ERL 2013

HZB Helmholtz Zentrum Berlin

START-TO-END BEAM DYNAMIC SIMULATIONS FOR THE FEMTO-SCIENCE-FACTORY

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Facility Introduction

Goal Parameters
Scalable Energy
Pre-injector Layout

Operation Modes

Suppression of Transversal Emittance Growth
Longitudinal Emittance Recovery

Start-to-Undulator

ASTRA input

Start-to-End

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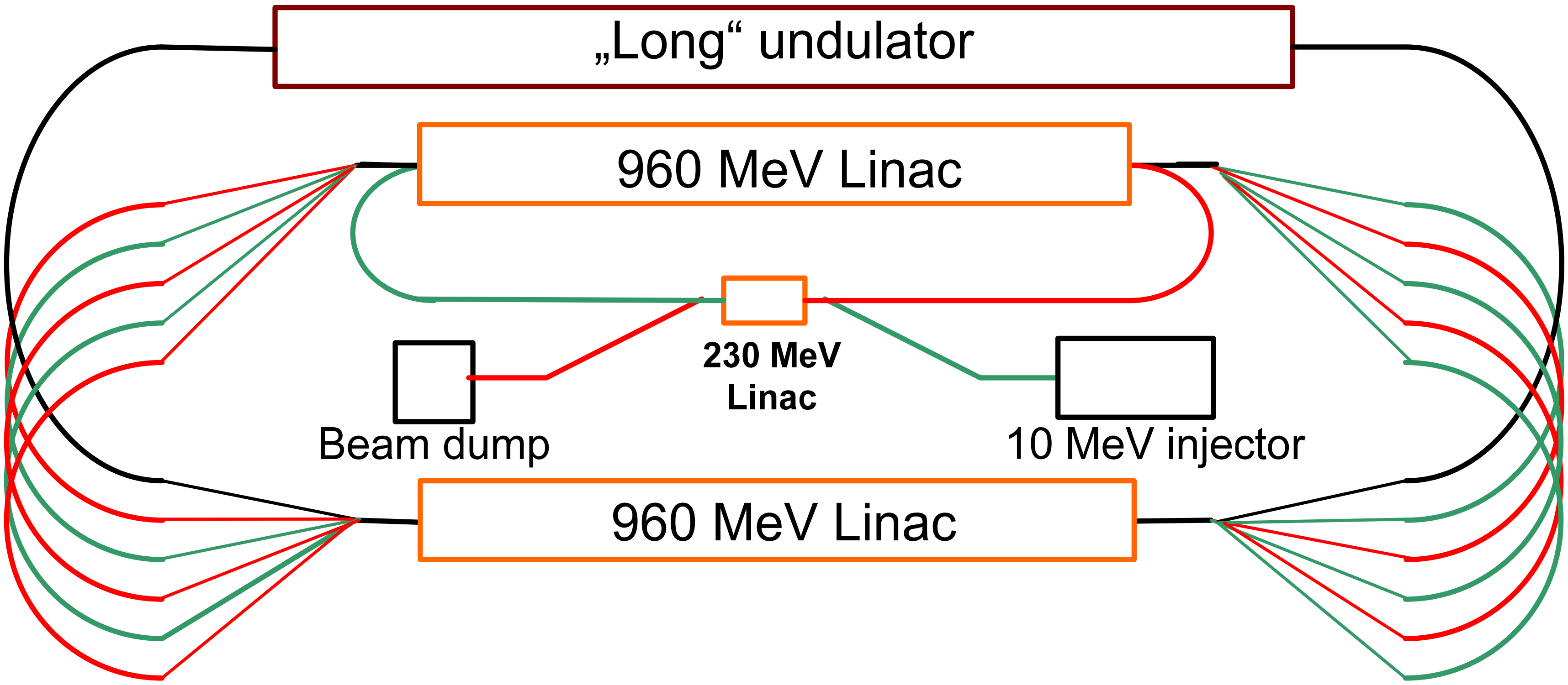
	Low Emittance Mode	Short Pulse Mode
Pre Injector (MeV)	230	230
Main Linacs (MeV)	960	960
Final Energy (GeV)	6	6
Charge (pC)	15	5
Bunch length (fs)	2000	10
Emittance (mm mrad)	0.1	0.5
Av. Brightness <B>	10^{22}	10^{21}
Peak Brightness B_{peak}	10^{26}	10^{26}

Sustain 0.1 mm mrad
over 4 km of machine !!!

5 pC, 10 fs bunch @ 6 GeV
If produced, can this bunch
be recovered ?


„Long“ undulator
960 MeV Linac
230 MeV
Linac
Beam dump
10 MeV injector
960 MeV Linac

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If due to unforseen circumstances

or maybe possible upgrades the energy changes ...

A re-design of the spreader is not neccessary

simply adjust the cavity field gradient.

$$E_f = (1 + 2kN)(E_i + E_{pre})$$

Taking E_i = 10 MeV, E_{pre} = 230 MeV, for N = 3 turns per linac

Up to a final Energy Ef = 6 GeV is reached then for say k = 4

the main linac energy is 960 MeV.

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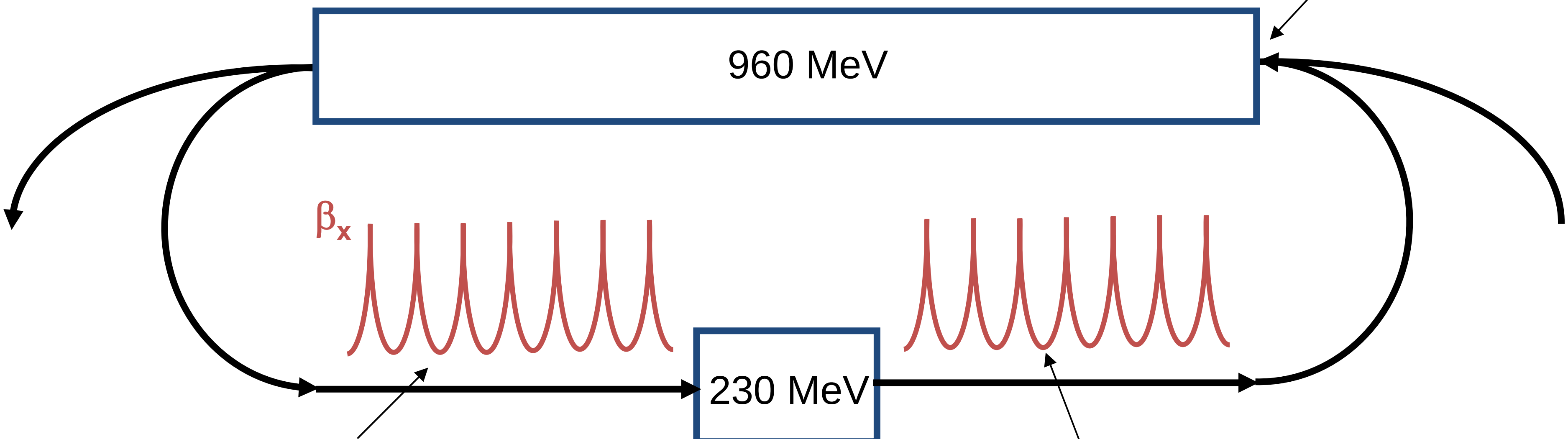
Possible scenario ...

Merger/Spreader share pre-injection Bending magnet



Rotator for BBU suppression?

$\beta_x \rightarrow \beta_y$
$\beta_y \rightarrow \beta_x$

Laser Heater to avoid Microbunching Instability

$$\lambda = \frac{d}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

k=2.5, d=9 cm, λ_{laser} ~ 0.8 µm → γ=480

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On-crest acceleration/deceleration in all linacs

Isochronous Optic

Pre-injector	2*TBA ($\mu_x \sim \pi$ bend)
Arc1	TBA
Arc2	TBA
$2 \rightarrow 6$ GeV	DBA with anti-magnet
$6 \rightarrow 2$ GeV	DBA with anti-magnet
Arc2	TBA
Arc1	TBA
Pre-injector	2*TBA ($\mu_x \sim \pi$ bend)

Goal: transversal normalised emittance 0.1 mm mrad !!

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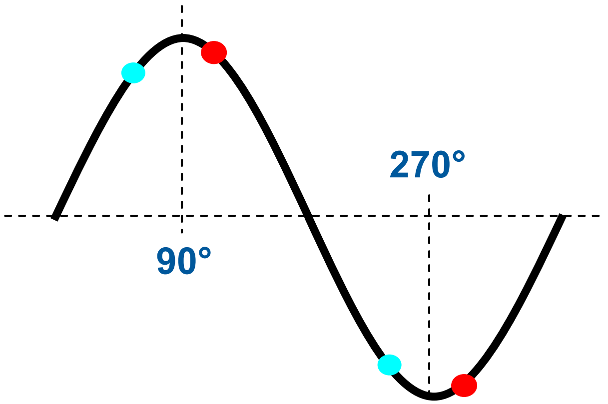
Off-crest phase in main linacs

$\phi_1 = 100°$ $\phi_2 = 70°$



Telescopic Compression

Pre-injector	BERLinPro*
Arc1	TBA R_{56} = 0.2 m
Arc2	TBA R_{56} = 0.05 m

High Energy Arcs

$2 \rightarrow 6$ GeV	DBA with anti-magnet
$6 \rightarrow 2$ GeV	DBA with anti-magnet

Telescopic Decompression

Arc2_d	TBA R_{56} = - 0.05 m
Arc1_d	TBA R_{56} = - 0.2 m
Pre-injector	BERLinPro*

change the signs of R_{56} on recovery

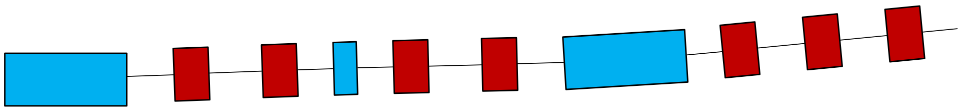
Goal: short bunch length

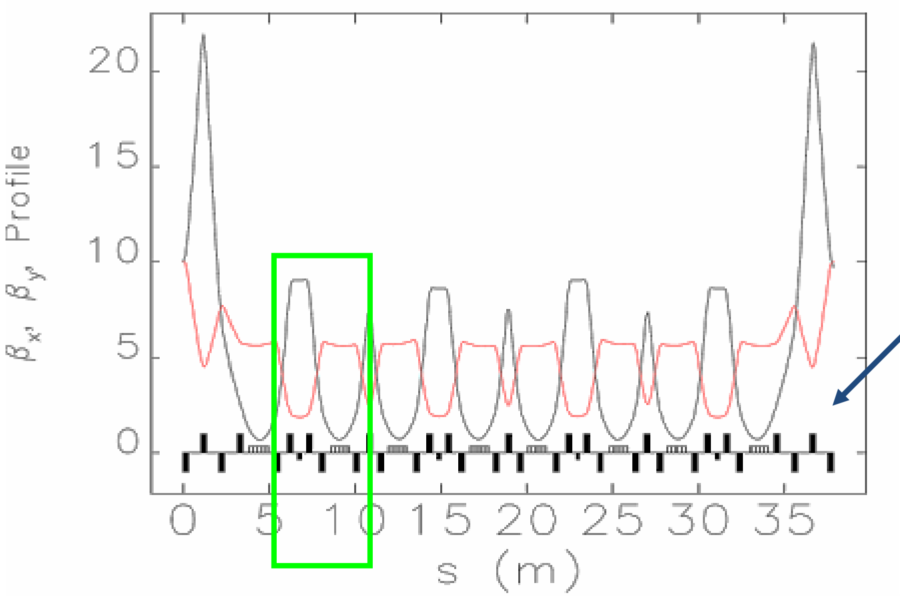
1D CSR regime without sheilding, $\delta_{CSR} R_{56} << \sigma_z$

For a system of N identical isochronous bends the CSR shift

$$\begin{pmatrix} \delta x \\ \delta x' \end{pmatrix}_N = \left(I \sum_{n=0}^{N} \cos n\mu_x + J \sum_{n=0}^{N} \sin n\mu_x \right) \begin{pmatrix} \delta x \\ \delta x' \end{pmatrix}_0$$

If $\mu_x = 2\pi \cdot k/N$ where k is an integer, the impact of CSR on the transversal emittance becomes zero ...



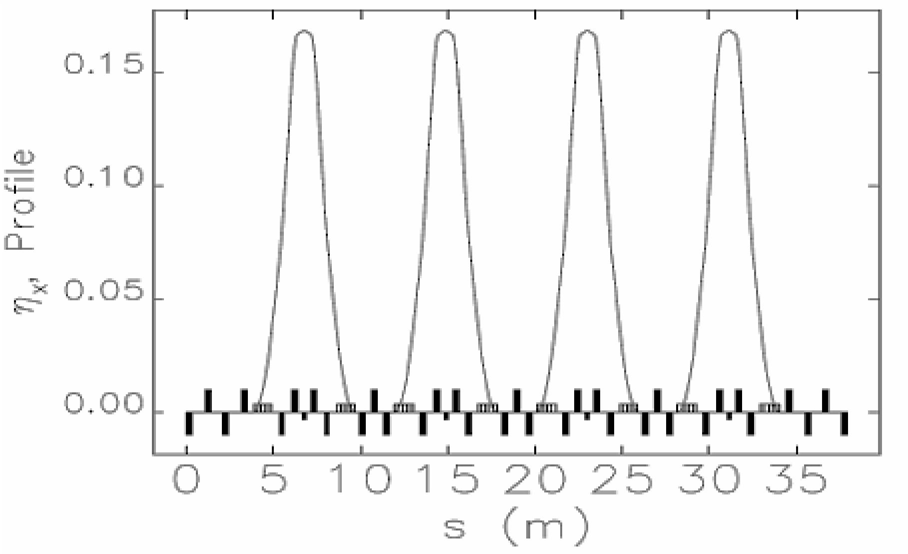


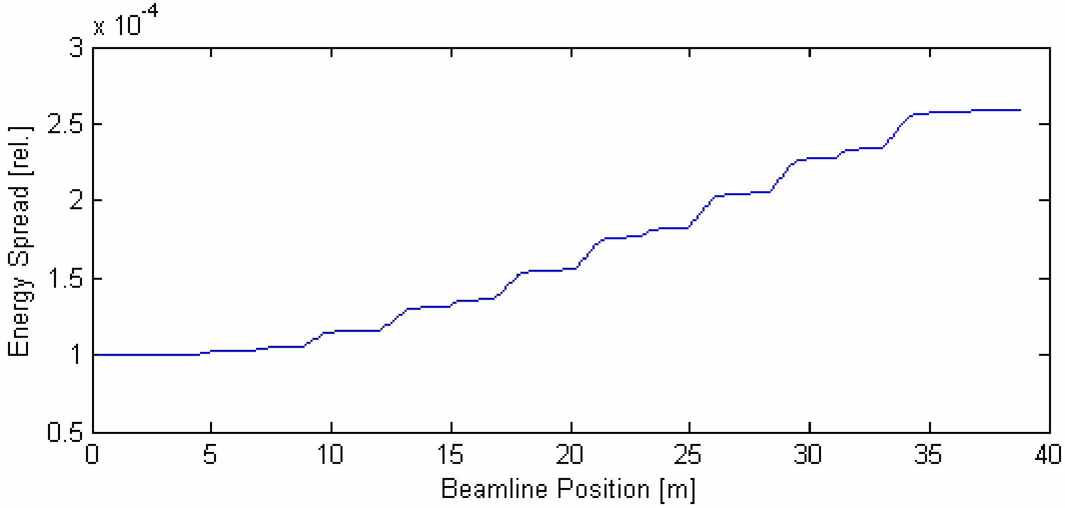
Matching quads for Arc undulators

Low dispersive optic

$\mu_x = 2\pi \cdot ¾$

Phase advance per cell



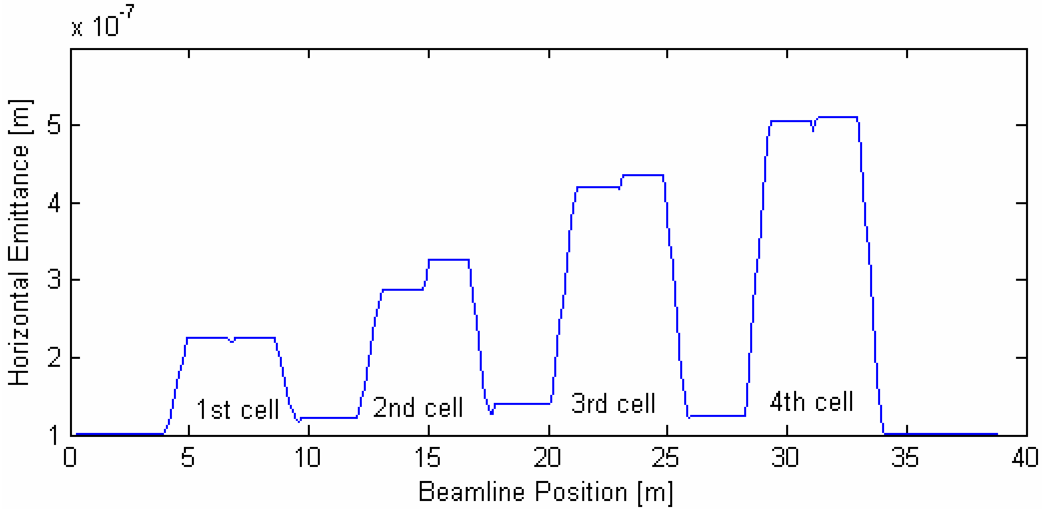


quick formula check

$\delta_{csr} \sim q / \sigma_z^{4/3} \sim 10^{-4}$ **per cell**

15 pC, 10 fs bunch
CSRtrack

ISR not included



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Chromatic aberrations in the horizontal plane

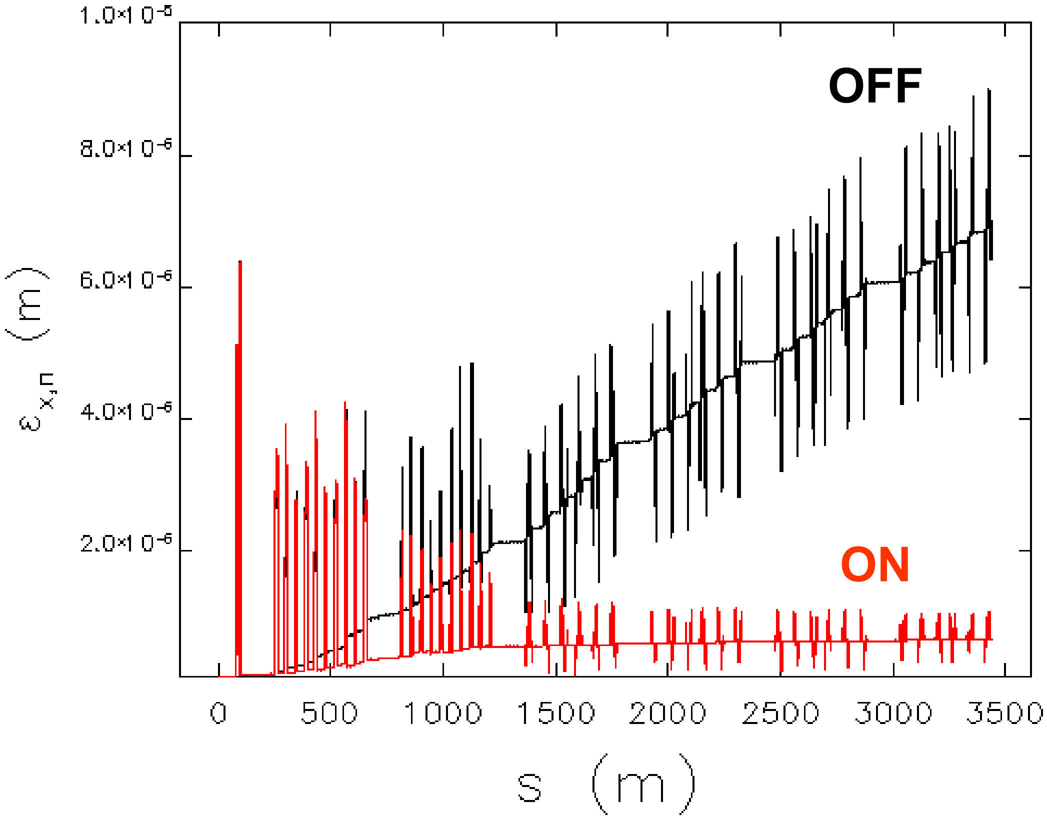
$$x_1 = T_{161}\delta_0 x_0 + T_{162}\delta_0 x'_0 + \ldots$$
$$x'_1 = T_{261}\delta_0 x_0 + T_{262}\delta_0 x'_0 + \ldots$$

Using the linear terms one can approximate the emittance change as

$$\varepsilon_1^2 = \left\langle x_1^2 \right\rangle \left\langle x'^2_1 \right\rangle - \left\langle x_1 x'_1 \right\rangle^2$$
$$\varepsilon_1^2 \approx \left(T_{161}T_{262} - T_{162}T_{261}\right)^2 \left(\left\langle \delta_0^2 x_0^2 \right\rangle \left\langle \delta_0^2 x'^2_0 \right\rangle - \left\langle \delta_0 x_0 x'_0 \right\rangle^2 \right)$$

By setting $T_{161}{}^*T_{262} = T_{162}{}^*T_{261}$ the $|\varepsilon_x| \rightarrow 0$

Normalised horizontal emittance plot



Factor 10 supression

$T_{161} * T_{262} = T_{162} * T_{261}$

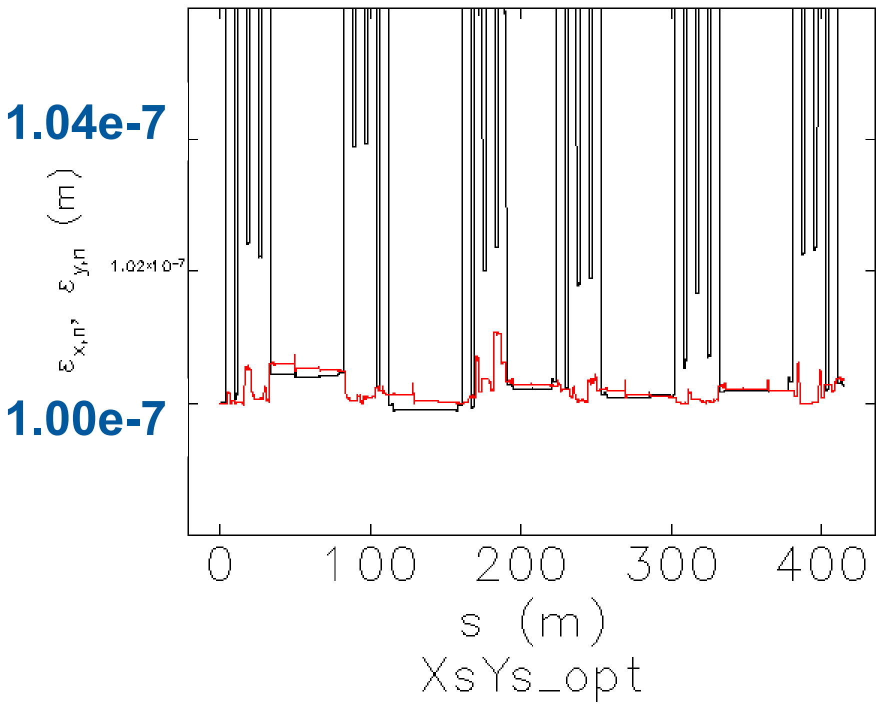
2 sextupole families per cell w/o radiation effects

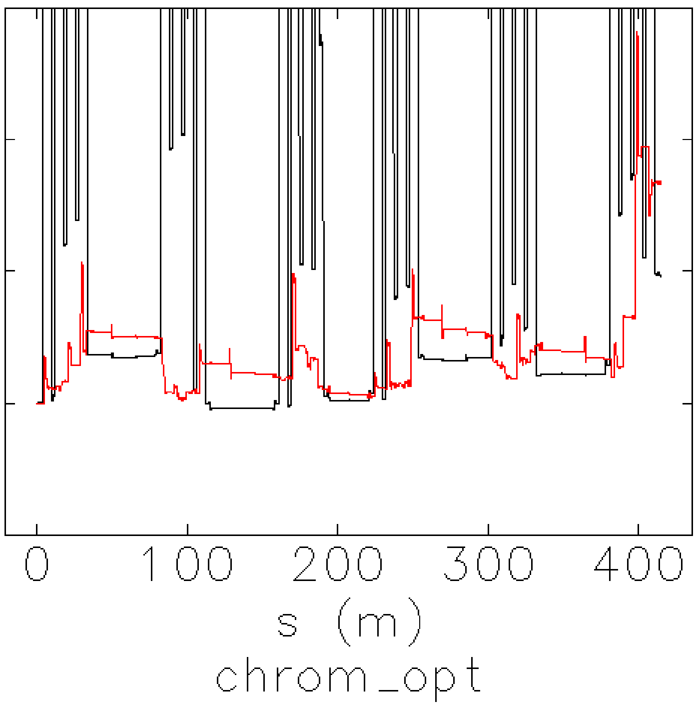
$T_{161}{}^{*}T_{262} - T_{162}{}^{*}T_{261} = 0$

$T_{363}{}^{*}T_{464} - T_{364}{}^{*}T_{463} = 0$

Chromaticity $\xi = \Delta\,\xi\,/\,(\Delta p/p)$

(dnux/dp , dnuy/dp) → 0





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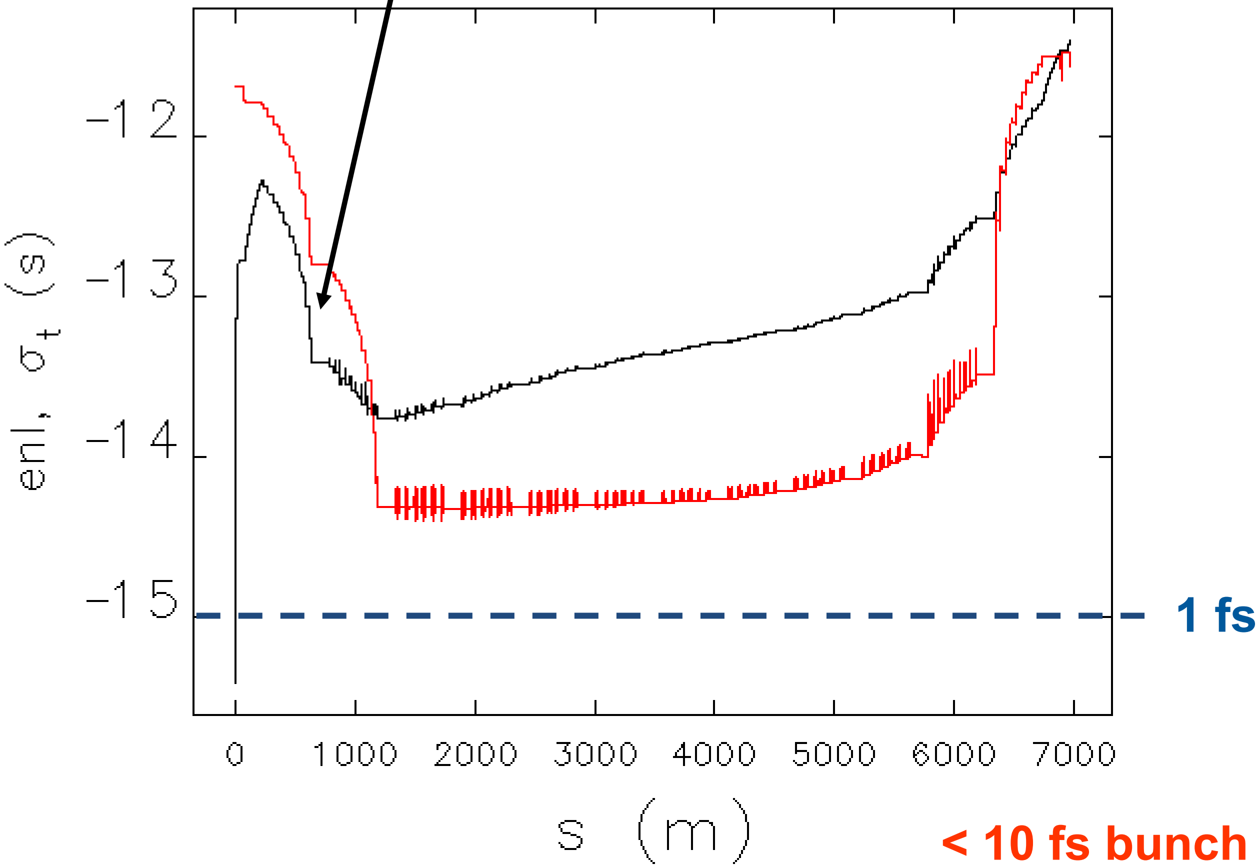
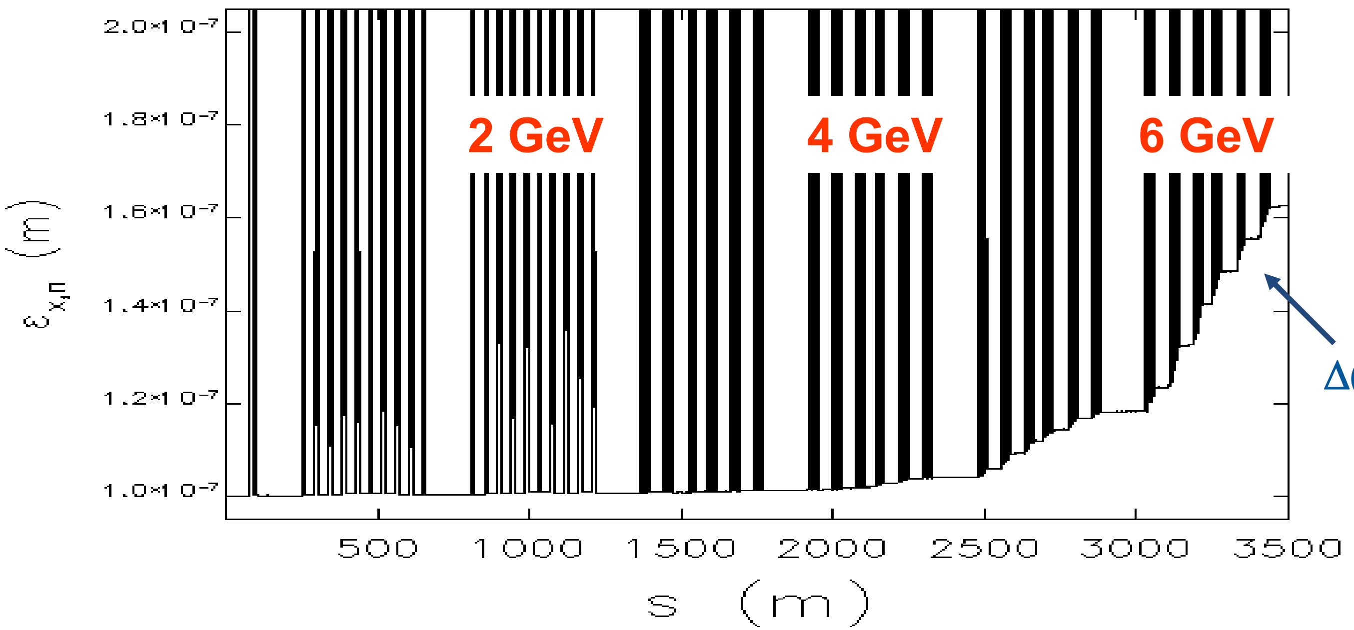
$$\varepsilon_{nl}^2 \approx \left(T_{566}R_{65} - T_{655}\right)^2 < (c\Delta t_0)^4 >< (c\Delta t_0)^2 >$$



< 10 fs bunch length



$\Delta(\gamma\varepsilon_{isr}) \sim 4\mathrm{x}10^{-8}\ E^6\ I_5$
$= 0.05$ mm mrad

Type	ε_{Nx} (mm mrad)	ε_{Ny} (mm mrad)	Bunch Length (fs)	$\Delta E/E$ (10^{-4})	Charge (pC)
Input	0.10	0.10	2000	0.10	-
SPM	0.22	0.11	6	10.2	1
SPM	0.21	0.10	20	7.01	5
LEM	0.17	0.10	2000	1.96	15

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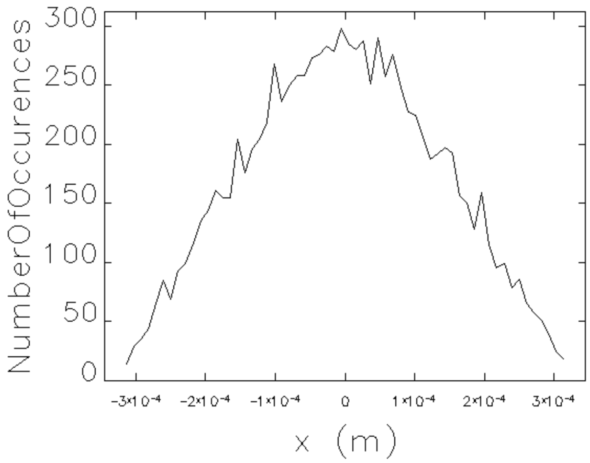
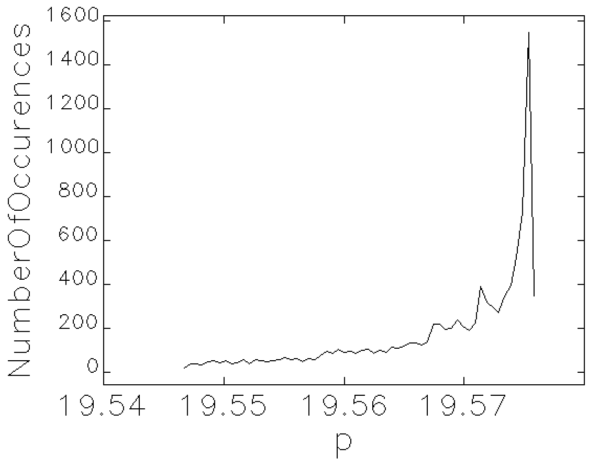
Gaussian like profile



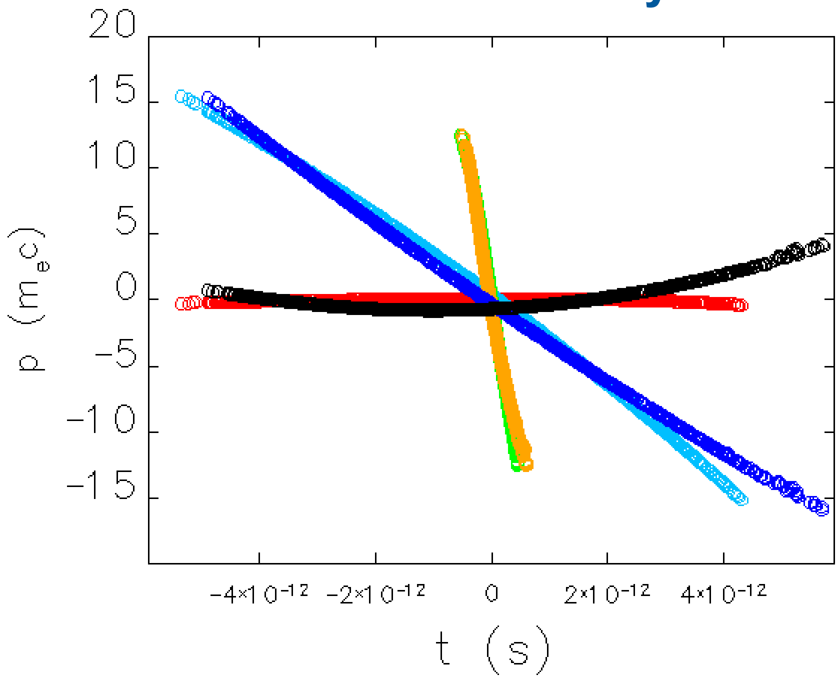
Low longitudinal emittance



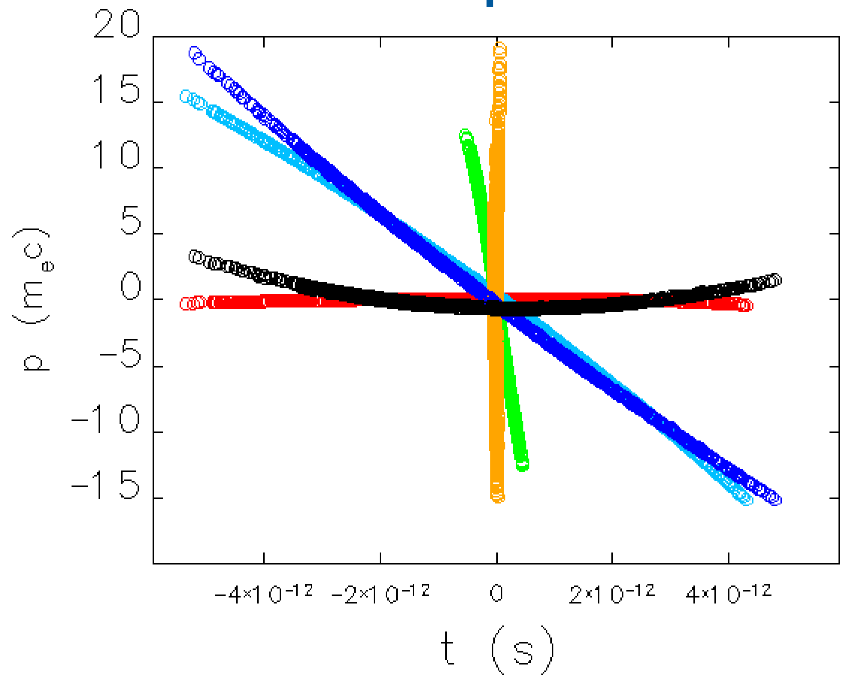
Pos	ε_x (mm mrad)	ε_y (mm mrad)	ε_z (keV mm)	bunch length (mm)	Energy Spread (10^{-4})	Energy (MeV)
Gun	0.15	0.15	0.40	0.65	2.10	2.80
Booster	0.16	0.16	1.20	0.67	3.10	10.0
Merger	0.28	0.18	1.17	0.70	3.79	10.0

Telescopic R56 symmetric bunch (de)compression

2nd order theory

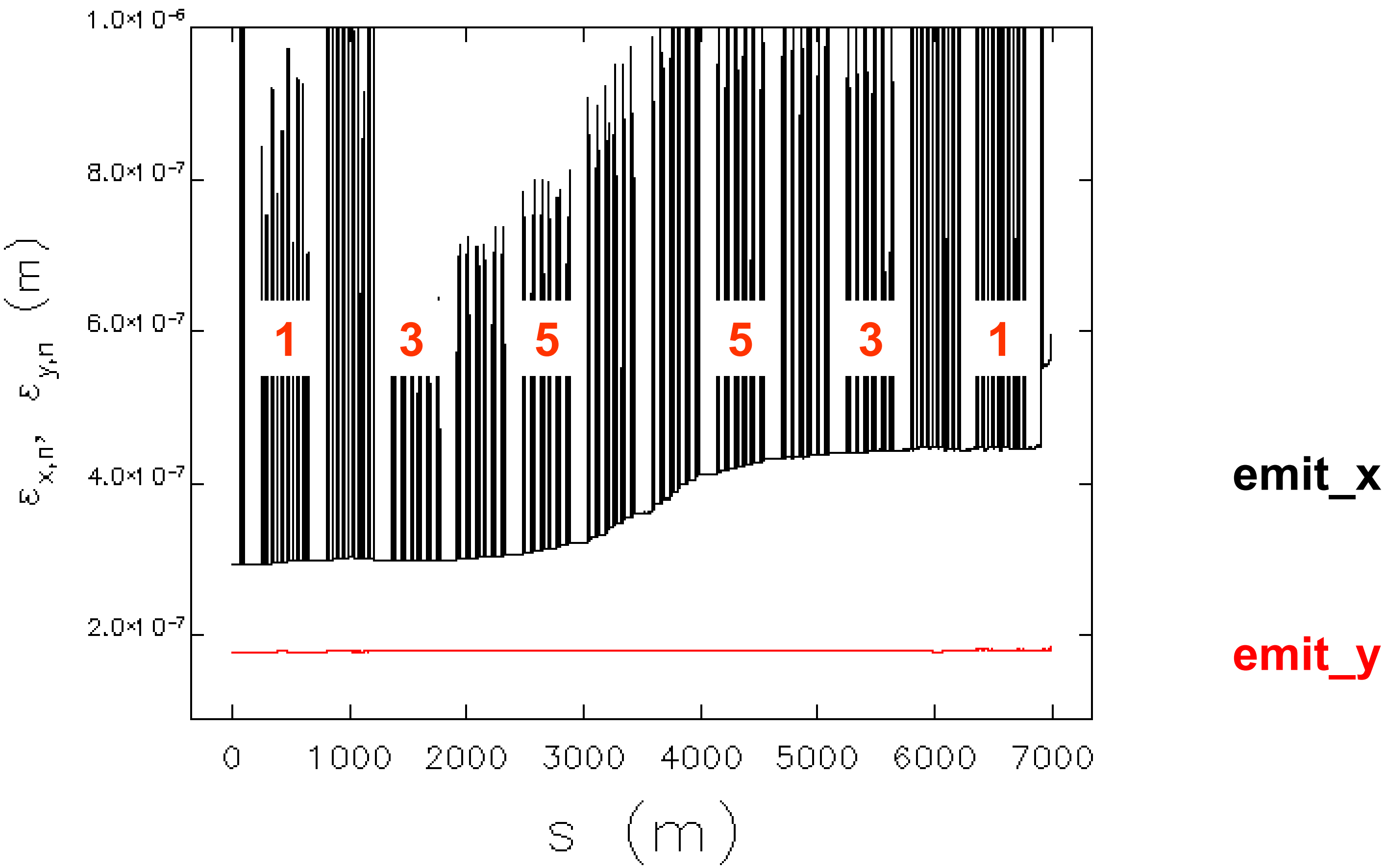


1 pC



240 MeV 1 GeV 2 GeV → 2 GeV 1GeV 240 MeV

acceleration → deceleration


1.0×10⁻⁶
8.0×10⁻⁷
6.0×10⁻⁷
4.0×10⁻⁷
2.0×10⁻⁷
$\varepsilon_{x,n}, \varepsilon_{y,n}$ (m)
0
1000
2000
3000
4000
5000
6000
7000
s (m)
1
3
5
5
3
1
emit_x
emit_y

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Rectangular Bunch CSR Model[Saldin et al.]

total energy loss of the bunch per turn

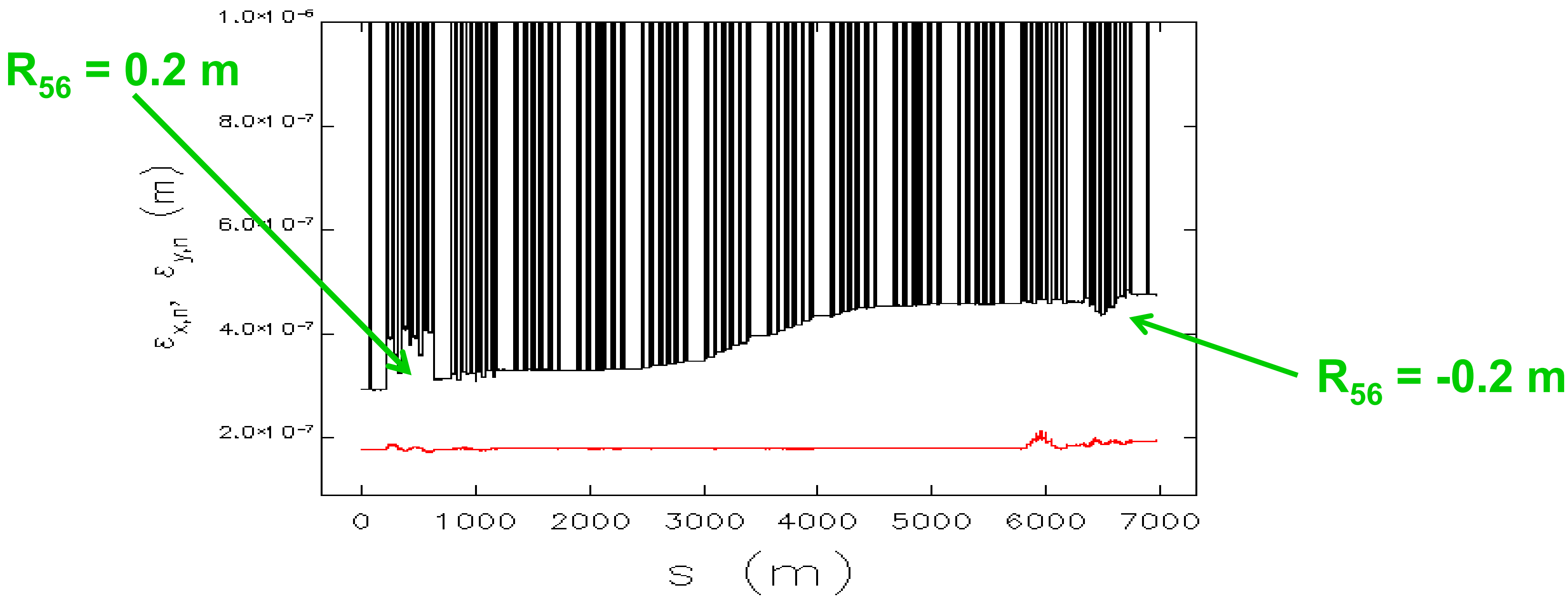
$$\Delta E_{CSR} \approx -\left(\frac{3^{2/3}q^2}{l_b^{4/3}R^{2/3}}\right)(R\vartheta)\left(1+\frac{3^{1/3}4}{9}\frac{l_b^{1/3}}{R^{1/3}\vartheta}\left[\ln\left(\frac{l_b\gamma^3}{R}\right)-4\right]\right)$$

For LEM 15 pC,	E_{CSR} ~ 0.3 MeV
SPM 1 pC,	E_{CSR} ~ 3.3 MeV
SPM 5 pC,	E_{CSR} ~ 16 MeV

Plus ISR component E_{ISR} ~ 0.088*E^4[GeV]/R[m] = 15 MeV

LEM 15 MeV , 300 kW SPM 30 MeV, 200 kW

„Booster Modules“ may suffice?



Type	ε_{Nx} (mm mrad)	ε_{Ny} (mm mrad)	Bunch Length (ps)	$\Delta E/E$ (%)	Charge (pC)
SPM	0.48	0.20	2.24	3.76	1
LEM	0.36	0.18	4.02	7.60	15

can a bunch with energy spread > 5% (rms) be ‚safely' transported to a dump?

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Cathode to pre-injector

Optimise the ASTRA input beam

Design „New“ pre-injector Arc, suitable for both Modes

Implement the Spreaders and Recombiners

Undulator Simulations using WAVE

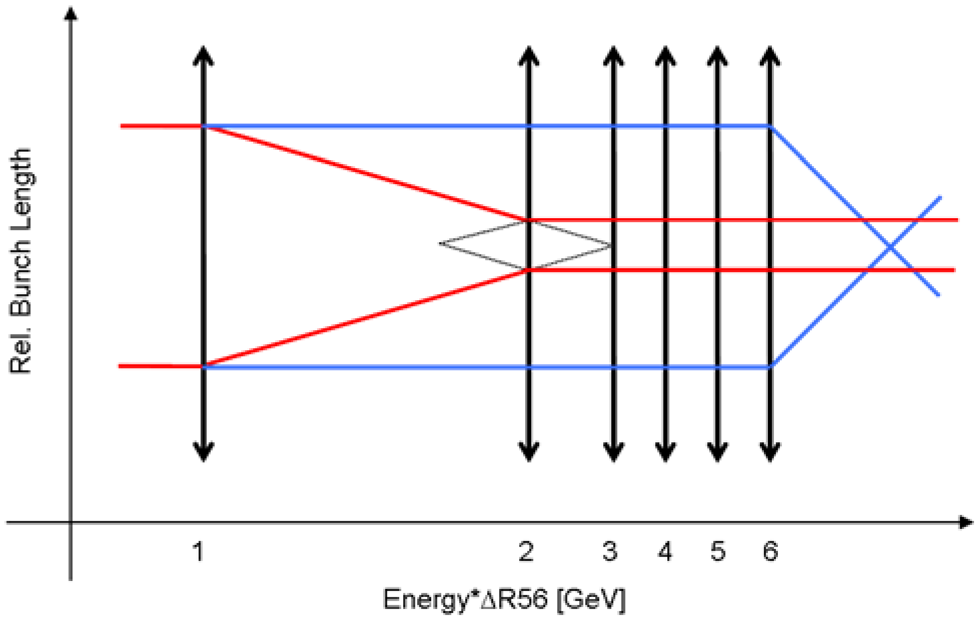
Implement the Beam Dump

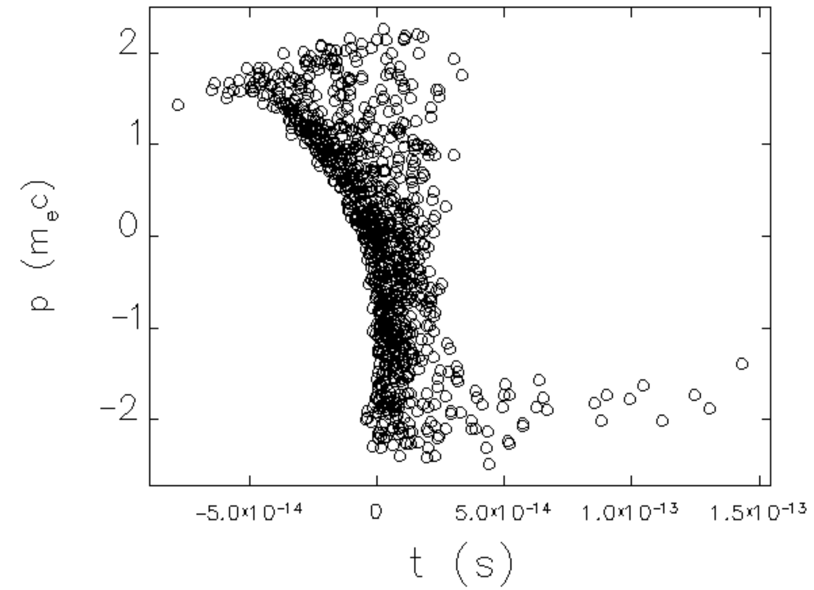
Thanks for listening ....

and thanks again to

A. Bondarenko
A. Matveenko
Y. Petenev

Concentrated on two stage telescopic bunch compression





Linac1 phi = +8° ARC1 R56 = 20 cm Linac2 phi = -20° ARC2 R56 = 5 cm

Start to „middle" beam simulations - Generates bunch length of 20 fs with energy spread 1e-4 rms at the Undulator entrance