HB2018
WEA2WB01

FRIB

Beam Loss Mechanism in Ion Linac and Development of Beam Collimation System

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Facility of Rare Isotope Beams

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U.S. DEPARTMENT OF ENERGY | Office of Science

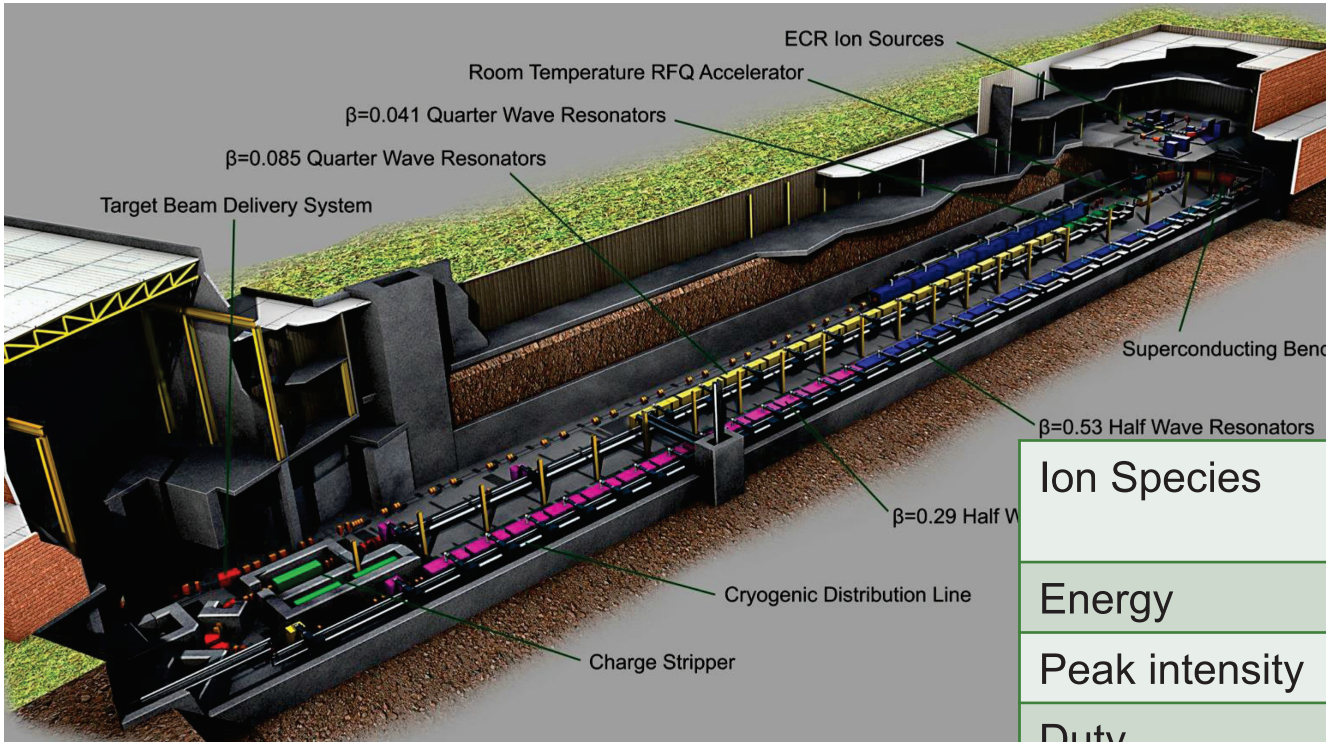
This material is based upon work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661, the State of Michigan and Michigan State University. Michigan State University designs and establishes FRIB as a DOE Office of Science National User Facility in support of the mission of the Office of Nuclear Physics.

Outline

- Parameters of FRIB driver linac
- Ions distribution of ECR ion source and charge-to-mass separation
- Beam loss in folding segment (FS) 1
  - Outline of FS1
  - Identification of loss mechanism
  - Design of collimator position and aperture
- Summary

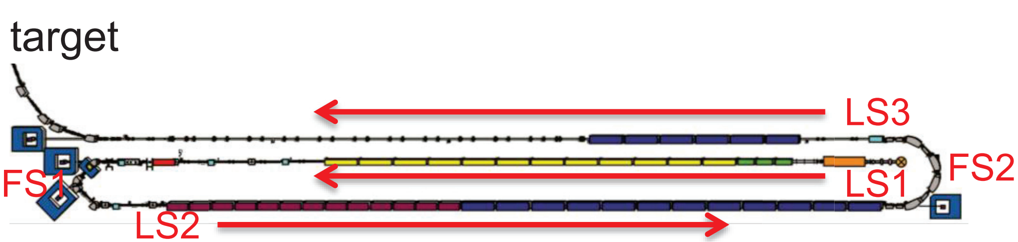
FRIB Driver Linac Layout

Folded Layout with Ion Source on Upper Level



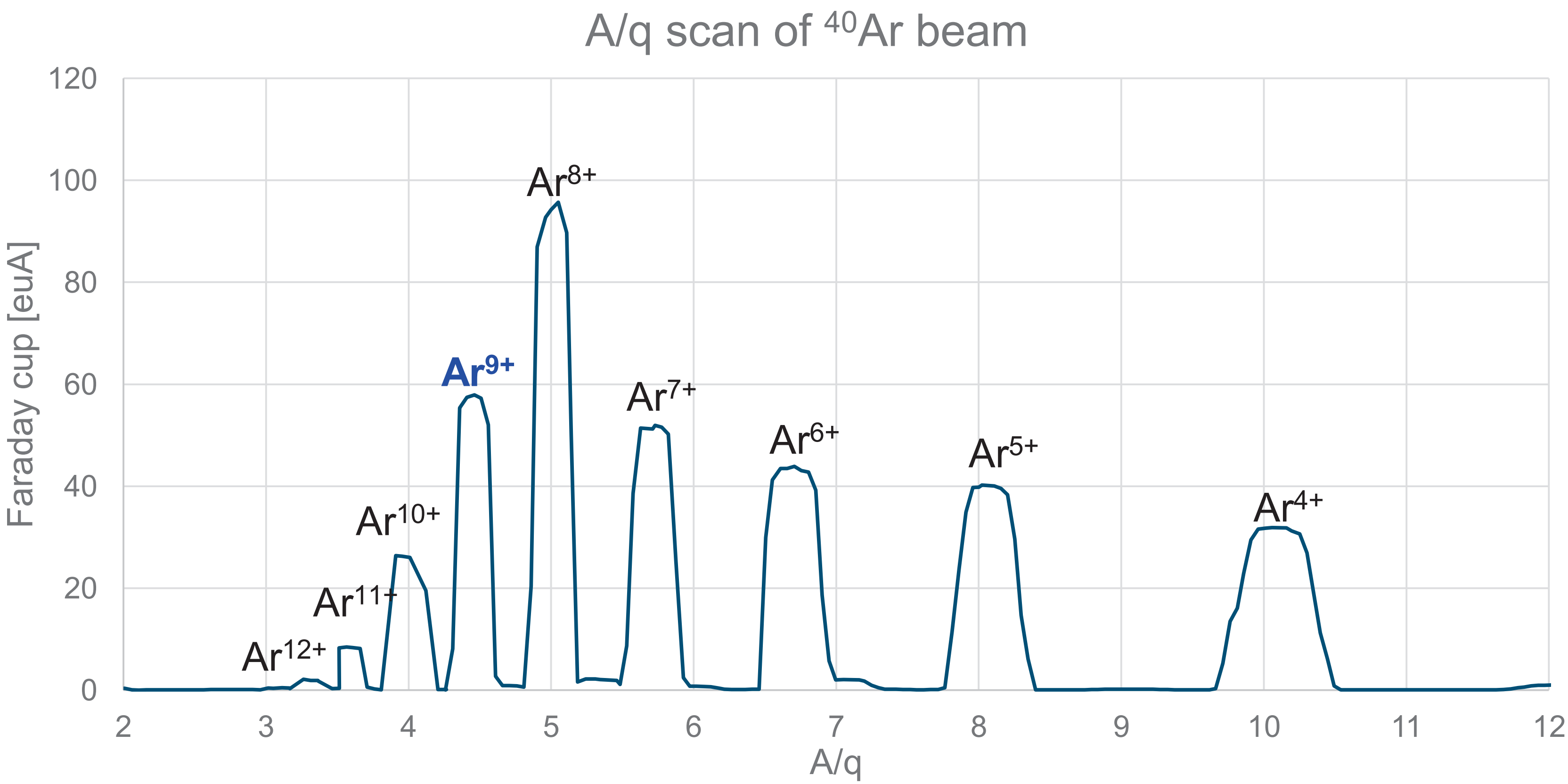
- ECR ion source is located on ground floor
- Three linac segments (LS) and double-folded layout

Ion Species	All stable ions up to uranium
Energy	200 MeV/u
Peak intensity	0.7 emA
Duty	100% (CW)
Average beam power	400 kW
Cavity type	SC QWR, SC HWR
Frequency	80.5/161/322 MHz
Status	Under construction



Ion Distribution from ECR Ion Source

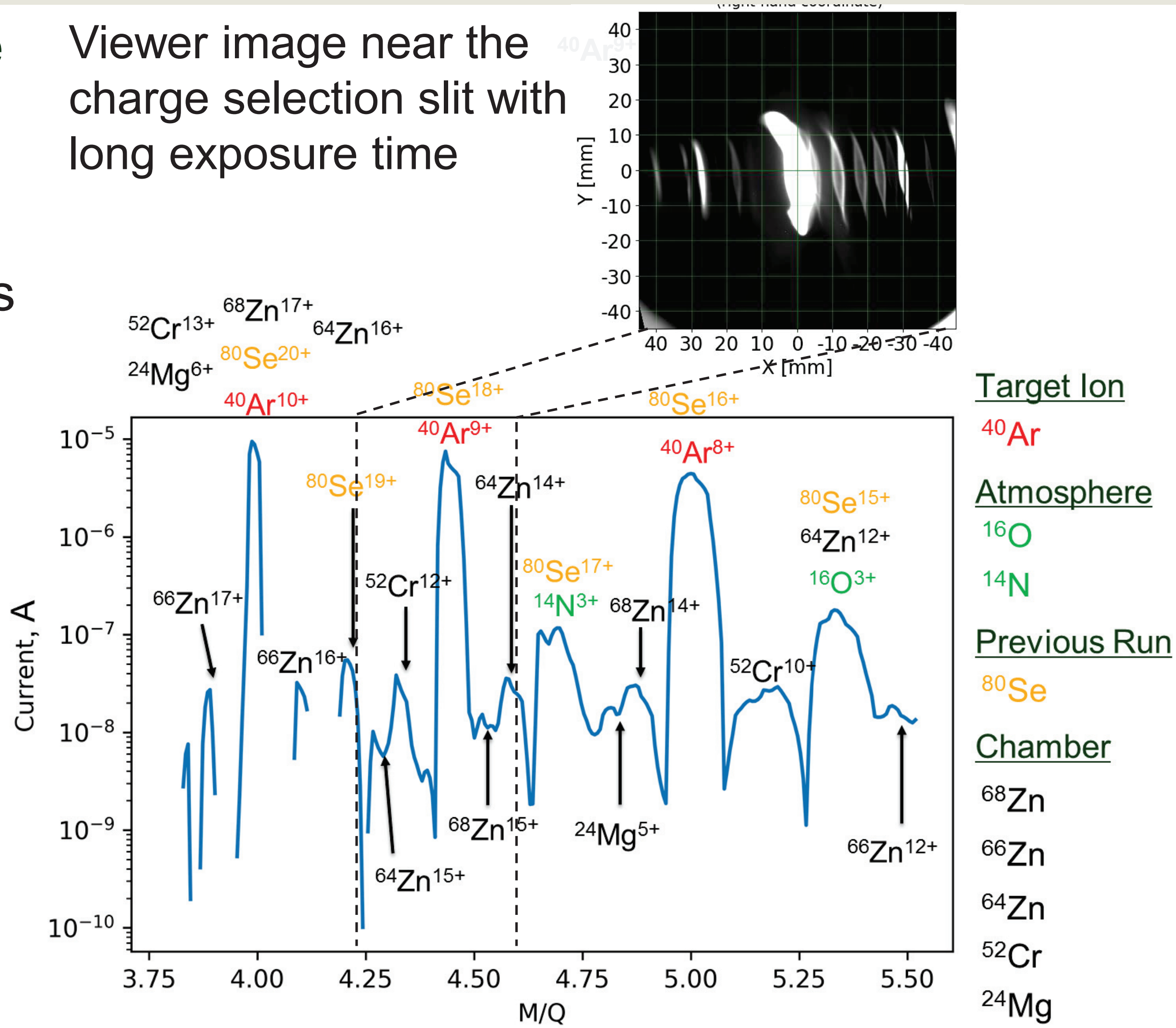
- Many charge states are simultaneously extracted from ECR ion source
  - $^{40}Ar^{9+}$ which is used for beam commissioning is only 10% of entire current
  - Unwanted 90% charge states should be collimated in LEBT



Beam Contaminants from ECR Detected Two Orders of Magnitude Less Intensity of $^{40}Ar^{9+}$

- Not only for other charge states, various ions are extracted from the ECR ion source
  - ^{16}O of plasma support gas
  - ^{14}N from atmosphere
  - ^{80}Se of previous run
  - Zn, Cr and Mg from plasma chamber material
- Intensity of beam contaminants is 10^{-2} of main ions

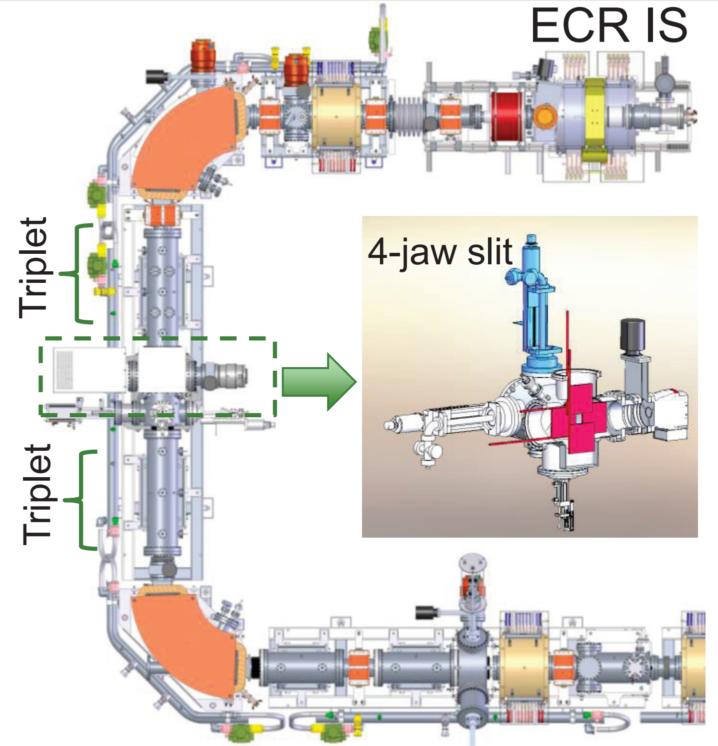
Viewer image near the charge selection slit with long exposure time

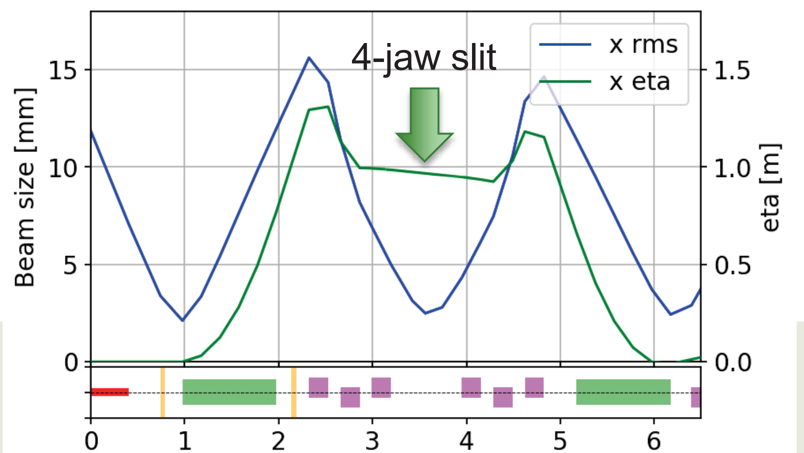


Collimation of Unwanted Charge States and Contaminants at Bending Section

- 180-deg arc section after ECR IS
  - 4-Jaw movable slit is placed in between two triplets
- When q/A difference of ions are over 7%, they are lost inside 1st 90-deg dipole
  - Ions are absorbed on water cooled side walls
- 4-jaw can intercept the ions without interruption of beam ions when q/A differs more than 1.5%
  - Optics is tuned to maximize the ratio of horizontal dispersion and beam size at 4-jaw
    - » RMS beam size: 2.5 mm
    - » Momentum dispersion: 1 m
- If q/A difference is below 1.5%, They reach to charge selector in folding segment 1 (FS1)
  - Ex: $^{238}U^{34+}$ ⟺ $^{14}N^{2+}$

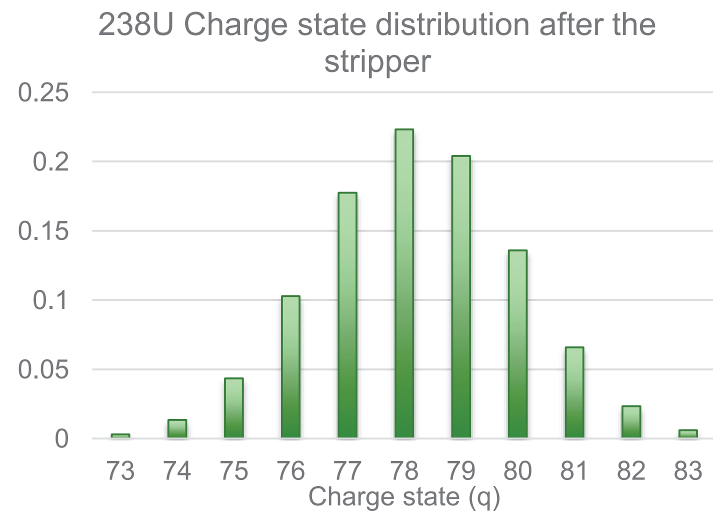
(q/A = 0.142)

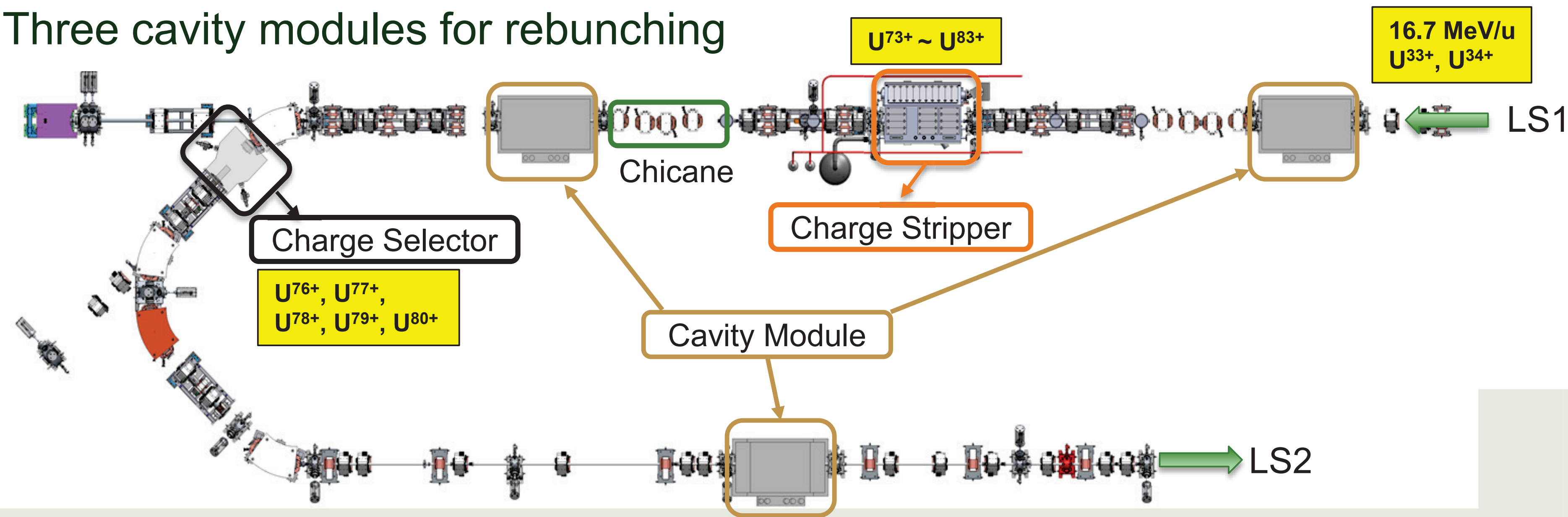




Outline of Folding Segment 1 (FS1)

- Beam transport line connecting Linac segment (LS) 1 and LS2
  - U^{33+} and U^{34+}, 16.7 MeV/u from LS1 in design
- A charge stripper module
  - Equilibrium charge state after the stripper is 78+
  - Wide distribution from 73+ to 83+
- Unwanted charge state are intercepted by the charge selector
  - Design to accelerate up to five charge states of 76+ to 80+
- Three cavity modules for rebunching



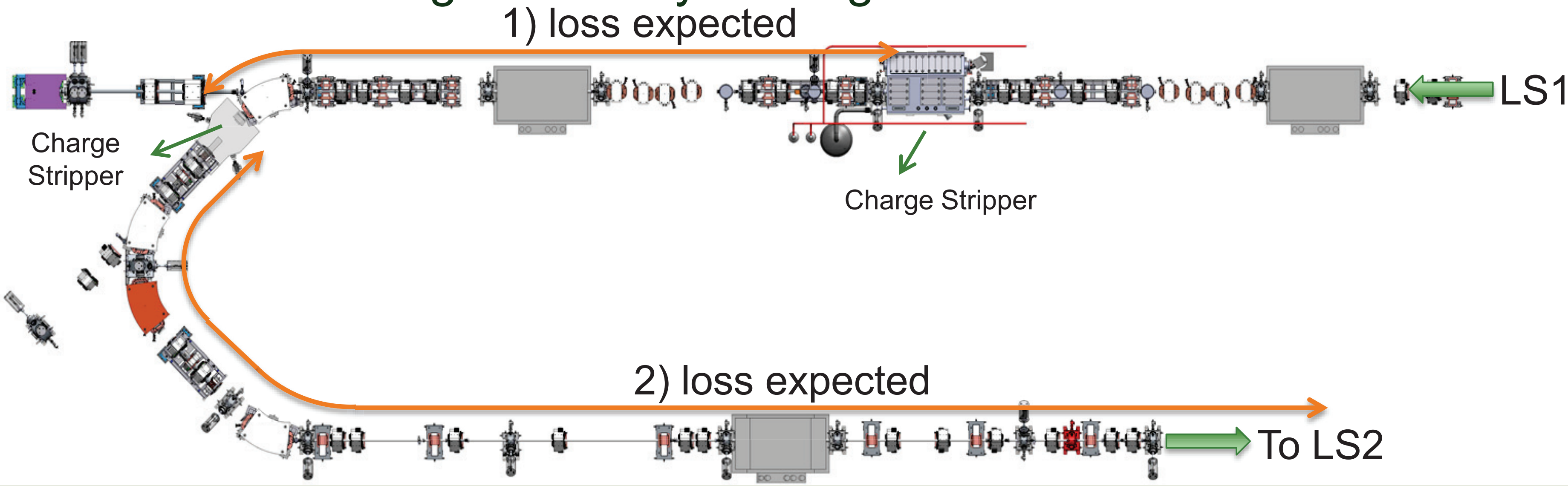


Beam Loss in Folding Segment 1
Loss Mechanism Identified

- Three loss mechanisms due to unique FS1 function are identified

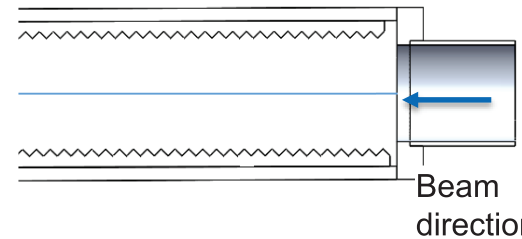
Loss Mechanism	Power	Loss Location
1) Contaminants from ECR source separated from beam after stripper	High	Stripper to charge selector
2) Charge exchange reaction to residual gas around charge selector	Low	Arc to LS2
3) Beam halo induced at stripper or mistuned bending magnets	Low	LS2

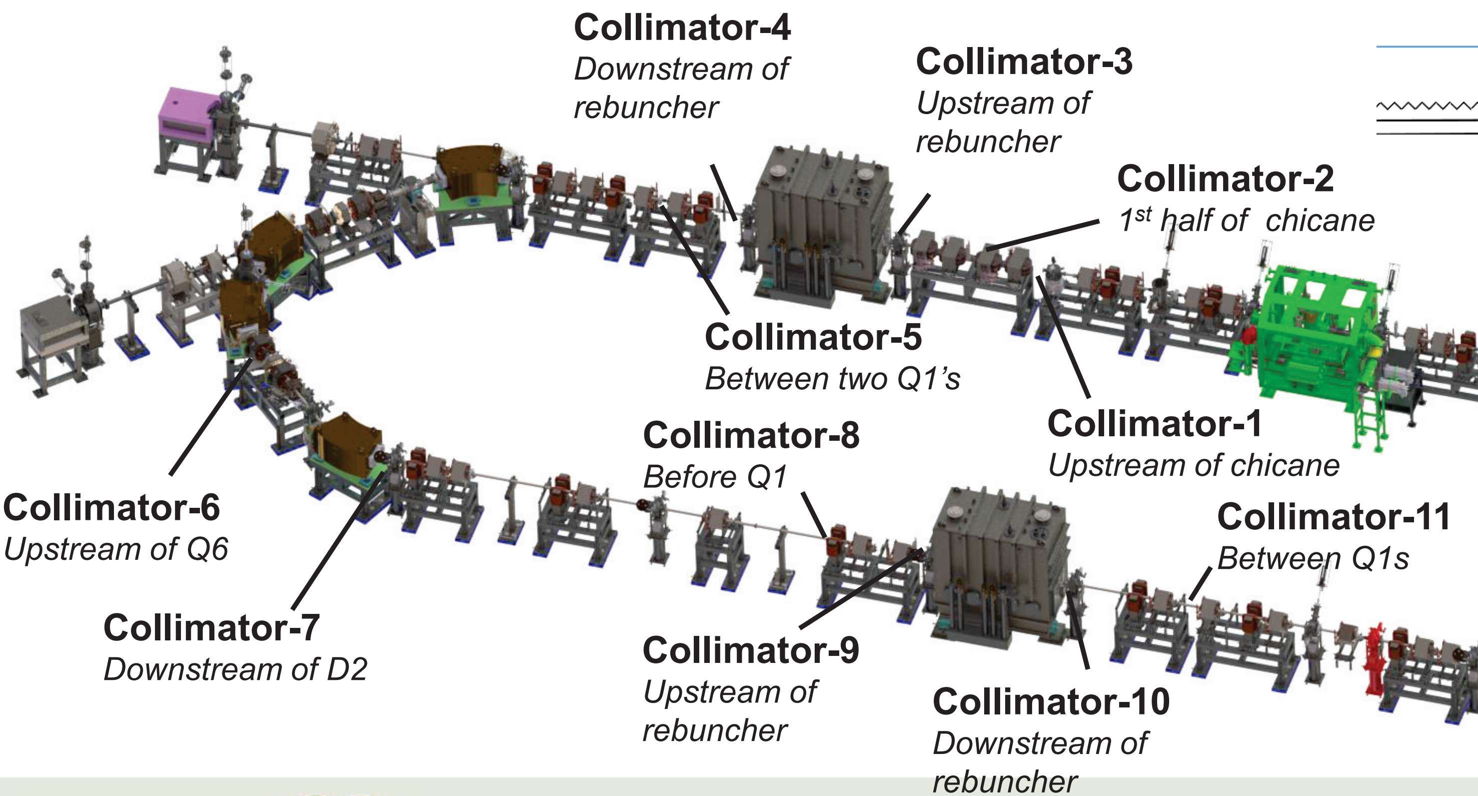
- Collimators are designed mainly to mitigate loss inside cavities

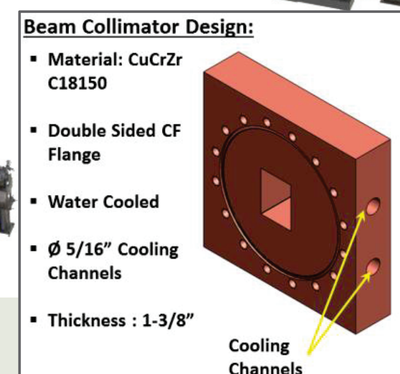


Layout of FS1 Collimators
11 Collimators are placed along FS1

- All collimators are water cooled CuCrZr
- Side wall of Chicane and 1st dipole chambers are water cooled and saw tooth geometry to avoid shallow injection angle







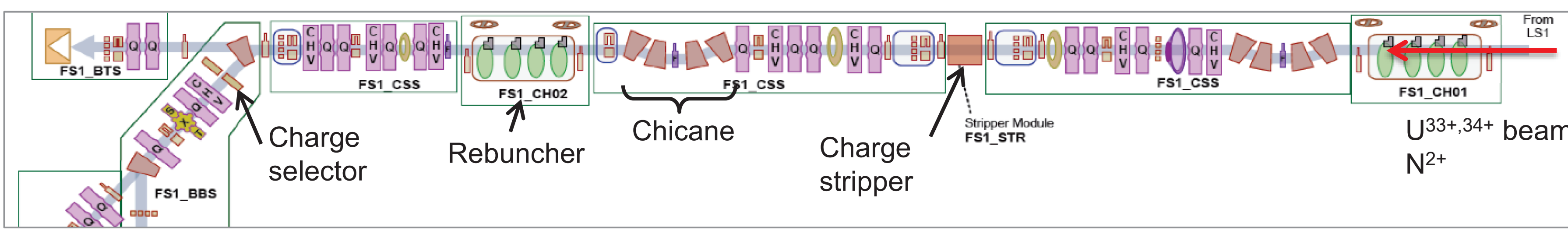
Outline of Contaminant Ion Loss

- In generating a heavy ion beam with ECR ion source, other ions but with similar Q/A can contaminate the beam
- Contaminant will be accelerated with intended ions
- After stripper, contaminant can have very different Q/A after charge stripper as lighter ions are easier to be fully stripped

Example: $^{238}U^{34+}$ (q/A=0.143) → **Stripper** → $^{238}U^{78+}$ (q/A=0.328)

$^{14}N^{2+}$ (q/A=0.143) → **Stripper** → $^{14}N^{7+}$ (q/A=0.5)

- Contaminant with very different q/A has a mismatch to the optics, which can result in a beam loss after charge stripper



Power of Contaminant Ions after Stripper
Contaminant Power is 2 kW at maximum

- Contaminant ions' current from ECRIS can be ~1% of total current
  - However, $^{14}N^{2+}$ is much higher, ~5% in 2-charge state $^{238}U^{33+,34+}$
- Main beam power at the stripper is 40 kW (84% in 5 charge states)

$$P_{cont} = \eta \frac{(q/A)_{beam}}{(q/A)_{cont}} \frac{P_{beam}}{F_{beam}}$$

η : Contaminant power
P_{cont} : Beam power at stripper
P_{beam} : Charge-to-mass of contaminant
$(q/A)_{cont}$: Charge-to-mass of beam
$(q/A)_{beam}$: Fraction of wanted charge states
F_{beam} : Contaminant fraction after ion source

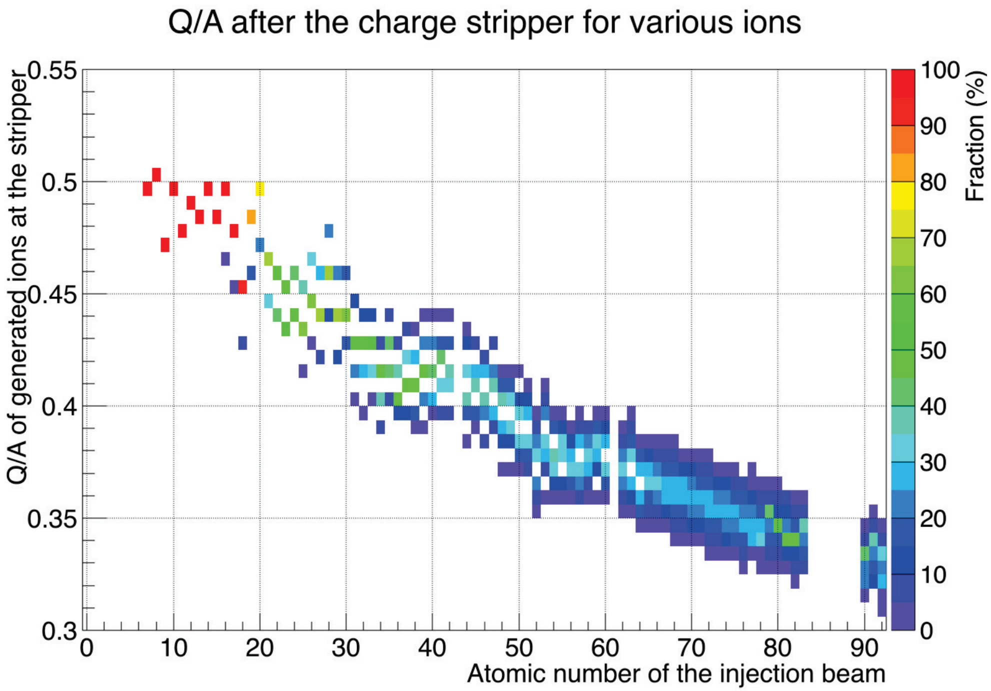
Beam	A	q	q/A	F_{beam}	P [kW]		Cont.	A	q	q/A	P [kW]
^{238}U	238	33.5	0.141	0.84	40		^{14}N	14	2	0.143	~2
^{204}Hg	204	29	0.142	0.80	42		^{14}N	14	2	0.143	~2
^{86}Kr	86	18	0.209	0.82	41		^{14}N	14	3	0.214	~2
^{58}Ni	58	15	0.259	0.90	37		^{16}O, ^{12}C	16,12	4,3	0.250	~0.5
^{78}Kr	78	18	0.231	0.82	41		^{48}Ca	48	11	0.229	0.41

Modification of q/A after Stripper

- Obviously, q/A after the stripper strongly depends from A
- Detailed study was performed for uranium case, q/A= 0.328
  - Contaminants' q/A from 0.35 to 0.5
- The ratio of q/A, r(q/A), of contaminant and beam is introduced to design the collimators

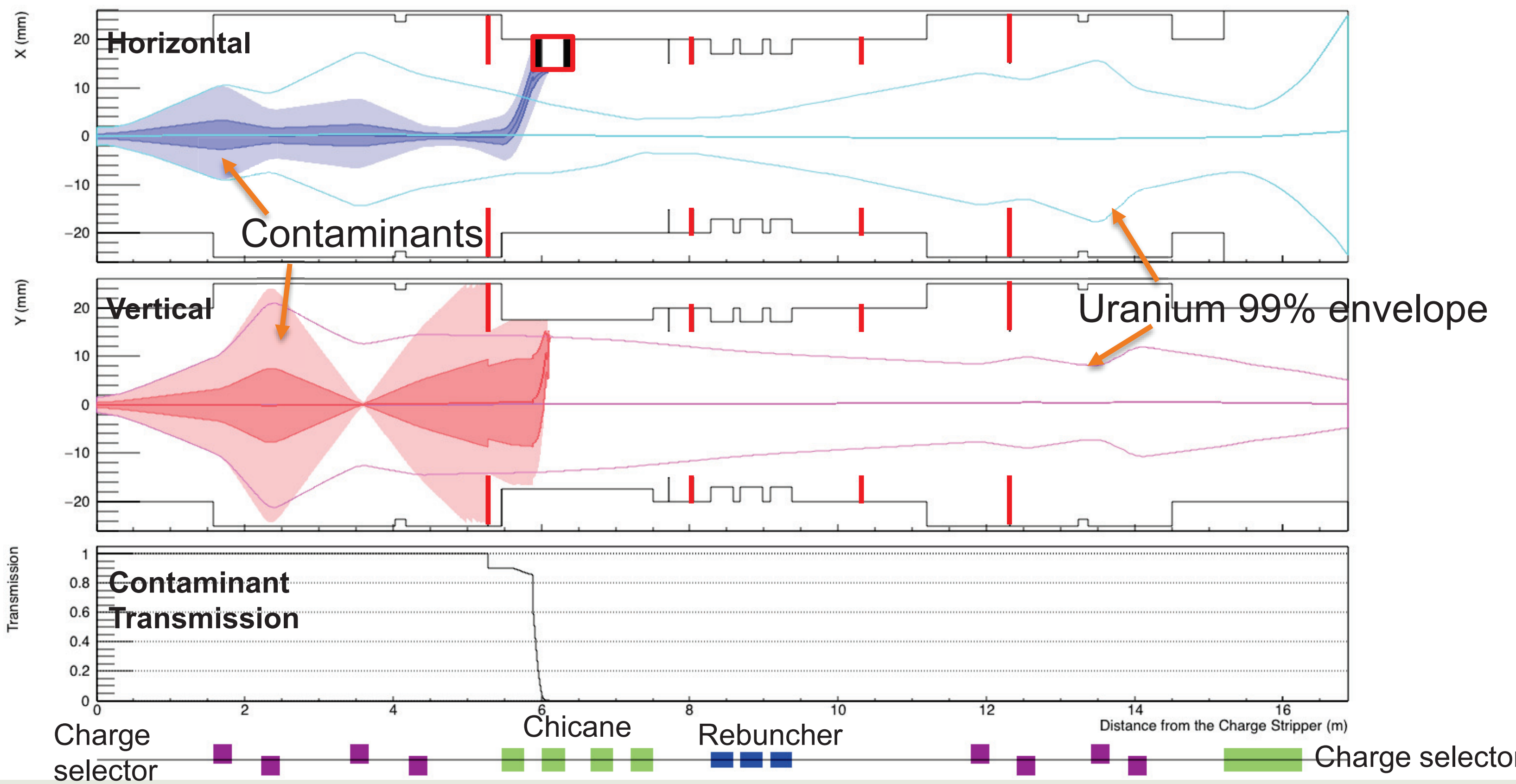
$$r(q/A) = \frac{(q/A)_{cont}}{(q/A)_{beam}}$$

  - r(q/A) range: 0.8 ~ 1.5
- Five collimators were designed to effectively collimate contaminants the entire r(q/A) range



Example of Contaminant Envelopes of q/A = 0.5

- Nitrogen component in uranium beam, r(q/A) = 1.52
  - 10% is lost on 1st collimator and rest are contained in the chicane
  - Chicane chamber is necessary to sustain 2 kW loss

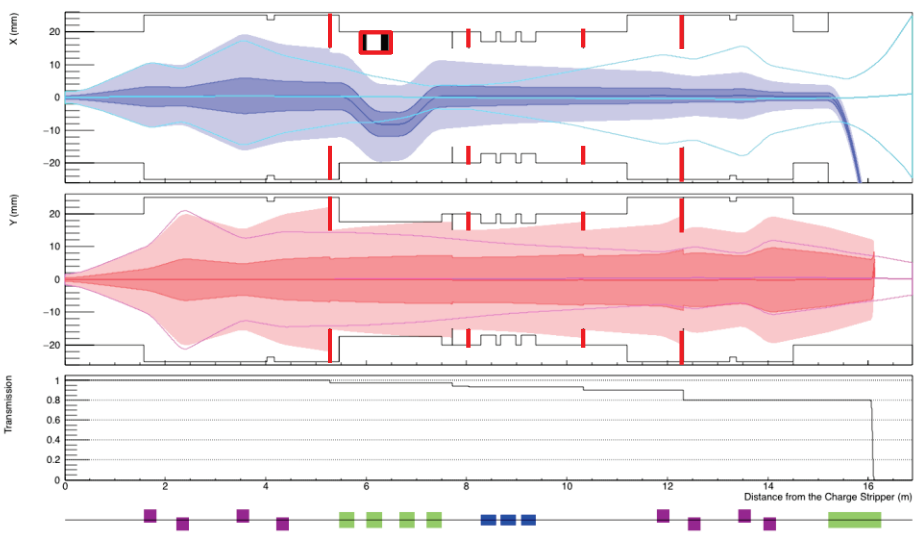


Example of Contaminant Beam Envelopes

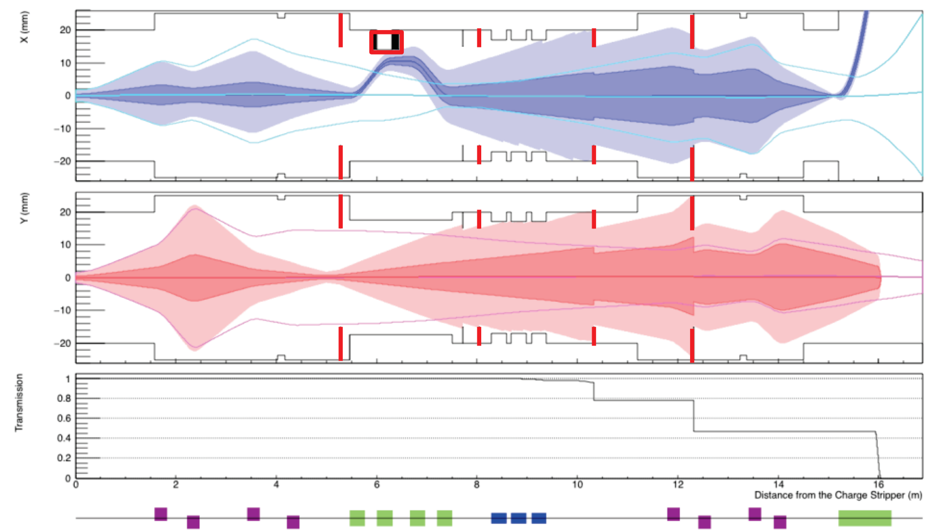
- To avoid direct losses inside the rebuncher, a collimator can be installed just upstream of the rebuncher module
- To avoid distributed losses, additional collimators are required downstream of the re-buncher
- These collimators compromise the performance of cavities

$$r(q/A) = \frac{(q/A)_{cont}}{(q/A)_{beam}}$$

r(q/A) = 0.82



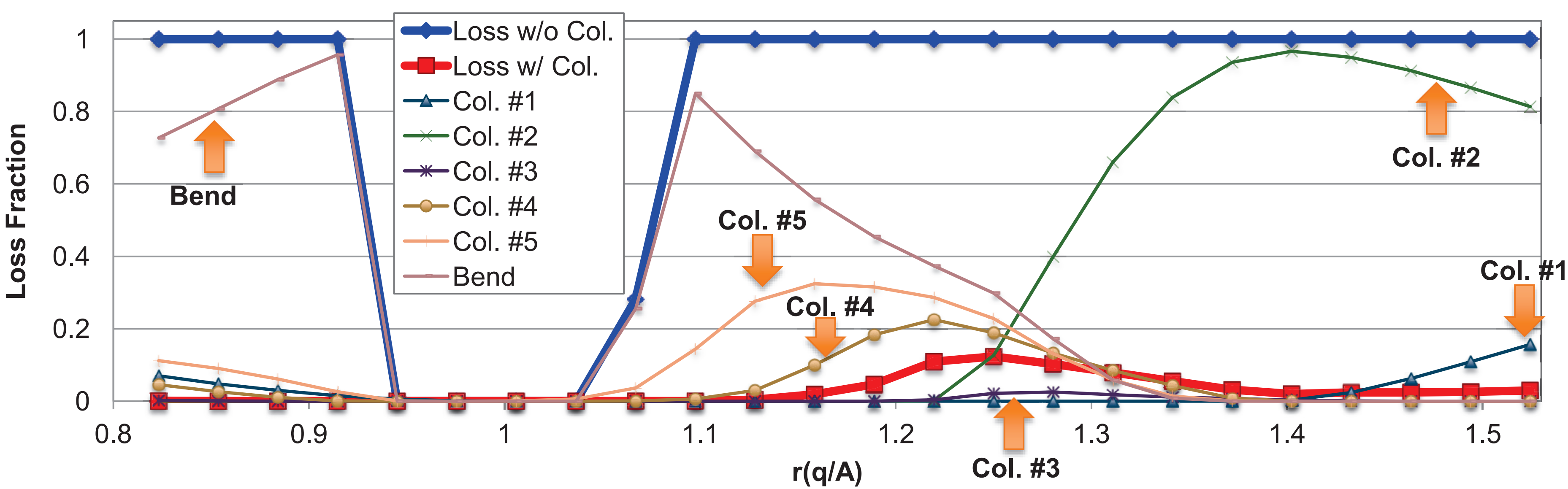
r(q/A) = 1.22



Contaminant Beam Losses on Collimators

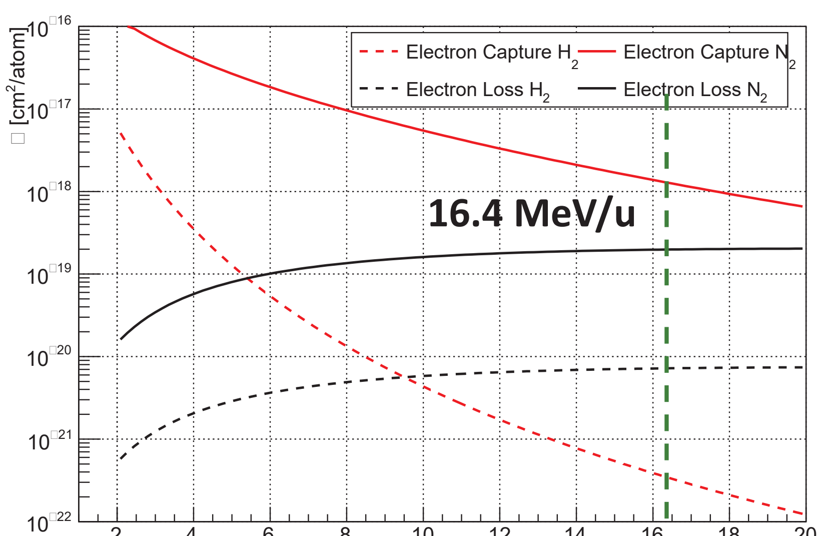
Contaminants are well intercepted in whole r(q/A) region

- Beam losses were calculated for wide range of q/A for contaminant beams
- The calculations are for uranium case, beam optics is similar for all other ions
  - The distribution of losses will change for the beam with larger emittance and in the presence of machine errors. Beam losses inside the re-buncher can reach several tens of watts
- Over 90% of loss are well localized to these collimators



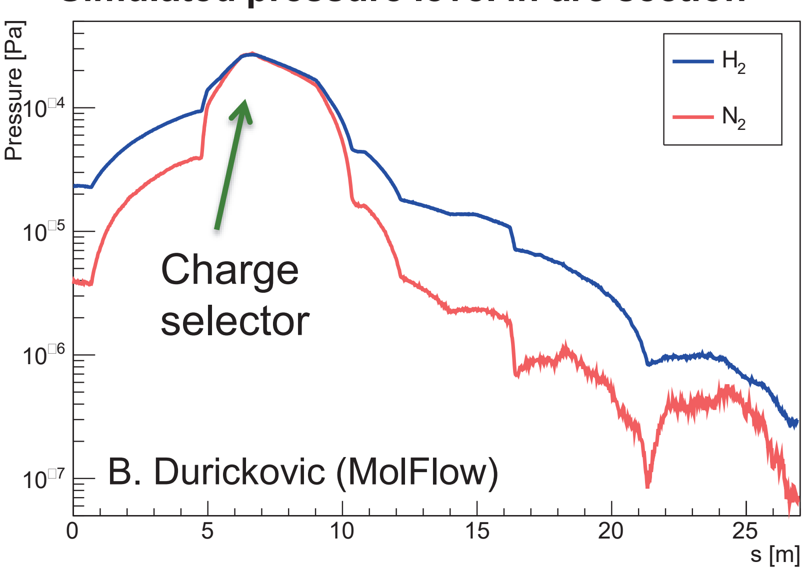
Residual Gas Stripping around the Charge Selector

- Charge selector is one of the highest pressure in entire FRIB accelerator due to intense beam interception and results in charge exchange reaction
- The gas stripping reaction changes charge-state of beam ions.
- When the gas stripping occurs in dispersive area, the generated ions with irregular charge state have different orbit and result in beam loss.
- The irregular charge-state is estimated to be 3.0 W for full power uranium beam.



V.P. Shevelko et al., NIMB 278 (2012) 63.

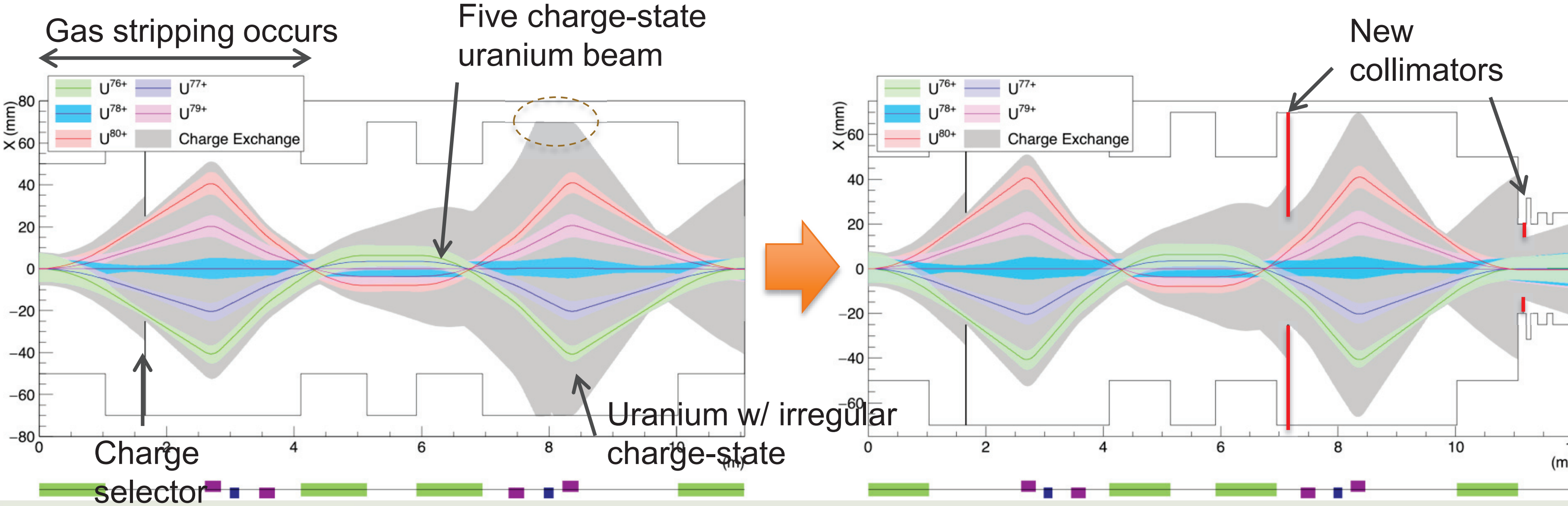
Simulated pressure level in arc section



Collimation of Residual Gas Stripping

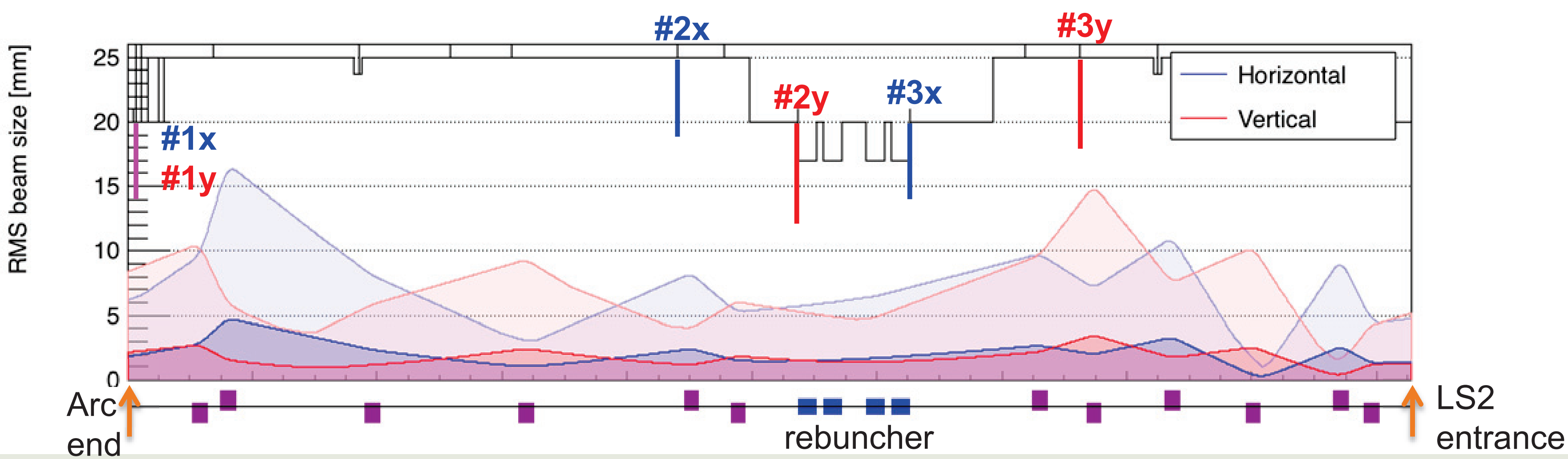
- The simulation with assuming that gas stripping mainly occurs around the charge selector, the irregular charge state ions are lost in the second half of the arc section
- The loss in arc section can be mitigated well when a horizontal collimator is placed after third dipole.
- Another

Horizontal envelopes in the FS1 arc section



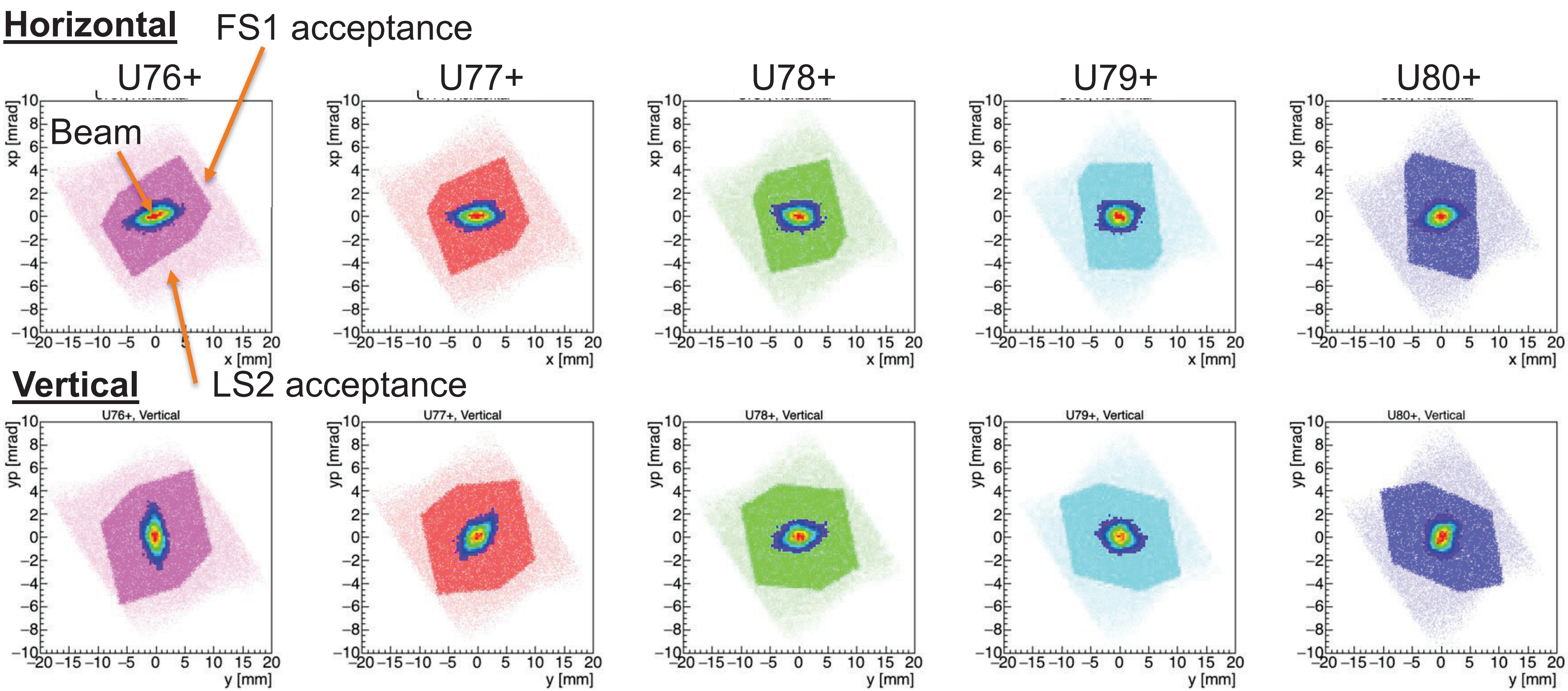
Collimators in FS1 Second Straight Section

- The beam halo and remaining charge exchanged ions are potentially lost in Linac segment 2
  - Beam loss inside cavity causes a deterioration of the cavity performance
- Five collimators are placed to limit transverse acceptance of this straight section with in the LS2 acceptance
  - Aperture is ~7 times of RMS beam size
  - Three collimators for each horizontal and vertical
  - Phase advance of these three collimators are set to 90 deg and 45 deg



FS1 – LS2 Acceptance Comparison

- Simulate the acceptance of uranium five charge states in FS1 and LS2 to confirm that the FS1 acceptance is narrower than LS2
- These five charge states, LS2 acceptance covers FS1 acceptance



Summary

- Beam loss mechanisms in folding segment1 are identified
  - The optics of 180-deg arc section after ion source is tuned to maximize rejection efficiency of unwanted ions
  - Unwanted charges states and beam contaminant which cannot collimated in Front-end
  - Beam halo generated on the charge stripper in FS1 or mistuned bending magnet setting
  - Charge exchange reaction around the charge selector

- Position and aperture of eleven collimators are designed to efficiently intercept these ions
  - 90% of contaminant loss is localized to the collimators
  - Charge exchange ions are well localized to collimators in arc section
  - FS1 acceptance is limit within LS2 acceptance