Accelerator Physics Issues of ERL Prototype

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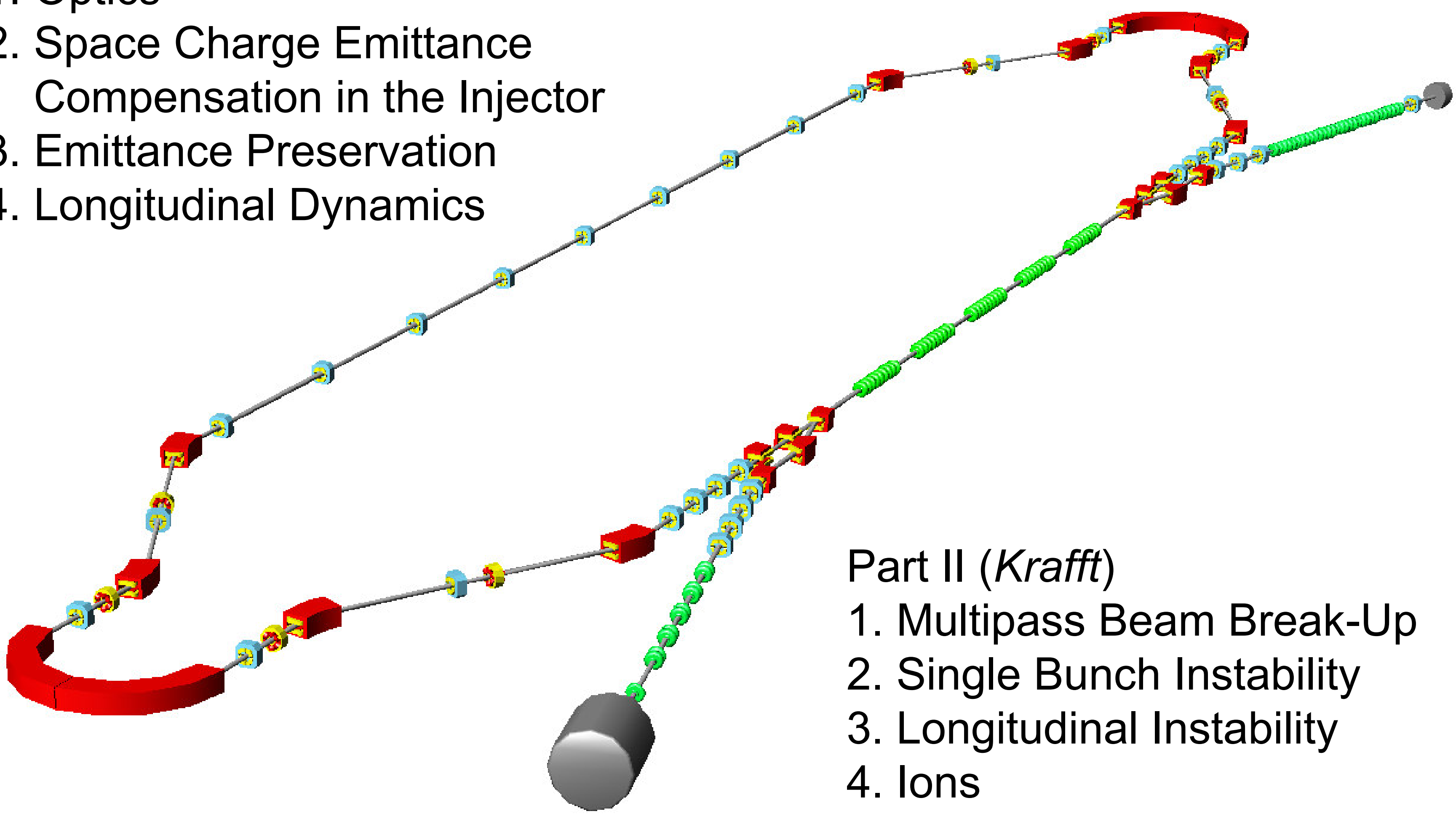
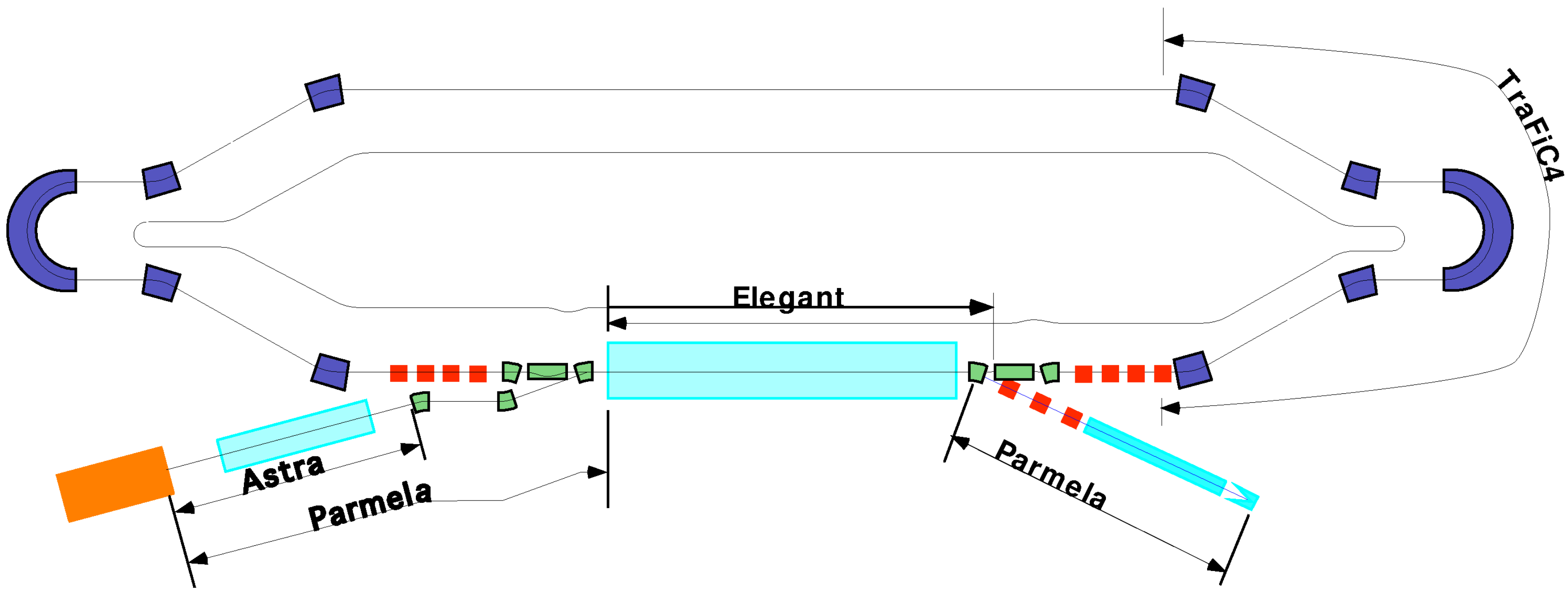
Talk Outline

Part I (*Bazarov*)
1. Optics
2. Space Charge Emittance Compensation in the Injector
3. Emittance Preservation
4. Longitudinal Dynamics



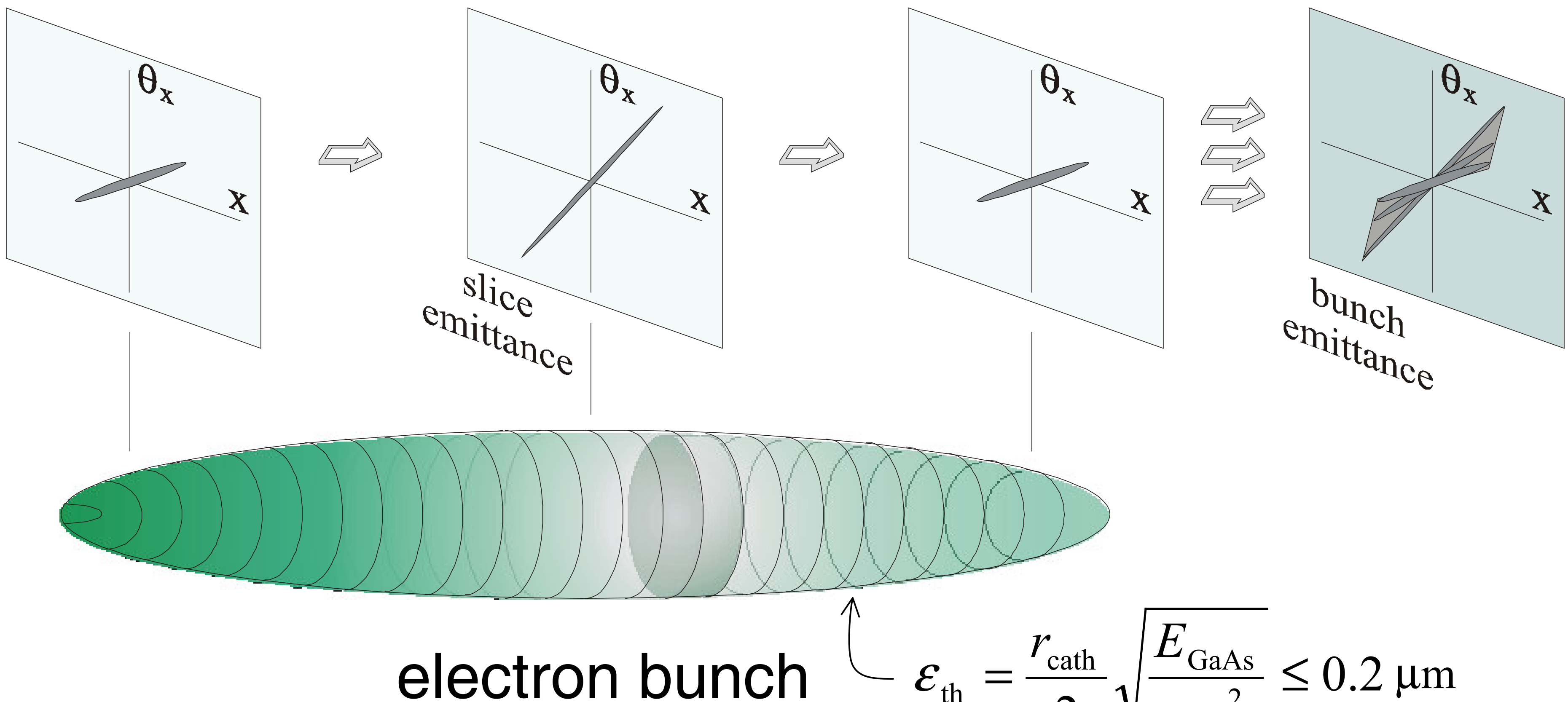
Part II (*Krafft*)
1. Multipass Beam Break-Up
2. Single Bunch Instability
3. Longitudinal Instability
4. Ions

Front-End Beam Dynamics Simulation



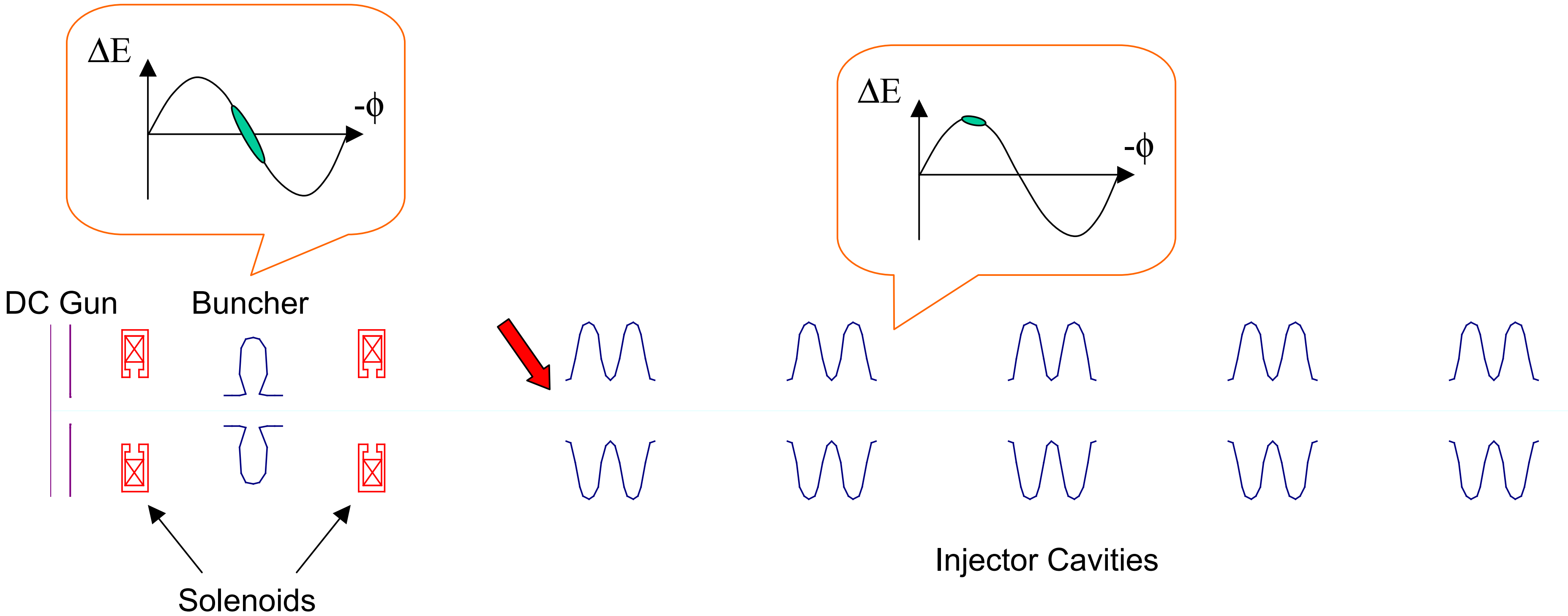
Astra, Parmela	–	Space Charge
TraFiC4, **`elegant`**	–	CSR
`elegant`	–	Optics, RF

Emittance Growth in the Injector



$$\varepsilon_{\text{th}} = \frac{r_{\text{cath}}}{2}\sqrt{\frac{E_{\text{GaAs}}}{mc^2}} \leq 0.2\ \mu\text{m}$$

Space Charge Emittance Compensation



"Invariant Envelope" Flow:

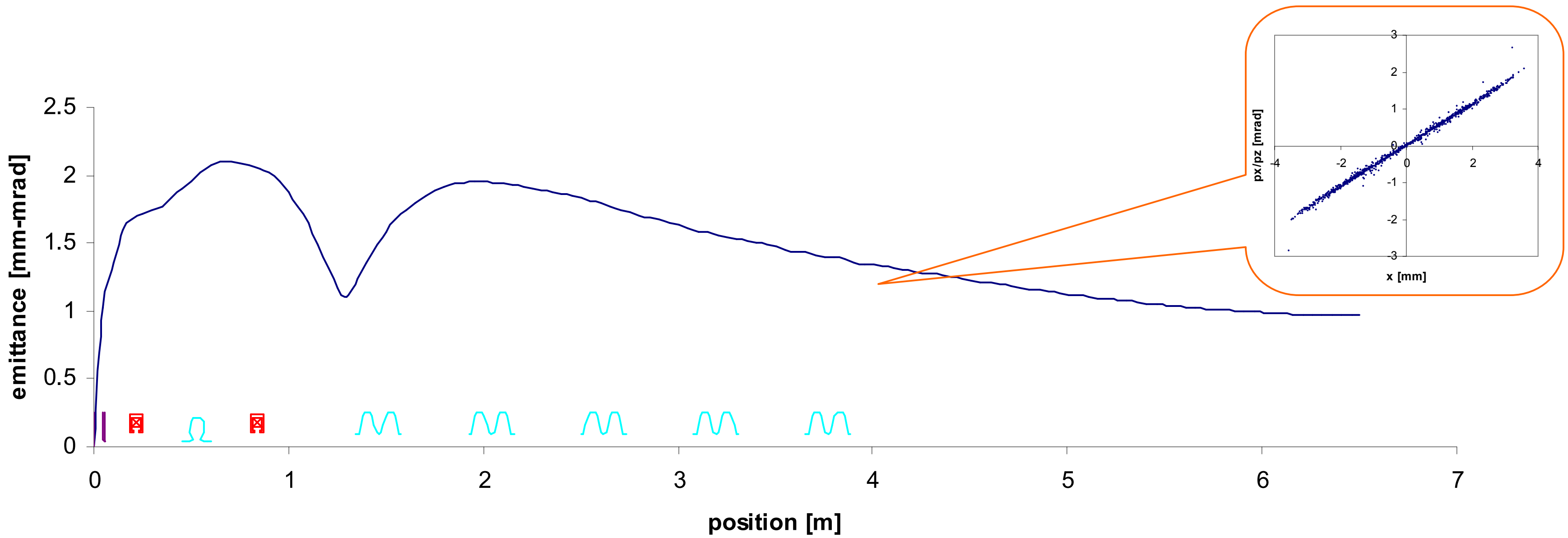
$$\sigma_r = \frac{2}{\gamma'}\sqrt{\frac{I_{\text{peak}}}{3I_{\text{Alfen}}\gamma}}$$

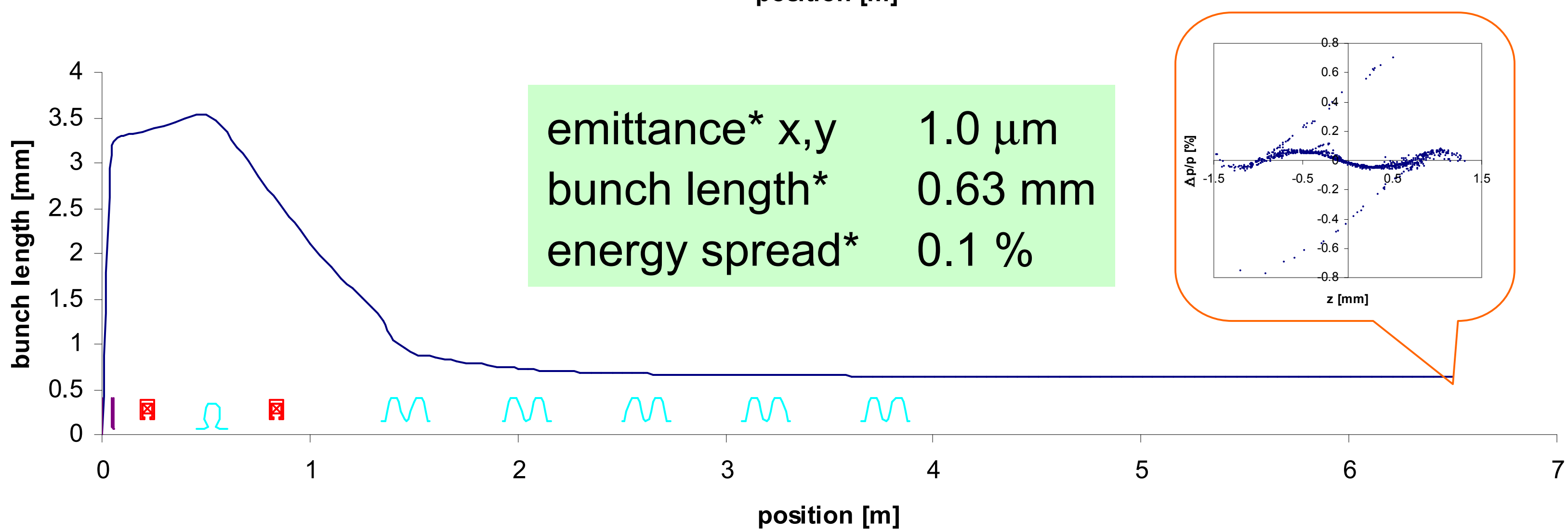
ERL Injector Parameters

Beam Energy Range	5 – 15[a] MeV
Max Average Beam Current	100 mA
Max Bunch Rep. Rate @ 77 pC	1.3 GHz
Transverse Emittance* (norm.)	≤ 1.5[b] μm
Bunch Length*	2.1 ps
Energy Spread*	0.2 %

* r.m.s. values are used throughout
[a] at reduced average current
[b] corresponds to 77 pC/bunch

Simulations Results ($\Delta E_{Injector\ RF}$ = 5 MeV)





emittance* x,y	1.0 µm
bunch length*	0.63 mm
energy spread*	0.1 %

* r.m.s. value

Laser Pulse Profiles Used in Simulations

Transverse:	Truncated Gaussian (+/- σ_r)
	σ_r = 1.8 mm
Temporal:	Gaussian
	FWHM = 28 ps

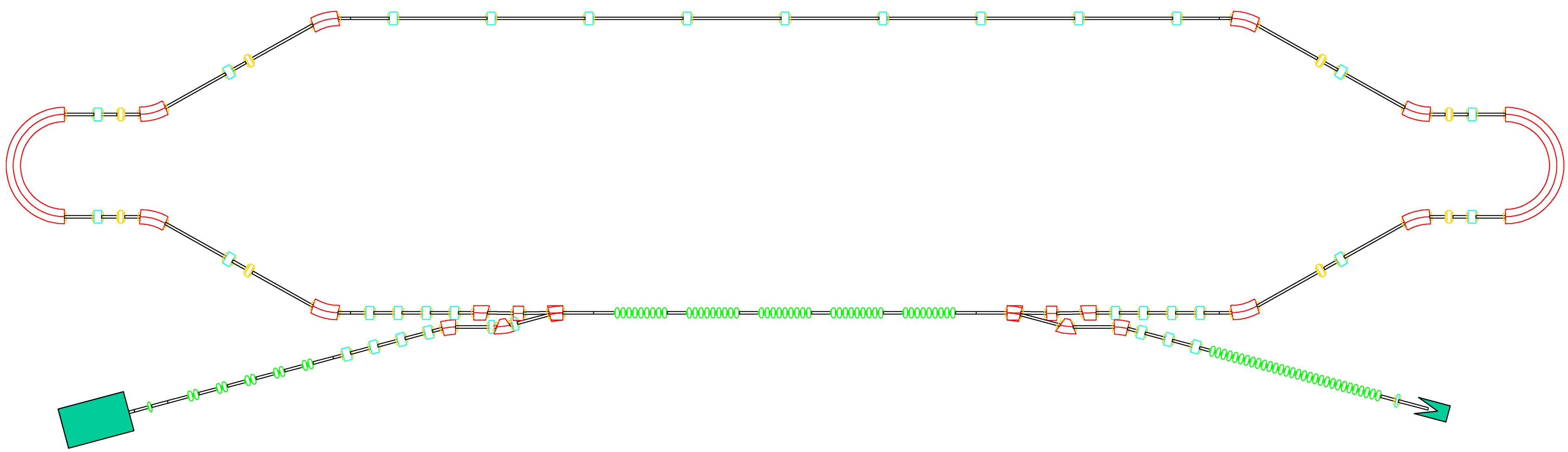
Pulse-To-Pulse Laser Tolerances

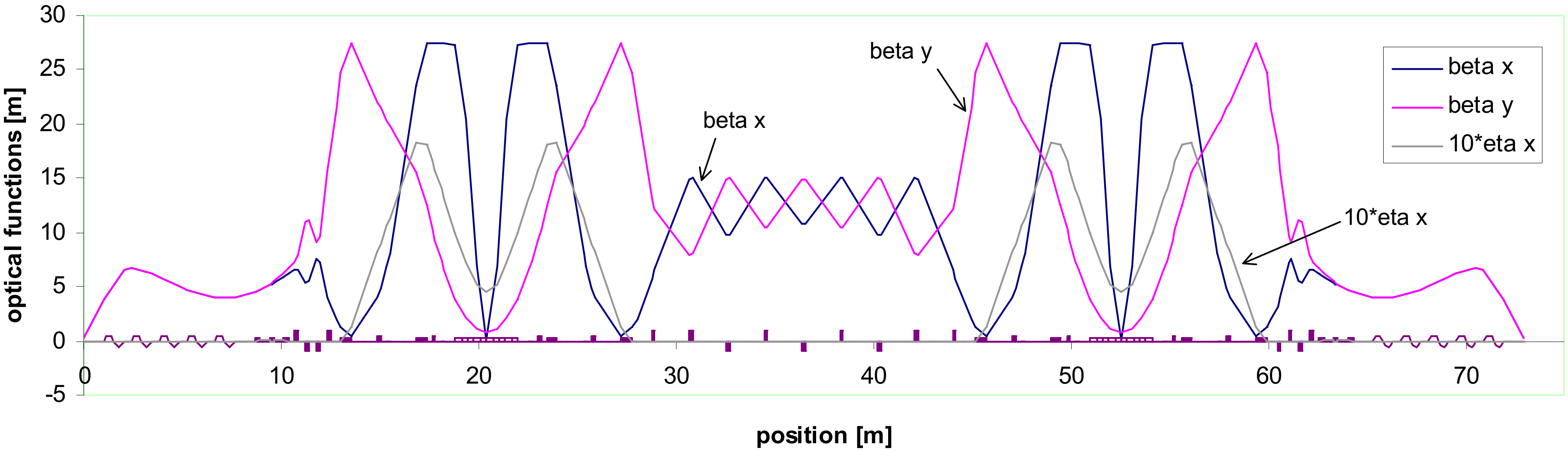
Arrival Time Jitter	$\leq$ 1.2 ps
Intensity Jitter	$\leq$ 3.5 %

Optics Requirements

- Low Chromatic and Geometric Aberrations
- Adjustable Momentum Compaction (R_{56})
- Second-Order Momentum Compaction (T_{566})
- Betatron Phase Advance Flexibility to study BBU and CSR Emittance Compensation

ERL I Optics

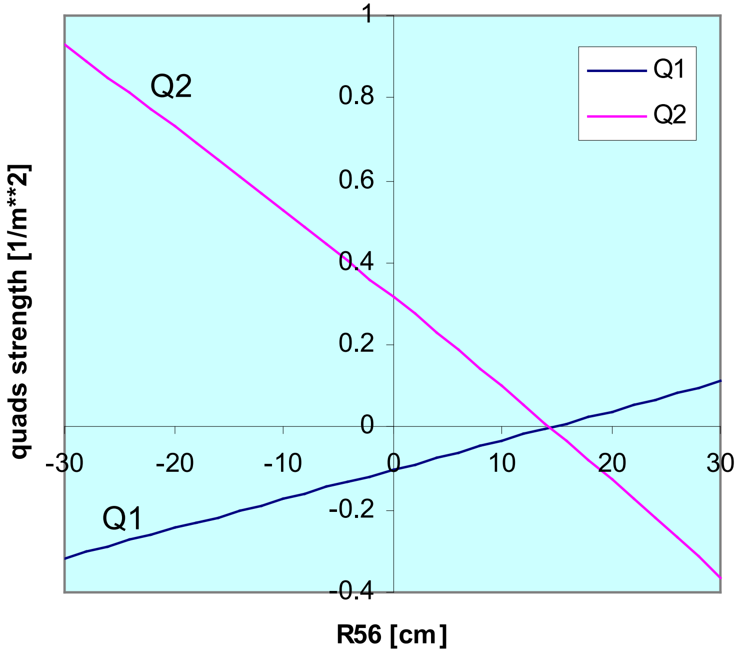


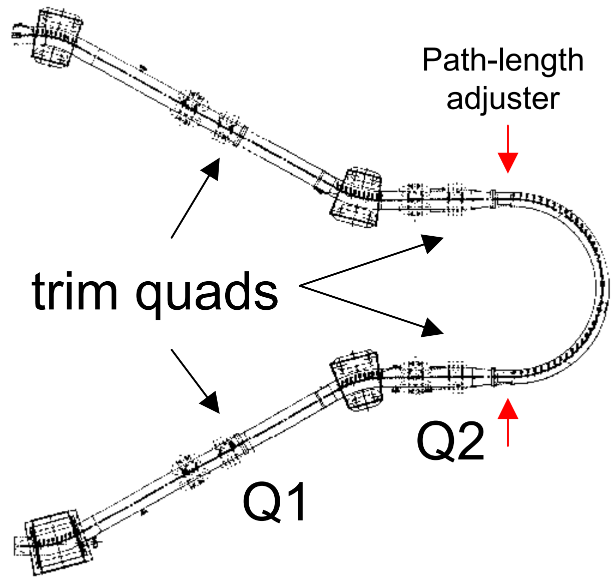


optical functions [m]
position [m]
beta x
beta y
10*eta x
beta x
beta y
10*eta x
30
25
20
15
10
5
0
-5
0
10
20
30
40
50
60
70

JLAB Demo IR-FEL Arcs

Adjustable R_{56}



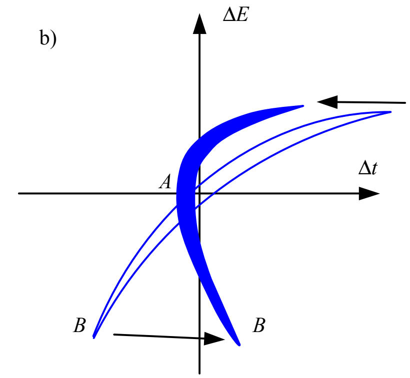


$$R_{56} = \int_1^2 \frac{\eta_x}{\rho} ds$$

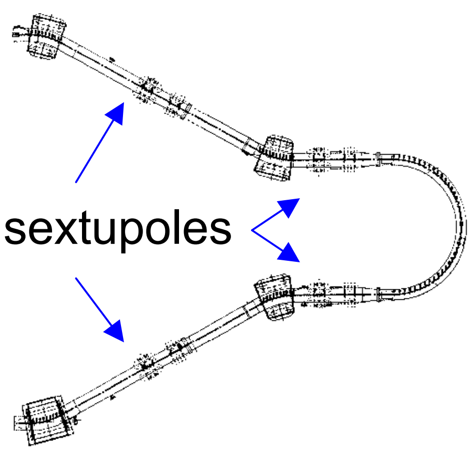
Sextupole "Linearizer"

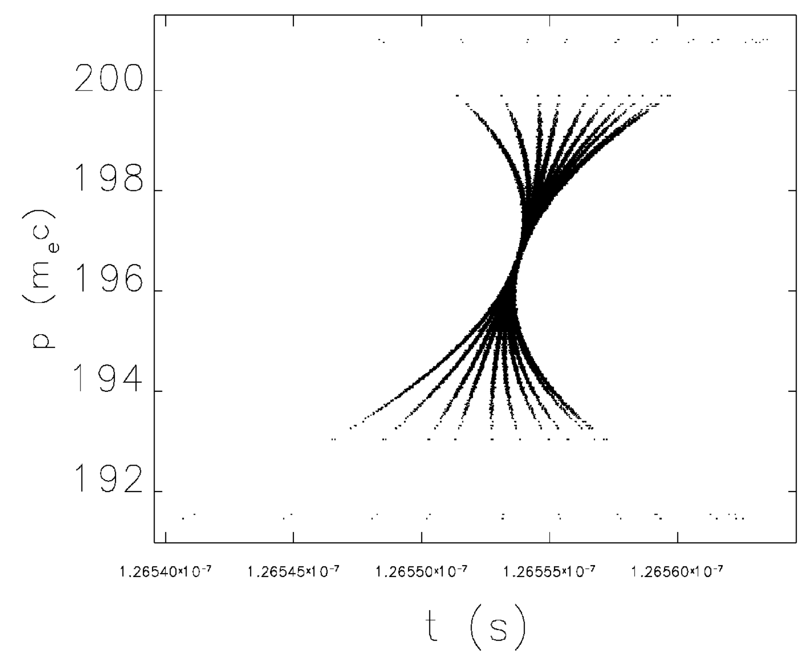
RF waveform
CSR
wakes
higher order optics effects

longitudinal phase
space curvature



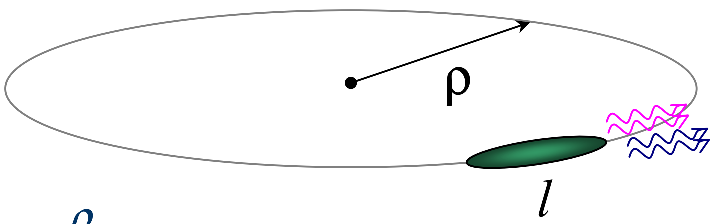
"Curvature" can be fixed with Sextupoles





changing sextupoles
strength in the Arc…

Coherent Synchrotron Radiation

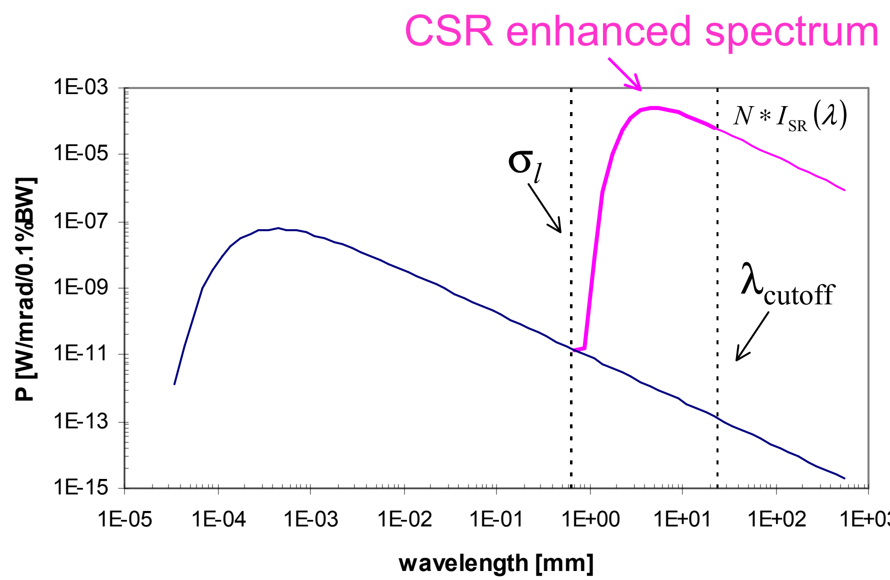


$\lambda_{SR} \propto \frac{\rho}{\gamma^3}$

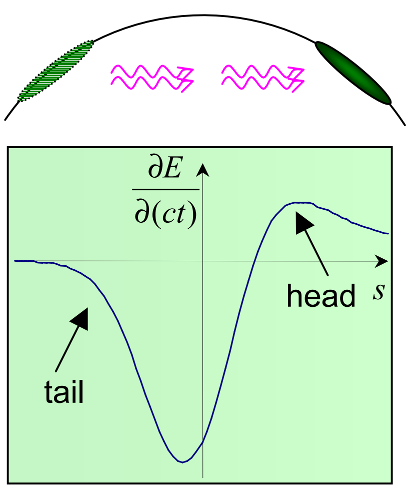
$P_{SR} \propto N \frac{\gamma^4}{\rho^2}$

$\lambda_{CSR} \geq l$

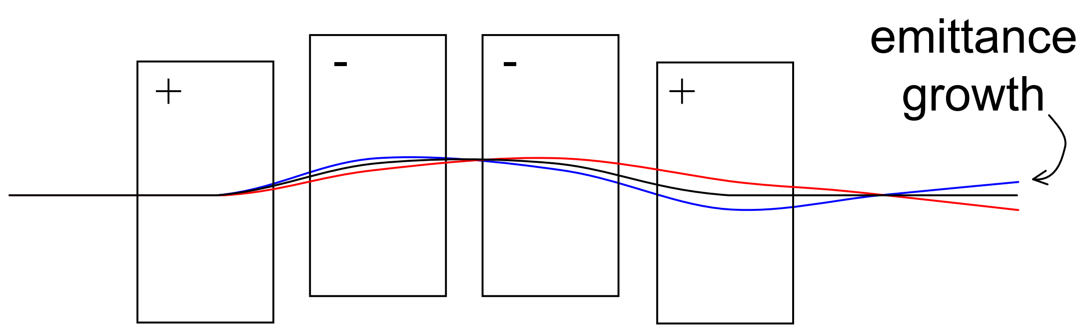
$P_{CSR} \propto N^2 \frac{1}{\rho^{2/3} l^{4/3}}$



Longitudinal Effect



Transverse Effect



Dispersion ≠ 0

CSR Calculation Tools Used For ERL I

TraFiC4

(DESY/SLAC)

Track and **Fi**eld of **C**ontinuous **C**harges in **C**artesian **C**oordinates

Pros: calculates CSR from the first principles

Cons: few bunchlets; slow; too noisy if coulomb forces are significant

`elegant` *(APS)*

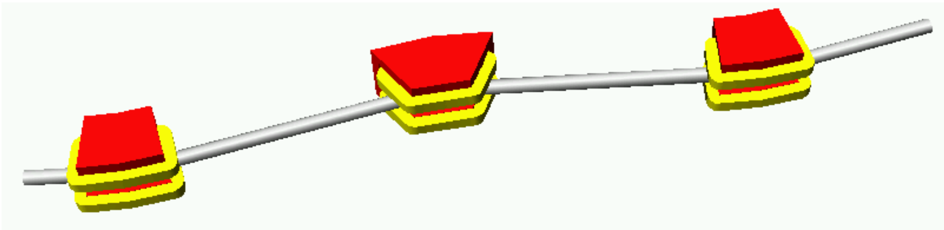
`ele`ctron **`g`**eneration **`and`** **`t`**racking

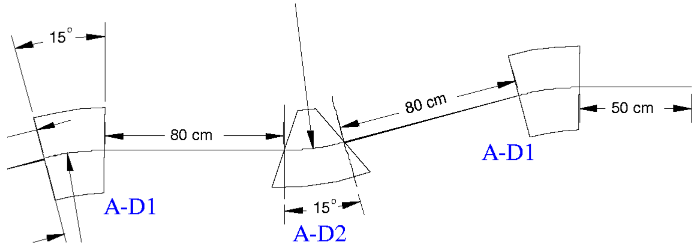
1-D CSR theory [Derbenev, Saldin] non-steady case, `CSRDRIFT` element

Pros: much faster

Cons: for small bend radii and large angles 1-D theory may not be strictly applicable

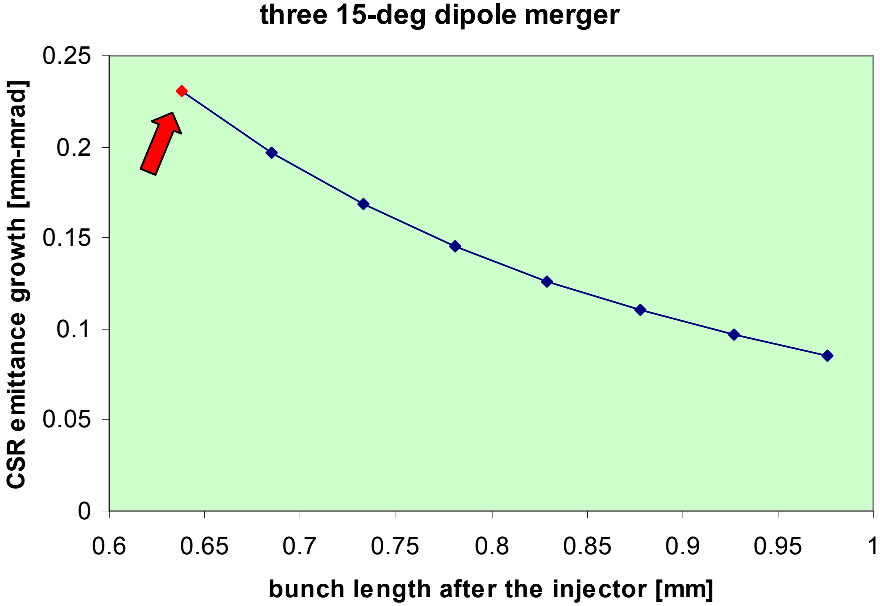
CSR Induced Emittance Growth (Merger)

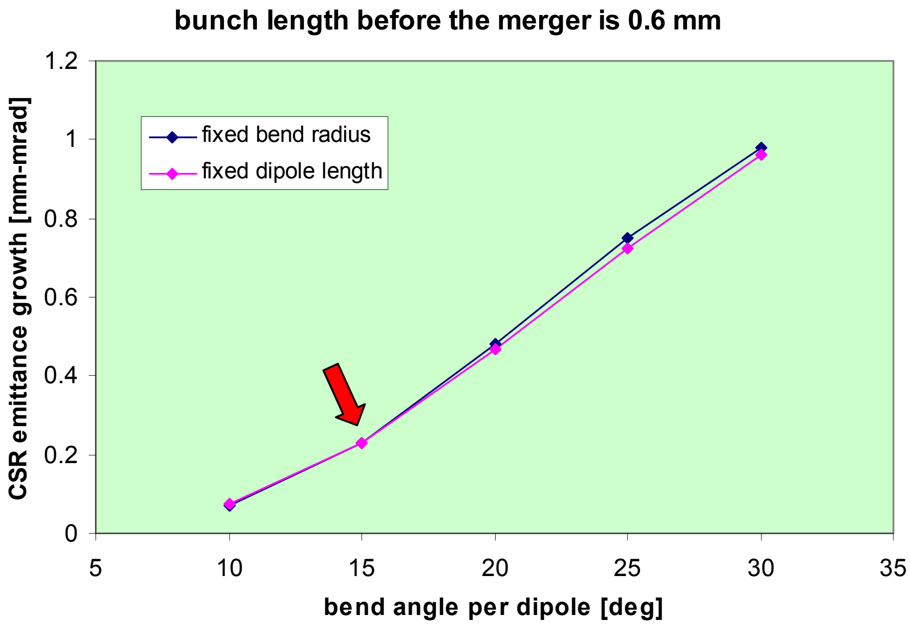




$$\Delta\varepsilon_{x,\mathrm{n,CSR}} \approx 0.2\ \mu\mathrm{m}$$

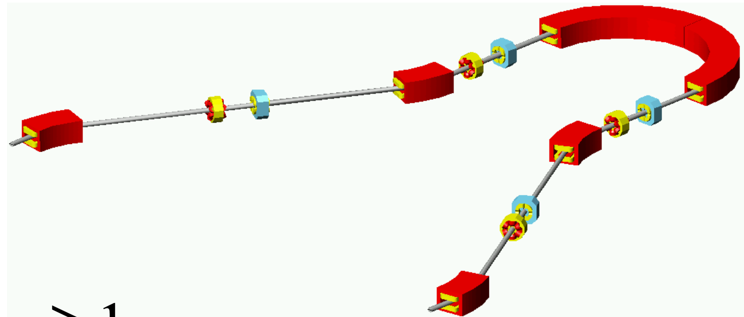
elegant





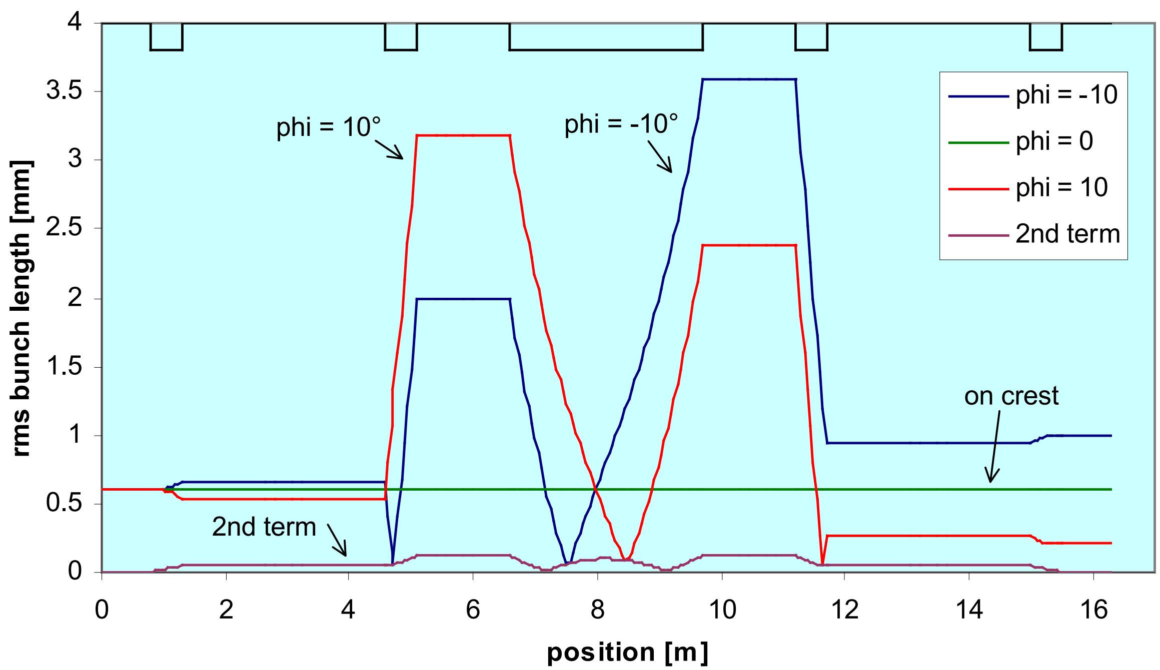
Bunch Length in the Arcs

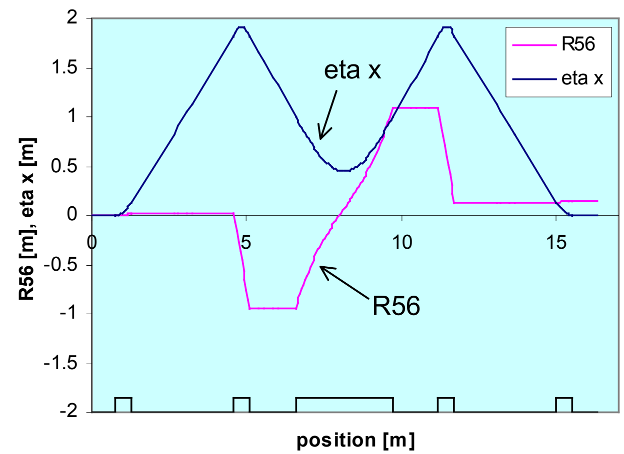
Bunch length in the Arcs:



$$\sigma_{l,t}^2 = \sigma_{l,0}^2\left(1+\frac{\partial\delta}{\partial l}R_{56}\right)^2 + \text{second\_term}^2$$

For off-crest of several deg: $\frac{\partial\delta}{\partial l}R_{56} \geq 1$

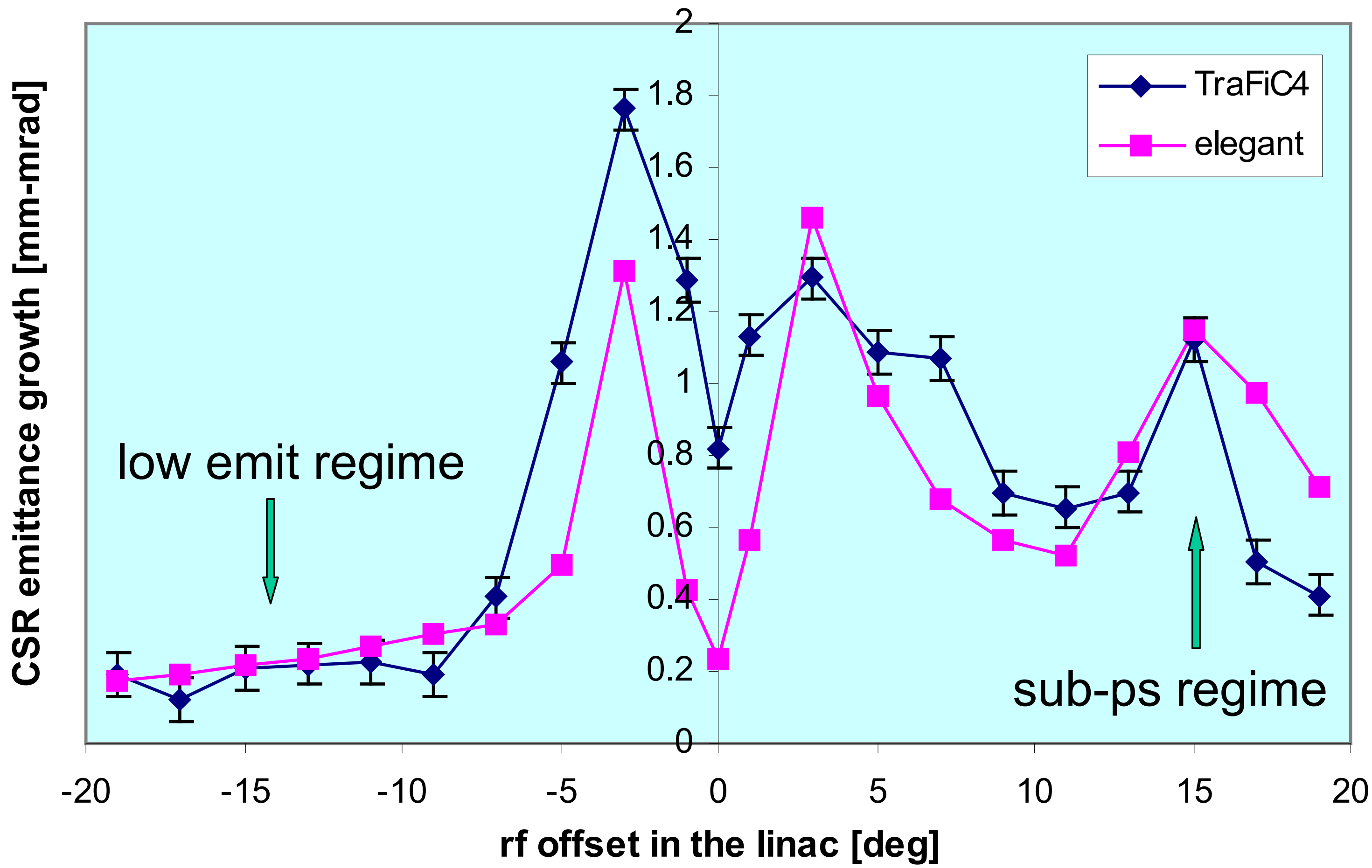




R_{56} = 14.4 cm
(trim quads off)

CSR Induced Emittance Growth (Arc)

Linac phase scan (final energy is 100 MeV); injection bunch length = 0.6 mm

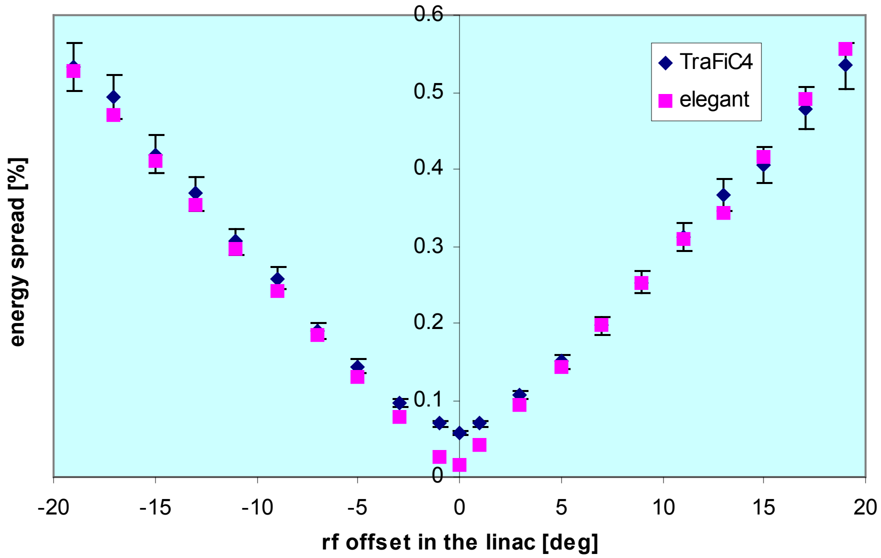


R_{56} = 14.4 cm

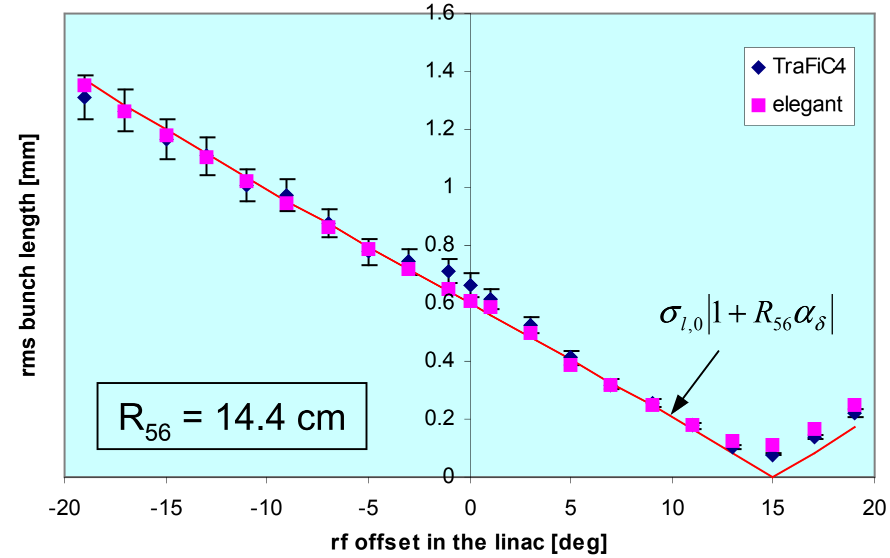
Bunch Length and Energy Spread

Linac phase scan (final energy is 100 MeV); injection bunch length = 0.6 mm

Energy Spread



Bunch Length After the 1st Arc



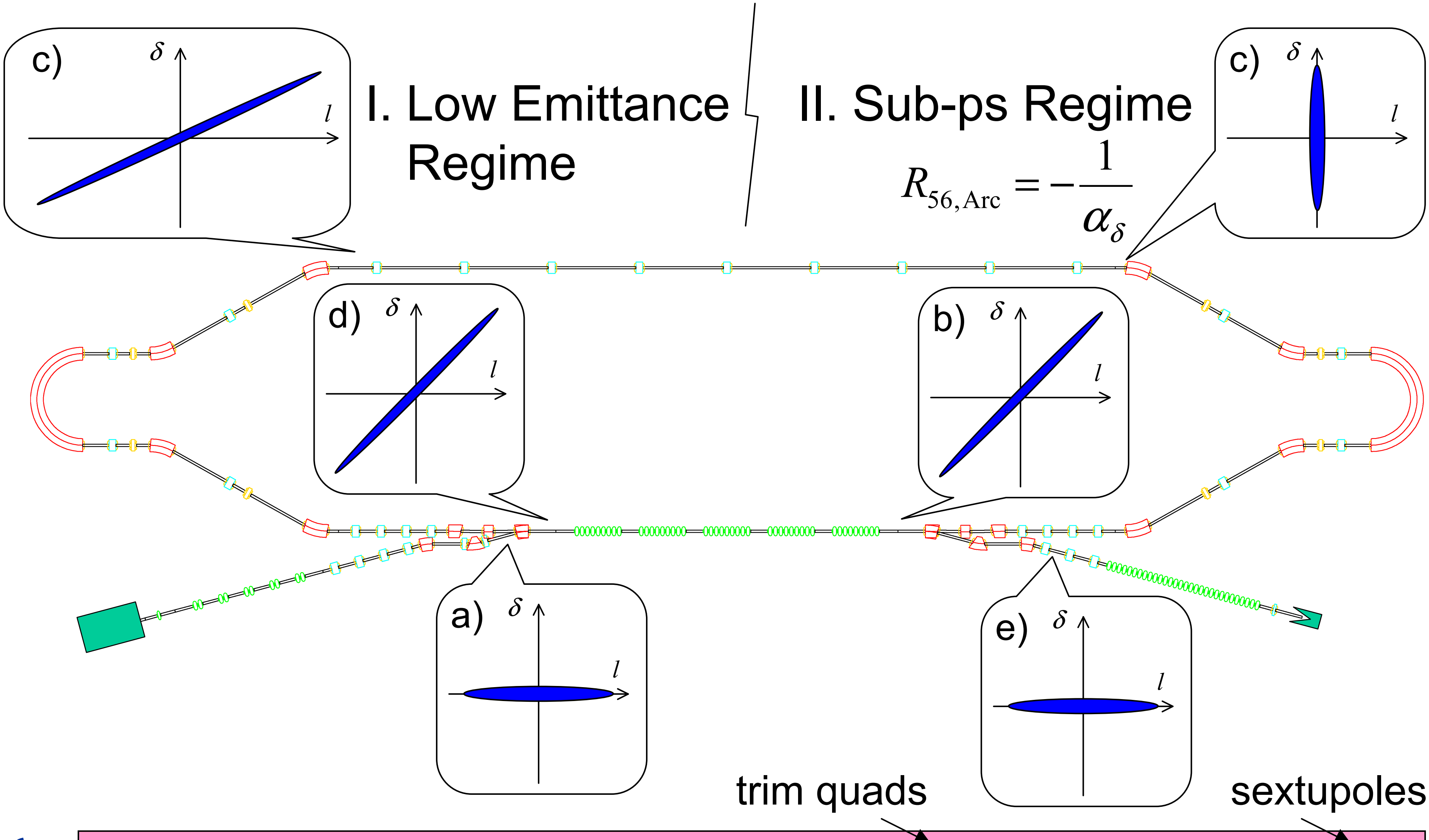
Energy Spread: $$\sigma_\delta = \sqrt{\sigma_{\delta_0}^2 + \alpha_\delta^2\sigma_l^2 + \frac{1}{2}\beta_\delta^2\sigma_l^4}$$

$$\alpha_\delta = \frac{\partial\delta}{\partial l} = -\frac{E_{\mathrm{cav}}\sin\varphi}{E_{\mathrm{fin}}}\frac{1}{\lambda\!\!\!^{-}_{\mathrm{RF}}}$$

$$\beta_\delta = \frac{\partial^2\delta}{\partial l^2} = -\frac{E_{\mathrm{cav}}\cos\varphi}{E_{\mathrm{fin}}}\frac{1}{\lambda\!\!\!^{-\,2}_{\mathrm{RF}}}$$

Longitudinal Emittance: $$\varepsilon_z = \sigma_l\sqrt{\sigma_{\delta_0}^2 + \frac{1}{2}\beta_\delta^2\sigma_l^4}$$

Longitudinal Phase Space Manipulations



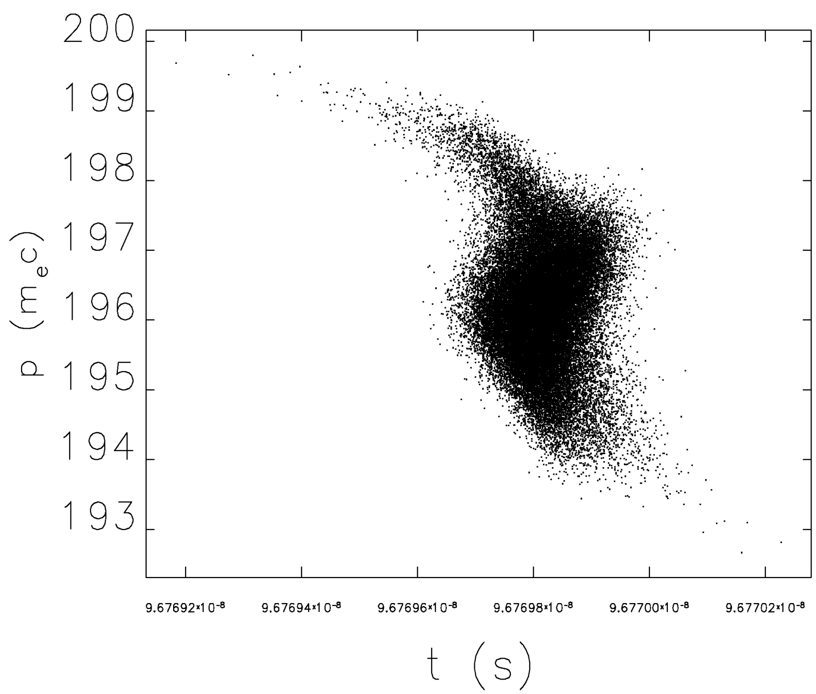
Rule of Thumb: Match $\alpha_{\delta,\mathrm{d)}} \rightarrow \alpha_{\delta,\mathrm{b)}}\,(R_{56})$, $\beta_{\delta,\mathrm{d)}} \rightarrow \beta_{\delta,\mathrm{b)}}\,(T_{566})$

Sub-ps Regime

Linac off-crest phase is 14.9 deg; injection bunch length = 0.6 mm

$R_{56,\ Arc}$ = 14.4 cm

longitudinal phase space after the 1st arc

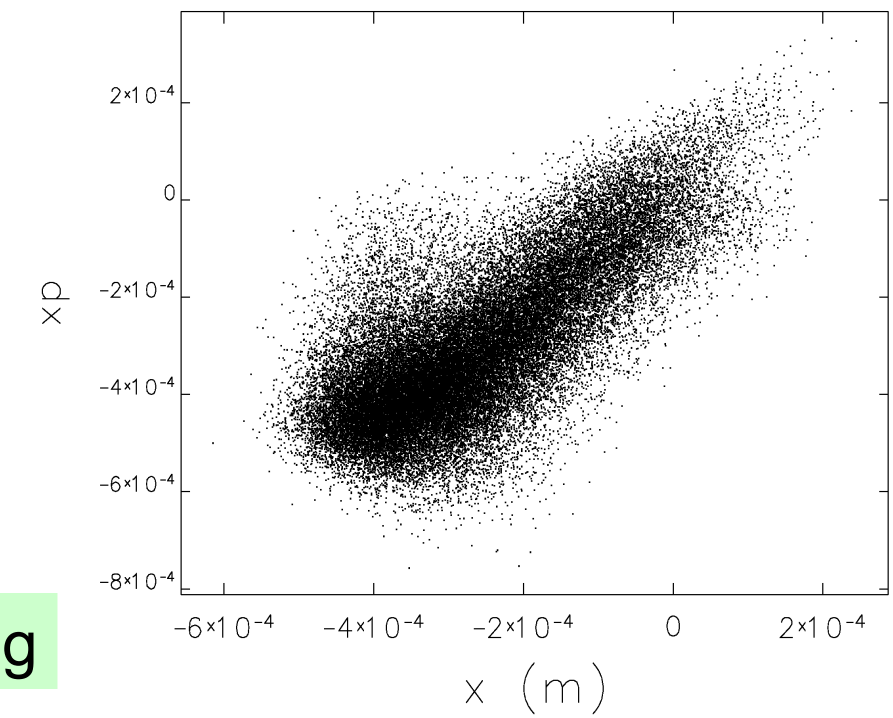


bunch length = 60 fs

$\Delta\varepsilon_{z,CSR} \approx 12 - 10 = 2$ keV·deg

$\Delta\varepsilon_{x,n,CSR} \approx 2.7 - 1.0 = 1.7\ \mu$m

transverse phase space after the 1st arc



Conclusions

- Producing and preserving a transverse emittance of 2 microns appears feasible
- CSR behavior of the prototype is understood and within bounds based on simulation results
- Flexible optics have been developed that allow detailed longitudinal phase space manipulations
- The ultra-short bunch regime has been addressed, although some work remains