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Jefferson Lab
Thomas Jefferson National Accelerator Facility

Suppressing Coherent Synchrotron Radiation Microbunching in Recirculation Arcs

Cheng-Ying Tsai

SLAC National Accelerator Laboratory

May 2, 2018

IPAC'18 at Vancouver, Canada

WEYGBE1

Outline

- Introduction and Overview
- Theoretical formulation of CSR microbunching in a single-pass system
- Suppressing CSR microbunching through optics balance
- Examples
- Suppressing CSR microbunching through magnetized beam
- Examples
- Summary and Conclusion

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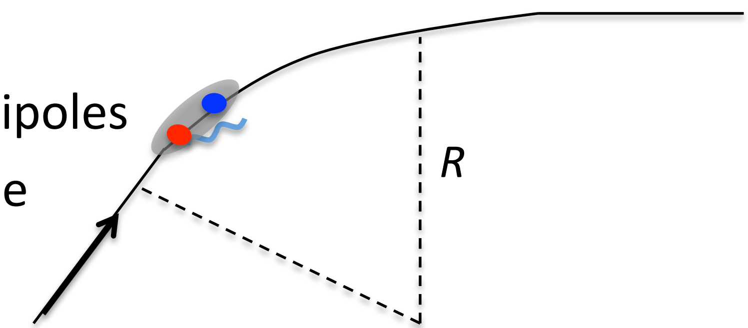
Coherent synchrotron radiation (CSR)

- When a source particle enters a dipole, it emits radiation
- Retardation condition must be met
  for test particle receiving radiation within dipoles
- Longitudinal field acting on the head particle
  from rigid line bunch:



$$E_s(z) = \frac{2e^2}{4\pi\epsilon_0 (3R^2)^{1/3}} \int_{-\infty}^{z} \frac{d\zeta}{(z-\zeta)^{1/3}} \frac{d\lambda(\zeta)}{d\zeta}$$

$$Z_{CSR}^{ss}(k) = -\frac{Z_0}{4\pi} \frac{iAk^{1/3}}{R^{2/3}}, A \approx 1.63i - 0.94$$

Ya. S. Derbenev et al., DESY Report No. TESLA-FEL 95-05 (1995)
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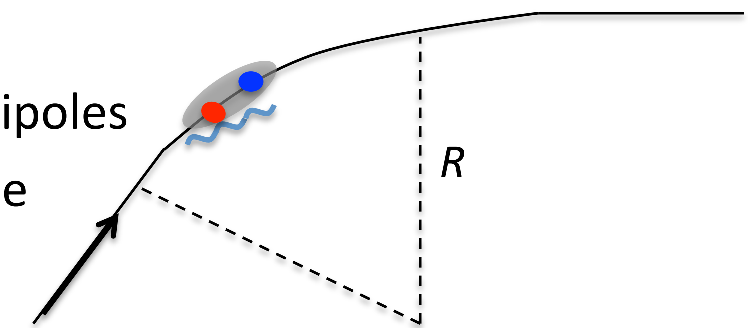

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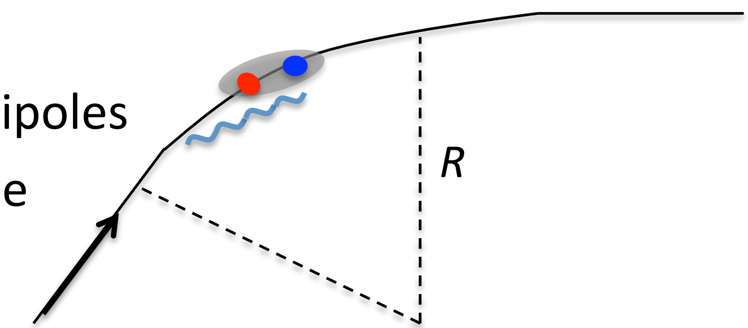

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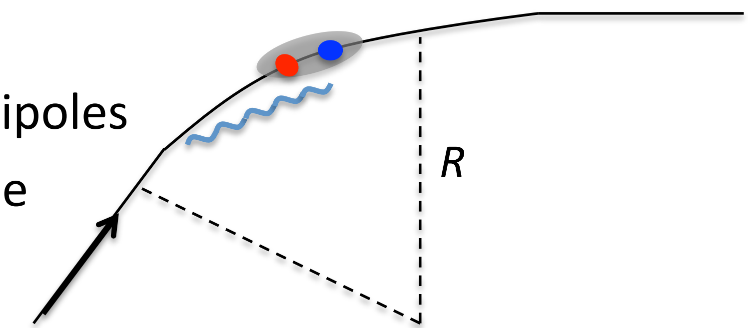

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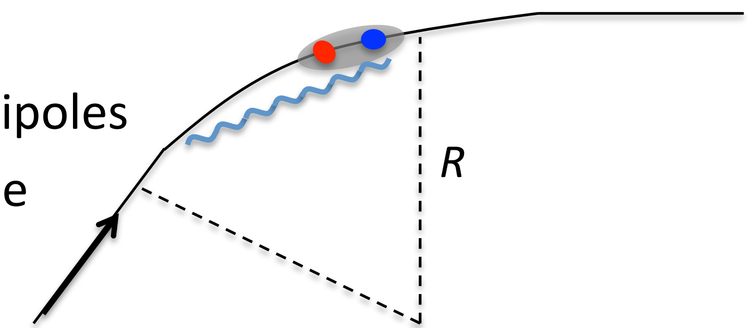

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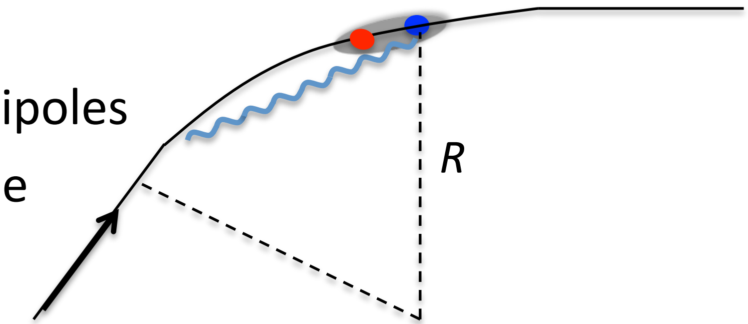

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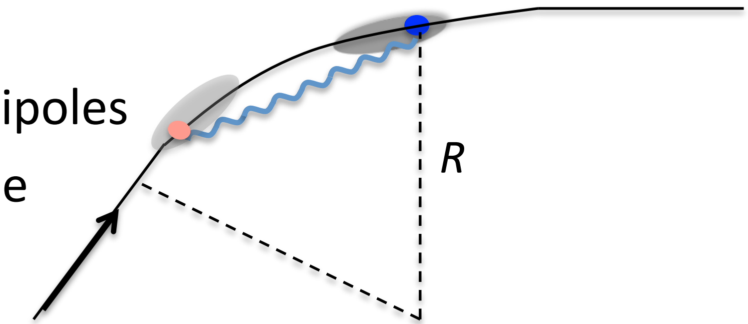

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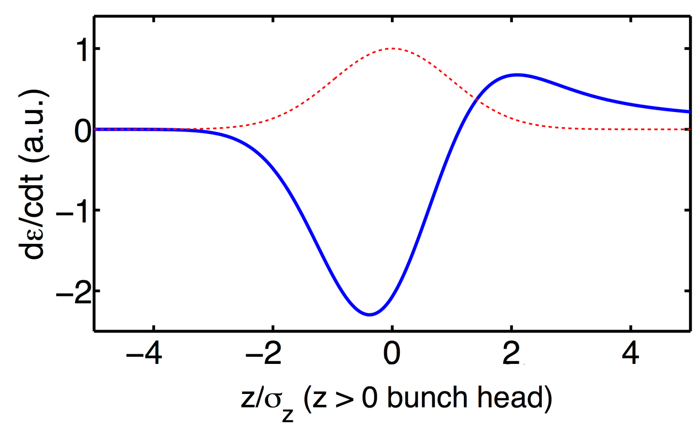
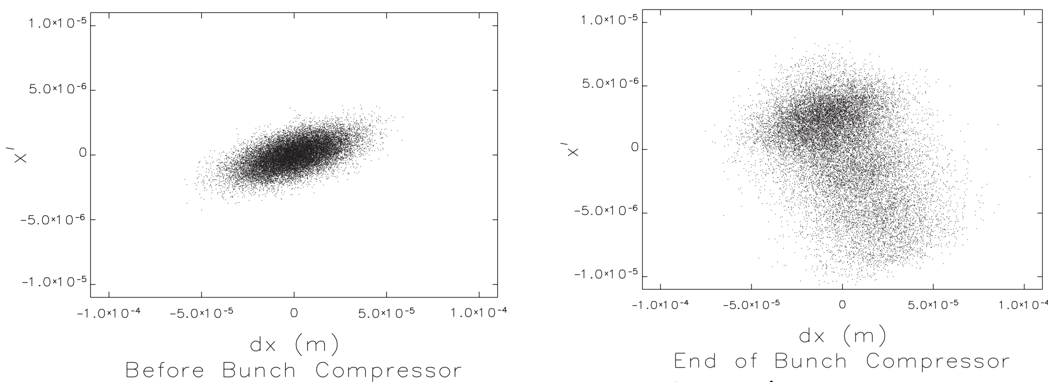


Ya. S. Derbenev et al., DESY Report No. TESLA-FEL 95-05 (1995)
E. L. Saldin et al., NIMA 398, 373 (1997)

CSR effects on the beam

- **Transverse: Phase space smearing ➔ Emittance Growth**



Y. Jing et al., PRSTAB 16, 060704 (2013)

Energy kick $\Delta\delta_{CSR}(z)$

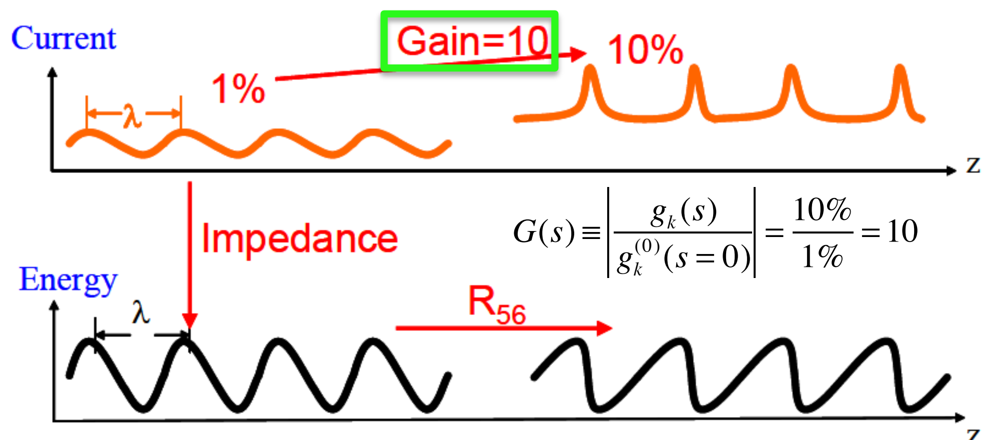
$R_{16} \Downarrow R_{26}$

$\Delta x_{CSR} \quad \Delta x'_{CSR}$

$\Downarrow$

possible ε-growth

- **Longitudinal: Microbunching Instability (MBI)**



Z. Huang and J. Wu, Beam Dynamics Newsletter, No. 38

Density modulation

$Z_{CSR}(k) \Downarrow \quad \Uparrow R_{56}$

Energy modulation

Overview of mitigation schemes

Mitigation of CSR effects on beam dynamics		
Domain	Mitigation schemes	Note
Transverse	**Cell-to-cell phase matching** (Douglas, Di Mitri *et al.*)	optics adjustment
	Beam **envelope matching** (Hajima)	
	Combination of the above concepts, application to DBA/TBA (Jiao *et al.*) or bunch compressor system (Jing *et al.*)	
	Longitudinal **bunch shaping** (Mitchell *et al.*)	tailor initial beam conditions
Longitudinal	Laser **heating** (Saldin *et al.*, Huang *et al.*)	Landau damping/Phase space smearing via σ_δ
	Magnetic **mixing** chicane (Di Mitri *et al.*)	
	Reversible electron beam **heating** (Behrens *et al.*)	
	Insertion of dipole pair in an accelerator system (Qiang *et al.*)	take advantage of ε_x via R_{51} and R_{52}

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	Insertion of dipole pair in an accelerator system (Qiang *et al.*)	take advantage of ε_x via R_{51} and R_{52}
	Optical balance satisfying the proposed conditions	**optics adjustment**
	Magnetized beam with specialized transport line design	**tailor initial beam conditions**

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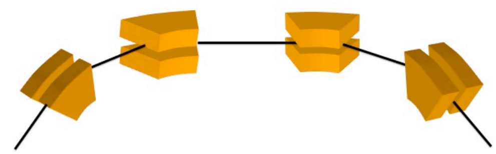
Vlasov treatment - a kinetic model

- Particle tracking: straightforward, subject to numerical noise (posing computational load)
- Vlasov method: more efficient in numerical simulation, free from numerical noise
- Vlasov equation + single-particle equations of motion for $(x, x', y, y', z, \delta)$

$$\frac{\partial f}{\partial s} + \left(\frac{dz}{ds}\right)\frac{\partial f}{\partial z} + \left(\frac{d\delta}{ds}\right)\frac{\partial f}{\partial \delta} + \left(\frac{dx}{ds}\right)\frac{\partial f}{\partial x} + \left(\frac{dy}{ds}\right)\frac{\partial f}{\partial y} + \left(\frac{dx'}{ds}\right)\frac{\partial f}{\partial x'} + \left(\frac{dy'}{ds}\right)\frac{\partial f}{\partial y'} = 0$$

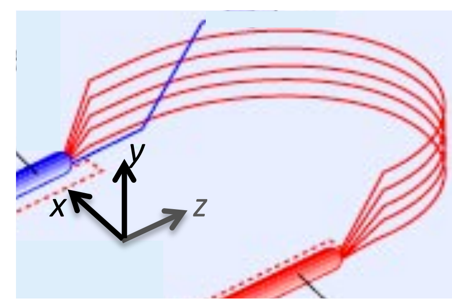
$$\frac{dz}{ds} = -\sqrt{\frac{E_0}{E_r(s)}}\left(\frac{x}{\rho_x(s)} + \frac{y}{\rho_y(s)}\right)$$



$$\frac{d\delta}{ds} = -\kappa(s)z - \frac{r_e}{\gamma}\int_{\infty}^{\infty} dz' W_{\parallel}\left(z - z', s\right) n\left(z', s\right)$$

$$\frac{dx}{ds} = x' \qquad \frac{dx'}{ds} = -K_x(s)x + \sqrt{\frac{E_0}{E_r(s)}}\frac{\delta}{\rho_x(s)}$$

$$\frac{dy}{ds} = y' \qquad \frac{dy'}{ds} = -K_y(s)y + \sqrt{\frac{E_0}{E_r(s)}}\frac{\delta}{\rho_y(s)}$$

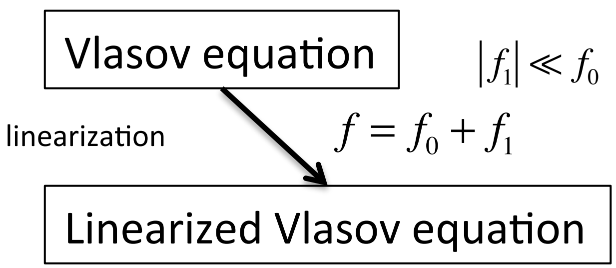


Including horizontal & vertical bend; combined-function bend; beam acceleration/deceleration; can also extend to transverse coupled beam

S. Heifets et al., PRSTAB **5**, 064401 (2002); Z. Huang and K. Kim, PRSTAB **5**, 074401 (2002); M. Venturini, PRSTAB **10**, 104401 (2007); C.-Y. Tsai et al., PRAB **19**, 114401 (2017) and PRAB **20**, 054401 (2017)

Vlasov treatment - a kinetic model

- Linearization of Vlasov equation
- Transform this problem **to frequency domain**
  - a beam modulation is Fourier component of its corresponding bunch distribution
- Derive the evolution of the **bunching factor**, which is used to characterize MBI
- Take into account the relevant collective effects



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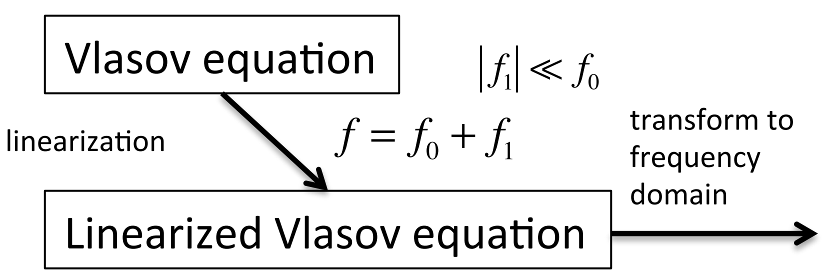

$$b_k(s) \equiv \int d\mathbf{X} f_1(\mathbf{X}; s) e^{-ikz}$$

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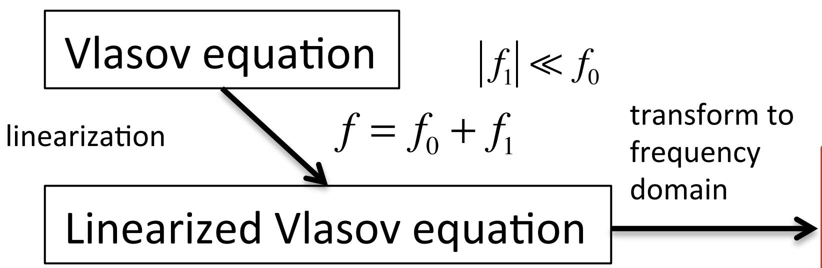

$$b_k(s) \equiv \int d\mathbf{X} f_1(\mathbf{X}; s) e^{-ikz}$$

$$b_k(s) = b_k^{(0)}(s) + \int_0^s K(s, s') b_k(s') ds'$$

$$G(s) = \left| \frac{b_k(s)}{b_k^{(0)}(s=0)} \right|$$ (amplification gain)

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Summary of mathematical formulas

◆ Integral form of the linearized Vlasov equation:

$$b_k(s) = b_k^{(0)}(s) + \int_0^s K(s,s')b_k(s')ds'$$

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$$K(s,s') = ik\frac{I(s)}{\gamma I_A}C(s')R_{56}(s' \to s)Z(k;s')\,\{\mathrm{L.D.}\}$$

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$$K(s,s') = ik \frac{I(s)}{\gamma I_A} C(s') R_{56}(s' \to s) Z(k;s') \{\mathrm{L.D.}\}$$

$$\{L.D.\} = \exp\left\{ \frac{-k^2}{2} \left[\epsilon_{x0}\beta_{x0}\left(R_{51}(s,s') - \frac{\alpha_{x0}}{\beta_{x0}} R_{52}(s,s')\right)^2 + \frac{\epsilon_{x0}}{\beta_{x0}} R_{52}^2(s,s') + \epsilon_{y0}\beta_{y0}\left(R_{53}(s,s') - \frac{\alpha_{y0}}{\beta_{y0}} R_{54}(s,s')\right)^2 + \frac{\epsilon_{y0}}{\beta_{y0}} R_{54}^2(s,s') + \sigma_\delta^2 R_{56}^2(s,s') \right] \right\}$$

intrinsic beam spread: {transverse emittances} {energy spread}

e.g., laser heating, magnetic mixing chicane,
or insertion of dipole pair in an accelerator system

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◆ Integral form of the linearized Vlasov equation:

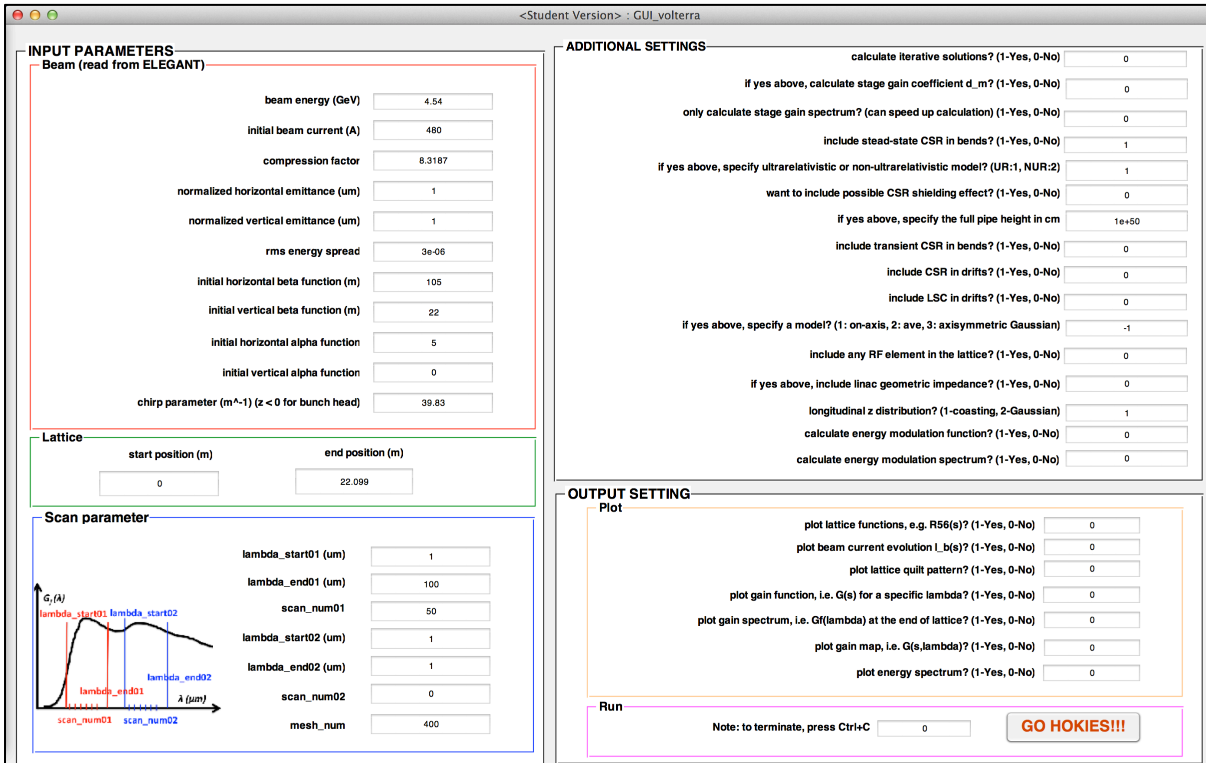
$$b_k(s) = b_k^{(0)}(s) + \int_0^s K(s, s')b_k(s')ds' \qquad G(s) = \left|\frac{b_k(s)}{b_k^{(0)}(s=0)}\right|$$

$$K(s, s') = ik\frac{I(s)}{\gamma I_A}C(s')R_{56}(s' \to s)Z(k; s')\,\{\text{L.D.}\}$$

$$R_{56}(s' \to s) = \left[\mathbf{R}(s' \to s)\right]_{56} = \left[\mathbf{R}(s)\mathbf{R}^{-1}(s')\right]_{56}$$

We aim to make this relative momentum compaction small because small $R_{56}(s' \to s) \Rightarrow$ small $K(s,s') \Rightarrow$ small $b_k(s)$

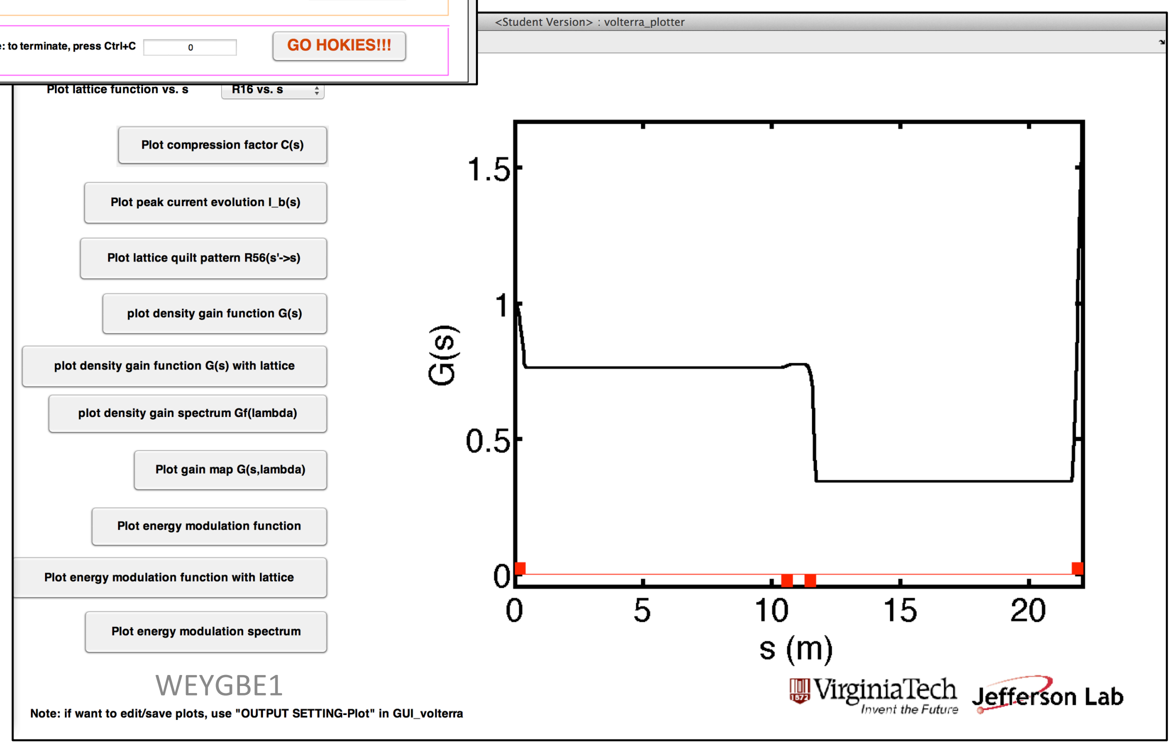
Optics balance can be employed to mitigate CSR effects



GUI: `volterra_mat`

Input: ELEGANT files (*.ele, *.lte)
Output: gain curves

A numerical code has been developed for the study and was benchmarked against ELEGANT. See, for detail, **JLAB-TN-14-016** and **JLAB-TN-15-019**.



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Features:

1. general (linear) lattice
2. fast
   (can be used for systematic study, or for lattice optimization if microbunching gain is of particular concern)
3. graphical user interface
4. most updated version v4.2 for non-magnetized beam; v2.0 for magnetized beam

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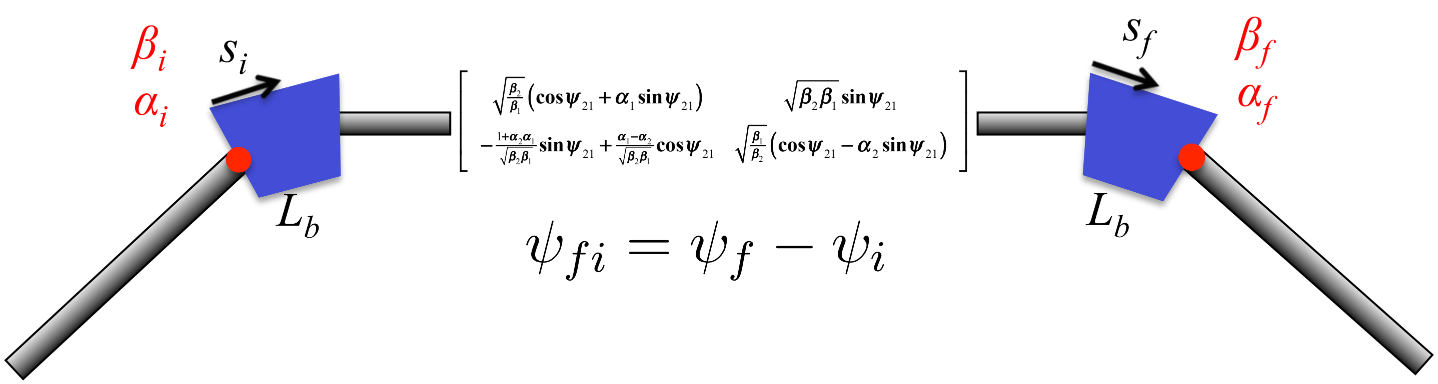
Linear optics analysis

- Linear transport matrix from s_i to s_f can be constructed via

$$\mathbf{R}_{6\times6}^{s_i\rightarrow s_f} = \mathbf{R}_{6\times6}^{dipole}\left(\theta = -\frac{L_b - s_2}{\rho_2}\right)\mathbf{R}_{6\times6}^{total}\mathbf{R}_{6\times6}^{dipole}\left(\theta = -\frac{s_1}{\rho_1}\right)$$

where the in-between section can be a general sequence of linear elements (achromatic or dispersive, isochronous or non-isochronous)



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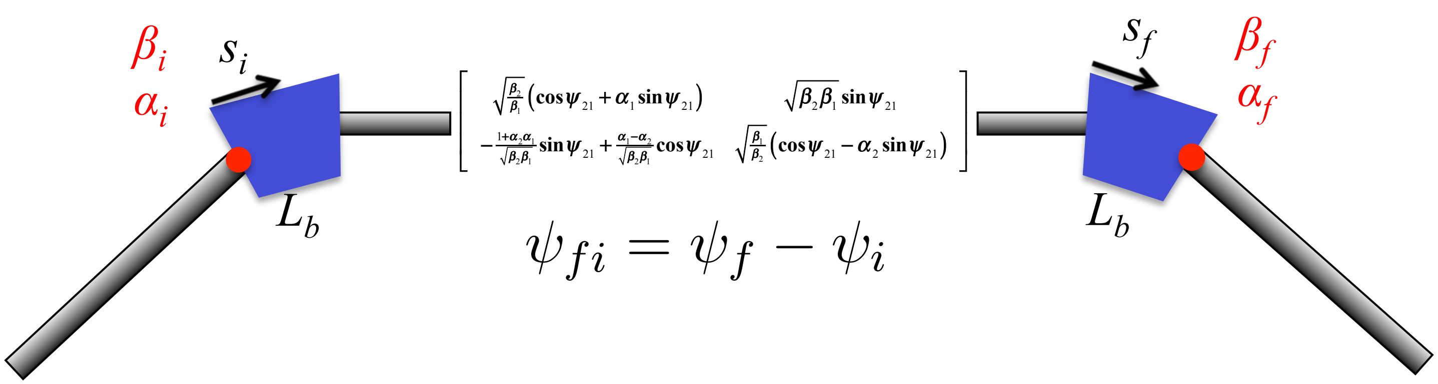

- <u>Sufficient</u> conditions to achieve small $R_{56}(s'\to s)$:
  - (1) prefer small β functions within dipoles
  - (2) avoid small α functions within dipoles
  - (3) ψ_{fi} close to $\sim\pi$ (or its integer multiple) for every dipole pairs

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Note: For emittance preservation, we usually require (3) among periodic units/cells

- These **empirical** conditions are examined over a wide range of beam energies and various types of transport lines and confirmed to be effective for suppressing CSR microbunching
- See PRAB **20**, 024401 (2017) for more details

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Examples

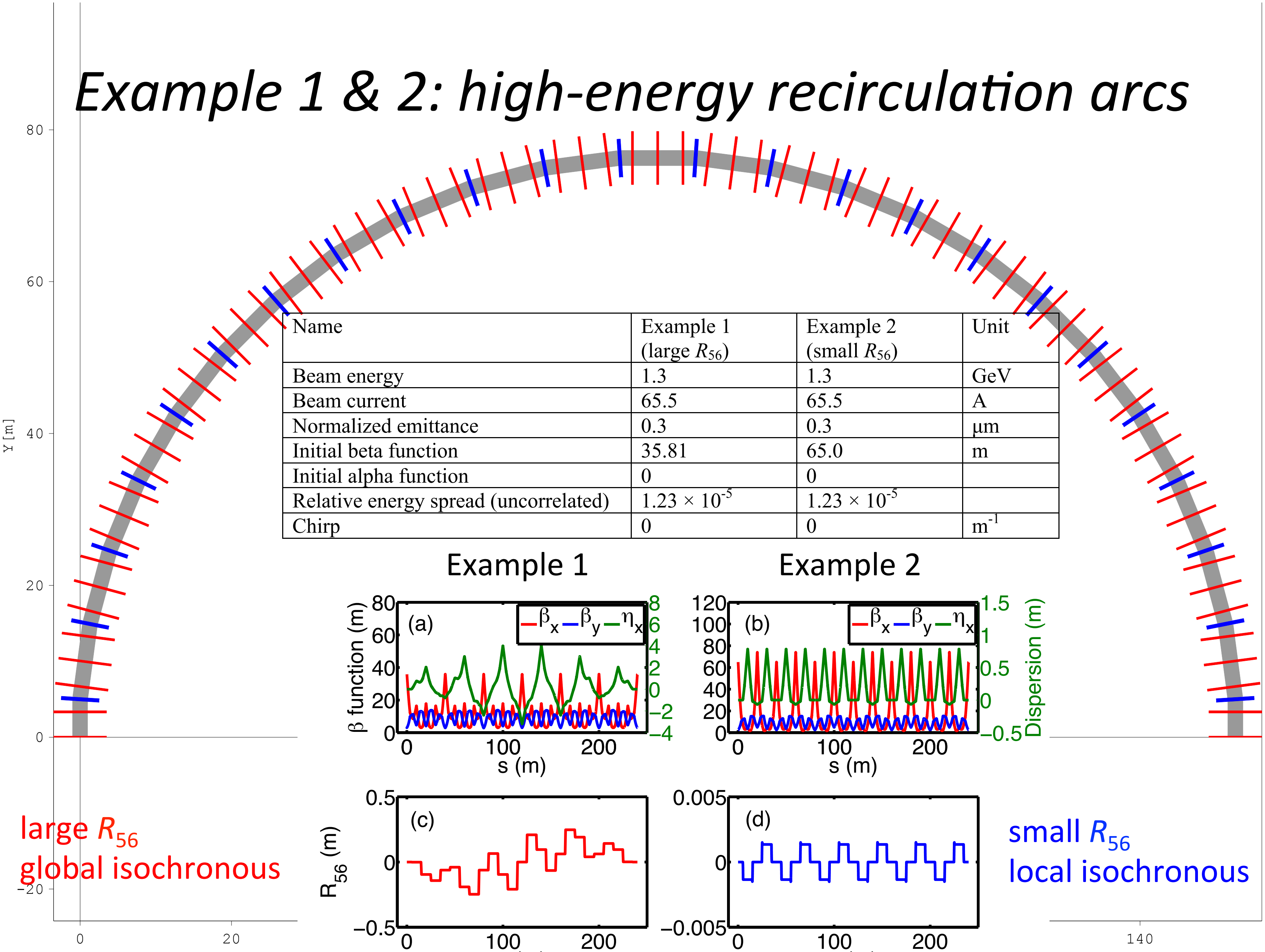
- Below we examine the proposed conditions by illustrating the following two sets of comparative example lattices

	Example 1	Example 2	Example 3	Example 4
ψ_{fi} description	(see next slides)	**~ 0 or $\sim \pi$** between dipoles	**$\sim \pi/2$** between dipoles	**~ 0 or $\sim \pi$** between dipoles
R_{56} description	**larger** R_{56} **global** isochronous	**smaller** R_{56} **local** isochronous	**larger** R_{56} **local** isochronous	**smaller** R_{56} **local** isochronous

D. Douglas et al., arXiv:1403.2318
D. Douglas et al., IPAC'15 (TUPMA038)

S. Di Mitri, PRSTAB **17**, 074401 (2014)

Example 1 & 2: high-energy recirculation arcs



Name	Example 1 (large R_{56})	Example 2 (small R_{56})	Unit
Beam energy	1.3	1.3	GeV
Beam current	65.5	65.5	A
Normalized emittance	0.3	0.3	µm
Initial beta function	35.81	65.0	m
Initial alpha function	0	0	
Relative energy spread (uncorrelated)	1.23×10^{-5}	1.23×10^{-5}	
Chirp	0	0	m^{-1}

large R_{56}
global isochronous

small R_{56}
local isochronous

D. Douglas et al., arXiv:1403.2318
D. Douglas et al., IPAC'15 (TUPMA038)

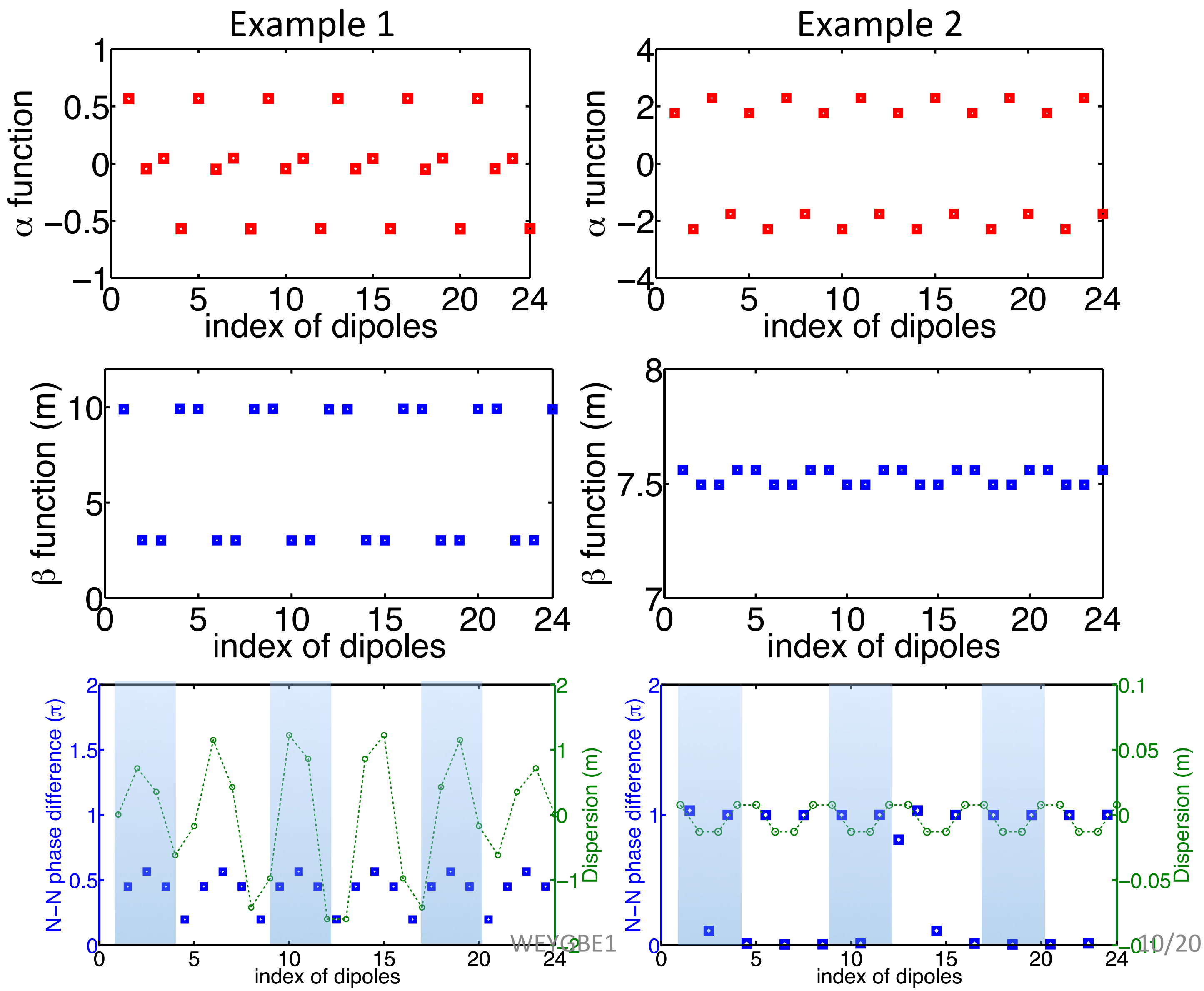
<u>Example 1:</u> *bad ε_{nx} preservation, bad gain suppression*

<u>Example 2:</u> *good ε_{nx} preservation, good gain suppression*

avoid small $|\boldsymbol{\alpha}|$ function

$\boldsymbol{\beta}$ functions as small as possible

phase difference close to $m\pi$



__Example 1:__ bad ε_{nx} preservation, bad gain suppression

__Example 2:__ good ε_{nx} preservation, good gain suppression

Example 1 | Example 2

avoid small $|\boldsymbol{\alpha}|$ function

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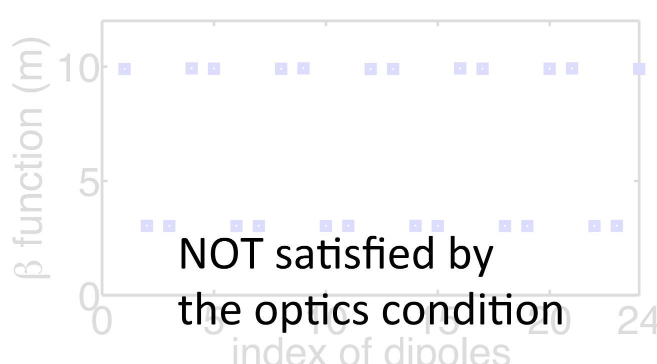
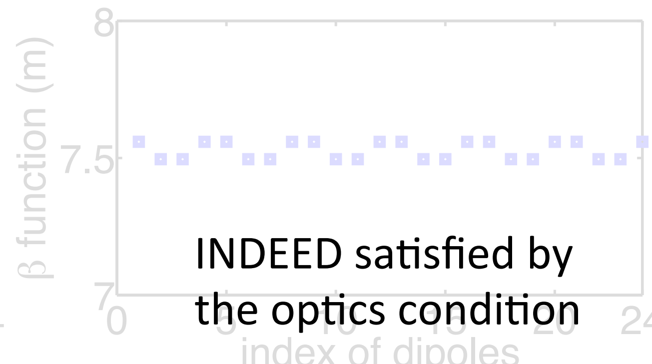
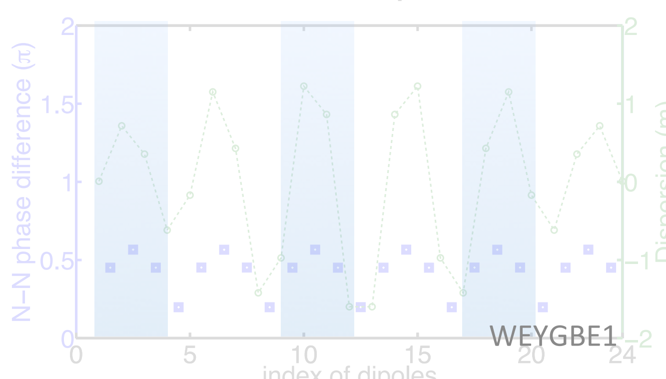


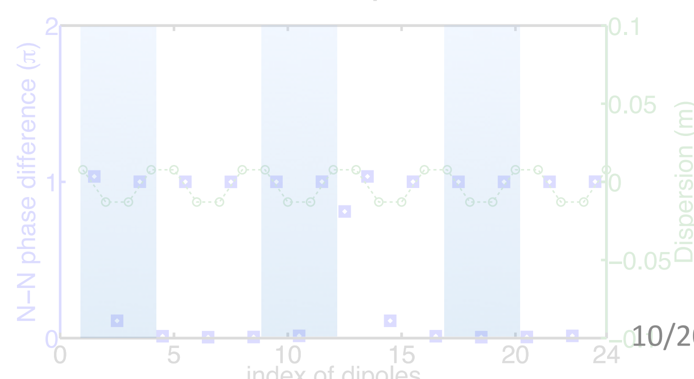
NOT satisfied by the optics condition



INDEED satisfied by the optics condition

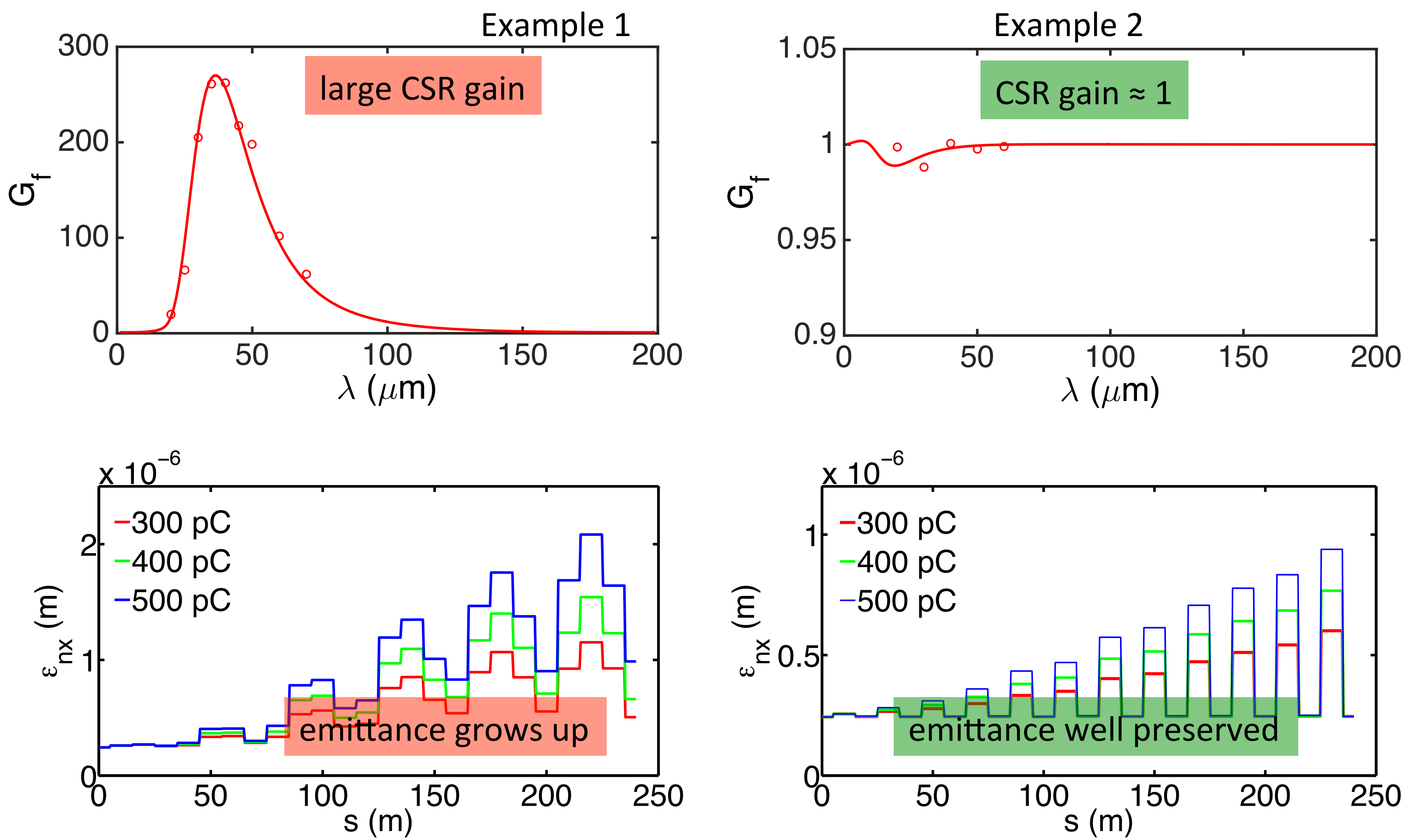
phase difference close to $m\pi$





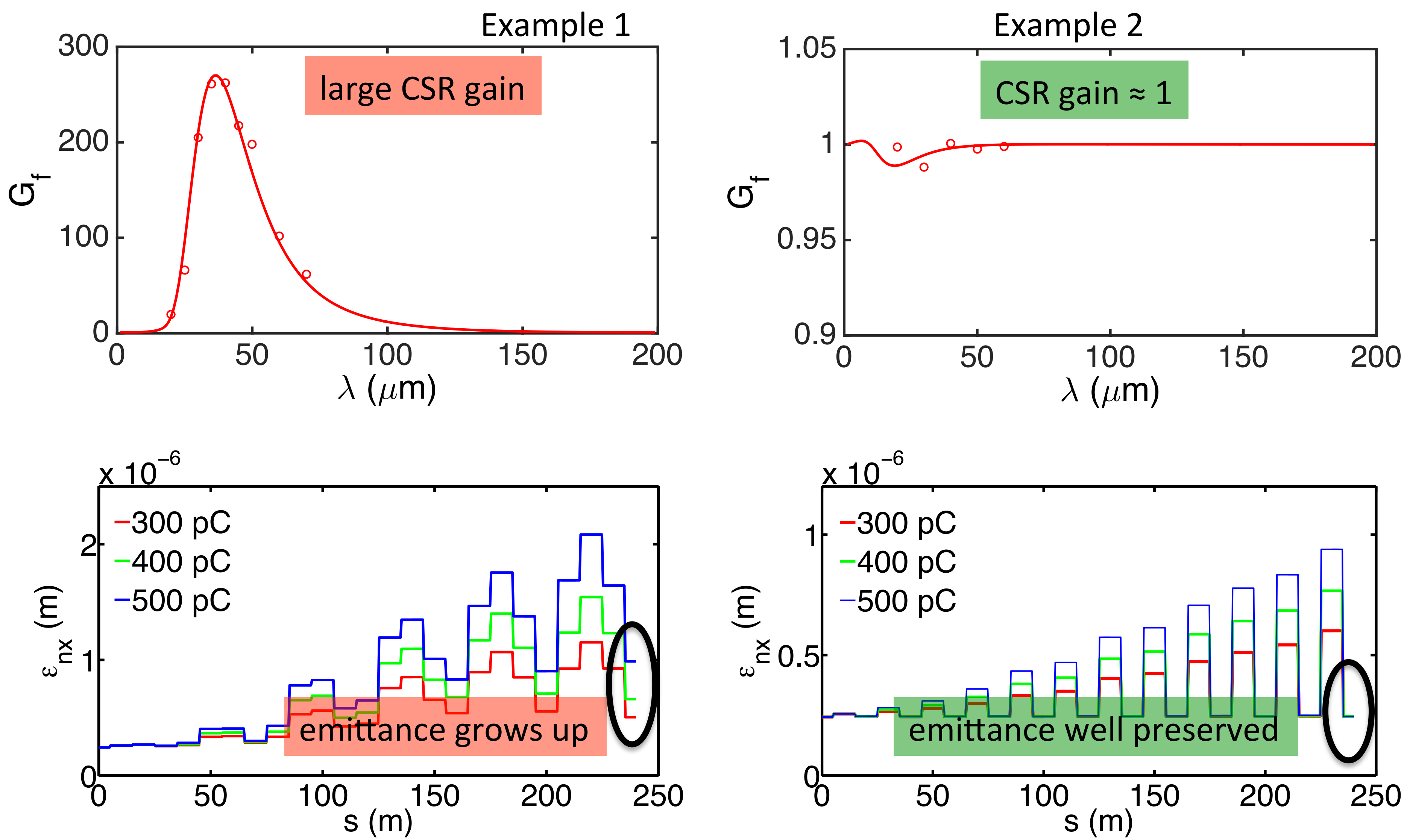
<u>Example 1:</u> bad ε_{nx} preservation, bad gain suppression

<u>Example 2:</u> good ε_{nx} preservation, good gain suppression



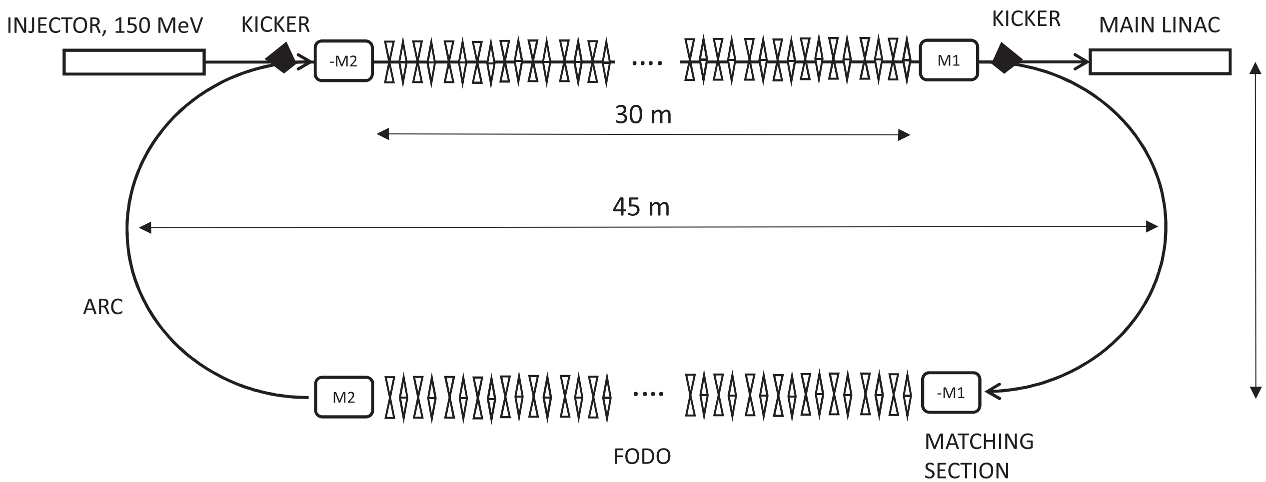
use **70M** macroparticles in ELEGANT tracking

Example 1: *bad ε_{nx} preservation, bad gain suppression*
Example 2: *good ε_{nx} preservation, good gain suppression*

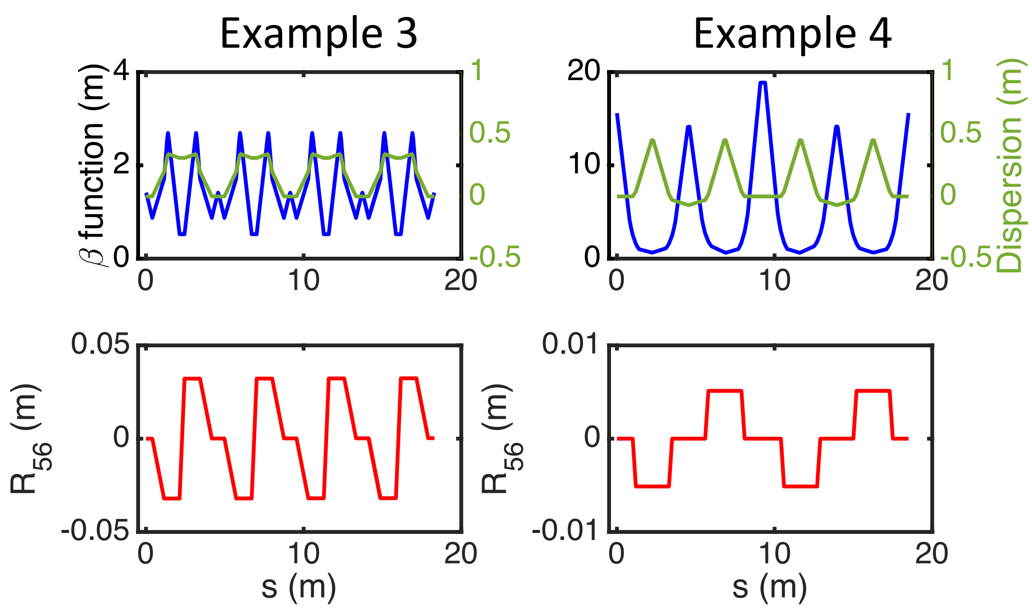


use **70M** macroparticles in ELEGANT tracking

Example 3 & 4: low-energy recirculation arcs



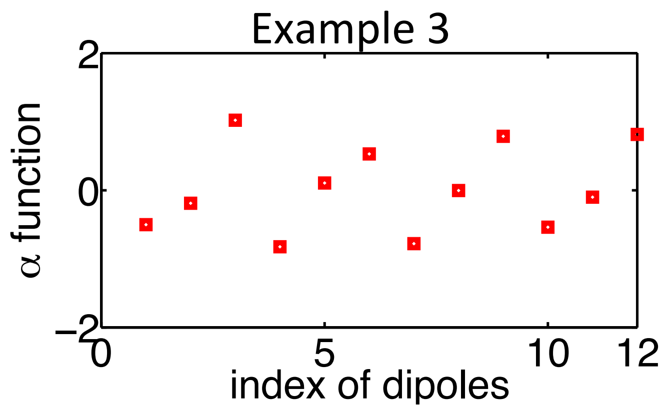
S. Di Mitri, PRSTAB **17**, 074401 (2014)

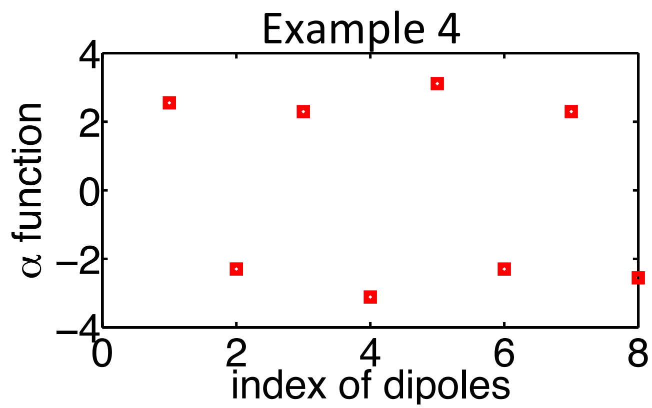


Name	**Example 3**	**Example 4**	**Unit**
beam energy	150	100	MeV
chirp	0	0	m^{-1}
bunch current (peak)	70	70	A
normalized emittance (H/V)	0.25/0.25	0.25/0.25	μm
relative rms energy spread	2×10^{-5}	2×10^{-5}	
bending radius	0.5	0.5	m

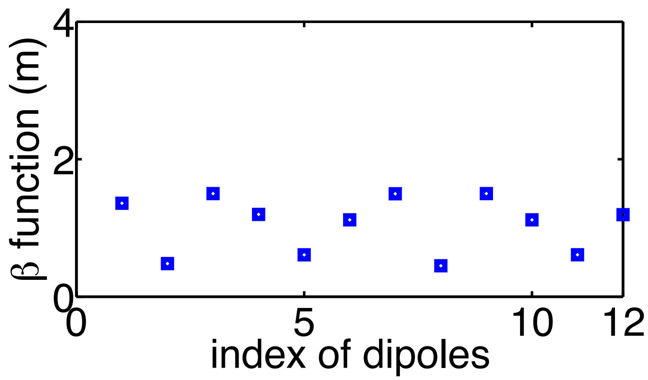
Example 3: *good ε_{nx} preservation, bad gain suppression*
Example 4: *good ε_{nx} preservation, good gain suppression*

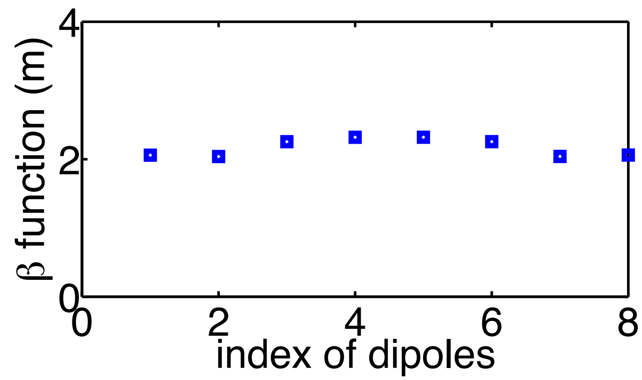
avoid small $|\boldsymbol{\alpha}|$ function



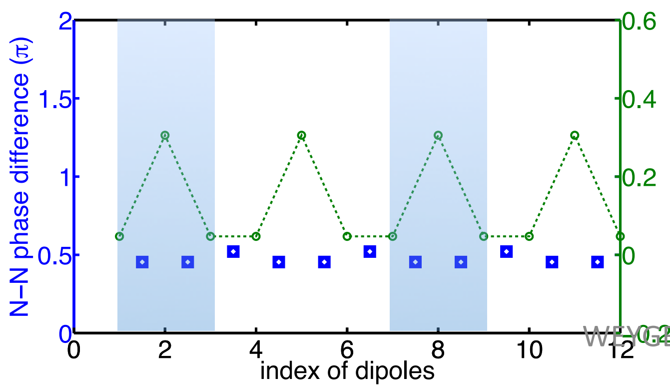


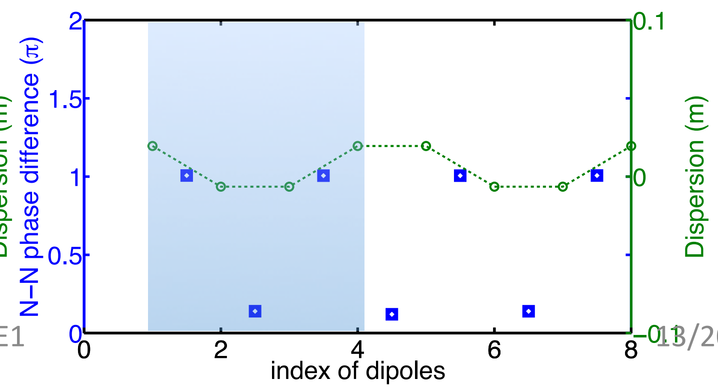
$\boldsymbol{\beta}$ functions as small as possible





phase difference close to $m\pi$

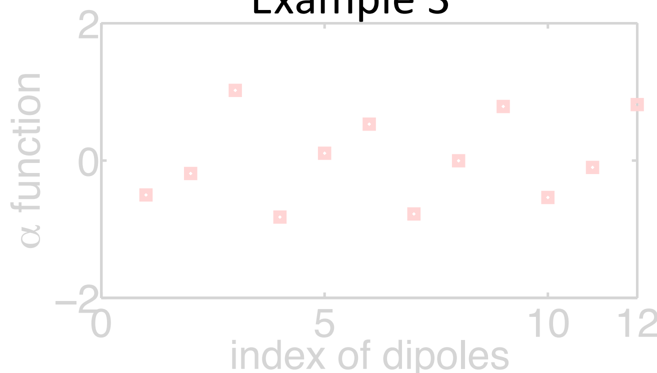


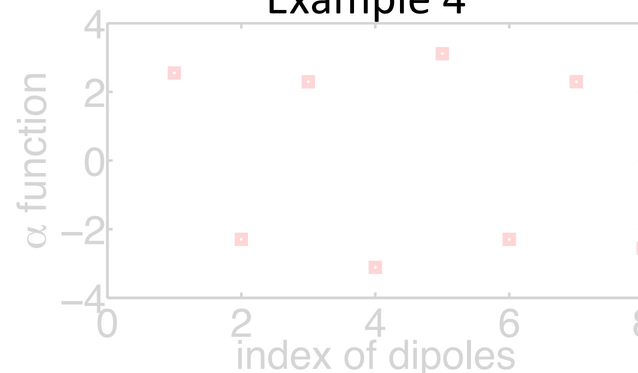


<u>*Example 3:*</u> *good ε_{nx} preservation, bad gain suppression*
<u>*Example 4:*</u> *good ε_{nx} preservation, good gain suppression*

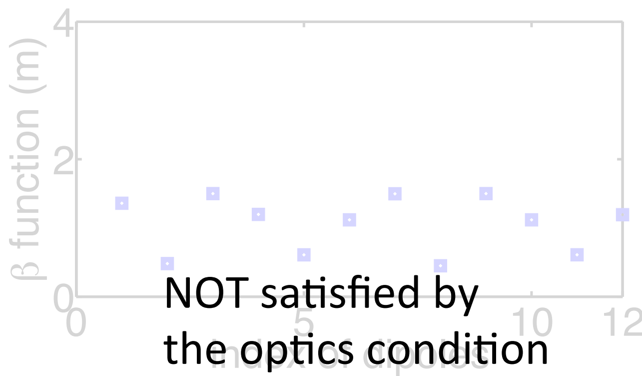
Example 3 | Example 4

avoid small $|\boldsymbol{\alpha}|$ function

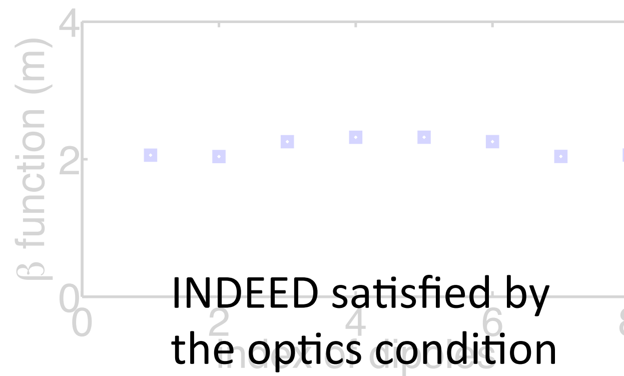




$\boldsymbol{\beta}$ functions as small as possible

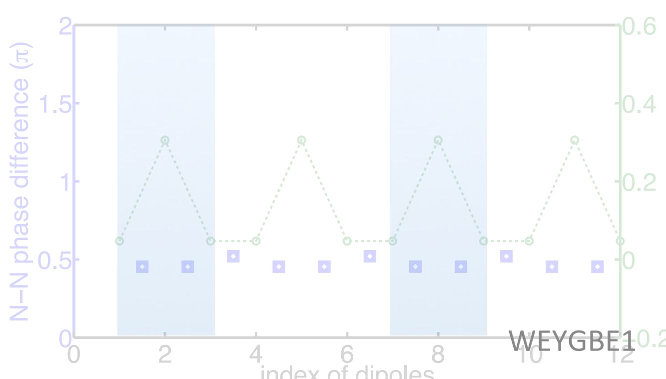


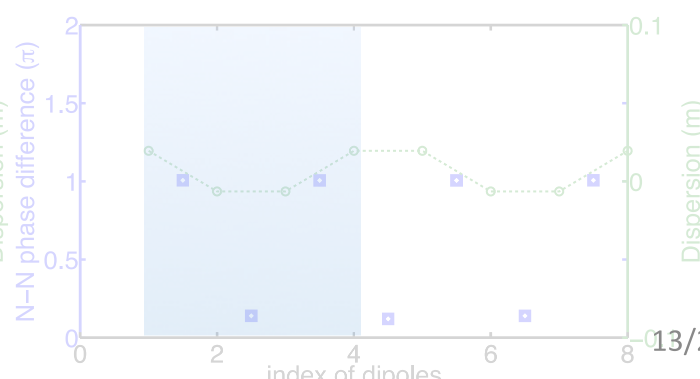
NOT satisfied by the optics condition



INDEED satisfied by the optics condition

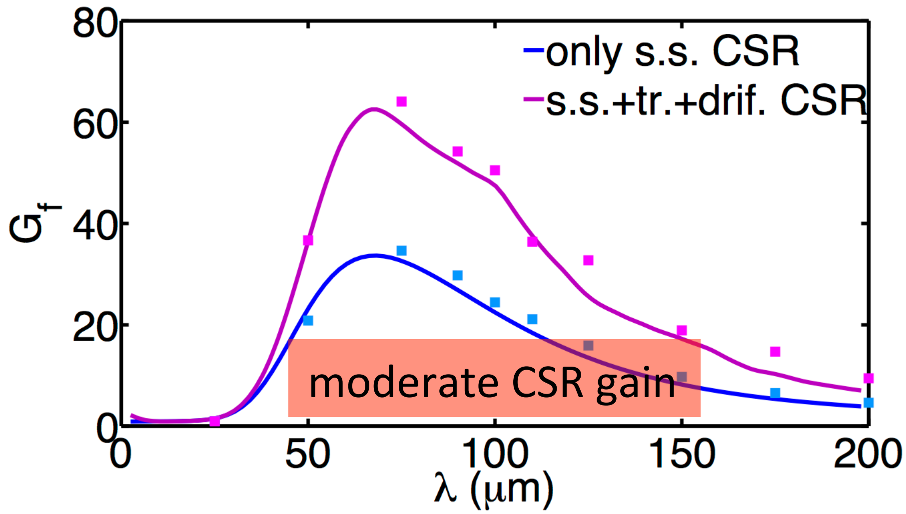
phase difference close to $m\pi$

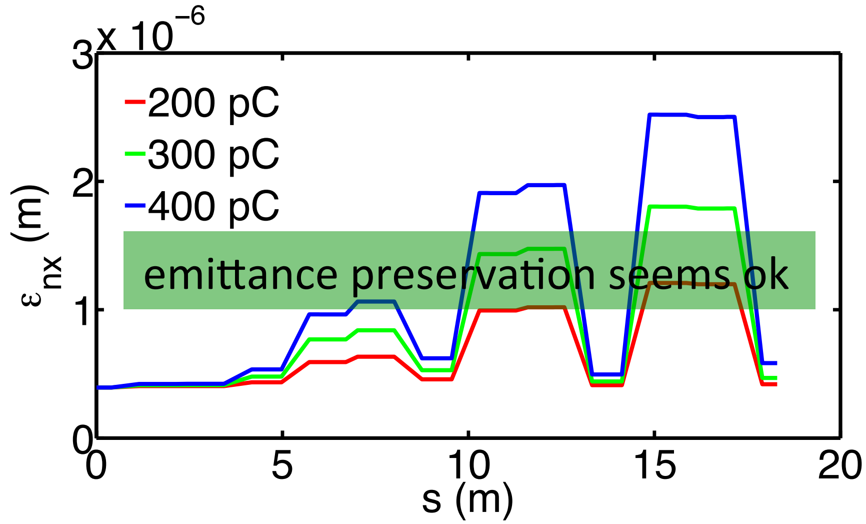




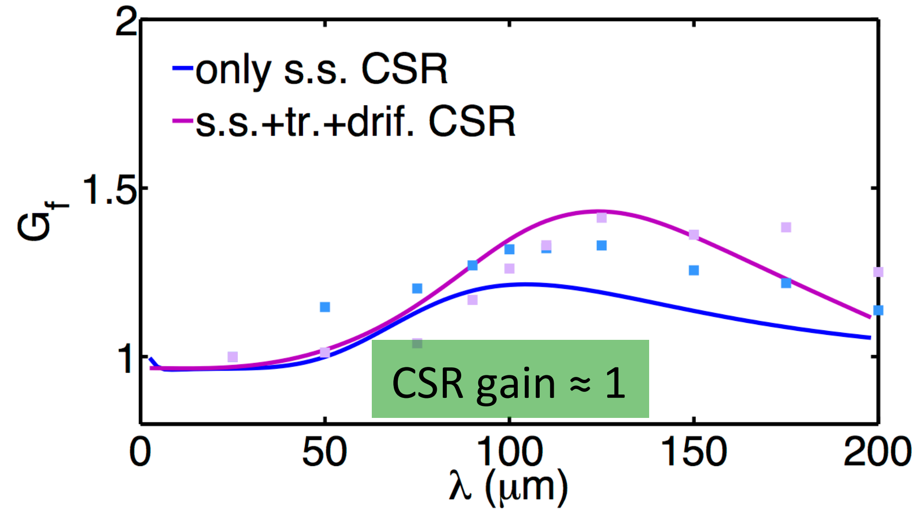
Example 3: *good ε_{nx} preservation, bad gain suppression*
Example 4: *good ε_{nx} preservation, good gain suppression*

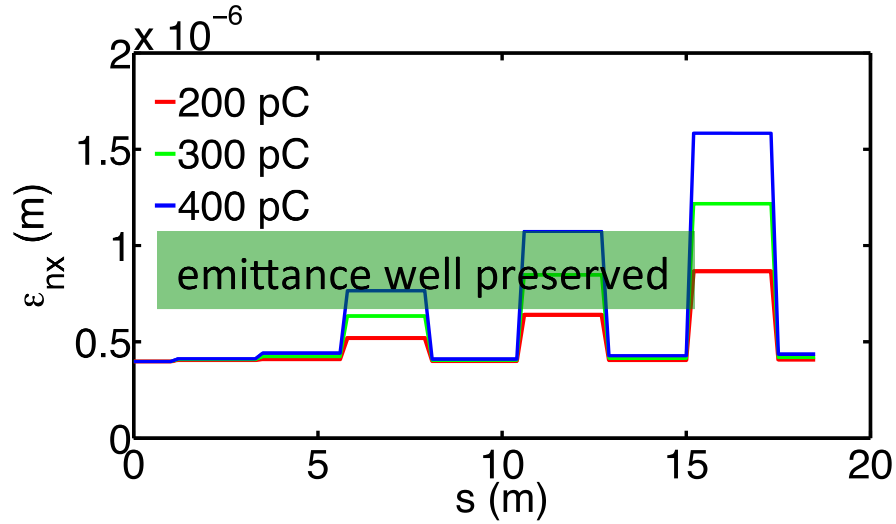
Example 3





Example 4





use **40M** macroparticles in ELEGANT tracking

Short summary

	Example 1	Example 2	Example 3	Example 4
ψ_{fi} description		**$\sim$0 or $\sim\pi$** between dipoles	**$\sim\pi/2$** between dipoles	**$\sim$0 or $\sim\pi$** between dipoles
R_{56} description	**larger** R_{56} **global** isochronous	**smaller** R_{56} **local** isochronous	**larger** R_{56} **local** isochronous	**smaller** R_{56} **local** isochronous
transverse emittance	bad	good	good	good
longitudinal microbunching gain	bad	good	bad	good

Outline

- Introduction and Overview
- Theoretical formulation of CSR microbunching in a single-pass system
- Suppressing CSR microbunching through optics balance
- Examples
- **Suppressing CSR microbunching through magnetized beam**
- Examples
- Summary and Conclusion

Basic idea

- Another way to suppress CSR microbunching can resort to transport of a magnetized beam (this idea was suggested by Ya. Derbenev)
- Cathode must be immersed in solenoid field; beam has non-zero angular momentum; beamline design requires special care to preserve the magnetization
- Such a magnetized beam will feature a larger transverse beam size, conceptually

$$\mathrm{Exp}\left\{-\frac{k^2}{2}\underbrace{\epsilon_{x0}\beta_{x0}}_{\sigma_{x0}^2}\left[R_{51}(s,s') - \frac{\alpha_{x0}}{\beta_{x0}}R_{52}(s,s')\right]^2\right\}$$

- Provide suppression to microbunching
- The present theory is only valid for non-magnetized beam and thus must be extended to transverse coupled beam for quantitative analysis; see PRAB **20**, 054401 (2017) for more details

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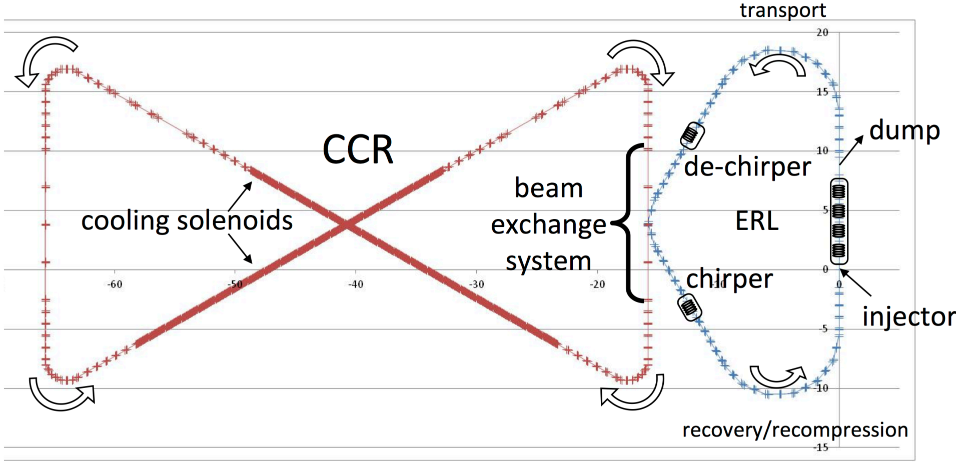
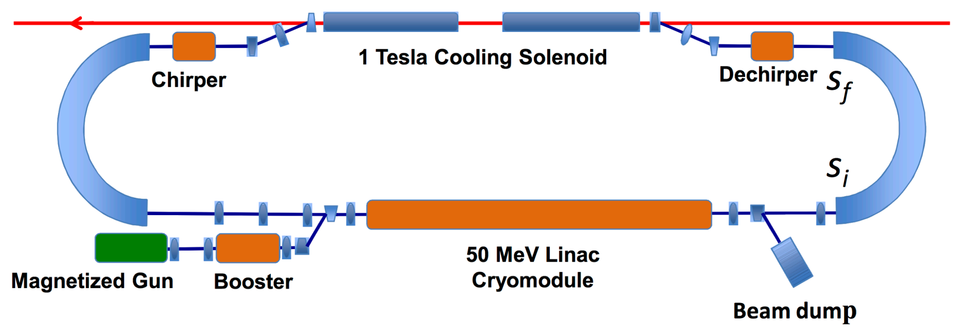
Example 5 & 6: CCR vs ERL cooler design

Example 5



Name	Value	Unit
Beam energy	54	MeV
Bunch charge	2	nC
Initial peak bunch current	60	A
Transverse normalized emittance	3	μm
Compression factor	1	
Chirp	0	m^{-1}
Energy spread (uncorrelated)	1.0×10^{-4}	

Example 6

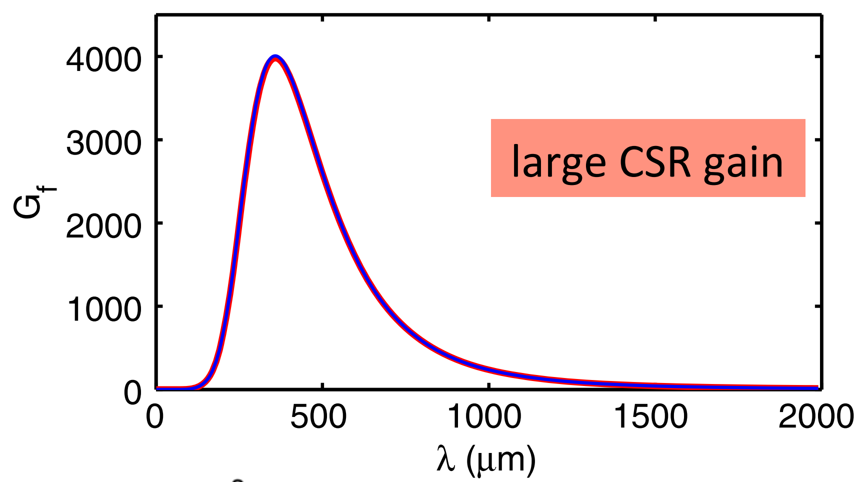


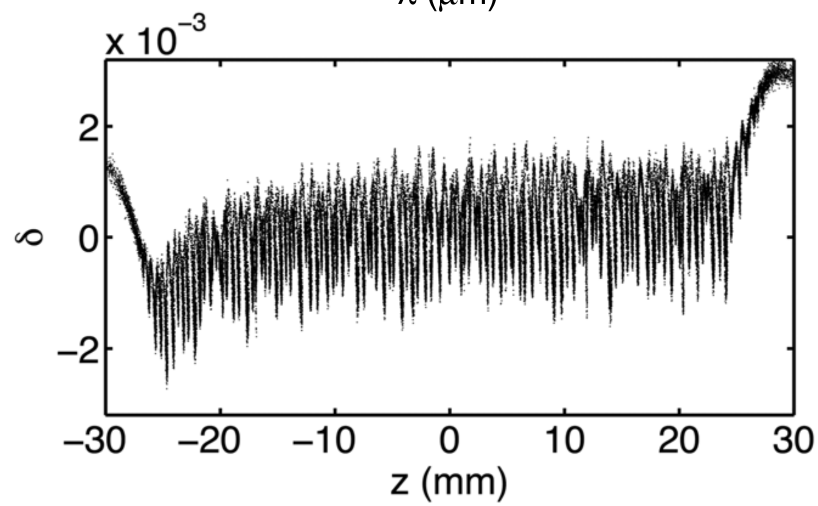
Name	Value	Unit
Beam energy	55	MeV
Bunch charge	420	pC
Initial peak bunch current	22.5	A
4D geometric emittance	0.11	μm
Compression factor	0.28	
Chirp	4.465	m^{-1}
Energy spread (uncorrelated)	1.5×10^{-4}	

MEIC Conceptual Design, arXiv (2012); S. Benson, JLEIC Collaboration Meeting, Spring 2016

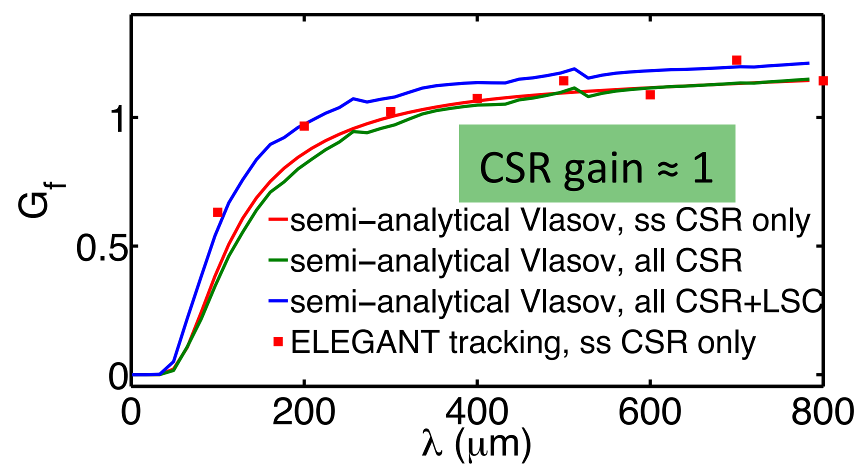
Example 5 & 6: CCR vs ERL cooler design

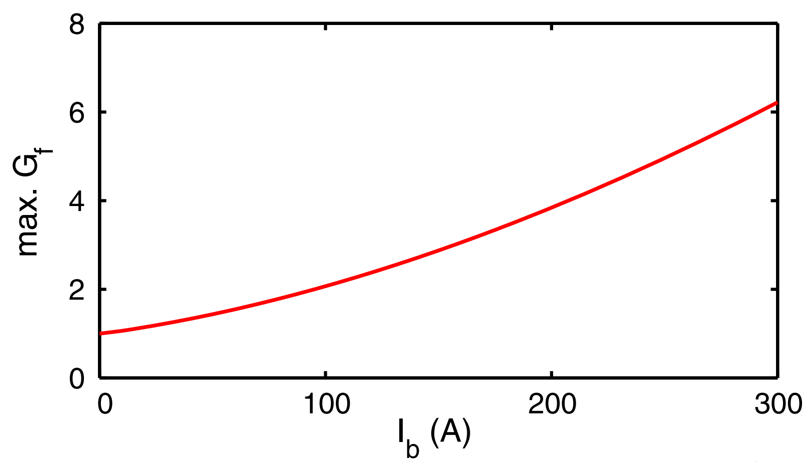
Example 5





Example 6





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Summary and Conclusion

- ✓ CSR effect: transverse: emittance growth; longitudinal: microbunching instability
- ✓ Linear Vlasov solver for study of MBI for general linear beamline lattices
- ✓ Optics conditions for CSR microbunching suppression
  - prefer small β within dipoles
  - avoid small α within dipoles
  - keep ψ close to $m\pi$ for every pair of dipoles
- ✓ Illustration of two sets of comparative examples to confirm the conditions: high energy (~1 GeV) and low energy (~100 MeV) cases
- ✓ Evaluate optics impact on microbunching amplification
- ✓ Tailoring beam conditions also provide an alternative way to suppress microbunching; illustrated a set of comparative example for non-magnetized CCR and magnetized ERL cooler design
- ✓ Large transverse beam size provides effective suppression of MBI

Thank you for your attention

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  - Steve Benson, Dave Douglas, Chris Tennant (JLab) and Simone Di Mitri (FERMI Elettra)
  - Juhao Wu, Xiaofan Wang, Chuan Yang, and Guanqun Zhou (SLAC)
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