Transverse Emittance Preserving Arc Compressor: Sensitivity to Beam Optics, Charge and Energy

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Where I come from...

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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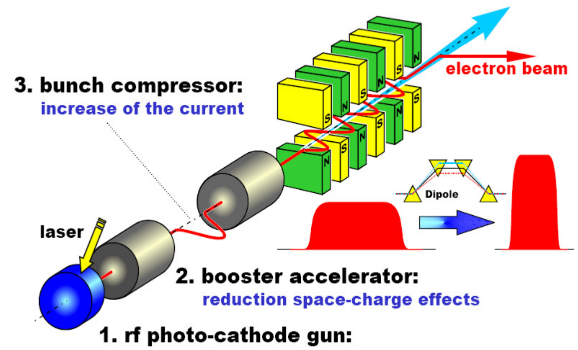
Outline

- Prologue
  - Motivations and Challenges
  - Arc Compressors in Literature
- Optics Balance in a Transfer Line (*C*=1)
  - 1-D CSR model & Experimental Proof
- Periodic Arc Compressor (*C*=45)
  - Optics Considerations
  - Analysis and Simulations: Emittance vs. Bunch Charge, Energy and Optics
- Conclusions & Outlook

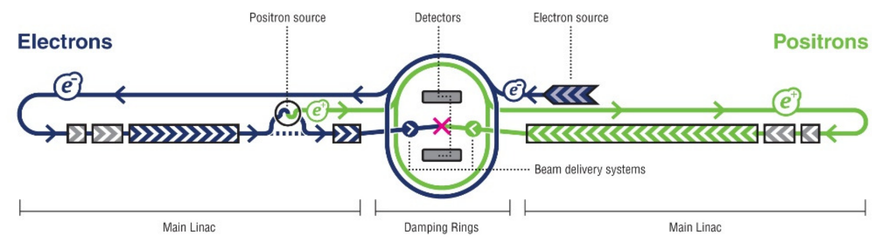
Motivations & Challenges

- ***Why*** magnetic bunch length compression?

• ***FELs:*** $P_{out} \propto I$

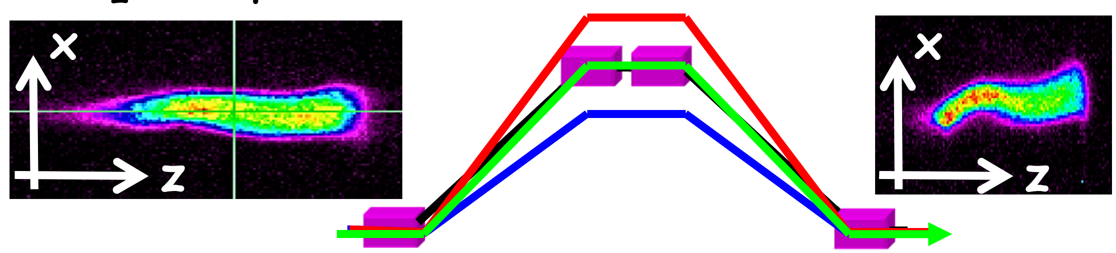


• ***Linear Colliders:*** $\Delta\varepsilon_{x,y}(w_{\perp}) \propto I^{-1}$



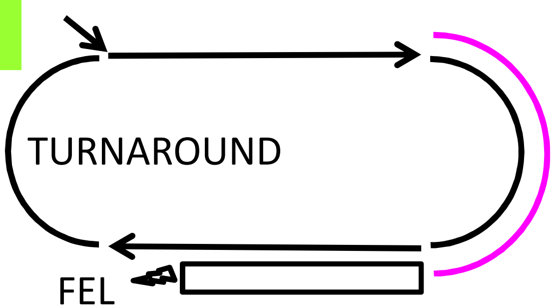
- ***What*** are the challenges of σ_z-compression?

• ***CSR:*** $\Delta\varepsilon_x \propto (\sigma_{z,CSR})^{-8/3}$



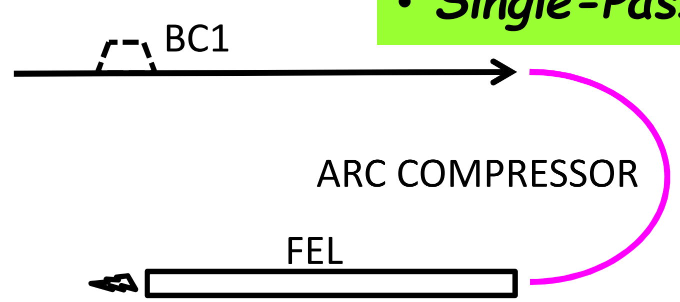
- Why an **arc compressor**?

• ***ERLs:***



Recirculation *AND* Compression

• ***Single-Pass:***



Arc Compressors in (Recent) Literature

- **Past ERLs design studies:** *BNL (2001), KEK (2007), ANL (2008), JLAB (2011), Cornell (2013).*

E >0.6 GeV
Q = 50–150 pC
C <30 (77pC,3.0GeV)
$\Delta\varepsilon_{nx} \sim 0.1\ \mu m$

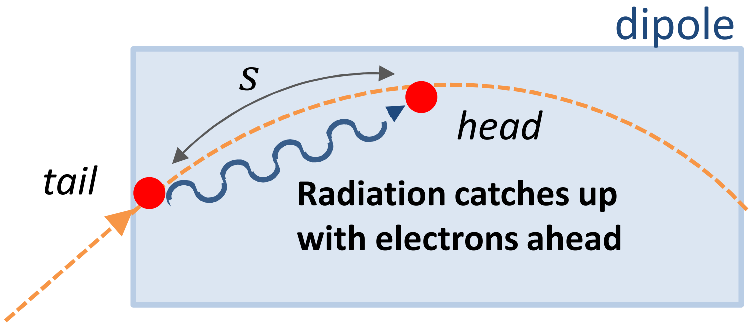
- **Minimize** the **CSR-dispersion** function. [R. Hajima, 528 (2004) 335].
- CSR primarily suppressed with a **low charge.**

- **Our proposal:**

E >0.5 GeV
Q = 100-500 pC
C = 45 (500pC,2.4GeV)
$\Delta\varepsilon_{nx} \sim 0.1\ \mu m$

- **Optics balance** to cancel successive CSR kicks… [Di Mitri, Cornacchia, Spampinati, PRL 110 014801 (2013)].
- …extended to a **varying bunch length.** [Di Mitri, Cornacchia, EPL 109 (2015) 62002].
- **Background:** D.Douglas, JLAB-TN-98-012 (1998); Y.Jiao et al., PRTSAB 17, 060701 (2014).

CSR Picture

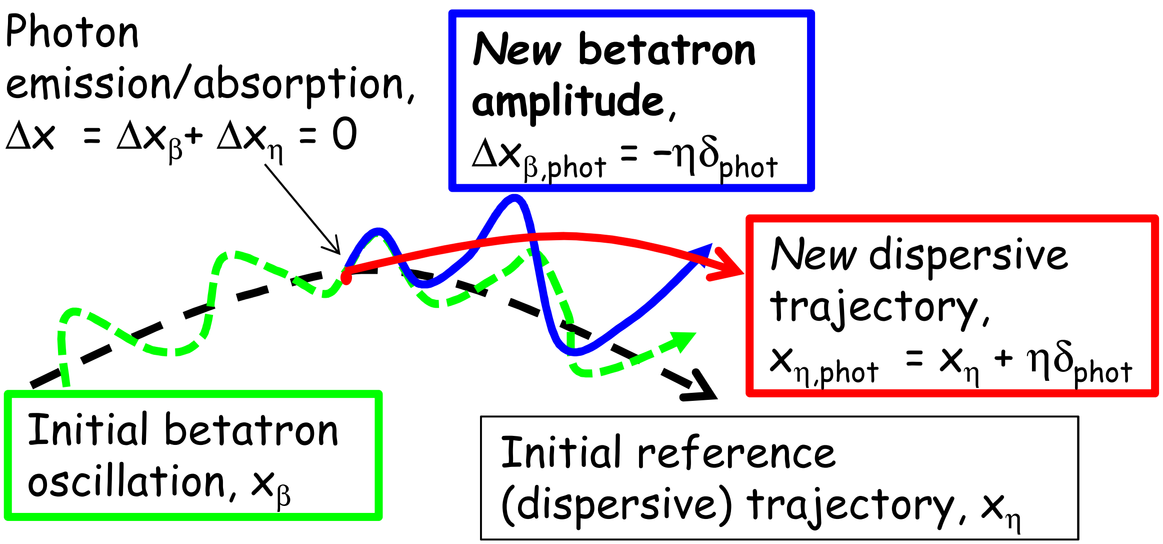


- Consider **1-D steady-state** CSR emission, and **linear optics**.
- Transient CSR effects and nonlinear dynamics will be included in the simulations.

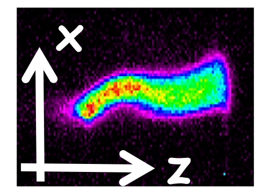
RELATIVE ENERGY SPREAD of GAUSSIAN bunch, per DIPOLE:

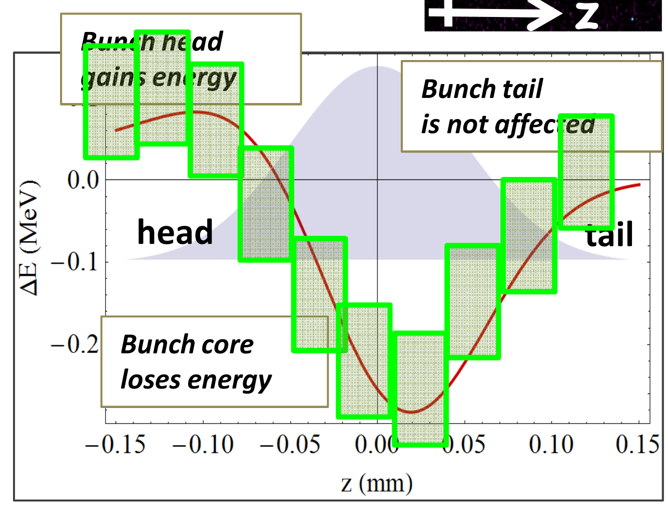
$$\sigma_{\delta,\,CSR} = 0.2459 \cdot r_e^{2} \frac{N_e}{\gamma} \frac{\theta R^{1/3}}{\sigma_z^{4/3}}$$

For a SINGLE PARTICLE:



For a BUNCH:





Note: distortion is both in x and x'

Projected Emittance Growth, σ_z = const.

➢ ***Multiple** and **identical CSR kicks*** (this applies to an isochronous transfer line):

A. Use the **Courant-Snyder formalism** for the particle coordinates, linear transport matrices, $\mathbf{x_1}=M\mathbf{x_0}$, and J(0)=0.

B. When traversing a dipole, add the CSR induced η-terms. This leads to an **increase** of the particle's **C-S invariant**:

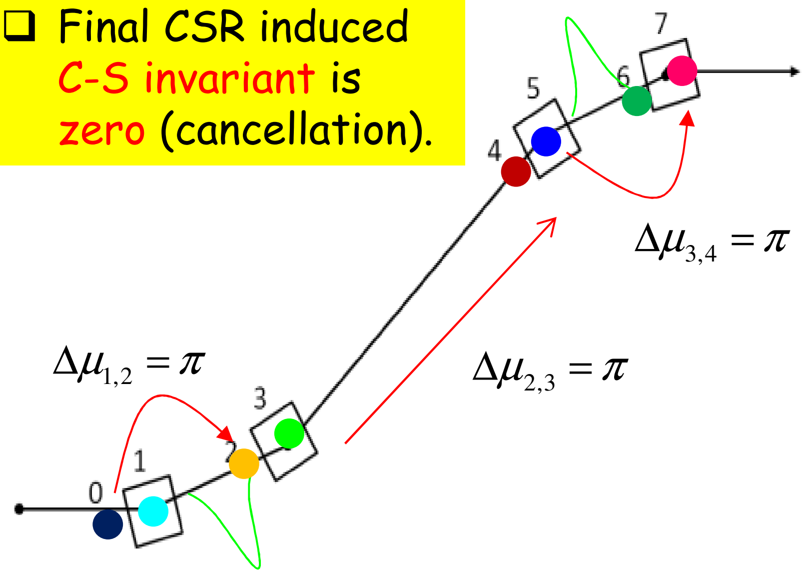
$$J_1 = \gamma_1 x_1^2 + 2\alpha_1 x_1 x_1' + \beta_1 x_1'^2 = \left(\gamma_1 \eta_1^2 + 2\alpha_1 \eta_1 \eta_1' + \beta_1 \eta_1'^2\right)\delta_{CSR}^2 \equiv H_1 \delta_{CSR}^2$$

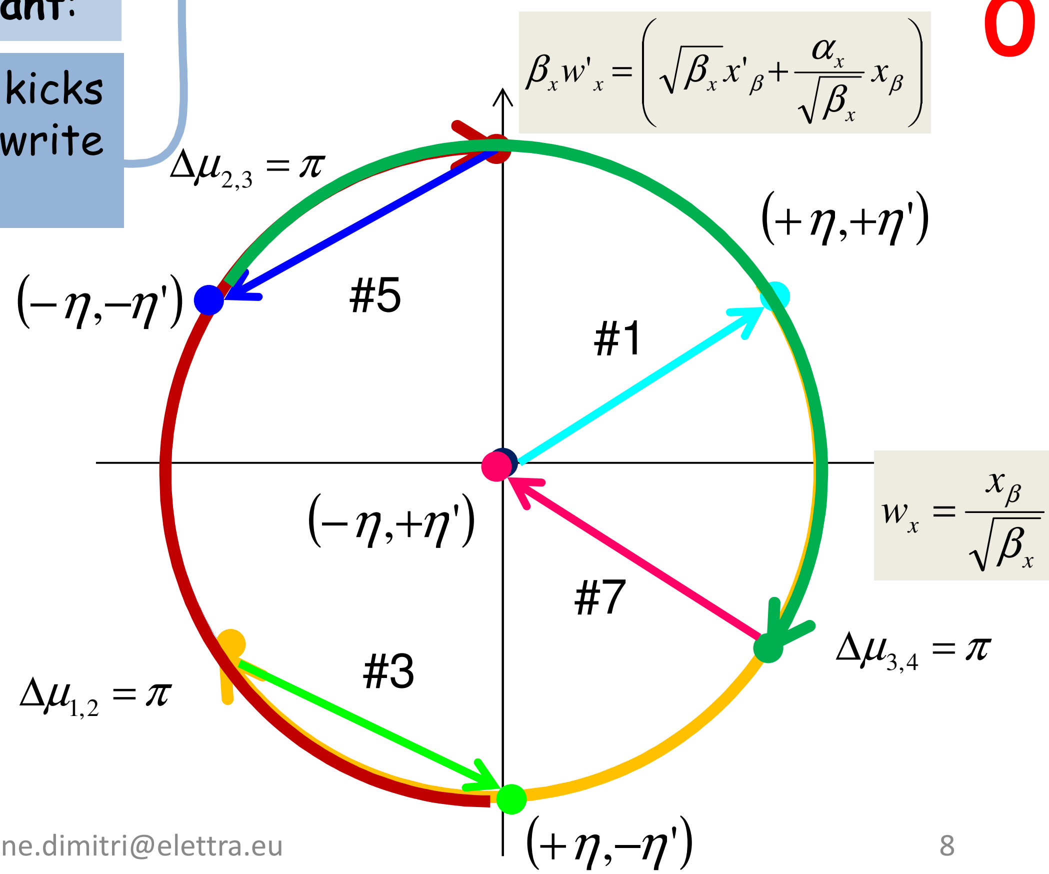
C. Repeat until the end of the line. All kicks are identical in module, and we can write $J_f=J_f(J_1)$. After averaging we find:

$$\varepsilon_{x,f}^2 = \varepsilon_{x,0}^2 + \varepsilon_{x,0} J_1\left(\sigma_{\delta,CSR}^2\right) X\left(\beta_x, \alpha_x, \mu_x\right)$$

0

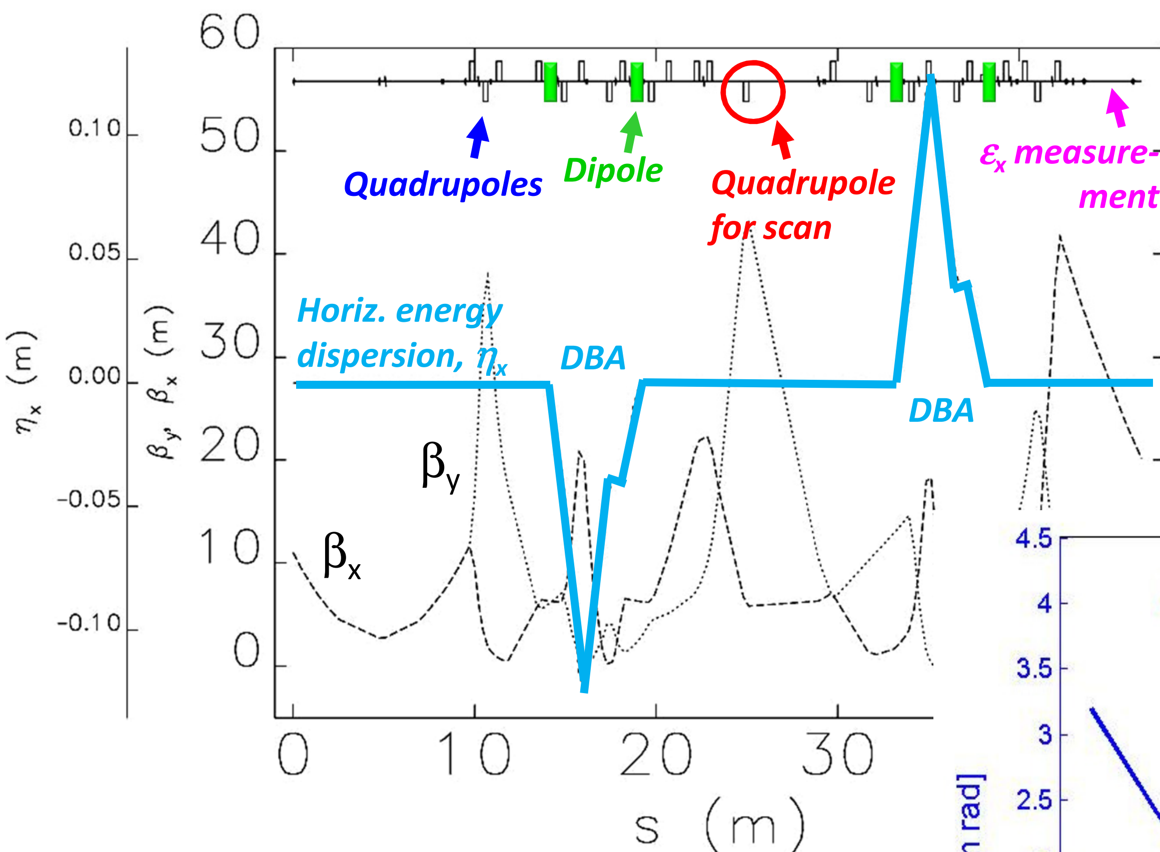
❑ Final CSR induced C-S invariant is zero (cancellation).





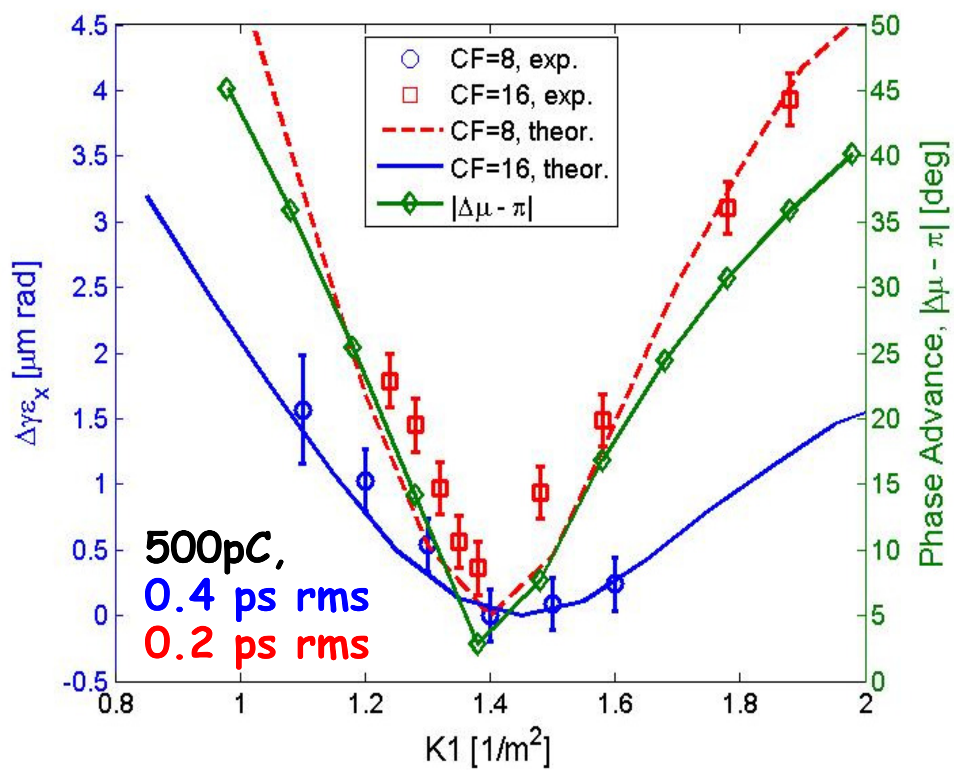
Experimental Proof at FERMI

PRL 109, 014801 (2013)
Phys. Reports 539, 1 (2014)



Quadrupoles ensure π-phase advance between dipoles and proper values of β_x, α_x to cancel the CSR-emittance.

One quadrupole's strength is scanned to vary the phase advance between the DBAs.



Results:

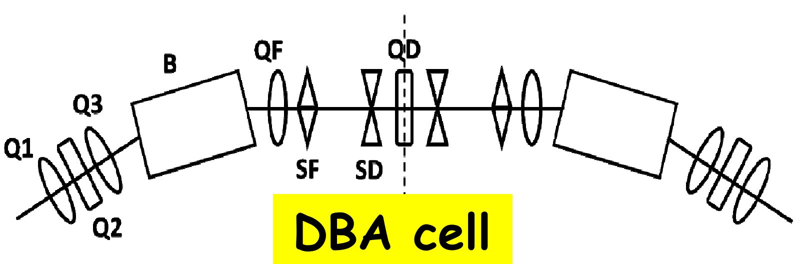
- Minimum $\varepsilon_{n,x}$ for nominal optics (π-phase advance and optimum Twiss parameters).
- Larger $\varepsilon_{n,x}$ for shorter beam.

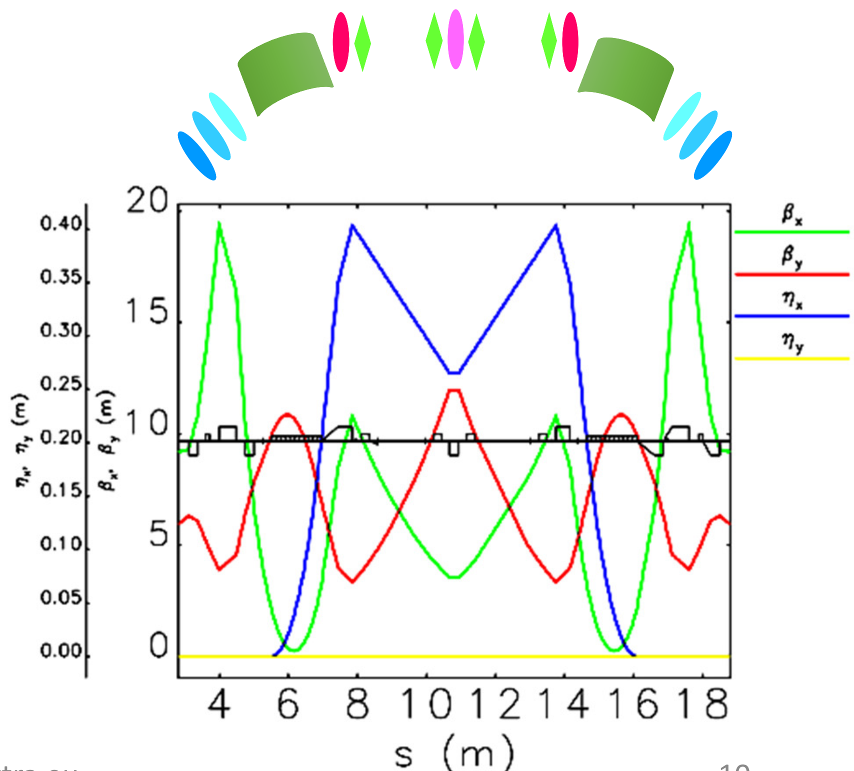
Periodic Arc Compressor

- ❑ H_x has to be small at the dipoles ⇒ *θ and β_x small*
- ❑ R_{56} has to large enough to cumulate a C>30 ⇒ *θ not too small*
- ❑ Suitable β_x, α_x, μ_x along the line for CSR cancellation ⇒ *many quadrupoles*
- ❑ We want to linearize the longitudinal phase during compression ⇒ *sextupoles*
- ❑ Possibly simple, robust and compact lattice

- **6 DBA cells** (Elettra-like lattice, *ECG*).
- **180°, 125 m long at 2.4 GeV**
- **R_{56} = +35 mm per cell**

Due to symmetry and short bends, $\Delta\mu_x \approx \pi$.





Optimum Optics in a Single DBA:

For a <u>single DBA</u>, at the exit of the 2nd dipole we have:

$$\begin{cases} x_3 = -\rho^{4/3}k_1\left(\theta C_\theta - 2S_\theta\right) + \rho^{4/3}k_2\left(\theta C_\theta - 2S_\theta\right) \\ x_3^{'} = -\rho^{1/3}k_1\theta S_\theta - \rho^{1/3}k_2\theta S_\theta - \dfrac{2\alpha_2}{\beta_2}\rho^{4/3}k_1\left(\theta C_\theta - 2S_\theta\right), \\ \delta_3 = \rho^{1/3}k_1\theta + \rho^{1/3}k_2\theta \end{cases}$$

where

$$C_\theta = \cos(\theta/2), \quad S_\theta = \sin(\theta/2)$$

$$k_i = 0.2459 r_e Q/(e\,\gamma\sigma_{z,i}^{4/3})$$

$$k_{i+1} = C_{i+1}^{4/3}k_i$$

CSR kick scales with σ_z

$$J_3 \cong \left(\frac{k_1\rho^{1/3}\theta^2}{2}\right)^2\left[\beta_2\left(C^{4/3}+1\right)^2 + \frac{1}{\beta_2}\left(\frac{l_b}{6}\right)^2\left[\left(C^{4/3}-1\right)^2 + \alpha_2^2\left(C^{4/3}-3\right)^2\right] + 2\alpha_2\left(\frac{l_b}{6}\right)\left(C^{4/3}+1\right)\left(C^{4/3}-3\right)\right]$$

Look for the <u>optimum Twiss parameters</u> at the dipoles:

$$\left(\frac{dJ_3}{d\alpha_2}\right)_{\beta_2} \equiv 0, \qquad \left(\frac{dJ_3}{d\beta_2}\right)_{\alpha_2} \equiv 0$$

$$\alpha_{2,opt} = -\frac{\beta_2}{\left(\frac{l_b}{6}\right)}\frac{\left(C^{4/3}+1\right)}{\left|C^{4/3}-3\right|}$$

$$\beta_{2,opt} = \left(\frac{l_b}{6}\right)\frac{\sqrt{\left(C^{4/3}-1\right)^2 + \alpha_2^2\left(C^{4/3}-3\right)^2}}{\left(C^{4/3}+1\right)}$$

$$J_3 = 0 \Leftrightarrow C = 1$$

$$\alpha_{2,opt}(C=1) = -\frac{6\beta_{2,opt}}{l_b},$$

as already in [Y. Jiao et al. PRTSAB 17, 060701 (2014)].

Optimum Optics *along* the Arc Compressor:

1. The local C_i depends on the upstream E-chirp, which varies along the arc:

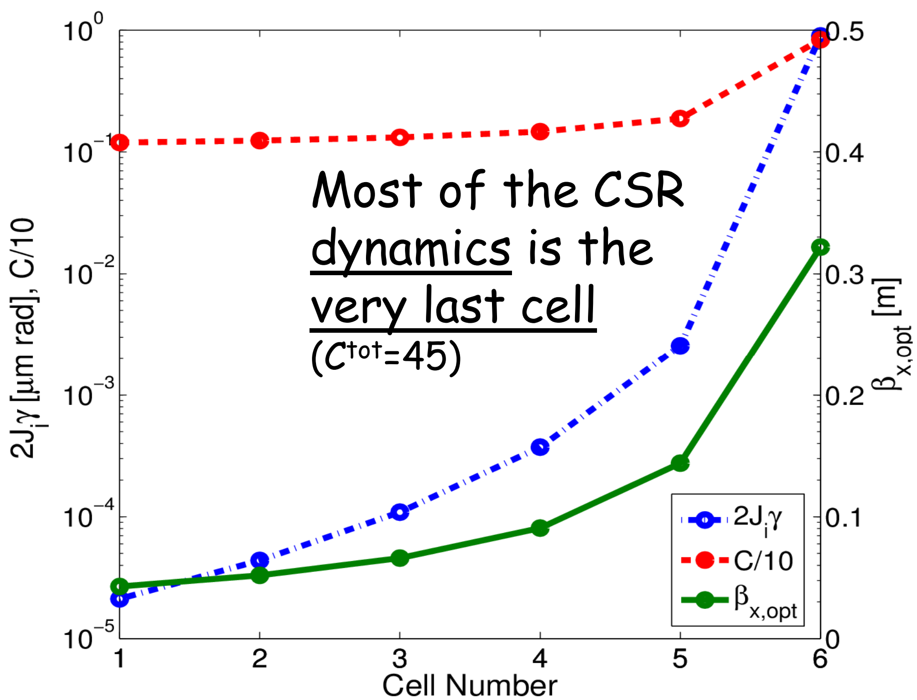
2. The optimum $\beta_{x,dip}$ depends on C_i, thereby it varies along the arc.

$$h_i = \frac{1}{E_0}\left(\frac{dE}{dz}\right)_i \approx \frac{\sigma_{\delta,0}}{\sigma_{z,i}}$$

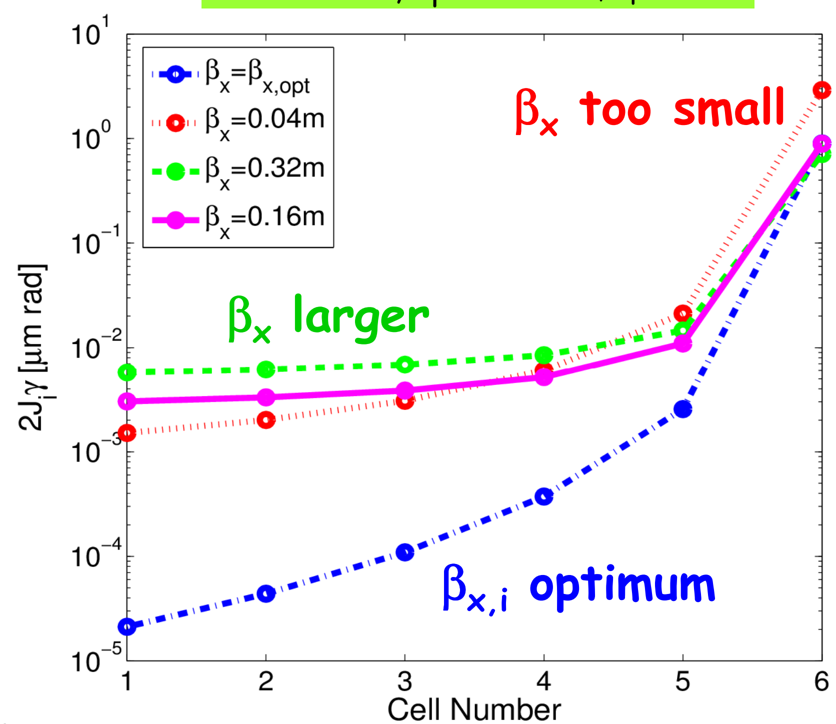
$$C_i^{loc} = \frac{1}{\left|1 + C_{i-1} h_{i-1} R_{56}\right|},$$

$$C_j^{tot} = \prod_{i=1}^{j} C_i^{loc} \qquad i, j = 1,\ldots,6$$

Optimum $\beta_{x,dip}$, C_i^{loc} and J_i, for $\alpha_{x,dip}=0$:



J_i vs. $\beta_{x,dip}$, for $\alpha_{x,dip}=0$:

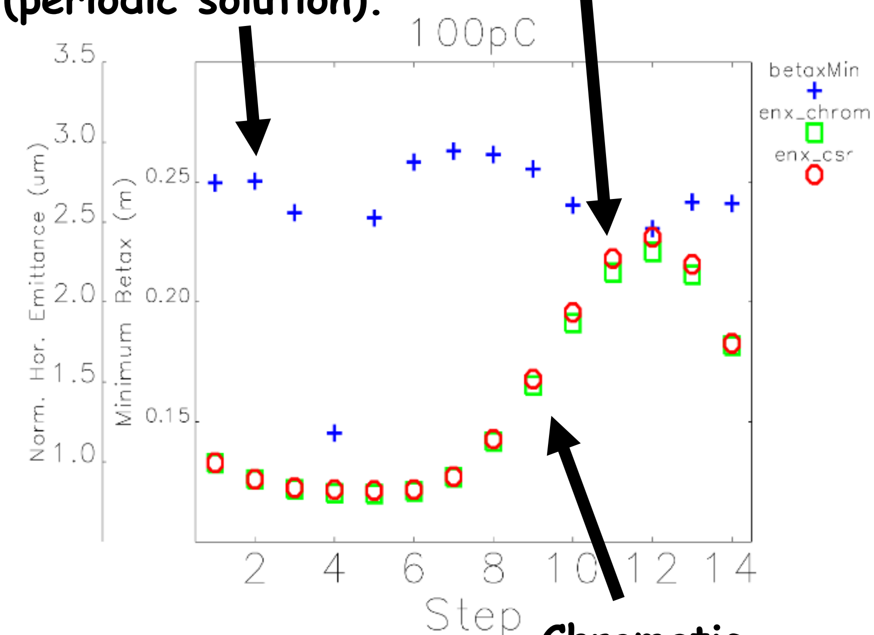


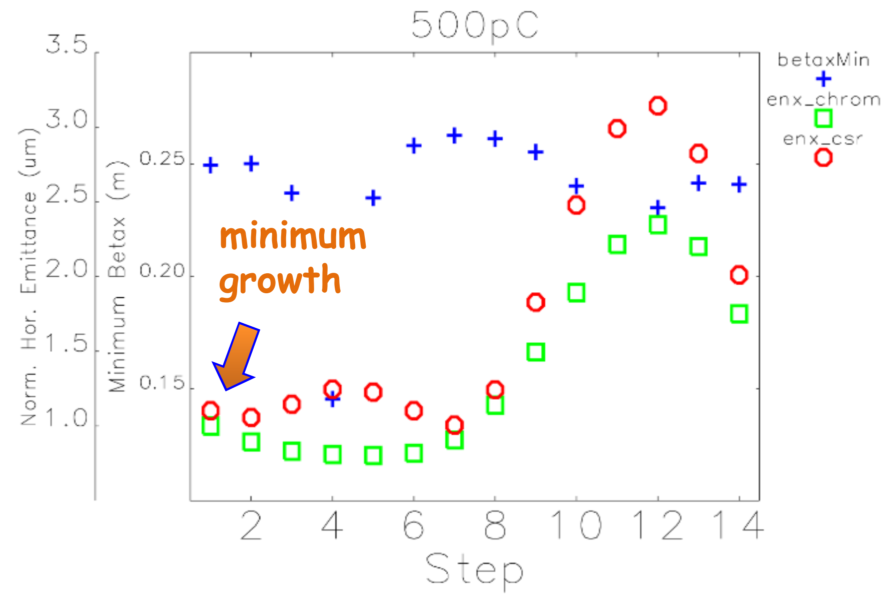
Final Emittance vs. Charge and Optics

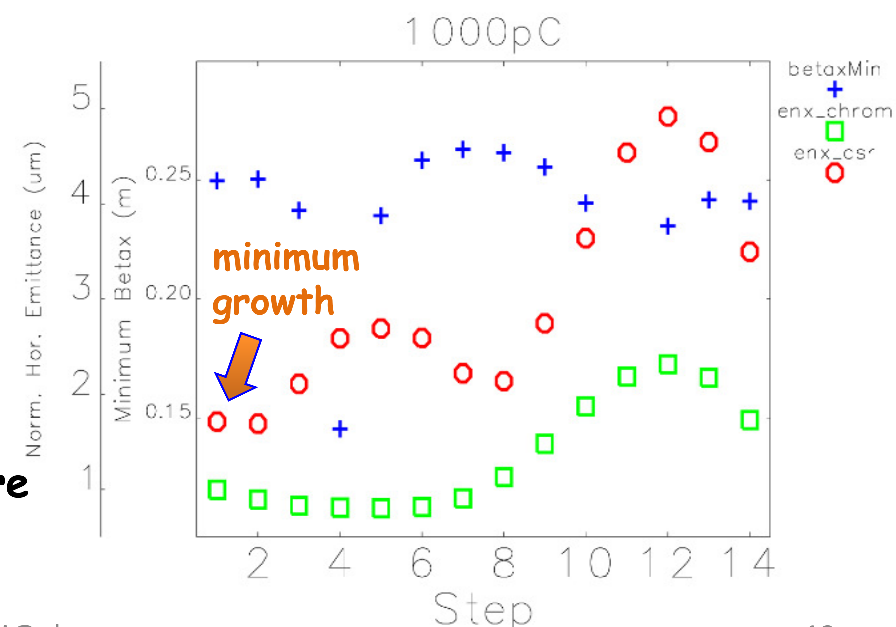
$E = 2.4$ GeV $C_{tot} = 45$
$\sigma_{z,0} = 3$ mm $\varepsilon_{nx,0} = 0.8$ μm
$h_0 = -4.7$ m^{-1}

$\beta_{x,dip}$ is the same for all the dipoles (periodic solution).

$\Delta\varepsilon_{x,CSR}$ = ○ − □







Each step corresponds to a different $\beta_{x,dip}$.

Chromatic aberrations (□) are *NOT* corrected at each step.

Final Emittance vs. Charge and Energy

Ansatz: the emittance sums in quadrature after each DBA:

$$\varepsilon_{x,i}^2 = \varepsilon_{x,i-1}^2 + \varepsilon_{x,i-1} J_{i-1}$$

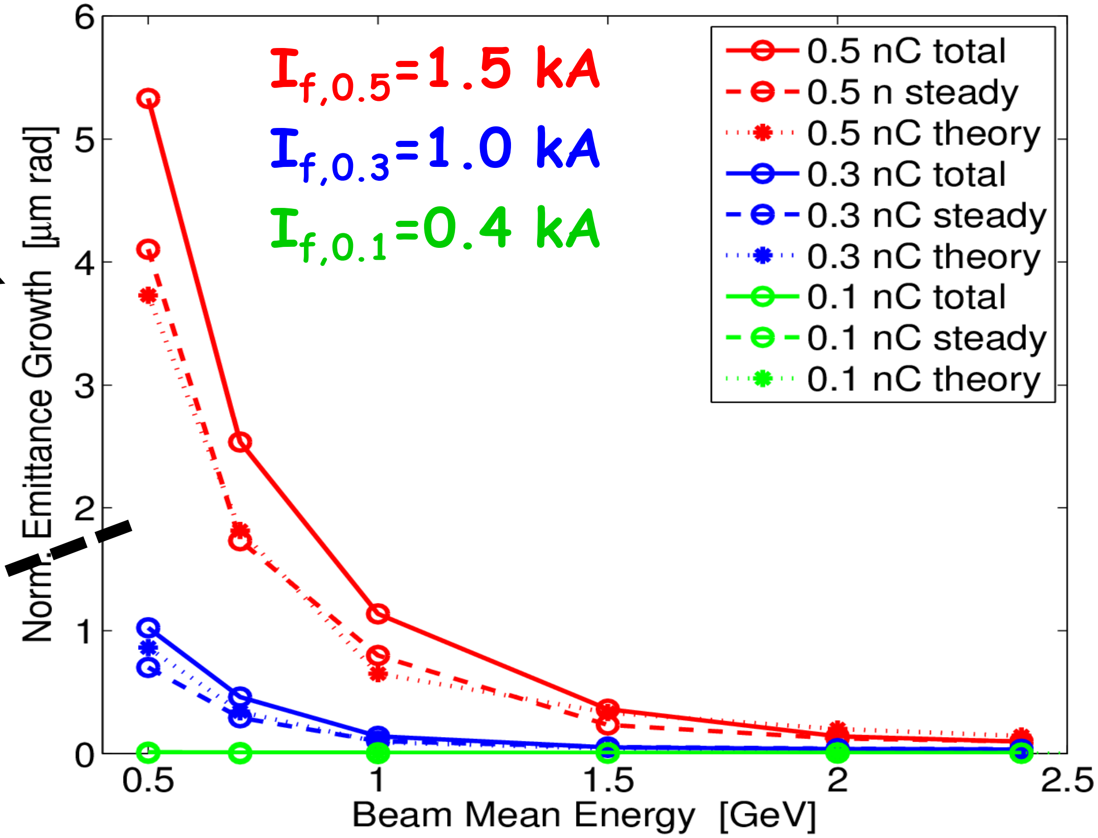
$$\varepsilon_{x,f}^2 \approx \varepsilon_{x,0}^2 + \varepsilon_{x,0} \sum_1^j J_{i-1} \Leftrightarrow \sum_1^j J_{i-1} << \varepsilon_{x,0}$$

- *Theory:* J_i as above.
- *Steady:* *1-D CSR in Elegant.*
- *Total:* *Steady + Edges + Drifts.*

This is:

sqrt[$(\varepsilon_{nx,f})^2 - (\varepsilon_{nx,0})^2$],

and $\varepsilon_{nx,0}$ = 0.8 μm.



We may achieve

$\Delta\varepsilon_{nx} \leq$ 0.1 μm for, e.g.:

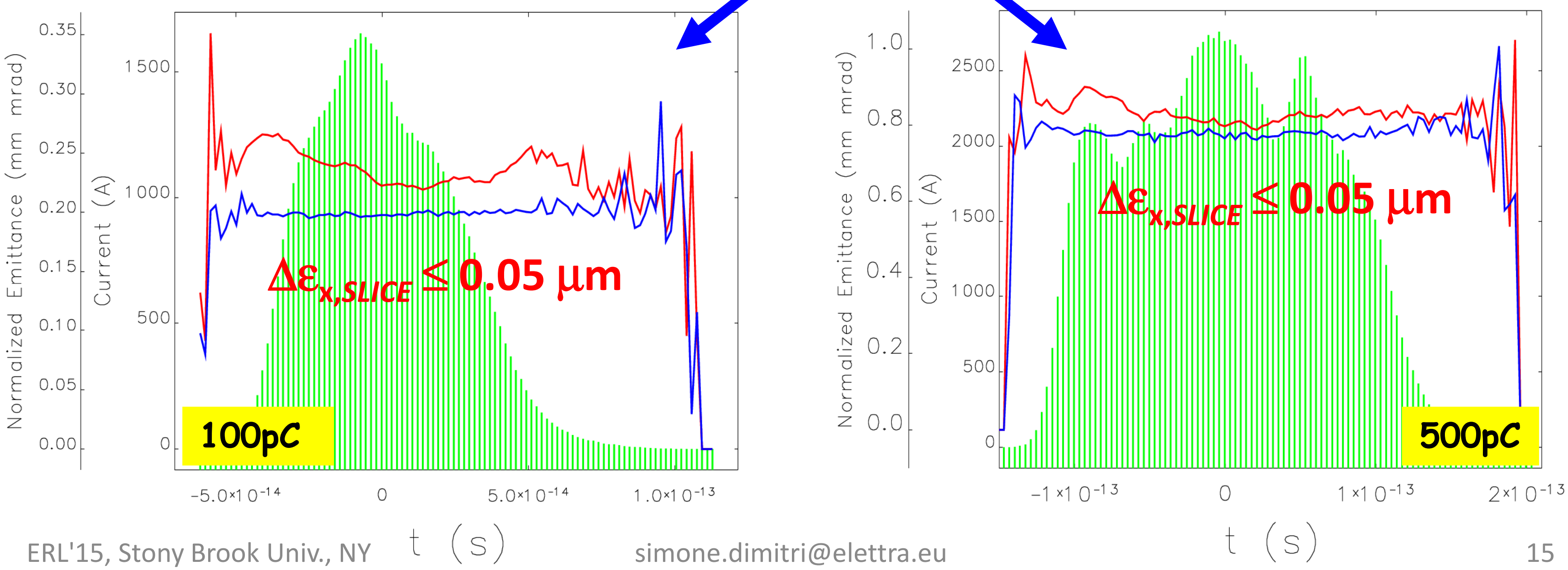
- 100pC, E > 0.5 GeV
- 300pC, E > 1.0 GeV
- 500pC, E > 2.0 GeV

EPL 109, 62002 (2015)

Full Particle Tracking (Elegant)

- Particle tracking now including:
  - 3rd order transport matrices, ISR and CSR transient effects,
  - CSR-induced microbunching from a quiet start and 5 M-particles
  - Enlarged uncorrelated energy spread, as from a laser heater (30 keV rms)
- Two sets of beam parameters at **2.4 GeV, C=45:**
  - **Q = 100 / 500 pC**
  - **I_f = 1.3 / 2.2 kA**
  - **$\sigma_{\delta,0}$ = 0.1 / 0.4 %**
  - **$\varepsilon_{nx,0}$ = 0.2 / 0.8 μm rad**

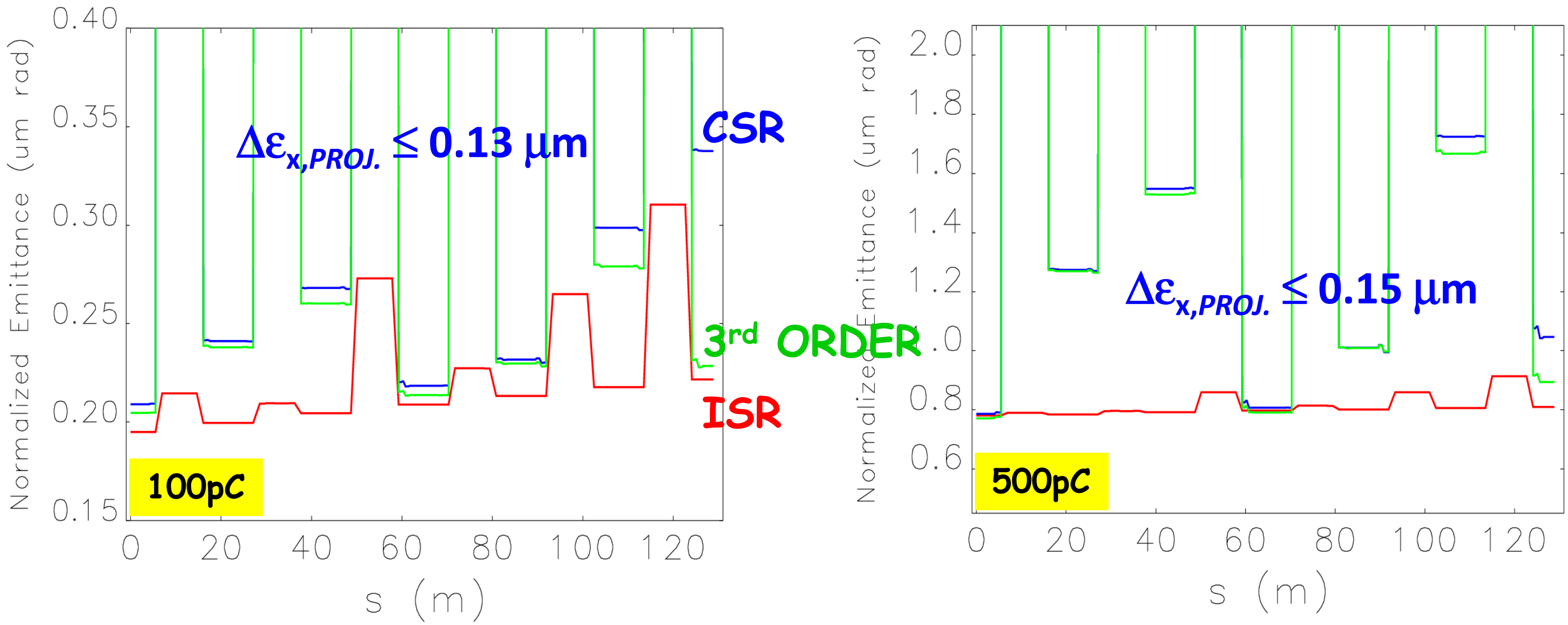
Slice emittances and peak current



Nonlinear Dynamics

EPL 109 (2015) 62002

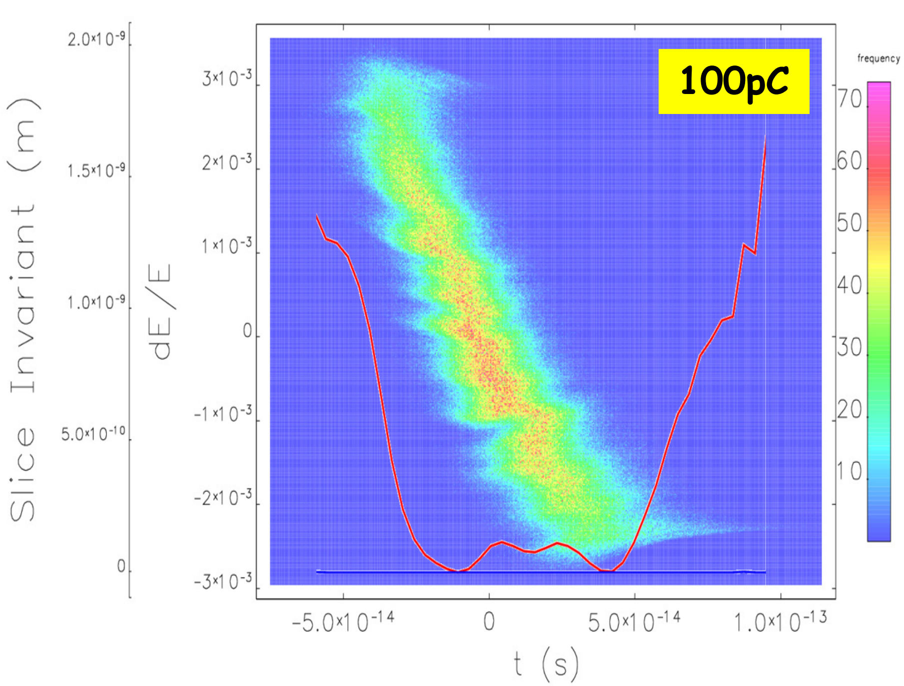
- Nonlinearities in the longitudinal phase space evolve during compression due to:
  - Incoming RF curvature,
  - T_{566} of the DBA cells,
  - Nonlinear CSR-induced energy chirp.
- **24 sextupole magnets linearize the compression**. Strengths and positions optimized for minimizing chromatic aberrations (these are responsible for the emittance modulation along the line, see below).

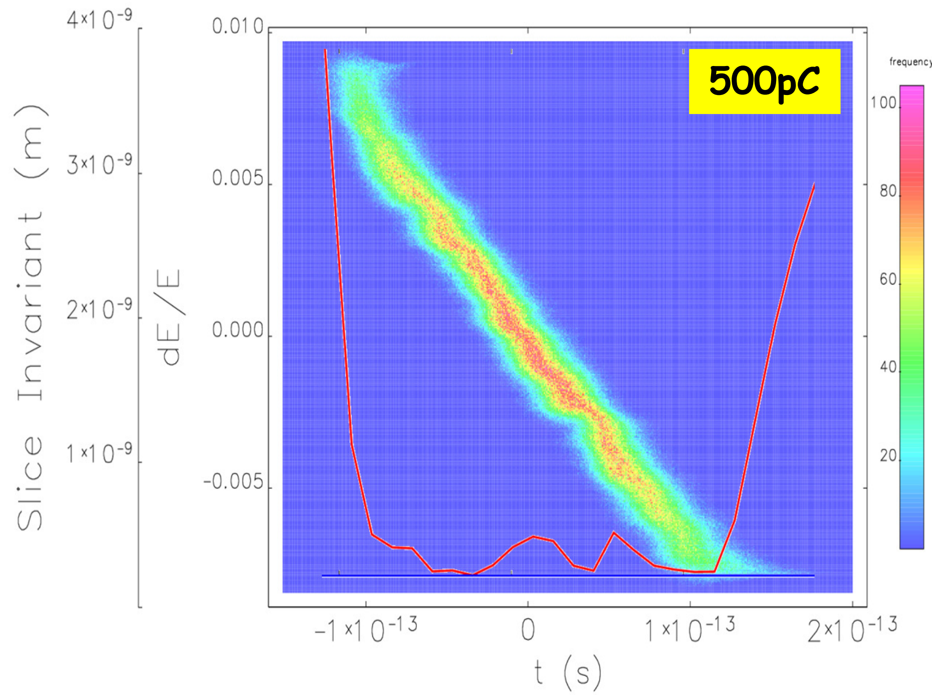


Microbunching Instability

EPL 109 (2015) 62002

- The effect of CSR-induced microbunching (MB) is damped by the initial beam heating. The strength of MB dynamics sounds over-estimated because:
  - E/I-modulations tend to smear as the # of particles increases from 0.1 to 5 M;
  - filtering suppresses $\lambda_f \leq 1$ μm, while MB appears at $\lambda_f > 10$ μm;
  - transverse emittance smearing effect *not* included.
- *Accurate MB analysis is pending. See, e.g., C.-S. Tsai's talk* (*today, this session*)





Conclusions & Outlook

✓ The extension of CSR-driven liner optics balance to the case of varying bunch length leads to a simple formula for a ***periodic*** system.

✓ The final ***emittance estimate*** is in reasonable agreement with 1-D tracking results (see also C.Hall's talk, this session).

✓ For a DBA-based 180° arc compressor, we expect a ***"gain"~ 10*** in "Q × C / E", w.r.t. the existing literature.

➢ Working plan:

- more accurate **microbunching** instability analysis;
- massive **numerical optimization** of the emittance vs. linear and nonlinear dynamics;
- scaling to a (low energy) **compact ERL**, and to a (high energy) **single-pass** beamline.

➢ A proof-of-principle ***experiment*** may be possible at the FERMI Main e-Beam Dump line (two big dipoles and quads available at 1.5 GeV).

Acknowledgements

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Thank You for Your attention