Elettra Sincrotrone Trieste

Emittance control in the presence of *collective effects* in the FERMI@Elettra FEL linac driver

S. Di Mitri, *on behalf of* ***FERMI Commissioning Team***

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Outline

- FERMI FEL and importance of *projected* transverse emittance
- Sources of emittance growth. Beam matrix formalism.
  - Coherent synchrotron radiation (CSR)
    - in magnetic compressor
    - in high energy transfer line
  - Geometric transverse wakefield (GTW)
    - in collimator
    - in RF linac
  - 4-D e-beam brightness in presence of CSR and GTW: model, validation and optimization studies
- FERMI linac emittance budget

Elettra
Sincrotrone
Trieste

is a nonprofit shareholder company of **national interest**, established in **Trieste, Italy** in 1987 to **construct and manage** synchrotron **light sources** as **international facilities**.

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FEL requirements for electron beam

- Compactness and high intensity of FEL require high 6-D e-beam brightness, $Q/(\varepsilon_x \varepsilon_y \varepsilon_z)$, on the scale length of the *FEL slippage*:

$$\boxed{P_{FEL}(z) \sim e^{z\frac{\rho}{\lambda_u}} \sim e^{z\left(\frac{I_{pk}}{\sigma_\perp}\right)^{1/3}}} \qquad \boxed{\varepsilon_n \leq \frac{\gamma\lambda}{4\pi}} \qquad \boxed{\sigma_\delta < \rho}$$

However…

- Collective effects may establish <u>*correlations*</u> between <u>*slices' coordinates*</u> (*i.e.*, projected emittance growth) that affect the FEL wavelength and bandwidth [G. Andonian et al., PRL 95, 054801 (2005); G.Penn et al., ST/F-TN-06/01 (2006)].
- Control of e-beam size and angular divergence requires <u>*optics matching*</u> (*i.e.*, projected Twiss functions).

Control of FEL and e-beam slice parameters is inferred by the measurement and control of e-beam projected values.

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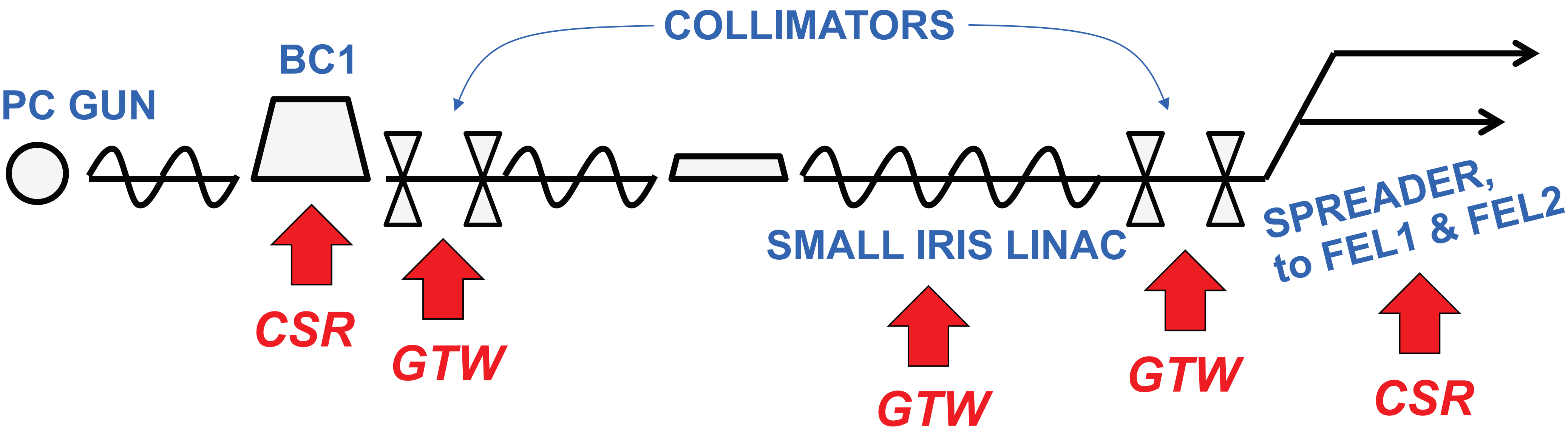
Sources of transverse emittance growth



Particle distribution is assumed to be *locally kicked* by $\Delta^2=\langle\Delta x'^2\rangle$. The perturbed emittance is estimated with the *beam matrix*:

$$\tilde{\varepsilon} = \sqrt{\det\begin{pmatrix}\langle x^2\rangle & \langle xx'\rangle \\ \langle xx'\rangle & \langle x'^2\rangle+\langle\Delta x'^2\rangle\end{pmatrix}} = \sqrt{\det \varepsilon\begin{pmatrix}\beta & -\alpha \\ -\alpha & \gamma+\Delta^2\end{pmatrix}} = \sqrt{\varepsilon^2\left(1+\frac{\beta\Delta^2}{\varepsilon}\right)} \qquad (1)$$

[M. Dohlus, T. Limberg, PAC’05; Emma, ICFA 38 (2005)]

It may work for CSR in a dipole and GTW in a collimator .

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 15, 020701 (2012)

Transverse emittance preservation during bunch compression in the Fermi free electron laser

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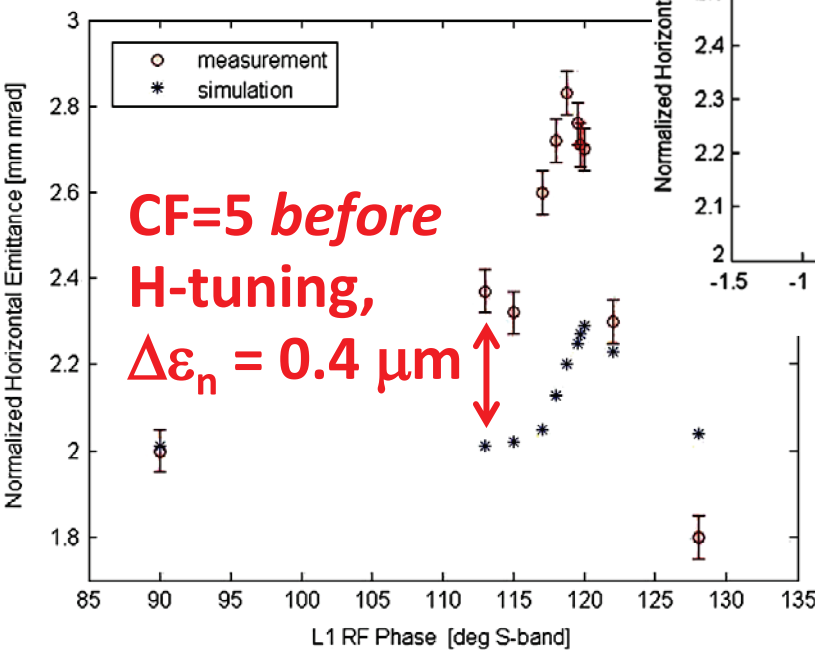
CSR in magnetic compressor (BC1)

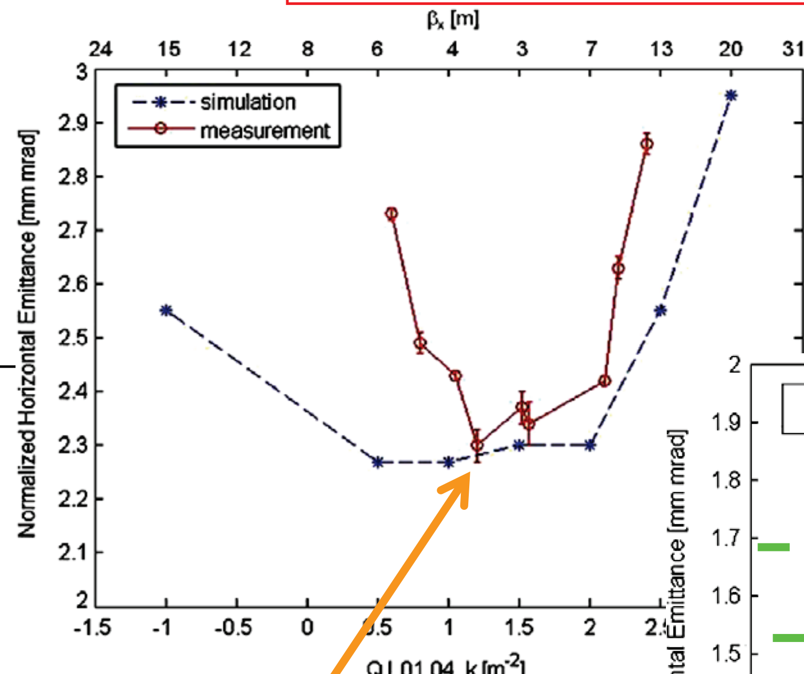
Assume ε-growth is dominated by CSR in the last dipole magnet.

$$\beta\Delta^2\ in\ Eq.1 \rightarrow H\sigma^2_{\delta,CSR} \quad \text{where} \quad \boxed{H = \left[\eta^2 + (\beta\eta' + \alpha\eta)^2\right]/\beta,} \quad \boxed{\sigma_{\delta,CSR} \propto 1/\sigma_z^{4/3}}$$

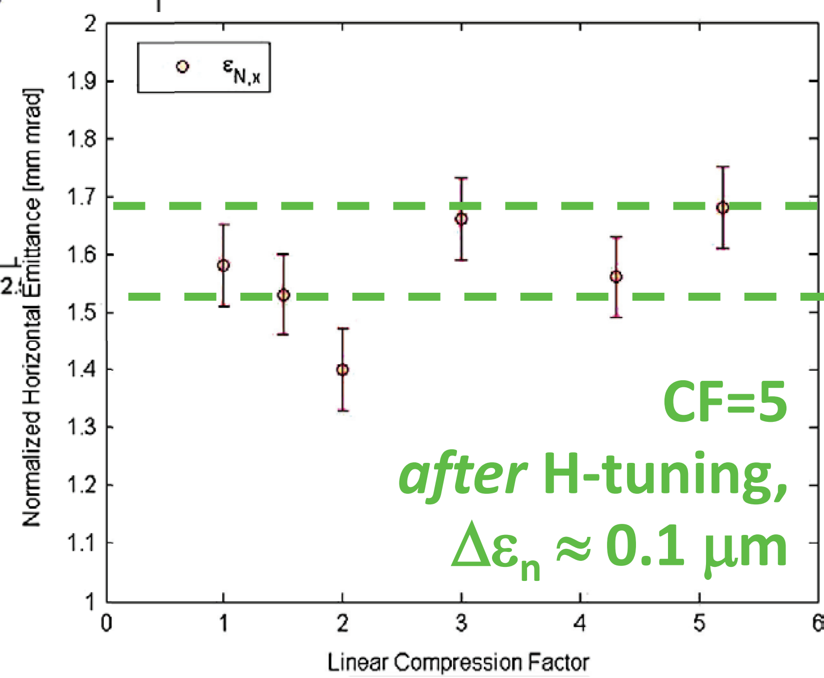
From injector:
200pC, 6ps FWHM



CF=5 *before* H-tuning, $\Delta\varepsilon_n$ = 0.4 μm



H-function shrunk by factor 3



CF=5 *after* H-tuning, $\Delta\varepsilon_n \approx$ 0.1 μm

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Cancellation of Coherent Synchrotron Radiation Kicks with Optics Balance

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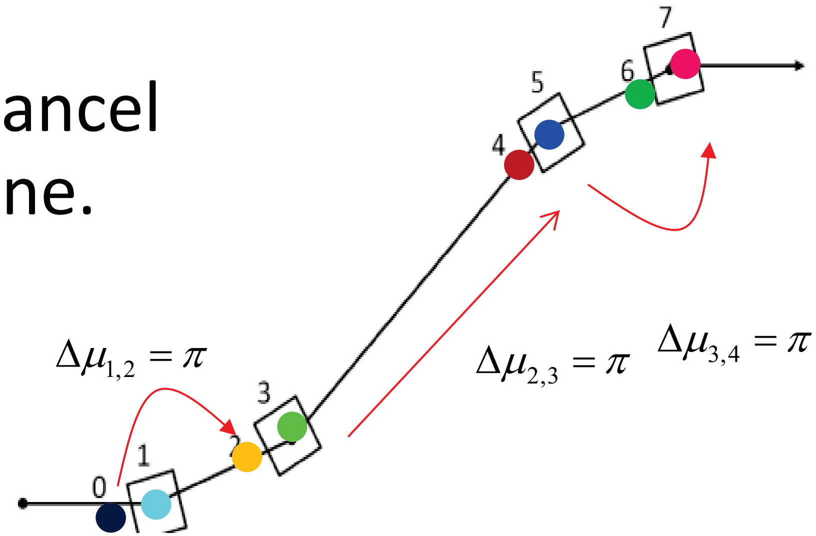
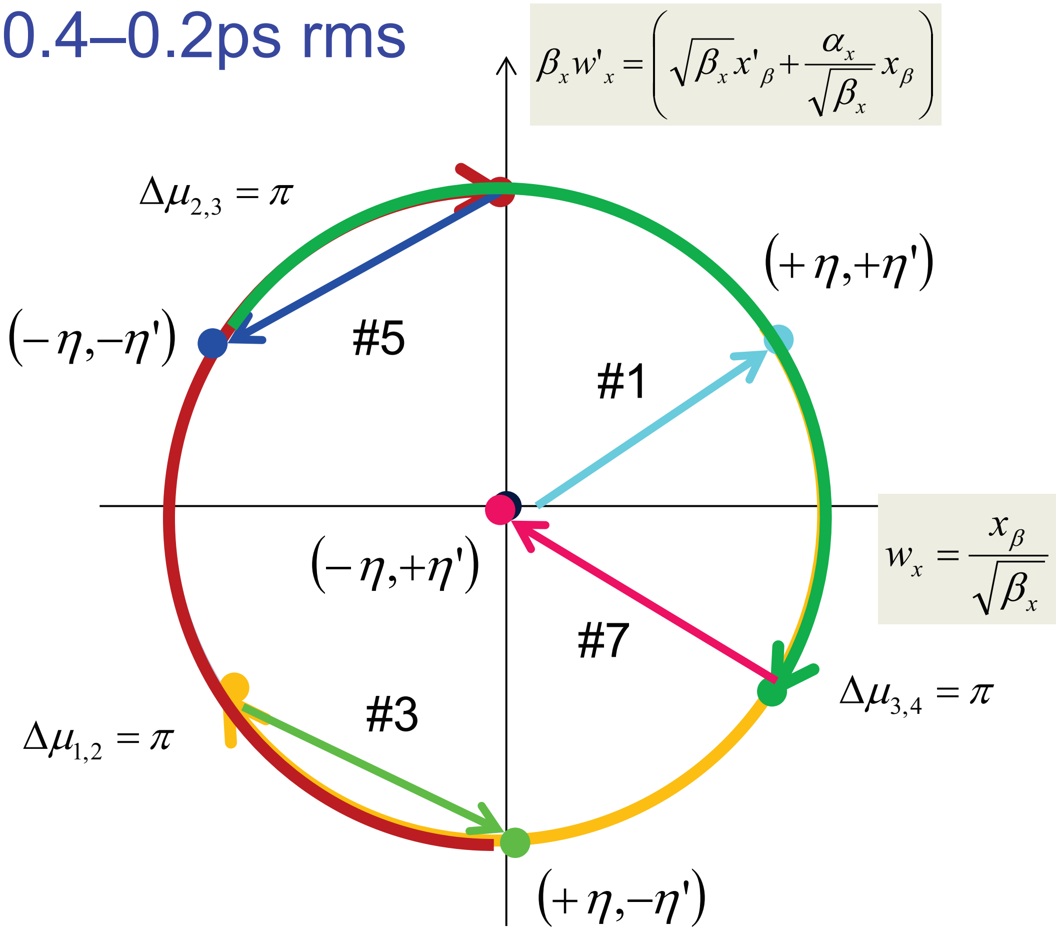
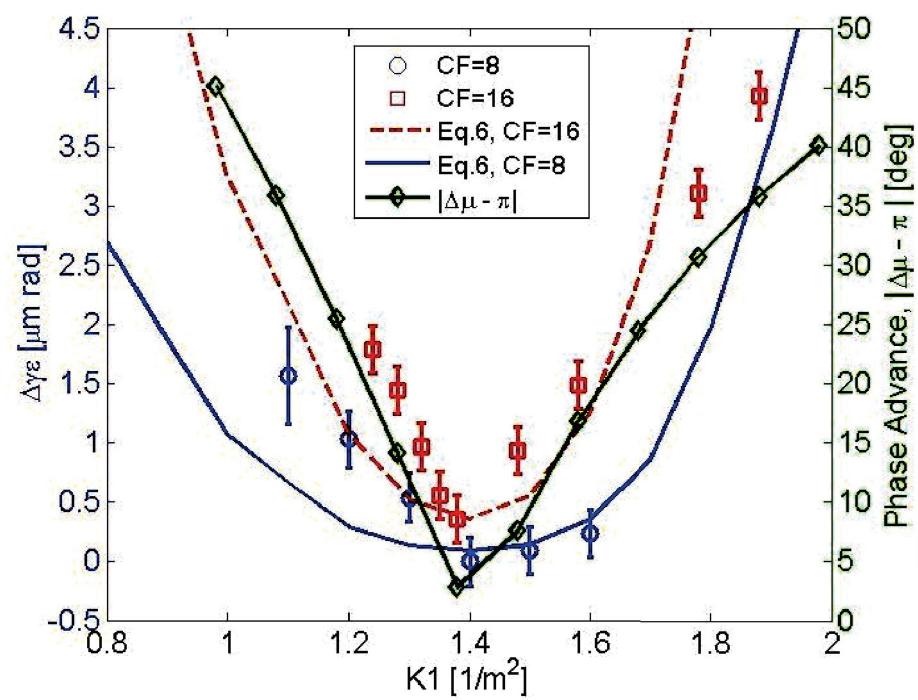
CSR in high energy transfer line (Spreader)

Sum of CSR kicks in all dipoles finally cancel by virtue of optics balance along the line.



500pC,
0.4–0.2ps rms





PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **15**, 061001 (2012)

Influence of longitudinally tapered collimators on a high brightness electron beam

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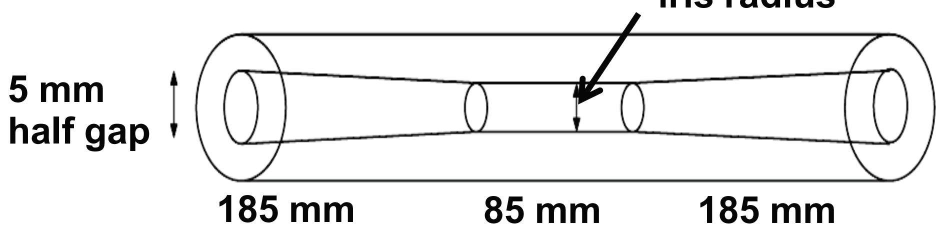
(Received 23 March 2012; published 13 June 2012)

GTW in collimator

Δ^2 in Eq.1 is here the GTW's rms kick, $\Delta = hQ\kappa_{rms}/E$

FERMI

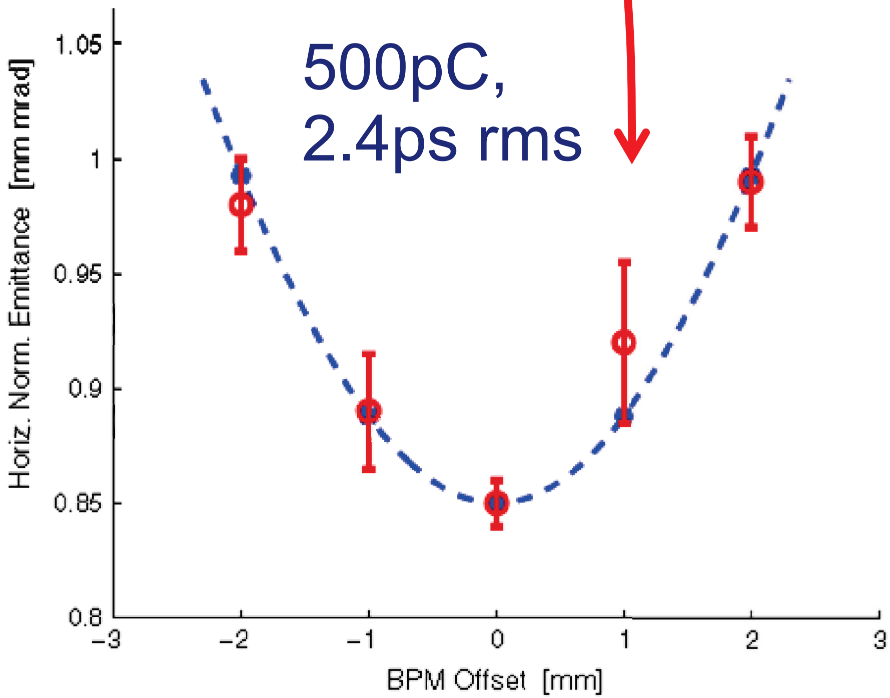


$$\kappa_{fit} = 2.20\ V/pC/mm$$

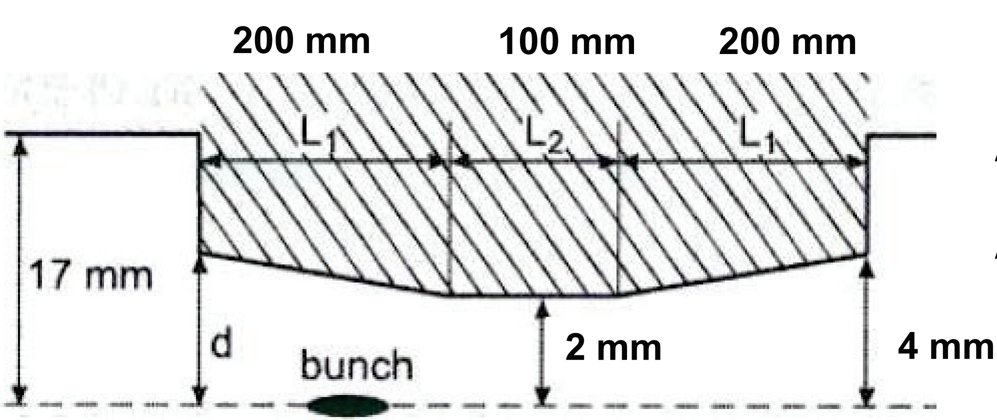
$$\kappa_{ABCi} < 4\ V/pC/mm$$

$$\bar{\kappa}_{theor} = 2.19\ V/pC/mm$$

[P. Craievich, C. Bontoiu, PAC09]



FLASH



κ_{FLASH}

$\bar{\kappa}_{FLASH}$

[A. Tsakanian et al., NIM A 659 (2011) 9]

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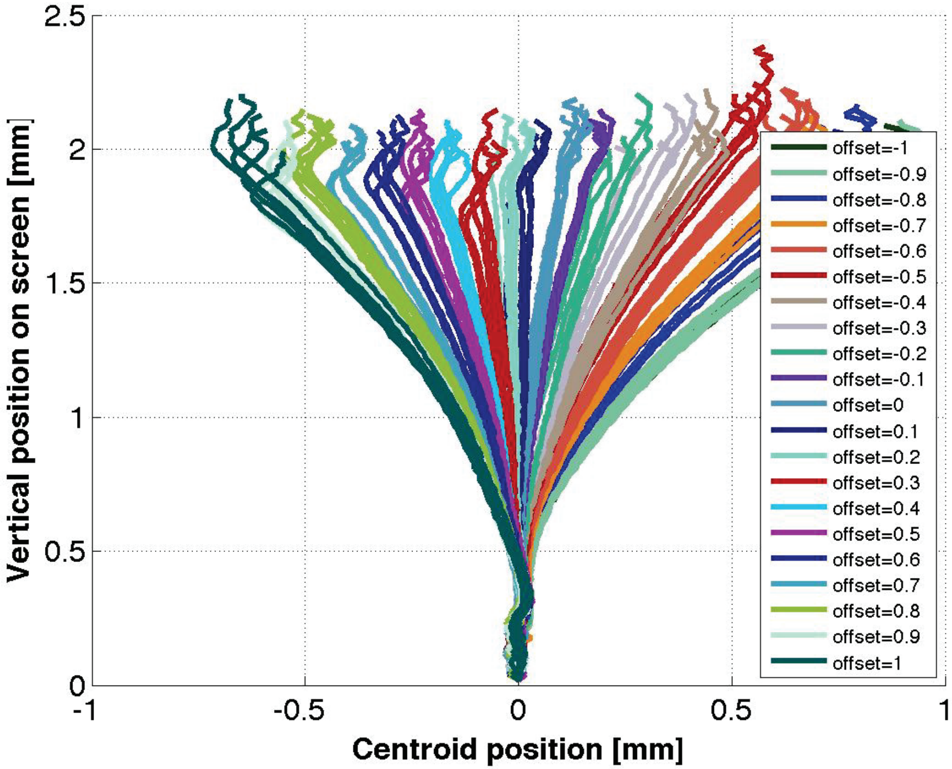
GTW in RF Linac

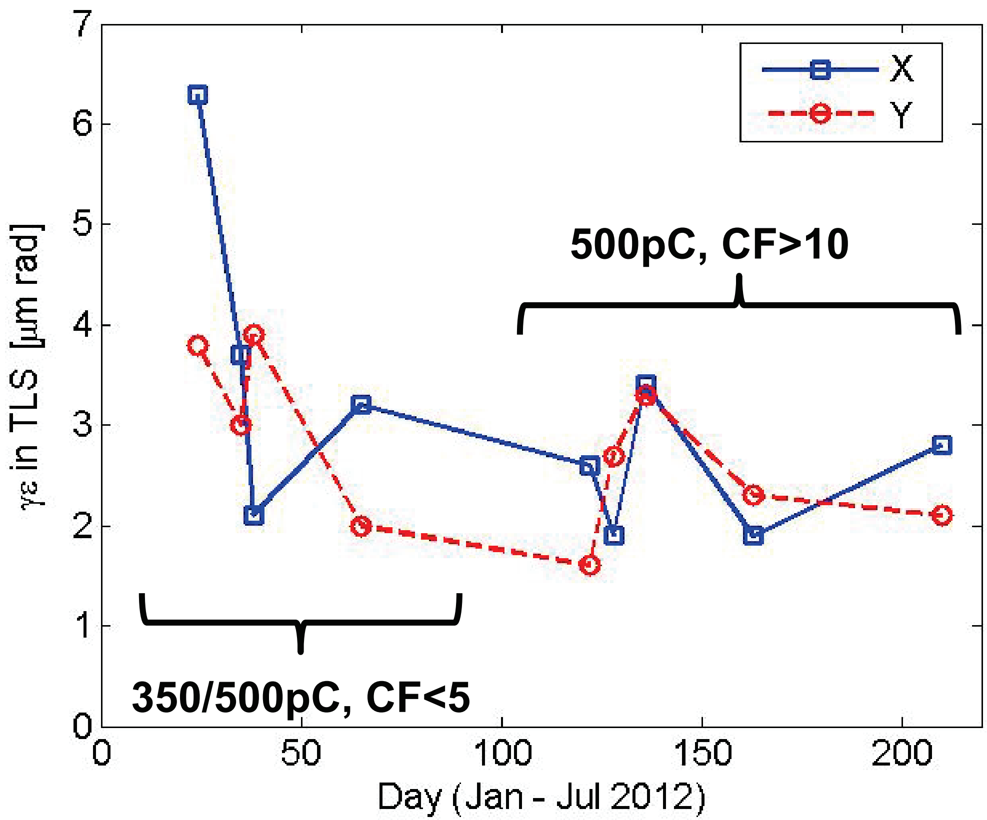
Trajectory bumps along last linac section (small iris structures) allow control of banana shape (*i.e.*, projected emittance) at the linac's end.

Banana shape vs. BPM offsets



[E. Ferrari, O. Kalberg, G. Penco, 2013]

Final Emittance vs. working point



PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **16**, 050701 (2013)

Maximum brightness of linac-driven electron beams in the presence of collective effects

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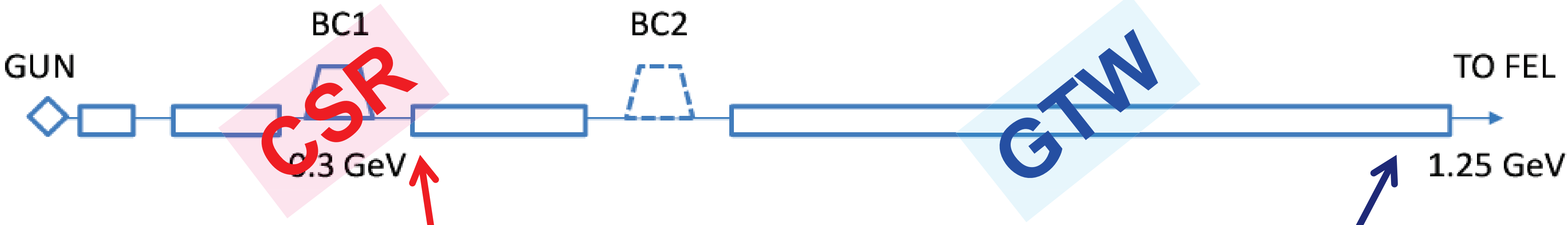
(Received 7 December 2012; published 7 May 2013)

4-D Brightness in presence of CSR and GTW



$$\Delta\varepsilon_n \propto \sigma_{\delta,CSR} \propto \frac{1}{\sigma_{z,f}^{4/3}}$$

$$\Delta\varepsilon_n \propto W_\perp\left(\sigma_{z,f}\right) \propto \sigma_{z,f}$$

$$B_{n,f} \equiv \frac{I}{\gamma_f^2 \varepsilon_{x,f}\varepsilon_{y,f}} = \frac{CI_0}{\left(\gamma_0\varepsilon_{i,0}\right)^2\sqrt{\left(1+X_W\right)\left(1+X_{CSR}+X_W\right)}} \equiv \frac{CB_{n,0}}{\sqrt{\left(1+X_W\right)\left(1+X_{CSR}+X_W\right)}}$$

There must be an optimum (compressed) bunch length that minimizes the combined effect of CSR and GTW on the final $\varepsilon_{n,f}$.

Longitudinal dynamics and effects on FEL in the next talks by Penco, Ferrari and Allaria.

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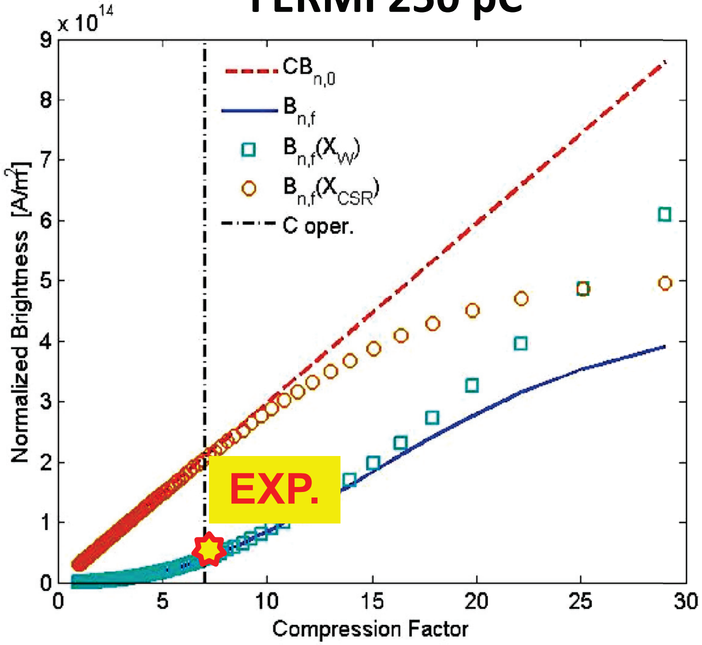
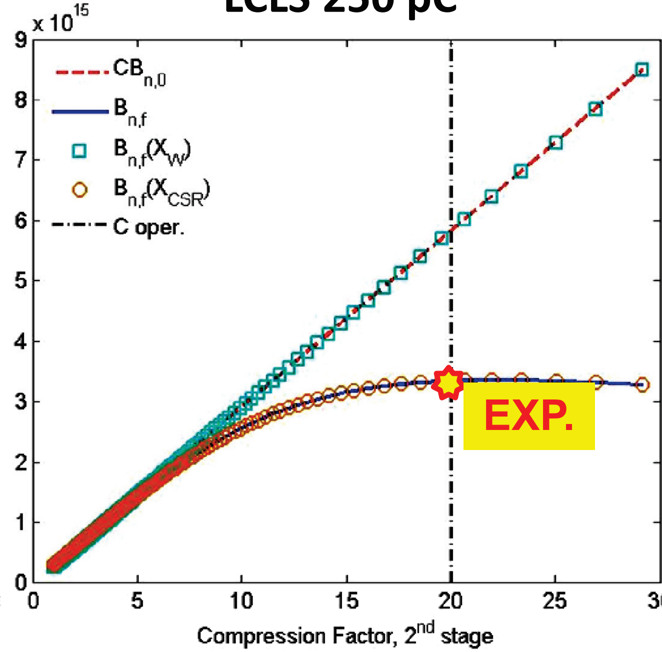
DI MITRI, PRSTAB 16, 050701 (2013)

Validation and optimization studies

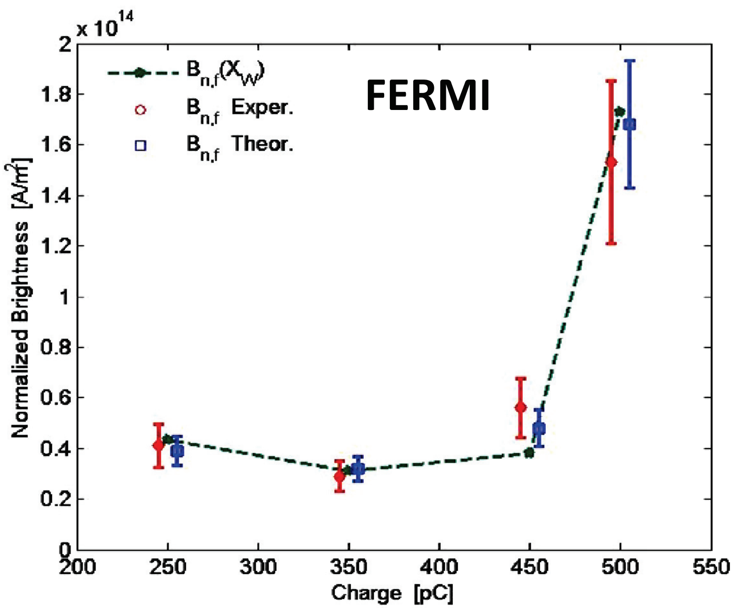
FERMI 250 pC



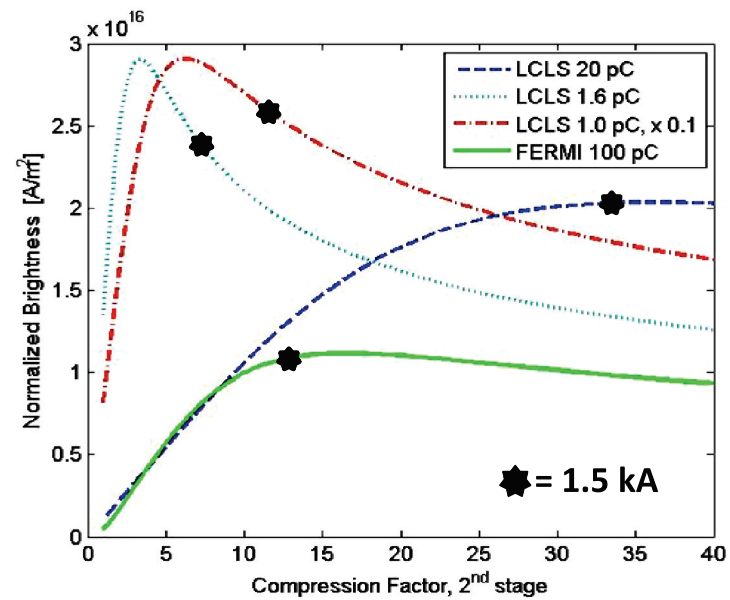
LCLS 250 pC



The model identifies the dominant source of ε-growth.

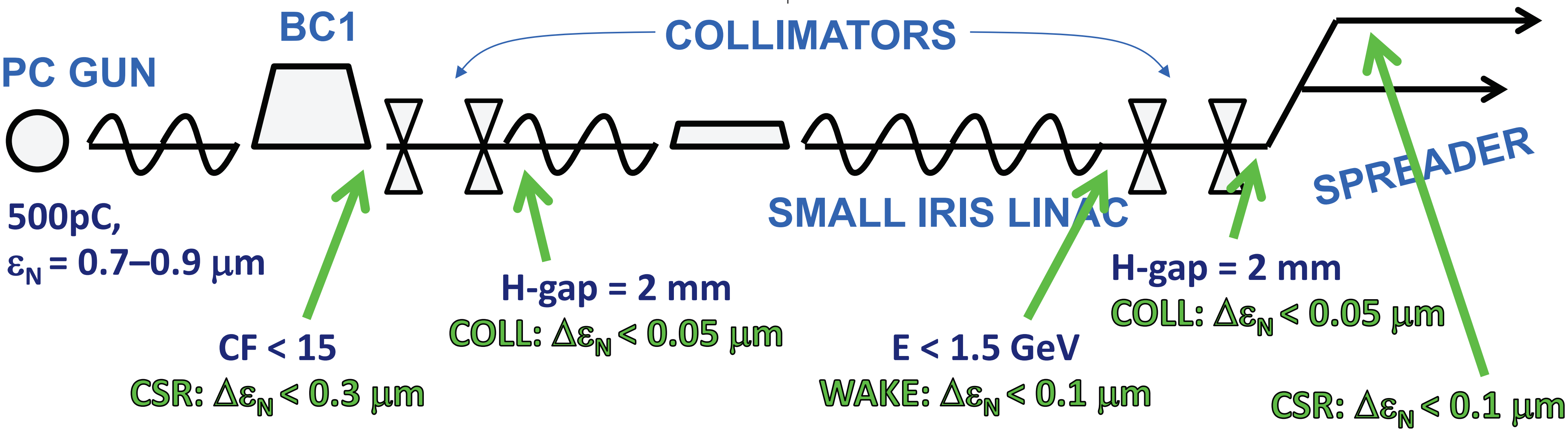


The model works well with different charges and CFs



Local maximum of $B_{4D,n}$ can be used for optimization studies

Current FERMI Linac emittance budget



- **Best 500pC projected norm. emittance is 1.5 μm in front of undulator. Slice emittance is estimated at 1 μm level. This meets the FEL requirements and allows lasing within users' specs.**
- **Interplay of residual CSR and GTW effect still requires manual tuning to minimize the final emittance. Annoying, but not critical.**
- **4-D brightness model agrees with experimental data and promises further optimizations of FERMI's working point.**

Acknowledgements

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Thank you for your kind attention