Dispersion Matching with Space Charge in MESA

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Motivation

For intense electron bunches traversing through recirculation arcs with bends

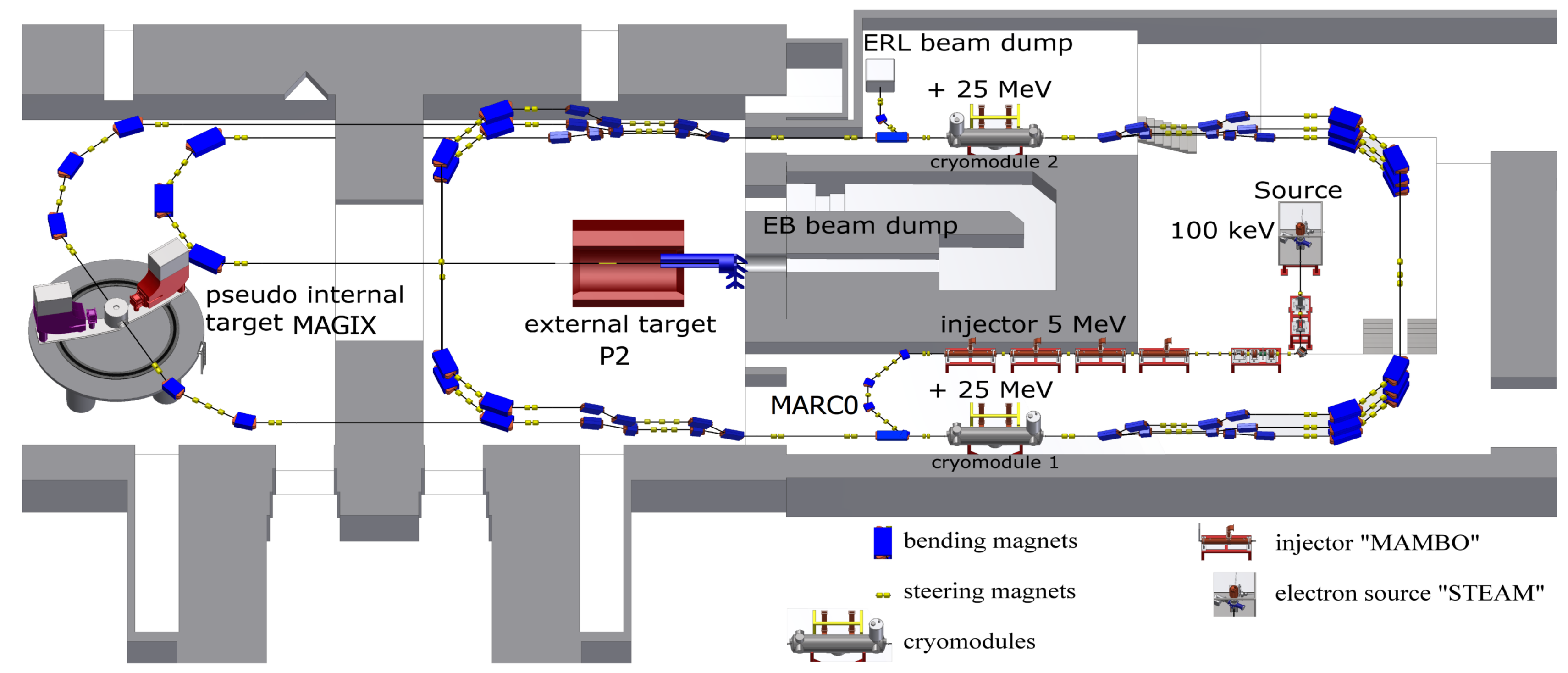
- Beam centroid off-set distorts the transverse phase space without space charge (SC).
- Dispersion with SC defocuses the beam and increases momentum spread.

Present study focuses on

- 180° low energy (5 MeV) injection arc of multi-turn Mainz Energy-recovering Superconducting Accelerator (MESA).
- MESA should deliver a CW beam at 105 MeV for electron scattering physics experiments with a pseudo-internal target in Energy Recovery (ER) mode.

Simulations are done with beam matrix approach and particle tracking.

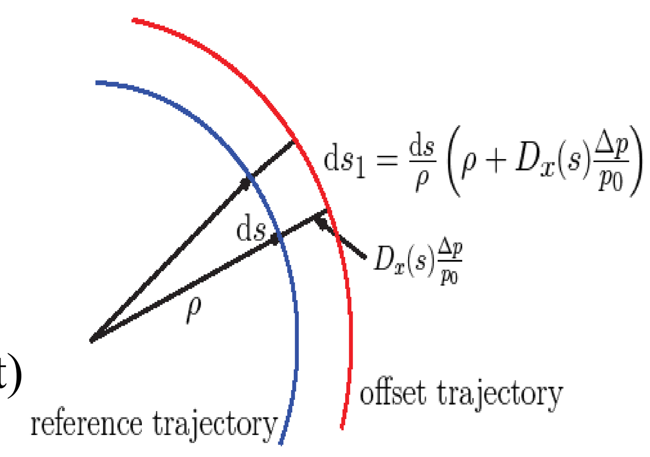
MESA Layout



Dispersion with Space Charge

Dispersion (D_x): deviation of particle trajectory from the reference trajectory due to different energy of particle.

- Horizontal displacement: $x \rightarrow x + D_x(s)\delta$
- D_x follows: $D_x''(s) + \kappa_x(s)D_x = \frac{1}{\rho}$
- Centroid dispersion: $D_{x,c} = \frac{<x>}{<\delta>}$ (SC independent)
- Individual particle dispersion: $D_x = \frac{<x\delta>}{<\delta^2>}$ (SC dependent)



Momentum compaction (R_{56}): change in path length of particles due to dispersion along the beamline.

- Momentum compaction: $R_{56} = \int_{s_1}^{s_2} \frac{D_x + D_y}{\rho} ds$ (SC dependent)
- Path length: $z = z_0 + R_{56}\delta$ ➔ R_{56} is used as a bunch compression parameter.

Numerical transformation of the lattice functions with space charge

$\sigma_{ij} \equiv \langle u_i u_j \rangle$ (Beam matrix) $\sigma_{s_1} = R_{s_0 \to s_1} . \sigma_{s_0} . R^T_{s_0 \to s_1}$ (Transportation of beam matrix)

where $u \equiv (x, x', y, y', z, \delta)^T$ and i, j runs from 1 to 6

Transport matrix with linear space charge (kick): $R(s_0, s_0 + \Delta s) = R_{\Delta s} R^{sc}_{\Delta s}$

MESA Injection Arc

Purpose of injection arc

- Dual-purpose, Energy Recovery (ER) and External Beam (EB) mode possible.
- Controllable R_{56} for bunch compression during ER injection.
- Optics matching to get fixed beam parameters after first cryomodule.

Design prerequisite	Design feasibility
Self-cancelling dispersion i.e. $D_x = 0, D_x' = 0$	✔
Acceptable beam envelopes	✔
Flexible R_{56}	✔
Space constraint	✔
Fixed beam parameters after first RF structure	✔

Parameters [unit]	Value
E_k [MeV]	5
I [mA]	1/10
Initial $\beta_{x,y}$ [m]	1.30, 0.90
Initial z_m [ps]	4.2
$\varepsilon_{nx,ny}$[π mm-mrad]	2/6

Simulation Results

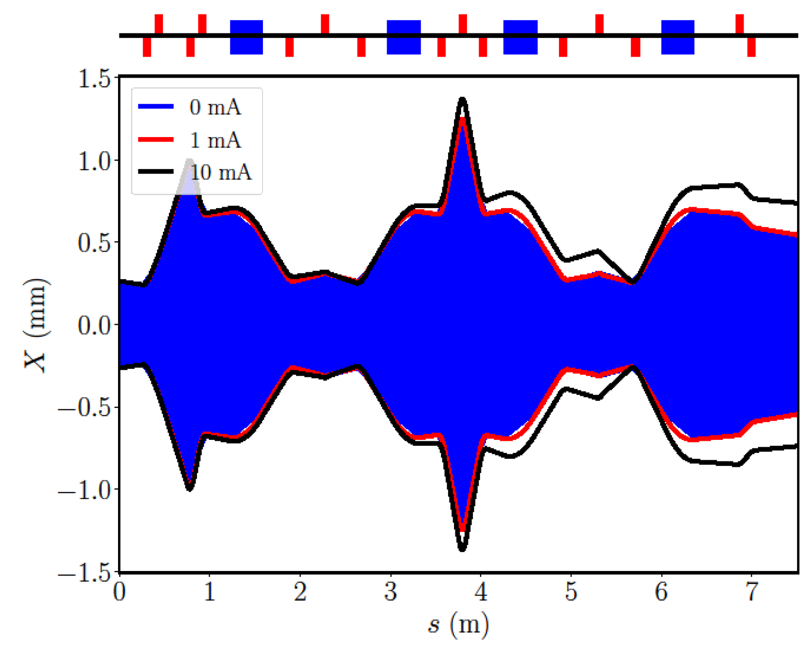


Fig. 1: Evolution of horizontal beam envelope along MARC0 at different currents.

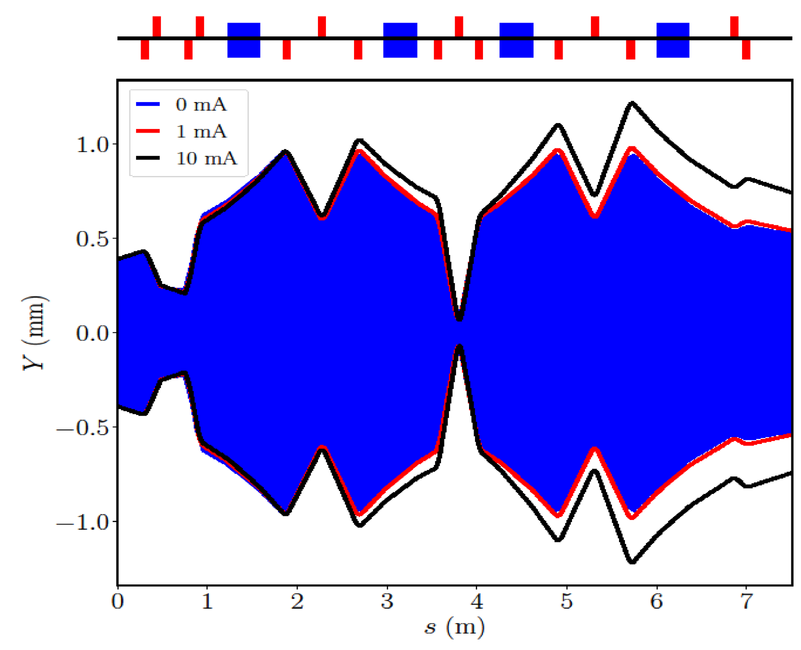


Fig. 2: Evolution of vertical beam envelopes along the MARC0 at different currents.

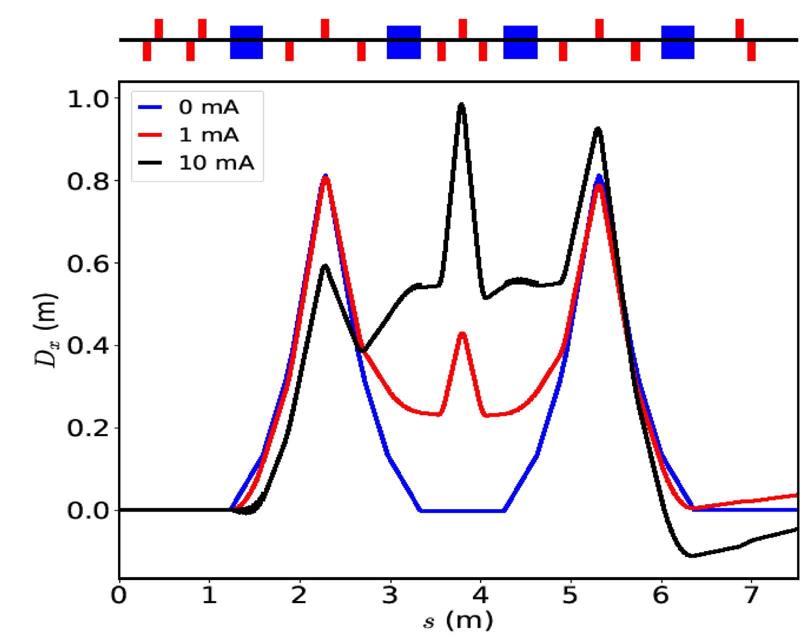


Fig. 3: Evolution of horizontal dispersion D_x along the MARC0 at different currents. Space charge modified dispersion makes the lattice non-achromatic.

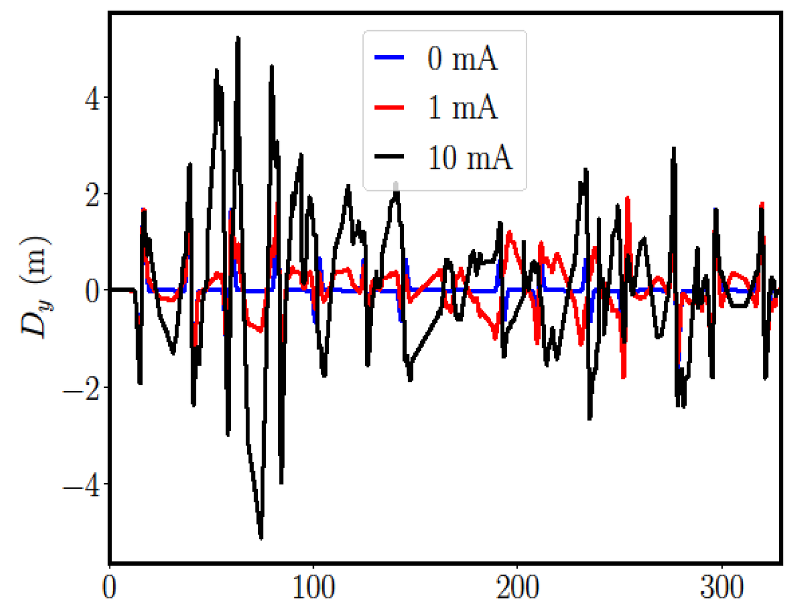


Fig. 4: Evolution of vertical dispersion D_y along the MESA beamline with space charge at different currents.

I (mA)	$\frac{\Delta\beta_x}{\beta_x}$ (%)	$\frac{\Delta\beta_y}{\beta_y}$ (%)	ΔD_x (m)
1	3.0	2.6	0.037
5	17.5	17.3	-0.017
10	39.7	41.0	-0.046
10 (matched)	0	0	0

- Mismatch of the horizontal and vertical beta functions, and the horizontal dispersion from the design values at the end of MARC0 with space charge.
- "Random walk" optimization is used to get the matched solution with space charge.
- A new set of quadrupole strengths is obtained with corrections of up to 15% in the original quadrupoles to get the matched solution.

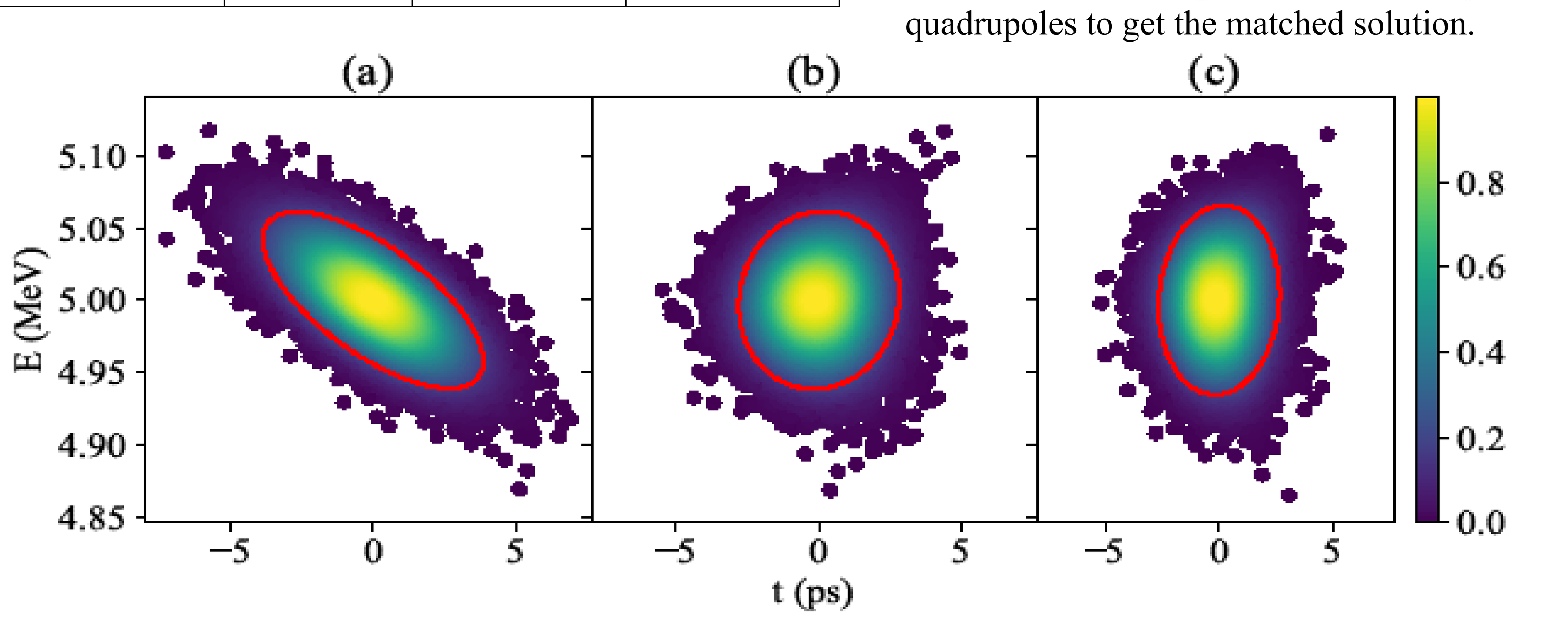


Fig. 5: Longitudinal phase spaces at (a) the start of MARC0, (b) the end of MARC0 for I = 1 mA of current, and (c) at the end of MARC0 for I = 10 mA. The red ellipses indicate the rms beam ellipse from beam matrix tracking. MARC0 works as a bunch compressor even at 10 mA when lattice is matched with space charge.

Conclusion and Outlook

Conclusion:

- Matching of both beam centroid dispersion and individual particle dispersion is important for an efficient ERL operation.
- Transverse-longitudinal coupling studies are necessary to understand the details and to improve the efficiency of energy recovery.
- Phase space degrades with SC at higher currents for small momentum deviation.

Future Plans:

- Study of wakefields along with space charge in the RF structures.
- Study of space-charge-induced microbunching instability in MESA using beam matrix approach.
- Validation of our space charge models and ELEGANT particle tracking with particle-in-cell codes.

Acknowledgment

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