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Dynamics in Arc Compressors

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

Arc Compressors in (Recent) Literature

- **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)
$\Delta\varepsilon_{nx} \sim 0.1\ \mu m$

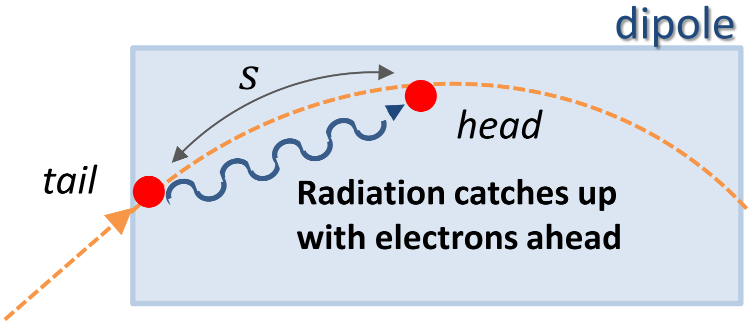
- **Minimize** the **CSR-dispersion** function. [R. Hajima, 528 (2004) 335].
- CSR primarily suppressed with a **low charge.**

- **More extreme parameters:**

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.

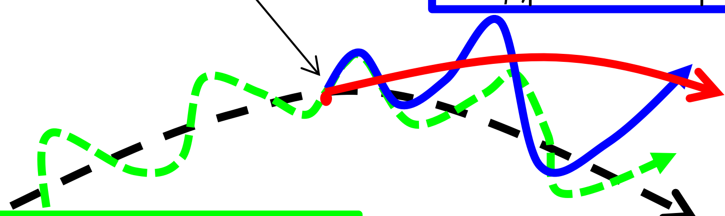
RELATIVE ENERGY SPREAD of GAUSSIAN bunch, per DIPOLE:

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

For a SINGLE PARTICLE:

Photon emission/absorption, $\Delta x = \Delta x_\beta + \Delta x_\eta = 0$

New **betatron amplitude,** $\Delta x_{\beta,phot} = -\eta\delta_{phot}$

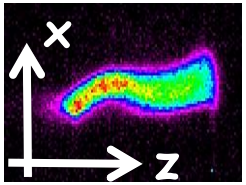


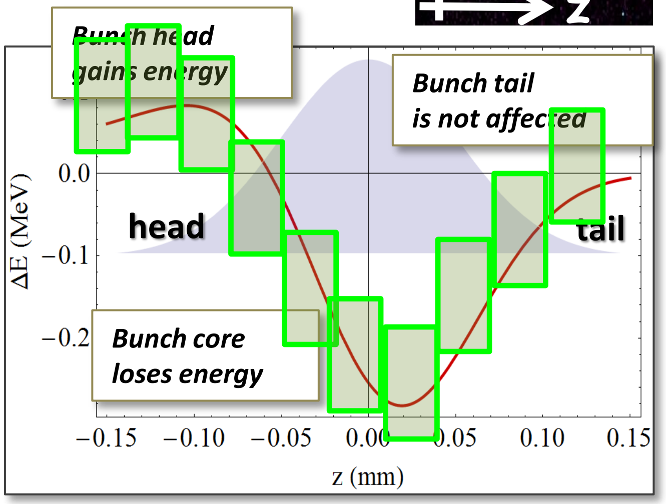
New dispersive trajectory, $x_{\eta,phot} = x_\eta + \eta\delta_{phot}$

Initial betatron oscillation, x_β

Initial reference (dispersive) trajectory, x_η

For a BUNCH:

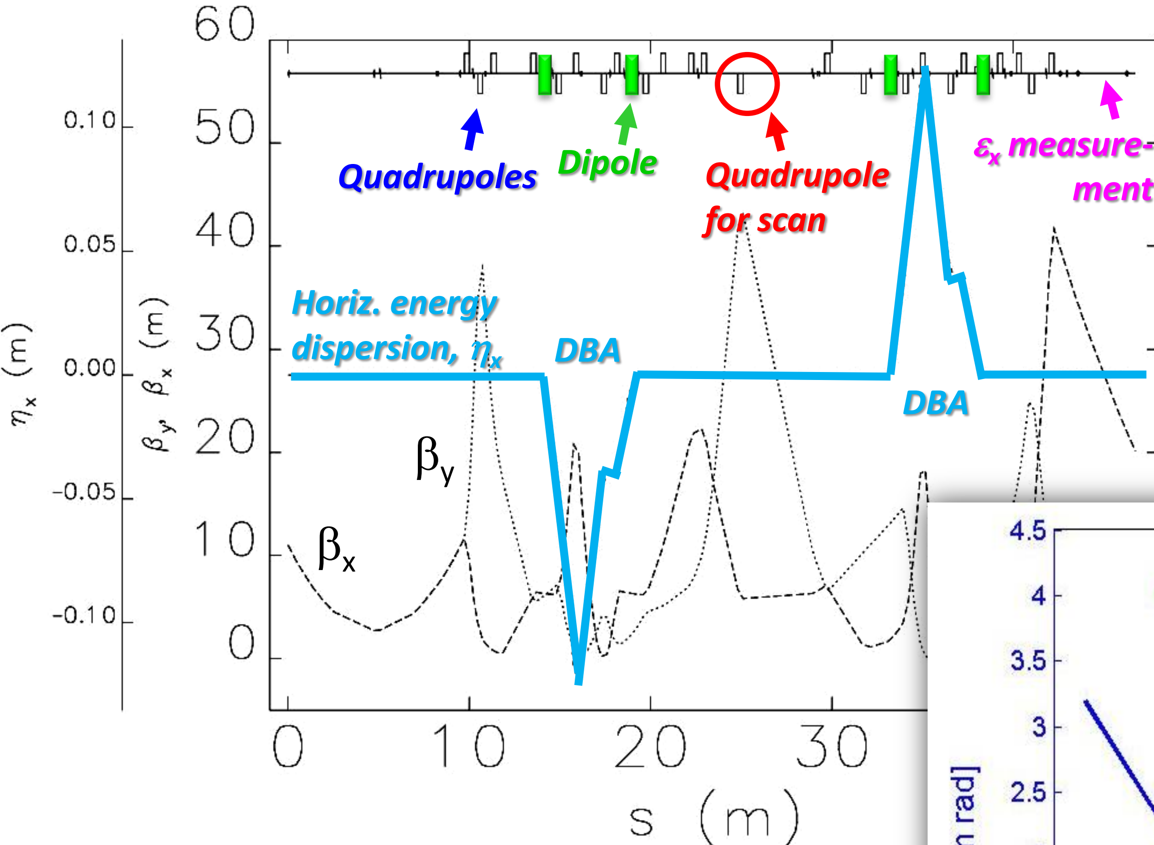




Note: distortion is both in x and x'

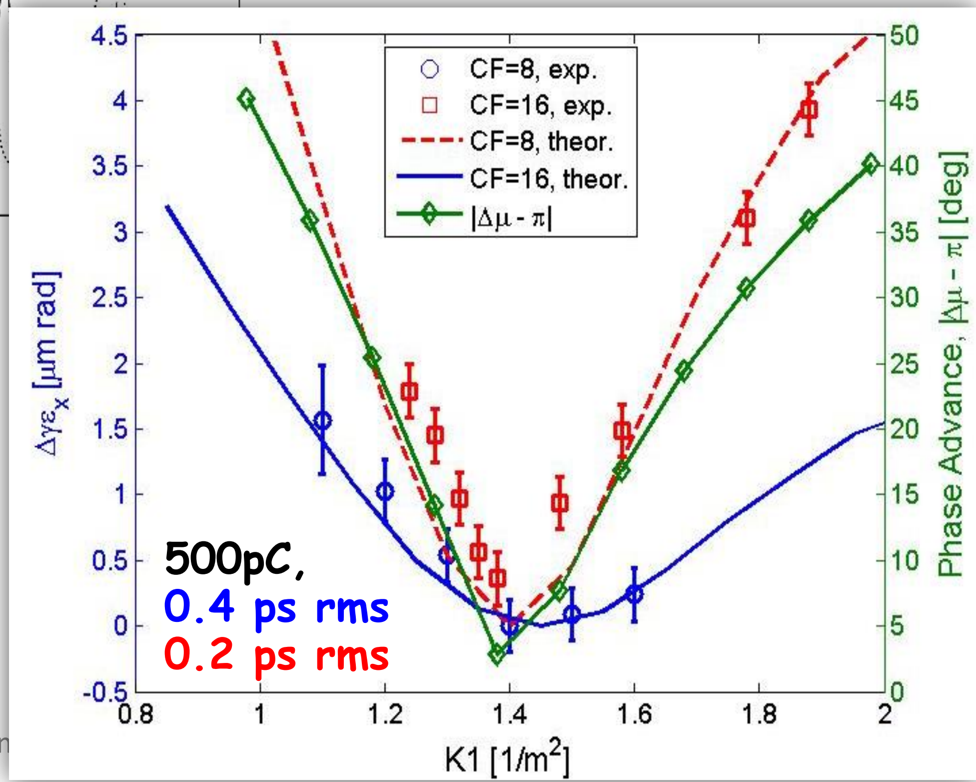
Experimental Proof at FERMI

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:

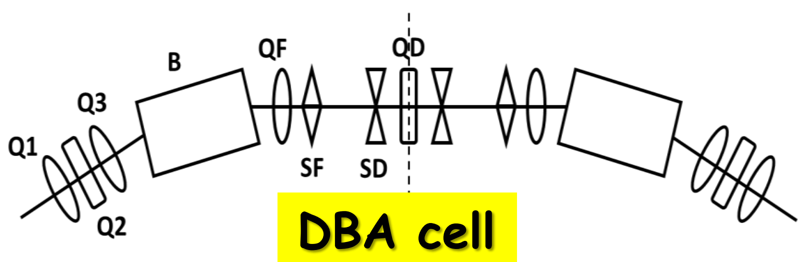
- Minimum $\varepsilon_{n,x}$ for nominal optics (π-phase advance and optimum Twiss parameters).
- Larger $\varepsilon_{n,x}$ for shorter beam.

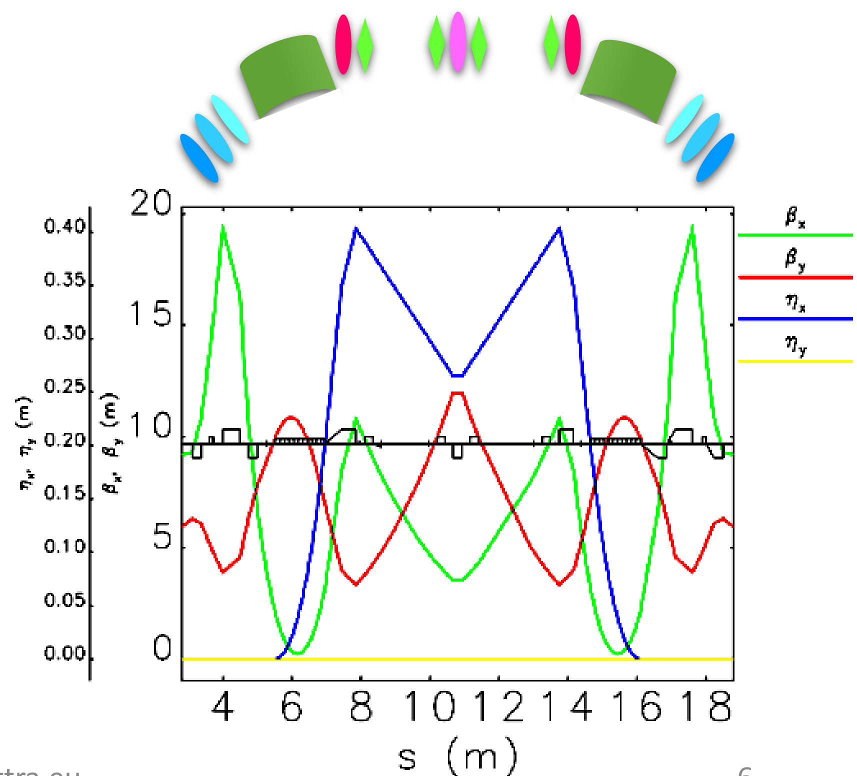
Periodic Arc Compressor

- ❑ H_x has to be small at the dipoles $\Rightarrow$ *θ and β_x small*
- ❑ R_{56} has to large enough to cumulate a C>30 $\Rightarrow$ *θ not too small*
- ❑ Suitable β_x, α_x, μ_x along the line for CSR cancellation $\Rightarrow$ *many quadrupoles*
- ❑ We want to linearize the longitudinal phase during compression $\Rightarrow$ *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 *along* the Arc Compressor:

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

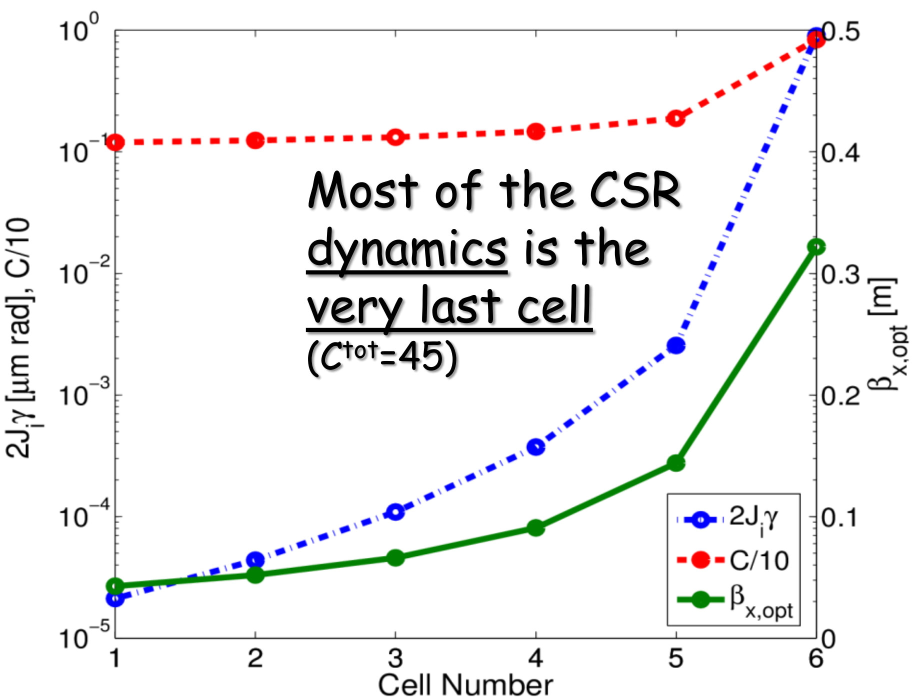
2. The optimum $\beta_{x,dip}$ depends on C_i, thereby it varies along the arc.

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

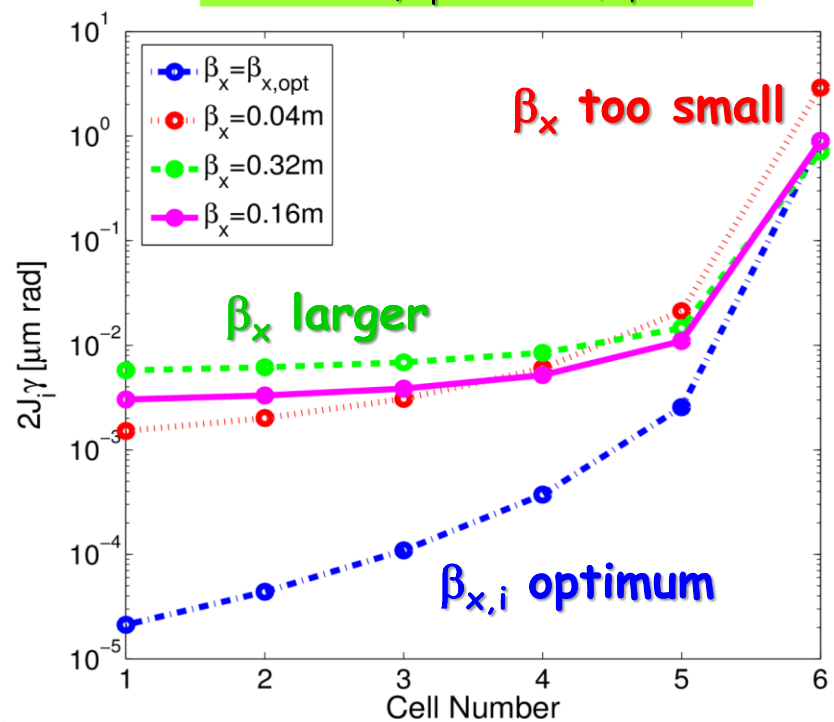
$$C_i^{loc} = \frac{1}{\left|1 + C_{i-1} h_{i-1} R_{56}\right|},$$

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

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 Energy

Ansatz: the emittance sums in quadrature after each DBA:

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

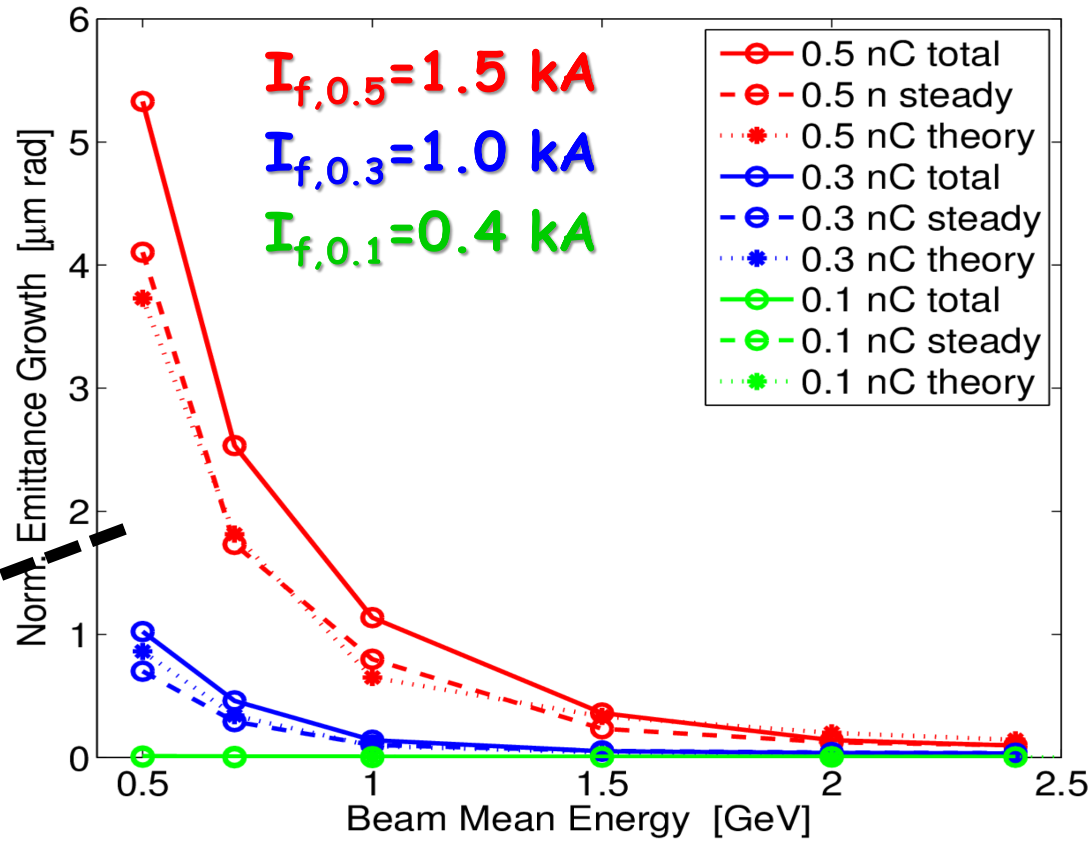
$$\varepsilon_{x,f}^2 \approx \varepsilon_{x,0}^2 + \varepsilon_{x,0} \sum_1^j J_{i-1} \Leftrightarrow \sum_1^j J_{i-1} << \varepsilon_{x,0}$$

- *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

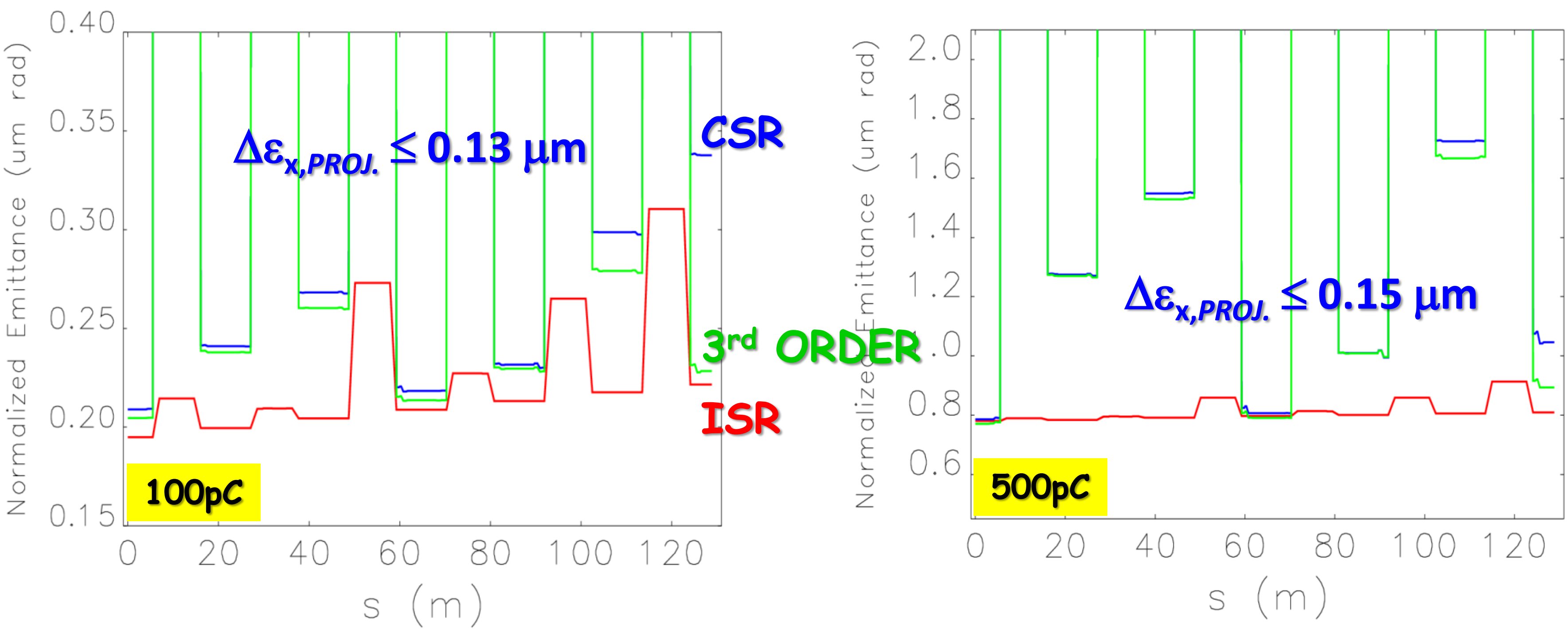
$\Delta\varepsilon_{nx} \leq$ 0.1 μm for, e.g.:

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

EPL 109 (2015) 62002

Nonlinear Dynamics

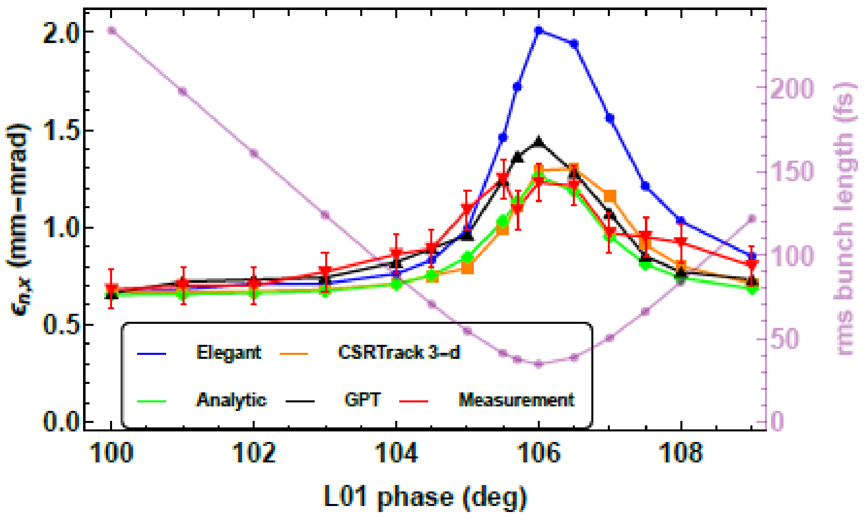
- Nonlinearities in the longitudinal phase space evolve during compression due to:
  - Incoming RF curvature,
  - T_{566} of the DBA cells,
  - Nonlinear CSR-induced energy chirp.
- **24 sextupole magnets linearize the compression**. Strengths and positions optimized for minimizing chromatic aberrations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



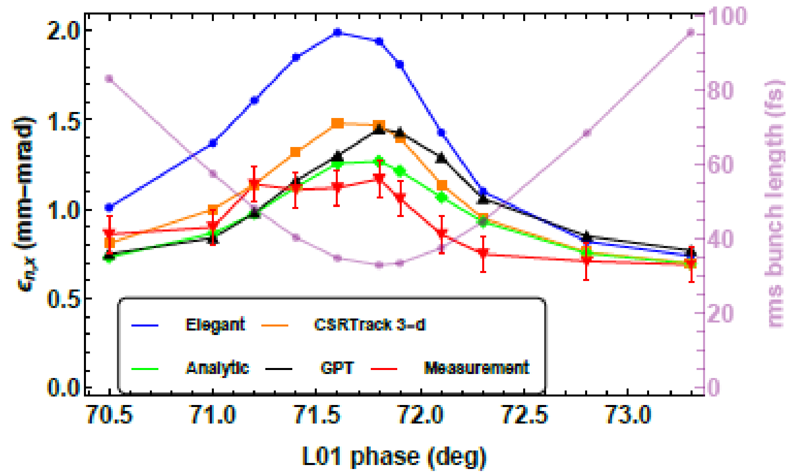
Caveat

A. Brynes et al., NJP 20, 073035 (2018)

- 3-D CSR effects neglected in Elegant. They are important when approaching full compression (upright phase space). Most likely, the hor. emittance growth is over-estimated by the code.



(a) Results from the L01 phase scan.



(b) Results from the BC01 angle scan.

Conclusions

- ✓ 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.
- ✓ A proof-of-principle ***experiment*** is still pending.