Methods for Characterizing Rare Isotope Beams at the REX/HIE-ISOLDE Linear Accelerator

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Beam Quality

Beam Intensity Optimization

Slow extraction

Charge-breeding performances

Beam Purity

EBIS partial pressures

Rare contaminants

Transverse properties

Quadrupole-scan

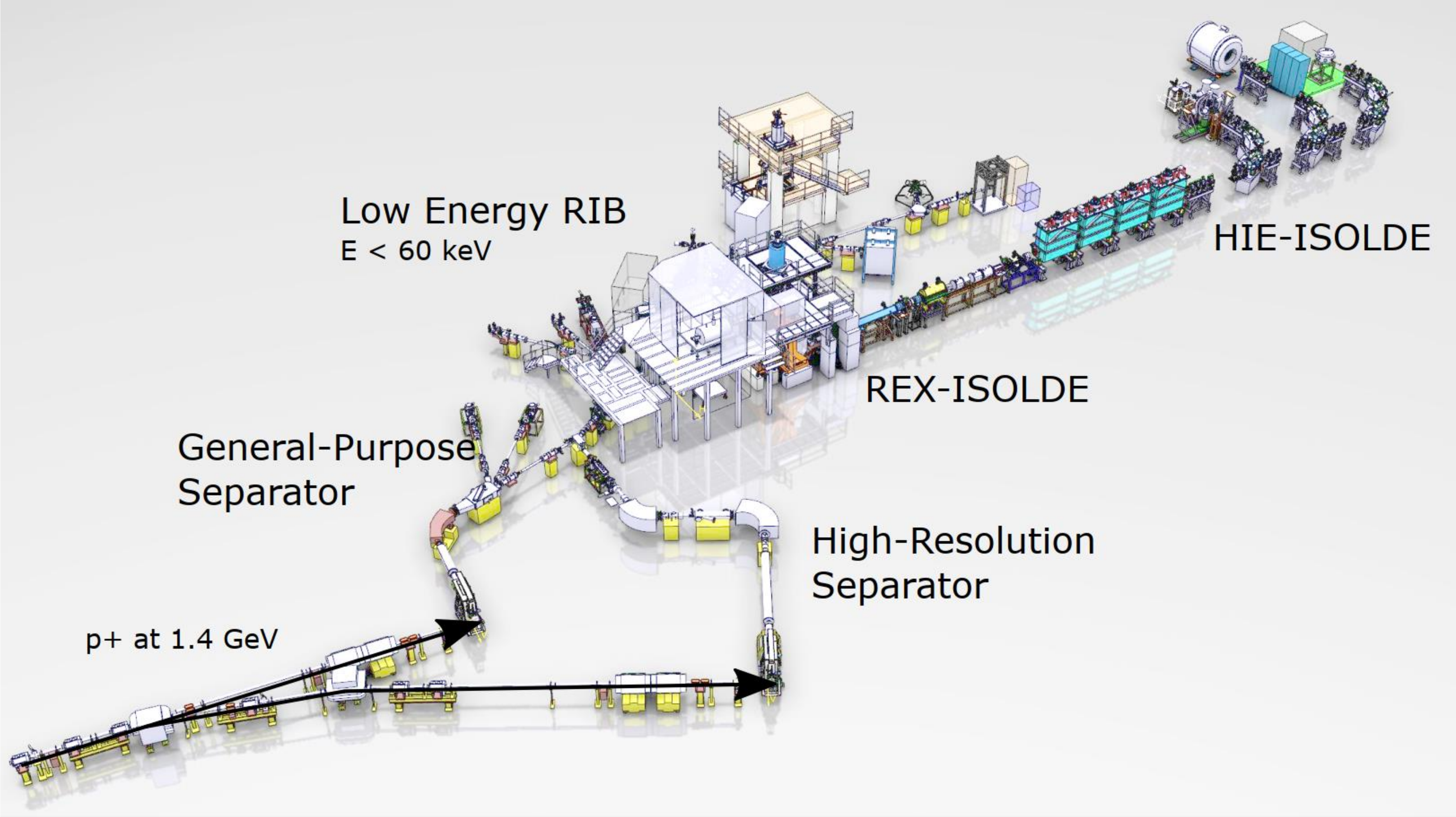
Trace space reconstruction

Longitudinal properties

Beam energy distribution

Bunch structure

Experimental Hall



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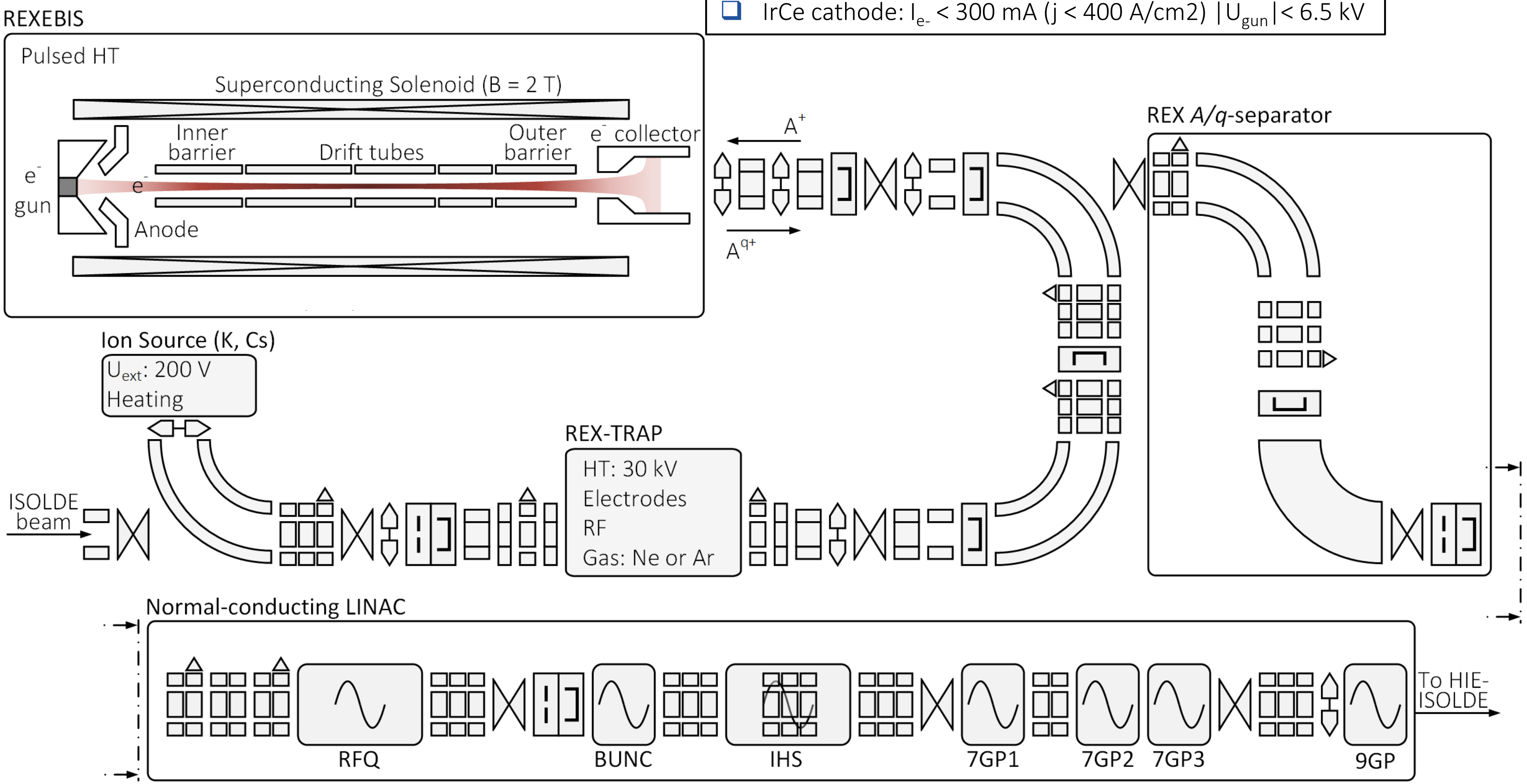
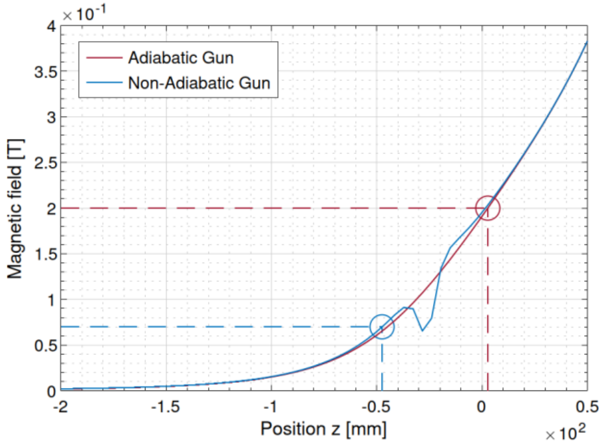
REX-ISOLDE

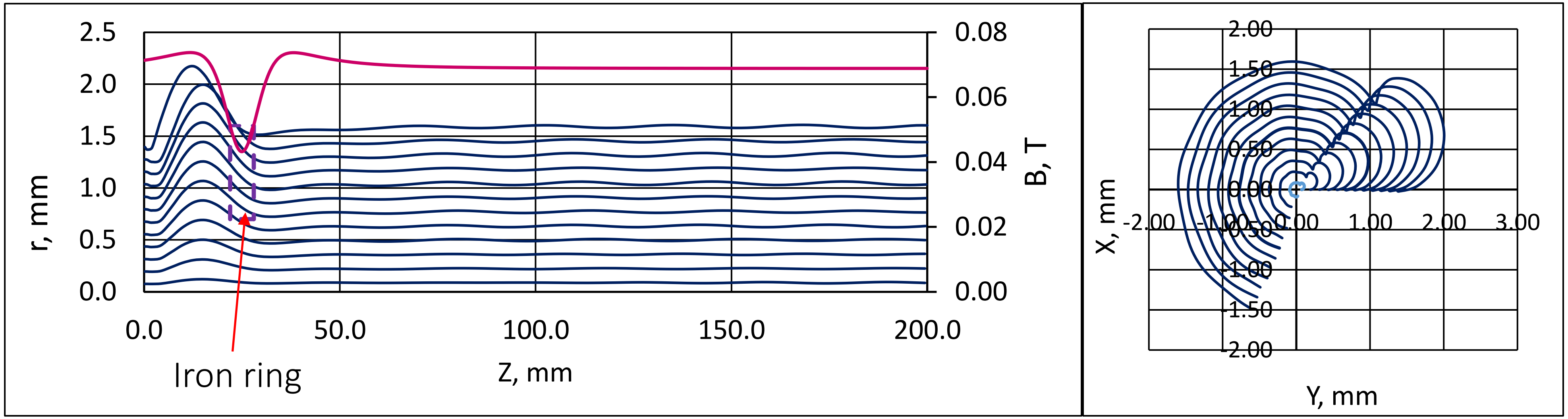
- LaB6 cathode : I_{e-} < 250 mA (j < 100 A/cm2) $|U_{gun}|$< 5 kV
- IrCe cathode: I_{e-} < 300 mA (j < 400 A/cm2) $|U_{gun}|$< 6.5 kV



Non-adiabatic immersed electron gun

- Immersed electron gun positioned in low B-field (few hundred Gauss)
- Reduce cyclotron motion with local magnetic element
- Produce a laminar beam that is thereafter adiabatically compressed by main B-field





A. Pikin et al., "A method of controlling the cyclotron motion of electron beams with a non-adiabatic magnetic field", accepted PRAB

Slow Extraction

Technique Discretization of the axial energy distribution and solve all $V_{barrier}(t_i)$ (barrier step-function) to obtain a constant escape rate.

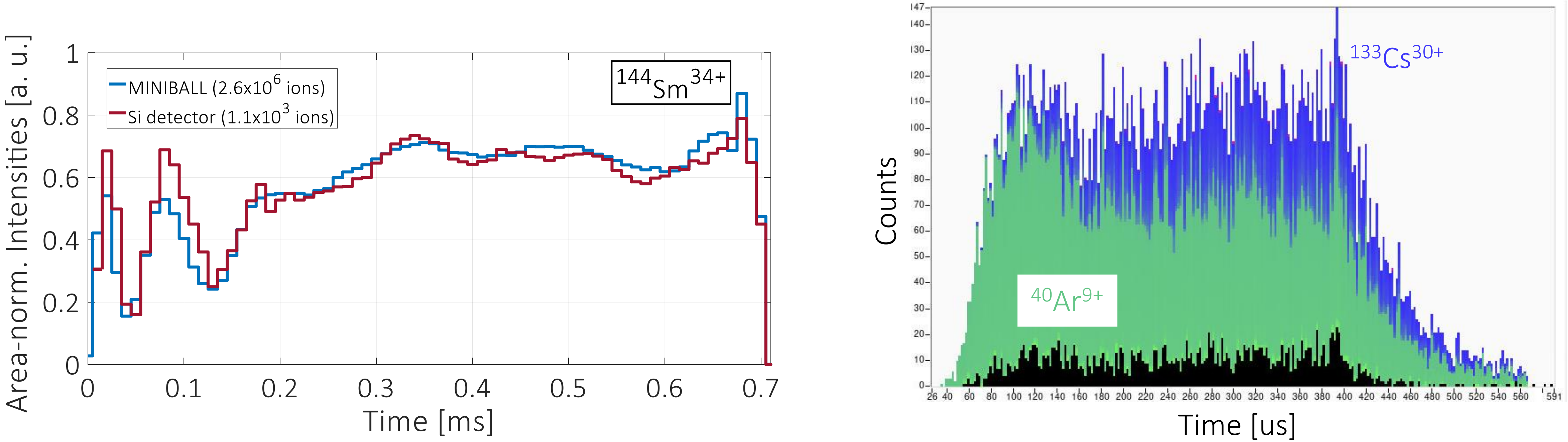


Figure Direct application of inversion formula, comparison between detectors.

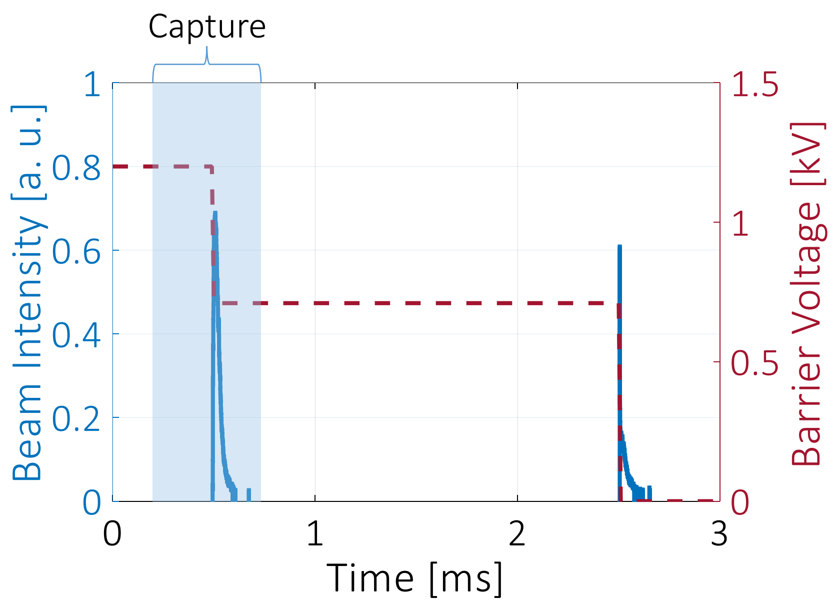
Ion energy distribution may be assumed a Maxwell-Boltzmann with 3 DoF: $f(E_i) = \frac{2}{kT_i}\left(\frac{E_i}{\pi k T_i}\right)^{1/2}\exp\left(-\frac{E_i}{kT_i}\right)$

Reduction of contamination via delayed extraction of the beam of interest (high CS) ca be improved, notably with higher current density.

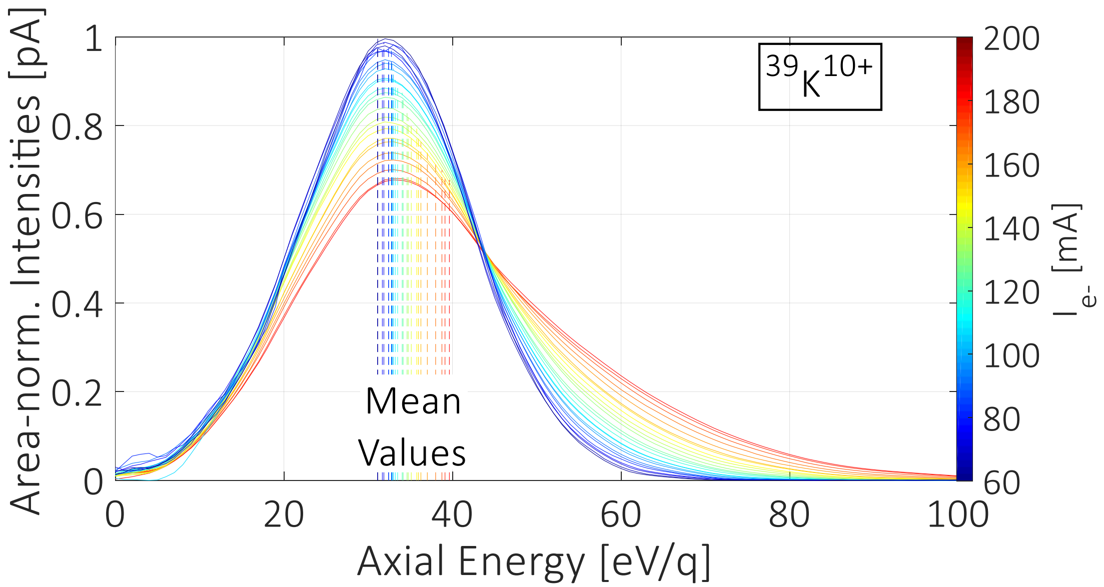
"Slow Extraction of Charged Ion Pulses from the REXEBIS", N. Bidault, *et al.,* AIP Conf. Proc. 2011 (2018) 070003.

Axial energy distribution

Technique Variation of REXEBIS extraction potential and monitoring of escaped ions to reconstruct the axial energy distribution.



Time-of-Flight measured after the *A/q*-Separator when gating with the outer barrier.



Ionic axial energy distribution measured at REXEBIS extraction, as a function of the electron beam current.

Energy dynamics

$$\frac{\mathrm{d}k_BT_i}{\mathrm{d}t} = \left(\frac{\mathrm{d}k_BT_i}{\mathrm{d}t}\right)^{\text{Spitzer}} + \left(\frac{\mathrm{d}k_BT_i}{\mathrm{d}t}\right)^{\text{Ionisation}} + \sum_j \left(\frac{\mathrm{d}k_BT_i}{\mathrm{d}t}\right)_j^{\text{Transfer}} - \left(\frac{\mathrm{d}k_BT_i}{\mathrm{d}t}\right)^{\text{Escape}}$$

EBISIM code: Charge state and energy dynamics

EBISIM package collection of tools for simulating the evolution of the charge state distribution inside an Electron Beam Ion Source / Trap (EBIS/T) using Python. GitHub (https://github.com/HPLegion/ebisim#readme). Developed by Hannes Pahl (CERN).

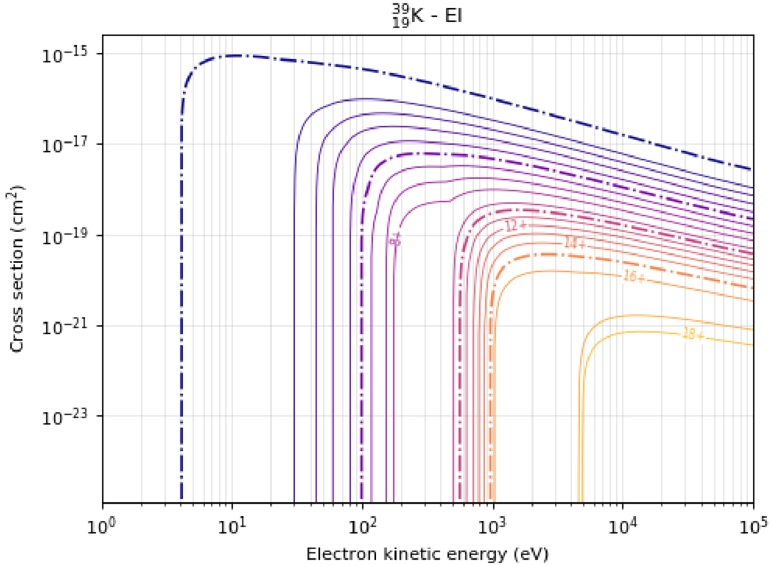


Figure Electron impact cross sections

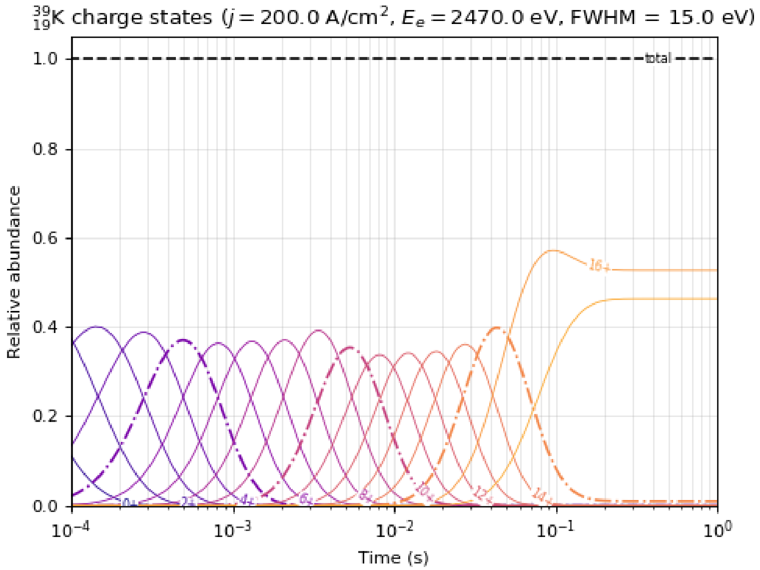


Figure Charge state distribution versus breeding time

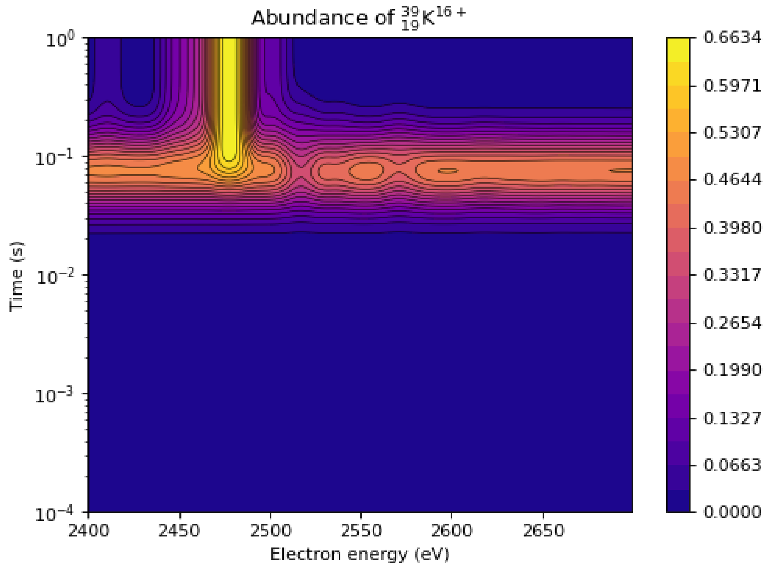


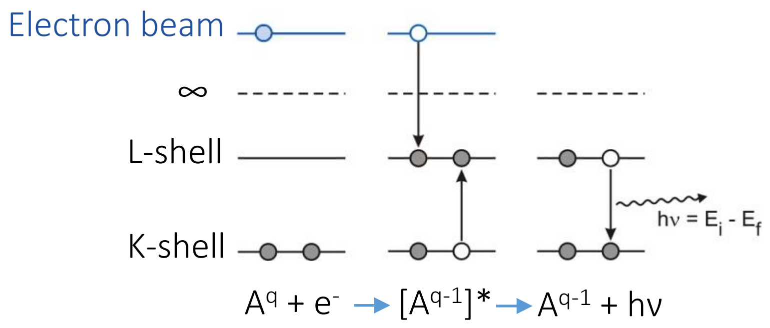
Figure Energy-scan across DR resonances.

Charge dynamics

$$\frac{\mathrm{d}N_q}{\mathrm{d}t} = \frac{j_e}{e} f_{i,e} \left(N_{q-1}\sigma_{q-1}^{\mathrm{EI}} - N_q\sigma_q^{\mathrm{EI}} + N_{q+1}\sigma_{q+1}^{\mathrm{RR}} - N_q\sigma_q^{\mathrm{RR}} + N_{q+1}\sigma_{q+1}^{\mathrm{DR}} - N_q\sigma_q^{\mathrm{DR}} \right) + \sum_j f_{i,j}(n_j \bar{v}_{q+1} N_{q+1}\sigma_{q+1}^{\mathrm{CX}} - n_j \bar{v}_q N_q \sigma_q^{\mathrm{CX}}) + N_q R_q^{\mathrm{esc}} + N_q^{\mathrm{source}}$$

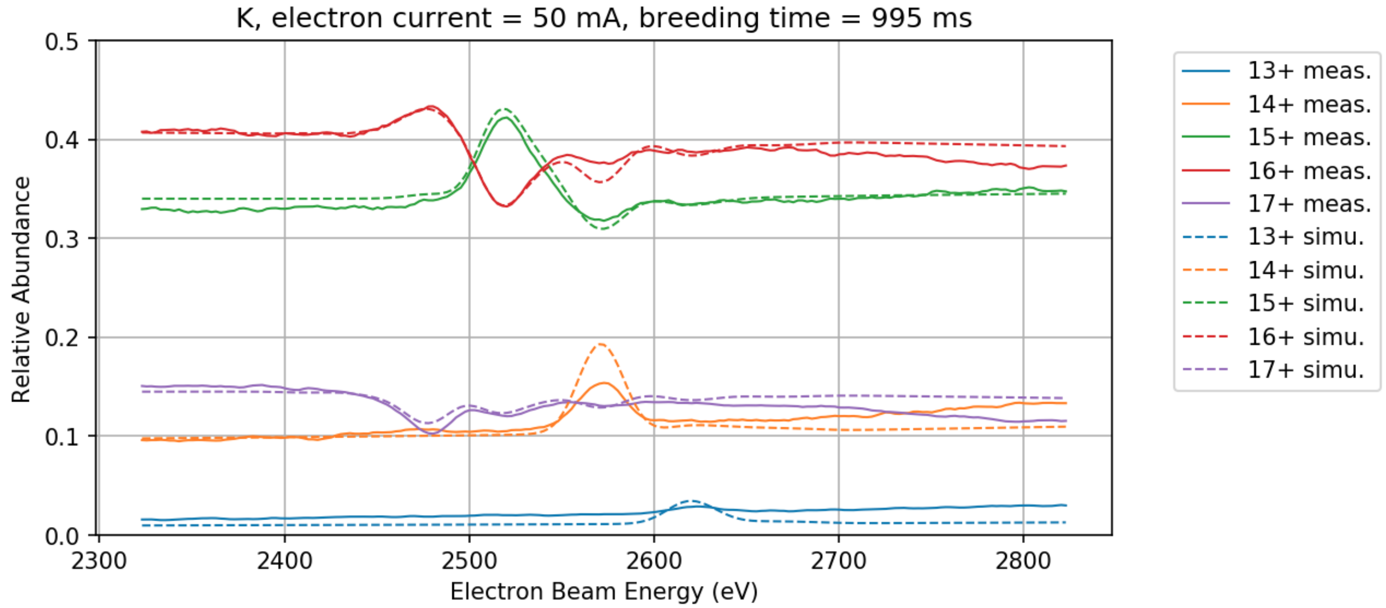
EBIS plasma: Dielectronic recombination process

Experimental setup $^{39}K^{q}$ for q = 13…17 @ 4 keV/u . RR = 1 Hz; Breeding time = 995 ms; I_{e-} = 50 mA. Potential use for charge state selectivity



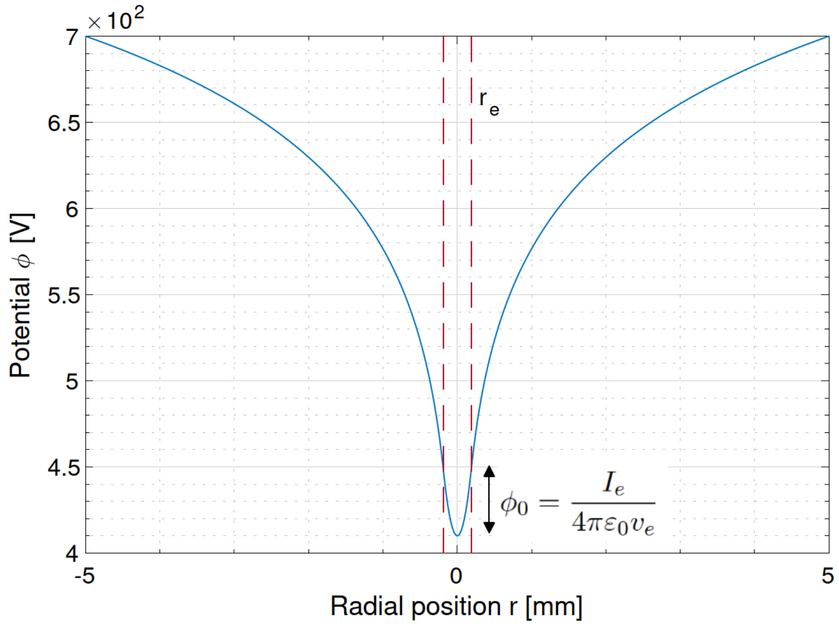
Figures of merit:

- ❑ Effective electron beam current density
- ❑ Space charge energy correction
- ❑ Electron energy spread

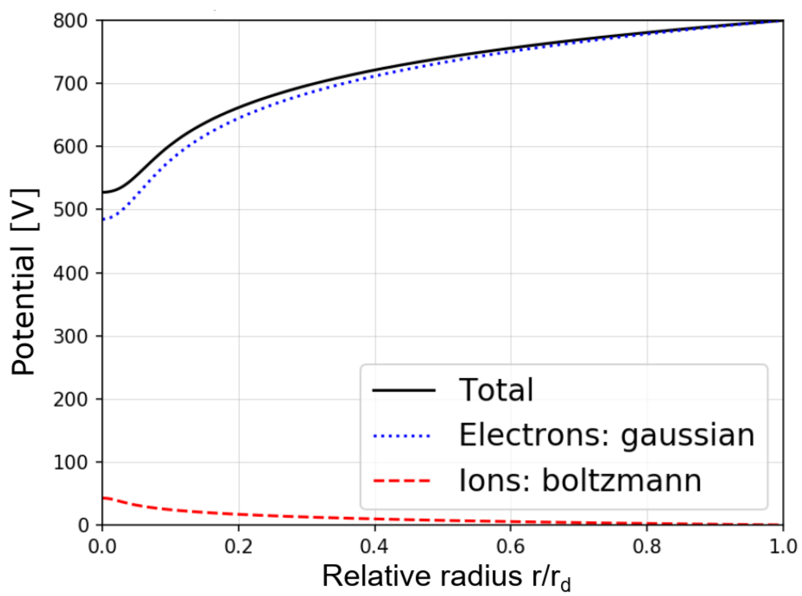


Measurement of the charge state relative abundancies and comparison with EBISIM code featuring dielectric recombination effects in REXEBIS.

EBIS plasma: Space charge potential



Space charge potential from the electron beam only.



Space charge potential including ion beam compensation.

Convergence inspection:

$$N_i(r > r_e) \propto \int_{r_e}^{+\infty} n_i(r) r \mathrm{d}r$$

$$\propto \int_{r_e}^{+\infty} r^{1-2Q_i\Phi_0/(k_B T_i)} \mathrm{d}r$$

Use Riemann criteria

With uniform e-beam:

$$\phi(r) = U_t - \phi_0 \cdot \begin{cases} \left(2\ln\frac{r_t}{r_e} - \frac{r^2}{r_e^2} + 1\right) & , |r| \leq r_e \\ 2\ln\frac{r_t}{|r|} & , |r| > r_e \end{cases}$$

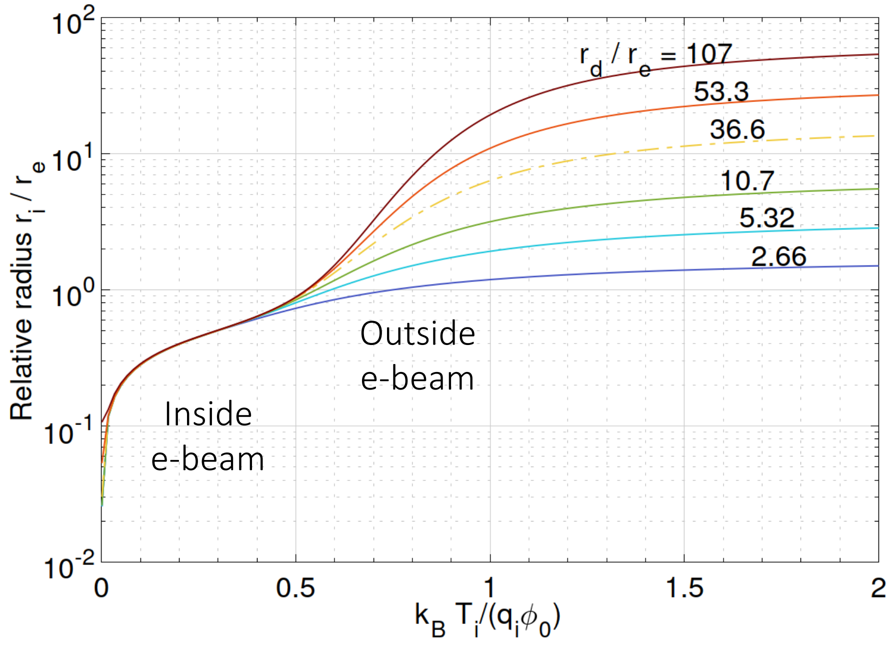
Gauss law:

$$\nabla \cdot \mathbf{E} = \frac{\partial}{\partial r}\left(r\frac{\partial\phi(r)}{\partial r}\right) = \frac{e}{\varepsilon_0}(n_e(r) - \sum_i \sum_q q_i n_{i,q}(r))$$

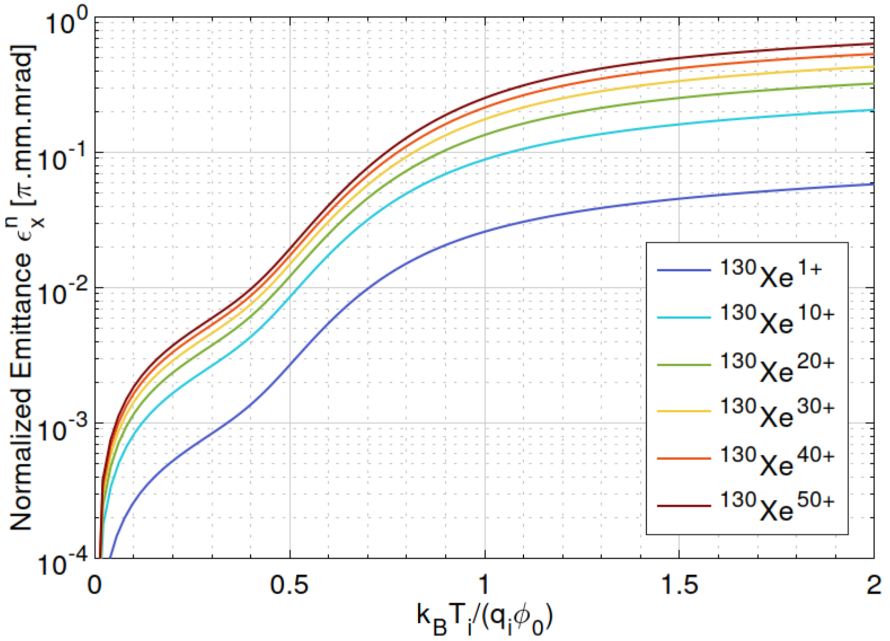
Using Boltzmann distribution:

$$n_i(r, t = \infty) = n_i(0)\exp\left(-\frac{Q_i\phi(r)}{k_B T_i}\right)$$

EBIS plasma: Extracted beam properties



Average radius of the ion cloud versus temperature.



Normalized emittance of extracted beam in a field free region.

Ion cloud characteristic radii:

$$r_i = \int_{\mathbb{R}_+} r^2 n_i(r) \mathrm{d}r \qquad r_i^{\mathrm{rms}} = \sqrt{\int_{\mathbb{R}_+} r^3 n_i(r) \mathrm{d}r}$$

Deduction of the overlap factor between electron and ion distributions.

Transverse emittance in EBIS (Cartesian):

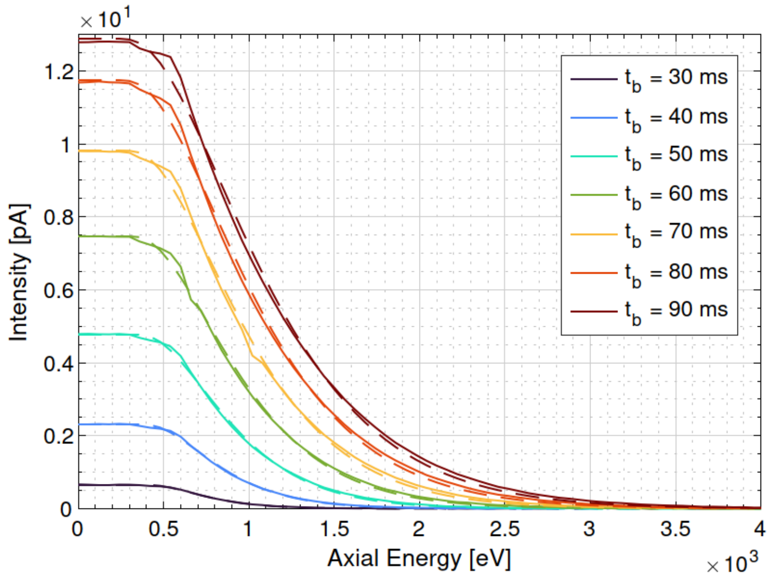
$$\varepsilon_x = \sqrt{\frac{k_B T_i}{2 m_i v_z^2}\left[(r_i^{\mathrm{rms}})^2 - \frac{r_i^2}{\pi} \right]}$$

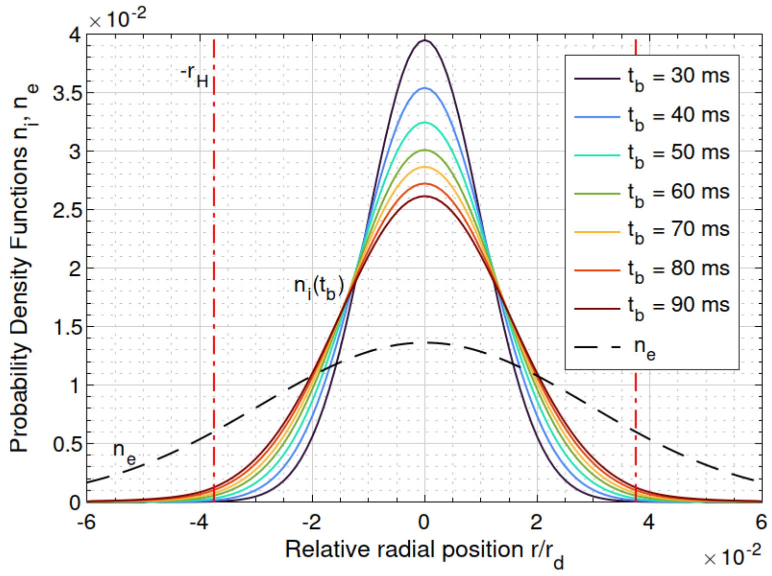
Conservation of canonical momentum

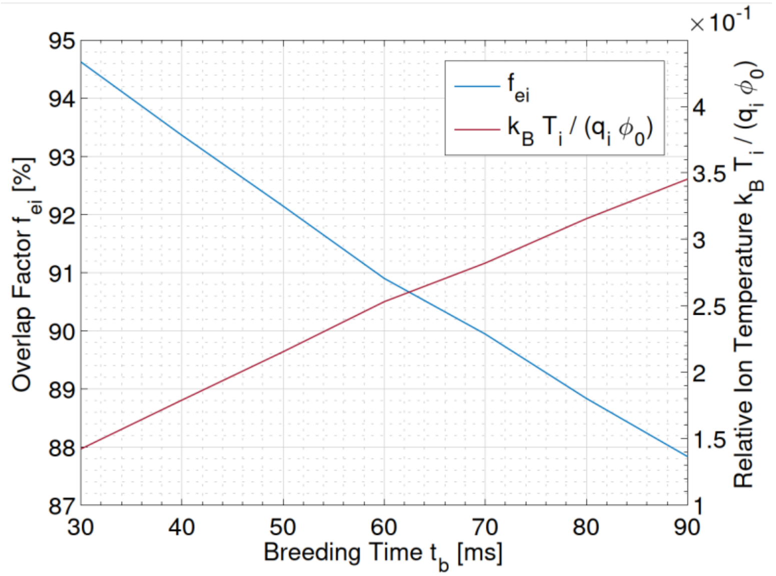
$$\varepsilon_x^2(B=0) = \varepsilon_x^2(B=B_d) + \frac{Q_i^2 B_d^2}{16 m_i^2 v_z^2} (r_i^{\mathrm{rms}})^4$$

Measurement of the overlap factor

Experimental setup Neutral gas injection of ^{129}Xe. Electron beam with a current of 200 mA and energy about 6 keV. Axial energy scans with varying breeding time.







Method

Fitting of three free parameters, using the lower gamma incomplete function:

$$f(U) = I_0(1 - \gamma\left(\frac{q_i U - E_0}{k_B T_i}, \frac{5}{2}\right))$$

Results

Estimate of the ion temperature.
Deduce the ion radial distribution.
Calculate of the overlap factor.

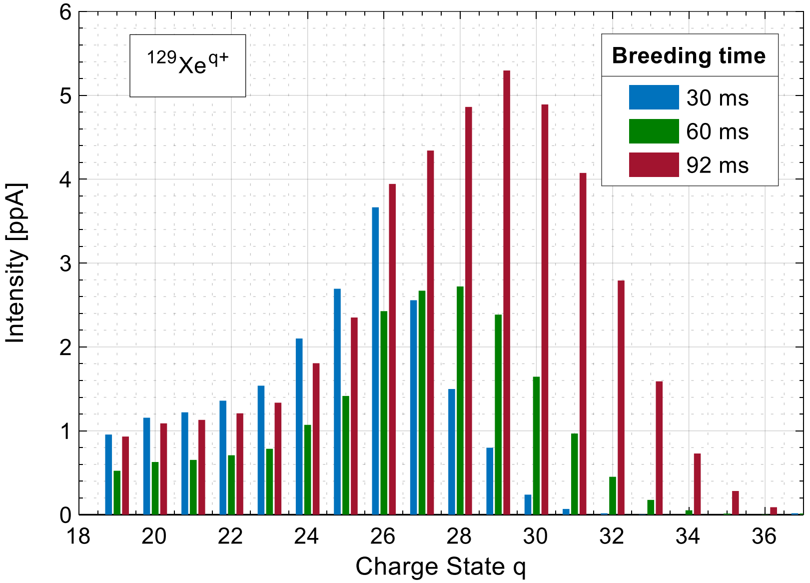
Conclusion

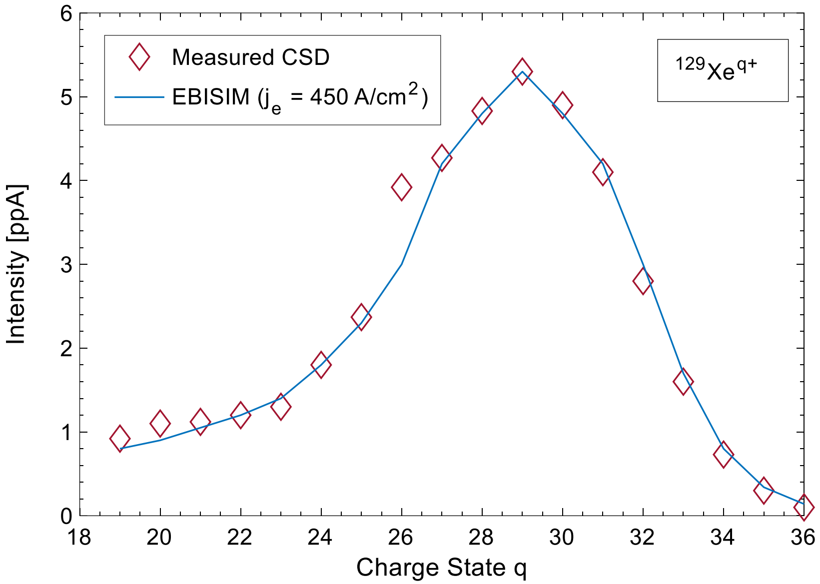
The ion cloud remains confined within the electron beam.
Heating rate:

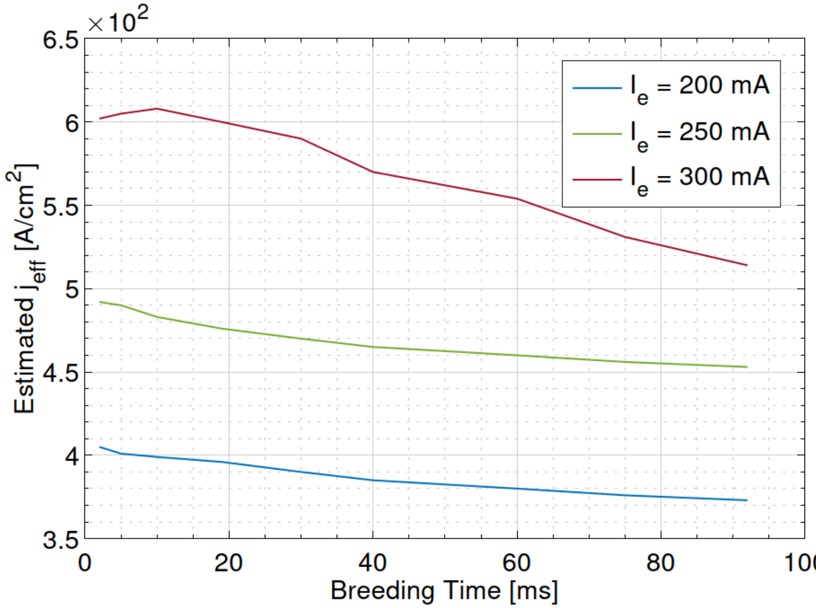
- Measured: 3.5 keV/s
- From Landau-Spitzer: 2.4 keV/s

Estimation of the effective electron current density

Objective Estimate the effective electron current density j_{eff}, when comparing the measured charge state distributions with the EBISIM code.







Method

Measurement of the charge state distribution of $^{129}Xe^{q+}$ for different breeding time.

Result

Deduce the effective electron current density from a least-square minimization between the EBISIM code and the measurements.

Conclusion

- j_{eff} = 600 A/cm^2 for I_{e-} = 300 mA.
- j_{eff} = 400 A/cm^2 for I_{e-} = 200 mA.

Decreasing trend can be explained with reduced overlap factor.

Beam Quality

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Slow extraction

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Beam Purity

EBIS partial pressures

Rare contaminants

Transverse properties

Quadrupole-scan

Trace space reconstruction

Longitudinal properties

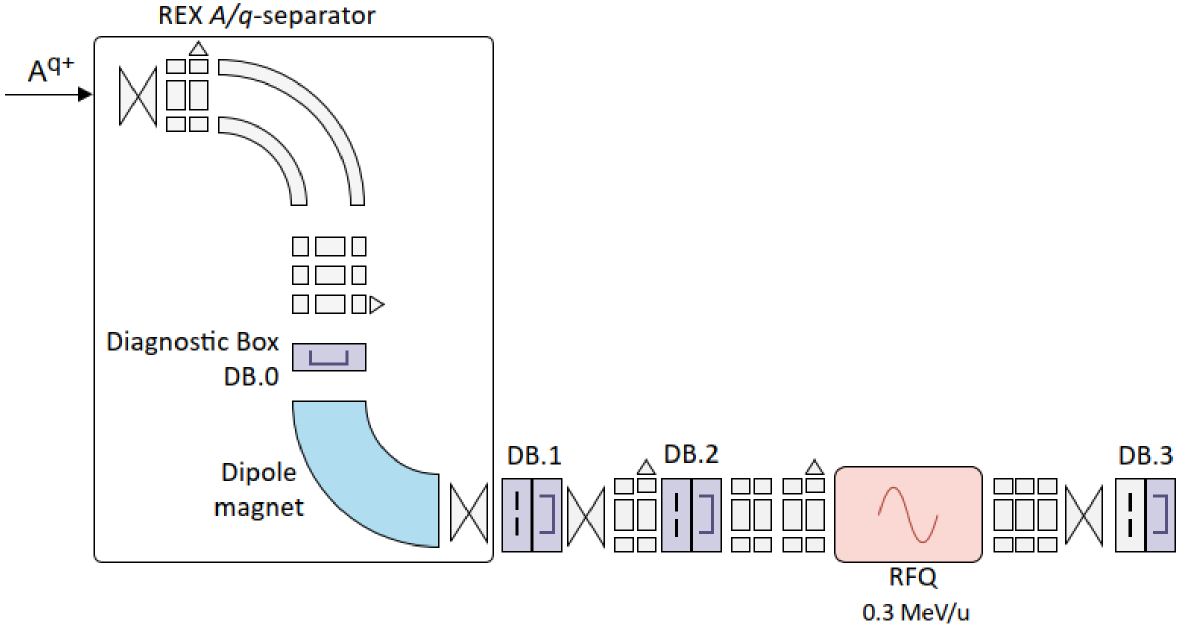
Beam energy distribution

Bunch structure

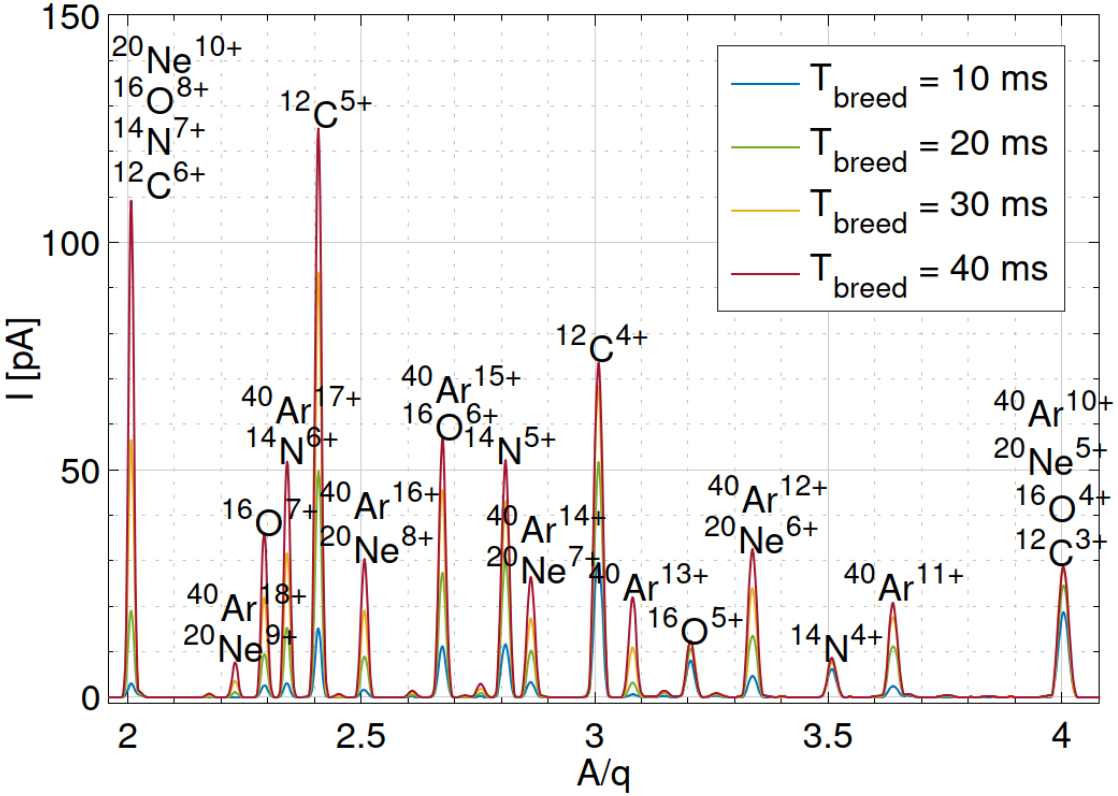
Abundant contamination

Technique Variation of REX *A/q*-Separator magnet, monitoring of current passing through slit on Faraday cup. Simplified model:

$$\frac{\mathrm{d}N_q}{\mathrm{d}t} \simeq \frac{Ie}{e}\frac{p}{k_B T_i} L_d \left[f_{q-1}\sigma_{q-1}^{\mathrm{EI}} - f_q\left(\sigma_q^{\mathrm{EI}} + \sigma_q^{\mathrm{RR}}\right) + f_{q+1}\sigma_{q+1}^{\mathrm{RR}} \right]$$



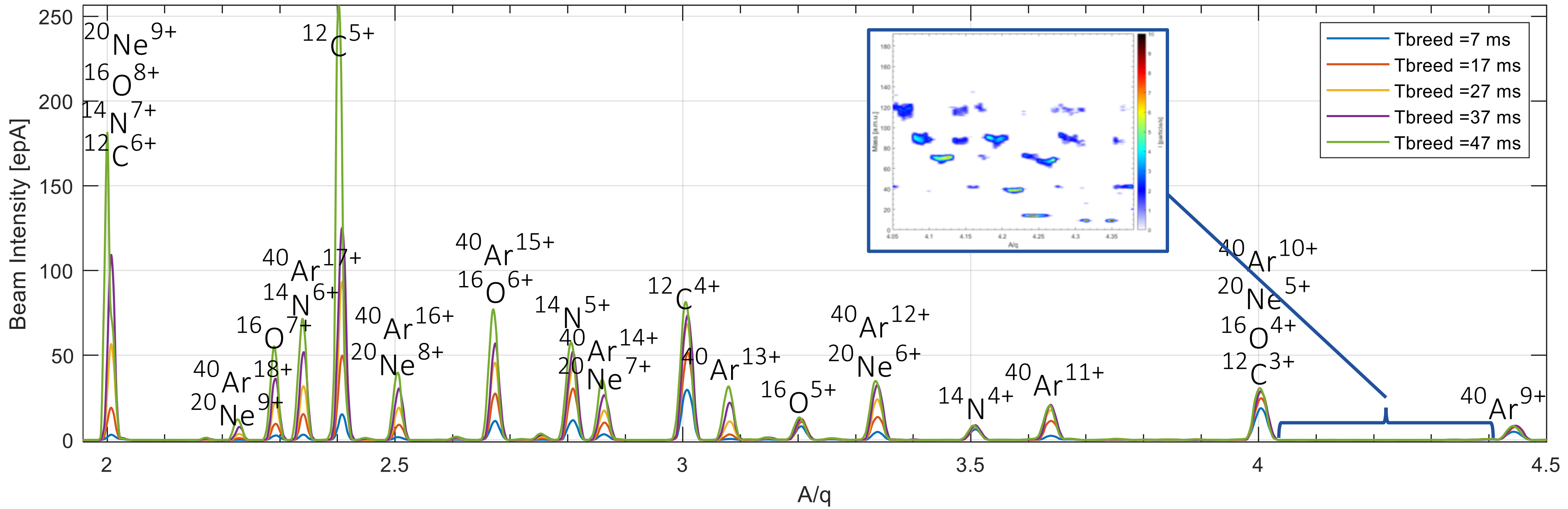
Element	Density [mm^{-3}]	Pressure [mbar]
Nitrogen	4.0 .10^{7}	1.6 .10 $^{-10}$
Oxygen	1.5 .10^{7}	6.0 .10 $^{-11}$
Carbon	6.0 .10^{7}	2.4 .10 $^{-10}$
Neon	2.0 .10^{6}	8.0 .10 $^{-12}$
Argon	5.0 .10^{6}	2.0 .10 $^{-11}$



A/q-scan measured with a Faraday cup. I_e = 200 mA, E_e = 6 keV.

From epA to single-ion detection

Technique Instead of varying REX *A/q*-Separator magnet, all necessary beam optics and RF, from REXEBIS to the Si detector, are scaled for each A/q step.

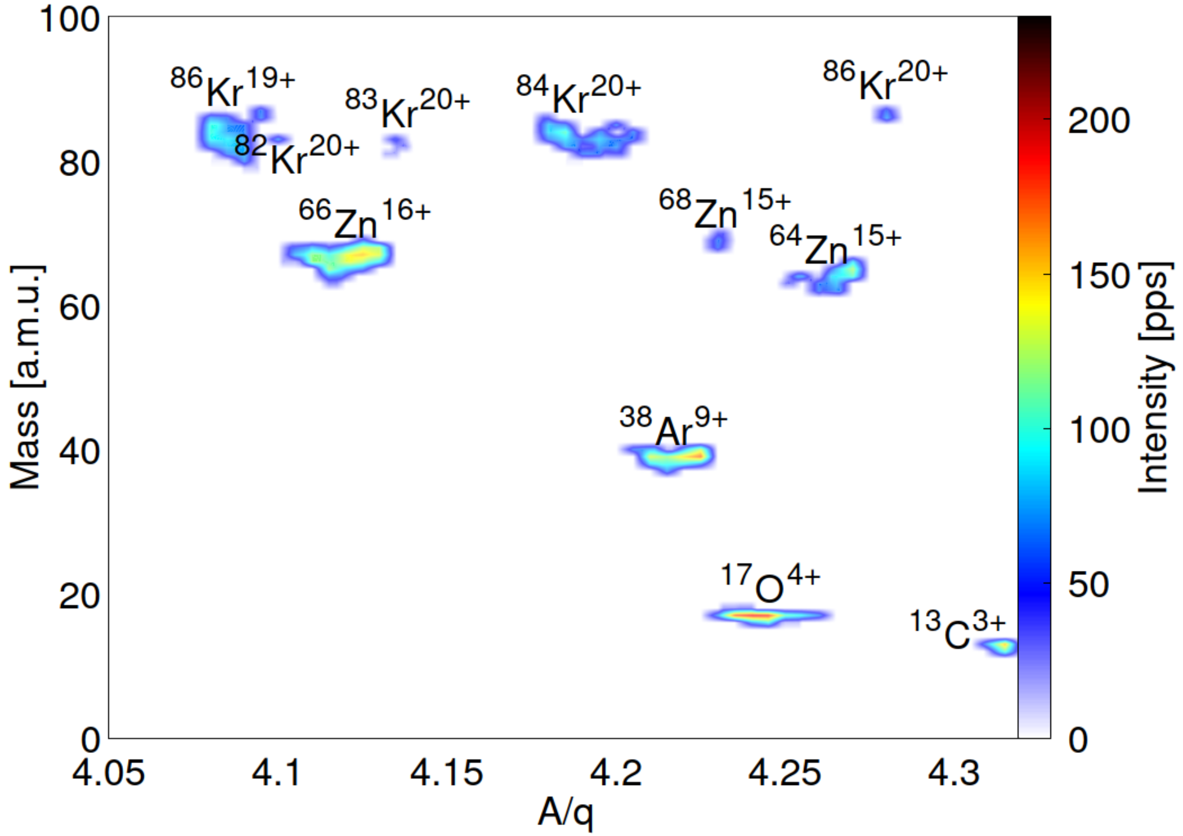


Objective Anticipate on the beam purity and probe *A/q*-areas where Faraday cups do not allow for identification

Experimental setup in 2020, using non-adiabatic gun with IrCe cathode at higher electron beam density:

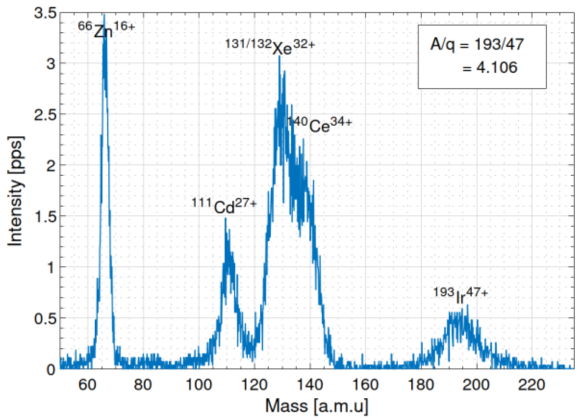
- Confirmation of the capability to probe rare contaminants.
- Residual gas ions were accelerated through the RFQ and acquired on a large Si detector installed directly afterward.
- Intensities are representative of reality.

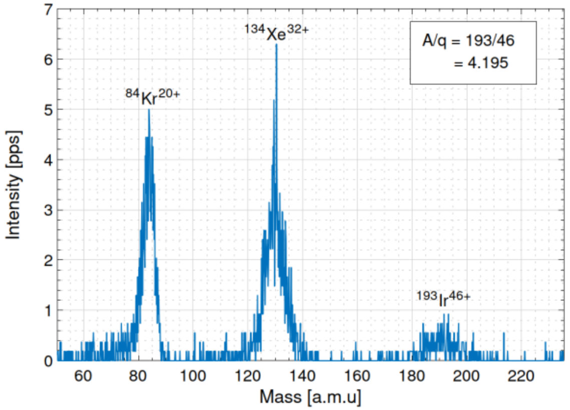
Rare contaminants

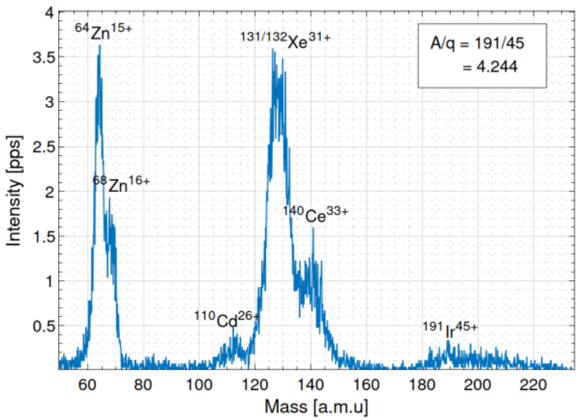


Method A/q-scan measured with a silicon detector. I_e = 200 mA, E_e = 6 keV.

Application Investigation on the presence of Ir or Ce from the electron gun cathode using the silicon detector energy histograms.







Results

- Correlation with neghboring CS
- Poor energy resolution
- Negligible Ir/Ce contamination
- Cathode can be used

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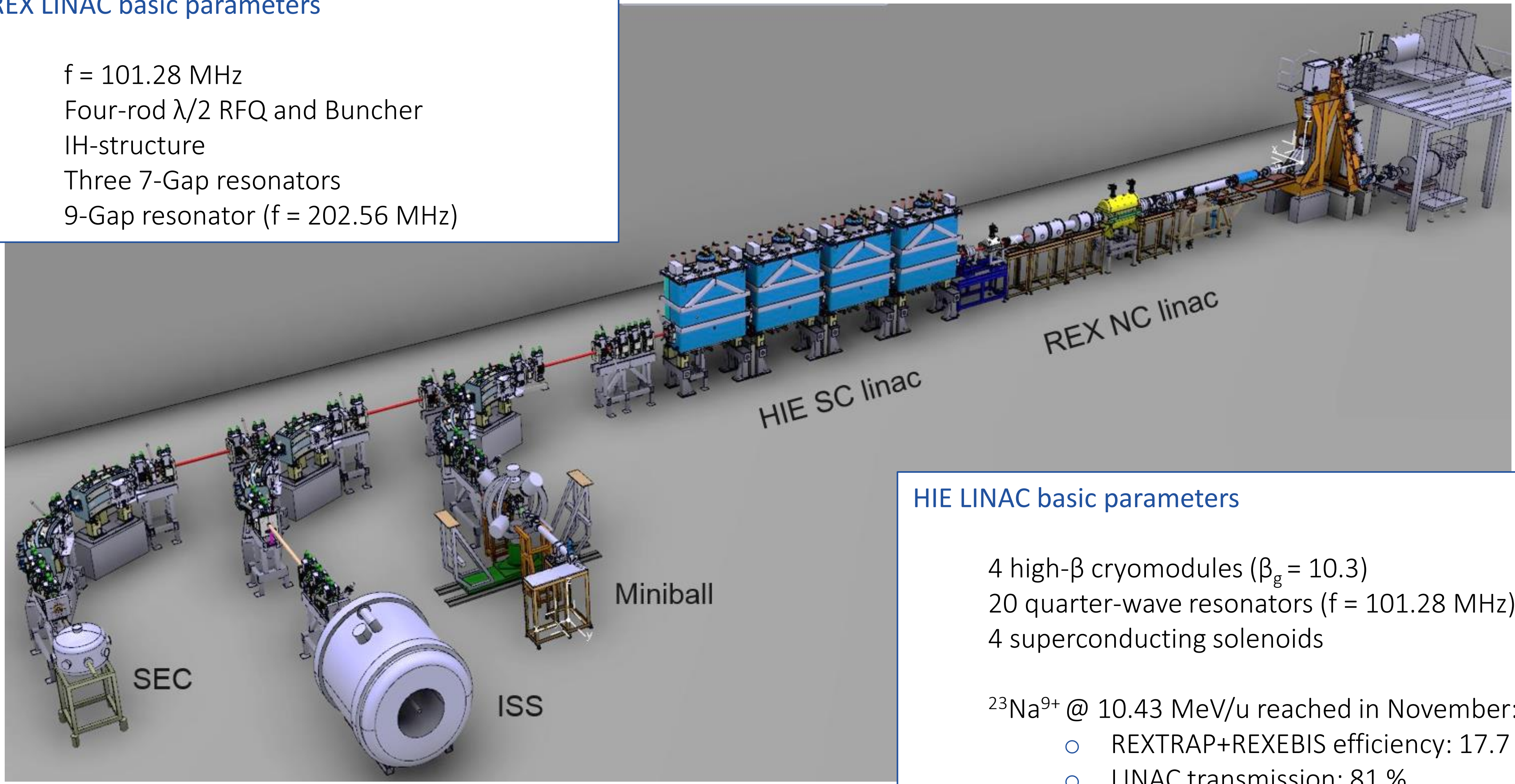
REX LINAC basic parameters

f = 101.28 MHz
Four-rod λ/2 RFQ and Buncher
IH-structure
Three 7-Gap resonators
9-Gap resonator (f = 202.56 MHz)



HIE LINAC basic parameters

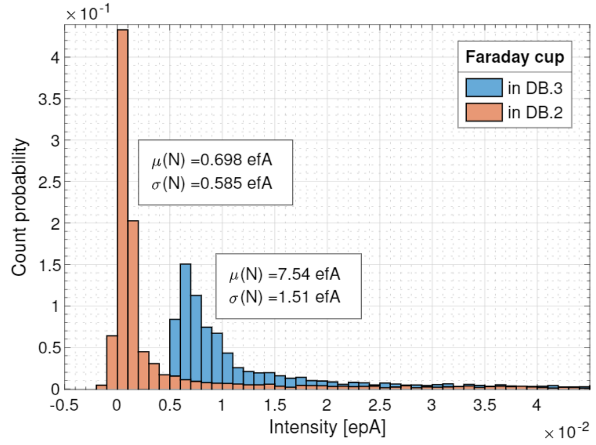
4 high-β cryomodules (β_g = 10.3)
20 quarter-wave resonators (f = 101.28 MHz)
4 superconducting solenoids

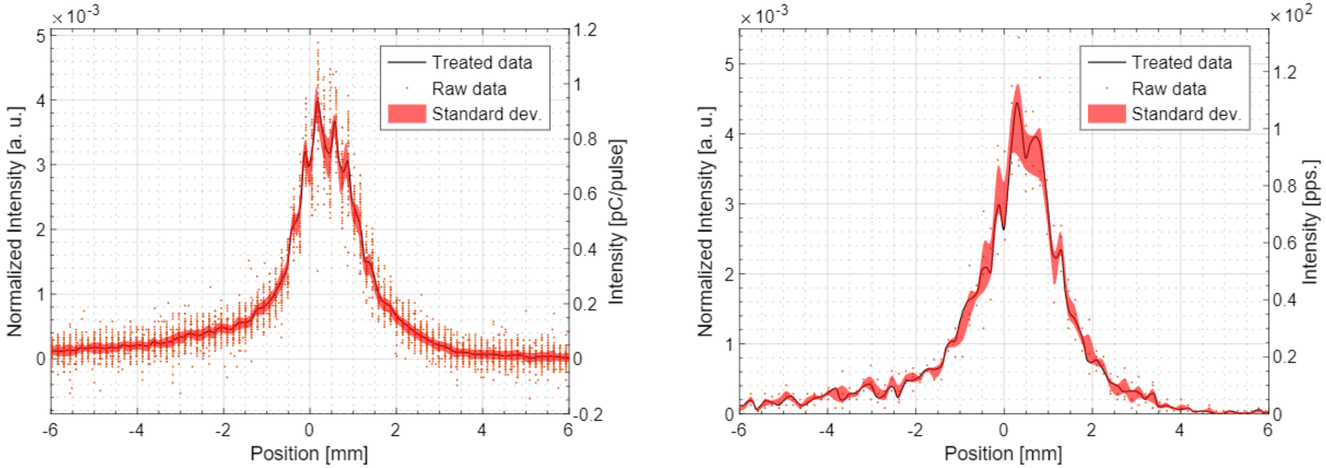
$^{23}Na^{9+}$ @ 10.43 MeV/u reached in November:
- REXTRAP+REXEBIS efficiency: 17.7 %
- LINAC transmission: 81 %

HIE-ISOLDE: Transverse beam profiles at low intensity

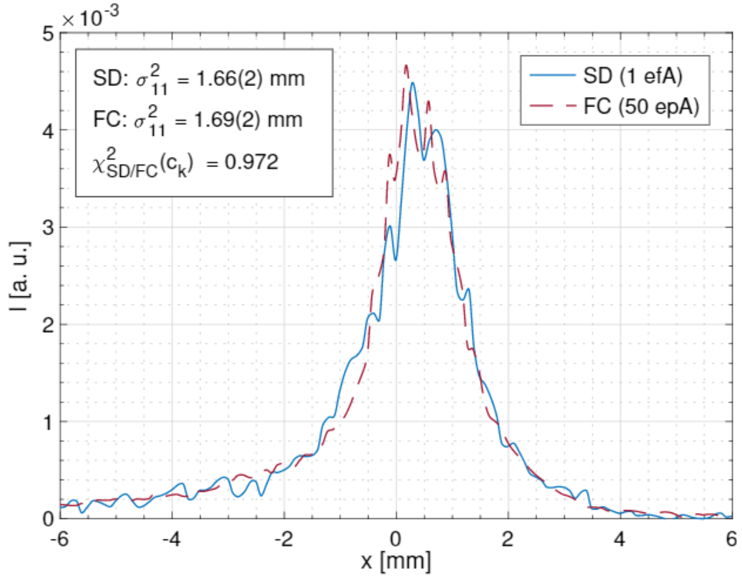
Method

- ❑ Measurement of transverse beam profiles at the same location, with a Faraday cup for pA current range or a silicon detector below 1 fA.
- ❑ Bias and exclusion (threshold) analysis.





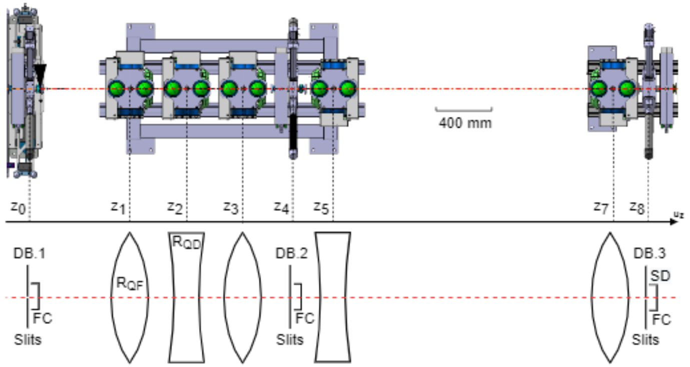
Faraday cup (left) and silicon detector (right) beam profile measurements



Result Capability to measure transverse profiles of very low intensity ion beams.

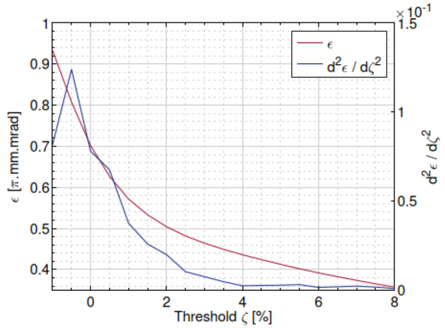
HIE-ISOLDE: Transverse beam properties characterization

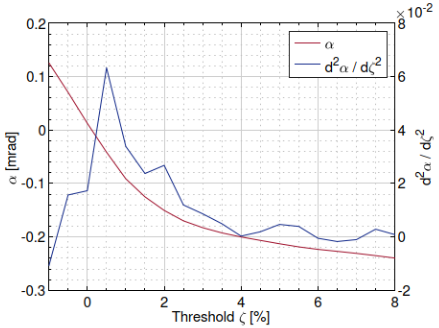
Experimental setup $^{39}K^{10+}$ @ 3.82 MeV/u, thin-slits and quadrupoles are used to probe the tranvserse phase-space for two ranges of intensity.

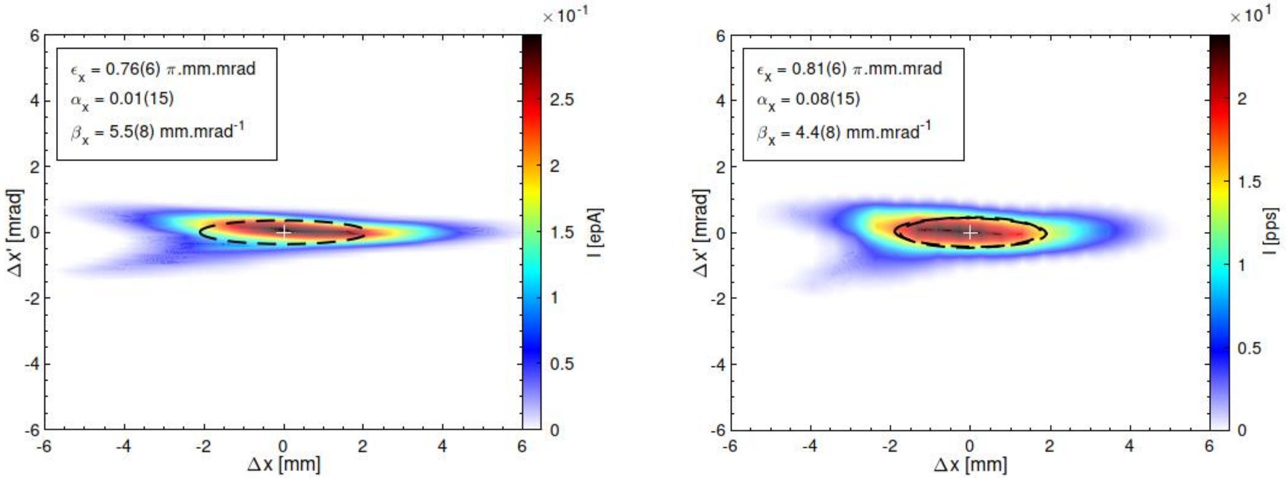


Treatment when using Faraday cup as beam collector

Exclusion ellipse: deduce a threshold from the evolution of the second derivatives of the Twiss paramaters.







Left: Double-slit scan using Faraday cup (>10 epA). Right: Silicon detector (<1 efA).

Technique

With the double-slit scan, the transverse phase-space is sliced twice. Beamlet acquired via a silicon detector or a Faraday cup.

Result

Validation of the new methodology with very low intensity ion beams. Correlation of the results for the two ranges of intensity.

"Characterization of the transverse properties of very low intensity ion beams at the REX/HIE-ISOLDE LINAC", N. Bidault, *et al.,* NIM-A, in-review.

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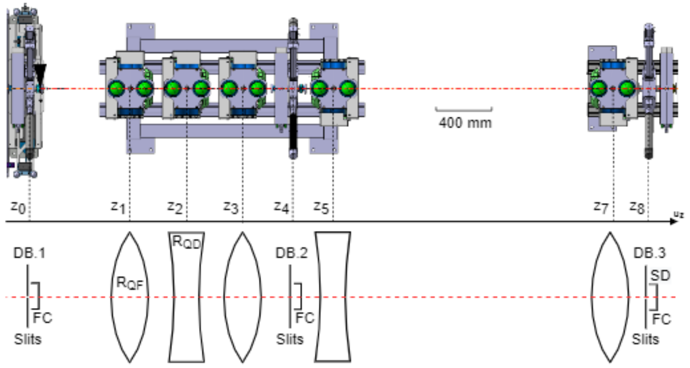
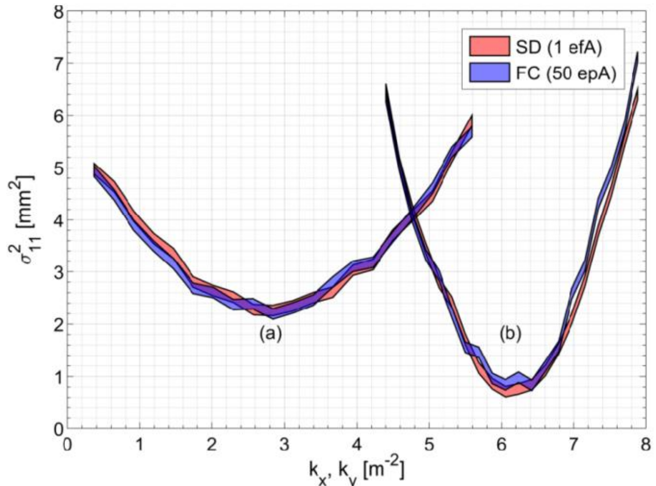


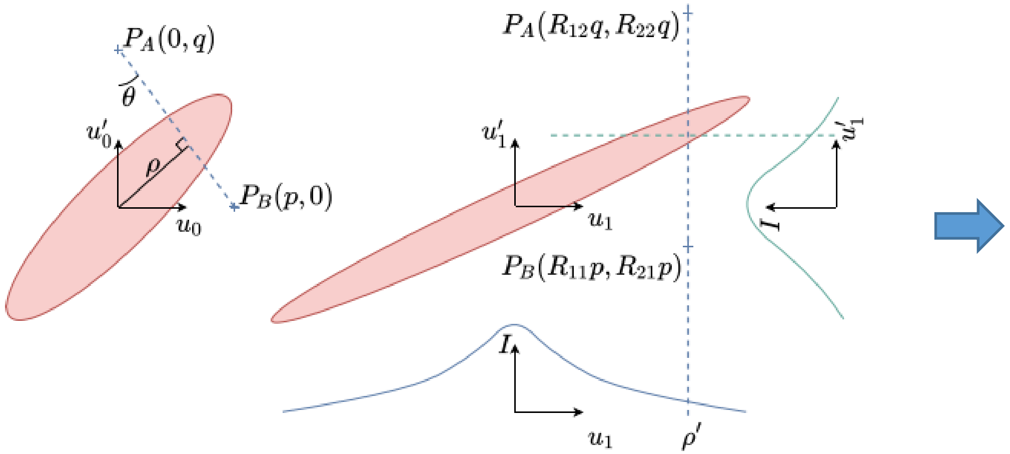


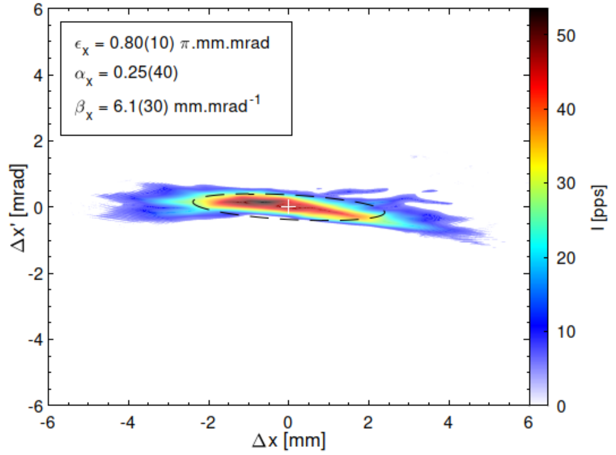
Results

Plane	Parameter	Value SD	Value FC
	ε_x [π.mm.mrad]	0.80(5)	0.82(5)
	α_x	−0.10(15)	0.05(15)
x-plane (a)	β_x [mm.mrad^{-1}]	4.8(5)	5.1(5)
	γ_x [mrad.mm^{-1}]	0.21(3)	0.20(3)
	$\chi^2_{SD/FC}(\sigma^2_{11})$	0.988	
	ε_y [π.mm.mrad]	0.71(5)	0.75(0.5)
	α_y	−0.64(15)	−0.60(15)
y-plane (b)	β_y [mm.mrad^{-1}]	2.4(3)	2.8(3)
	γ_y [mrad.mm^{-1}]	0.25(11)	0.23(9)
	$\chi^2_{SD/FC}(\sigma^2_{11})$	0.984	

Method With the quadrupole scan the tranvserse phase-space is sliced once and rotated.

Tomography
Reconstruction of the trace space from the quadrupole-scan





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Rare contaminants

Transverse properties

Quadrupole-scan

Trace space reconstruction

Longitudinal properties

Beam energy distribution

Bunch structure

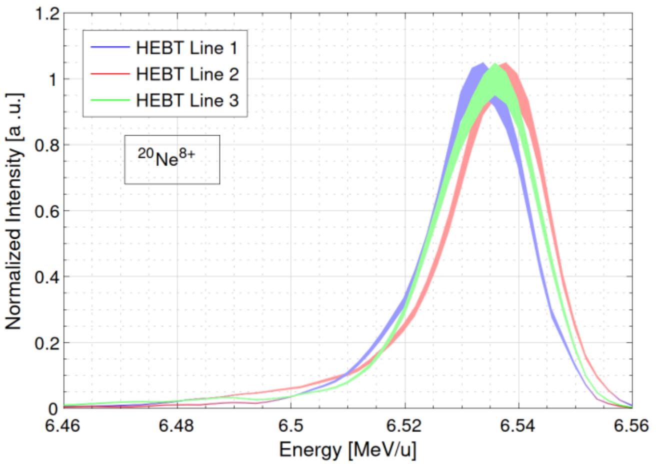
HIE-ISOLDE: Beam energy distribution measurement

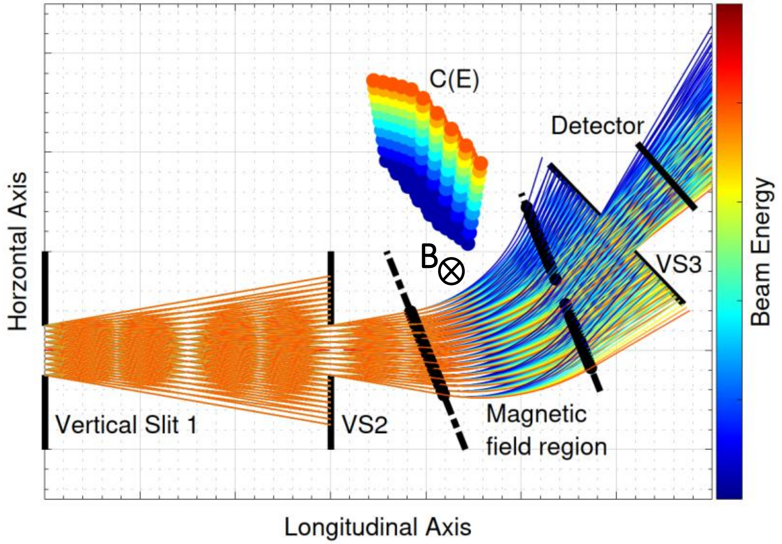
Technique Use of an HEBT dipole as energy-spectrometer and three vertical slits. Acquisition of the beamlet current with a silicon detector.

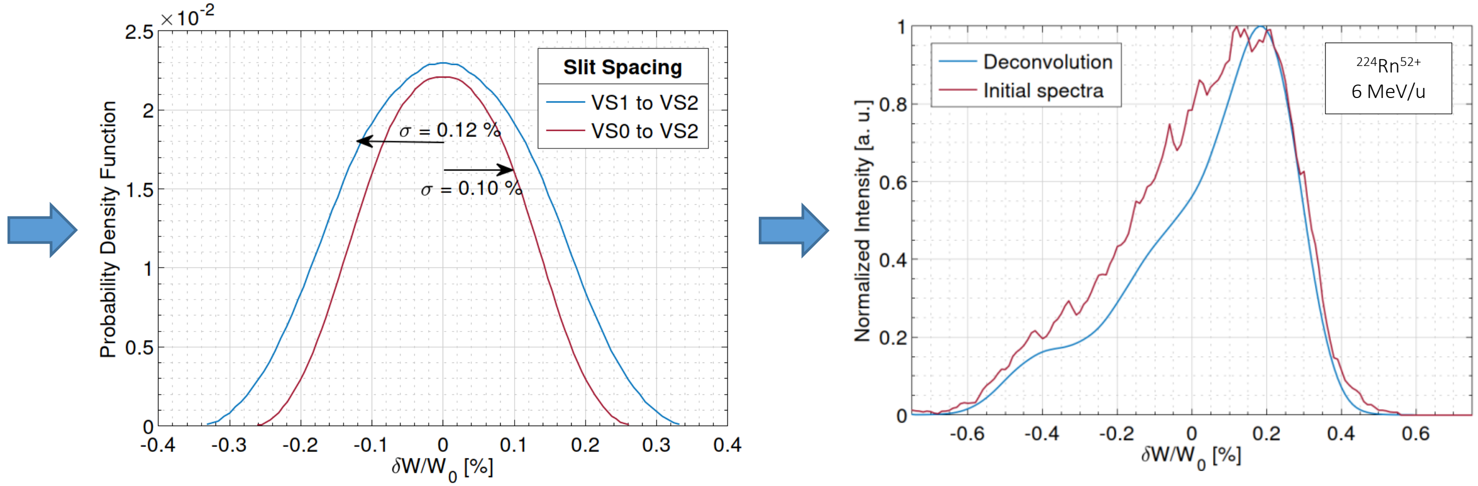
Measurements using the three HEBT dipoles confirmed to be similar.

The energy spread derived is overestimated depending on the beam transverse emittance and the spacing between the 1-mm vertical slits.

Proven capability to measure the energy distribution of very low intensity ion beams.







Method Estimation the inherent spread introduced by the thin slits in the measurement channel and deconvolution on typical energy distribution measured from a RIB.

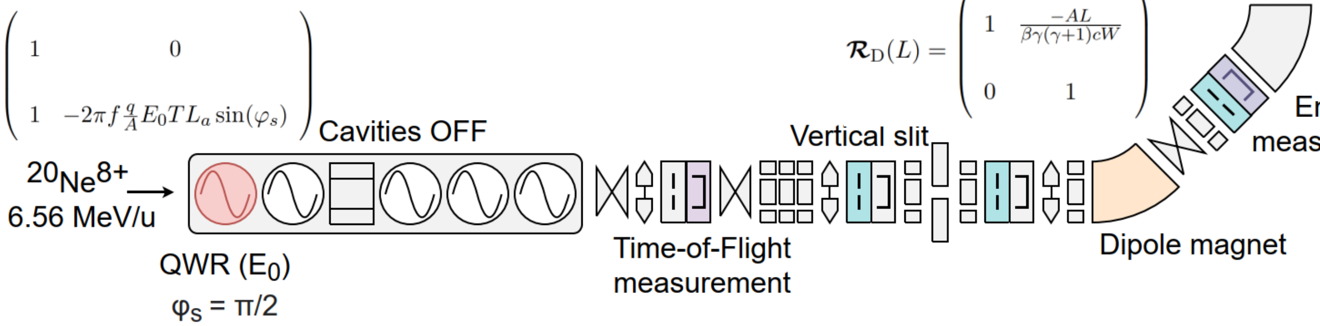
HIE-ISOLDE: Longitudinal phase-space characterization

$$\mathscr{E}(z_0) : \gamma_z(\Delta t)^2 + 2\alpha_z \Delta t \Delta W/A + \beta_z(\Delta W/A)^2 = \varepsilon_z$$

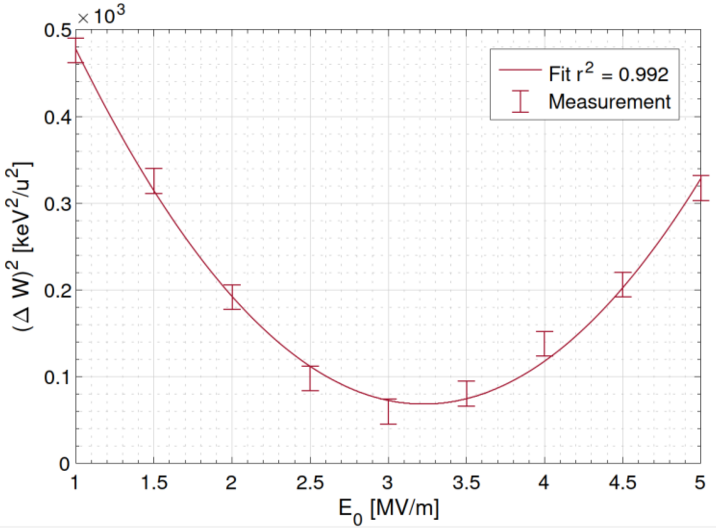
$$\mathcal{R}_{\mathrm{RF}}(E_0) = \begin{pmatrix} 1 & 0 \\ 1 & -2\pi f \frac{q}{A} E_0 T L_a \sin(\varphi_s) \end{pmatrix}$$

$$\mathcal{R}_{\mathrm{D}}(L) = \begin{pmatrix} 1 & \frac{-AL}{\beta\gamma(\gamma+1)cW} \\ 0 & 1 \end{pmatrix}$$

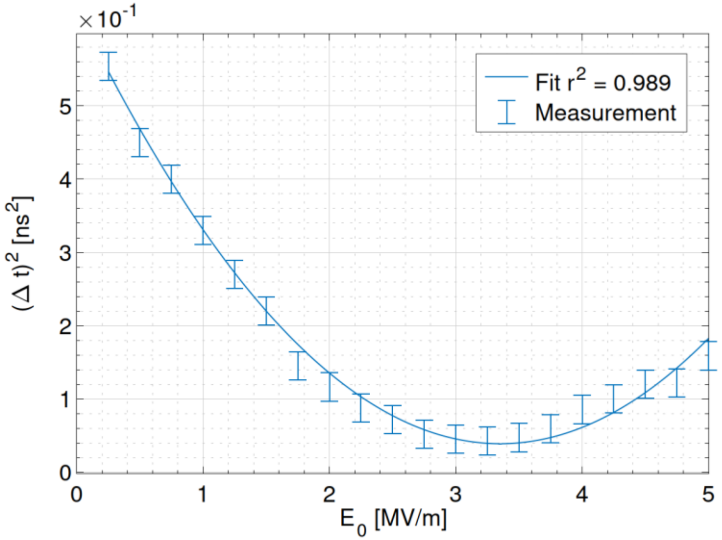
$$\boldsymbol{\sigma}(z_1) = \mathcal{R} \cdot \boldsymbol{\sigma}(z_0) \cdot {}^t\mathcal{R}$$



Experimental setup $^{20}Ne^{8+}$ @ 6.64 MeV/u, 10 superconducting cavities (SCC) at nominal accelerating phase, 1 SCC acting as a buncher at zero-crossing phase.



Method Energy spread measurement.



Method Time structure measurement.

Results

Beam Property	From ΔW	From Δt
ε_z [π.ns.keV/u]	1.25(8)	1.18(10)
α_z	-3.54(30)	-4.68(50)
β_z [ns.(keV/u)$^{-1}$]	0.0183(20)	0.0194(30)
γ_z [keV/u.ns^{-1}]	970(40)	1110(50)

"Longitudinal beam properties characterization of very low intensity ion beams at REX/HIE-ISOLDE", N. Bidault, *et al.*, NIM.A, in prep.

Summary

Analysis of REXEBIS performance and produced ion beam quality

Estimation of REXEBIS electron current density for the new electron gun
Capability to measure rare contaminants over wide A/q range
Access to ion distribution of axial energy

Post-accelerated ion beam characterization

Reliability on transverse beam profile measurements in the sub-femto A range
Method for probing the transverse beam properties at very low intensity
Consolidation of beam energy measurement technique
Method for characterizing the longitudinal phase-space at very low intensity

Thank you for your attention

This work is the result of a collaborative effort involving in particular the following teams at CERN:

ISOLDE Operation (BE-ISO-OP):

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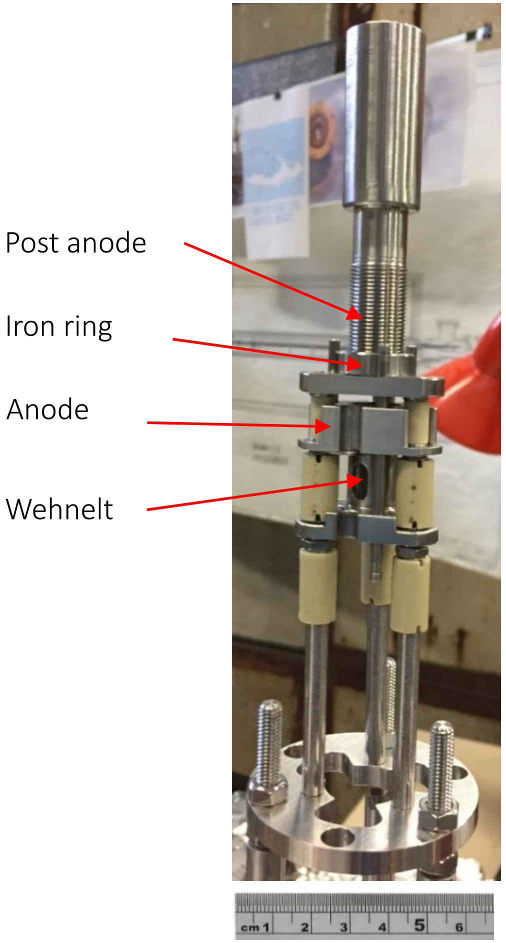
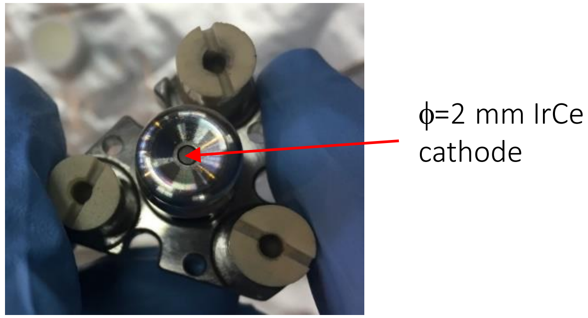
Non-adiabatic immersed electron gun

Design





Post anode used to adjustment the phase of cyclotron wrt iron ring for different beam currents

Results

Current and losses

I_e well behaved to 300 mA
<15 uA anode losses
<100 uA losses on drift tube in front of suppressor

EBIS breeding efficiency

19.7% for $^{39}K^{1+}$ to $^{39}K^{10+}$
Almost as high as for old gun

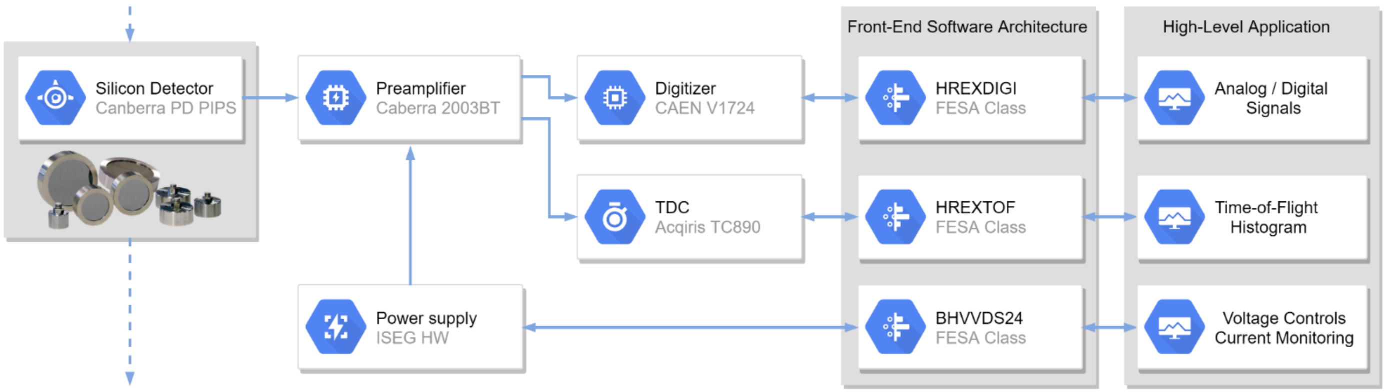
Effective current density

T_{breed}=44 ms for $^{133}Cs^{1+}$ to $^{133}Cs^{31+}$
j_e estimated to ~400 A/cm^2

Problems

1. Excessively high cathode work function (activation not helpful)
2. Electron beam losses rises exponentially when I_e > 300 mA. Believed to be caused by back-scattered or elastically reflected electrons from the collector region.

Silicon Detector specifications



Figures Diagram of the Silicon Detectors DAQ at HIE-ISOLDE.

Type	Canberra's model	Radius [mm]	Resolution	
			Energy* [keV]	Time [ns]
1	PD50-11-300RM	4.0	11	5
2	TMPD50-16-300RM	4.0	15	0.2
3	PD600-20-300RM	13.8	20	5

Table Basic parameters of 300 µm-thick PD-PIPS detectors used at HIE-ISOLDE (* ^{241}Am, 5.486 MeV alphas).

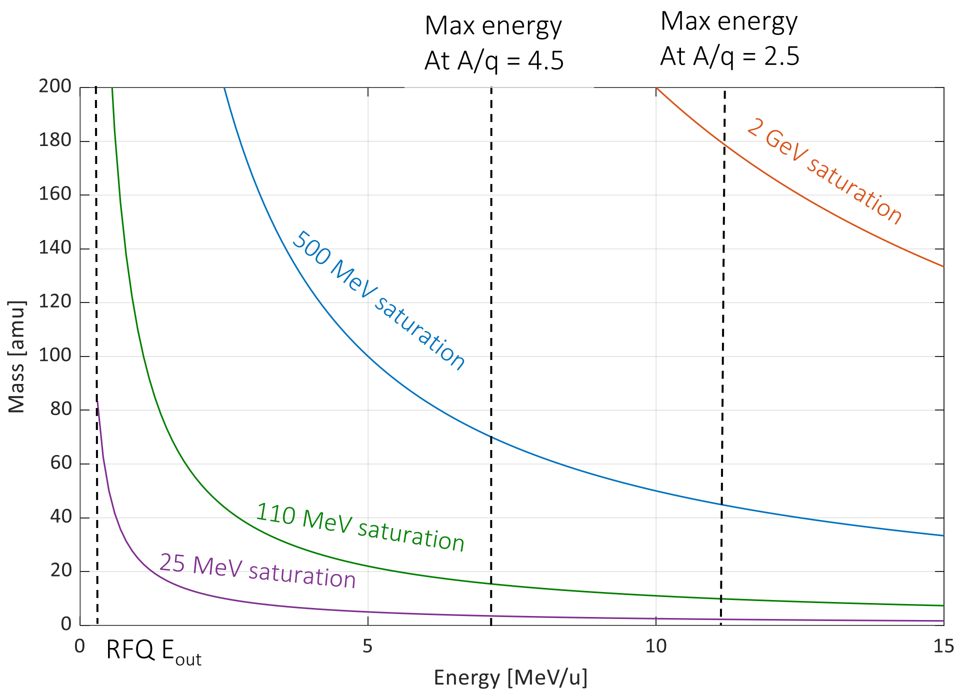


Figure Saturation curves.