Dynamics of Beams With Canonical Angular Momentum in Non-Axisymmetric Optical Elements

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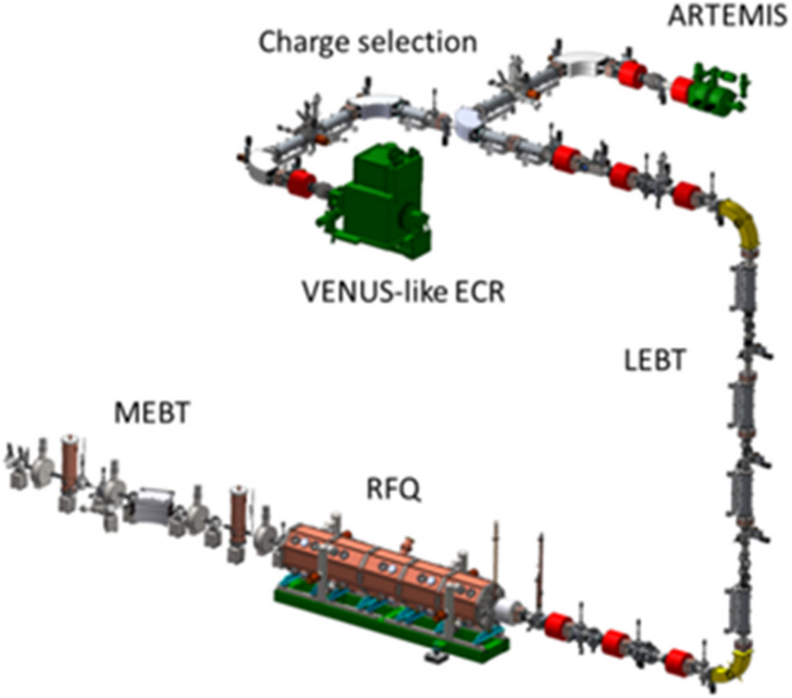
Facility for Rare Isotope Beams (FRIB): front end soon begins early commissioning

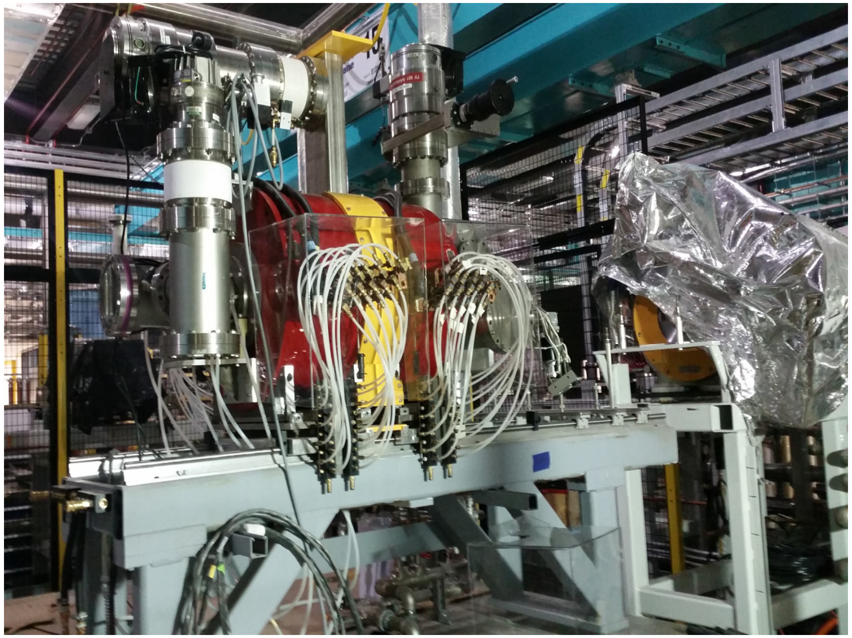
Highlights:

- Sep 2016: Ion source beam commissioning starts
- Dec 2016: RFQ high power test to start
- Feb 2017: RFQ beam commissioning start
- May 2018: Linac segment 1 (post RFQ/MEBT) commissioning start
- 2021: Start of user operation and beam power ramp up

FRIB Front End



Artemis ECR Source now installed, Front end under assembly



Beamline of the FRIB Front End

Ions

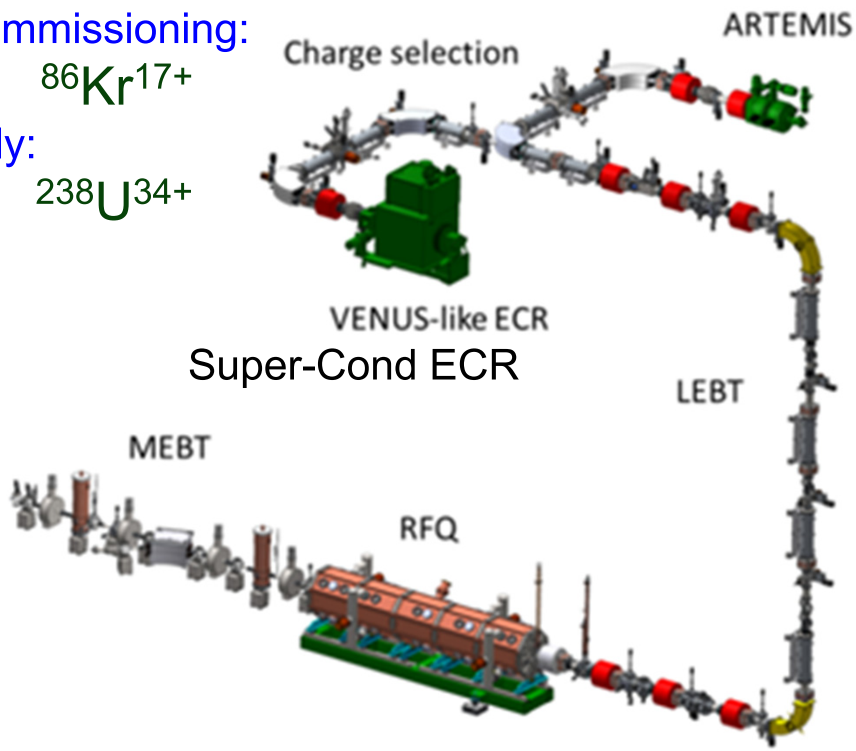
Early Commissioning:

$^{36}Ar^{18+}$ $^{86}Kr^{17+}$

Ultimately:

$^{238}U^{33+}$ $^{238}U^{34+}$

Normal-Cond ECR



- ECR Ion Source
- Short Solenoid
- ES Accel Gap
- Solenoid
- Magnetic Dipole
- ESQ Triplets
- …
- Ultimately to RFQ

Initial simulations through species selection

Many types of lattice elements to model up to RFQ:

Solenoids	Grated Electrostatic Gap	Collimation Apertures
Magnetic Dipoles	Electric Dipoles	Steering Dipoles
Electric Quadrupoles	Bunching Cavities	RFQ

Intense, DC multi-species ion beam emerging from ECR ion sources with part electron neutralization in magnetic optical elements

Overview: Warp PIC Simulations

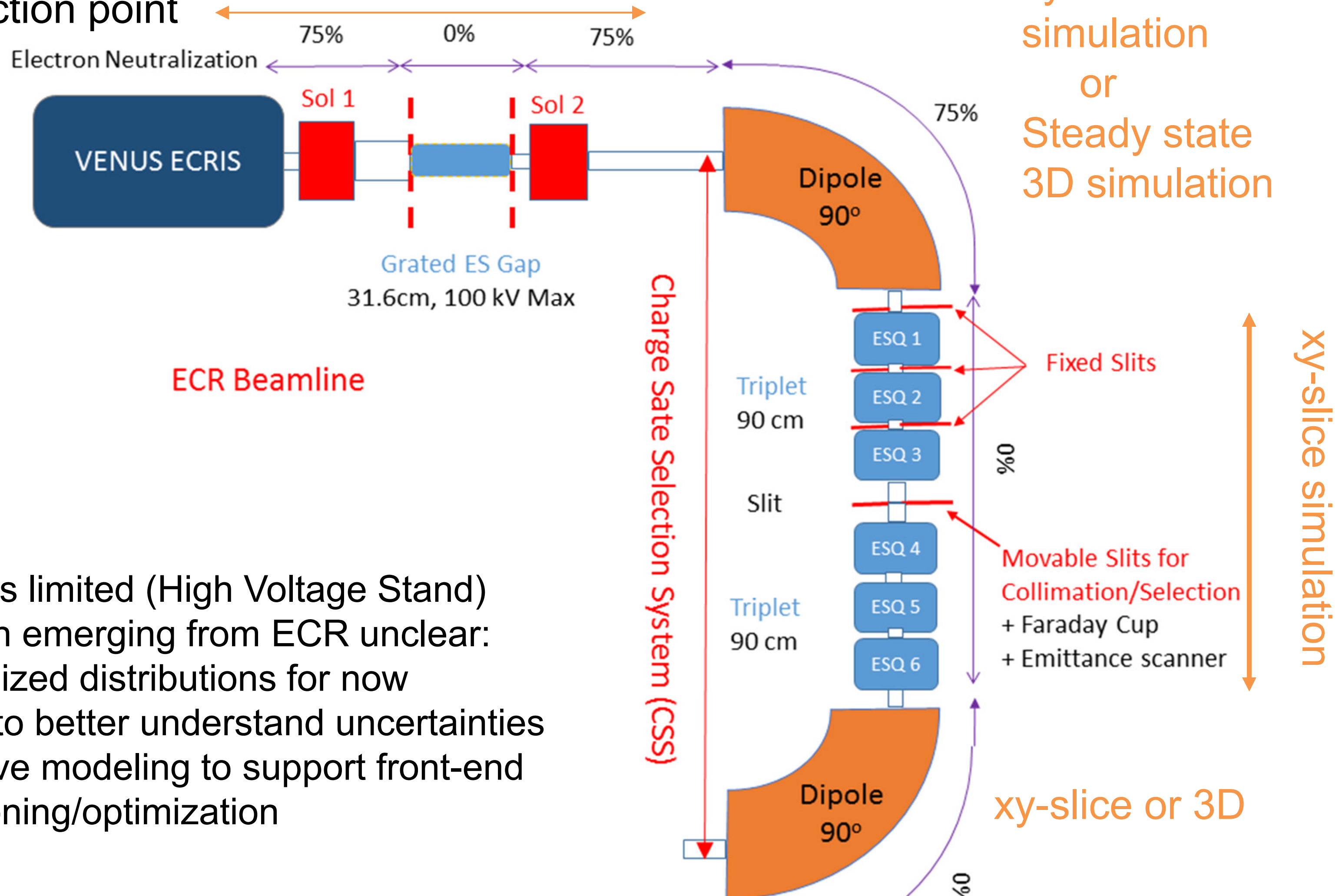
Apply open source Warp PIC code tools for adaptable/efficient simulation on front end

- Formulation for many species with part electron neutralization
- xy transverse slice with 3D element fields (bent mesh in dipoles)
  Particles move in time with dt iterated to move slice to slice => only z-self field not included
- Also full 3D steady state in linked simulations where potential 3D self-field issues

Begins at ECR extraction point

xy-slice simulation

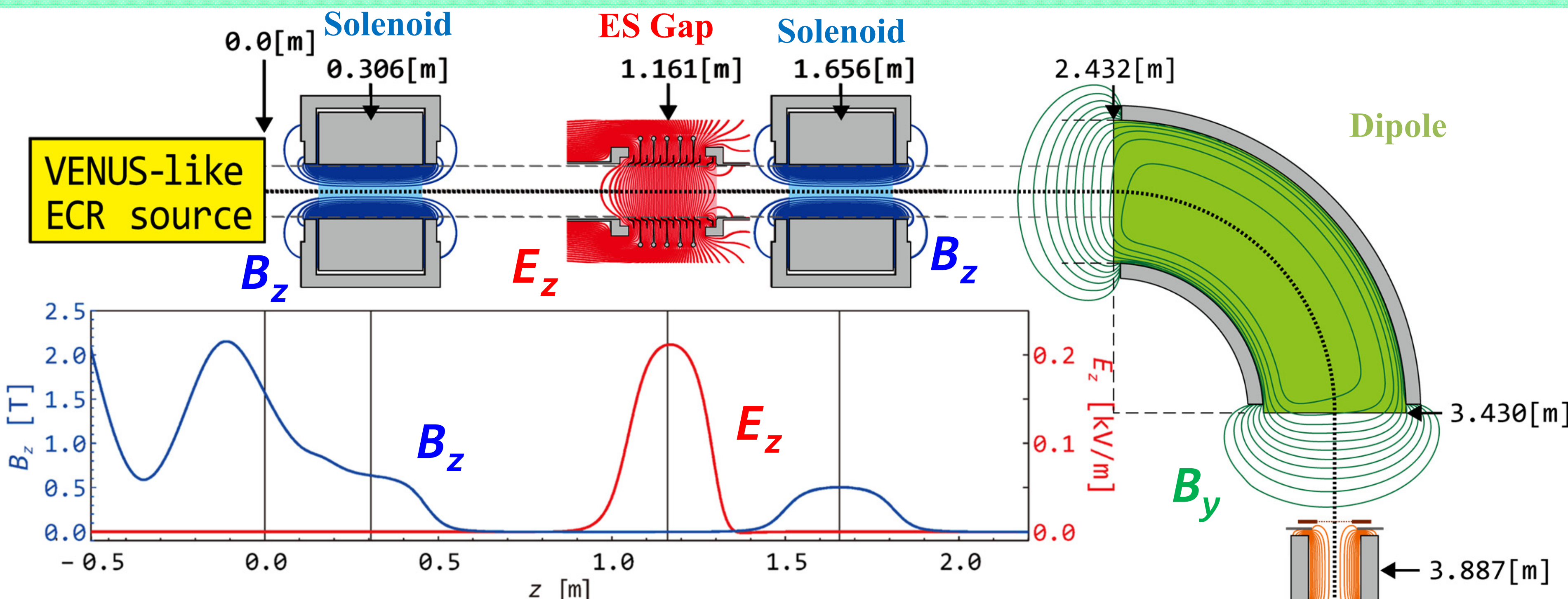
xy-slice simulation or Steady state 3D simulation



- Diagnostics limited (High Voltage Stand)
- Distribution emerging from ECR unclear:
- inject idealized distributions for now
- Desirable to better understand uncertainties
- and improve modeling to support front-end commissioning/optimization

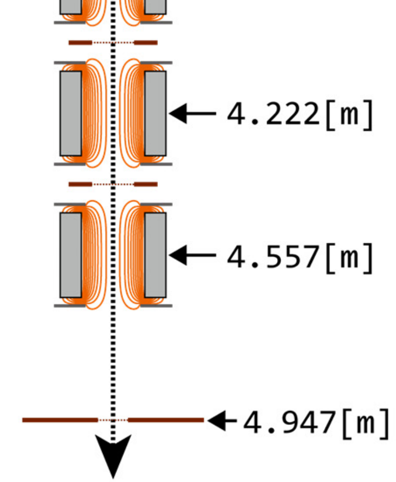
xy-slice or 3D

Lattice elements modeled at high levels of detail for importing into simulations



Elements short with wide apertures

- Nonlinear fields significant
  - Setup to turn nonlinear terms on/off in code while keeping physical fringe variation
- Fringe fields neighboring elements can overlap
  - Modeled in code: find implications

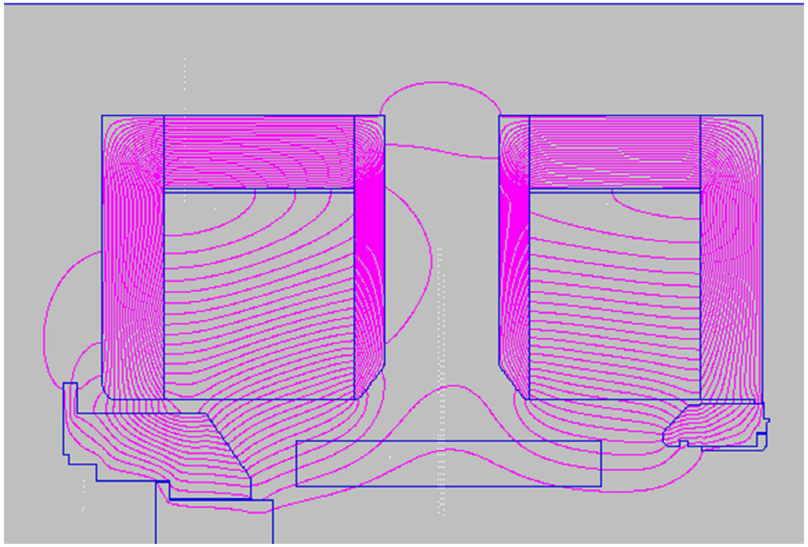


Apply with filed data from optics design codes

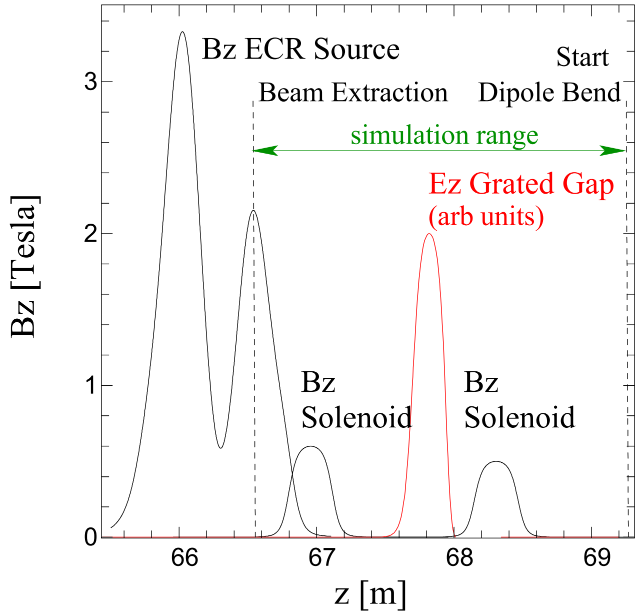
- CST Studio   Opera   Maxwell   Poisson

Example details of lattice element models: ECR source

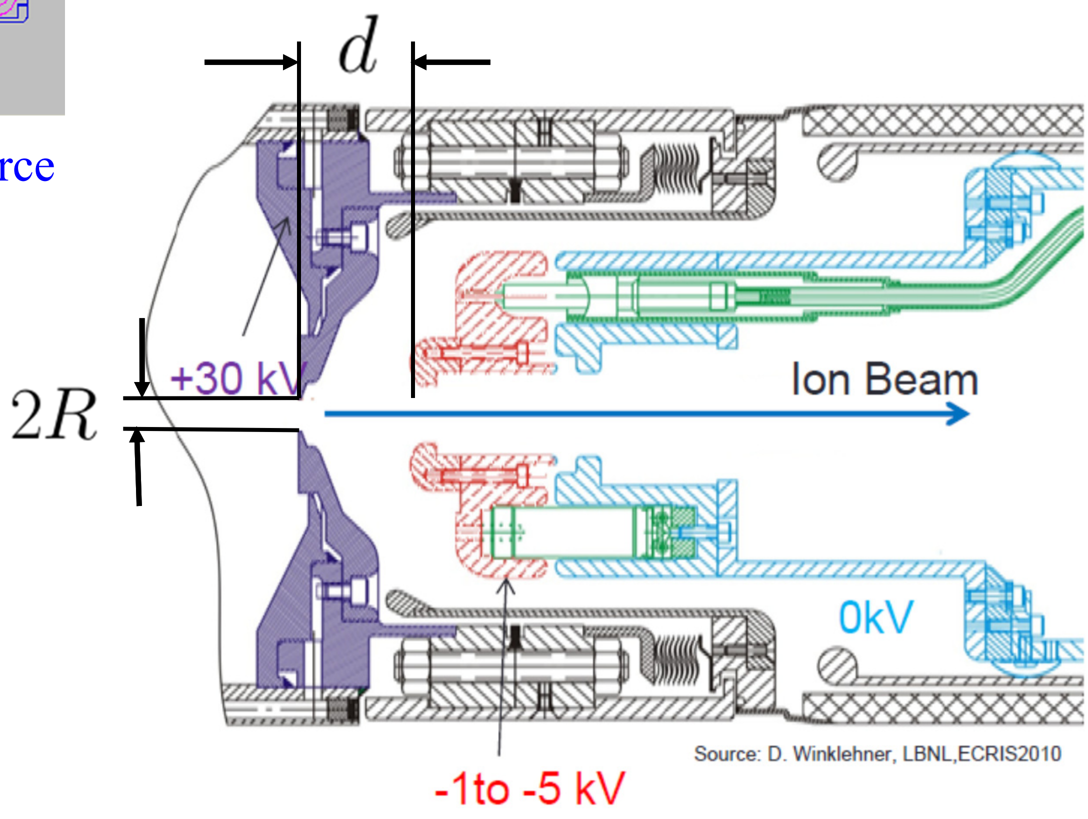
Poisson Model: Solenoid of NC Artemis ECR



Axial Field Overlaps Near ECR Source

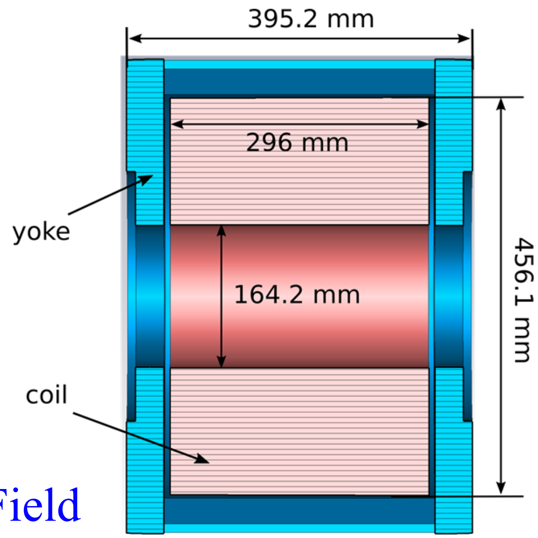


Puller Electrodes of SC Venus ECR

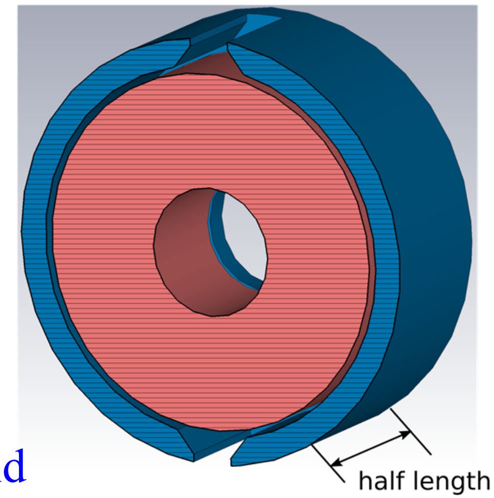


Example details of lattice element models: Solenoids

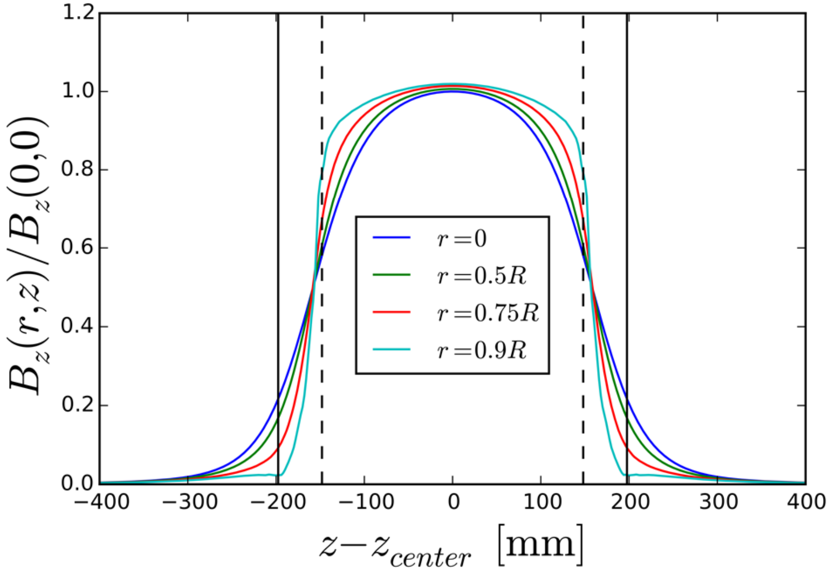
Cross Section



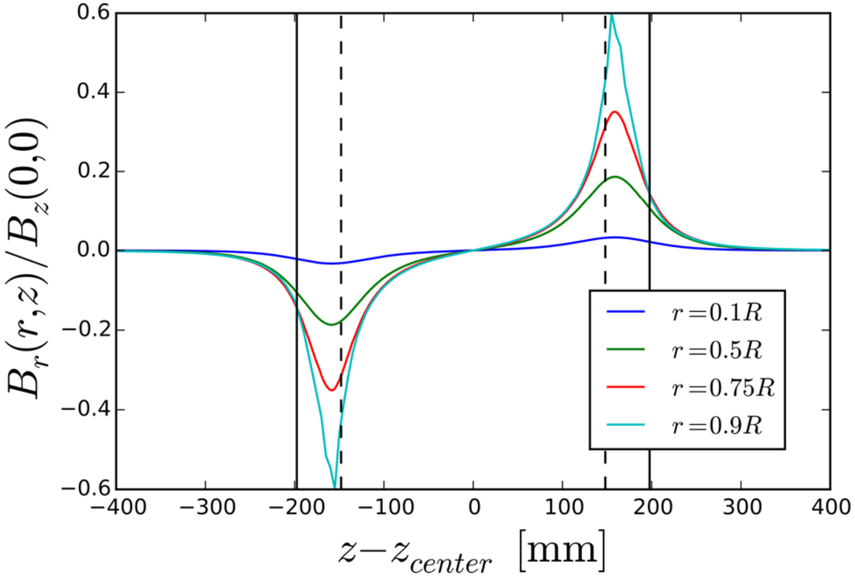
Half (Cut) Perspective View



Axial Field



Radial Field



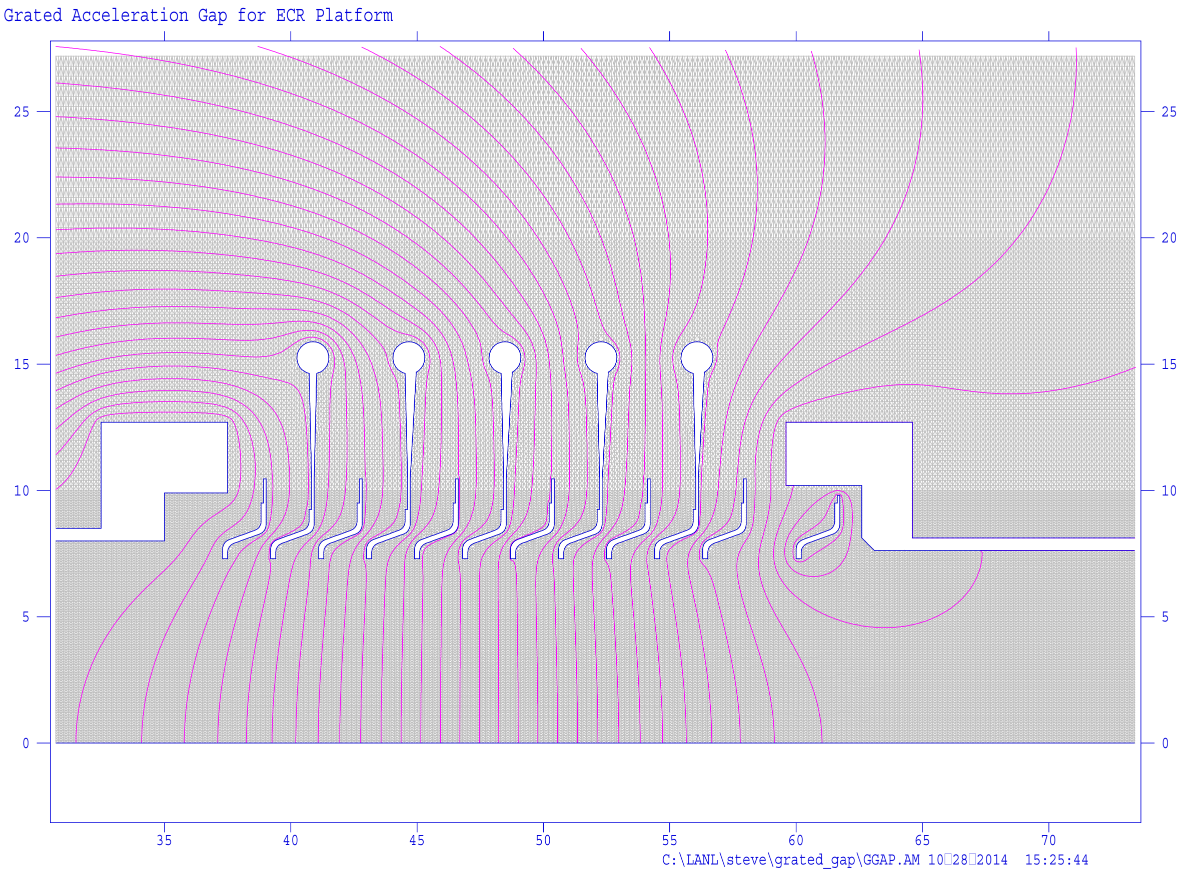
Models imported in high detail from optics design codes Poisson (r-z mesh) and CST Studio

Lattice element model: Grated Electrostatic Accel Gap

Nonlinear r-z Poisson Model

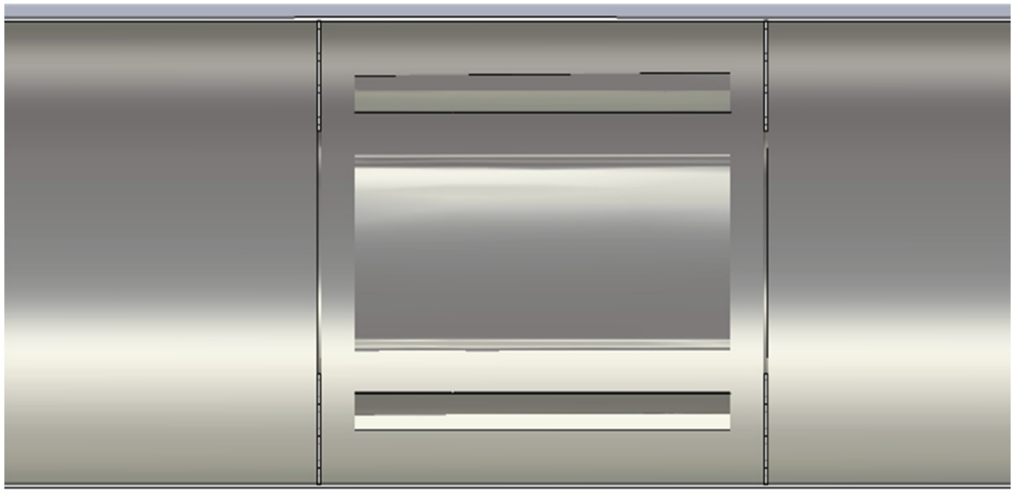
» Fringe well resolved

» Downstream electron suppressor electrode included

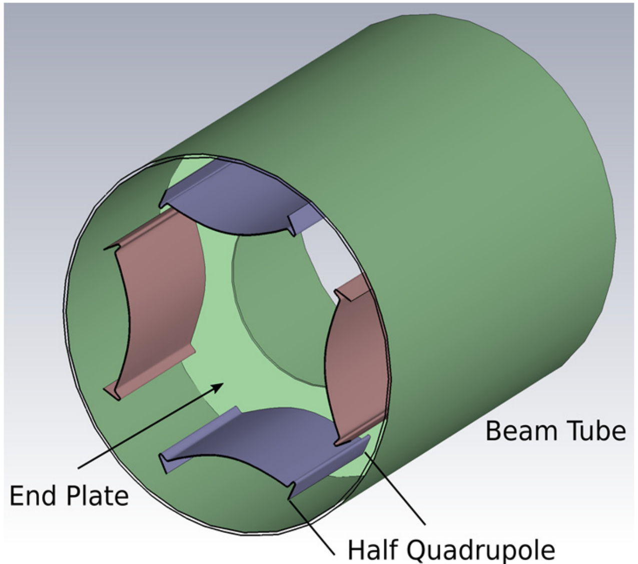


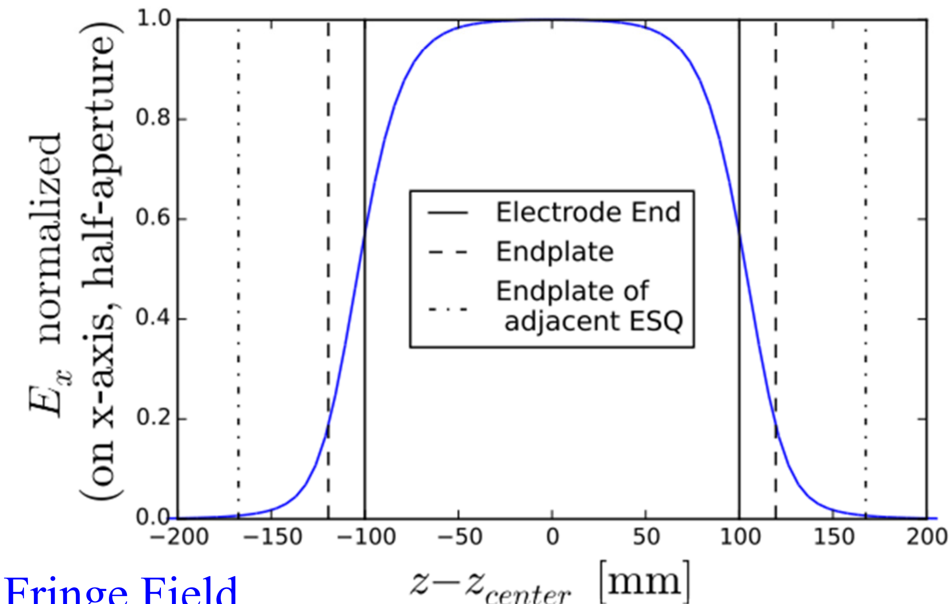
Lattice element model: Electrostatic quadrupoles

Cross Section



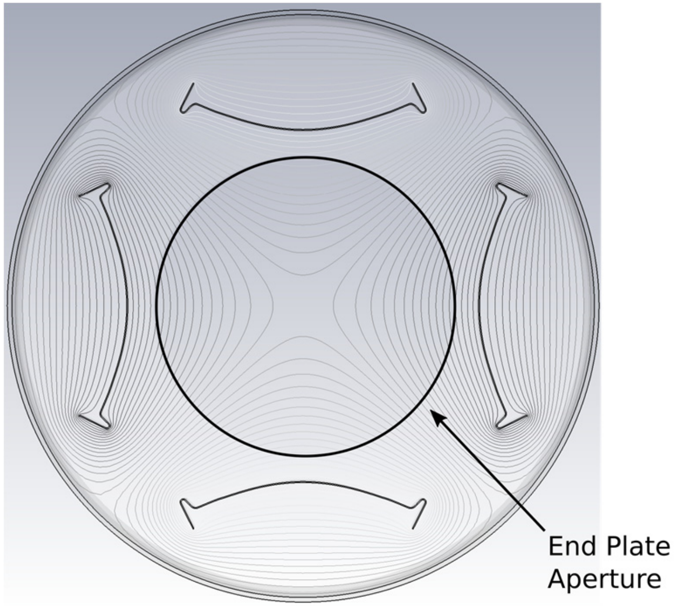
Half (Cut) Perspective View





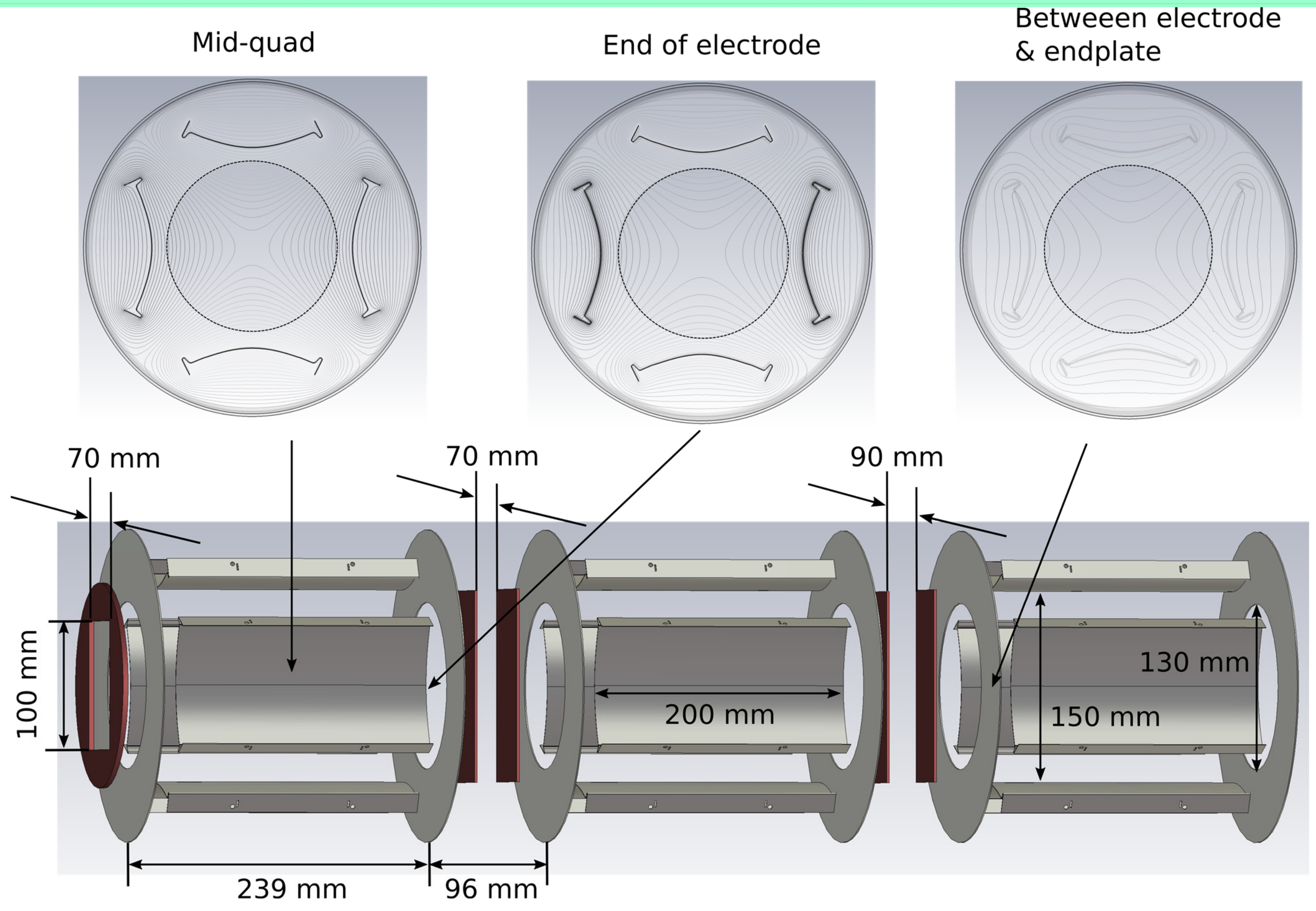
Fringe Field
(Perp Gradient)

Mid-Plane Potential Contours



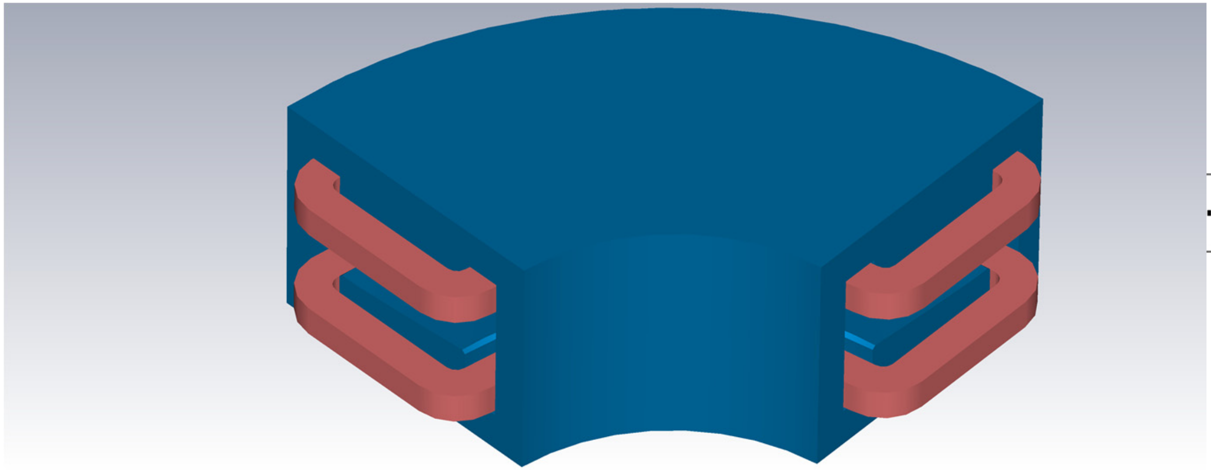
Models imported from CST Studio

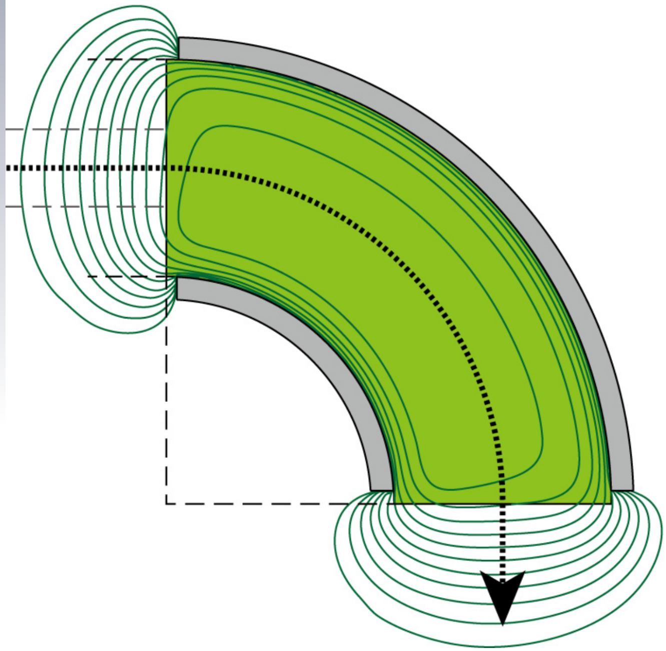
Lattice element model: Electrostatic quadrupoles and collimation electrodes



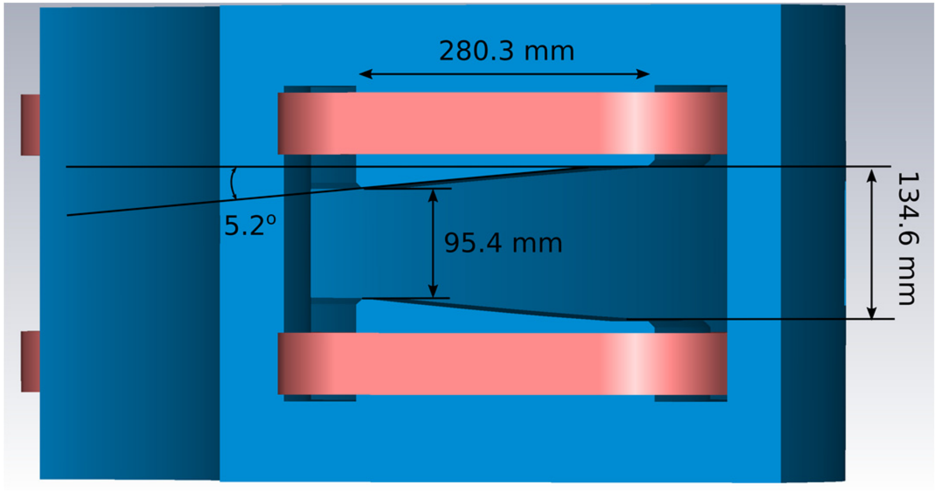
Lattice element model: Magnetic bending dipole with slanted poles

Perspective View





End View Illustrating Slanted Poles



Dipole Fields modeled in 3D using:

Opera

CST Studio

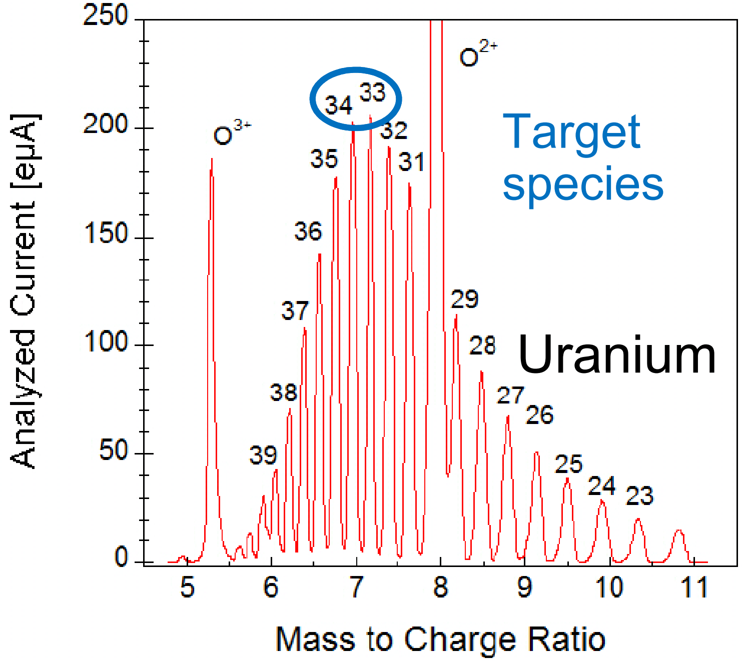
Properties of idealized initial distribution expected from ECR also incorporated: Example ^{238}U

Ion	I (emA)	Q/A	$[B\rho]$ (Telsa-m)
U^{+25}	0.035	0.105	0.0831
U^{+26}	0.051	0.109	0.0815
U^{+27}	0.068	0.113	0.0800
U^{+28}	0.088	0.118	0.0785
U^{+29}	0.115	0.122	0.0772
U^{+30}	0.150	0.126	0.0759
U^{+31}	0.175	0.130	0.0746
U^{+32}	0.192	0.134	0.0735
U^{+33}	0.210	0.139	0.0723
U^{+34}	0.205	0.143	0.0713
U^{+35}	0.178	0.147	0.0702
U^{+36}	0.142	0.151	0.0693
U^{+37}	0.11	0.155	0.0683
U^{+38}	0.072	0.160	0.0674
U^{+39}	0.043	0.163	0.0665
U^{+40}	0.031	0.168	0.0657
O^{+1}	0.3	0.063	0.1077
O^{+2}	0.3	0.125	0.0762
O^{+3}	0.3	0.188	0.0622
O^{+4}	0.2	0.250	0.0539

Target Species

- Many species possible
  - » Uranium most rigid
  - » Rigidity:

$$[B\rho] = \frac{\gamma\beta mc}{q}$$

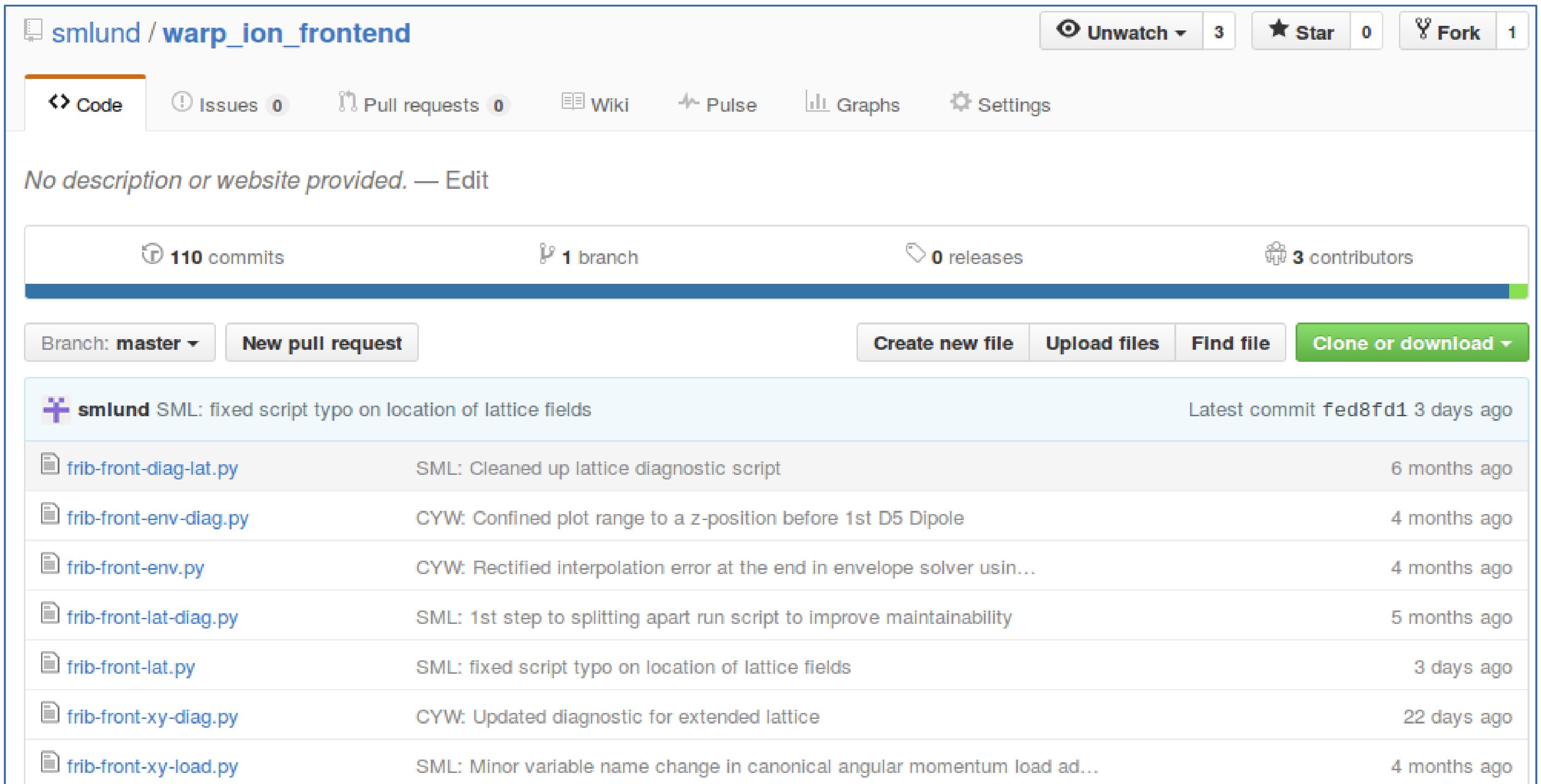


[D. Leitner, M. L. Galloway, T. J. Loew, and C. M. Lyneis, Rev. Sci. Instrum. 79, 02C710 (2008)]

Warp code tools for front ends setup for maintainability/extension while analyzing many ion species and lattices under a range of models with multiple users simultaneously using/extending

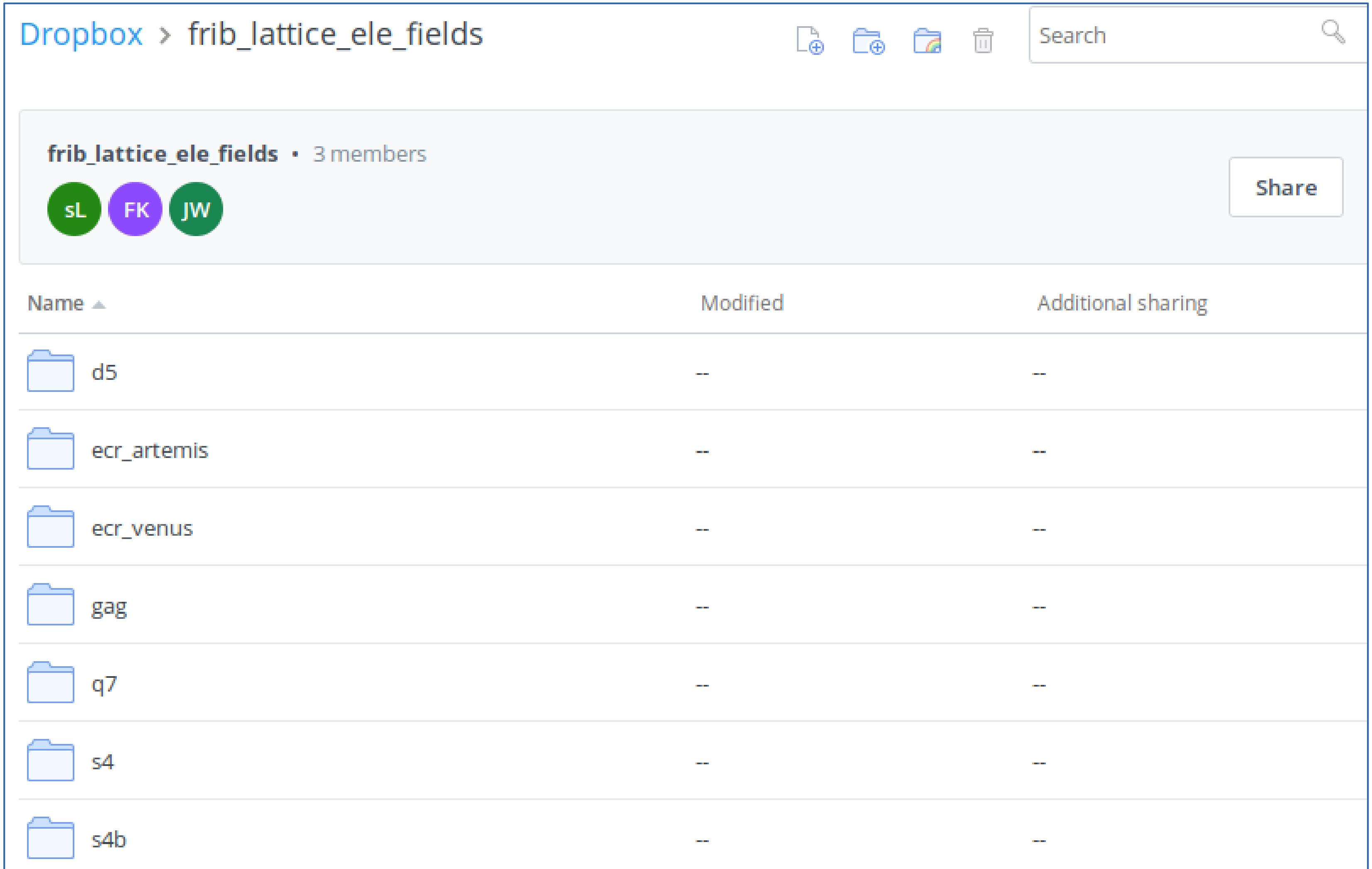
Github source code repo used to maintain/distribute python based Warp scripts for front-end simulation and input parameters for runs

- Structured to allow simultaneous users to update/extend while using at same time with different levels of model description
- Allows roll-back, project forking, etc.



Dropbox file sharing used to maintain/distribute field element data for lattice element description

- Allows large binary/ascii data files for 3D/2D field maps generated with optics design codes on windows/linux/osx platforms
- Archive input, plots, analysis, and code interfaces for each lattice element
- Allows use of links contained in git distribution for data reading without account



Initial phase-Space areas set consistently with magnetized ions born in source: Multi-species envelope model (described later) helps setup

Initial Phase-Space set by guesses of ECR values

Normalized Thermal Emittance:

$$\boxed{\varepsilon_{nrj}^{\mathrm{rms}} = \sqrt{\left(\frac{T_j}{m_j c^2}\right)} R_j \sim 0.015 \text{ mm-mrad}}$$

T_j = Temp (Energy Units) jth Species Ion

R_j = Edge Radius jth Species (Uniform Density)

Uranium 34+ emerging from ECR

$R_j = 4$ mm beam edge radius

$T_j = 3$ eV

Normalized Canonical Angular Momentum (same scale expressed):

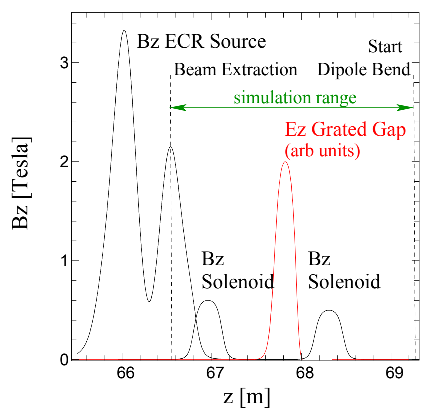
$$\boxed{\frac{\langle P_\theta \rangle_j}{m_j c} = \frac{q_j B_{z0}}{4 m_j c} R_j^2 \sim 0.39 \text{ mm-mrad}}$$

At particle "birth" location:

$B_{z0} = B_z(r=0, z) = 2.2$ Tesla (at extraction)

R_j = Edge Radius jth Species (Uniform Density)

~ 25 x Thermal Emittance contribution to phase-space area defocusing!



20 species initial ECR distribution injected in xy transverse slice simulation using this method

- Smooth, space-charge adapted distributions used
- Energy consistent with ECR extraction bias (~35 kV)
- Low longitudinal energy spread

Real ECR distribution expected to have much more asymmetry

- Will inject better "guesses" from ECR simulations in future

Warp simulations are being applied to the FRIB front end to both identify/analyze physics issues and will be used to support upcoming commissioning activities

Many issues being examined. Illustrate a subset in this talk for ^{238}U operation with a VENUS type ECR source:

- Multispecies evolution from ECR source with intricate space-charge dynamics
- Matching the beam into the CSS: simulations verify efficient envelope model
- Identifying where non-target species are collimated in the CSS
- Physics impact on CSS resulting from:
  - > Beam Space Charge + Electron Neutralization
  - > Nonlinear applied field + Nonparaxial effects
  - > Strongly Magnetized Beam
  - > Relative PS Contributions from Thermal/Magnetized effects
- Optimal placement of 3D dipole with slanted poles and extended fringe
- 3D Space charge effects in initial species separation in dipole

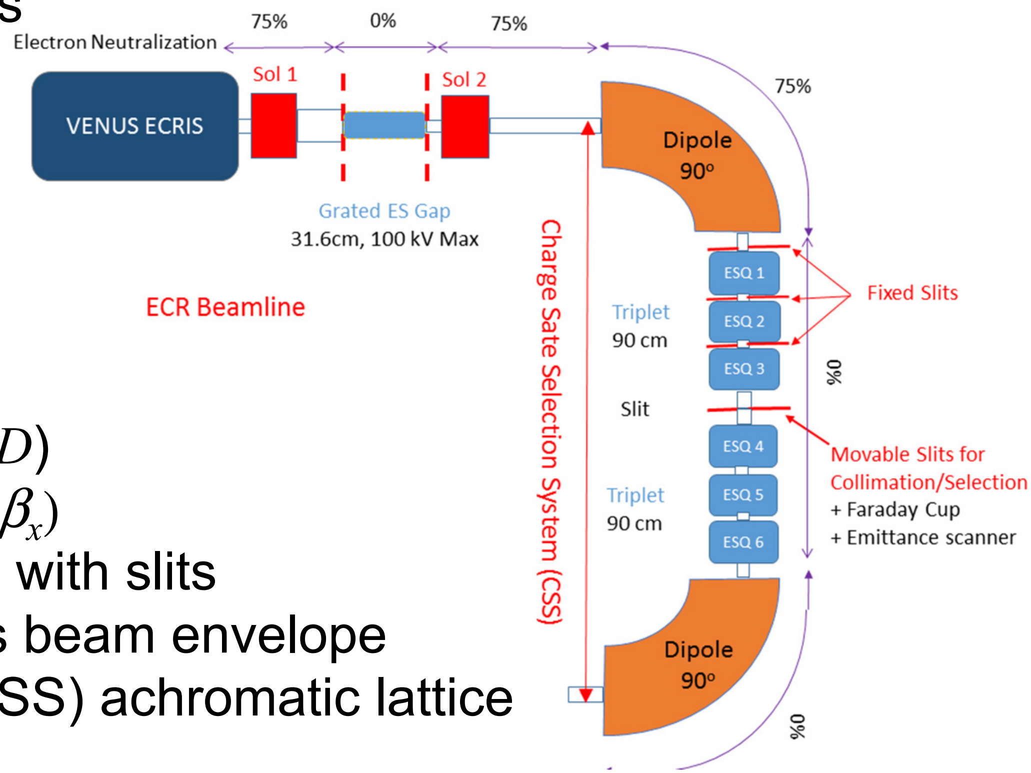
Reported on HB 2016 + Linac 2016

Code augment limited laboratory diagnostics to gain more insight, identify physics issues, and support tuning of system for highest quality beam

Charge Selection System (CSS) designed to select up to two "target" species with no losses and minimal emittance growth

Goals:

- Transport target species with minimal loss in brightness
- Collimate all non-target species



Approach:

- Linearly achromatic
- At mid CSS: large dispersion (D) and small x-betatron function (β_x) to improve selection resolution with slits
- Output with well-controlled rms beam envelope
- Adopt symmetric (about mid CSS) achromatic lattice similar to fragment separator
  - » Eases tuning
  - » Less sensitivity to nonlinear applied field effects for low energy beam

Linear optics CSS designed using MADX for ideal hard-edge lattice

Impose conditions:

- Mid-plane mirror symmetry

$$D'_{\rm mid} = \beta'_{x-{\rm mid}} = \beta'_{y-{\rm mid}} = 0$$

Then lattice functions have mirror symmetry with:

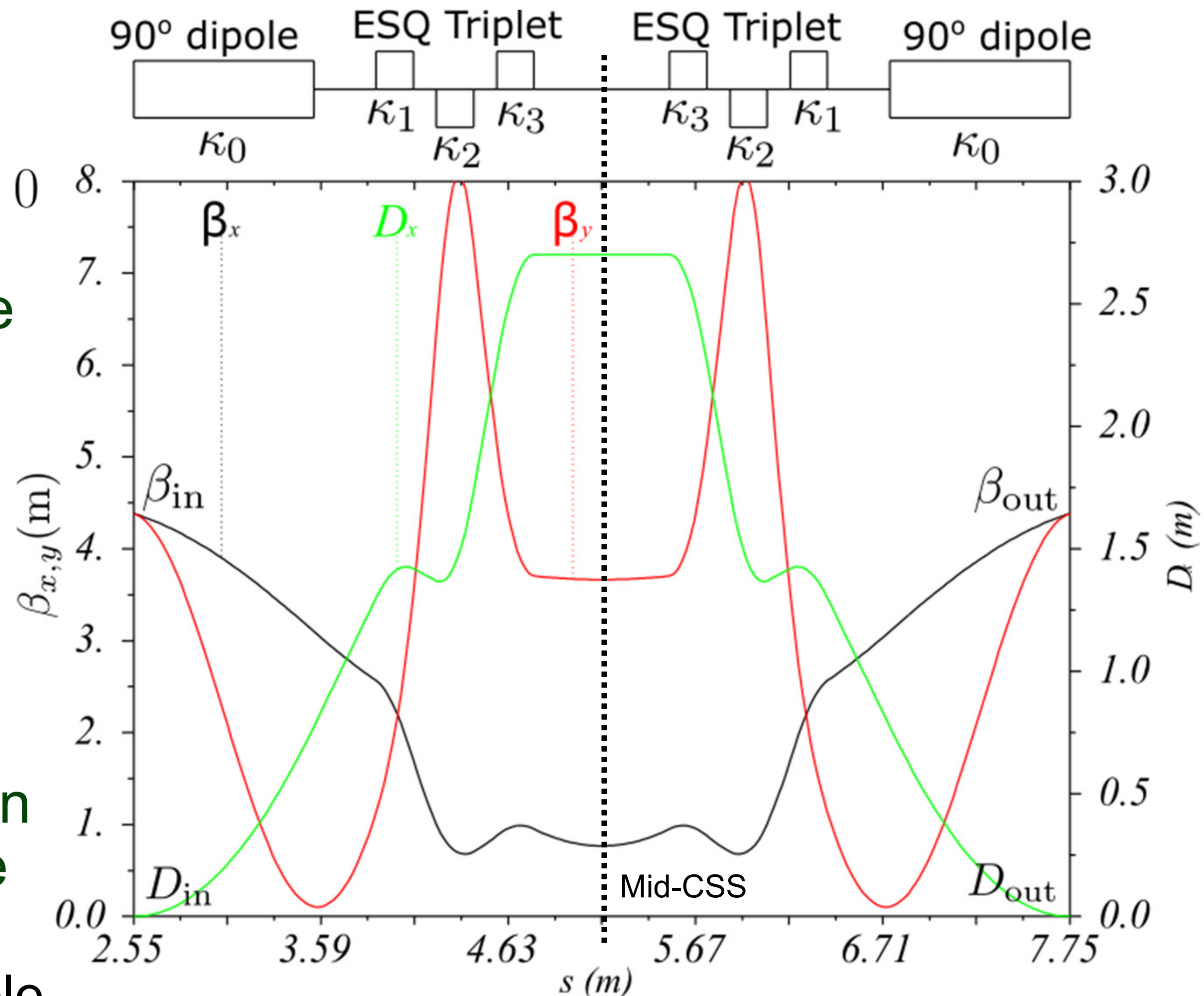
$$\beta_{\rm in} = \beta_{\rm out} \qquad \beta'_{\rm in} = -\beta'_{\rm out}$$

$$D_{\rm in} = D_{\rm out} = 0$$

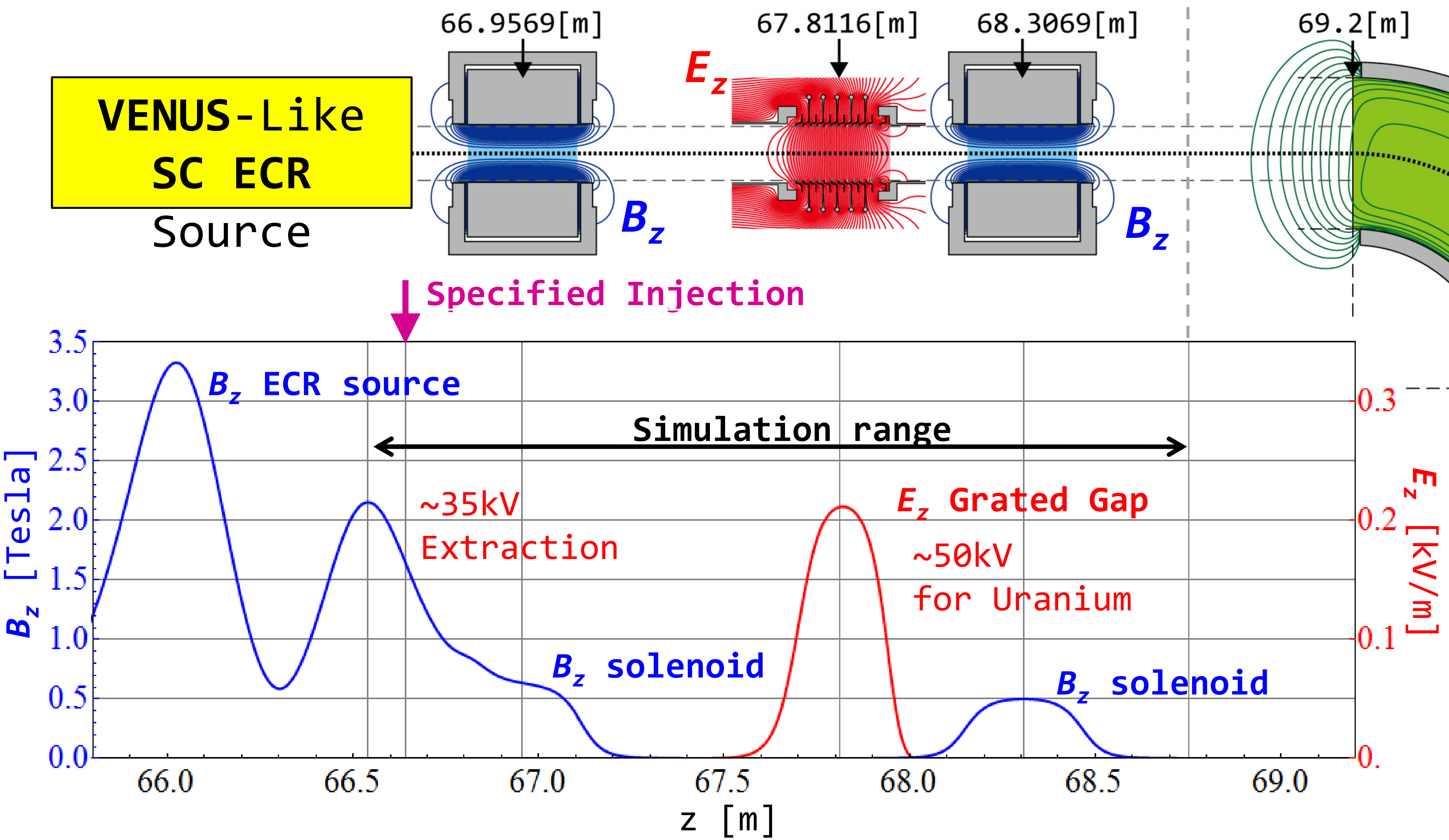
$$D'_{\rm in} = -D'_{\rm out} = 0$$

Adjust $\beta_{\rm in}$ and $\beta'_{\rm in}$ to obtain desired envelope structure within CSS

- Numerous choices possible

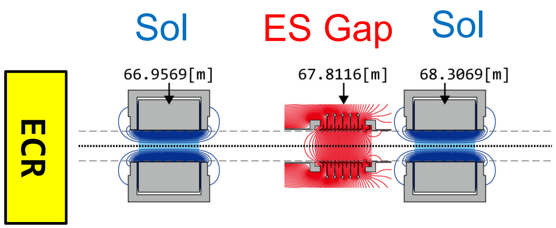


Lattice fields up to 1st dipole



Envelope model derived and applied to model multi-species beam in axisymmetric transport

Applied to model beam from ECR to 1st dipole:



$$\sigma''_{xj} = \frac{q_j V'}{2\mathcal{E}_{kj}}\sigma'_{xj} + \frac{q_j V''}{4\mathcal{E}_{kj}}\sigma_{xj} - \left(\frac{q_j B_{z0}}{2m_j\beta_{bj}c}\right)^2 \sigma_{xj} + \sum_{s,\text{species}} Q_{js} f_s \frac{\sigma_{xj}}{\sigma_{rj}^2 + \sigma_{rs}^2} + \frac{(\varepsilon_{rj}^{\text{rms}}/2)^2 + \langle P_\theta \rangle_j^2 / (2m_j\beta_{bj}c)^2}{\sigma_{xj}^3}$$

- Takes into account: magnetized beam, multi-species (j) space-charge + neutralization, linear accel + solenoid (B_z) focusing

$V =$ on-axis potential of ES gap $\quad B_{z0} =$ on-axis axial B-field of solenoids / ECR

$Q_{js} =$ space charge coupling factor (perveance) between j-th and s-th species

$f_j =$ neutralization factor $(0 = \text{full}, 1 = \text{bare})$ $\quad \mathcal{E}_{kj} =$ kinetic energy (eV)

- Helps understanding of phase-space area contributions

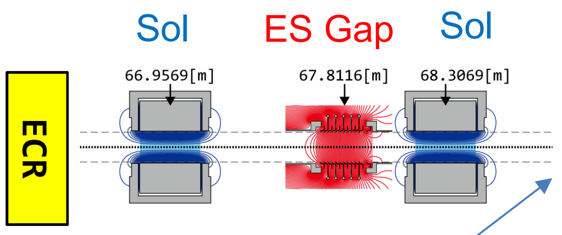
$\sigma_x = \sqrt{\langle x^2 \rangle} =$ rms beam size $\quad \varepsilon_{\text{r}}^{\text{rms}} =$ beam thermal emittance $\sim \langle T_{\text{ion}} \rangle^{1/2} \sigma_x$

$\langle P_\theta \rangle / (2m\beta_b c) =$ canonical angular momentum (emittance units)

Employ envelope model to efficiently match beam to the CSS

Envelope model used for matching by integrating from ECR to 1st dipole:

$$\sigma''_{xj} = \frac{q_j V'}{2\mathcal{E}_{kj}}\sigma'_{xj} + \frac{q_j V''}{4\mathcal{E}_{kj}}\sigma_{xj} - \left(\frac{q_j B_{z0}}{2m_j \beta_{bj} c}\right)^2 \sigma_{xj}$$
$$+ \sum_{s,\text{species}} Q_{js} f_s \frac{\sigma_{xj}}{\sigma_{rj}^2 + \sigma_{rs}^2} + \frac{(\varepsilon_{rj}^{\text{rms}}/2)^2 + \langle P_\theta \rangle_j^2 / (2m_j \beta_{bj} c)^2}{\sigma_{xj}^3}$$



Start integration at ECR extraction point

End at entrance of 1st dipole

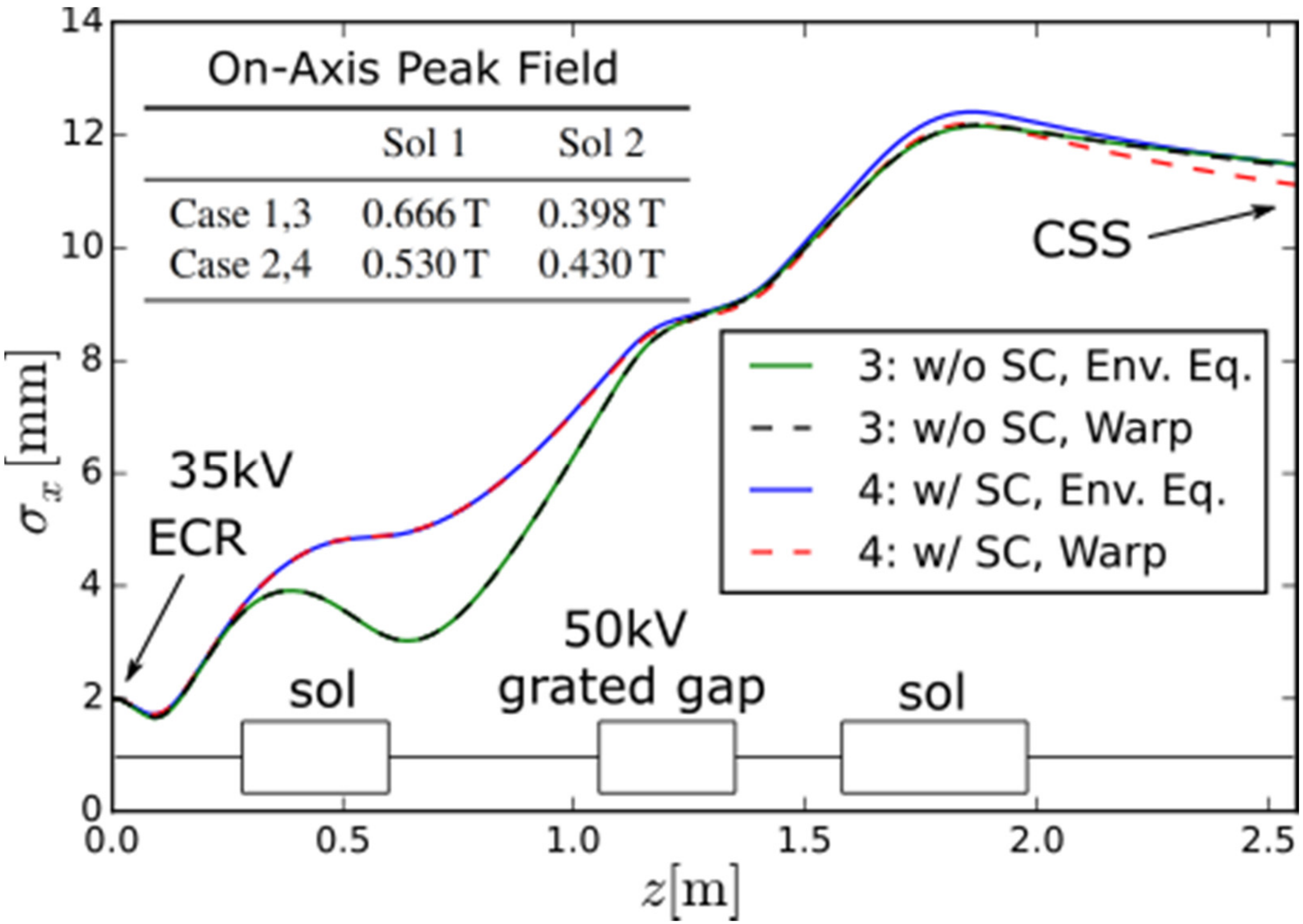
- Integrated along with the energy equation using linearized fields
- Much faster than PIC simulations of the same linear section

Employed to adjust strengths of the two solenoids to match axisymmetric ($\sigma_x = \sigma_y$) beam conditions entering the CSS

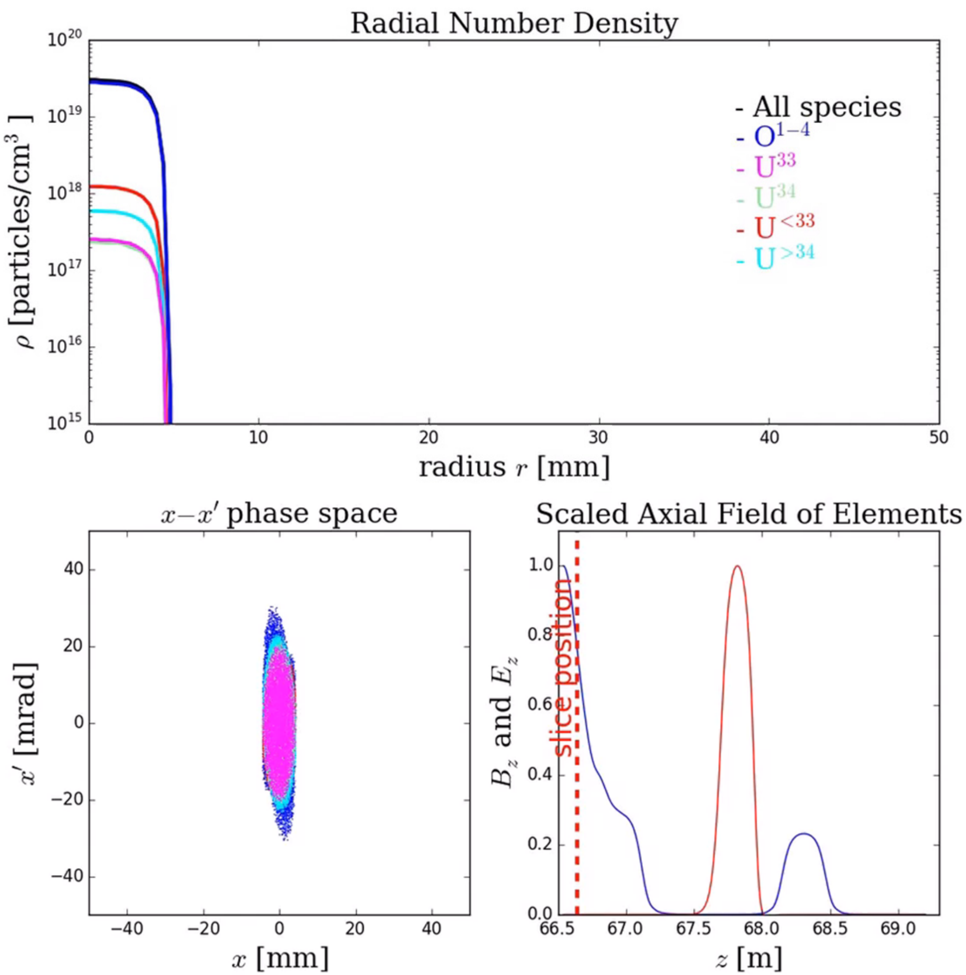
- Convert between lattice functions and beam envelope of the reference species with:

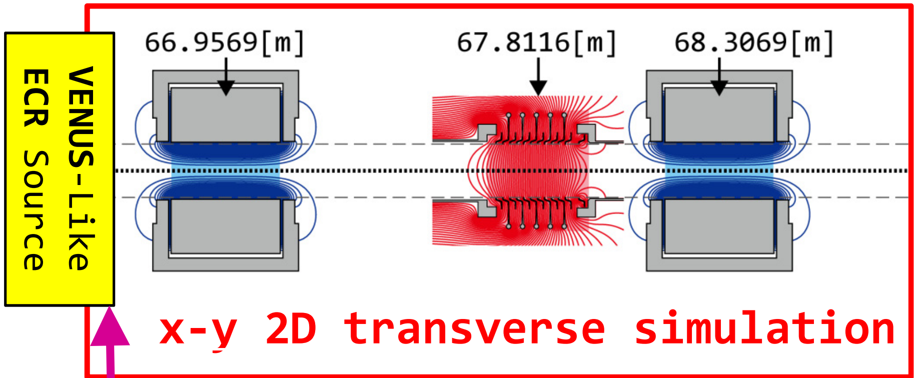
$$\beta_x = \sigma_x^2/\varepsilon_x \qquad \varepsilon_x = \varepsilon_{\text{eff}} = \sqrt{(\varepsilon_r^{\text{rms}}/2)^2 + \langle P_\theta \rangle^2 / (2m\beta_b c)^2}$$
$$\alpha_x = -\sigma_x \sigma'_x/\varepsilon_x$$

Simulations are compared to envelope model to verify accuracy matching procedure for a 20 species U beam emerging from the ECR



Agreement with envelope model good in spite of Intricate evolution of many species beam *xy*-slice simulations of multi-species ion beams emerging from ECR source show little issues in preserving beam quality of target species in spite of intricate phase-space evolution. Good agreement with envelope model dispite intricate evolution.





Specified Injection
66.640938 [m]
N_f = 75%

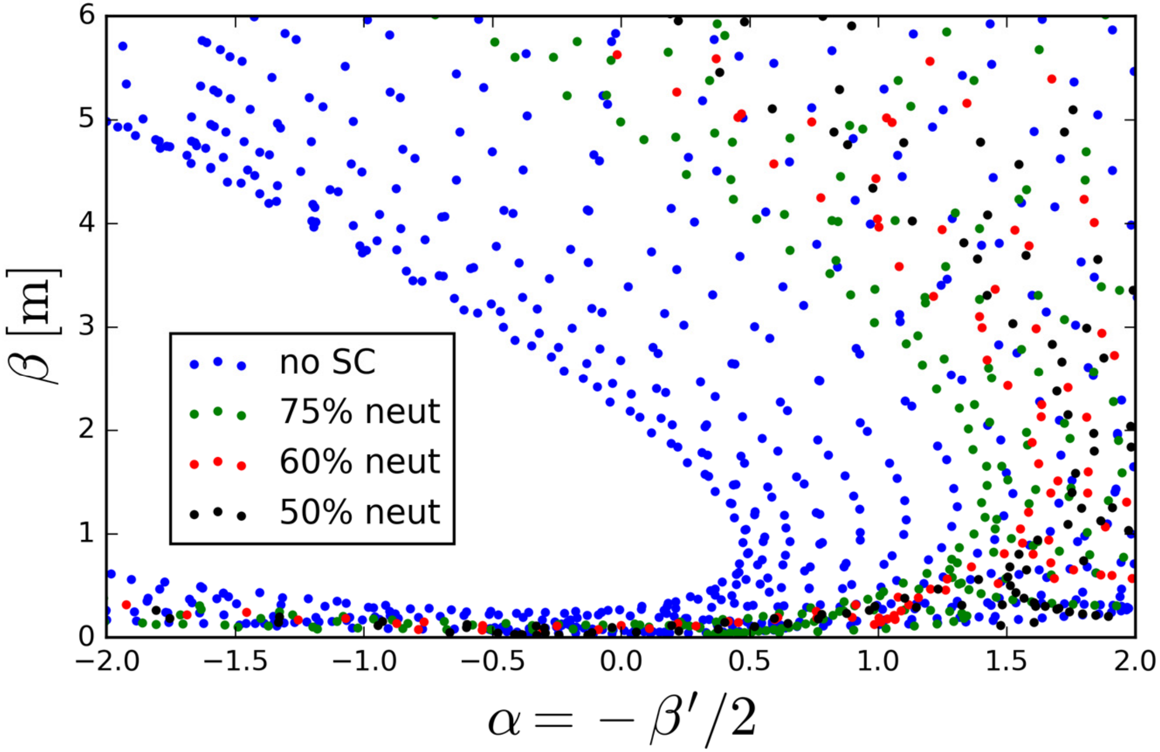
Design lattice functions may not be attainable for all beams produced by ECR sources

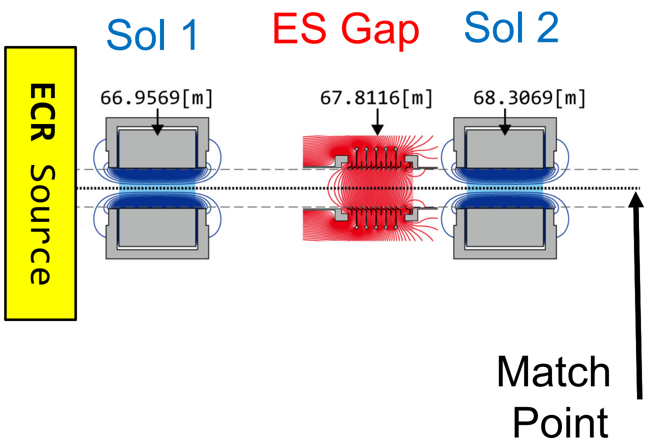
Design incident beam conditions at CSS must be deliverable by the solenoid transport line

- Alternative CSS operating point can be formulated in many cases if not
- Stronger space-charge reduces attainable lattice functions
  - » Boundary shifts to larger beam size and steeper envelope angles

<u>Accessible lattice functions</u>

(Solenoids: $0\ \mathrm{T} \leq B_{peak} \leq 1.5\ \mathrm{T}$)





Four run cases explore range of physics in the charge selection system (CSS)

Effective normalized phase space area of beam emerging from ECR:

$$\boxed{\varepsilon_{\text{n,eff}} = \sqrt{(\beta_b \varepsilon_r^{\text{rms}}/2)^2 + \langle P_\theta \rangle^2 / (2mc)^2}}$$

(Axisymmetry)

Two contributions (norm units):

1) Thermal emittance: $\beta_b \varepsilon_r^{\text{rms}} = R_{\text{source}} \sqrt{2T_{\text{ion}}/(mc^2)}$

2) Canonical angular momentum: $\dfrac{\langle P_\theta \rangle}{2mc} = \dfrac{qR_{\text{source}}^2 B_{\text{birth}}}{8mc}$

Launch beams with same $\varepsilon_{\text{n,eff}}$, but different compositions from thermal emittance and canonical angular momentum

Magnetized beam: $\beta_b \varepsilon_r^{\text{rms}}/2 = 0.008$ mm-mrad

$\langle P_\theta \rangle / (2mc) = 0.152$ mm-mrad

From U^{34+} in ECR with:

$T_{\text{ion}} = 3$ eV $\quad \sigma_x = 2$ mm

$B_{\text{birth}} = 1.67$ T $\quad \mathcal{E}_k = 5$ keV/u

Thermal beam: $\langle P_\theta \rangle = 0 \quad \beta_b \varepsilon_r^{\text{rms}}/2 = 0.153$ mm-mrad

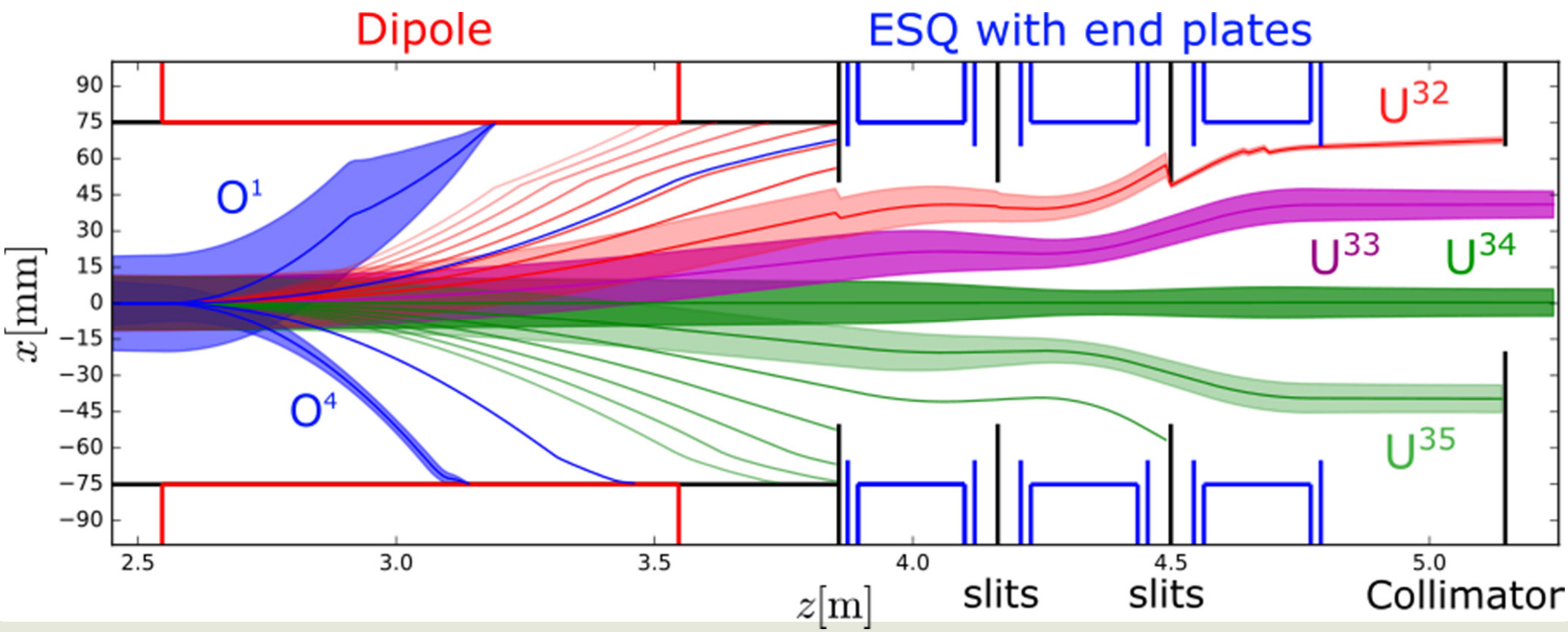
- Simulate thermal and magnetized beams, w and wo space charge (SC)
- Magnetized beam with SC likely closest to lab case
- All 4 cases (magnetized , thermal both w and wo SC) independently matched

Charge collimation example (target: U^{33} & U^{34})

Chose U^{34+} as reference species to emphasize effects due to centroid offset for 2nd non-reference "target" species U^{33+}

- Lab case: Apply virtual $U^{33.5}$ particle for two target species to reduce centroid offset

Ideal hard-edge elements are used to better understand source of deviations from linear optics MADX design

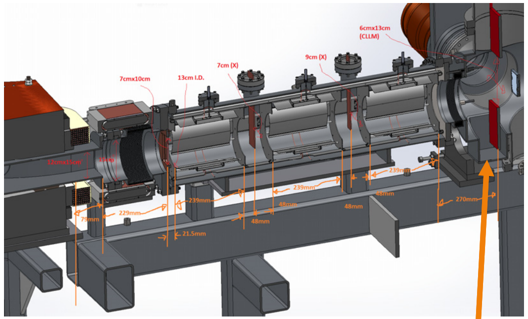


Canonical angular momentum induces xy beam rotation

Large initial $\langle xy' \rangle$ and $\langle x'y \rangle$ moments in the magnetized beam causes $\langle xy \rangle$ to evolve

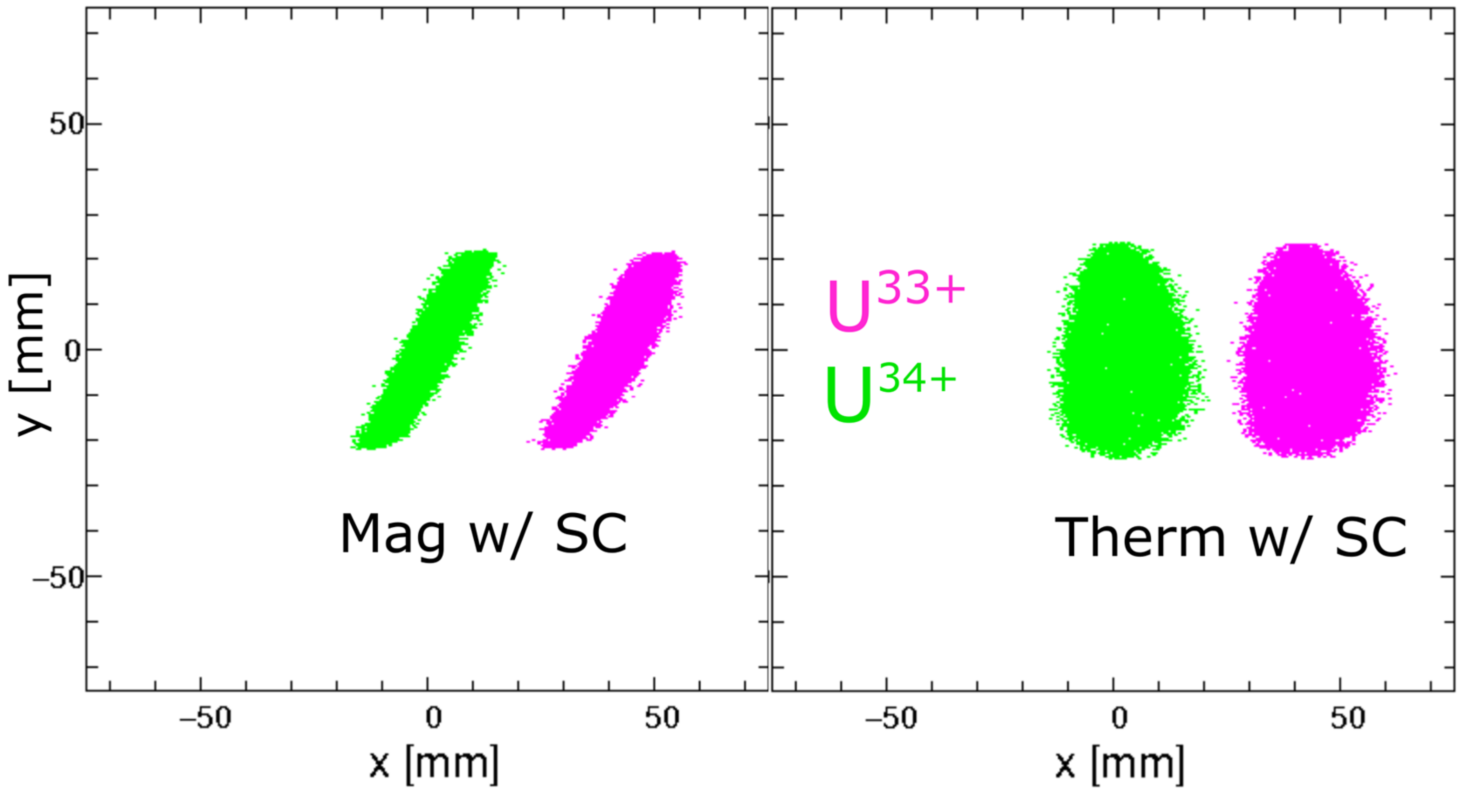
xy-particle projections at CSS mid-point:

- Rotation may alter optimal mid-CSS collimator aperture



Mid-CSS Collimation Slits

Mid-CSS xy Beam Profiles



Mostly reversible emittance growth in x and xy emittance exchange observed

Significant x-emittance growth that is mostly reversed

- Nonlinear optical effects in ideal dipole become significant in tight bend
- Reversed growth manifests advantage of symmetric lattice design

Combined effects of canonical angular momentum and space charge causes xy emittance exchange

Solid: x-emit

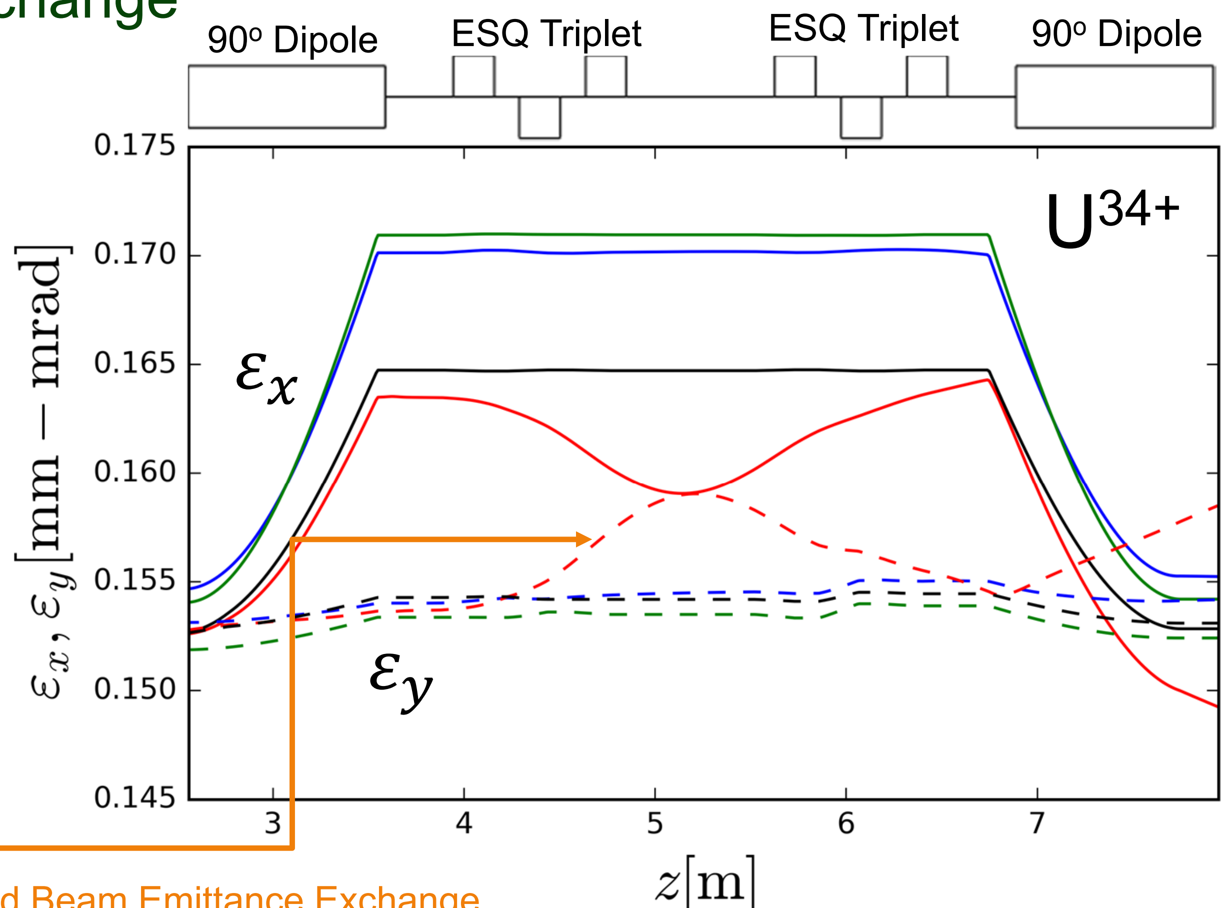
Dotted: y-emit

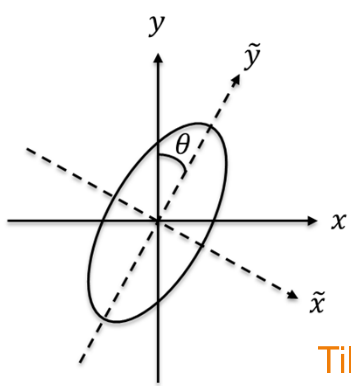
Thermal wo SC

Thermal w SC

Magnetized wo SC

Magnetized w SC





Tilted Beam Emittance Exchange

Rms beam envelopes track ideal MADX design

Larger deviation in x than y due to x-plane emittance growth

Space charge induced deviation in 1st dipole appears limited

- Species lost both sides of target species may part mitigate impact
- Full 3D simulations of bend appear largely consistent

Solid:

MADX design

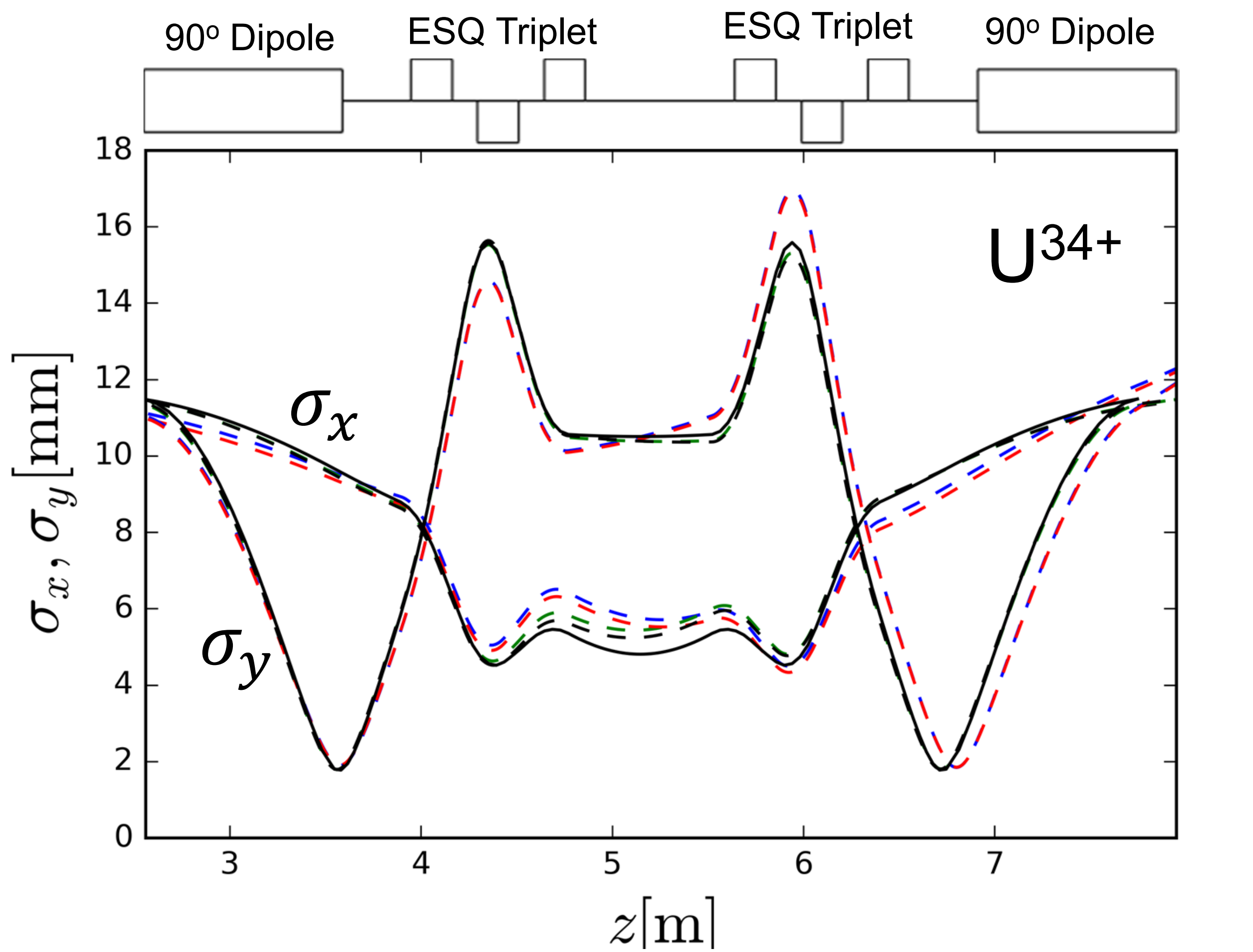
Dotted:

Thermal wo SC

Thermal w SC

Magnetized wo SC

Magnetized w SC



Space charge induces centroid shift

Centroid offset at CSS exit for non-ref species when space charge included

- Space charge much stronger in the first half of the CSS
- Causes asymmetric dispersion evolution despite symmetric lattice design
- Retune entails an asymmetric CSS: risk emittance growth?

Solid:

MADX design

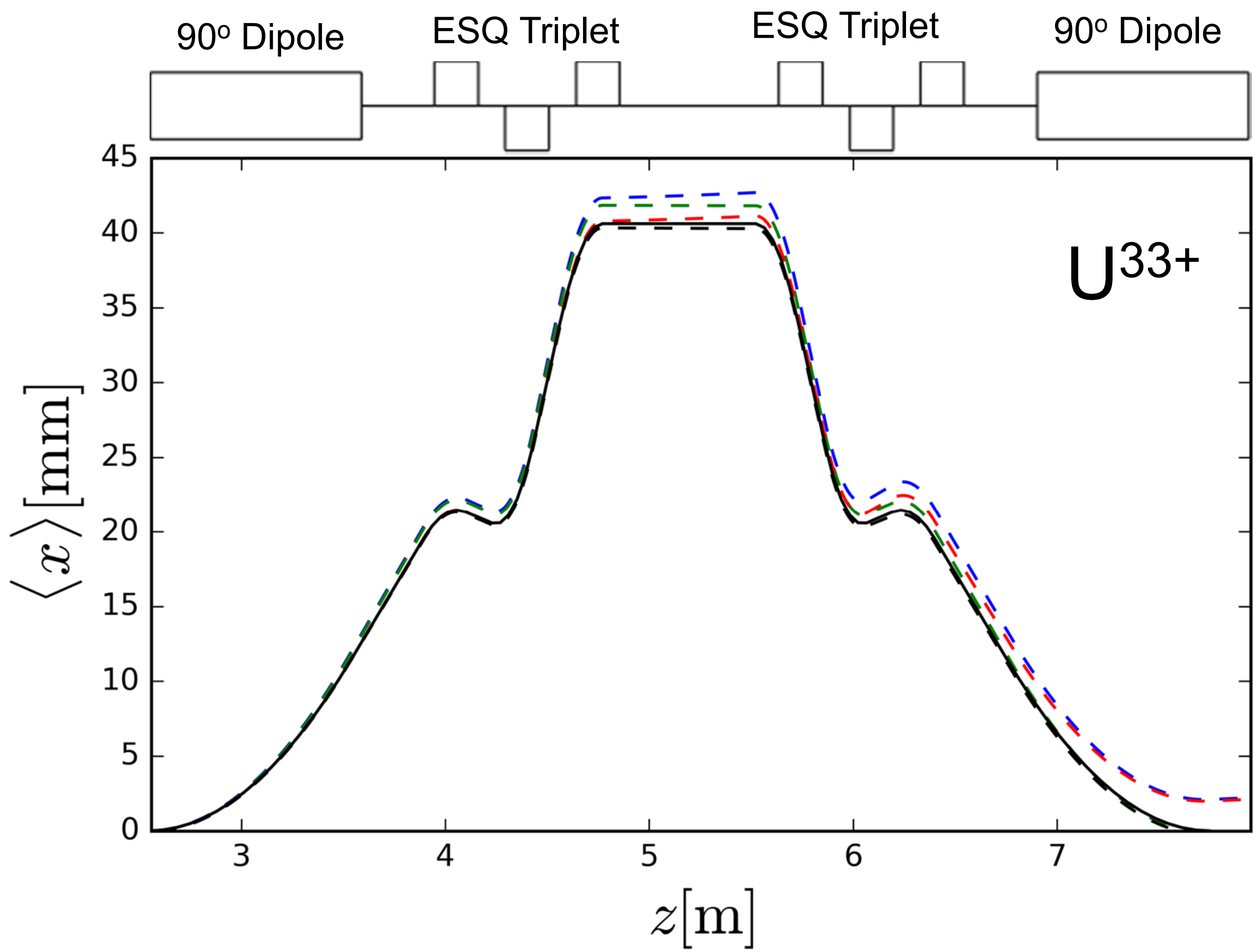
Dotted:

Thermal wo SC

Thermal w SC

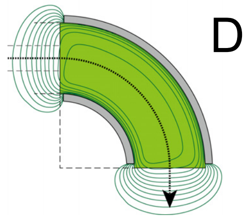
Magnetized wo SC

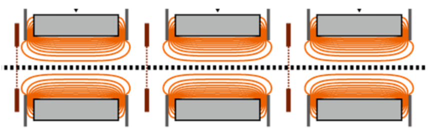
Magnetized w SC



Further deviations from MADX design occur when ideal hard edge elements in CSS are replaced by 3D field maps

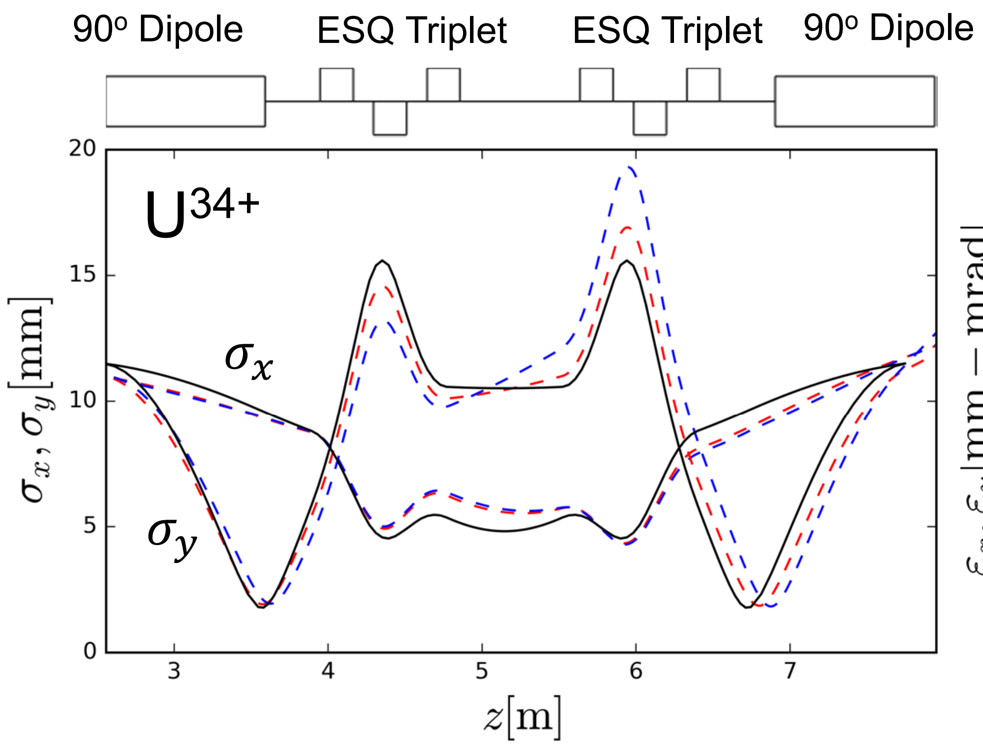
Field maps contain nonlinearities of dipoles and ESQs + extended fringe

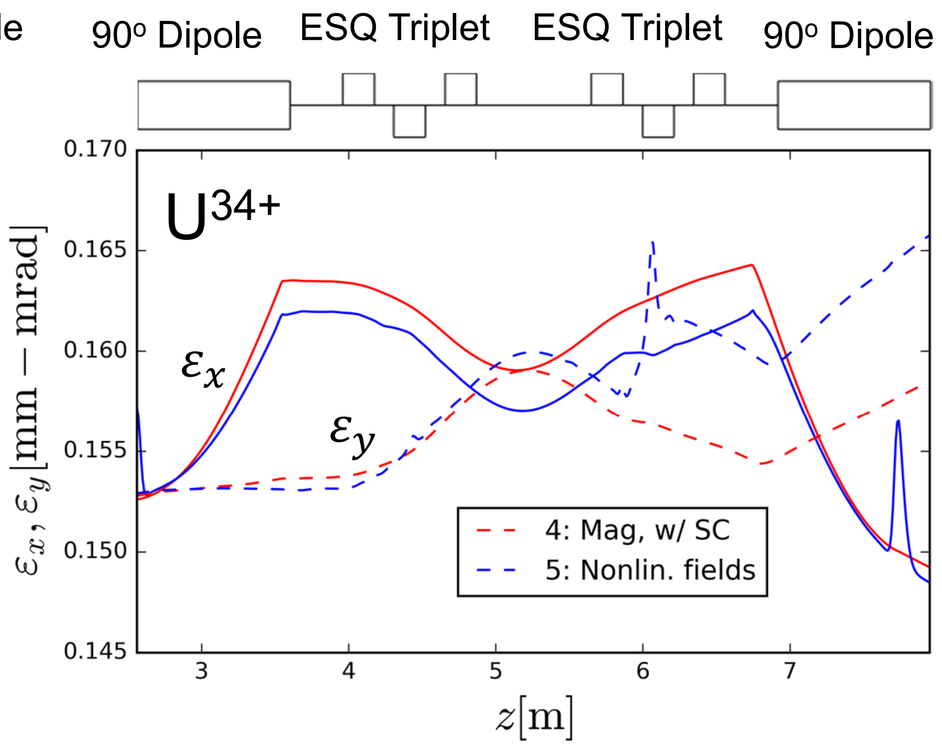


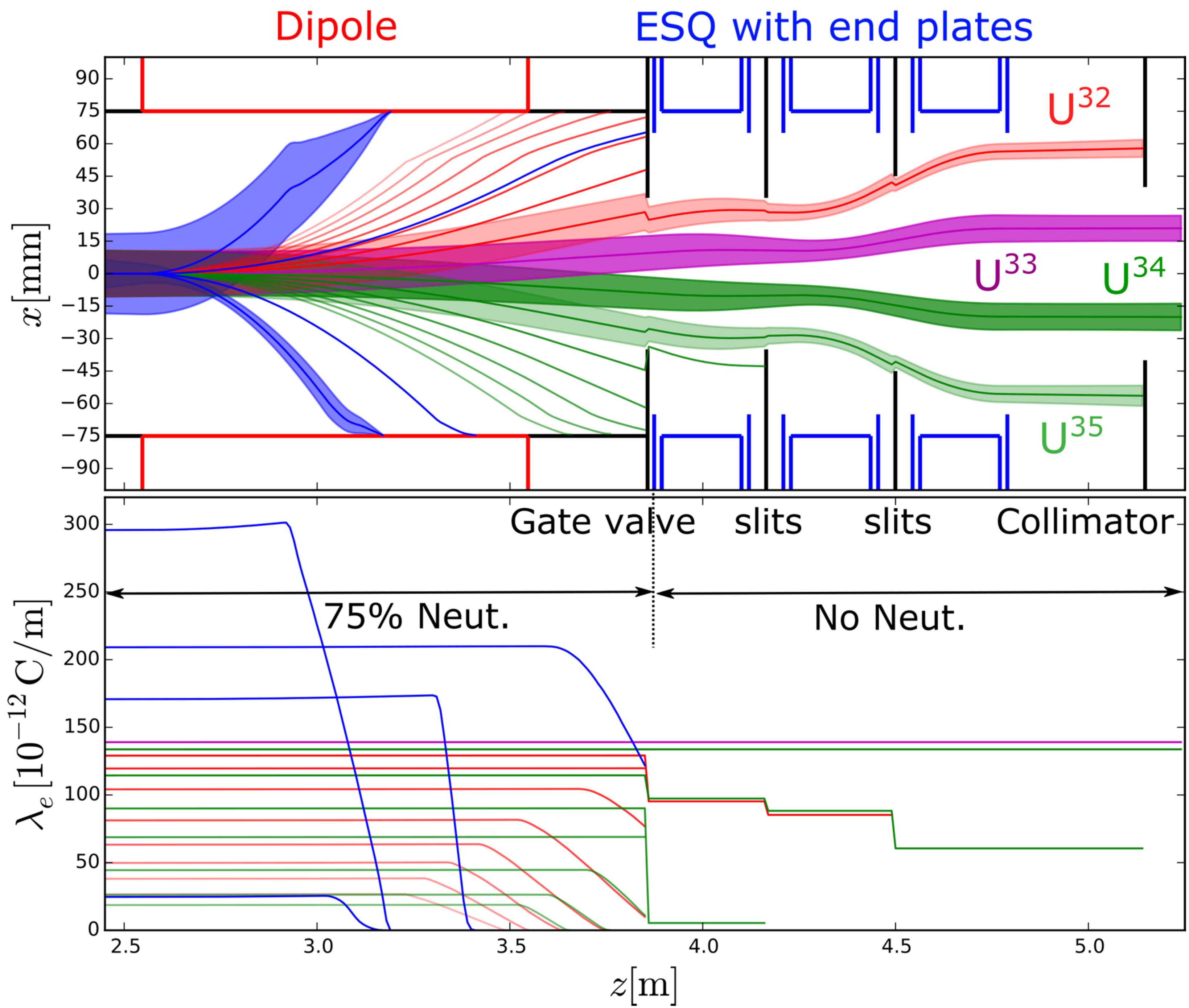


Simulations compare ideal + 3D fields for Case 4 (~lab magnetized beam)

- Overall emittance growth at CSS exit in addition to emittance exchange
- Unclear if lattice can be retuned to suppress







Dipole
ESQ with end plates
U^{32}
U^{33}
U^{34}
U^{35}
$x\,[\mathrm{mm}]$
Gate valve
slits
slits
Collimator
75% Neut.
No Neut.
$\lambda_e\,[10^{-12}\,\mathrm{C/m}]$
$z\,[\mathrm{m}]$

Conclusions

Framework for simulation of ion front-ends developed and being used to support FRIB commissioning/operations

- Built around open source Warp family of PIC code tools
- Formulated to ease maintenance/extension with multi-users and many ion and lattice cases
  - » Allows collaborative work while extending
  - » Wide range model levels possible

Challenges significant: much physics unclear and lab diagnostics limited

- Beam emerging from ECR ion sources complex and poorly understood
- Electron neutralization models need improvement: PhD project

Insight being gained from simulation will support lab activities

- 3D dipole bend: placement of slanted pole magnet + 3D space-charge effects
  HB 2016 + LINAC 2016
- Efficient matching procedure into Charge Selection System (CSS) developed together with linear design procedure for symmetric CSS lattice
- Space charge effects surprisingly benign (for species analyzed): centroid + envelope
- Canonical angular momentum impacts optimization of species collimation
  impact not yet fully understood
- Nonparaxial beam leads to (mostly reversible) emittance growth
  symmetric CSS lattice significant benefit

Much more to do: Real tests coming soon with application to FRIB data from early lab commissioning of front-end

THANK YOU!

Summary: CSS reference parameter design

63.7cm-long 90° dipole:

slanted poles create

$\kappa_0 = 0.365\mathrm{m}^{-2}$

20.7cm-long ESQ:

$\kappa_1, \kappa_2, \kappa_3 = 0.731, \text{-}1.63, 0.861\ \mathrm{m}^{-2}$

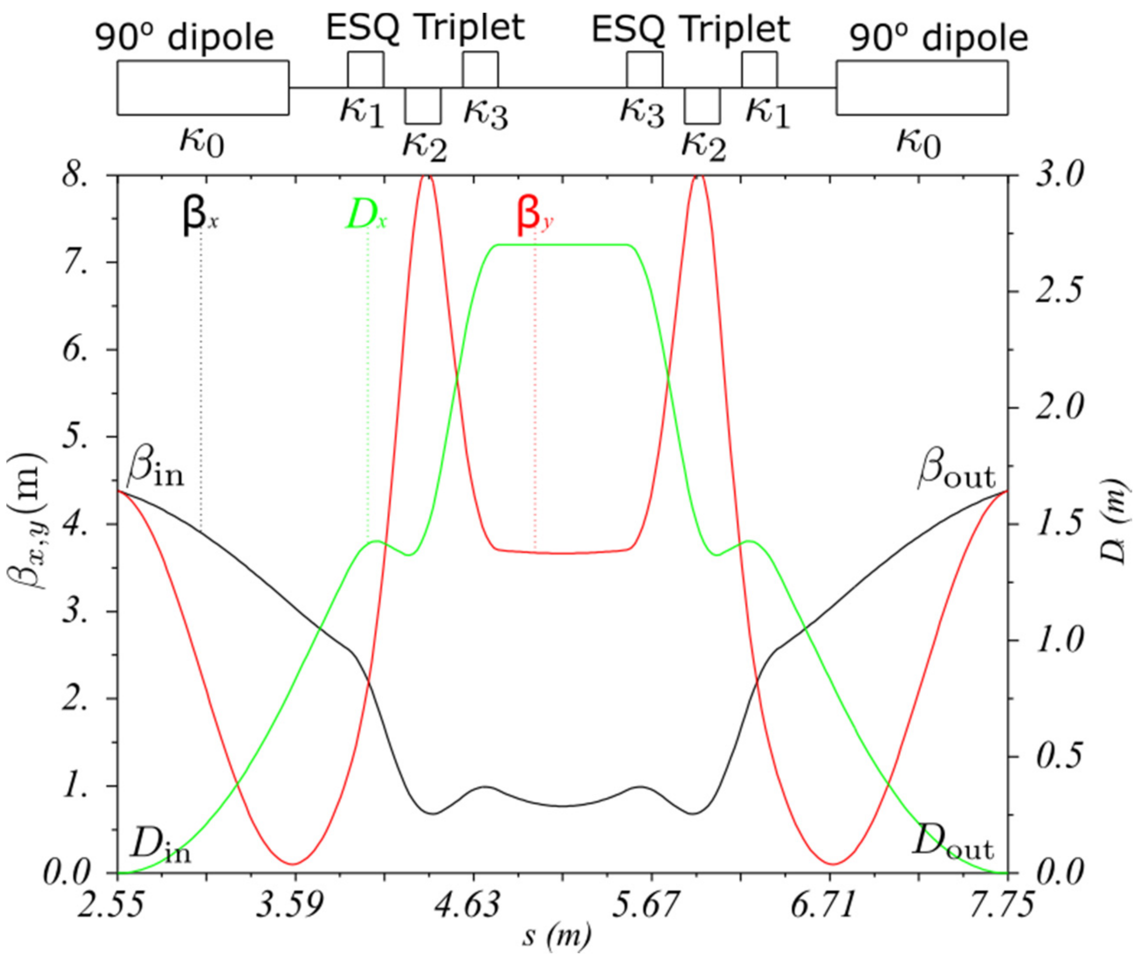
12 keV/u U^{34+} as ref species:

$G_1, G_2, G_3 = 0.731, \text{-}1.63, 0.861\ \mathrm{T/m}$

Incident beam conditions:

$\beta_{\mathrm{in}} = 4.383\mathrm{m}$

$\alpha_{\mathrm{in}} = -\beta'_{\mathrm{in}}/2 = 0.306$



Centroid offset for reference species observed at CSS exit due to space charge

Reference species has centroid offset at mid-point of CSS despite ideal dipole field model

- The effect is much stronger for thermal beams than magnetized beams

Shift only disappears at CSS exit in the absence of space charge

- Compensation with asymmetric lattice may worsen emittance evolution

Solid:

MADX design

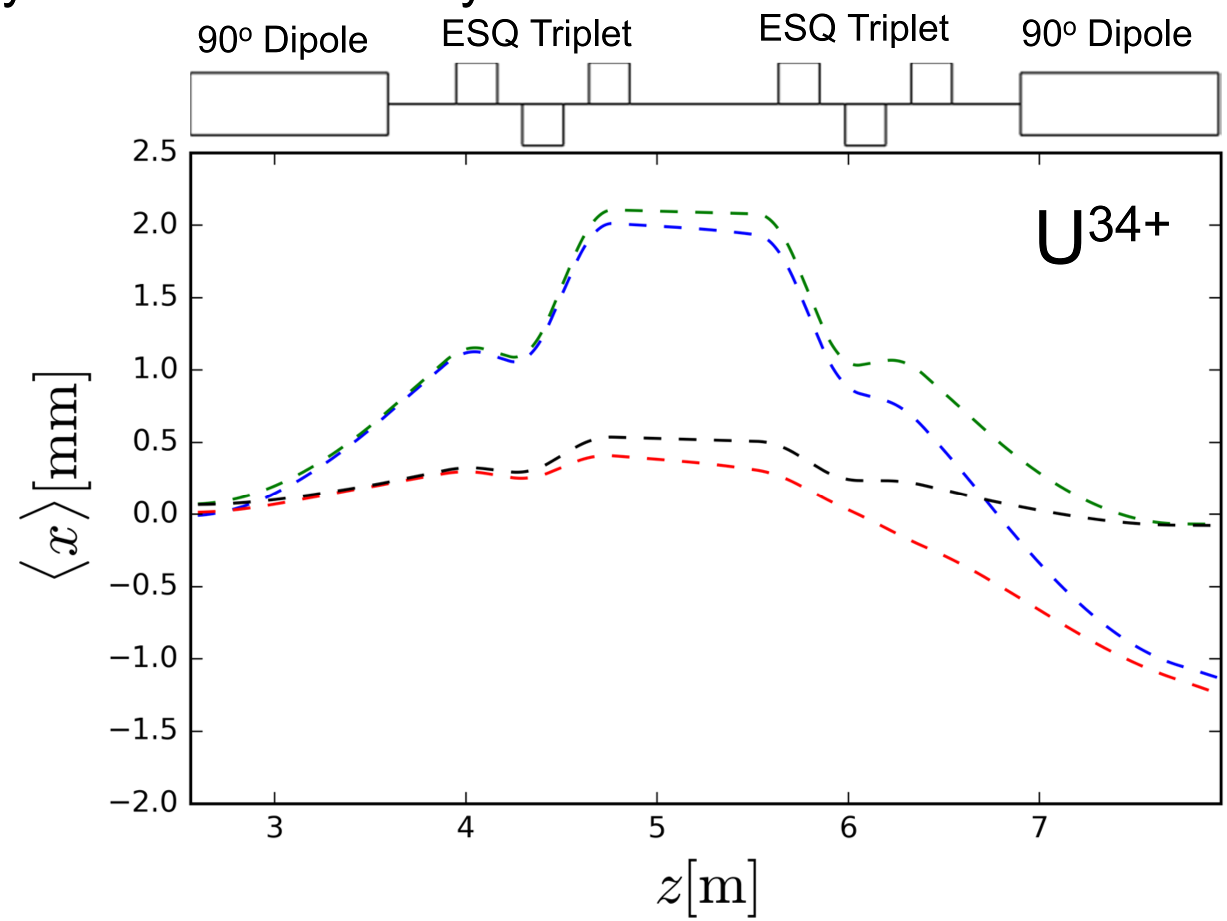
Dotted:

Thermal wo SC

Thermal w SC

Magnetized wo SC

Magnetized w SC



Centroid offset induces little impact on envelope and emittance evolution