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Trieste

Compact Arc Compressor for Light Sources

S. Di Mitri, ELETTRA SINCROTRONE TRIESTE

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Prologue

- High gain EUV/X-ray FELs require electron bunch length **compression to sub-ps duration**.

- When **turn-around lattices (arcs)** are involved, cost-efficiency suggests to use them as magnetic compressors, within a compact footprint.
  - 1st example: *ERL-driven FEL*
  - 2nd example: *FEL-driven Compton source*

- **Compactness** of arc compressors may lead to:
  - large CSR-induced emittance growth
  - large MBI gain

- Strategies and design studies for **CSR and MBI minimization** are presented.
  - Recent theoretical and experimental studies

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Collaborators – Acknowledgements

- **M. Cornacchia** (SLAC, retired) → *Cancellation of CSR kicks in multi-bend lines*
- **I. Akkermans, I. Setjia,** (ASML), **D. Douglas** (JLAB) → *Compact ERL-UV FEL for nm-litography*
- **M. Placidi, G. Penn** (LBNL), **C. Pellegrini** (SLAC, UCLA) → *Compact FEL-driven ICS for geo-archeology*

- **P. Smorenburg** (ASML) , **C.-Y. Tsai** (JLAB, now SLAC), **B. Van der Geer** (Pulsar), **P. Williams** and **A. Brynes** (ASTeC)

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ERL–FEL Scope

EUV LITHOGRAPHY Nature Photonics 2010

Lithography gets extreme

Christian Wagner and Noreen Harned

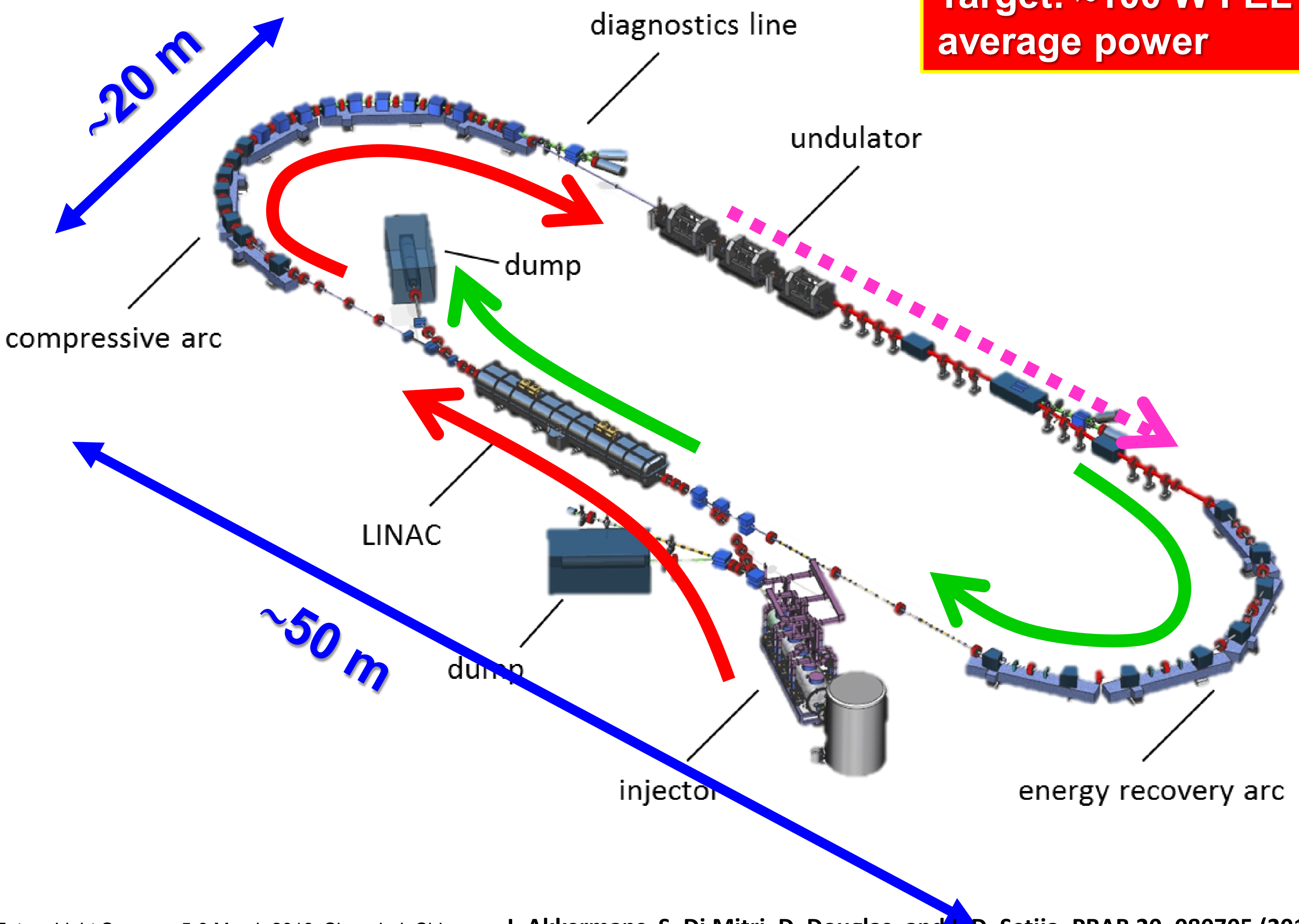
Extreme ultraviolet lithography extends photolithography to much shorter wavelengths and is a cost-effective method of producing more-advanced integrated circuits. Although some infrastructure challenges still remain, this technology is expected to begin high-volume microchip production within the next three years.

EUV Source Power Progress reaching 55 W

Supporting 43 Wafers/hr, 250 W target to be reached in 2015

Compact ERL–FEL

Target: ~100 W FEL average power



Charge	100 pC
Initial Bunch Duration	2 ps
Initial Projected Emittance	0.5 μm

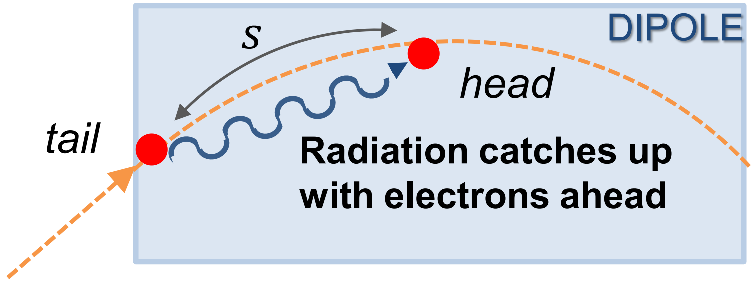
Energy	1 GeV
Current	1 kA
Relative Energy Spread	< 0.1%
FEL Wavelength (SASE)	13.5 nm
FEL Peak Power	~1 GW

Compression Factor	*~56*
Arc R_{56}	*~0.5 m*
Proj. Emittance Growth	*< 0.2 μm*

$$C = \frac{1}{|1 + h_i R_{56}|} \approx \frac{1}{\left|1 - \frac{\sigma_{\delta,i}}{\sigma_{z,i}} R_{56}\right|}$$

J. Akkermans, S. Di Mitri, D. Douglas, and I. D. Setija, PRAB 20, 080705 (2017).

CSR Tail-Head Interaction

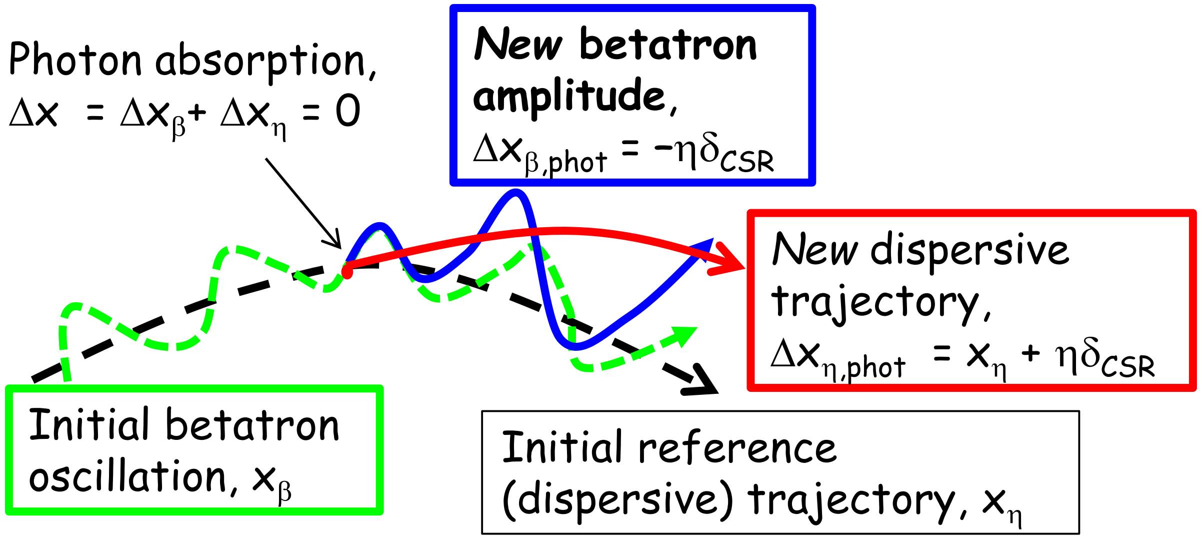


- Consider **1-D steady-state** CSR emission, and **linear optics**.
- Transient CSR effects and nonlinear dynamics will be included in simulations.

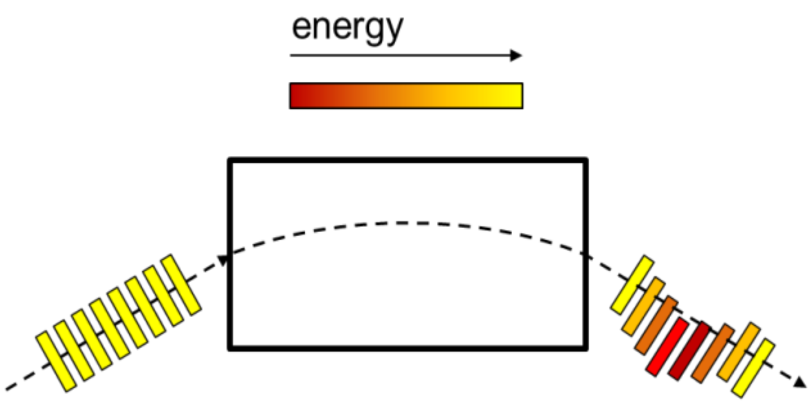
RELATIVE ENERGY SPREAD of GAUSSIAN bunch, per DIPOLE:

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

For a SINGLE-PARTICLE:



For a BUNCH:



CSR Kick in Single-Particle Motion

- Particle coordinates transform according to:

$$x(s) = x_\beta(s) + R_{16}(s_0 \to s)\delta(s) \equiv x_\beta + \Delta x$$
$$x'(s) = x'_\beta(s) + R_{26}(s_0 \to s)\delta(s) \equiv x'_\beta + \Delta x'$$

~ Energy-dispersion functions

they depend on the dipole bending angle θ and radius ρ

Change of longitudinal momentum by absorption of radiation

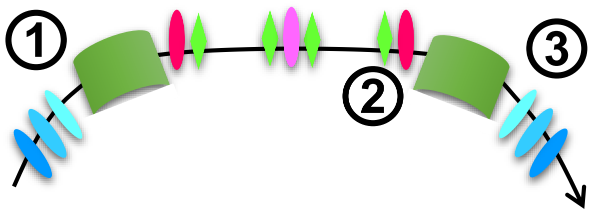
it depends on the bunch length, i.e., compression factor:

$$C = \frac{1}{|1 + h_i R_{56}|}$$

Now calculate the Courant-Snyder invariant…

$$J_3 = \gamma_x x_3^2 + 2\alpha_x x_3 x_3' + \beta_x x_3'^2$$

- Calculate the single-particle Courant-Snyder invariant through the beam line (e.g., DBA):



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

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

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

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

CSR kick scales with σ_z

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RMS Emittance Growth

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

Look for optimum Twiss parameters at the dipoles (i.e., minimum of the C-S invariant):

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

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

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

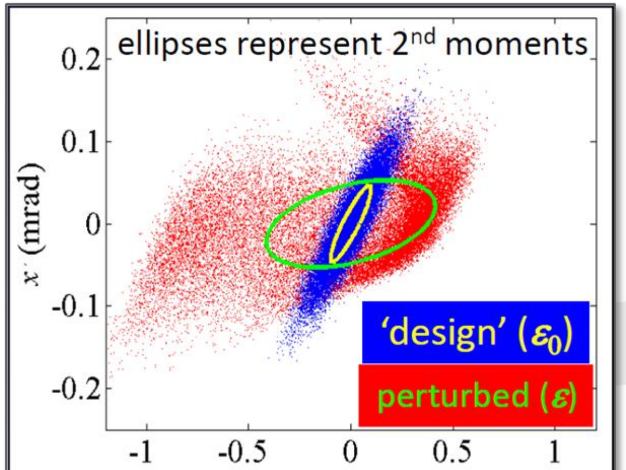
$$J_3 = 0 \Leftrightarrow C = 1$$

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

RMS EMITTANCE

$$\varepsilon^2_{x,3} = \langle x_3^2 \rangle \langle x'^2_3 \rangle - \langle x_3 x'_3 \rangle^2 = \langle J_3^2 \rangle$$

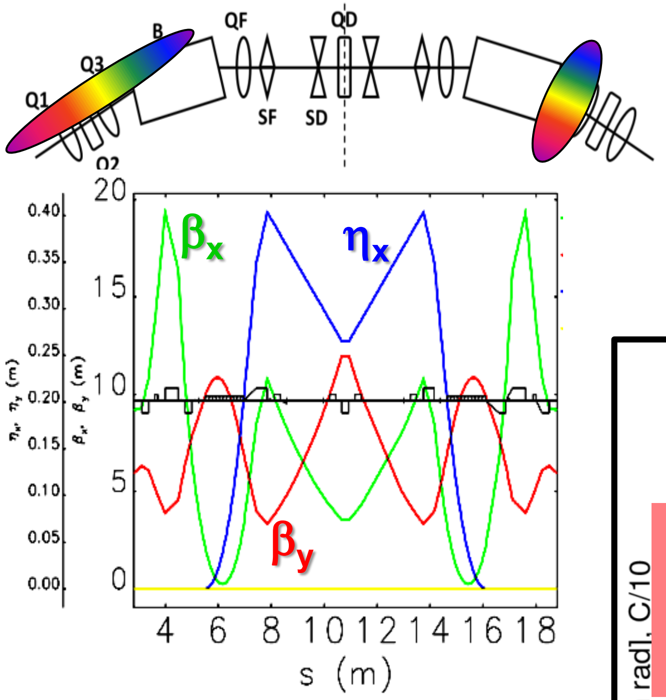
$$\varepsilon_x^2 = \varepsilon_{x,0}^2 + \varepsilon_{x,0} H_x(s_1) \sigma^2_{\delta,CSR} X\left(\alpha_x, \beta_x, \Delta\mu_x\right)_{s_f}$$



Courtesy of P. Emma

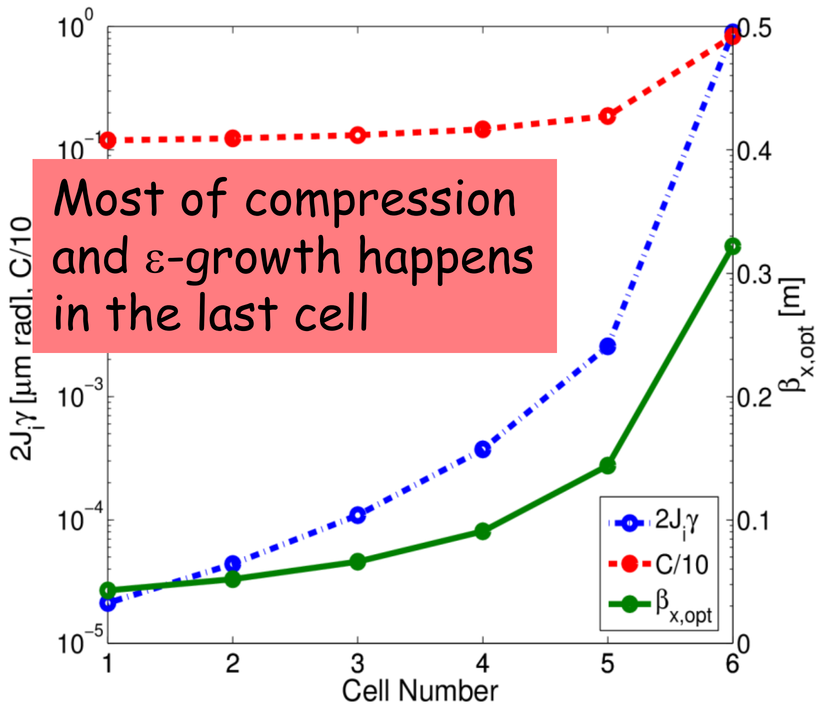
S. Di Mitri and M. Cornacchia, EPL 109 (2015) 62002.

DBA Arc Compressor

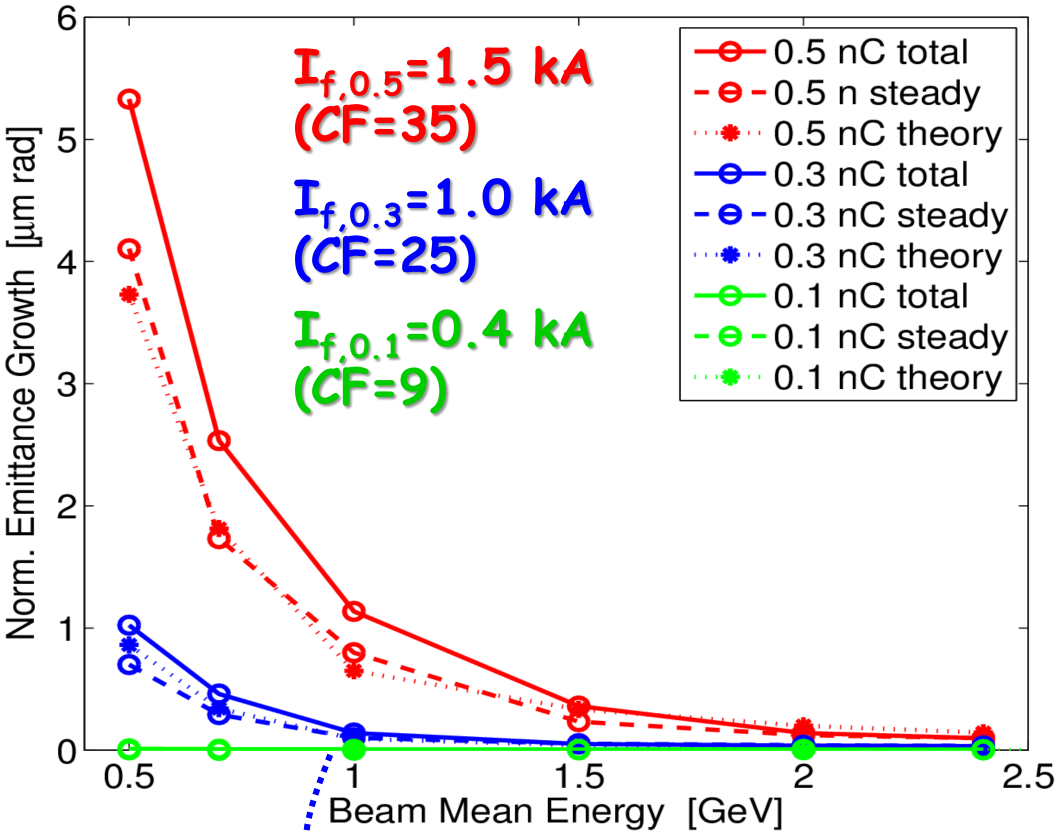


DBA cell
R_{56} = 35 mm

× 6 → 180°, 125 m @ 2.4 GeV, 60 m @ 1.0 GeV



Most of compression and ε-growth happens in the last cell



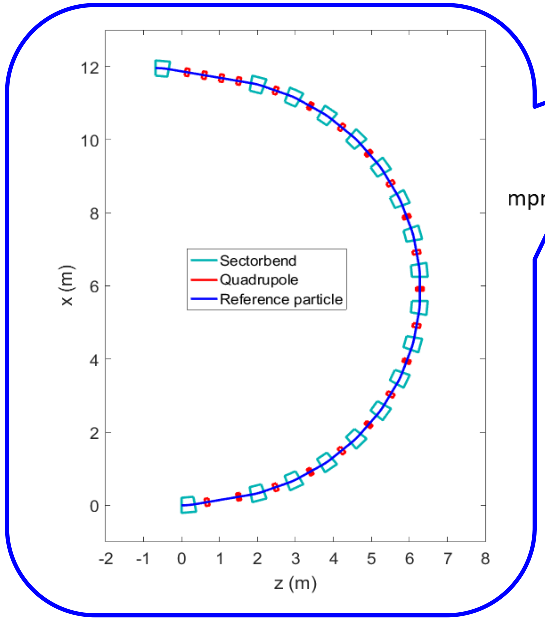
Good starting point for ERL-FEL but…. the arc is still 50% longer than desired.

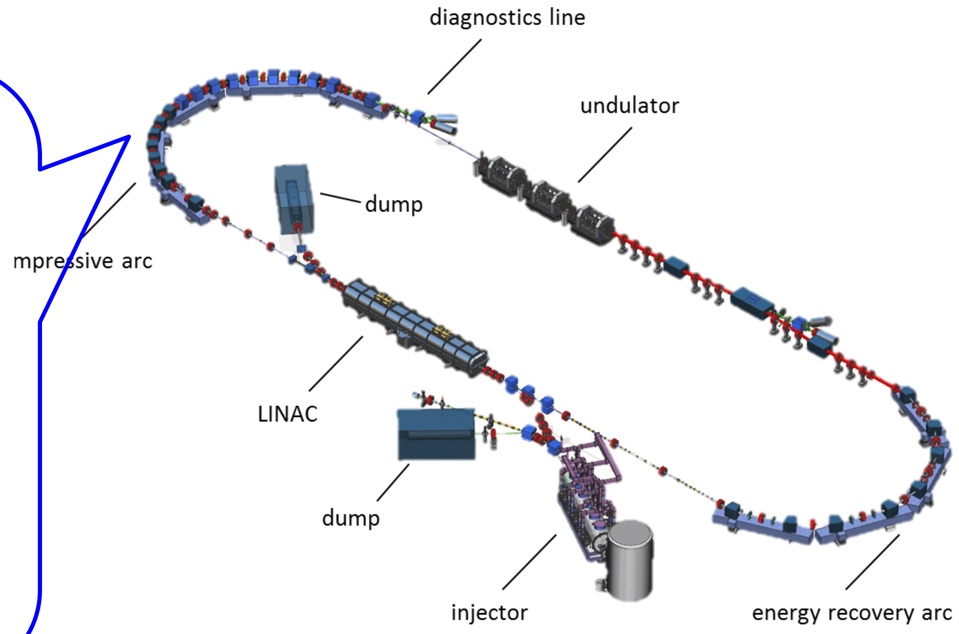
S. Di Mitri, NIM A 806 (2016) 184–192

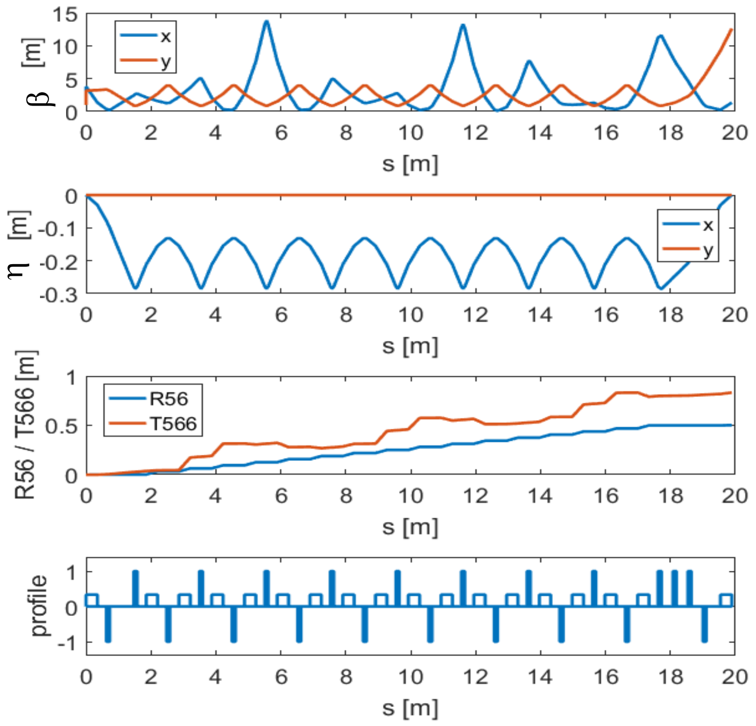
FODO Arc Compressor

In order to make it more compact:

1. **relax** the **achromatic** condition at each cell *(except the last one)*
2. **relax** the **optimum-beta** condition through the arc *(except in the last cell)*
3. **reduce** the number of **quadrupole** magnets
4. **Cancel CSR** kicks in the very **last cell only** (local correction)







J. Akkermans, S. Di Mitri, D. Douglas, and I. D. Setija, PRAB 20, 080705 (2017).

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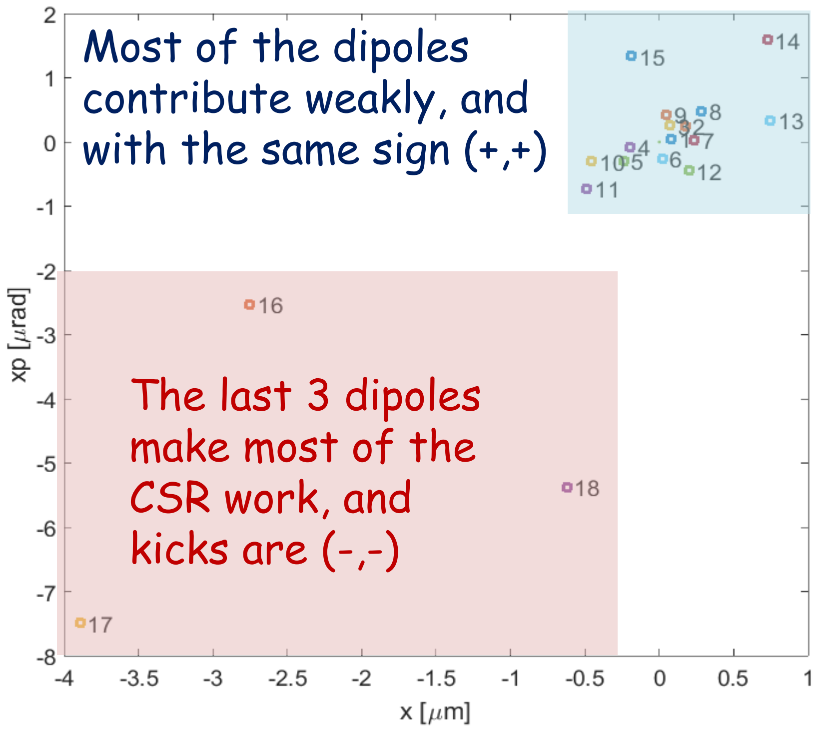
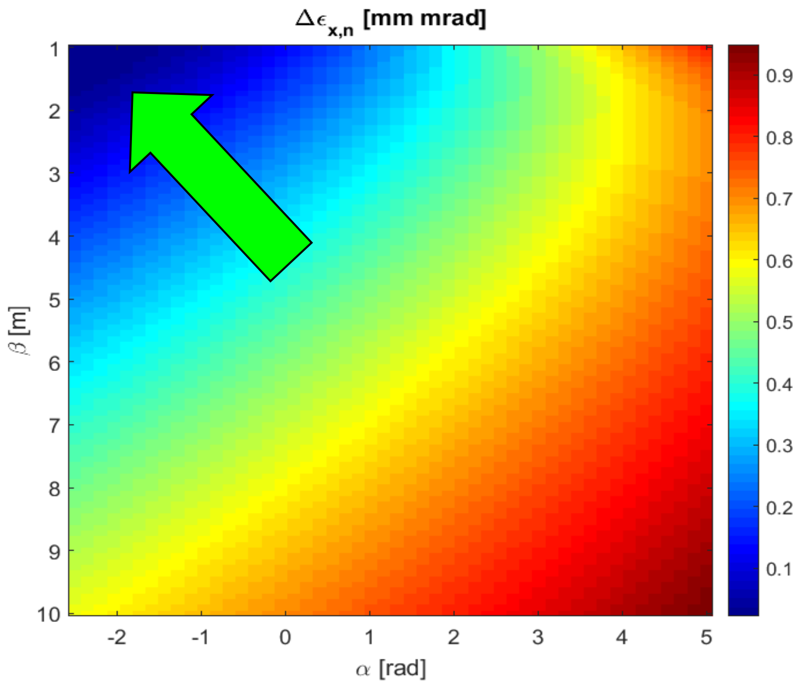
Semi-Analytical Optimization

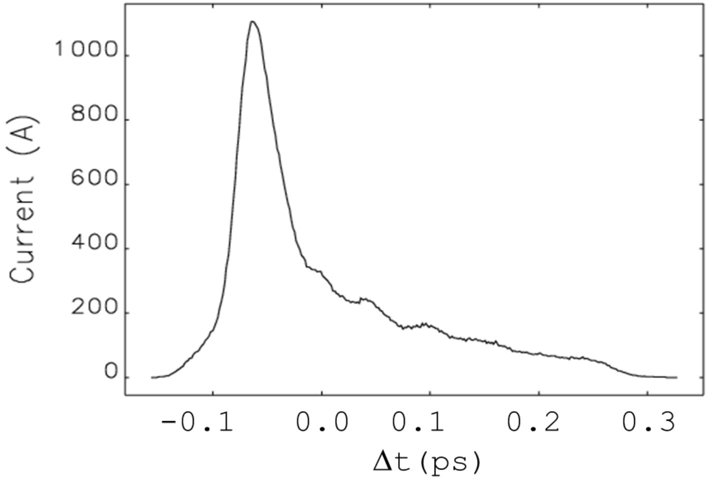
1. **Calculate CSR kick** (Δx_{CSR}, $\Delta x'_{CSR}$) **at each dipole** (steady-state, 1-D, thin lens approx.)

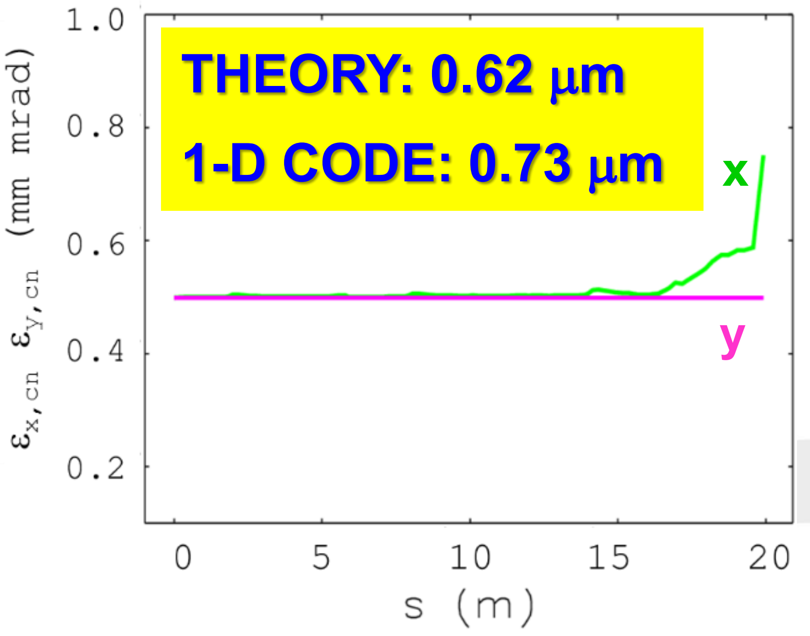
2. **Choose** β_x **and** $\Delta\mu_x$ **in the last cell** to make the **sum of all kicks** $\rightarrow 0$.

3. **Scan initial Twiss params.** for fine tuning and minimum emittance.









J. Akkermans, S. Di Mitri, D. Douglas, and I. D. Setija, PRAB 20, 080705 (2017).

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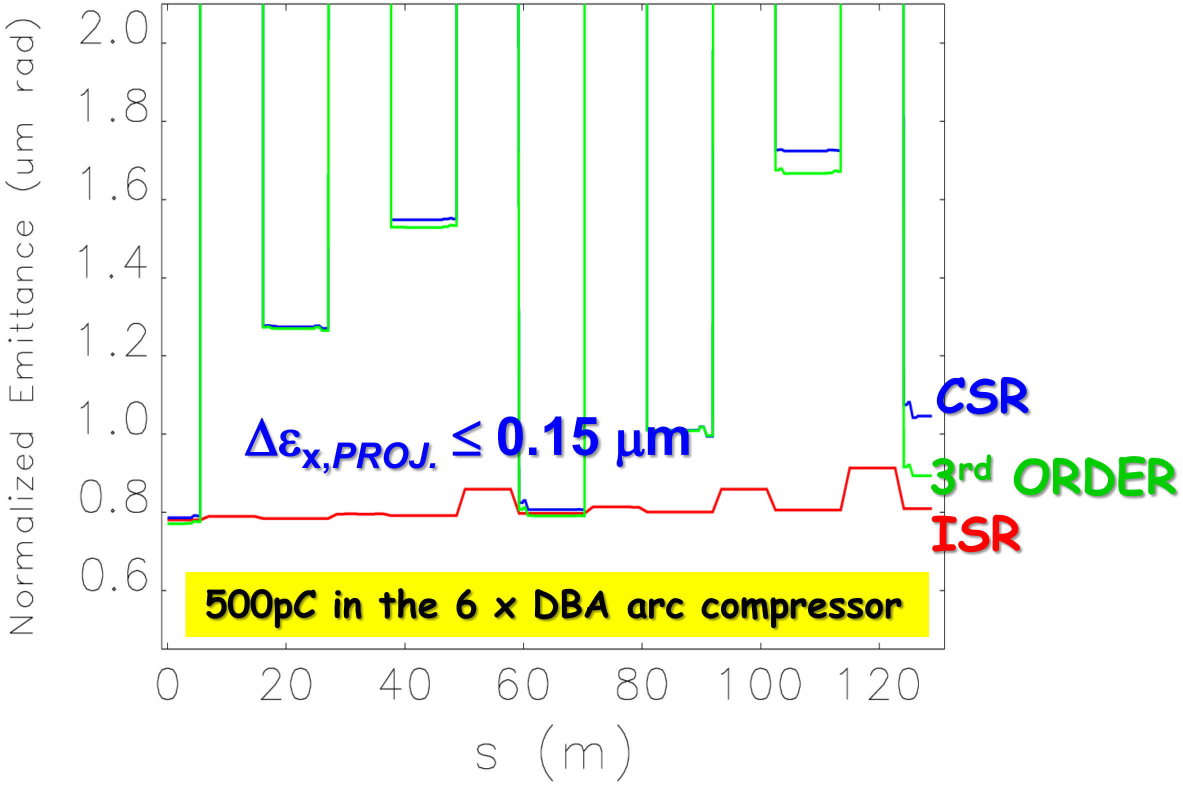
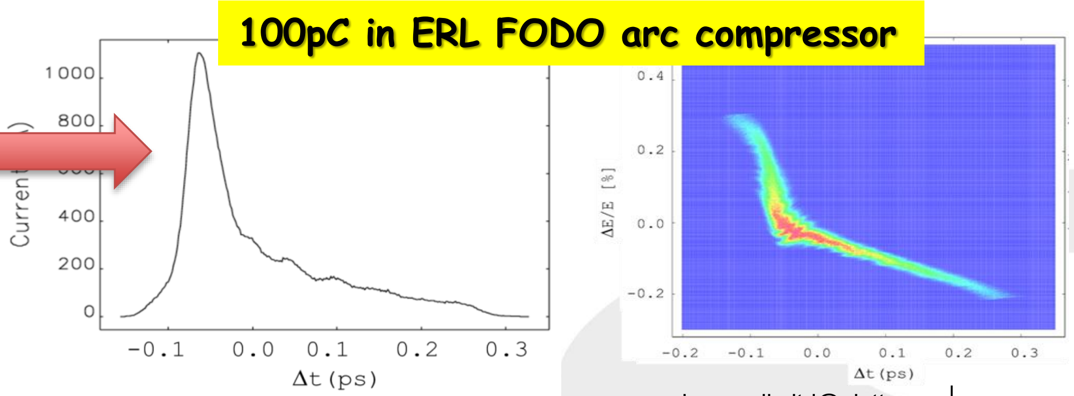
Nonlinear Dynamics

- **Nonlinearities** in **longitudinal phase space** from:
  - incoming RF curvature,
  - intrinsic T_{566} in the arc,
  - nonlinear CSR-induced energy chirp.
- **Sextupoles** can **linearize the compression**…
  - …but strengths and positions must be optimized for minimizing (chromatic) **aberrations**.
- **Alternatively:**
  - tune upstream **RF phase** and $\mathbf{T_{566}}$ for cancelling nonlinearities in the arc compressor and/or…
  - …takes advantage of the leading **CSR-induced linear chirp** to compress the bunch head.





S. Di Mitri and M. Cornacchia, EPL 109 (2015) 62002.
J. Akkermans, S. Di Mitri, D. Douglas, and I. D. Setija, PRAB 20, 080705 (2017).

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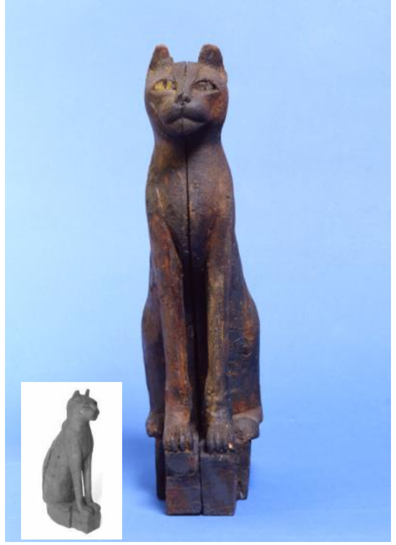
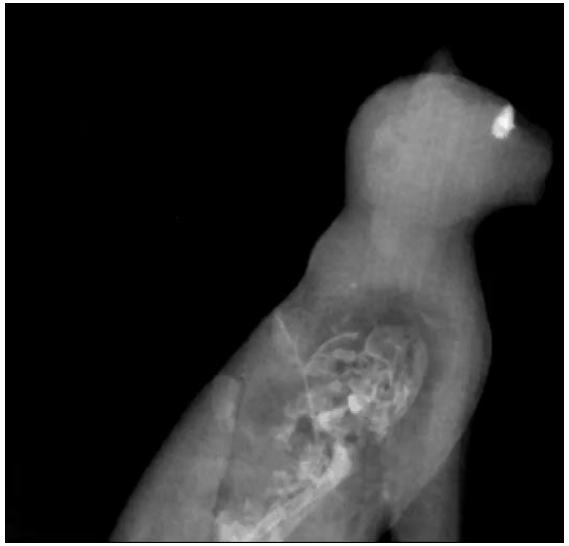
FEL-ICS Scope

> MeV photon energy radiation finds application in:

- Cargo automated radiography (non-intrusive inspection)
- Nuclear detection (high-Z material discrimination, nuclear threats)
- Phase contrast radiography of fusion targets
- ***Computed tomography*** of cultural heritage: preservation, investigation and restoration

Revealing a cat skeleton inside….
Museo Civico Archeologico di Bologna, Italy

Unlocking carbonized Herculaneum papyri..
V. Mocella at CEA Grenoble

Unveiling casting procedures, internal structure and repairs of the Riace Bronzes….

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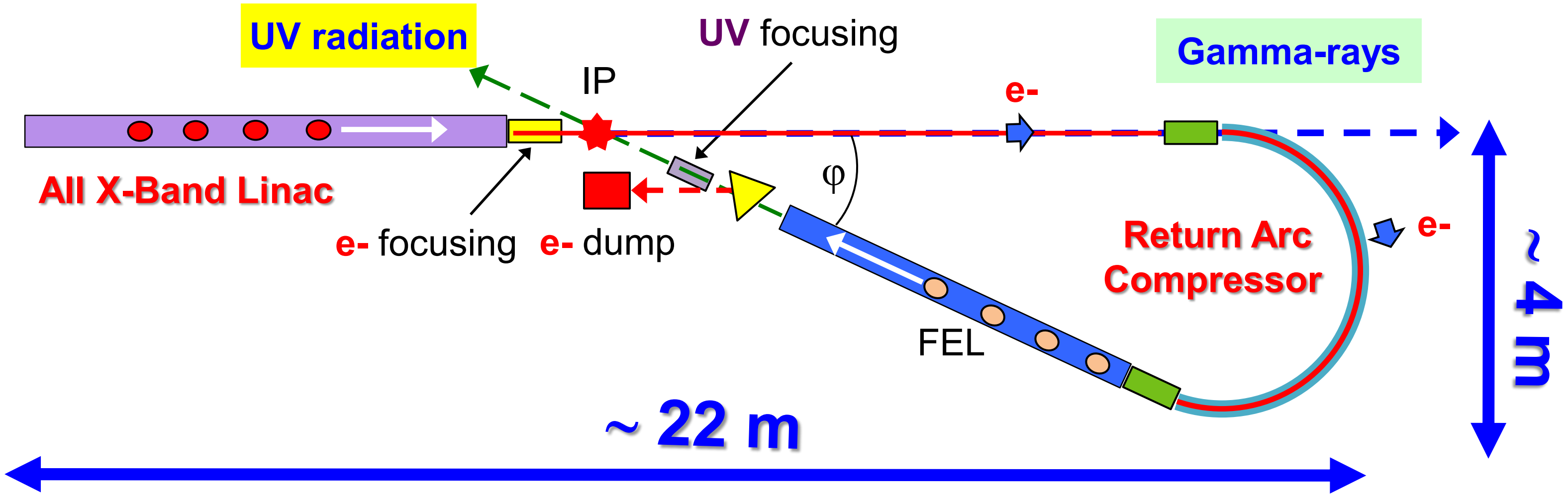
Compact FEL–ICS

$$E_{ICS} = \frac{a_C a_u}{\lambda_u} \gamma_e{}^4$$



Charge	350 pC
Energy	0.3 GeV
Current	0.5 kA
Projected Emittance	< 1.0 μm
Relative Energy Spread	< 0.2%
FEL Wavelength (SASE)	150 nm
FEL Peak Power	~0.7 GW
FEL Average Flux	$2x10^{19}$ ph/s
γ-ray Average Flux	$1x10^{8}$ ph/s

Compression Factor	*~15*
Arc R_{56}	*~0.2 m*
Proj. Emittance Growth	*< 0.3 μm*

Trains of electron bunches from an **"all X-band" Linac** travel through an **arc compressor** to an undulator emitting **UV FEL** radiation before being dumped.

→ **Inverse Compton Scattering** of UV on trailing e-bunches produces **~10 MeV Gamma-rays**

→ Most of UV FEL radiation available to experimentation as well

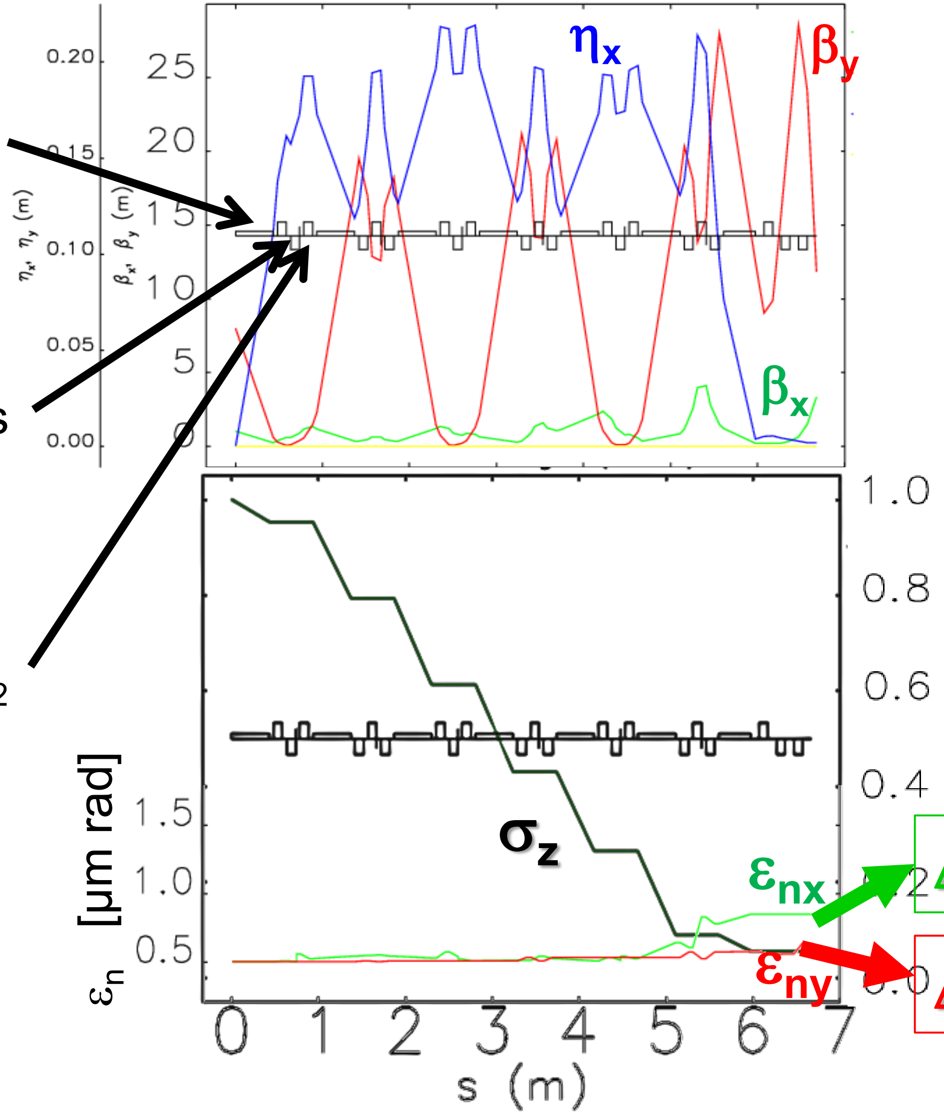
M. Placidi, S. Di Mitri, C. Pellegrini, G. Penn, NIM A 855 (2017) 55–60

Scaling to 2 m Arc Radius

7 Dipoles,
30°, 25°
$B \leq 1.2$ T

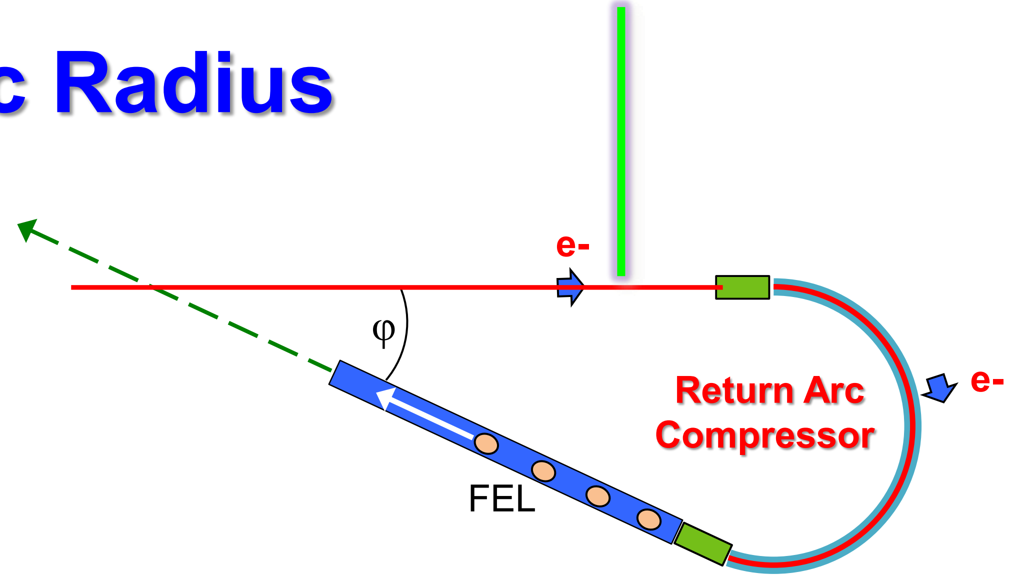
21 Quadrupoles
$g1 \leq 60$ T/m

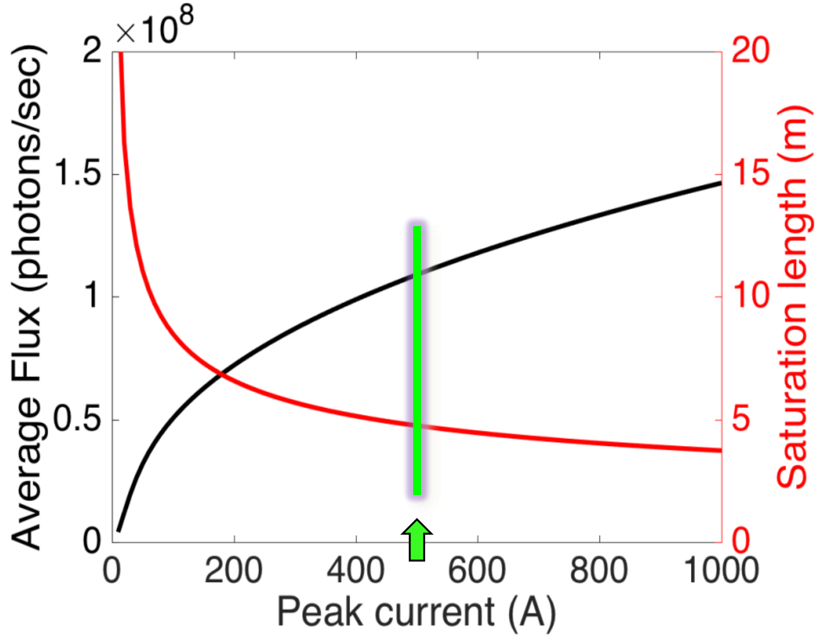
4 Sextupoles
$g2 \leq 200$ T/m^2



$\Delta_x = 0.3\ \mu m$

$\Delta_x = 0.1\ \mu m$





M. Placidi, S. Di Mitri, C. Pellegrini, G. Penn, NIM A 855 (2017) 55–60

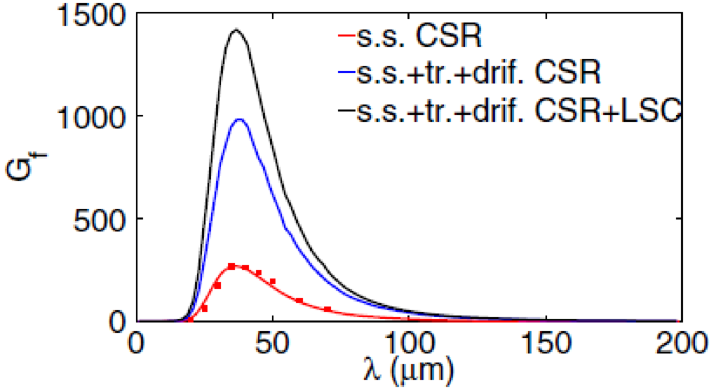
Microbunching Instability

- In a multi-dipole line, CSR commonly drives the instability.
- Optics prescriptions for simultaneously minimizing **emittance growth** & **microbunching gain** include *local isochronicity*, π-phase advance, small betas, etc.

MERIT Function for MBI

$$\xi = \left| \max\{R_{56}^{s'\to s}\} \frac{k_0^{1/3}}{\rho^{2/3}} \Delta L \right|$$

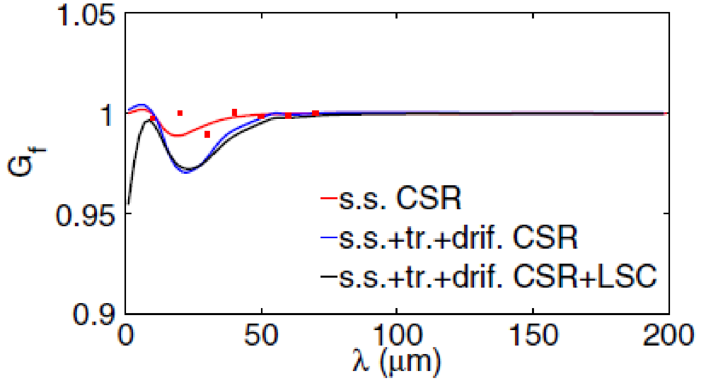
CALCULATE & DESIGN



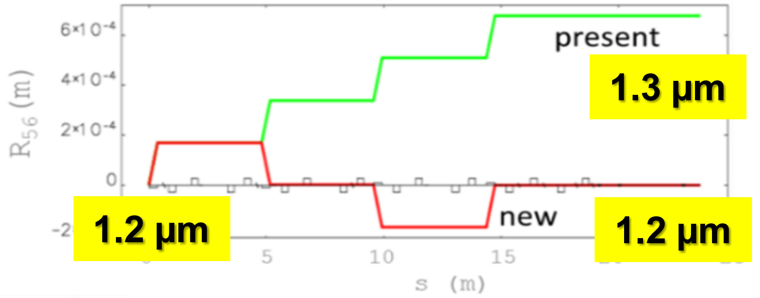
MERIT Function for $\Delta\varepsilon_x$

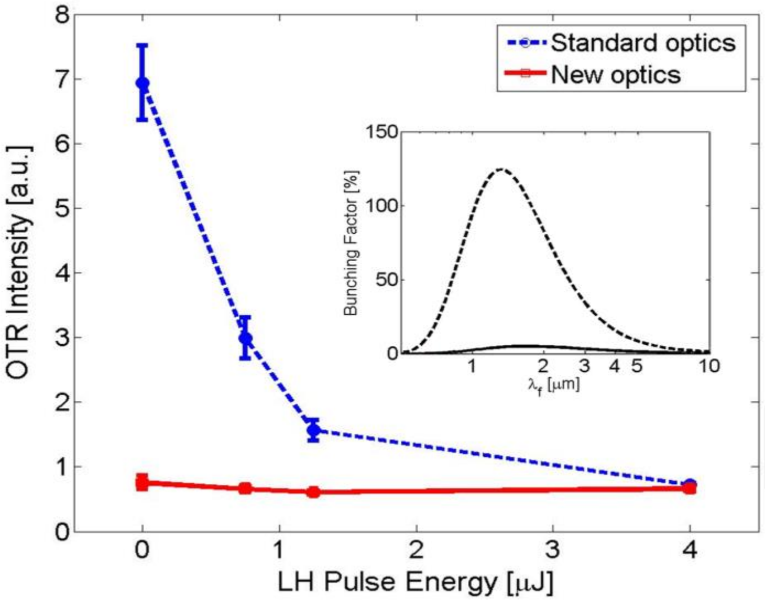
$$\varepsilon_{x,0} H_x(s_1) \sigma^2_{\delta,CSR} X(\alpha_x, \beta_x, \Delta\mu_x)_{s_f}$$

CALCULATE & DESIGN



EXPERIMENT @ FERMI





C.-Y. Tsai, S. Di Mitri, D. Douglas, R. Li, and C. Tennant, PRAB 20, 024401 (2017).
S. Di Mitri and S. Spampinati, PRAB 20, 120701 (2017).

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Conclusions

- **1-D steady-state analytical formulas** guide to the design of compact arc compressor:
  - $\Delta\varepsilon_{n,x} \sim 0.1\ \mu m$ **accuracy of prediction** (vs. codes) for E > 300 MeV, I < kA.
    - Optics control of CSR kicks is **well-established.**
    - Starting point for **MOGA-like** optimizations: $\Delta\varepsilon_{n,x} \sim 0.01\ \mu m$?!

- **Emittance** and **microbunching** control **at once**:
  - Some more complexity in the optics design: validation is in progress for isochronous lines.
  - New path of research for arcs with large R_{56}.

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Thank you for Your attention

Discussion is very welcome

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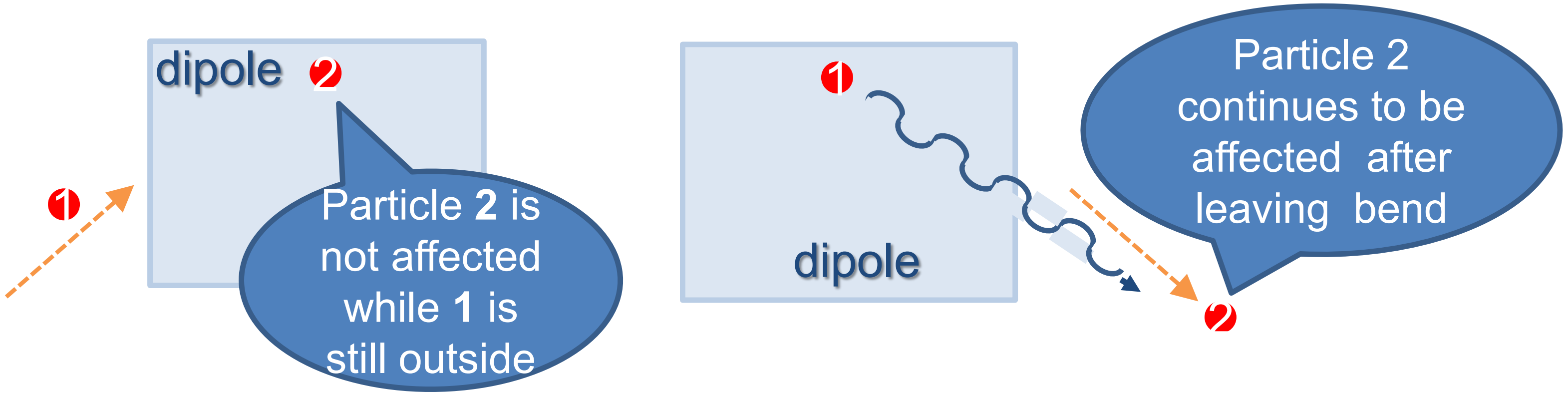
References

1. S. Di Mitri and M. Cornacchia, "Transverse emittance-preserving arc compressor for high-brightness electron beam-based light sources and colliders", EPL 109 (2015) 62002.
2. S. Di Mitri, "Feasibility study of a periodic arc compressor in the presence of coherent synchrotron radiation", NIM A 806 (2016) 184–192.
3. J. Akkermans,S. Di Mitri, D. Douglas, and I. D. Setija, "Compact compressive arc and beam switchyard for energy recovery linac-driven ultraviolet free electron lasers", PRAB 20, 080705 (2017).
4. M. Placidi, S. Di Mitri, C. Pellegrini, G. Penn, "Compact FEL-driven inverse Compton scattering gamma-ray source", NIM A 855 (2017) 55–60.
5. C.-Y. Tsai, S. Di Mitri, D. Douglas, R. Li, and C. Tennant, "Conditions for coherent-synchrotron-radiation-induced microbunching suppression in multibend beam transport or recirculation arcs", PRAB 20, 024401 (2017).
6. S. Di Mitri and S. Spampinati, "Microbunching instability study in a linac-driven free electron laser spreader beam line", PRAB 20, 120701 (2017).

CSR Transient and 3-D Effects

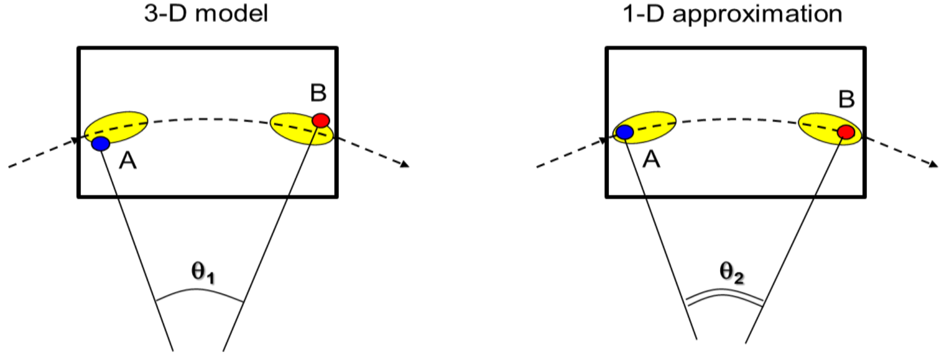
- **CSR transient effects** are relevant over lengths $L_t \simeq (24R^2\sigma_z)^{1/3} \simeq$ 0.1 – 1 m

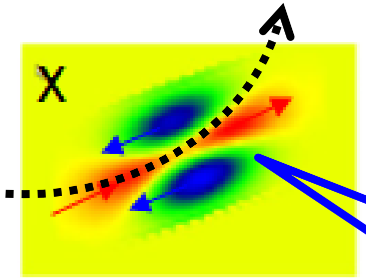


- Stupakov's model for transient field is *substantially* correct.
- 3-D effects tend to alleviate the projected emittance growth.

➢ Deeper analytical and simulation insights in **B. Van der Geer's talk, TODAY WG-C**

- **CSR 3-D effects** are relevant for Derbenev-parameter ≥ 1





2-D CSR field modifies the beam energy distribution. Energy spread is correlated both along z and x.

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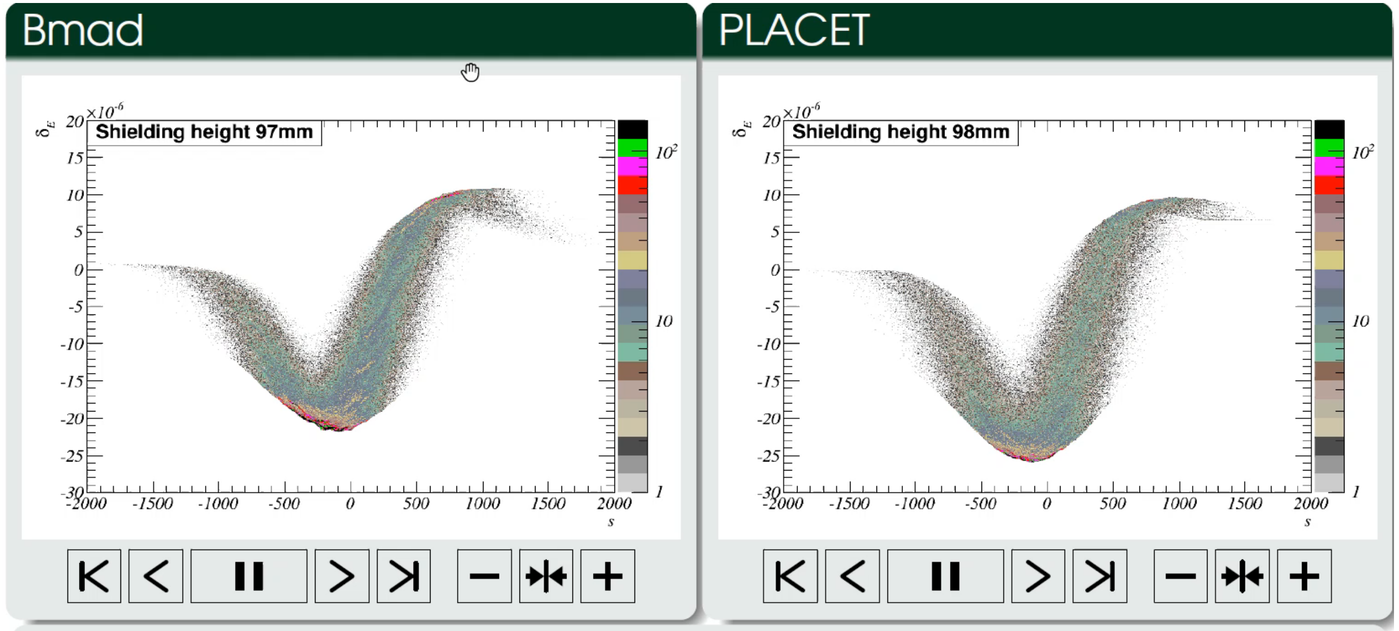
Shielding

- ❑ Shielding of CSR field would require pipe gap as small as < 2 mm or so.

J. Esberg et al. for CERN (2015)



- Without shielding, there is some discrepancy between Bmad and PLACET.
- PLACET with no shielding shows perfect agreement with ELEGANT (E. Adli).
- When decreasing the parallel plate distance, the shielding wake can start to interact with the tail of the bunch.
- Large difference between Bmad and new PLACET implementation for small plate separations.

D. Sagan et al. (2009)

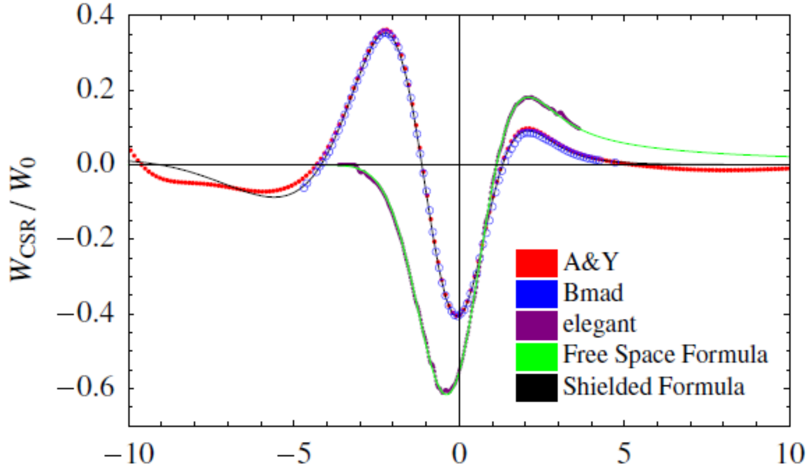


FIG. 14. (Color) Realistic magnets: Parameter set E (JLab TH2 magnet) line (top), set F (CESR analyzer magnet) (bottom). Bmad agrees with the CSR-wake formula Eq. (53) better than the other codes at the bunch tail.

V. Yakimenko et al. @ ATF (2012)