The Femto-Science Factory: A Multi-turn ERL Based Light Source

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- **High brilliance**

  - at least a magnitude larger than 3rd generation storage rings (SR)

- **Full transversal coherence**

  - transversal emittance at the diffraction limit $\lambda / 4\pi \rightarrow \lambda = 1$ Å

- **High temporal resolution**

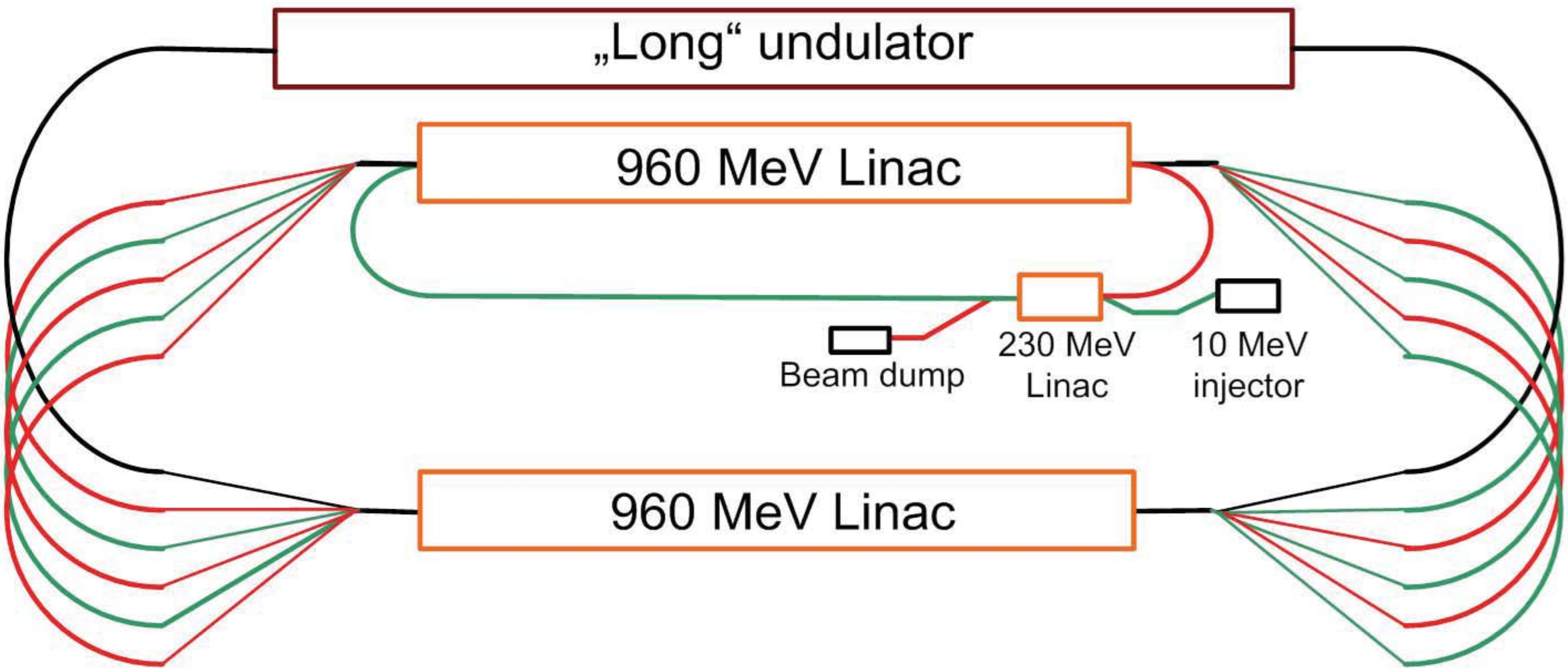
  - providing experiments with fs photon pulses

- **Multiple beam energies**

  - flexible energies up to 6 GeV

CW operation ... ERL required!

- Split Linacs, multiple beam energies, large arcs and long undulator sections



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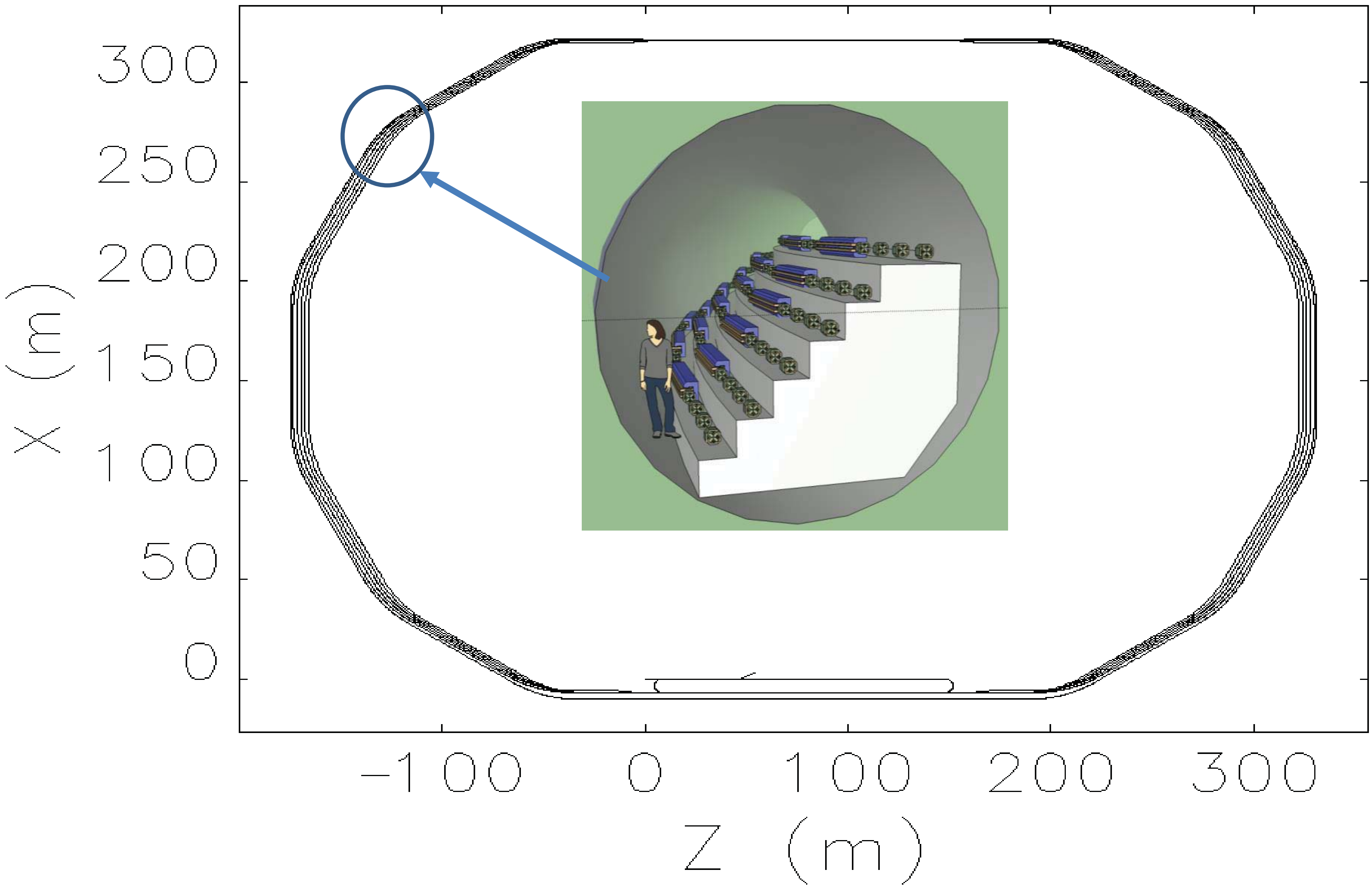
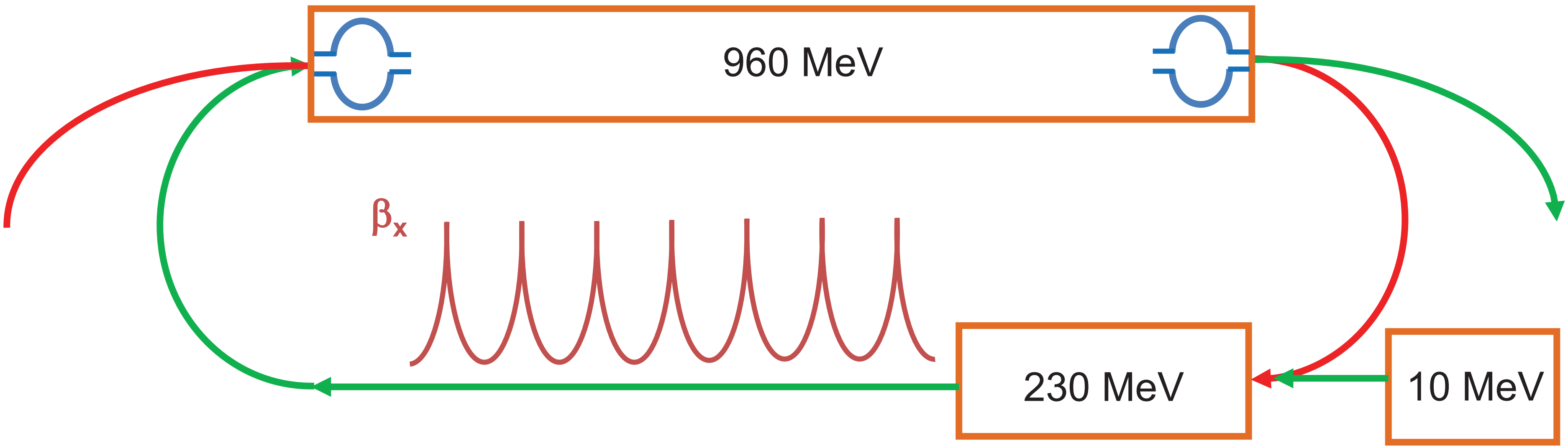


Two-Stage Injection

TBBU calculations help identify the position of critical cavities

$$I_b \propto \frac{1}{\sqrt{\sum_{m=1}^{2N-1} \sum_{n=m+1}^{2N} \frac{\beta_m \beta_n}{\gamma_m \gamma_n}}}$$

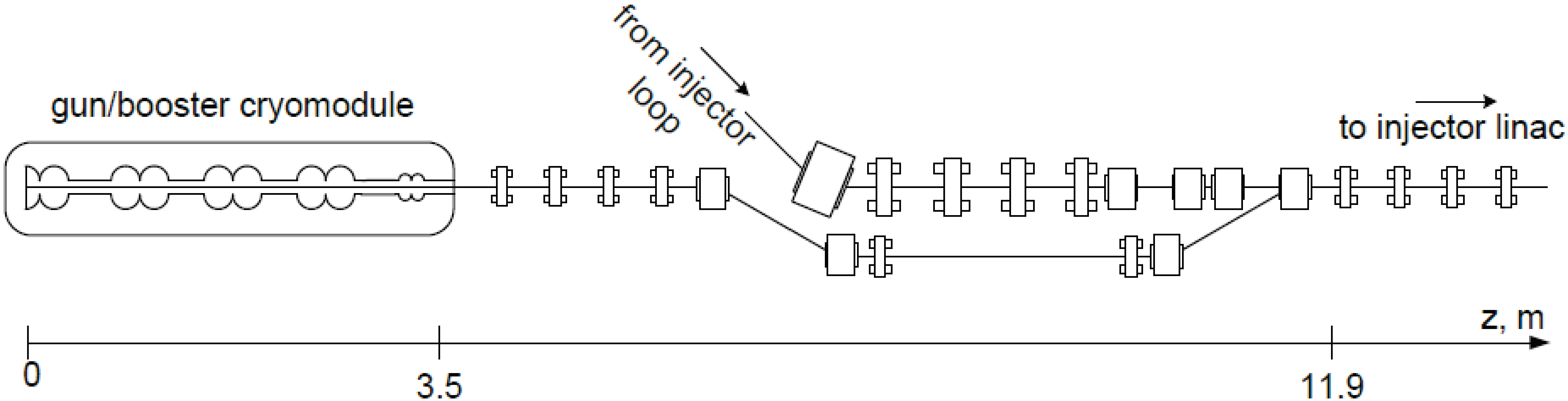


Laser Heater to avoid Microbunching Instability

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

$k = 2.5$, $d = 9$ cm, $\lambda_{laser} \sim 0.8$ µm $\rightarrow \gamma = 480$

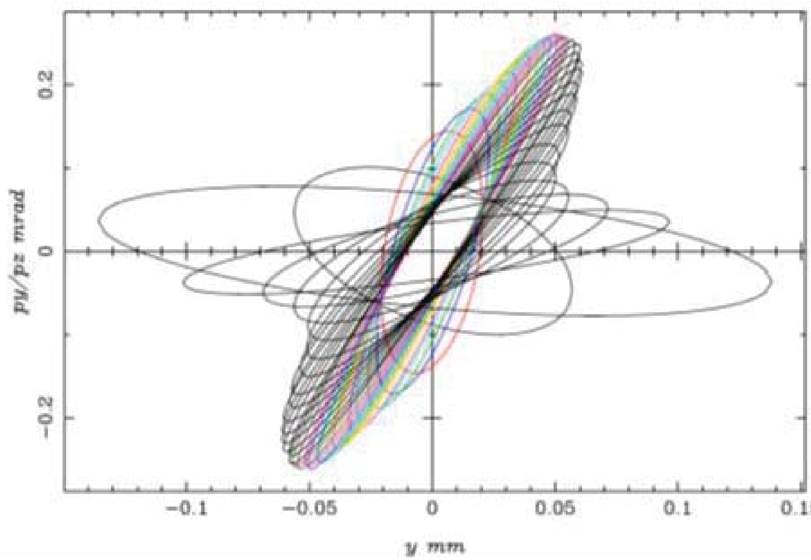
• ASTRA and "SCO" used to optimize the injector + linac for minimal emittance



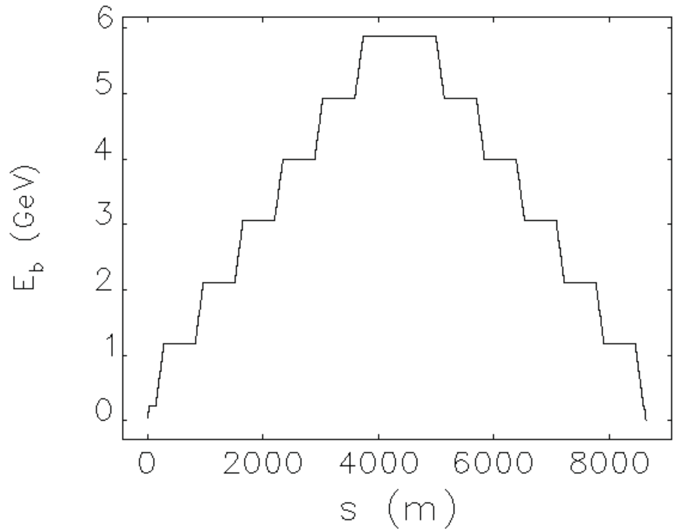
• Kapchinsky-Vladimirsky emittance compensation scheme possible on the "rotation" of the sliced phase ellipses

$$x'' = -k_x x + \frac{j}{x+y}$$

$$y'' = -k_y y + \frac{j}{x+y}$$



- Elegant used to track particles through the 8km of optic



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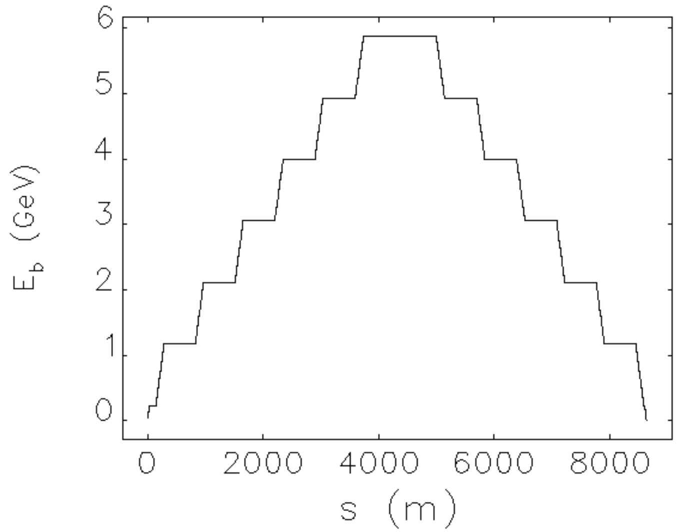
ASTRA up to 50 MeV



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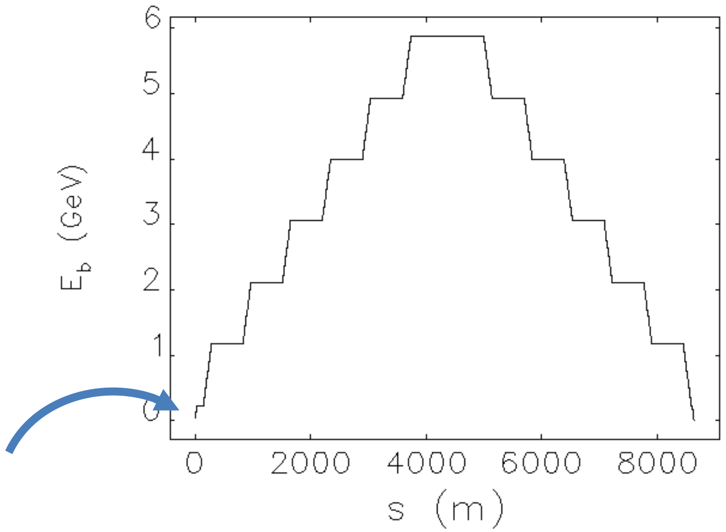

Start-to-End: High Brilliance Mode (LEM)

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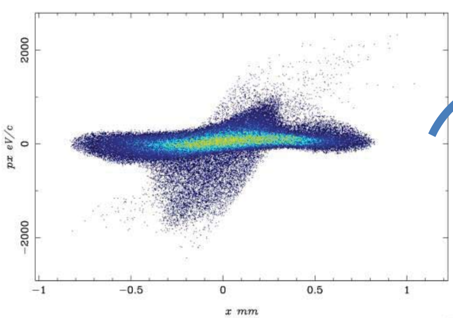
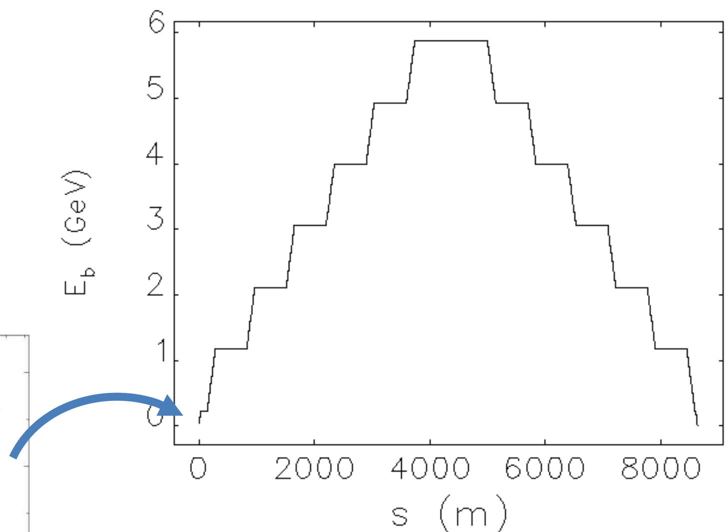
ASTRA up to 50 MeV





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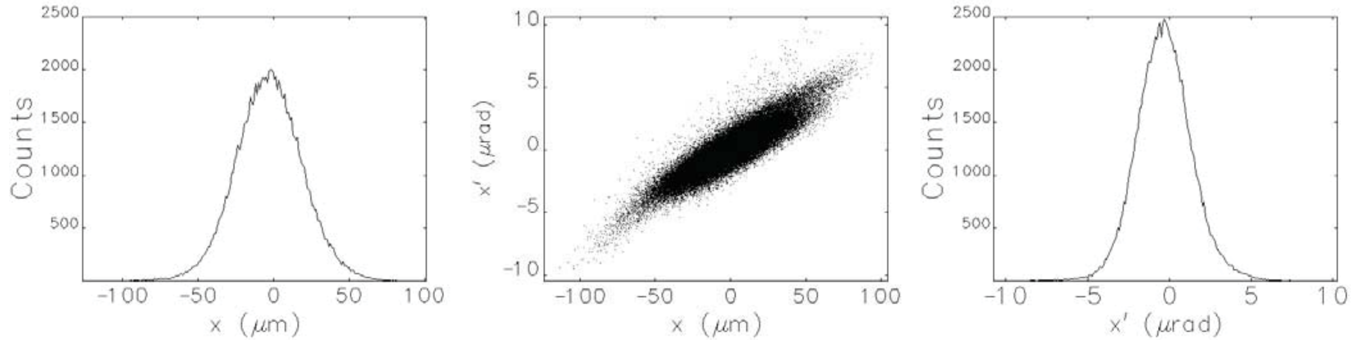
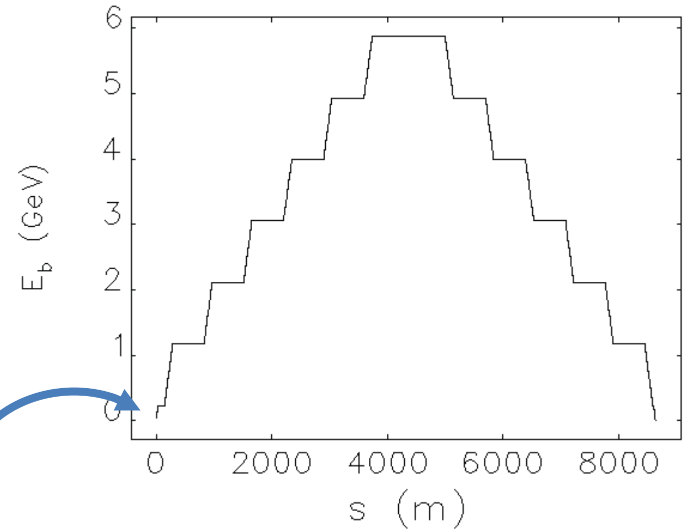
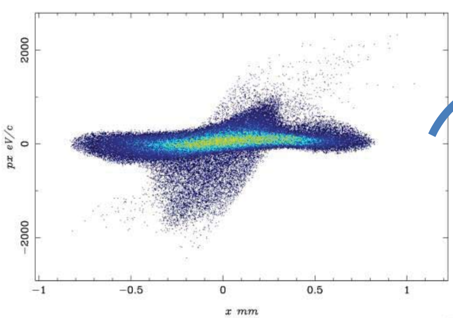




ASTRA up to
50 MeV



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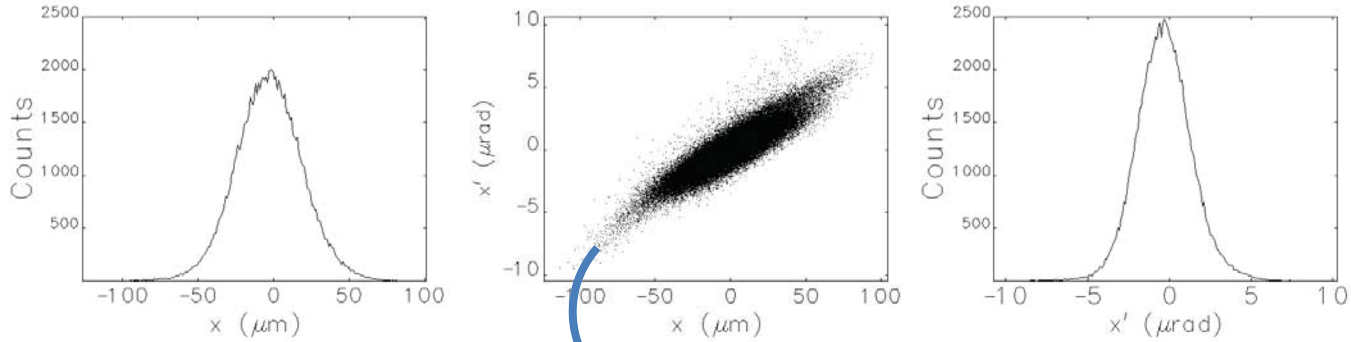
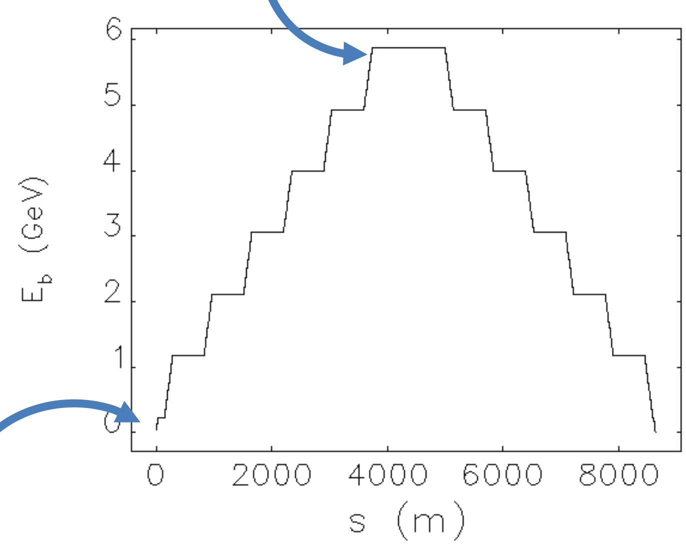
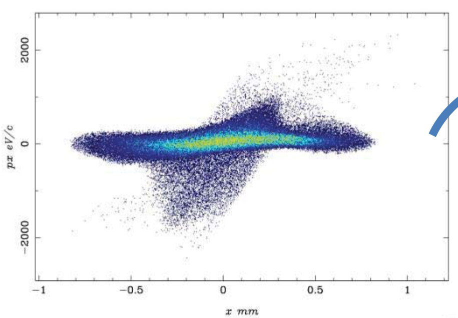




ASTRA up to 50 MeV



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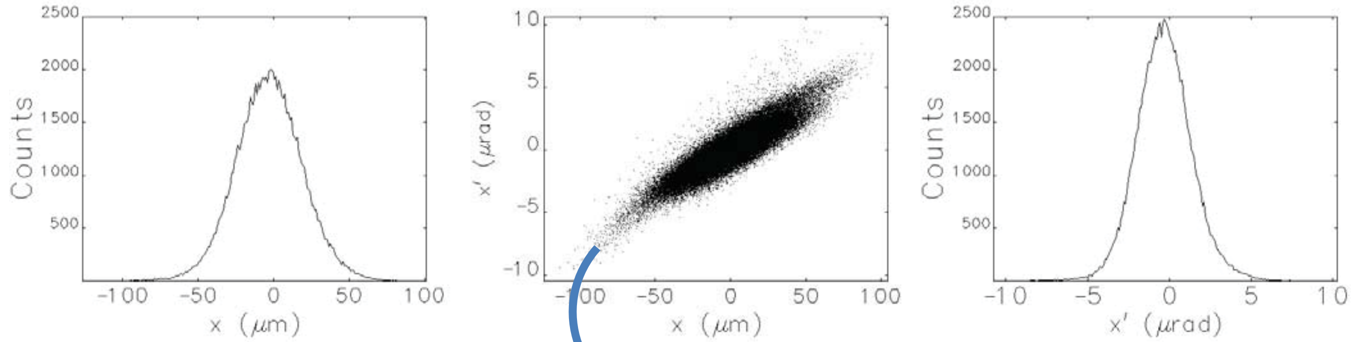
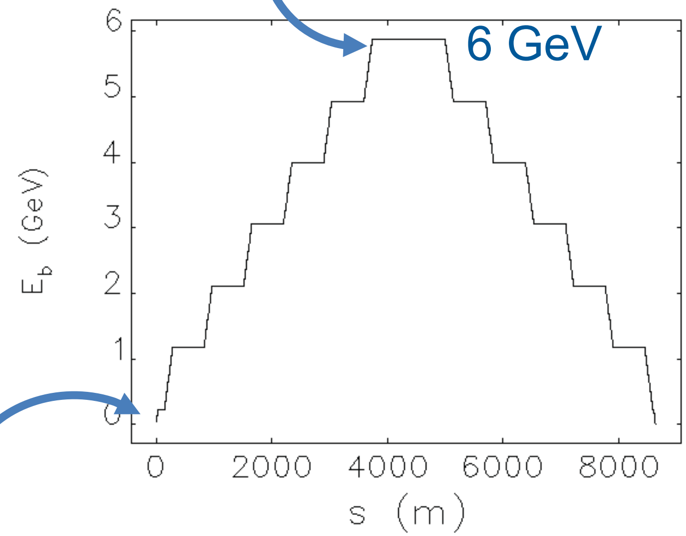
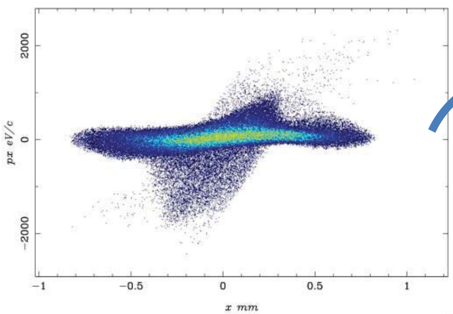


6 GeV



ASTRA up to
50 MeV



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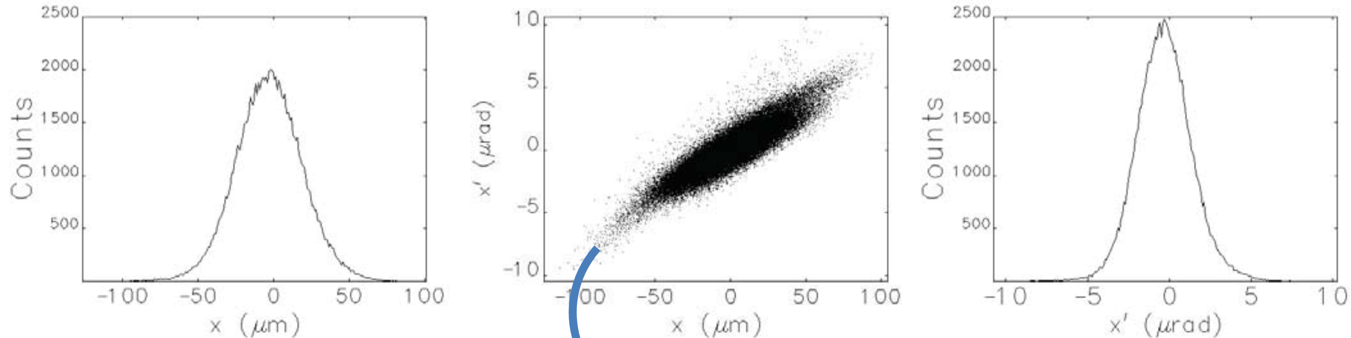
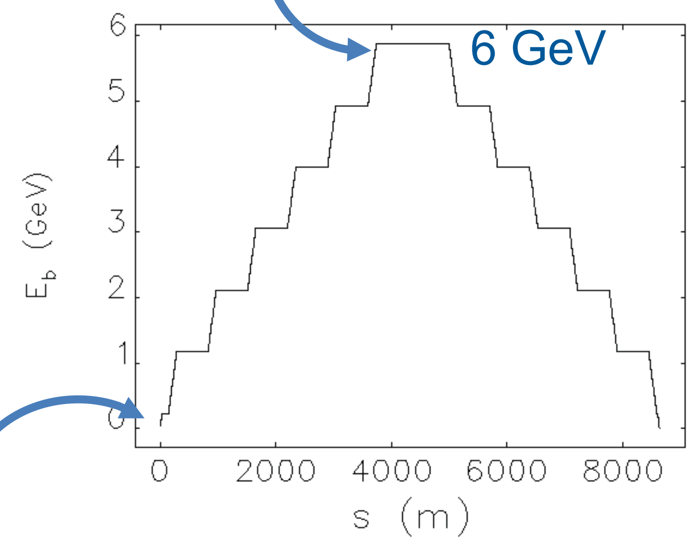
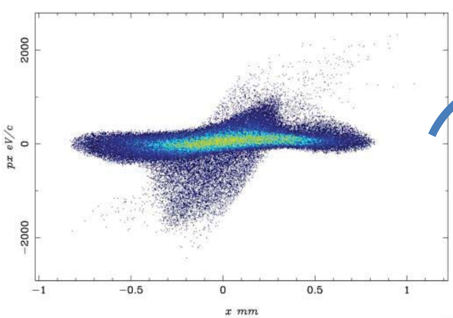
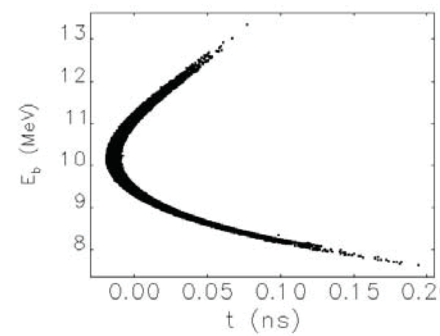


6 GeV



ASTRA up to 50 MeV





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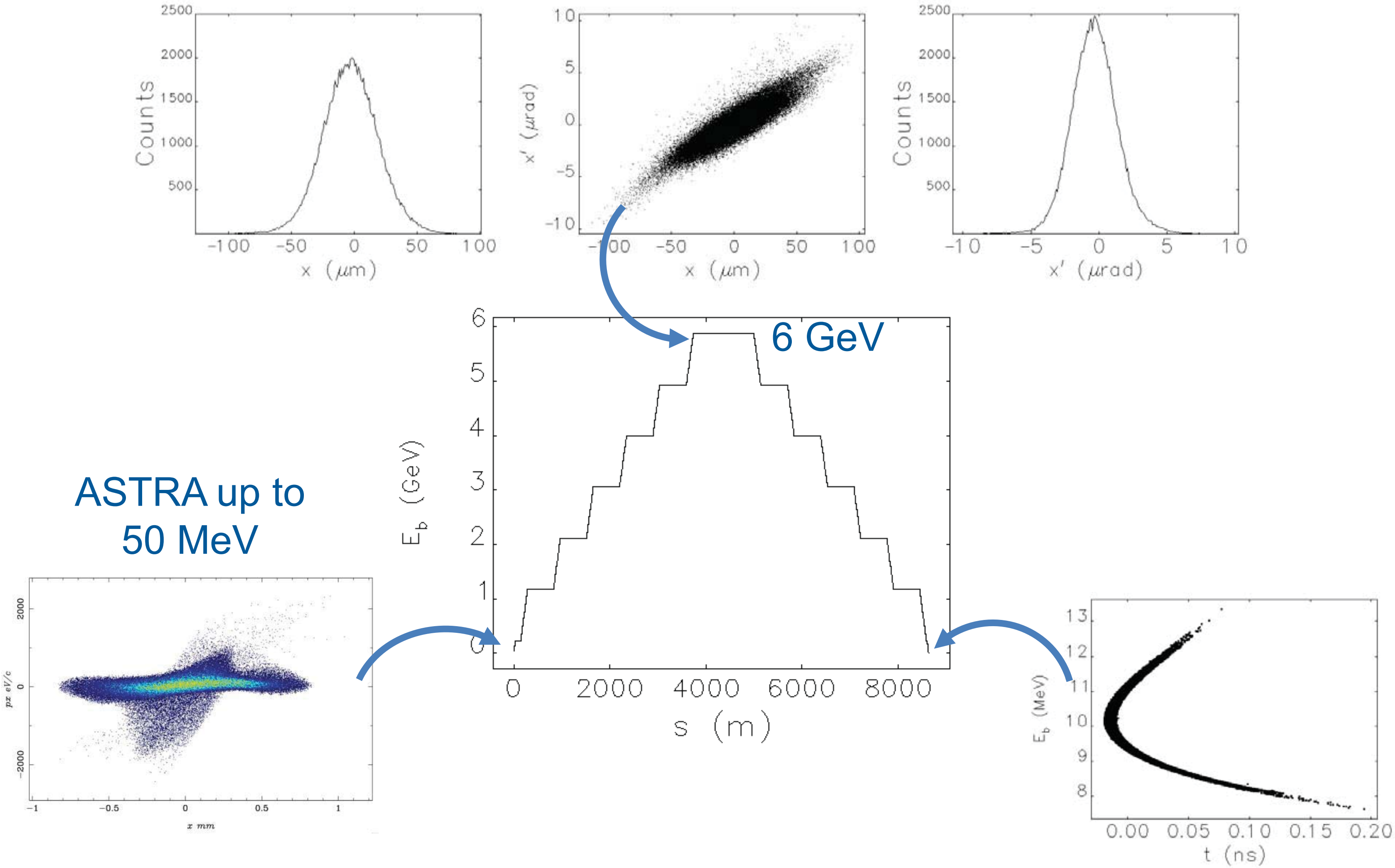

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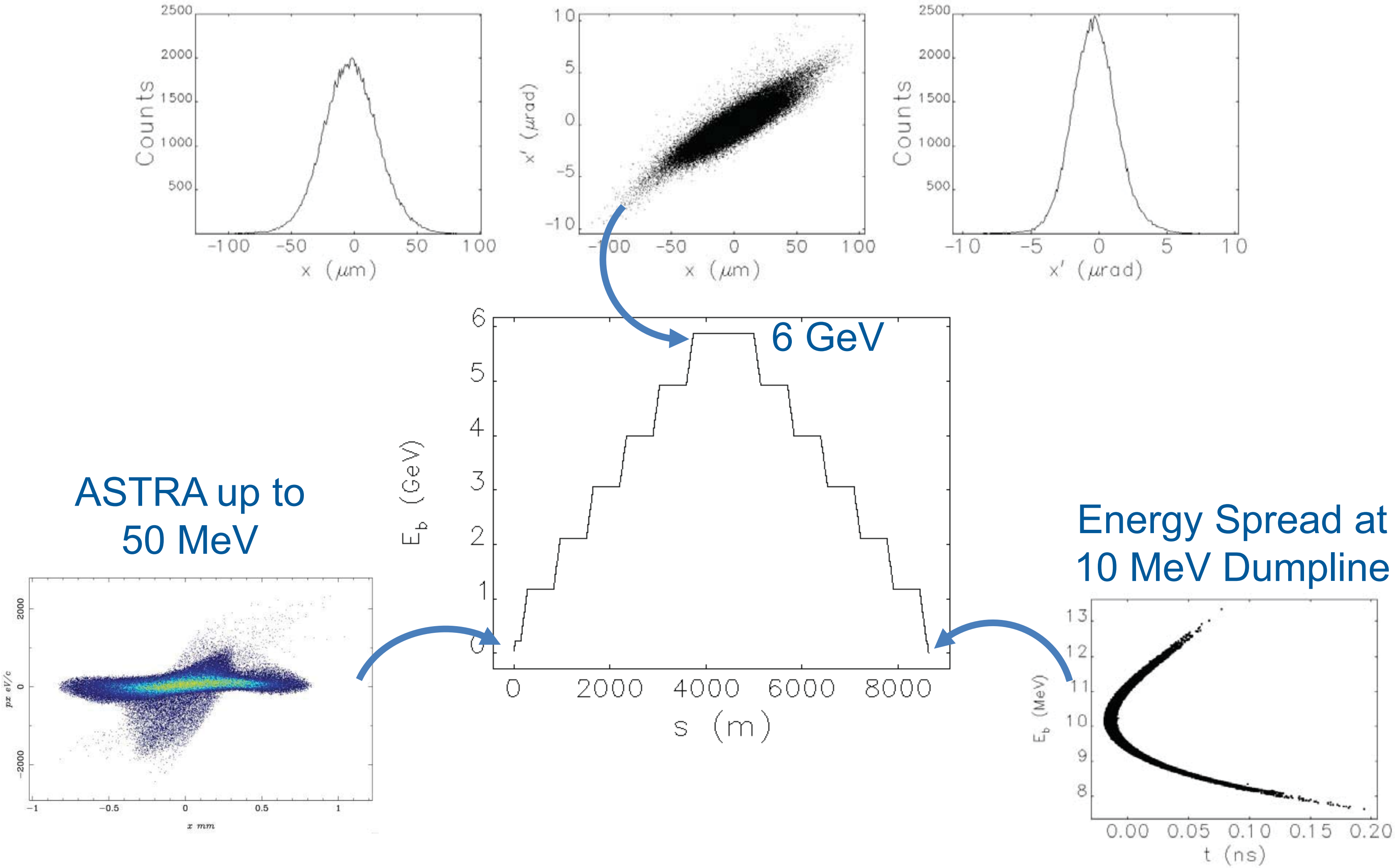
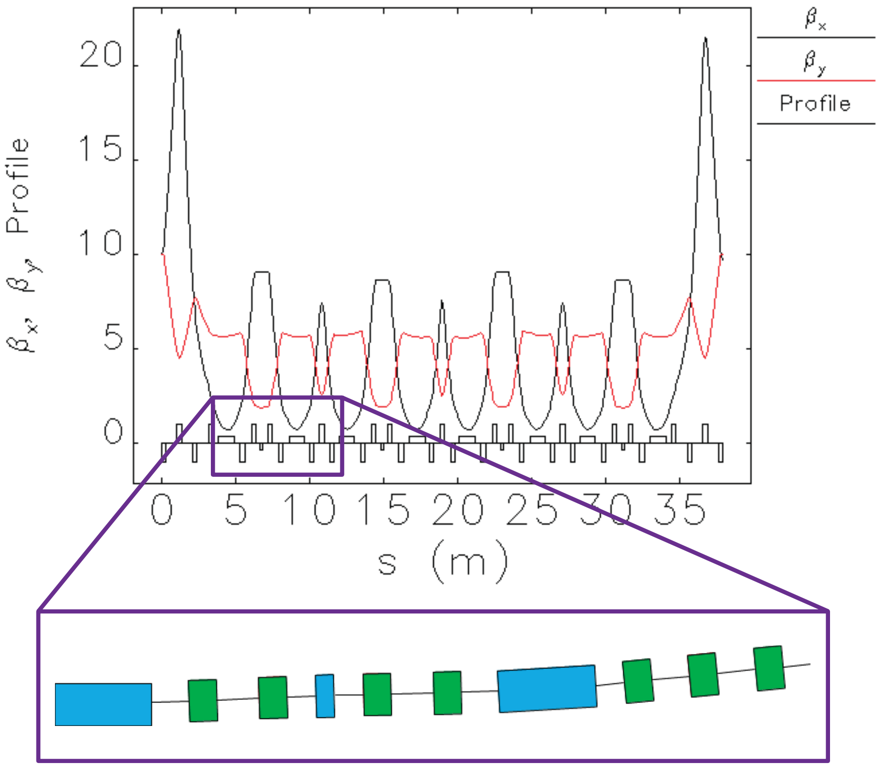


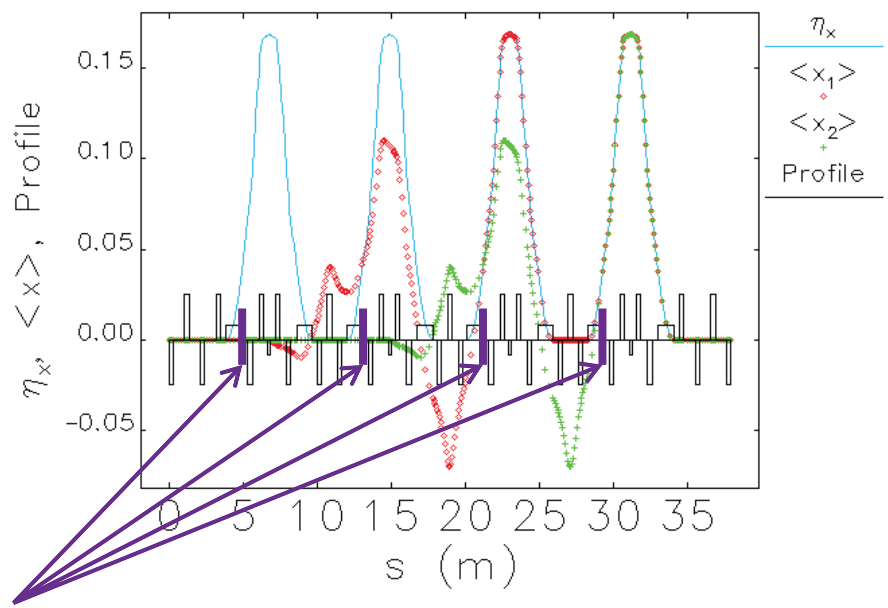
- 1D CSR wakes in consecutive cells are identical …



30° arc as four 7.5° cells

can manipulate the phase advance to nullify the emittance growth!

$$\Delta\mu_x = 2\pi \cdot 3/4$$



CSR “kicks”

Start-to-End: Low Emittance 15 pC Mode

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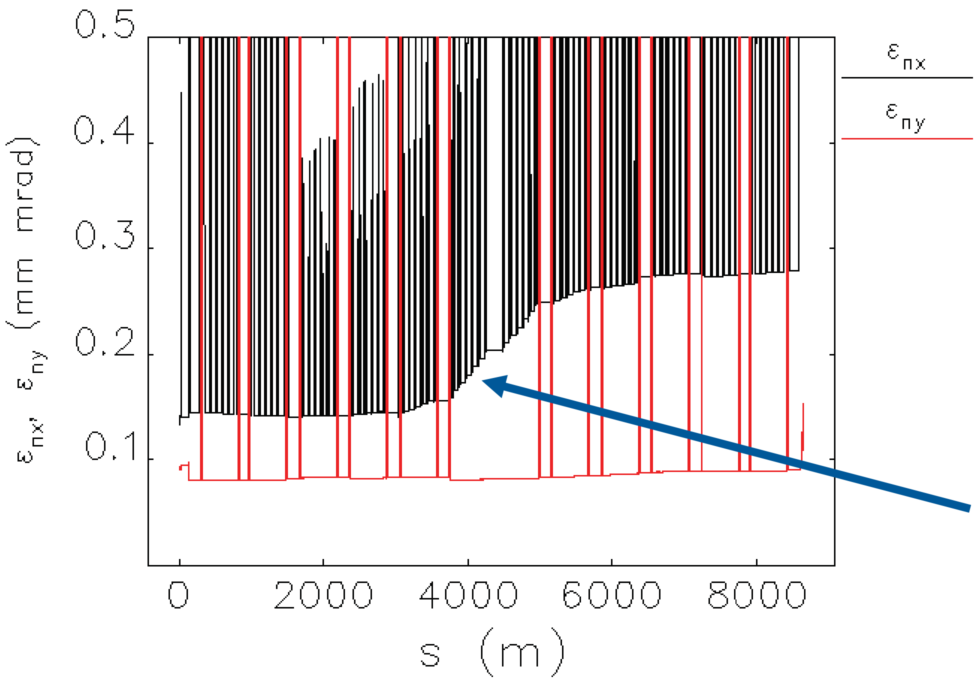


- Emittance growth due to ISR
  - unavoidable -

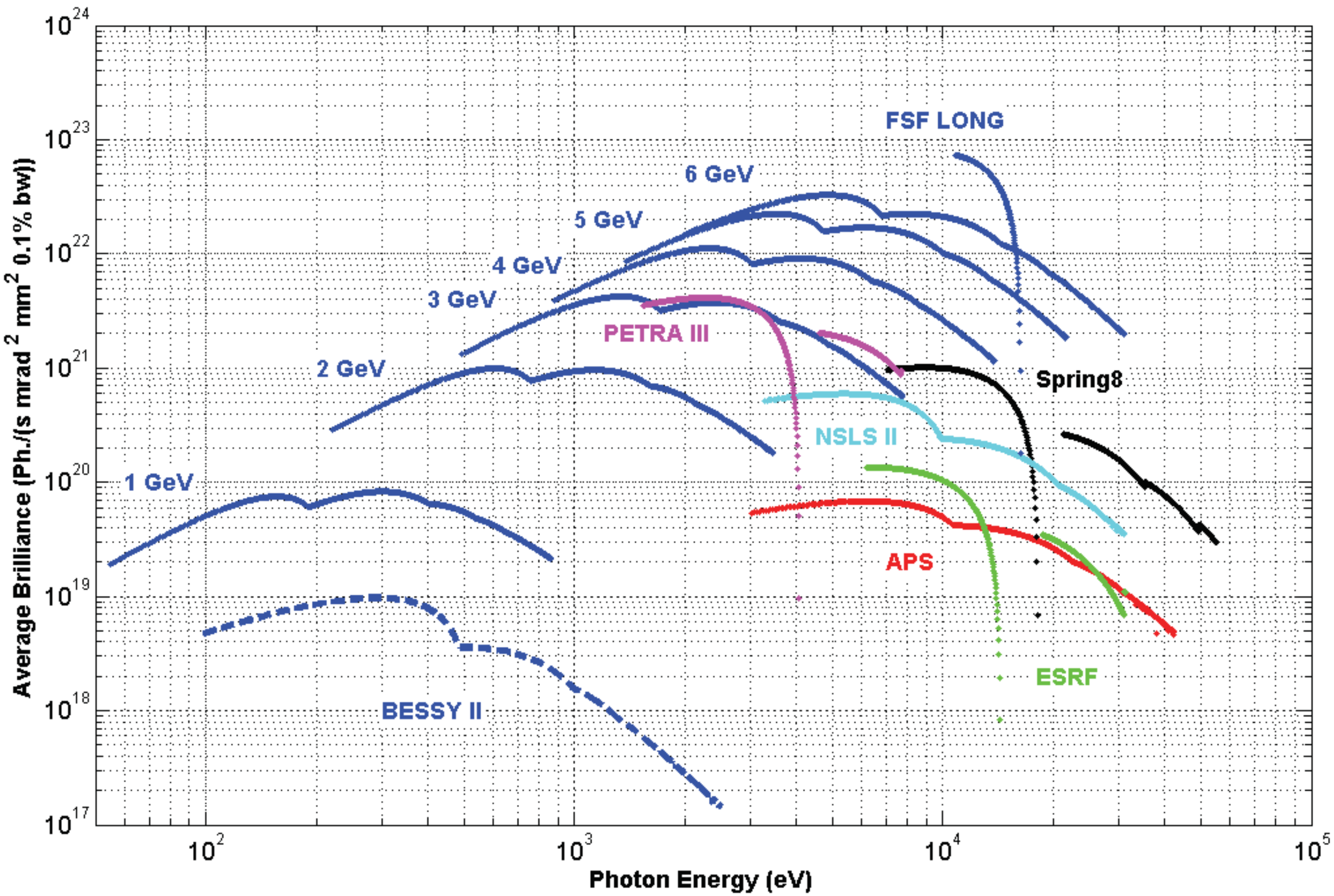
$$I_5 = \int \frac{\mathcal{H}}{|\rho|^3}\, ds \sim \frac{\theta^3}{\rho} \simeq 2 \cdot 10^{-5}\,[\mathrm{m}^{-1}]$$

In the 6 GeV arc …

$$\Delta\varepsilon_{n,\mathrm{ISR}} \sim 4 \cdot 10^{-8}\, E_b^6[\mathrm{GeV}]\, I_5[\mathrm{m}^{-1}] = 0.04\,\mathrm{mm\,mrad}$$

Pos	ε_{nx} (mm mrad)	ε_{ny} (mm mrad)	σ_t (ps)	σ_E (10^{-3})	Energy (MeV)
Input	0.13	0.09	3.09	2.93	50
1st user station	0.14	0.08	2.13	0.21	1000
Undulator	0.20	0.08	2.13	0.18	6000
Final user station	0.28	0.09	2.13	0.66	1000
Dumpline	1.24	0.11	3.60	7.26 %	10

- Comparison with existing 3rd generation light sources



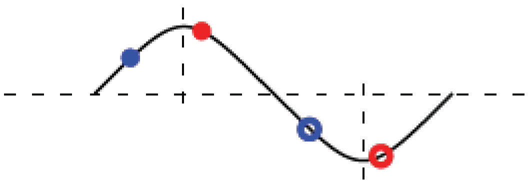
General compression scheme for the FSF SPM

Off-crest acceleration $\phi_{1a} = 100°$, $\phi_{2a} = 70°$

Telescopic compression

Arc1 TBA $R_{56_1} = 20$ cm

Arc2 TBA $R_{56_2} = 5$ cm



High energy arcs

3 GeV → 6 GeV DBA with anti-magnet,

Off-crest deceleration $\phi_{1d} = 280°$, $\phi_{2d} = 250°$

High energy arcs

6 GeV → 3 GeV DBA with anti-magnet

Telescopic decompression

Arc2 TBA $R_{56_2} = -5$ cm

Arc1 TBA $R_{56_1} = -20$ cm

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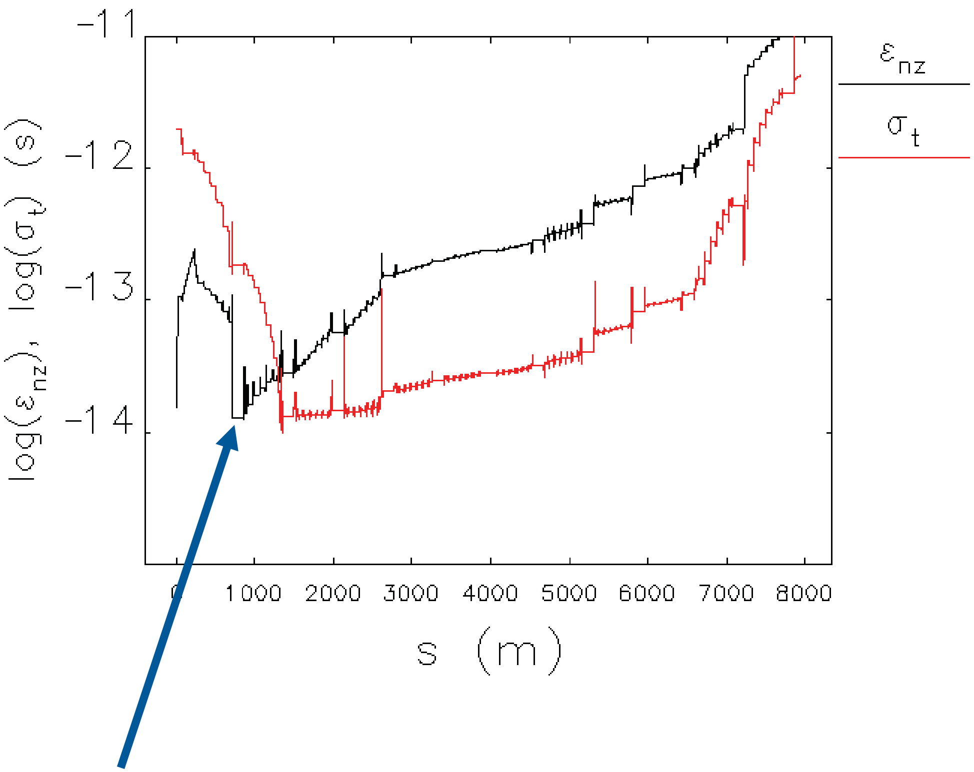
• RF curvature can alter the phase space distributions which varies the emittance. The optic can "correct" it !!!

LINAC:

$$c\Delta t_1 = c\Delta t_0$$
$$\delta_1 = \delta_0 + R_{65} c\Delta t_0 + T_{655}(c\Delta t_0)^2$$

ARC:

$$c\Delta t_2 = c\Delta t_1 + R_{56}\delta_1 + T_{566}\delta_1^2$$
$$\delta_2 = \delta_1$$

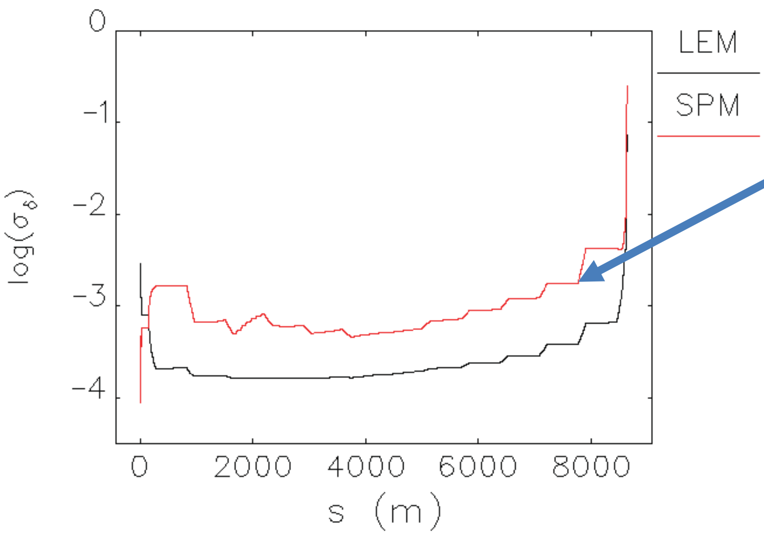


Emittance

$$\varepsilon_2^2 = \langle (c\Delta t_2)^2\rangle\langle\delta_2^2\rangle - \langle c\Delta t_2 \delta_2\rangle^2$$

$$\boxed{\varepsilon_2^2 = \langle (c\Delta t_0)^4\rangle\langle (c\Delta t_0)^2\rangle\left(T_{566}R_{65}^3 - T_{655}\right)^2}$$

R65, **T655** – linac phase + **T566** in arc → **FULL Long. Emitt RECOVERY**



Chromatic correction scheme required due to high energy spread on recovery

$$T^C_{ijk} = \sum_l^6 R^B_{il} T^A_{ljk} + \sum_l^6 \sum_m^6 T^B_{ilm} R^A_{lj} R^A_{mk}$$

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

Pos	ε_{nx} (mm mrad)	ε_{ny} (mm mrad)	σ_t (fs)	σ_E (10^{-3})	Energy (MeV)
Input	0.11	0.06	1990.09	0.46	50
Two stage injection	0.12	0.06	1281.99	0.57	240
Low energy arcs	0.18	0.06	7.39	0.71	2000
High energy arcs	0.30	0.08	22.59	0.62	4000
Undulator	0.49	0.10	24.73	0.52	6000
High energy arcs	1.00	0.23	48.70	0.92	4000
Low energy arcs	2.52	0.49	452.22	1.77	2000
Two stage recovery	8.47	0.93	3924.42	6.34	240
Dumpline	32.88	0.64	4430.29	14.66 %	10

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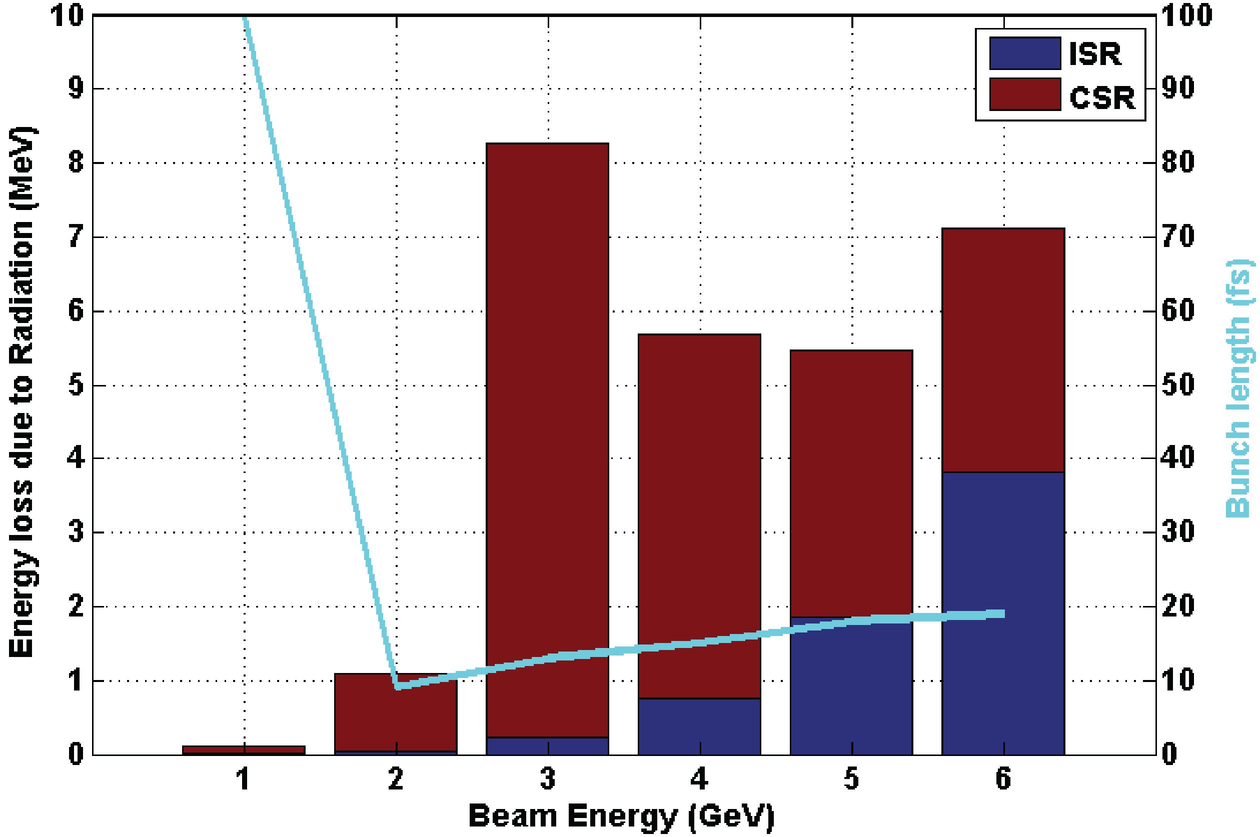
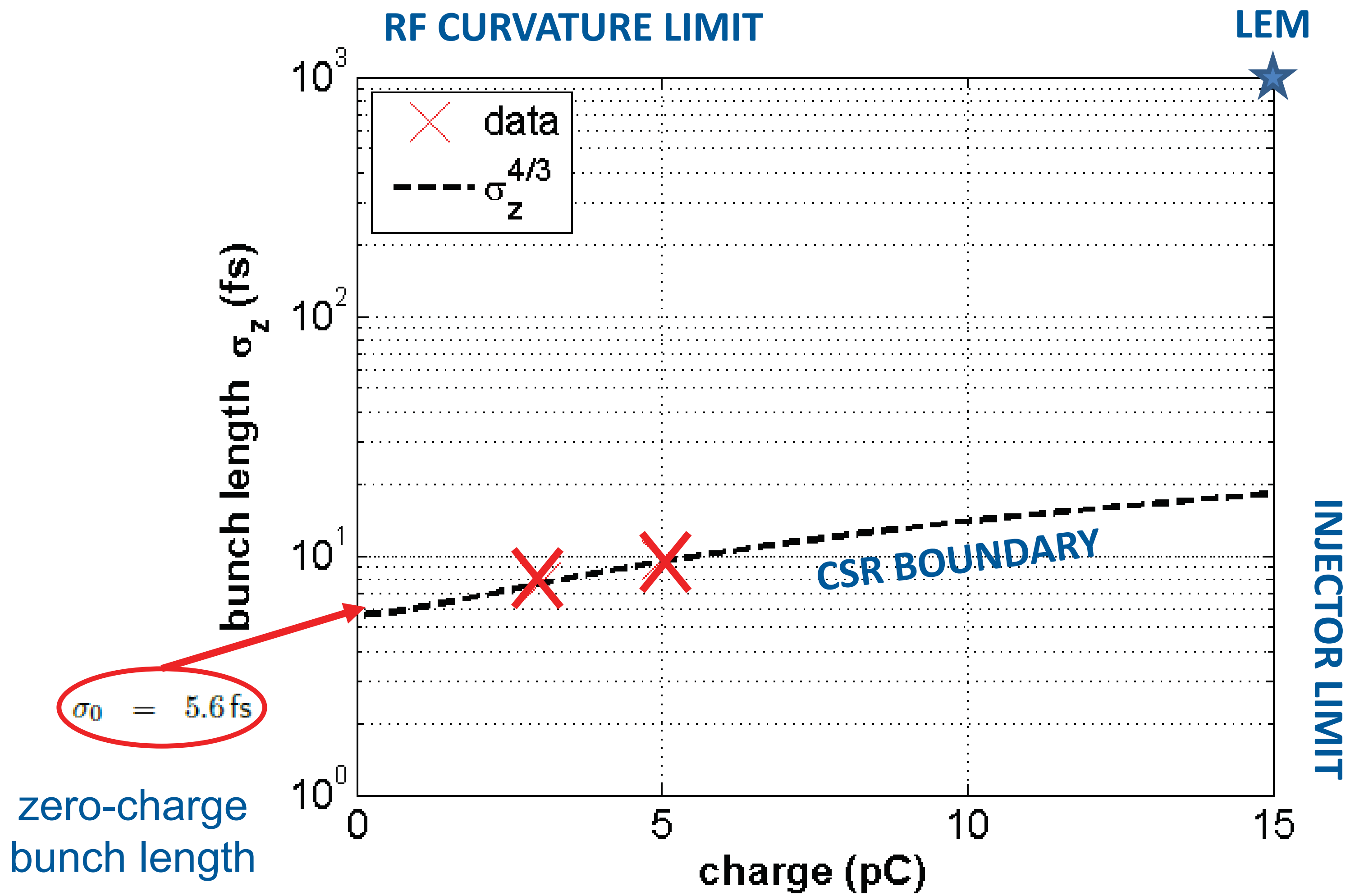
- Additional Boosters required to supplement the beams energy loss

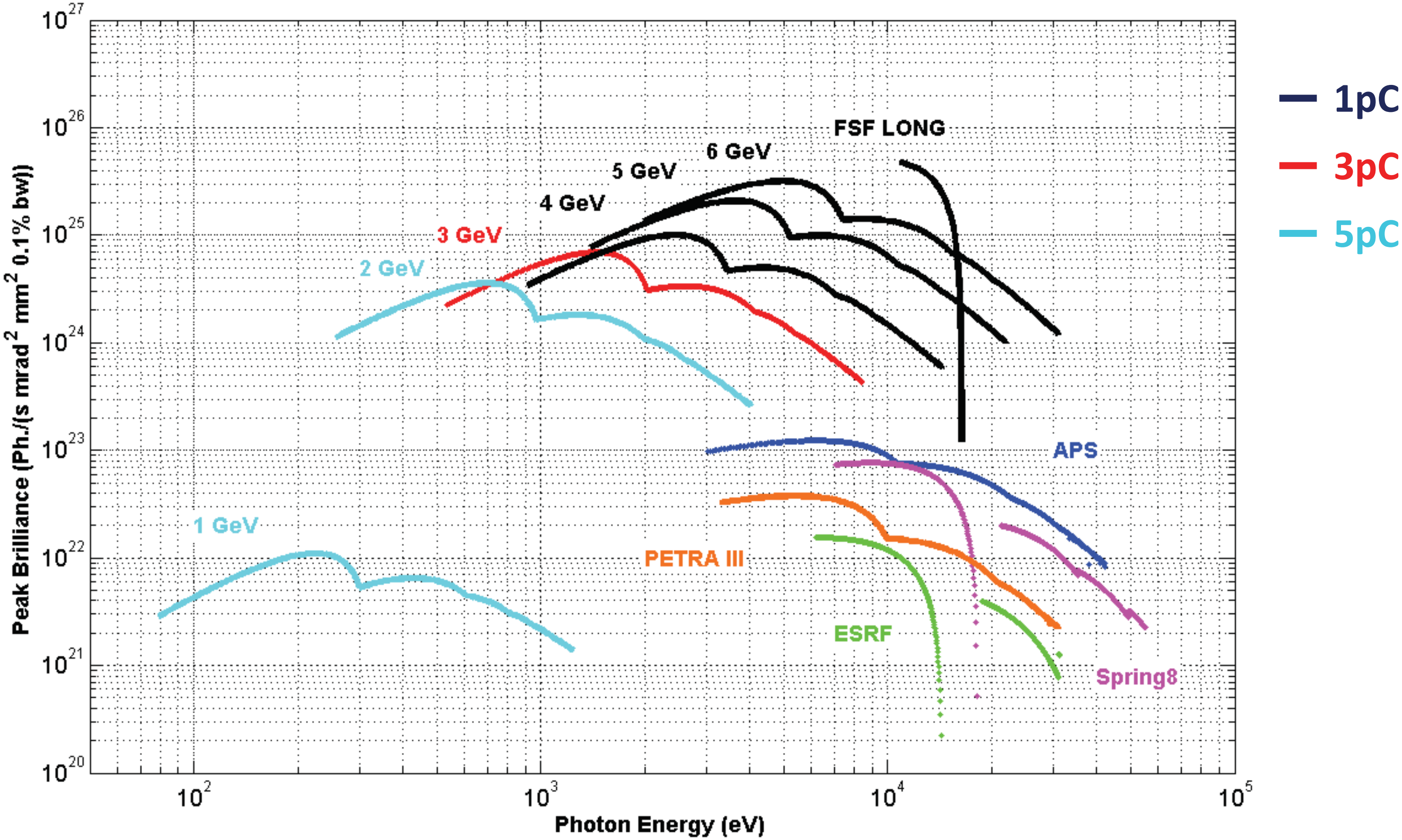


CSR dominates the SPM → $\mathbf{E_{CSR}}$ **= 20 MeV** on the acceleration side



Energy loss due to CSR* $\Delta E_{\mathrm{CSR}} \sim q/\,(\sigma_t^2 - \sigma_0^2)^{2/3} \sim \mathrm{const}$

- Comparison with existing 3rd generation light sources



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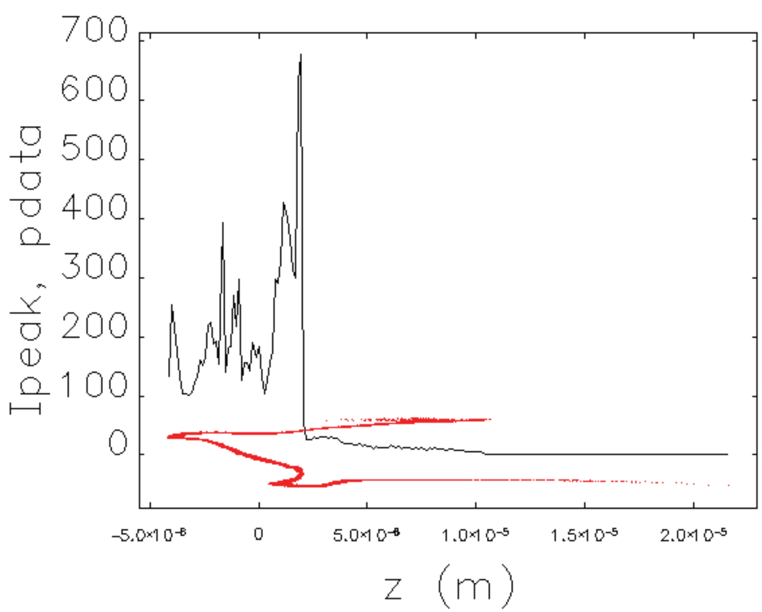
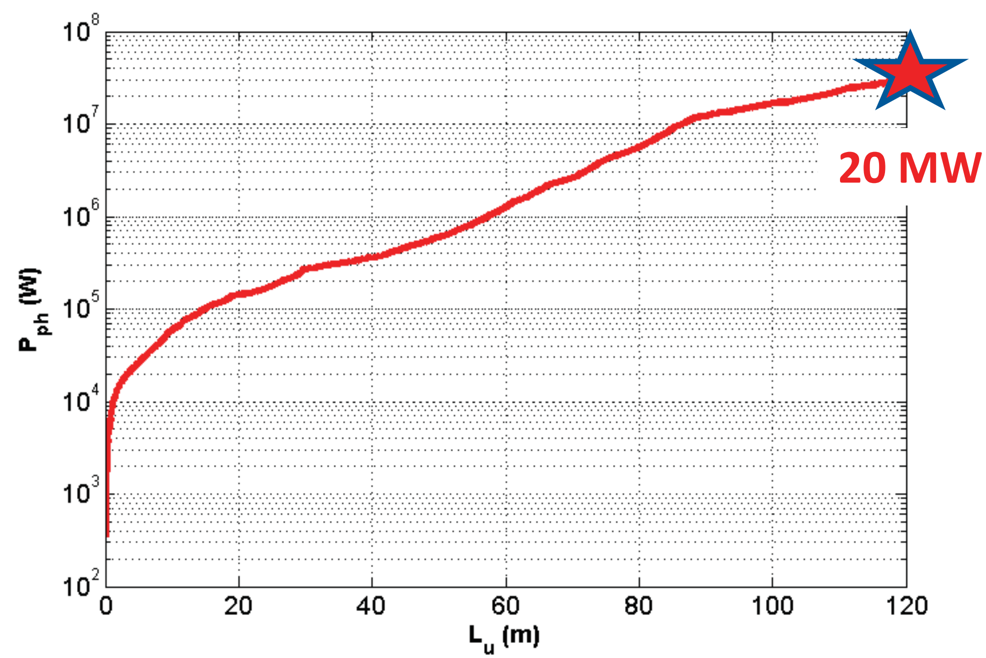
- SPM beam parameters at the diffraction limit …

$$\varepsilon_{\text{limit}} < \frac{\lambda_{\text{ph}}}{4\pi}$$

Energy (GeV)	$\varepsilon_x \cdot 10^{-11}$ (m rad)	$\varepsilon_y \cdot 10^{-11}$ (m rad)	σ_t (fs)	σ_E (10^{-3})	$\varepsilon_{\text{limit}} \cdot 10^{-11}$ (m rad)
1	4.65	2.73	185.0	1.68	59.7
2	3.70	1.65	11.45	0.68	14.9
3	3.70	1.16	25.03	1.00	6.63
4	4.18	0.92	31.27	0.71	3.73
5	4.12	0.76	32.05	0.66	2.39
6	4.26	0.97	31.71	0.65	1.66

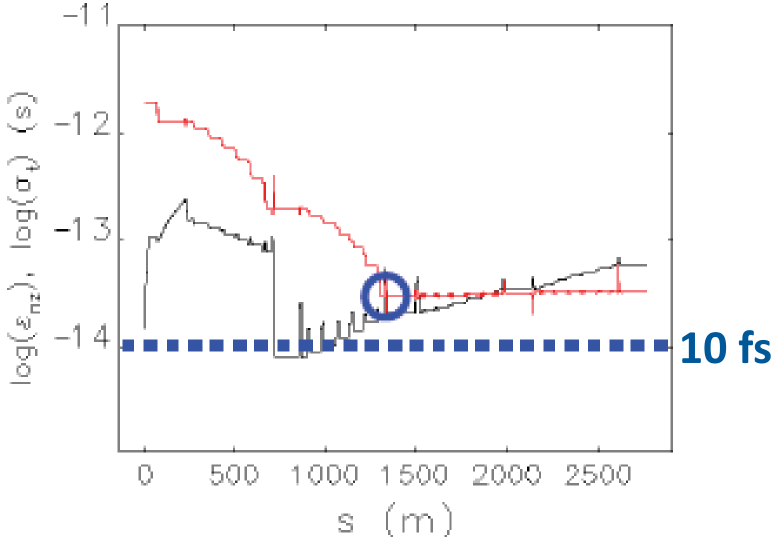




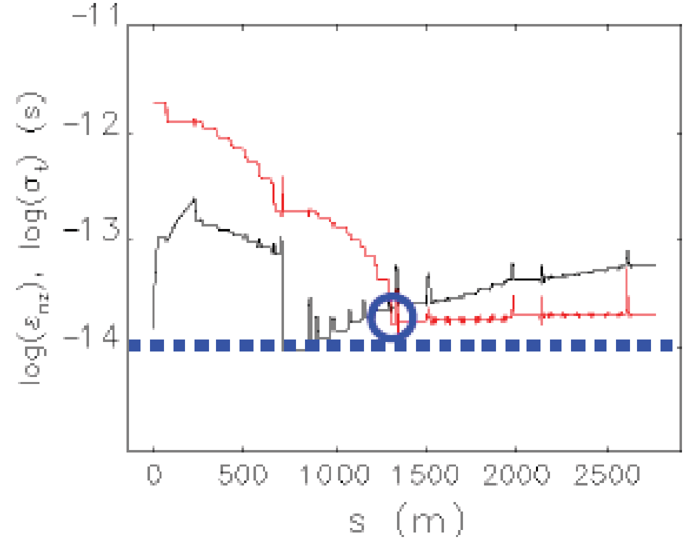
is I_{peak} ~ **700 A** enough for **FEL** ?

Genesis results

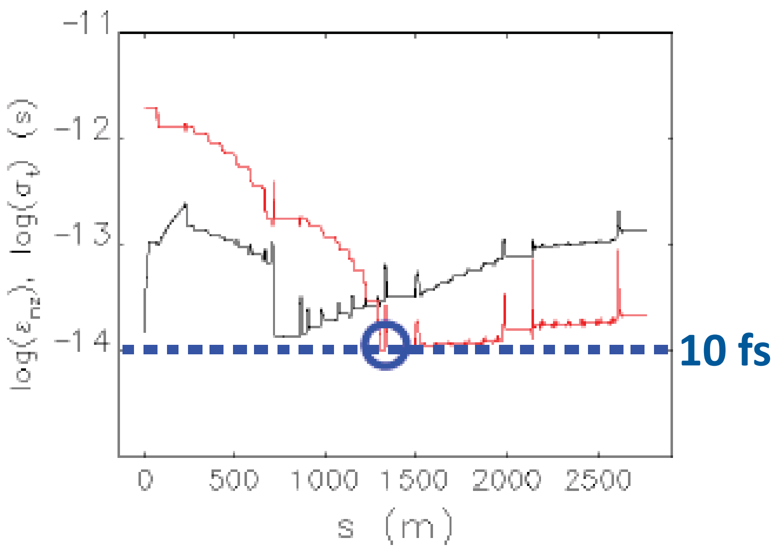
Linac Phase Sensitivity



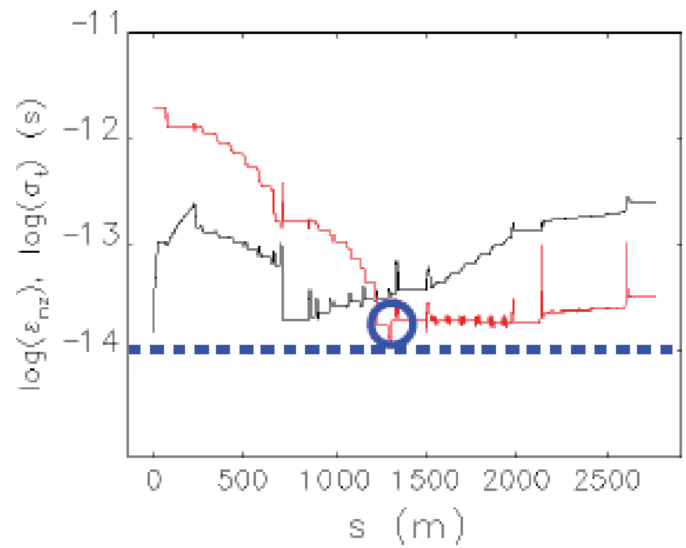
(a) $\phi_2 = 100.3\,°$



(b) $\phi_2 = 100.4\,°$



(c) $\phi_2 = 100.5\,°$



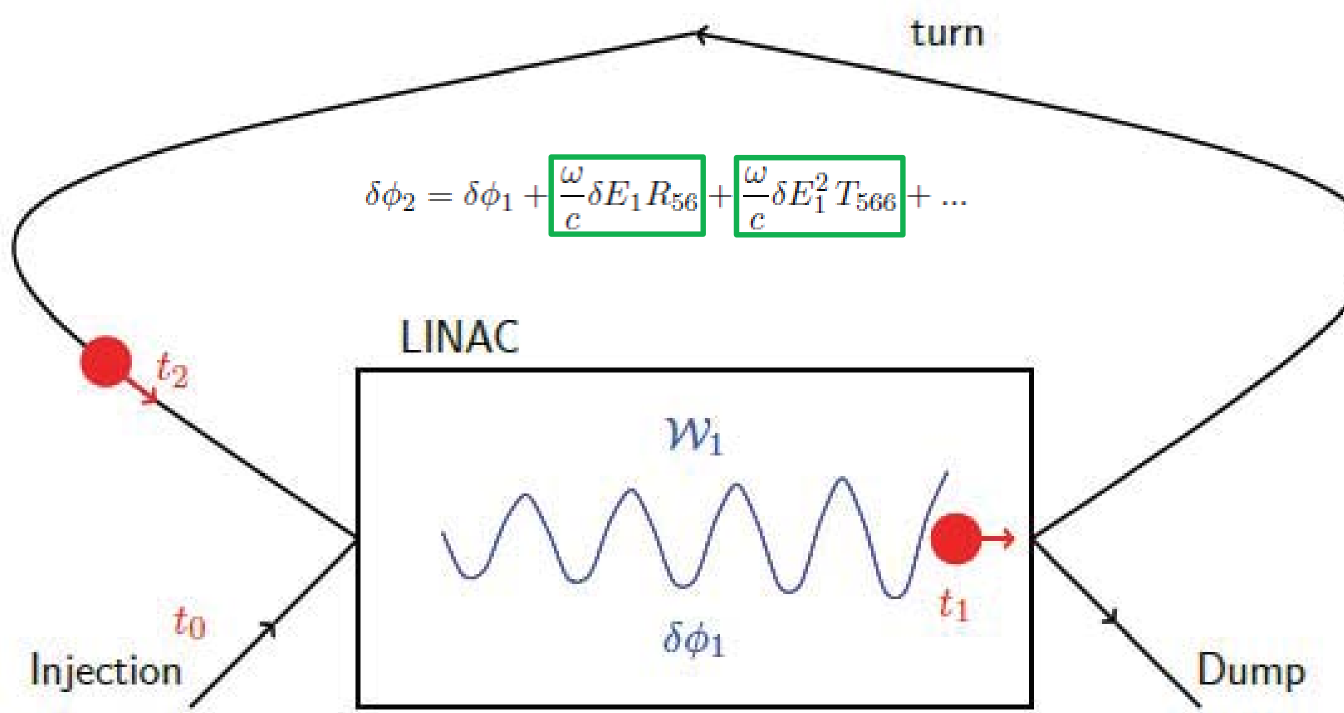
(d) $\phi_2 = 100.6\,°$

• recurrent system, bunch is short induces a wake

$$\mathcal{W}_1 = q\frac{\omega R}{Q}\, e^{-\frac{\omega t_0}{2Q}}\, e^{-i(\omega t_0+\delta\phi_1)}$$

and traverses a ERL loop with longitudinal dispersion
R56 can influence the phase deviation

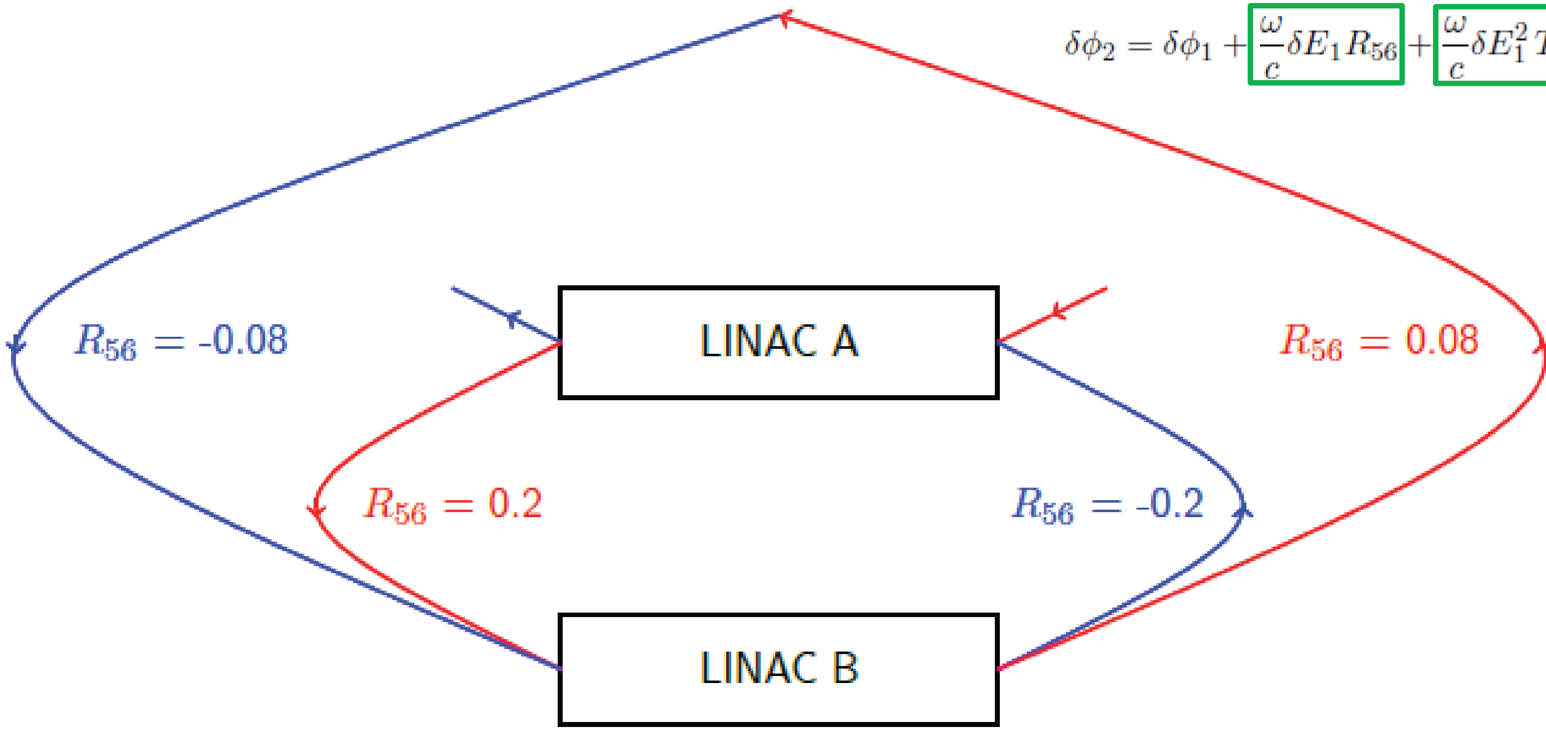
$$I_{\text{th}} = \frac{2pc^2}{\rho Q e\omega R_{56}\sin(\omega T_0+\phi)\cos\phi}$$



- Multi-turns, off-crest split linacs and varying R56 used for SPM bunch compression

f	R/Q	Q	t_b	ϕ_A	ϕ_B	R_{56_1}	R_{56_2}	R_{56_3}	R_{56_4}
1.3 GHz	111 Ω	$5 \cdot 10^7$	2^*T_0	100°	70°	0.2 m	0.08 m	-0.08 m	-0.2 m

$$\delta\phi_2 = \delta\phi_1 + \frac{\omega}{c}\delta E_1 R_{56} + \frac{\omega}{c}\delta E_1^2 T_{566} + \ldots$$



Single bunch model LBBU Threshold ~ **17 mA**

Thank you for your attention

- Conceptual Design Report is finished and is being internally reviewed …

Lots of publications
LINAC12, IPAC13, ERL13, IPAC14

Special thanks again to
A. Matveenko
A. Bondarenko
and
Y. Petenev

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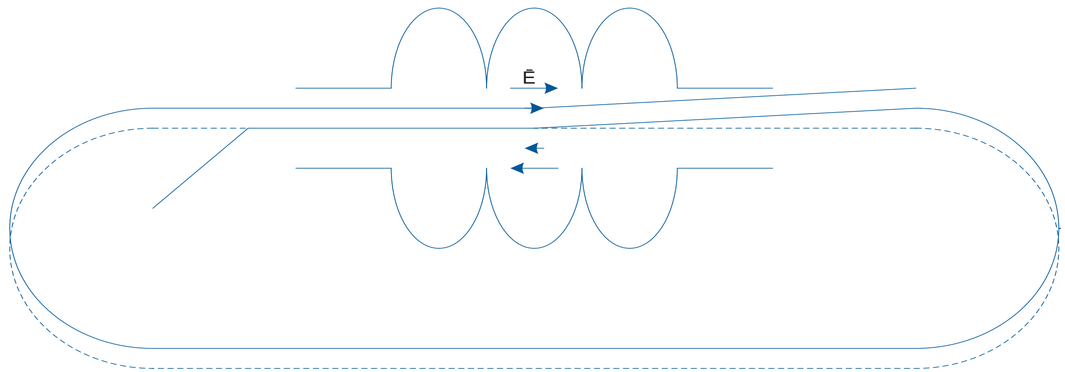
- Instability can limit the maximum current …



Wavelength of associated dipole mode

$$I_b \approx I_0 \frac{\lambda^2}{QL_{eff}\sqrt{\sum_{m=1}^{2N-1}\sum_{n=m+1}^{2N}\frac{\beta_m\beta_n}{\gamma_m\gamma_n}}}$$

Magnetic optic can be used to manipulate these terms …

Cavity specific values

Triplets in the linac increase threshold by a factor **3**

- Why E_{inj} = 230 MeV injection linac? Why E_{linac} = 960 MeV main linac?

BBU implies full energy injection is „best" $E_{inj} \rightarrow E_{final}$ then $E_{linac} \rightarrow 0$

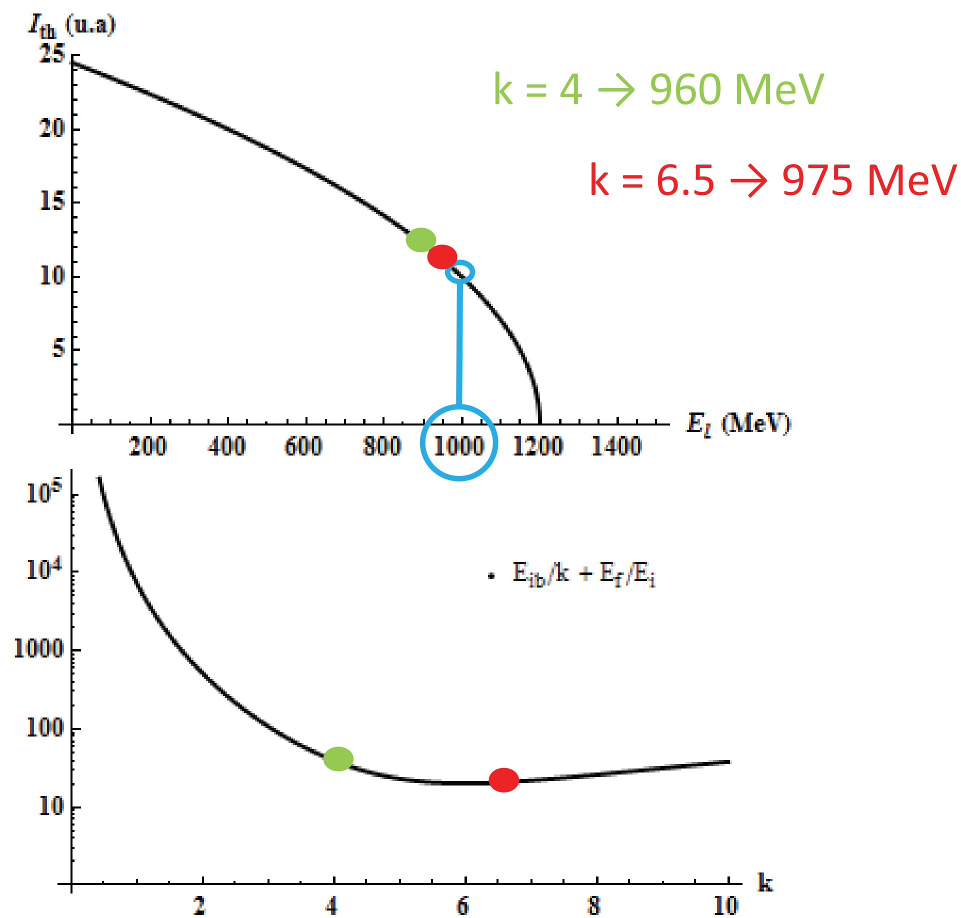
but

we want **N=6 TURNS !!!**

$$I_b \propto \frac{1}{\sqrt{\sum_{m=1}^{2N-1} \sum_{n=m+1}^{2N} \frac{\beta_m \beta_n}{\gamma_m \gamma_n}}}$$

Searching for integer values for the energy in each turn

$$E_{final} = (1 + 2kN)(E_0 + E_{inj})$$



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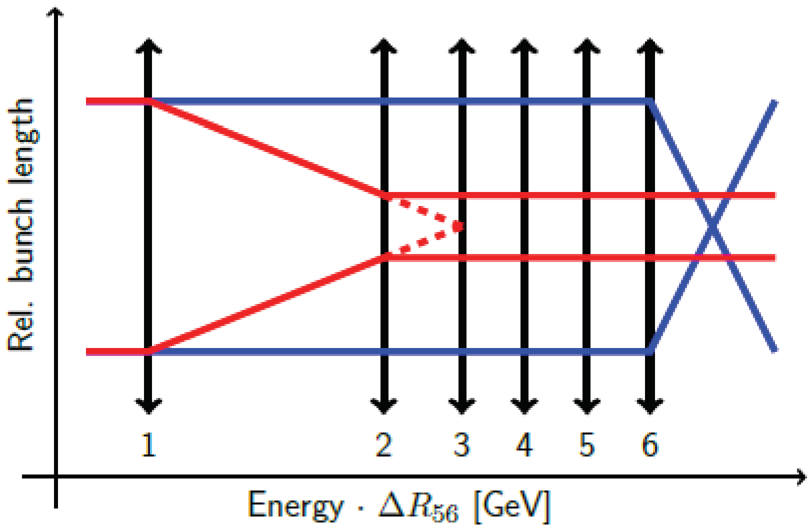
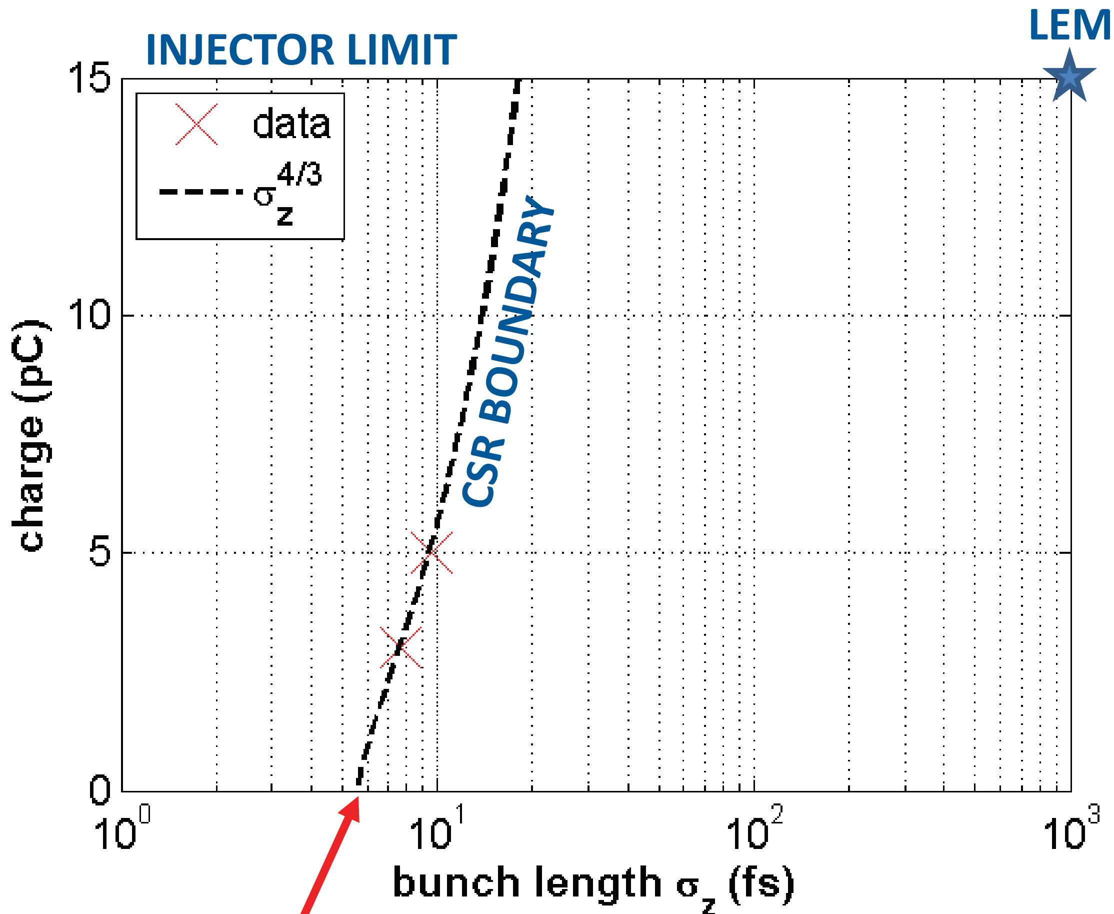
• F – focusing and f defocusing “linacs + arcs” to maximize the “magnification” and remove the correlated energy spread

$$\begin{pmatrix} c\Delta t \\ \delta \end{pmatrix}_1 = \begin{pmatrix} f/F & F-f \\ 0 & F/f \end{pmatrix} \begin{pmatrix} c\Delta t \\ \delta \end{pmatrix}_0$$





$\sigma_0 = 5.6\,\mathrm{fs}$ zero-charge bunch length

Energy loss due to CSR*

$$\Delta E_{\mathrm{CSR}} \sim q / \left(\sigma_t^2 - \sigma_0^2\right)^{2/3} \sim \mathrm{const}$$

$$5\,[\mathrm{pC}] = C_1(9.6\,[\mathrm{fs}]^2 - \sigma_0^2)^{2/3}$$
$$3\,[\mathrm{pC}] = C_1(7.6\,[\mathrm{fs}]^2 - \sigma_0^2)^{2/3}$$

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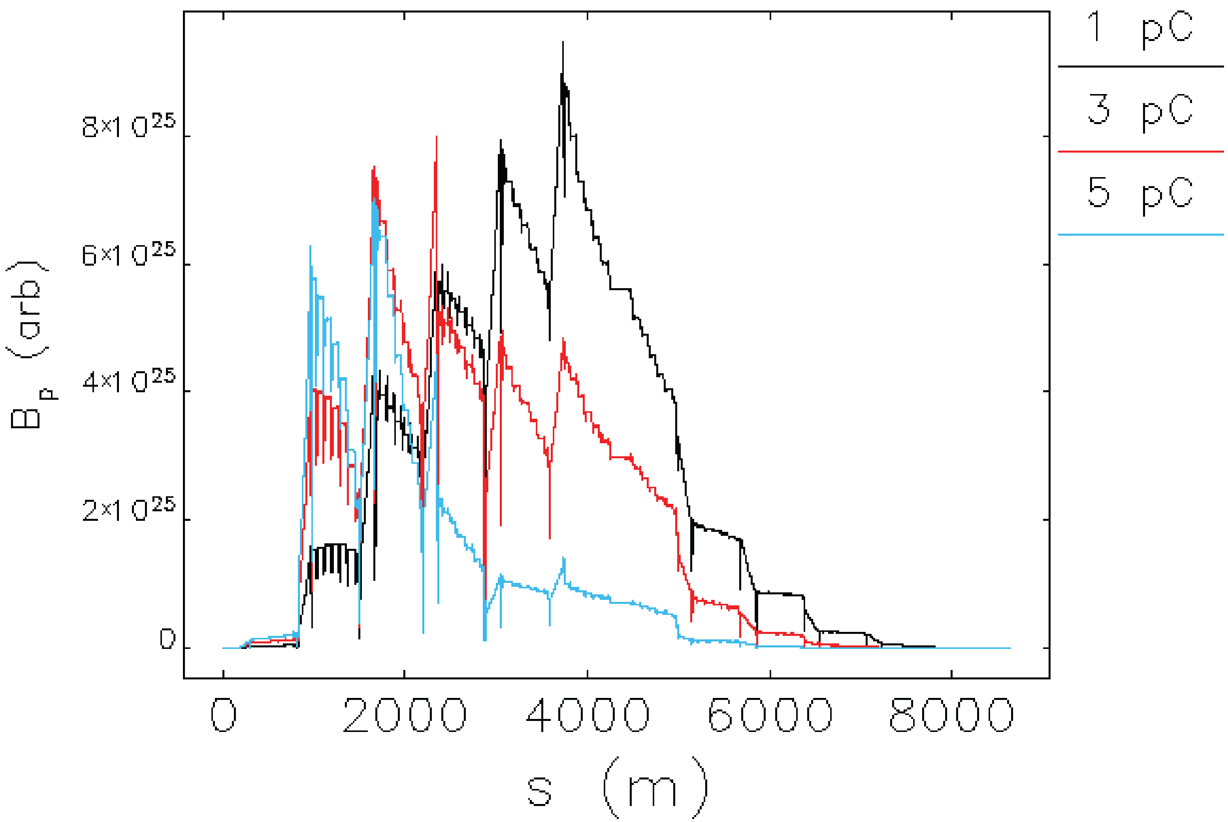
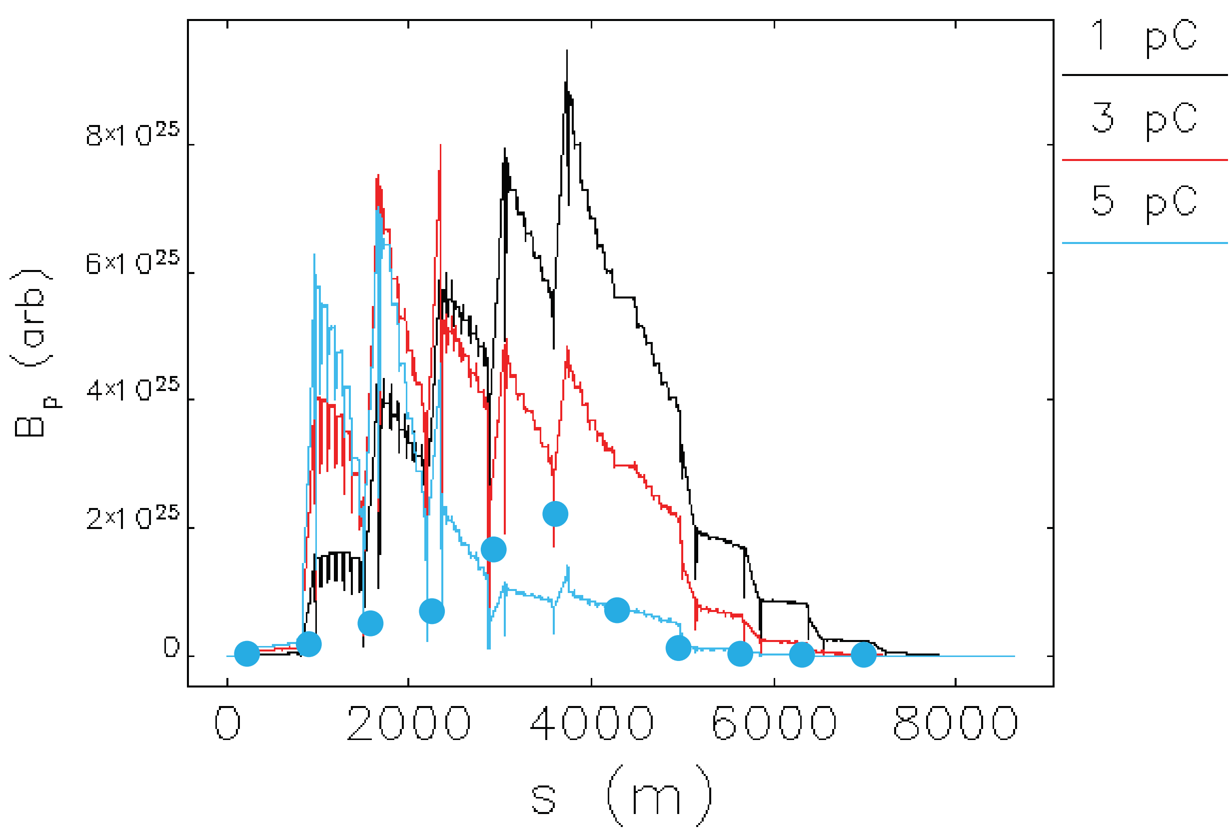
- “equivalent” peak brilliance



$$B_p = \frac{N_{ph}}{(2\pi)^2 \varepsilon_x \varepsilon_y \varepsilon_z} \equiv \frac{q\, C_\gamma}{(2\pi)^2 \varepsilon_x \varepsilon_y \varepsilon_z}$$

- “equivalent” peak brilliance



$$B_{\mathrm{p}} = \frac{N_{\mathrm{ph}}}{(2\pi)^2 \varepsilon_x \varepsilon_y \varepsilon_z} \equiv \frac{q\, C_\gamma}{(2\pi)^2 \varepsilon_x \varepsilon_y \varepsilon_z}$$

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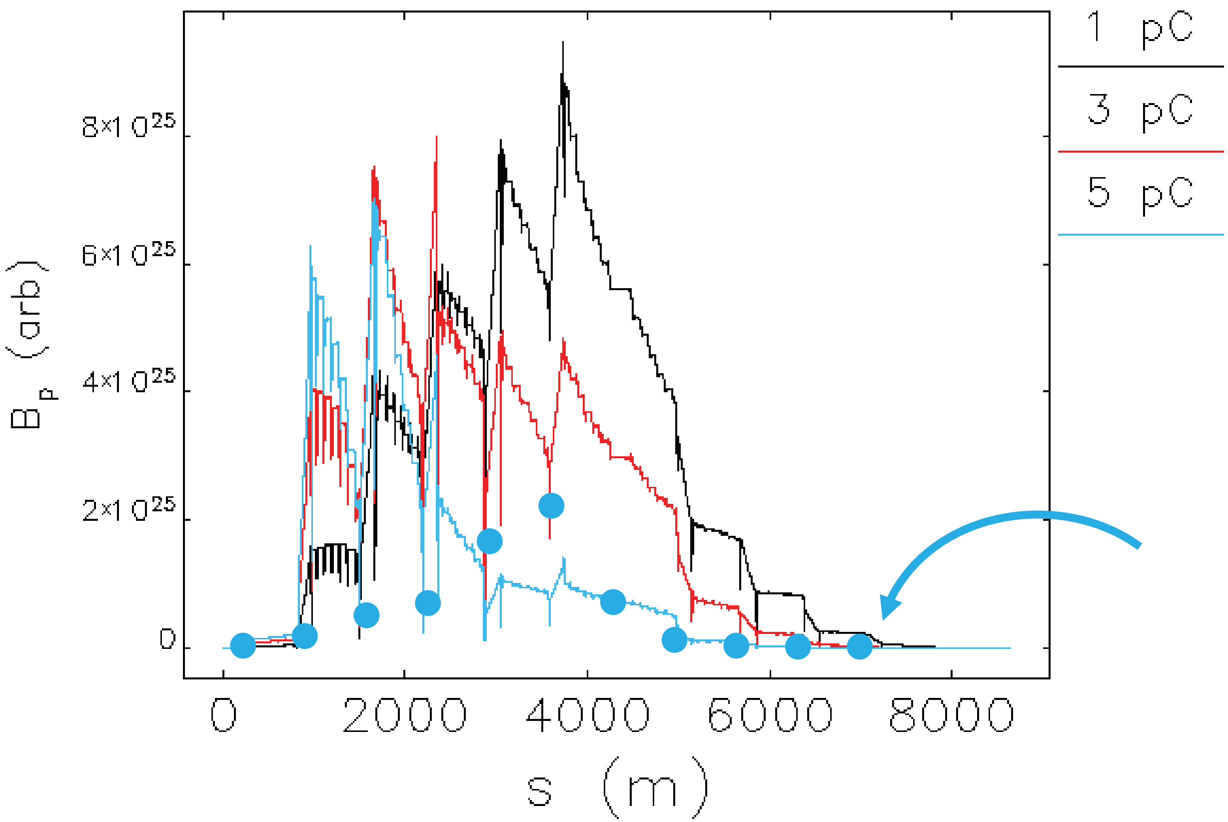

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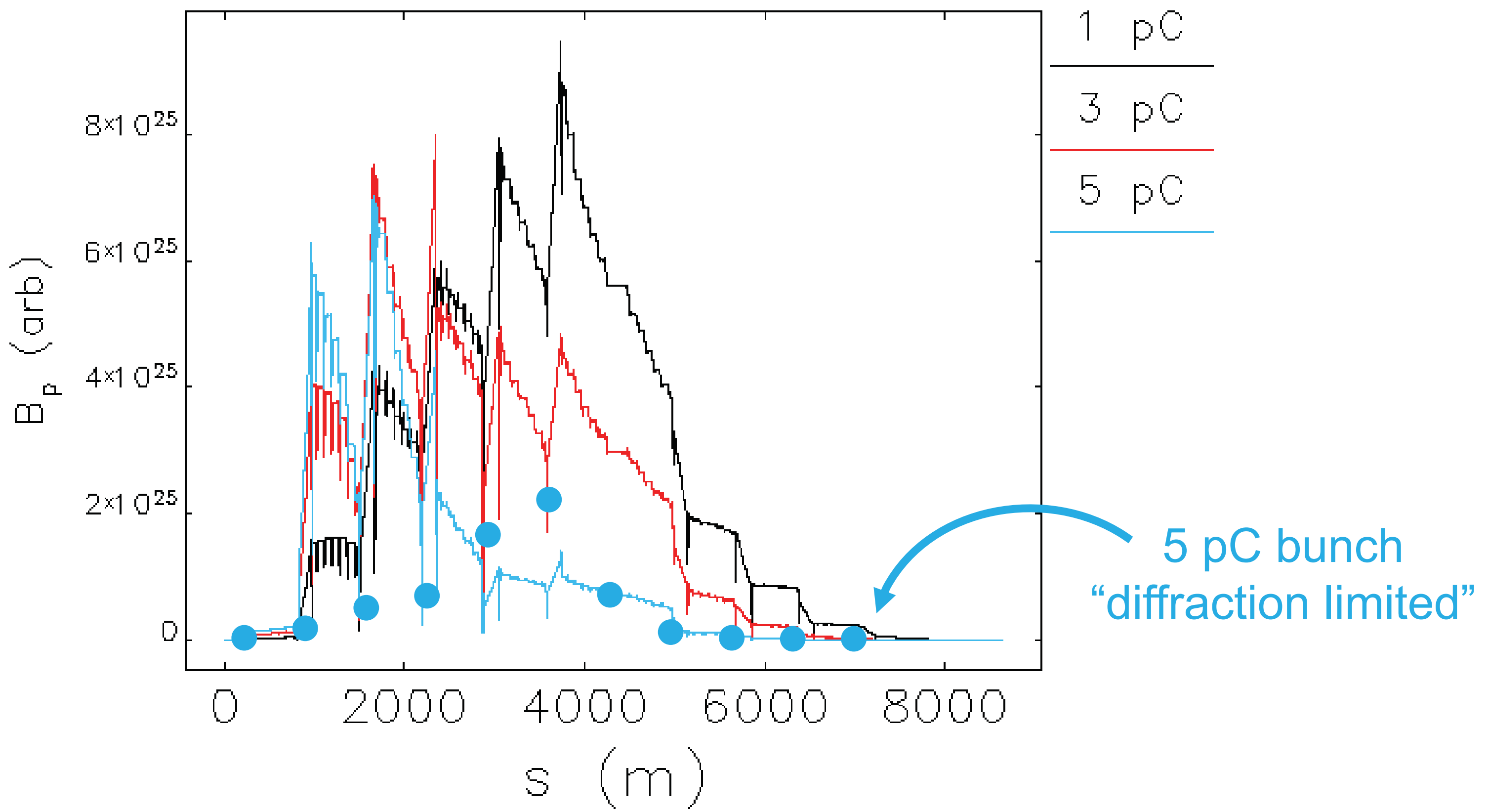

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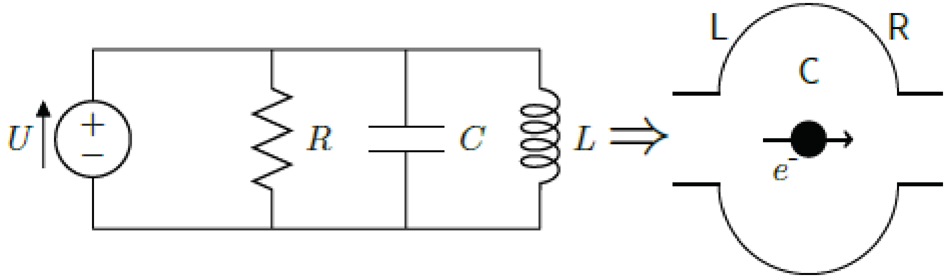
• On passing through the cavity the electron bunch induces some voltage variation that is seen by the recirculating bunch

Importance → Acts on the <u>fundamental</u> mode

$$I_{\text{th}} = \frac{2pc^2}{\rho Q e \omega R_{56} \sin(\omega T_0 + \phi)\cos\phi}$$

Single RLC cavity approximation



Can derive a „Stability Matrix*"
unstable exponential growth when Tr(M) > 0

$$\mathrm{Tr}(M(t)) = \frac{qR}{t_b Q}\left(\Re\frac{\partial\phi(t)}{\partial\mathcal{W}(t)} + \Im\frac{\partial\phi(t)}{\partial\mathcal{W}(t)}\right) - \frac{2}{Q}$$

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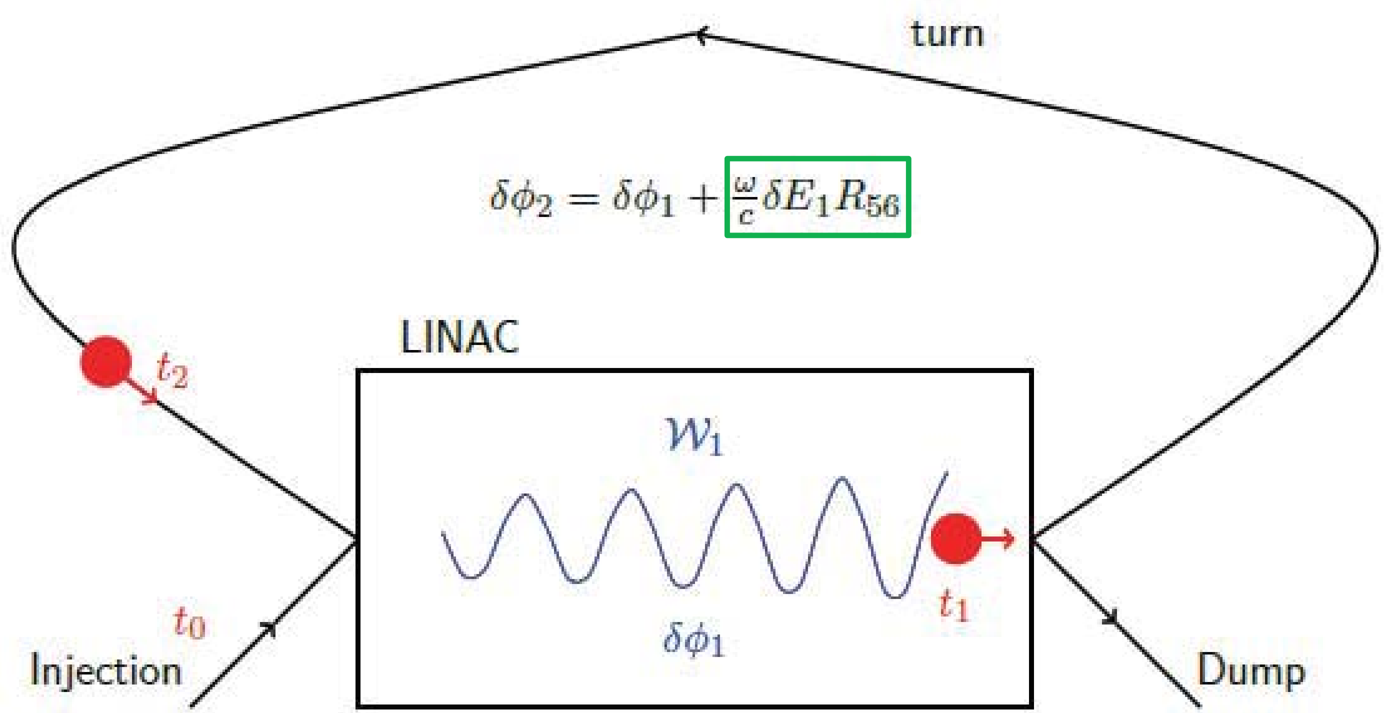
- recurrent system, bunch is short induces a wake

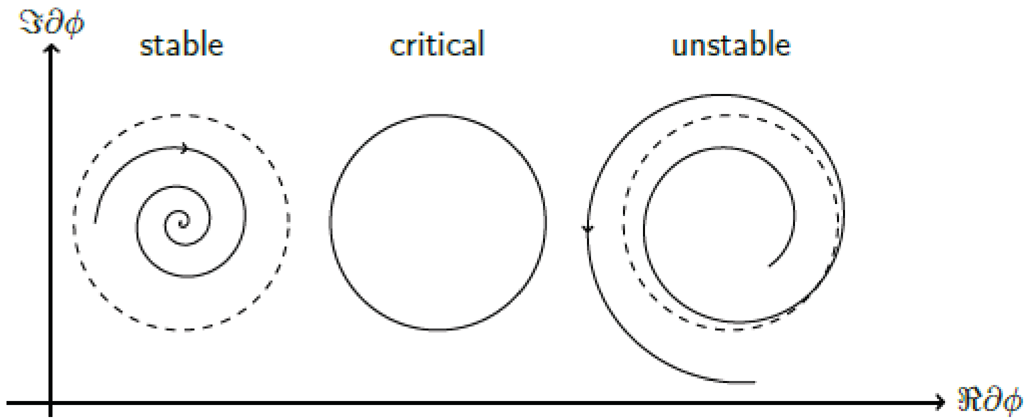
$$W_1 = q\frac{\omega R}{Q}\, e^{-\frac{\omega t_0}{2Q}}\, e^{-i(\omega t_0 + \delta\phi_1)}$$

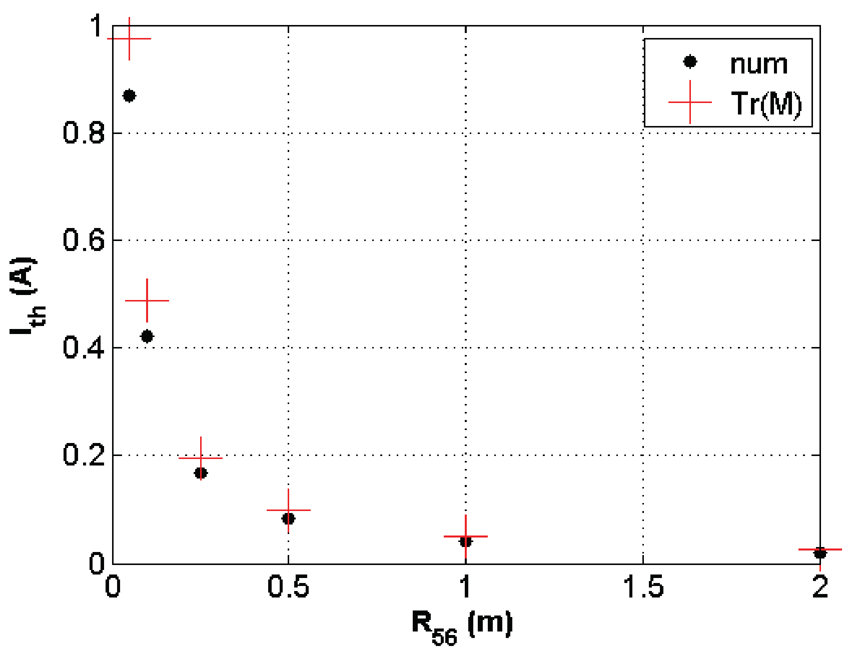
and traverses a ERL loop with longitudinal dispersion
R56 can influence the phase deviation

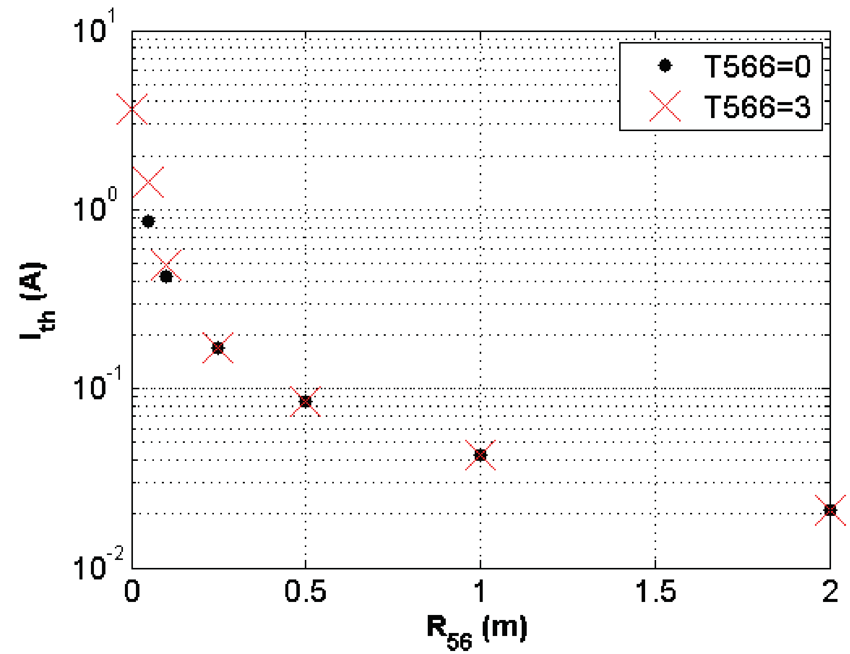
When R56 → 0
I_{th} → infinity



- stability criteria







including higher order terms →

$$\delta\phi_2 = \delta\phi_1 + \boxed{\frac{\omega}{c}\delta E_1 R_{56}} + \boxed{\frac{\omega}{c}\delta E_1^2 T_{566}} + \ldots$$