Emittance-Partitioning Strategies for Future Accelerator Applications

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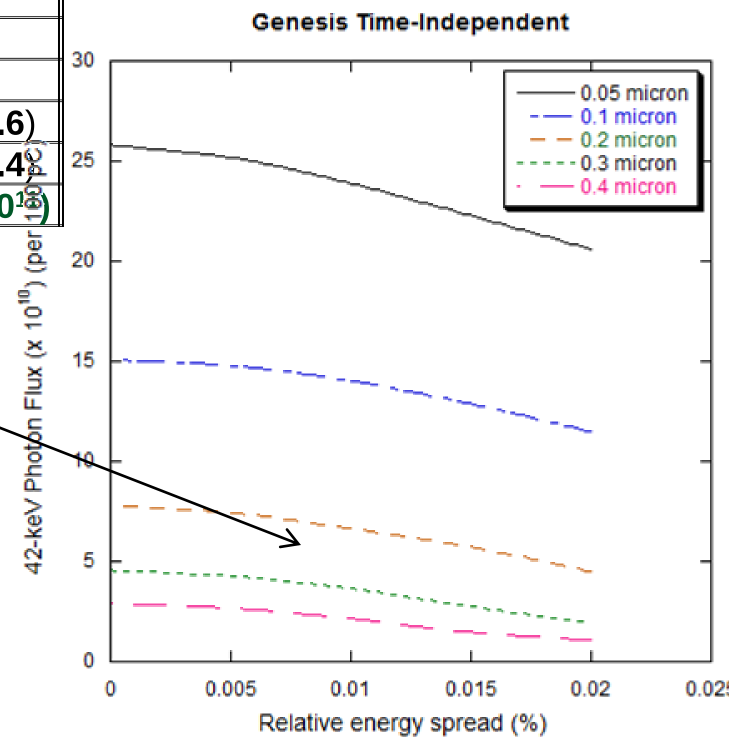
MaRIE: Achieving 2e10 – 2e11 photons at 42 keV

	UNIT	LCLS	MARIE 1.0
Wavelength	Å	1.5	0.293
Beam energy	GeV	14.35	12.0
Bunch charge	pC	250*	100 (**250**)
Pulse length (FWHM)	fs	80*	30 (**75**)
Peak current	kA	3.0*	3.4
Normalized rms emittance	um	0.3-0.4	0.2 (**0.1**)
Energy spread	%	0.01	0.01
Undulator period	cm	3	1.86
Peak magnetic field	T	1.25	0.70
Undulator parameter, a_w		2.48	0.86
Gain length, 1D (3D)	m	(3.3)*	(6.0)
Saturation length	m	65	80
Peak power at fundamental	GW	30*	8 (**17.6**)
Pulse energy	mJ	2.5*	0.24 (**2.4**)
# of photons at fundamental		2×10^{12}*	2×10^{10} (**2×10^{11}**)

**Y. Ding, HBEB, 11/09*

PITZ photoinjector scaling: $\varepsilon_n = 0.7\,(\mu\mathrm{m})\sqrt{q(\mathrm{nC})}$

Normalized emittance	PITZ photo-injector	REDUCTION TECHNIQUES
0.1 mm	25 pC	**250 pC**
0.2 mm	**100 pC**	1 nC



Eigen-emittances: Two new concepts

1) With the common discussion of highly-correlated beams, the term eigen-emittance has emerged to define the emittances of a particle distribution once all correlations are removed. It has been shown that the eigen-emittances are constants of linear, symplectic (collective) transforms.

2) Non-symplectic transforms are the method to change eigen-emittances.

$$\sigma_{x,x',z,\delta} = \begin{pmatrix} 1.0 & 0 & 0 & 0 \\ 0 & 1.0 & 0 & 0 \\ 0 & 0 & 1.0 & 0 \\ 0 & 0 & 0 & 1.4 \end{pmatrix} \qquad \varepsilon^E_{x,z} = 1, 1.4\ \mu m$$

symplectic →

$$\begin{pmatrix} 1.0 & 0 & 0 & 0.8 \\ 0 & 1.0 & 0 & 0 \\ 0 & 0 & 1.4 & 0 \\ 0.8 & 0 & 0 & 2.1 \end{pmatrix}$$

conventional beamline elements

$$\varepsilon^E_{x,z} = 1, 1.4\ \mu m$$

non-symplectic →

$$\begin{pmatrix} 1.0 & 0 & 0 & 0.8 \\ 0 & 1.0 & 0 & 0 \\ 0 & 0 & 1.0 & -0.6 \\ 0.8 & 0 & -0.6 & 2.2 \end{pmatrix}$$

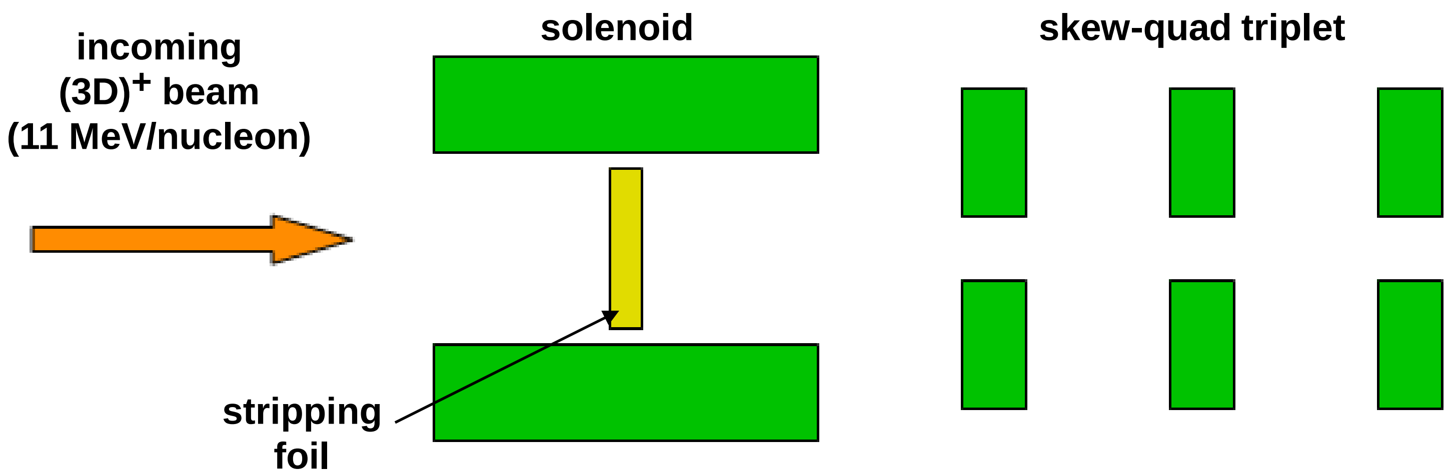
FBT (14x), wedge foil, ISR, etc?

$$\varepsilon^E_{x,z} = 7, 0.2\ \mu m$$

Our motto: "*Create a correlation non-symplecticly; then remove it symplecticly*."

Example (x-y): Charge-stripping foil

C. Xiao, L. Groening: MOPB-098, PRST-AB 14-064201



The solenoid spins the D_3^+ beam in one direction. Total angular momentum is still zero.

The stripping foil changes the current $3D^+$. Now total angular momentum is not zero.

The skew-quad triplet removes the beam's angular momentum.
It removes cross-correlations.

Incident emittances are ~ 0.56 microns.
Without the repartitioning solenoid, the stripped emittances are ~ 0.65 microns.
With the solenoid, they are ~ 0.35, 1.24 microns (+1.3% each).

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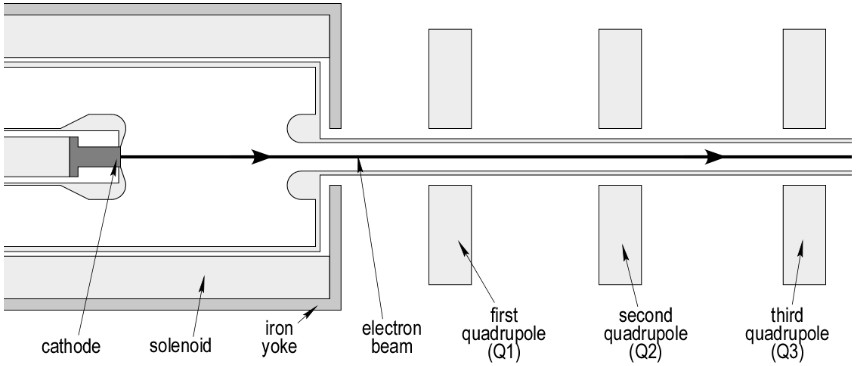
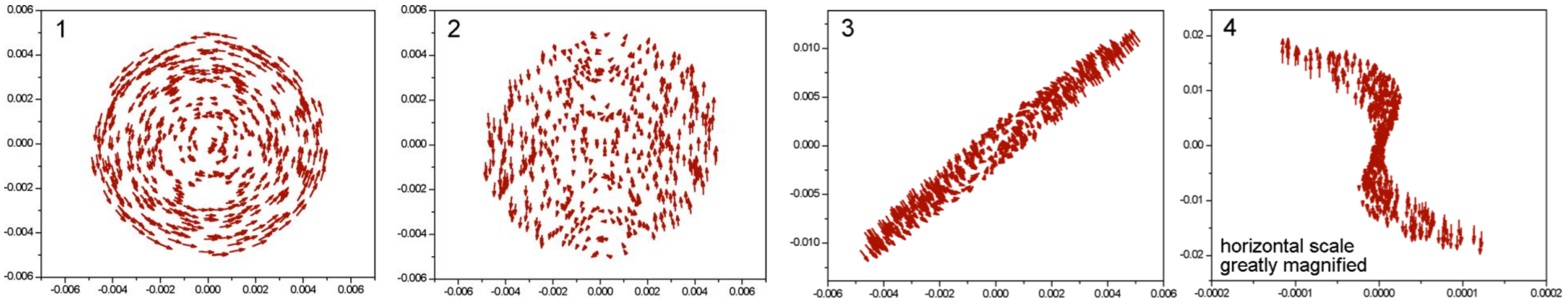
Example (*x*-*y*): Flat-Beam Transformer

P. Piot: LINAC'06, PRST-AB 9-031001

Start with 250 pC round beam at cathode (0.35/0.35/4 μm)



FBT in the usual way gives 1.2, 0.1 emittances



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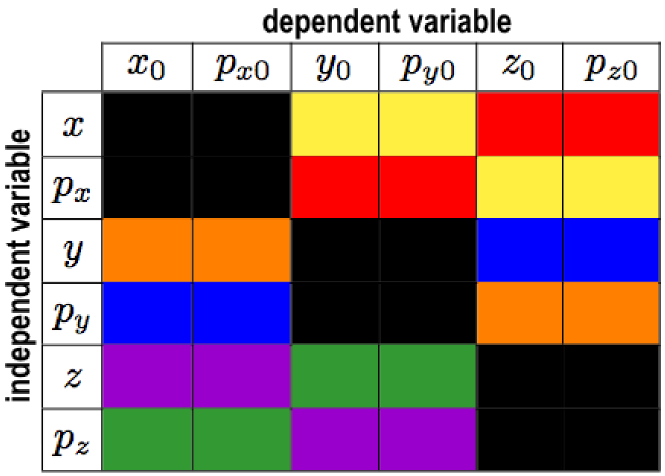
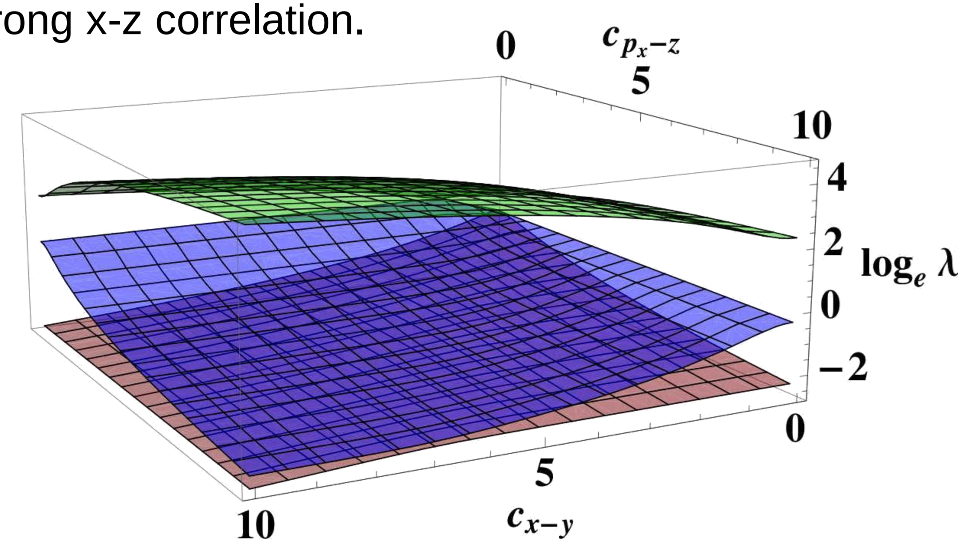
Example (x-y & x-z): Simultaneous initial correlations

In order to reduce two eigen-emittances, two associated correlations must be generated non-symplecticly.

Option 1: Along with an FBT (x'-y), hitting the cathode with the laser at an oblique angle generates a strong x-z correlation.





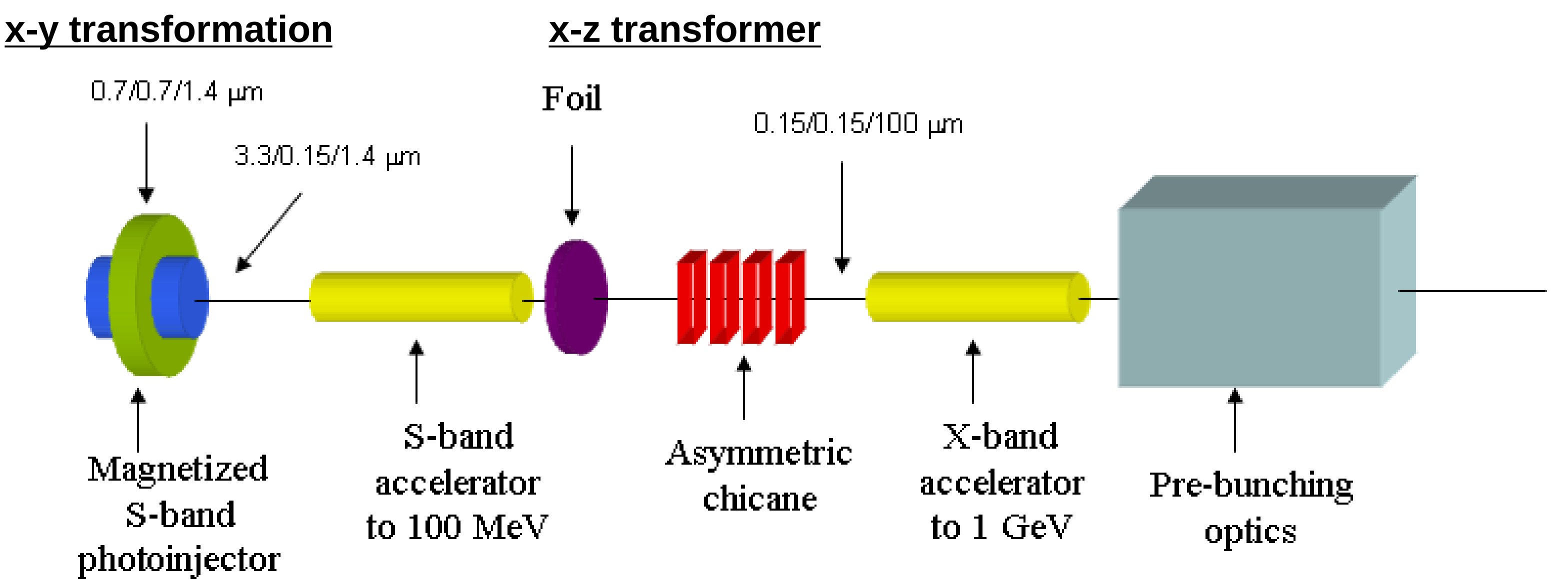
Option 2: Using a highly elliptical cathode relaxes the time constraints on the oblique laser.

$$x_1 = x_0 \qquad c\Delta t_1 = c\Delta t_0 + x_0 \tan\theta$$

A major concern with all initial correlations is nonlinear forces before the beam is accelerated. Emittance dilution will impair the extreme emittance MaRIE requires.

Example (*x-y* & *x-z*): Staged Transformations

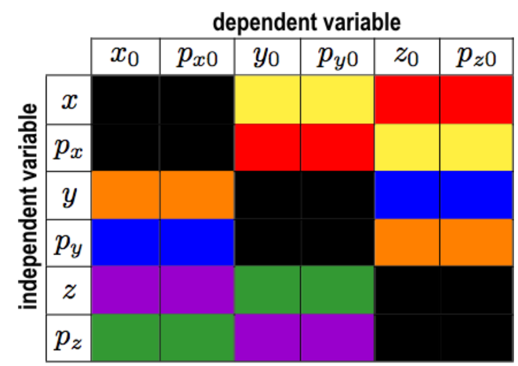
An “easier” option is to stage the two transformations.



1) Reduce y-emittance at expense of x-emittance.

2) Accelerate beam.

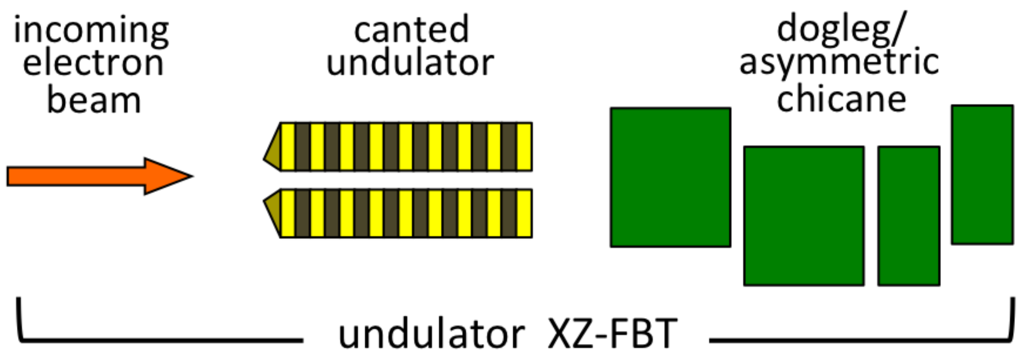
3) Reduce x-emittance at expense of z-emittance.



Example (*x*-*z*): XZ-FBT with canted undulator

B. Carlsten: PRST-AB 11-050706

Being a non-collective phenomenon, ISR acts as a non-symplectic transformation. By varying the magnetic field across the horizontal dimension of the the undulator, different electrons lose differing amounts of energy, generating the x-p_z correlation.



$$P = 632 \times E^2 B^2 L I$$

$$\Delta E = 632 \cdot E^2 B^2 L$$

E in [GeV]
ΔE in [eV]
otherwise [mks]

$$\varepsilon_<^N = \frac{\delta_{\text{int}}}{\delta_{\text{slew}}} \times \varepsilon_x^N \qquad \varepsilon_>^N = \gamma\beta\delta_{\text{slew}}\sigma_z$$

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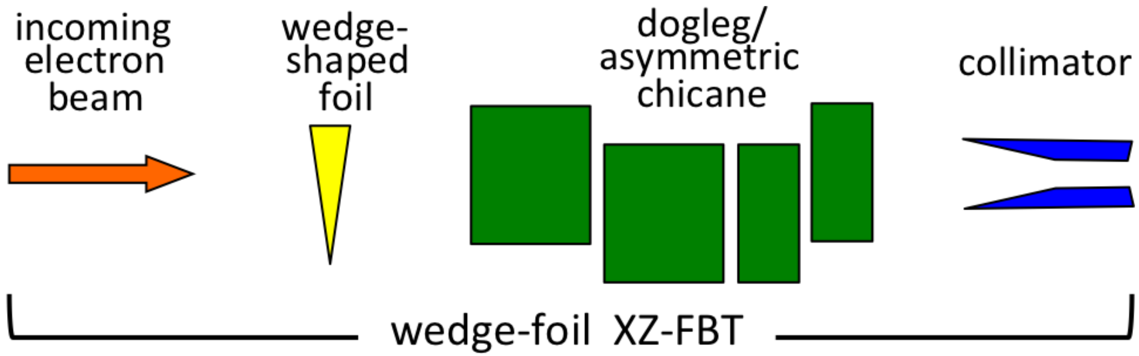
A 100 MeV beam with a 100-m long undulator with a 3-T field provides about 5 E-4 energy slew (about 5 keV), so may be appropriate after about an initial compression of 10 to 20.

$$\frac{\delta_{\text{diff}}}{\delta_{\text{slew}}} = \frac{1.5}{\sqrt{L \cdot B_{\text{rms}}}}$$

Example (*x*-*z*): XZ-FBT with wedge-shaped foil

B. Carlsten: PRST-AB 11-050706

A second approach to generating a proper x-p_z correlation is a wedge-shaped foil that the beam passes through. One side of the beam loses more energy than the other side. However, the foil also scatters particles, creating an additional uncorrelated spread δ_{ind}.



$$e_<^N = gb\frac{\sqrt{d_{\mathrm{int}}^2 + d_{\mathrm{ind}}^2}}{d_{\mathrm{slew}}}\sqrt{e_{x,\mathrm{ind}}^2 + e_{x,\mathrm{int}}^2}$$

$$e_>^N = gbd_{\mathrm{slew}}s_z$$

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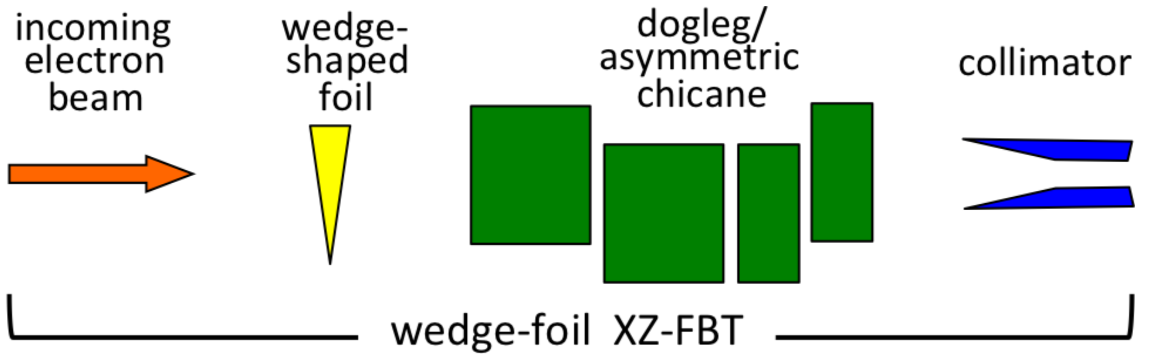
XZ-FBT analysis: Asymmetric chicane

Both the canted-wiggler and wedge-foil techniques are non-symplectic methods to alter the beam’s eigen-emittances. In order to remove the correlations (symplecticly), we can use a dogleg.

An asymmetric chicane can also be used, and keeps the beam on the same trajectory (making it adjustable as well).



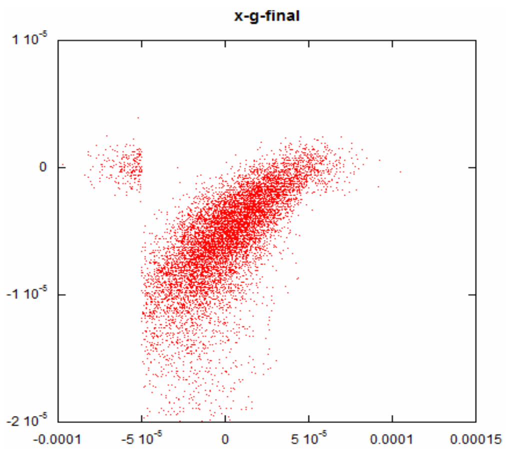
$$M_{asym} = \begin{pmatrix} 1 & L_1 & 0 & \eta_1 \\ 0 & 1 & 0 & 0 \\ 0 & \eta_1 & 1 & \varepsilon_1 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & L_2 & 0 & -\eta_2 \\ 0 & 1 & 0 & 0 \\ 0 & -\eta_2 & 1 & \varepsilon_2 \\ 0 & 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} 1 & L_t & 0 & \Delta\eta \\ 0 & 1 & 0 & 0 \\ 0 & \Delta\eta & 1 & \varepsilon_t \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$\varepsilon_x^2 = \chi\varepsilon_{x0}^2 , \qquad \chi \equiv \delta_{\mathrm{rms}}/\delta_{\mathrm{slew}}$$

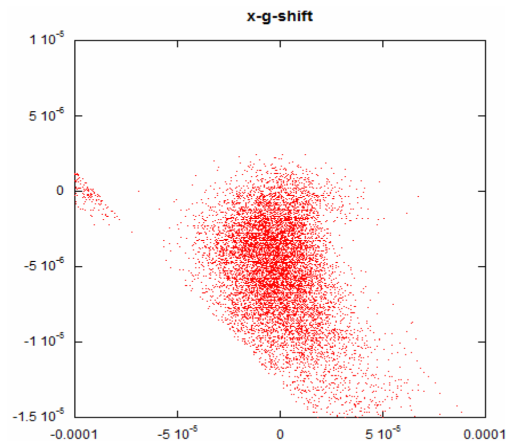
$$\varepsilon_x^2\varepsilon_z^2 = \varepsilon_{x0}^2\varepsilon_{z0}^2 + \chi^2\varepsilon_{x0}^2\left(\varepsilon_{x0}^2 + \varepsilon_{z0}^2\right) + \chi^4\varepsilon_{x0}^4$$

Nonzero elements contribute ~1% emittance growth.

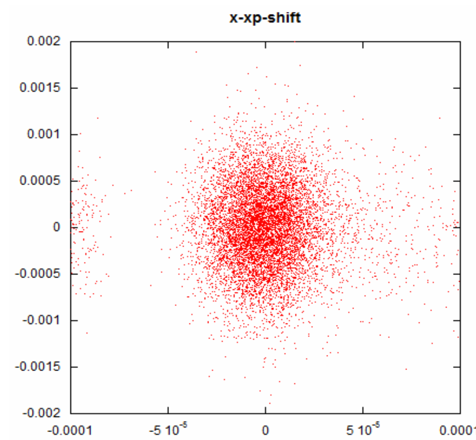
XZ-FBT analysis: Asymmetric chicane



x-γ after wedge
oops! small foil!



x-γ after dogleg

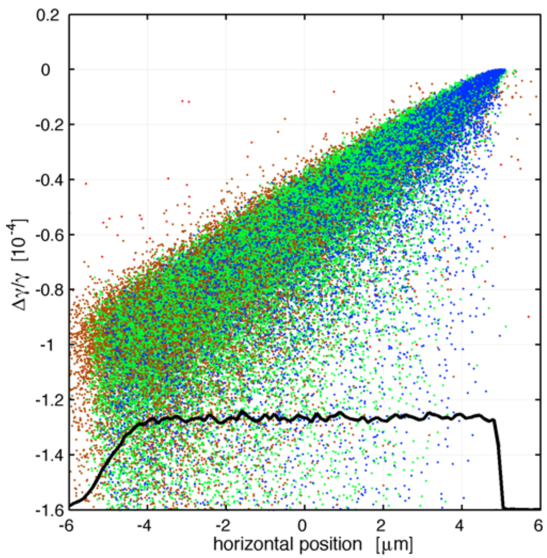


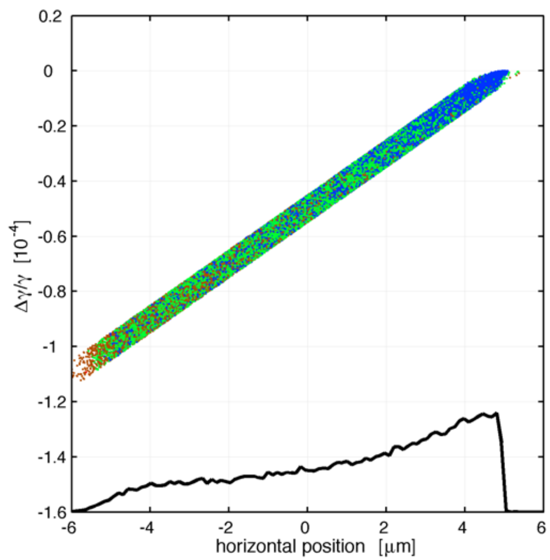
x-x' after dogleg

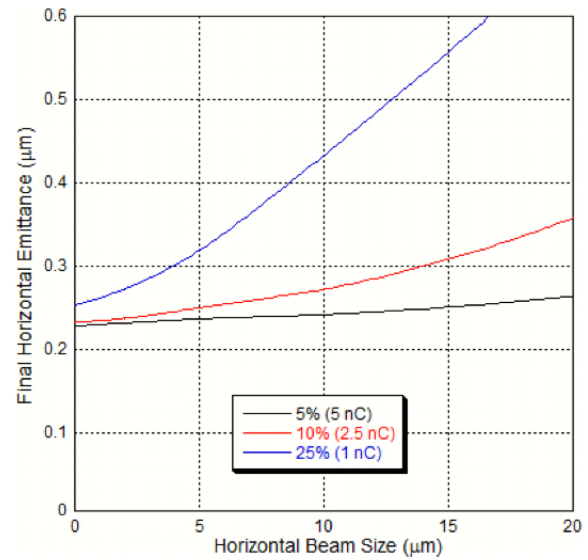
Optimal collimation uses the densest core of the x-x' phase space after the dogleg. The core tends to have uniform phase-space density.

Simulation results: Wedge-shaped foil

Using G4Beamline (Geant4), scattering and energy loss through the foil can be simulated. The following shows particle plots at 1 GeV:





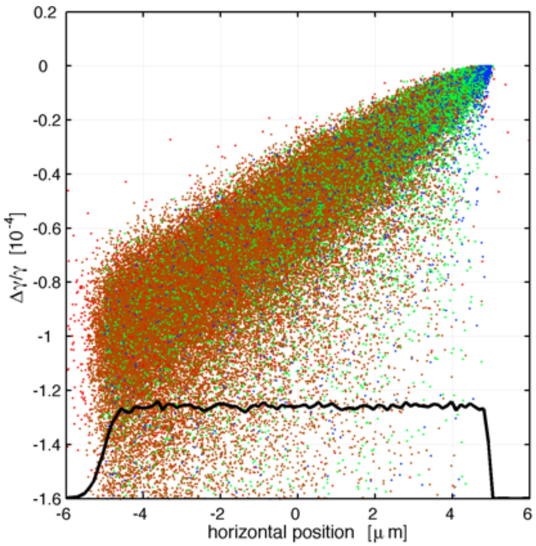


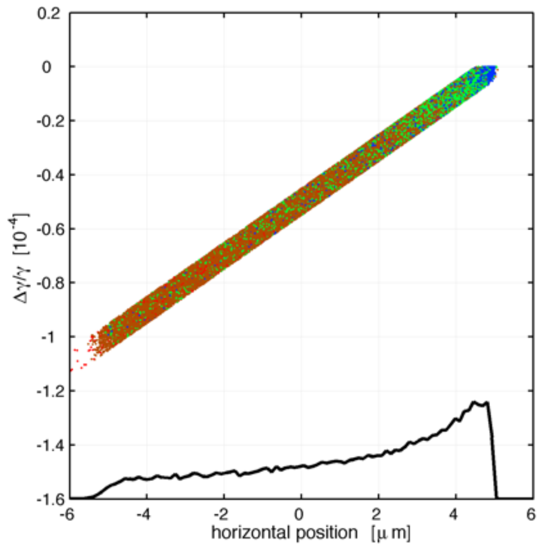
Due to the large energy distribution, it is necessary to collimate the remaining particles.

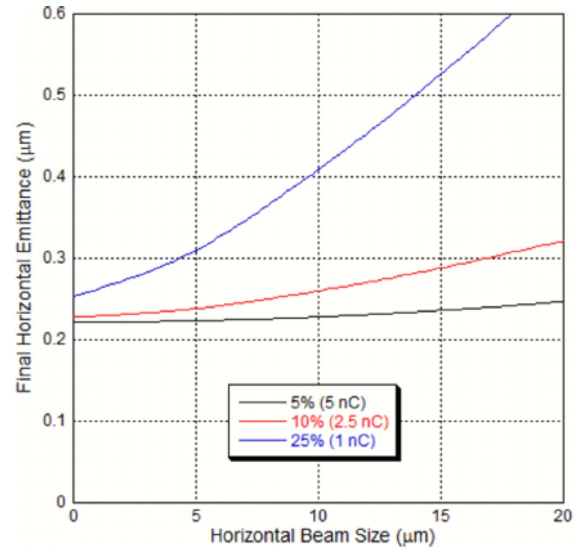
The effectiveness of this technique increases with the severity of the collimation. Therefore starting with 1 nC to 5 nC, and collimating to 250 pC are considered for the wedge approach.

Simulation results: Wedge-shaped foil

Similar results are shown for 100 MeV: Again, 0.23 μm is achievable.







$$\varepsilon_{\perp}^{N} = \gamma\beta \frac{\sqrt{\sigma_{\rm int}^2 + \sigma_{\rm ind}^2}}{\sigma_{\rm slew}} \sqrt{\varepsilon_{x,\rm ind}^2 + \varepsilon_{x,\rm int}^2}$$

10^{-6}

$5\ 10^{-5}$

$\varepsilon_x = 10\ \mu m$

Simulations indicate that we need to lose at least 75% of particles to maintain the partitioned emittance:

1 nC → 250 pC

$\varepsilon_x = 0.23\ \mu m$

$\varepsilon_y = 0.12\ \mu m$

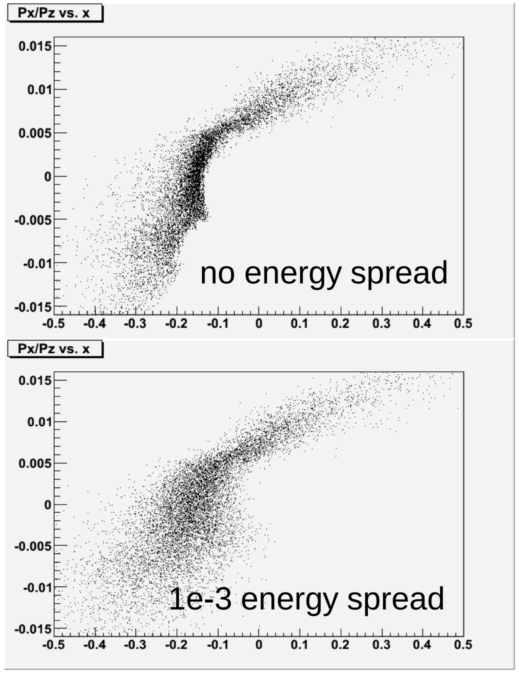
"slice" ε_z ~ 6 mm by 12.5 keV = 150 μm

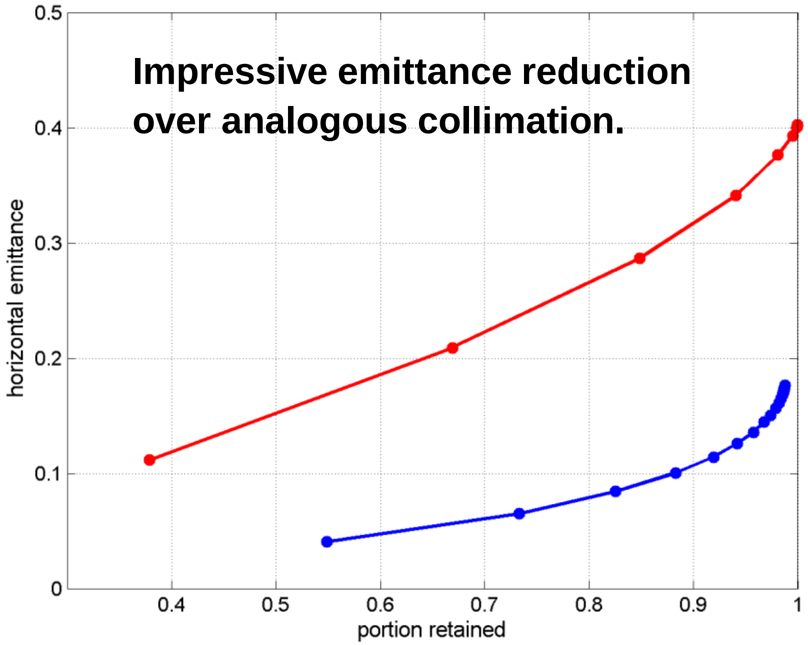
Simulation Results: Protons at LANSCE

Simulation results for pushing 800-MeV protons through a foil have been studied.

This would be the first demonstration of an XZ-FBT. Other experiments of a combined FBT/XZ-FBT beamline would be pursued elsewhere.

2e-3 energy slew





Summary

- Several options exist for production of a 0.1-µm-emittance beam at significant charge (250 pC) for future XFEL applications.
- It is possible that future photoinjectors possess this capability with built-in correlations.
- It is more attractive to have adjustable, staged FBT and XZ-FBT emittance reduction options. The XZ-FBT stage has yet to be demonstrated.
- Canted wigglers appear far superior to wedged-foil approaches. At high energies, the wiggler dimensions are not unrealistic.
- We are planning a demonstration at LANSCE with 800-MeV protons.
- We are also pursuing collaboration on an electron beamline.

NEWS FLASH

We were granted funds to perform an experimental demonstration of the XZ-FBT foil technique.

We are pursing a demonstration on the LANSCE 800-MeV proton beamline.

We are also interested in collaborating on an electron beamline, leading to a staged FBT/XZ-FBT system.

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