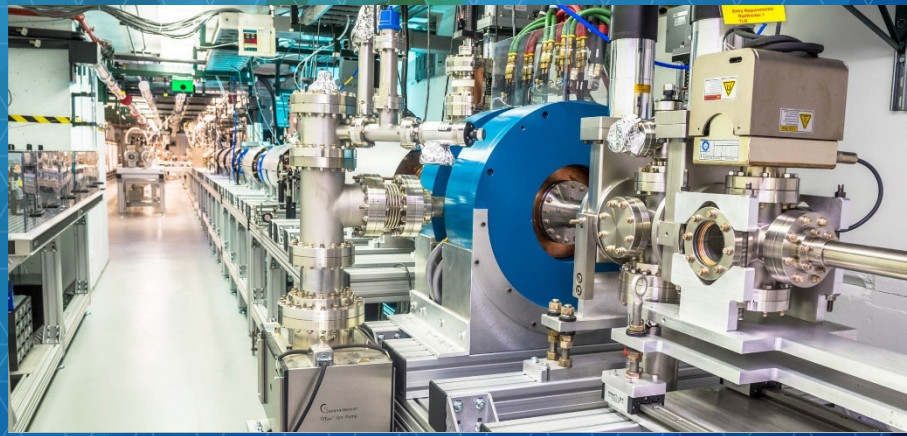
FEBRUARY 18, 2022

DEVELOPMENT OF A DAMPING-RING-FREE ELECTRON INJECTOR FOR LINEAR COLLIDERS



TIANZHE XU
Northern Illinois University

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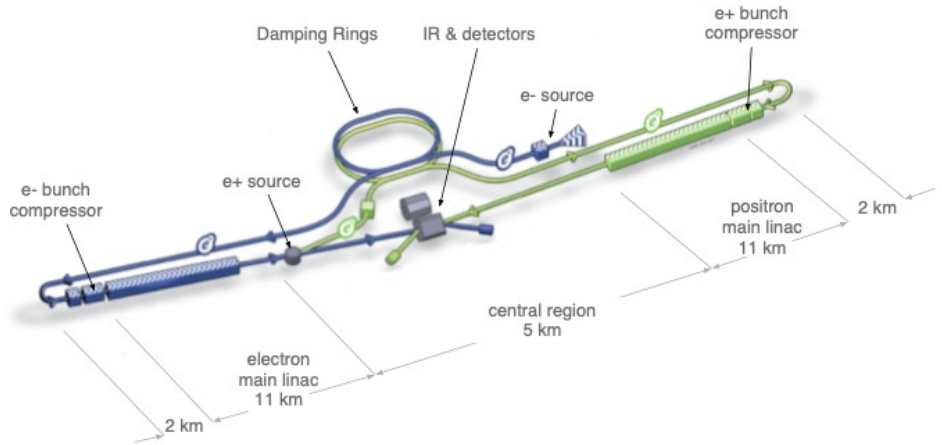
MOTIVATION FOR FLAT BEAMS

- Flat beams required for linear colliders to suppress beamstrahlung.
- Extremely asymmetric transverse emittance in current designs:

$$(\varepsilon_x, \varepsilon_y, \varepsilon_z) \sim (10\mu\mathrm{m}, 35\mathrm{nm}, 0.27\mathrm{m})^*.$$

- Achieved through complex damping rings.
- 6D brightness lower than the one produced in state-of-the-art photoinjector.



*ILC Technical Design Report, 2013

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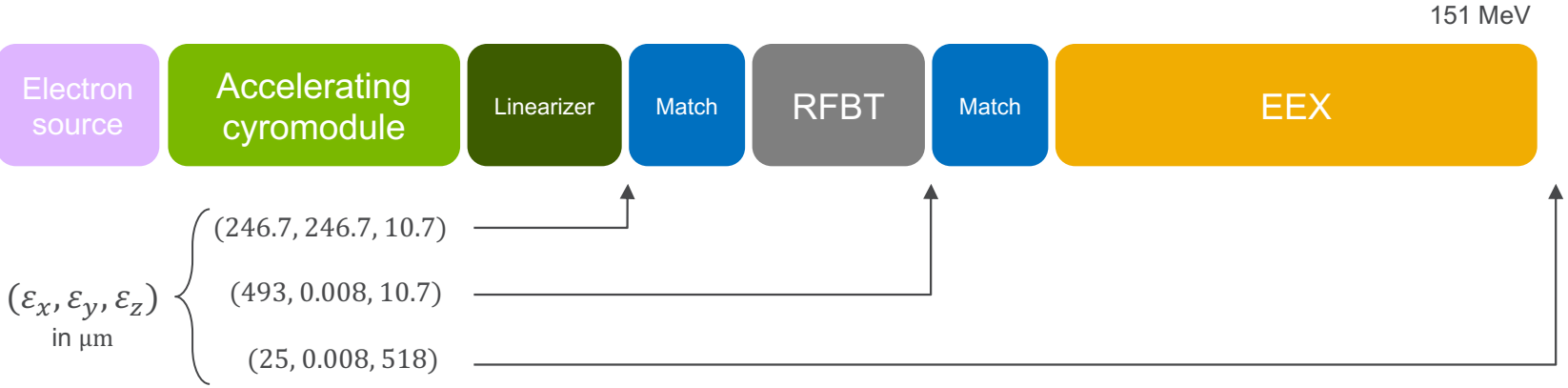
A DAMPING RING FREE INJECTOR BEAMLINE

- Emittance repartition with round-to-flat beam transform and emittance exchange (initially proposed for high-gain FEL)*.
- $(\varepsilon_x, \varepsilon_y) \sim (\mathbf{25\mu m}, \mathbf{8nm})$ achieved at **3.2nC** within 40 meters.
- ε_z is significantly lower than the DR design and enables shorter bunch length.



*P. Emma et al, PhysRevSTAB.9.100702

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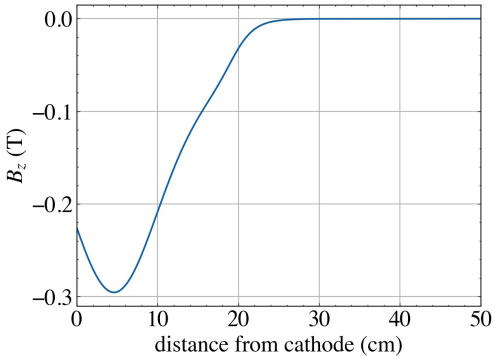
EIGEN-EMITTANCES

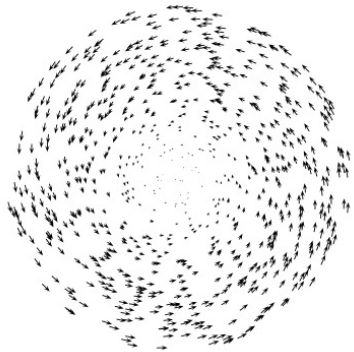
- Determines the real limit of beam brightness without damping or radiation.
- Alter eigenemittances by introducing coupling (e.g. canonical angular momentum).
- Can be mapped into projected emittances via linear transform.

uncoupled: $\Sigma = \begin{bmatrix} \langle \mathbf{X}\mathbf{X}^T \rangle & 0 \\ 0 & \langle \mathbf{Y}\mathbf{Y}^T \rangle \end{bmatrix}$ $\quad \varepsilon_\pm = \varepsilon_{x,y} = [\det(\Sigma)]^{1/4}$

coupled: $\Sigma = \begin{bmatrix} \langle \mathbf{X}\mathbf{X}^T \rangle & \langle \mathbf{X}\mathbf{Y}^T \rangle \\ \langle \mathbf{Y}\mathbf{X}^T \rangle & \langle \mathbf{Y}\mathbf{Y}^T \rangle \end{bmatrix}$ $\quad \varepsilon_\pm = \frac{1}{2}[\xi_+^{1/2} \pm \xi_-^{1/2}]$, where $\xi_\pm \equiv \varepsilon_x^2 + \varepsilon_y^2 + 2\det(\langle \mathbf{X}\mathbf{Y}^T \rangle) \pm 2\varepsilon_{4d}^2$



transverse plane of a magnetized/coupled beam



canonical angular momentum (CAM):

$$L = \gamma m r^2 \dot{\phi} + \frac{1}{2} e B_z(z) r^2$$

magnetization:

$$\mathcal{L} \equiv \frac{\langle L \rangle}{2mc}$$

For a CAM-dominated beam,

$$\mathcal{L} \gg \varepsilon_{4d}$$

$$\varepsilon_+ \simeq 2\mathcal{L}$$

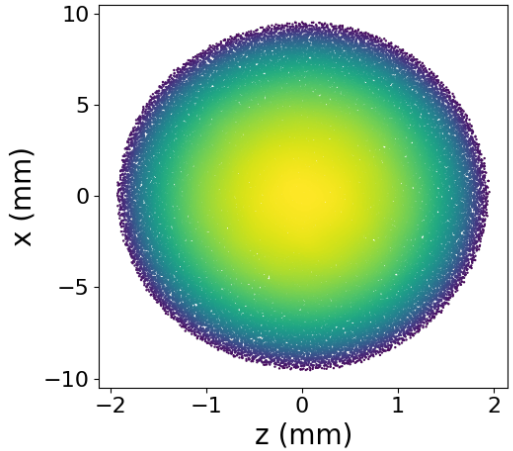
$$\varepsilon_- \simeq \frac{\varepsilon_{4d}^2}{2\mathcal{L}} = \frac{\sigma_{px}^2 mc}{eB_z}$$

asymmetric eigenemittances

ELLIPSOIDAL MAGNETIZED BEAM

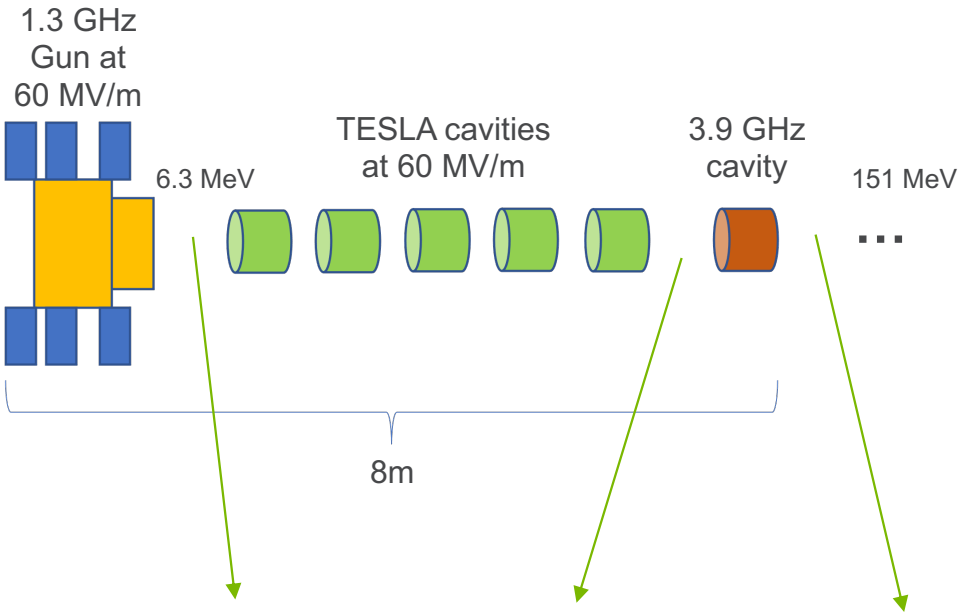
- Slice-independent space-charge defocusing minimizes 4D emittance growth.
- Linear space-charge mitigates growth in ε_z.
- Blow-out scheme limited by gun-gradient. Spatiotemporal laser shaping required.

Z-X distribution after gun

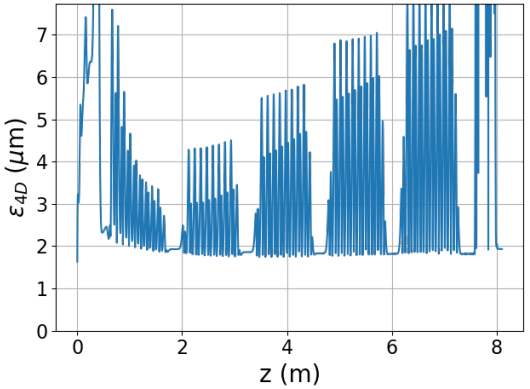


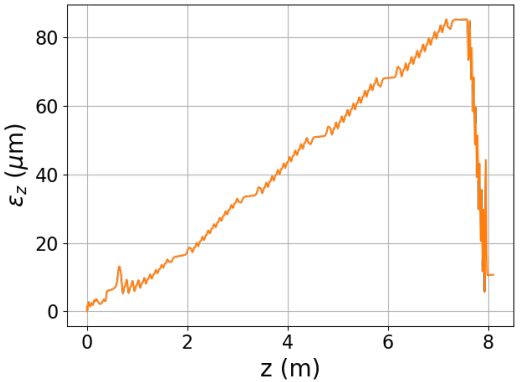
Parameter	Value	Unit
Charge	3.2	nC
B on cathode	0.226	T
$\varepsilon_{\text{thermal}}$	1.63	μm
ε_{4D}	1.9	μm
Laser pulse	10	ps
Laser spot radius	4.3	mm

INJECTOR BEAMLINE



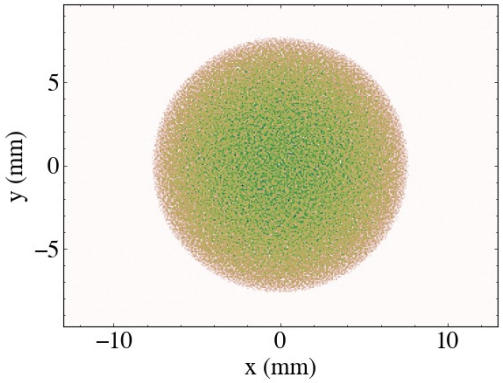
LPS
along
beamline



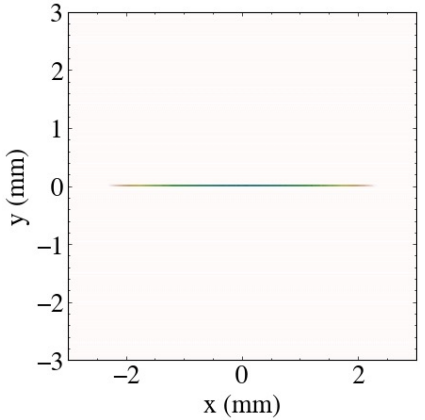


End of injector
4D emittance: 1.9 μm
ε_z: 10.7 μm, σ_z: 0.87mm

ROUND-TO-FLAT BEAM TRANSFORM



Skew quads

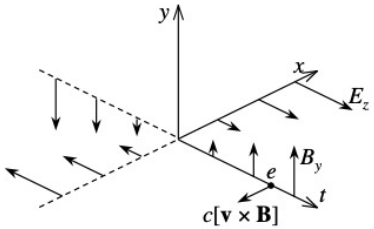


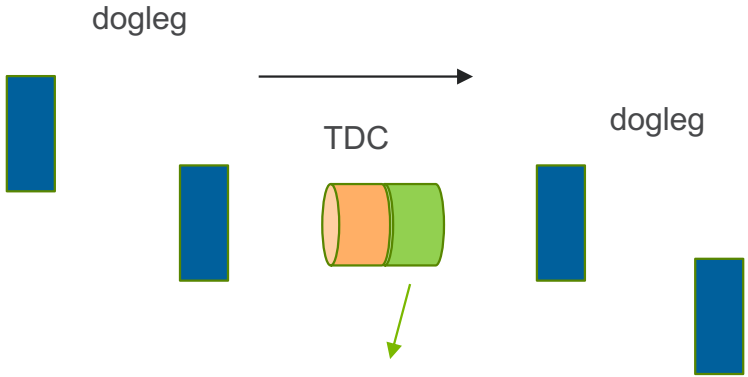
$$\Sigma_0 = \begin{bmatrix} \varepsilon T_0 & \mathcal{L}J \\ -\mathcal{L}J & \varepsilon T_0 \end{bmatrix} \qquad \Sigma = M\Sigma_0\widetilde{M} \longrightarrow \qquad \Sigma = \begin{bmatrix} \varepsilon_- T_- & 0 \\ 0 & \varepsilon_+ T_+ \end{bmatrix}$$

$$T_0 = \begin{bmatrix} \beta & -\alpha \\ -\alpha & \frac{1+\alpha^2}{\beta} \end{bmatrix} \qquad J = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}$$

$$\varepsilon_\pm = \sqrt{\varepsilon_{4d}^2 + \mathcal{L}^2} \pm \mathcal{L} \overset{\mathcal{L} \gg \varepsilon_{4d}}{\longrightarrow} \begin{cases} \varepsilon_+ \simeq 2\mathcal{L} \\ \varepsilon_- \simeq \frac{\varepsilon_{4d}^2}{2\mathcal{L}} \end{cases}$$

TRANSVERSE-TO-LONGITUDINAL EMITTANCE EXCHANGE





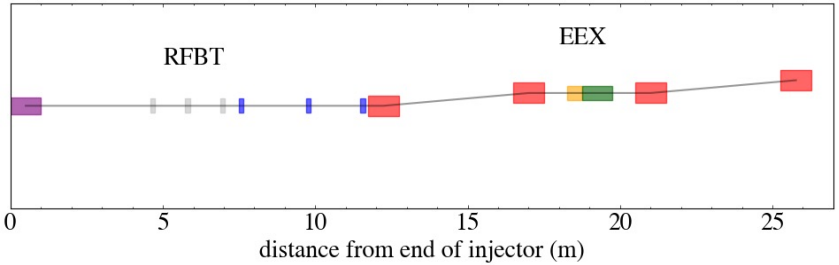
Fundamental mode cavity at zero crossing
to cancel thick cavity effect from TDC

$$\begin{pmatrix} x_f \\ x'_f \\ z_f \\ \delta_f \end{pmatrix} = \begin{pmatrix} 0 & 0 & \kappa L & \eta + \kappa\xi L \\ 0 & 0 & \kappa & \kappa\xi \\ \kappa\xi & \eta + \kappa\xi L & 0 & 0 \\ \kappa & \kappa L & 0 & 0 \end{pmatrix} \begin{pmatrix} x_i \\ x'_i \\ z_i \\ \delta_i \end{pmatrix}$$

η: dogleg dispersion
ξ: dogleg momentum compaction
κ: TDC kick strength

exchange condition:
$1 + \eta\kappa = 0$

PERFORMANCES OF RFBT AND EEX



Thick cavity effect in TDC

Thick-lens TDC $\begin{pmatrix} 1 & L_c & \frac{L_c}{2}\kappa & 0 \\ 0 & 1 & \kappa & 0 \\ 0 & 0 & 1 & 0 \\ \kappa & \frac{L_c}{2}\kappa & \frac{L_c}{4}\kappa^2 & 1 \end{pmatrix}$ cancel R_{65} with a linac $\begin{pmatrix} 1 & L_a & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & -\frac{L_c}{4}\kappa^2 & 1 \end{pmatrix}$

Second order effect in dogleg

- Minimizing $T_{122}{x_0'}^2$ and $T_{522}{x_0'}^2$ with a large beta function
- Other terms can be minimized by certain correlations in x and z planes

$$x_f = \eta\delta_0 + (L + L_d + L_a + \frac{L_c}{2})\sigma_2 + \underbrace{T_{122}\sigma_2^2 + T_{126}\sigma_1\sigma_2 + T_{166}\sigma_1^2}_{\text{2nd order terms}}$$

$$x_f' = \sigma_2$$

, where $\sigma_1 = \kappa[x_0 + (L + L_d + \frac{L_c}{2})x_0']$ $\sigma_2 = \kappa(z_0 + \xi\delta_0)$

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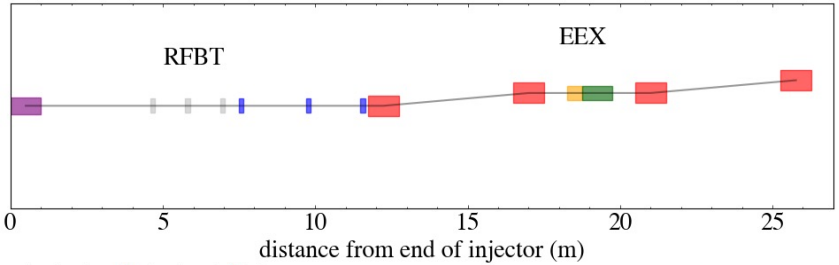
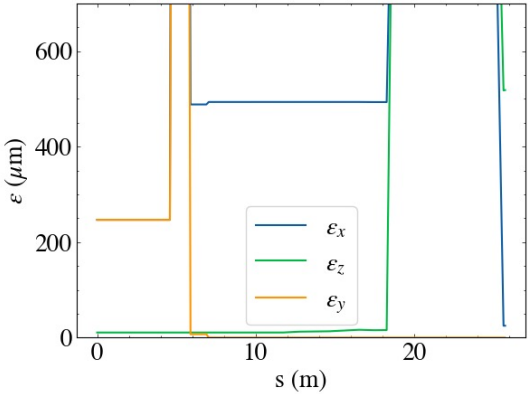
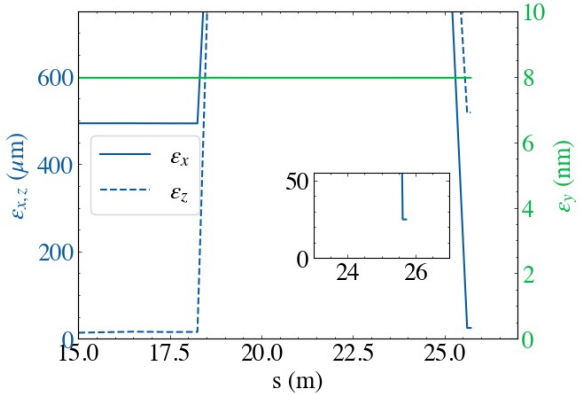
PERFORMANCES OF RFBT AND EEX



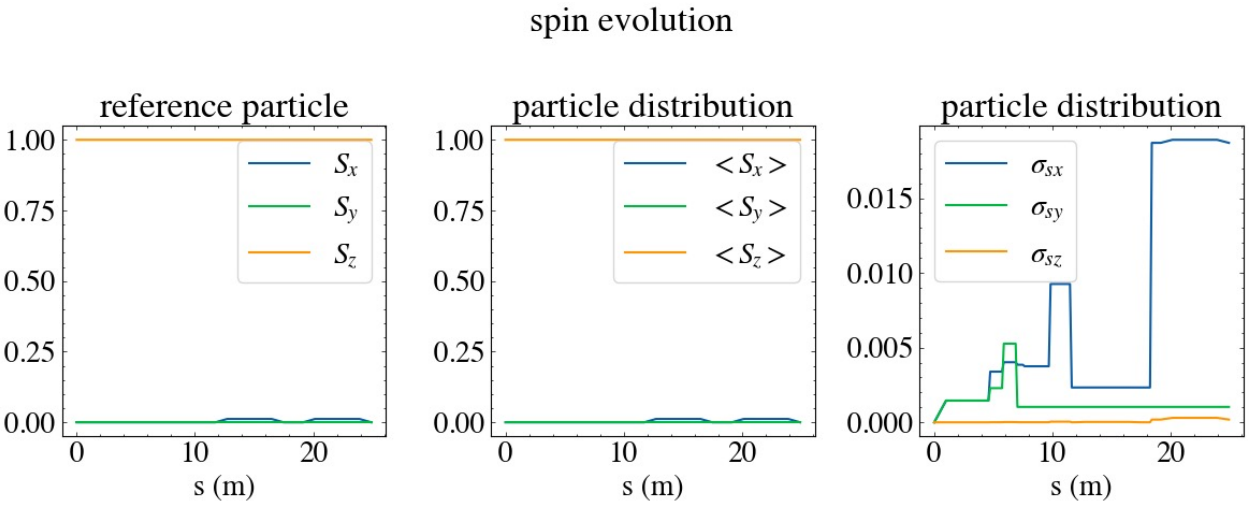




Emittances	Before RFBT	After RFBT	After EEX (with CSR)
ε_{nx}	246.7 μm	493 μm	25 μm
ε_{ny}	246.7 μm	8 nm	8 nm
ε_{nz}	10.7 μm	10.7 μm	518 μm

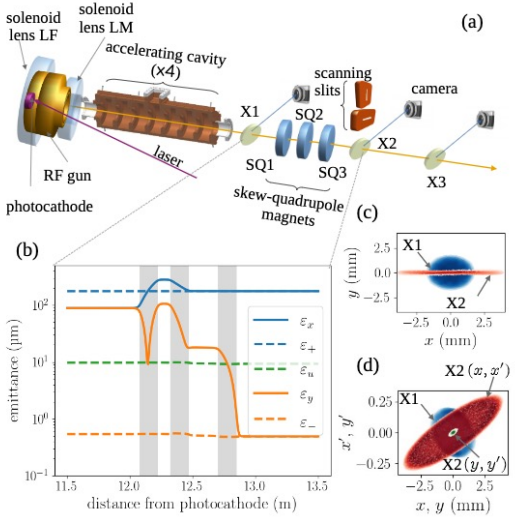
SPIN DYNAMICS

- Started with longitudinally spin polarized beam.
- Simulated with Bmad with Romberg integration of the spin rotation matrix.
- Negligible depolarization through RFBT+EEX.
- More studies needed on spin-polarized, magnetized electron sources

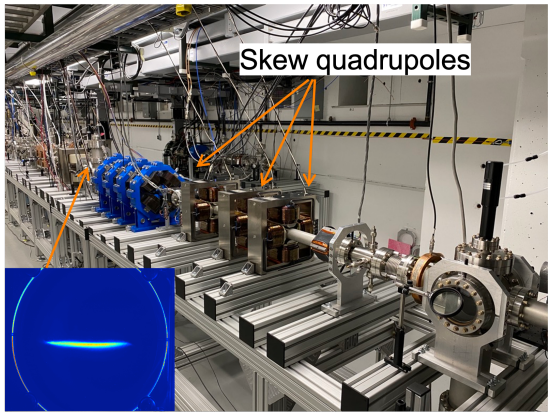


EXPERIMENTS AT AWA

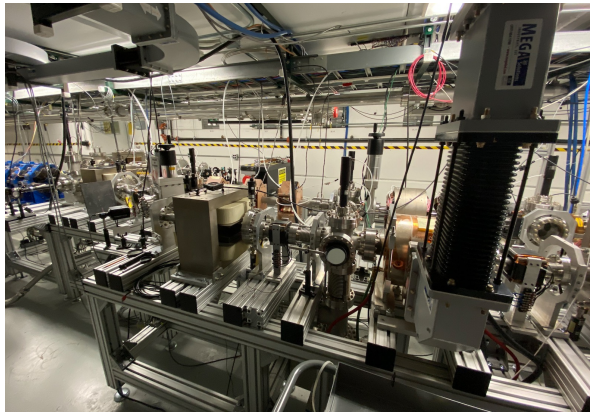
- Unique RFBT+EEX beamline for electron beam manipulation.
- High-charge flat beams to support structure wakefield studies (dipole-mode suppression).
- Proof-of-principle experiment planned for arbitrary emittance repartition.



RFBT beamline

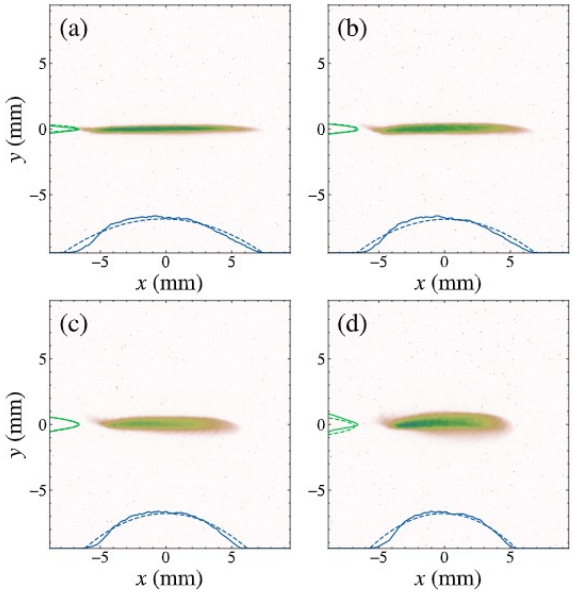


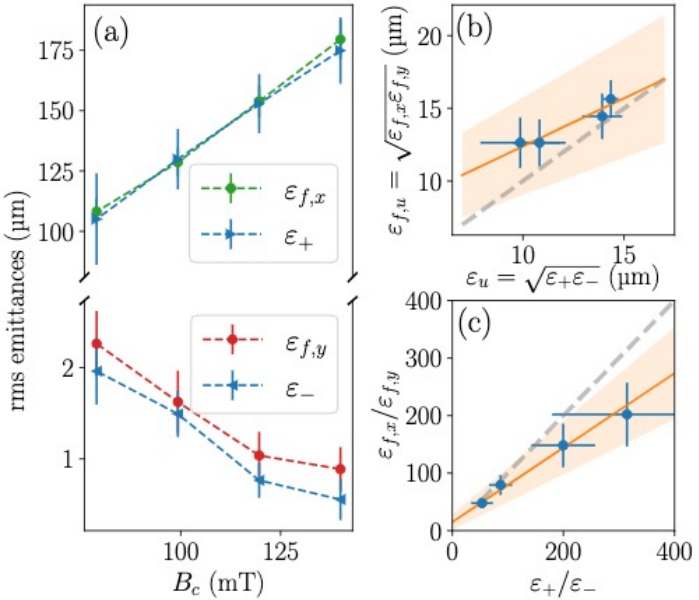
EEX beamline



EXPERIMENTAL STATUS

- Variable emittance ratio $\varepsilon_x/\varepsilon_y$ from 48 to 200 at 1nC
- Ellipsoidal flat beam generation (blow-out scheme)
- Eigen-emittance mapping



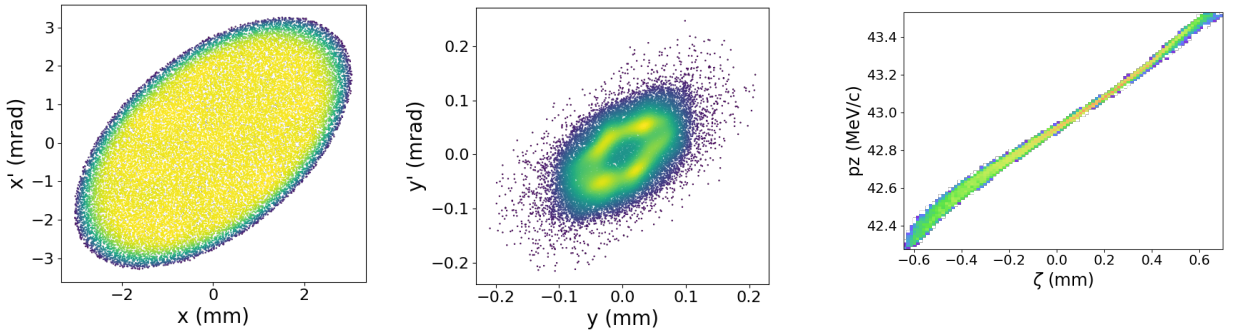


arXiv:2111.15549

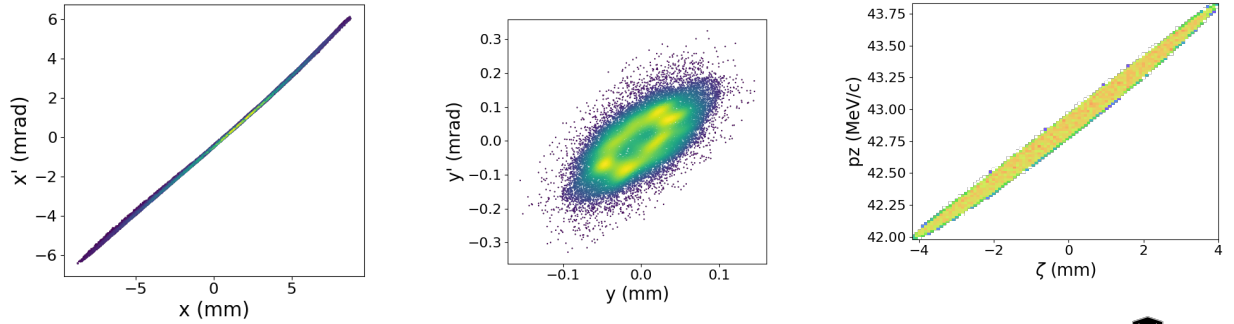
SIMULATION FOR RFBT + EEX AT AWA

Before EEX (after RFBT)			After EEX		
ε_x	176.5	μm	ε_x	40	μm
ε_y	0.23	μm	ε_y	0.23	μm
ε_z	20	μm	ε_z	184.7	μm

Phase spaces before EEX



Phase spaces after EEX



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CONCLUSION

- RFBT+EEX achieves $(\varepsilon_x, \varepsilon_y) \sim (25\mu\text{m}, 8\text{nm})$ at 3.2nC and is a viable candidate for damping-ring-free linear colliders.
- Smaller ε_z allows short bunch for linear colliders.
- Spin polarization preserved through RFBT+EEX.
- 1nC flat beam with transverse emittance ratio up to 200 demonstrated at AWA.
- Proof-of-principle experiments planned for arbitrary emittance repartition.
- Concept possibly extended to positron injectors.

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