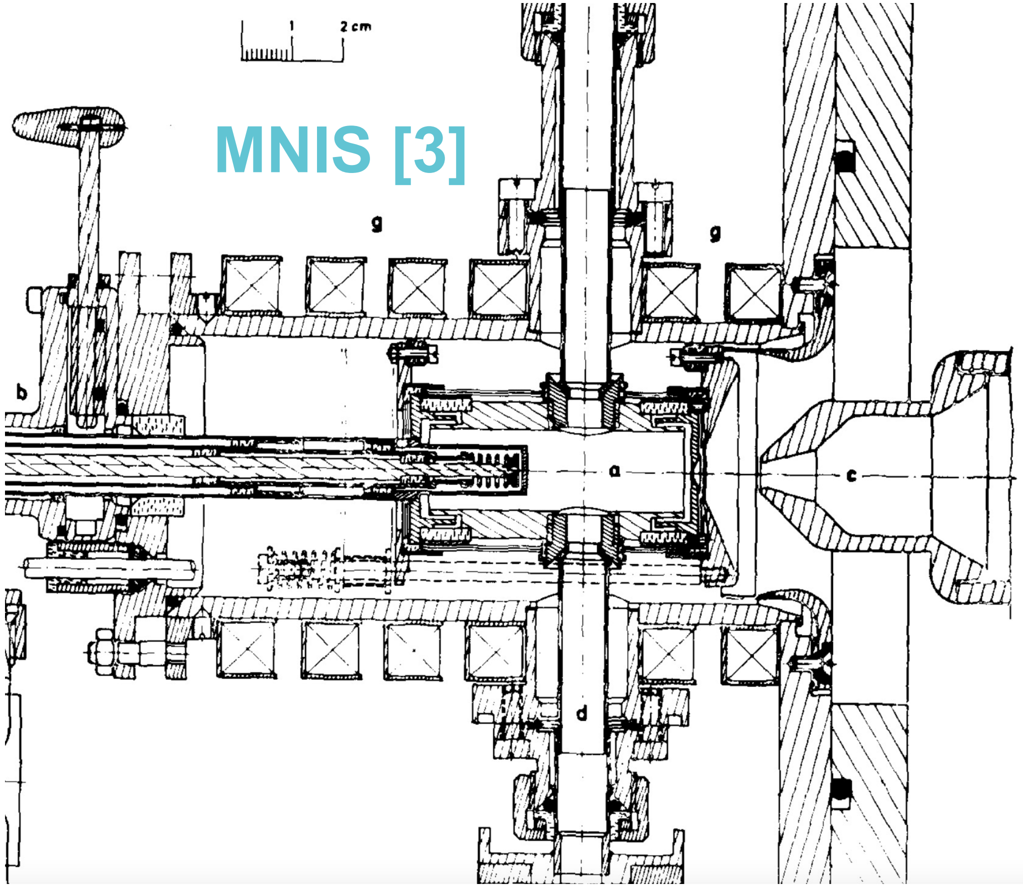
- A filament contained in a magnetic field which confines electrons, ionization via plasma discharge [1]
- Modified to protect the fragile cathode [2]

Modified Nielsen ion source

- reduced dimensions to increase temperature and reduce condensation – higher efficiencies [3]
- required stringent control of gas injection to sustain plasma discharge.

Forced Electron Beam Induced Arc Discharge (FEBIAD) ion source

- Electron extraction by a grid biased at the anode voltage [4]
- Addition of a transfer line, combined transfer line and cathode heating [5].

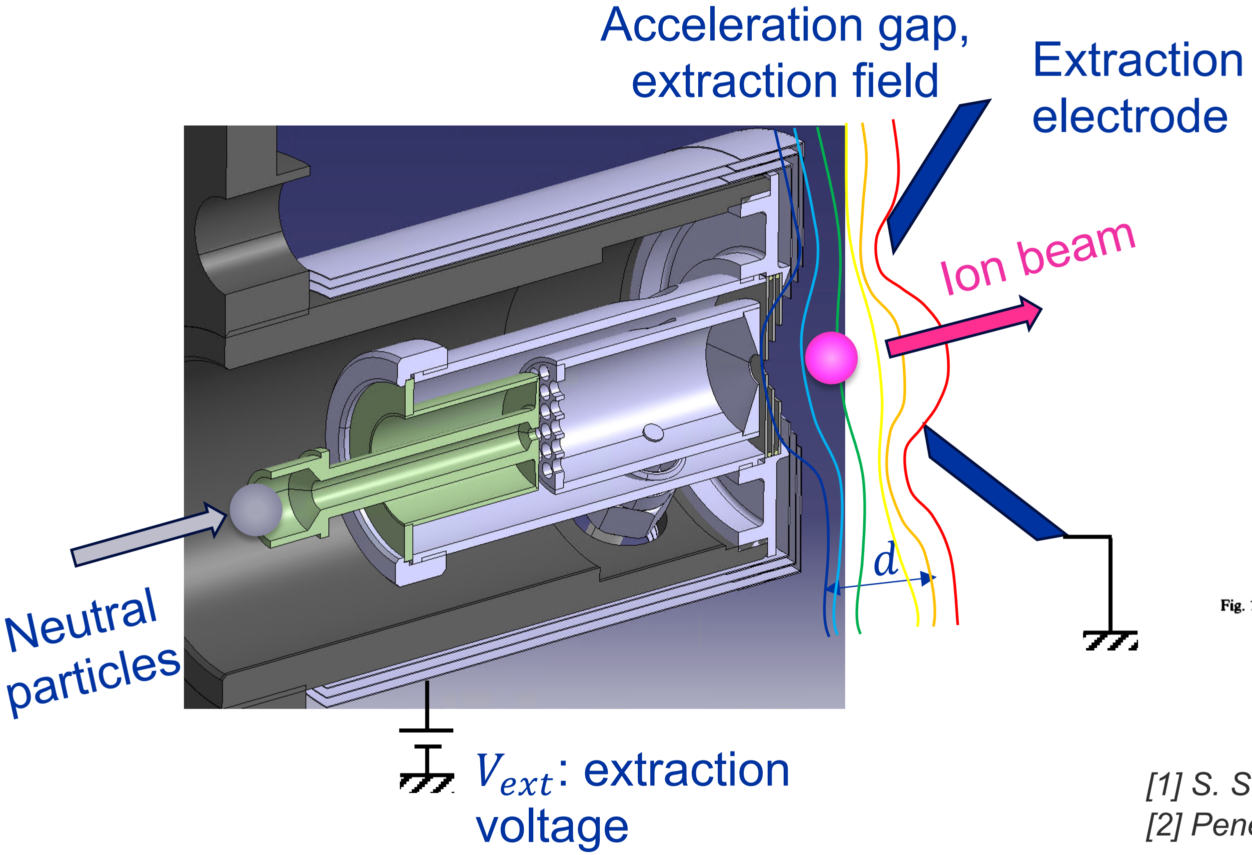


[1] K.O. Nielsen NIM 1(6) (1957), p. 289
[2] R. Kirchner and E. Roeckl NIM 127(2) (1975), p. 307
[3] R. Kirchner and E. Roeckl, NIM 133(2) (1976), pp. 187
[4] R. Kirchner and E. Roeckl NIM 139(C) (1976), p. 291
[5] S. Sundell and H Ravn. NIM B 70 (1992) p.160

FEBIAD-type ion sources

Versatile Arc Discharge Ion Source (VADIS)

- Modified FEBIAD ion source with a molybdenum grid [2]
- Hot, warm, and cold transfer lines



MK-series [1]

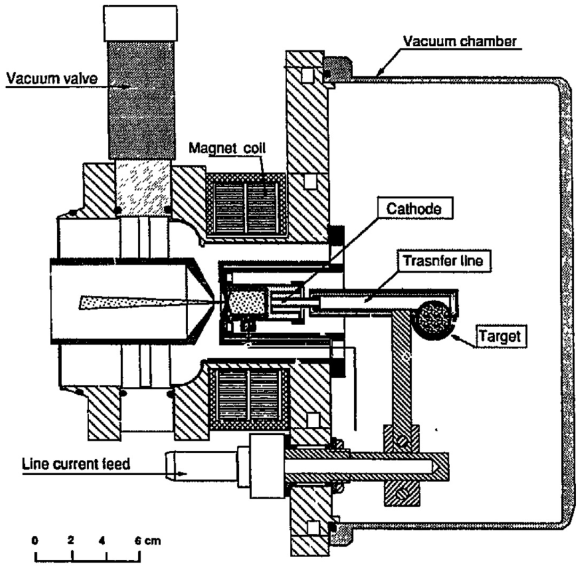


Fig. 1. Target and ion source assembly with plasma ion source MK5. The vacuum valve is part of the assembly.

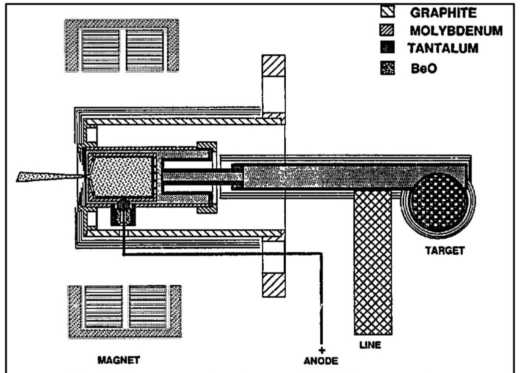


Fig. 3. High temperature plasma ion source, MK5, with target container.

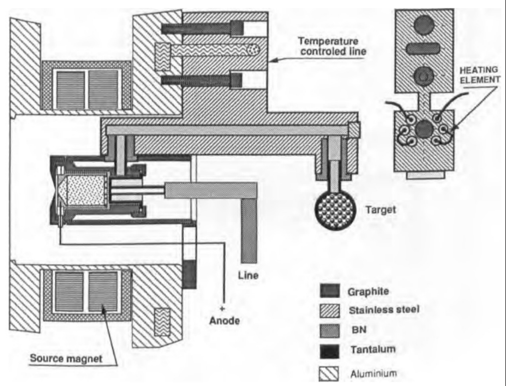


Fig. 5. Medium temperature plasma ion source, MK6, with heated transfer line.

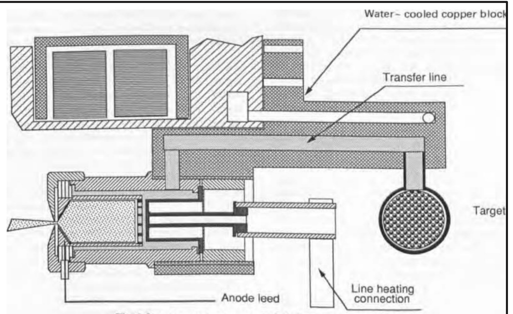


Fig. 6. Low temperature, water-cooled plasma ion source, MK7.

[1] S. Sundell and H Ravn. NIM B 70 (1992) p.160
[2] Penescu et al, Rev. Sci. Instrum. 81 (2010) 02A906

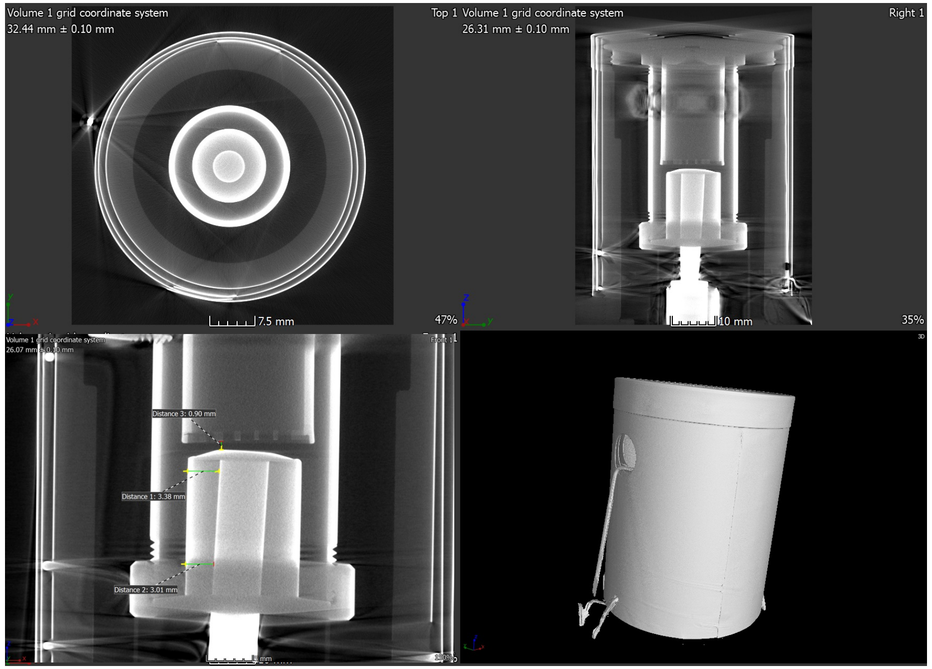
Developments in FEBIAD-type ion sources

(some) failure modes

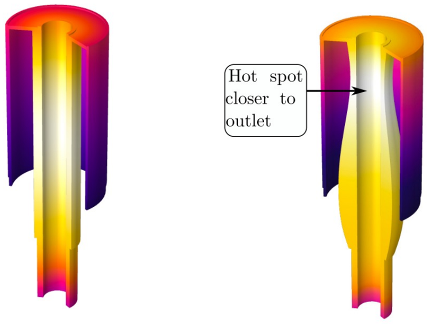
- Coated insulators
- Grid melting
- Cathode overheating and deformation: short-circuits or open circuits

Temperature optimization

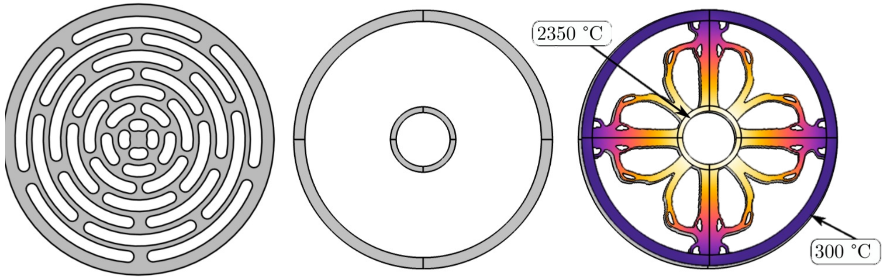
- Cathode and anode [1,2]



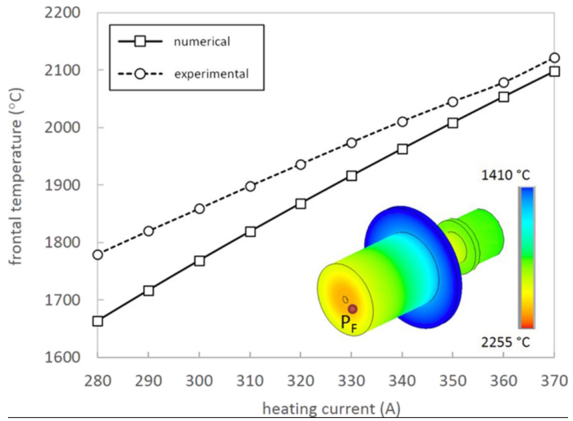
Non-destructive 3D reconstruction by X-ray computed tomography (ZEISS METROTOM 1500/225 kV) – images courtesy of S. Rothe



(a) Nominal geometry (b) Optimized geometry



(a) Nominal geometry (b) Initial geometry (c) Optimized geometry



[1] F. Maldonado, PhD thesis, University of Victoria (2022)
[2] Manzolaro et al., Rev. Sci. Instrum. 87, 02B502 (2016)

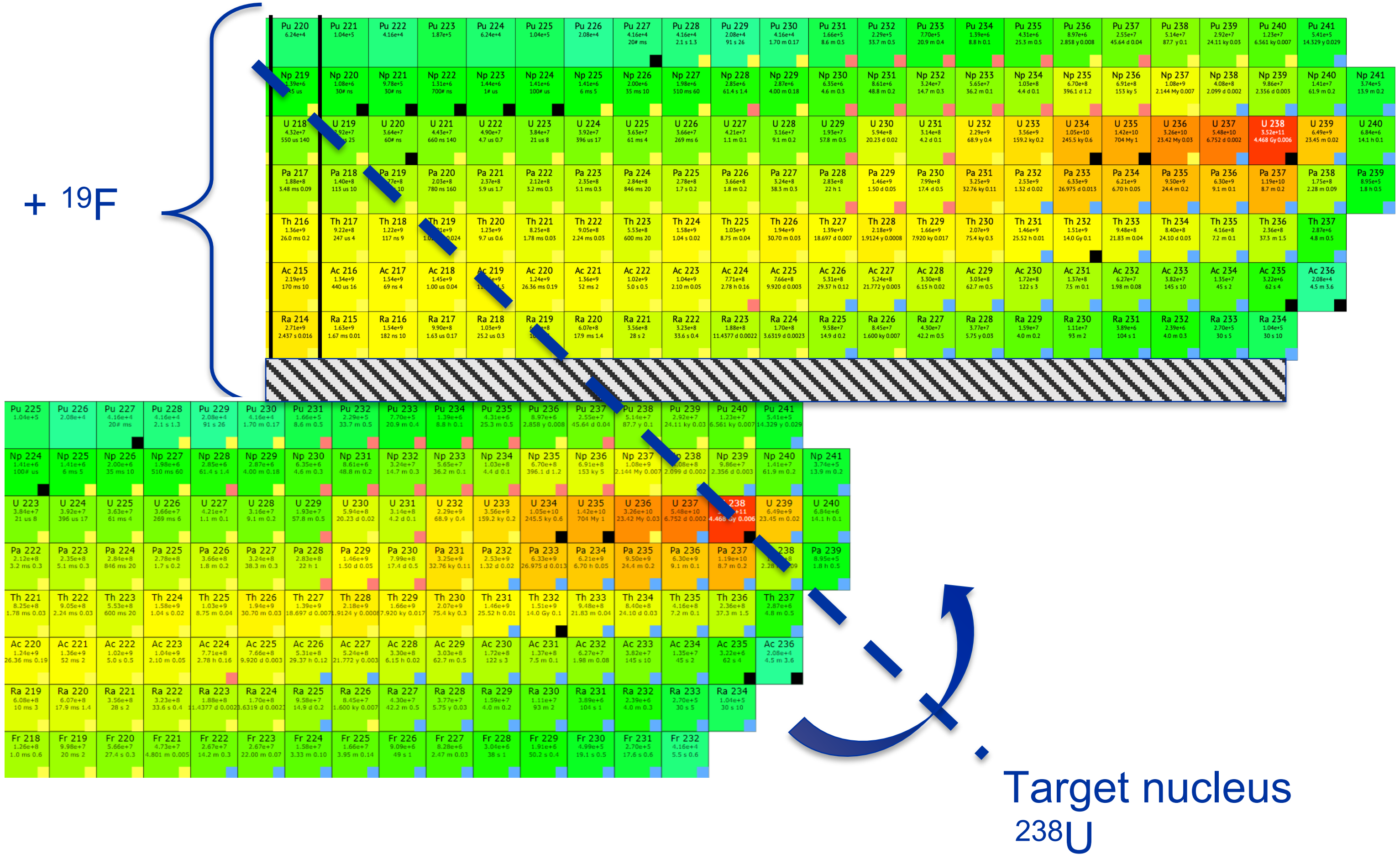
Developments in FEBIAD-type ion sources: molecular beams

Sideband extraction

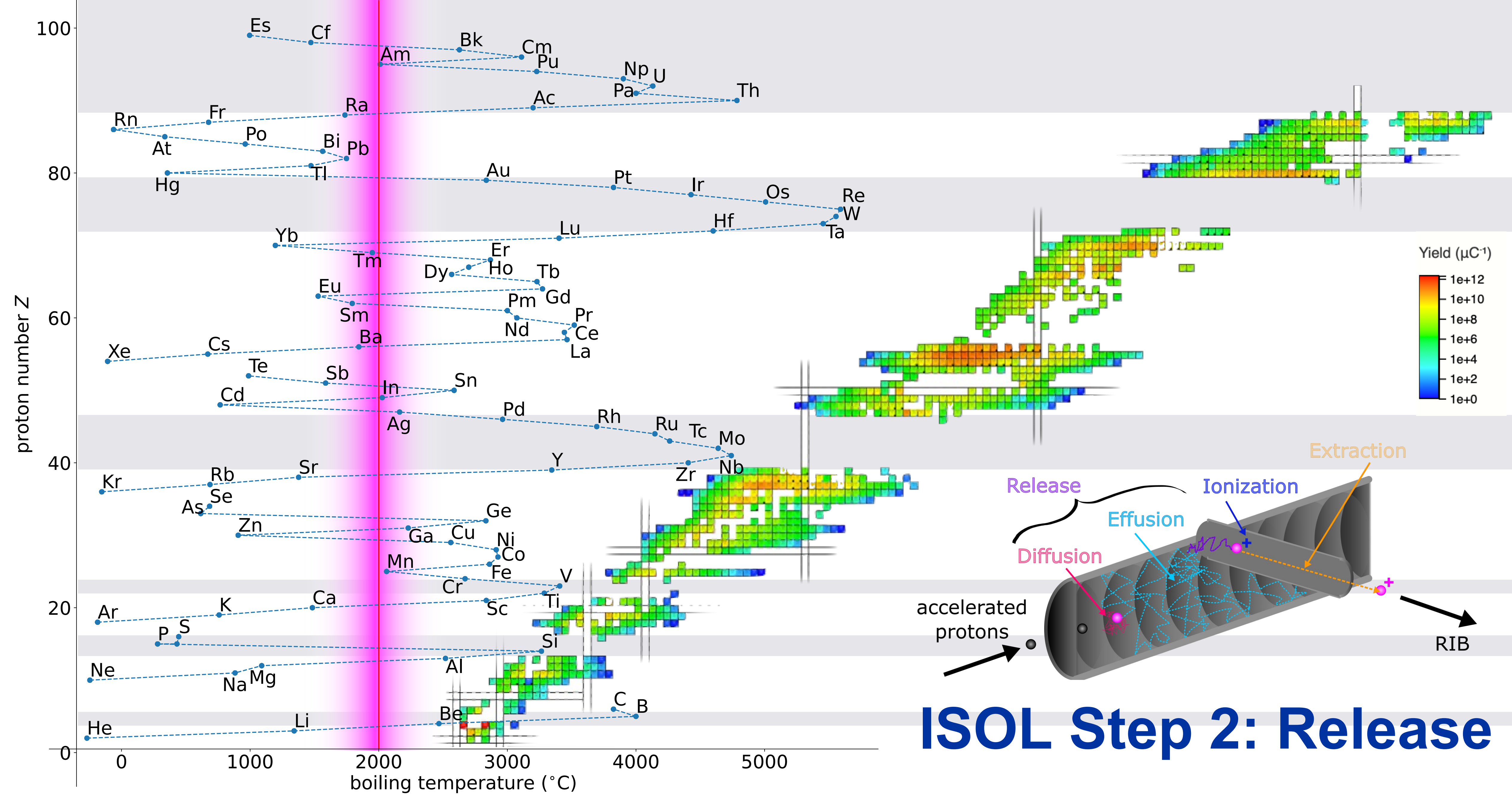
- Operation of mass-separator on an isobar-free mass setting [1,2]

Volatilization

- Extraction of volatile compounds of otherwise refractory elements [1,2]

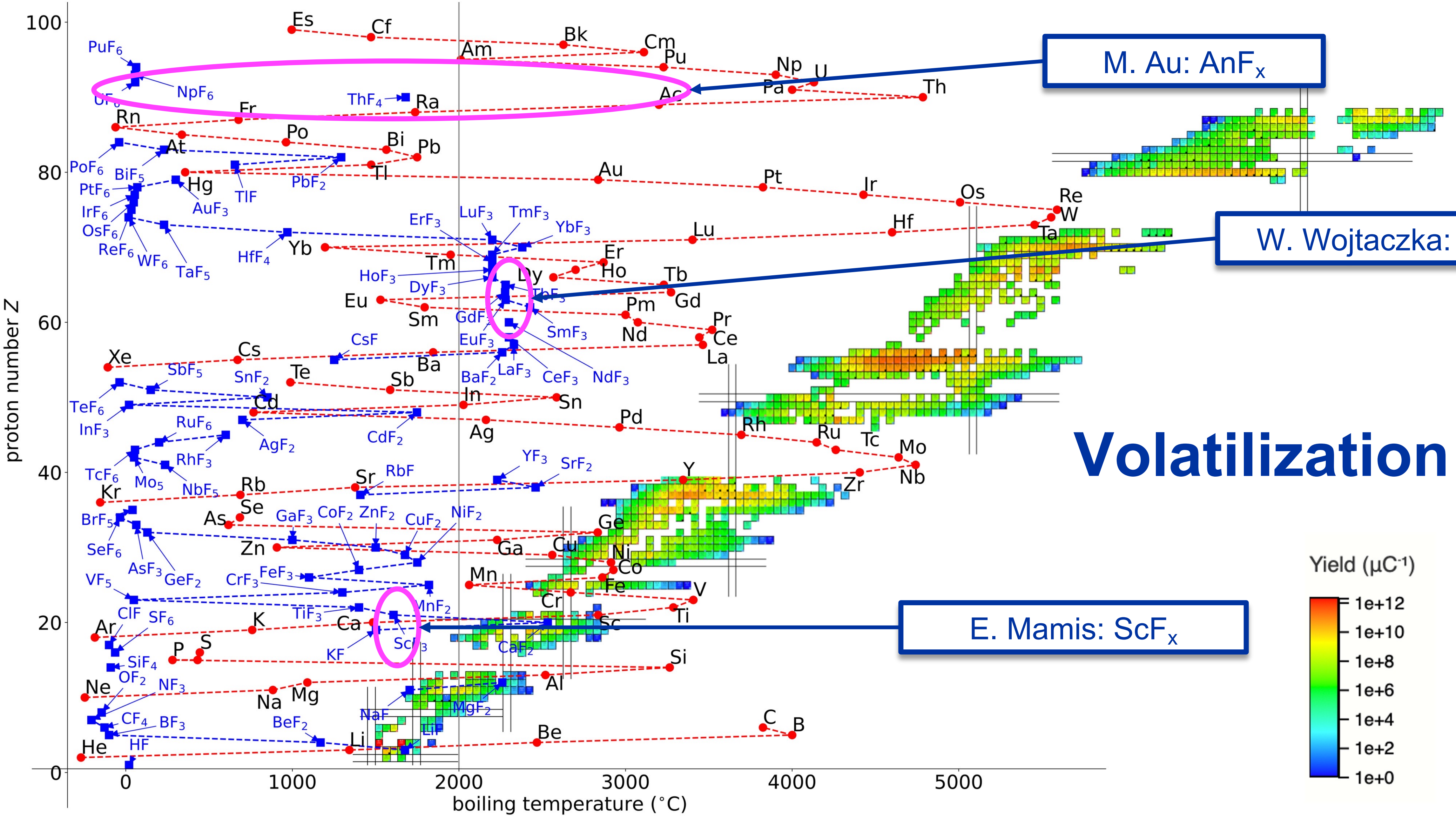


[1] J. Ballof, PhD thesis, JGU Mainz (2021)
[2] M. Au, PhD thesis, JGU Mainz (2023)



ISOL Step 2: Release

Volatilization



Developments in FEBIAD-type ion sources: molecular beams

Sideband extraction

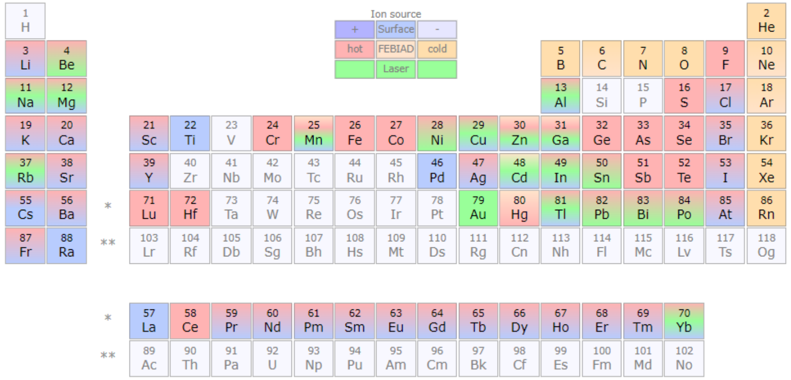
- Operation of mass-separator on an isobar-free mass setting [1,2]

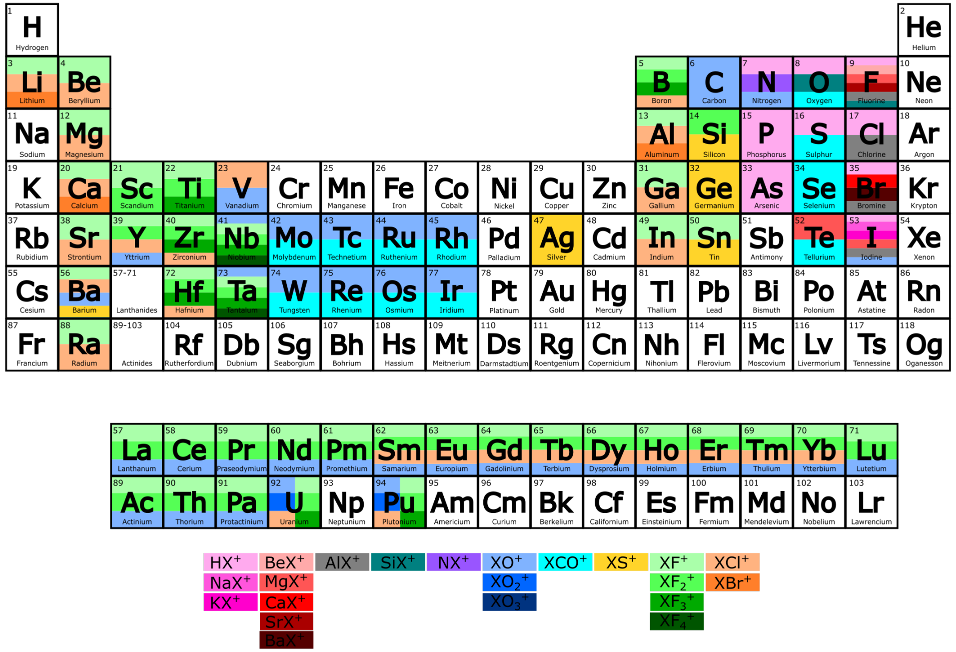
Volatilization

- Extraction of volatile compounds of otherwise refractory elements [1,2]

Technical developments

- Robustness to reactive gas injection
- Controlled injection from external ovens





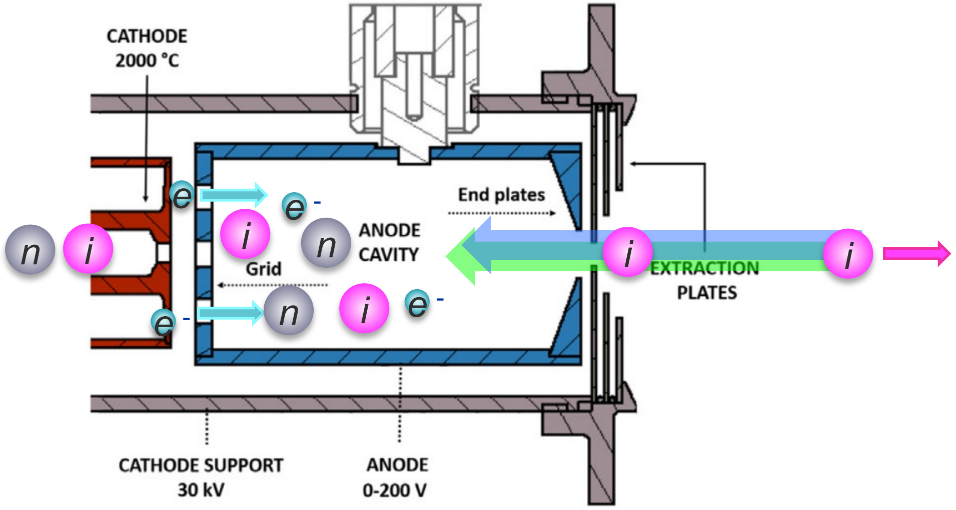
Au and Ballof, (2022) *Zenodo* 10.5281/zenodo.6884293

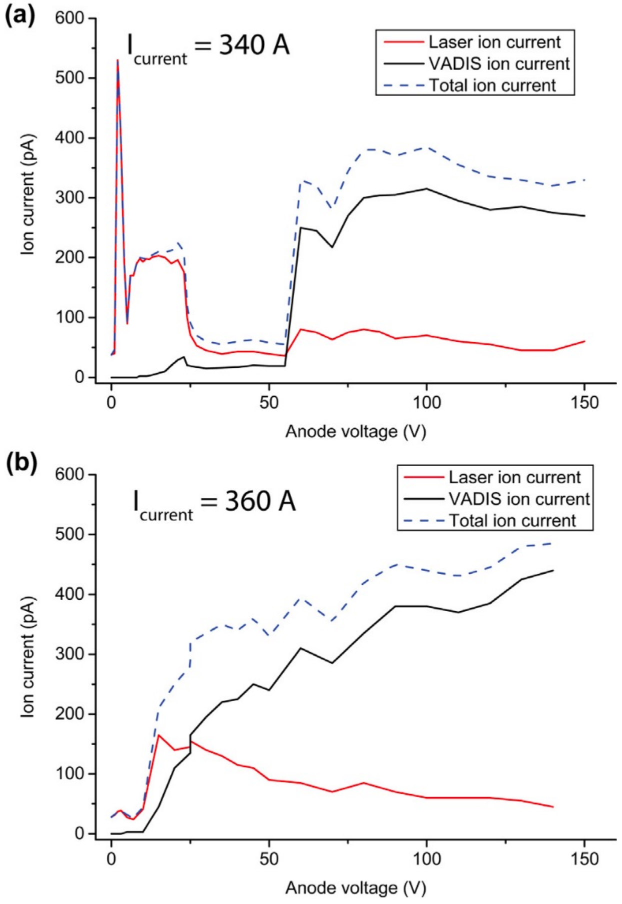
[1] J. Ballof, PhD thesis, JGU Mainz (2021)
[2] M. Au, PhD thesis, JGU Mainz (2023)

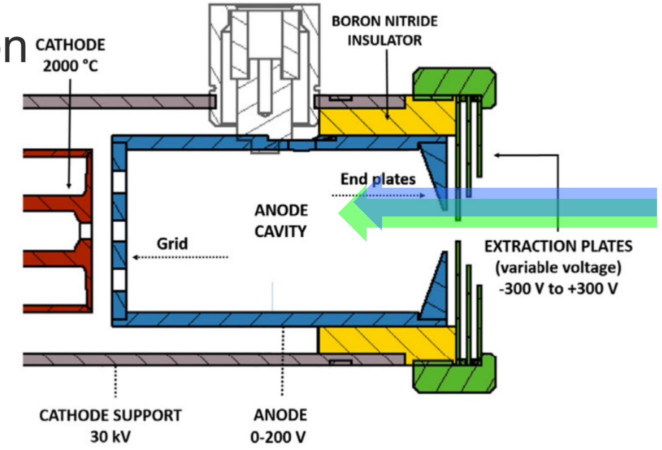
Resonance laser ionization in FEBIAD-type ion sources

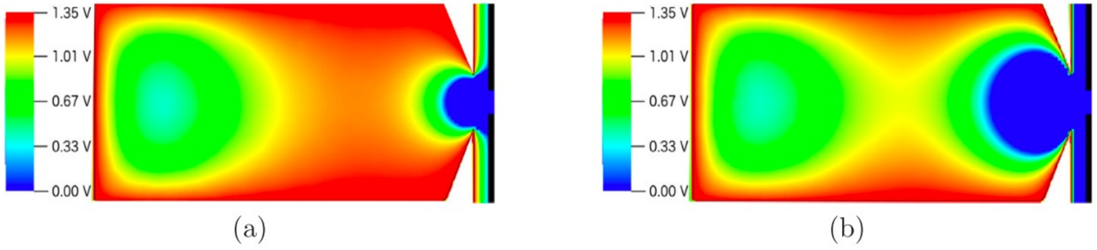
VADLIS

- RILIS inside a VD5 geometry [1]
  - Central potential well
  - Repelling effect of anode voltage
  - Reversible polarity cathode
- Addition of biasable extraction plates [2]









[1] *T. Goodacre et al, NIM B 376 (2016) p.39*
[2] *Y. Martinez Palenzuela et al., NIM B 431 (2018) p. 59*

Photocathode sources

Photocathode electron sources

- High pulse energy lasers, low ϕ_W surfaces
- Ex. CERN's Compact Linear Collider (CLIC)
  - CALIFES [1] photo-injector [2]:
    - Cs_2Te with UV (262 nm) laser, > 370 nJ/pulse [3]

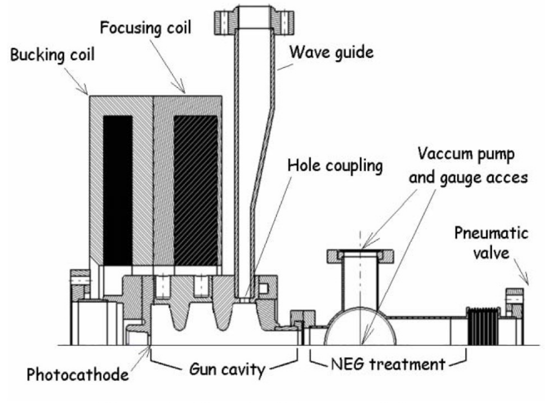


Figure 4 : Sketch of the photo-injector.

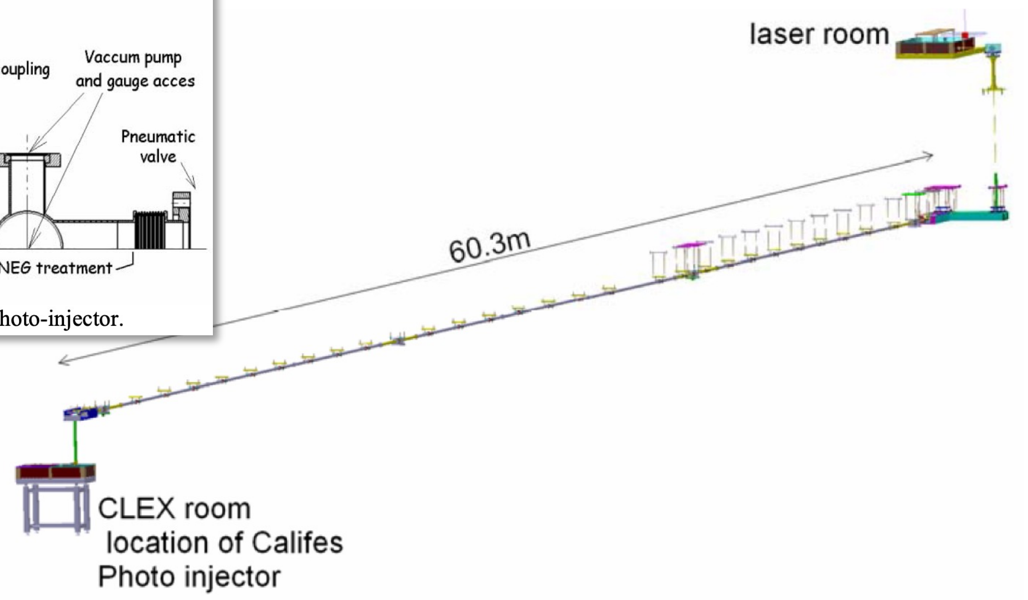
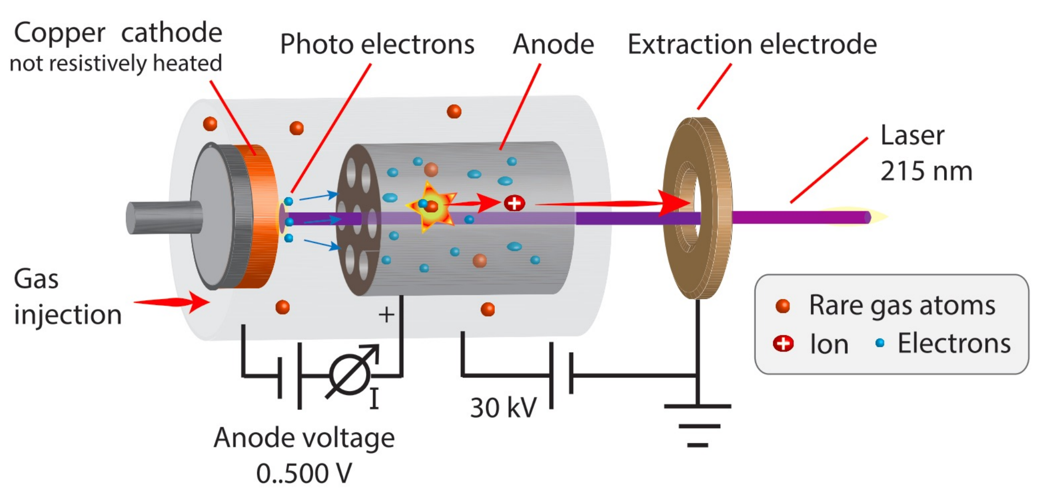


Figure 15: View of the beam transport between laser room and CLEX experimental area.

Photocathode ion sources

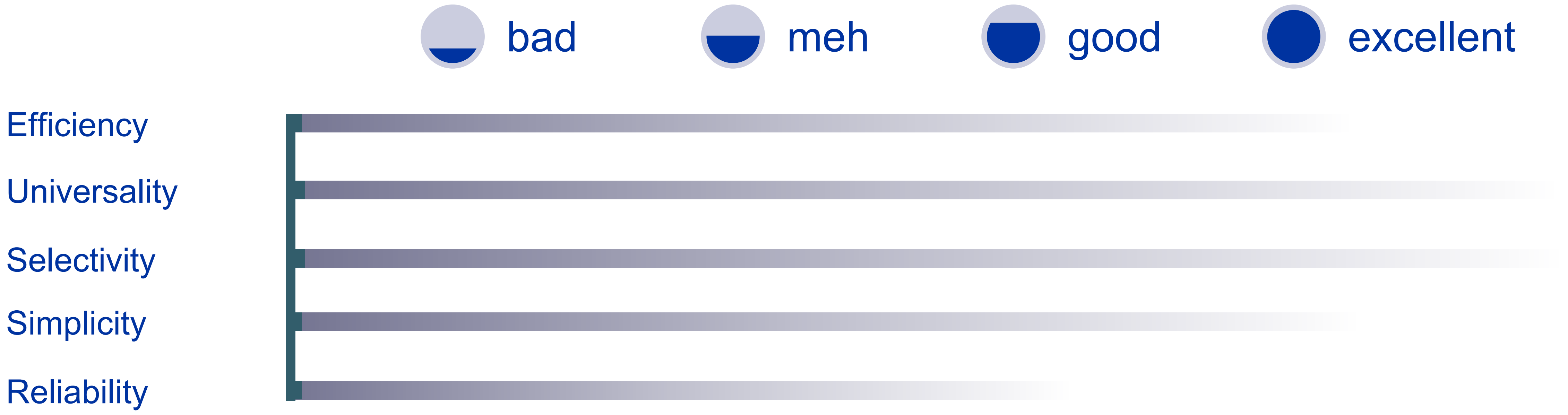
- Room temperature operation of FEBIAD [4]
- Volatile gases and molecules
- Quantum efficiency of copper



[1] J. L. Navarro Quirante, et al. 27th International Linear Accelerator Conference (LINAC14), p.MOPP030 (2014)
[2] J. Brossard et al., Conf. Proc.: EPAC 2006, Edinburgh, Scotland. (2006)
[3] E. Granados et al., Capabilities and performance of the CLEAR facility photo-injector, CERN, "CERN-OPEN-2020-002" (2019) https://cds.cern.ch/record/2705786
[4] J. Ballof, et al., J. Phys. Conf. Proc. ICIS2021, 2244 (2022) 012072

FEBIAD-type ion sources – properties for ISOL

Questions about FEBIAD-type ion sources?



Negative ion sources

Surface ion sources

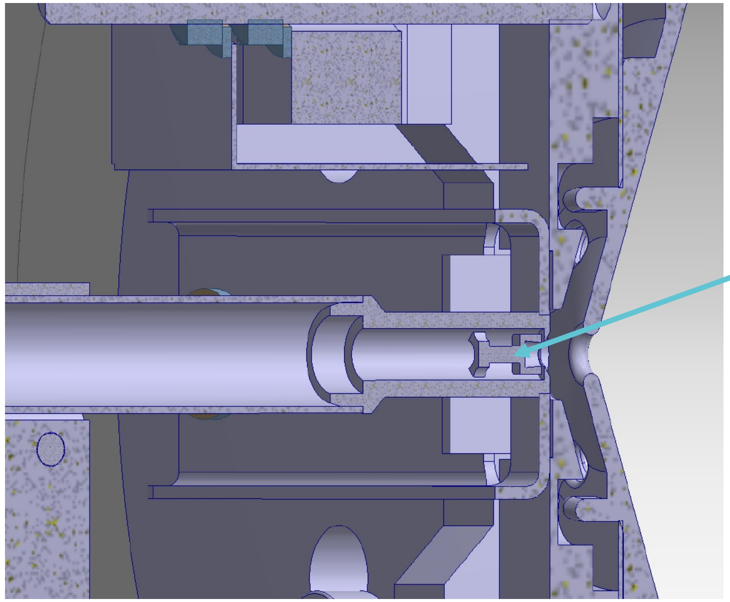
- Low work function surfaces:
  - LaB_6 pellet [1,2]
- Surface poisoning

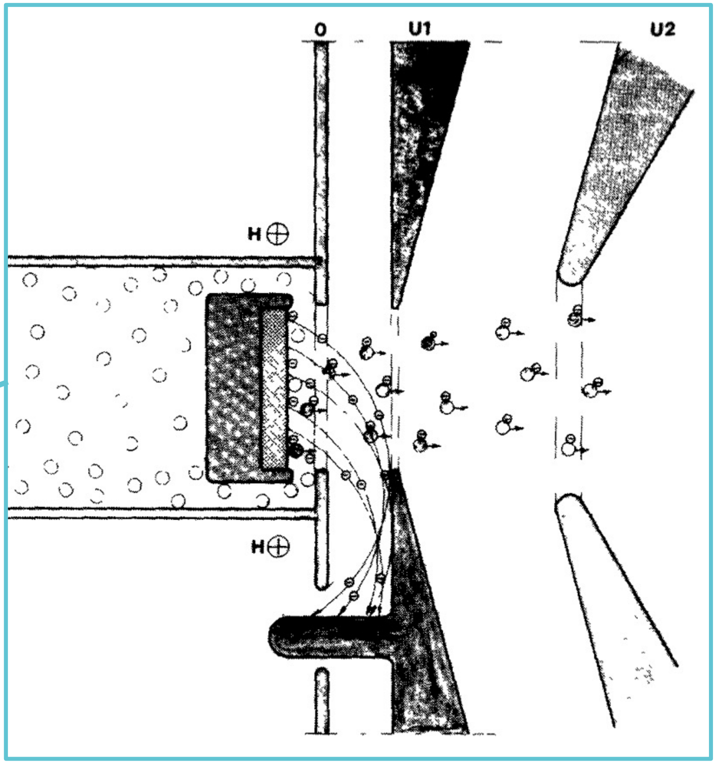
Kinetic ejection negative ion source (KENIS)

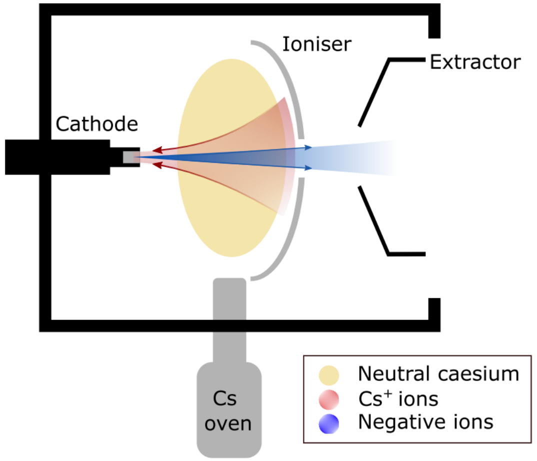
- Cs sputtering [3]

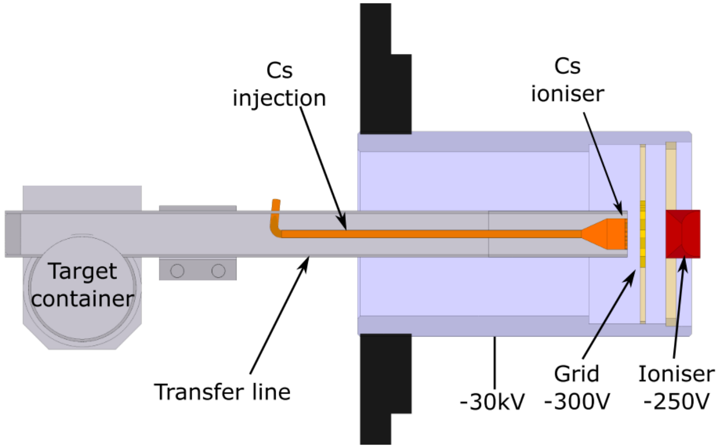
VADIS in negative mode

- Cs_2CrO_4
- Efficiency "$\approx 2.8 \times 10^{-4}$ % at most" [2]





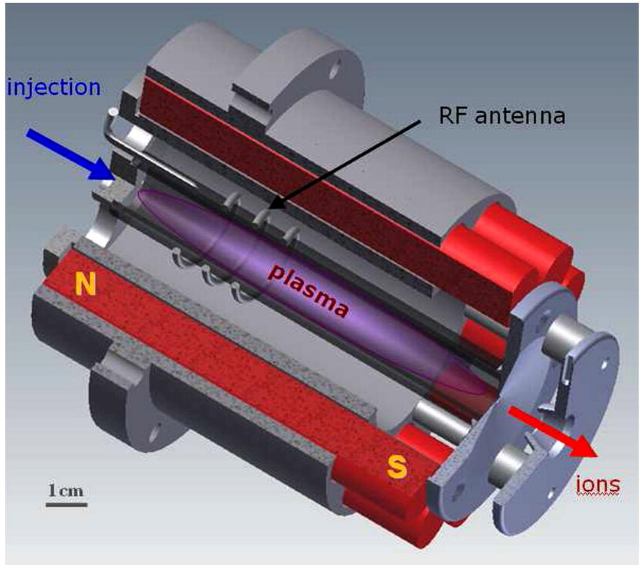




[1] B. Vosicki et al. NIM Phys. Res. 186.1 (1981), p. 307
[2] D. Leimbach, PhD thesis, JGU Mainz (2021)
[3] G.D Alton et al. NIMB 170.3 (2000), p. 515
[4] R. Middleton. NIM Phys Res. 214.2 (1983), pp. 139– 150. 90580-X.

ECR ion sources

- Electron cyclotron resonance (ECR) ion sources (ECRIS)

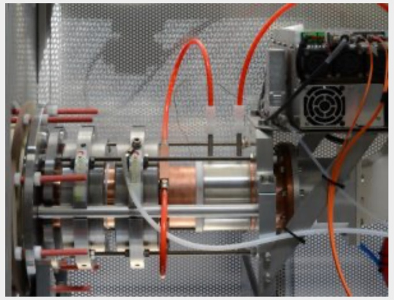


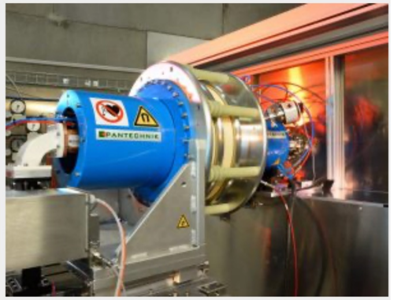
Principle

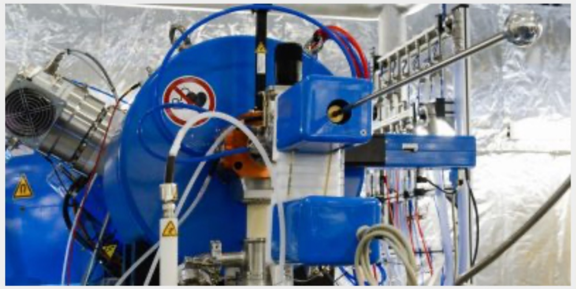
- Magnetic field and injection of RF or microwaves
- Plasma heating by resonantly exciting electrons :
  - $\omega_{ECR} = 2\pi f_{ECR} = \frac{eB}{m}$

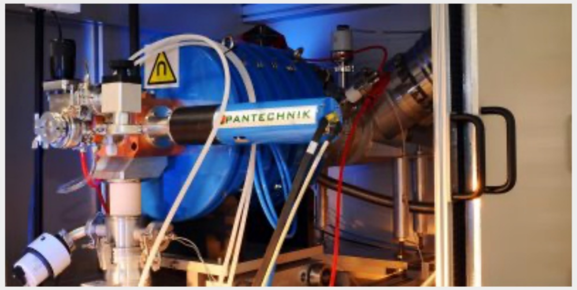
Examples

- CERN-ISOLDE helicon ion source [1]
  - efficiencies ~10% [2,3] CO: 2.5% Ar: 4%
- Commercial ECRIS [4]







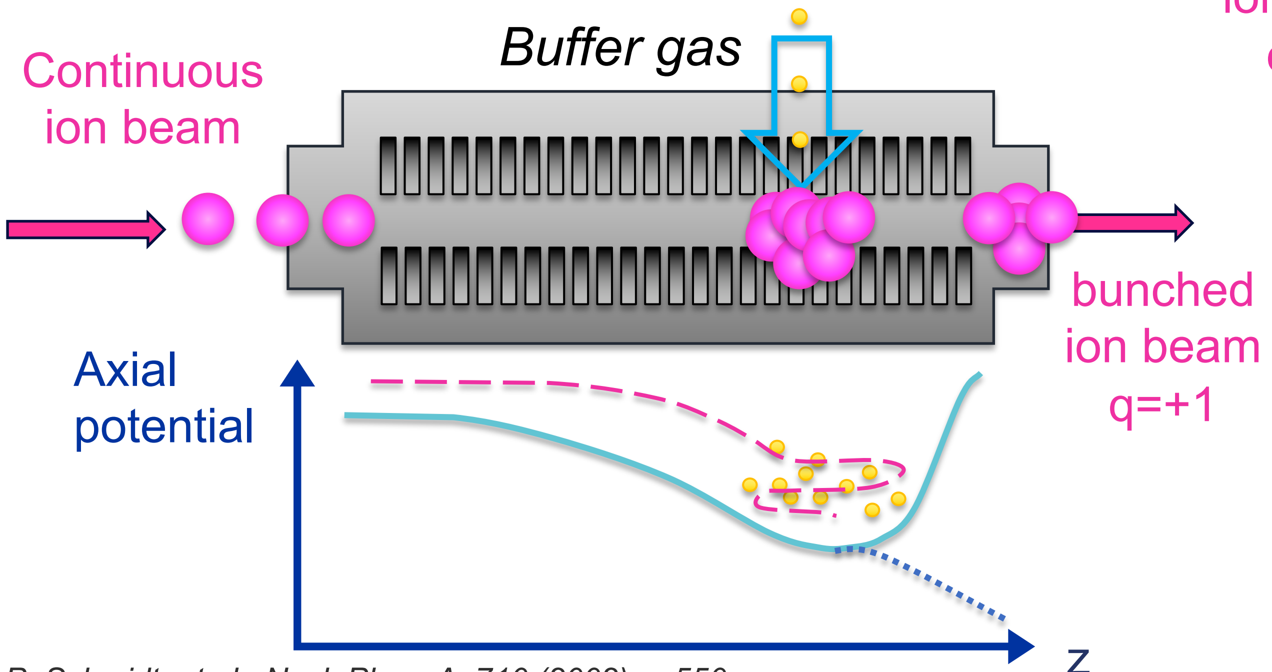


[1] M. Kronberger, et al., NIM B, 317 (2013) p. 438
[2] F. Chen, in: O.A. Popov (Ed.), High Density Plasma Sources, Noyes, Park Ridge, NJ, (1995)
[3] P. Suominen, T. Stora, ISOLDE Newsletter, 20, Spring (2011)
[4] https://www.pantechnik.com/ecr-ion-sources/

Electron bombardment ion sources and traps

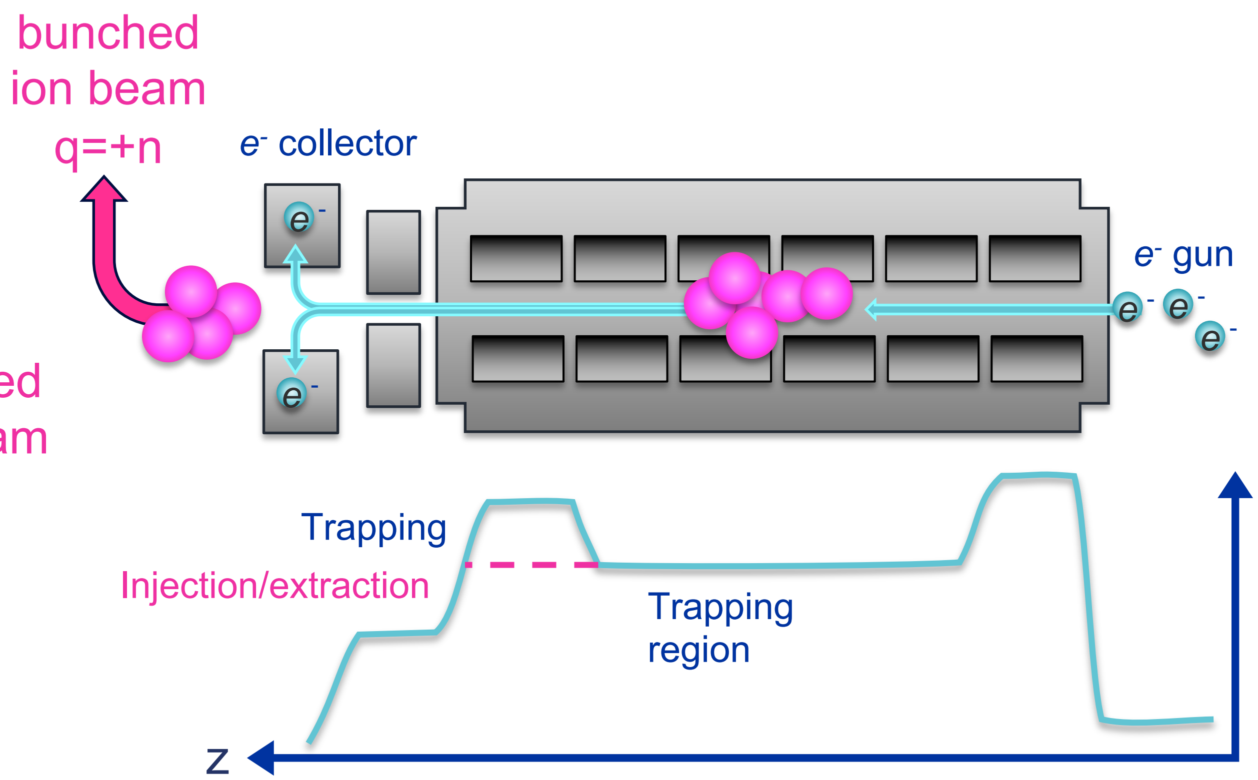
Ion beam bunching and cooling

- Radiofrequency quadrupole cooler-buncher (RFQ-cb) [1]



Charge breeding: EBIS / EBIT

- Electron beam ion source (EBIS) / Electron beam ion trap (EBIT) [2,3]

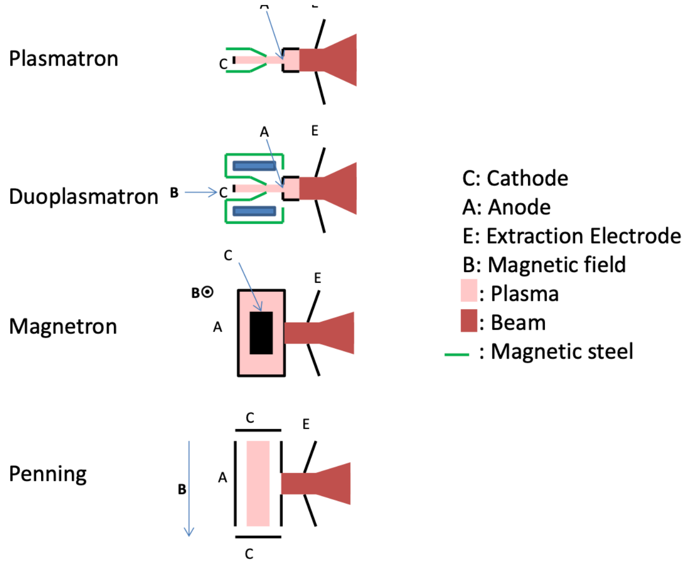


[1] P. Schmidt, et al., Nucl. Phys. A. 710 (2002) p. 550
[2] F. Wenander, JINST 5, (2010) C10004
[3] N. Bidault et al., AIP Conf. Proc. 2011 (2018) 070009

Other ion sources – there are many!

Plasma discharge ion sources [1]

- Magnetron
- Multicusp
- Penning/Phillips ion gauge (PIG)
- Plasmatron, duoplasmatron
- RF



Neutral beam injectors (NBIs)

- Ionization of fast neutral beams by plasma collisions

H- ion sources

- Surface production
- Volume production
- at CERN: LINAC4 [2,3]
  - Intensity: 35 mA

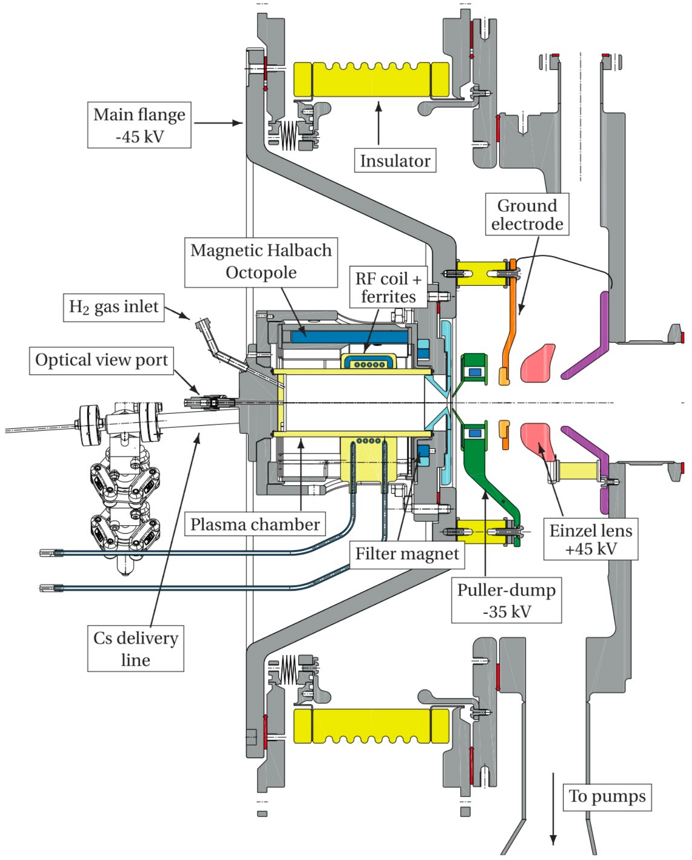


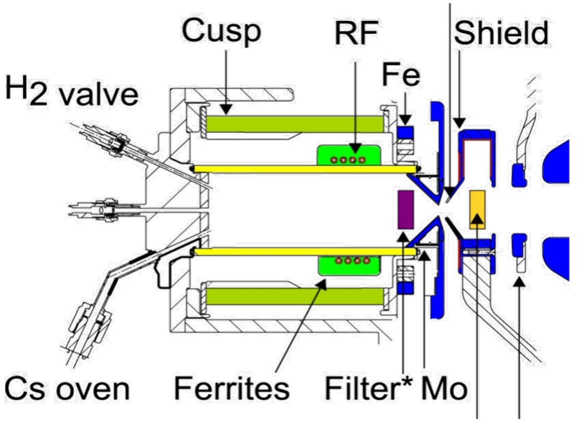
Figure 1.12 – Cross-sectional view of the Linac4 H⁻ ion source with its plasma generator and extraction system.

[1] R. Scrivens, CAS Lectures on ion sources
[2] J. Lettry, et al., CERN's Linac4 cesiated surface H− source. AIP Conf. Proc. 9 August 2017; 1869 (1): 030002.
[3] S. Mattei PhD thesis, (2017) CERN-THESIS-2017-109
[4] R. F. Welton (2002) 21st International Linear Accelerator Conference, Gyeongju, Korea, 19 - 23 Aug 2002, e-proc. TH101

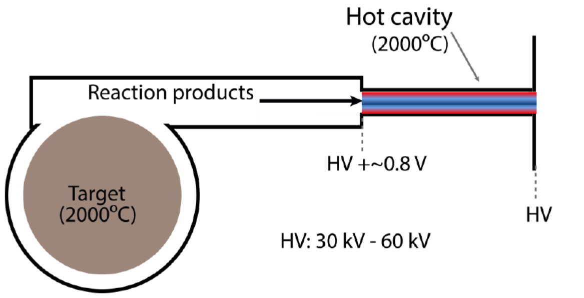
Ion source comparisons

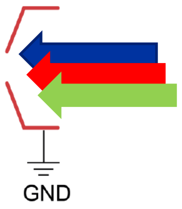
Adapted from Y. Martinez Palenzuela, K. Chrysalidis, B. Marsh et al., (2017)
Int. Conf. Ion. Sources presentation - Young Speaker Award

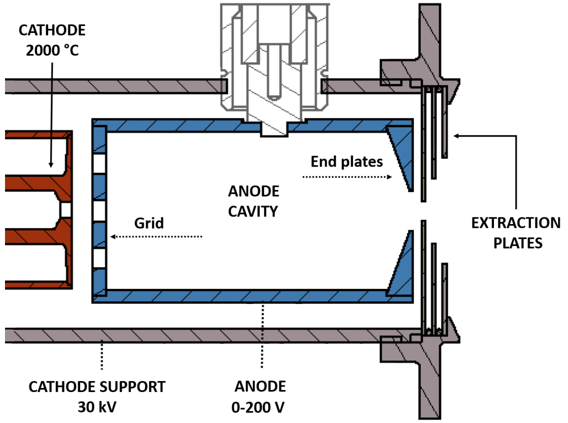
LINAC 4



ISOL ion sources







Hot cavity

Surface ionization | Laser ionization | FEBIAD

- supply is unlimited
- supply is limited and contaminated

Ion source applications

In the ISOL community

A small part of a big field

1 RIB production and considerations

2 In-source spectroscopy

3 Fundamental properties

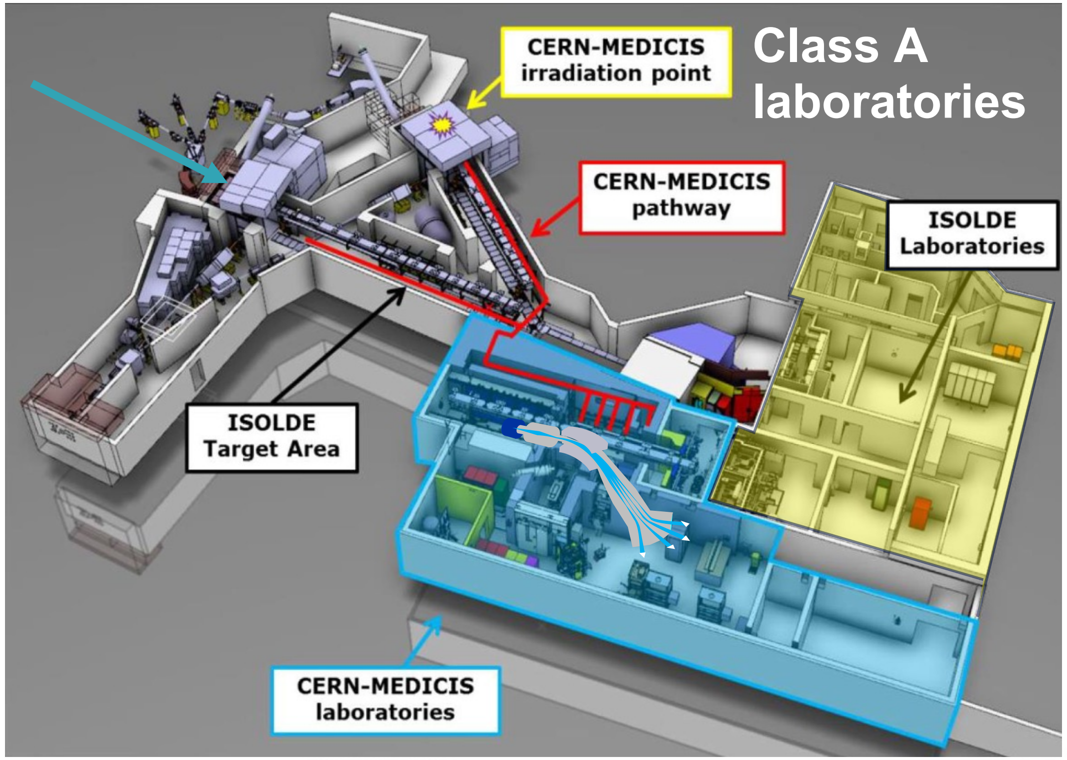
4 Production of medical isotopes

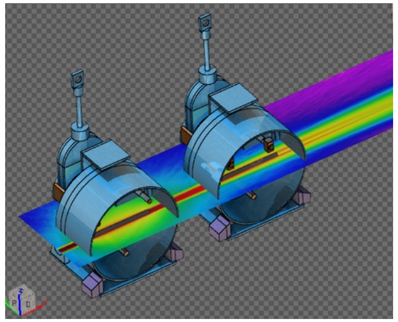
Catherall et al. (2017) *J. Phys G* **44**, 094002
isolde.web.cern.ch

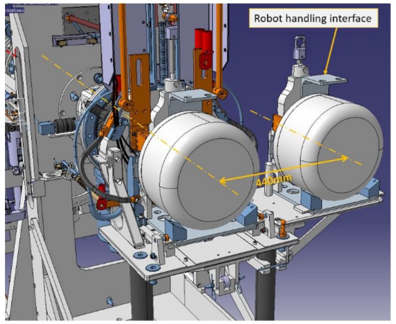
ISOL

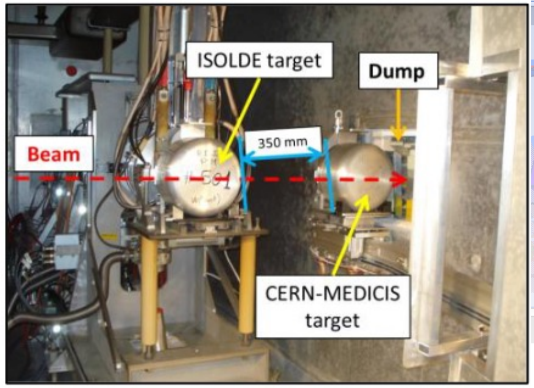
"On-Line":

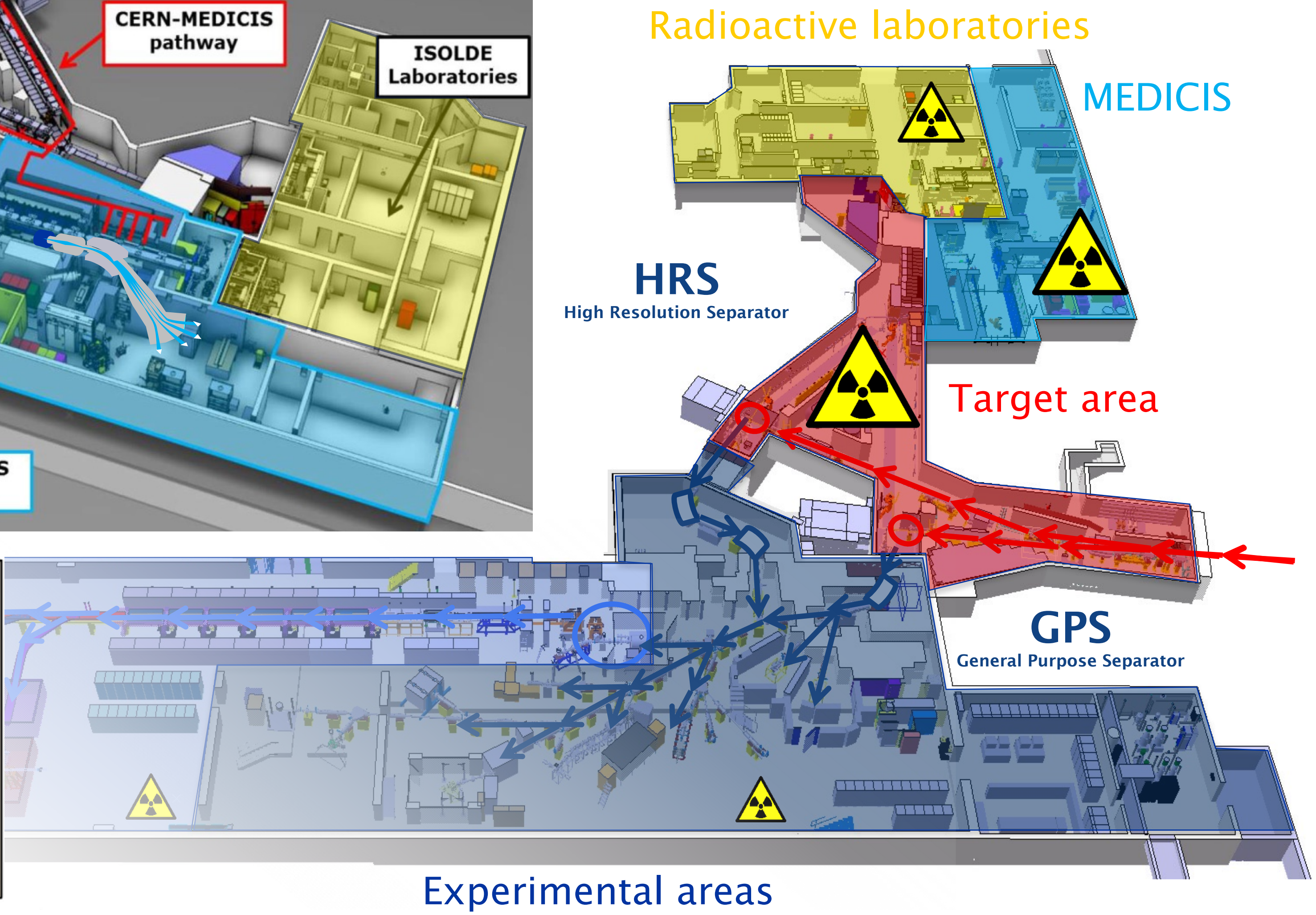
- Production
- Release
- Ionization
- Extraction





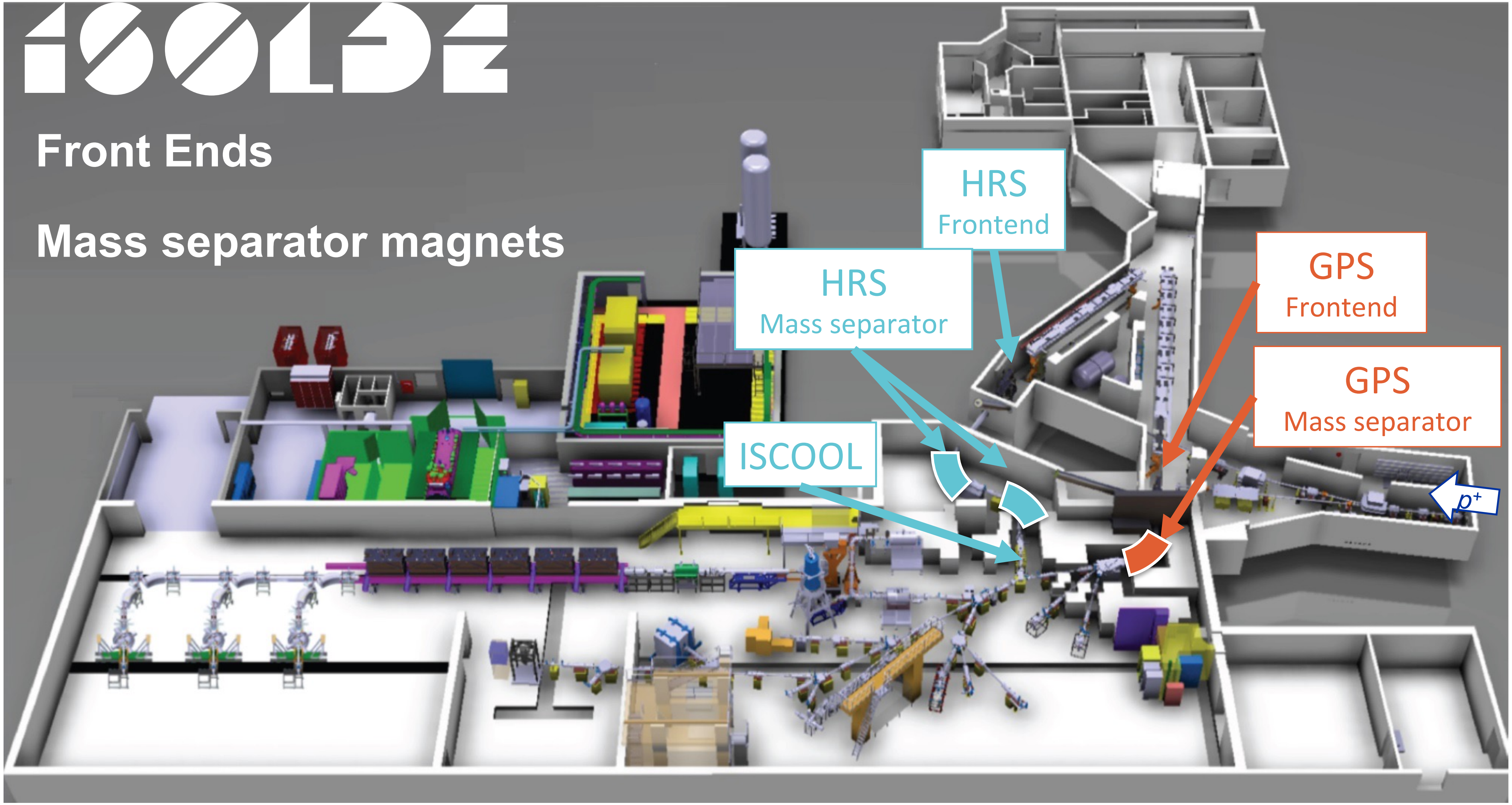






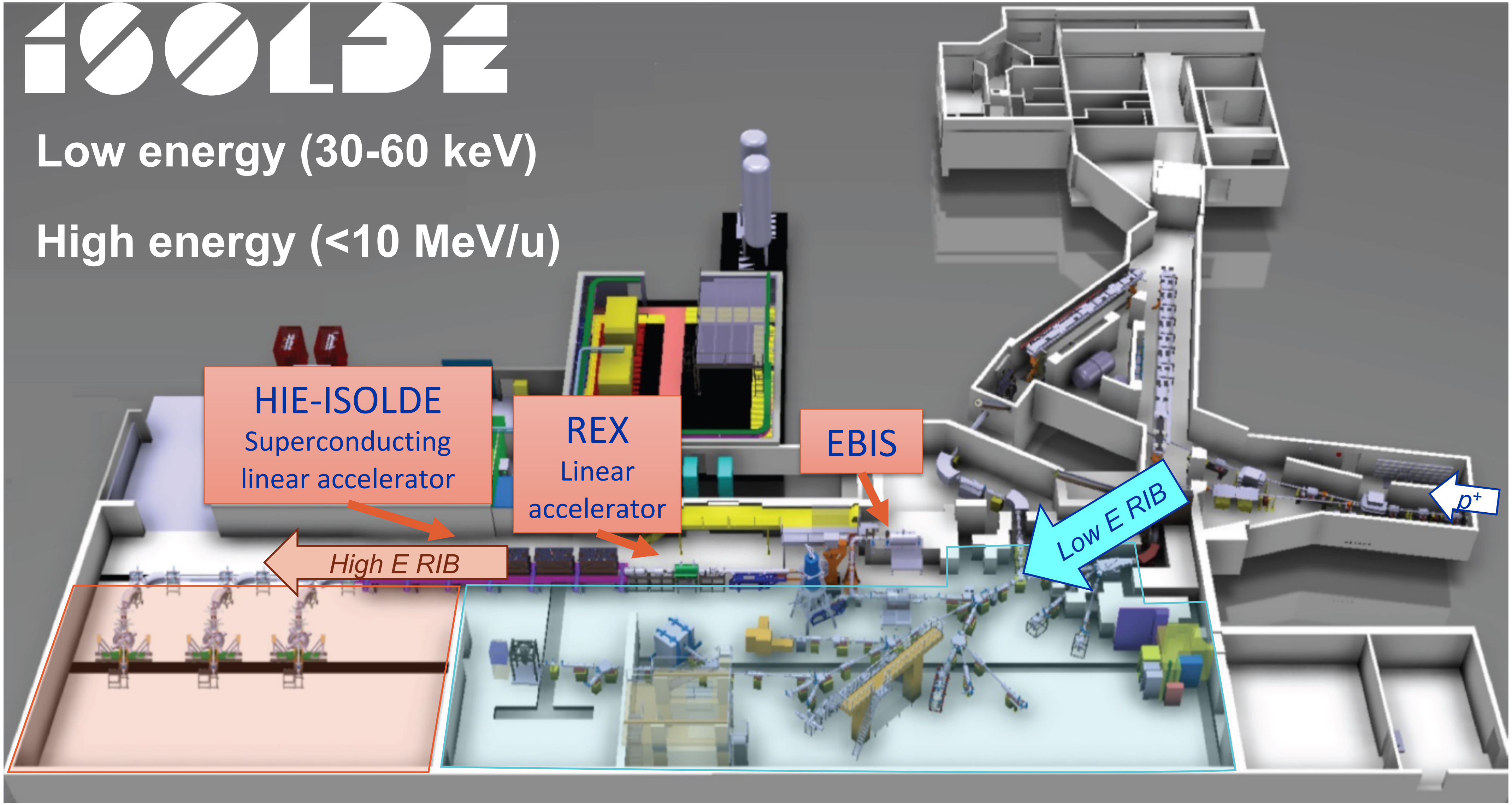
ISOL Step 4: Mass separation

Catherall et al. (2017) *J. Phys G* **44**, 094002
isolde.web.cern.ch



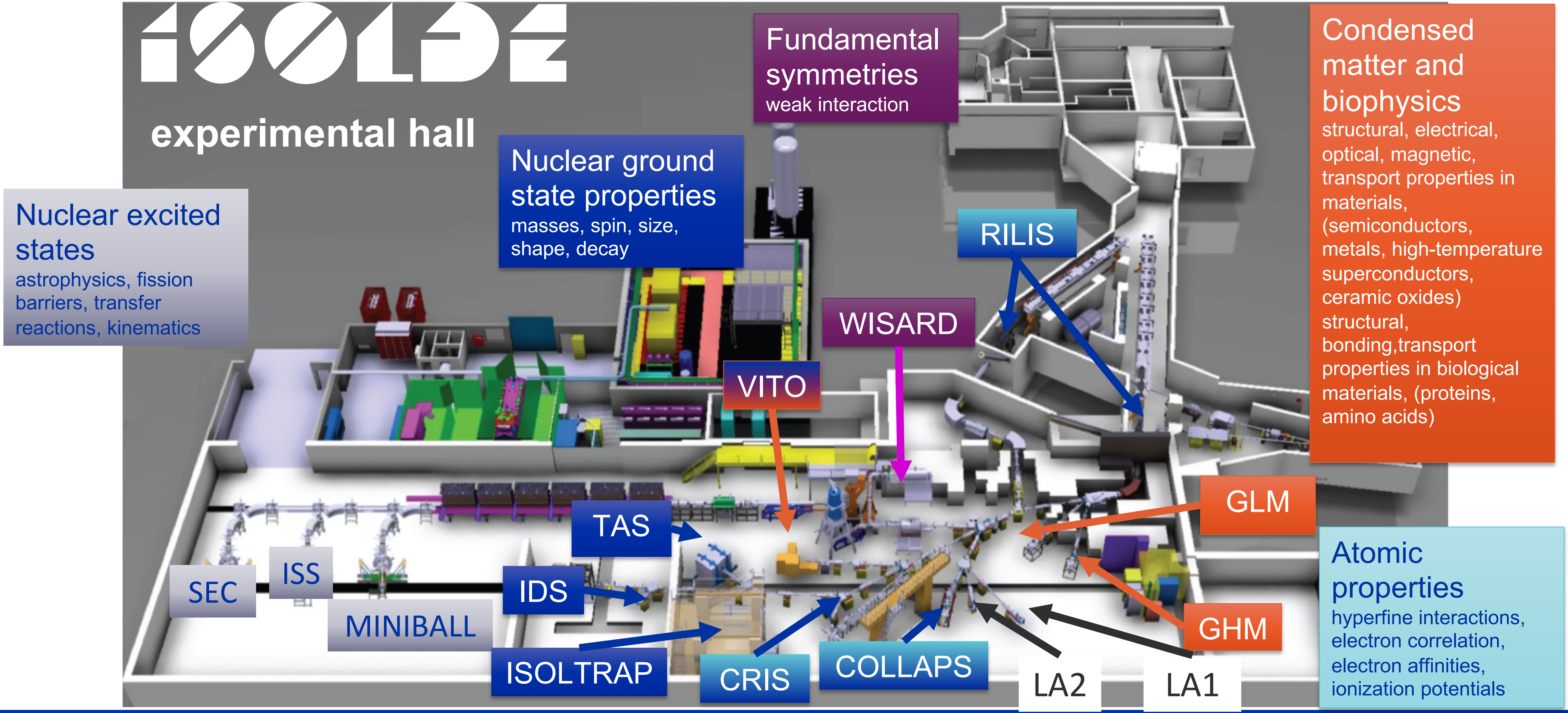
ISOL Step 5: Delivery to Experiments

Catherall et al. (2017) *J. Phys G* **44**, 094002
isolde.web.cern.ch



ISOL Step 5: Delivery to Experiments

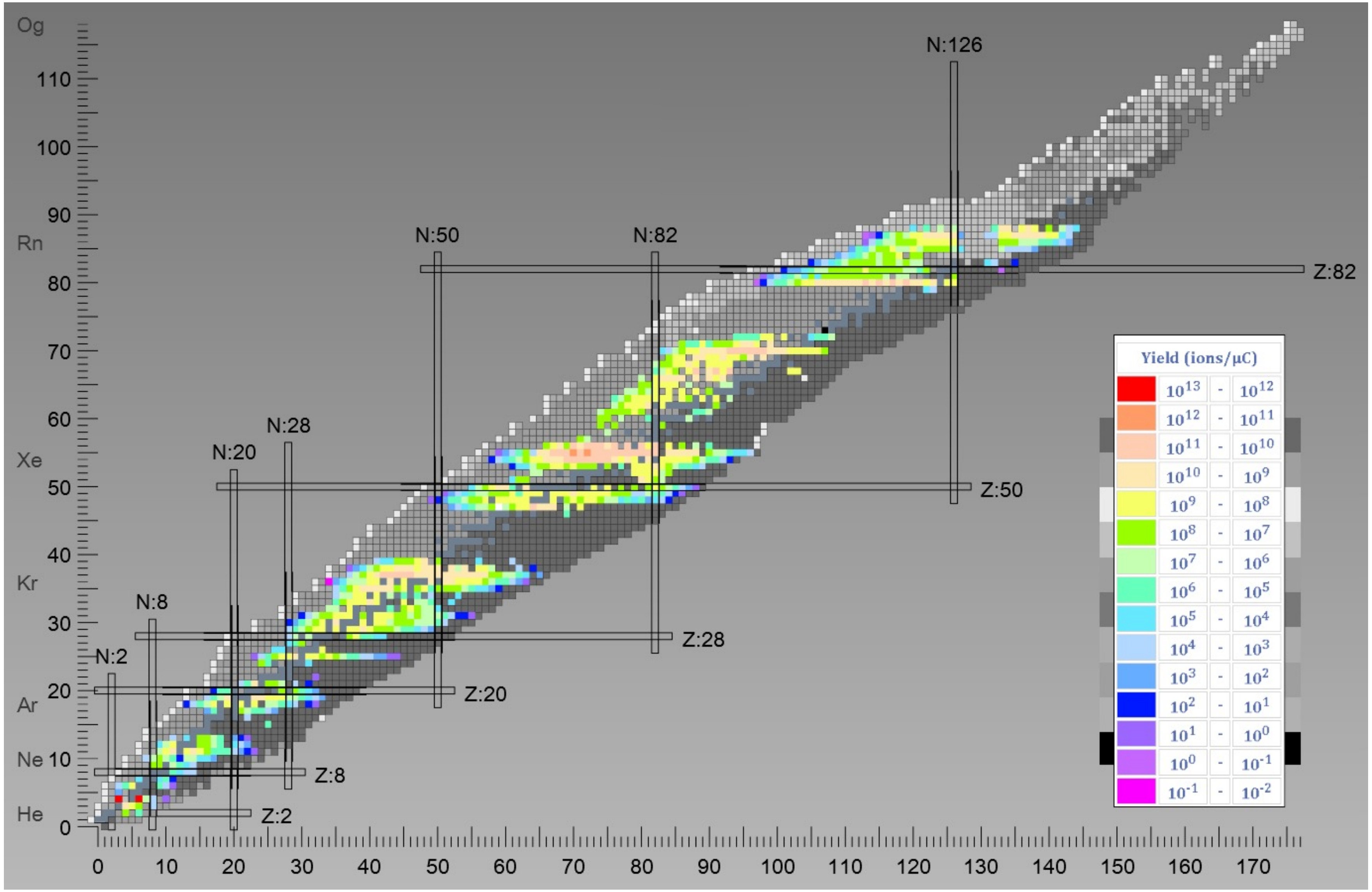
Catherall et al. (2017) *J. Phys G* **44**, 094002
isolde.web.cern.ch



CERN-ISOLDE

>1000 isotopes and isomers

74 elements



Ballof *et.al,* (2020) *NIM B* **463**, 211-215
cern.ch/isolde-yields

www.nucleonica.com
Dataset: JEFF-3.1 Nuclear Data Library, NEA (2023)

TISD 2023

Back-of-line heating:
Dy collections

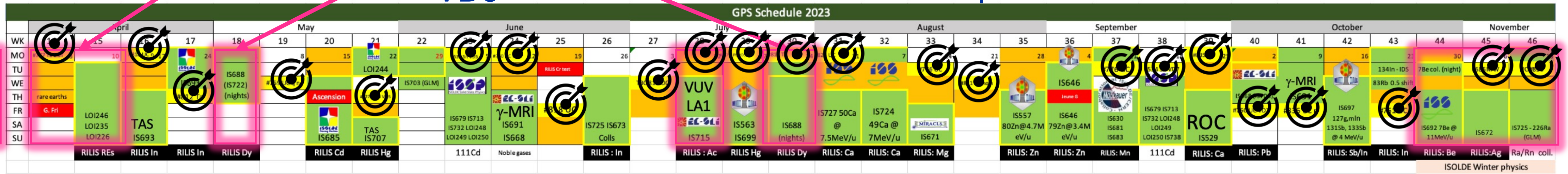
LIST: lanthanides

VD5

Hot
quartz

VD7

MK1



LIST: actinides

VD5

VD7

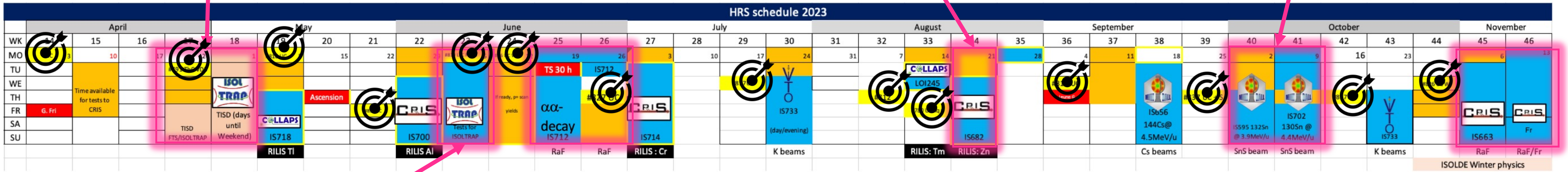
MK1

VD5+CF_4

hot quartz

MK1

VD5 SnS



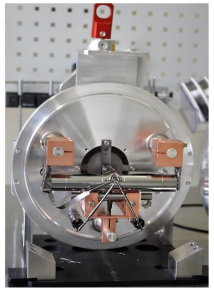
prototype
ion source

MK1
molecules

MK1

MK1

MK1
molecules

=  (~ 50 kCHF)

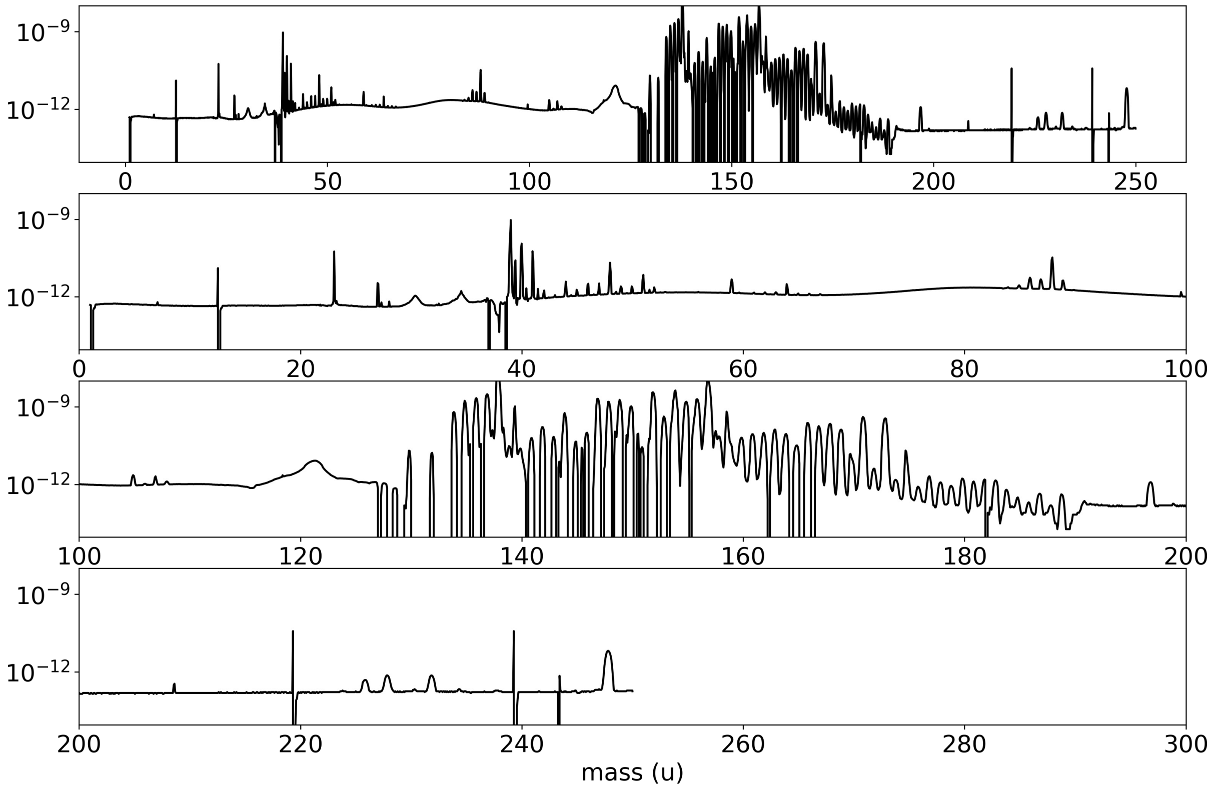
= Yield measurements, proton scans, setup

RILIS 23 : U, Np, Pu, Dy, Tm, Pm, Er, Gd, Yb, In, Cd, Hg, Al, Cr, Ac, Ca, Mg, Zn, Mn, Pb, Sb, Be, Ag

Operating ion sources: mass scans

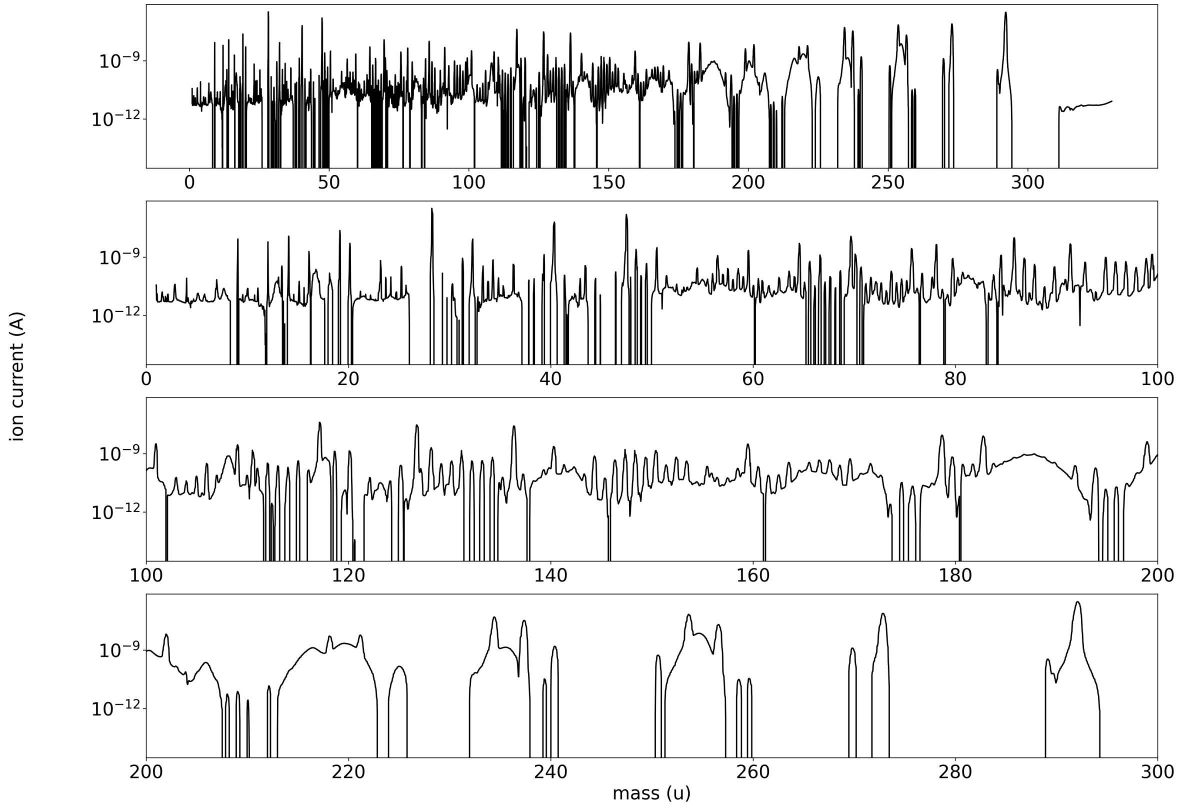
Surface

- Low IPs
- Surface ionization efficiency

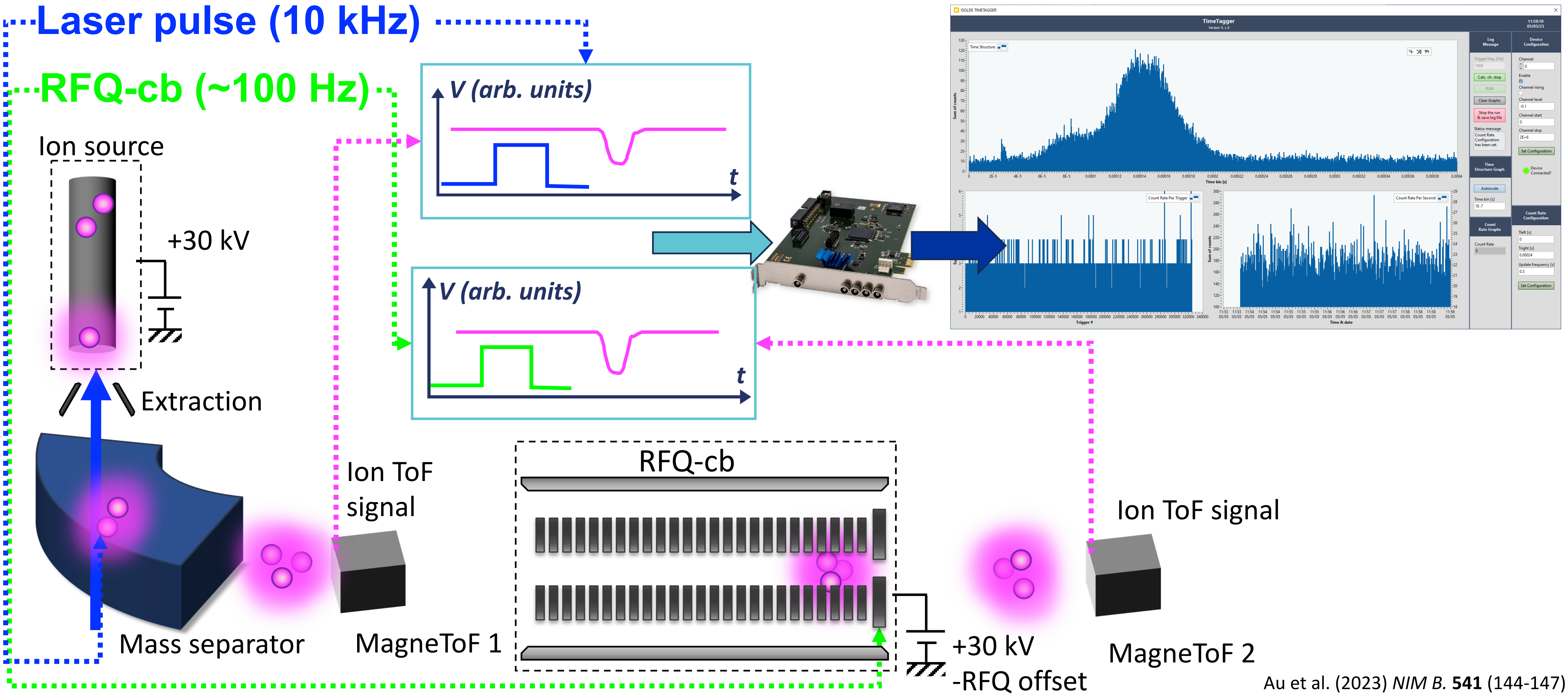


FEBIAD

- High/unknown IPs
- High efficiency

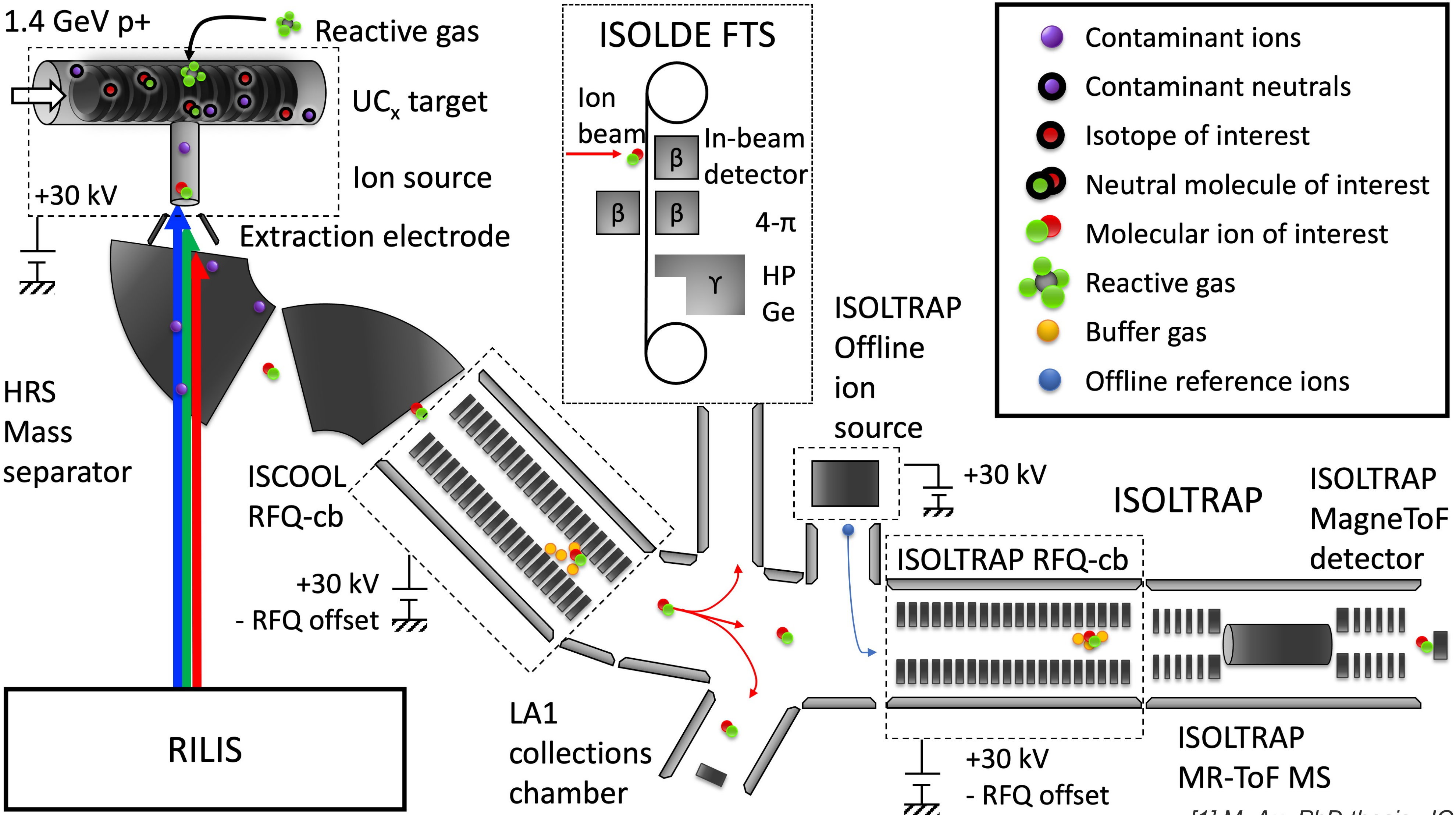


Operating ion sources: time structures



Au et al. (2023) *NIM B.* **541** (144-147)

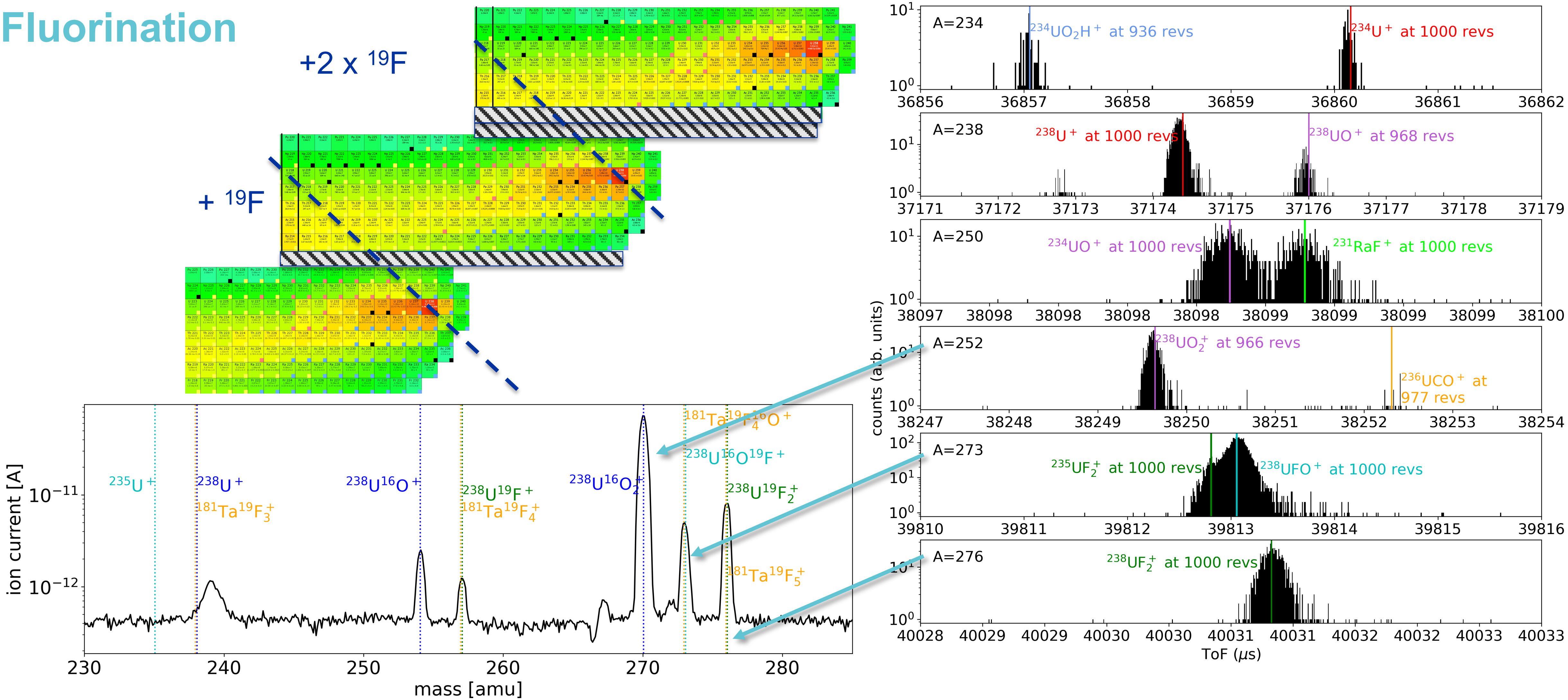
Developing ion sources: diagnostics



[1] M. Au, PhD thesis, JGU Mainz (2023)

Molecular formation: identification

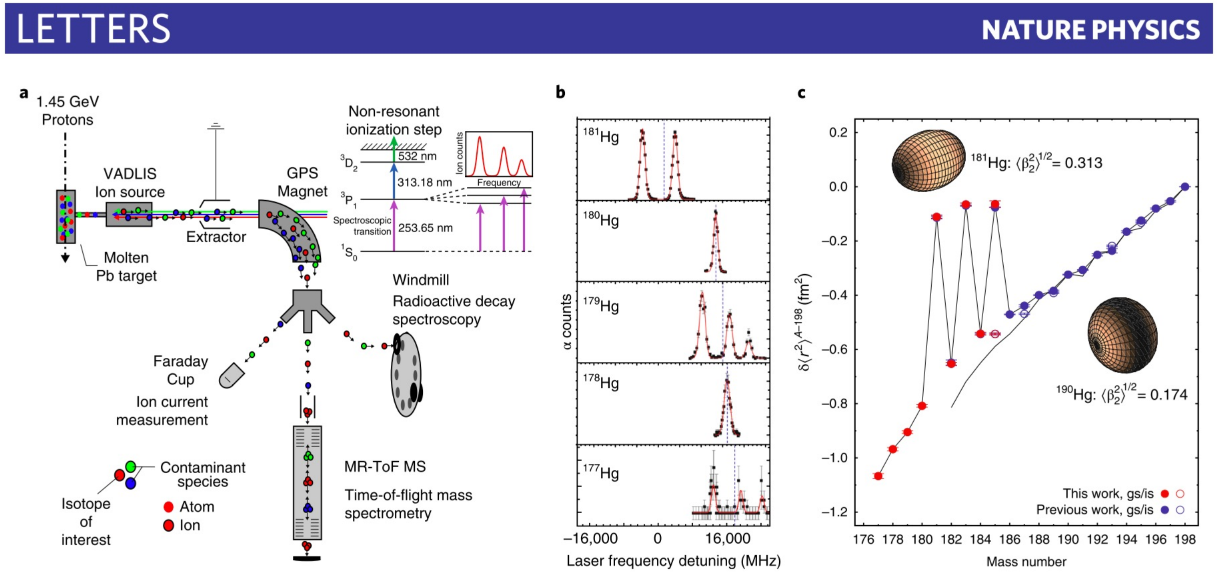
Fluorination



Au et al. (2023) *NIM B.* **541** (375-379)

Applications: RIS as a spectroscopy tool

- For stable and sufficiently small laser linewidth, ionization efficiency is sensitive to hyperfine structure
- Sensitivity to nuclear structure observables: charge radius, electromagnetic moments
- Highlight: shape co-existence phenomenon, odd–even shape staggering of n-deficient Hg [1]

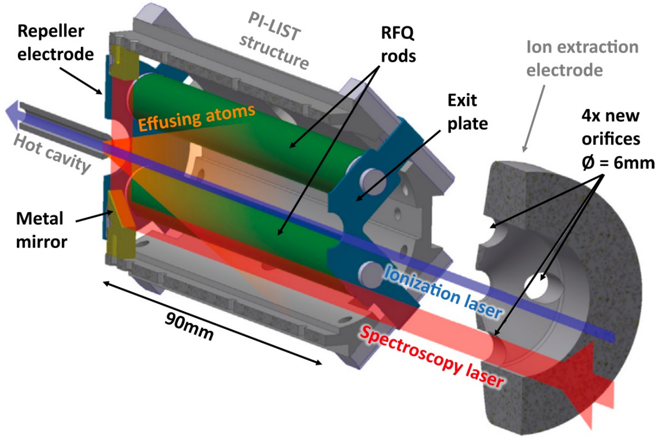


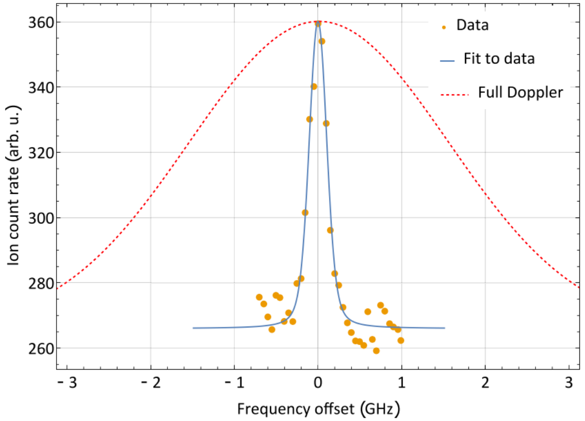
In-source resonance ionization spectroscopy (RIS) [2]

- Resolution limited by Doppler broadening

LIST and PI-LIST

- Sub-Doppler hot-cavity in-source spectroscopy
- CERN-ISOLDE implementation [3]

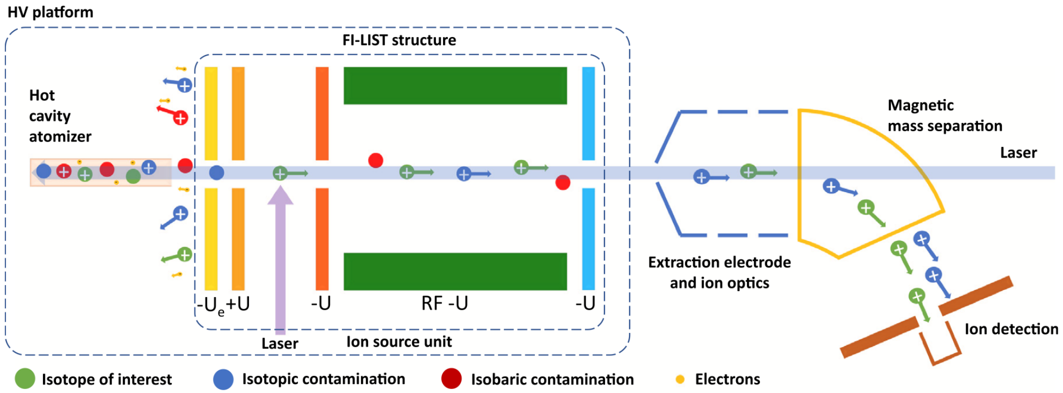




[1] Marsh *et al., Nat. Phys. 14 (2018) p 1163*
[2] Fedosseev *et al.,* NIM B. 204 (2003) 353
[3] Heinke et al. (2023) *NIM B.* **541** (8-12)

Applications: Ionization potentials

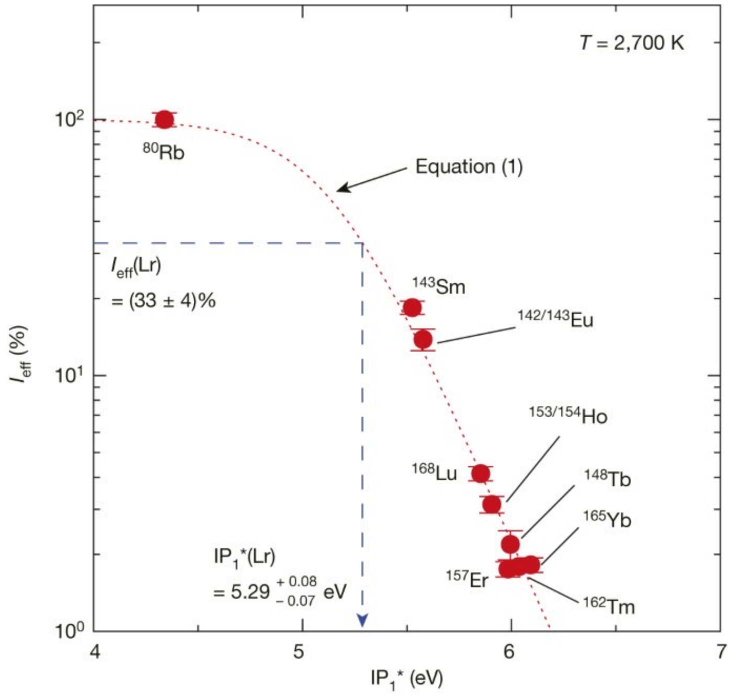
FI-LIST: IP of Yb



- Application of field ionization from excited states in a LIST ion source geometry [1]

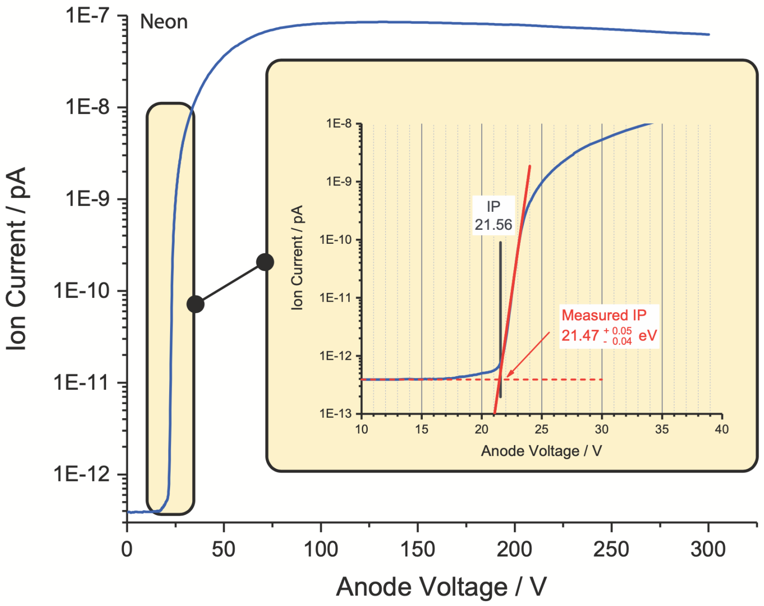
Surface ionization efficiency

- Use of surface ionization efficiency expression to perform the first measurement of the IP of superheavy Lr [2]



FEBIAD

- For species with higher IP: noble gases [3]



[1] M. Kaja *et al.*, *NIM B. 547 (2024) 165213*
[2] Sato *et al.*, *Nature* 520 (2015) p. 209–211
[3] Ballof *et al.*, *6th Int. Conf. Chem. Phys. of Transactinide Elements (2019)*

Applications: ionization of medical radionuclides

Actinium-225

- Targeted α-therapy
- Half-life 9.9 days

Production routes

- Collect $^{225}Ra \rightarrow {}^{225}Ac$
  - Surface ion source [1,2]
- Collect ^{225}Ra and ^{225}Ac
  - Surface ion source + RILIS for Ac [1,2]
- Collect only ^{225}Ac
  - VD5 and molecular sidebands [3]

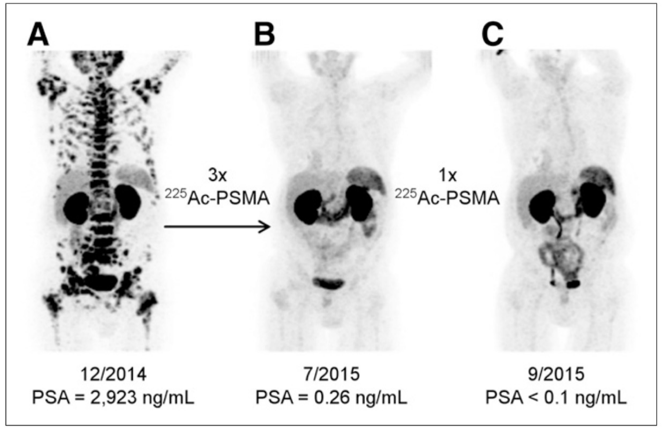


Figure published in: Kratchowil *et al.* (2016) J. Nucl. Med. **57** 1941-1944

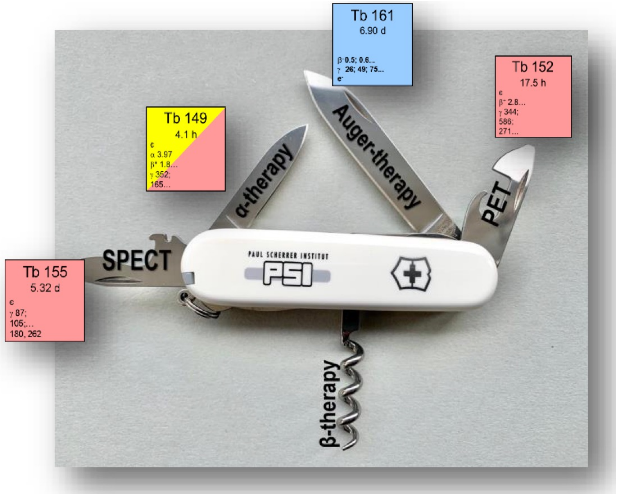


Figure 1 The quadruplet of theragnostic terbium radioisotopes. [5]

Terbium-149

- Targeted α-therapy and PET
- Half-life 4.1 h

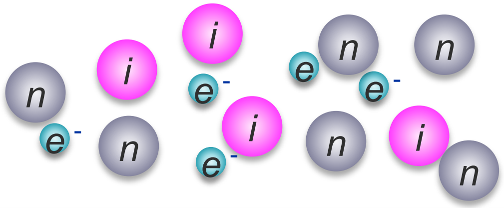
Production routes

- Collect $^{149}Dy \rightarrow {}^{149}Tb$ [4,5]
- Target and ion source development [6]

[1] E. Jajčišinová, *et al., Sci Rep* 14, 11033 (2024)
[2] Johnson *et al., Sci Rep* 13, 1347 (2023)
[3] M. Au *et al., PhD thesis, JGU Mainz* (2023)
[4] C. Müller *et al., EJNMMI Radiopharm Chem 1* (2017) 5. PMID: 29564382
[5] Grundler, Johnston, Köster, Müller, Talip, van der Meulen, *IS688 CERN-INTC-P-593 (2023)*
[6] W. Wojtaczka *et al., in preparation* (2024)

ISOLDE

Summary



1 Basic processes in ion sources

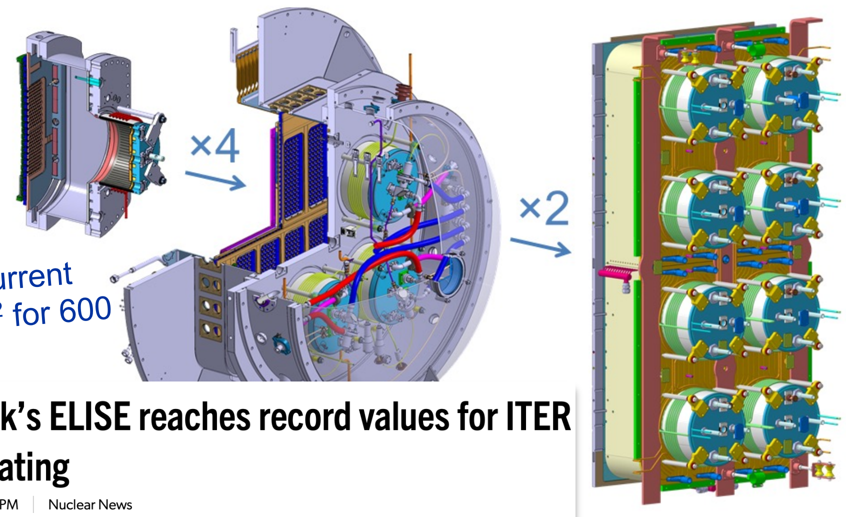
2 Ion sources used for ISOL

3 Applications of ion sources

4 Lots of research done, lots more to do!

iFAST Innovation Fostering in Accelerator Science and Technology

ICIS'23 International Conference on Ion Sources Victoria, BC, Canada



New record: H^- current density 300 A m^{-2} for 600 seconds

Max Planck's ELISE reaches record values for ITER plasma heating

Wed, May 8, 2024, 5:01PM | Nuclear News