End-to-end Beam Dynamics Simulations for the RIA Driver Linac

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on behalf of RIA team

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RIA related posters:
MOP01, MOP71, MOP90
TUP26
THP05, THP06, THP15

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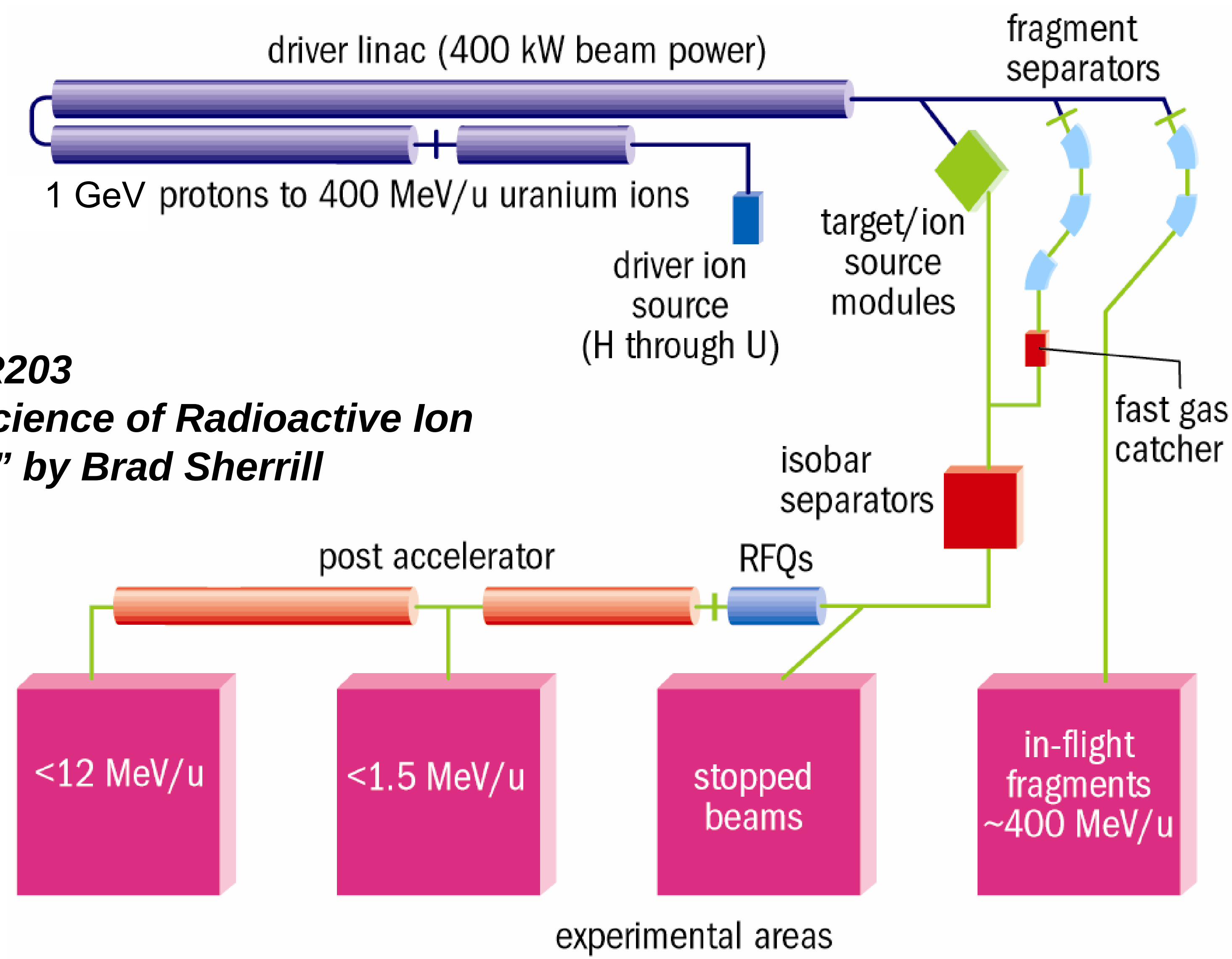
Outline

1. **RIA Facility**
   - Layout
   - Major requirements
2. **Beam Dynamics in the Driver Linac**
   - Major components of the Driver Linac
   - Scope of the Beam Dynamics Studies
     - *Design codes*
     - *Features of the new code TRACK*
   - Front End
   - Stripping/Collimation
   - End-to-end simulation
3. **Beam Loss calculations**
   - Typical errors
   - Beam-based steering algorithm
   - Two options of the Driver Linac
   - Results
4. **Conclusion**

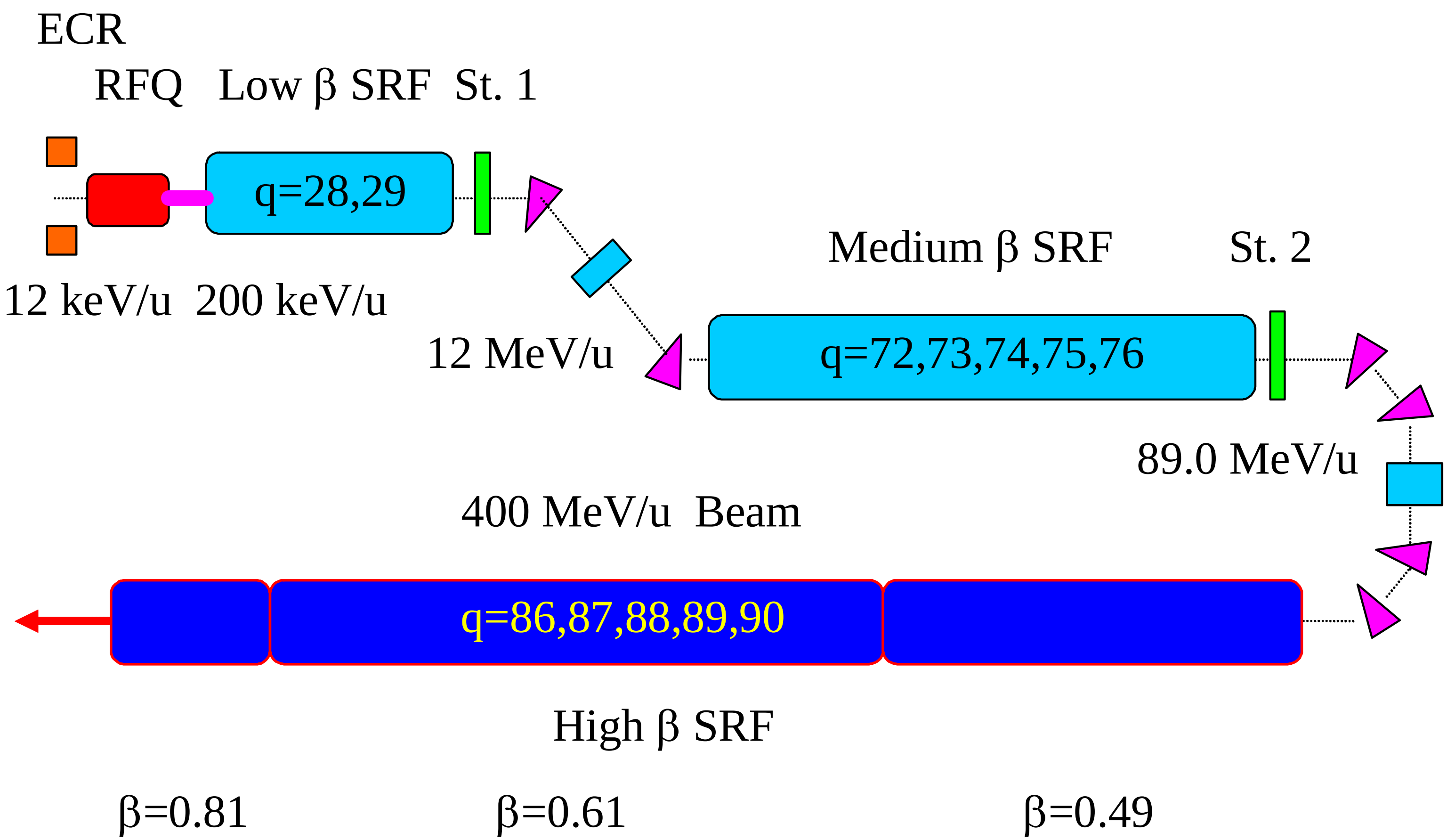
Schematic of the RIA facility



Talk FR203
"The Science of Radioactive Ion Beams" by Brad Sherrill

RIA Driver Linac

Multi-ion, multi-charge-state, 1.4 GV Ion Linac
400 kW beams of ALL ions from protons to Uranium



Baseline Design: 393 SC cavities of 9 different types arrayed in three linac sections

Scope of the Beam Dynamics studies

- **Overall linac architecture design to satisfy user requirements:**
  - Choice of initial parameters (frequency of SRF, # of strippers …)
  - Choice of focusing and accelerating lattice;
  - Transition from RT to SC structures;
  - Stripper locations;
- **Beam matching**
  - Longitudinal&transverse matching between the segments of the linac
  - Optimize stripper location to obtain lowest effective emittance of multi-q beam
  - Beam spot on the strippers ~ ϕ1 mm, short bunches
  - 6D matching of multi-q beams after the strippers
- **Iteration of the BD design with SRF performance**
  - Peak surface field;
  - Mechanical design of cavities and cryostats;
  - Overall accelerator footprint.

Scope of the Beam Dynamics studies (cont'd)

- **Detailed BD simulations**
  - Develop realistic model of the linac
    - *Include realistic 3D-fields for all elements*
    - *Stripper effects*
    - *Space charge effects in the ECR extraction region and LEBT*
  - Perform end-to-end simulations;
  - Establish tolerance budget for errors and misalignments;
  - Failure modes and reliability&availability analysis.
- **Beam loss studies for various options of the linac.**

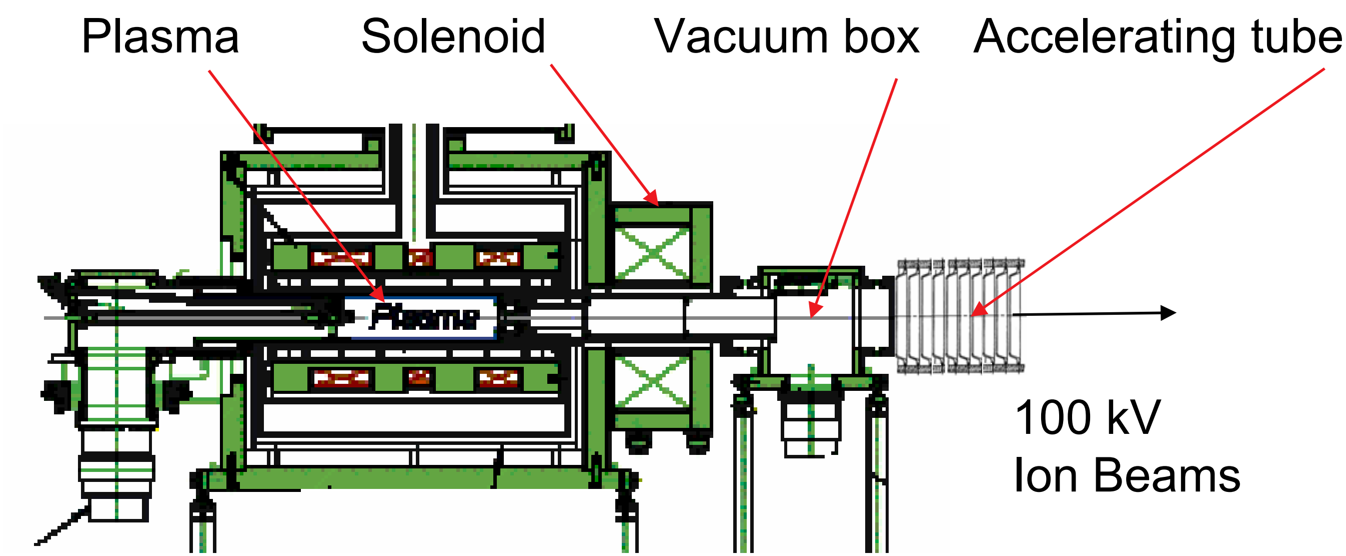
Beam Dynamics Studies in the Driver Linac

- **Significant design&simulation work has been performed in previous years**
  - multi-q beam acceleration and transport,
  - bunching and RFQ acceleration of dual-charge state heavy-ion beams,
  - steering compensation
  - ……
- **Recently we have concentrated on three main areas of the Driver Linac to complete End-to-End simulations:**
  - Beam extraction from the ECR and acceleration up to 100 KV
  - Design of the achromatic LEBT to bring the dual charge state heavy-ion beam to the MHB
  - Massive parallel-processor simulations including all types of errors with the goal to detect controlled and uncontrolled beam losses along the linac

Main tool for the End-to-End simulations: the code TRACK

- **Tracking of ions from ECR extraction aperture to the targets**
- **Integration of particle trajectories of multi-component ion beams in 6D phase space;**
- **Fields for all linac elements are obtained from 3-dimensional external codes.**
- **Misalignments and random errors are included. Beam-based corrective steering is an integral part of the code.**
- **Space charge of multiple component ion beams is obtained as a solution of 2D&3D Poisson equation.**
- **Beam passage through stripping foils&films is included**
- **LINUX version of the TRACK code runs on multi-processor computer cluster JAZZ at ANL.**

Beam extraction from the VENUS ECR



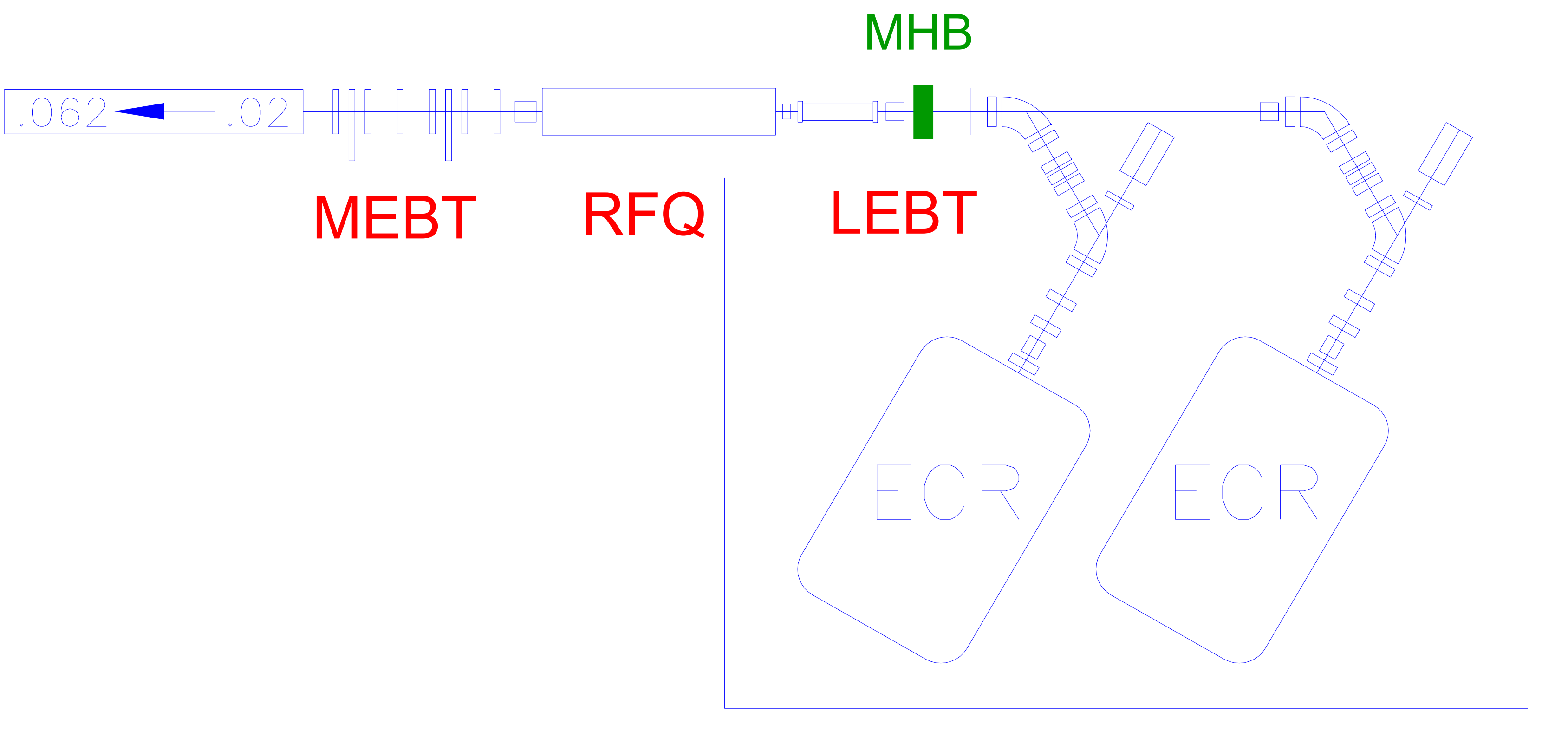
Simulation of 13 ion species with total current 4 mA including 125 eμA for each charge state of Uranium 28+ and 29+

Our findings: **a)** $\varepsilon_{T,rms}$ **= 0.1 π mm mrad**

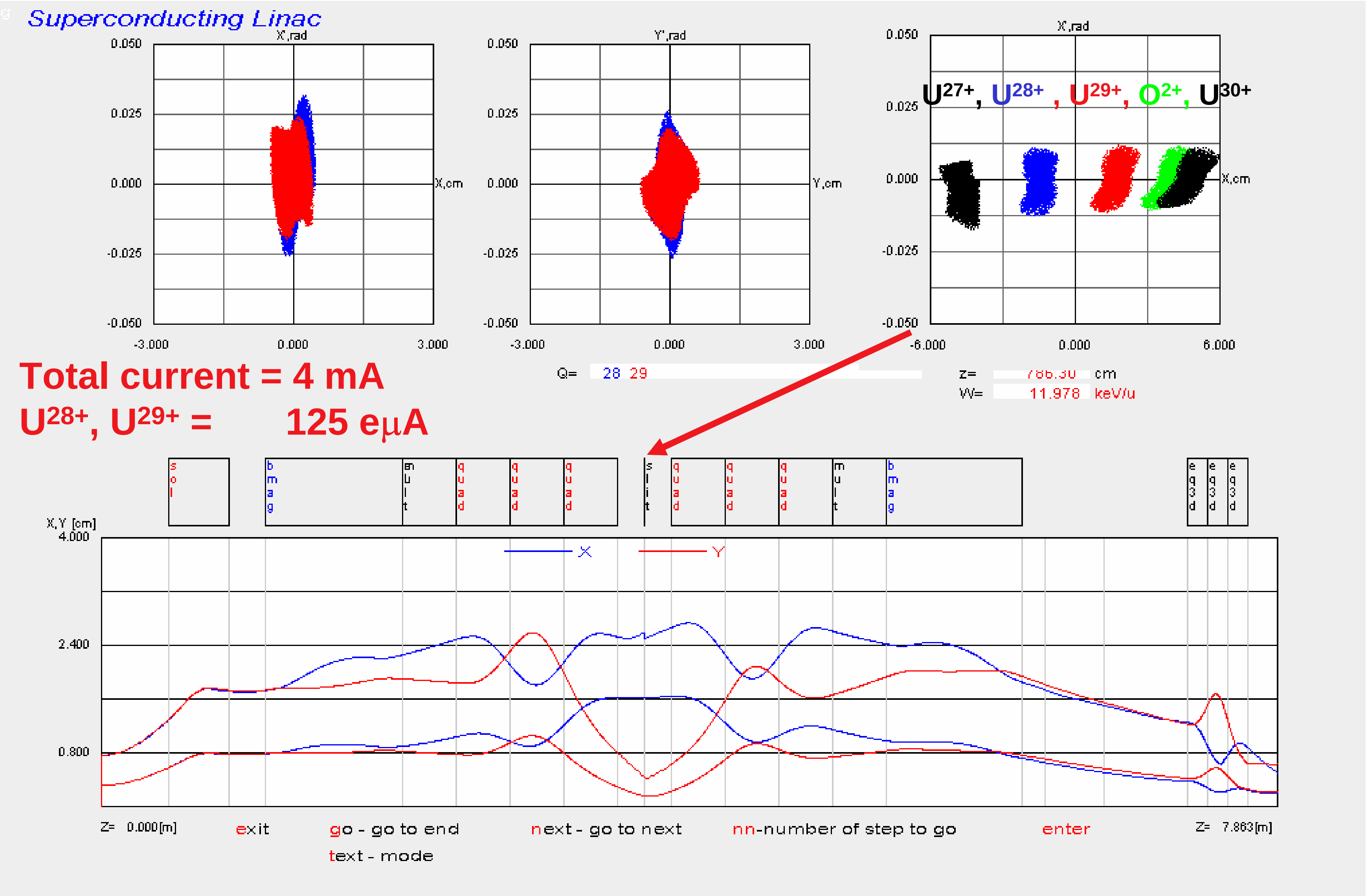
b) ε_{Total} **= 0.6 π mm mrad**

c) Beam waist downstream of the accelerating tube can be formed

Front End of the Driver Linac



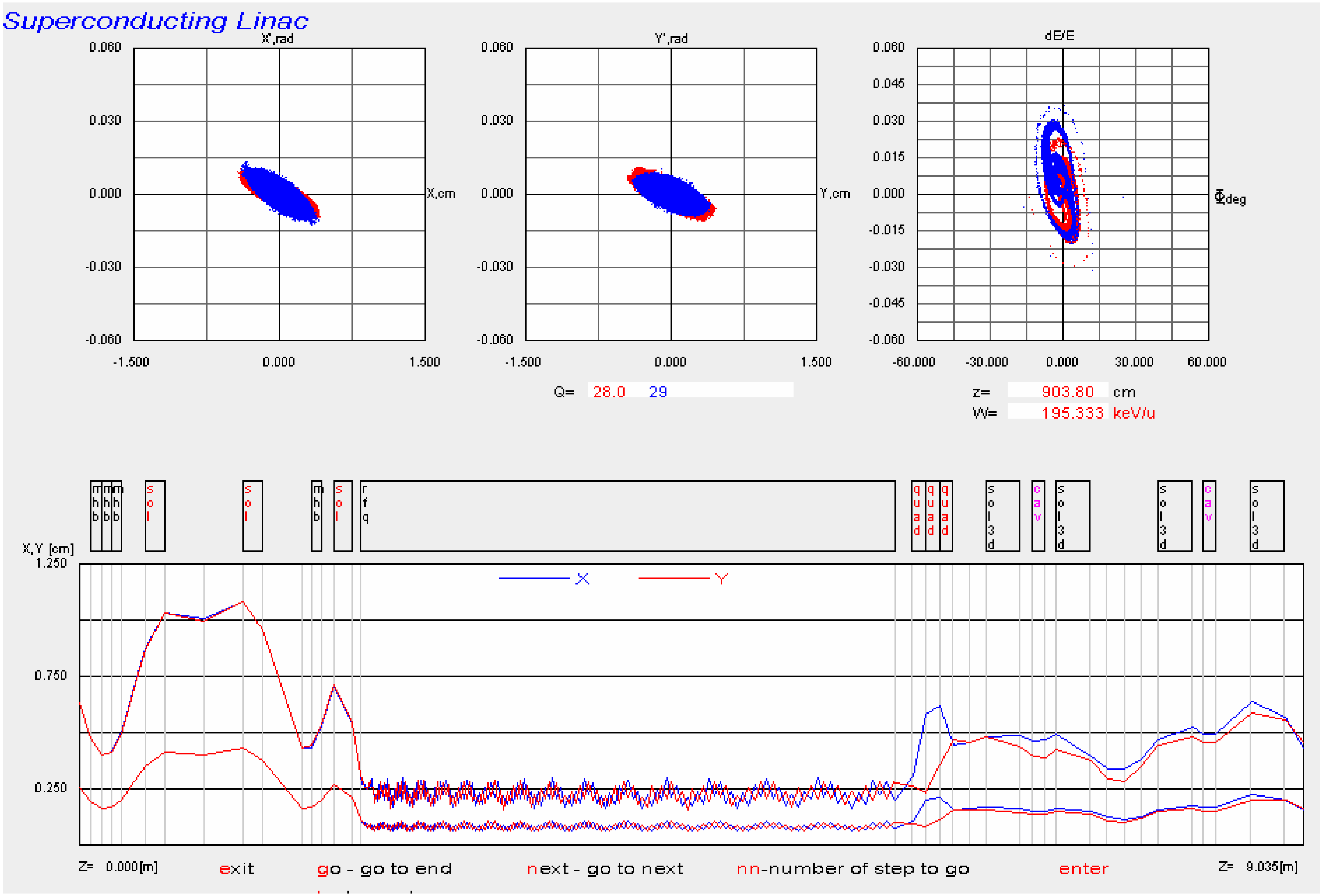
LEBT must be designed for high current beams



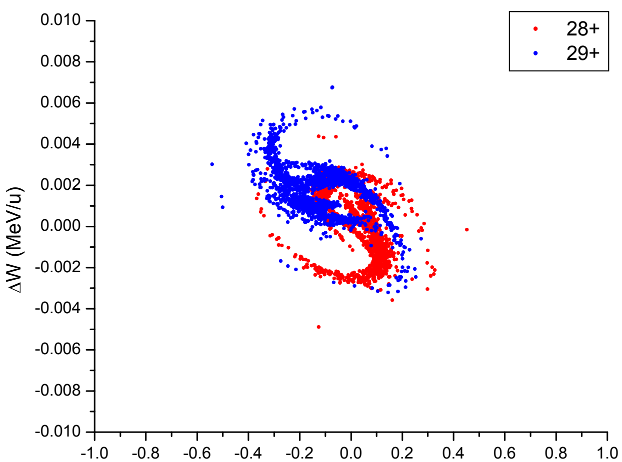
Total current = 4 mA

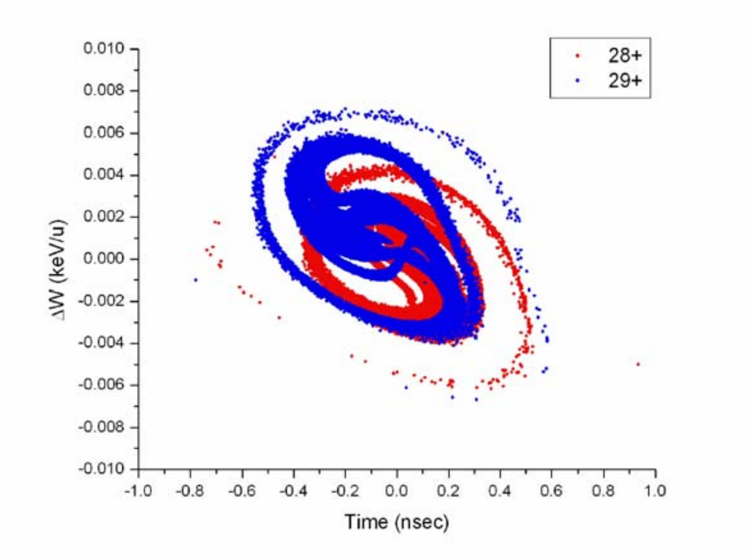
U^{28+}, U^{29+} = 125 eμA

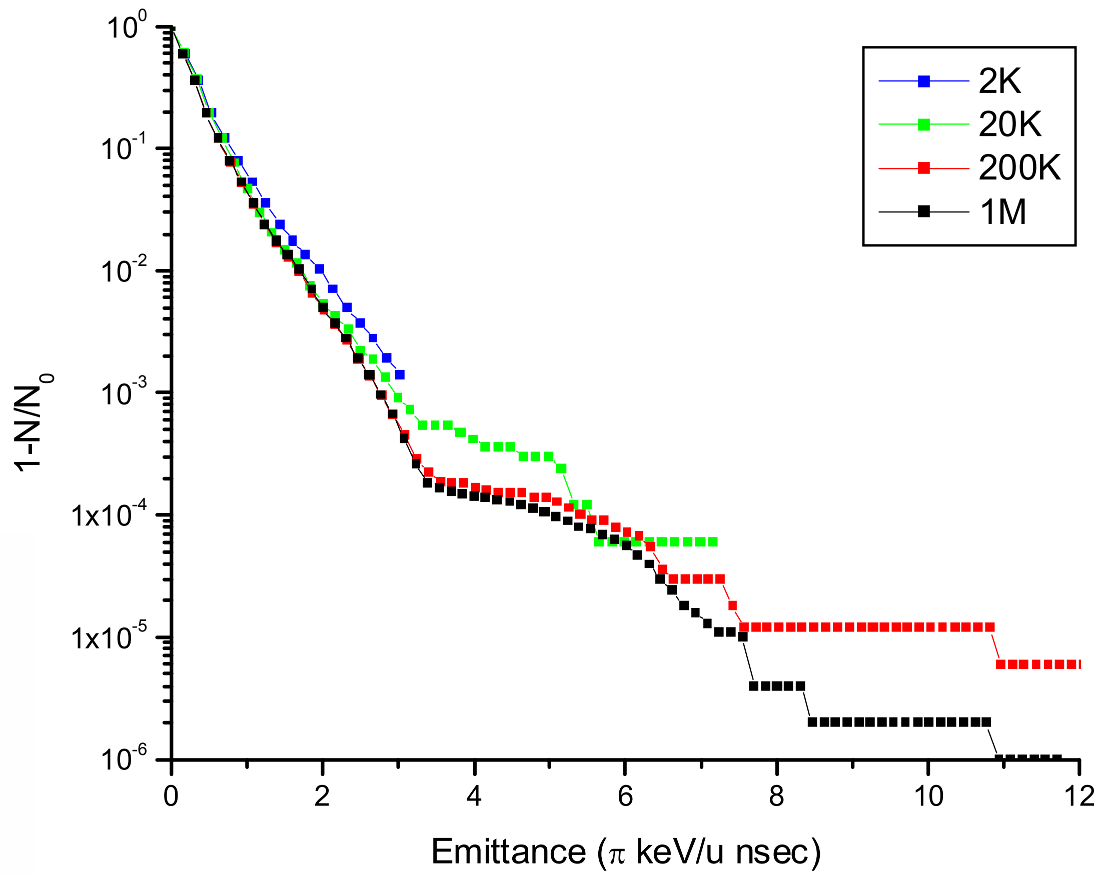
MHB-RFQ-MEBT


Superconducting Linac
X',rad
Y',rad
dE/E
X,cm
Y,cm
Φ,deg
Q= 28.0 29
z= 903.80 cm
W= 195.333 keV/u
X,Y [cm]
X
Y
Z= 0.000[m]
exit
go - go to end
next - go to next
nn-number of step to go
enter
Z= 9.035[m]

Longitudinal emittance of 2q-beam at the entrance of the SC linac

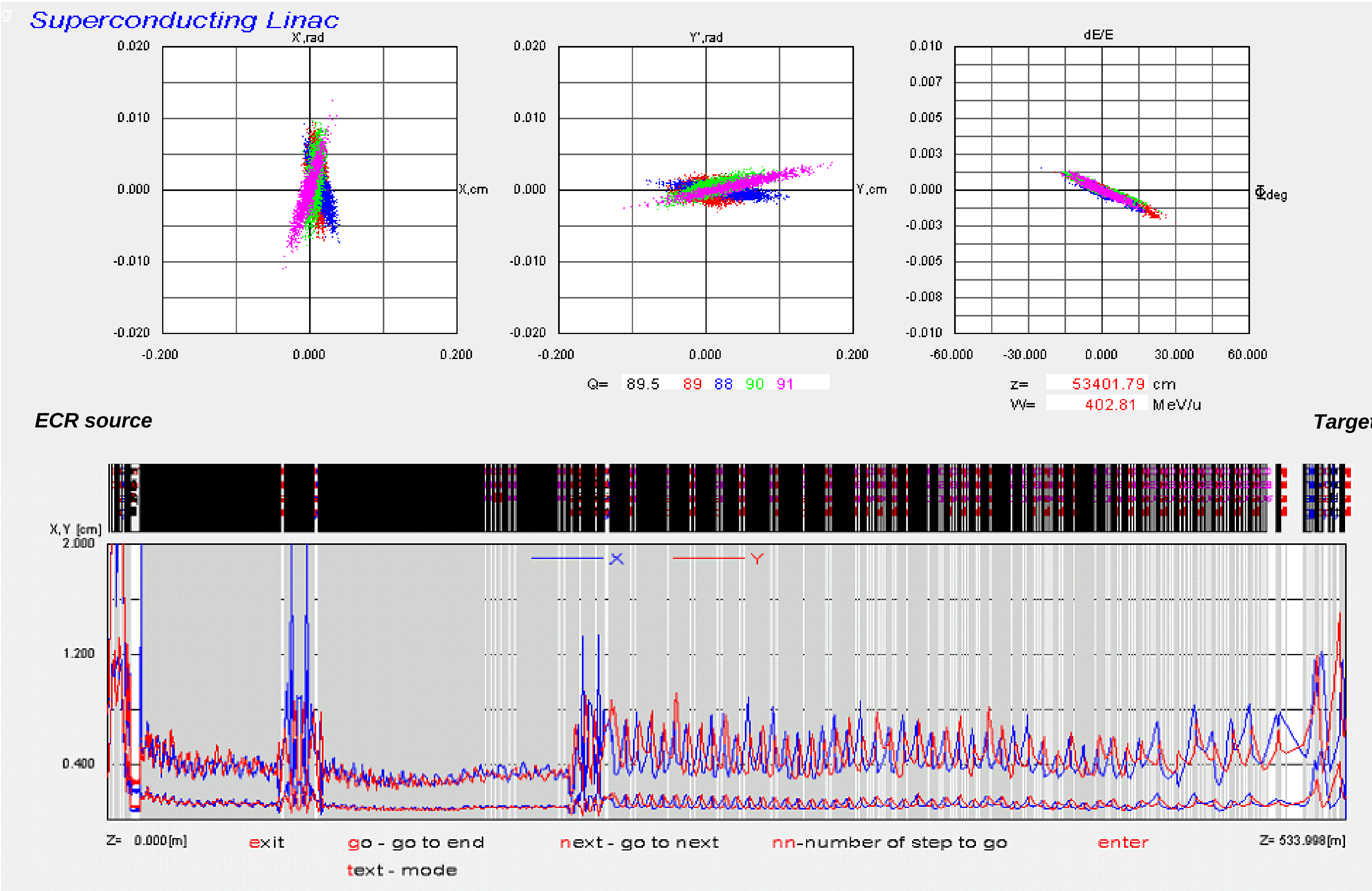






Fraction of particles outside of a given longitudinal emittance as a function of the emittance.

BD studies: End-to-end simulation



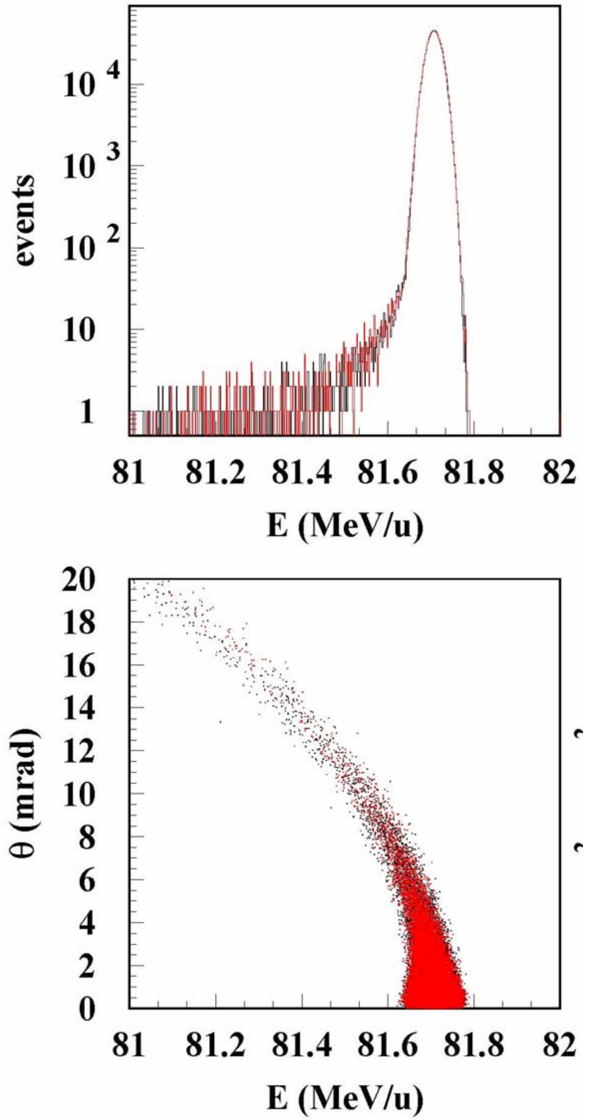
TRACK Features: stripper parameterization

U-238 at 85 MeV/u on

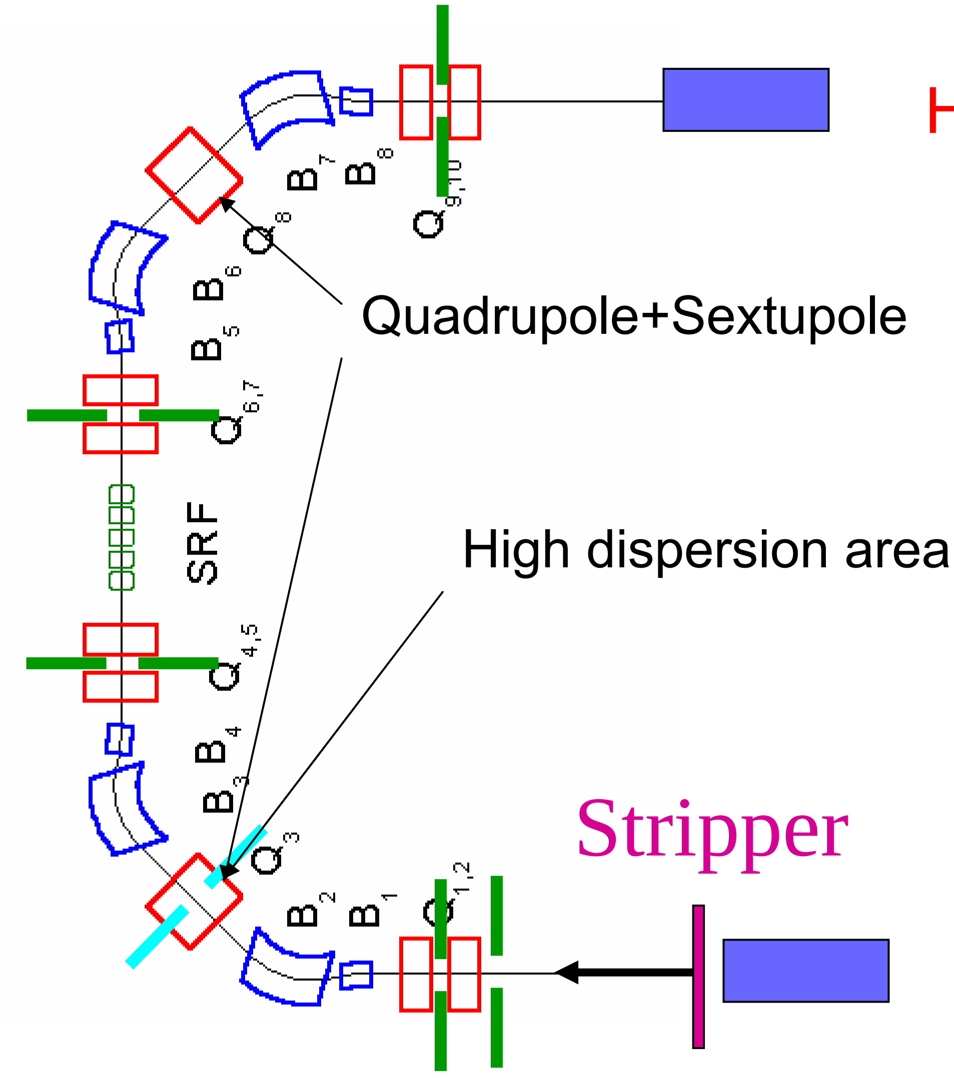
15 mg/cm^2 carbon stripper

Energy loss: 3.4 MeV/u

Thickness fluctuation ±5% produces ±170 keV/u energy spread



Multi-Q beam matching, 180° bend, collimation



86 MeV/u (after the stripping)

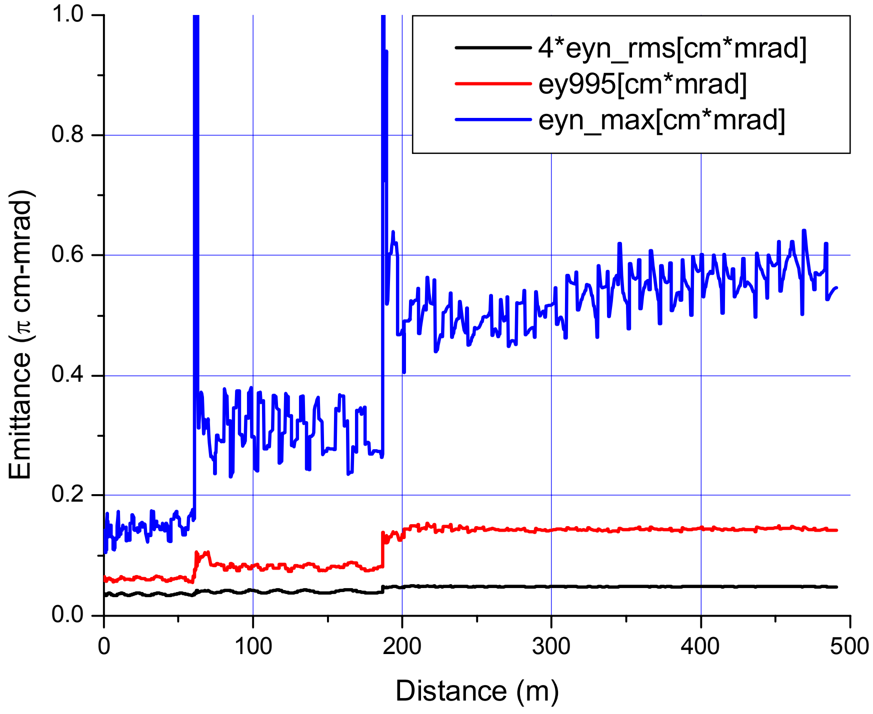
Beam losses for the 400 kW driver beam

“main” collimator: ~2 kW
“cleaning” collimators: ~85 W

Emittance (million particles, 5% FWHM thickness fluctuation)

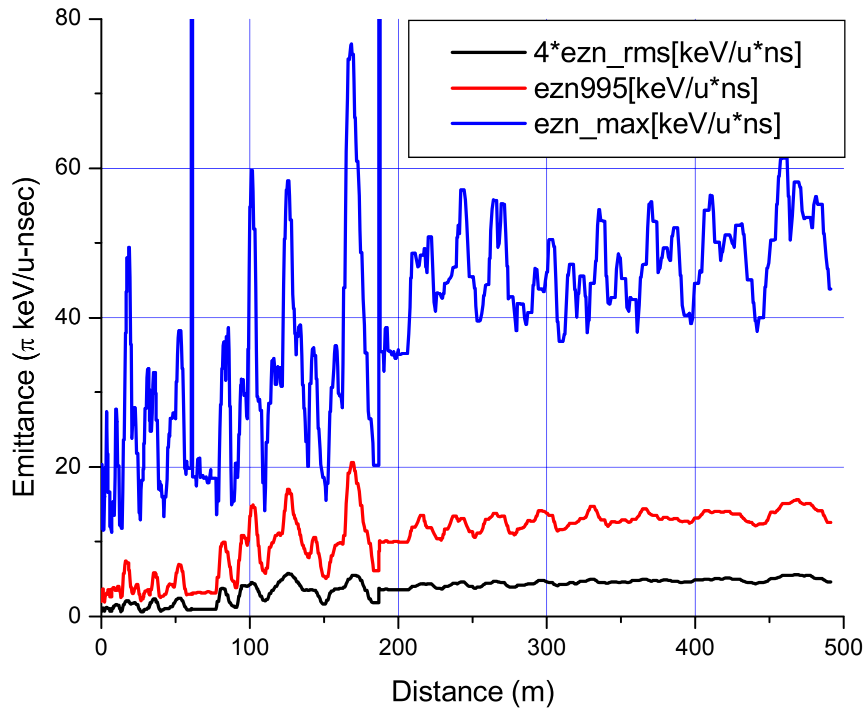
Vertical emittance

Chicane-1 Chicane-2



Longitudinal emittance

Chicane-1 Chicane-2



Errors & their typical values

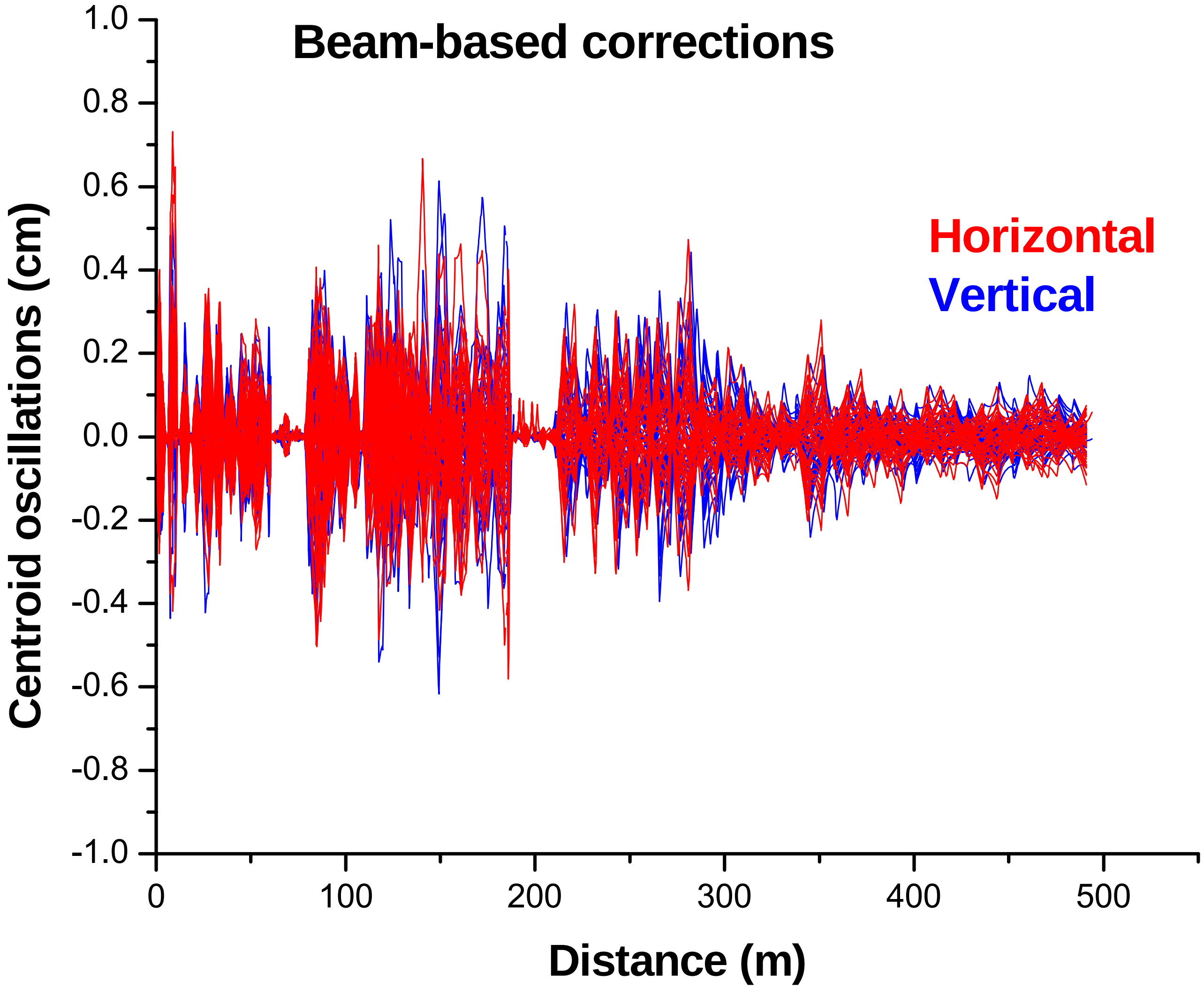
Error	Description	Value	Distribution
1	Cavity end displacements	.05 cm (max.)	Uniform
2	Sol. end displacements	.015-.05 cm (max.)	Uniform
3	Quad. end displacements	.01 cm (max.)	Uniform
4	Quad. rotation	2 mrad (max.)	Uniform
5	Cavity field error	0.5 % (r.m.s.)	Gaussian
6	Cavity phase error	0.5 deg (r.m.s.)	Gaussian
7	Stripper thickness Fluc.	5-10 % (FWHM)	Gaussian

Beam-Based Steering

- **Multiple charge states: effective transverse emittance growth.**
- **Frequent machine-settings: retuning to accommodate many different ion species.**
- **Algorithm is an integral part of the TRACK code.**
- **Is capable of being implemented in real machines.**
- **Method:**
  - Measure beam positions at BPMs
  - Apply known deflections (kicks) to the trajectory
  - Measure the new beam positions and calculate the differences
  - Measure beam responses to induced kicks
  - Find $\vec{\theta}$ that minimizes $\Phi \; \alpha \; (\vec{X} + R\vec{\theta})^2$
  - Apply steering
- **Compensates 'static' misalignment errors.**

Correction of multi-q beam position (50 seeds)

Residual deviation of beam centroid along the linac

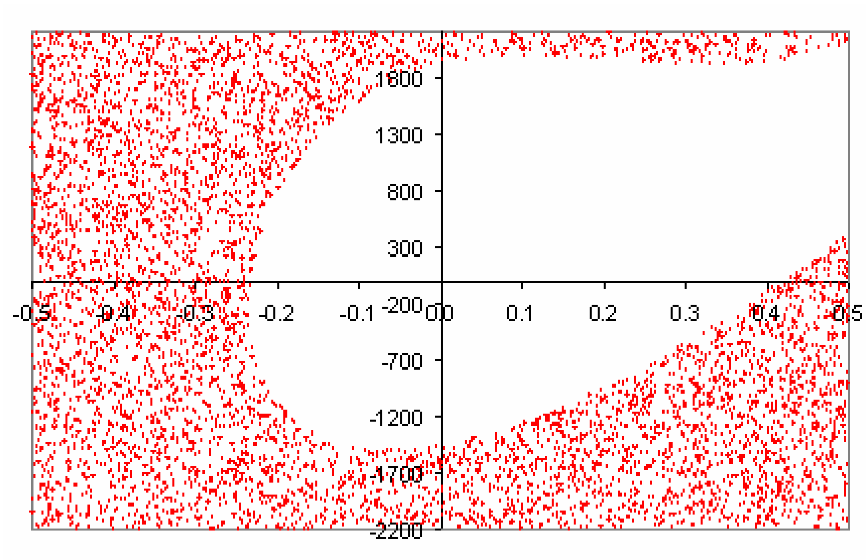


Beam-Loss Calculations

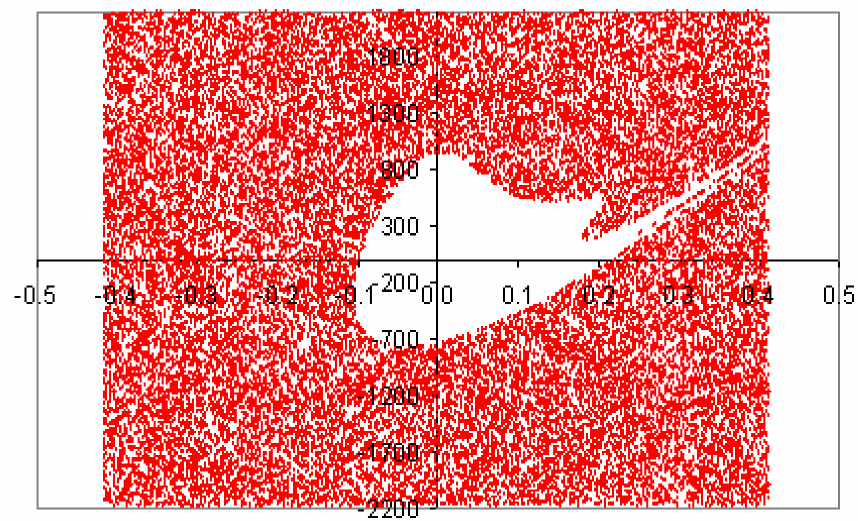
- **Final step of BD design studies**
- **Simulations on the multi-processor computer**
- **Up to 500 randomly seeded accelerators with all types of errors and misalignments, typically 200 seeds**
- **Beam steering is applied**
- **Wide range of rf errors, thickness fluctuation and their combinations have been studied**
- **Number of tracked particles:**
  - Up to 10^6, typically $2 \cdot 10^5$ in each seed
  - Total number of simulated particles 40 million, some cases up to 200 million.

Two options of the Driver Linac

Triple-spoke resonators
345 MHz
E_{peak}= 27.5 MV/m



Baseline Design: 6-cell elliptical cavities 805 MHz
E_{peak}=27.5 MV/m



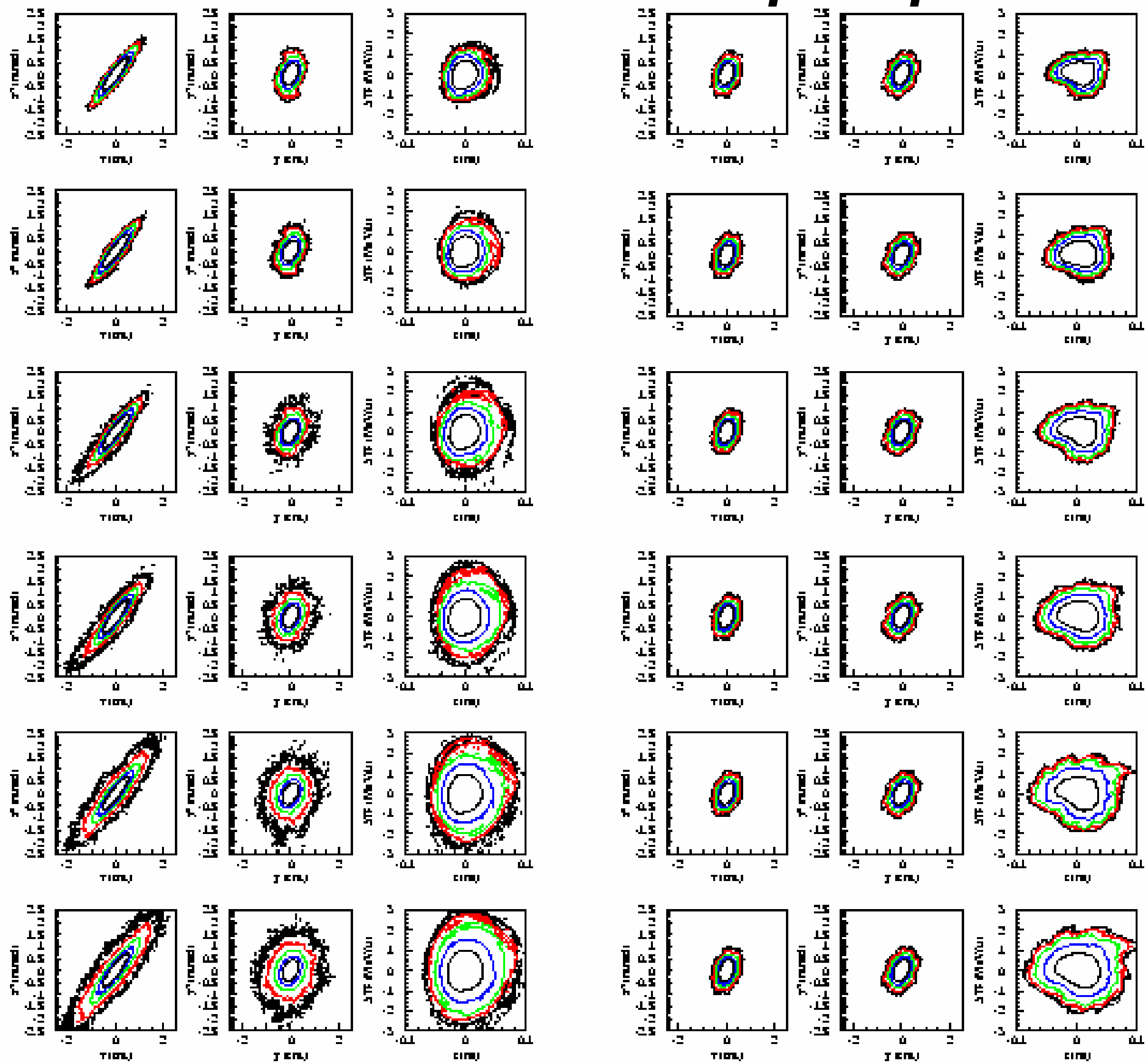
Beam losses: Fractions & Locations

- **Two types of losses:**
  - Controlled losses: Beam halo particles intercepted by collimators placed at designated areas of the accelerator (example: MTS after a stripper).
  - Uncontrolled losses: Beam particles lost in the structures of the accelerator resulting in the radio-activation of the equipment.
- **Case with only stripper thickness 5% (FWHM) fluctuations :**
  - No uncontrolled losses.
  - Controlled losses: ~ 0.2 % in MTS-1 and ~ 0.3 % in MTS-2.
- **Case with errors:**
  - 6 combinations of errors have been studies (see next table).
  - Uncontrolled losses observed in the high-β section of the baseline design.
  - Controlled losses: slight increase but remains in the 0.2-0.4% range.

Beam emittances, image of 40 million particles

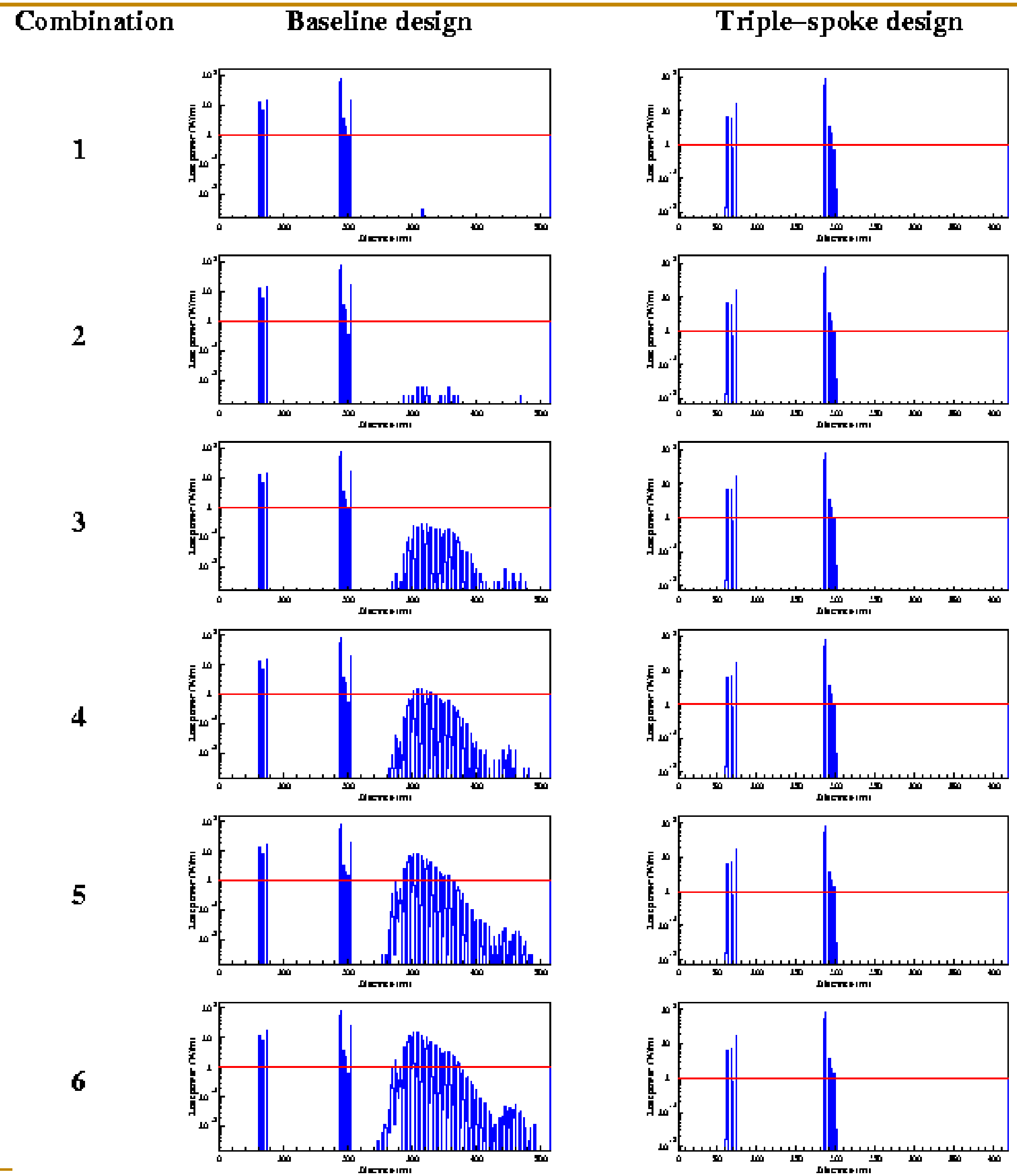
RF errors, Field, Phase	Thickness fluct. FWHM
0.3%, 0.3°	5%
0.3%,0.3°	10%
0.5%, 0.5°	5%
0.5%, 0.5°	10%
0.7%, 0.7°	5%
0.7%, 0.7°	10%

Baseline ***Triple-spoke***



Beam losses in Watts/m

Baseline
3.0 E-8
8.2 E-7
5.5 E-5
2.7 E-4
1.4 E-3
2.6 E-3



Results of beam loss studies

- **Most critical sources of error:**
  - RF errors (field & phase).
  - Fluctuations in stripper thickness.
- **The Triple-spoke design is more tolerant of errors than the Baseline design.**
- **Uncontrolled losses observed for the Baseline design. To keep the losses below the 1 Watt/m limit:**
  - RF errors: field < 0.5 % and phase < 0.5 deg.
  - Stripper thickness fluctuation < 5 % FWHM.
- **No uncontrolled losses observed for the Triple-spoke design even with RF errors (0.7%, 0.7deg, RMS) and thickness fluctuation of 10% FWHM.**

- **More details:**

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Beam loss studies in high-intensity heavy-ion linacs

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(Received 9 June 2004)

Conclusion

- **Beam dynamics design and simulations tools are ready to support value engineering and construction phase of the RIA facility;**

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