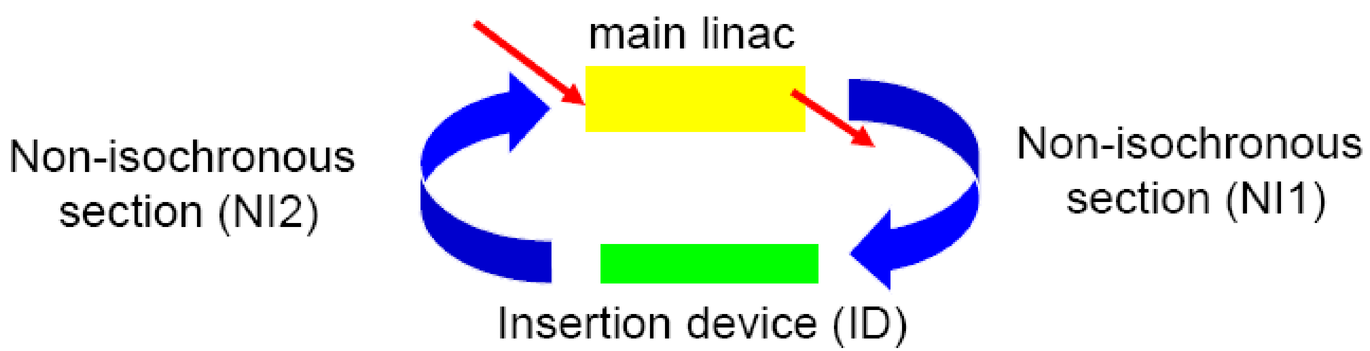
FLS2006 - ERL Compression Schemes

Hywel Owen

Generic ERL

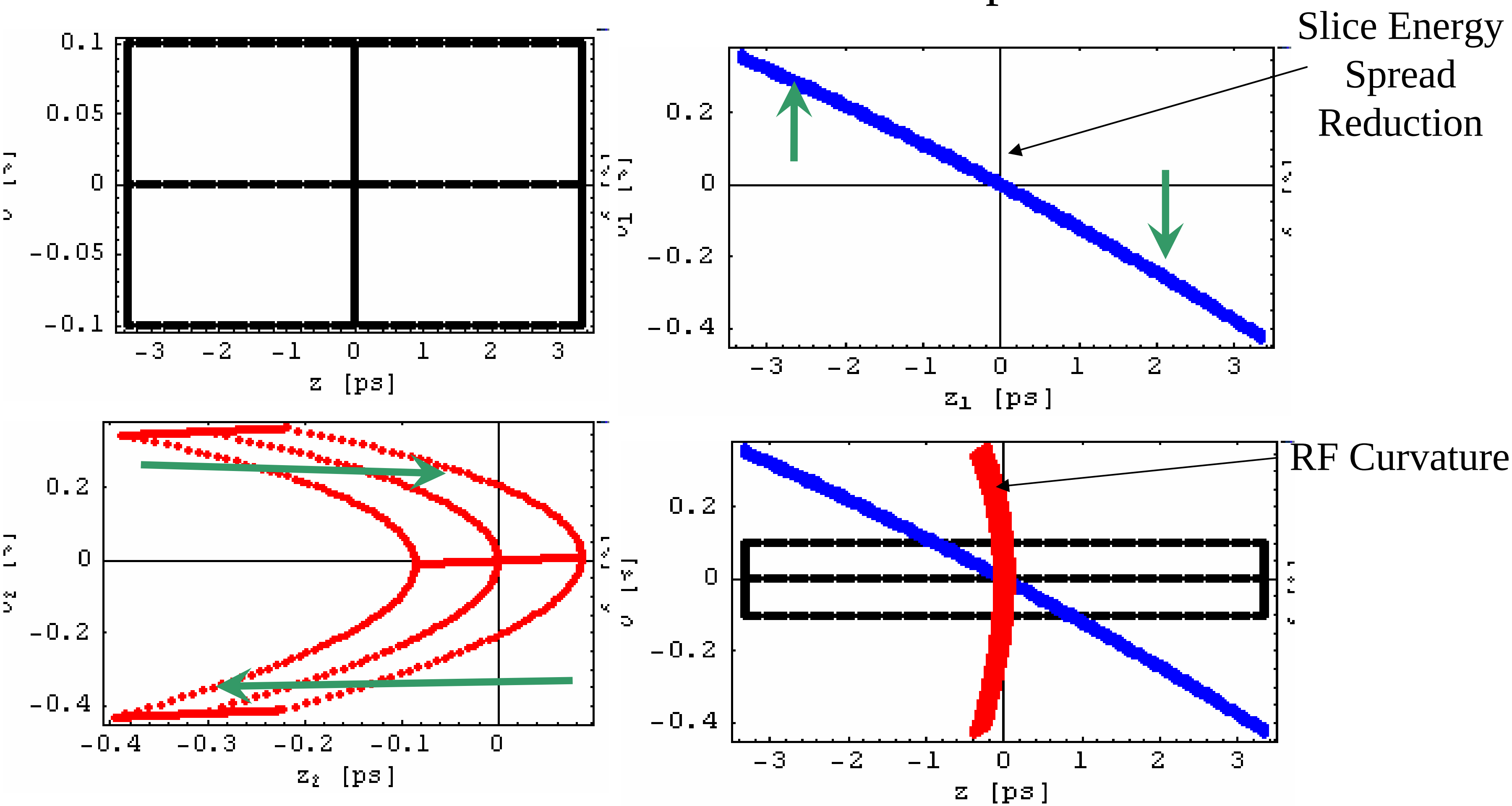

main linac
Non-isochronous
section (NI2)
Non-isochronous
section (NI1)
Insertion device (ID)

Questions to Keep In Mind

- Method of Compression
  - Single Stage (JLab, ERLP)
  - Stepped/2-Stage (FLASH, XFEL, LCLS etc.)
  - Progressive/Modular (4GLS)
  - Large Dispersion/Split Linac Approach (Cornell)
  - Velocity Bunching (JAERI)
- Sextupoles or 3rd-Harmonic for Linearisation?
  - Higher-Order Terms
- Problems in Particular Machines
    - Combined Beams (4GLS)
    - Topology (Cornell)

Basics of Chirp/Compression

RF Chirp



Magnetic Compression

1D Transport Elements

$$
\begin{aligned}
z_1 &= z_0 \\
\delta_1 &= \frac{(1+\delta_0)E_0 + eV_{rf}\cos(\phi_{rf} - k_{rf} z_0)}{E_0 + \Delta E} - 1
\end{aligned}
$$

RF Acceleration/Chirp

$$
\begin{aligned}
z_2 &= z_1 + R_{56}\delta_1 + T_{566}\delta_1^2 + U_{5666}\delta_1^3 + O(\delta_1^4) \\
\delta_2 &= \delta_1,
\end{aligned}
$$

Magnetic Transport

$$
R_{56} = -\frac{\lambda_{rf}}{2\pi \tan(\phi_{rf})} \frac{E_0 + \Delta E}{\Delta E} \qquad T_{566} \approx -\frac{3}{2} R_{56}
$$

Required Compression (Linear Only)

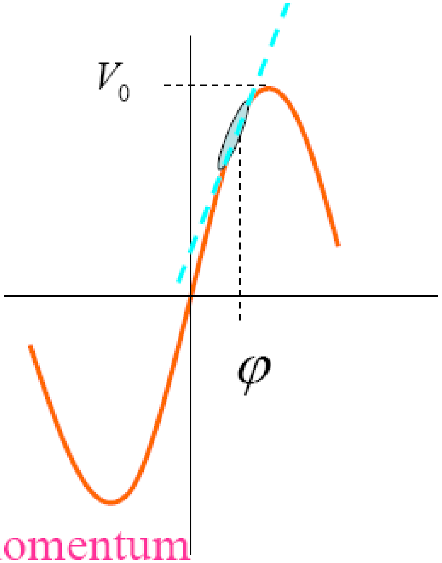
Linear Theory

- Energy time correlation:

$$E(z) = E_0 + eV_0 \cos(kz + \varphi)$$

$$\delta = \frac{eV_0}{E_0 + eV_0 \cos\varphi}\left[\cos(kz+\varphi) - \cos\varphi\right] = \kappa z + O(z^2)$$

chirp: $\kappa \equiv \dfrac{d\delta}{dz} = \dfrac{-keV_0}{E_0 + eV_0\cos\varphi}\sin\varphi$



- Bunch compressor

1st order momentum compaction

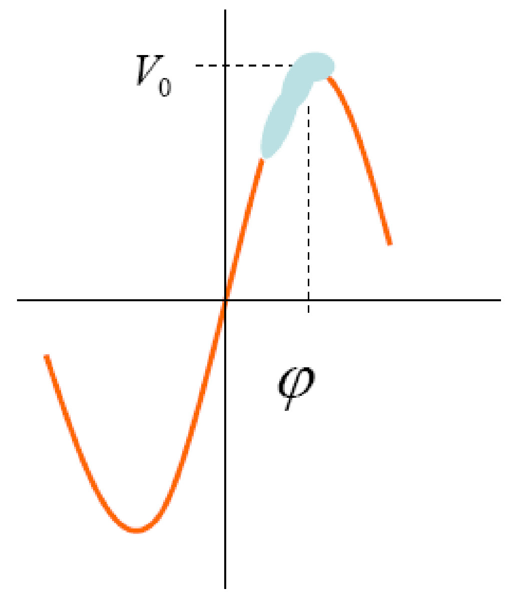
$$z_f = z_i + R_{56}\delta_i$$

- Final bunch length and energy spread (1st order):

$$\sigma_{z,f} = \sqrt{(1+\kappa R_{56})^2 \sigma_{z,i}^2 + \underbrace{R_{56}^2 \sigma_{\delta,i}^2 E_0^2 / E^2}_{\text{Min bunch length}}}, \quad \sigma_{\delta,f} = \sqrt{\kappa^2 \sigma_{z,i}^2 + \sigma_{\delta,i}^2 E_0^2 / E^2}$$

getting very small at high energy!

2nd-Order Theory



- Energy time correlation:

$$\delta = \kappa z + \mu z^2 + O(z^3)$$

- Bunch compressor

$$z_f = z_i + R_{56}\delta_i + T_{566}\delta_i^2$$

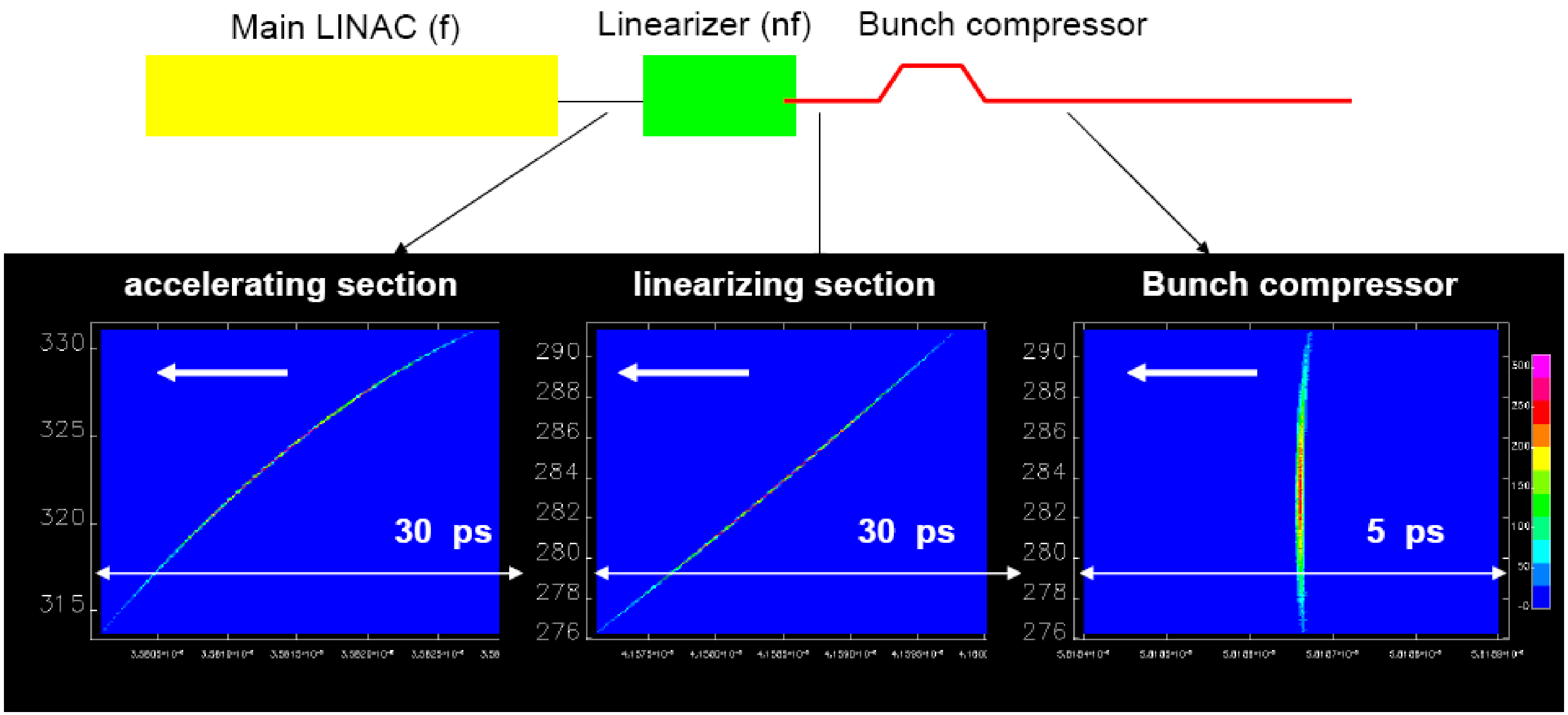
- Final bunch length is minimized if

$$0 = z_i(1 + \kappa R_{56}) + \underbrace{z_i^2(\mu R_{56} + \kappa^2 T_{566})}_{\text{Limit achievable minimum Bunch length}}$$

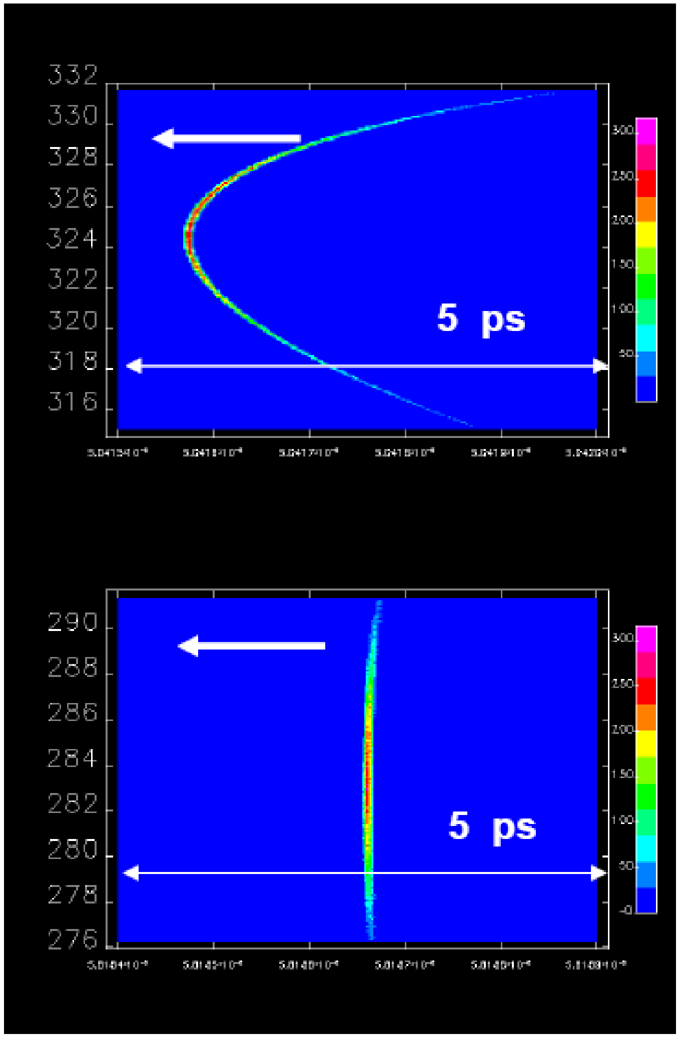
2nd order momentum compaction

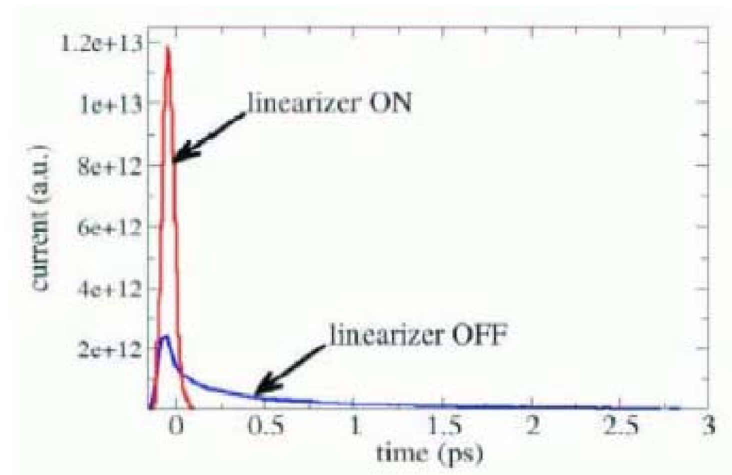
3rd-Harmonic Linearisation

- Correction with higher harmonic rf-field provide two independent knobs (κ and μ parameters to minimize σ_z given R_{56} and T_{566}),
- sextupoles to some extent also provide these knobs



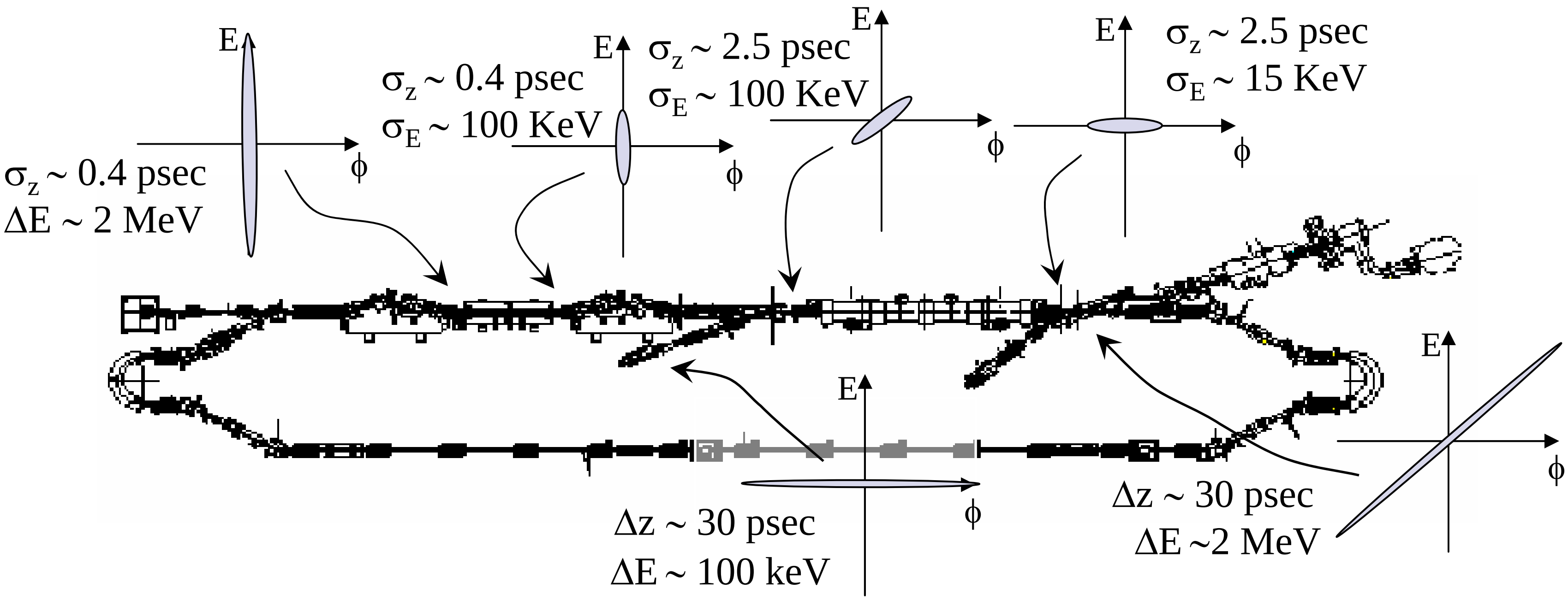
3rd-Order Linearisation





JLab IR-Demo

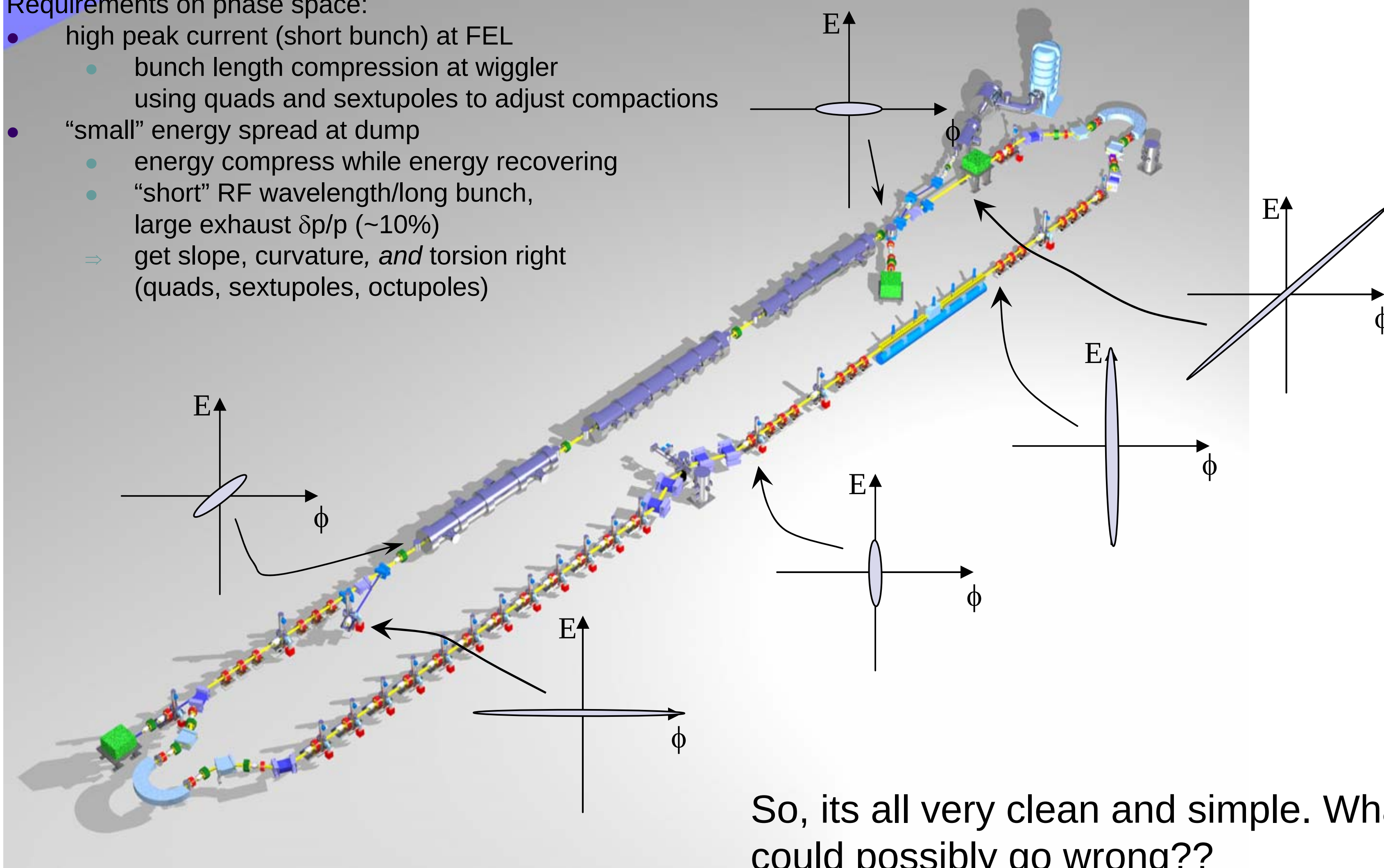
- Requirements on phase space:
  - high peak current (short bunch) at FEL
    - bunch length compression at wiggler
  - “small” energy spread at dump
    - energy compress while energy recovering
    - “short” RF wavelength/long bunch ⇒ get slope and curvature right



JLab - Longitudinal Matching Scenario

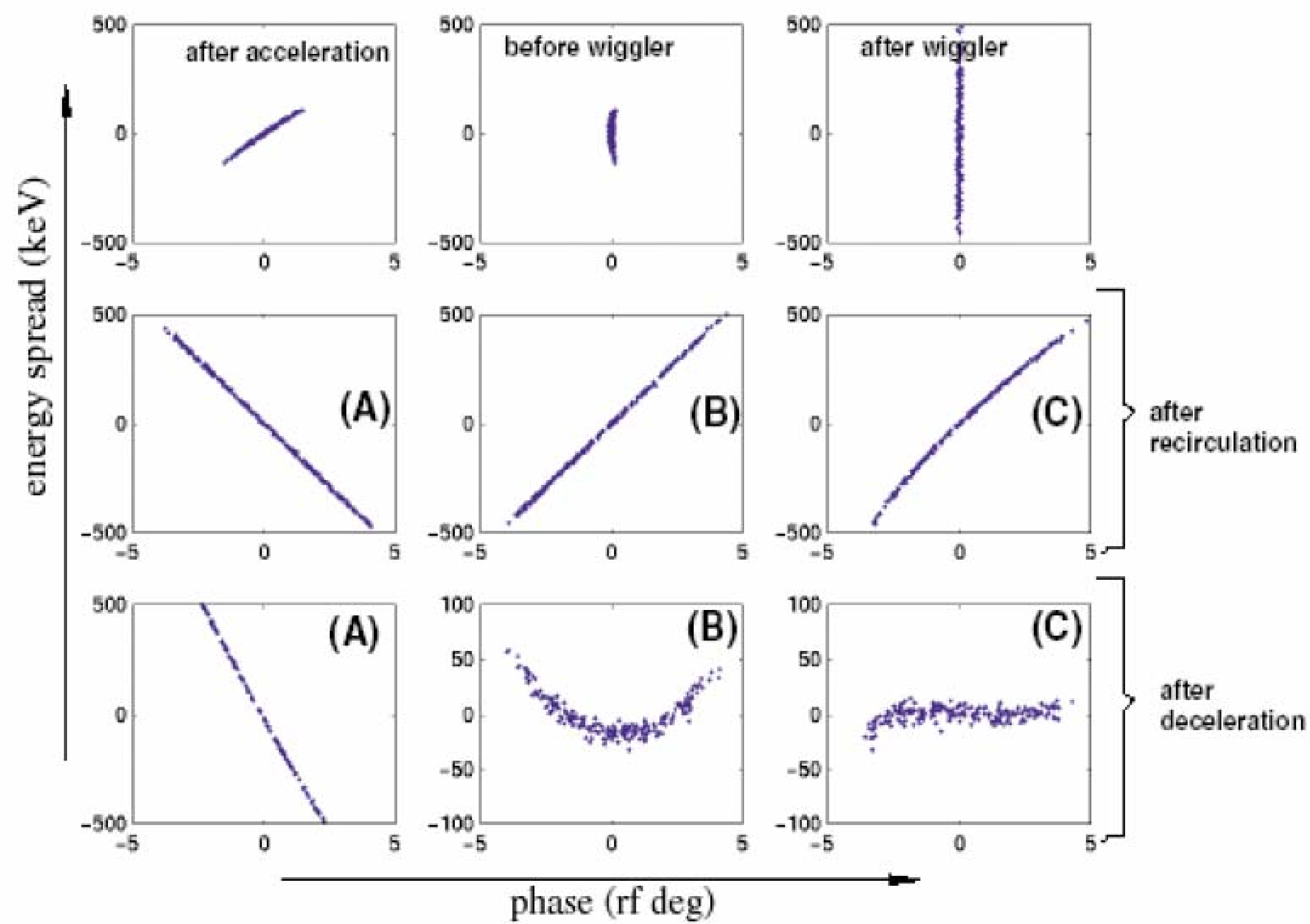
Requirements on phase space:

- high peak current (short bunch) at FEL
  - bunch length compression at wiggler
    using quads and sextupoles to adjust compactions
- "small" energy spread at dump
  - energy compress while energy recovering
  - "short" RF wavelength/long bunch,
    large exhaust $\delta p/p$ (~10%)
  - ⇒ get slope, curvature, *and* torsion right
    (quads, sextupoles, octupoles)

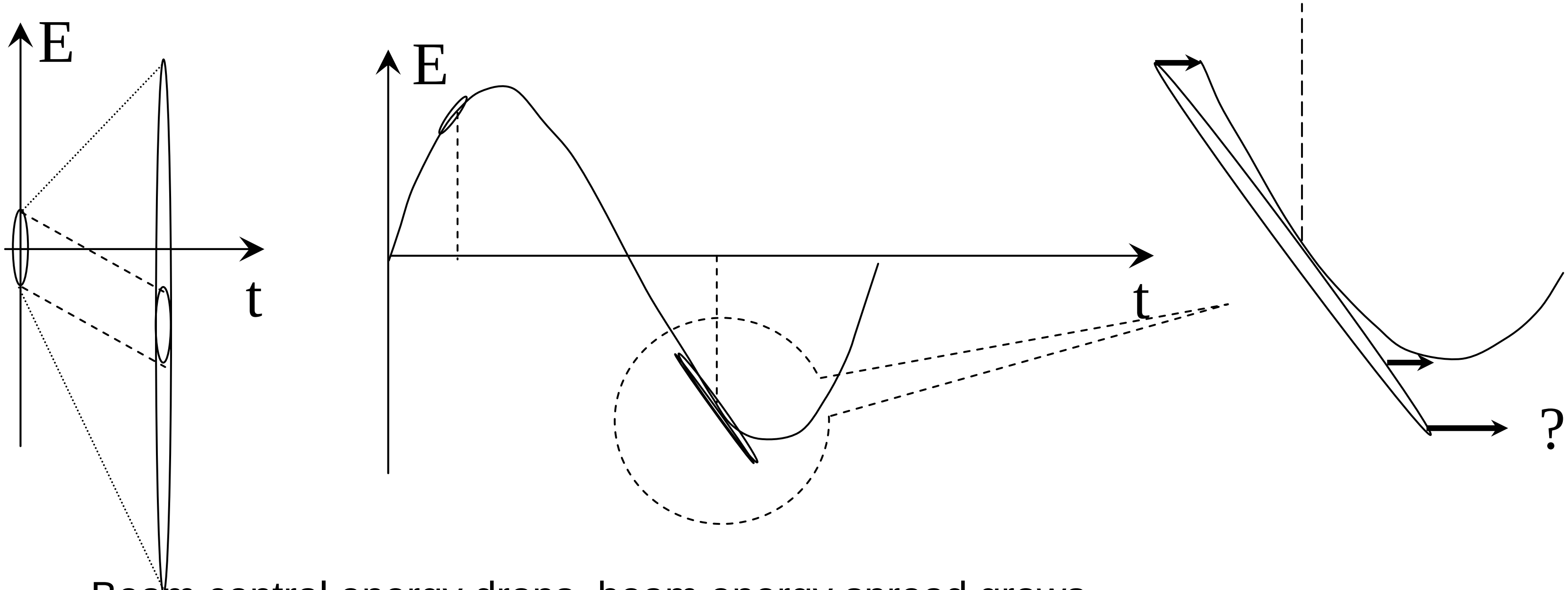


So, its all very clean and simple. What could possibly go wrong??

JLab – Longitudinal Matching

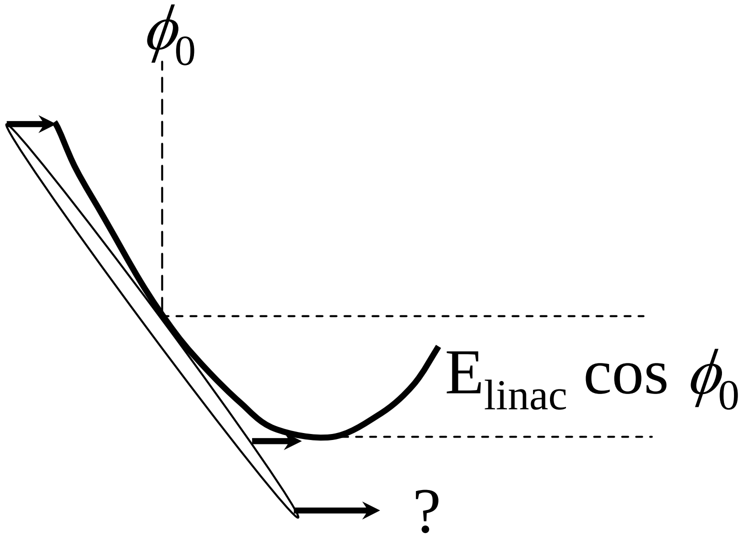


Energy Compression



- Beam central energy drops, beam energy spread grows
- Recirculator energy must be matched to beam central energy to maximize acceptance
- Beam rotated, curved, torqued to match shape of RF waveform
- Maximum energy can’t exceed peak *deceleration* available from linac!

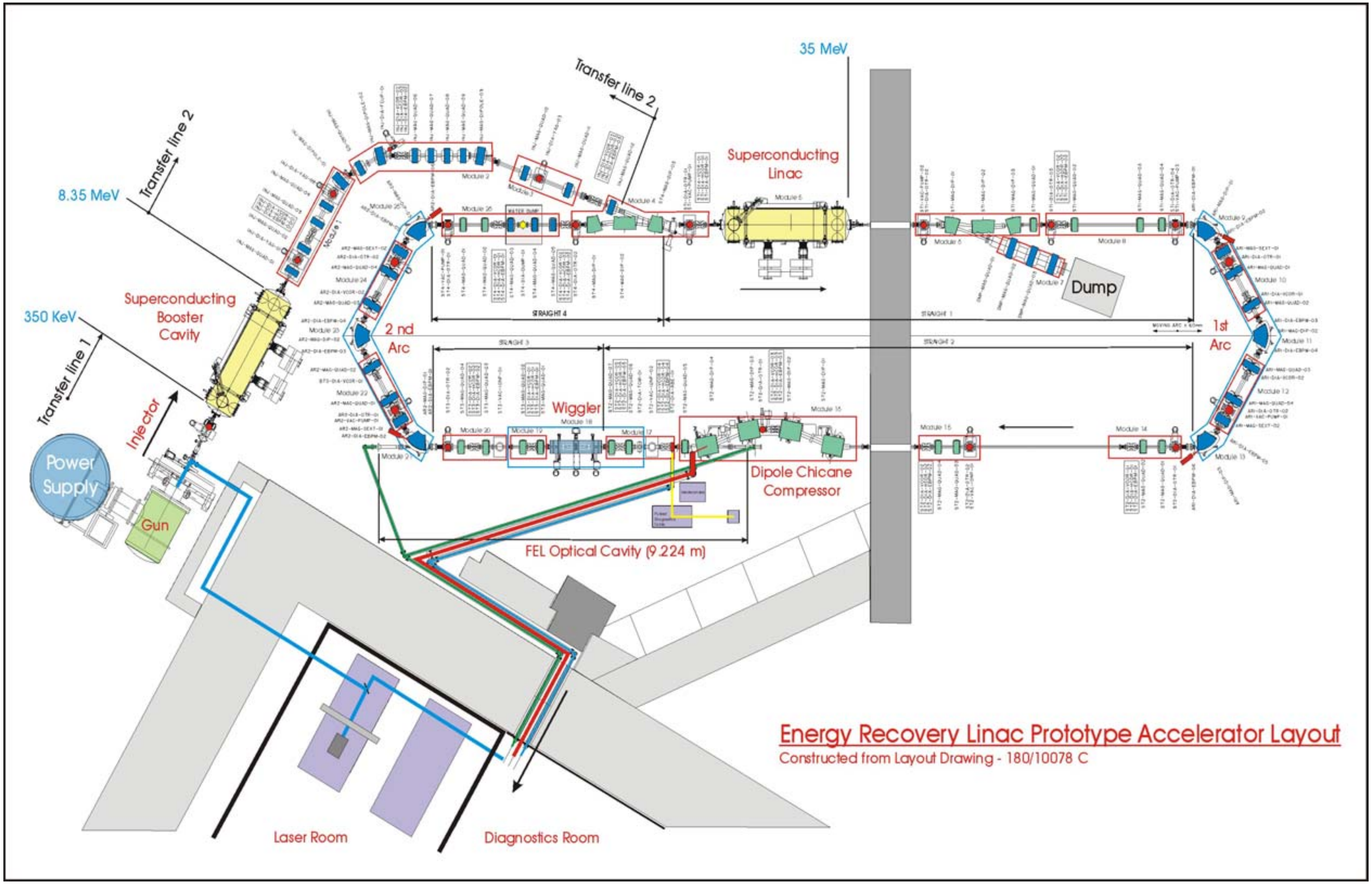
Limits of Energy Compression



- Quads rotate bunch to match waveform slope; sextupoles curve bunch to match waveform curvature; octupoles torque bunch to match waveform torsion
- No magnet can change largest energy offset to make up limit of available gradient!!

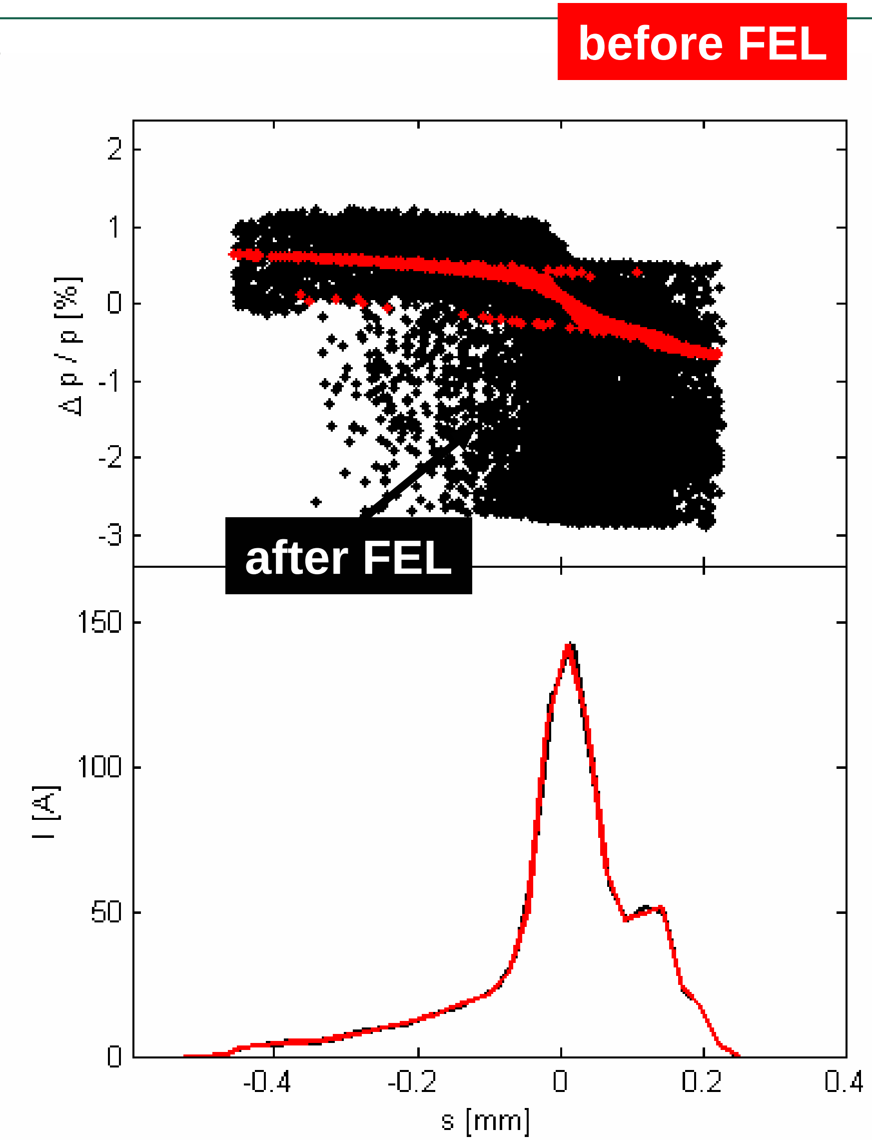
$$(\Delta E/E)_{FEL}/2 < E_{linac} \cos \phi_0$$

ERLP – Layout

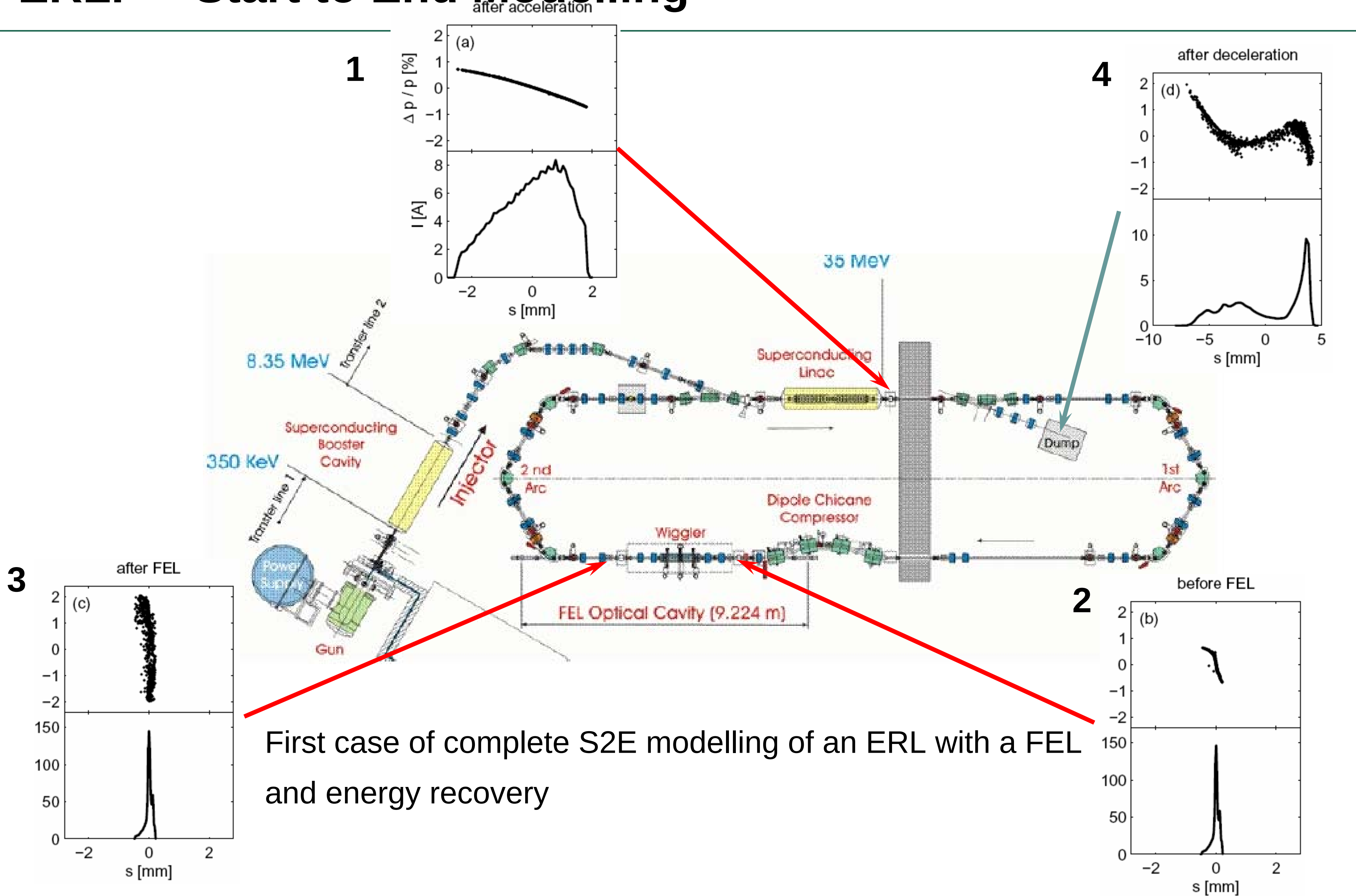

35 MeV
Transfer line 2
Superconducting Linac
Transfer line 2
8.35 MeV
Dump
Superconducting Booster Cavity
350 KeV
2 nd Arc
1st Arc
Transfer line 1
Injector
Wiggler
Power Supply
Gun
Dipole Chicane Compressor
FEL Optical Cavity (9.224 m)
Energy Recovery Linac Prototype Accelerator Layout
Constructed from Layout Drawing - 180/10078 C
Laser Room
Diagnostics Room

FEL Modelling – GENESIS 1.3

- Modeling of FEL interaction using in Genesis 1.3;
- Major tool used for design of 4GLS sources;
- Commissioning measurements will confirm validity of code and other calculations.



ERLP – Start to End Modelling

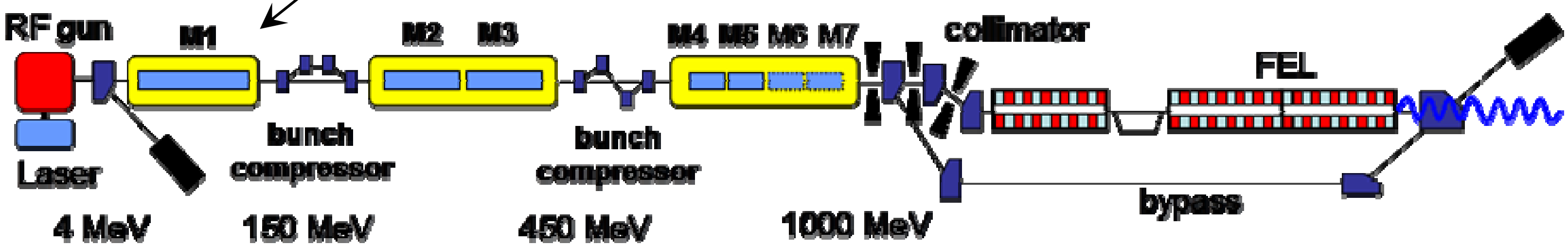


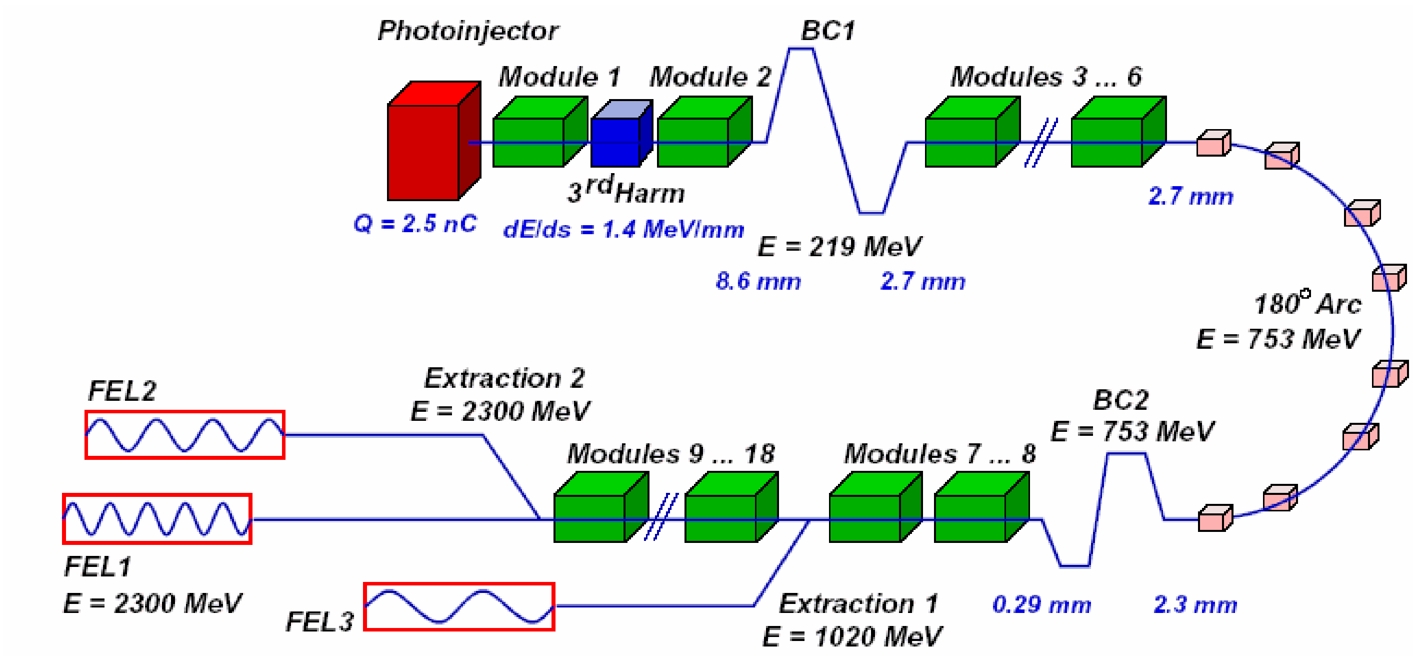
First case of complete S2E modelling of an ERL with a FEL and energy recovery

TTF-II/VUV-FEL and BESSY-FEL

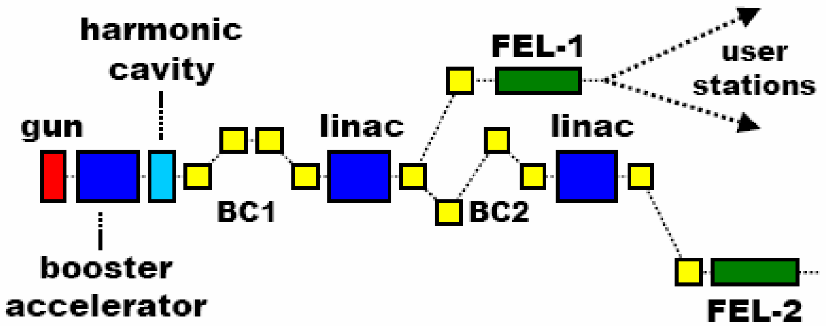
3^{rd}-harmonic RF

M1 operates at 120MeV because of limited gradient

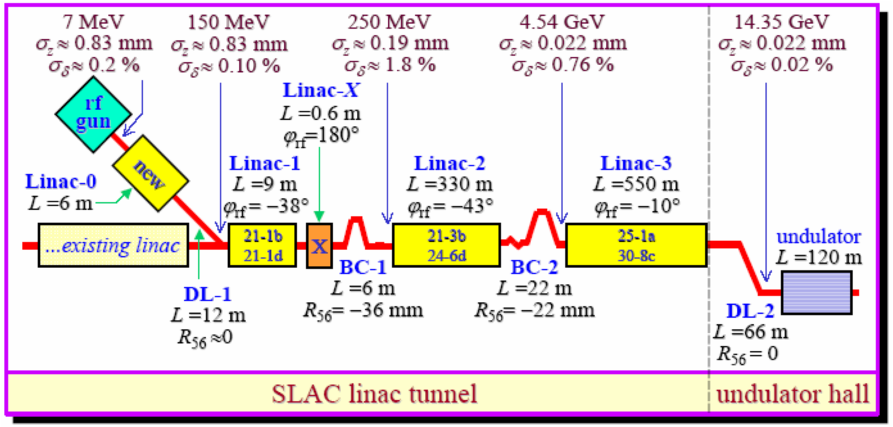




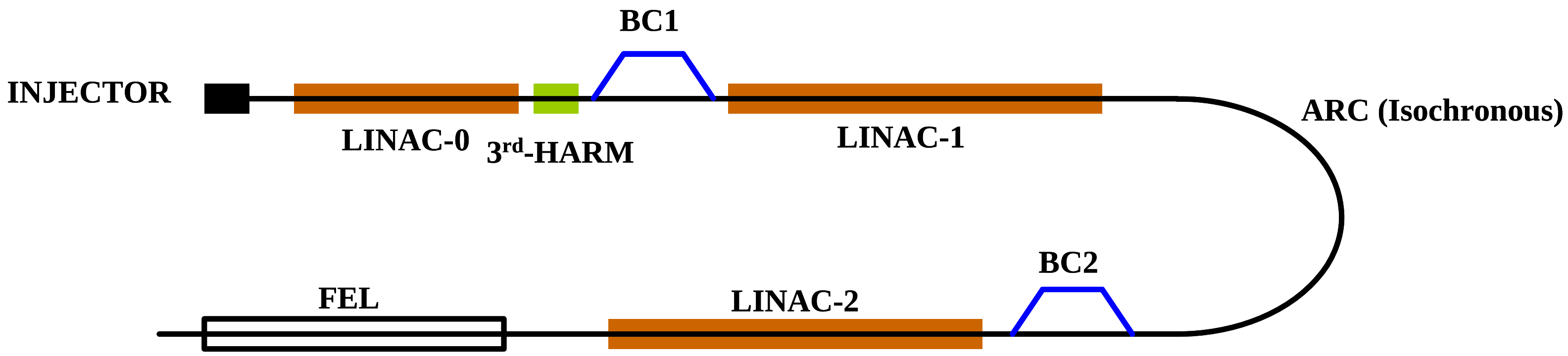
FERMI & LCLS



	FEL-1		FEL-2		
Wavelength Target	100	40	40	10	nm
	10	31	25	124	eV
Electron Beam Energy	0.70		0.55	1.00	GeV
Bunch Charge	1.0		1.0		nC
Peak Current	0.8		2.5		kA
Bunch Duration (rms)	500		160		fs
Energy Spread (rms)	0.7		1.0		MeV
Normalized Emittance	2.0		1.5		$\times10^{-6}$ m
Undulator Period	52		36.6		mm

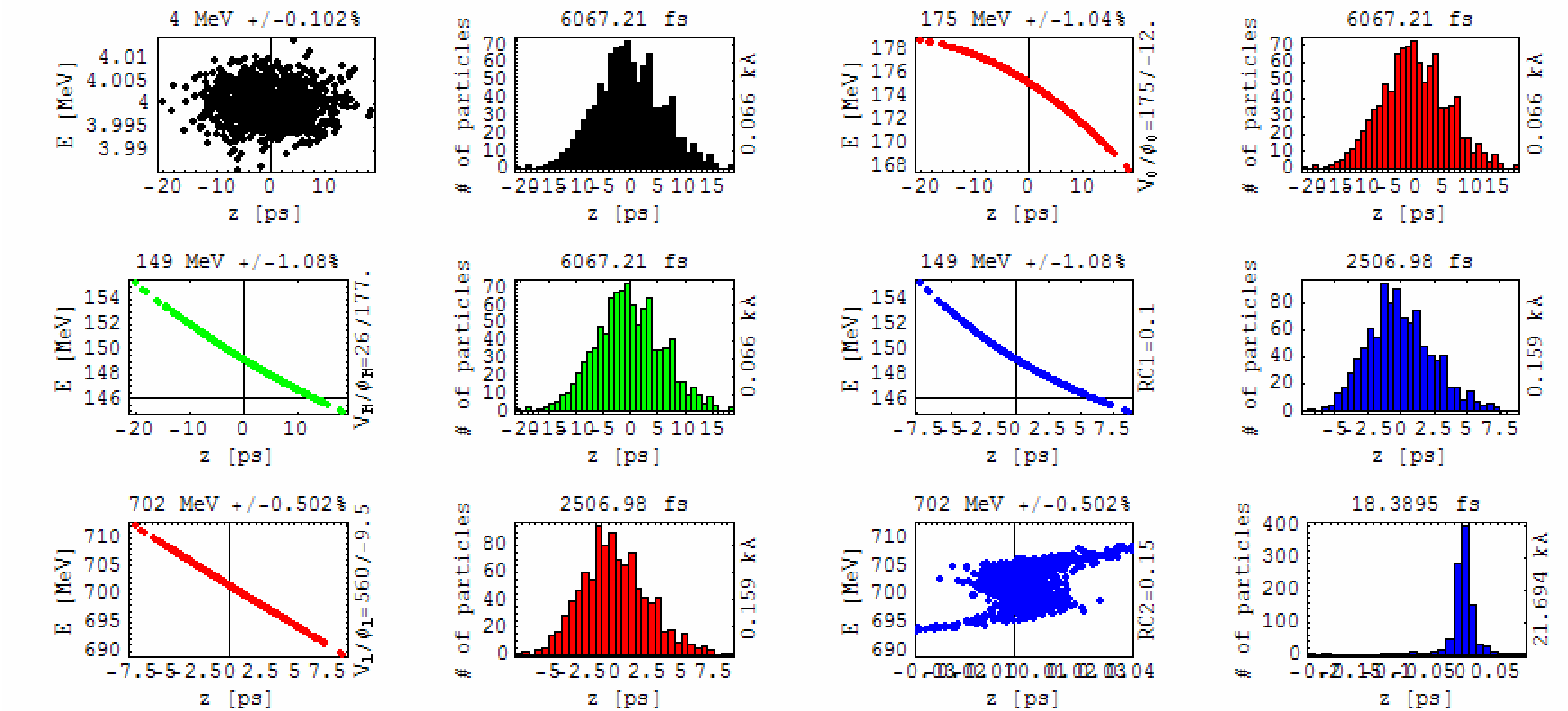


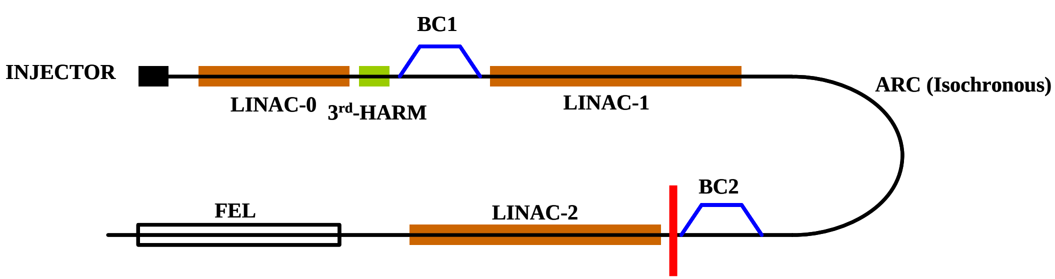
4GLS FEL Branch Options

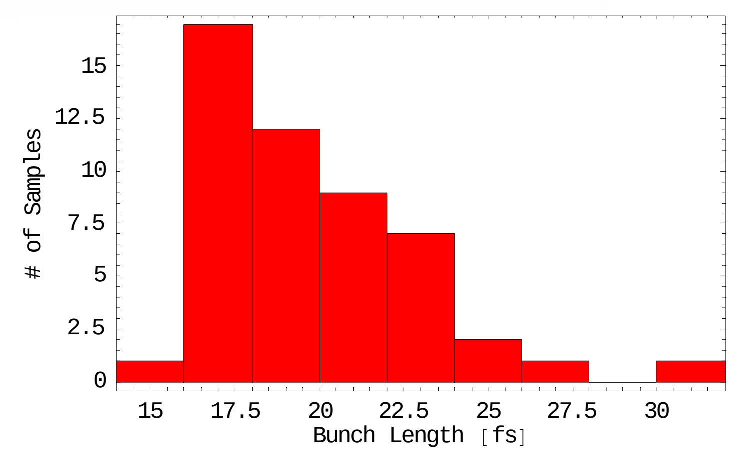


- 2-stage:
  - Vary first stage energy: 100 to 250 MeV (BC values fixed)
  - Vary injector bunch length and energy spread:
    - 0.5 to 50ps, 0.01% to 1%
  - Need for 3rd-harmonic cavities
- 1-stage:
  - All combinations of BC and 3rd-Harmonic position examined (before/after acceleration)
- 'Realistic' limits on BC1/BC2 and RF assumed

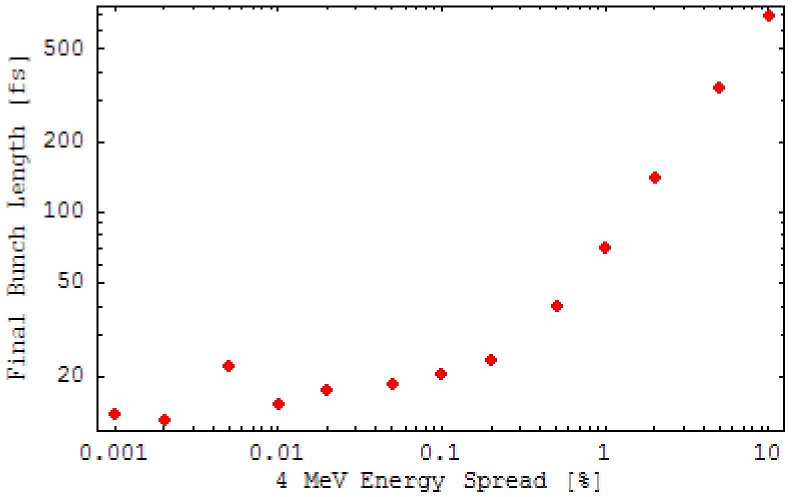
2 Stage, BC1 at 150 MeV

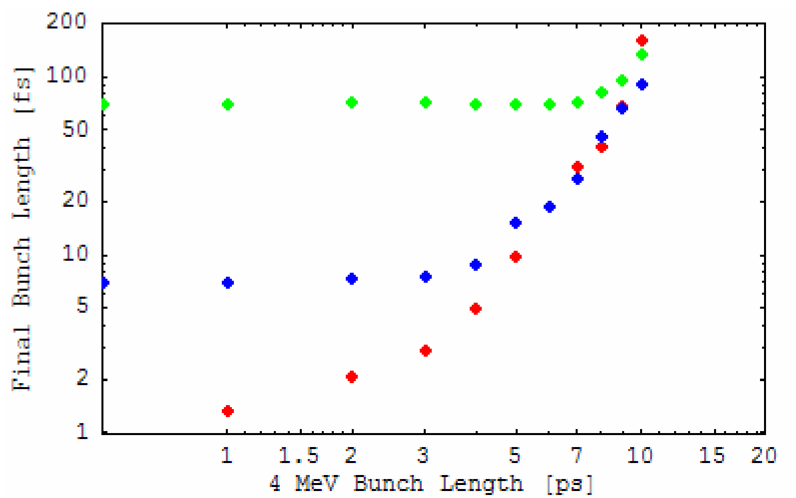




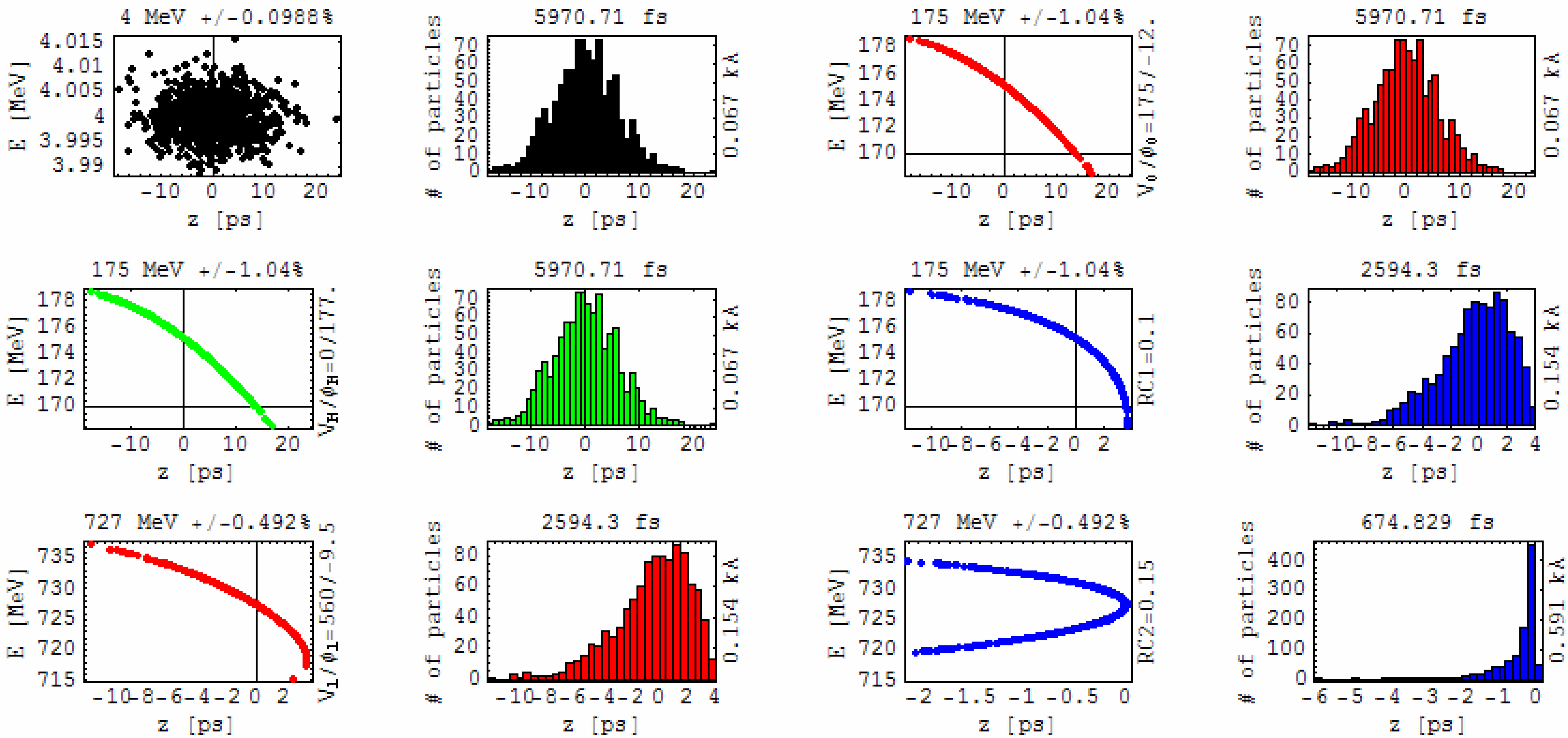


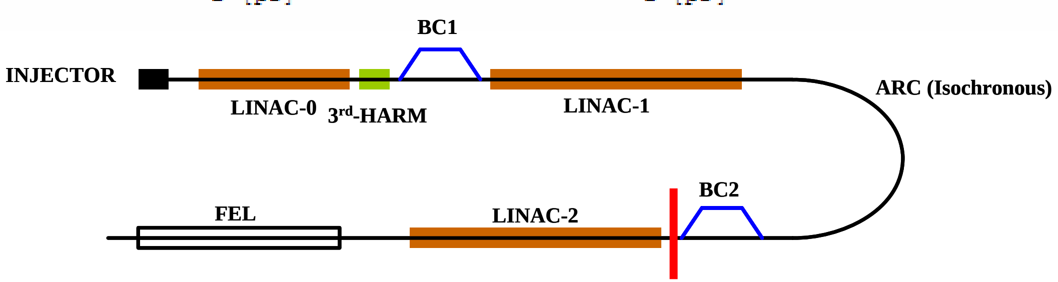
2 Stage Compression: Bunch Length and Energy Spread



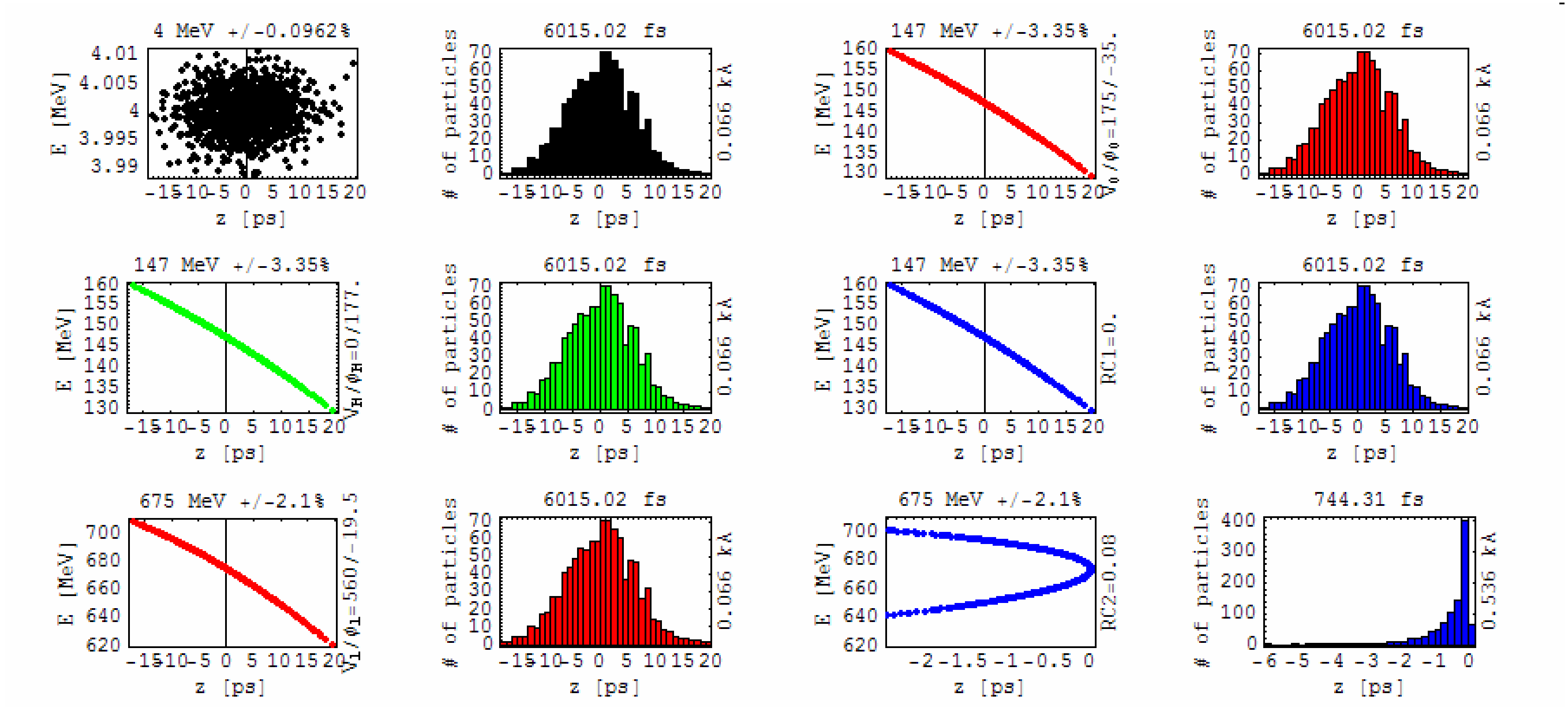


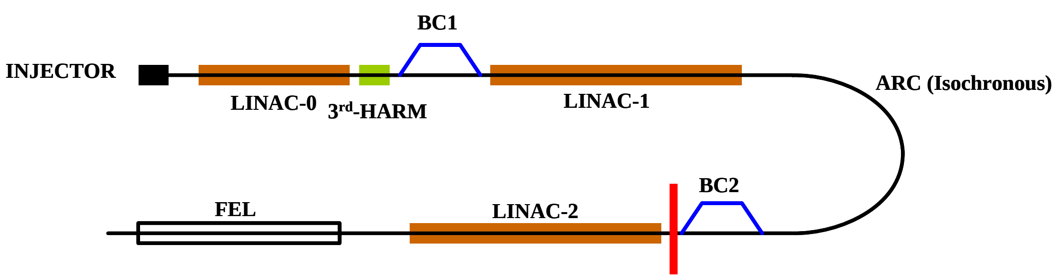
2 Stage Compression without 3rd-Harmonic RF



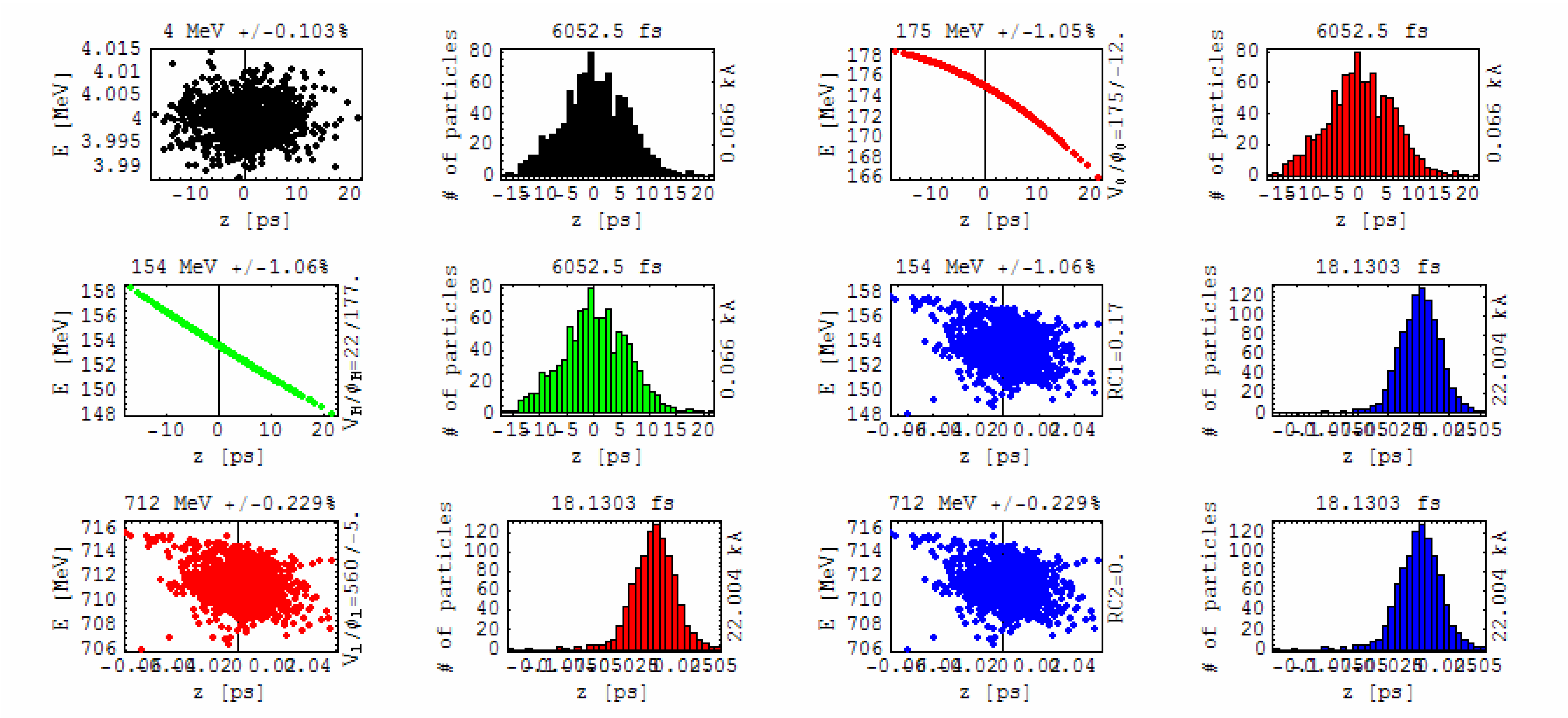


2 Stage without 3rd-Harmonic RF: Very Off-Crest



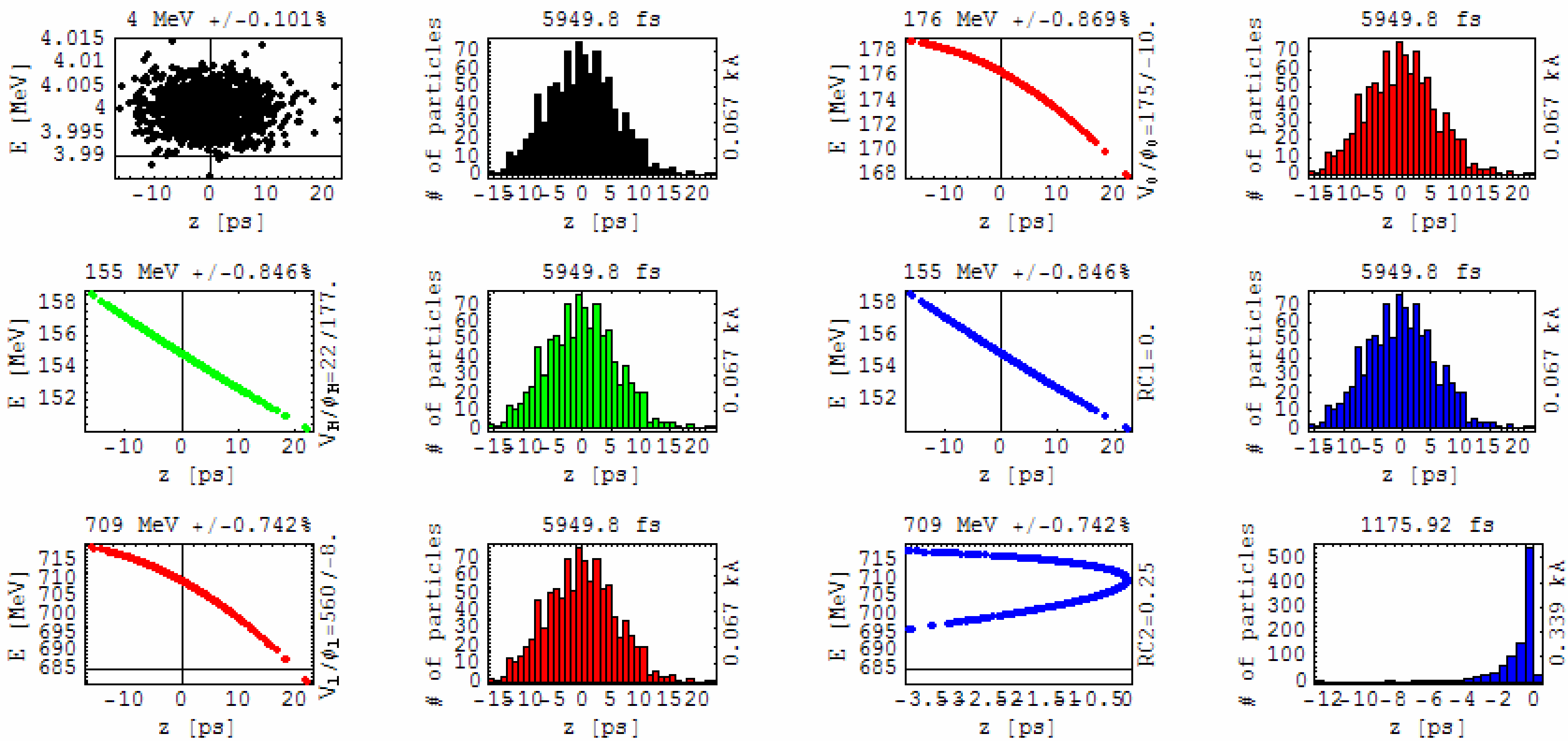


1-Stage: Compress @ Low Energy + 3rd @ Low Energy



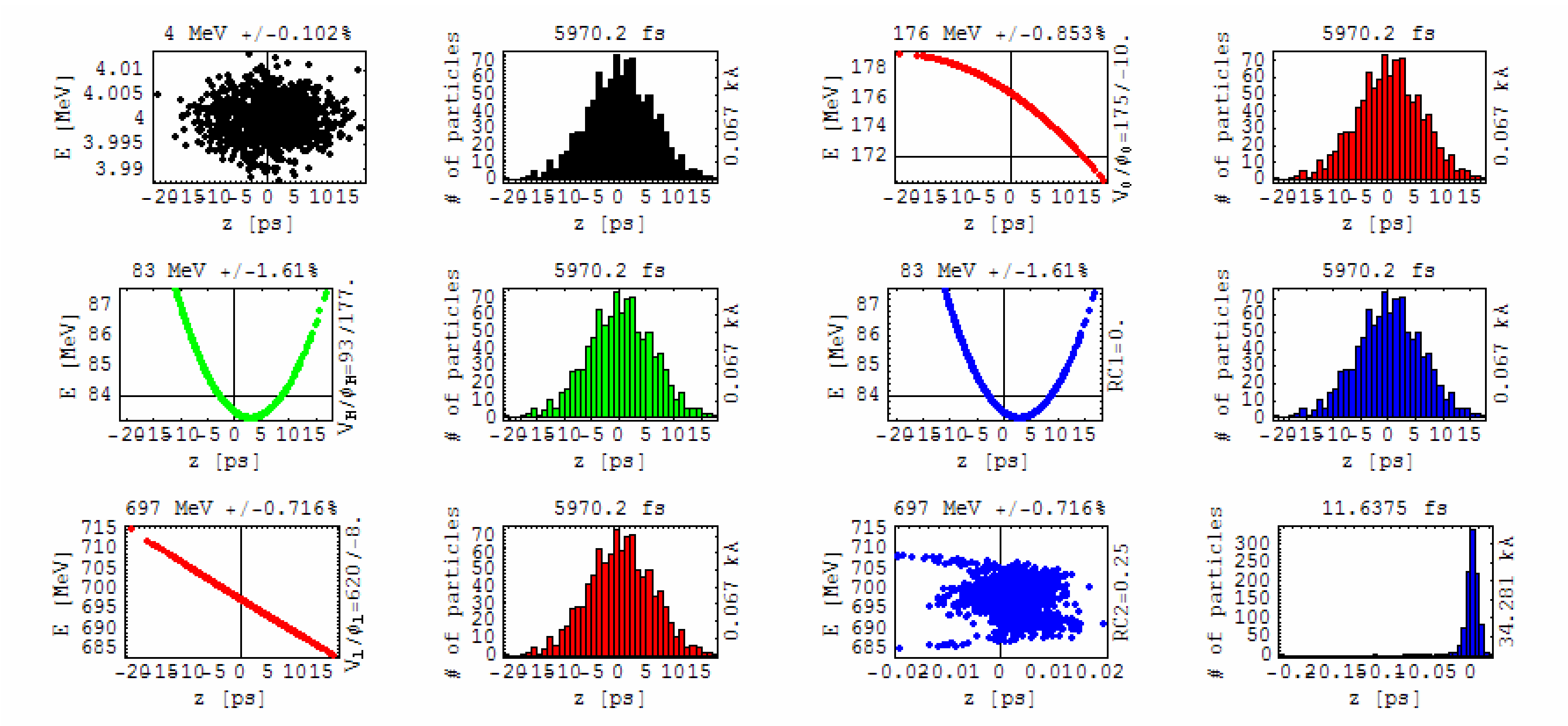
Not realistic at all!
Short bunch transport through arc and linac not possible

1-Stage: Compress @ High Energy + 3rd @ Low Energy



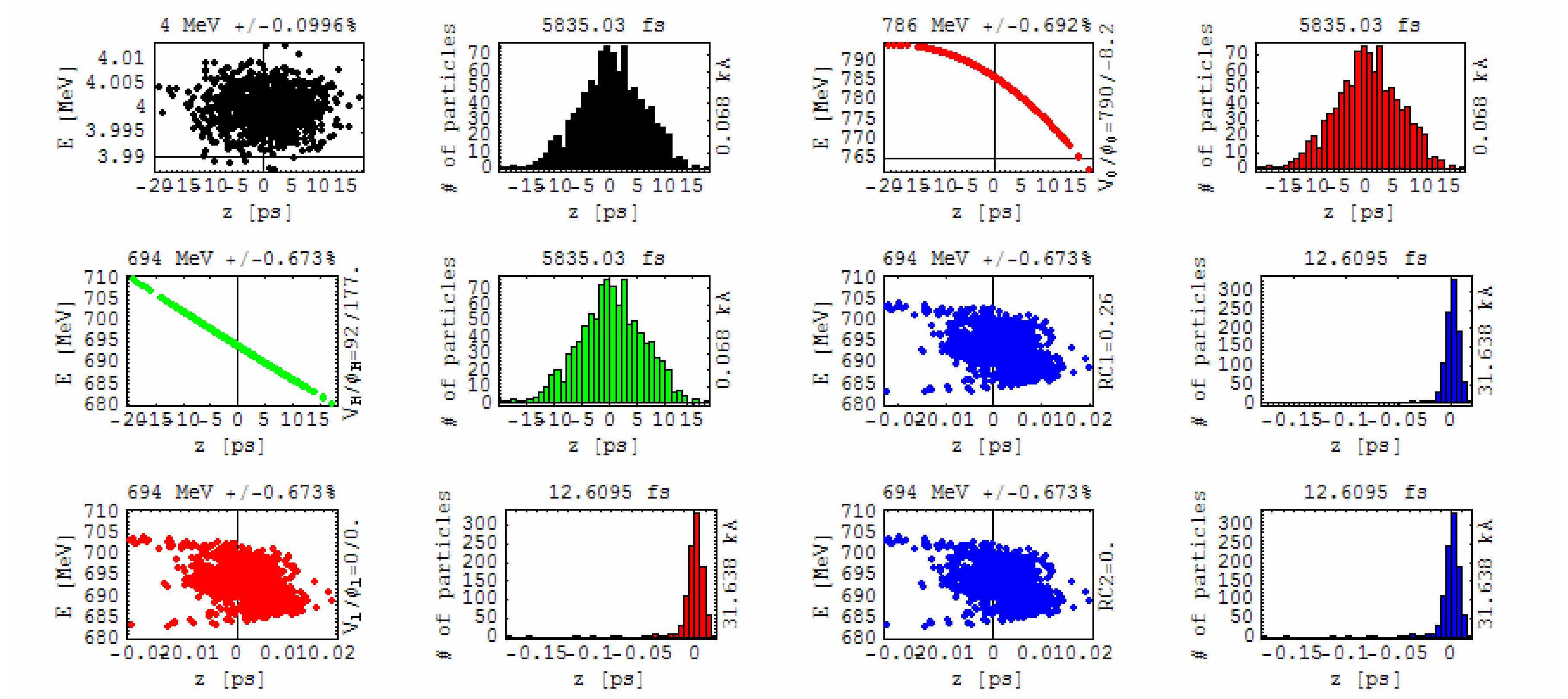
Linearisation – but without too much deceleration

1-Stage: Compress @ High Energy + 3rd @ Low Energy



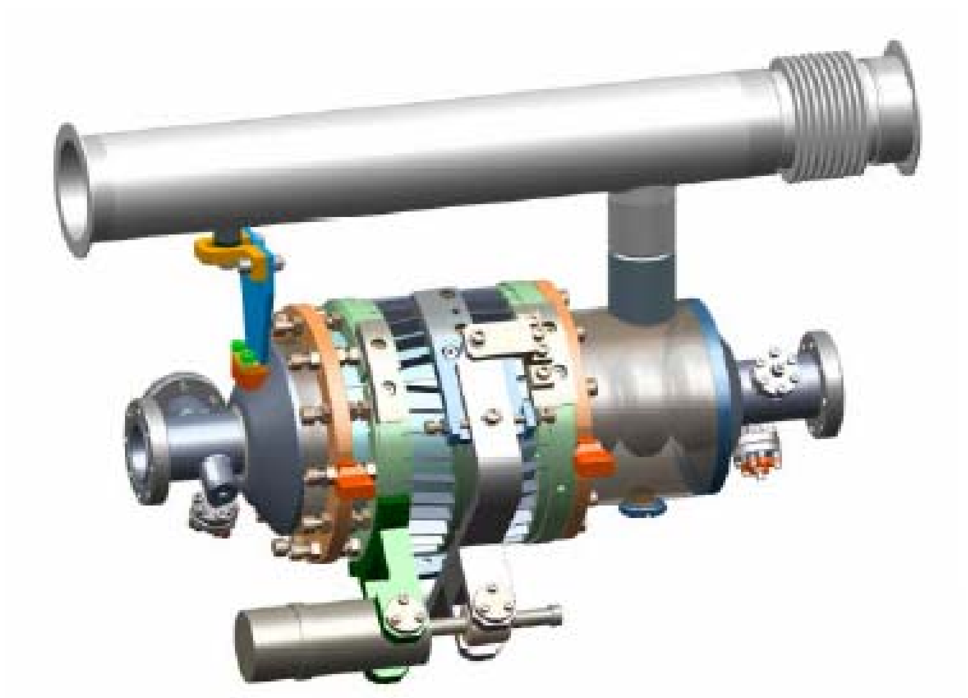
Over-Linearisation – with significant deceleration

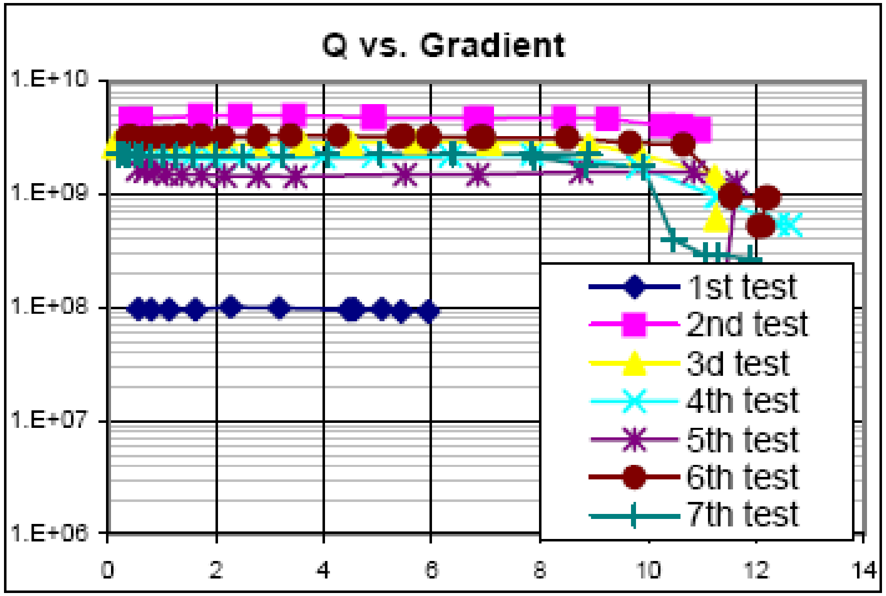
1-Stage: Compress @ High Energy + 3rd @ High Energy



Linearisation – significant deceleration
Same overall voltages for L0/L1 and 3rd harmonic

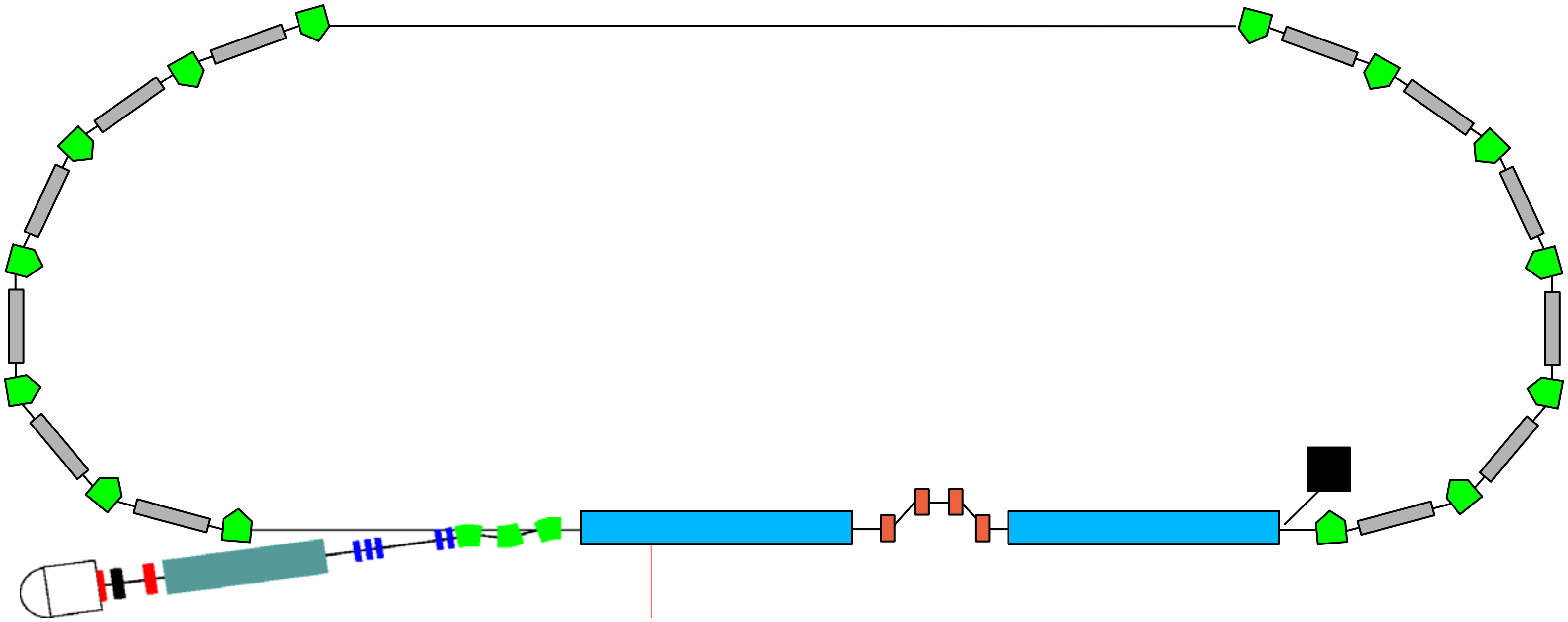
3rd-Harmonic Cavity





Simply 2 x scaled 9-cell TESLA/TTF cavities

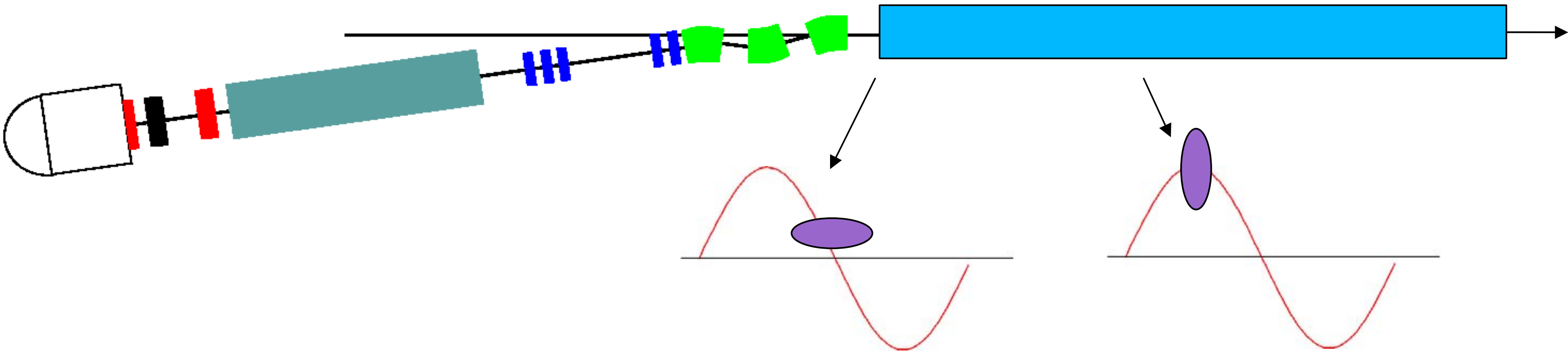
Bunch compression in an ERL light source - JAERI



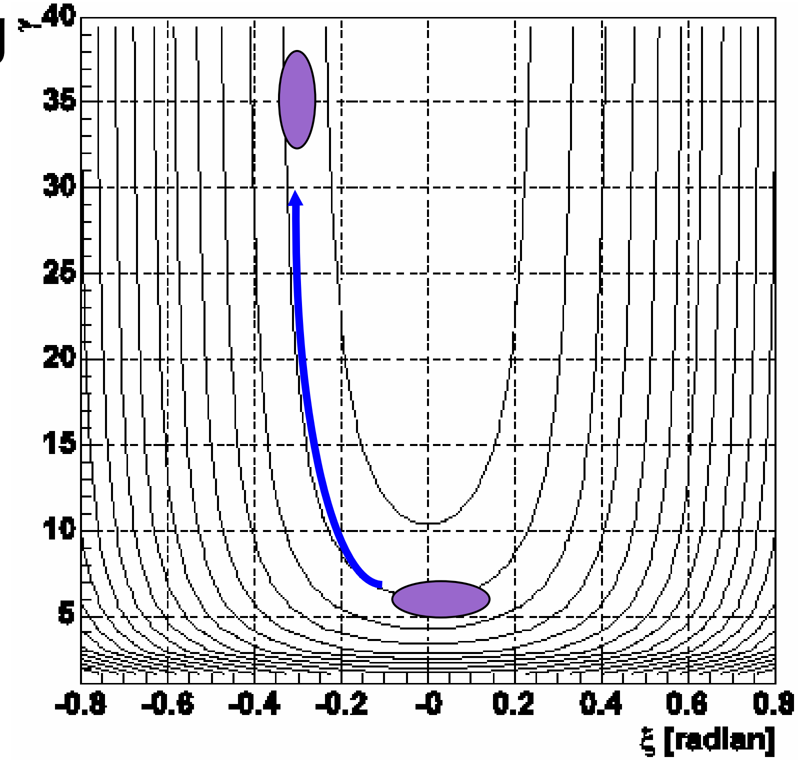
possible location for bunch compression

- magnetic bunching : merger, mid-energy, arc
- velocity bunching : injector, main linac

Velocity Bunching (Hajima)



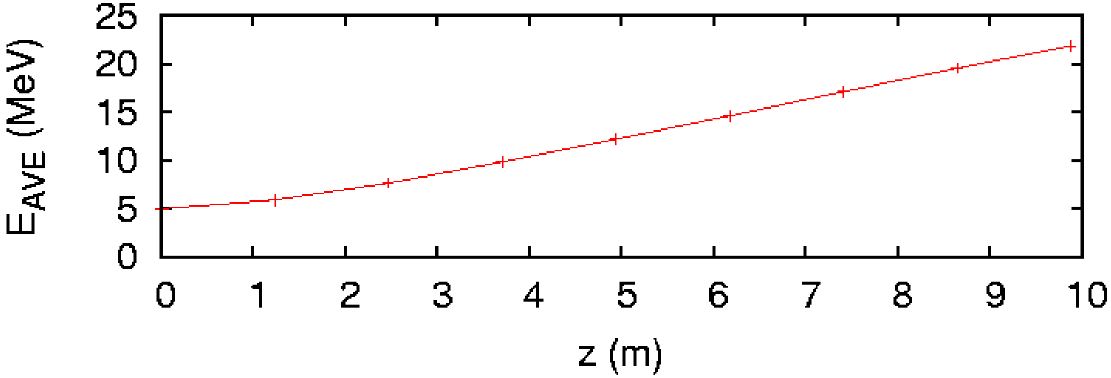
Is it possible to make velocity bunching at the beginning of main linac ?

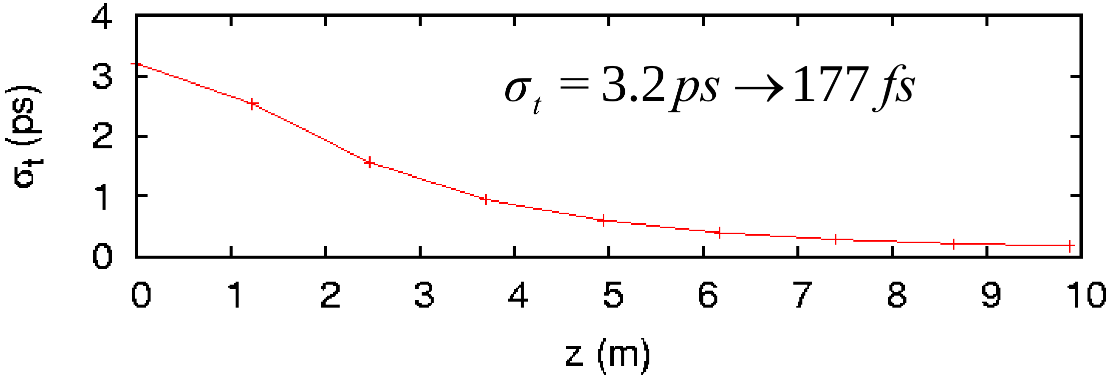


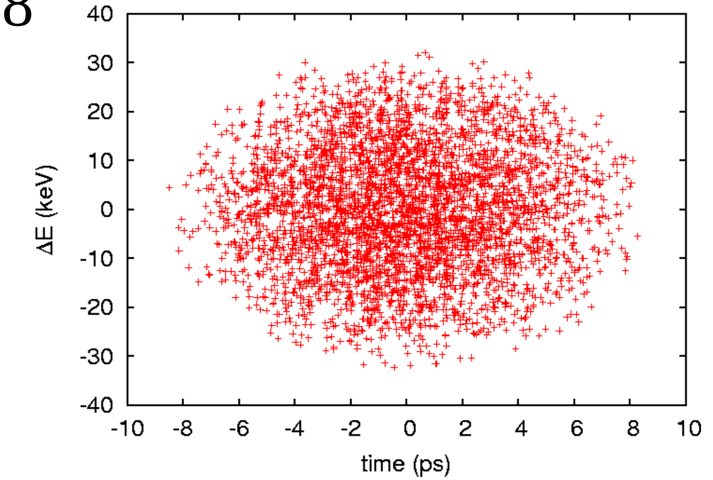
- how short bunch ?
- merging energy ?
- emittance growth ?
- energy-recovery OK ?
- HOM loading to the main linac ?
- residual energy spread ?

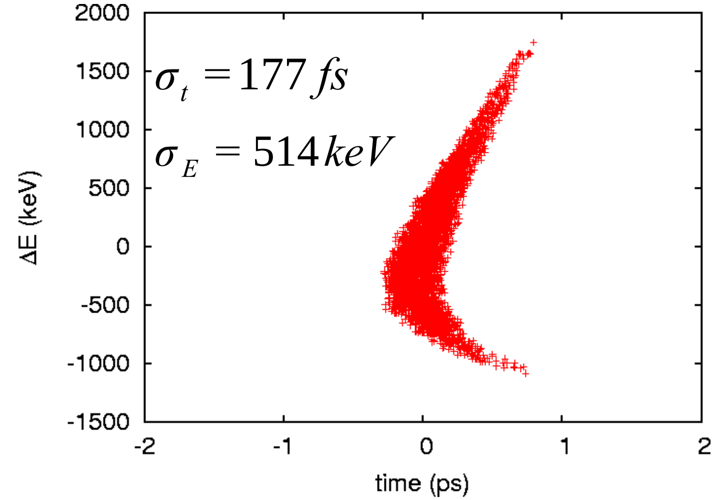
initial bunch parameters: 5 MeV, 3.2 ps, σ_E=12.5 keV, 77 pC, ε_n=1 mm-mrad

Eacc=8.2 MV/m (α=0.64), TESLA 9-cell x 8

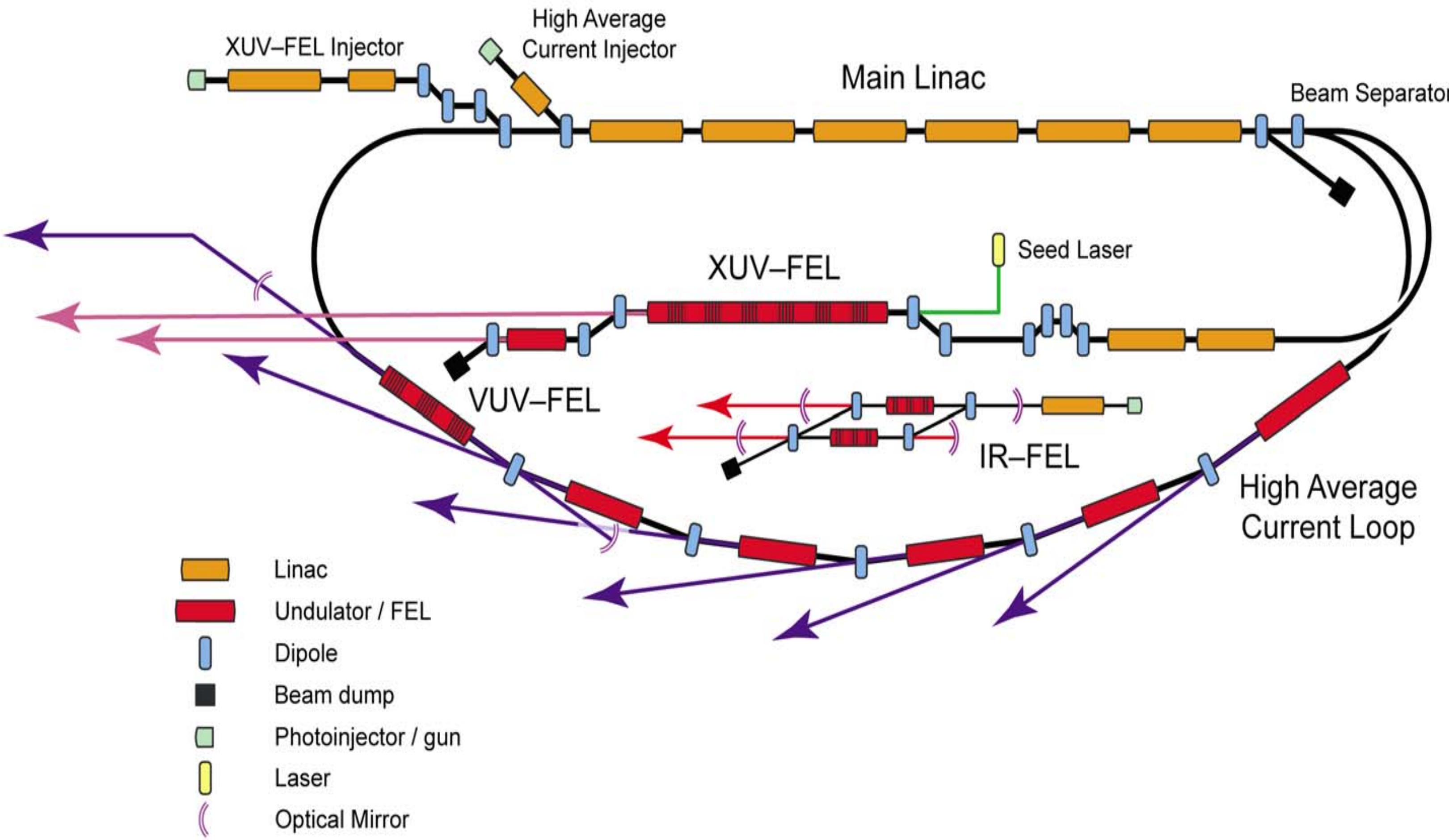




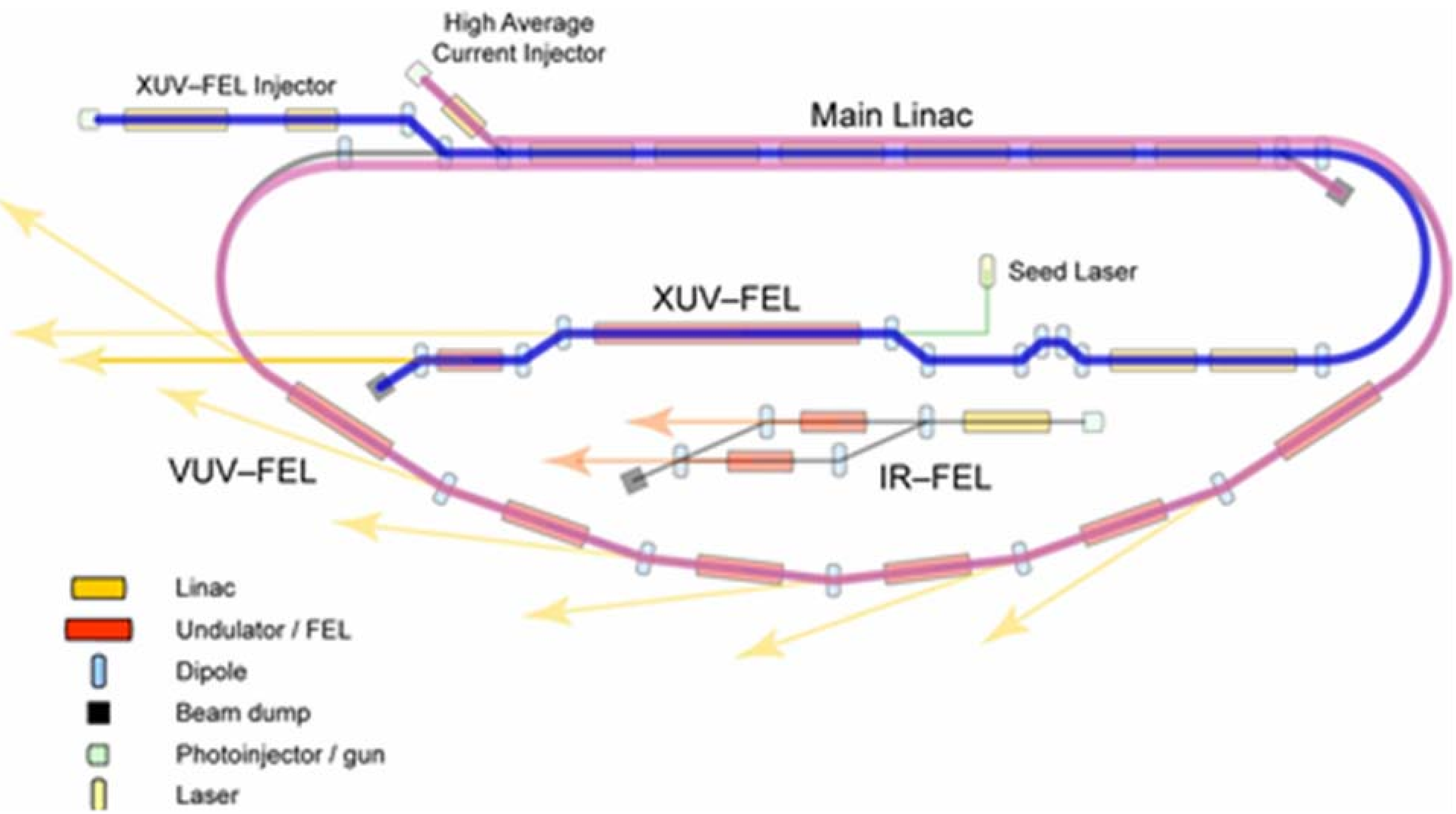




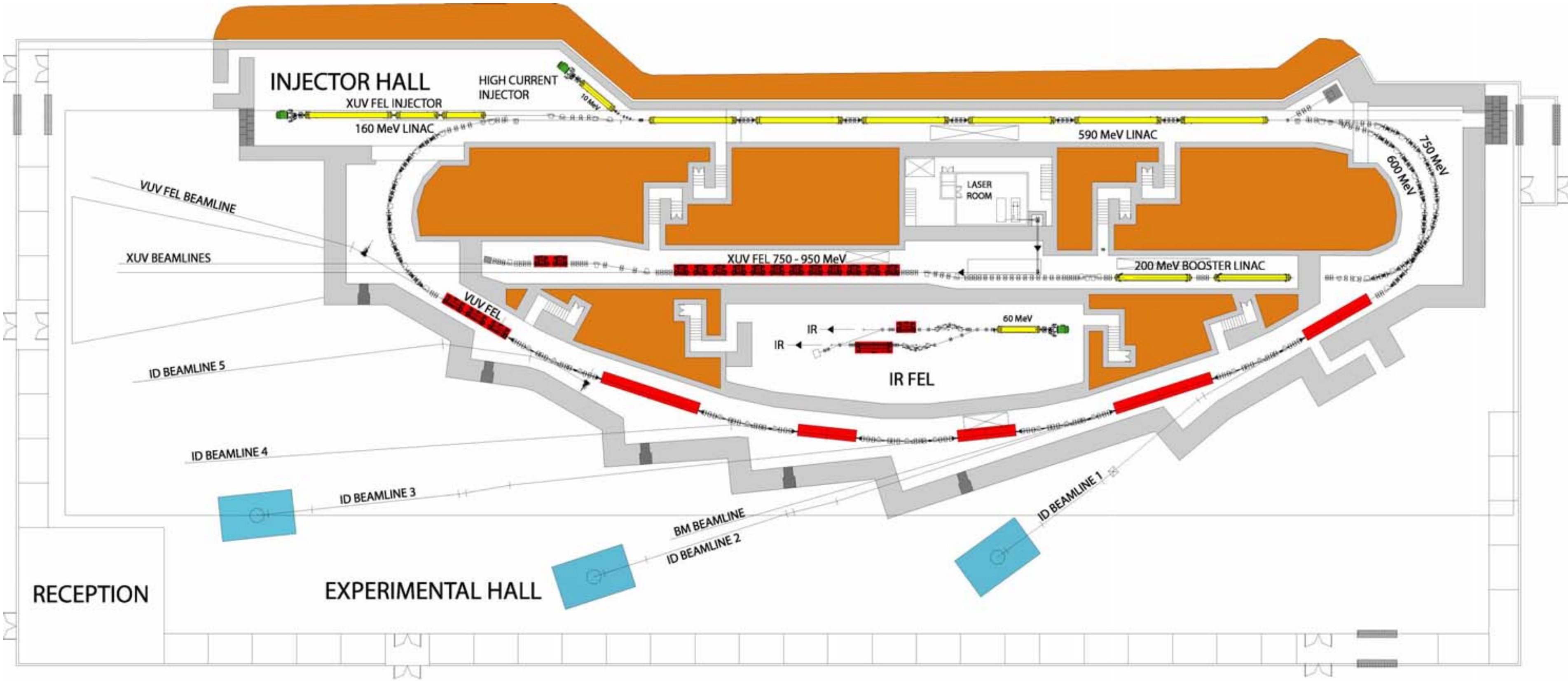
4GLS Conceptual Layout



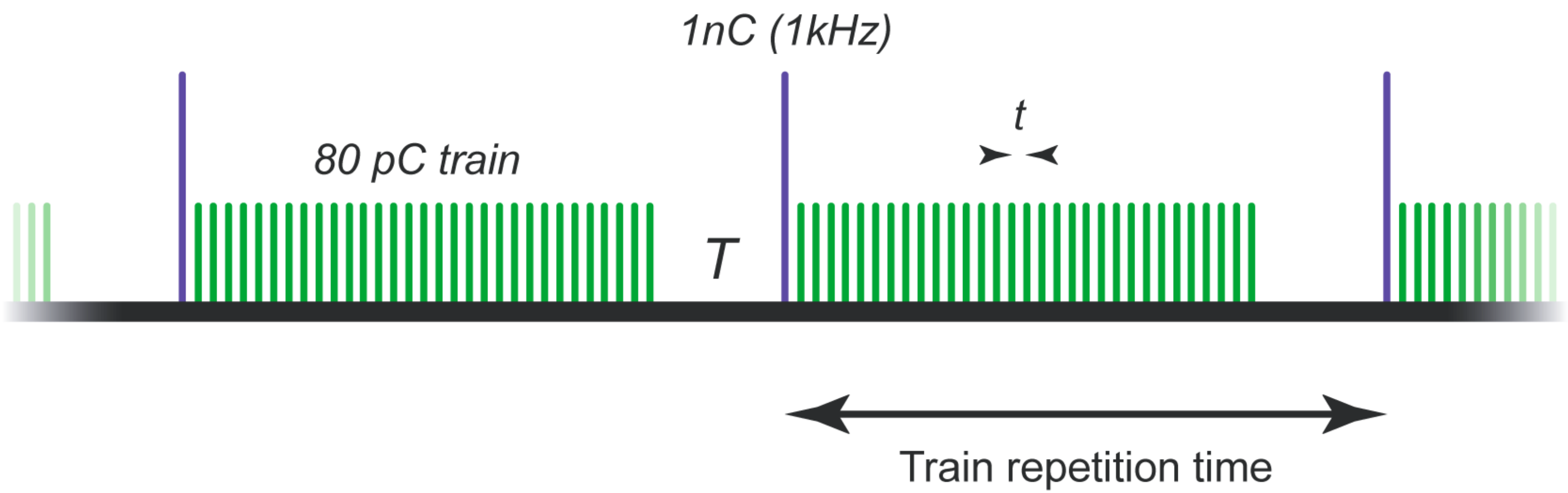
Beam Paths


High Average Current Injector
XUV–FEL Injector
Main Linac
Seed Laser
XUV–FEL
VUV–FEL
IR–FEL
Linac
Undulator / FEL
Dipole
Beam dump
Photoinjector / gun
Laser

Present Layout

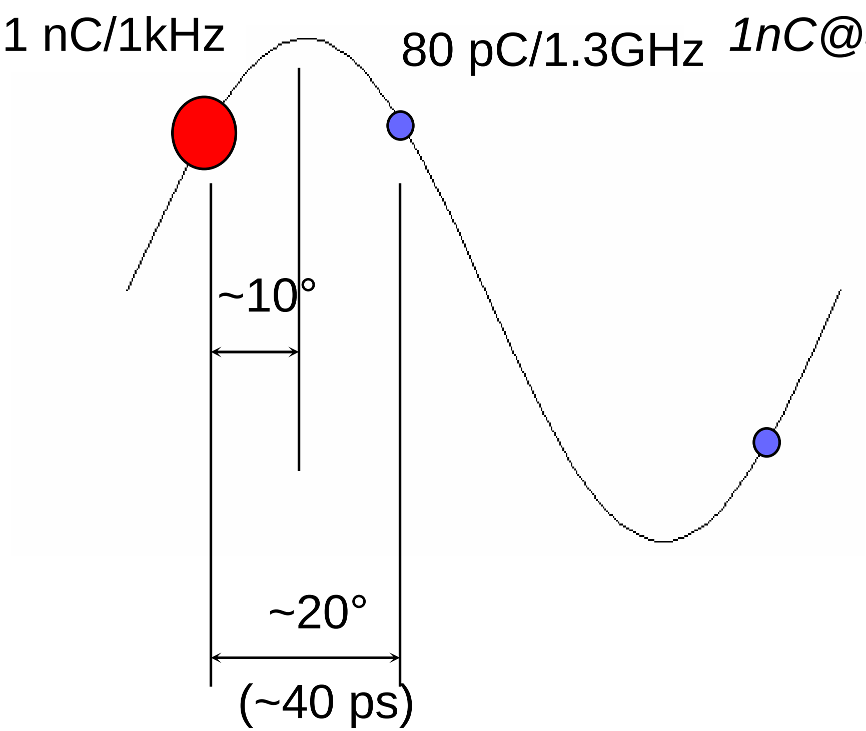


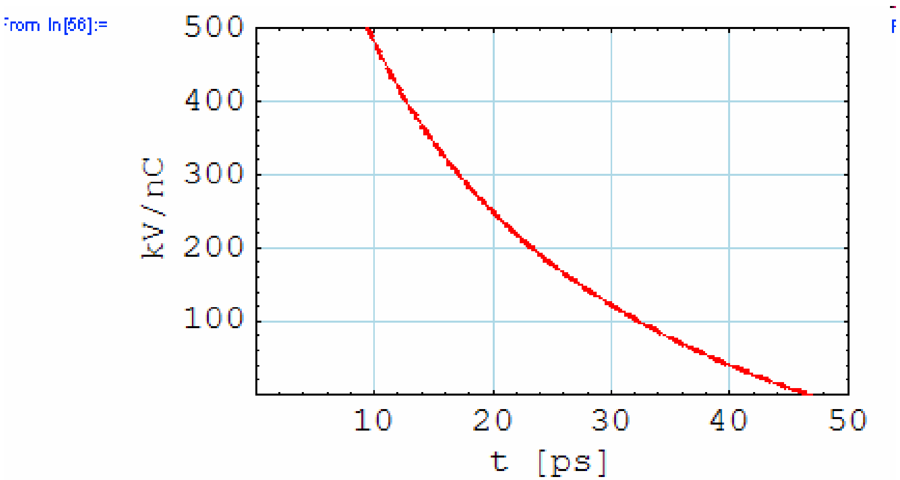
4GLS - Electron Bunch Patterns



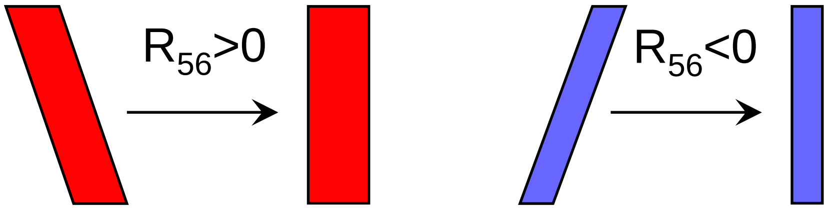
Wakefields

1nC@40ps gives ~50kV shift to CW bunch (~10^{-4})





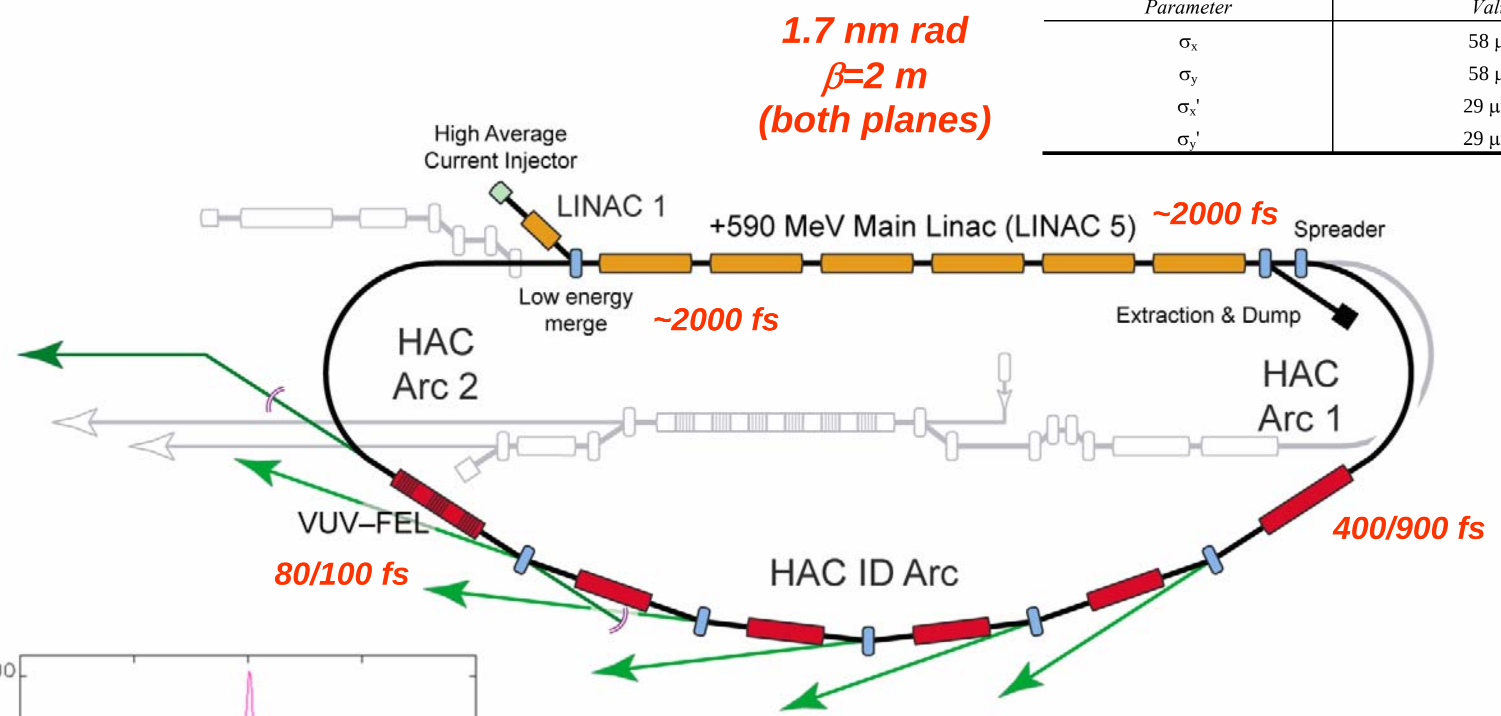
Long. wake from 5 modules each of 8 cavities

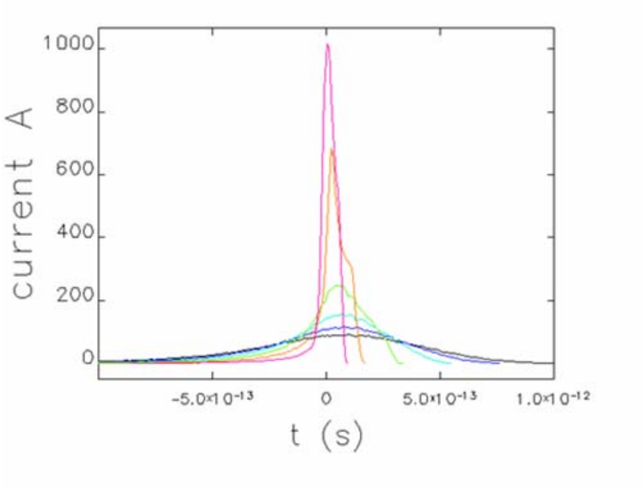


Beam loading from 1nC bunch passage through cavities is also an issue – changes the accelerated voltage seen by following CW bunches. To be determined.

HAC Loop – Nominal Operating Mode

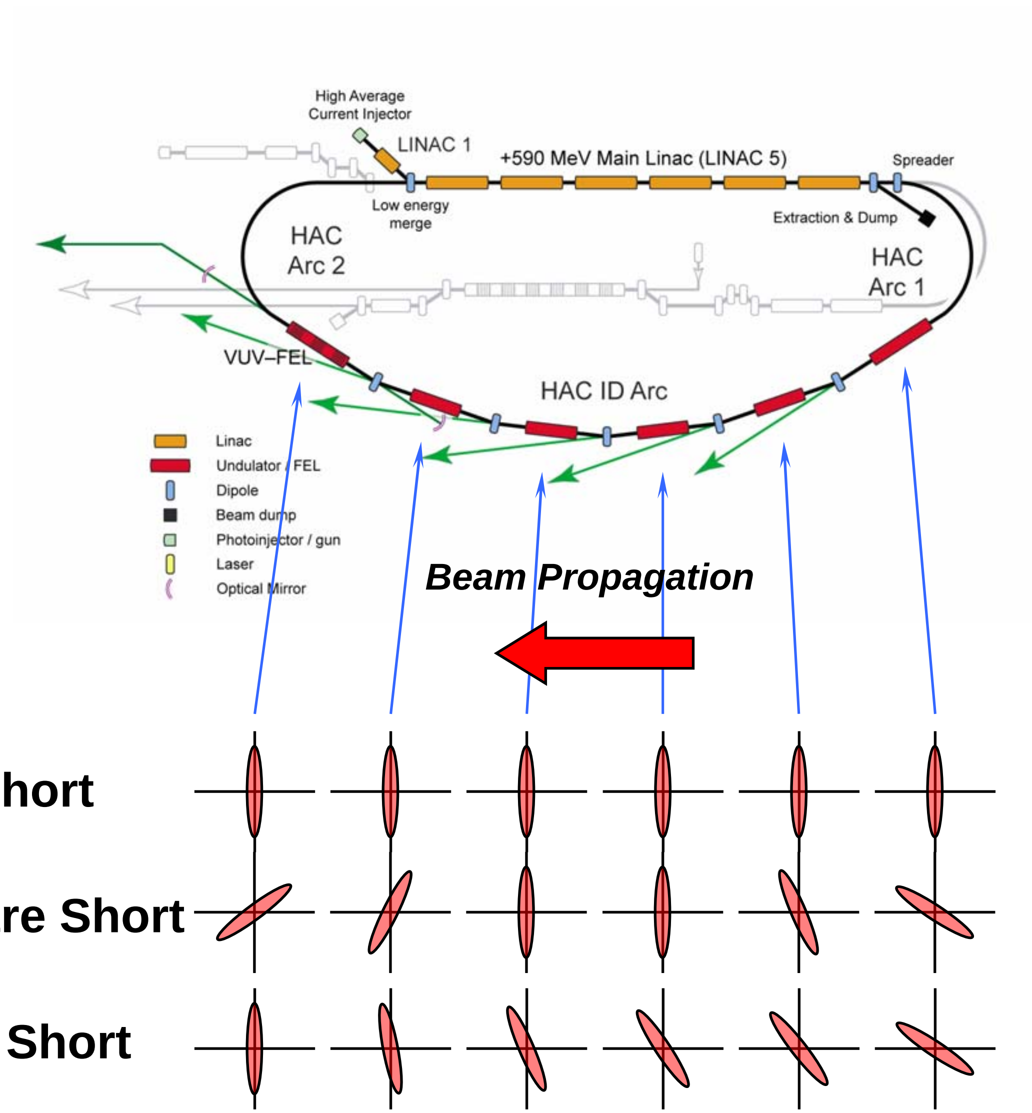
Parameter	*Value*
σ_x	58 µm
σ_y	58 µm
σ_x'	29 µrad
σ_y'	29 µrad





HACL Bunch Parameter	*100 mA Operation*	*VUV-FEL Operation*
Energy at VUV-FEL, E	600 MeV	600 MeV
Normalised Emittance at 600 MeV, ε	2 mm mrad	2 mm mrad
RMS Projected Energy Spread	0.1 %	0.1 %
RMS Bunch Length at Device	100-900 fs in six straights	100 fs
Bunch Charge	77 pC	77 pC
Bunch Repetition Rate	1.3 GHz	$n \times 4.33$ MHz
Electron Beam Average Power at 600 MeV	60 MW	$n \times 200$ kW
Injector Energy	10 MeV	10 MeV
Dump Energy	~ 10 MeV	~ 10 MeV

Variability of ID Arc Bunch Lengths



Mode 1: All Short
(Wakefield limit)

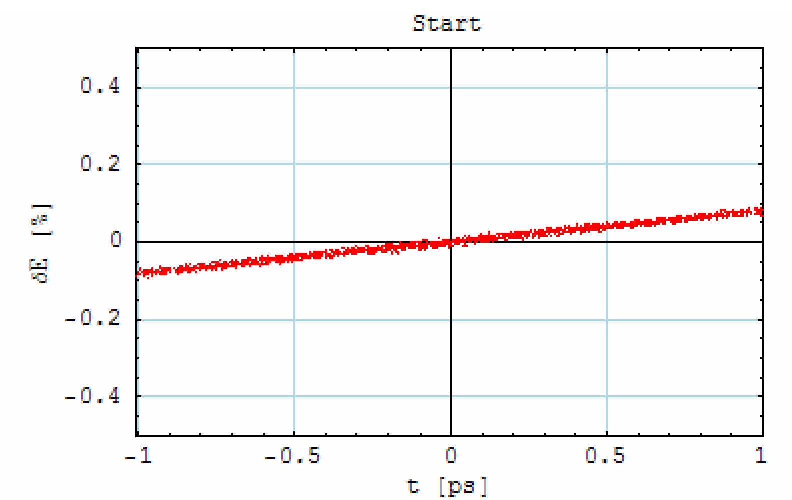
Mode 2: Centre Short

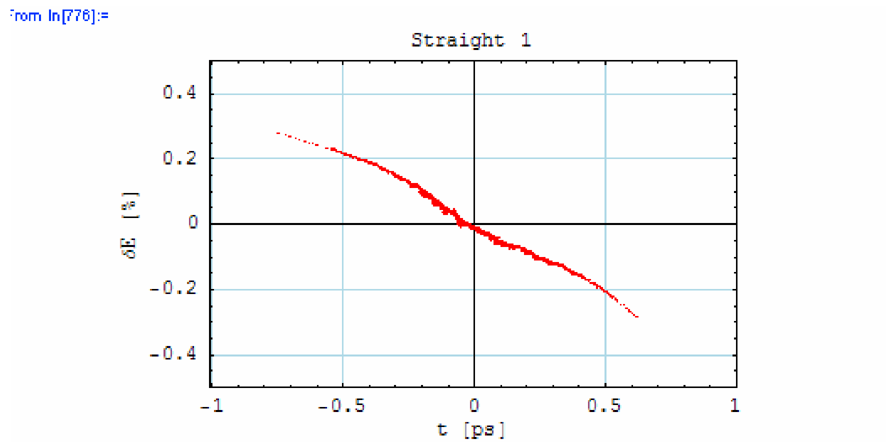
Mode 3: VUV Short

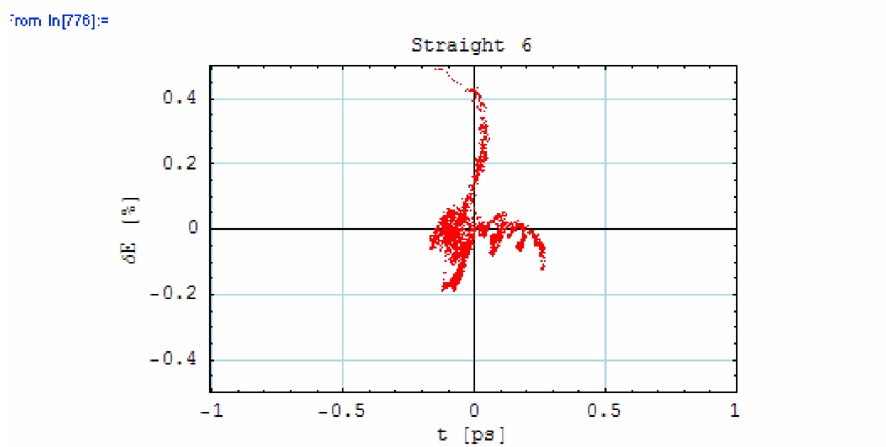
Golden Rule:
beam 'compression' (i.e. shear) only goes one way.

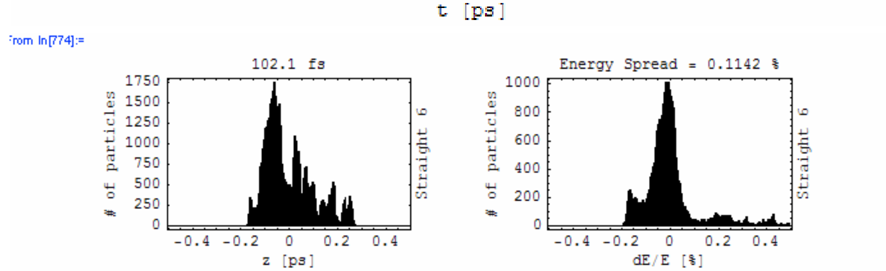
CW ‘Start’ to ‘End’ Simulation

- 50,000 particles
  - CSR, cavity wakes included

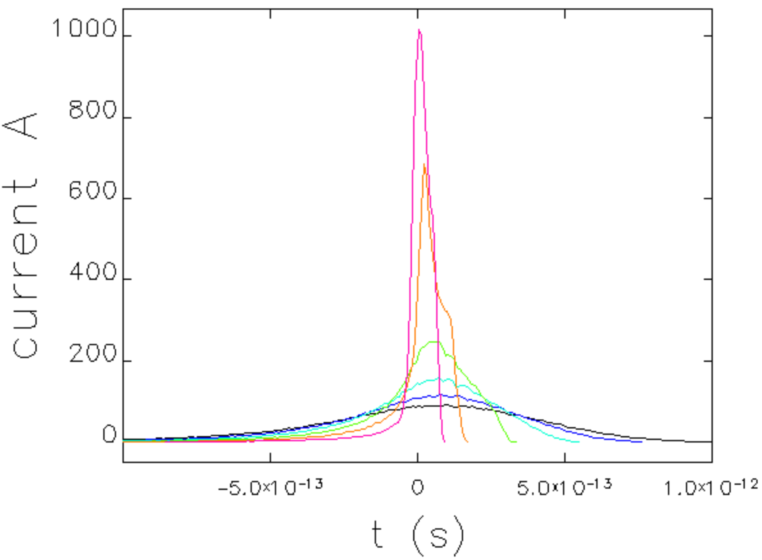




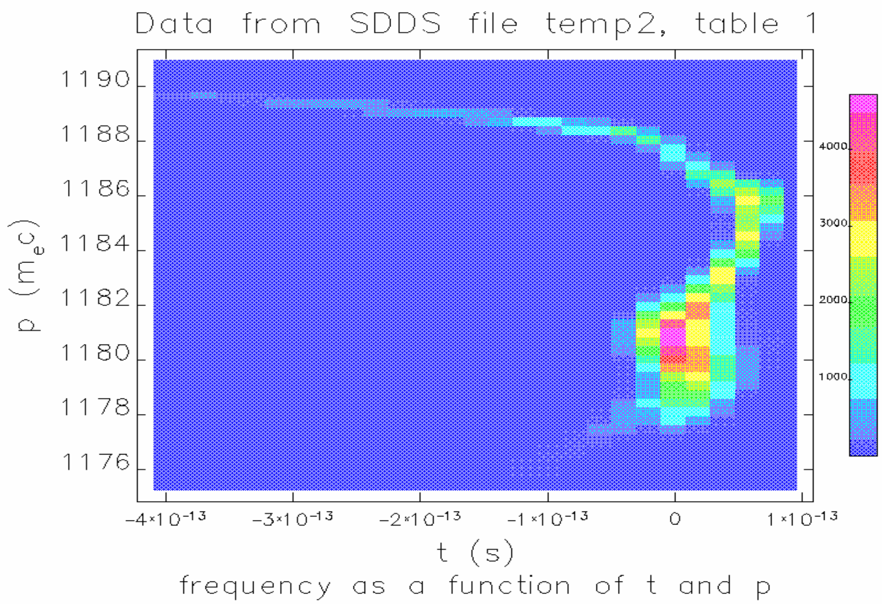


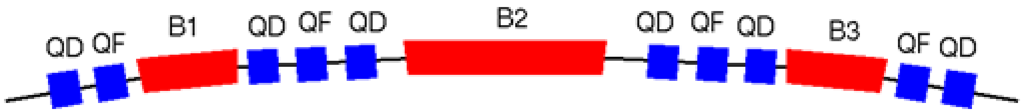


CW Near Start to FEL Simulation



Bunch profiles at each of the ID straights, with CSR.

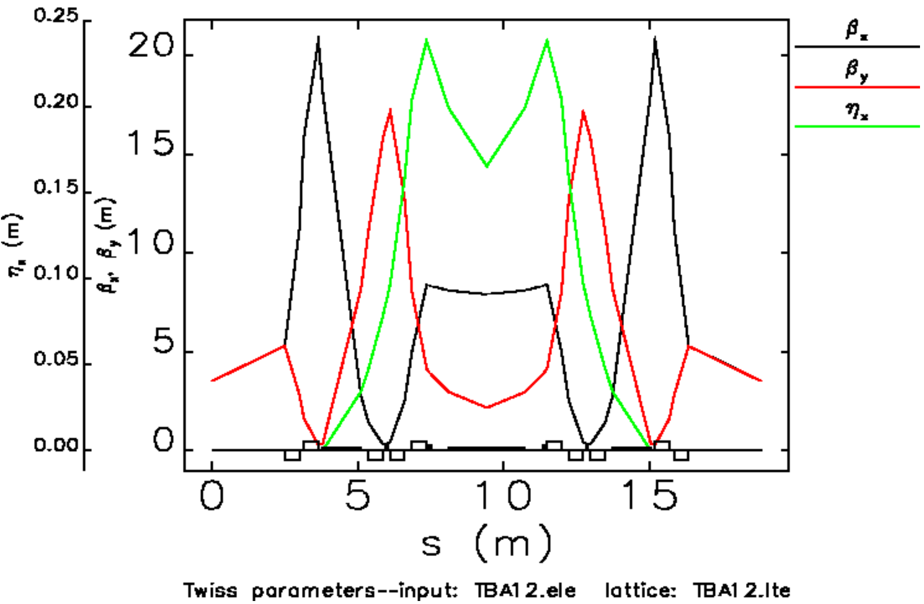


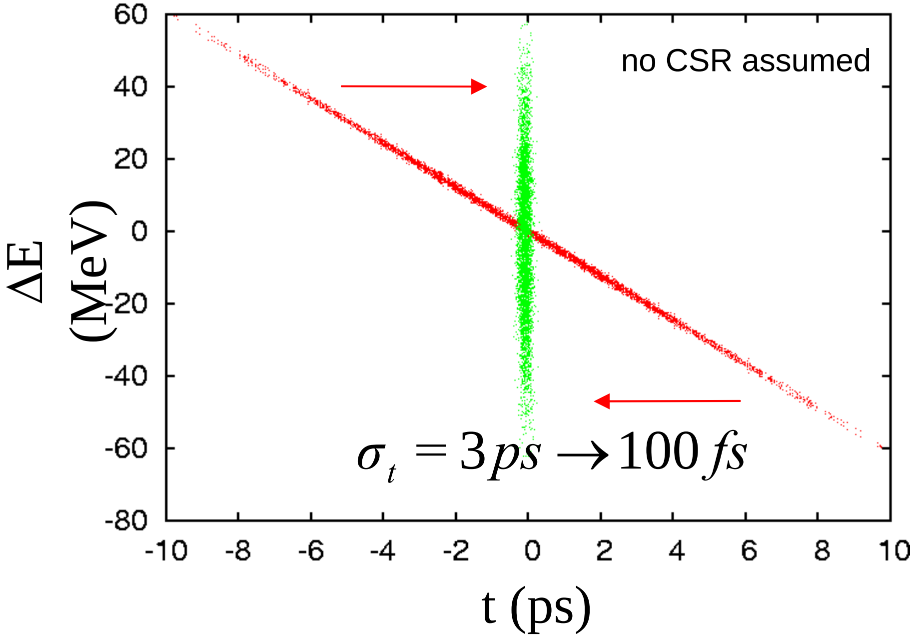


Triple Bend Achromat

$$\rho = 25\text{m}, \theta = 3+6+3 = 12 deg.$$

$$R_{56} = 2\, cm\, /\, cell$$



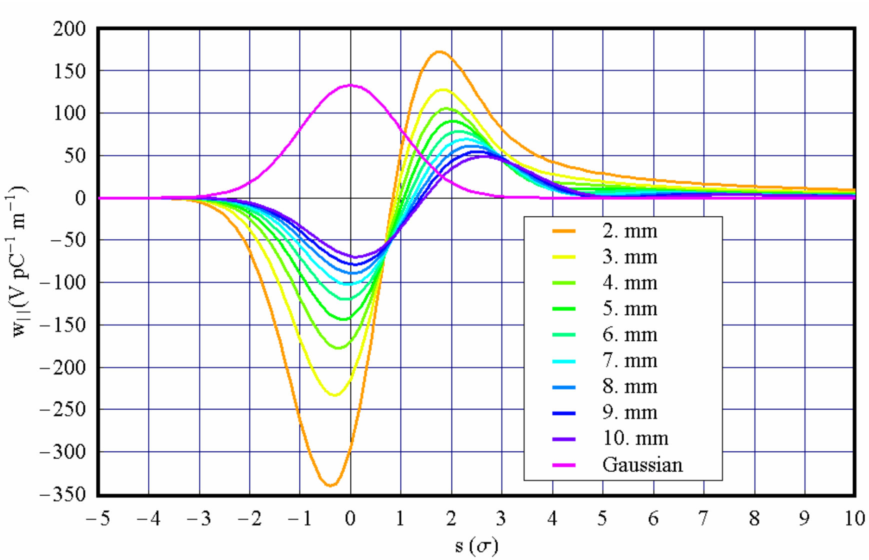


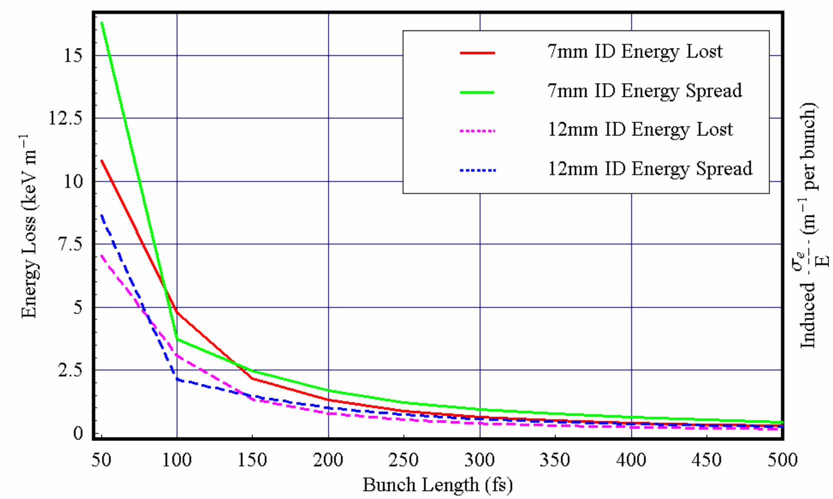
- a 3-ps bunch is compressed into 100 fs after 15-cell (half arc)
- fairly linear compression with sextupole correction
- relatively large energy spread remains $\sigma_E / E = 0.34\%$

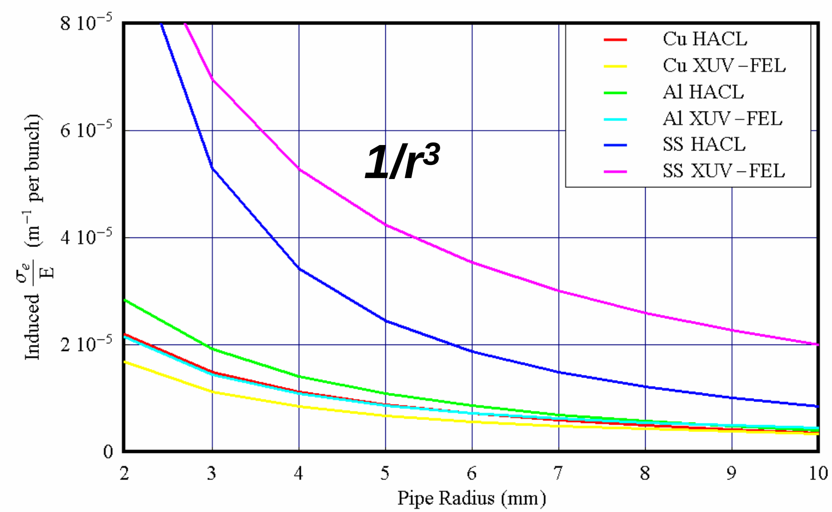
-- may degrade brilliance of a long undulator

The Effect of Wakefields

Cu, 1 nC, 50 fs

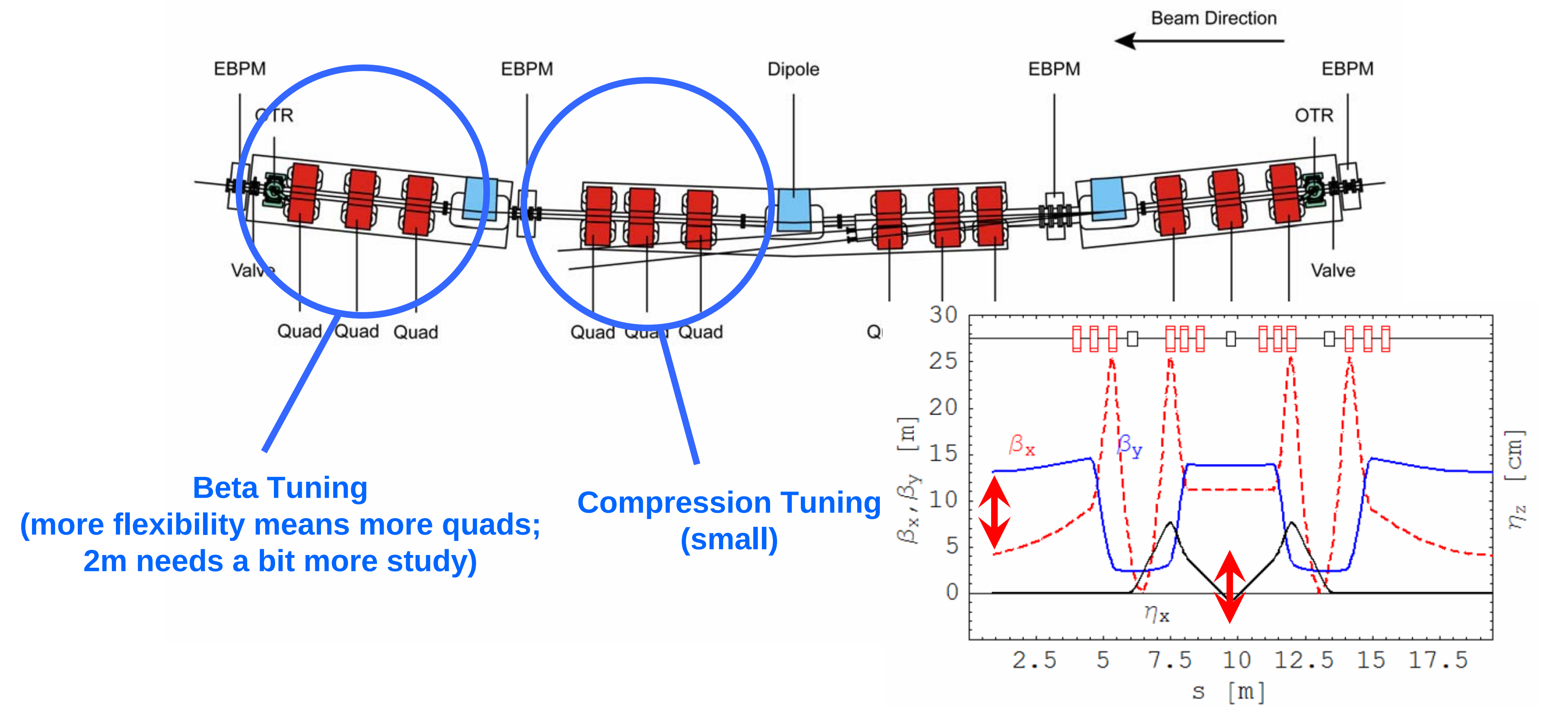




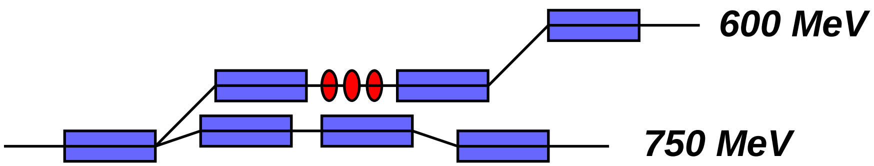


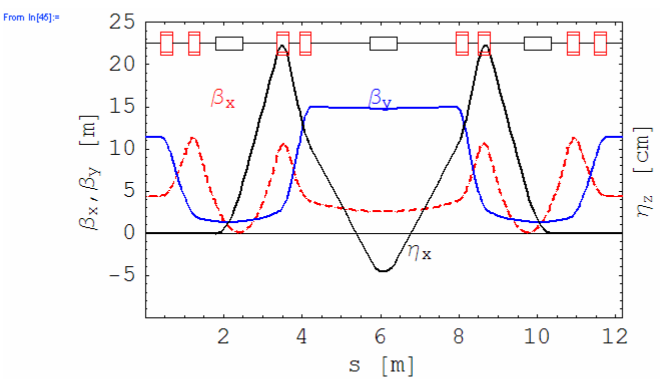
(In reality bunches will not be Gaussian)

ID Arc Tuning

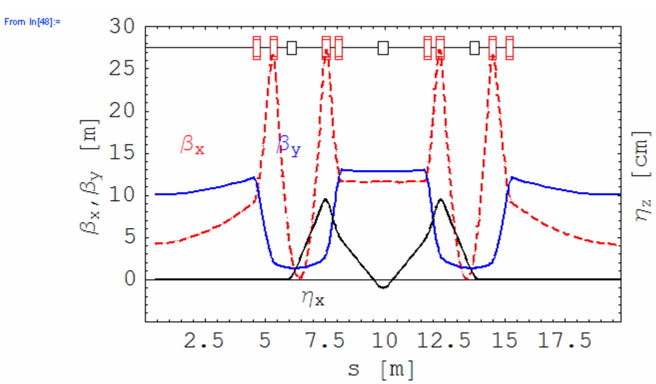


Iteration #1





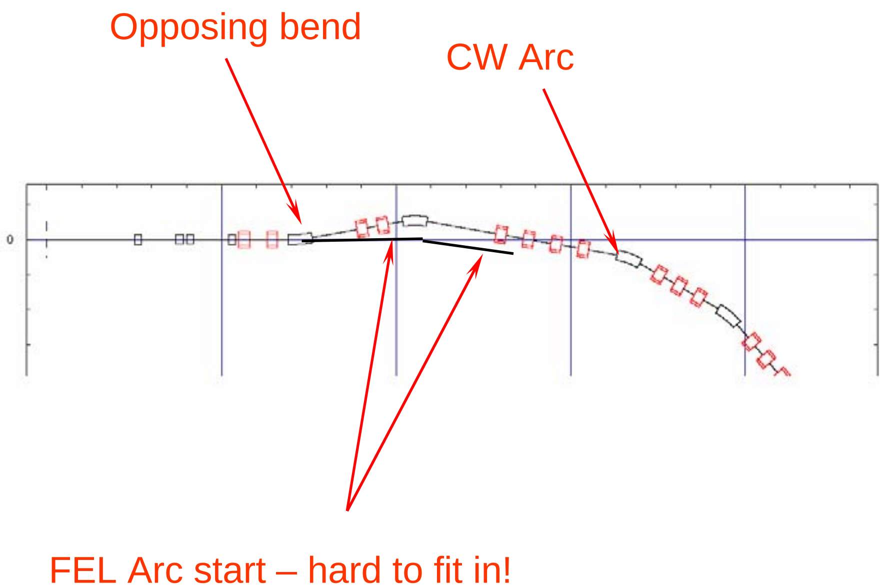
CW Loop



CW ID

- Iteration #1 is same as CEBAF, LUX, BESSY-FEL etc
  - Chicane/Slide spreader
- Advantages:
  - Allows variable energy ratio between lines
  - Large apertures and beam separation
- Disadvantages:
  - Overcompression of FEL section
  - Large size
  - Tuneability of CW Loop arc/FEL arc limited – can’t compensate spreader compression
- Handling the beam separation is the single most complicated problem in the optics design!!

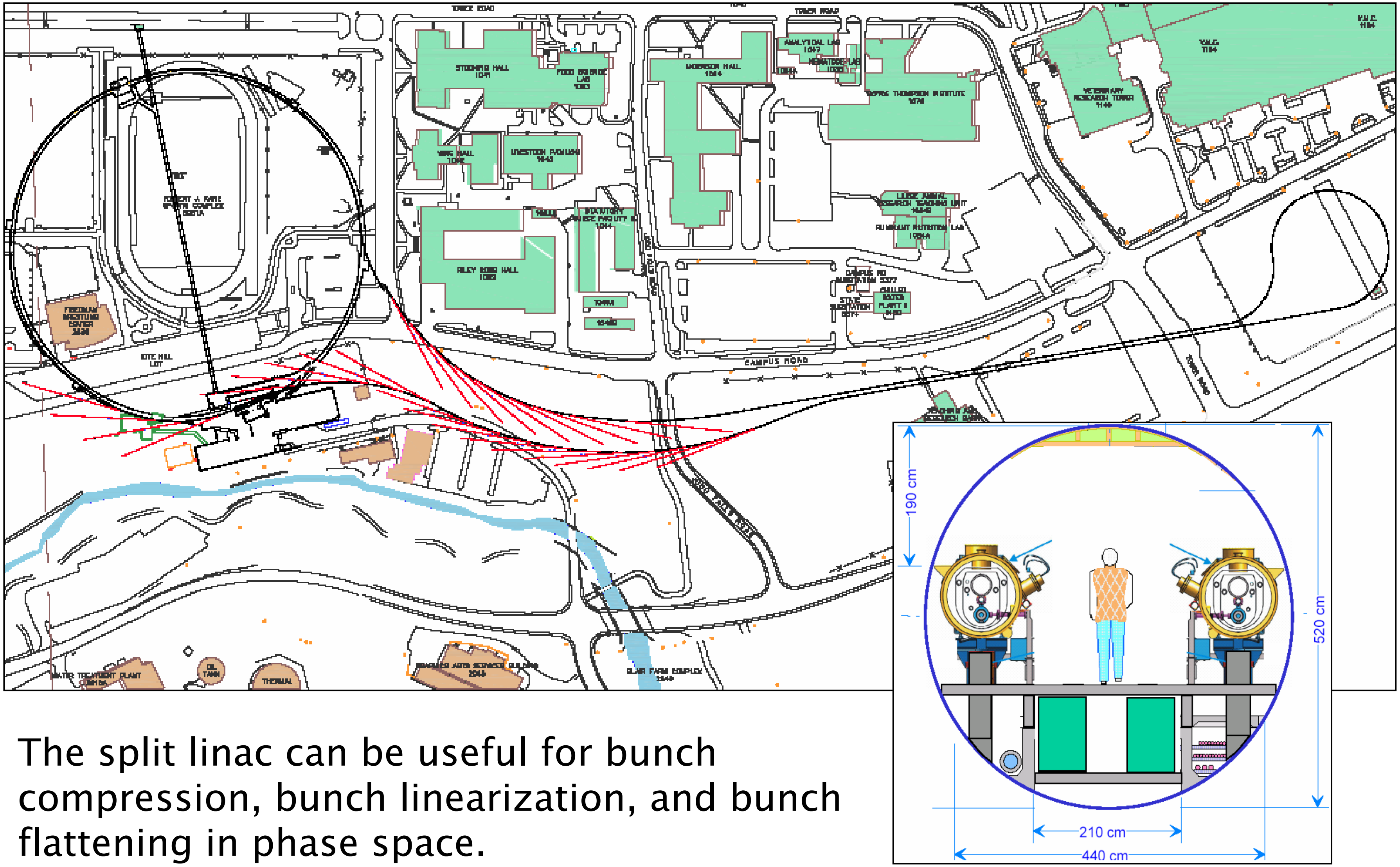
Iteration #2



- Look at alternative:
  - Spectrometer spreader + FODO arc
- Advantages:
  - Size is smaller
  - Compression in spreader is much lower
  - FODO can compensate spreader – correct overall compression
- Disadvantages:
  - Energy ratio now fixed between lines
  - Apertures much reduced (10 vs. 100 mm)
  - Much more complicated optics (>10 quads for matching vs. 4)
  - Geometrical difficulty in fitting FEL arc inside CW arc.
  - Opposing bends worsen CSR and waste elements
- Note: All spreaders must have positive (chicane-like compression
  - this is always bad for the FEL branch, and must be kept small

ERL Layout

CHESS & LEPP

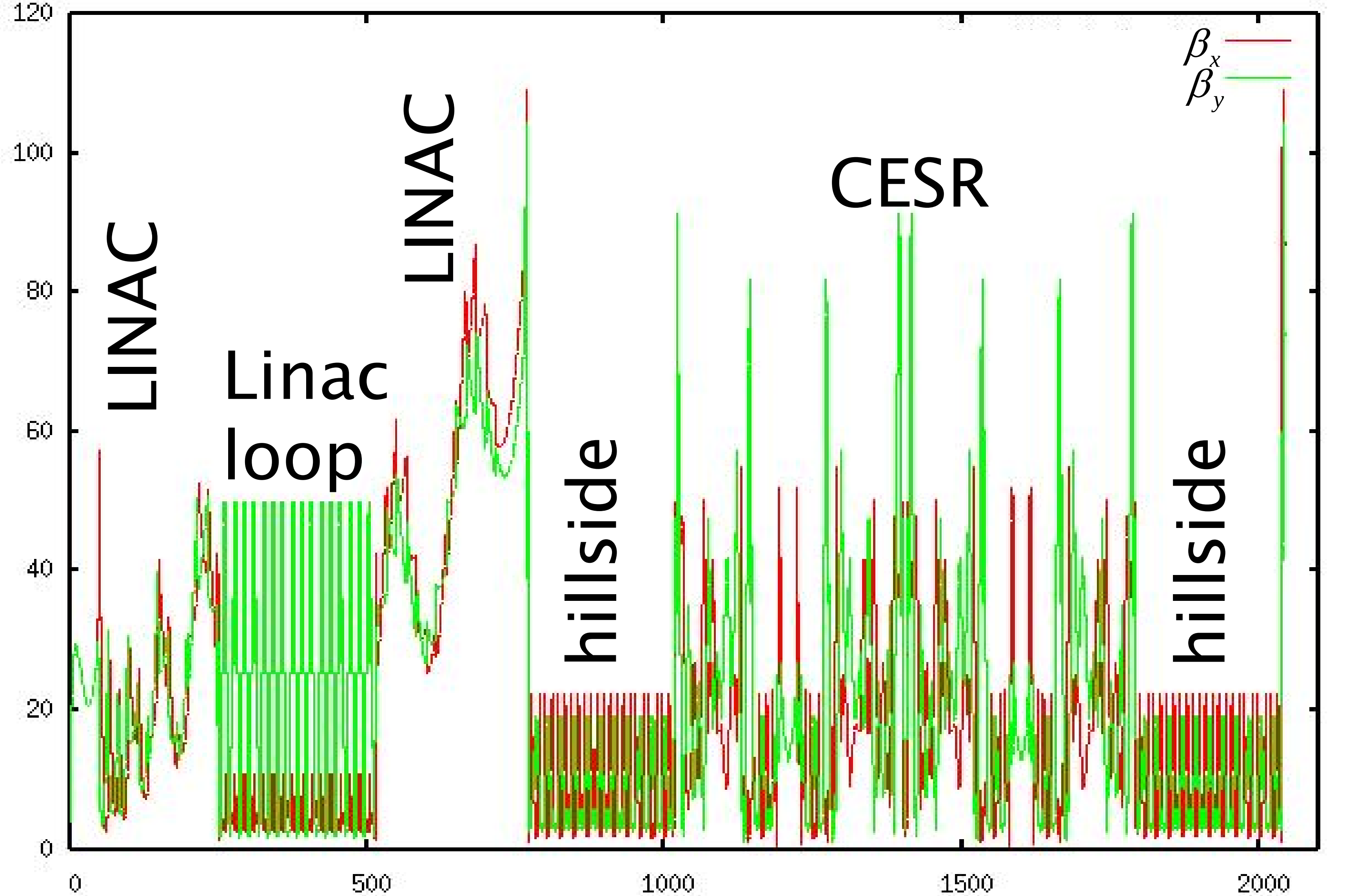


The split linac can be useful for bunch compression, bunch linearization, and bunch flattening in phase space.

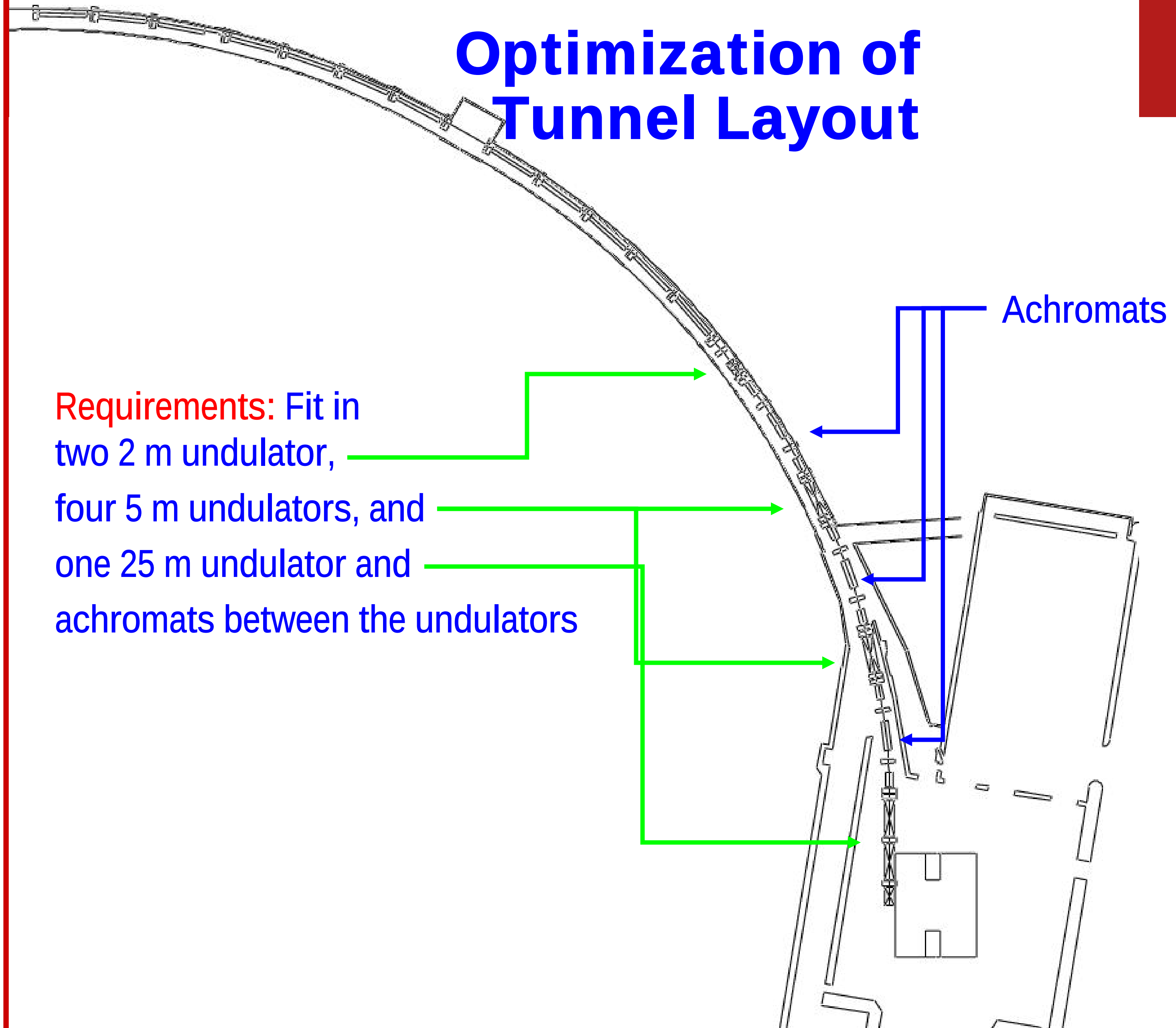
Cornell University

OPTICS

CHESS & LEPP



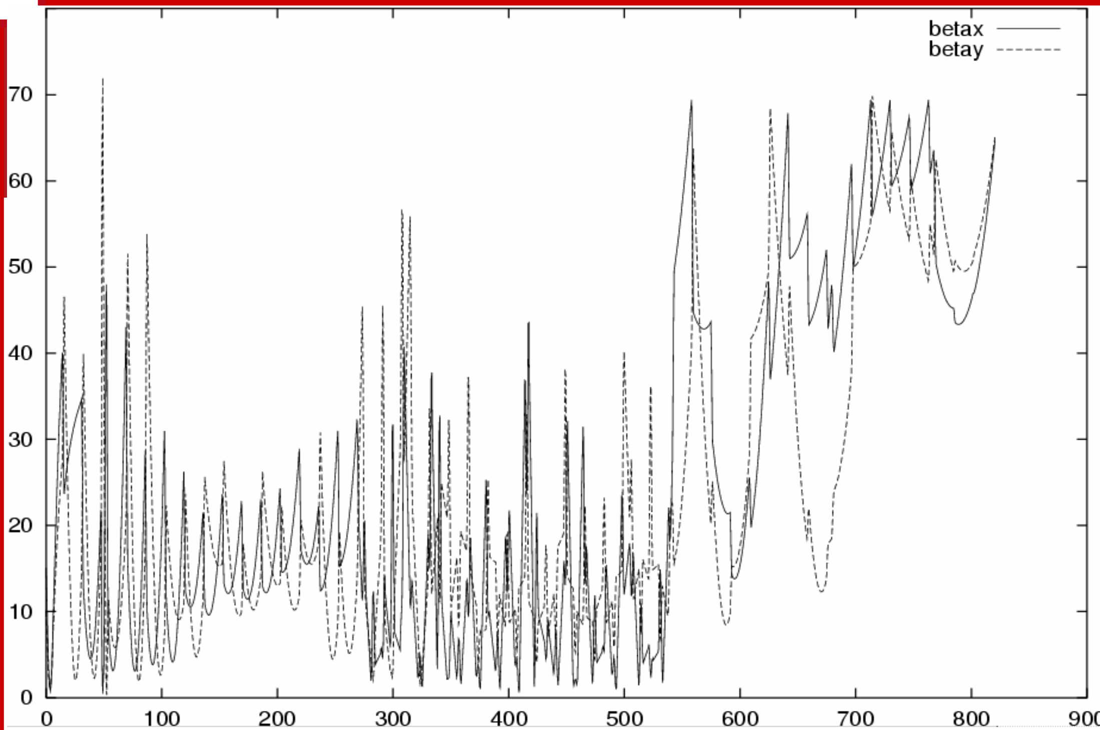
Optimization of Tunnel Layout



Requirements: Fit in
two 2 m undulator,
four 5 m undulators, and
one 25 m undulator and
achromats between the undulators

Linac optics

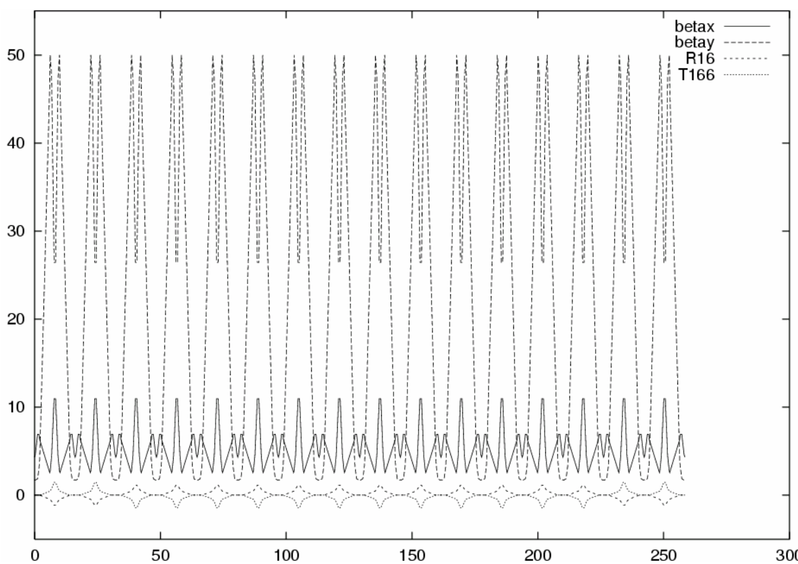
CHESS & LEPP

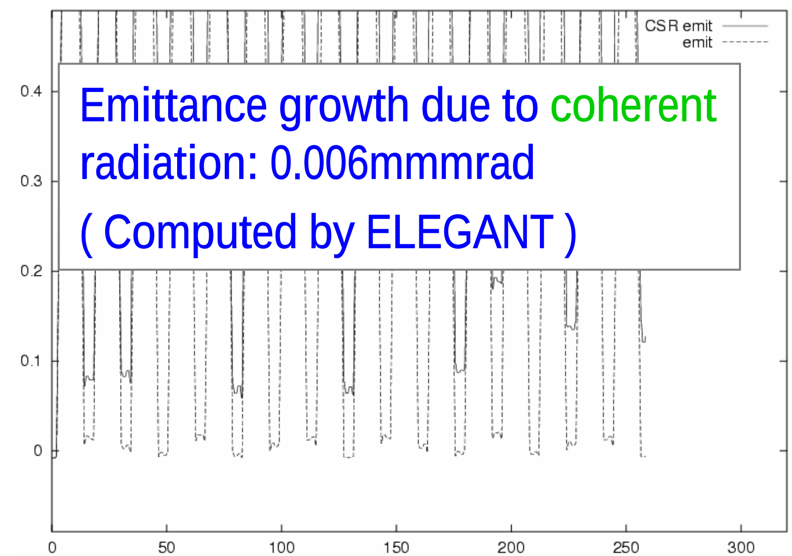


Optimize optics in the Linac for the accelerated and the decelerated energy.

Emittance growth due to incoherent radiation: 0.04mmmrad

Return arc optics



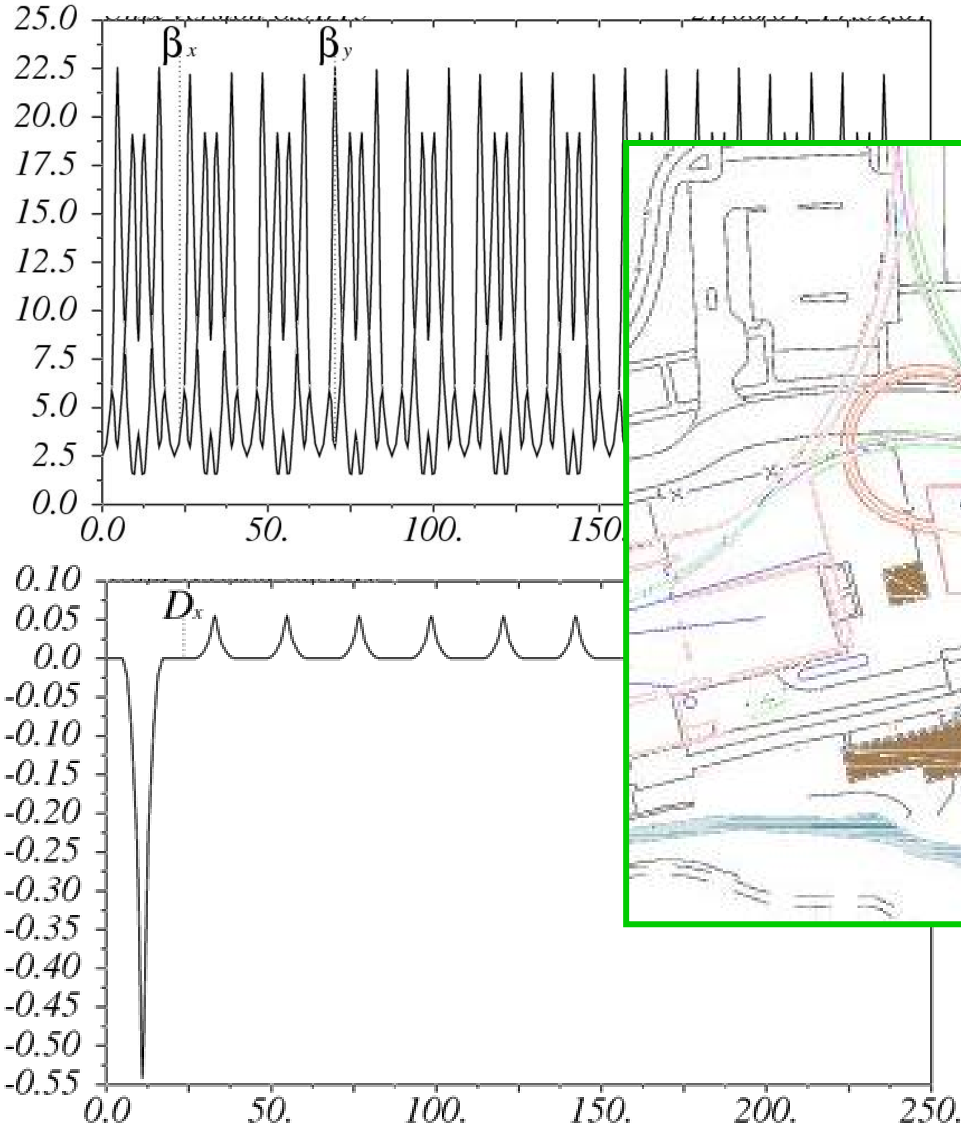


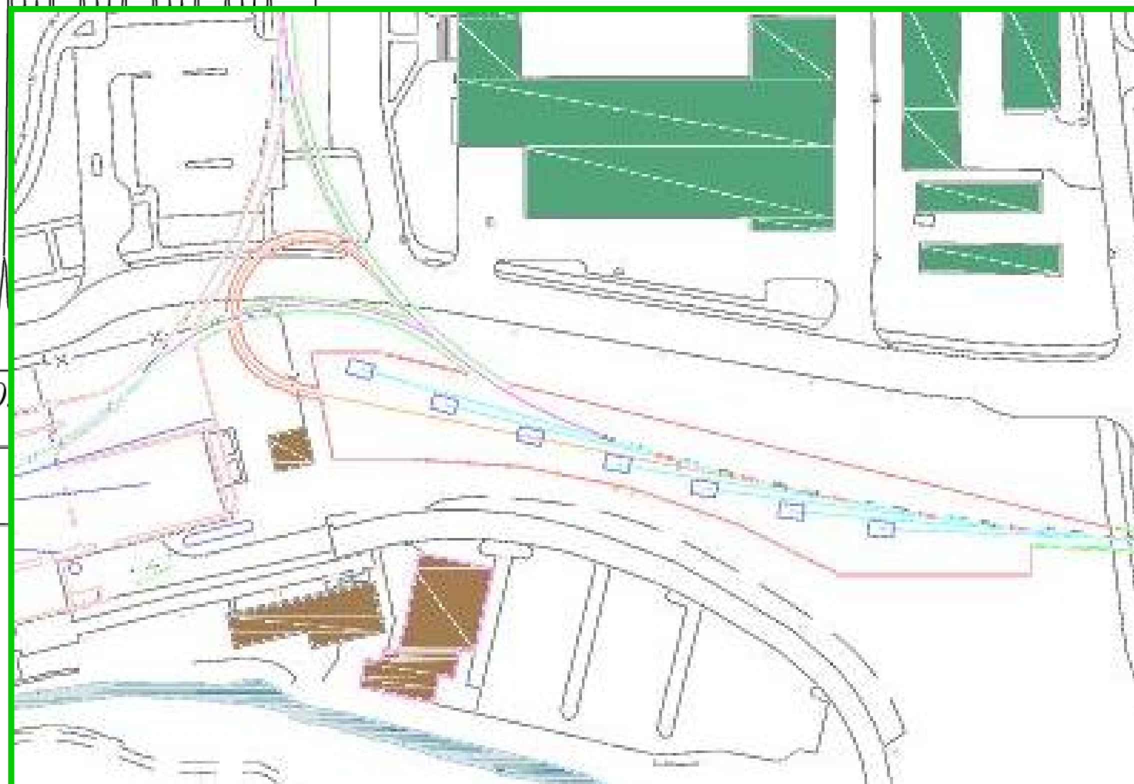
Emittance growth due to coherent radiation: 0.006mmmrad

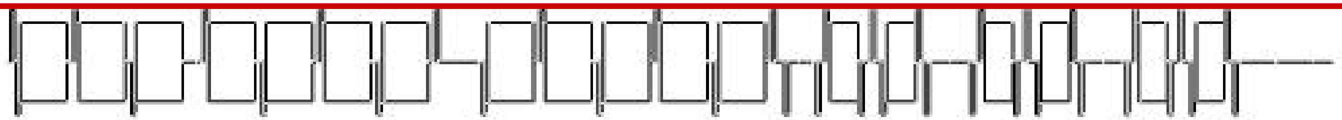
(Computed by ELEGANT)

Optics for the linac-ring connection

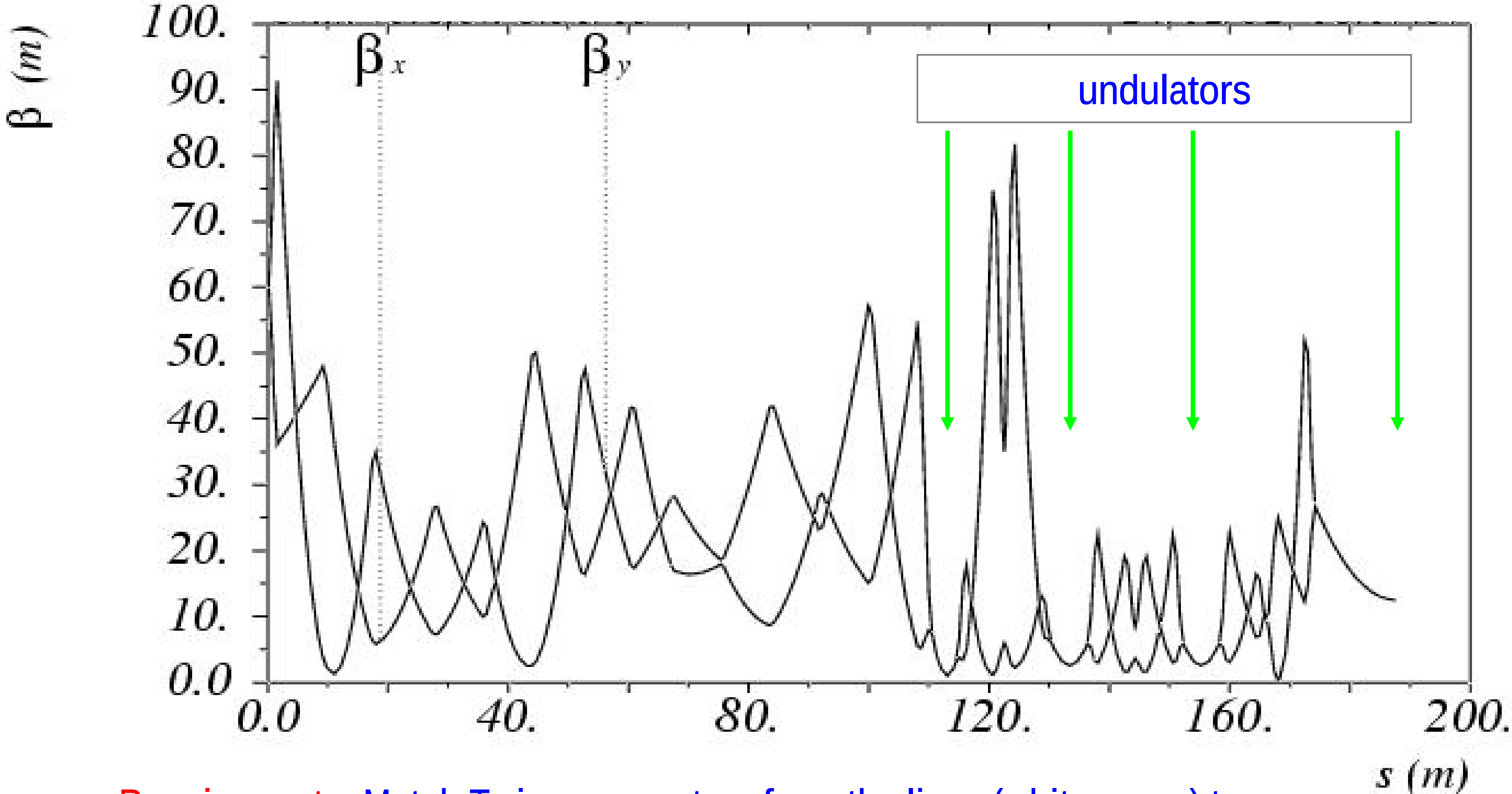
CHESS & LEPP





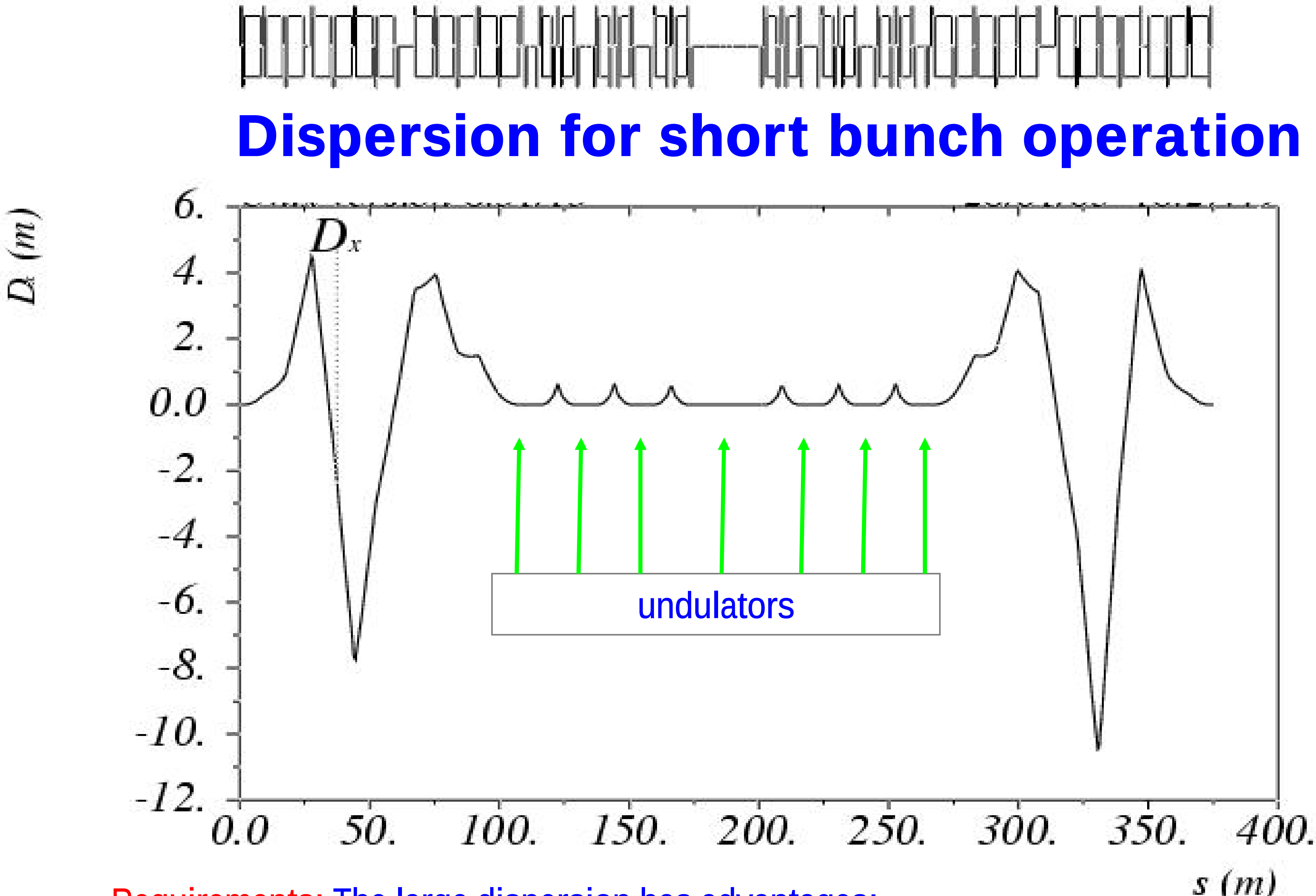


ERL optics for the CESR arcs



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.

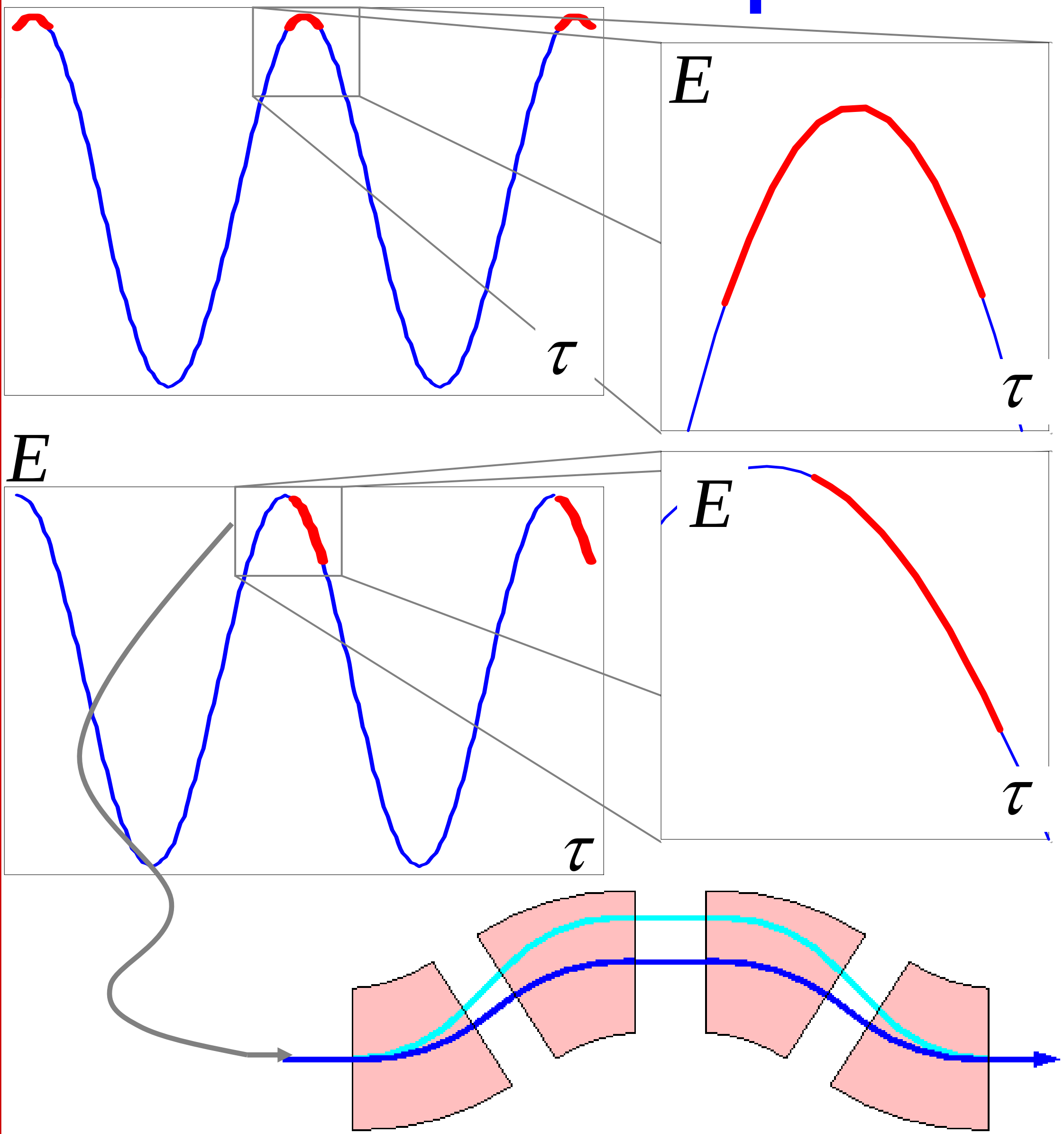
Dispersion for short bunch operation



Requirements: The large dispersion has advantages:

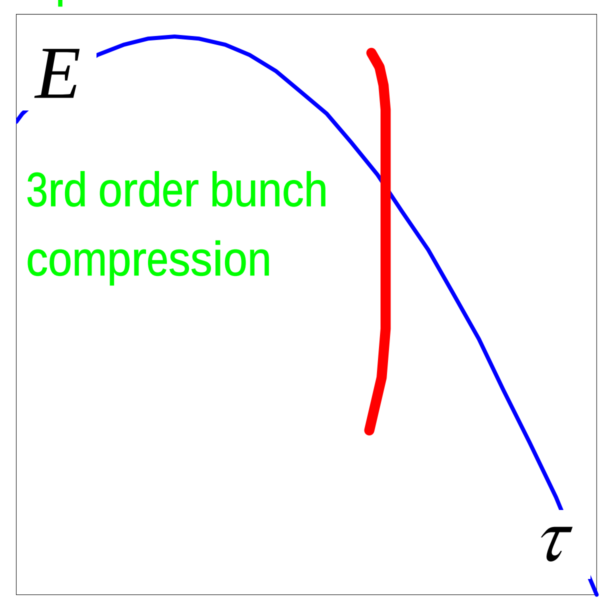
Can be used to manipulate R56, and with sextupoles also higher chromatic orders.

Bunch compression



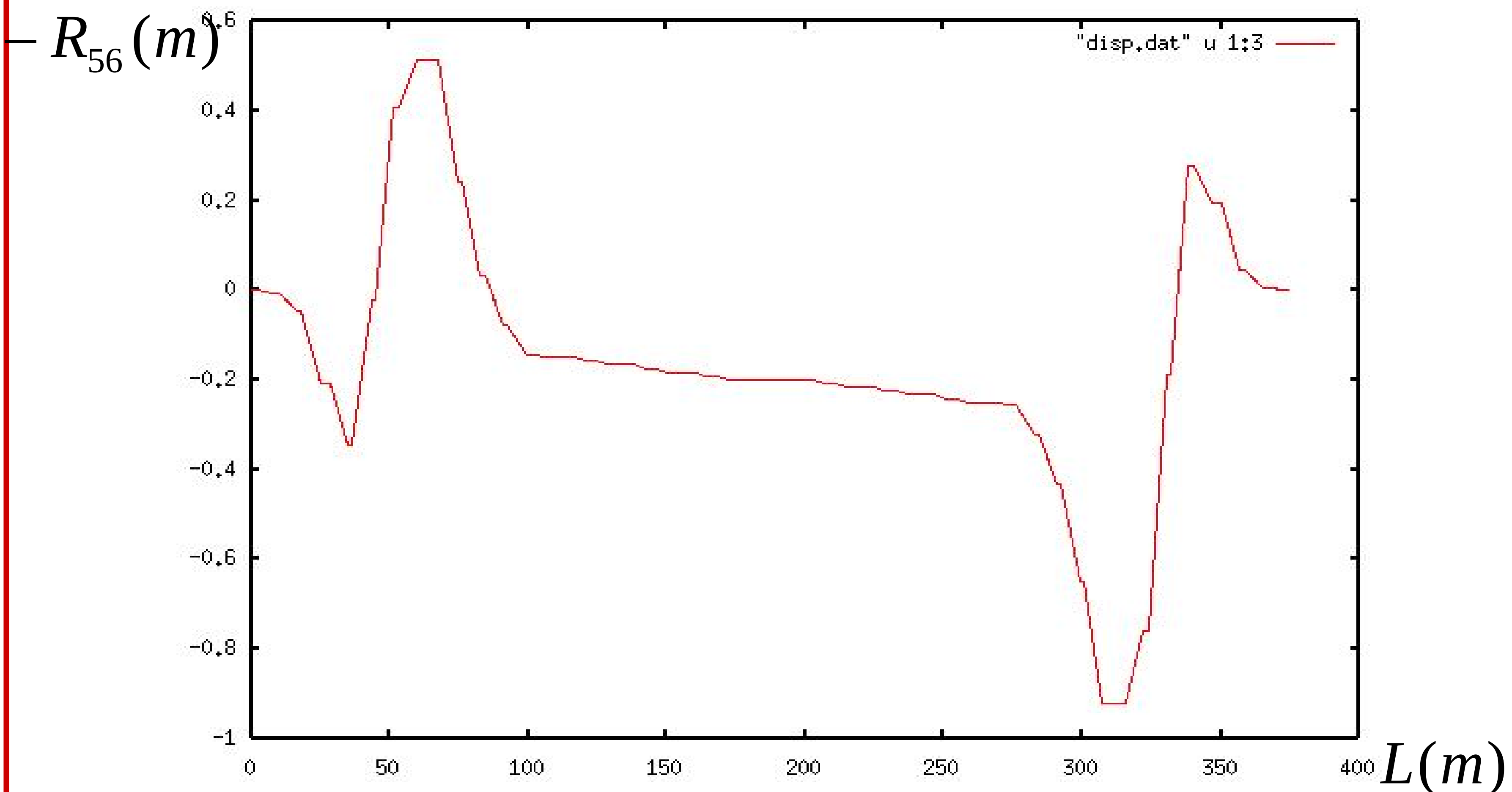
Here low energy particles fly longer

- 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



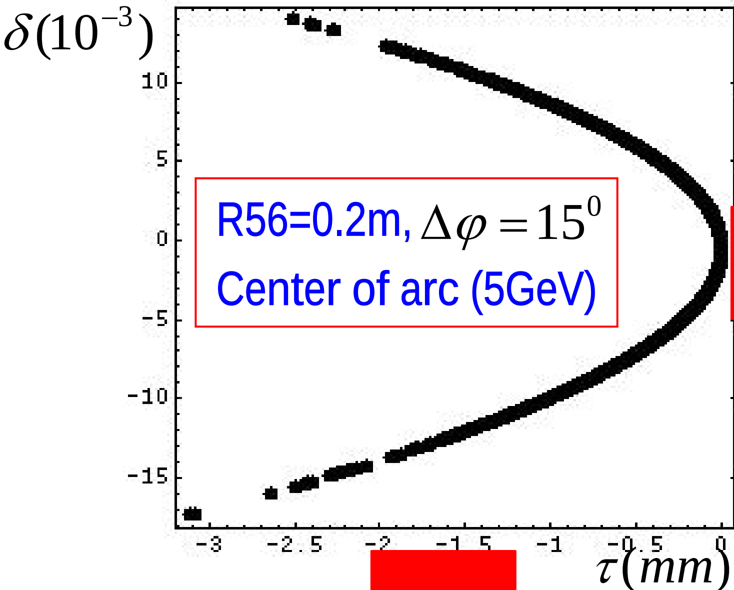
First order bunch compression

CHESS & LEPP



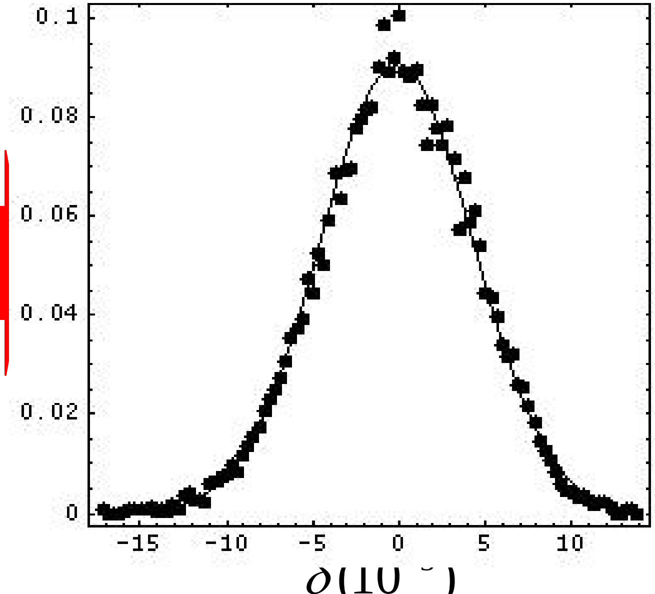
Requirements: Matching of beta functions and dispersion from the linac to the undulators, R56 to 20cm at the center and R56 to 0 at the end is possible with current quadrupoles.

Short bunches with large energy

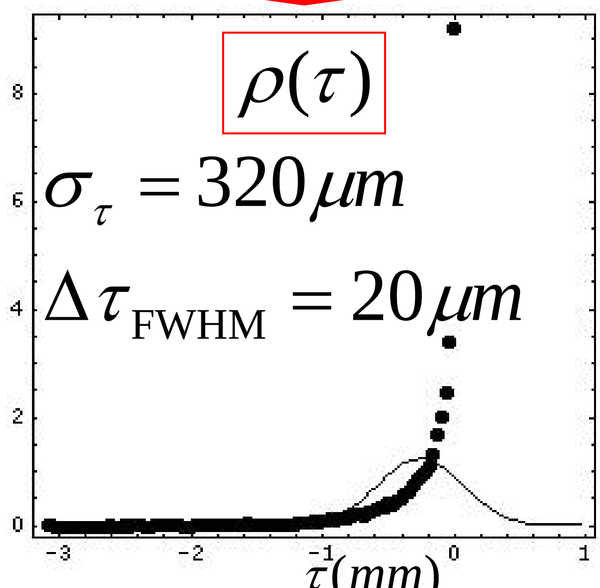


R56=0.2m, $\Delta\varphi = 15^0$

Center of arc (5GeV)



$: 4.4 \cdot 10^{-3}$

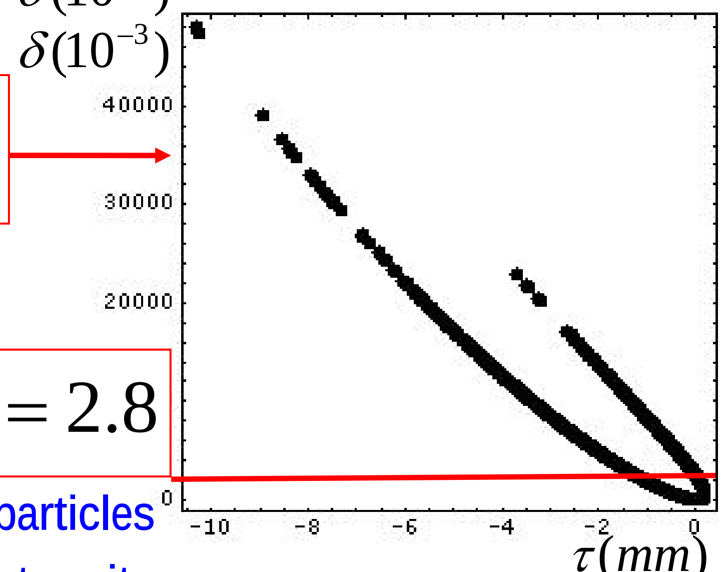


$\rho(\tau)$

$\sigma_\tau = 320\mu m$

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

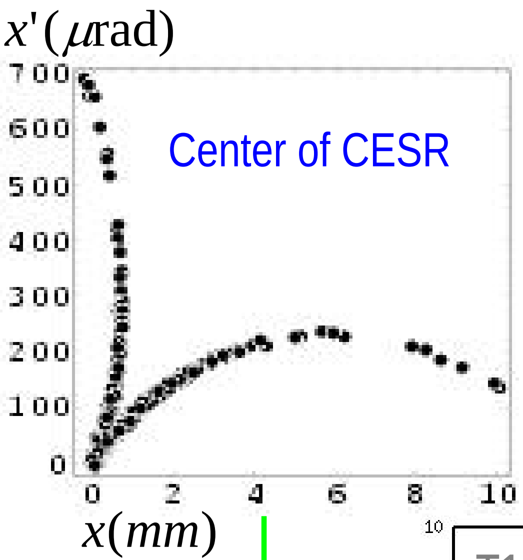
After ERL (10MeV)



$\langle\delta\rangle = 2.8$

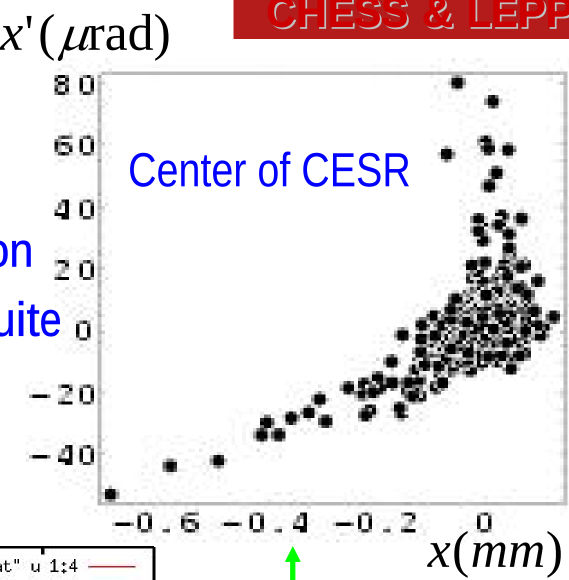
The low energy particles are lost in the last cavity

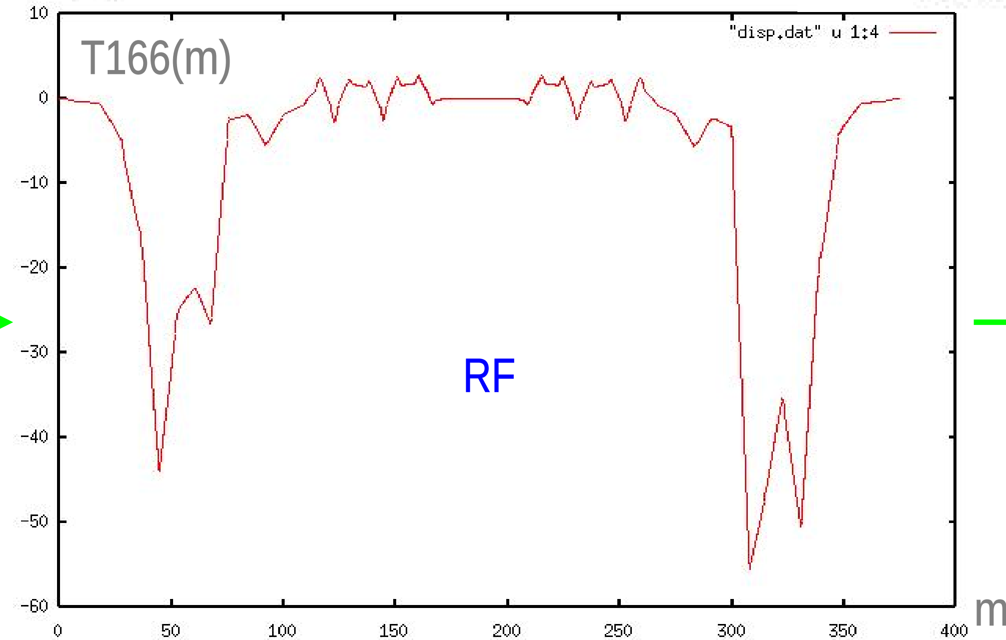
Transverse motion with large energy spread



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.



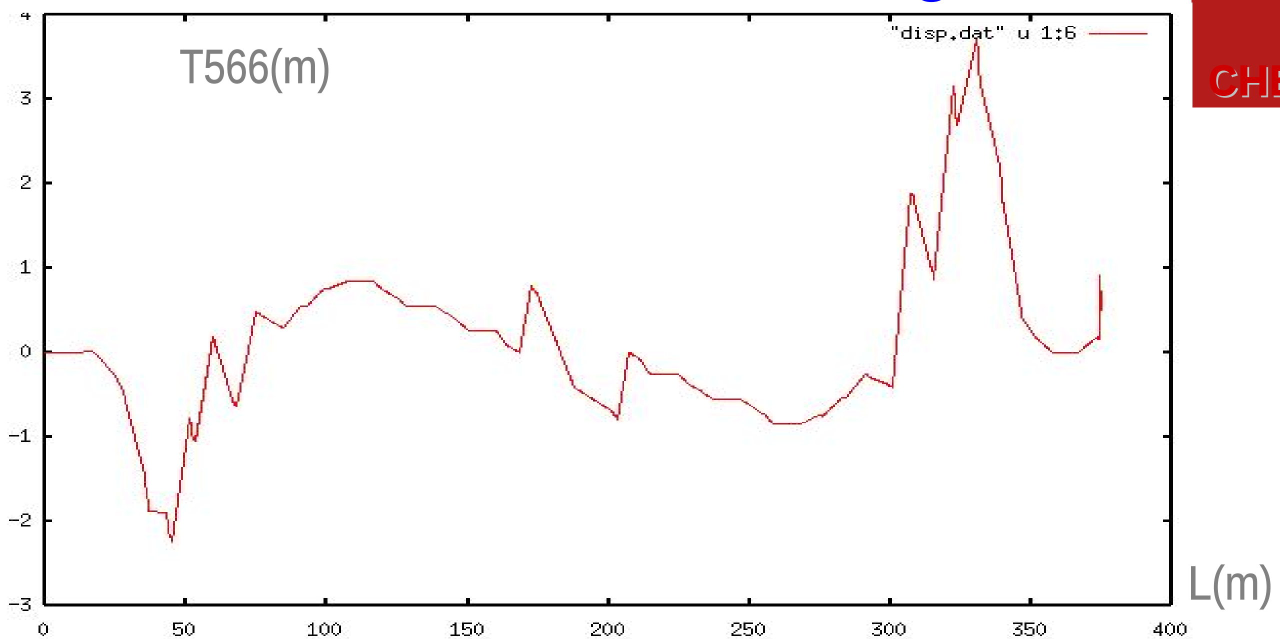


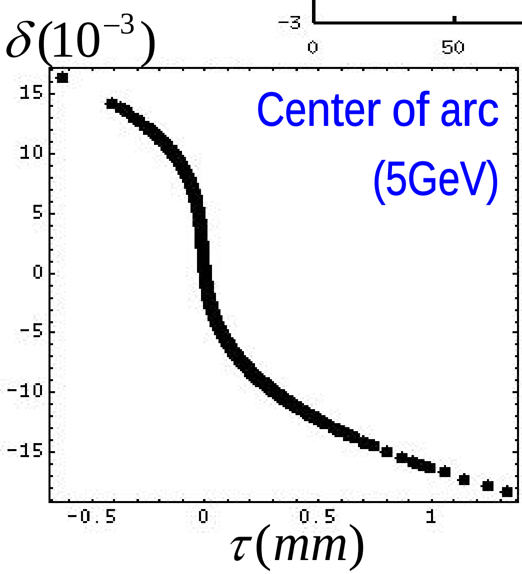
$\Delta\varphi = 15^0$

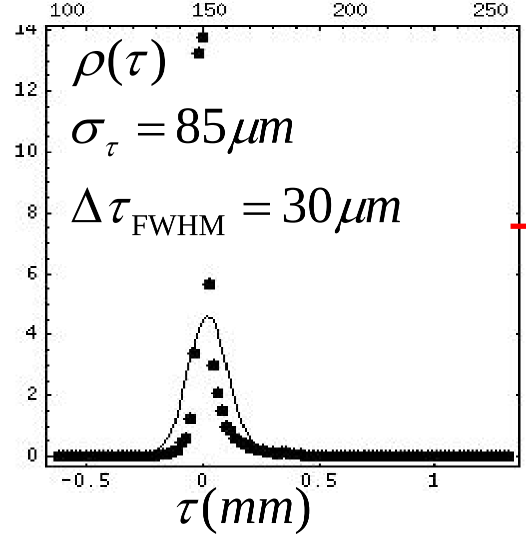
0.44% energy spread

Second Order Time of flight

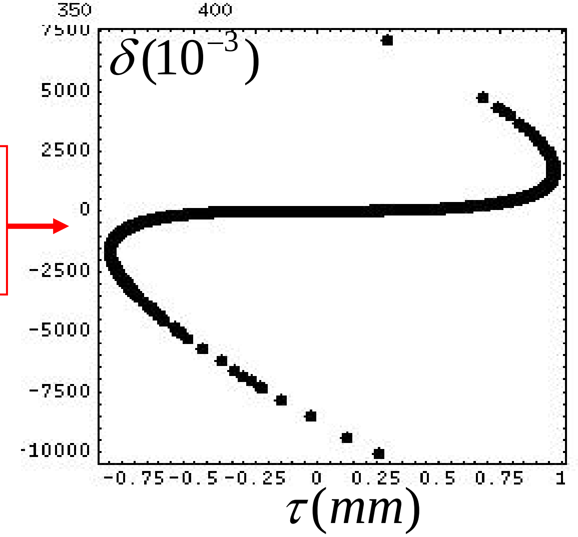
$\Delta\varphi = 15^0$ RF
0.44% energy spread







After ERL

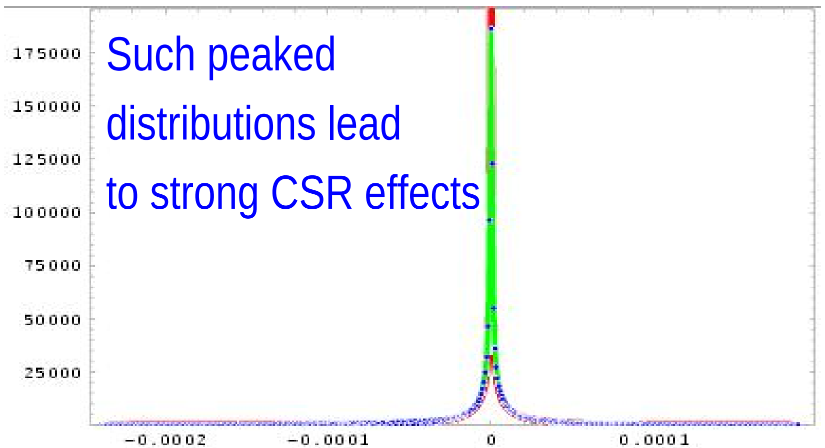


- The energy spread is too large

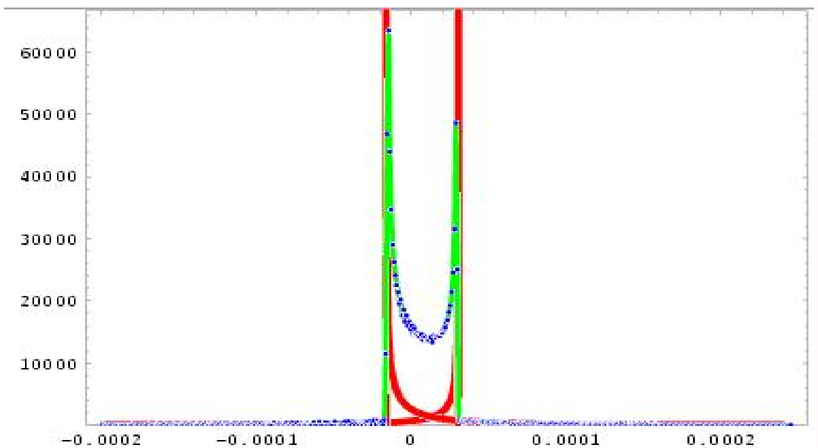
Undercompression

CHESS & LEPP

Peak at 6^0 RF phase



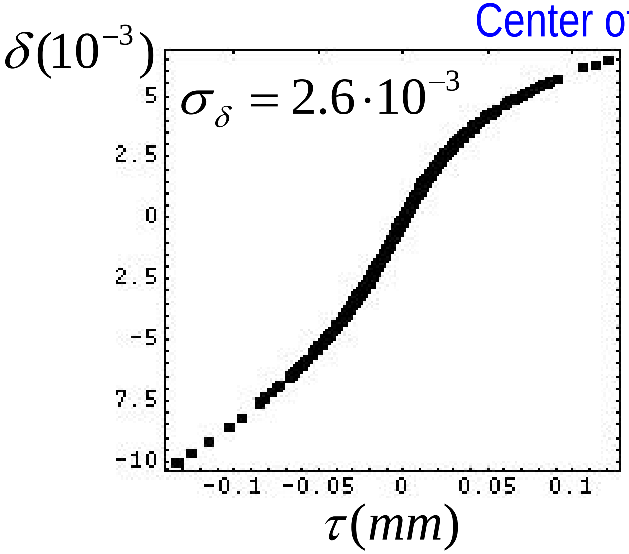
Overfocused peaks

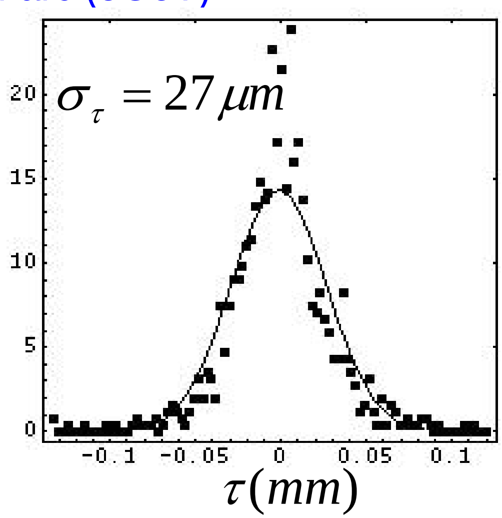


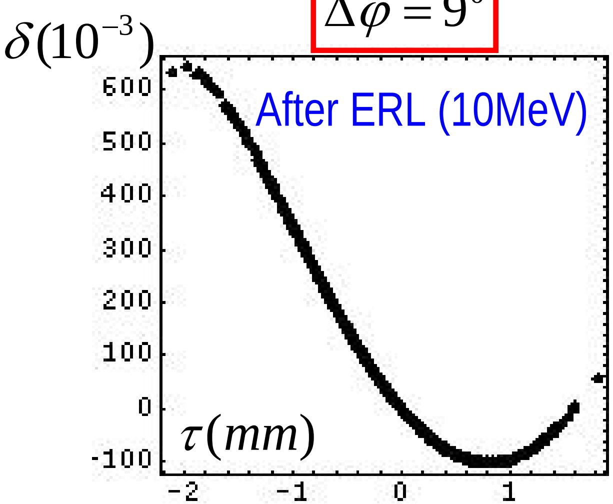
With second order optimization: 9^0 RF phase and undercompression

Center of arc (5GeV)

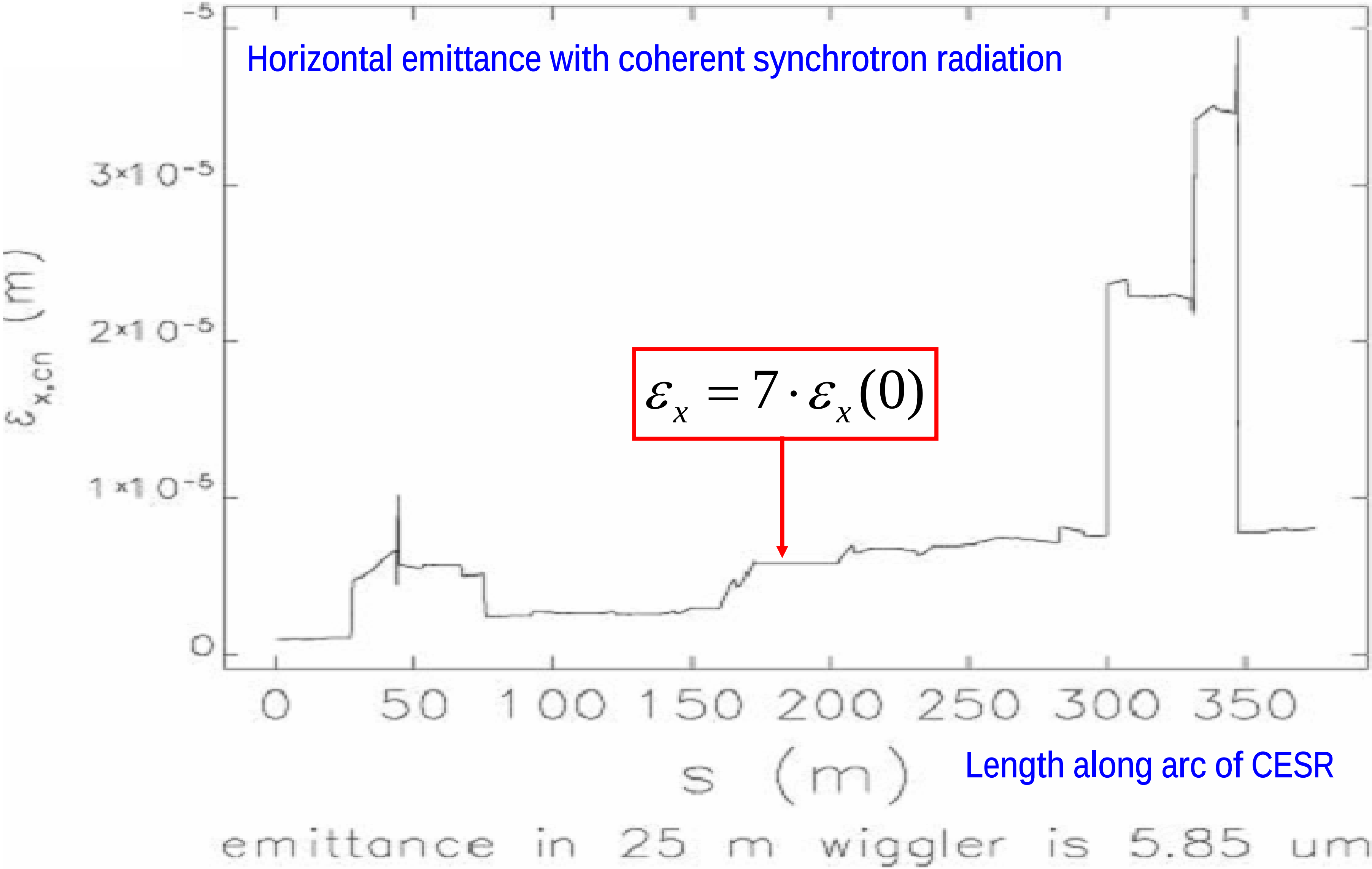
$\Delta\varphi = 9^0$







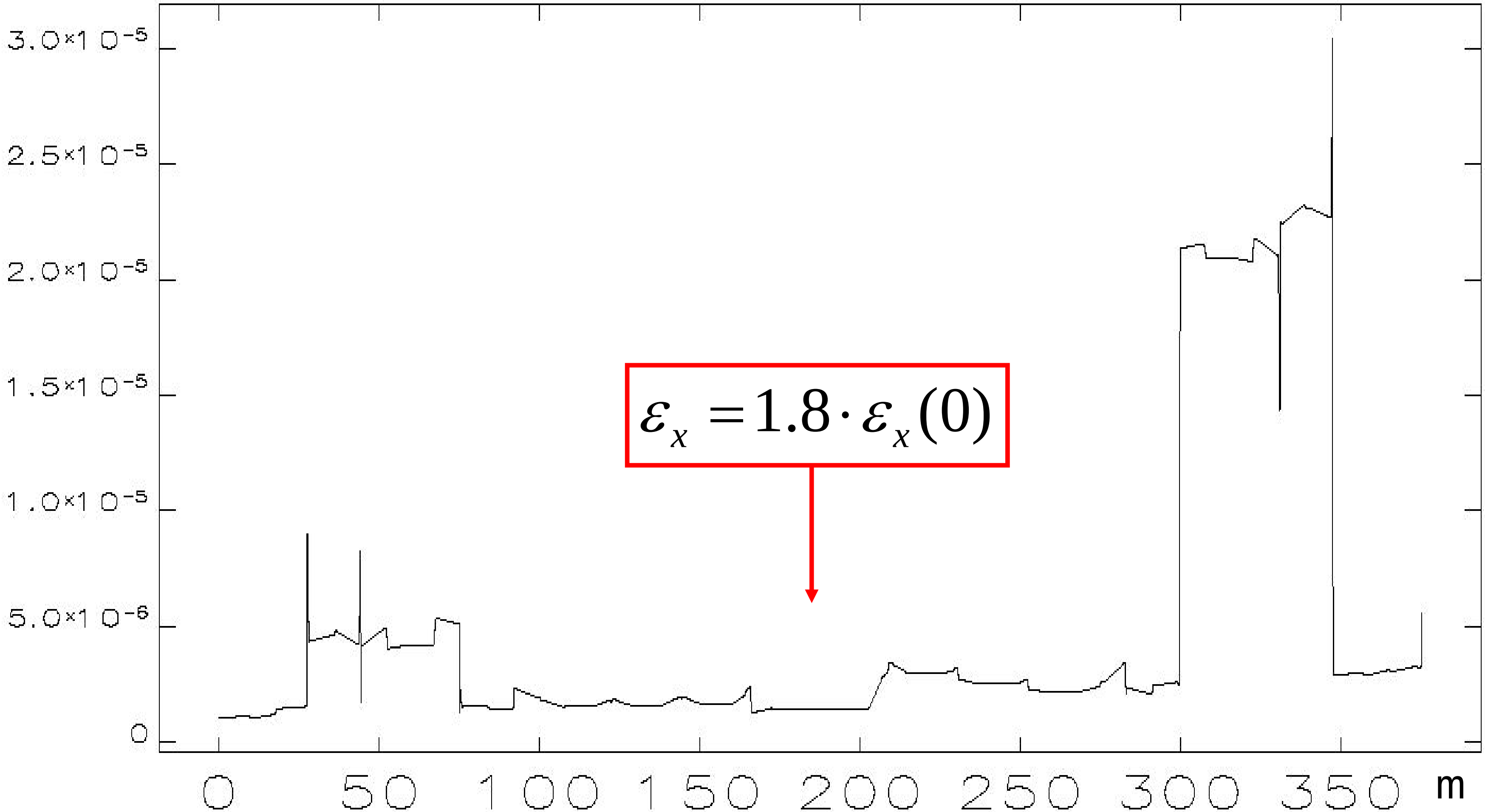
6^0 RF phase, peaked bunch



Emittance with CSR and nonlinear optics

CHESS & LEPP

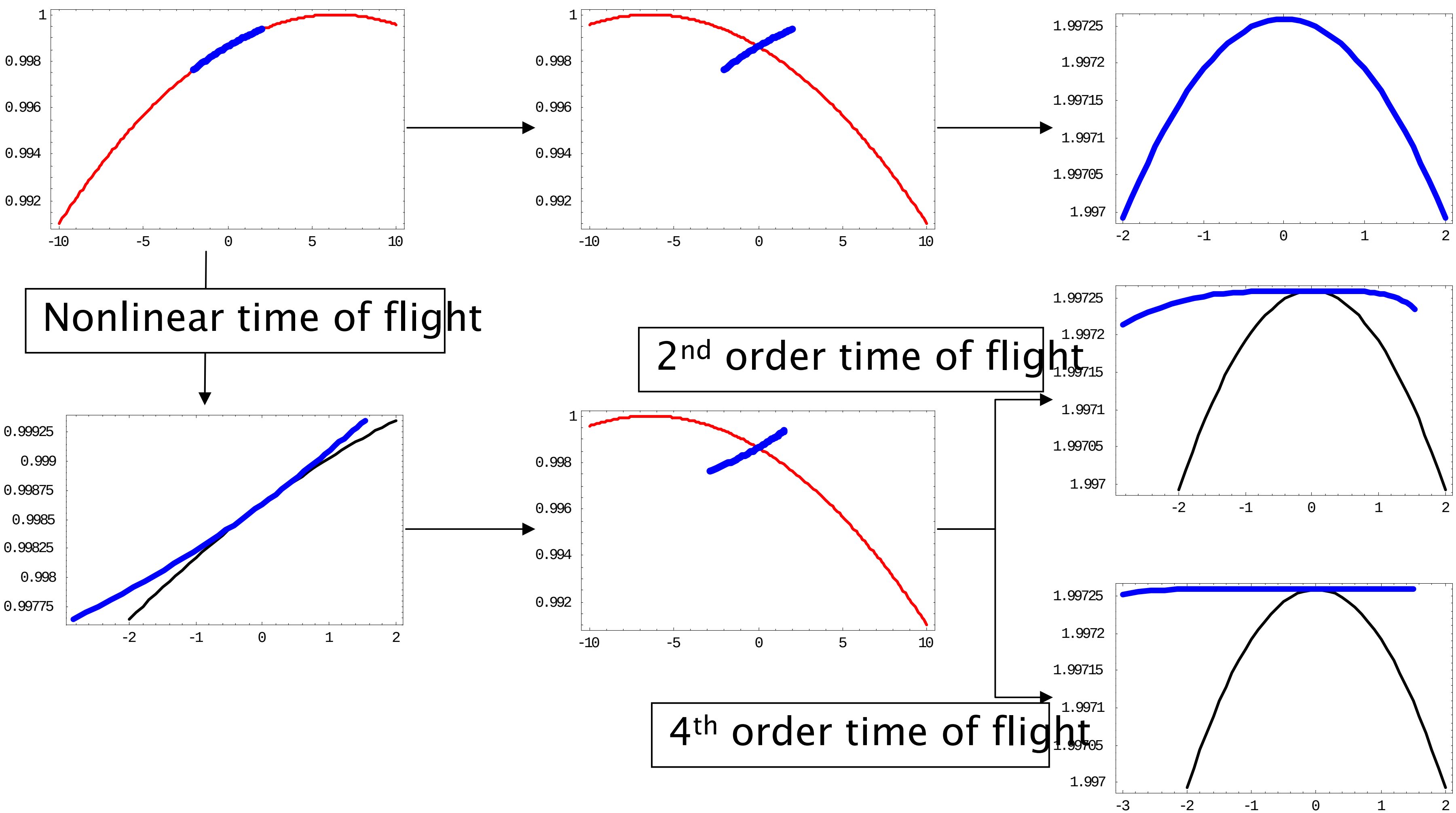
Horizontal emittance with coherent synchrotron radiation



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

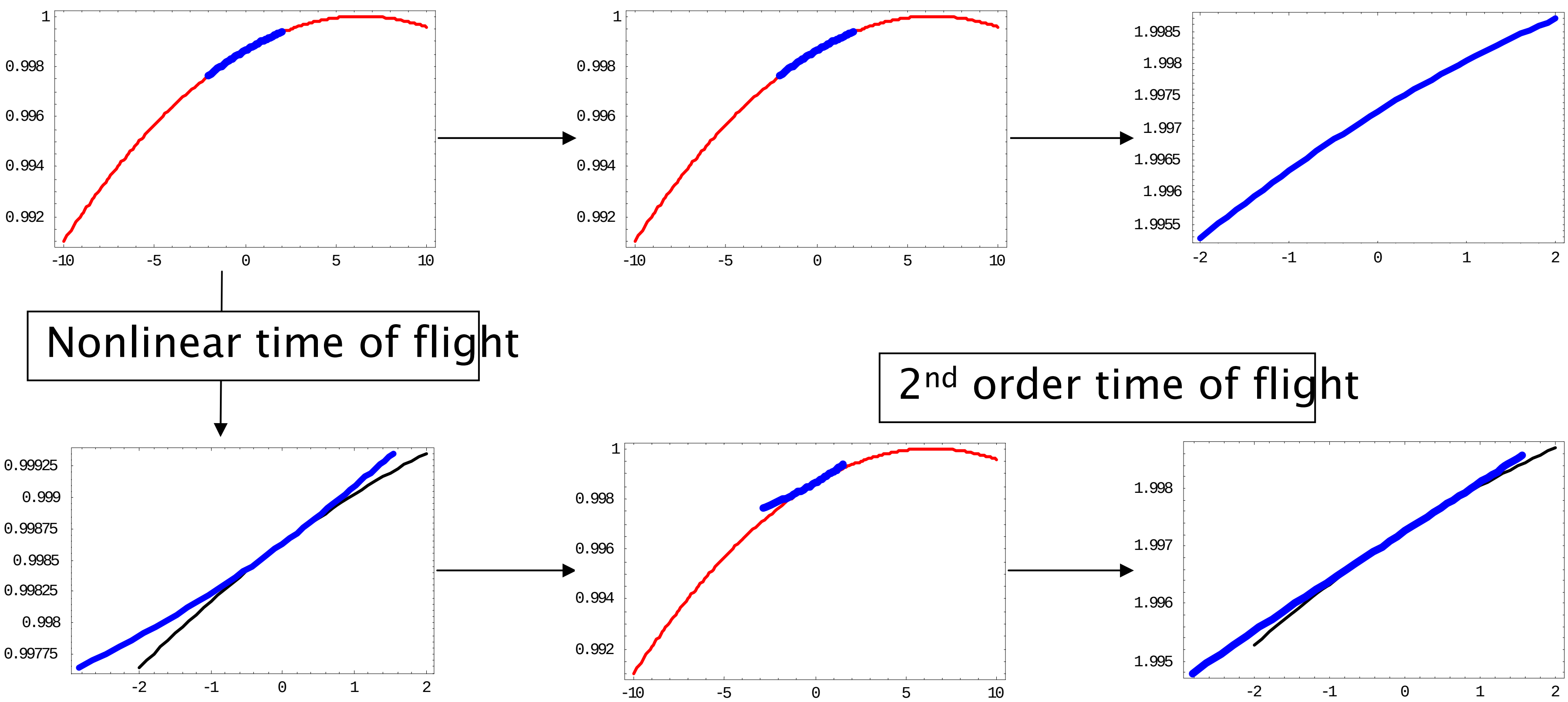
Split Linac Bunch Flattening

CHESS & LEPP



Split Linac Bunch Linerizing

CHESS & LEPP



Subsequent bunch compression is linearlized and relatively simple

End of Talk

Arc Choices

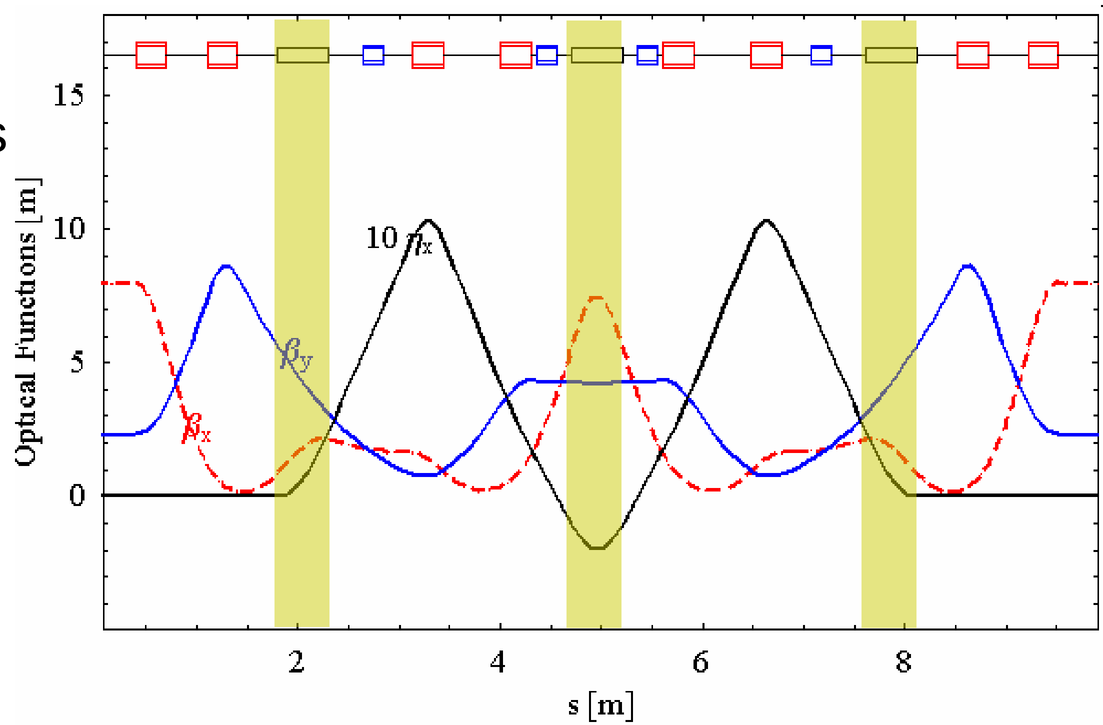
S-Dalinac (TBA)

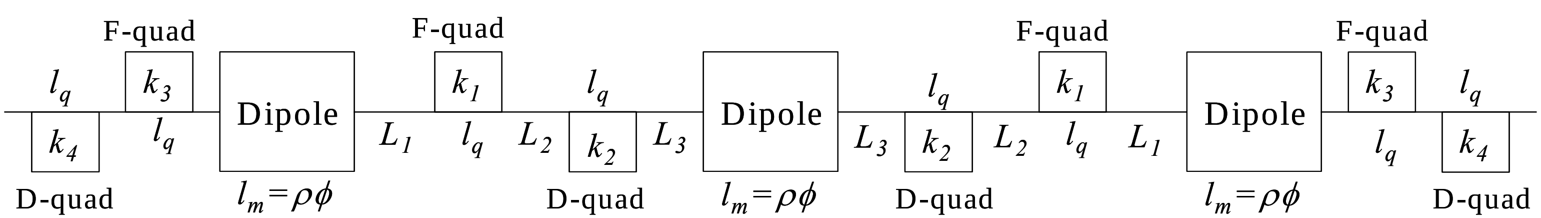
JAERI-FEL (TBA)

IR-Demo (Bates)

TBA

- TBA:
  - Usually 3 identical bends (doesn't have to be)
  - quadrupoles control dispersion and isochronous tuning
  - drift spaces required to be set for both isochronous and achromatic solution





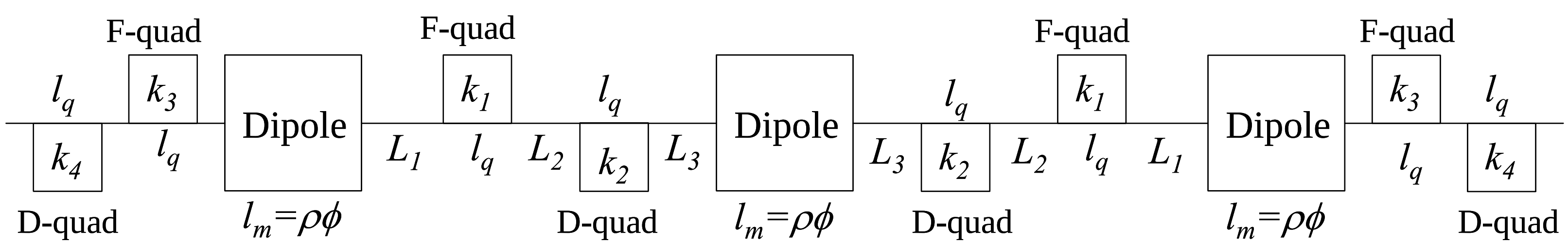
TBA Matching

- Series of equations govern drift lengths

$$
\begin{aligned}
L_1 &= a\frac{C_2 q_1}{C_1 q_2}\left(L_3 - \frac{D_j}{D'_j} + q_2\right) - l + q_1 \\
L_2 &= q_1 - q_2 + \frac{b}{L_3 - D_j/D'_j + q_2},
\end{aligned}
$$

$$
\begin{aligned}
l = \rho_1 \tan(\phi_1/2), \qquad & a = -D'_j/\sin(\phi_1), \\
b = \frac{q_2}{C_2}\left(\frac{q_2}{C_2} + \frac{q_1}{aC_1}\right), \qquad & q_i = \frac{C_i}{S_i\sqrt{k_i}} \ (i = 1 \text{ or } 2), \\
C_1 = \cos(l_q\sqrt{k_1}), \qquad & S_1 = \sin(l_q\sqrt{k_1}), \\
C_2 = \cosh(l_q/\sqrt{k_2}), \qquad & S_2 = \sinh(l_q\sqrt{k_2},)
\end{aligned}
$$

- Scan over L_1, L_2, L_3 and k_1, k_2 ranges of interest to find isochronous achromat solution
- Scan over k_3, k_4 to find optical solution



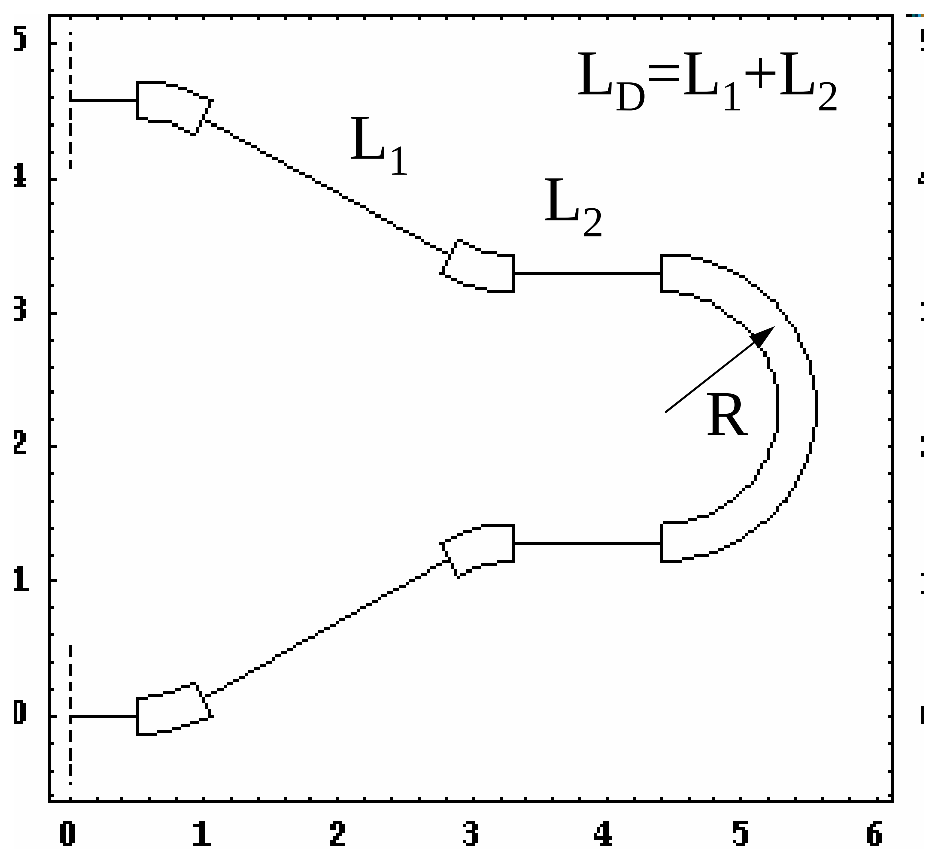
Bates Bend

- 4-dipole chicane split in two by a 180-degree dipole.
- Bend R_{56} cancels chicane R_{56}. No quadrupoles required.
- L_D determined for a particular bend radius by:

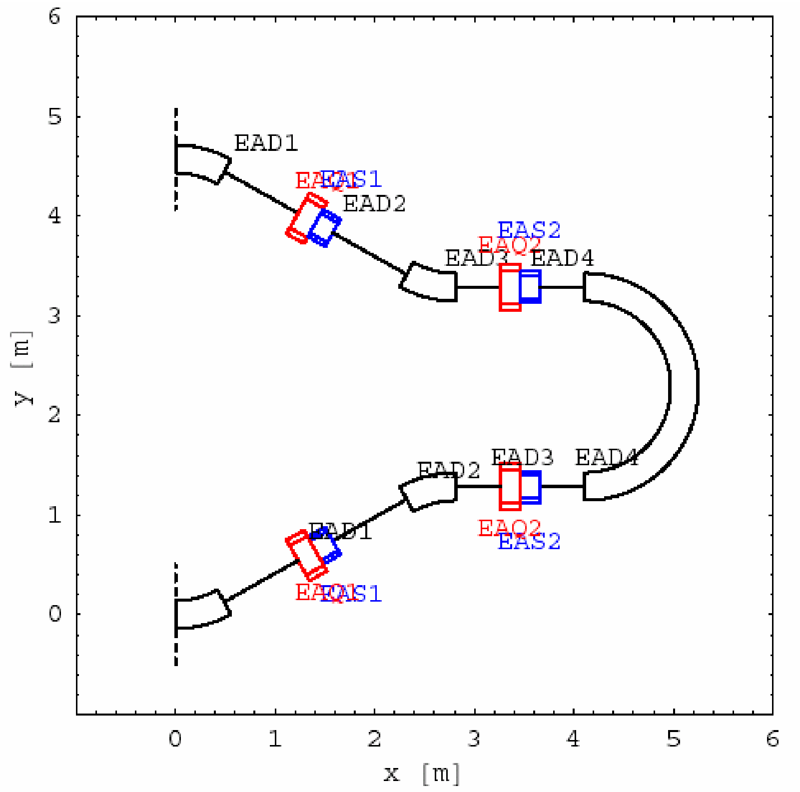
180-degree dipole: $R_{56} = -L = -R\pi,$

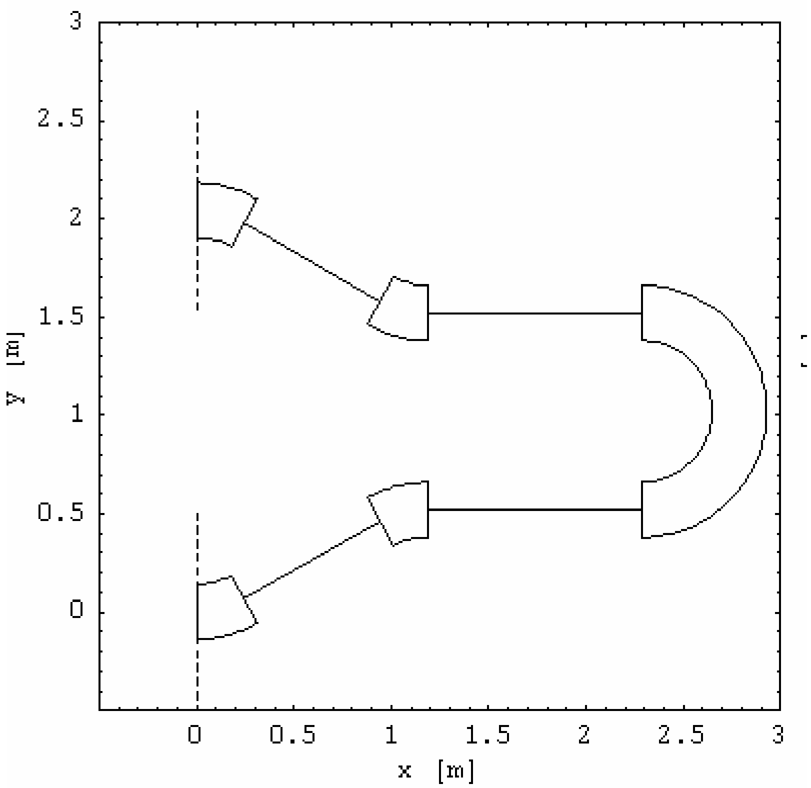
Chicane drift length to cancel: $L_D \simeq \frac{4L_B}{3} + \frac{\pi R}{2\theta^2}.$

small



Bates Solutions





1m radius (0.16 T at 50MeV)   0.5m radius (0.32 T at 50MeV)

You can’t easily make the Bates wide and short.

Path Length Control

- Required to adjust for energy recovery:
  - ~1 λ range, i.e. 23 cm (real or effective path length)
  - ~degree accuracy - ~1mm
- Methods of changing path length:
  - Physically move the arc – e.g. JAERI-FEL
  - Trajectory change in dipoles
    - Bates bend central dipole
    - JAERI dog-leg adjustment?
    - Global perturbation (v. complicated)
  - Change of RF frequency
    - 23cm = 5.7 MHz over ~50m at 1.3GHz
    - only for fine adjustment
  - Need to be aware of impact on energy, FEL etc.

Trajectory Adjustment

General equation:

$$\delta l = R_{51}x + R_{52}x'.$$

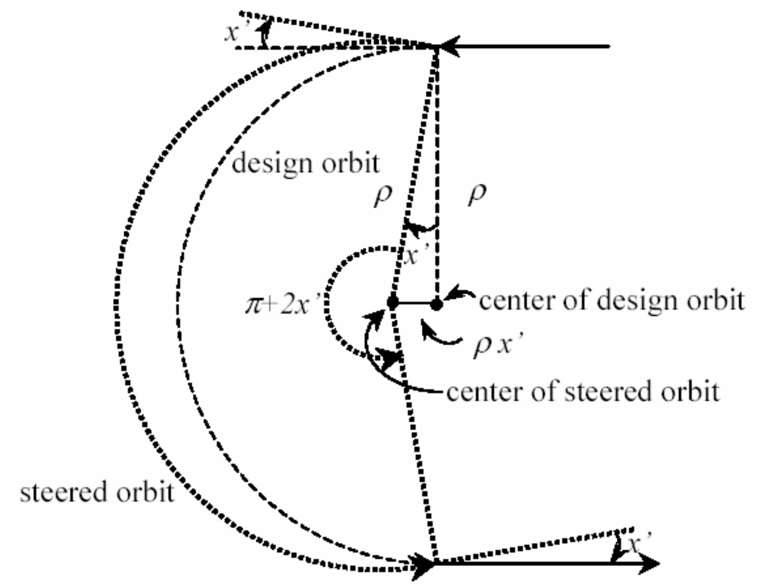
Dipole length L_B, angle θ:

$$\delta l = -\frac{L_B x' \cos\theta}{\theta} - x\sin\theta.$$

Symmetric condition on x and x':

$$x = \frac{L_B x' \csc\theta(1+\cos\theta)}{\theta} \qquad \delta l = -\frac{2L_B x'}{\theta}.$$

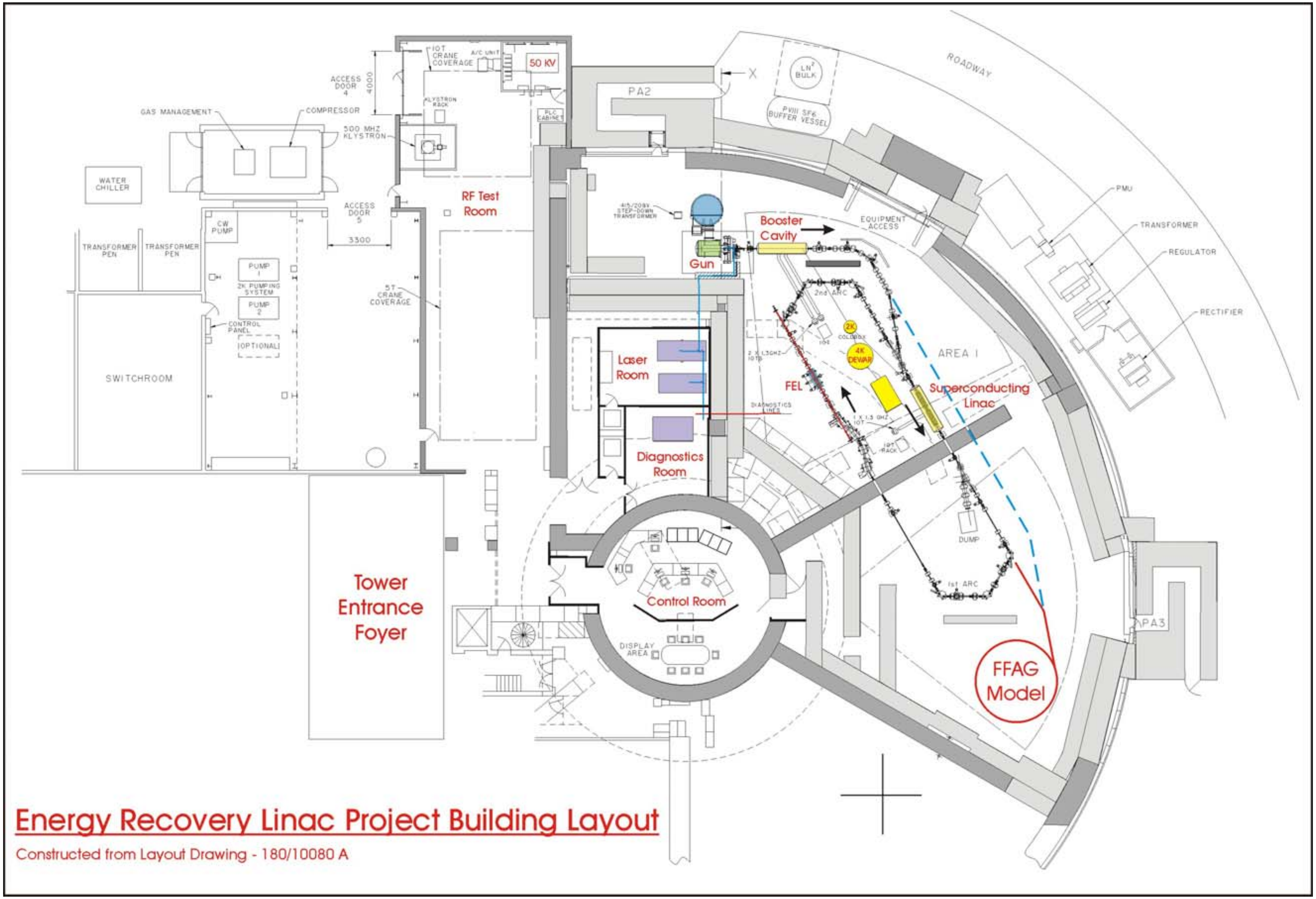
Requires two correctors each side to set x and x',
unless θ = π, then x = 0 and only 1 corrector each side is needed



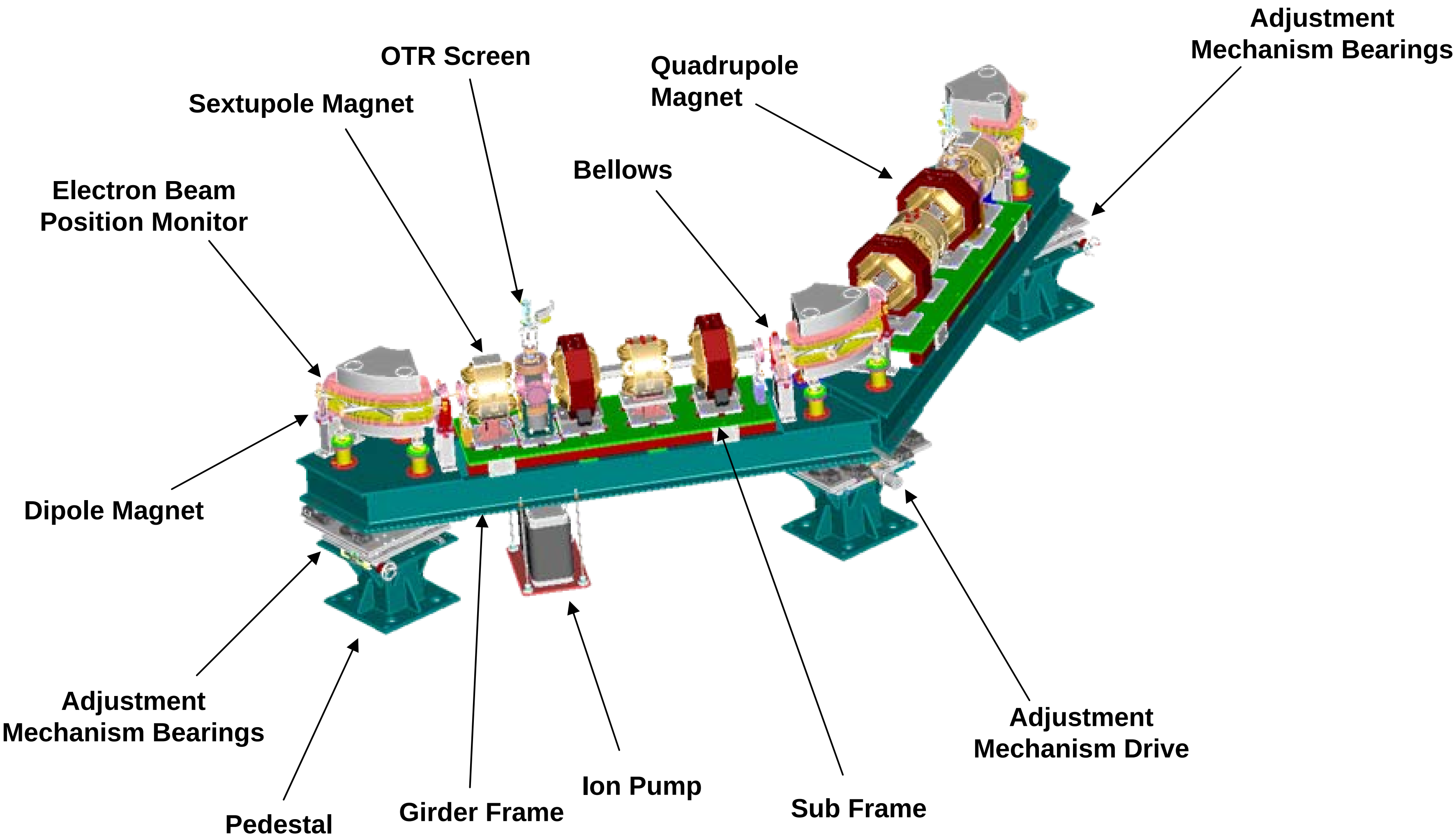
Path length adjustment in a π-bend (e.g. JLab IRDemo)

In 0.35T TBA, an extra 120mm of transverse aperture is needed for 23cm path adjustment in one magnet.

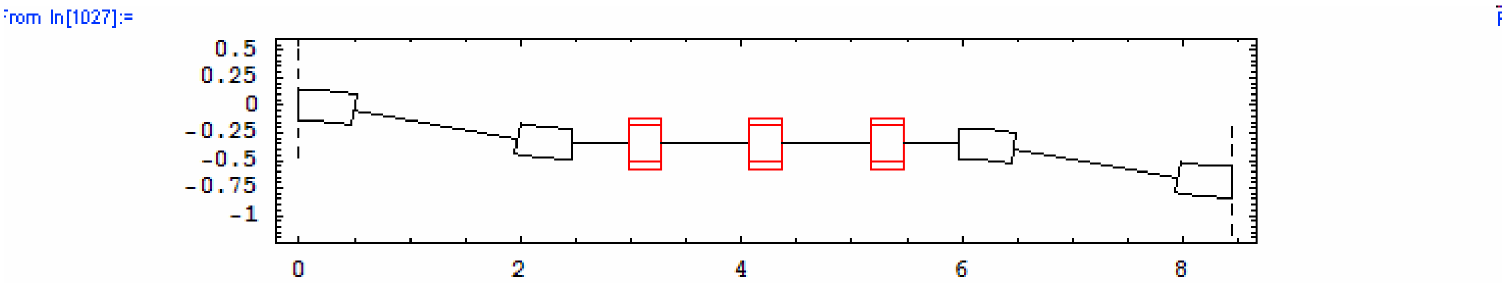
ERLP In The Tower

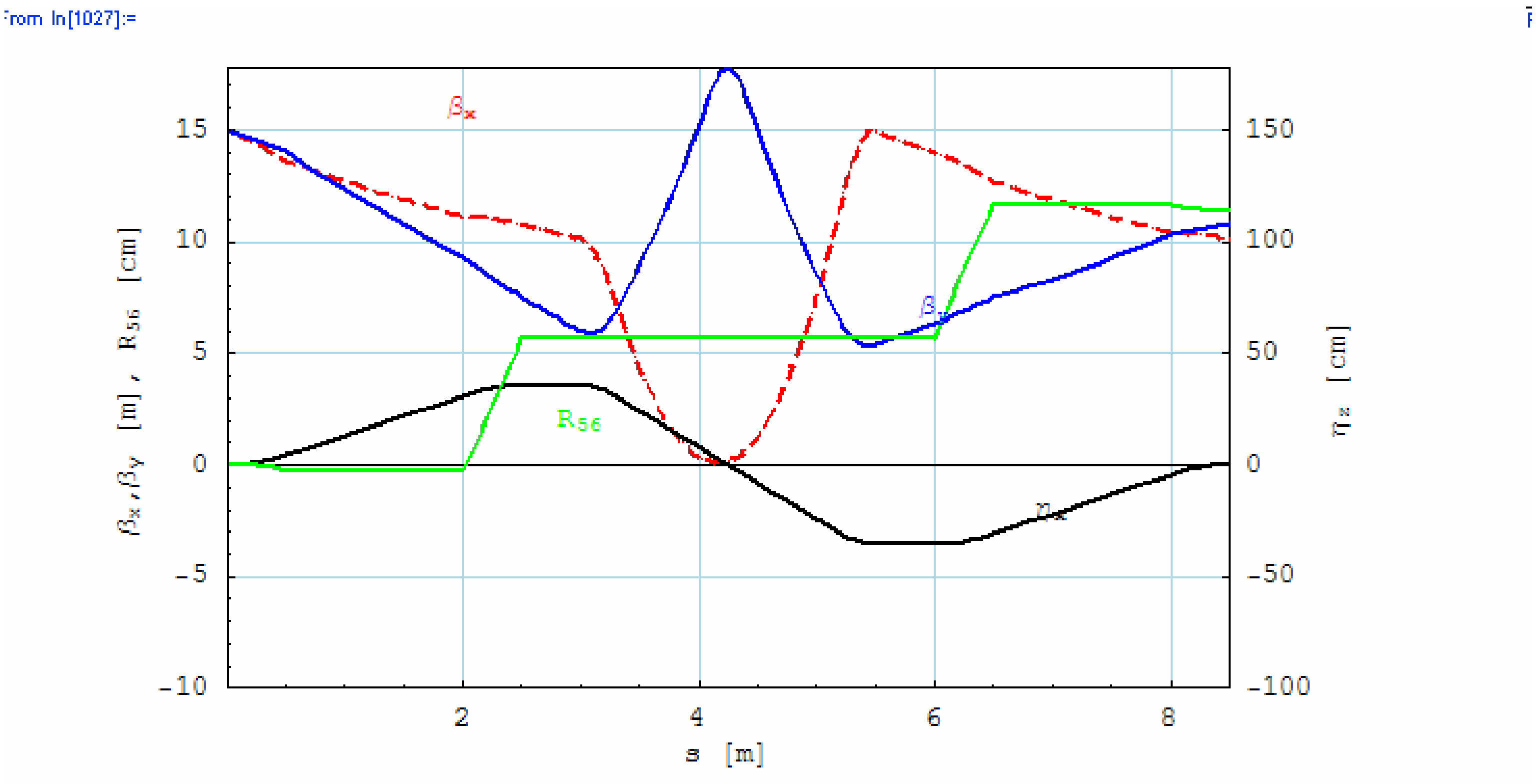


ERLP – Moving Arc (Arc 1)

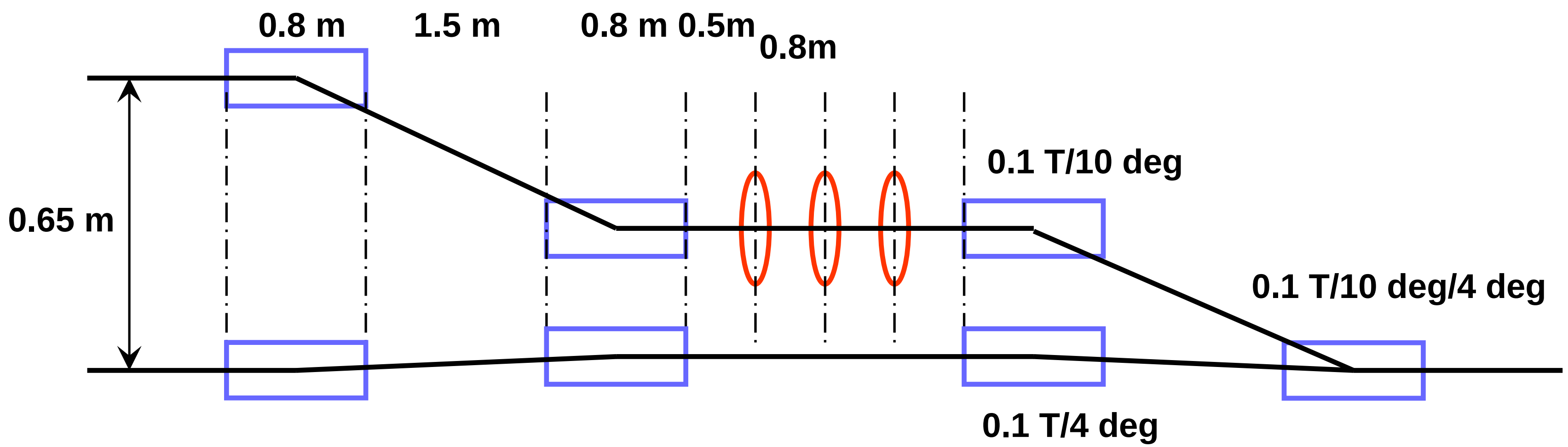


FEL Branch - BC1 Layout and Optics

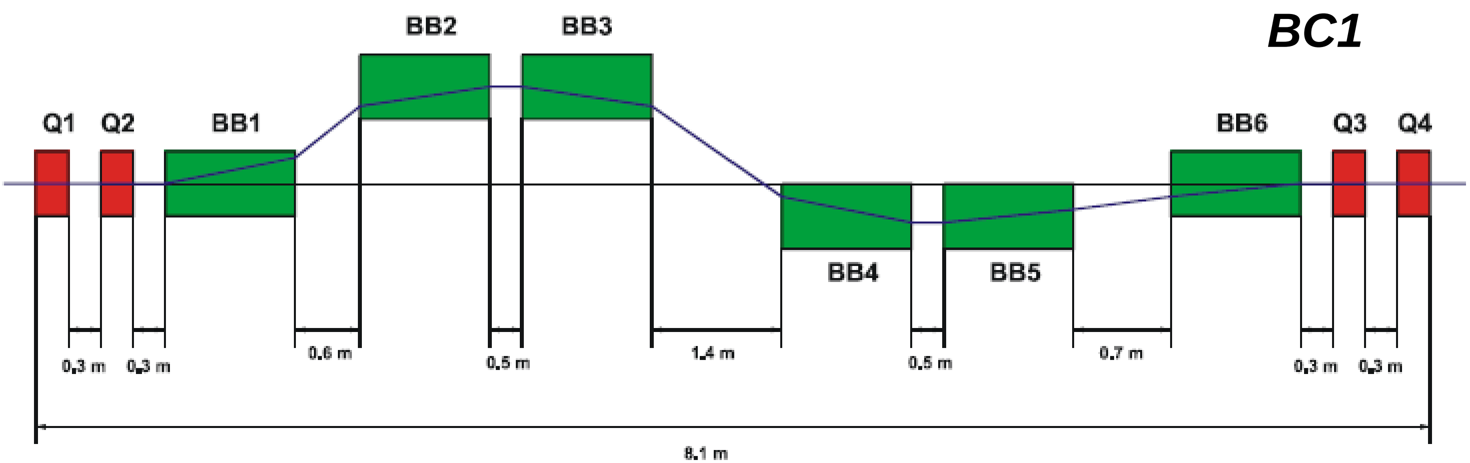


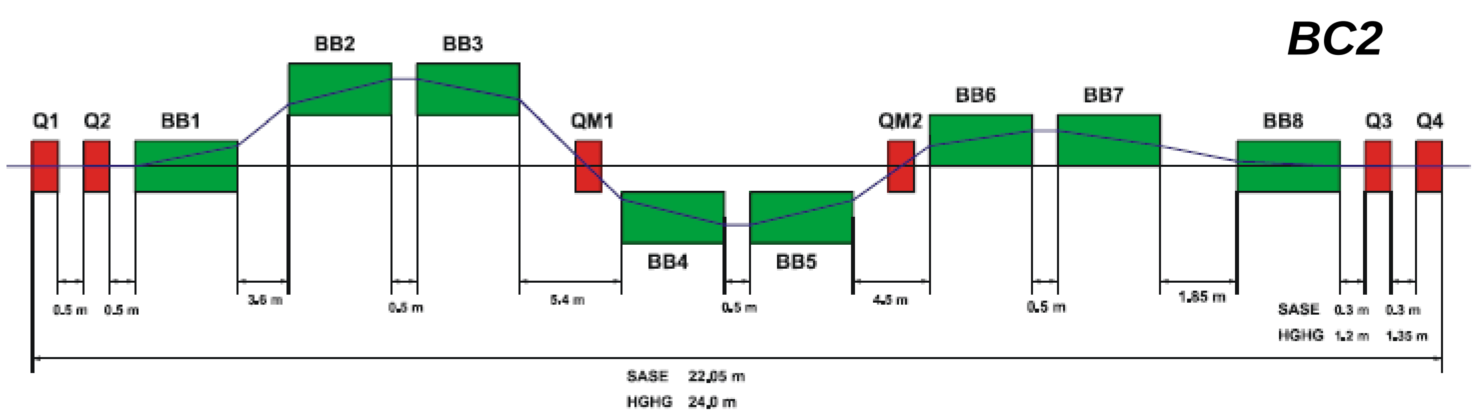


BC1 Layout Diagram



BESSY FEL Bunch Compressors





Increase bend radius towards end to reduce CSR effects