



Alessandra Valloni

# TF DESIGN UPDATE AFTER JLAB VISIT

Thanks to A. Bogacz, D. Douglas, P. Evtushenko,  
C. Tennant, C.Y. Tsai

8 April 2014, LHeC meeting



# Outline

## 1. UPDATES ON THE OPTICS LATTICE

- DOGLEG FOR PATH-LENGTH ADJUSTMENT
- END-TO-END SIMULATIONS
- TRACKING

## 2. CSR IN ARC OPTICS

- CSR EFFECTS
- MICROBUNCHING INSTABILITY

for two different arc lattices and for different longitudinal distributions

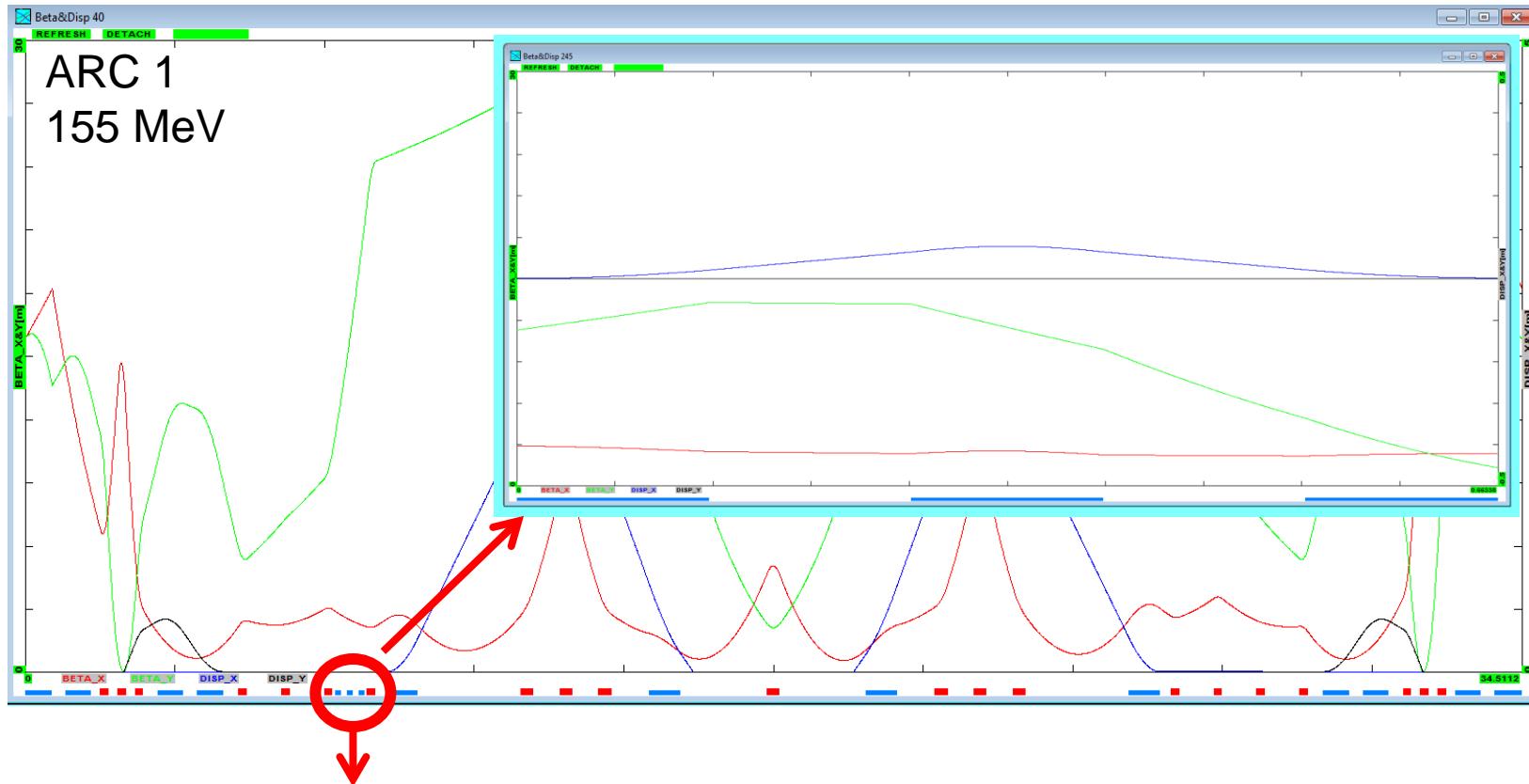
## 3. MERGER DESIGN ISSUES

- POSSIBLE SCHEMES (zigzag, chicane, dog-leg)
- BEAM DYNAMICS SIMULATIONS (??)
- INJECTOR SCHEMES

## 4. BEAM DIAGNOSTIC



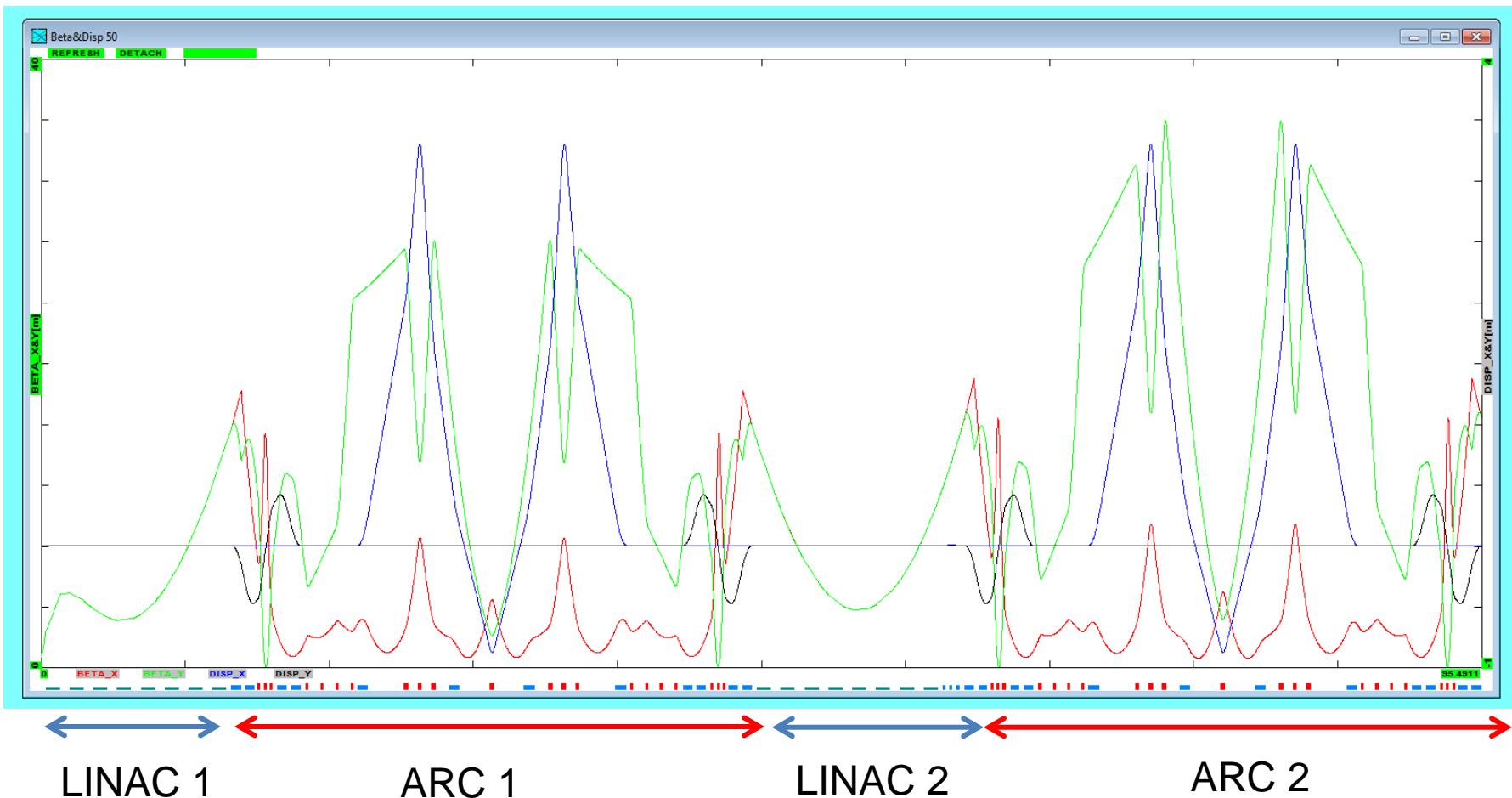
# Horizontal dogleg for path-length adjustment



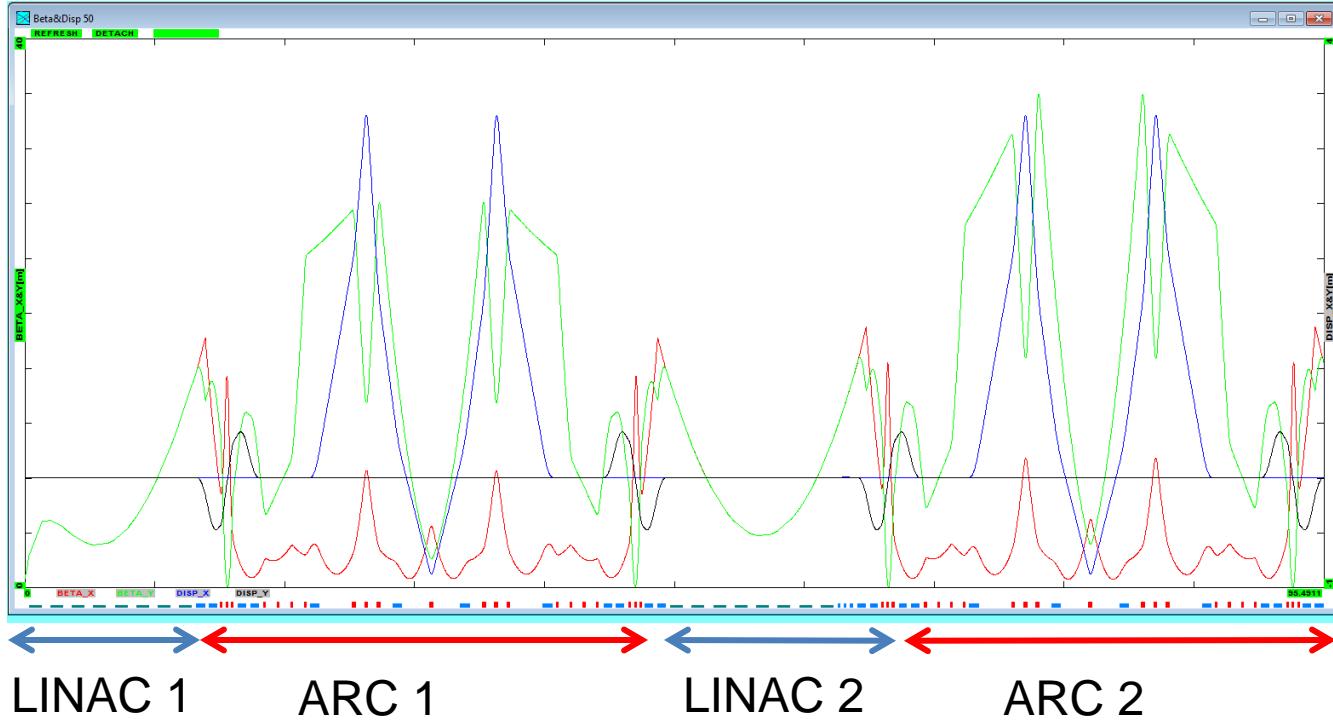
3 - 13 cm long dipoles  
Bending angle 18°  
 $B = 1.3 \text{ T}$

Adjustment: 10° of RF  $\rightarrow 1.04 \text{ cm} @ 801.58 \text{ MHz}$

# End-to-end simulations



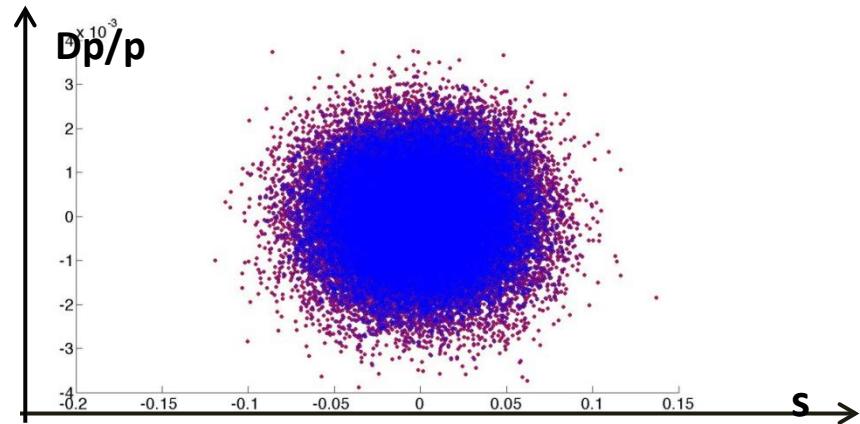
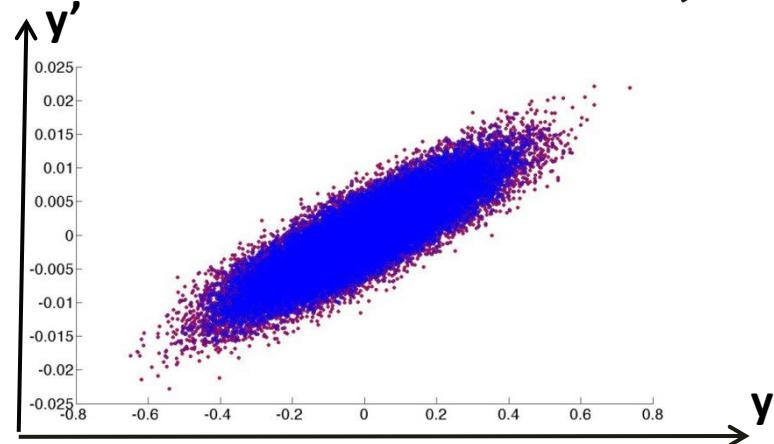
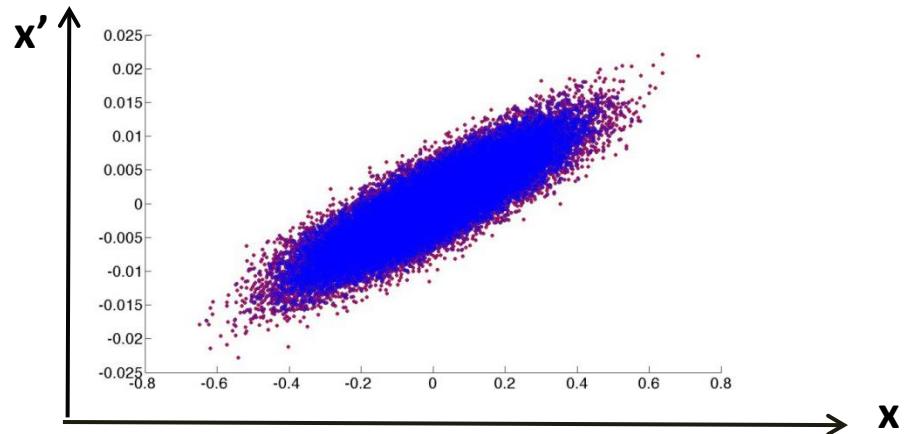
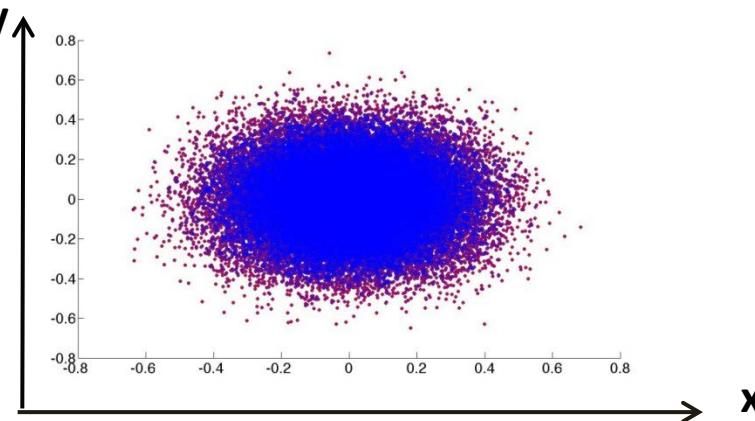
# End-to-end simulations



Tracking using OPTIM

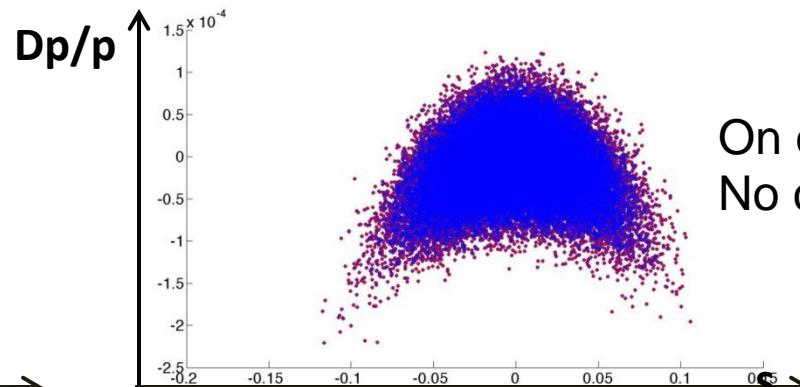
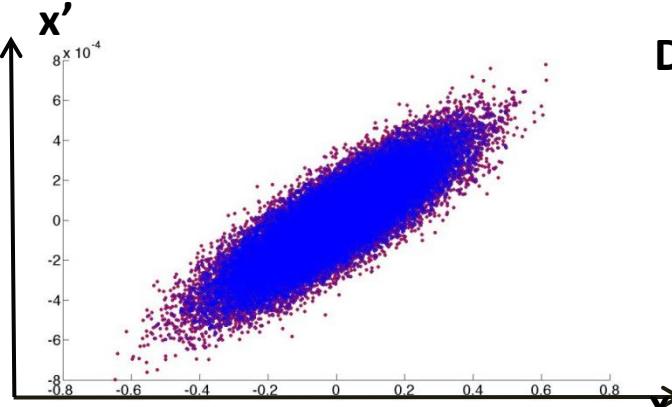
Performs multiparticle and single and multiturn tracking  
Gaussian particle distribution in 6D phase space  
Number of particles up to 10000000  
No space charge included

# Input Beam distribution



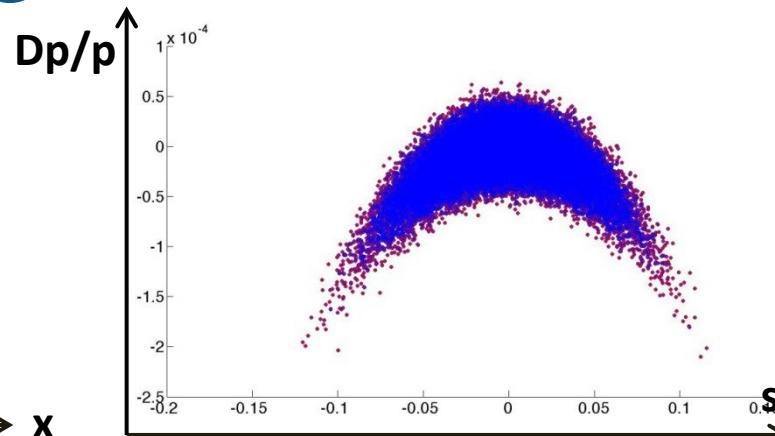
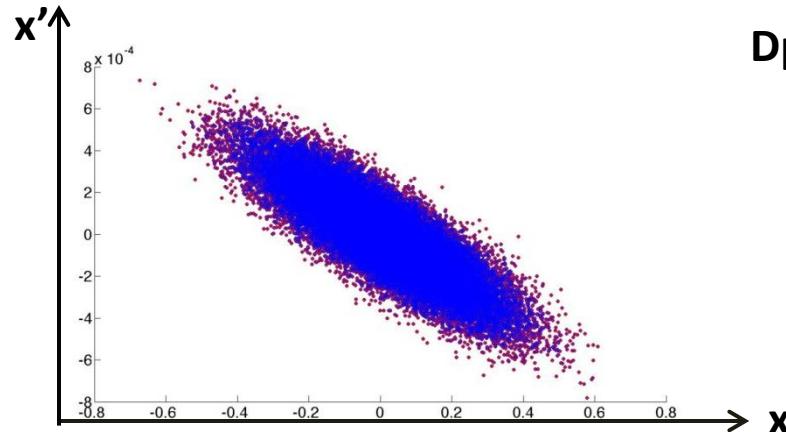
PARAMETER	VALUE	PARAMETER	VALUE
Energy	5 MeV	$\sigma_x, \sigma_y$	1.72 mm
Normalized emittance $\gamma\epsilon_{x,y}$	50 $\mu\text{m}$	$\sigma_t$	300 $\mu\text{m}$
Energy spread ( $Dp/p$ )	0.001(5.5keV)	Number of particles	50000

# Beam distribution @ Linac1



On crest acceleration  
No compression

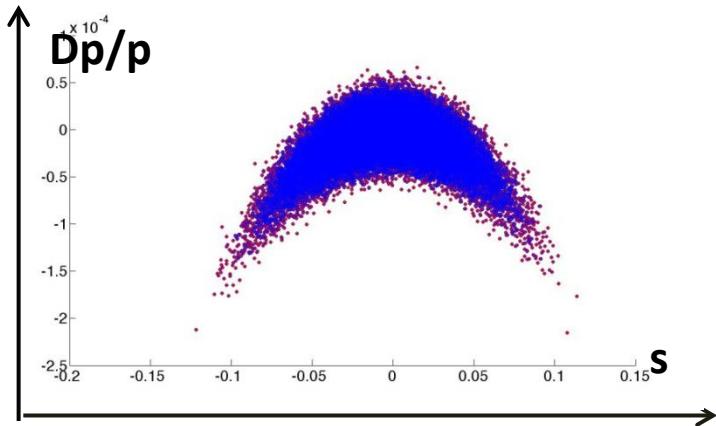
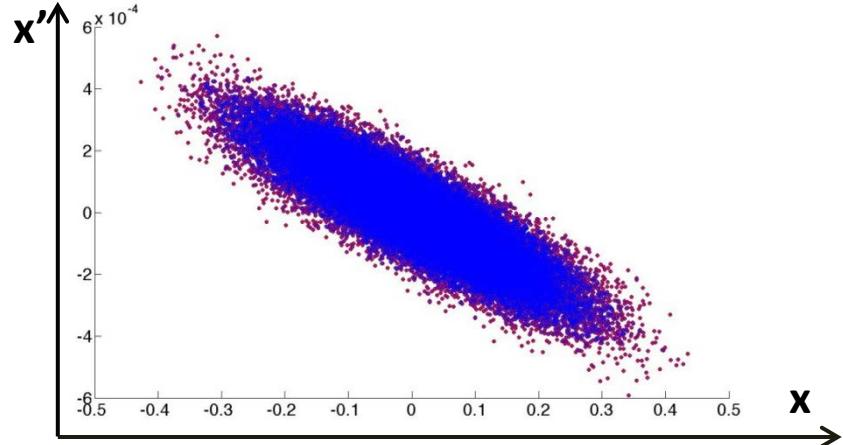
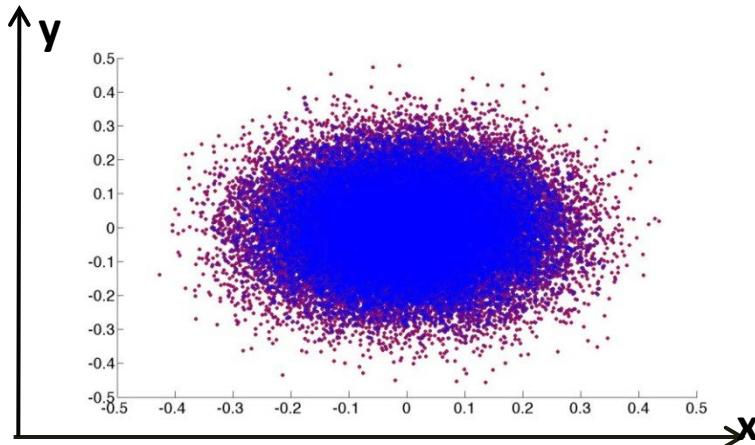
# Beam distribution @ Arc1



PARAMETER	VALUE	PARAMETER	VALUE
Energy	155 MeV	$\sigma_x, \sigma_y$	1.62 mm
Energy spread (Dp/p)	4.1e-5 (6.4keV)	$\sigma_t$	301 um



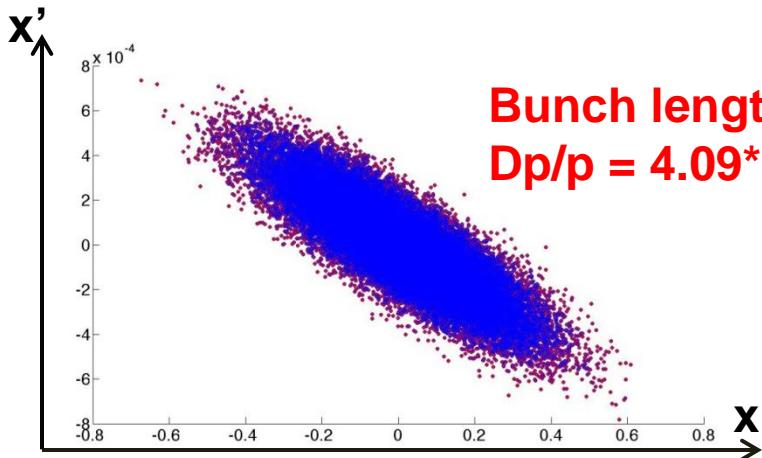
# Beam distribution @ Pass1



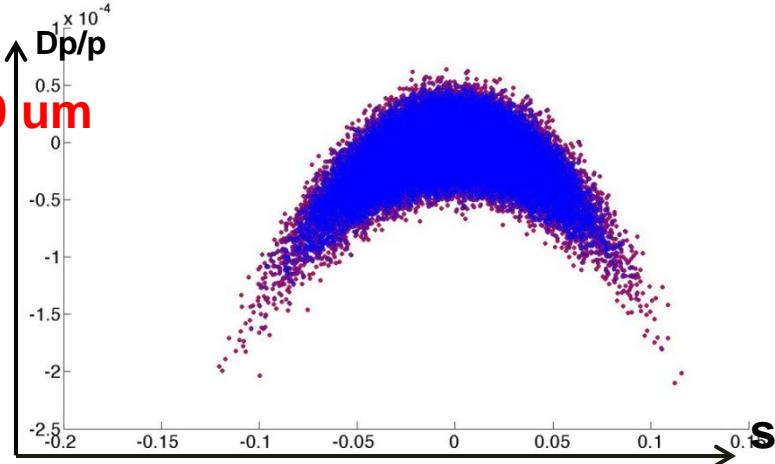
PARAMETER	VALUE	PARAMETER	VALUE
Energy	305 MeV	$\sigma_x, \sigma_y$	1.16 mm
Energy spread ( $Dp/p$ )	2.8e-5 (8.55keV)	$\sigma_t$	305 um

# Beam compression

@ arc1, on-crest acceleration,  $M_{56}=0$ , Momentum compaction= $e-07$

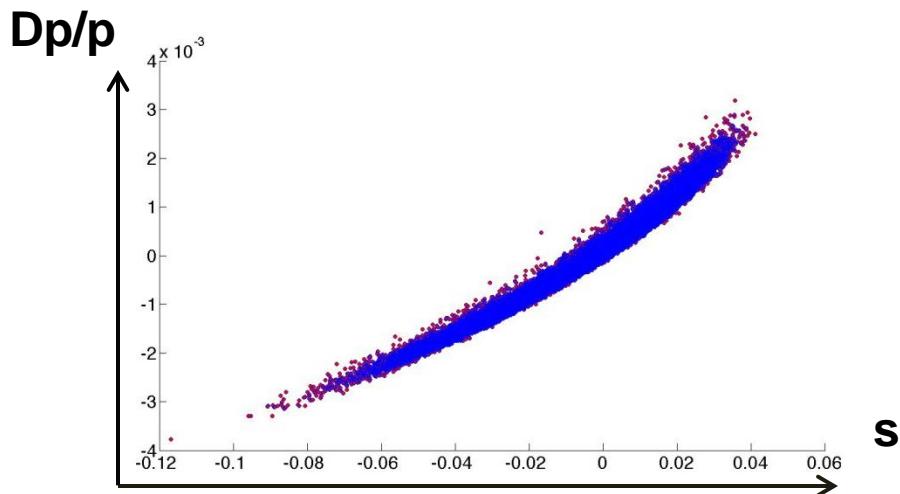


Bunch length = 300 um  
 $Dp/p = 4.09 \times 10^{-5}$



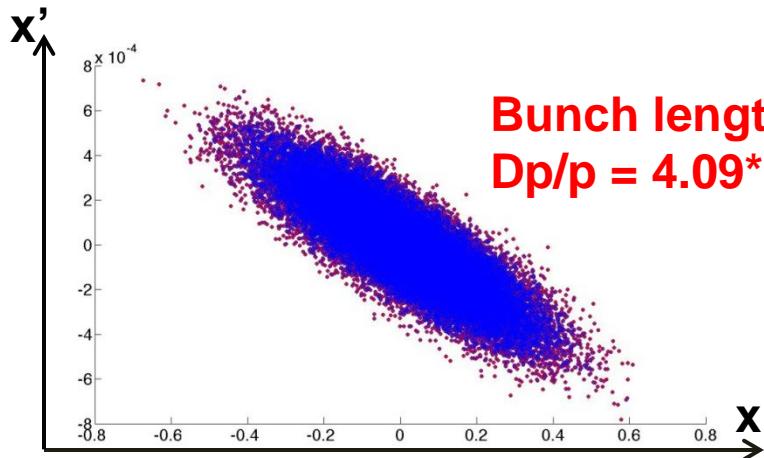
Off crest acceleration (10 deg)  
 $M_{56} = -15$  cm  
Momentum compaction 0.0043473

Beam compression  
**Bunch length = 184 um**  
 **$Dp/p = 8.6 \times 10^{-4}$**

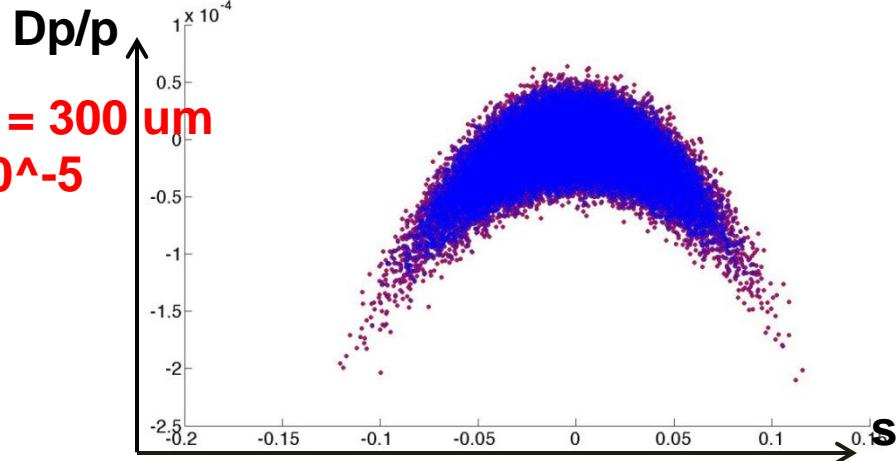


# Beam stretching

@ arc1, on-crest acceleration,  $M_{56}=0$

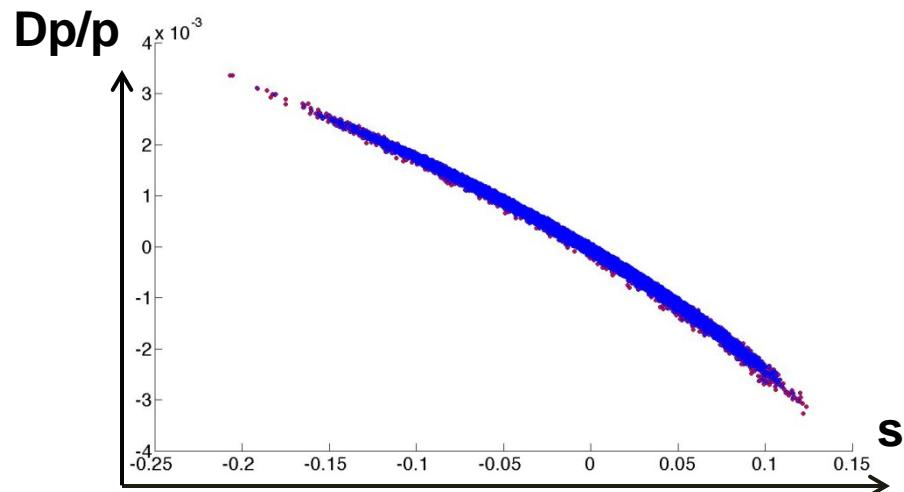


Bunch length = 300 um  
 $Dp/p = 4.09 \times 10^{-5}$



Off crest acceleration (-10deg)  
 $M56 = -15\text{cm}$

Beam compression  
Bunch length = 430 um  
 $Dp/p = 8.5 \times 10^{-4}$



# Next steps

- Add sextupoles to see linearization of longitudinal phase space
- Correct the curvature with sextupoles in the arc
- Decide what is the longest bunch we can transport in the ERL
- Analyze the evolution of the longitudinal phase-space → end-to-end beam dynamics simulations



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## 2. CSR IN ARC OPTICS

- CSR EFFECTS (*Christopher Tennant*)
- MICROBUNCHING INSTABILITY (*Cheng-Ying Tsai*)

for two different arc lattices and for different longitudinal distributions

## 3. MERGER DESIGN ISSUES

- POSSIBLE SCHEMES (zigzag, chicane, dog-leg)
- BEAM DYNAMICS SIMULATIONS (??)
- INJECTOR SCHEMES

## 4. BEAM DIAGNOSTIC



# Input Beam Parameters

PARAMETER	VALUE
Energy	455 MeV
Normalized emittance $\gamma\varepsilon_{x,y}$	50 $\mu\text{m}$
Bunch population	$2 \times 10^9$
Bunch charge	320 pC

## Distribution A:

$$\sigma_t = 0.1 \text{ ps (30um)} \rightarrow I_{\text{peak}} = 1362 \text{ A}$$

$$\sigma_{DE} = 5.5 \text{ keV}$$

## Distribution B:

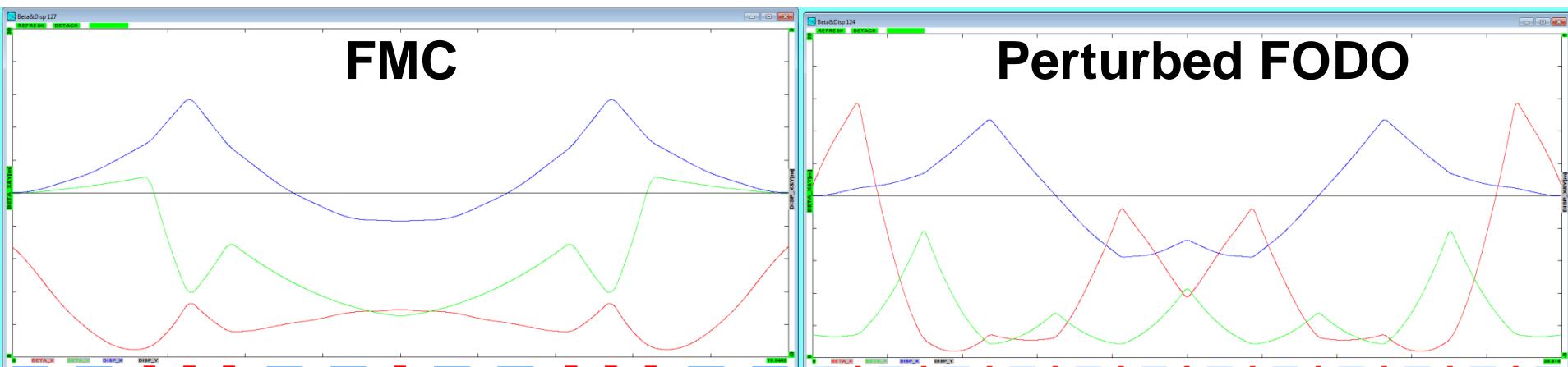
$$\sigma_t = 1 \text{ ps (300um)} \rightarrow I_{\text{peak}} = 136 \text{ A}$$

$$\sigma_{DE} = 5.5 \text{ keV}$$

## Distribution C:

$$\sigma_t = 4 \text{ ps (1.2 mm)} \rightarrow I_{\text{peak}} = 34 \text{ A}$$

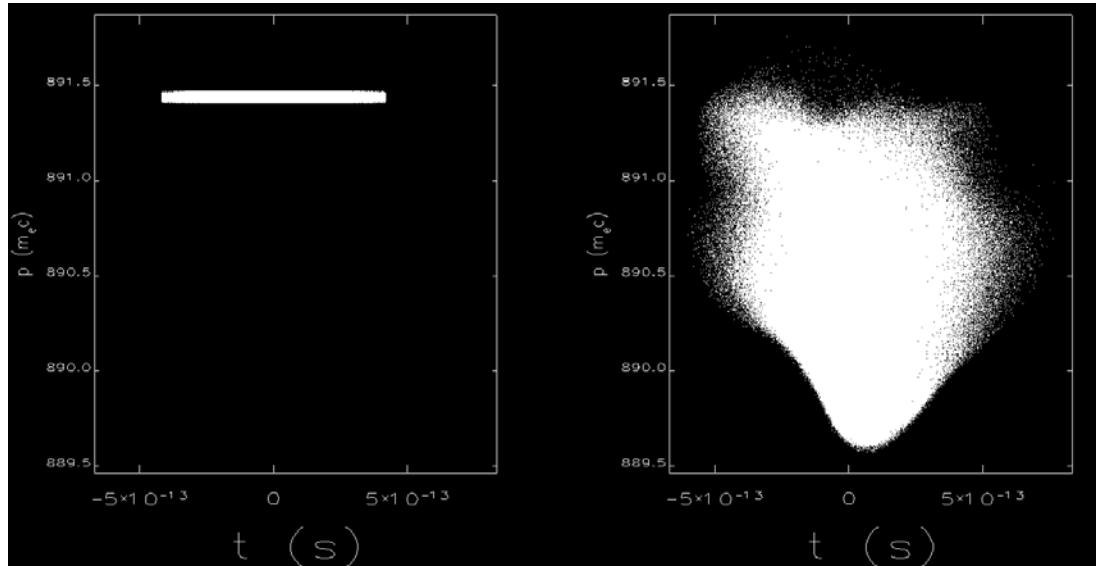
$$\sigma_{DE} = 5.5 \text{ keV}$$



# FMC arc

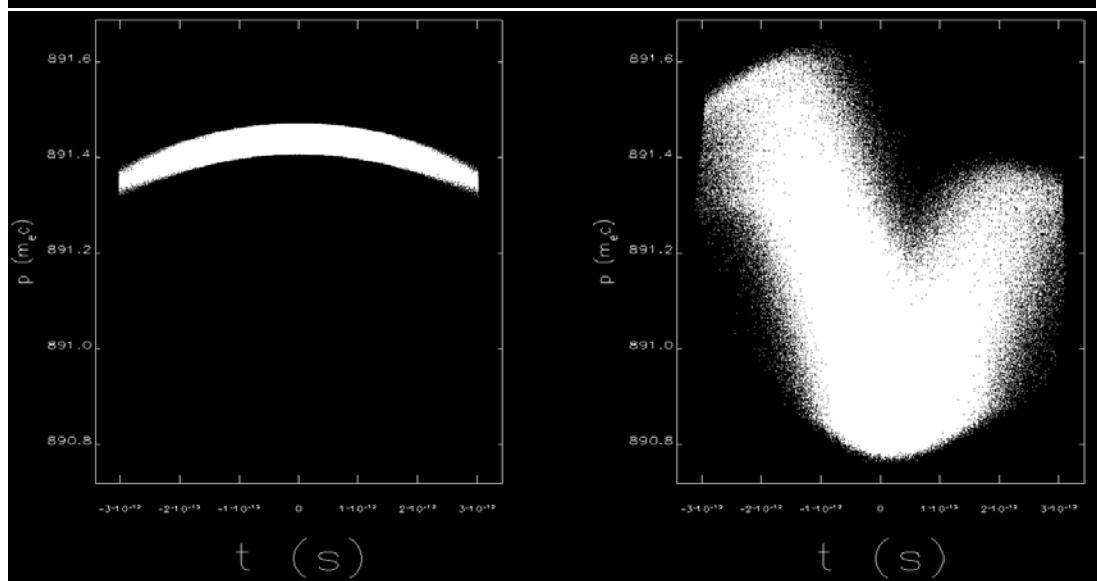
## Longitudinal Distribution

$\sigma_t = 0.1 \text{ ps}$



## Longitudinal Distribution

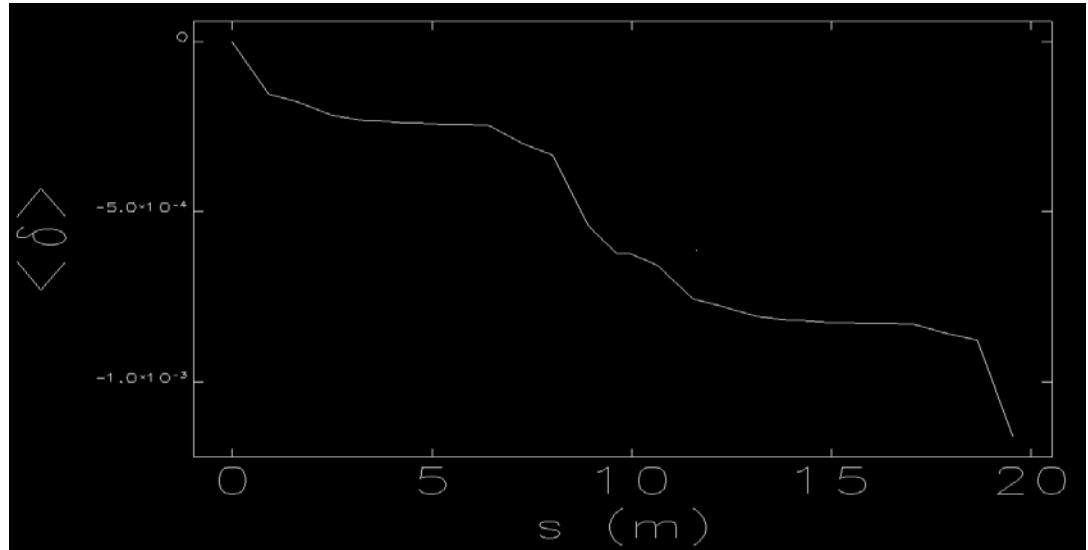
$\sigma_t = 1 \text{ ps}$



# FMC arc

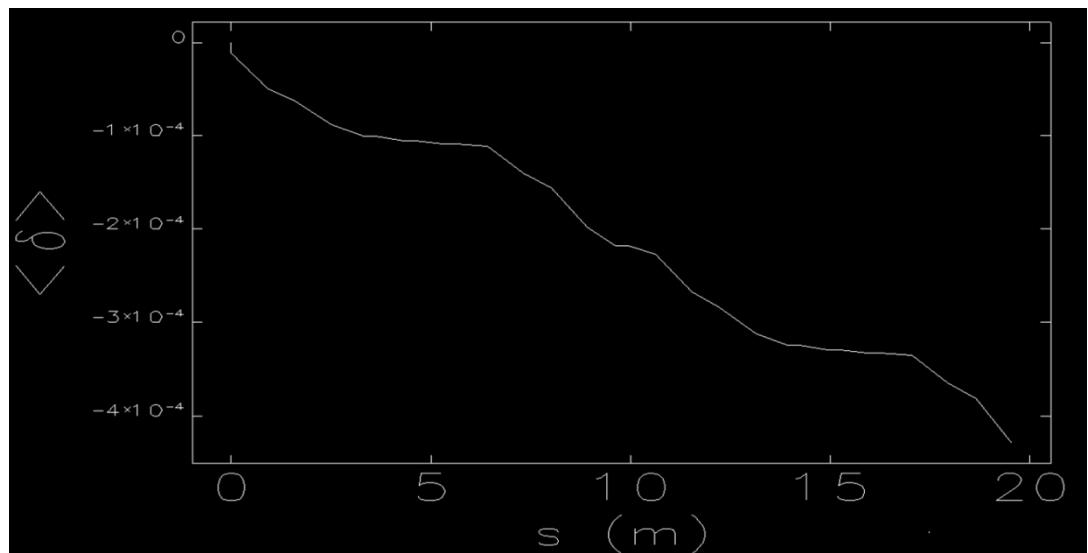
Centroid Energy loss due to ISR and **CSR** (dominant) during transport through arc  
~5 kW at 10 mA

$$\sigma_t = 0.1 \text{ ps}$$



Centroid Energy loss due to ISR and **CSR** (dominant) during transport through arc  
~2 kW at 10 mA

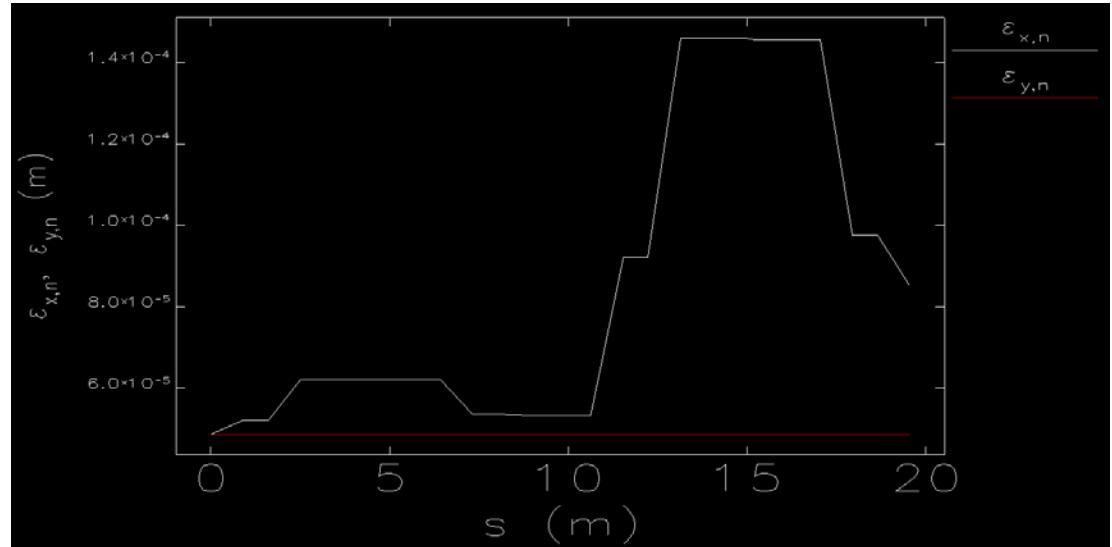
$$\sigma_t = 1 \text{ ps}$$



# FMC arc

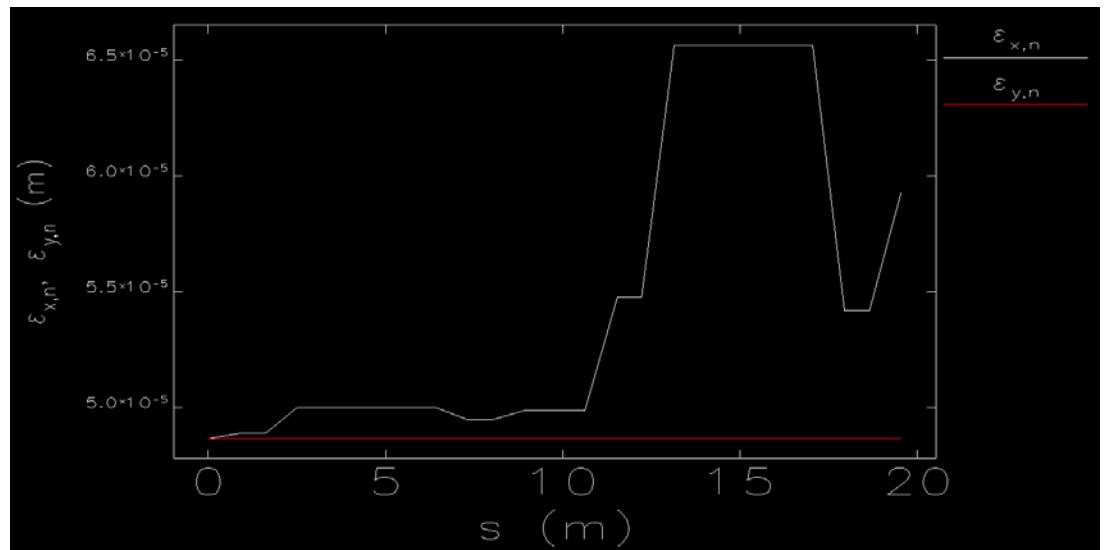
Evolution of transverse normalized emittance through arc

$\sigma_t = 0.1 \text{ ps}$



Evolution of transverse normalized emittance through arc

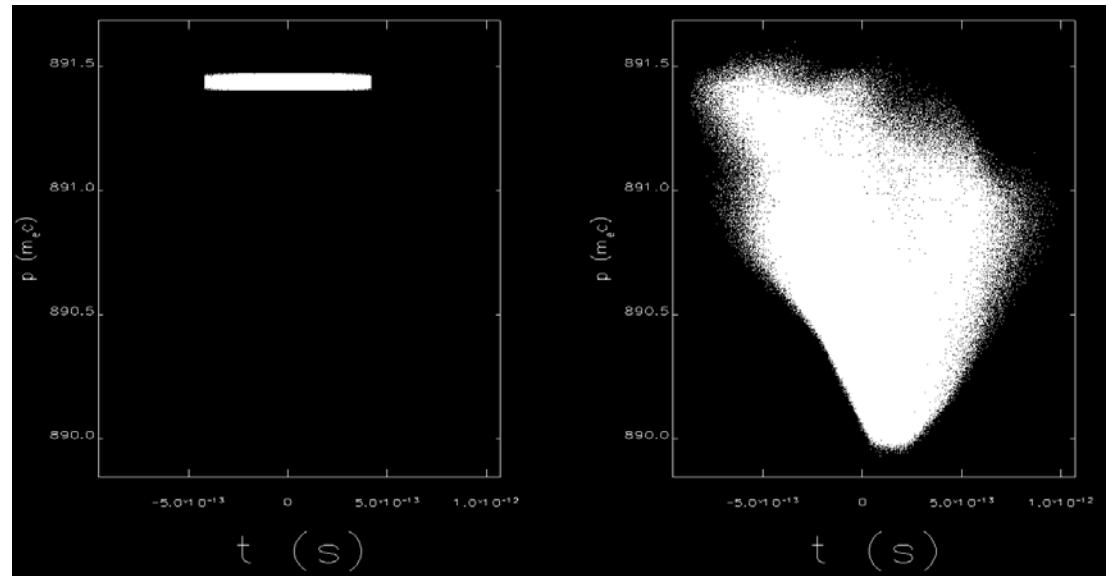
$\sigma_t = 1 \text{ ps}$



# FODO arc

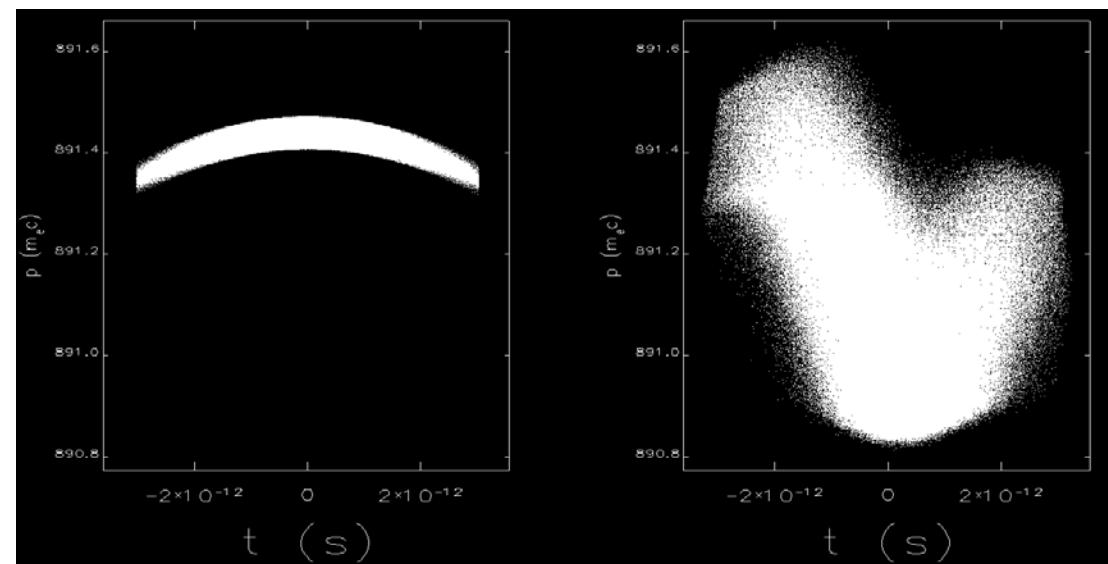
## Longitudinal Distribution

$\sigma_t = 0.1 \text{ ps}$



## Longitudinal Distribution

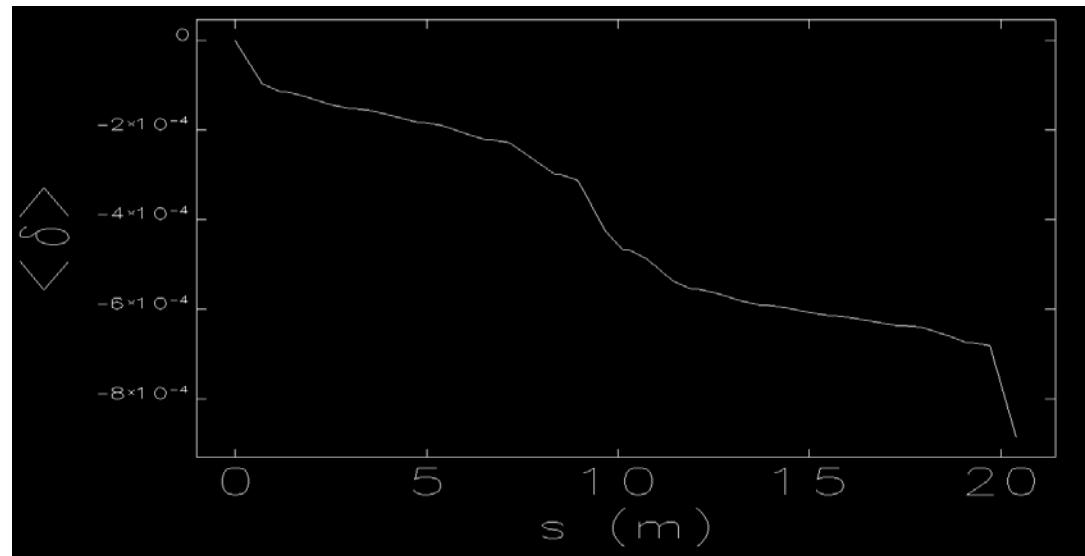
$\sigma_t = 1 \text{ ps}$



# FODO arc

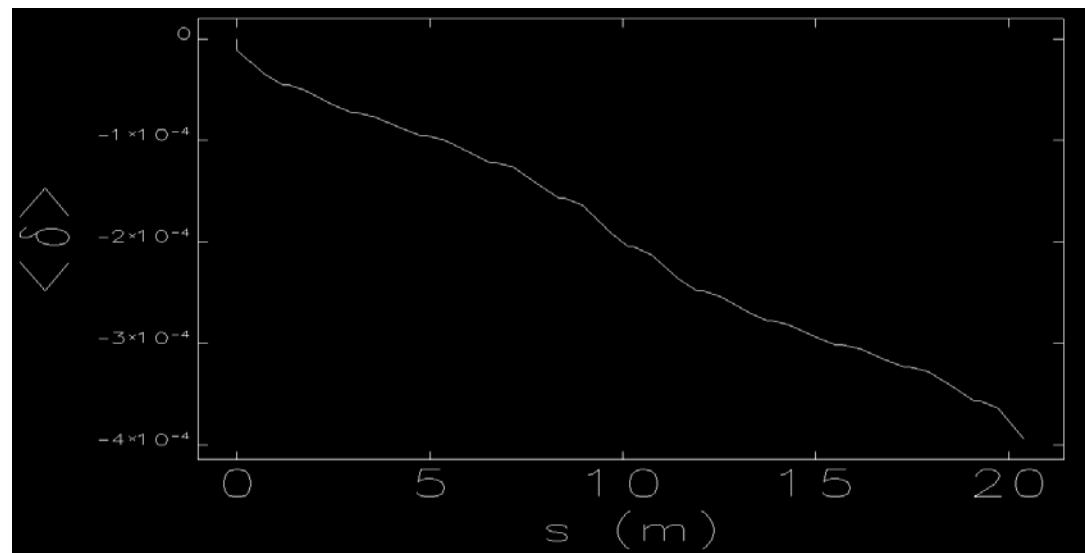
Centroid Energy loss due to ISR and **CSR** (dominant) during transport through arc  
~4 kW at 10 mA

$$\sigma_t = 0.1 \text{ ps}$$



Centroid Energy loss due to ISR and **CSR** (dominant) during transport through arc  
~2 kW at 10 mA

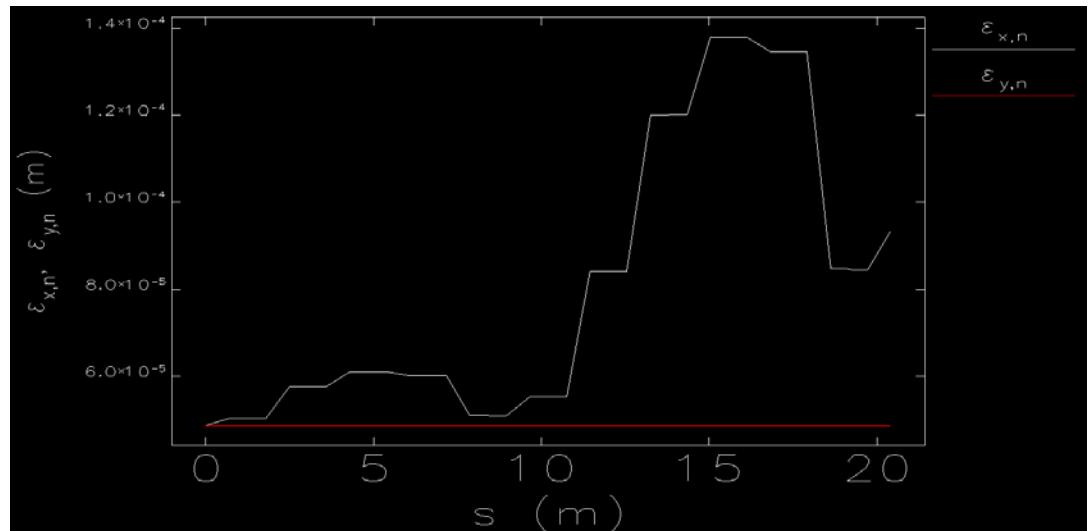
$$\sigma_t = 1 \text{ ps}$$



# FODO arc

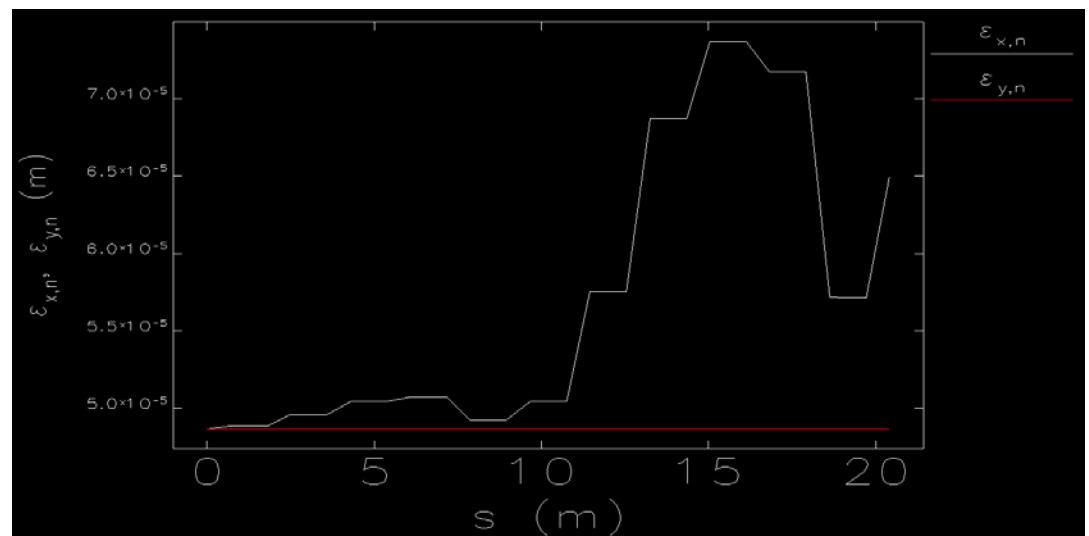
Evolution of transverse normalized emittance through arc

$$\sigma_t = 0.1 \text{ ps}$$



Evolution of transverse normalized emittance through arc

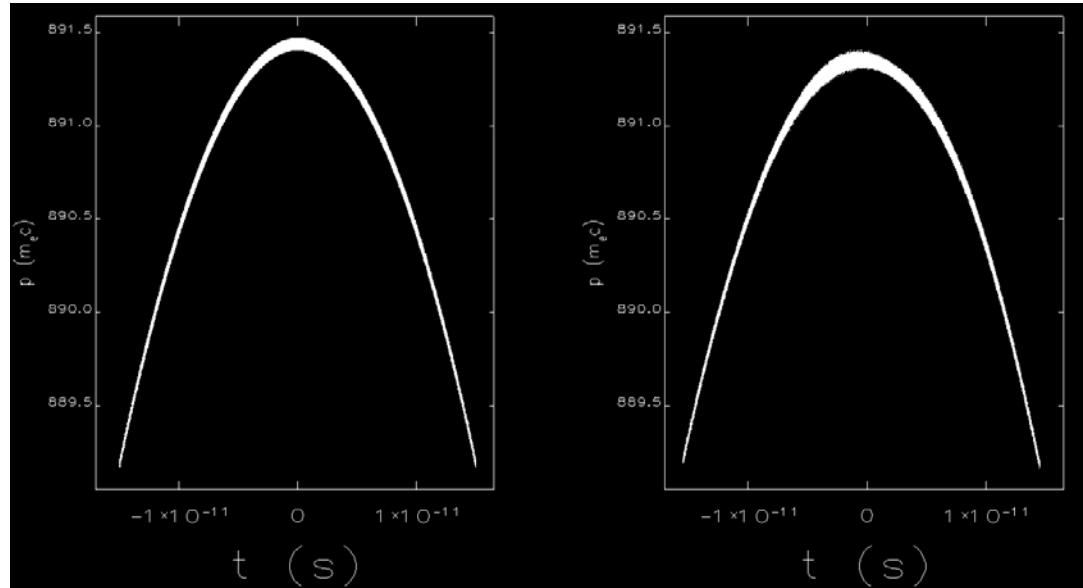
$$\sigma_t = 1 \text{ ps}$$



# FMC arc

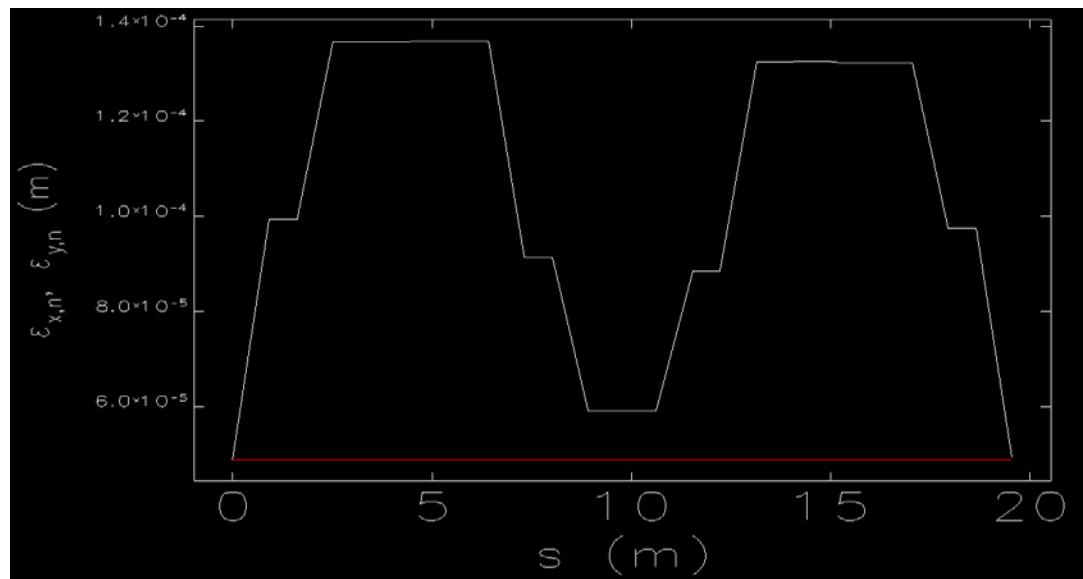
## Longitudinal Distribution

$\sigma_t = 4 \text{ ps}$



Evolution of transverse normalized emittance through arc

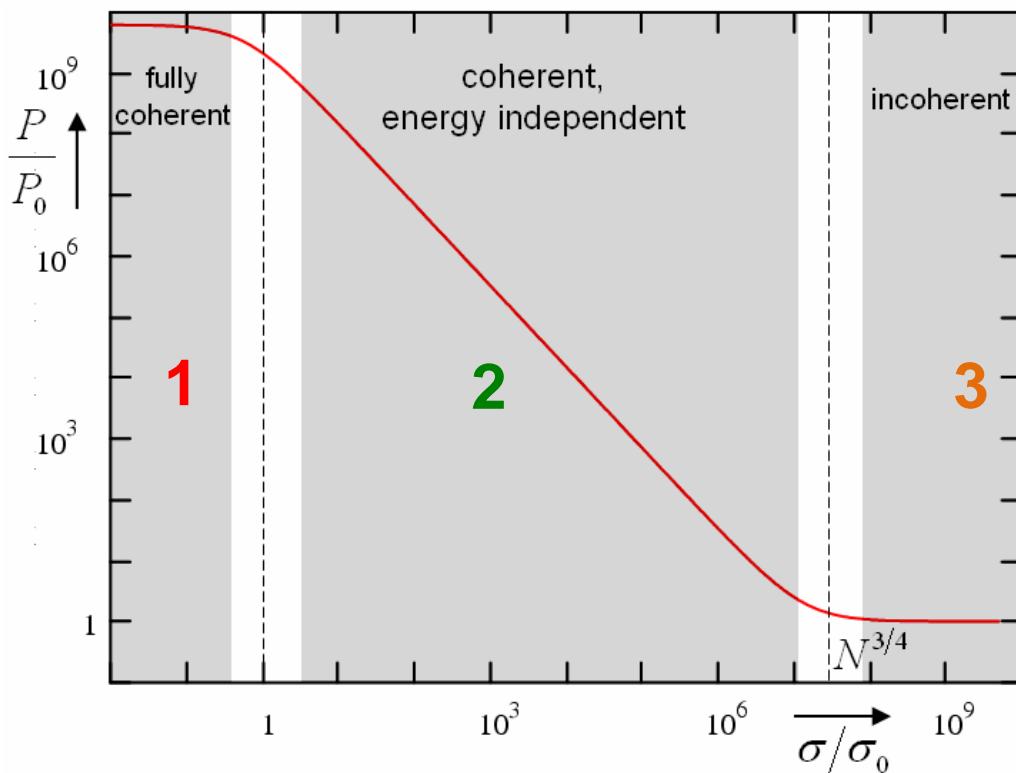
$\sigma_t = 4 \text{ ps}$



# CSR and ISR in return arcs : analytical calculation

Three regimes can be distinguished as a function of  $\sigma/\sigma_0$   
 $\sigma$  bunch length

$$\sigma_0 \approx R/\gamma^3$$



Total radiated power as a function of the bunch length

1.  $\sigma/\sigma_0 < 1$

**FULLY COHERENT REGIME**

$$P_f = N^2 \frac{1}{6\pi} \frac{e^2 c}{\epsilon_0} \frac{\gamma^4}{R^2}$$

2.  $1 < \sigma/\sigma_0 < N^{3/4}$

**ENERGY-INDEPENDENT  
COHERENT REGIME**

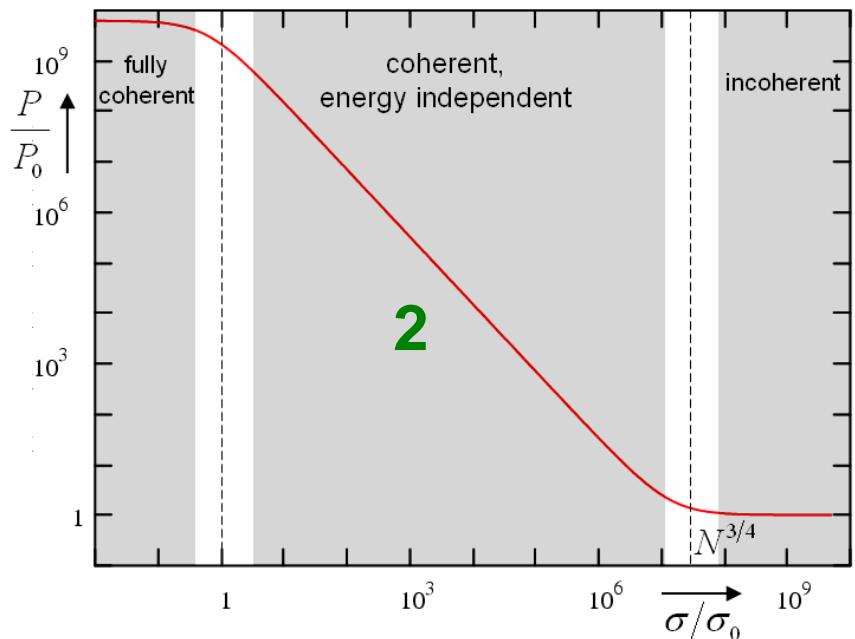
$$P_{csr} = N^2 x \frac{e^2 c}{\epsilon_0} \frac{1}{R^{2/3} \sigma_z^{4/3}}$$

3.  $\sigma/\sigma_0 > N^{3/4}$

**INCOHERENT REGIME**

$$P_0 = N \frac{1}{6\pi} \frac{e^2 c}{\epsilon_0} \frac{\gamma^4}{R^2}$$

# CSR and ISR in return arcs



2.  $1 < \sigma/\sigma_0 < N^{3/4}$   
ENERGY-INDEPENDENT  
COHERENT REGIME

$$P_{csr} = N^2 x \frac{e^2 c}{\epsilon_0} \frac{1}{R^{2/3} \sigma_z^{4/3}}$$

@  $\sigma_z = 300$  um up to 900 MeV

**CSR is dominant**

$P_{CSR} = 2.7$  kW

@  $\sigma_z = 1200$  um

$P_{CSR} = 435$  W

# CSR effects

Shielding is important if

$$\sigma_z > \sqrt{\frac{h^2 w}{\pi^2 \rho}} *$$

with  $h$  and  $w$  the full height and full width of the vacuum chamber and  $\rho$  the bending radius.

For LHeC, if we take  $h=w=20$  mm,  $\rho=760$  m

Shielding is important if  $\sigma_z > 33 \mu m$

For the ERL-TF, if we take  $h=20$  mm,  $w=40$  mm,  $\rho=2.3$  m

Shielding is important if  $\sigma_z > 800 \mu m$

## REQUIRE FURTHER ANALYSIS

\*The formula for shielding condition is based on Derbenev et al paper [DESY TESLA FEL 95-05, 1995] and Warnock et al paper [SLAC-PUB-5523, 1991].



# CSR effects → Possible Solution

## Control of Coherent Synchrotron Radiation and Micro-Bunching Effects During Transport of High Brightness Electron Beams

D.R. Douglas, S.V. Benson, A. Hutton, G.A. Krafft, R. Li, G.R. Neil, Y. Roblin, C.D. Tennant, C.-Y. Tsai  
Thomas Jefferson National Accelerator Facility, Newport News, VA 23606

### Abstract

Beam quality preservation during transport of high-brightness electron beams is of general concern in the design of modern accelerators. Methods to manage incoherent synchrotron radiation have been in place for decades [1]; as beam brightness has improved coherent synchrotron radiation (CSR) and the microbunching instability ( $\mu$ BI) have emerged as performance limitations. We apply the compensation analysis of diMitri, Cornacchia, and Spampinati [2] – as previously used by Borland [3] – to the design of transport systems for use with low-emittance beams, and find that appropriately configured second order achromats [4] will suppress transverse emittance growth due to CSR and appear to limit  $\mu$ BI gain.

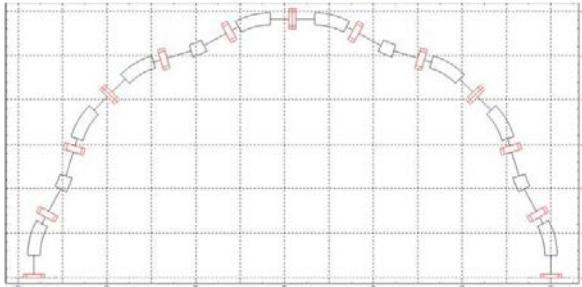
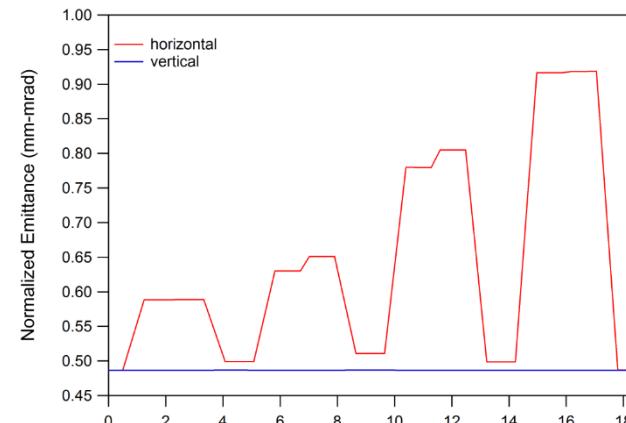


Figure 2: Full 180° arc of four TBA superperiods.



A second-order achromat composed of superperiods that are individually linearly achromatic and isochronous meets all requirements for the suppression of CSR effects. CSR induced momentum shift will be paired to a matching shift at a downstream location with the same lattice parameters and the same bunch length

1.0 ps x 25 keV with 25 mm-mrad at 350 pC and 200 MeV/c, no transverse emittance growth and usual CSR wake imposed on the longitudinal distribution.

# Preliminary study of CSR → induced microbunching gain

Analysis done for two different arc lattices FMC and Perturbed FODO:

- gain function  $G(s)$
- gain spectrum  $G(\lambda)$

## Input Beam Parameters

PARAMETER	VALUE
Energy	455 MeV
Normalized emittance $\gamma \varepsilon_{x,y}$	50 $\mu\text{m}$
Bunch population	$2 \times 10^9$
Bunch charge	320 pC

### Distribution C:

$$\sigma_t = 4 \text{ ps} (1.2 \text{ mm}) \rightarrow I_{\text{peak}} = 34 \text{ A}$$

$$\sigma_{DE} = 5.5 \text{ keV}$$

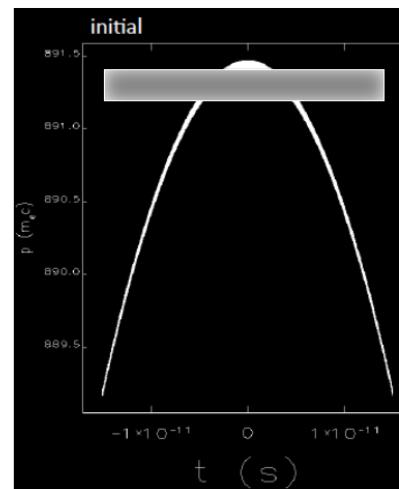
# Preliminary study of CSR → induced microbunching gain

## ASSUMPTIONS

- In the simulation we assume the initial 4D phase space distribution is Gaussian in both transverse plane and longitudinal momentum coordinate, and make coasting beam approximation,

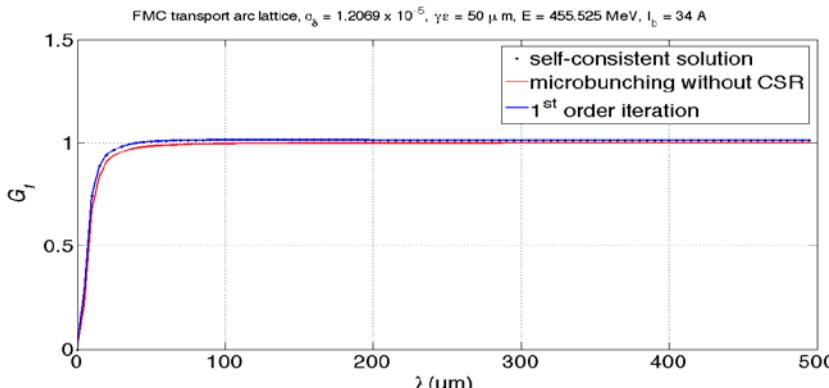
$$f_0 = \frac{n_b}{2\pi\epsilon_0} \exp\left(-\frac{x_0^2 + (\beta_0\theta_0)^2}{2\epsilon_0\beta_0}\right) \frac{1}{\sqrt{2\pi}\sigma_p} \exp\left(-\frac{p^2}{2\sigma_p^2}\right)$$

- That is, for the initial longitudinal phase space distribution as Chris showed, we ignore the ‘curvature’ effect in our simulation.
- In the simulation, we also neglect transient CSR effect; we could if the dipole length (70-90 cm) is not that short. In our two cases, this model is valid.



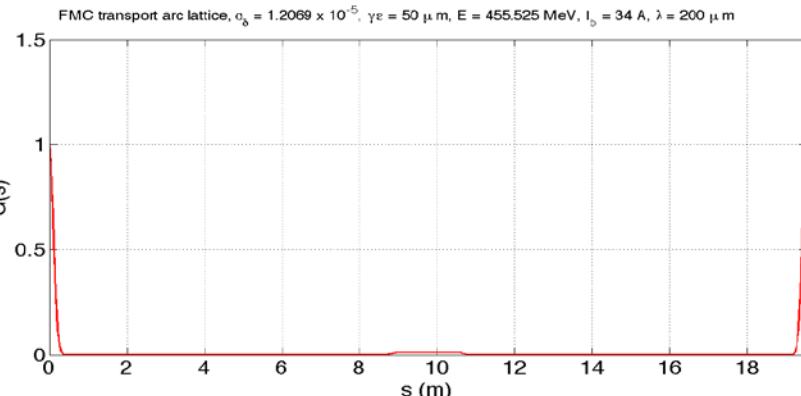
# Induced microbunching gain

## FMC, Gain spectrum $G_f(\lambda)$



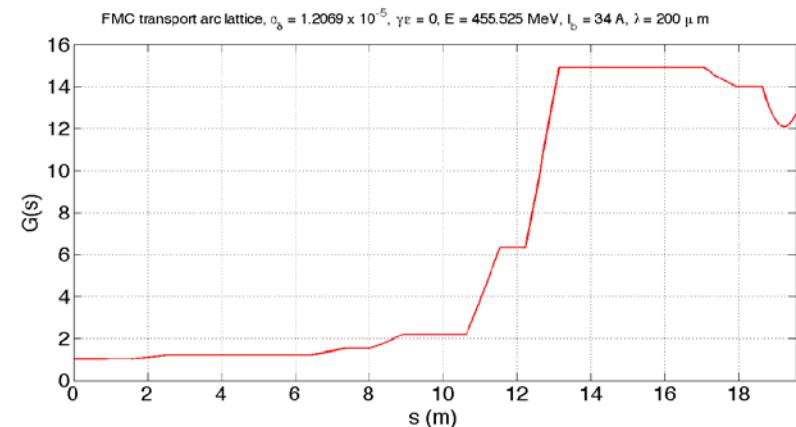
It appears no CSR gain in the broad spectral range, due to large emittance-induced Landau damping. (see next 2 slides)

## FMC, Gain function $G(s)$



Looking at how CSR gain evolves along the lattice, it is found the gain is almost suppressed throughout. Let's see if  $\gamma\varepsilon = 0$ ...

## FMC, Gain function $G(s)$



Then, CSR gain grows due to the lack of emittance.

# Induced microbunching gain

## Summary

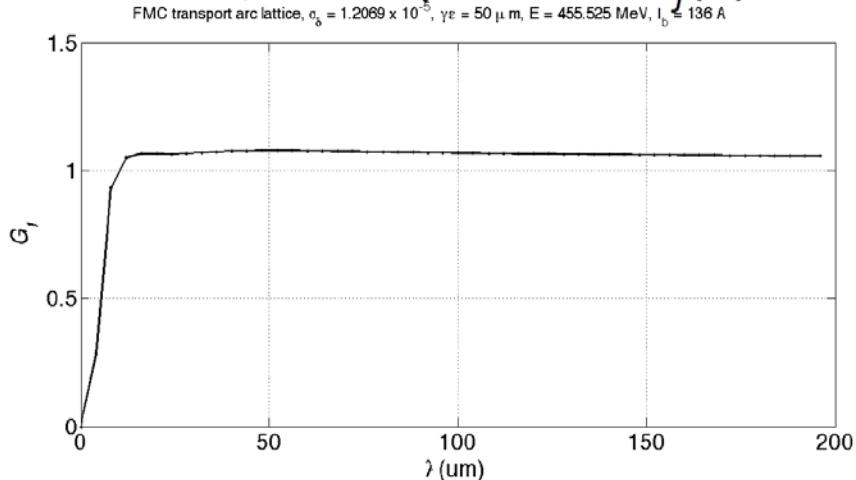
- For the given parameters of both FMC and Perturbed FODO lattices, it appears no obvious CSR gain in the present parameter range.
- The physical mechanism is Landau damping due to (relatively) large transverse emittance ( $50 \mu\text{m}$ ) of the beam, compared with energy spread.
- For the case of *smaller* emittance, it looks the Perturbed FODO lattice may be subject to CSR more than the FMC lattice.

Increasing the beam current  
by decreasing the bunch length  
(keeping the bunch charge fixed)....



# Induced microbunching gain

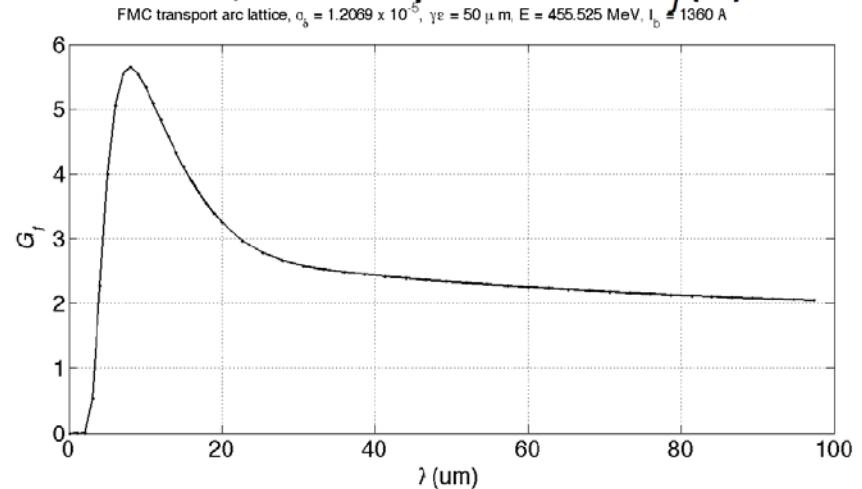
FMC, Gain spectrum  $G_f(\lambda)$



Longitudinal Distribution

$$\sigma_t = 1 \text{ ps}$$

FMC, Gain spectrum  $G_f(\lambda)$



Longitudinal Distribution

$$\sigma_t = 0.1 \text{ ps}$$

The gain is still (relatively) not that large  
but CSR introduces emittance growth....



# Summary

- Add sextupoles to see linearization of longitudinal phase space
- Correct the curvature with sextupoles in the arc
- Decide what is the longest bunch we can transport in the ERL
- Analyze the evolution of the longitudinal phase-space
- **End-to-End beam dynamics simulations**

## 3. MERGER DESIGN ISSUES

- POSSIBLE SCHEMES (zigzag, chicane, dog-leg)
- BEAM DYNAMICS SIMULATIONS (???)
- INJECTOR SCHEMES

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