BEAM PHYSICS IN THE RIA ACCELERATORS

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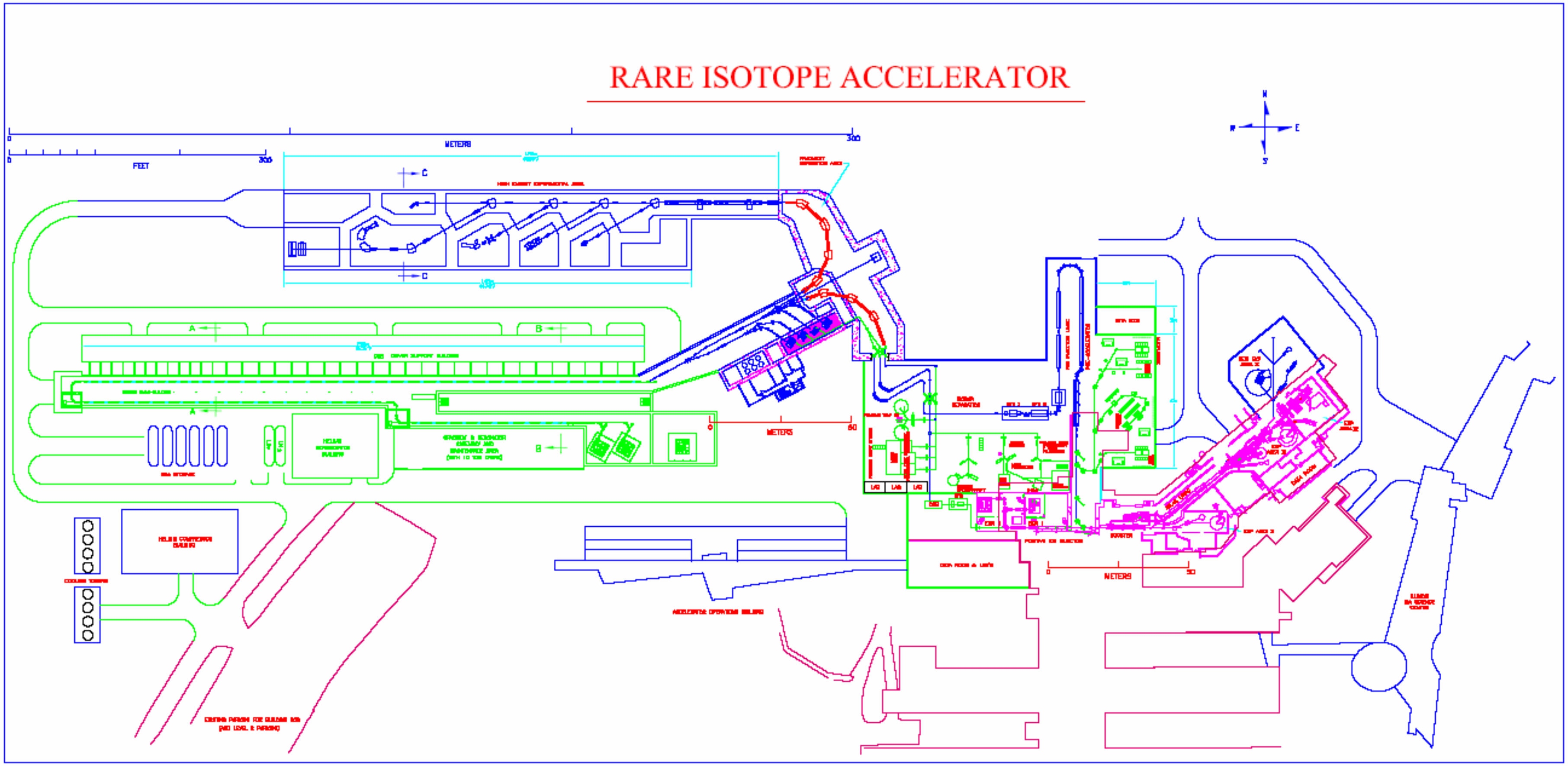
Outline

- **RIA Facility**
  - Layout
  - Technical features
  - Production of secondary beams
- **Driver linac**
  - **General design philosophy;**
  - **Acceleration of multiple-charge state beam;**
  - **Front end**
    - ***ECR***
    - ***2q-LEBT***
    - ***RFQ***
  - **Isopath transport of multi-q beams;**
  - **Stripping of heavy ions;**
  - **Beam loss studies, concept of "beam-halo cleaning";**
  - **Tunes for different Ions;**
- **Beam Dynamics code TRACK;**
- **Post-Accelerator.**

What is RIA?

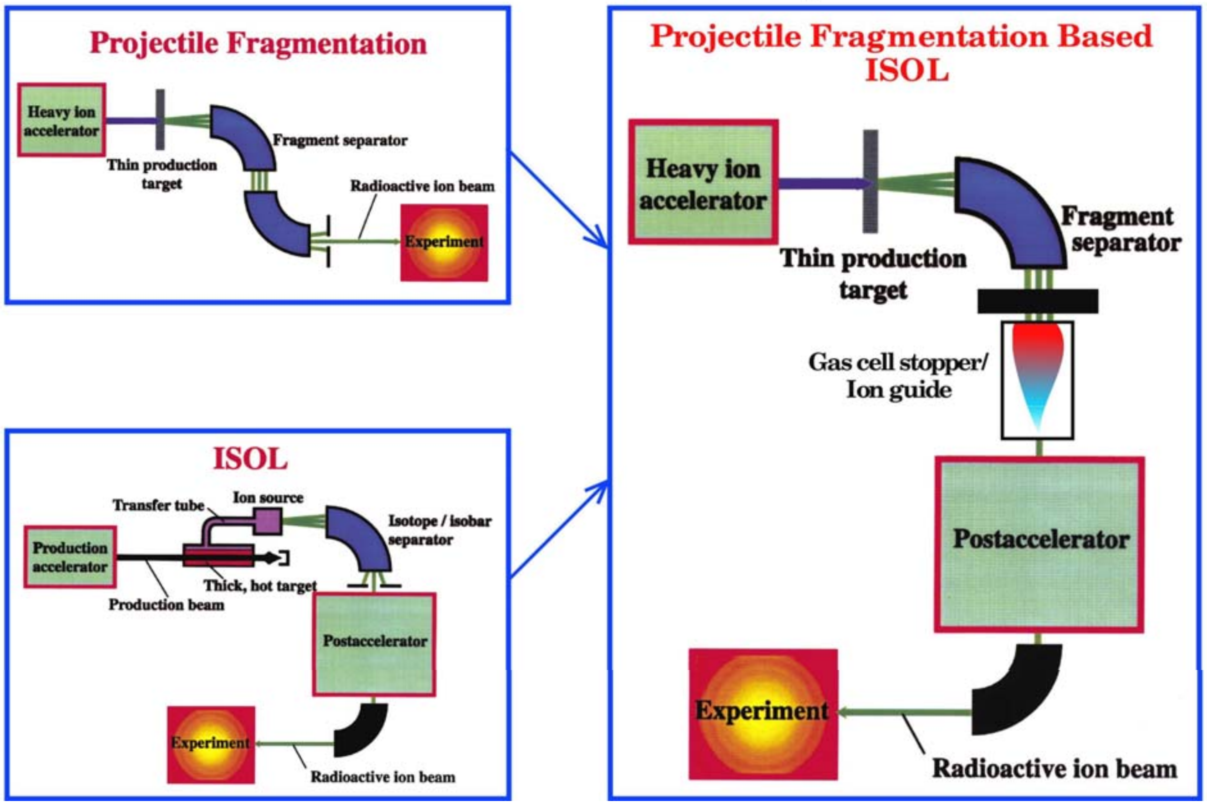


Important Technical Features of RIA

- High power CW SC Linac Driver (1.4 GV, 400 kW)
  - Advanced ECR Ion Source
  - Accelerate 2 charge states of U from ECR
  - All beams: protons-uranium
  - Superconducting linac over extended energy range: 0.25 – 1020 MeV/u
  - Multiple-charge-state acceleration after strippers
  - Multi-user facility: RF switching to multiple targets with independent beam intensity adjustment by means of fast chopper
- Large acceptance fragment separators
  - 1) "Range Bunching" + Fast gas catcher
  - 2) High resolution and high purity for in-flight
- High power density ISOL and fragmentation targets
  - Liquid lithium as target for fragmentation and cooling for n-generator
- Efficient post-acceleration from 1+ ion sources
- Next-generation instrumentation for research with rare isotopes

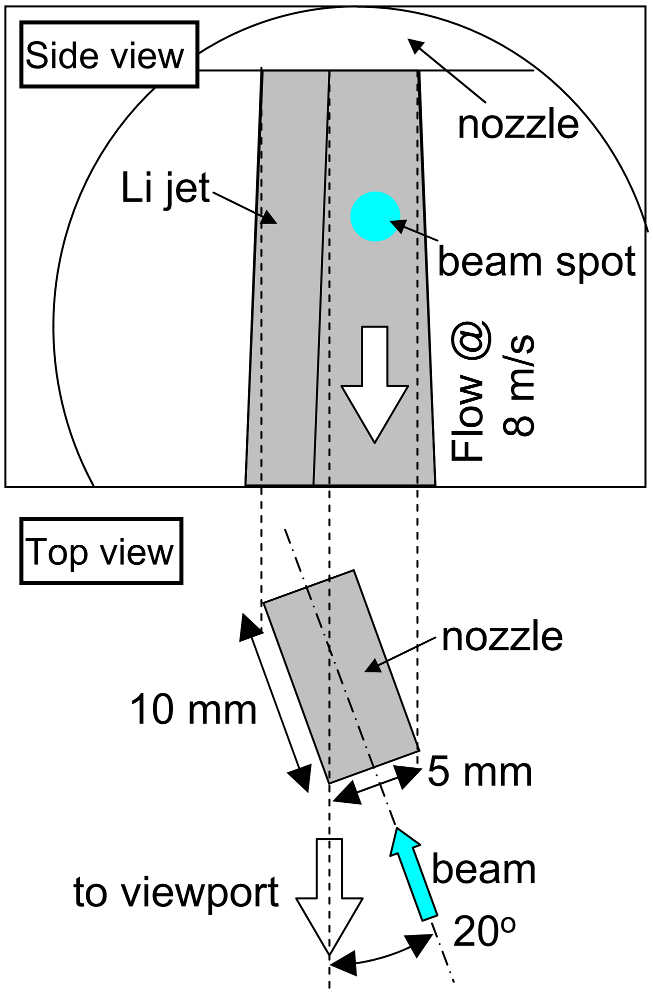
The Key Elements of the RIA Concept

- Fast Extraction Times (~msec)
- Chemical independence
- Isobar separation



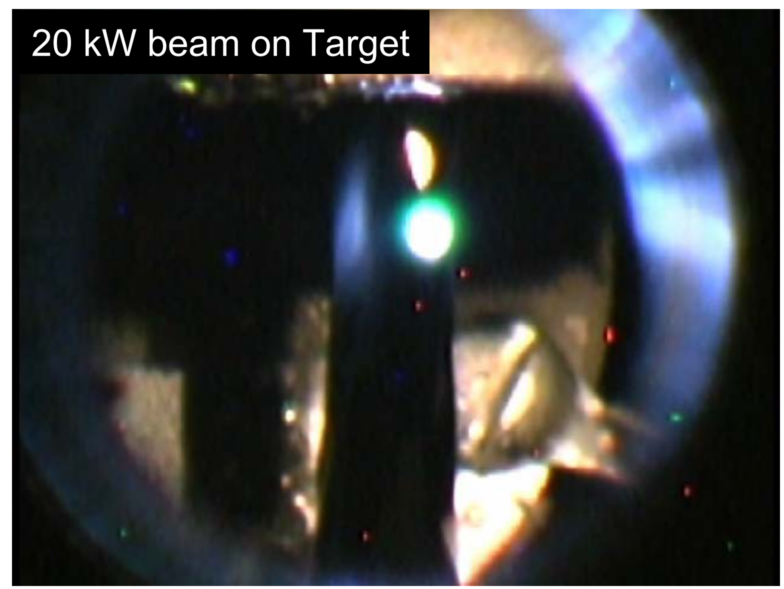
- Fast Gas Catcher to combine advantages of fragmentation and stopped beams
- Superconducting driver linac and post-accelerator for all ions from hydrogen to uranium.
- Acceleration of ions in multiple charge states to increase performance (x 25).
- Realizable designs for efficient high power (>100 kW) targets.
- Efficient reacceleration of 1+ charge states.

High Power Test of the Windowless Liquid Lithium Target

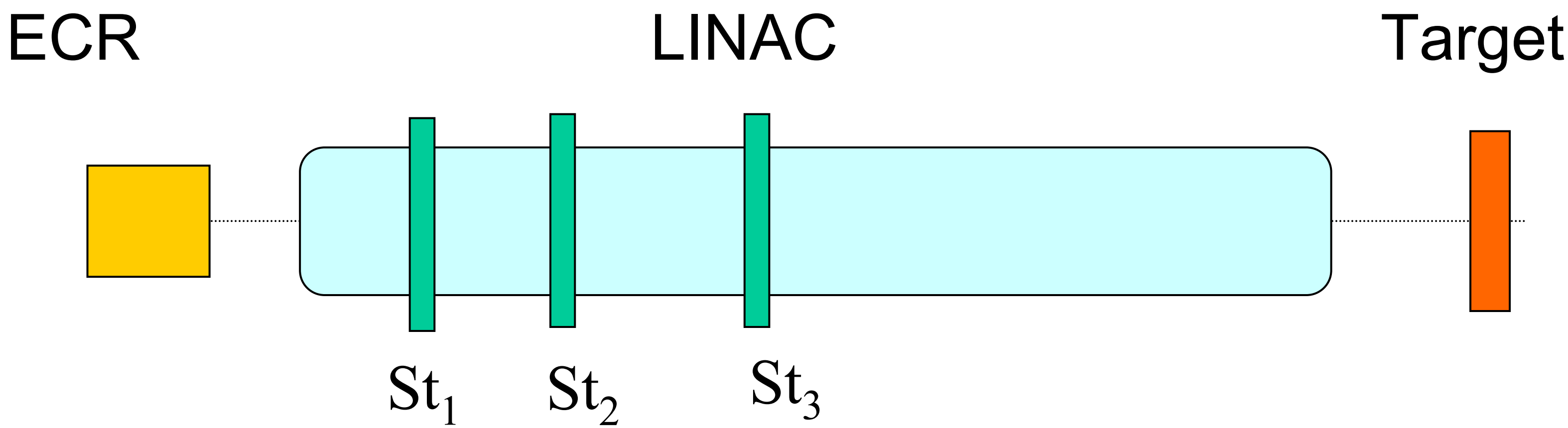


A 20 kW electron beam produces the same thermal load as a 200 kW U beam on the windowless liquid Li target.

Li jet is confirmed stable in vacuum with a U beam equivalent thermal load.



Heavy-Ion Linac



Particles	Uranium
Energy/nucleon Total kinetic energy	400 MeV/u 95.2 GeV
Power	400 kW
Velocity	0.005c-0.715c

$$\Delta W_n = \frac{q}{A} e V_{eff} \cos \varphi_s$$

$$V = \frac{A}{q_1 e \cos \varphi_s} \Delta W_{n,1} + \frac{A}{q_2 e \cos \varphi_s} \Delta W_{n,2} + \frac{A}{q_3 e \cos \varphi_s} \Delta W_{n,3} + \frac{A}{q_4 e \cos \varphi_s} \Delta W_{n,4}$$

How many strippers?

Bunching efficiency =80% $\varphi_s = -30°,$

q	V, MV	Efficiency (%)	St.	I_{ECR} (pμA)
29	3790	100	no	5.25
29-82	1677=458+1219	25	1	21
29-71-89	1352=379+973	6.3	2	83
29-59-81-89	1292=319+973	1.33	3	395

Multi-q beam acceleration

St.	From ECR	After St_1	After St_2	After St_3	Efficiency (%)	I_{ECR} (pμA)
2	28-29	69-73	88-91	-	147	3.6
3	28-29	58-61	79-83	88-91	97	5.4

Acceleration of multi-q heavy-ion beams

$$\Delta W_{s,u} = \frac{q}{A} eE_0 T L_c \cos\varphi_s$$

Fixed velocity profile
(RFQ, RT DTL)

$$\frac{q}{A} E_0 = const, \quad E_0 = \frac{const}{q/A}$$

Variable velocity profile
(SC Linac)

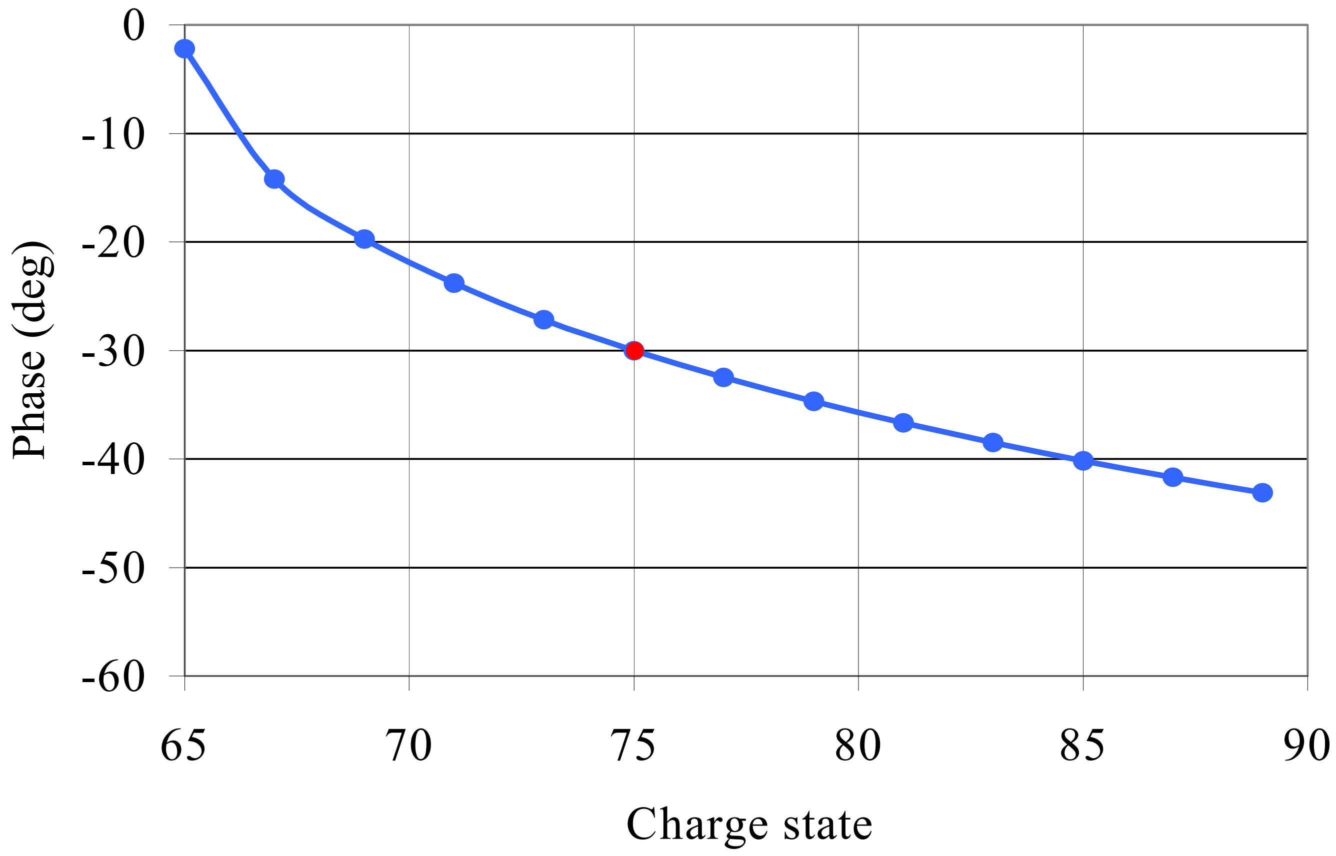
E_0=*const,*
Tune phases of individual cavities

Multi-q heavy-ion beam acceleration

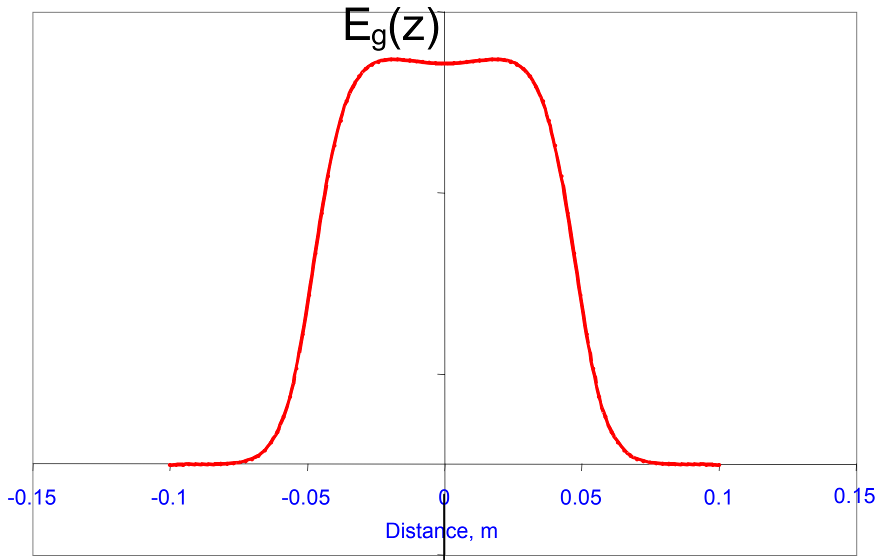
$$\frac{q_n}{A} E_0 \cos\varphi_{sn} = const, \quad \cos\varphi_{sn,q_n} = \frac{const}{\frac{q_n}{A} E_0}$$

$$\frac{q_n}{A} \cos\varphi_{sn} = \frac{q_0}{A} \cos\varphi_{s,0}$$

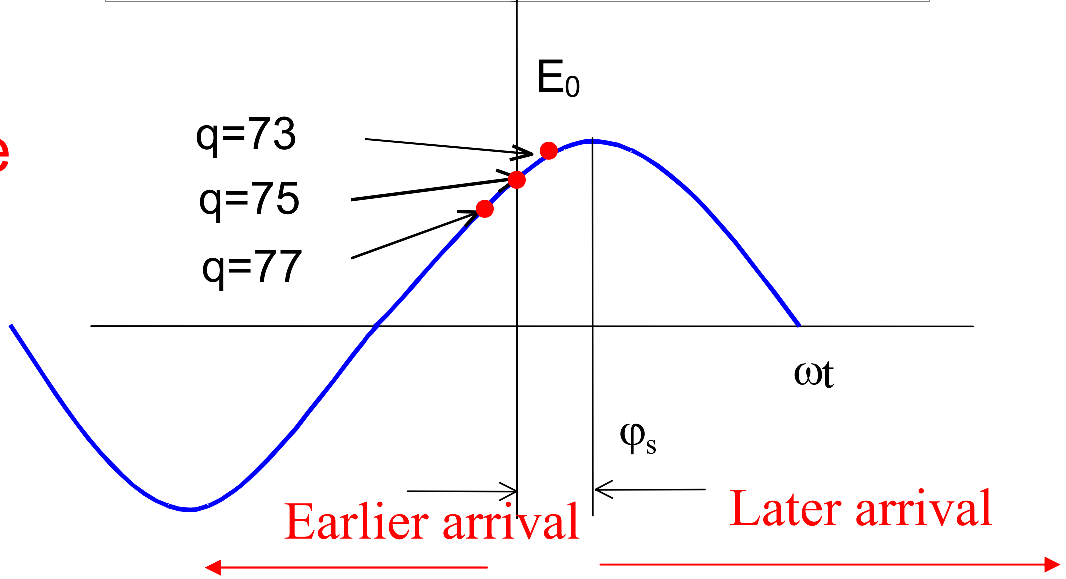
Synchronous phase as a function of uranium ion charge state. The designed synchronous phase is –30° for q_0=75.



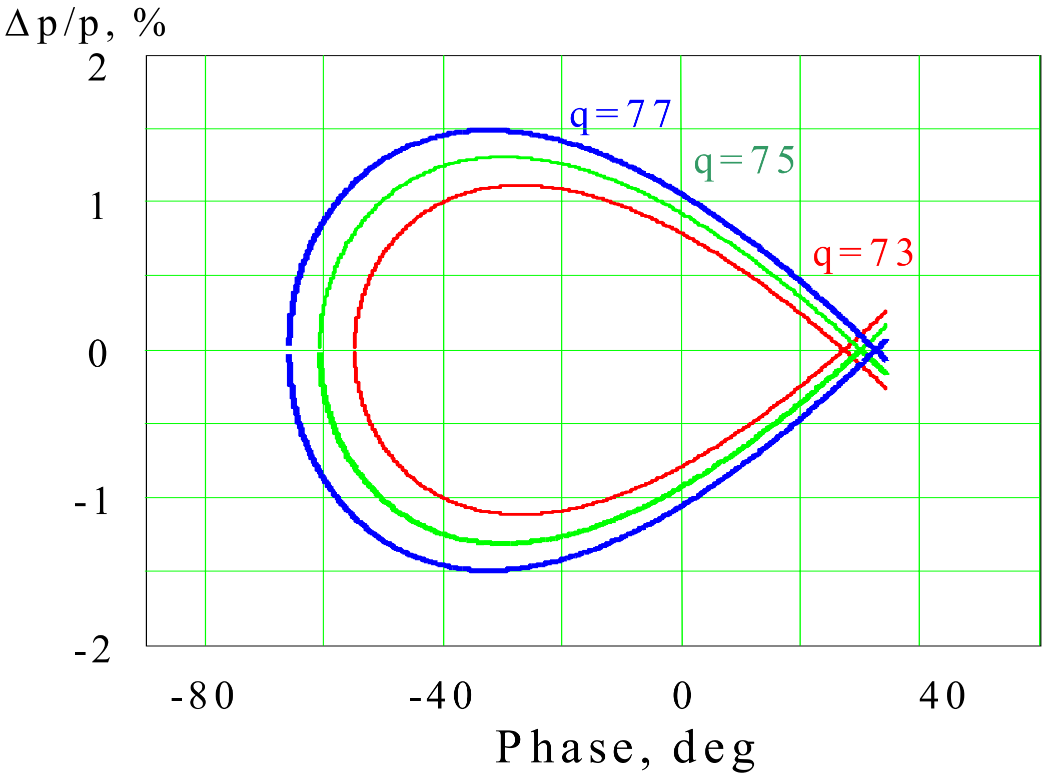
Single accelerating gap

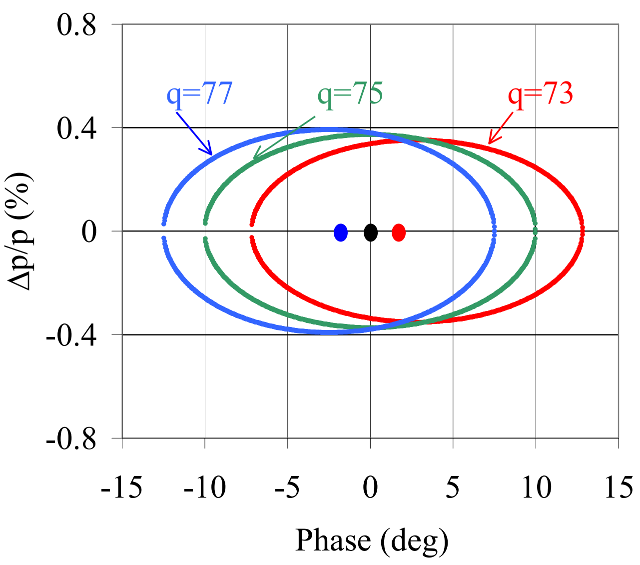


Synchronous phase of multi-q beam

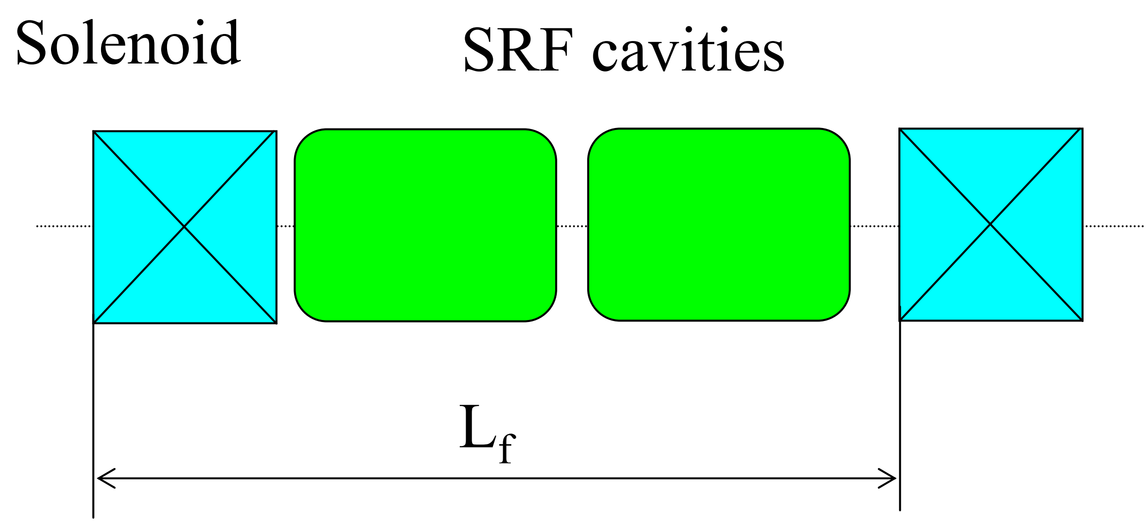


Separatrix and small longitudinal oscillations





Transverse beam dynamics



$$M = \begin{bmatrix} \cos\mu_x + \alpha_x \sin\mu_x & \beta_x \sin\mu_x \\ -\gamma_x \sin\mu_x & \cos\mu_x - \alpha_x \sin\mu_x \end{bmatrix}$$

$$\gamma_x x^2 + 2\alpha_x x x' + \beta_x x'^2 = \varepsilon_x$$

Transverse beam dynamics

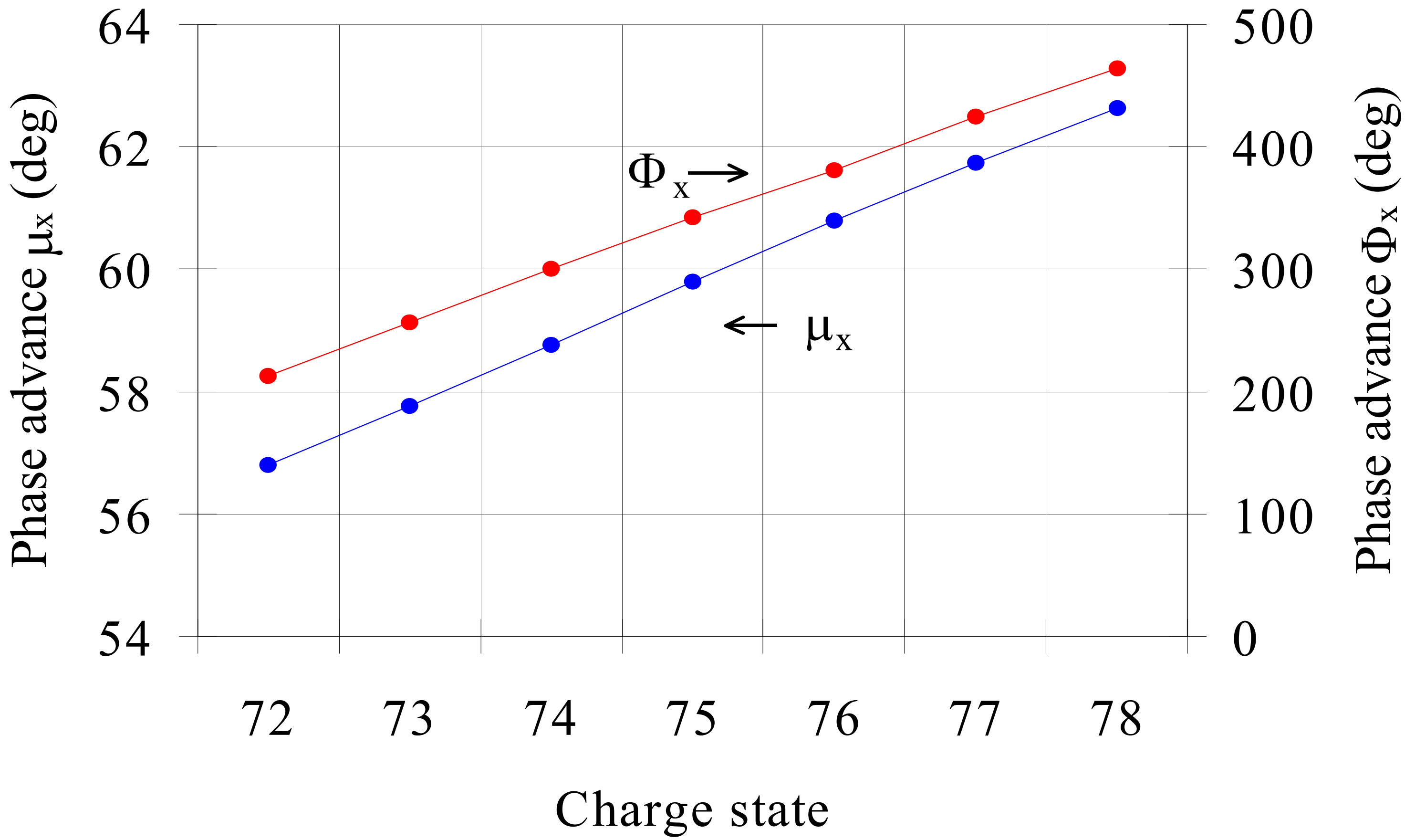
Twiss parameters

q	α	β	γ
73	0.428	1.536	0.770
74	0.435	1.518	0.783
75	0.441	1.500	0.783
76	0.448	1.483	0.809
77	0.455	1.467	0.823

Effective emittance growth

$$K_{\varepsilon} = \sqrt{\frac{1}{2} R + \sqrt{R^{2} - 4}} = 1.065$$

Phase advance over the period μ_x and total phase advance Φ_x (modulo 360°) in the medium-beta section (12 MeV/u – 85 MeV/u)



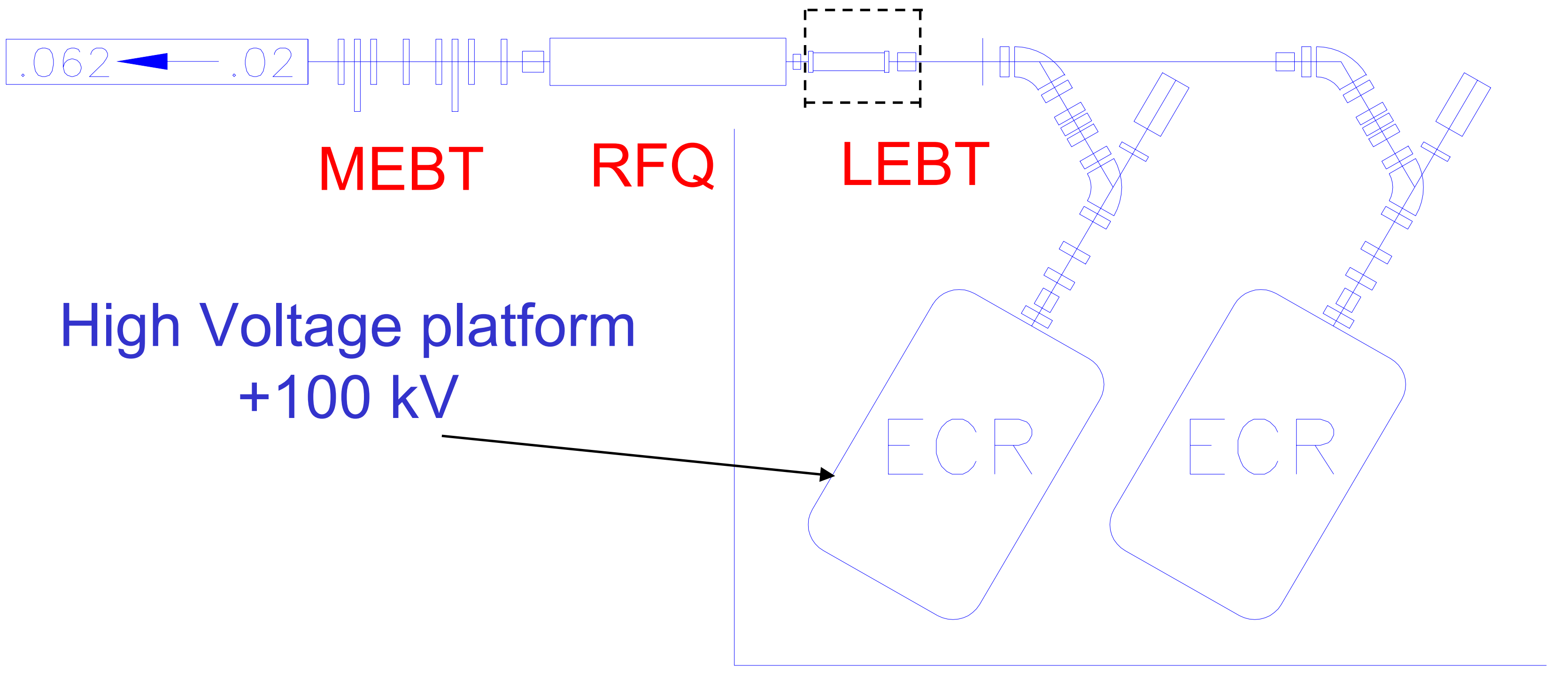
TRACK code (developed at ANL):

- Lattice optimization and high-statistic end-to-end simulations.
- Integration of particle trajectories of multi-component ion beams in 6D phase space including space charge.
- Electrostatic, magnetostatic and electromagnetic fields of all RIA elements are obtained from 3-dimensional external codes.
- Misalignments and random errors are included. Automatic beam steering procedure in both longitudinal and transverse phase space is applied in the linac with static errors.
- Optimization of linac tunes for different ions, off-normal tunes to compensate missing resonator.
- Beam passage through stripping foils&films is included. SRIM data of particle distribution in 6D phase space is incorporated.
- Parallel computing on multiprocessor computer cluster JAZZ at ANL. Simulation of total 10^7 particles in 15 hours is demonstrated.
- Compared with many beam optics code for common elements (TRANSPORT, COSY, RAYTRACE, IMPACT…).
- More updates are coming: parallelization at 10K processors
- Concept of “Model-driven accelerator”:

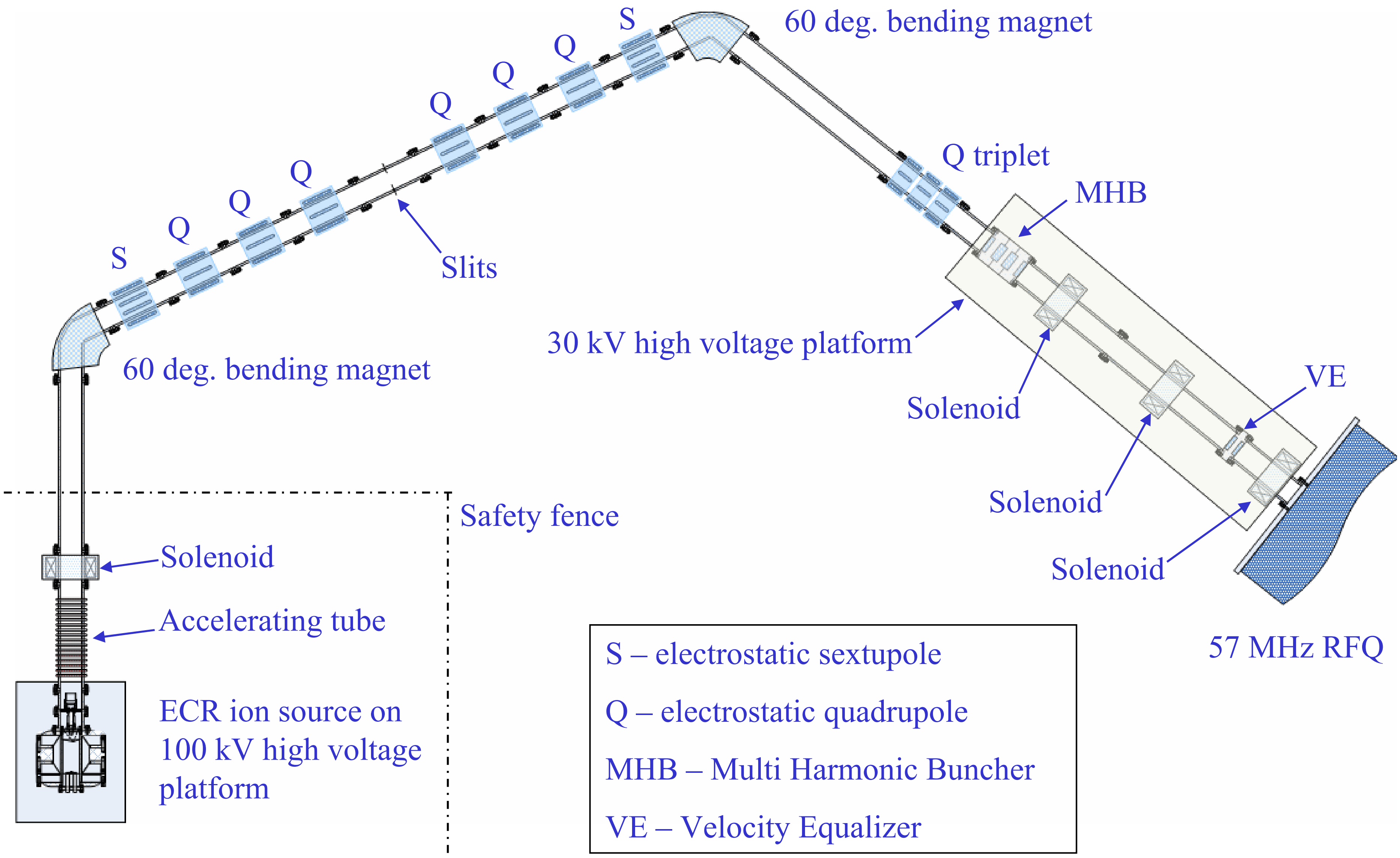
Layout of the RIA injector

RFQ

W_{out}=254 keV/u W_{in}=14.5 keV/u



ECR+LEBT (prototype)



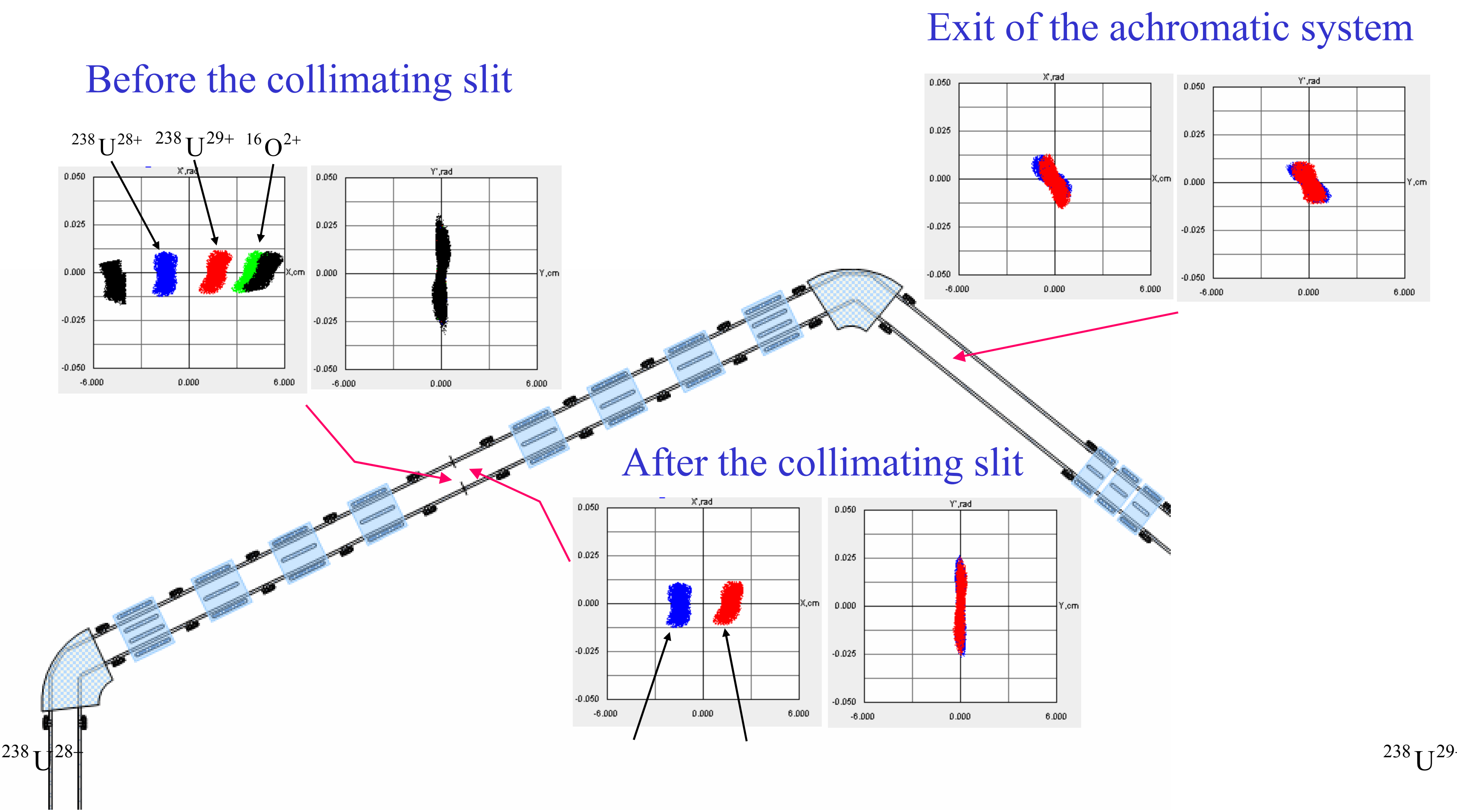
S – electrostatic sextupole

Q – electrostatic quadrupole

MHB – Multi Harmonic Buncher

VE – Velocity Equalizer

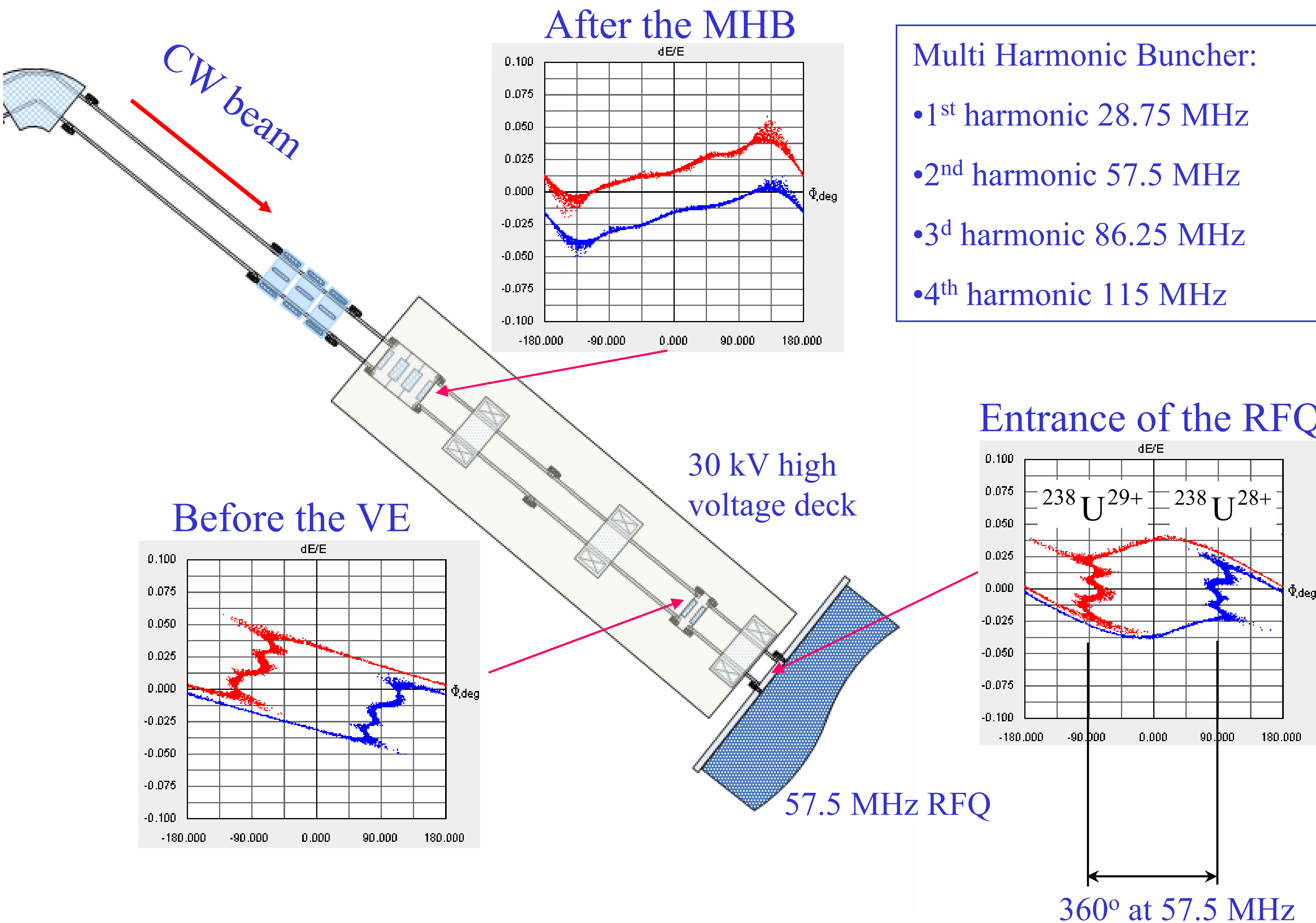
Achromatic bending system



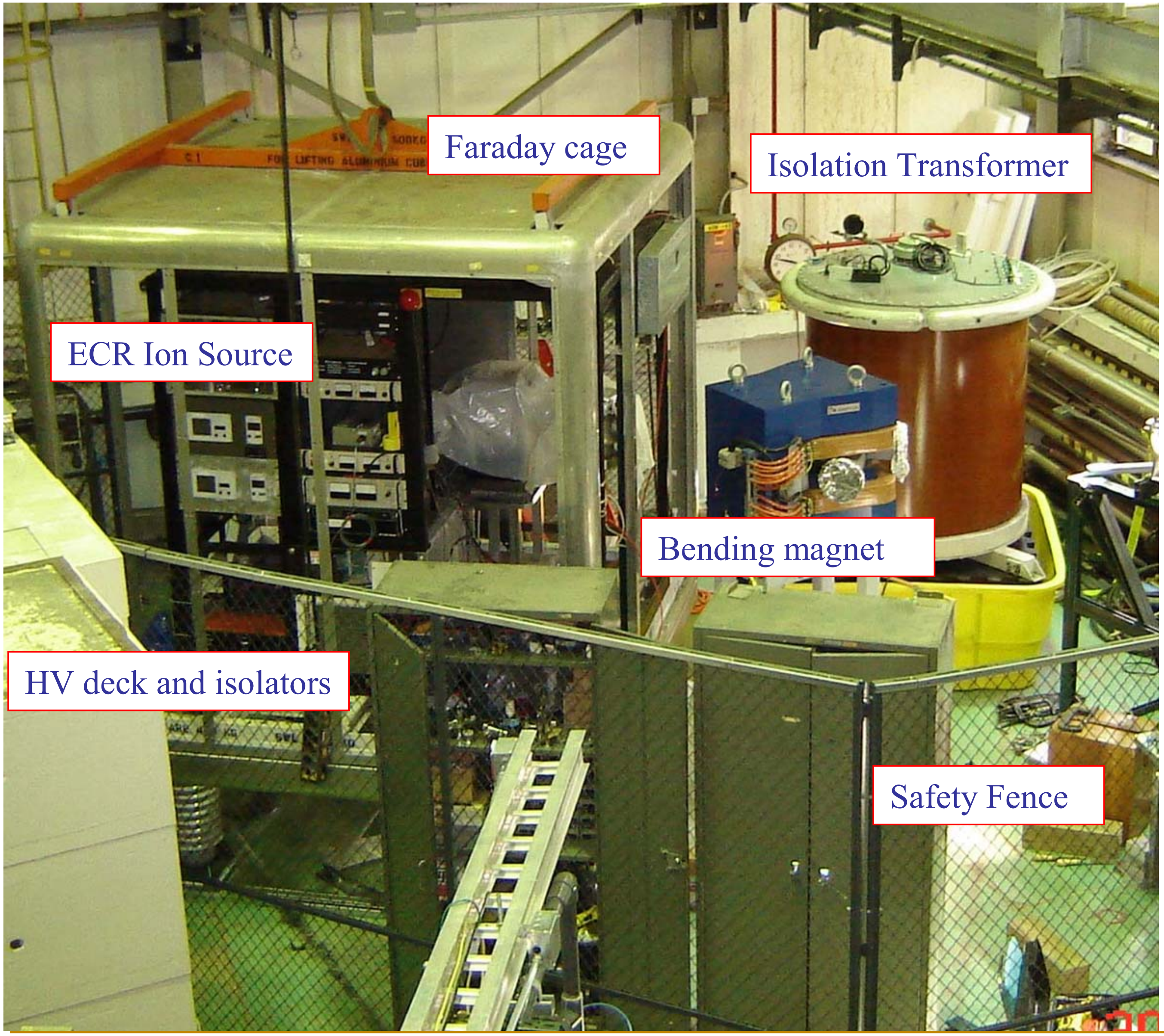
Multi Harmonic Buncher

Multi Harmonic Buncher:

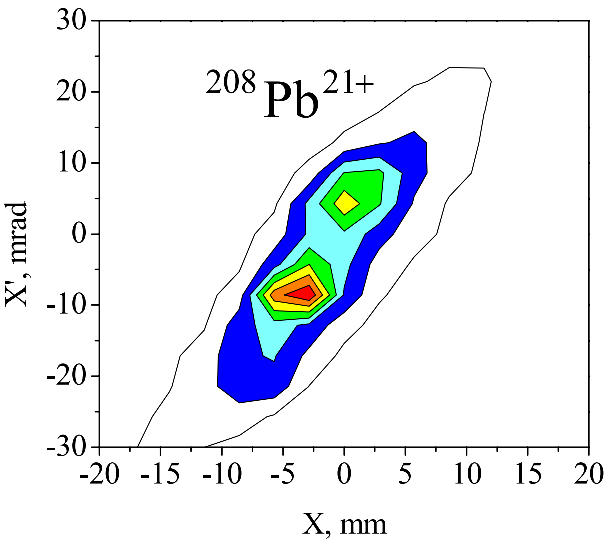
- 1st harmonic 28.75 MHz
- 2nd harmonic 57.5 MHz
- 3d harmonic 86.25 MHz
- 4th harmonic 115 MHz

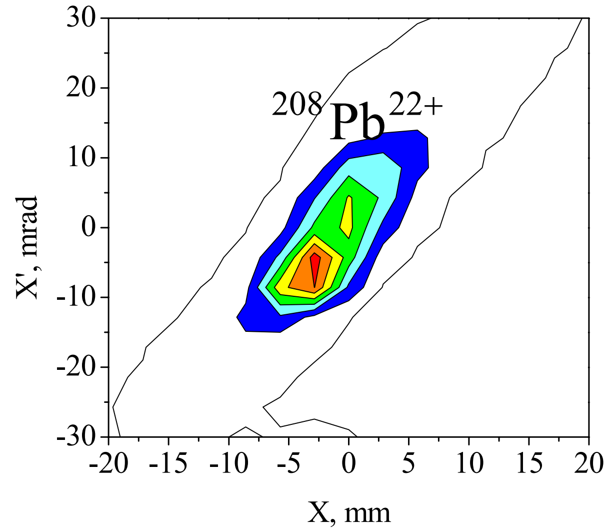


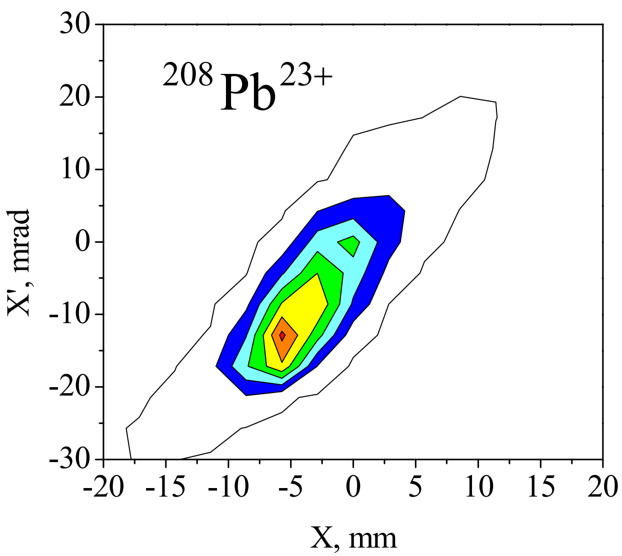
ECR+LEBT (prototype)



Emittance measurements: Lead beam







Charge State	Intensity, emA	Normalized RMS emittance, p mm mrad	RMS a	RMS b, mm/mrad
21	15	0.053	-2.6	2.39
22	14.5	0.05	-2.31	1.55
23	14	0.049	-2.24	1.65

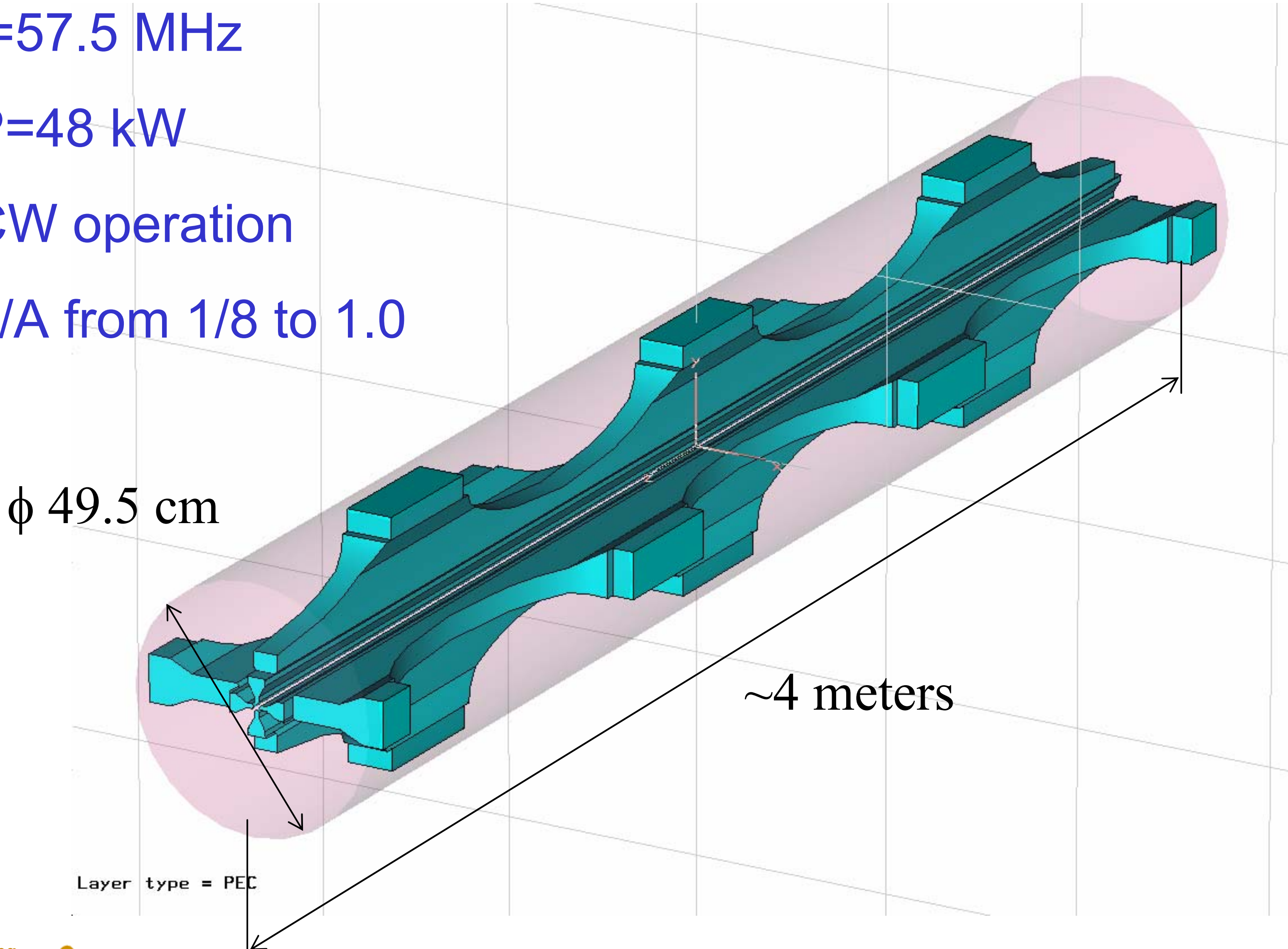
Radio Frequency Quadrupole Accelerator

f=57.5 MHz

P=48 kW

CW operation

q/A from 1/8 to 1.0

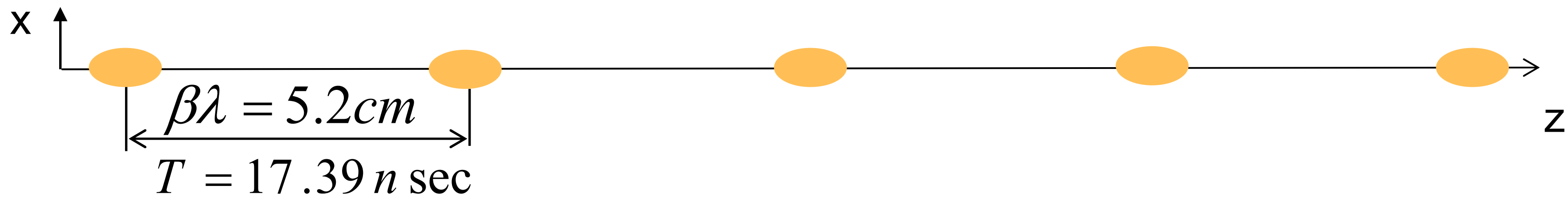


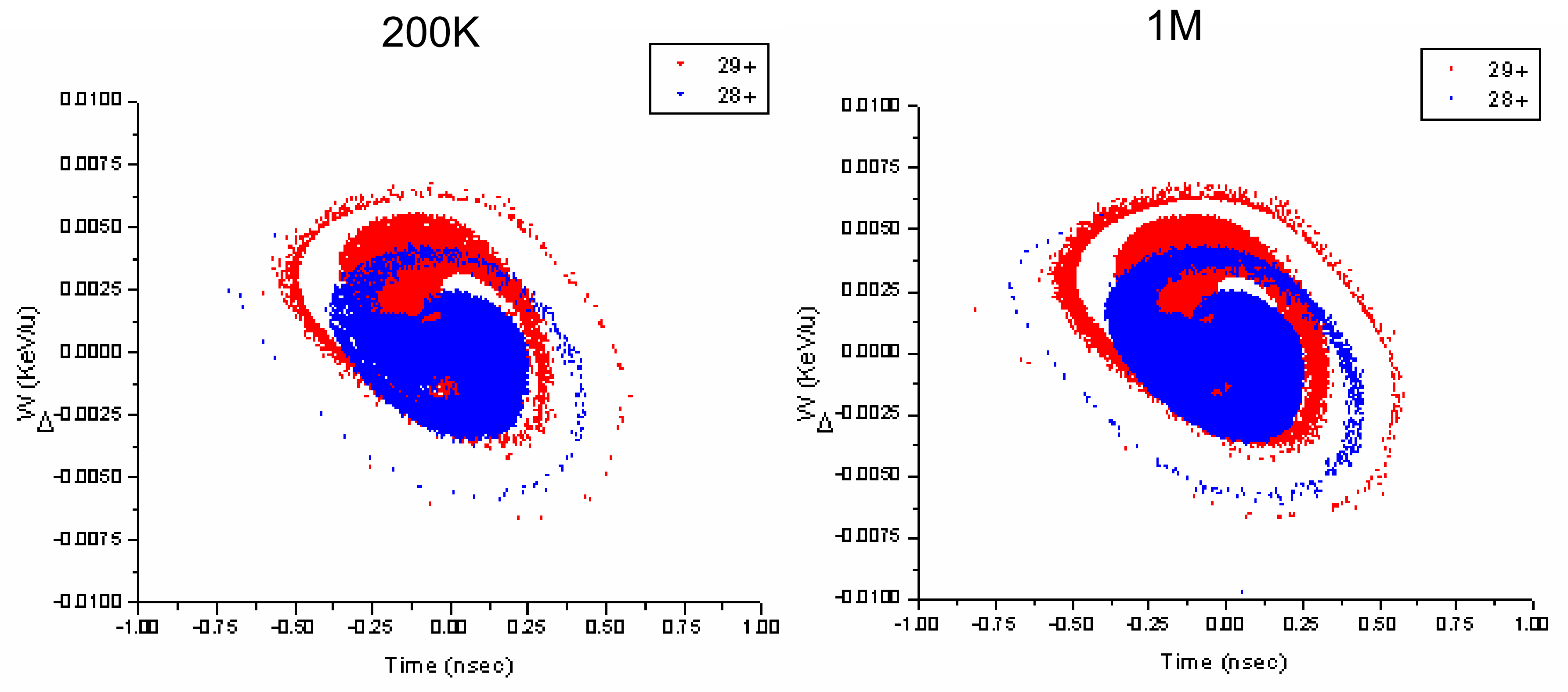
RFQ resonant structure

One segment of the
RFQ resonator

20 kW 57.5 MHz, CW

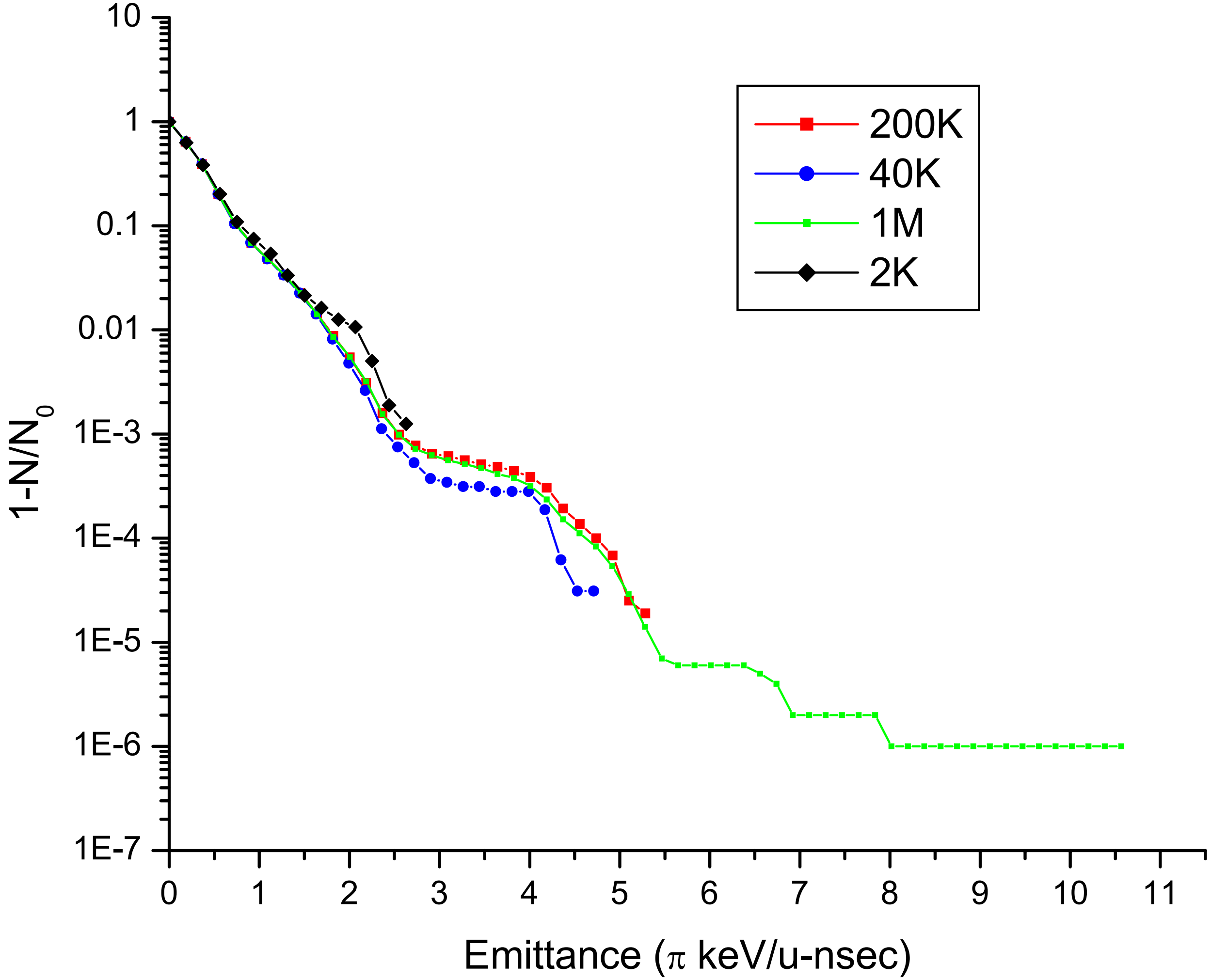
Longitudinal emittance at the entrance of the SC linac



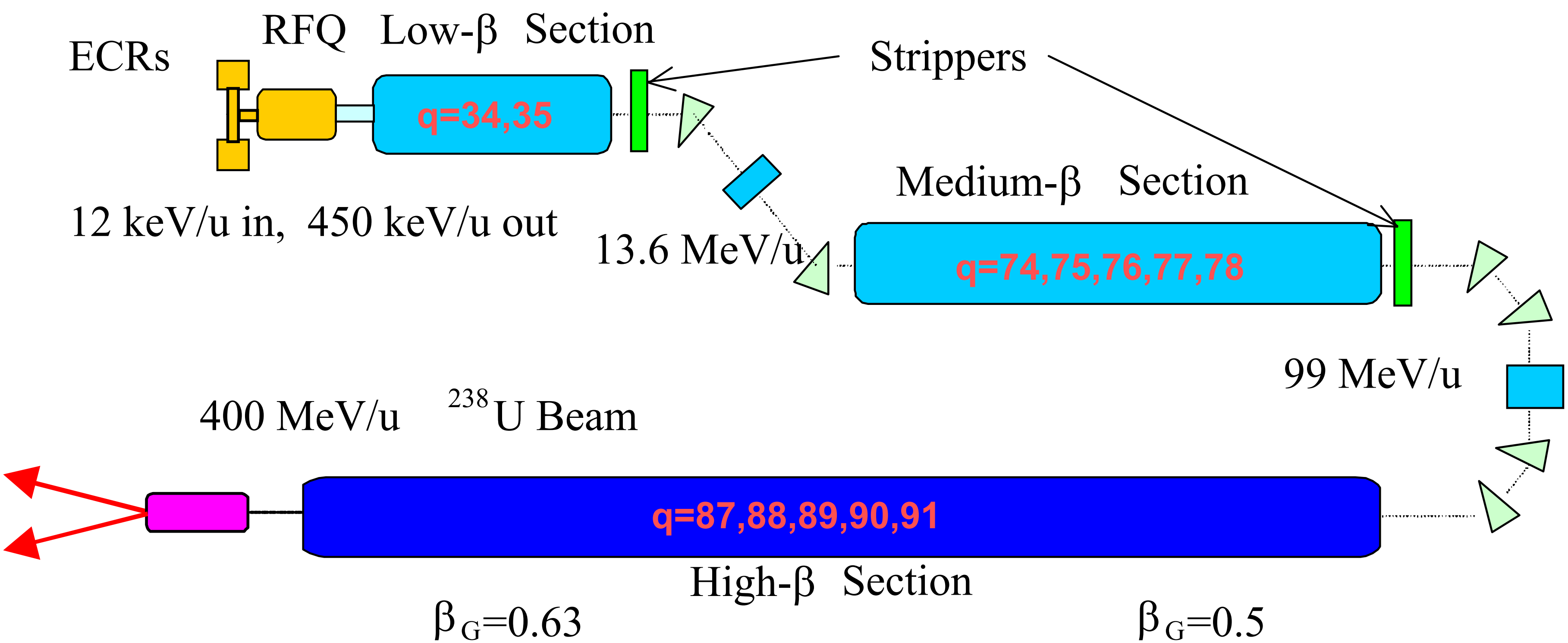


Intensity distribution in the longitudinal phase space

Beam halo studies



RIA Driver Linac Structure With Multiple Charge State Capability



RIA driver – Some Beam Parameters

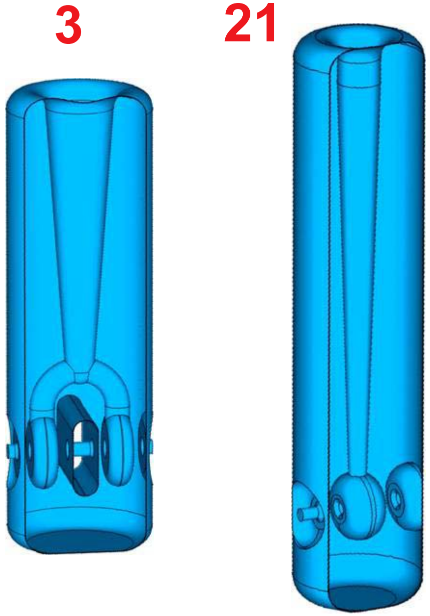
Species	Input Q	Strip	Energy MeV/A	Output Power (kW) multi-Q	Output Power (kW) single-Q
H	1	none	1020	400	400
^{3}He	2	none	733	400	400
D	1	none	591	400	400
^{40}Ar	8	once	531	400	400
^{136}Xe	18	twice	451	400	160
^{238}U	28-29	twice	402	102	6

Assumes 400 kW RF power and present-day ion source limits

With expected advances in source performance, 400 kW of all beams.

RIA Driver Linac Nb SC Cavity Array (total 302 cavities)

3 **21**

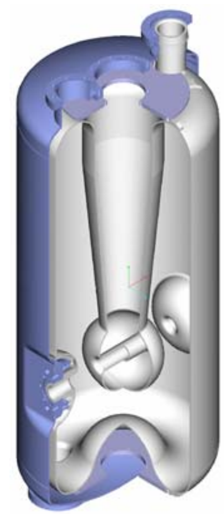


57.5 MHz QWR-based structures .02< β <0.14

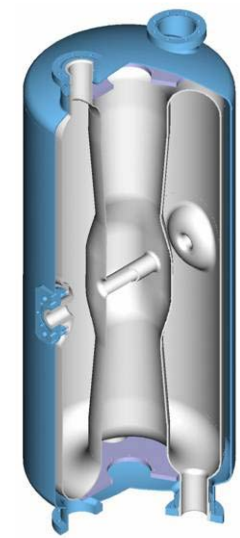
40

115 MHz β=0.15

Corrected QWR

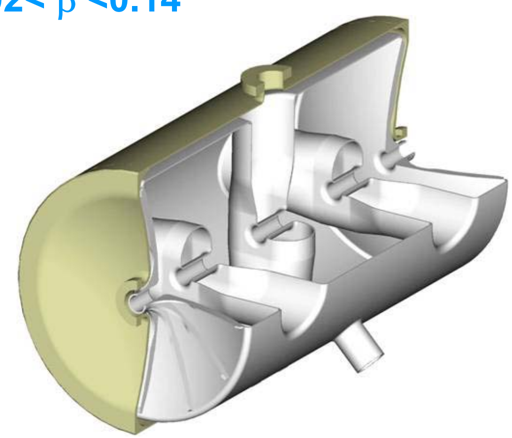


72



172.5 MHz β=0.14 HWR

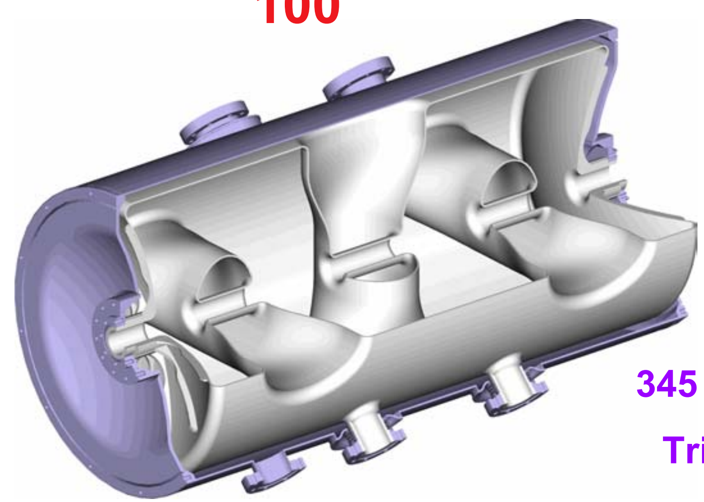
64



345 MHz β=0.5

Triple-spoke

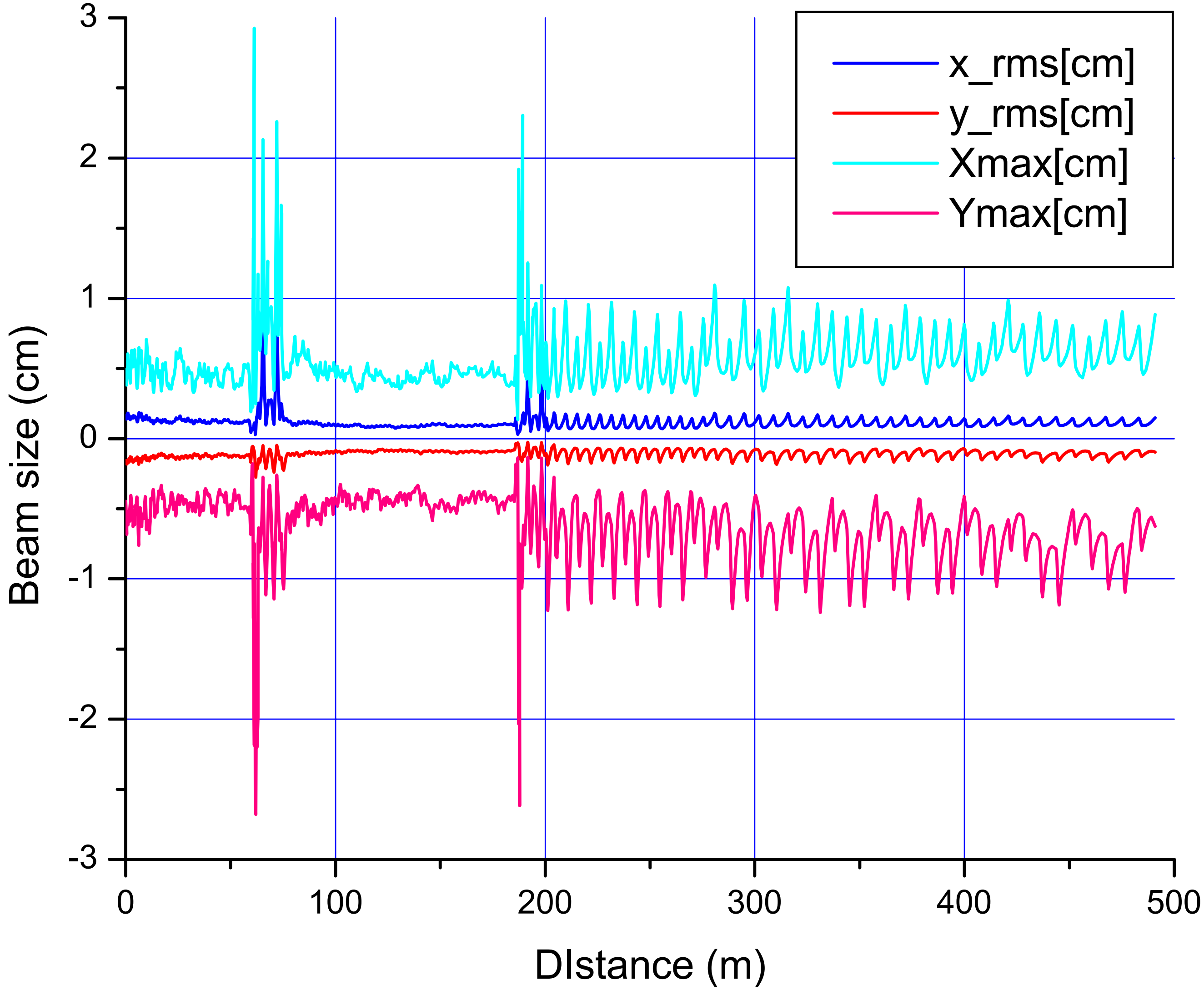
100

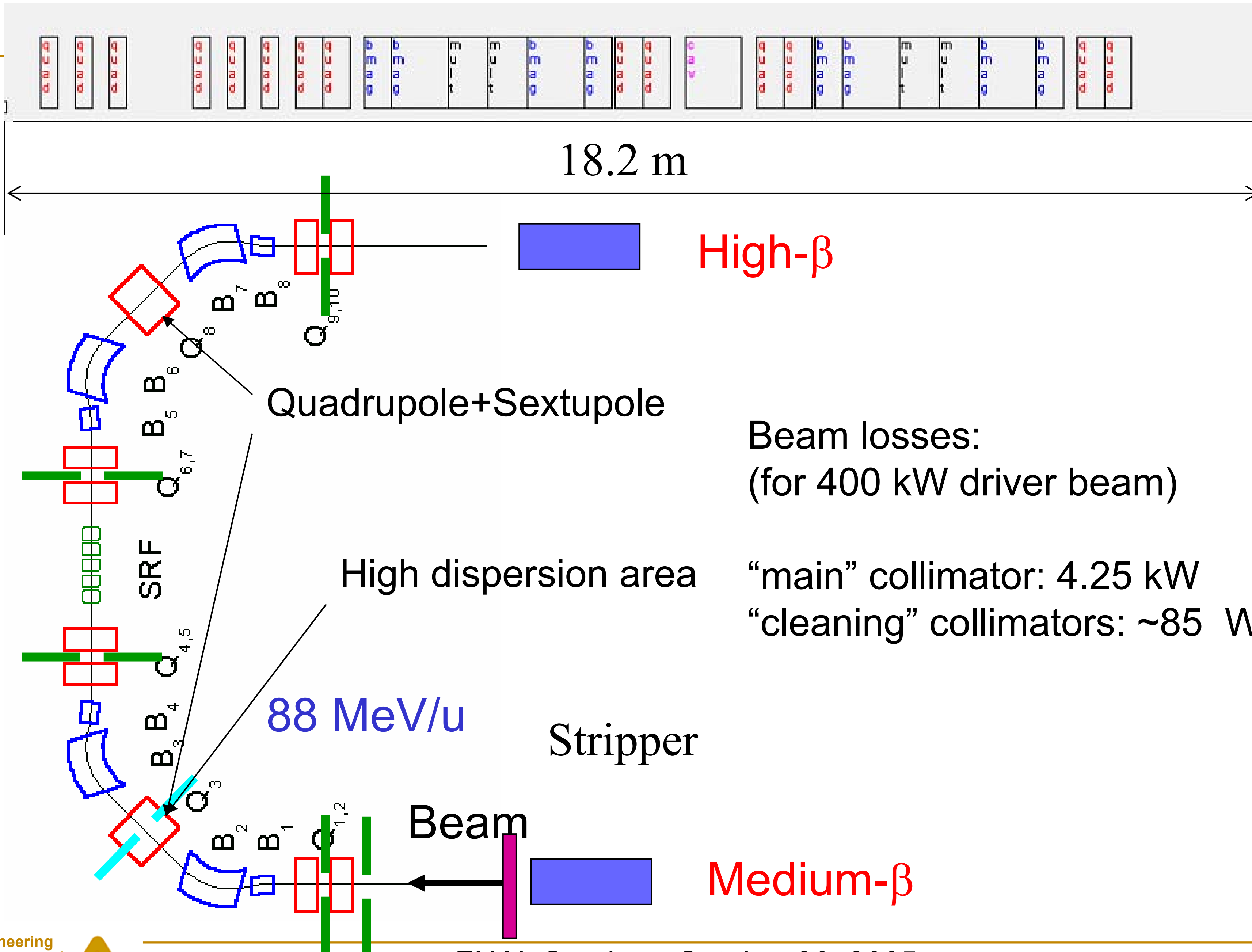


345 MHz β=0.62

Triple-spoke

Beam envelopes (Uranium beam)





Beam losses:
(for 400 kW driver beam)

“main” collimator: 4.25 kW
“cleaning” collimators: ~85 W

Passage through the stripper, SRIM results of elastic scattering

U-238 at 85 MeV/u

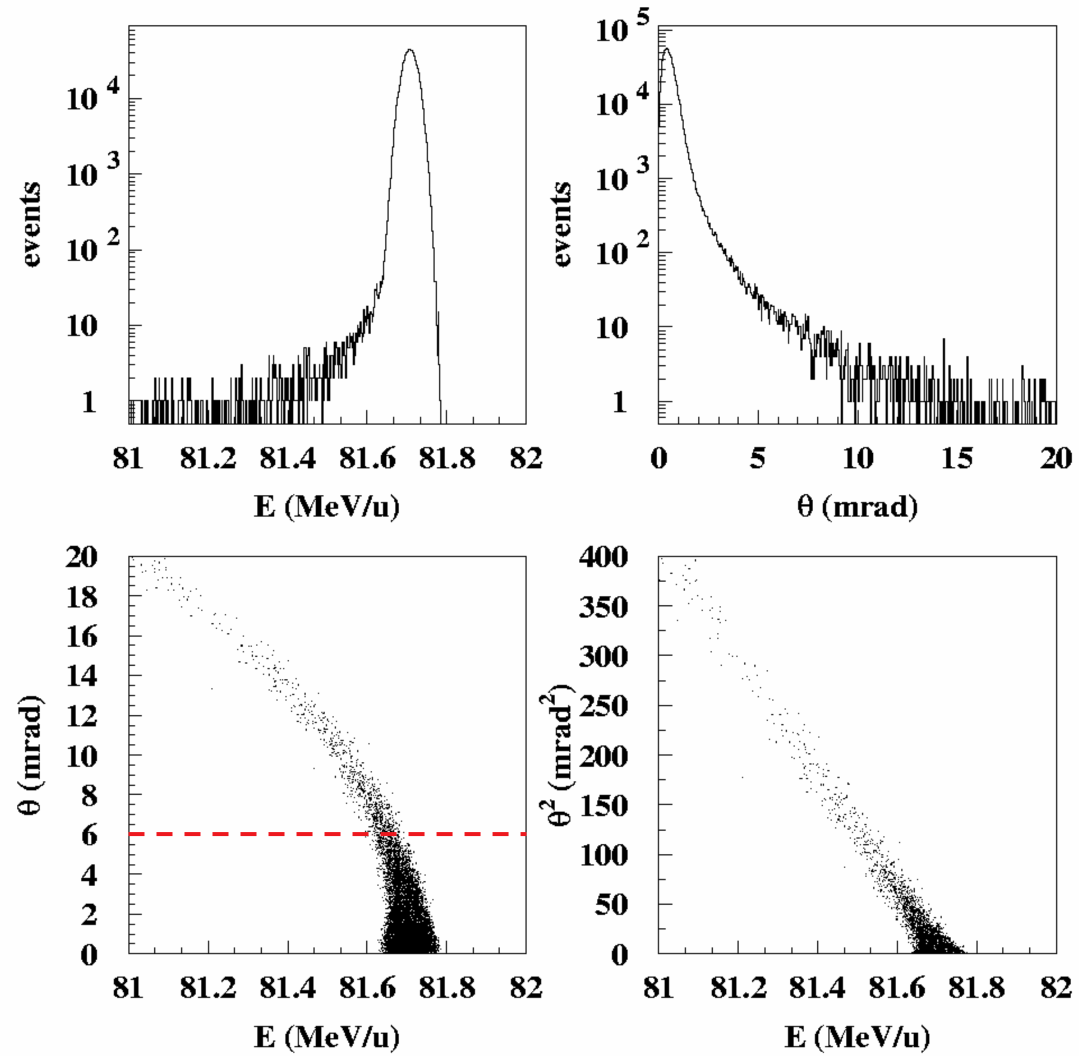
on

15 mg/cm² carbon stripper

1M events

(~ 1 week on 1.8 GHz PC)

$\Delta W = 3.29$ MeV/u
$\sigma_W = 17.6$ keV/u
$\sigma_T = 0.5$ mrad



Consequences:

- Thickness fluctuation is an important parameter due to the large ~3.3 MeV/u energy loss.
- Use lower frequency SC resonators. Triple Spoke in the high–β section: larger longitudinal acceptance.
- Collimate beam in the transverse phase space: can be effectively performed in the post-stripper transport line
- Nuclear reactions: <0.2% of ions, not included. Estimated losses are ~10^{-6}. Tracking of radioactive products are required.

Beam Loss Studies

- Beam dynamics optimization along the driver linac:
  - ECR-LEBT-RFQ-MEBT including space charge and multi-component ion beams;
  - Different accelerating-focusing lattice (QWR, HWR, TSR);
  - Higher-order optimization of the post-stripper sections.
  - Minimize effective emittance growth of the multi-q beam.
- Simulation in 3D focusing and accelerating fields.
- Include passage of ions through the strippers.
- Effective cleaning of beam halo by collimation in designated areas.
- Simulate 200 seeds with errors and misalignments (automatic steering is applied for static misalignments).
- Register controlled and uncontrolled beam losses.

Error Simulations: Parallel Computing,

- **The study of error tolerances and beam losses requires:**
  - Simulation of different combinations of error amplitudes.
  - For each combination: Simulate a large number of error sets (or accelerators), up to 500 (typically 200).
  - For each error set: Simulate a large number of particles, up to 1.E+6 (typically 2.E+5).

- **Computing time, a conservative guess:**
  - For 1 error set:: 2.E+5 takes about 7 hours on a single 2.4-GHz PC
  - For 1 error amplitude combination (200 sets): 1400 hours
  - For 1 linac option (10 combinations): 14000 hours = 1.6 year

⇒ **Parallel computing using the ANL-JAZZ cluster**:

1.6 year → 3 days

Most Critical errors: RF errors and stripper

- An earlier study including misalignments and RF errors as well as fluctuations in the stripper thickness showed that
  - RF errors: amplitude and phase
  - Stripper thickness fluctuations

  are the most critical errors affecting the beam emittances and eventually inducing beam loss.

- Let's focus on RF errors and stripper fluctuation

RF errors: Static & Dynamic (jitter)

- **RF Field errors: Amplitude & Phase**

- **Static or Systematic errors:**
  - **Measurements errors**
  - **Difference between the computer model and actual machine**
  - **Restoring an old tune**

  => Usually, we can correct for these errors

- **Dynamic or jitter errors:**
  - **Fluctuation in time during the same tune**
  - **Usually smaller than the static errors**

  => can not be corrected for

Typical Values

Description	Typical value	Distribution
Static amplitude error	1-2 % (max)	Uniform
Static phase error	1-2 deg (max)	Uniform
Dynamic amplitude error	0.3-0.5 % (r.m.s.)	Gaussian
Dynamic phase error	0.3-0.5 deg (r.m.s)	Gaussian

- **The code TRACK was recently updated to treat the RF static and dynamic errors separately.**
- **A new procedure has been developed to correct for RF static errors using a limited number of correcting cavities.**

Two linac options

I. **Old baseline design :** Elliptical cell cavities in the high-β section.

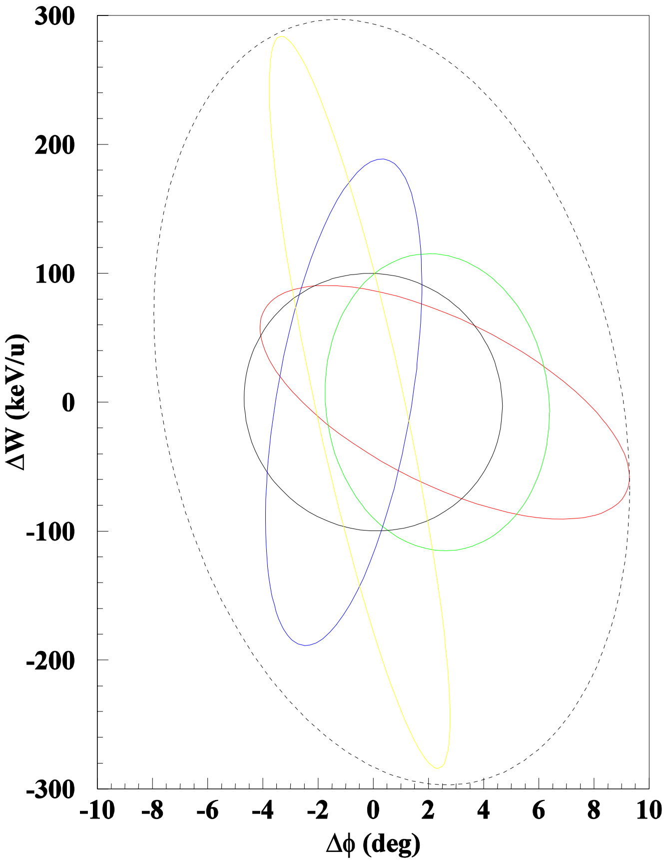
II. **Triple-spoke design (Baseline-2005):** Triple-spoke cavities in the high-β section.

New automatic tuning algorithm: obtain good time focus of the bunch at the stripper location

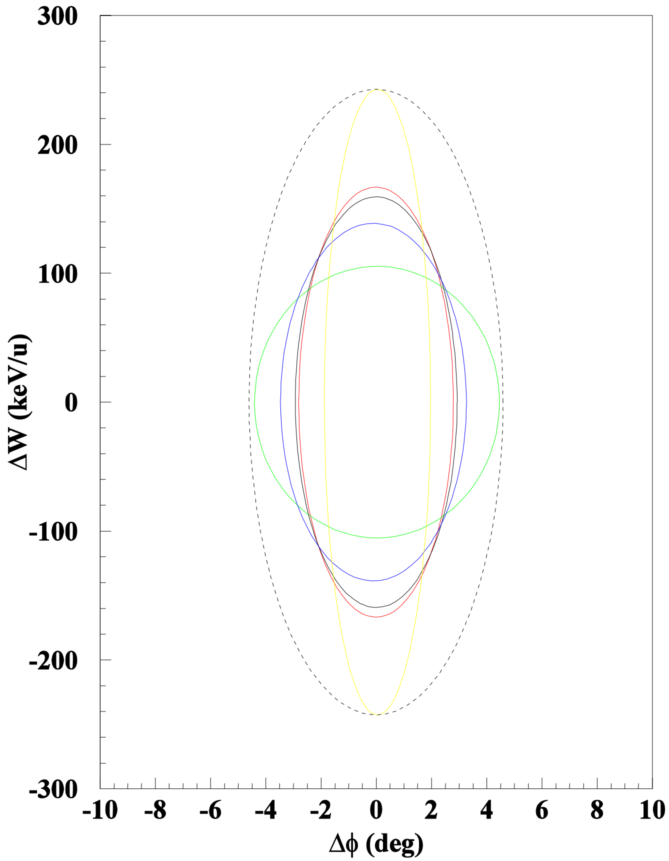
Colors:
Individual charge states.

……… :
Effective beam ellipse of all charge states.

Original manual tune



Automatically obtained tune

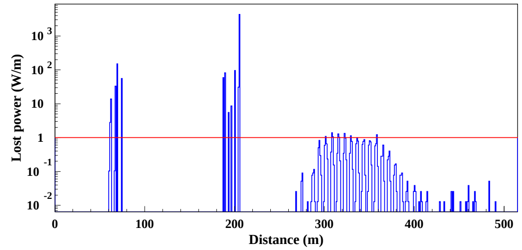


➢**A reduction of a factor of ~ 2 in the overall emittance**

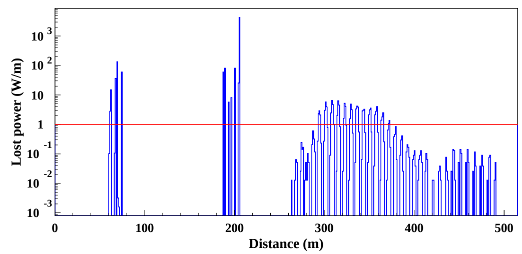
Baseline design: Losses in Watts/m

Static /Dynamic err.

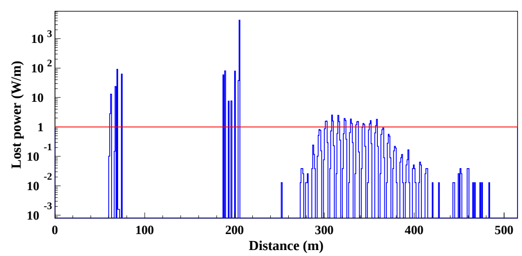
1.5 % / 0.3 %
1.5 deg / 0.3 deg



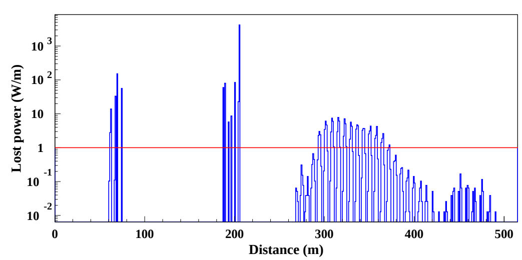
2.0 % / 0.3 %
2.0 deg / 0.3 deg



1.0 % / 0.5 %
1.0 deg / 0.5 deg



1.5 % / 0.5 %
1.5 deg / 0.5 deg



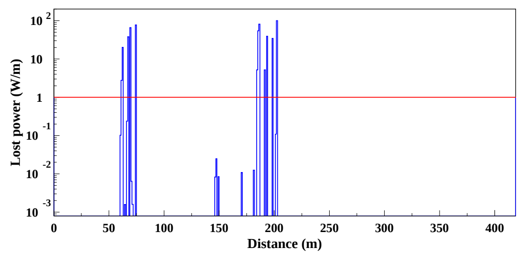
- **Misalignment errors are kept at their typical values.**
- **Stripper thickness fluctuation: 10% FWHM.**
- **Transverse correction applied**
- **Correction for RF static error applied**
- **Simulated: 50 seeds with 2E+5 particles.**

➢ **To keep the losses below the 1 W/m limit, the static errors should be about (1%, 1 deg) and the dynamic errors about (0.5 %, 0.5 deg).**

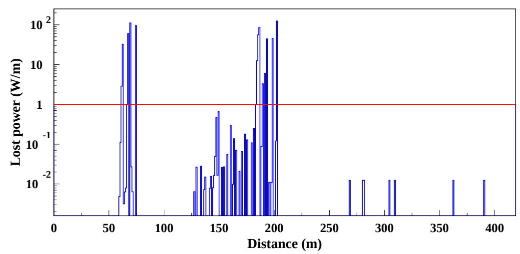
Triple-Spoke design: Losses in Watts/m

Static /Dynamic err.

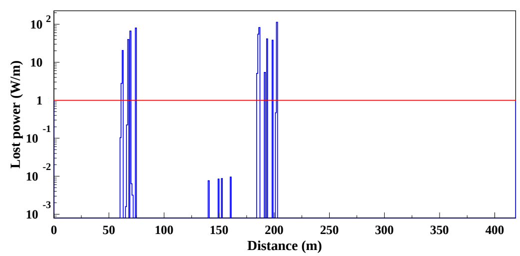
3.0 % / 0.3 %
3.0 deg / 0.3 deg



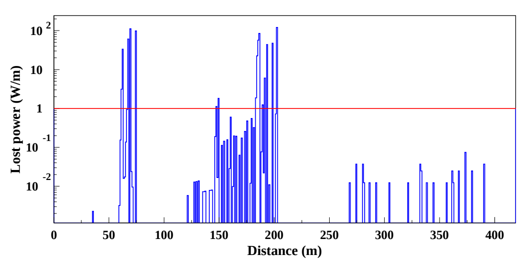
4.0 % / 0.3 %
4.0 deg / 0.3 deg



3.0 % / 0.5 %
3.0 deg / 0.5 deg



4.0 % / 0.5 %
4.0 deg / 0.5 deg



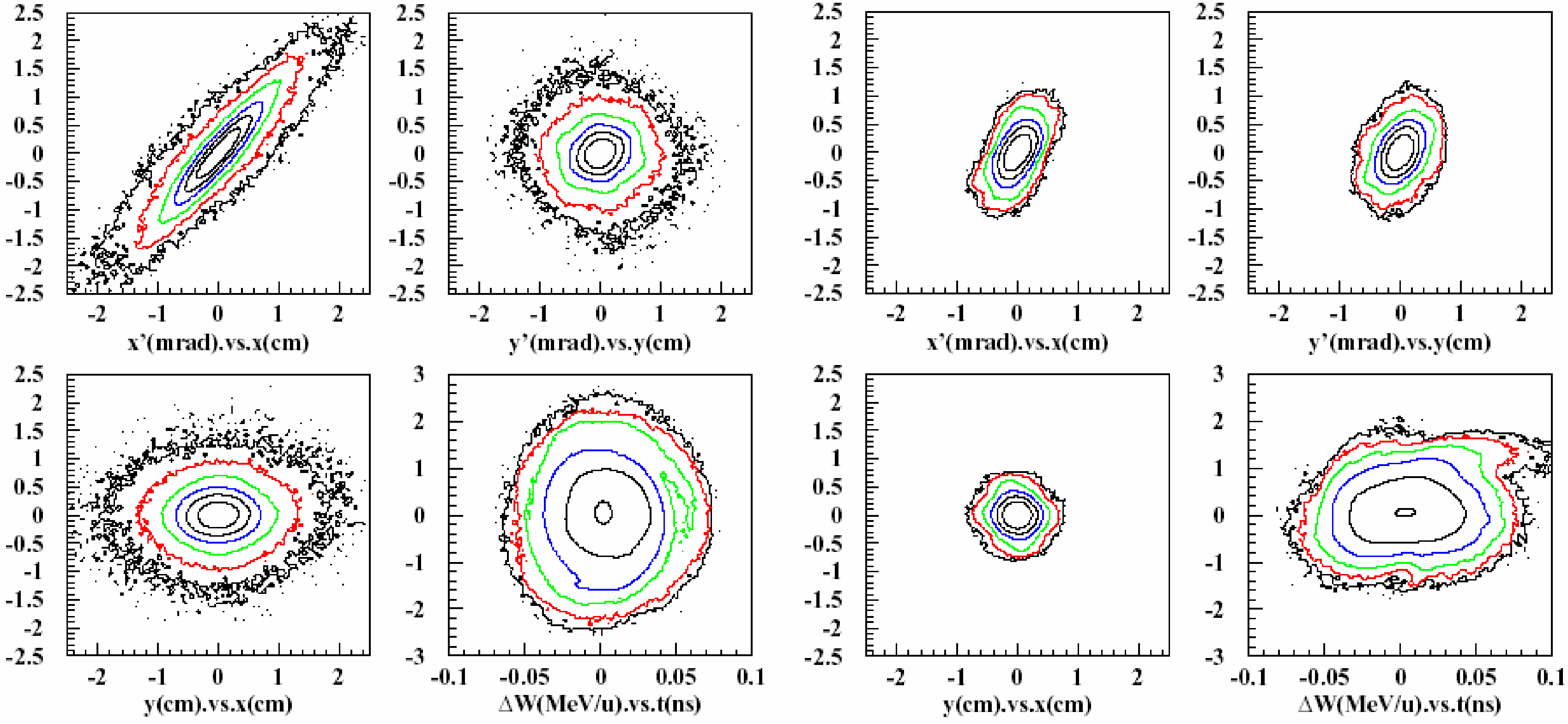
- **Same conditions as for the Baseline design except for RF static and dynamic err.**
- **Double the RF static & dynamic errors used for the Baseline design.**

- **No losses observed at the typical error values of (2%, 2 deg) static and (0.5%, 0.5 deg) dynamic**
- **Up to static errors of (4%, 4 deg) and dynamic errors of (0.5%, 0.5 deg) the losses are still below the 1 W/m limit.**
- **The Triple-Spoke design is more tolerant of errors**

Beam data at the exit of linac, image of 32 million particles

Design with elliptical cavities

Triple-spoke (baseline -2005) design



Note: logarithmic levels of the density isolines

Error analysis and beam loss studies for the two options:

- Identify most critical errors: RF errors & stripper thickness.
- The Triple-spoke design is more tolerant of errors than the design based on eleliptical cavities.
- Baseline: RF error limits are (1.0%, 1deg) and (0.3%, 0.3deg)
- Triple-Spoke: RF error limits are (4.0%, 4deg) and (0.5%, 0.5deg)
- Acceptable values: (2.0%, 2deg) and (0.5%, 0.5deg),

Conclusion

- **Basically, we are ready for CDR**
- **Meanwhile, pre-conceptual R&D is in progress**
  - End-to-end simulations, linac lattice optimization
  - Tunes for different ions
  - Design of strippers (beam sweeping, thermal analysis, stripper material)
  - Switchyard design optimization
  - Radioactive products and beam contamination
  - Fragment separators
  - Post-accelerator
  - Many projects for prototyping (SC ECR, RIA driver front end, post-accelerator front end, cavities, gas cell, targets,…)