REX/HIE-ISOLDE Machine Development

Studies on the REXEBIS charge-breeder and new capabilities of characterization for post-accelerated ion beams

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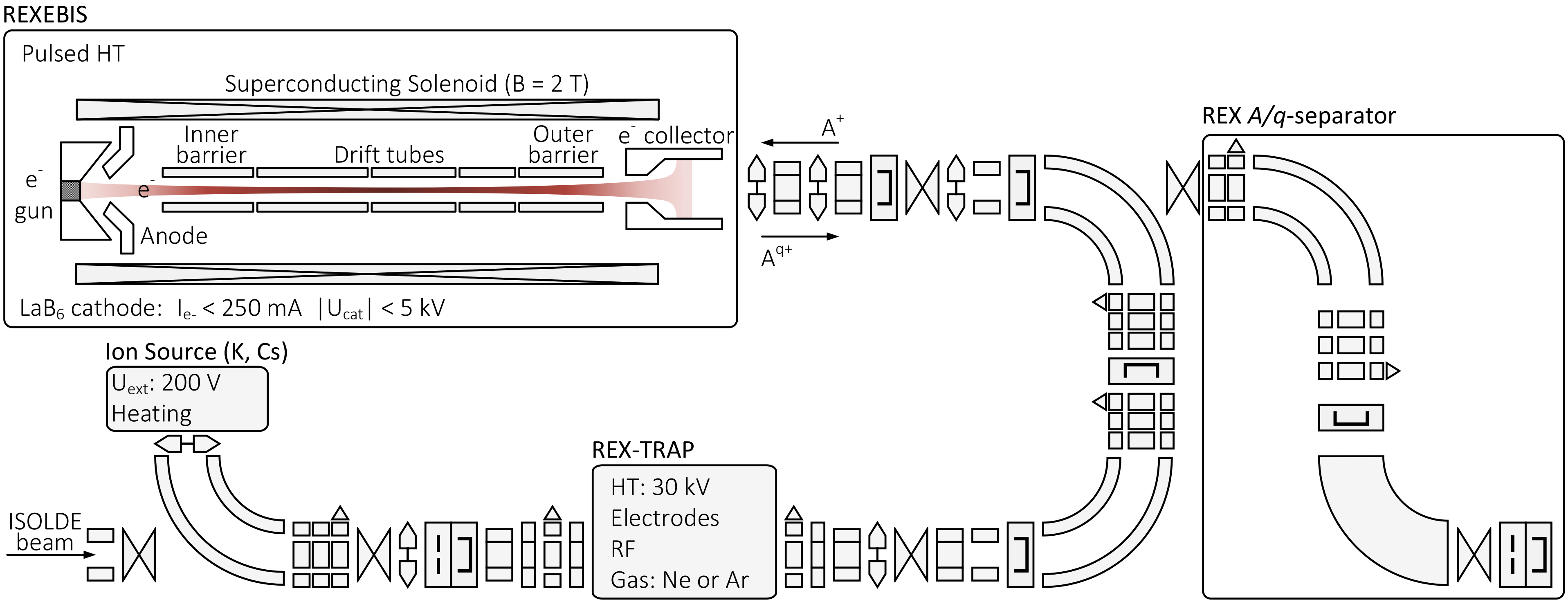


Figure Schematic of REX-ISOLDE, without the normal-conducting LINAC.

REX/HIE-ISOLDE Machine Development

- Residual gas ions spectra
- Slow Extraction
- Dielectric recombination process
- Very low intensity beam characterization
- Twiss parameters measurements
- Longitudinal phase-space

Residual gas ions spectra (1/2)

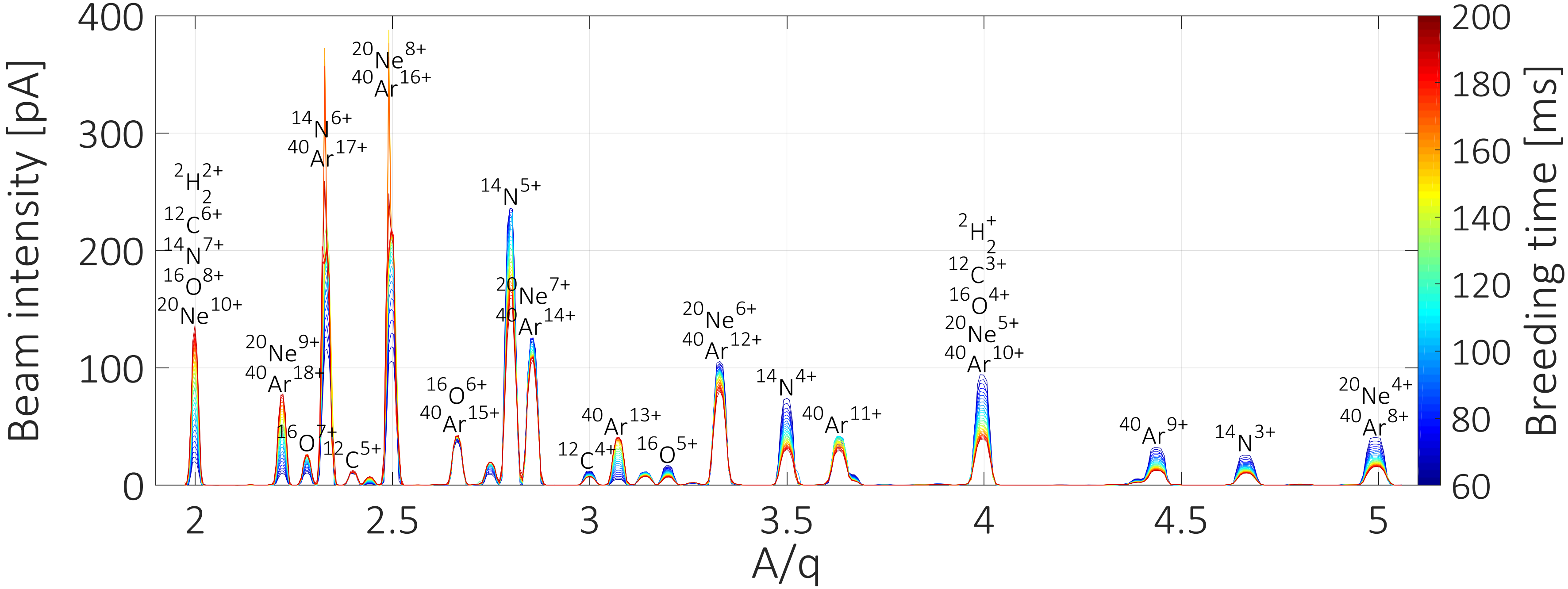


Figure *A/q*-Spectra of the multi-charged residual gas ions extracted from REXEBIS, as a function of the trapping time.

Charge dynamics

$$\frac{dN_q}{dt} = \frac{j_e}{e}\Big(\underbrace{N_{q-1}\sigma_{q-1}^{EI} - N_q\sigma_q^{EI}}_{\text{Electron impact ionisation}} + \underbrace{N_{q+1}\sigma_{q+1}^{RR} - N_q\sigma_q^{RR}}_{\text{Radiative recombination}} + \underbrace{N_{q+1}\sigma_{q+1}^{DR} - N_q\sigma_q^{DR}}_{\text{Dielectronic recombination}}\Big) + \underbrace{\mathbf{n_0\bar{v}_{q+1}N_{q+1}\sigma_{q+1}^{CX} - n_0\bar{v}_qN_q\sigma_q^{CX}}}_{\text{Charge exchange}} + \underbrace{N_q R_i^{esc}}_{\text{Escape rate}}$$

Residual gas ions spectra (2/2)

Technique Instead of solely sweeping the REX *A/q*-Separator, full machine *A/q*-scaling from the REXEBIS to the detector.

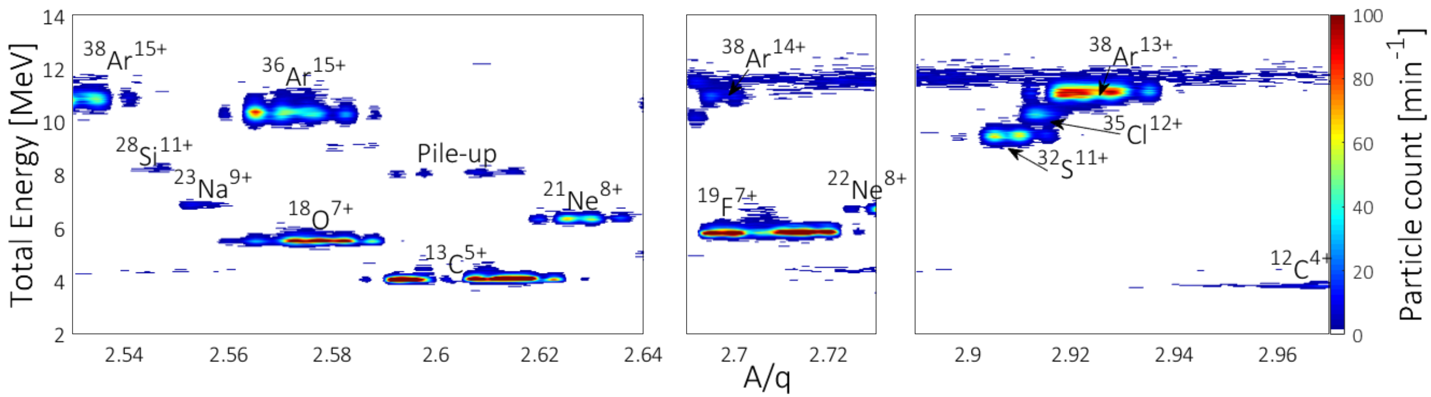


Figure Contour of energy histograms acquired on *9 mm*-SD. Beam defocused. RR = 20 Hz; breeding time = 10 ms; I_{e-} = 160 mA.

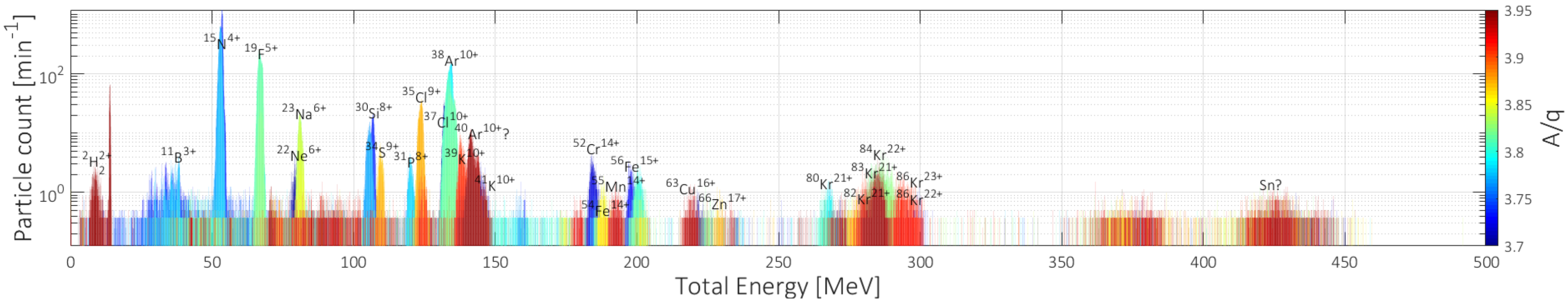


Figure Energy histograms acquired on *15 mm*-SD. Foil 5%. RR = 20 Hz; breeding time = 35 ms; I_{e-} = 140 mA (preliminary).

“Residual Gas Ions Characterization from the REXEBIS”, N. Bidault, *et al.,* IPAC2018, Vancouver, 10.18429.

Slow Extraction from REXEBIS

Technique Measure the ion beam of interest axial energy distribution by modulating the barrier voltage.

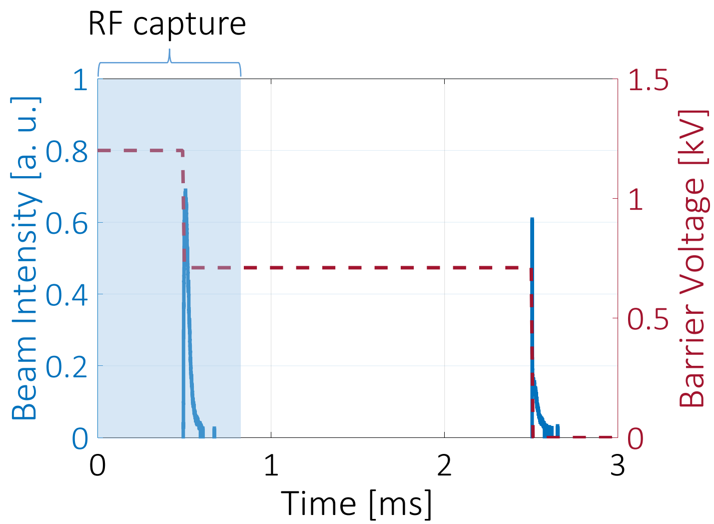


Figure Time-of-Flight measured after the *A/q*-Separator when gating with the outer barrier.

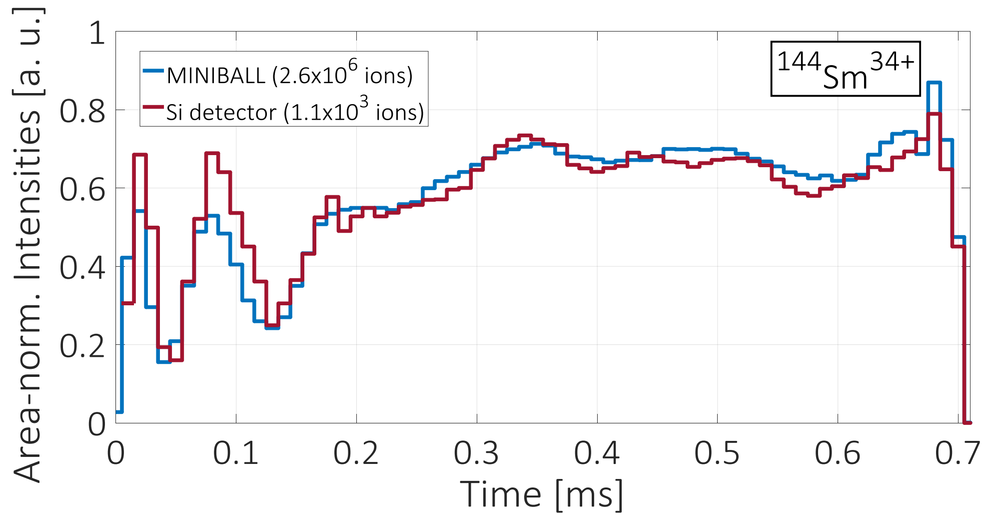


Figure Ion beam pulse lengthening obtained from direct application of the inversion formula.

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

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

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

Compensation and heating in REXEBIS

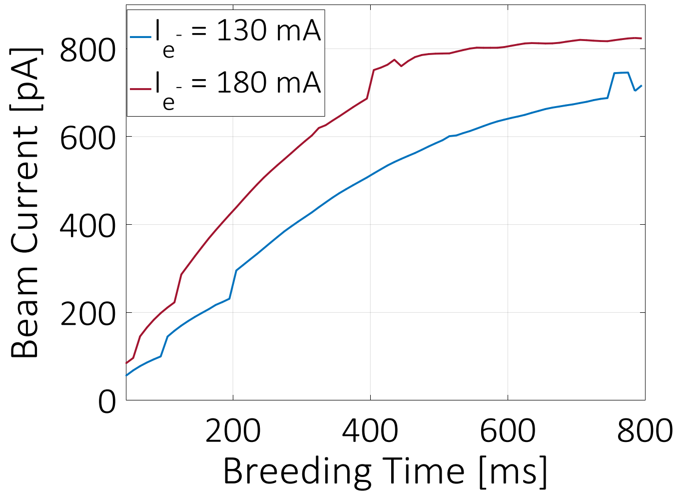


Figure Total ion beam current extracted from REXEBIS before *A/q*-separation.

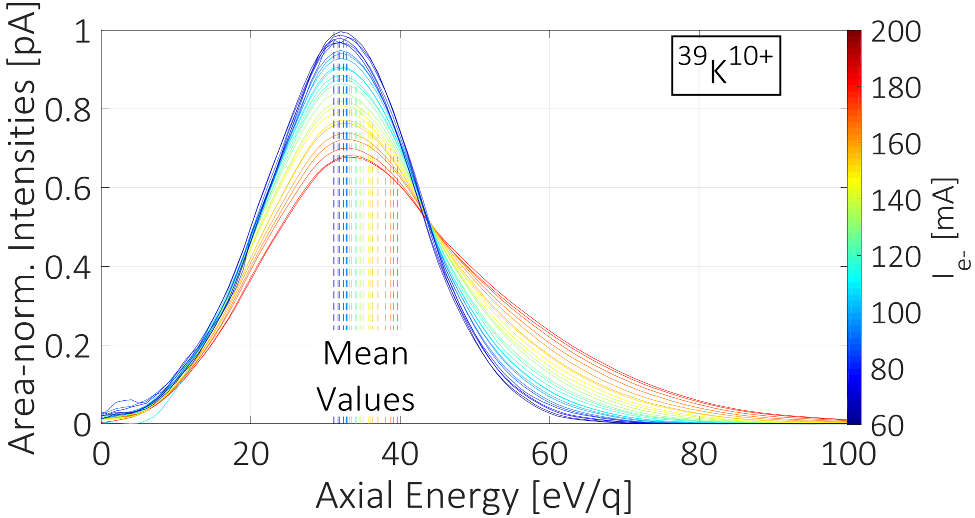


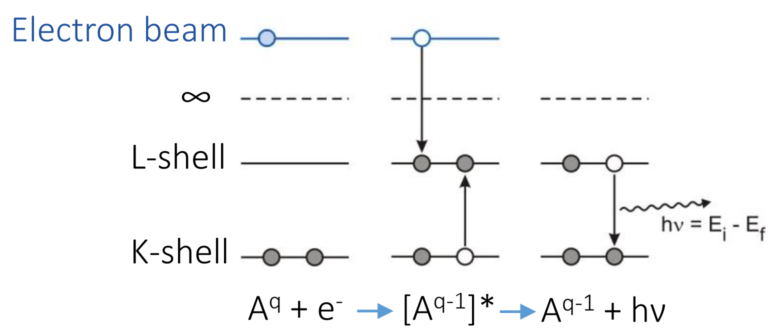
Figure Ionic axial energy distribution measured at REXEBIS extraction, as a function of the electron beam current.

Energy dynamics $$\frac{dN_ikT_i}{dt} = \left(\frac{\mathbf{dN_ikT_i}}{\mathbf{dt}}\right)^{\mathbf{Coulomb}} + \left(\frac{dN_ikT_i}{dt}\right)^{\mathbf{Ionisation}} + \sum_j \left(\frac{dN_ikT_i}{dt}\right)^{\mathbf{Transfer}} + \left(\frac{dN_ikT_i}{dt}\right)^{\mathbf{Escape}}$$

Spitzer formalism: $$\Delta E_q^{axial}(eV) = \frac{e^3}{16\pi\varepsilon_0^2}\left(\frac{m_e}{M_i}\right)\frac{1}{E_e}\left[e\sum_{i=1}^{q-1}\frac{i^2}{\sigma_i^{EI}} + j_e q^2 \Delta t\right] \quad \text{and} \quad \Delta E_q^{radial}(eV) = 2C_\lambda \Delta E_q^{axial}$$

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.



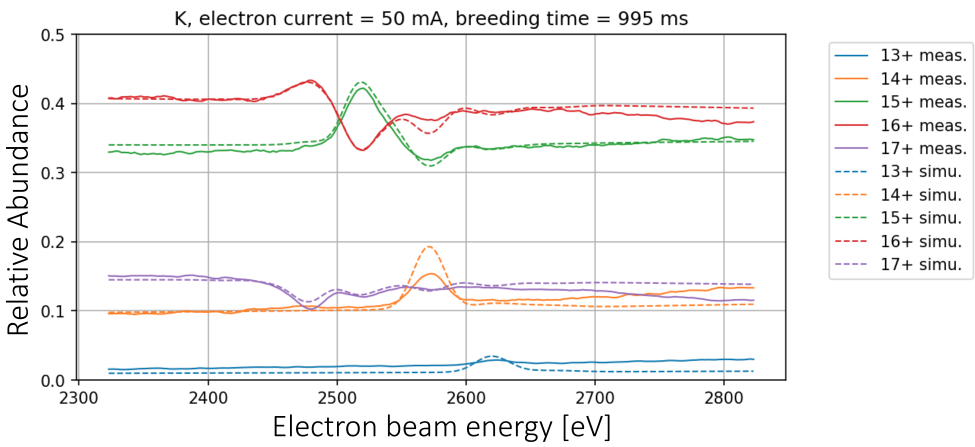


Figure Simulated and measured charge-states relative abundancies feature dielectric recombination effects in REXEBIS.

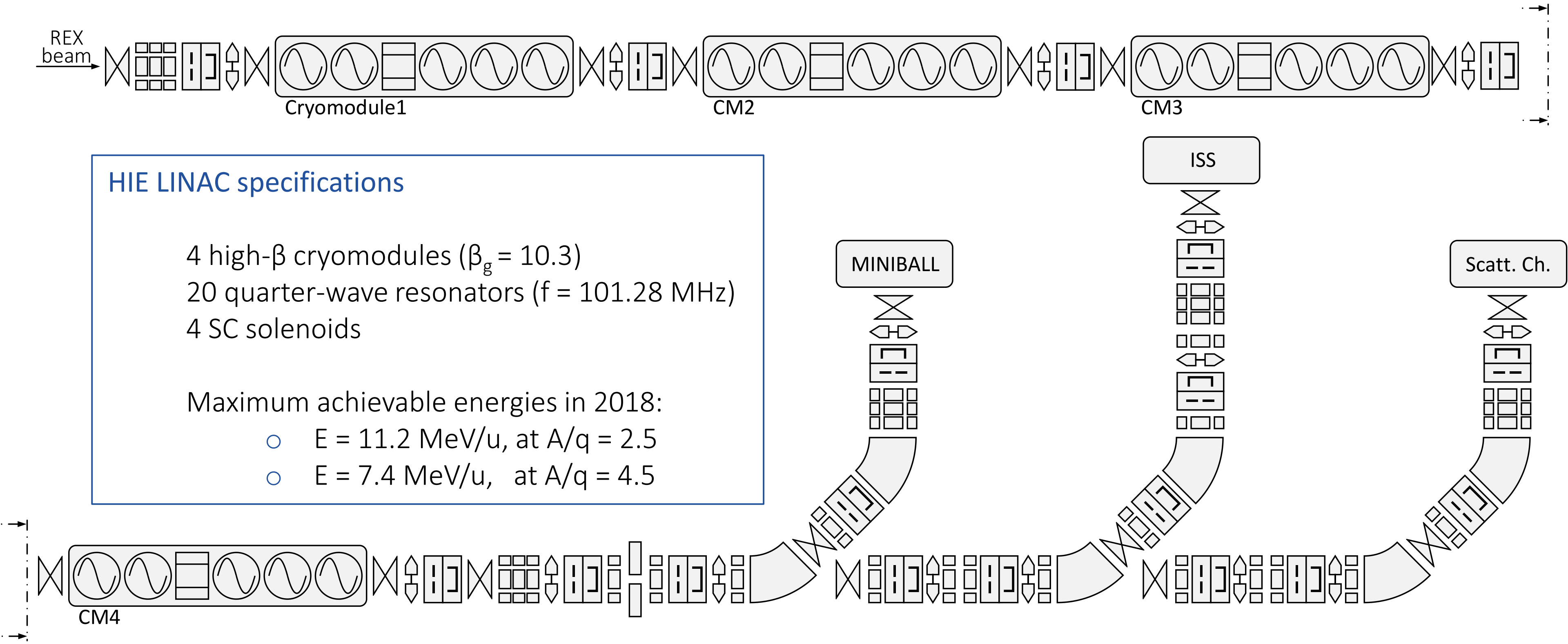
Charge dynamics

$$\frac{dN_q}{dt} = \frac{j_e}{e}\Big(\underbrace{N_{q-1}\sigma_{q-1}^{EI} - N_q\sigma_q^{EI}}_{\text{Electron impact ionisation}} + \underbrace{N_{q+1}\sigma_{q+1}^{RR} - N_q\sigma_q^{RR}}_{\text{Radiative recombination}} + \underbrace{\mathbf{N_{q+1}\,\sigma_{q+1}^{DR} - N_q\sigma_q^{DR}}}_{\text{Dielectronic recombination}}\Big)$$

$$+ \underbrace{n_0\bar{v}_{q+1}N_{q+1}\sigma_{q+1}^{CX} - n_0\bar{v}_q N_q\sigma_q^{CX}}_{\text{Charge exchange}} + \underbrace{N_q\,R_i^{esc}}_{\text{Escape rate}}$$

"The impact of dielectronic recombination on the charge state distribution at REXEBIS", H. Pahl, *et al.*, IWUM 2018, poster.

HIE-ISOLDE studies overview



HIE LINAC specifications

4 high-β cryomodules ($\beta_g = 10.3$)
20 quarter-wave resonators (f = 101.28 MHz)
4 SC solenoids

Maximum achievable energies in 2018:

- E = 11.2 MeV/u, at A/q = 2.5
- E = 7.4 MeV/u, at A/q = 4.5

Figure Schematic of HIE-ISOLDE, without the normal-conducting LINAC.

Twiss parameters measurements

Linear transformation, with Louiville's theorem: $\sigma_1 = (M_{Drift}M_{QP})\sigma_0(M_{Drift}M_{QP})^t$

Beam matrix for transverse phase-space: $\sigma_1 = \begin{pmatrix} \langle x_1^2 \rangle & \langle x_1 x_1' \rangle \\ \langle x_1' x_1 \rangle & \langle x_1'^2 \rangle \end{pmatrix}$ Courant-Snyder metric: $\sigma_0 = \begin{pmatrix} \beta_0 \varepsilon & -\alpha_0 \varepsilon \\ -\alpha_0 \varepsilon & \gamma_0 \varepsilon \end{pmatrix}$

With the thin-lens approximation, $\langle x_1^2 \rangle$ (measure) is reduced to a quadratic function of the focusing strength.

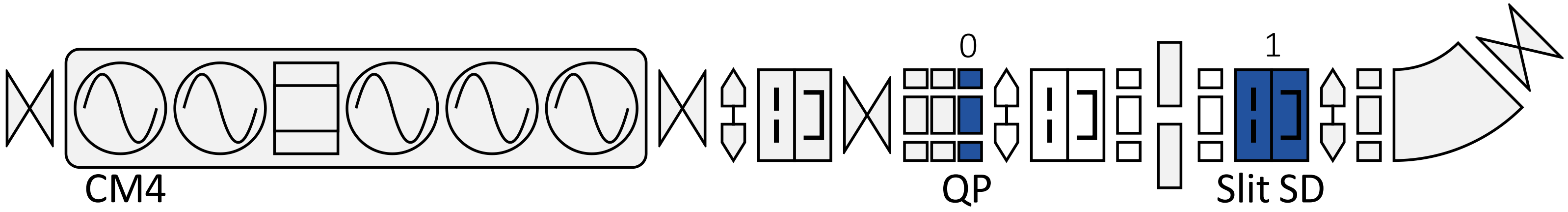


Figure Schematic of the «quadrupole-scan» method with a silicon detector.

Silicon detector:

- Capture all the beam: use *15 mm*-diameter SD in XT00.1300
- Avoid saturation (total energy < 500 MeV/pulse): decrease energy and increase RR.
- Avoid pile-ups: use Slow Extraction.

Twiss parameters determination

Experimental setup $^{133}Cs^{31+}$ @ 3.5 MeV/u (3 SCC). RR = 10 Hz; breeding time = 93 ms; I_{e-} = 160 mA. ≈100 ions/s.

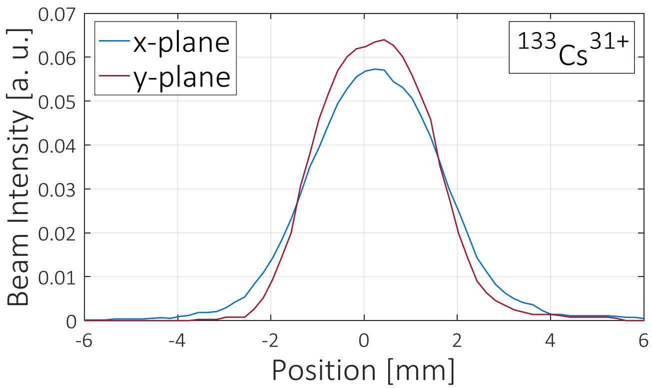


Figure Beam profiles at waist on both plane.

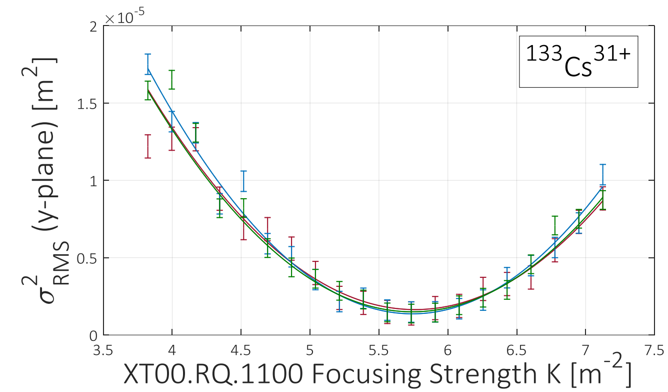


Figure Variance as a function of focusing strength.

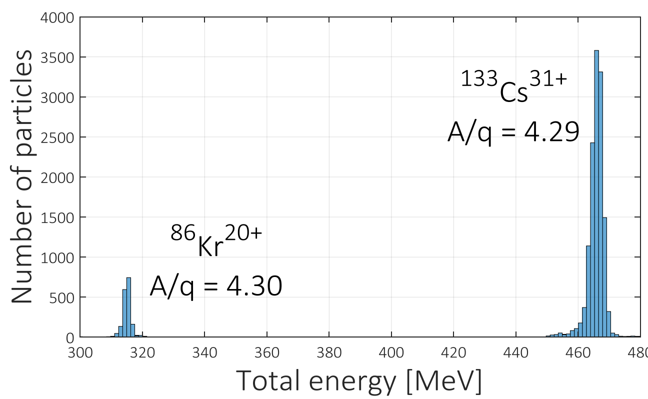


Figure Energy histogram during scans.

Results:

- X-plane:
  ε_{rms} = 1.09 ± 0.05 π.mm.mrad
  α_{rms} = -1.36 ± 0.08 rad; β_{rms} = 2.32 ± 0.11 m
- Y-plane:
  ε_{rms} = 1.24 ± 0.12 π.mm.mrad
  α_{rms} = -3.21 ± 0.41 rad; β_{rms} = 5.16 ± 0.30 m

Transverse phase-space reconstruction

Experimental setup $^{39}K^{10+}$ @ 3.8 MeV/u (5 SCC). RR = 20 Hz; breeding time = 21 ms; I_{e-} = 160 mA.

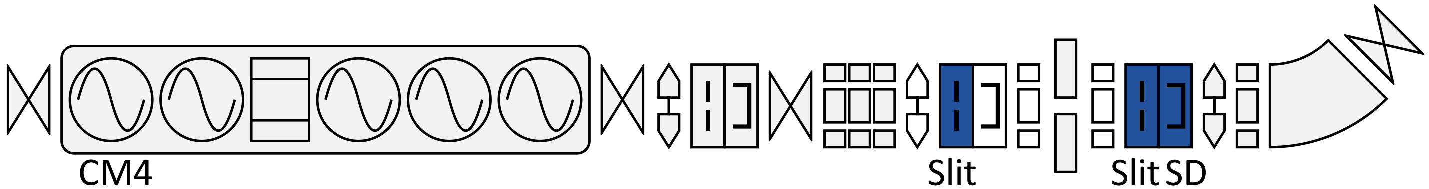


Figure Schematic of the «double-slit» method with a silicon detector.

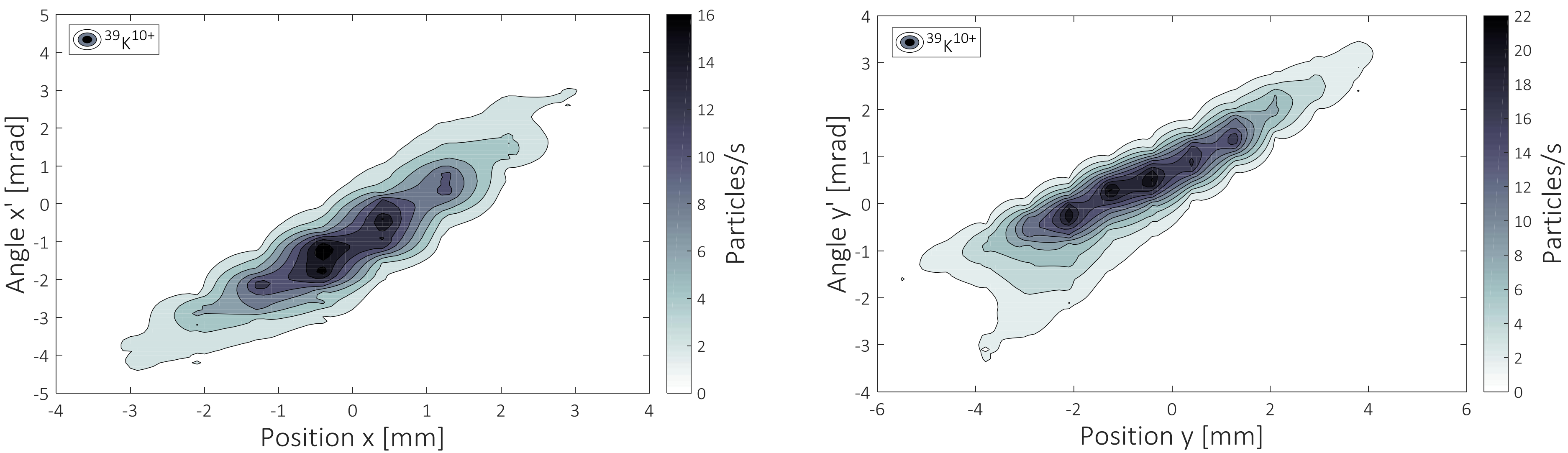


Figure Phase-space reconstruction from «double-slit» method measurement.

Longitudinal beam parameters

Technique One Super-Conducting Cavity is operated as a buncher in order to apply the «three-gradient» method.

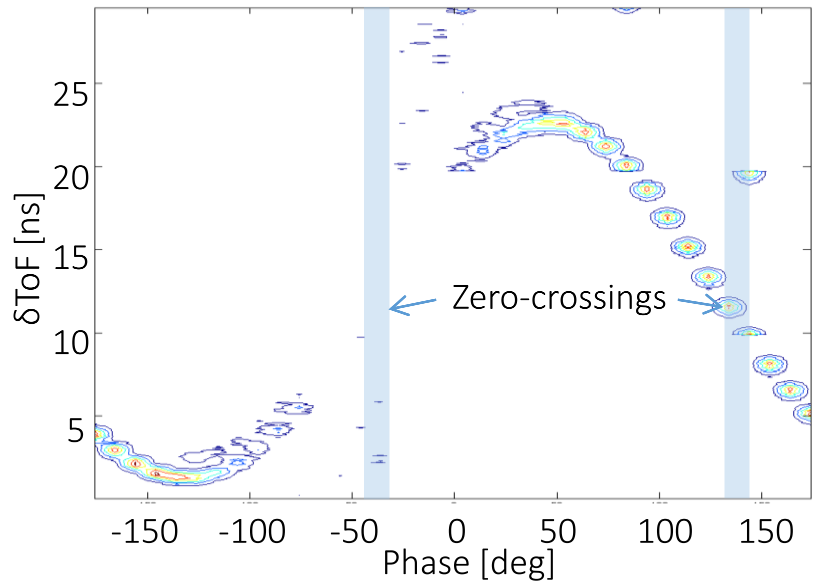


Figure Measurement of δToF when phasing a SCC (courtesy of S. Sadovich).

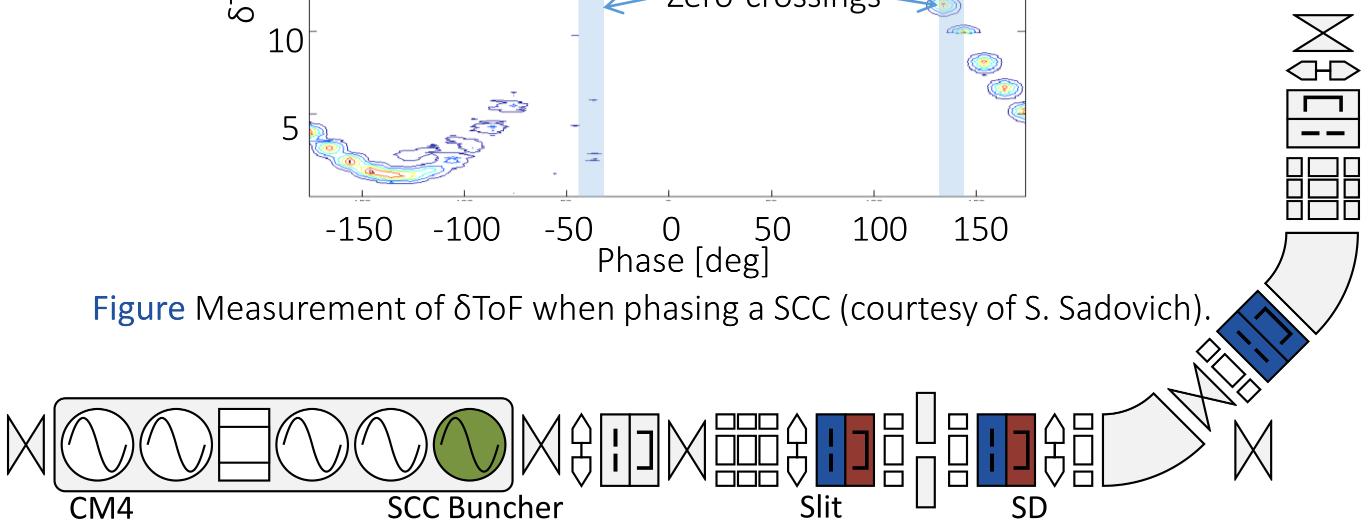


Figure Schematic of the elements used for the energy measurements and the bunch structure measurement.

"Characterization of the Beam Energy Spread at the REX/HIE-ISOLDE LINAC", M. Lozano, *et al.*, IPAC2018, 10.18429

Energy and TOF measurements

Experimental setup $^{14}N^{4+}$ @ 3.8 MeV/u (5 SC Cavities). 15th SC Cavity operated as a buncher. RR = 20 Hz.

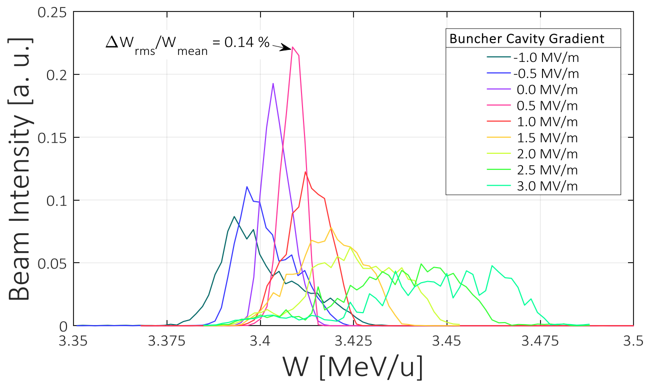


Figure Resulting beam energy distributions.

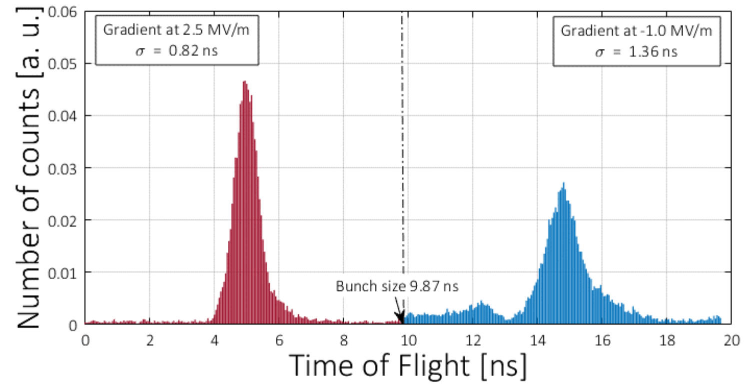


Figure Two examples of obtained bunch structure.

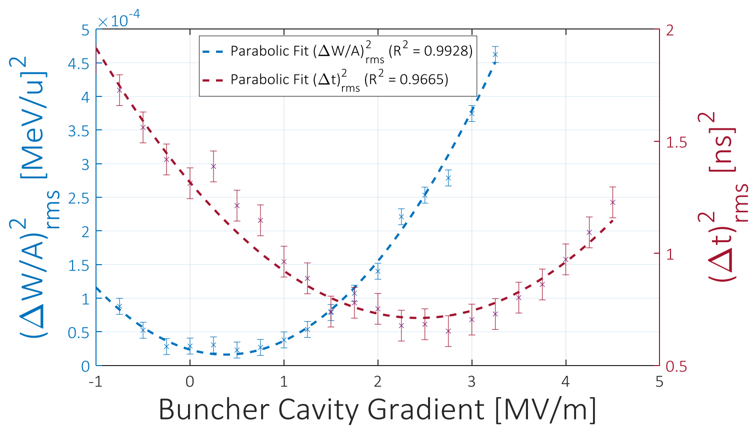


Figure Variations of energy spread and bunch length.

Method «Three-gradient», with RF gap as a thin element:

- Drift L: $$\begin{pmatrix}\Delta t_1\\ \Delta W_1\end{pmatrix} = \begin{pmatrix}1 & \dfrac{-L}{\beta\gamma(\gamma+1)cW_0}\\ 0 & 1\end{pmatrix}\begin{pmatrix}\Delta t_0\\ \Delta W_0\end{pmatrix}$$
- RF gap: $$\begin{pmatrix}\Delta t_1\\ \Delta W_1\end{pmatrix} = \begin{pmatrix}1 & 0\\ -\dfrac{q}{A}\omega_{RF}E_0TL_g\sin(\varphi_s) & 1\end{pmatrix}\begin{pmatrix}\Delta t_0\\ \Delta W_0\end{pmatrix}$$

Conclusion

REXEBIS studies, toward a better understanding of the performances.

Consolidated methodology for the Slow Extraction.

Potential operational use of Dielectronic recombination.

Technique for the measurement of transverse beam properties at very low intensity.

Measurements of the longitudinal parameters via multi-projections on the ToF or energy plane.

Perspectives

Combine CS and energy dynamics measurements with charge breeding simulations.

Analyze data of transverse beam properties measured for different REXEBIS parameters.

Analyze data of longitudinal beam properties measured at different beam energies.

Combine beam dynamics simulations with measurements.

Thank you for your attention!