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Optics considerations for ERL x-ray sources

CHESS & LEPP

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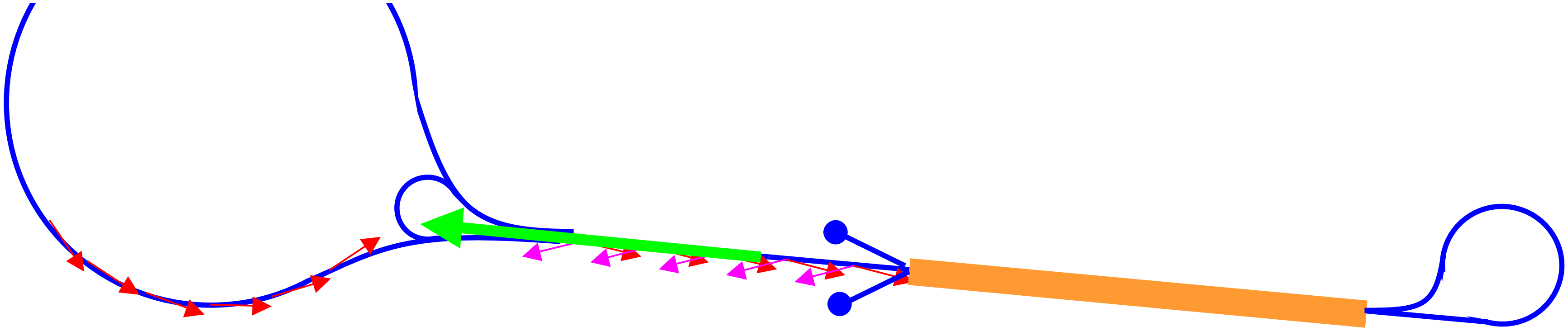


1. Overview of Parameters
2. Critical Topics
3. Phase Ia and Ib
4. Ongoing Activities
5. Plans and Timeline
6. Conclusion

Overview of Parameters

- The ERL parameters are dramatically better than present 3rd generation storage rings
- The use of ERL microbeams, coherence, and ultra-fast timing will lead to new unique experiments that can be expected to transform the way future x-ray science experiments are conducted
- Most critical parameters to achieve in an ERL are therefore, narrow beams, small emittances, short bunches, at large currents.

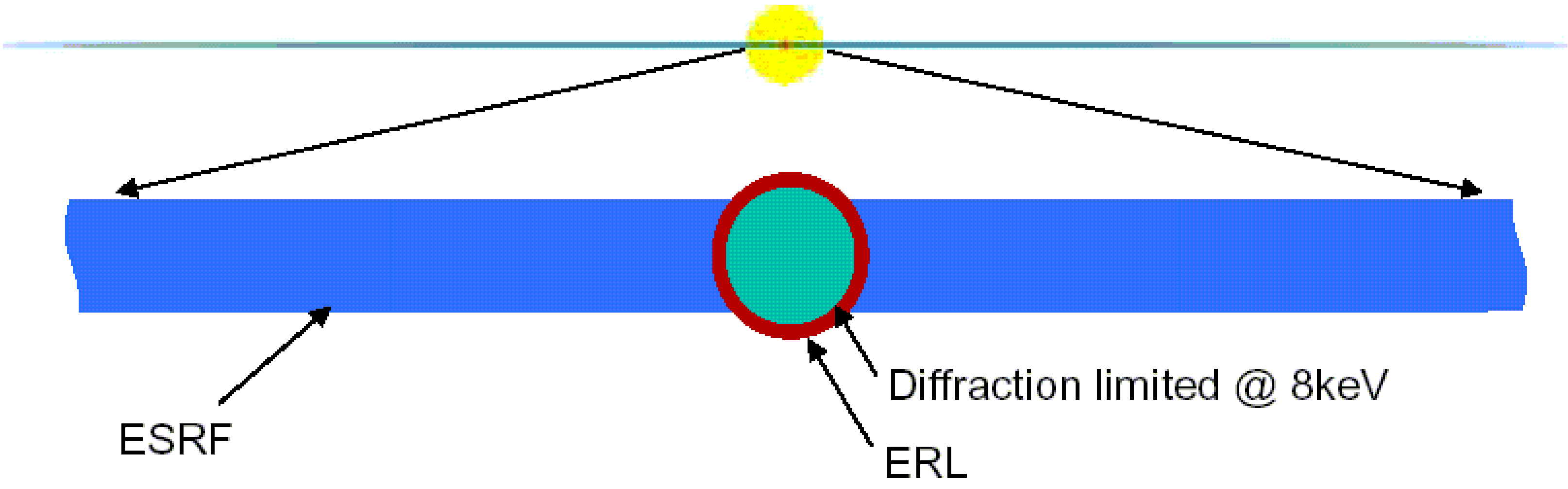
Parameter	APS ring	ERL*	Gain factor
Rms source size(μm)	239(h) x 15(v)	2(h) x 2(v)	1/900 in area
x-ray beamsize	100nm - 1μm	1 nm	100 to 1000
Coherent flux x-rays/s/0.1% bw	3 x 10^{11}	9 x 10^{14}	3,000
Rms duration	32 ps	0.1 ps	over 300

Beam size in a linear accelerator

The beam properties are to a very large extend determined by the injector system:

- **The horizontal beam size can be made much smaller than in a ring**
- **While the smallest beams that are possible in rings have almost been reached, a linear accelerator can take advantage of any future improvement in the electron source or injector system.**

ESRF 6GeV@200mA → ERL 5GeV@100mA

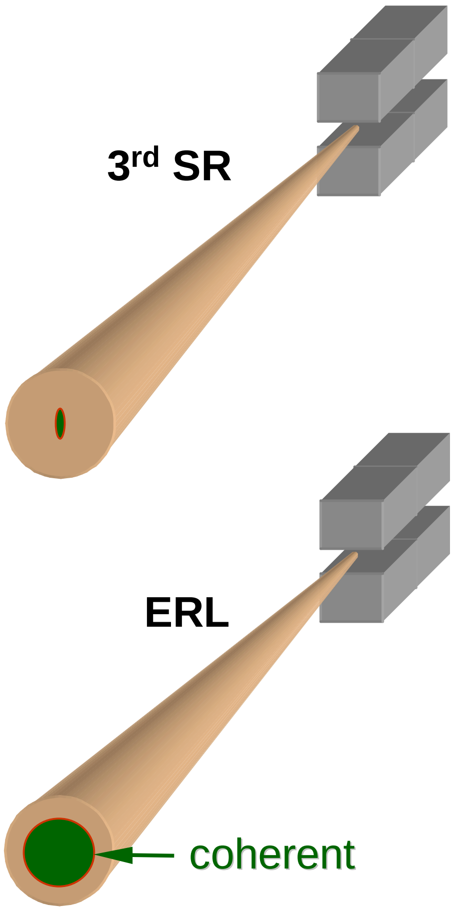


courtesy Ivan Bazarov

Smaller Beam z more Coherence

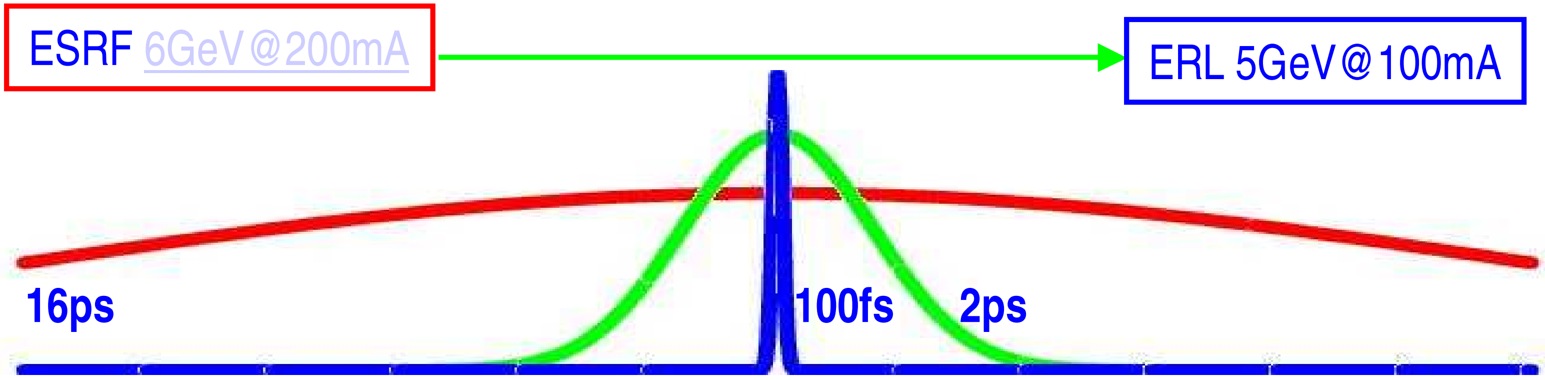
- Coherent x-ray diffraction imaging
- It would, in principle, allow atomic resolution imaging on non-crystalline materials.
- This type of experiments is completely limited by coherent flux.

Factor 100 more coherent flux for ERL
for same x-rays, or provide coherence for harder x-rays



Bunch length in a linac

- The bunch length can be made much smaller than in a ring
- While the shortest bunches possible in rings have almost bean reached, a linear accelerator can take advantage of any future improvement in the source source or injector system.



Parameters

Operation mode	High Flux	Coherence	Short pulse
Current (mA)	100	10	1
Charge/b (nC)	0.08	0.008	1.0
$\epsilon_{x/y}$(nm)	0.1	0.015	1
Energy (GeV)	5.3	5.3	5.3
Rep. rate (GHz)	1.3	1.3	0.001
Av. flux $(\frac{\text{ph}}{0.1\%\ \text{s}})$	$9\ 10^{15}$	$9\ 10^{14}$	$9\ 10^{12}$
Av. brilliance $(\frac{\text{ph}}{0.1\%\ \text{s}\ \text{mm}^2\ \text{mrad}^2})$	$1.6\ 10^{22}$	$3.0\ 10^{22}$	$2.0\ 10^{17}$
Bunch length (ps)	2	2	0.1

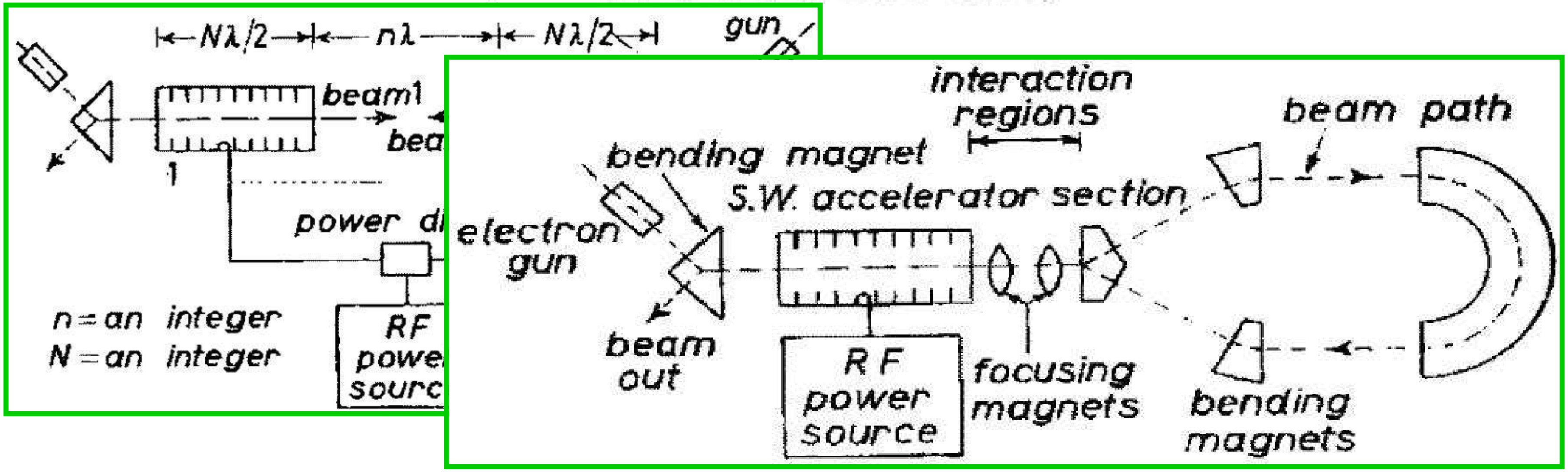
Energy Recovery & Linear Coll.

A Possible Apparatus for Electron Clashing-Beam Experiments (*).

M. TIGNER

Laboratory of Nuclear Studies, Cornell University - Ithaca, N. Y.

(ricevuto il 2 Febbraio 1965)



Energy recovery needs continuously fields in the RF structure

- Normal conducting high field cavities can get too hot.
- Superconducting cavities used to have too low fields.

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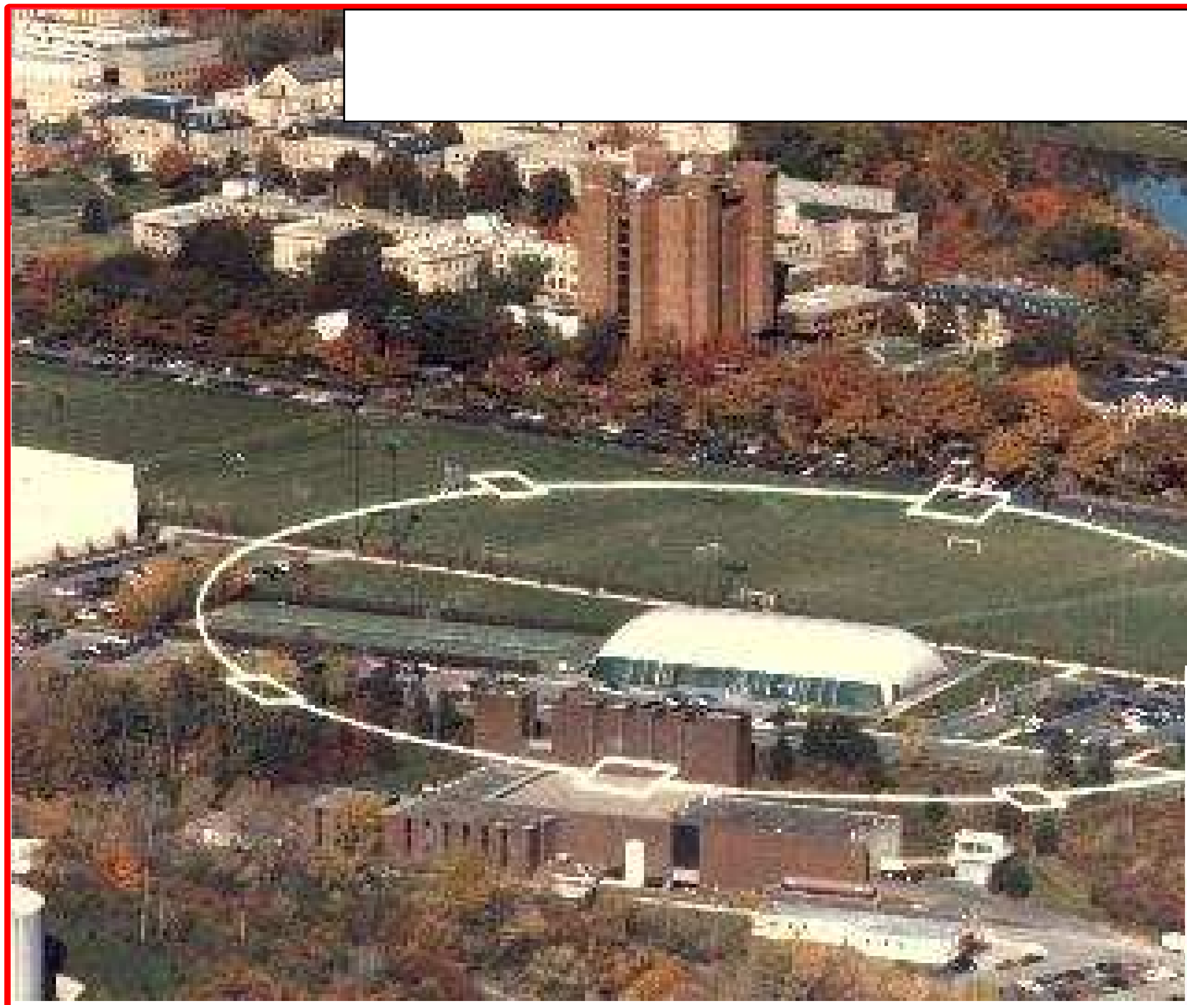

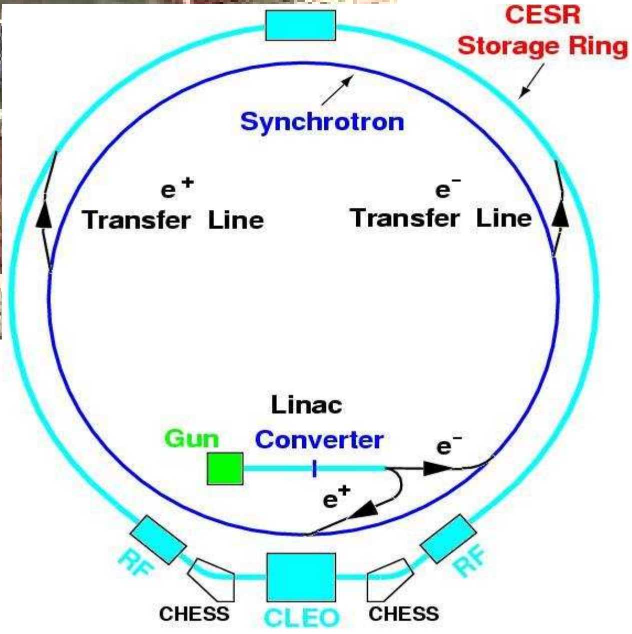

- An extension of the tunnel could easily conflict with buildings
- But the tunnel sealing is at about 836 ft ASL whereas
- The base of the deepest relevant building’s foundation is at 862ft ASL, yielding about 10m of space.

5GeV ERL Upgrade for CESR

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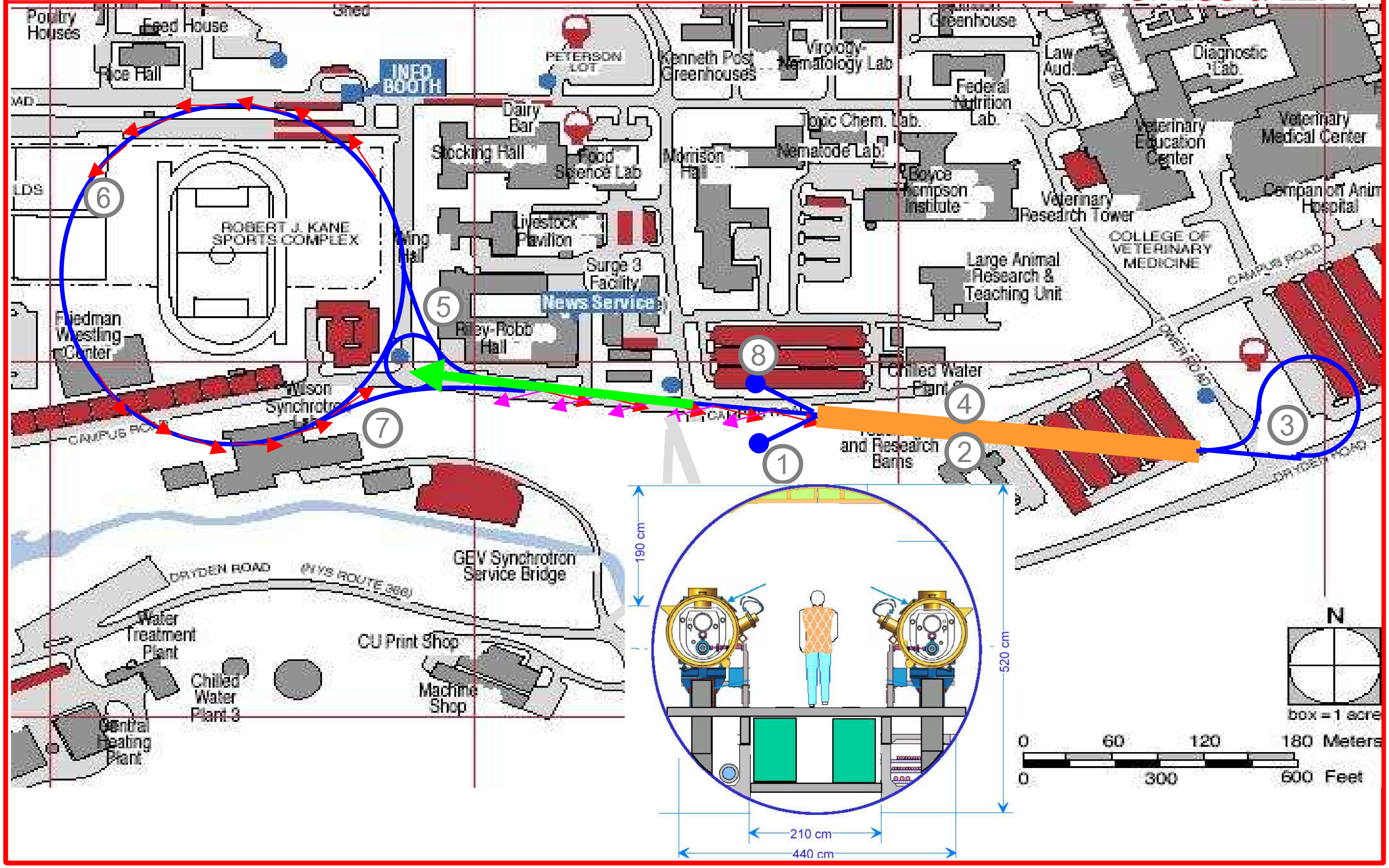
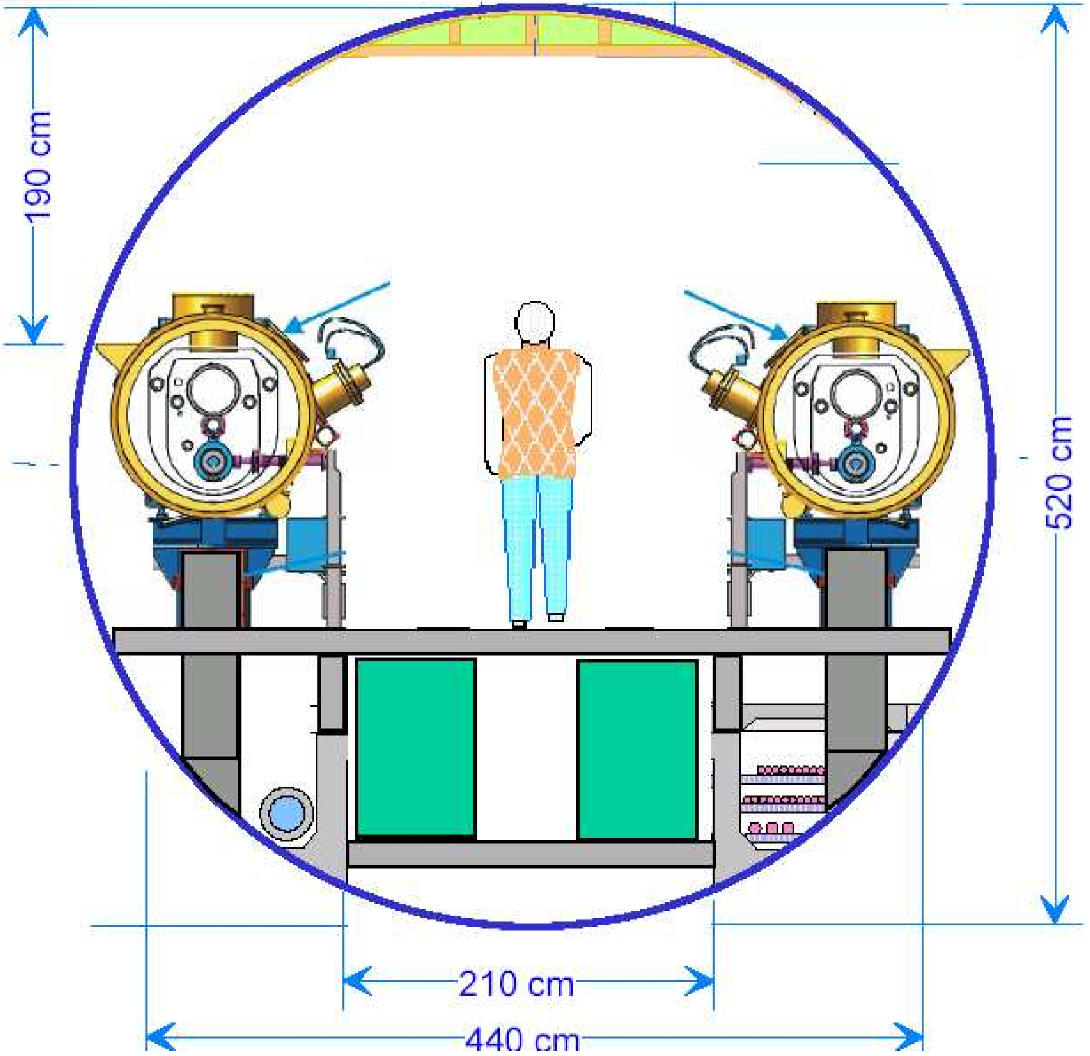


Double linac tunnel

CHESS & LEPP



courtesy Mathias Liepe

Two modified TESLA type cryomodules, two times the 17kW IOTs, etc. in one tunnel.

Advantages of ERL@CESR

- Operation of CESR and ERL test simultaneously.
- Use all of the CESR tunnel.
- Lots of space for undulators.
- Space for future upgrades, like an FEL.
- No basements of existing buildings to worry about.
- Only one tunnel for two linacs.
- Less competition, since other sights cannot offer upgrades.
- Example character for other existing light sources.

Limits to ERLs

Limits to Energy :

- Length of Linac and power for its cooling to 2K

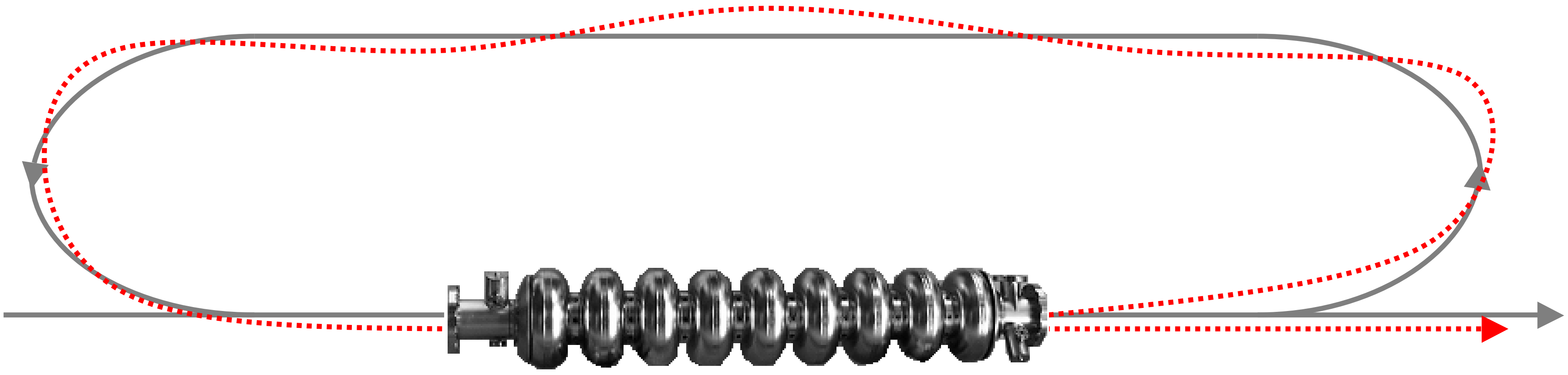
Limits to Current :

- Beam Break Up (BBU) instability

For small emittances in all 3 dimensions :

- Coulomb expulsion of bunched particles (Space Charge)
- Radiation back reaction on a bunch (CSR)

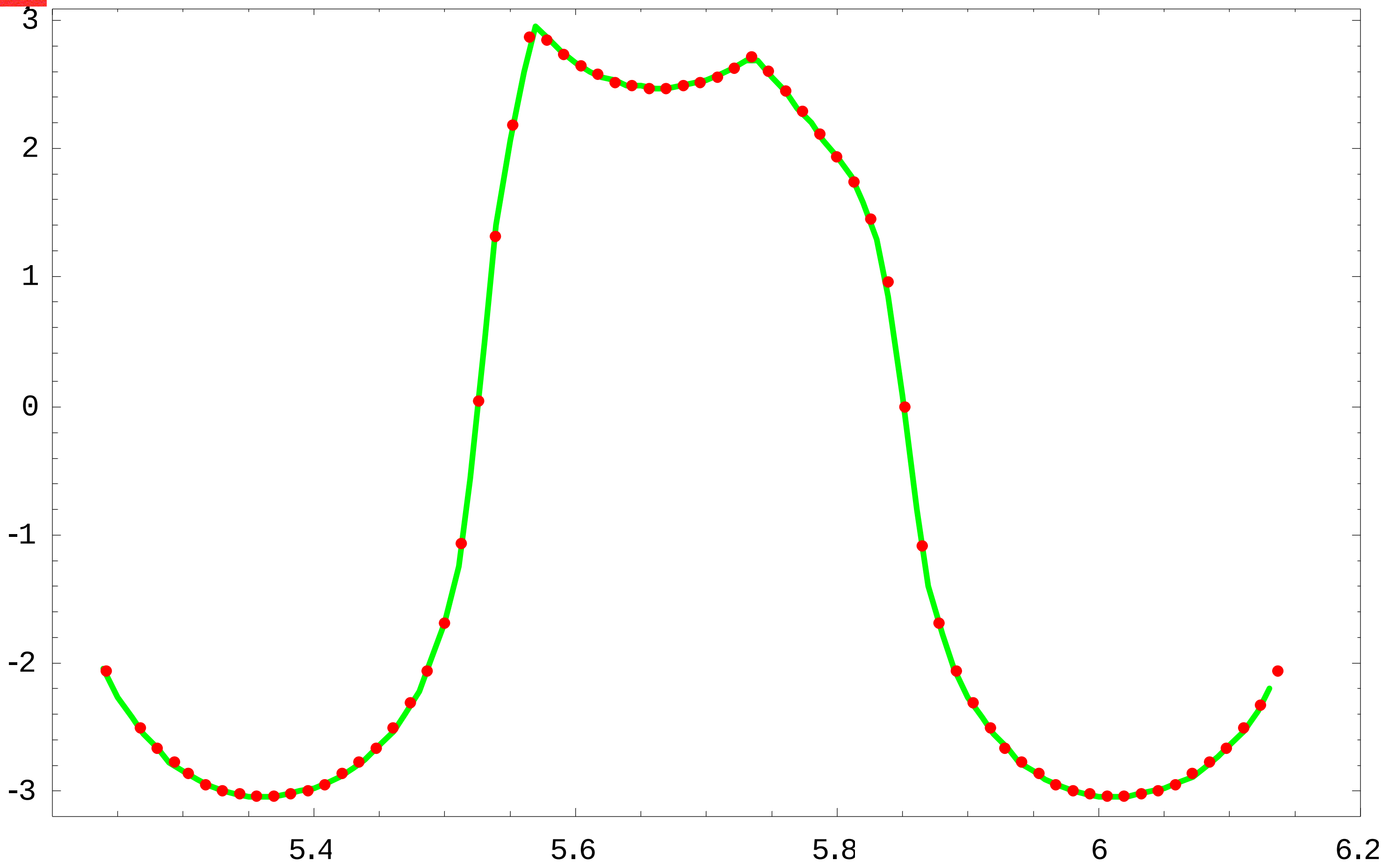
Instability with a single cavity and single Higher order mode



$$V_x(t) = \int_{-\infty}^{t} W_x(t-t')\,d(t')\,I(t')\,dt', \quad d_x(t) = T_{12}\,\tfrac{e}{c}\,V(t-t_r)$$

$$\boxed{V_x(t) = T_{12}\,\tfrac{e}{c}\int_{-\infty}^{t} W_x(t-t')\,V(t'-t_r)\,I(t')\,dt'}$$

Comparison with Tracking



This agreement shows both, the quality of tracking and that of the theory.

Results on BBU

Many HOMs in one cavity :

- only the most dangerous HOM contributes to the threshold.

HOMs in different cavities :

- HOMs in different cavities cannot cancel, but they can be decoupled by optical choices.

Multi turn recirculation :

- The threshold decreases approximately quadratically with the number of turns.

Closed orbit drift instability :

- Allways has a threshold that is larger than the coherent oscillation BBU

- ERL@CESY: 400mA BBU limit for 7-cell TESLA-like cavities.

See PRST-AB May 2004

Simultaneous optimization

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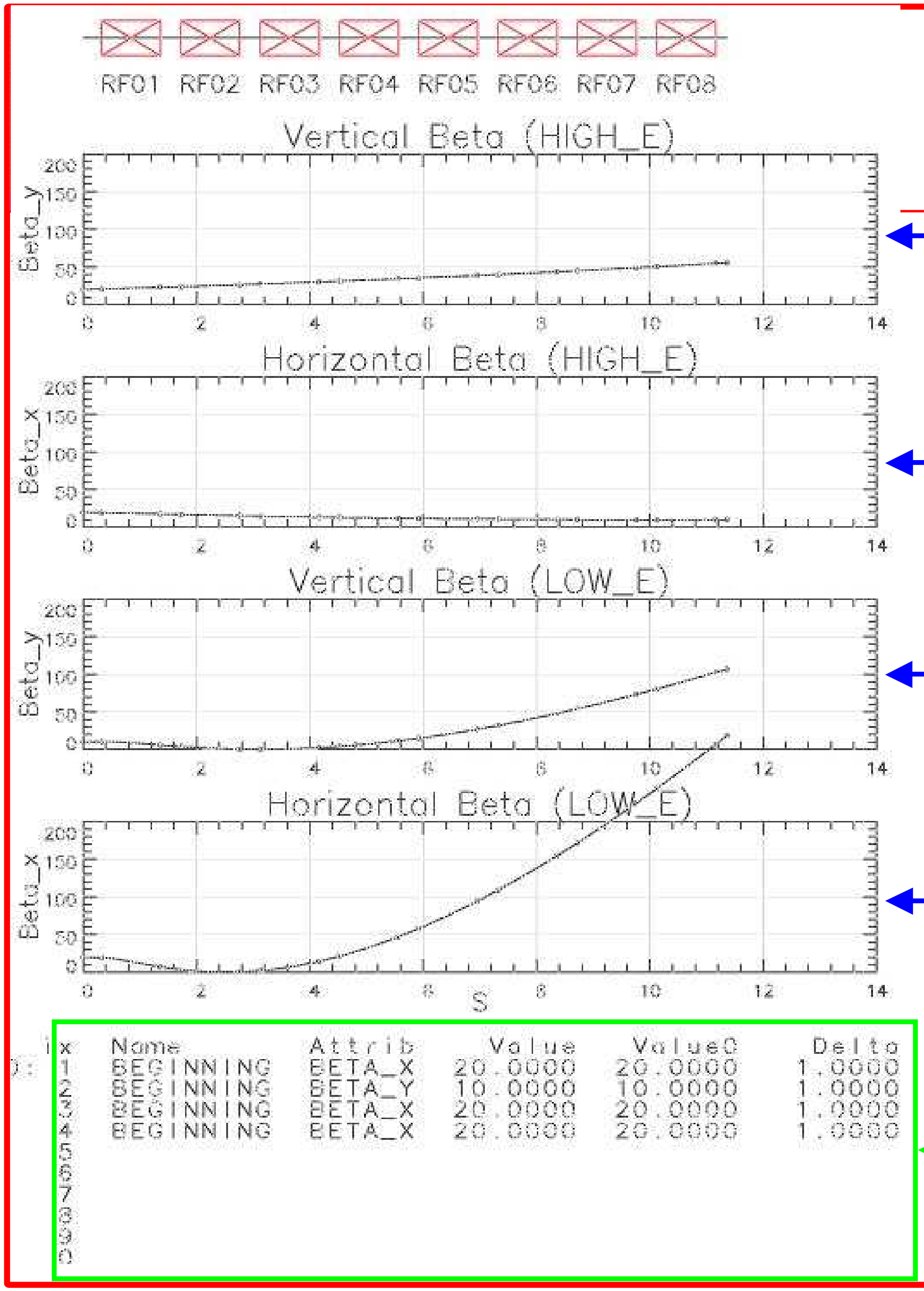

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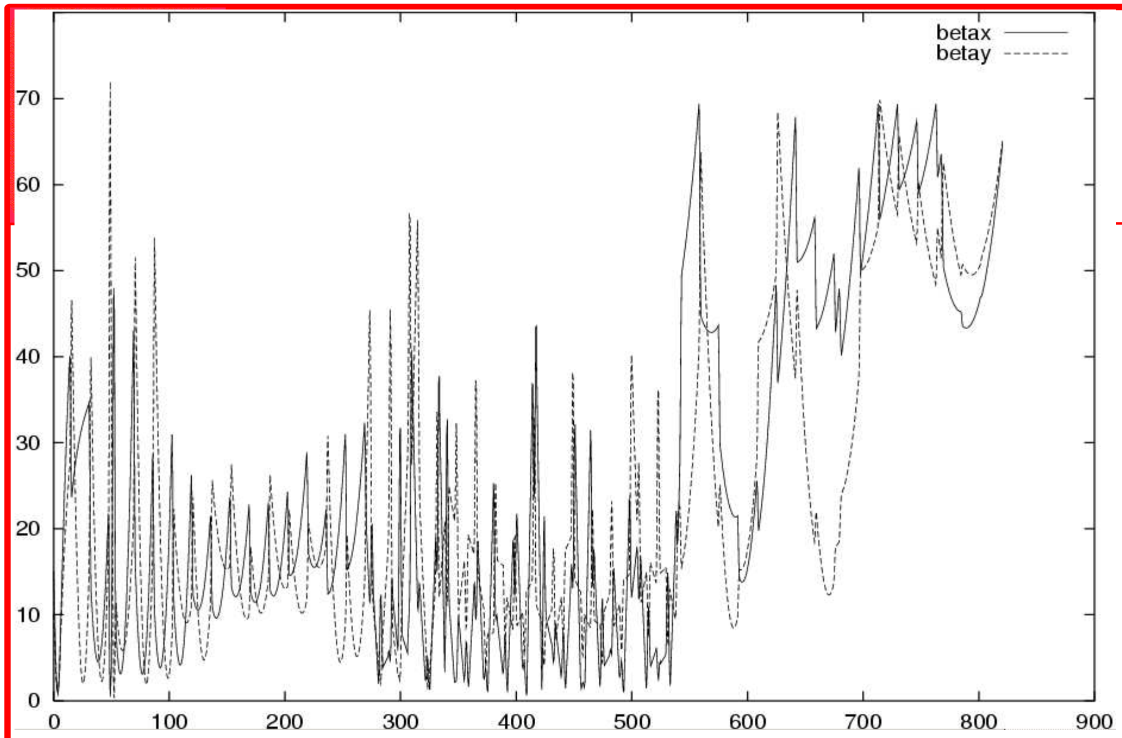
2    BEGINNING   BETA_Y    10.0000    10.0000     1.0000
3    BEGINNING   BETA_X    20.0000    20.0000     1.0000
4    BEGINNING   BETA_X    20.0000    20.0000     1.0000
5
6
7
8
9
0
```

New feature in TOP:

Optimize optics in the Linac for the accelerated and the decelerated energy.

Manually variable parameters



Linac optics

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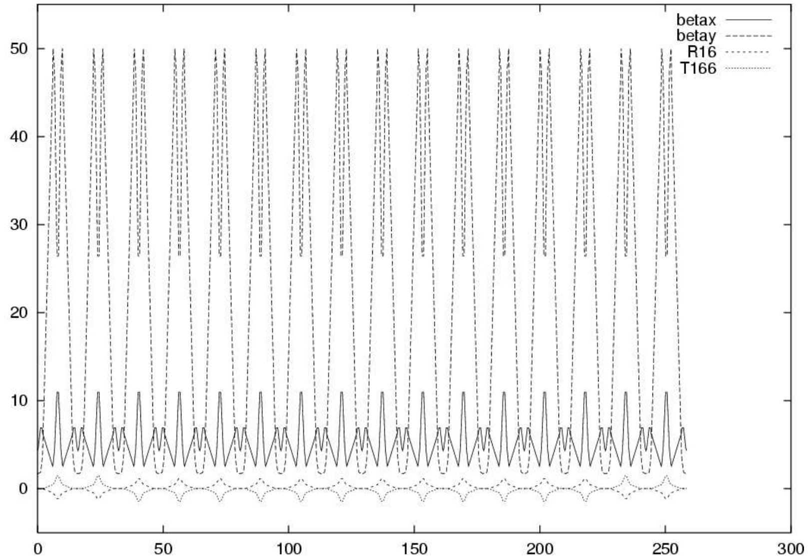
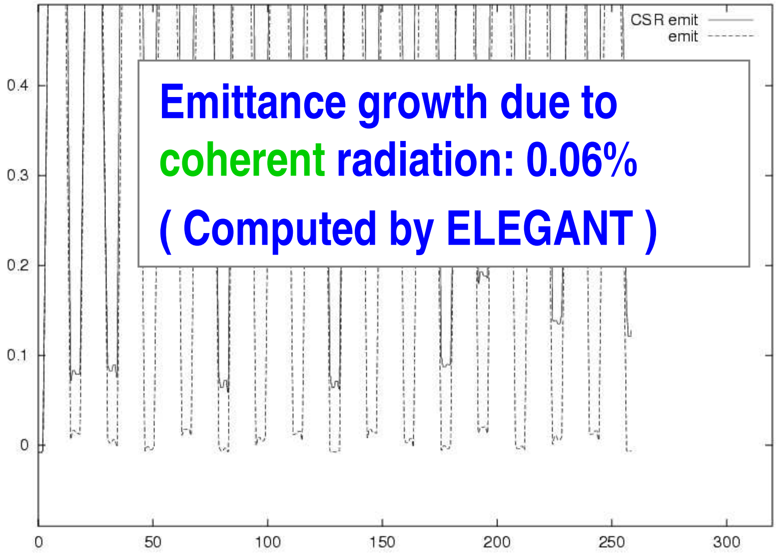
Optimize optics in the Linac for the accelerated and the decelerated energy.

Emittance growth due to incoherent radiation: 0.4%

Return arc optics





Emittance growth due to coherent radiation: 0.06%

(Computed by ELEGANT)

Optics for the linac-ring connection

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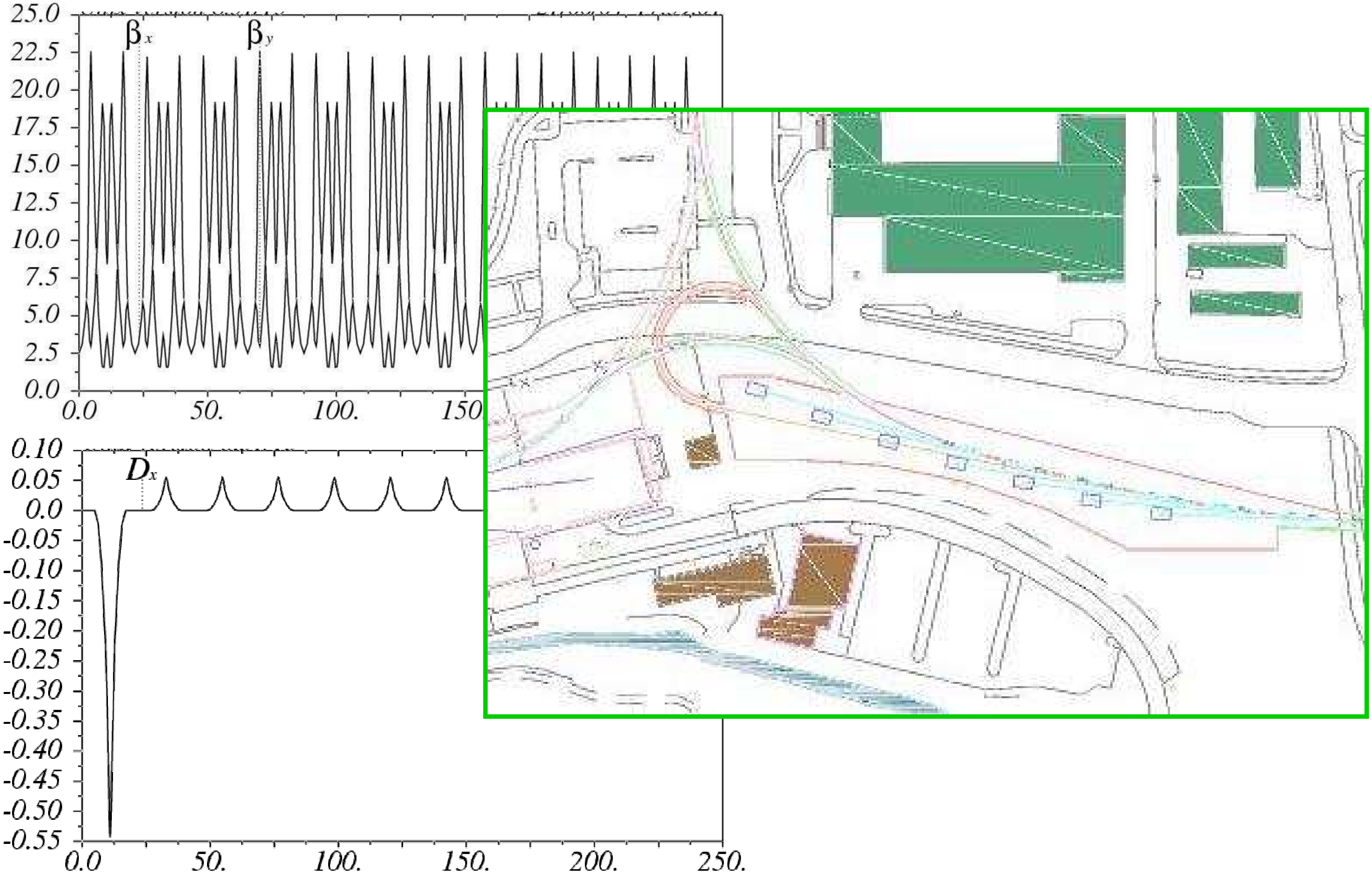

Optimization of Tunnel Layout

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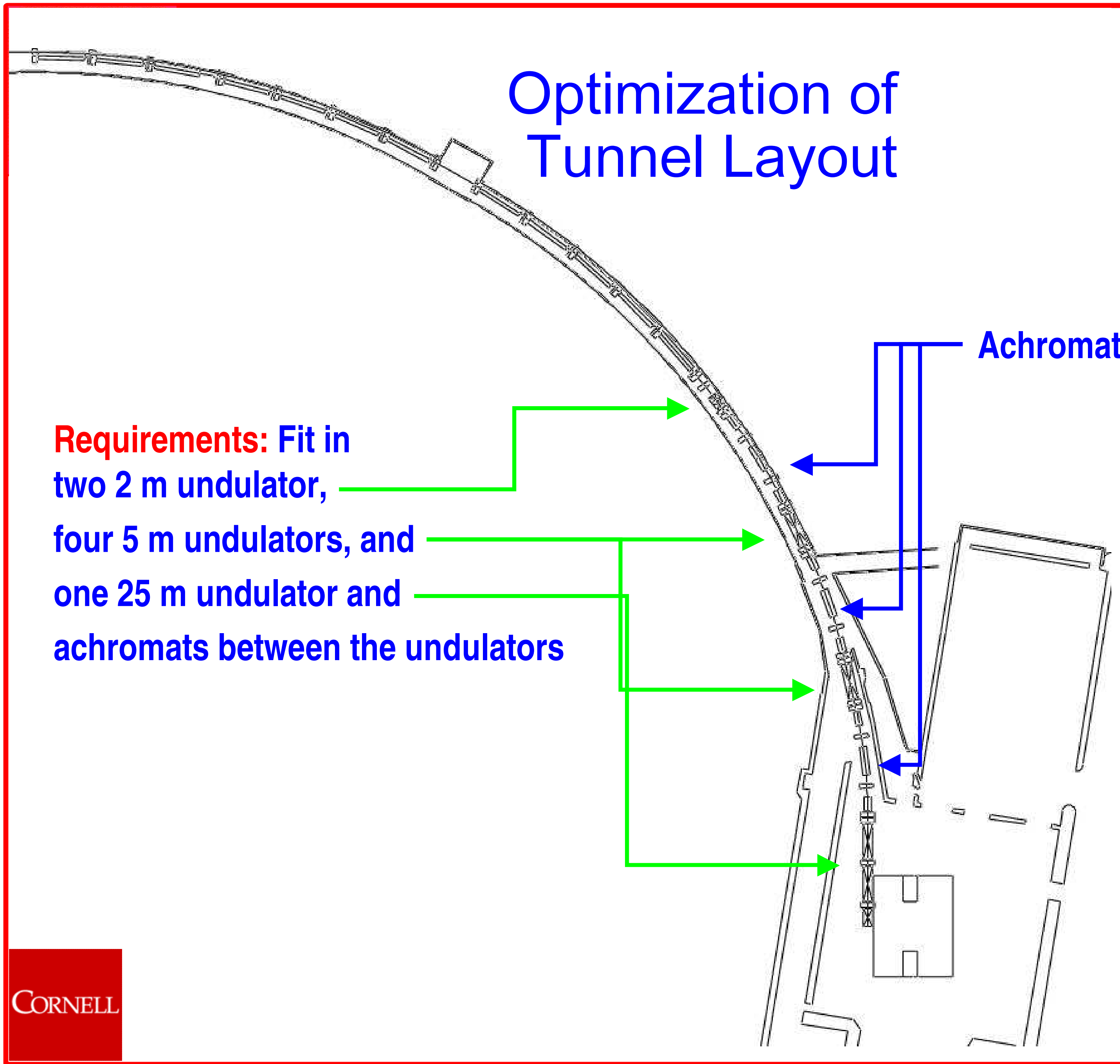

Achromats

Requirements: Fit in two 2 m undulator,

four 5 m undulators, and

one 25 m undulator and

achromats between the undulators

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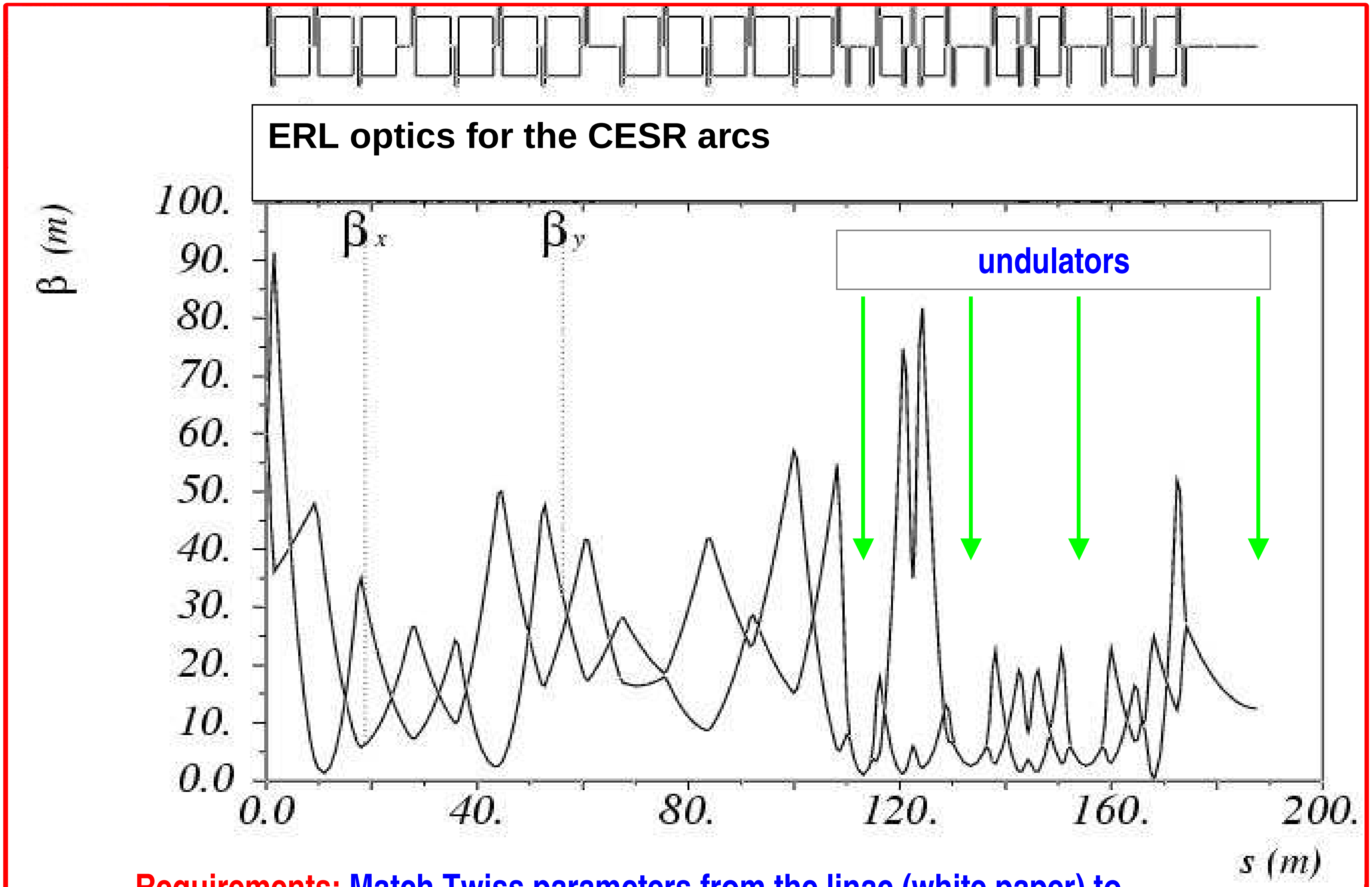
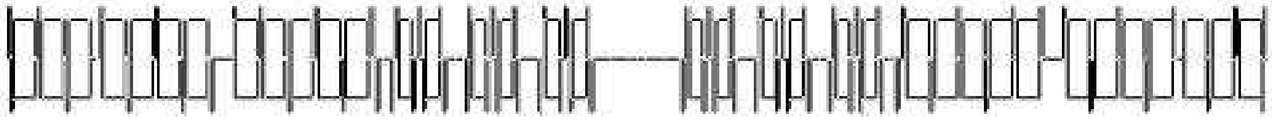
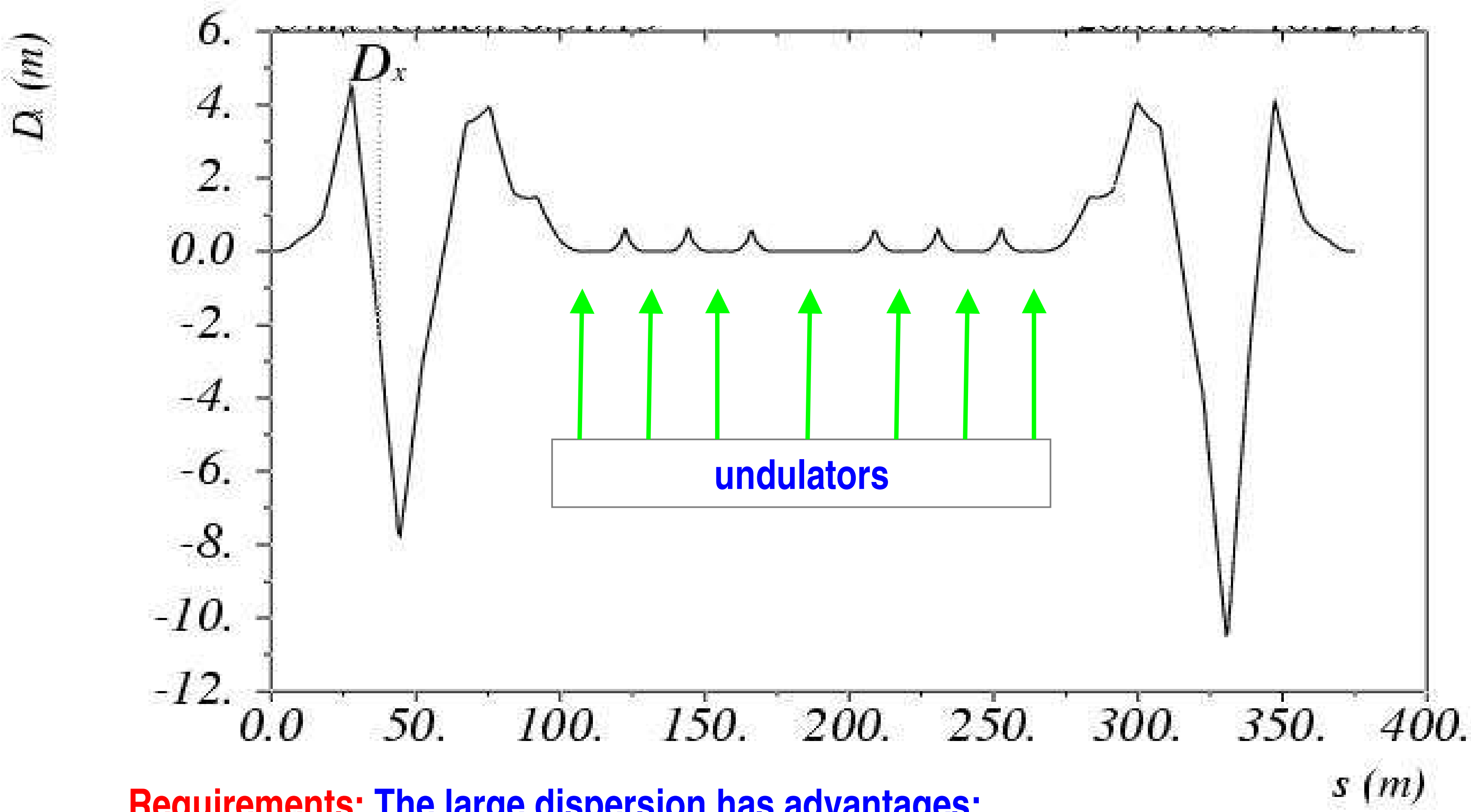
ERL optics for the CESR arcs



Requirements: Match Twiss parameters from the linac (white paper) to beta=0.5 * undulator length and waist in the undulators. D=0, D’=0 in undulators. Quad strength mostly achievable with current CESR.



Dispersion for short bunch operation



Requirements: The large dispersion has advantages:

Can be used to manipulate R56, and with sextupoles also higher chromatic orders.

Bunch compression

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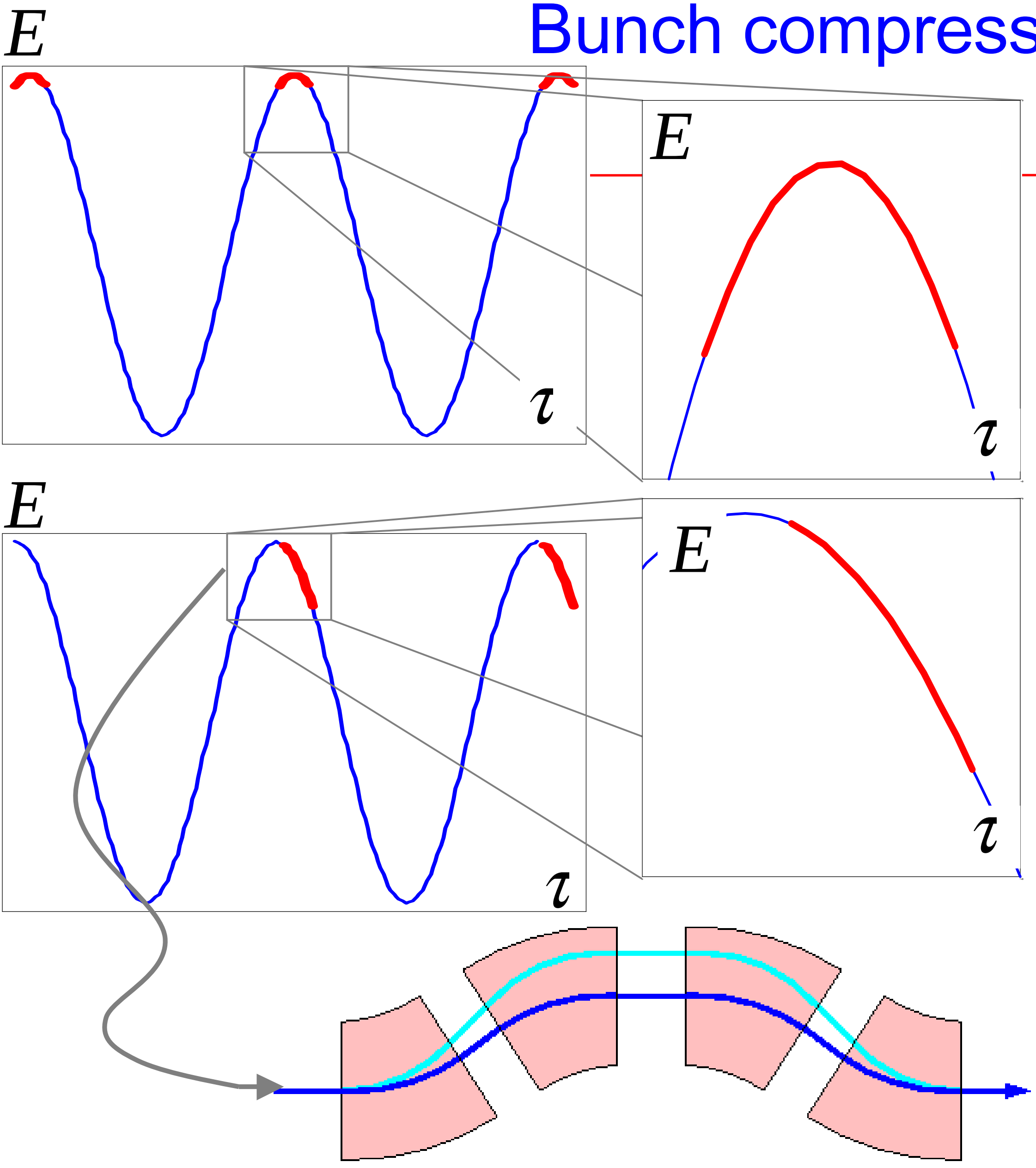
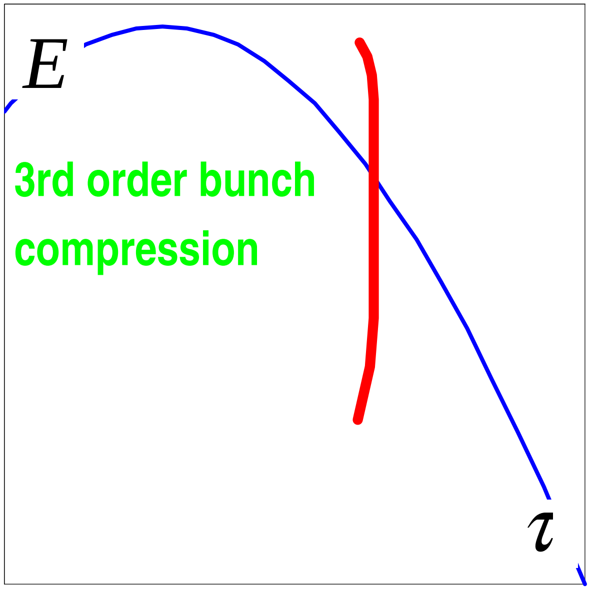
- On crest acceleration leads to long Bunches with small energy spread.
- Off crest acceleration leads to short Bunches with more energy spread.
- The bunch length can be made even shorter by nonlinear bunch compression



Here low energy particles fly longer



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First order bunch compression

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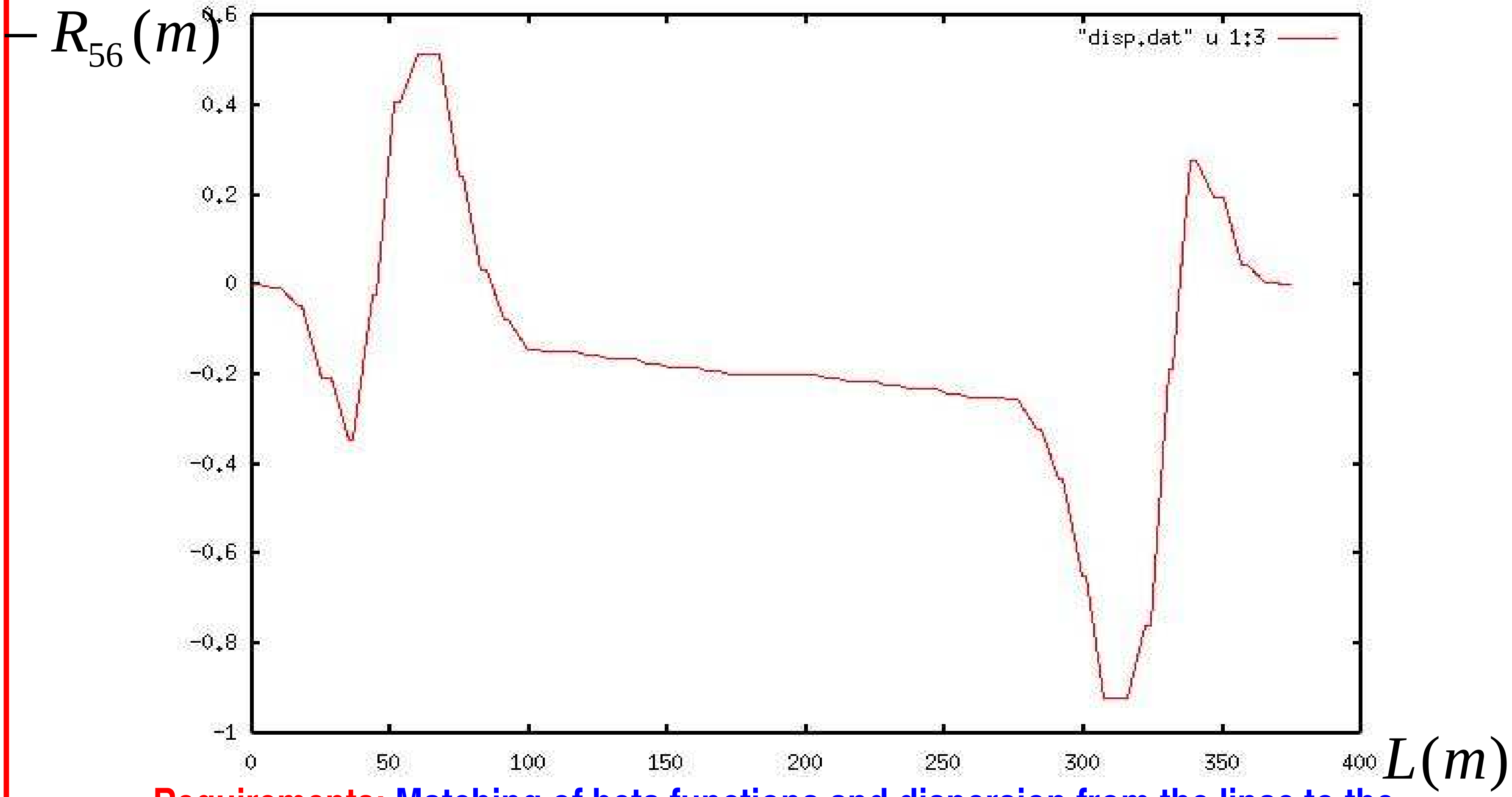
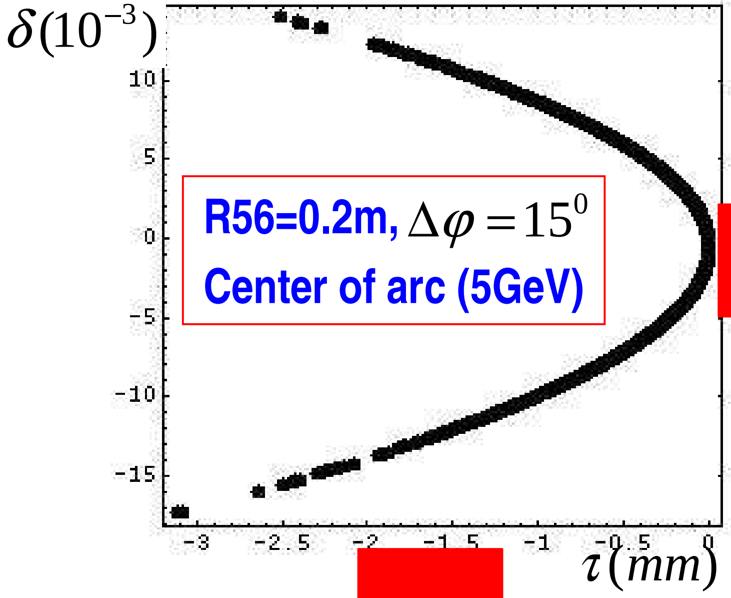


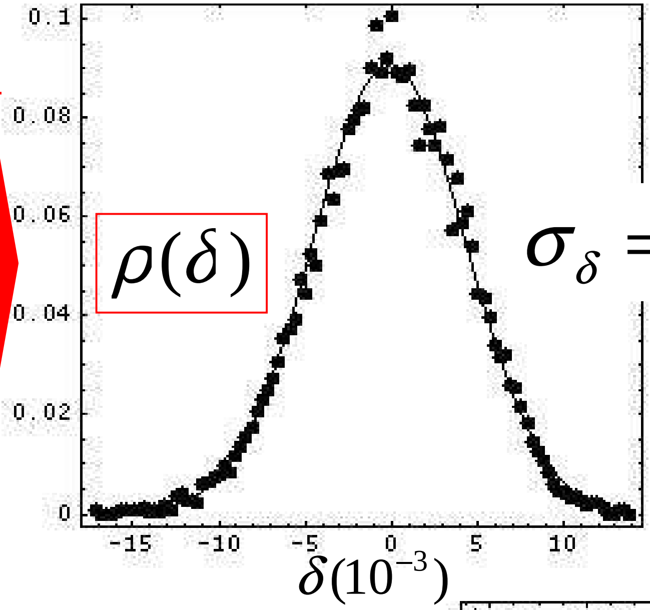
Requirements: **Matching of beta functions and dispersion from the linac to the undulators, R56 to 20cm at the center and R56 to 0 at the end is possible with current quadrupoles.**

Short bunches with large energy spread



R56=0.2m, $\Delta\varphi = 15^0$

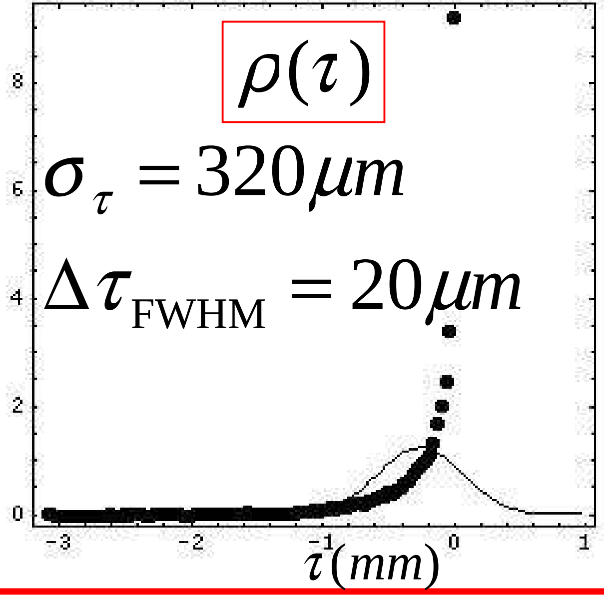
Center of arc (5GeV)



$\rho(\delta)$

CHE $\delta = \frac{\Delta E}{E}$ PP

$$\sigma_\delta = 4.4\cdot 10^{-3}$$

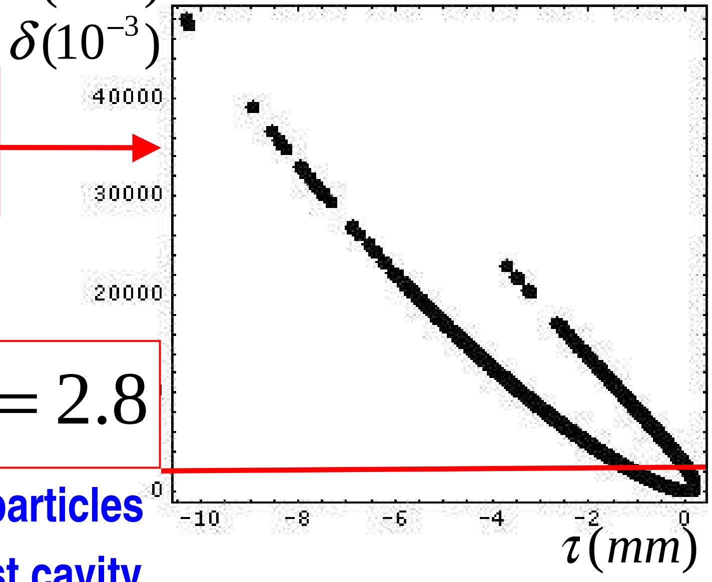


$\rho(\tau)$

$$\sigma_\tau = 320\mu m$$

$$\Delta\tau_{\mathrm{FWHM}} = 20\mu m$$

After ERL (10MeV)



$$\langle\delta\rangle = 2.8$$

The low energy particles are lost in the last cavity

Transverse motion with large energy spread

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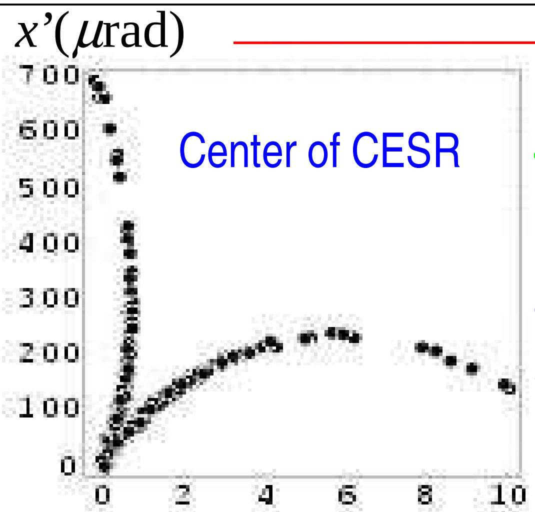
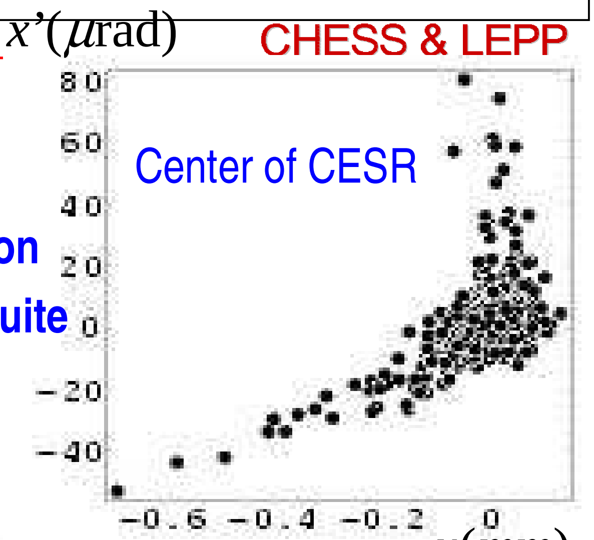
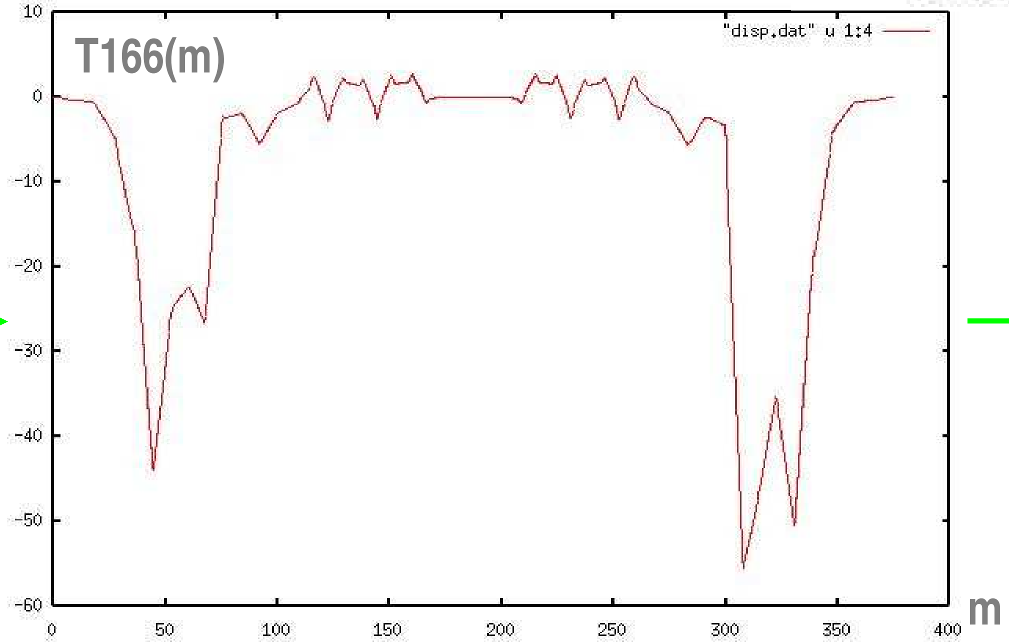


Second order dispersion has to be corrected:

Due to the large first order dispersion at the beginning of the arc, this is quite simple with CESR sextupoles.





$\Delta\varphi = 15^0$ **RF**

0.44% energy spread

Second Order Time of flight

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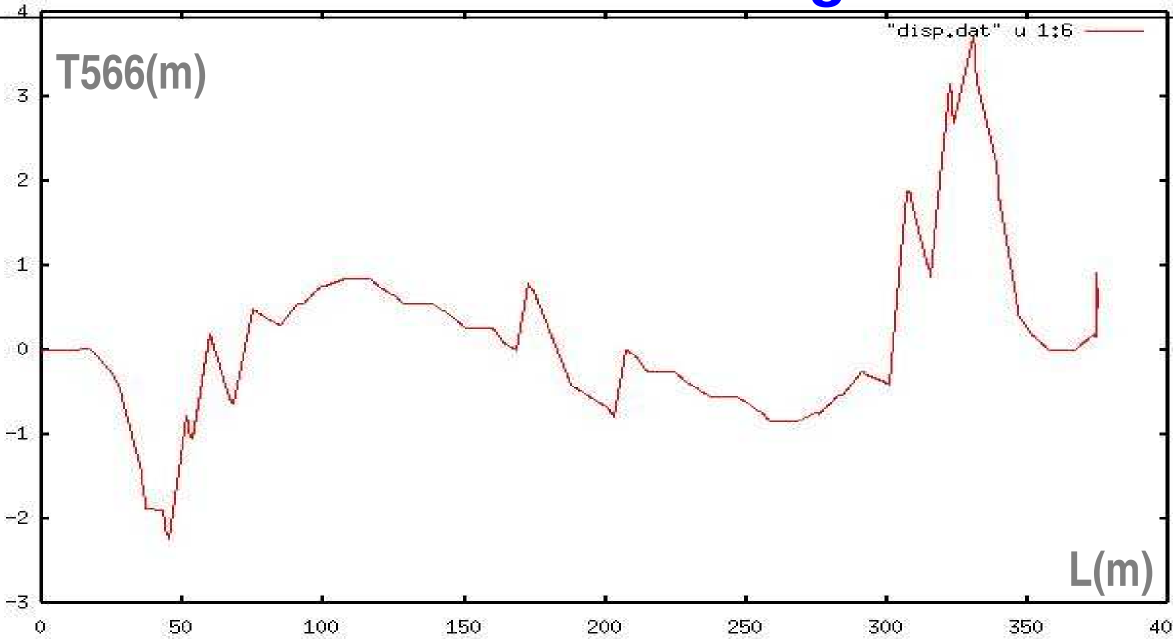
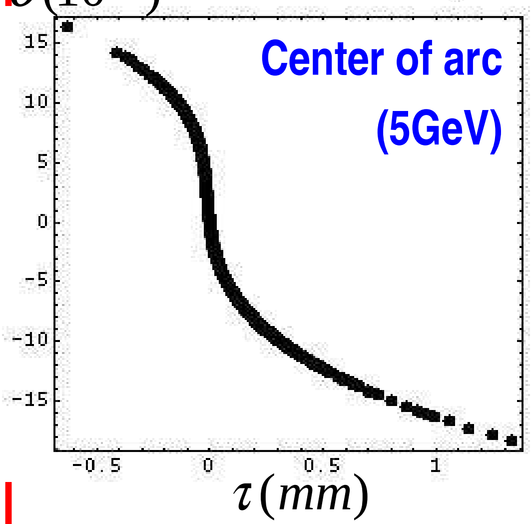
$\Delta\varphi = 15^0$ **RF**

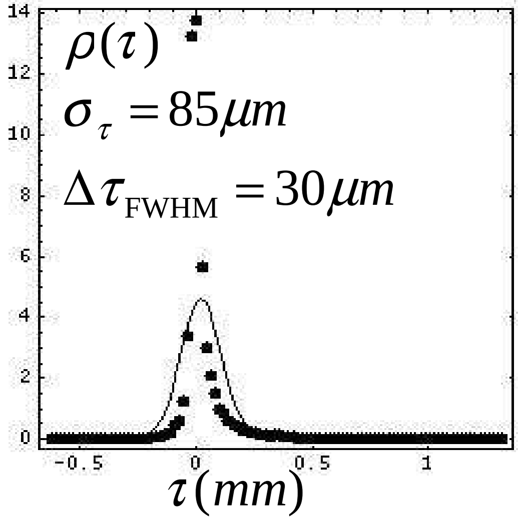
0.44% energy spread





Center of arc

(5GeV)

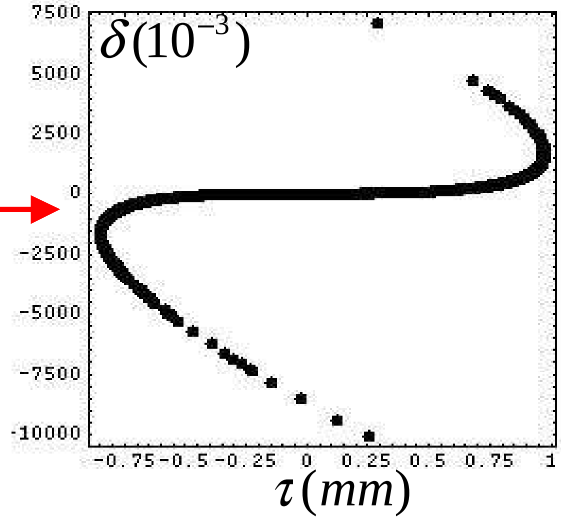


$\rho(\tau)$

$\sigma_\tau = 85\mu m$

$\Delta\tau_{\mathrm{FWHM}} = 30\mu m$

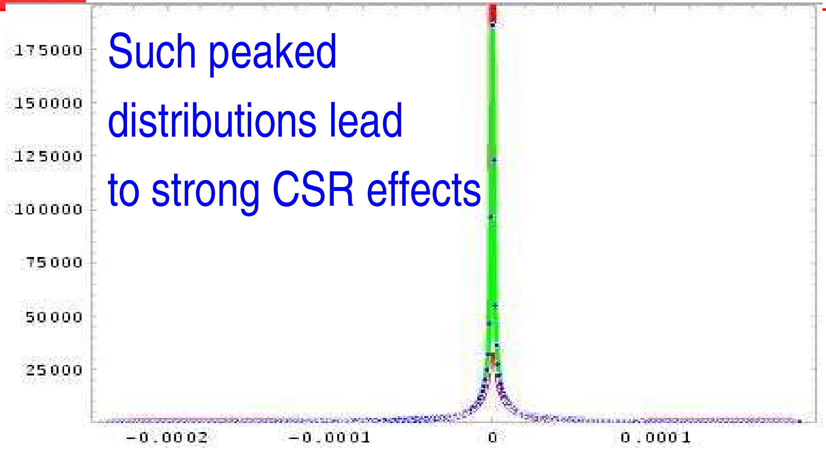
After ERL



- **The energy spread is too large**

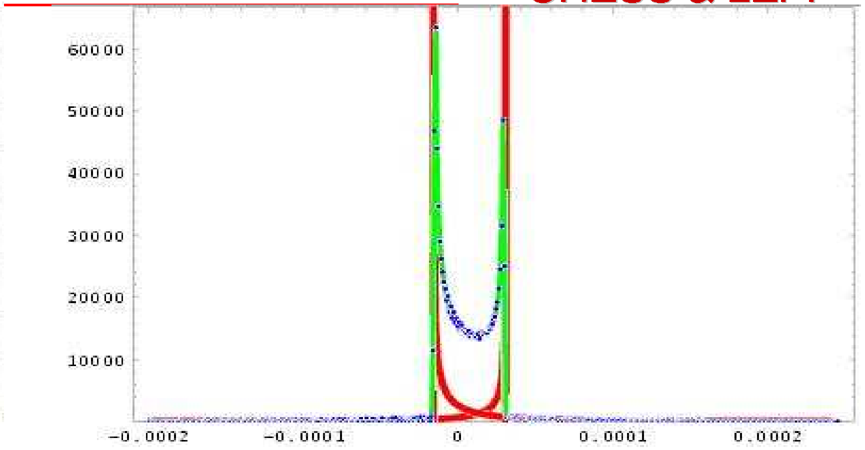
Undercompression

Peak at 6^0 RF phase



Such peaked distributions lead to strong CSR effects

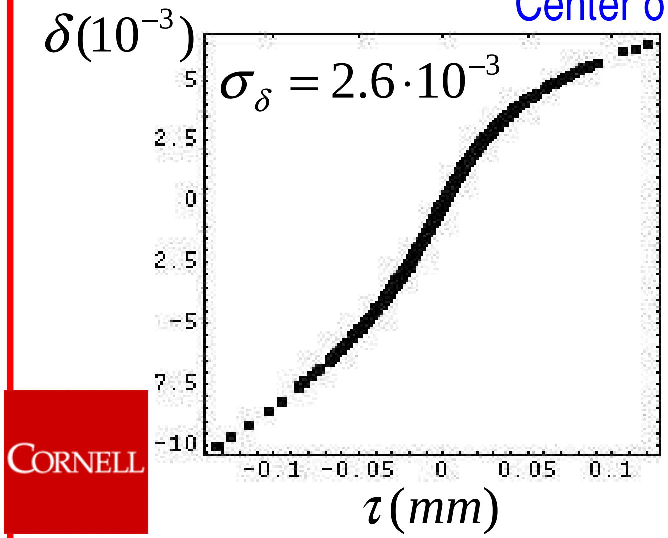
Overfocused peaks



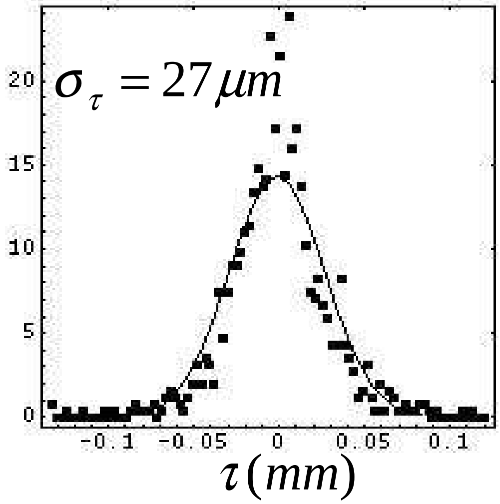
With second order optimization: 9^0 RF phase and undercompression

$$\boxed{\Delta\varphi = 9^0}$$

Center of arc (5GeV)

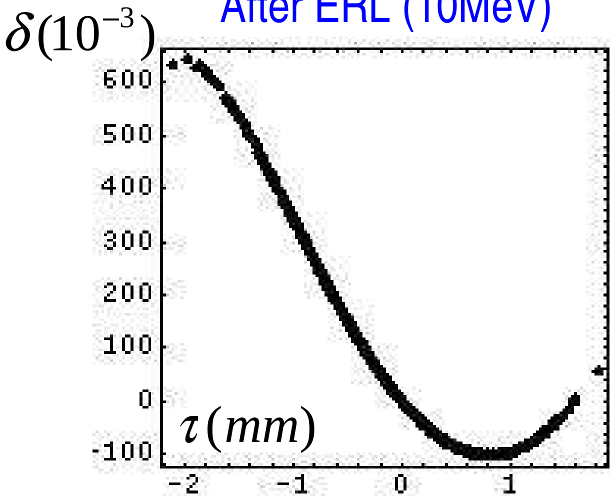


$\sigma_\delta = 2.6 \cdot 10^{-3}$

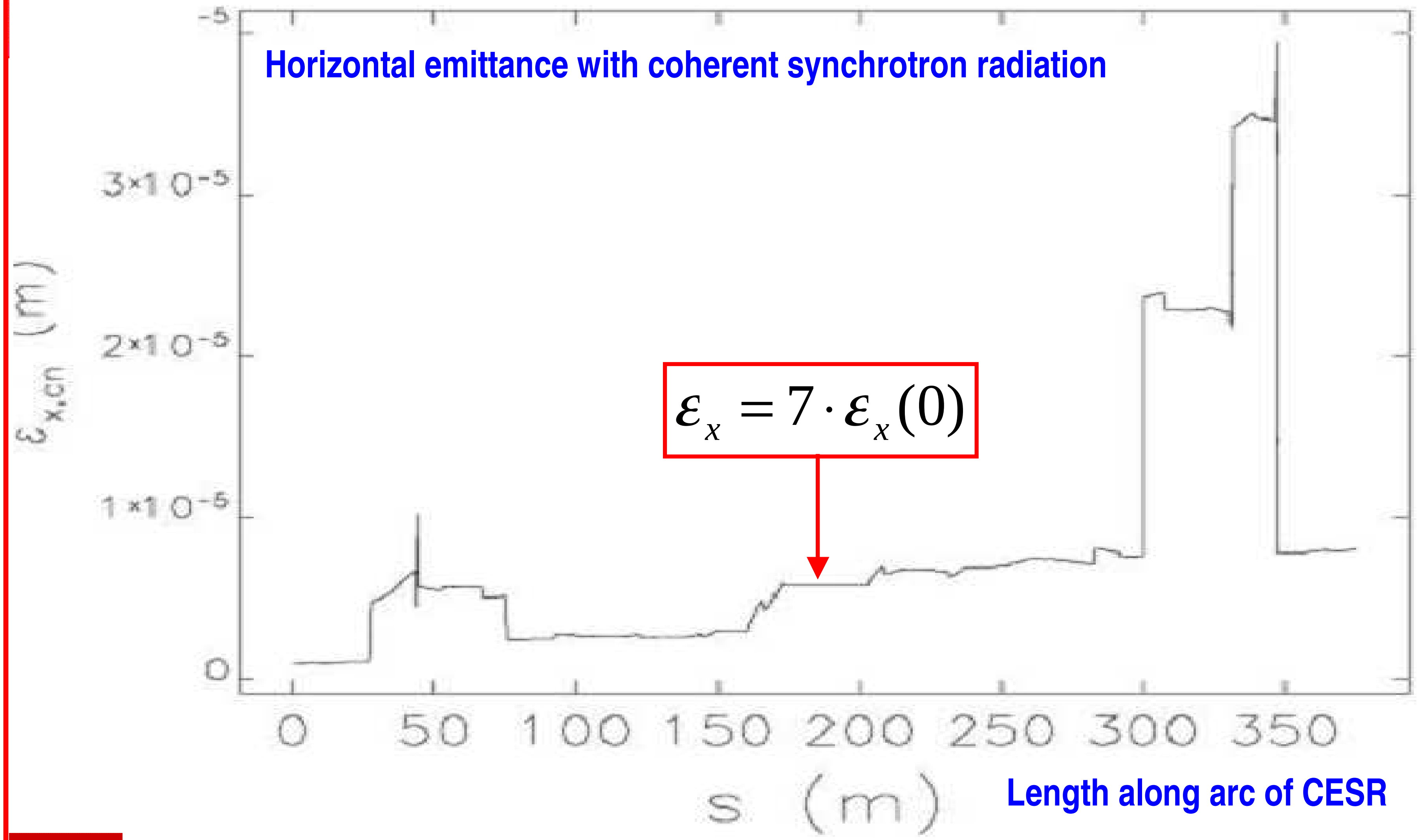


$\sigma_\tau = 27\mu m$

After ERL (10MeV)



6^0 RF phase, peaked bunch



Horizontal emittance with coherent synchrotron radiation

$$\varepsilon_x = 7 \cdot \varepsilon_x(0)$$

Length along arc of CESR

emittance in 25 m wiggler is 5.85 um

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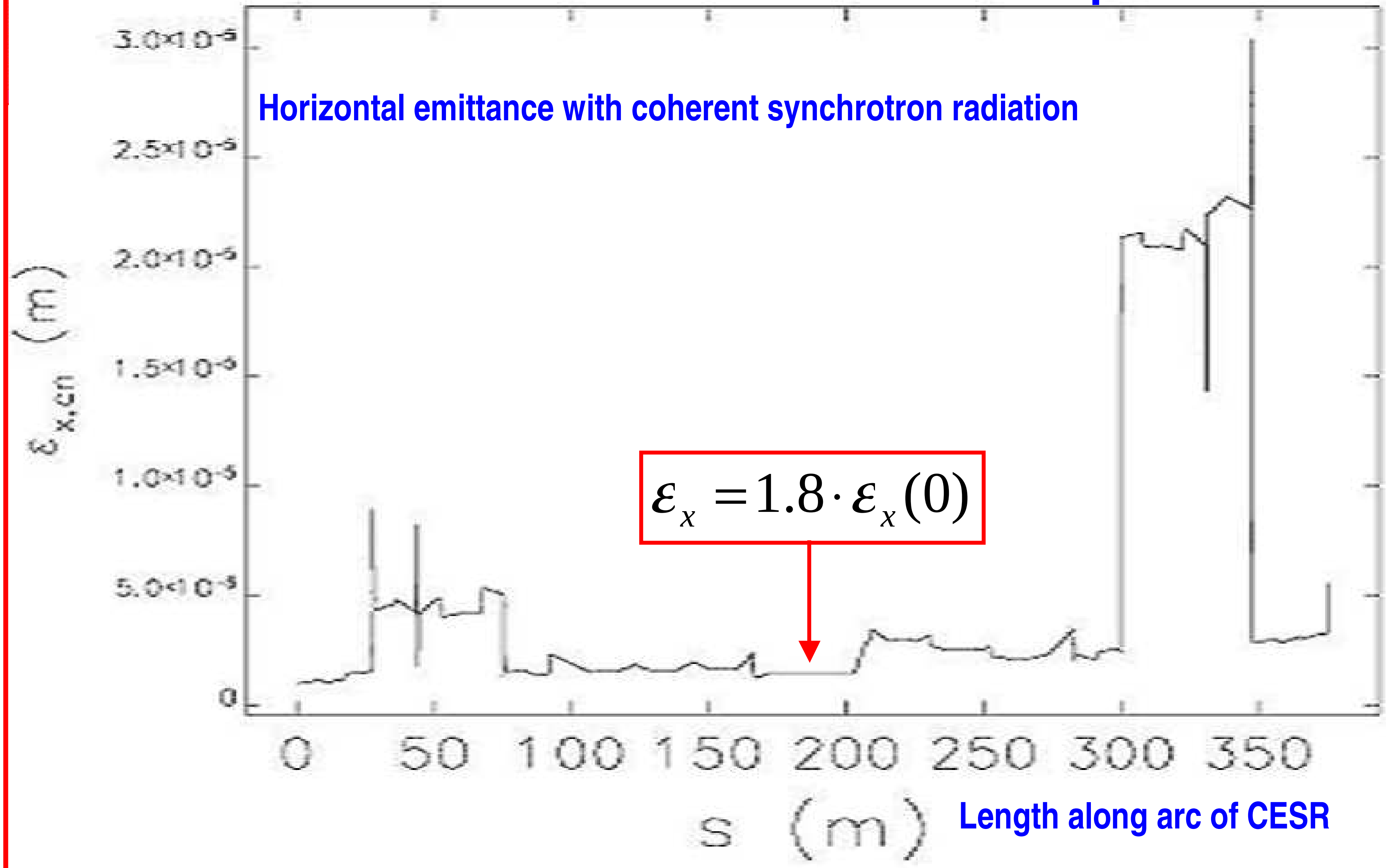
Emittance with CSR and nonlinear optics



Horizontal emittance with coherent synchrotron radiation

$$\boxed{\varepsilon_x = 1.8 \cdot \varepsilon_x(0)}$$

Length along arc of CESR

Result: After suitable nonlinear bunch length manipulation, the emittance growth can be controlled in all undulators.

Nota bene on Instrumentation

Issues for discussions on diagnostic necessities:

a) Number and location of BPMs
b) BPMs for two beams
c) Number and location of beam size measurements
d) Longitudinal beam profile measurements
e) Longitudinal tomography
f) Optic measurement procedures
g) Beam based alignment procedures
h) Commissioning strategies
i) Emittance control
j) Phase space tomography

What needs testing ?

- Full average current injector with the specified emittance and bunch length
- Emittance preservation during acceleration and beam transport:
  - Nonlinear optics (**code validation at CEBAF**), coherent synchrotron radiation (**JLAB,TTF,SPPS**), space charge
- Delivery of short duration (ca. 100 fs, and less in simulations), high charge bunches (**TTF, SPPS**)
- Dependence of emittance on bunch charge
- Stable RF control of injector cryomodule at high beam power
- Stable RF control of main linac cavities at high external Q, high current, and no net beam loading (**JLAB to 10mA**)
- Understanding of how high the main linac external Q can be pushed (**JLAB**)
- Study of microphonic control using piezo tuners (**JLAB, SNS, NSCL, TTF**)
- Recirculating beam stability as a function of beam current with real HOMs, and benchmarking the Cornell code BI (**JLAB**)
- Feedback stabilization of beam orbit at the level necessary to utilize a high brightness ERL
- Photocathode operational lifetime supporting effective ERL operation
- Performance of high power RF couplers for injector cryomodule
- Demonstration of non-intercepting beam size and bunch length diagnostics with high average current at injector energy and at high energy (**TTF**)
- HOM extraction and damping per design in injector and main linac (**code validation from Phase Ia**)
- Performance of HOM load materials to very high frequency
- Performance of full power beam dump
- Detailed comparison of modeled and measured injector performance
- Study of halo generation and control in a high average current accelerator at low energy and with energy recovery (**JLAB**)
- Study of beam losses and their reduction in recirculation of high average current with energy recovery (**JLAB**, **NAA**)
- Precision path length measurement and stabilization (**Phase Ia**, **JLAB**)

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Conclusion

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- First and second order optics have been found for an ERL in the CESR tunnel
  - which uses the current CESR tunnel and many of its components
  - which can be used to compress 2ps bunches to 100fs
  - which leads to less than a factor of 2 in transverse emittance increase due to CSR
  - Nearly all quadrupoles and sextupoles have a strength which can be achieved in CESR today
  - The BBU limit is computed to be > 600mA

- This upgrade of CESR to an ERL light source would be a demonstration of an upgrade path that could then be open to many existing X-ray rings.