Computational beam dynamics requirements for FRIB

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Outline

- FRIB driver linac status
  - Simulations of multi-charge ion beam acceleration
  - Physics application development and use
  - Virtual accelerator (FLAME, IMPACT and TRACK)
  - Model driven accelerator
    - » Include actual misalignments and field maps
- First beam acceleration in FRIB
- ECR simulations
- Bayesian statistics for accelerator tuning
- Computational needs for FRIB
  - Gas stripper
  - On-line determination of reference trajectory in fragment separators
  - LISE^{++}
  - Rare Isotope Beam Preparation for Post-Acceleration
    - » Gas cell,
    - » RFQ CB
    - » MR-TOF
    - » EBIS

Acknowledgements

- FRIB Accelerator Physics Department
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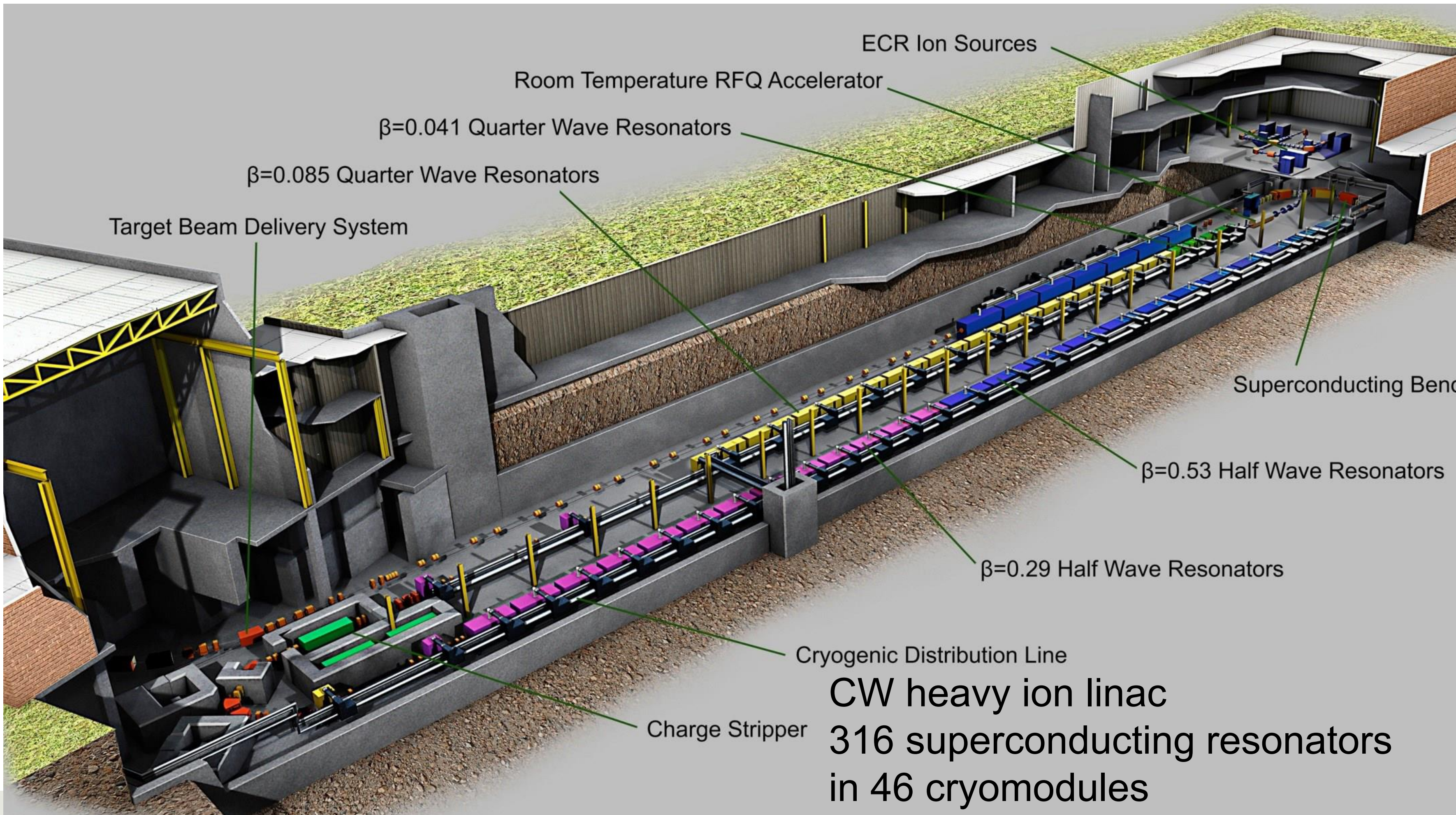
  - M. Hausmann
  - M. Portillo
  - O. Tarasov

Faculty for Rare Isotope Beams

- Currently is being commissioned with beam
- First operation for physics experiments is planned in 2022

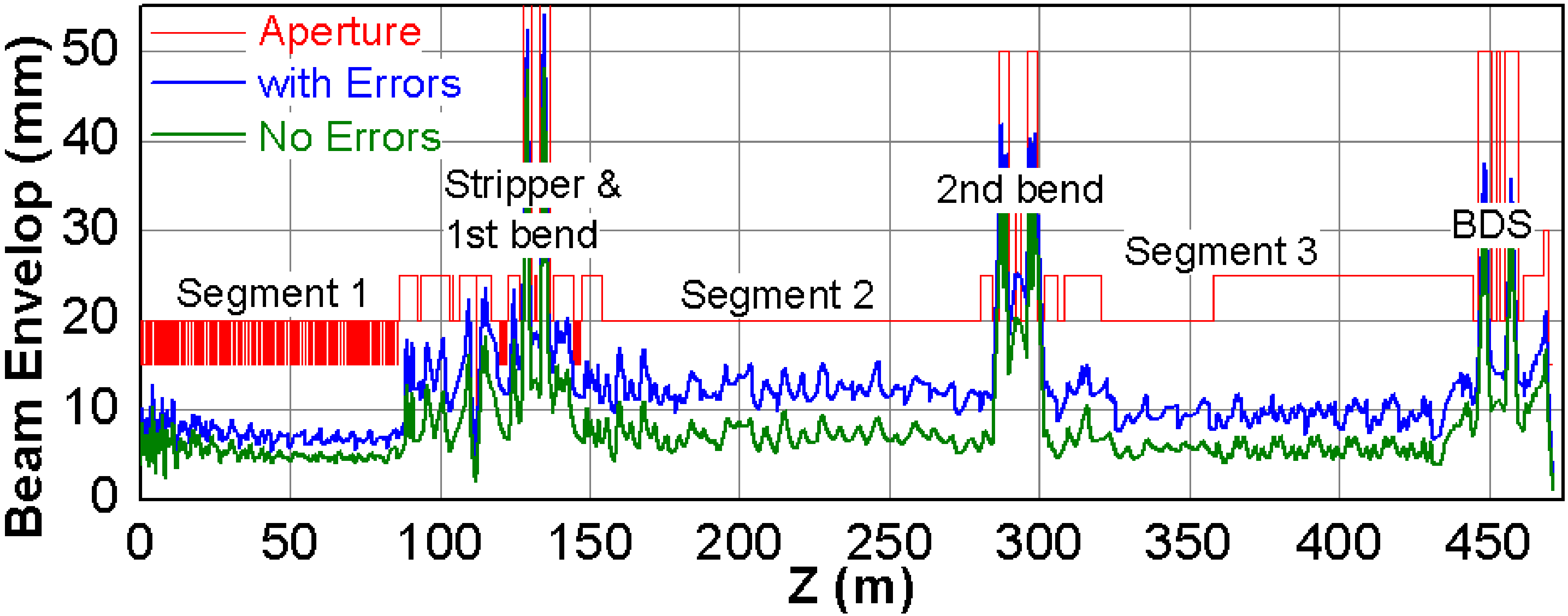


FRIB Beam Dynamics Challenges for Multi-Charge-State Simultaneous Acceleration and Transport

- Lattice with large acceptance
  - Accommodate mismatch and offset among the charge states
- Manipulation of phase space
  - Prebuncher, velocity equalizer and HV platform scheme at LEBT
- Achromatic and isochronous bending optics design
  - Reduce emittance growth in both transverse and longitudinal planes
- Superimposition of multi-charge states at critical locations
  - Minimize emittance growth on charge stripper
  - Achieve small beam size on target
- Three optimization and simulation codes are in use at FRIB:
  - FLAME - Fast Linear Accelerator Modeling Engine, developed at FRIB/MSU
    - » Matrix-based
    - » High level python wrapper and API available for convenient work flow control and interface to high level control system
  - IMPACT – PIC code, developed in LBNL
    - » In the development network, will be available in production network
  - TRACK – PIC code, developed at ANL/MSU
    - » Off-line, will be available in production network

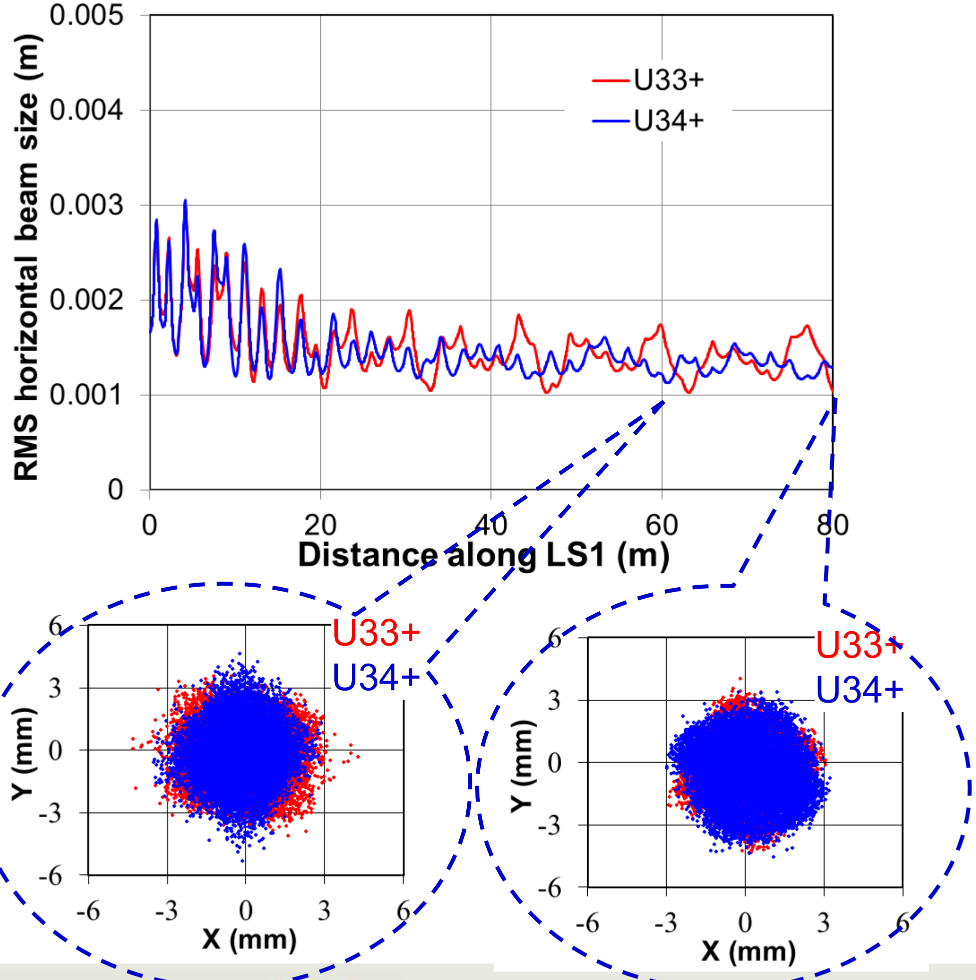
Beam Evaluation Results with Machine Errors

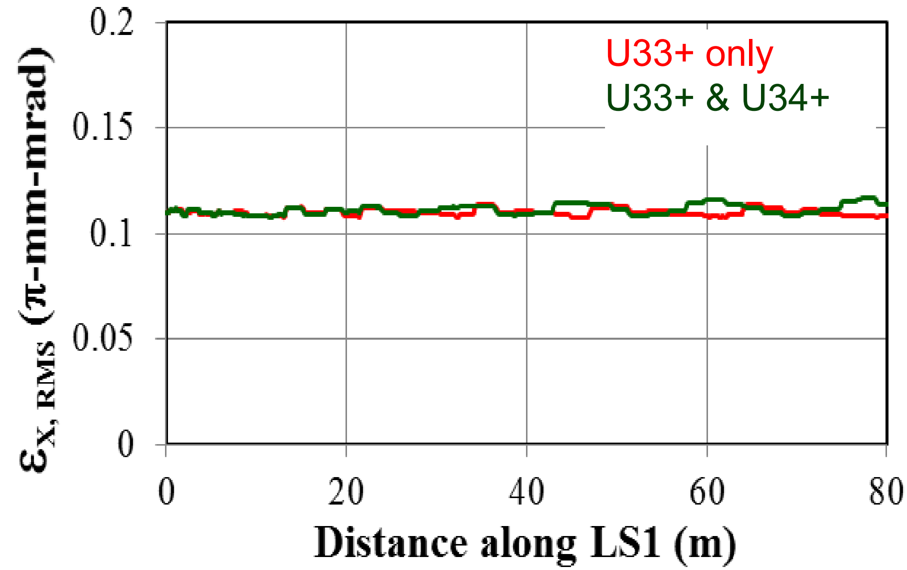
- IMPACT and TRACK simulations, multi-particle, multi-seed
- Beam envelope growth (within aperture) mainly due to misalignment
  - Steering correctors turned on
- RF errors cause significant longitudinal emittance growth but not coupled into transverse
- No uncontrolled beam losses observed



Transverse Beam Size and Emittance along LS1

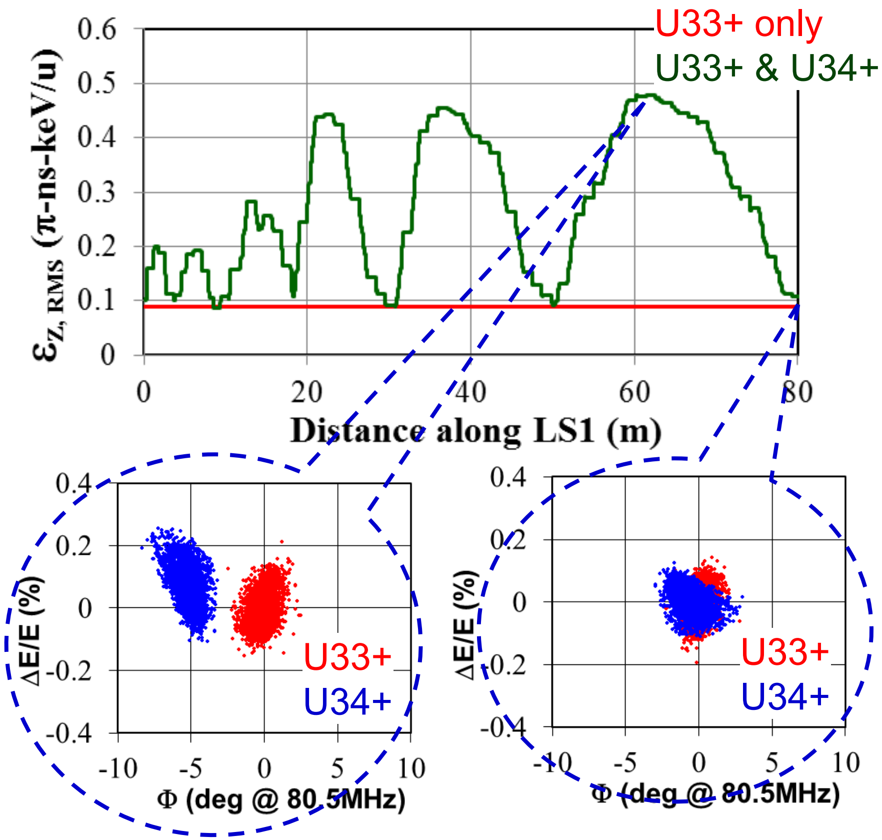
- Two charge states (U33+ & U34+) reasonably overlapped
  - Very similar transverse dynamics

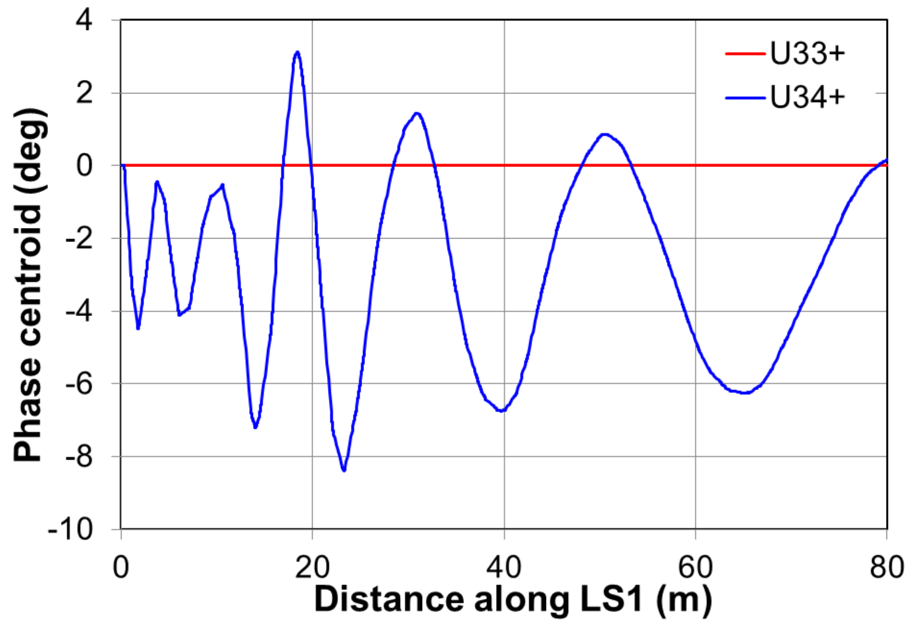




Longitudinal Overlap of 2q Beam at LS1 Exit

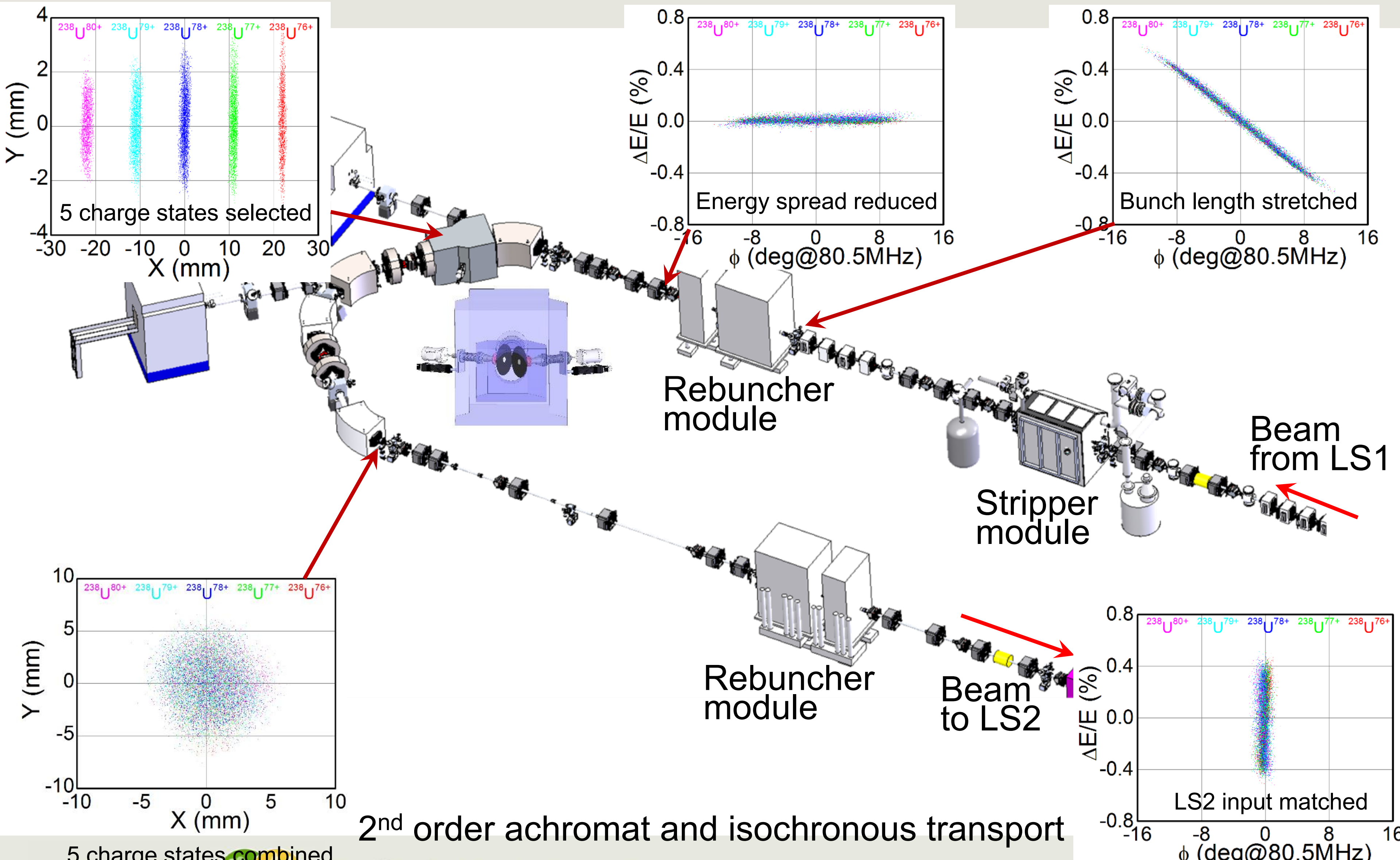
- Longitudinal oscillation of two-charge-state beam along Segment 1





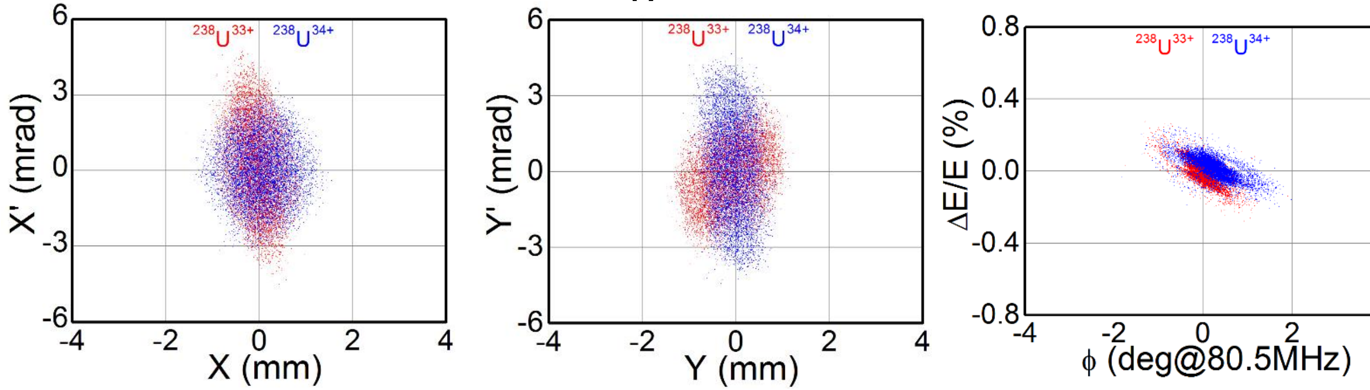
- Phase of cavities are adjusted for the overlap of the two-charge-state beam at the exit of Segment 1 by measuring the timing of each charge state beam

Charge Stripper and Selection in FS1

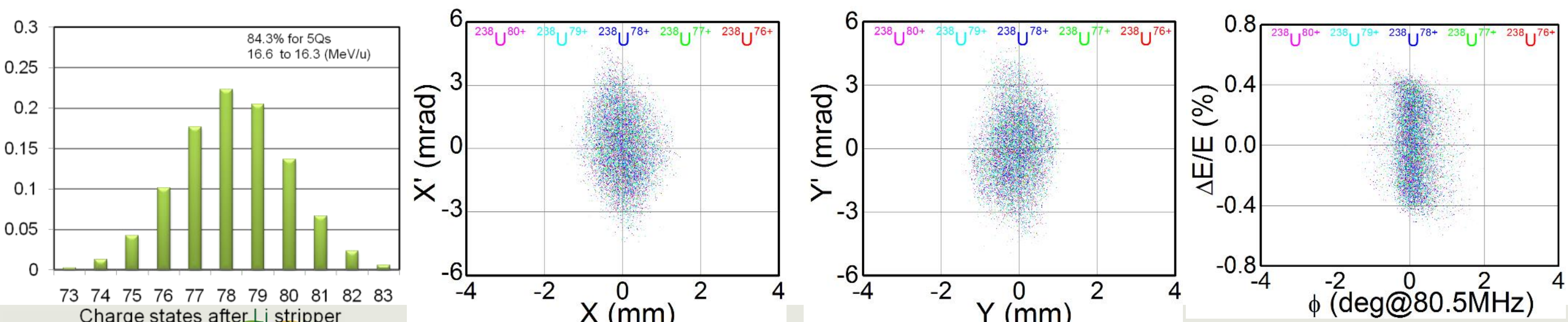


Uranium Beam Distributions at Li Stripper

- U33+ and U34+ at the input of stripper
  - Small beam size and short bunch length achieved

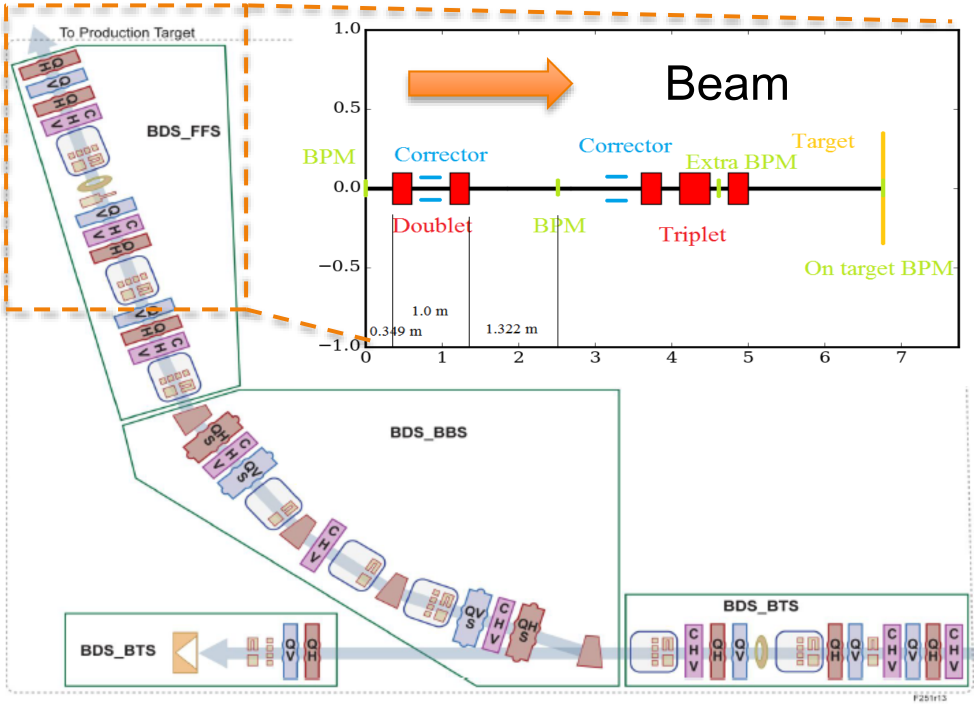


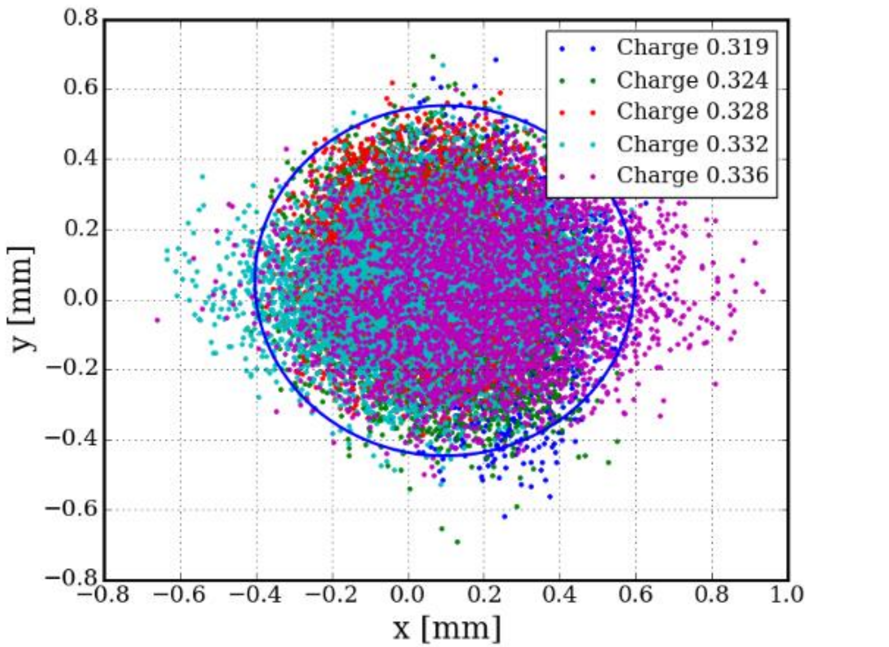
- Multi-charge state distribution at the output of stripper
  - 85% beam in 5 charge states (from U76+ to U80+)



Five-charge-state Uranium Beam on Target

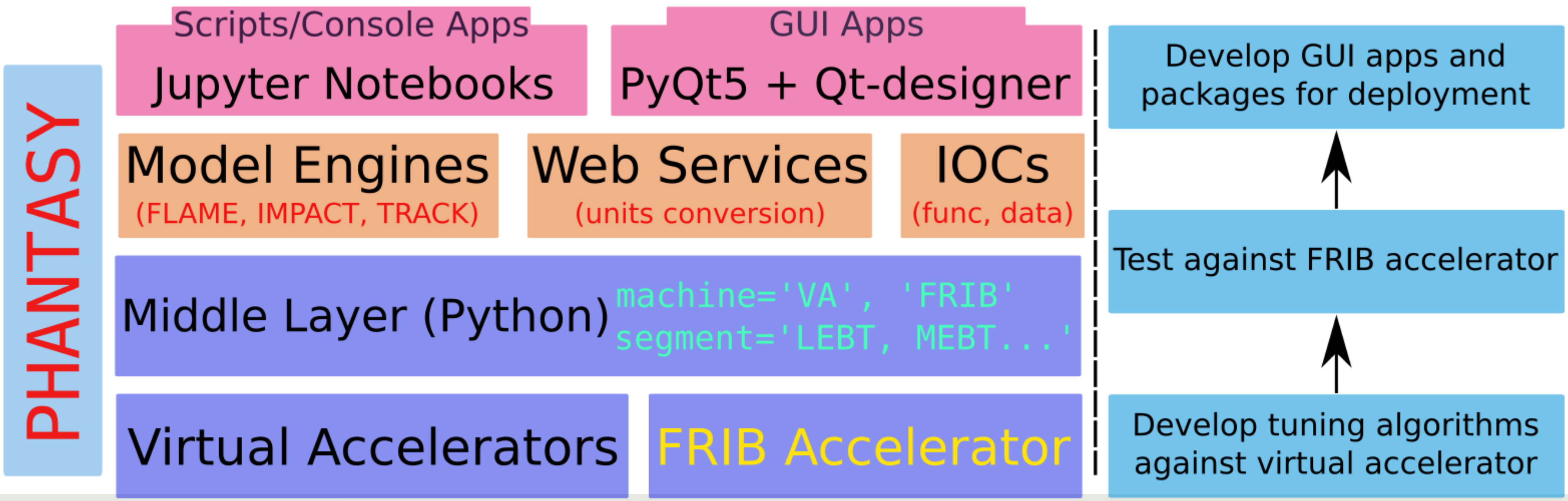
- The last critical point for FRIB Linac is beam tuning into the target.
  - 90% of beam within 1 mm diameter.
  - Beam on-target position should be adjustable within +/- 3 mm range.
- Studies have been performed to ensure these requirements can be met with baseline beam diagnostics and realistic errors





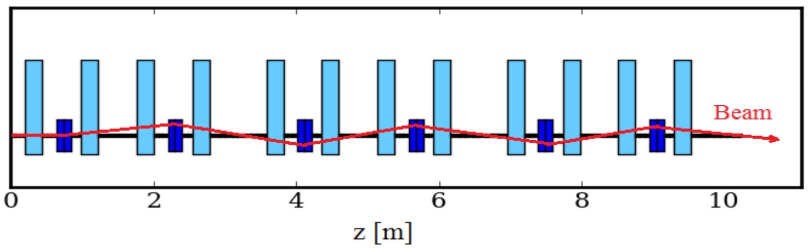
Physics High-level Controls

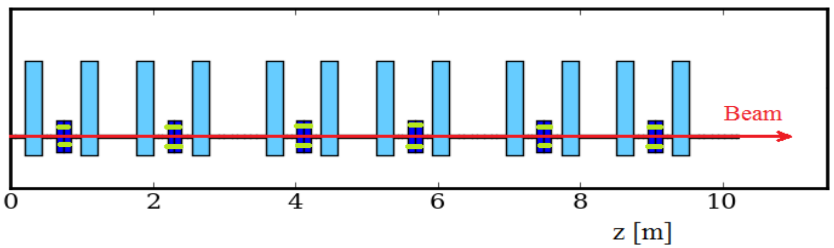
- **P**hysics **H**igh-level **A**pplications a**n**d **T**oolkit for **A**ccelerator **Sy**stem (PHANTASY)
  - Python 2.7 and 3.x, Jupyter-notebook scripting environment
  - Accelerator/device abstraction to full object-oriented programming environment
  - Online modeling: FLAME, IMPACT, TRACK, etc.
  - Virtual accelerator based on EPICS control environment
    - » Virtual accelerator model is being continuously updated
  - Web service integration (channelfinder, unicorn, scanserver, etc.)
  - PyQt GUI applications built upon this framework
  - Automatic deployment with Debian packages



Physics Applications: Central Trajectory Correction

- Correct the beam central trajectory at each BPM using steering magnets
- 4D problem due to focusing with solenoids





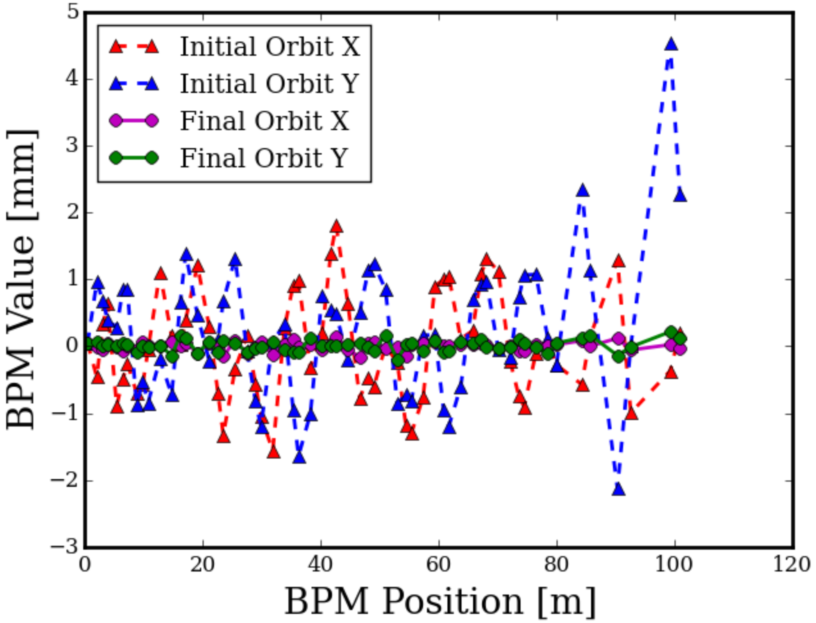
Orbit Response Matrix:

$$A\vec{\theta} = \vec{d};\ \vec{\theta} = \sum_{\alpha=1}^{N} \frac{C_\alpha}{\omega_\alpha} \vec{\tau}^{(\alpha)};$$

$$C_\alpha = \vec{d} \cdot \vec{\delta}^{(\alpha)};\ A = DWT^t.$$

Optimization, minimize M:

$$M = \left|\vec{d} + \alpha\left(\overrightarrow{d_c} - \overrightarrow{d_t}\right)\right|^2.$$



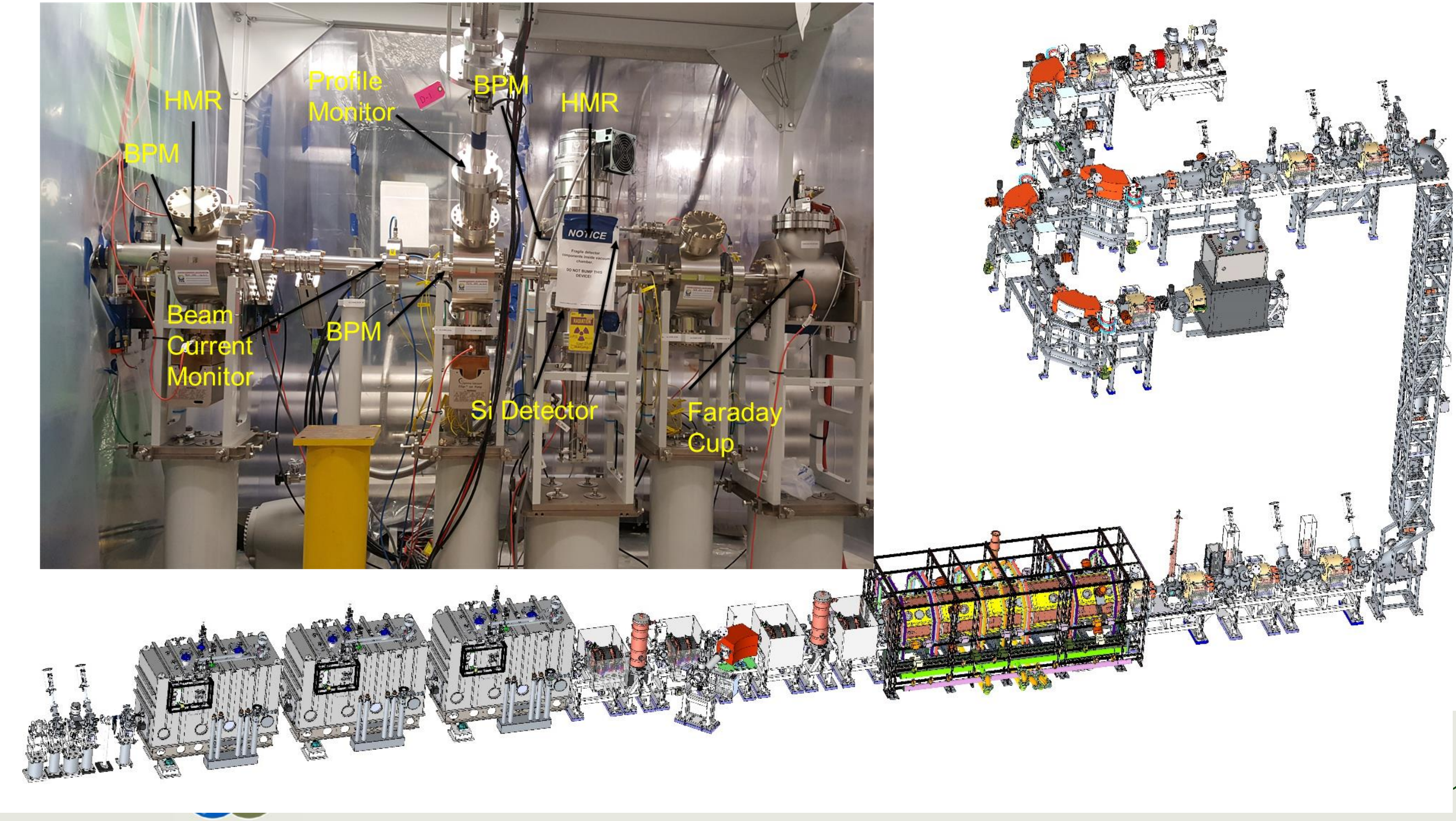
FRIB Tunnel is Being Filled with Cryomodules

- LS1 cryomodule production is finished
- Module production rate is steady at one per month in the past 12 month
- LS2, LS3 installation is ongoing in the tunnel
- On track to complete all cryomodule assembly work by the end of 2019

β=0.53 HWR coldmass assembly on-going

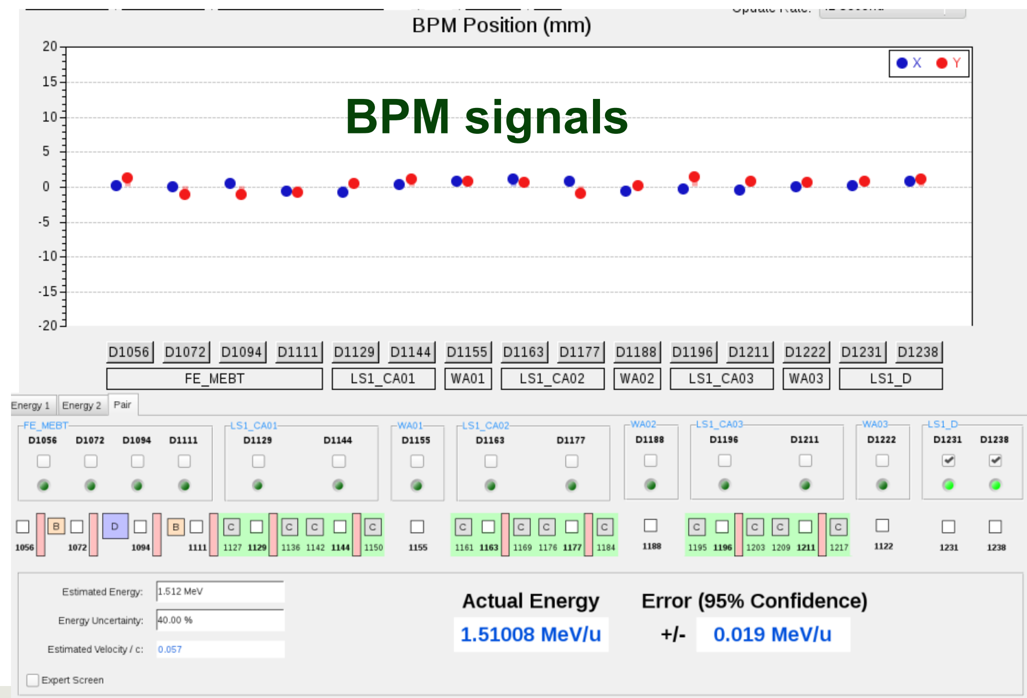
First Experience with On-line Beam Tuning: Front End and Three Cryomodules

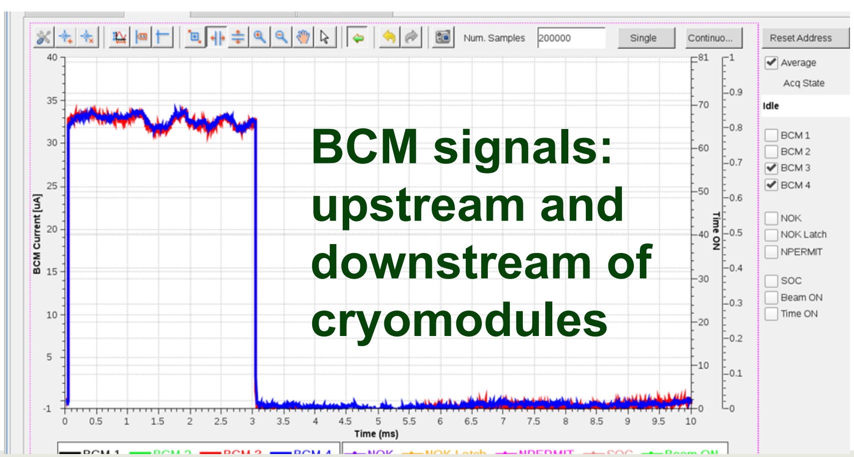
- Front End including 500 keV/u RFQ and MEBT
- Three cryomodules of β_{OPT}=0.041 SC cavities: 12 cavities and 6 solenoids
- Diagnostics station



Acceleration of 33 μA Argon Beam to 1.5 MeV/u

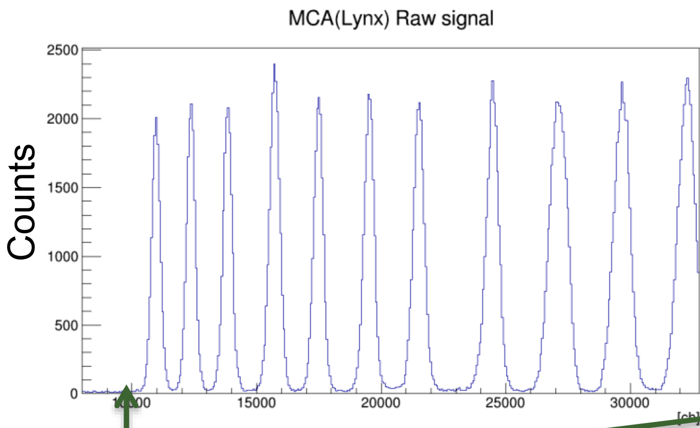
- 33 uA Ar^{9+} accelerated to 1.5 MeV/u with 30% duty factor
- Can produce 38 kW on target if accelerated to the design energy in CW mode
- 3 msec pulse at 100 Hz repetition rate. MPS was activated using differential signals from BCMs
- “Halo monitor rings” (HMR) were used as Faraday Cups for “quick” beam tuning during the phase scan:
  no beam losses after tuning
- No beam losses observed



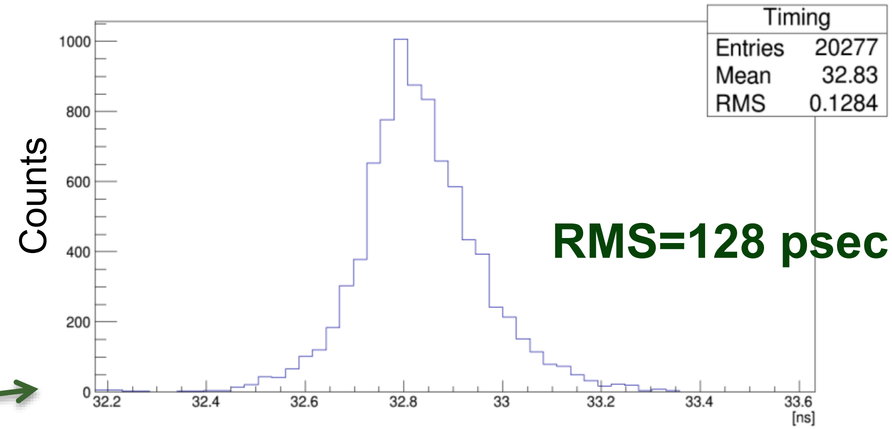


Beam Measurement Results

Argon beam energy after each cavity

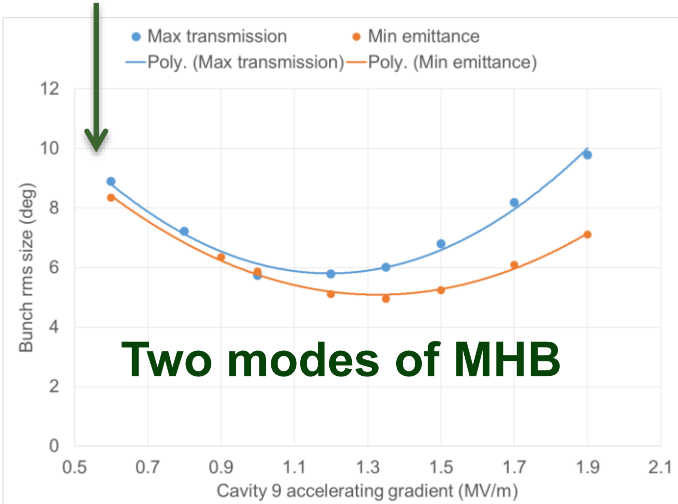


Bunch shape



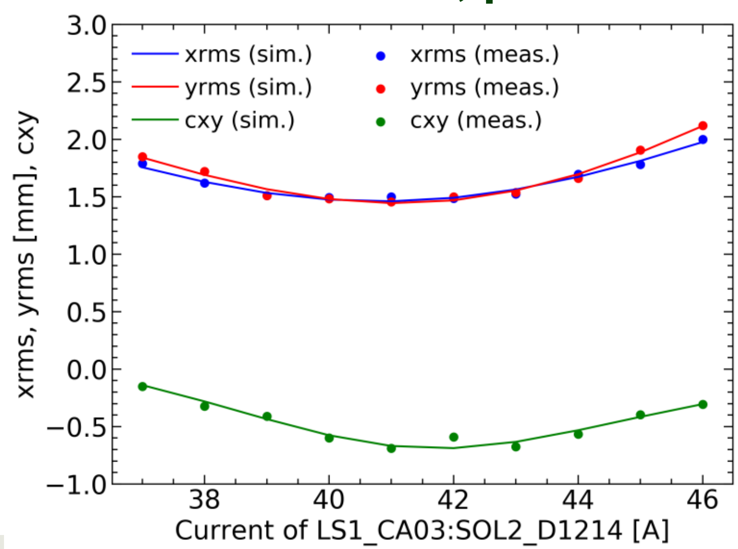
RMS=128 psec

Silicon detector



Two modes of MHB

Solenoid scan, profile monitor



Beam Dynamics in Electron Cyclotron Resonance Ion Source

- Plasma, strong magnetic field, RF heating, ionization, recombination,…
- There are no simulation codes which include all processes in an ECR
- V. Mironov (Dubna): PIC simulations, ionization assumes that electrons do not move and create background
- V. Toivanen (CERN): magnetic field, space charge, plasma potential, extraction
- V. Skalyga, I. Izotov, IAP, Nizhny Novgorod, O.Tarvainen, Jyvaskyla [2008-2017]
- P. Spadtke (GSI). RSI, **89.** Simulation with KOBRA-3 in external magnetic field

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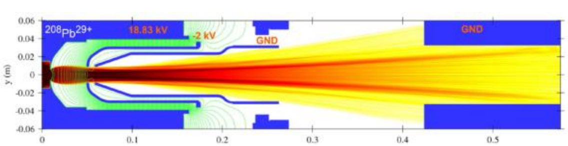
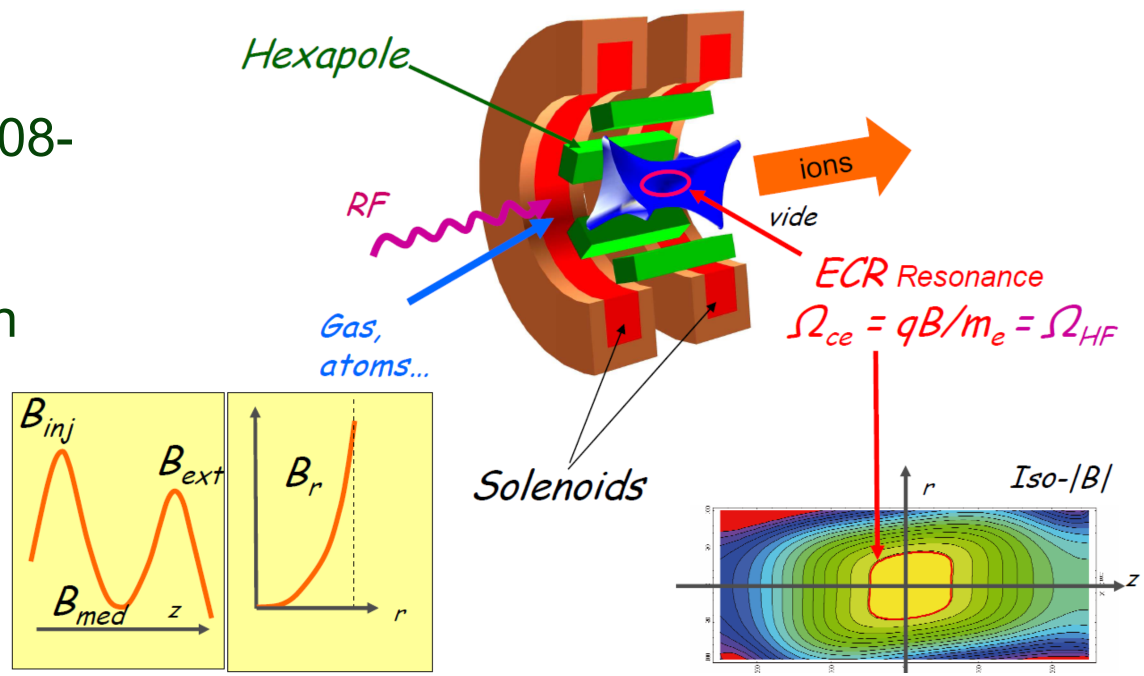
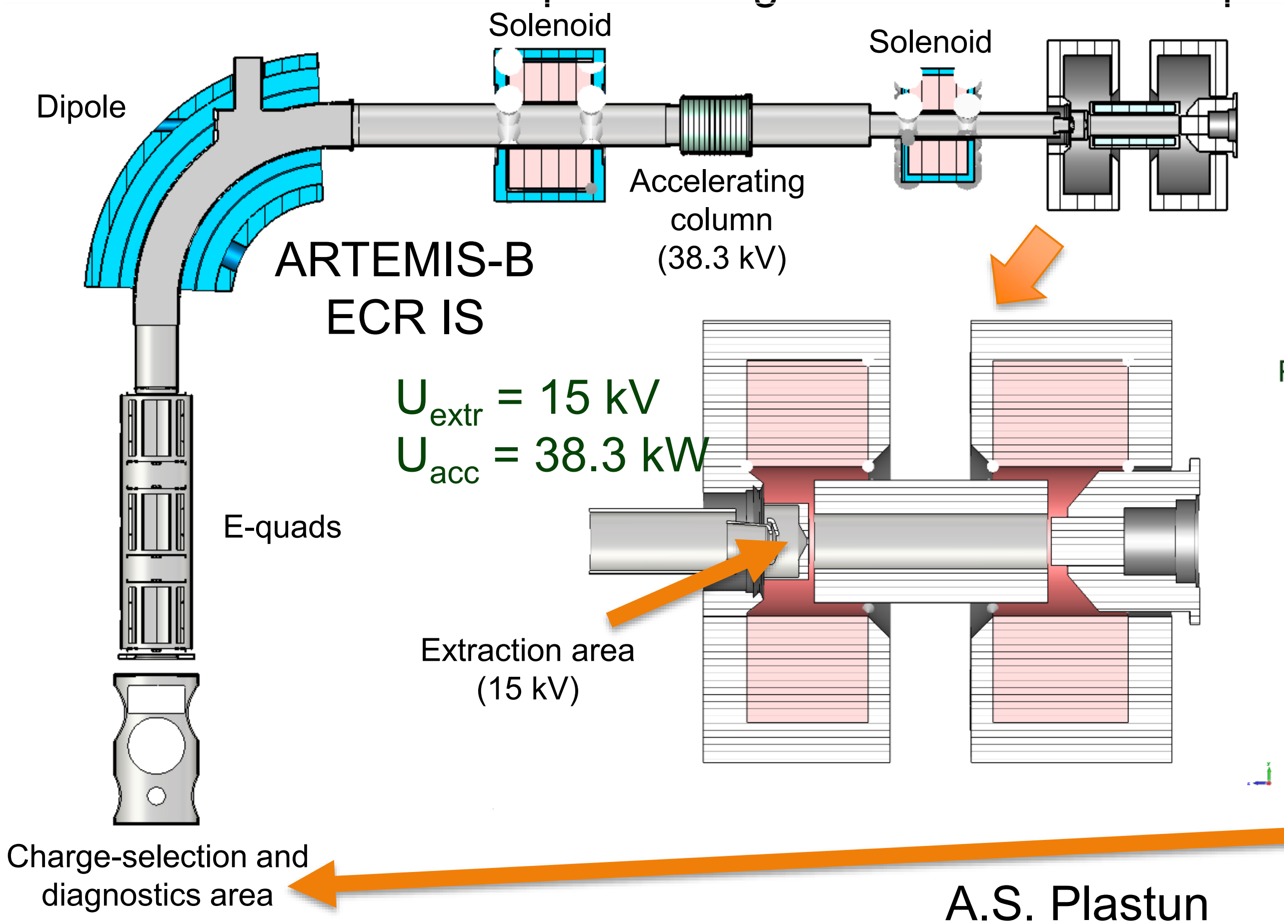


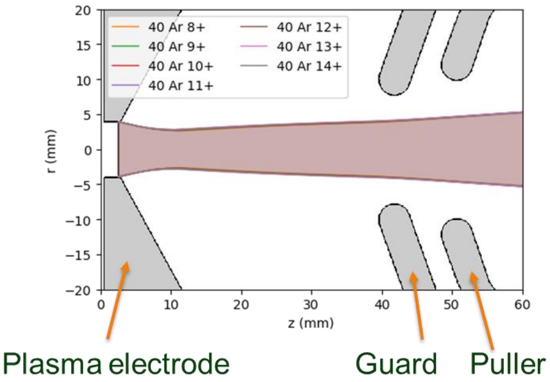
$^{208}Pb^{29+}$
5 mA
40 mm gap

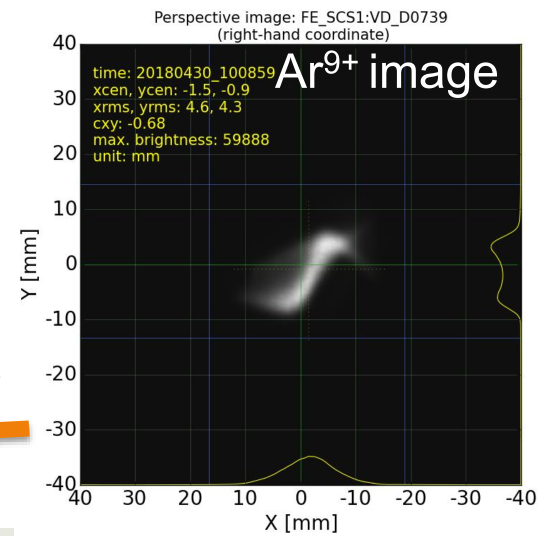


FRIB ECR

- Simulation of ion beam extraction from ECR using CST Particle Studio
  - Simulation starts from the plasma surface
  - Includes 3D fields and space charge of ions outside the plasma





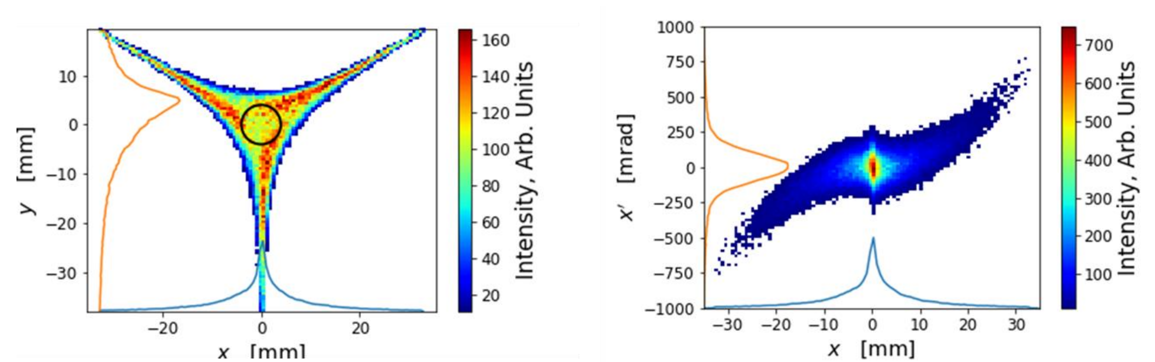


A.S. Plastun

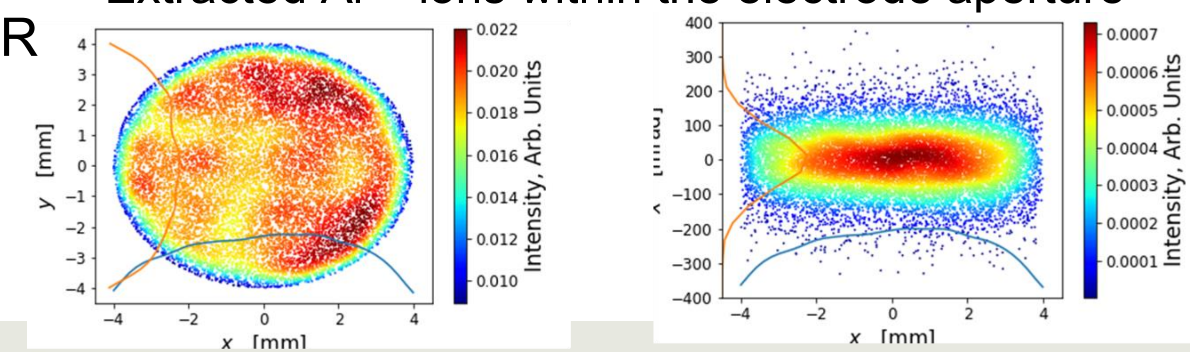
Simulated Initial ECR Beam Distribution with Mironov's Code

- ECR produces very complicated beam distribution
  - Angular momentum due to strong axial magnetic field
  - Multiple ion beams, multiple charge states
  - Complex configuration of the magnetic field
- So far we can fit only rms parameters to some general distribution in simulation codes (Waterbag, Gaussian,…)
- We observe hollow beam distribution in the LEBT
  - Initial distribution from ECR
  - Contribution of space charge effects
  - Further beam studies are being performed

All Ar^{8+} ions on plasma electrode plane

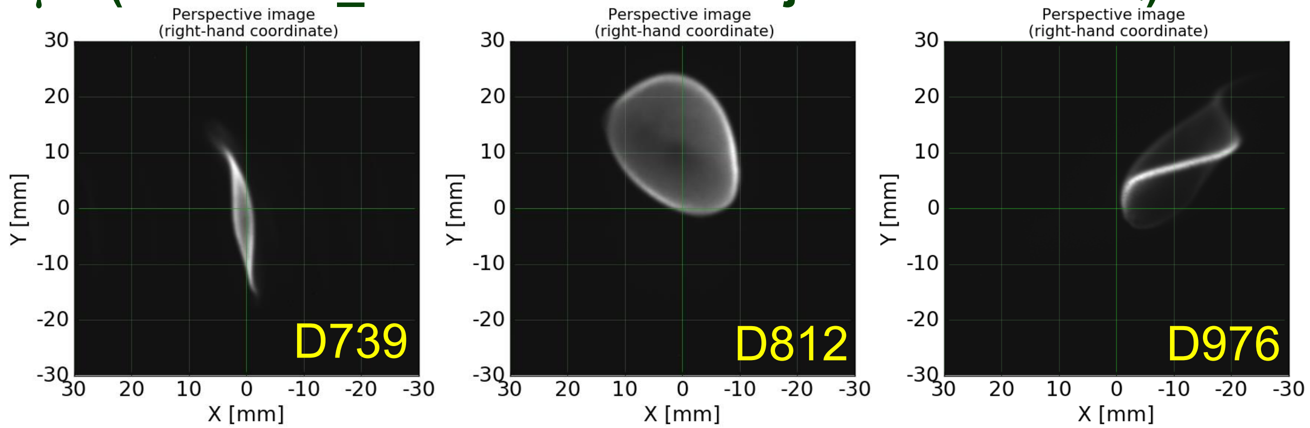


Extracted Ar^{8+} ions within the electrode aperture

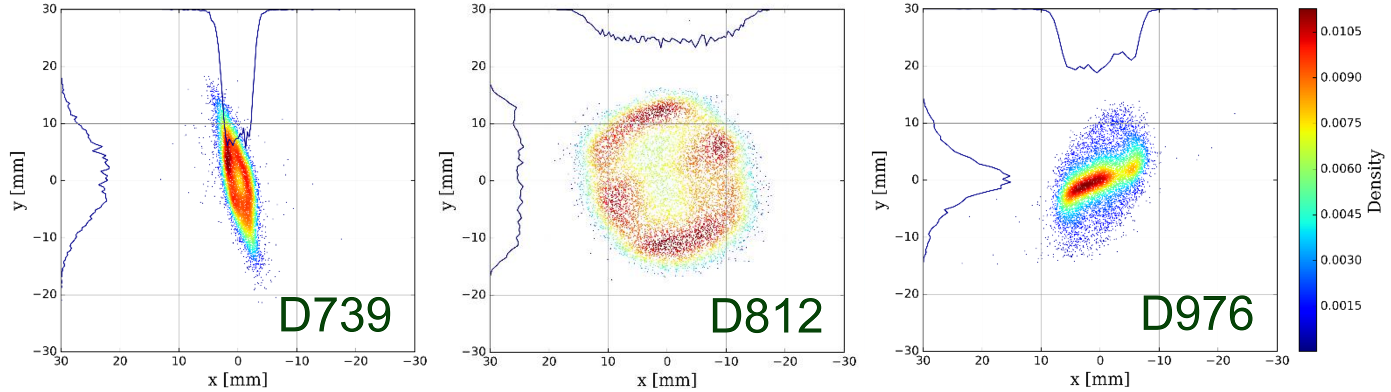


Comparison of Measured and Simulated Beam Images for Ar^{9+}

Ar^{9+} beam 20 eμA (20170828_90% transmission just before RFQ)

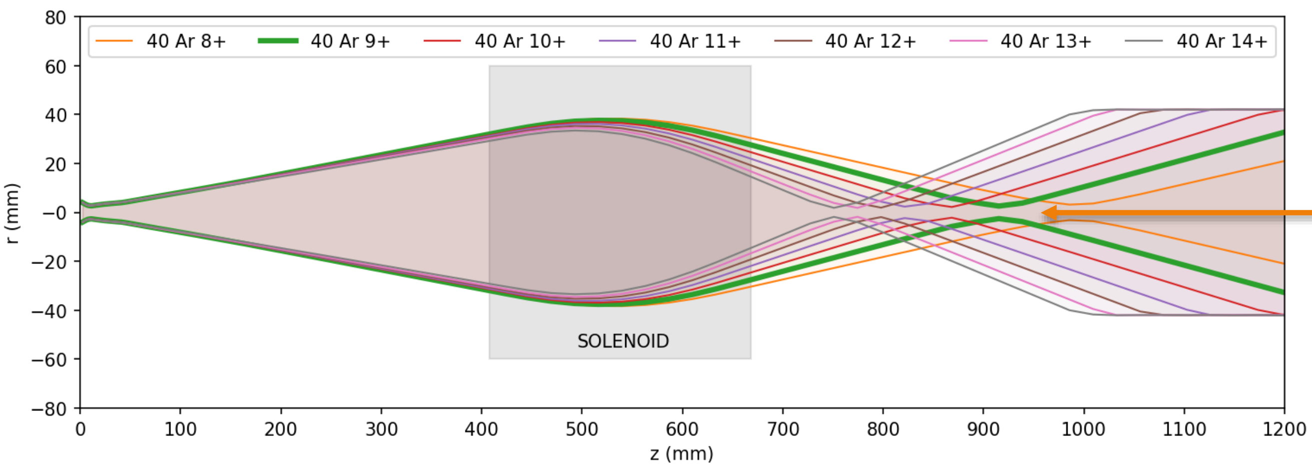


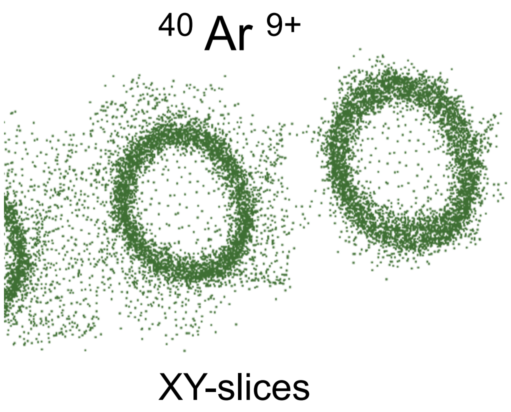
Ar^{9+} beam 20 eμA in TRACK simulation with multi-charge-state beam



Hollow Ion Beam in LEBT with CST PS

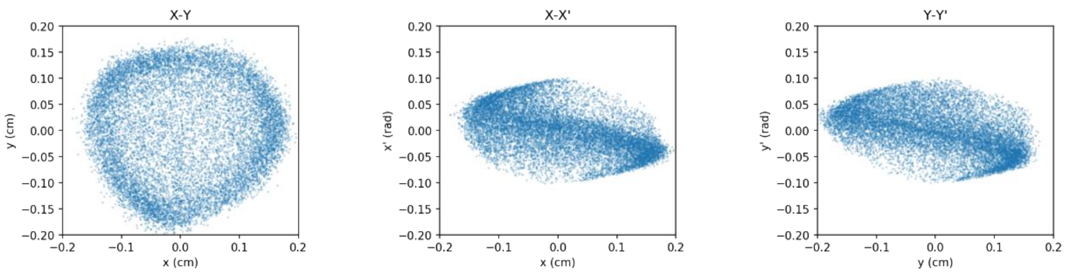
- After the extraction, ion species with different M/Q are focused differently by a beamline solenoid. It results in a highly non-linear space-charge forces producing the aberrations. For example, these forces can create the hollow beam downstream the solenoid.
- This hollow beam is formed due to the space-charge forces from higher charge states which’s focus is loacted upstream and a spherical aberration from the solenoid.



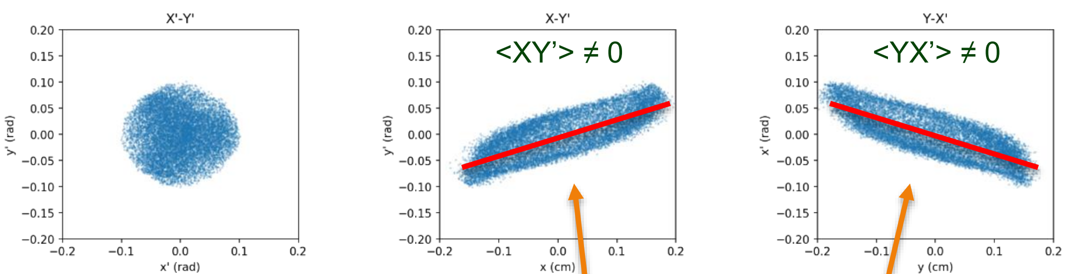


Magnetized Beam from ECR

- In Cartesian coordinate system the presence of non-zero angular momentum of beam particles appears as a tilt of a phase-space is XY' and YX' plane.



Phase-space plot at the solenoid focus (simulation)



Non-zero angular momentum

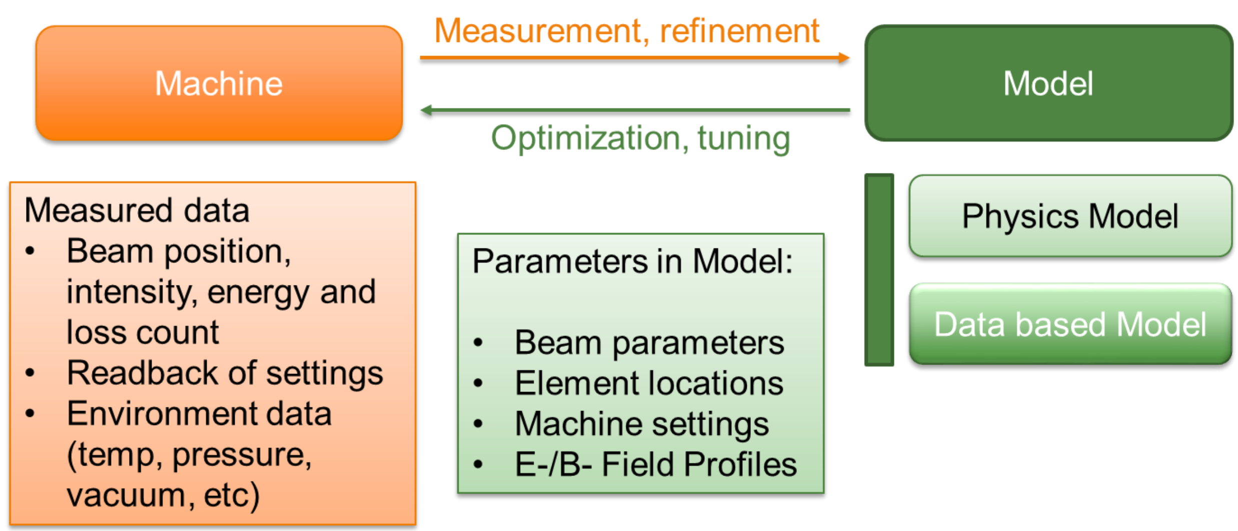
Non-zero angular momentum results in a XY-tilt after the beam passing the non-axisymmetric optics, for example, dipole.

$$\begin{pmatrix} \langle xx \rangle & \langle xx' \rangle & \langle xy \rangle & \langle xy' \rangle \\ \langle xx' \rangle & \langle x'x' \rangle & \langle x'y \rangle & \langle x'y' \rangle \\ \langle xy \rangle & \langle x'y \rangle & \langle yy \rangle & \langle yy' \rangle \\ \langle xy' \rangle & \langle x'y' \rangle & \langle yy' \rangle & \langle y'y' \rangle \end{pmatrix}$$

Bayesian Statistics for Accelerator Tuning

- Motivation:
  - Some parameters in accelerator can not be measured directly
  - These parameter can be used in accelerator model to predict the machine
  - Fitting the model to the measured data using optimizers
    - » Only results are given, how reliable?
    - » Prone to be have local minimum problem
    - » Hard to scale to high dimensional problem
    - » Depend on the definition of the penalty function

- Expectations from Bayesian method
  - Provide statistics information on reliability
  - Better scaling to high dimensional problem
  - Less local minimum problem
  - Suggest the future experiment



Question:
How statistics can help us to tune the machine, if it is a better option?

Y. Hao

Example of Using Bayesian Statistics to Find Beam Sigma-Matrix

- Beam image is taken with upstream quadrupoles' scan in wide range
- We measure $\sigma_i = (\sigma_x, \sigma_x, \sigma_{xy})_i$, i is the number of measurements at different setting of machine (quads) $V=(v_1, v_2, \ldots, v_n)$
- We need to find $\theta = (\epsilon_x, \beta_x, \alpha_x, \epsilon_y, \beta_y, \alpha_y, c_{xy}, c_{xy'}, c_{x'y}, c_{x'y'})$ upstream of the quadrupoles

Model

$$\sigma_{\text{model}} = f(V, \theta)$$

Machine

$$\sigma_{\text{measure}} = \sigma_{\text{model}} + \delta\xi$$

$$\xi = \text{randn}(); \delta = (\delta_x, \delta_y, \delta_{xy})$$

Bayesian Theorem

$$P(\theta, \delta \mid (\sigma_1, V_1), \cdots, (\sigma_i, V_i), \cdots) = \frac{P((\sigma_1, V_1), \cdots, (\sigma_i, V_i), \cdots \mid \theta, \delta)\, P(\theta, \delta)}{P((\sigma_1, V_1), \cdots, (\sigma_i, V_i), \cdots)}$$

The likelihood

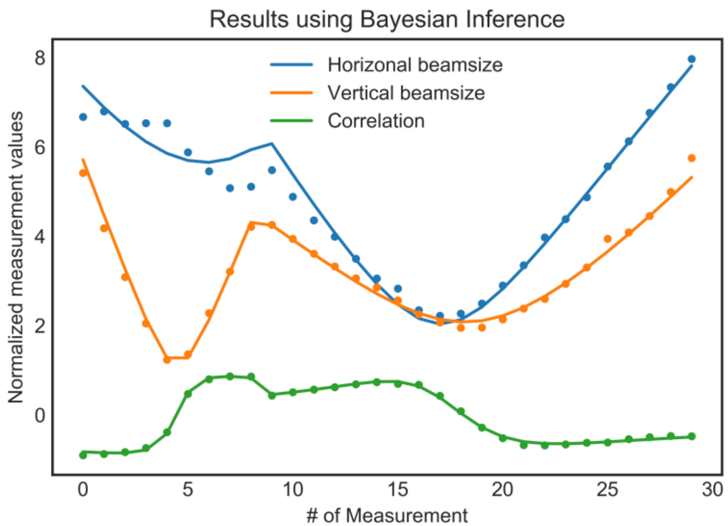
$$P((\sigma_1, V_1), \cdots, (\sigma_i, V_i), \cdots \mid \theta, \delta) = \prod_i P((\sigma_i, V_i) \mid \theta, \delta)$$

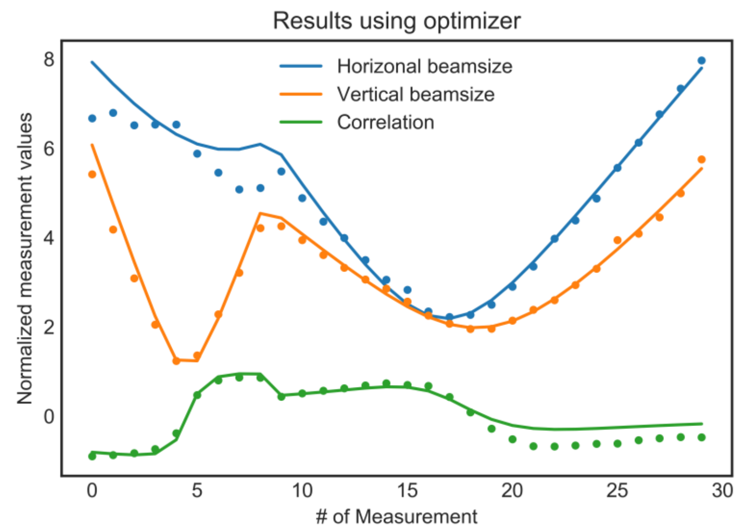
$$\sim \prod_i \frac{1}{\delta_x \delta_y \delta_{xy}} \exp - \frac{(\sigma_{\text{measure}} - \sigma_{\text{model}})^2}{2\delta^2}$$

The prior | Uniform / Gaussian / beta prime distributions

Quad Scan, Results Comparison

- We implemented the Metropolis-Hasting method in Python to sample the posterior distribution.
- The in-house linear model, FLAME, as the accelerator model. The linear model is fast enough to get converged result in ~10^3 seconds on laptop.

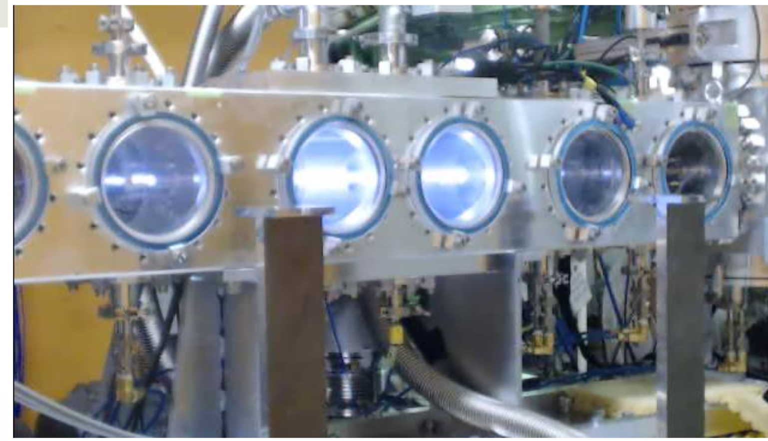


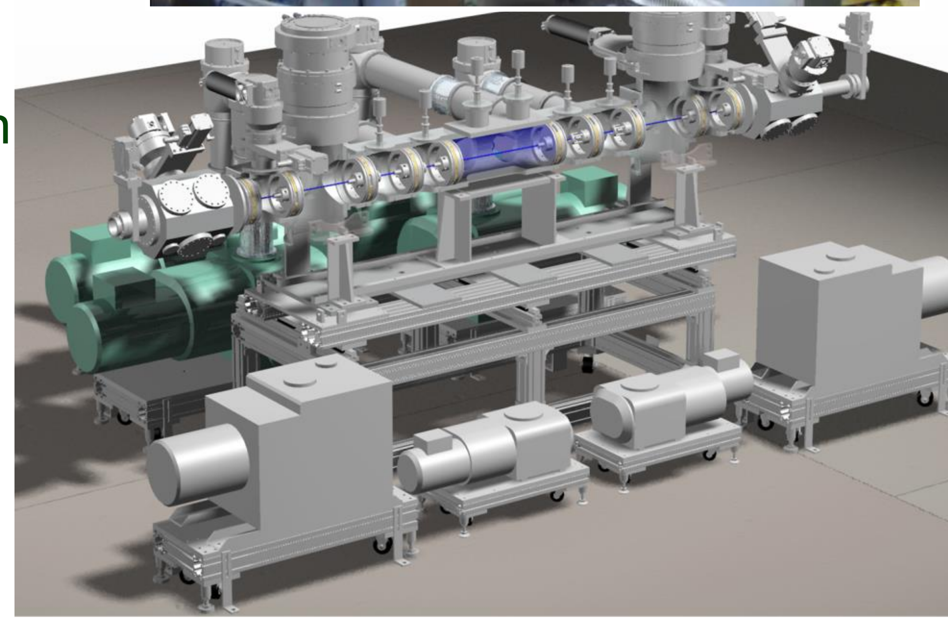


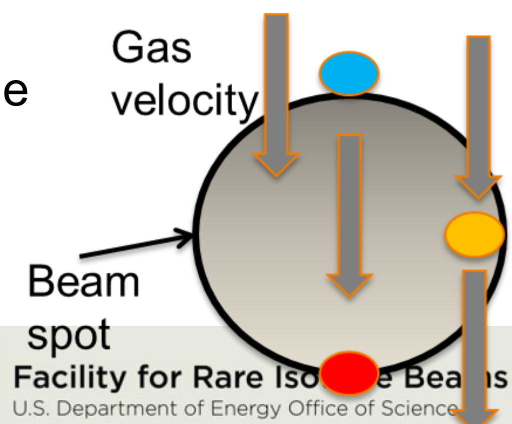
	emit_x [mm-mrad]	β_x [m]	α_x	emit_y [mm-mrad]	β_y [m]	α_y	C_{xy}	$C_{xy'}$	$C_{x'y}$	$C_{x'y'}$
Bayesian	0.104	2.76	-2.38	0.049	1.37	-0.31	0.26	0.63	-0.08	0.51
Optimizer	0.119	2.76	-2.26	0.05	1.51	-0.42	0.34	0.26	-0.06	0.01

Helium Gas Stripper

- A backup option for FRIB
- Technically feasible
- Drawback: differential pumping
- Using various available codes we can calculate:
  - Energy loss and straggling, roughly
  - Prediction of charge states
- There is no comprehensive model of high power heavy ion beam interaction with gas
  - Gas heating and expansion
  - Higher accuracy of energy loss
  - Optimize gas pressure as a function of beam energy
  - Charge exchange



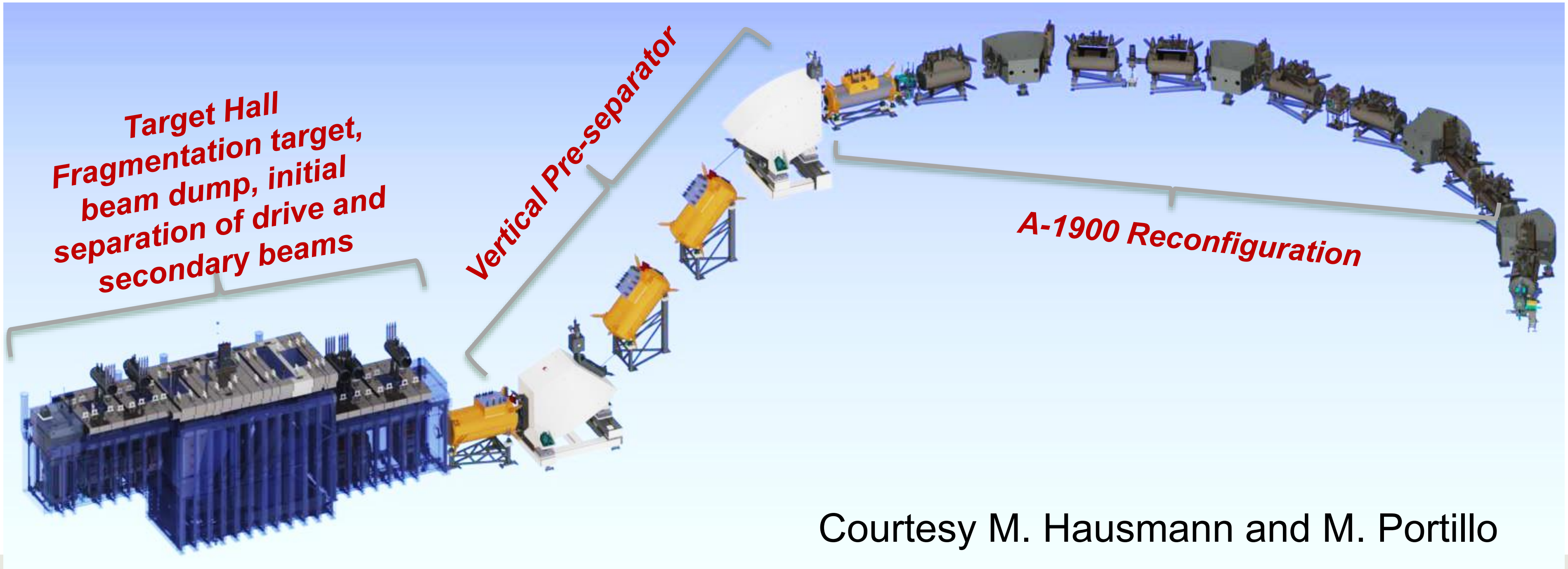




Courtesy of H. Okuno, F. Marti

FRIB Fragment Separators

- Design optimization up to 5th order using COSY INFINITY
  - http://bt.pa.msu.edu/index_cosy.htm
- Monte Carlo simulations of benchmark examples: COSY and LISE++
  - http://lise.nscl.msu.edu
- Next step is development of on-line tuning algorithms, possibly using stable beams
  - Main task is to find a reference trajectory to be able to apply COSY settings



Courtesy M. Hausmann and M. Portillo

FRIB Secondary Beams

- 5th order optimization is required due to
  - Reactions in the target increase the emittance significantly
  - Large aperture magnets
  - Large momentum acceptance of the fragment separators
- Reference trajectory
  - Different species with very similar $B\rho$ can be very close to each other spatially (few mm) at the location of the slits.
  - Since the fragment of interest may be much weaker than others, one needs particle-ID for successful tuning
  - Large scale calculations would be necessary for quick set-up of the experiment

LISE^{++}: Exotic Beam Production with Fragment-Separators and their Design

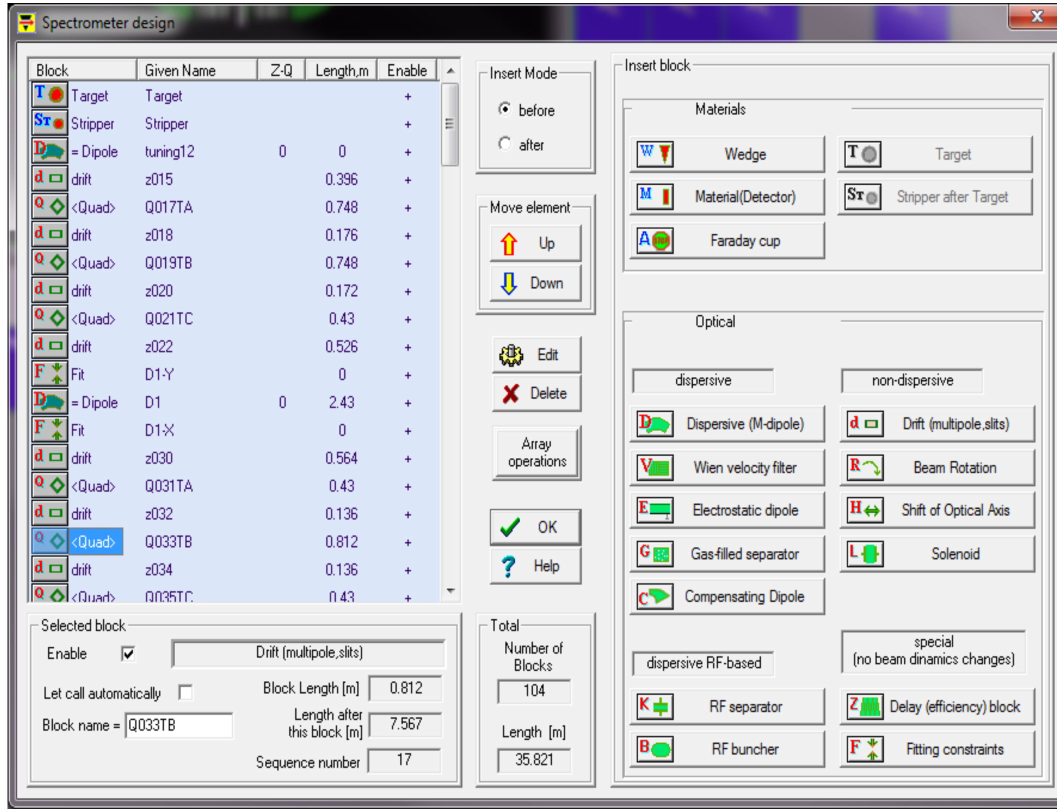
The code simulates nuclear physics experiments where fragments are produced then selected with a spectrometer:

- Tune separator,
- Fragment production,
- Transmission and purity calculation,
- Visualization of fragment distributions calculation results.

Optical matrices can be input by user, linked to COSY maps (up to 5th order) or calculated in the LISE++ code (up to 2nd order).

Calculation transmission methods:

- Fast analytical
- Detailed Monte Carlo analysis



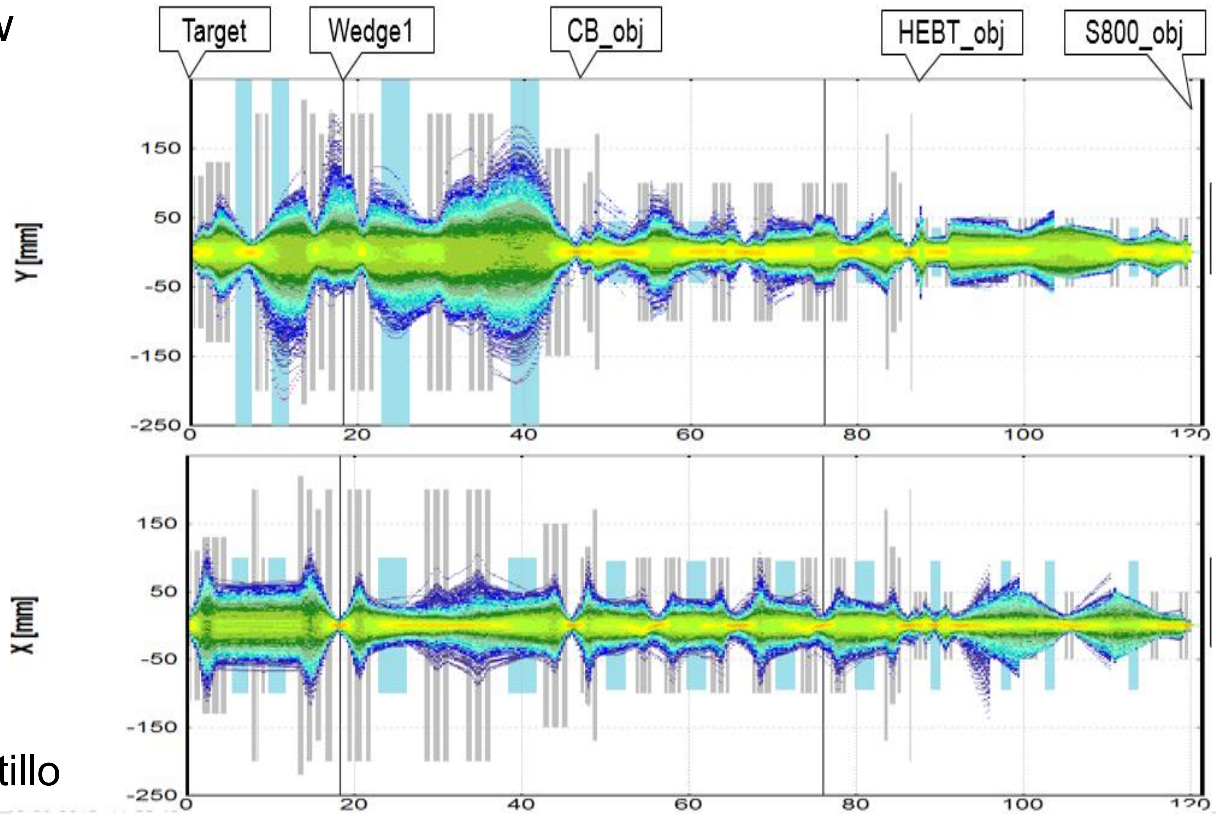
Main features:	O.B. Tarasov, D. Bazin, NIM B 266 (2008) 4657
Current status:	O.B. Tarasov, D. Bazin, NIM B 376 (2016) 185.
Plans:	M.P. Kuchera, et al., NIM B 376 (2016) 168.
LISE^{++} website:	http://lise.nscl.msu.edu

Each Isotope Tuning Requires Optimization

- Large scale computing is for the optimization of the fragment separator setting for particular isotope including wedges, slits and TOF mass separation
  - Calculate a lot of particles before we can get sufficient statistics on the one of interest
  - Parallel COSY is available
  - LISE^{++} needs to be moved to a modern framework with new compilers and parallelized

In the pre-separator (up to label "CB_obj"), the bending plane is vertical, while it is horizontal downstream of this point. The gray and light blue rectangles in the background represent the apertures of the focusing and bending magnets, respectively.

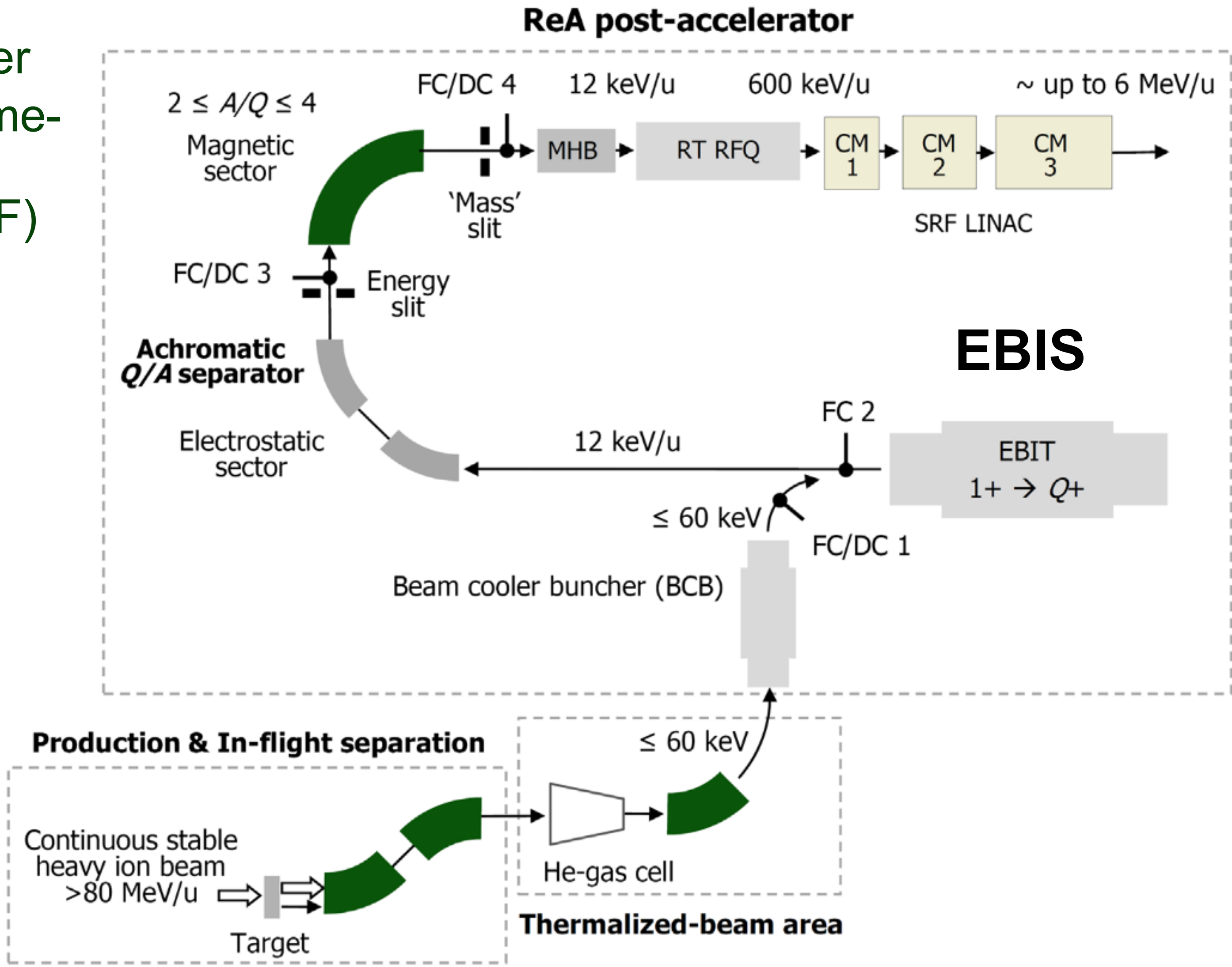
Ray density plot from LISE^{++} of ^{100}Sn products



Courtesy M. Hausmann and M. Portillo

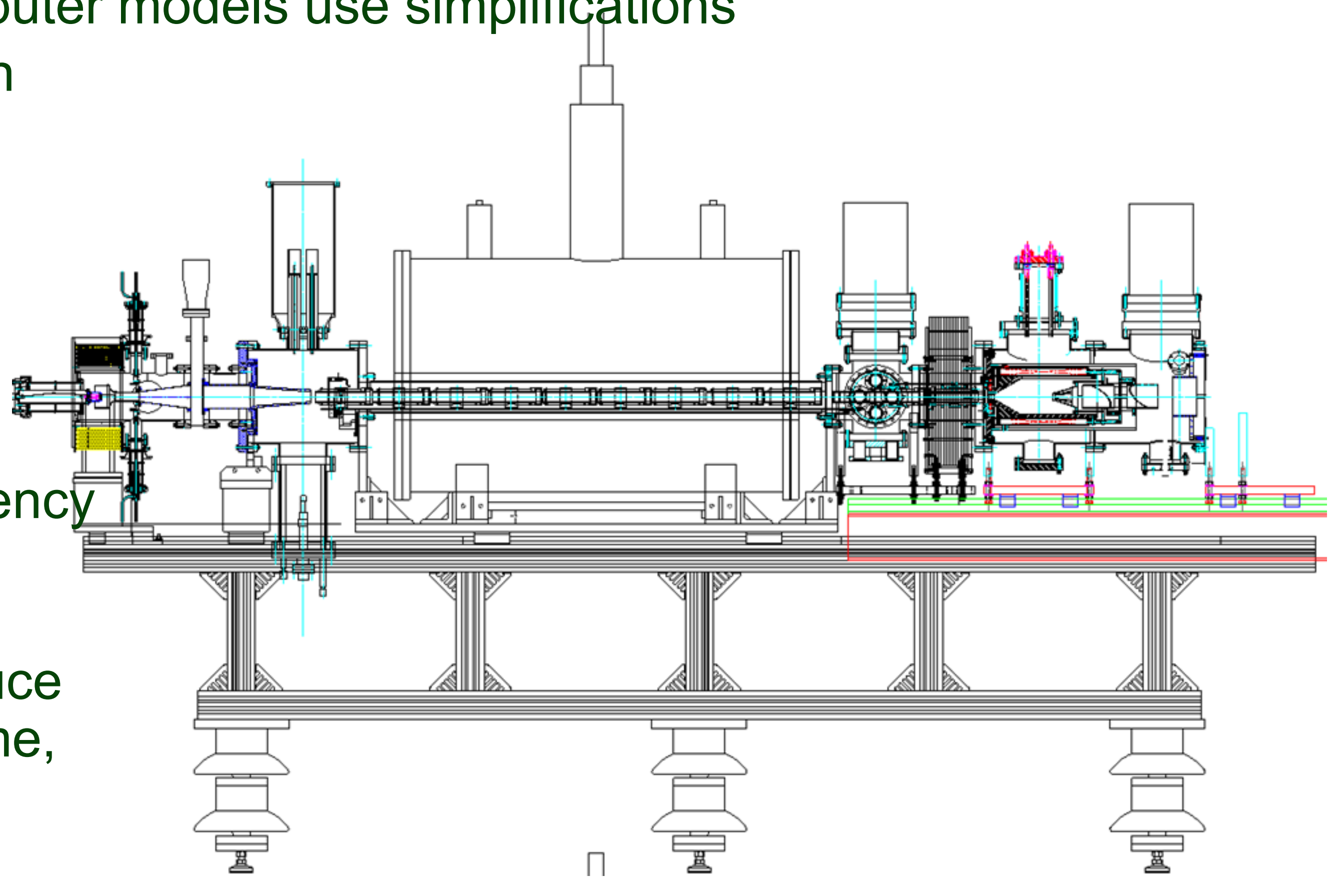
Rare Isotope Beam Preparation for Post-Acceleration

- Helium gas cell
- RFQ cooler-buncher
- Multi-Reflection Time-of-Flight Mass Separator (MR-TOF)



Electron Beam Ion Source or TRAP (EBIST)

- High current, low energy electron beam, up to 20 A
  - Magnetized or electrostatic electron gun
- 6 Tesla solenoid; stripping of ions by electron impact
- Existing EBIS computer models use simplifications
- Limitations: electron beam losses
- Effect of secondary electrons
- Emittance and time structure of the extracted ion beam
- Transmission efficiency of ions
- Electron gun optimization to reduce charge breeding time, increase charge capacity



Further Development of Simulation Codes is Required

- Helium gas stripper
  - 6D beam dynamics
  - Radioactive ion beam collisions with helium gas
  - Charge exchange
  - Ion beam space charge
- RFQ cooler-buncher
  - 6D beam dynamics
  - Radioactive ion beam cooling due to collisions with helium gas
  - Ion beam space charge
  - Charge exchange
- LISE^{++}
  - Plans for performance and model improvements in the LISE^{++} software
    Nuclear Instruments and Methods in Physics Research B 376 (2016) 168–170

Conclusion

- Design of accelerator and experimental systems is complete
  - Reliable set of computational codes exists
- Focus on development of on-line physics applications and update of the virtual accelerator model
- Fast parallel codes are required for simulation of rare isotope production, transport and separation
- On-line tuning of fragment separators: development of physics applications is required
- New codes are required for simulation and optimization of FRIB systems to prepare rare isotope beams for post-acceleration