Beam dynamics around transition

in a high brightness Linac for

short wavelength SASE-FEL experiments

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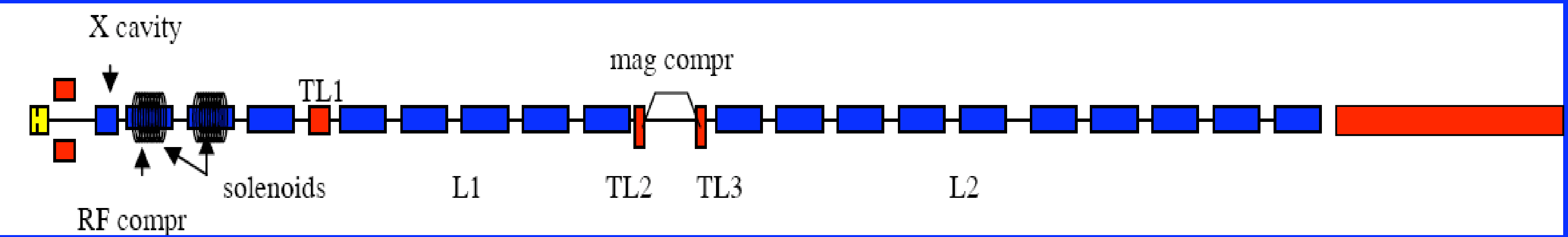
Outline

Invariant Envelope solution when ρ -> 1

$$\sigma'' + \frac{\gamma'}{\beta^2\gamma}\sigma' + K_r\,\sigma - \frac{\kappa_s}{\beta^3\gamma^3\,\sigma} - \frac{\epsilon_n^2}{\beta^2\gamma^2\,\sigma^3} = 0$$

Sparxino global optimization

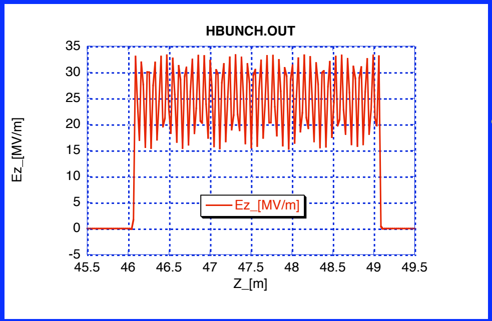


$$\sigma'' + \frac{\gamma'}{\beta^2\gamma}\sigma' + K_r\,\sigma - \frac{\kappa_s}{\beta^3\gamma^3\,\sigma} - \frac{\epsilon_n^2}{\beta^2\gamma^2\,\sigma^3} = 0$$

$$K_r = \left(\frac{\gamma'}{\gamma}\right)^2\Omega^2 \,, \qquad \Omega^2 = \frac{1}{\sin^2\phi}\left[\frac{\eta}{8} + \left(\frac{B_z c}{E_0}\right)^2\right] \,, \qquad \kappa_s = I g(\zeta)/2I_0$$

$$\eta(\varphi) \equiv \sum_{n=1}^{\infty}\left(a_n^2 + a_{-n}^2 + 2a_n a_{-n}\sin(2\varphi)\right)$$

$$\gamma = 1 + \alpha k z \sin\varphi$$



TW*

$$0 < \eta < 1$$

the alternating gradient focusing effect arises from the existence of non-synchronous spatial harmonics (Hartmann, Rosenzweig, Serafini)

Looking for an "equilibrium" solution

$$\sigma'' + \frac{\gamma'}{\beta^2\gamma}\sigma' + K_r\,\sigma - \frac{\kappa_s}{\beta^3\gamma^3\,\sigma} - \frac{\epsilon_n^2}{\beta^2\gamma^2\,\sigma^3} = 0$$

Serafini-Rosenzweig (Cauchy)

$$y = \ln(\gamma/\gamma_0)$$

$$\frac{d^2\sigma}{dy^2} + \Omega^2\sigma - \frac{S}{\gamma_0}\frac{e^{-y}}{\sigma} + \frac{\epsilon_n^2}{\gamma'^2\sigma^3} = 0$$

C. Wang (Lawson)

$$\hat{\sigma} = \sqrt{\beta\gamma}\,\sigma$$

$$\hat{\sigma}'' + \left(\frac{\gamma'}{\beta\gamma}\right)^2\left(\Omega^2 + \frac{1}{4}\right)\hat{\sigma} - \left(\frac{\gamma'}{\beta\gamma}\right)^2\frac{S}{\hat{\sigma}} - \frac{\epsilon_n^2}{\hat{\sigma}^3} = 0$$

$$\sigma'' + \frac{\gamma'}{\beta^2\gamma}\sigma' + K_r\,\sigma - \frac{\kappa_s}{\beta^3\gamma^3\,\sigma} - \frac{\epsilon_n^2}{\beta^2\gamma^2\,\sigma^3} = 0$$

Looking for an "equilibrium" solution $\sigma_{eq} = \sigma_o \gamma^n$ (KJ Kim)

==> all terms must have the same dependence on γ

Space charge dominated beam

$$\sigma_q = \frac{1}{\gamma'}\sqrt{\frac{2I}{I_A\left(1+4\Omega^2\right)\beta\gamma}}$$

Emittance dominated beam

$$\sigma_\varepsilon = \sqrt{\frac{2\varepsilon_n}{\gamma'\sqrt{\left(1+4\Omega^2\right)}}}$$

Beam around transition

$$\sigma_T = \sqrt{\frac{1}{2}\left(\sigma_q^2 + \sqrt{\sigma_q^4 + 4\sigma_\varepsilon^4}\right)} \xrightarrow{\gamma\to\infty} \sigma_\varepsilon$$

L. Serafini and M. Ferrario, SPIE-LASER'99 Conf., San Jose, CA 1999.

$$\sigma'' + \frac{\gamma'}{\beta^2\gamma}\sigma' + K_r\,\sigma - \frac{\kappa_s}{\beta^3\gamma^3\,\sigma} - \frac{\epsilon_n^2}{\beta^2\gamma^2\,\sigma^3} = 0$$

Space charge parameter

$$\rho = \frac{I\sigma^2}{2\beta\gamma I_A \varepsilon_n^2} = \left(\frac{\sigma_q}{\sigma_\varepsilon^2}\sigma_T\right)^2$$

Transition Energy (ρ=1)

$$(\beta\gamma)_{tr} = \frac{I\sqrt{2}}{\gamma' I_A \varepsilon_n \sqrt{\left(1+4\Omega^2\right)}}$$

Beam spot @tr

$$\sigma_{tr} \approx 1.2\sigma_\varepsilon$$

Emittance Compensation in a Photoinjector: Controlled Damping of Plasma Oscillations

∀ ε_n oscillations are driven by Space Charge and chromatic effects

•propagation close to the "invariant envelope" solution allows control of ε_n oscillation "phase"

∀ε_n sensitive to SC up to the transition energy

Emittance Compensation in a HB Linac:

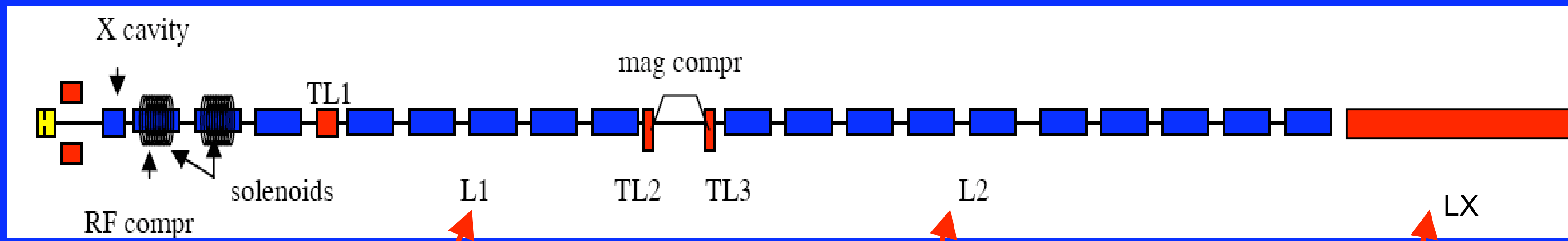
∀ HB Linac behaves like a HB Photoinjector

•propagation close to the equilibrium solution allows control of plasma oscillation "phase" and does not require external focusing (no quads)

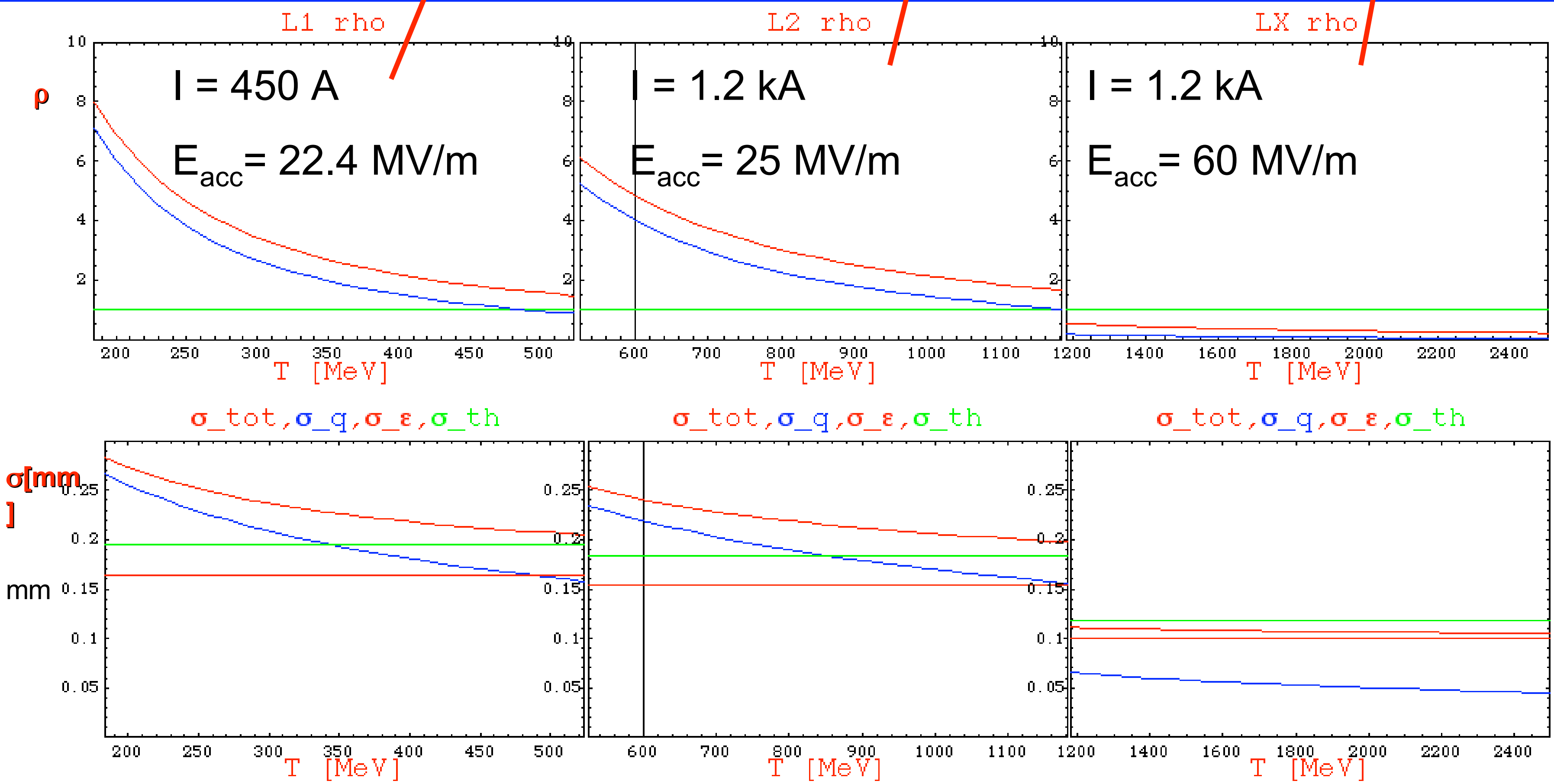
∀ε_n sensitive to SC up to the transition energy

•the goal is to have a minimum ε_n at the exit of the linac

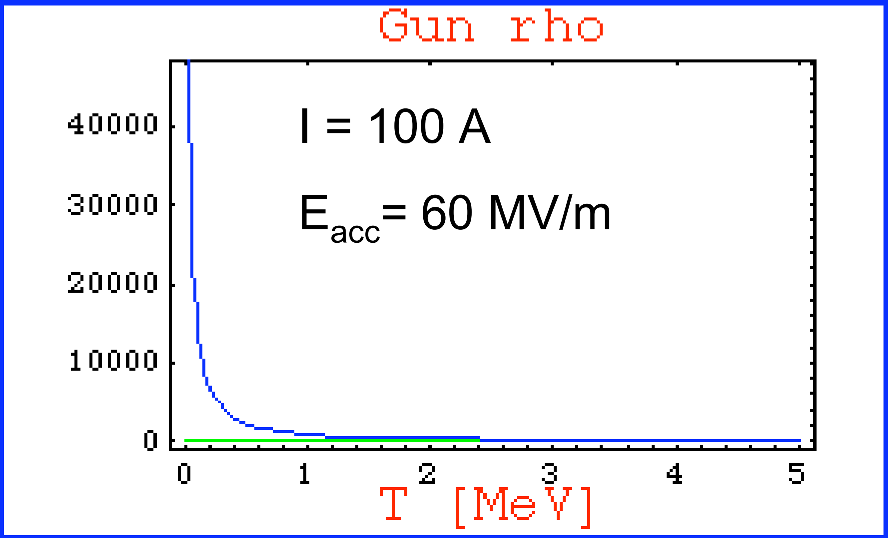
The S-band TW example (1 GeV - 1 kA)

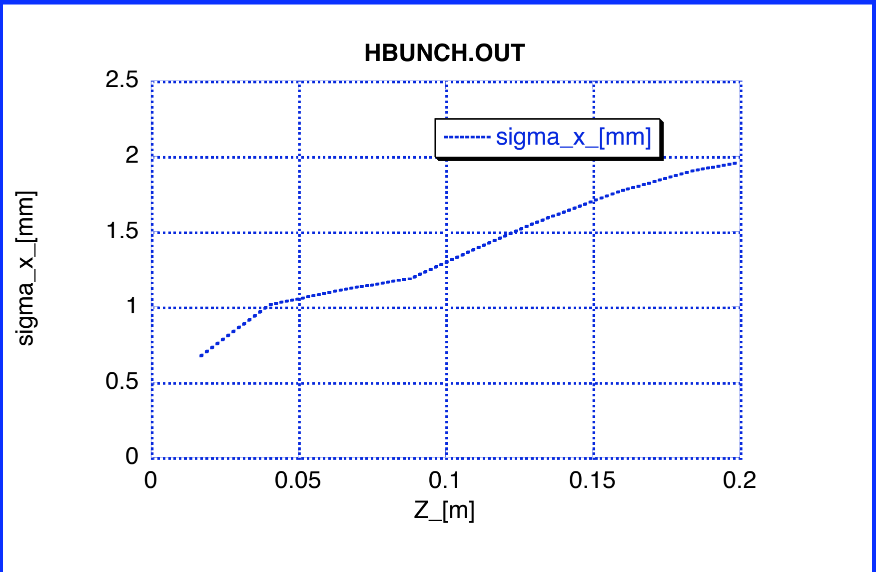


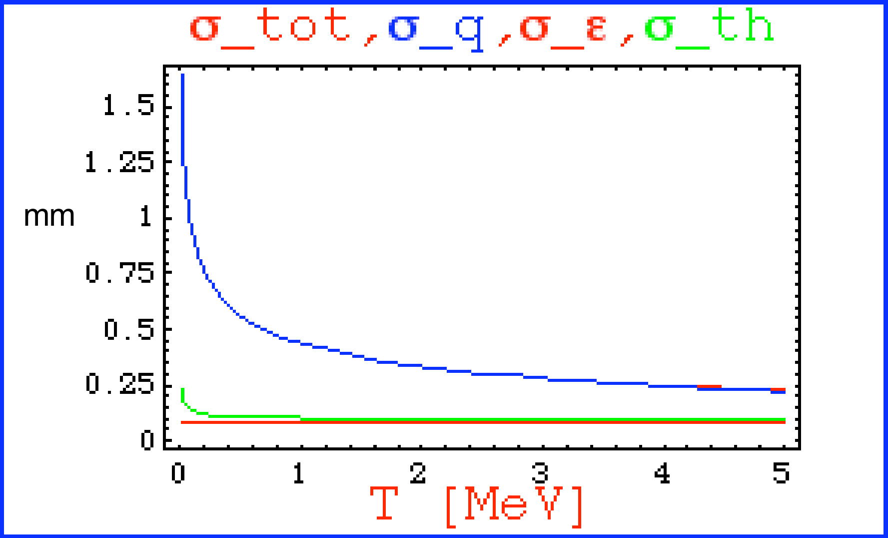
$$\varepsilon_{th} = 0.6\mu m$$



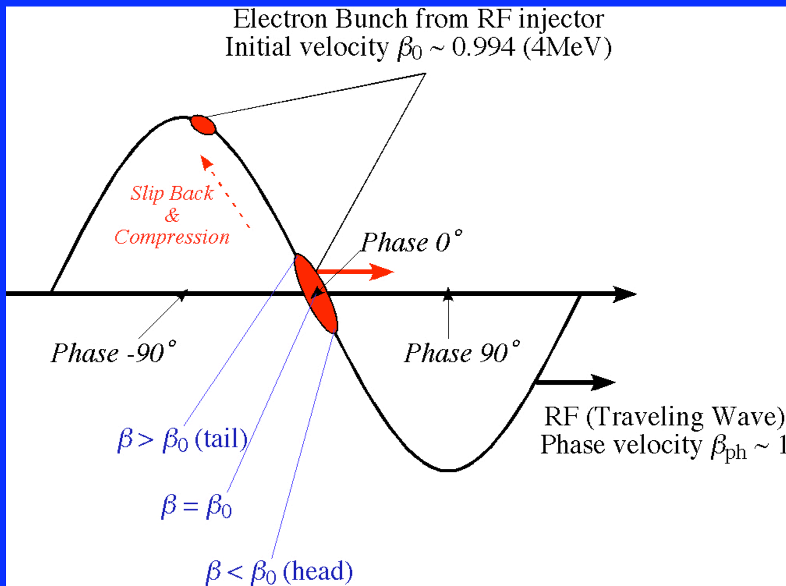
Matching in the gun





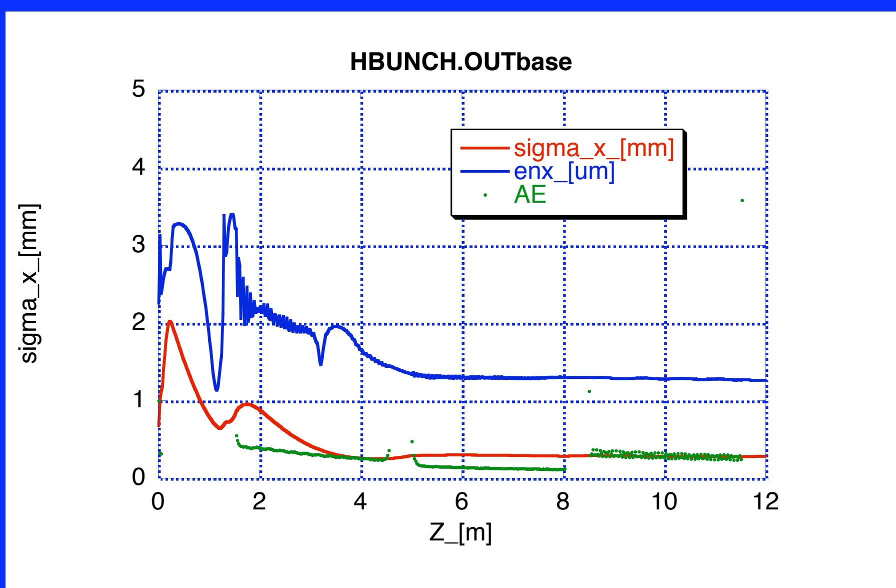


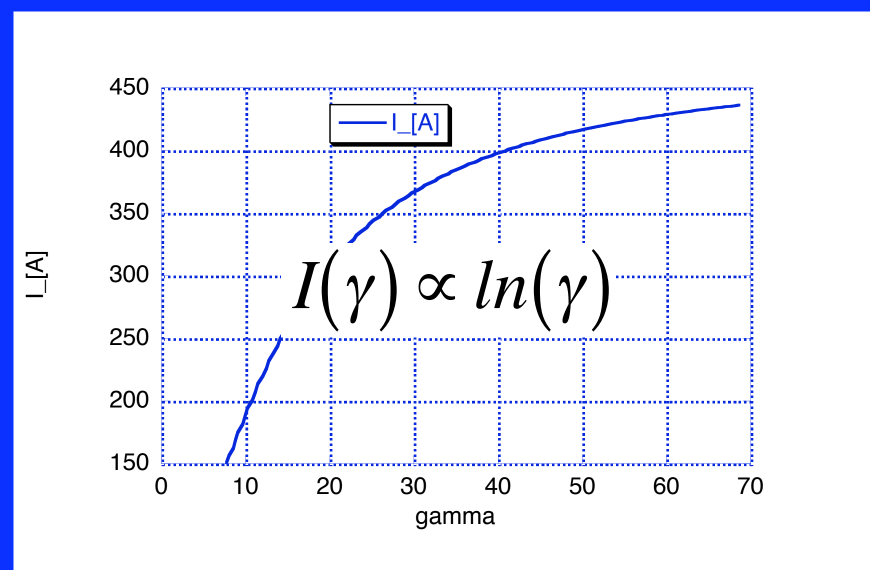
Matching in the RF compressor



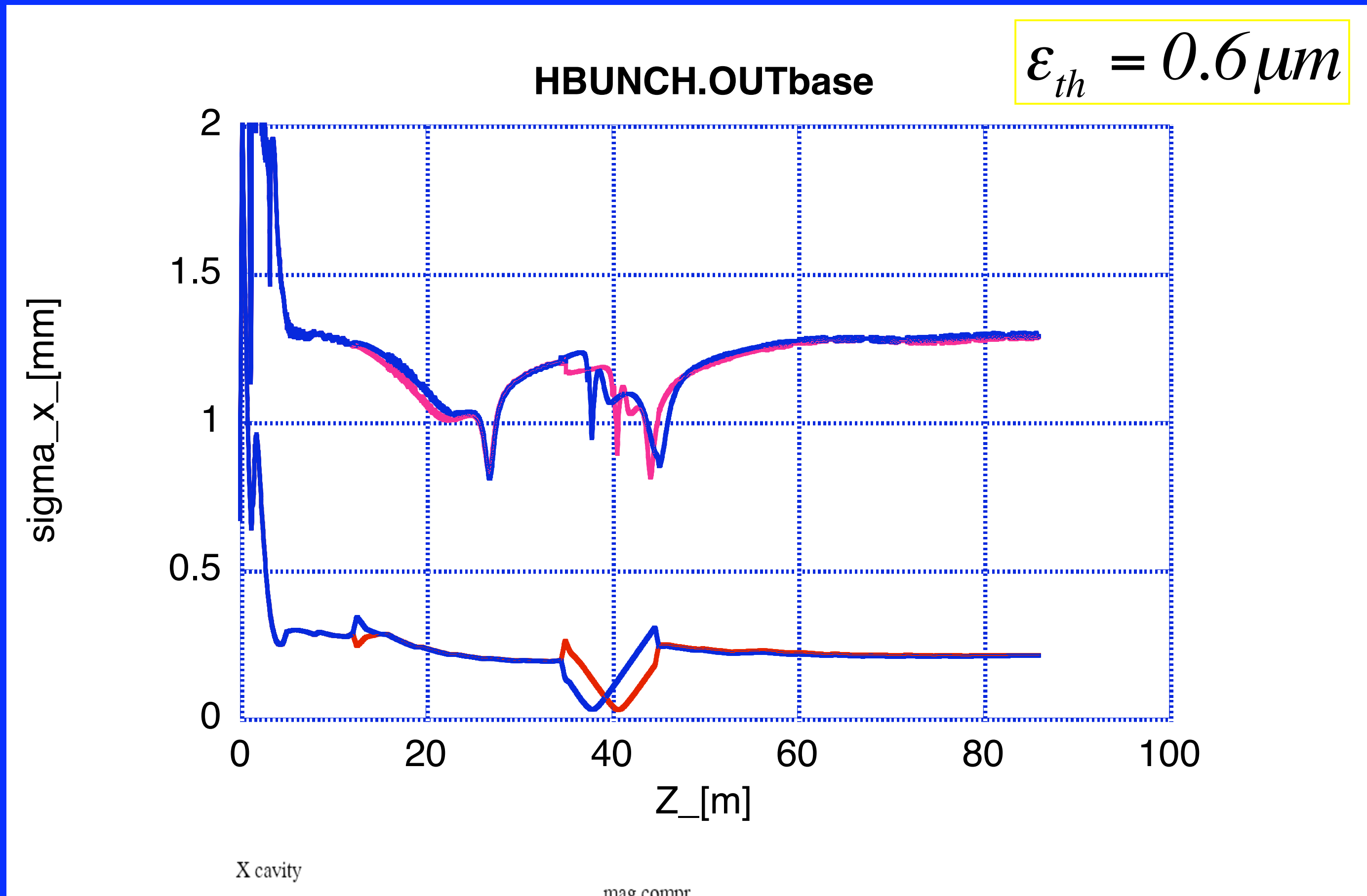
$$\sigma_q = \frac{1}{\gamma'(z)}\sqrt{\frac{2I(z)}{I_A\left(1+4\Omega^2(z)\right)\beta\gamma(z)}}$$

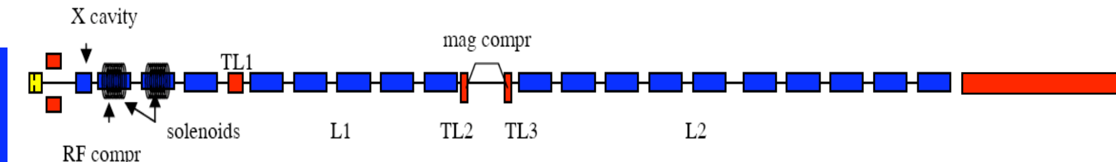
$$\Omega(z) = f(z) \Rightarrow \sigma_q = const\,?$$





Step by step optimization not always sufficient





BEAM DYNAMICS STUDIES FOR THE SPARXINO LINAC*

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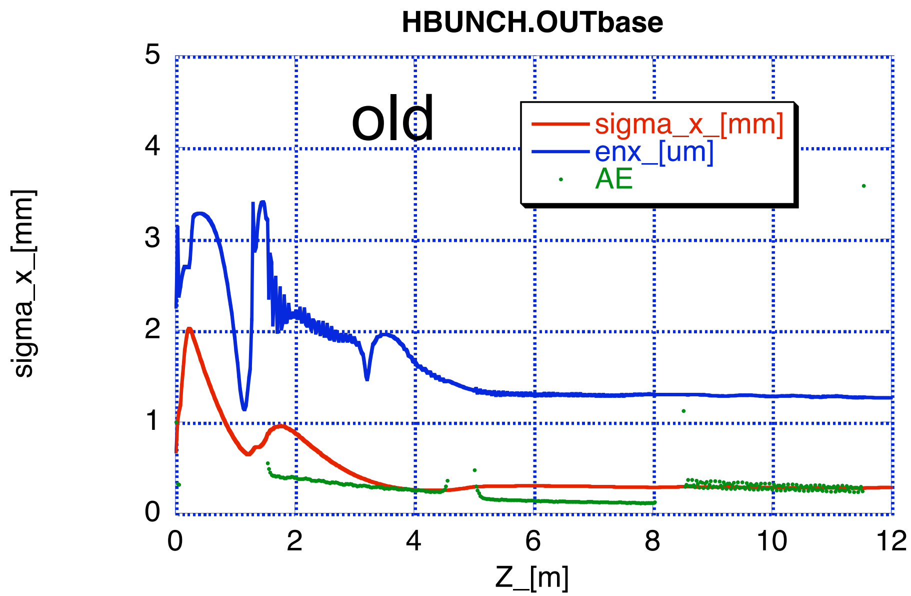
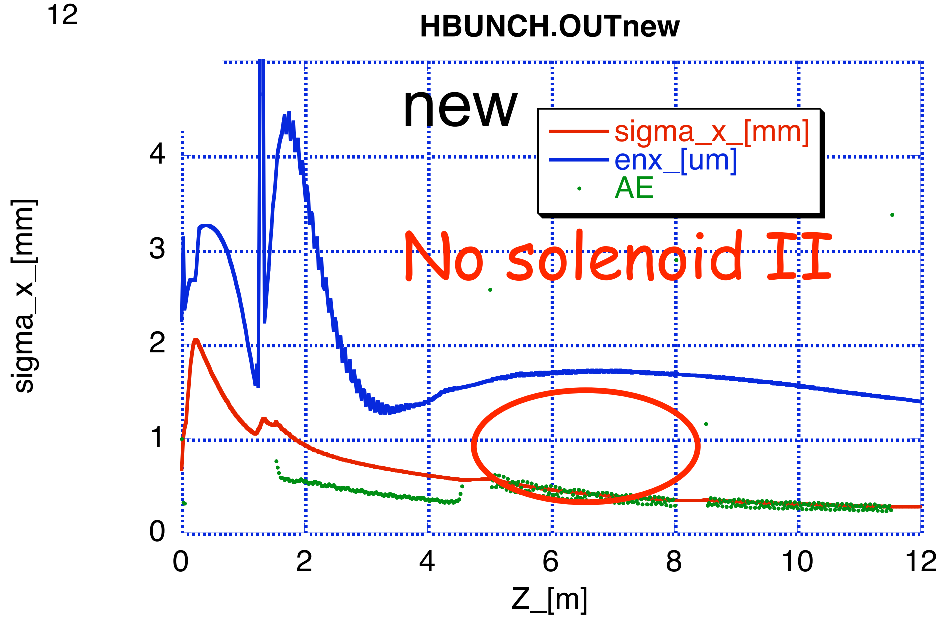
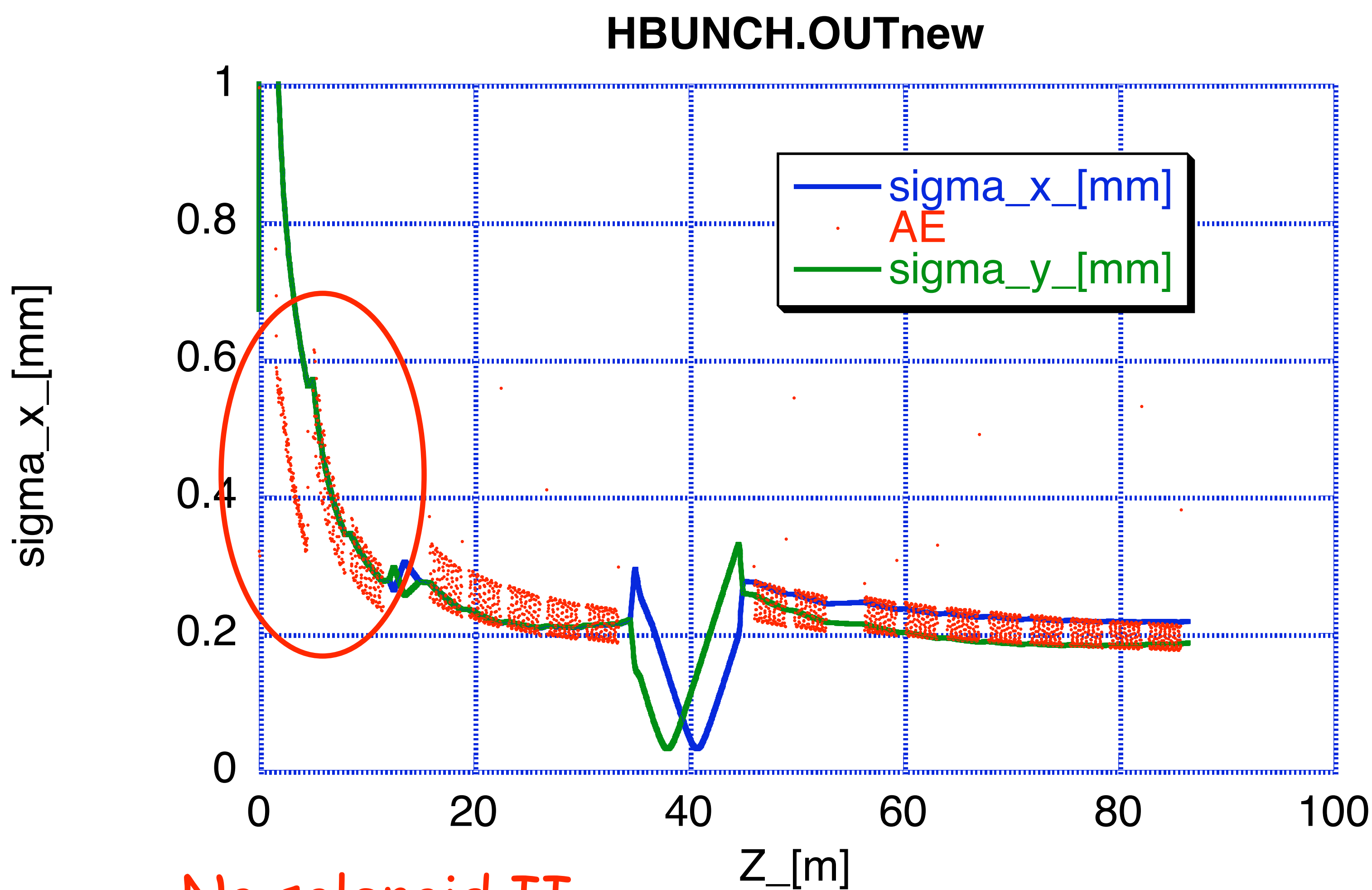
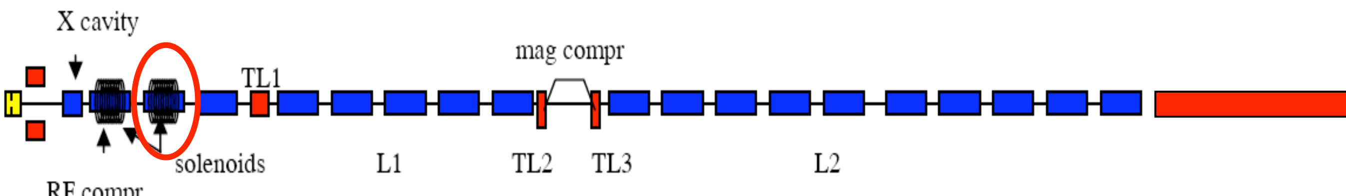
Velocity Bunching Tuning



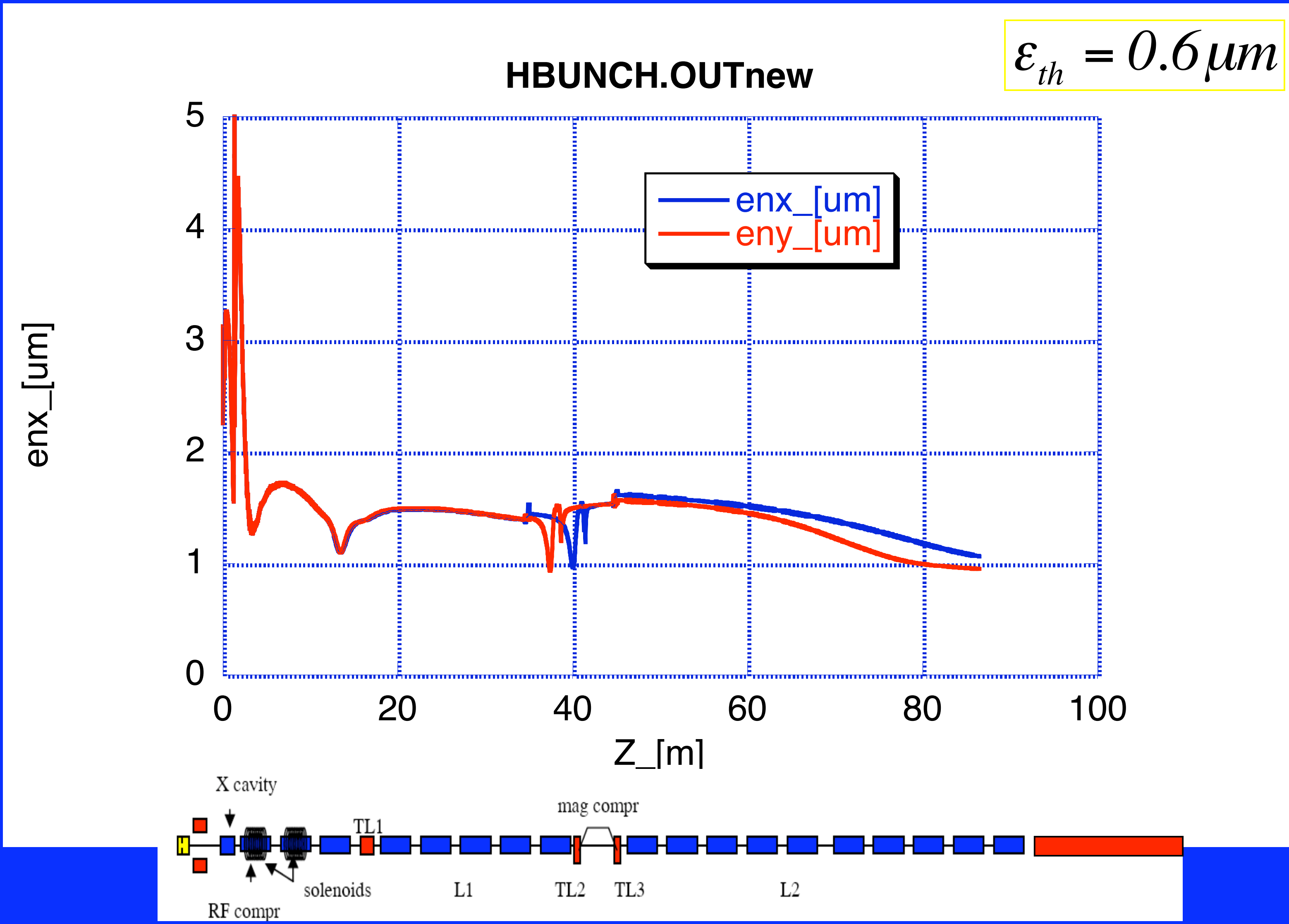




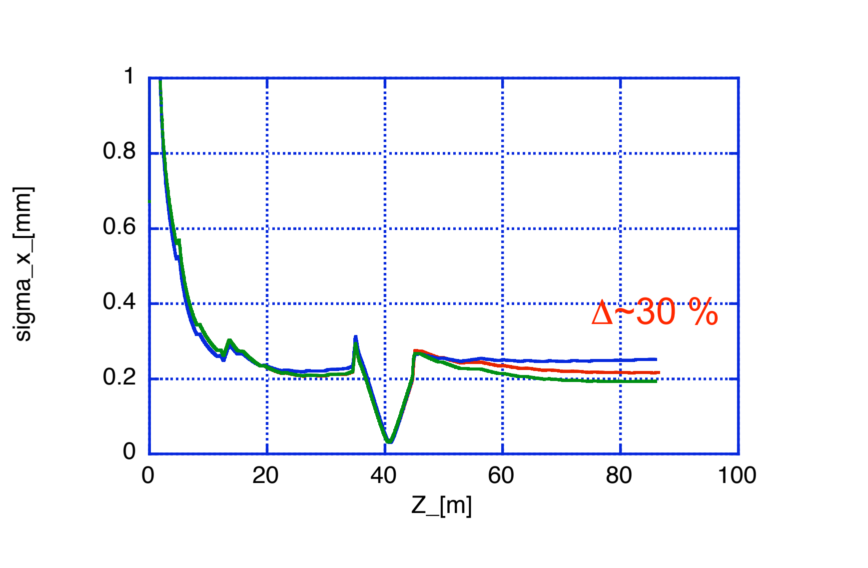
No solenoid II

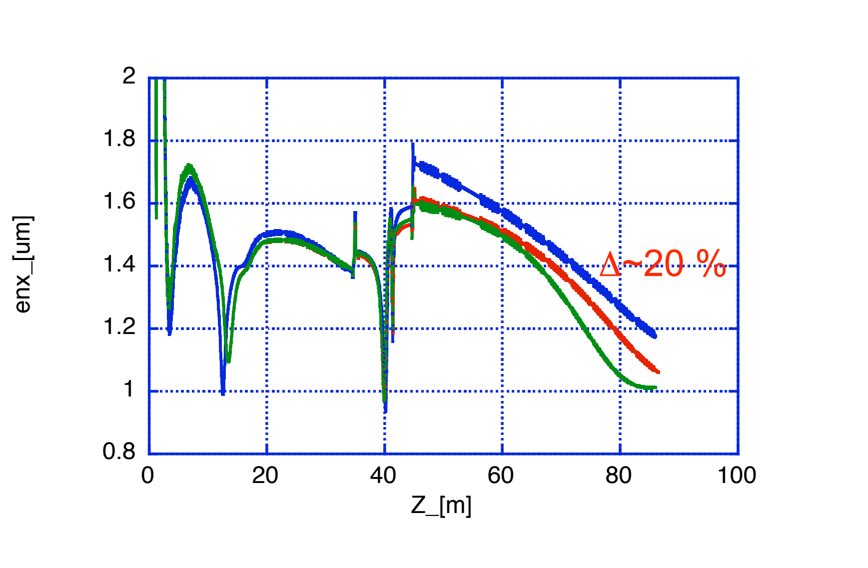


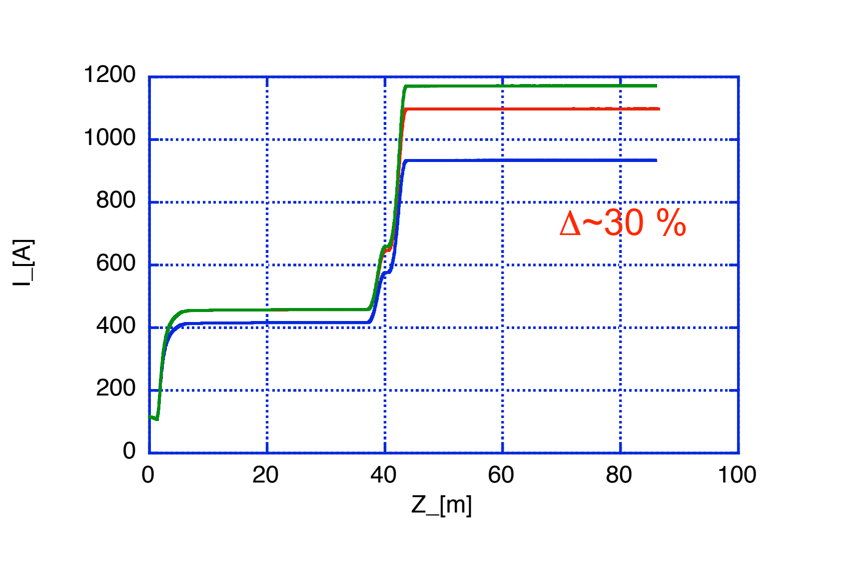
The final phase of the plasma oscillation can be tuned at the injector level ("global" optimization)



+-1 deg RF phase error



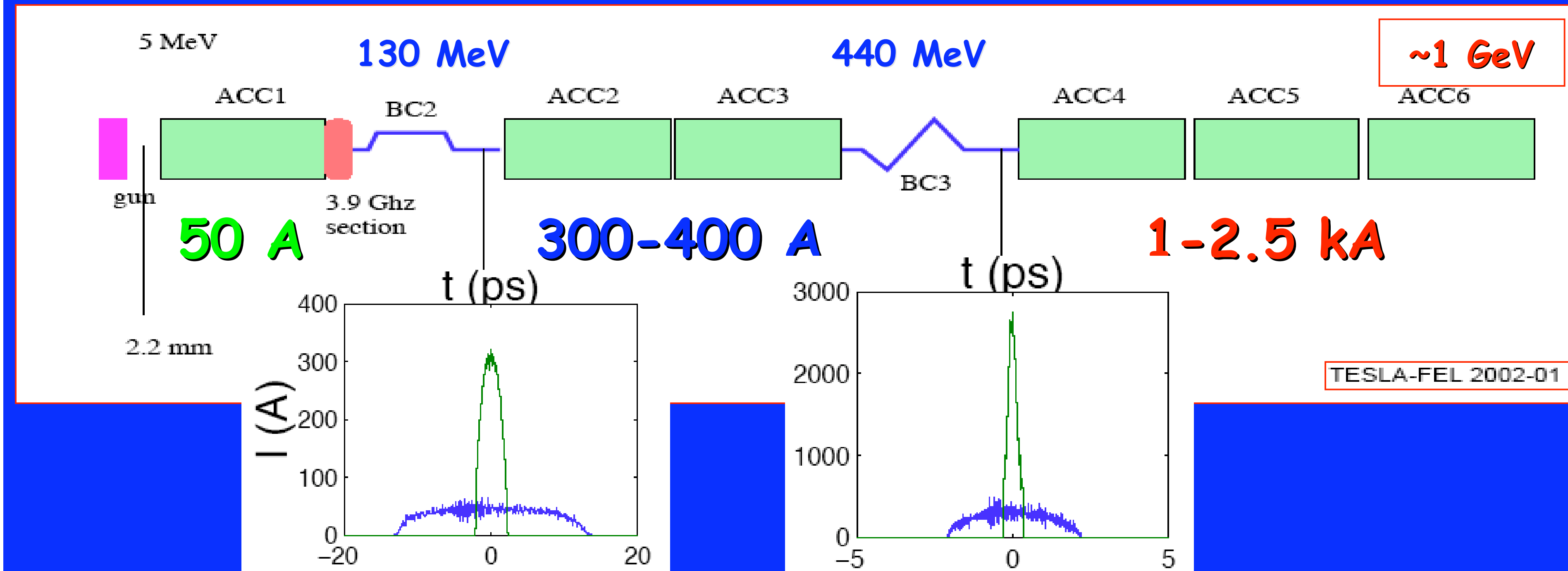




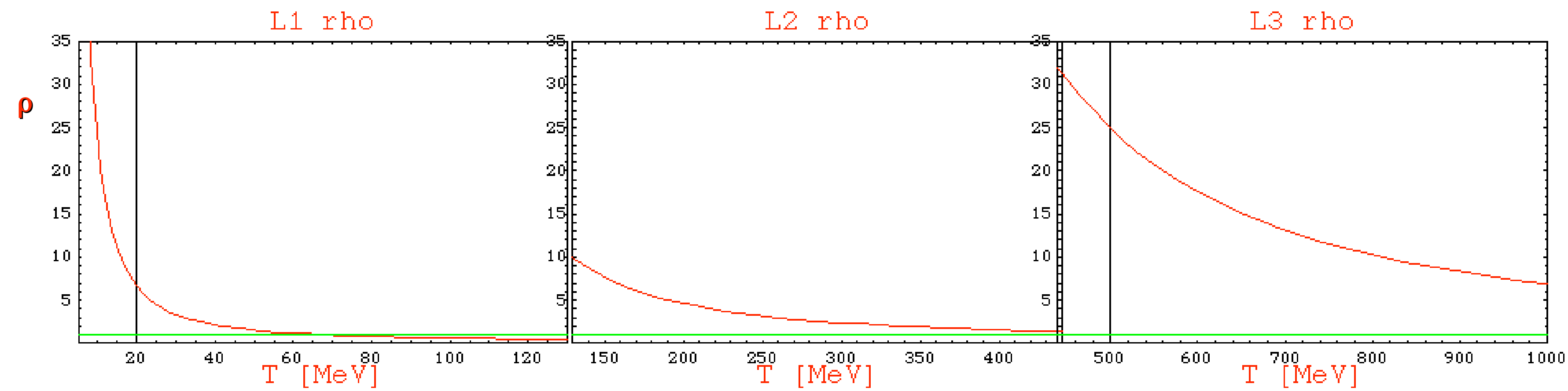
Emittance fluctuations driven by current phase dependent fluctuations (as expected)

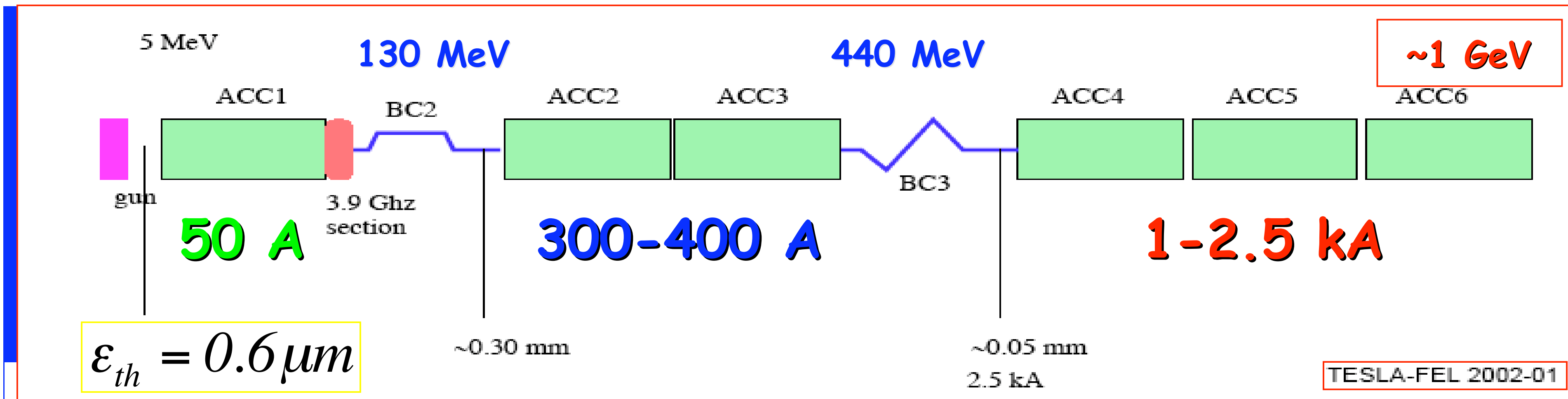
The L-band SW example (1 GeV - 2.5 kA)

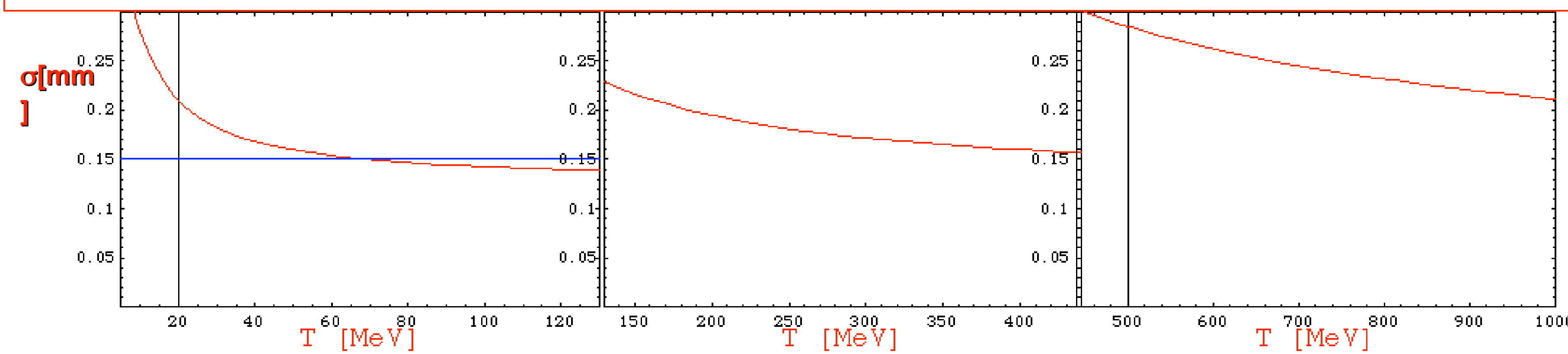
SASE FEL at the TESLA Facility - Phase 2



Linacs:			
parameters	ACC1	ACC2-3	ACC4-5-6
Grad (Mv/m)	12.5/20(4 last cav.)	20	20
RF phase (°)	-9.80	-30.0	0.0
input E (GeV)	0.005	0.13	0.44
final E (GeV)	0.13	0.44	0.95
final $\delta p/p$ (%)	0.93	0.55	0.22
σ_z (μm)	2200	300	50
Compressors:			
parameters	BC2	BC3	
type	standard	S-chic	
Angles (°)	18	3.8	
R_{56} (mm)	-181	-49	
T_{566} (mm)	295	75	
E (GeV)	0.13	0.44	
final $\hat{I}$ (A)	320	2500	


L1 rho
L2 rho
L3 rho
ρ
T [MeV]
T [MeV]
T [MeV]


5 MeV
130 MeV
440 MeV
~1 GeV
ACC1
BC2
ACC2
ACC3
ACC4
ACC5
ACC6
gun
3.9 Ghz section
BC3
50 A
300-400 A
1-2.5 kA
$\varepsilon_{th} = 0.6\mu m$
~0.30 mm
~0.05 mm
2.5 kA
TESLA-FEL 2002-01

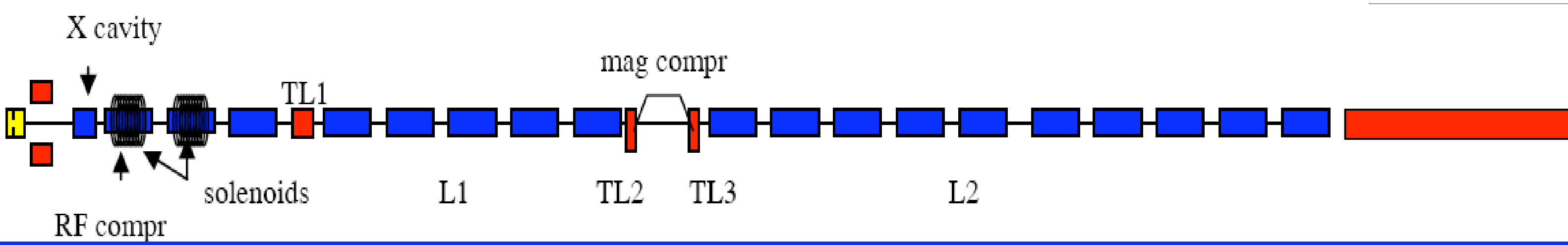

σ[mm]
T [MeV]
T [MeV]
T [MeV]

Conclusions

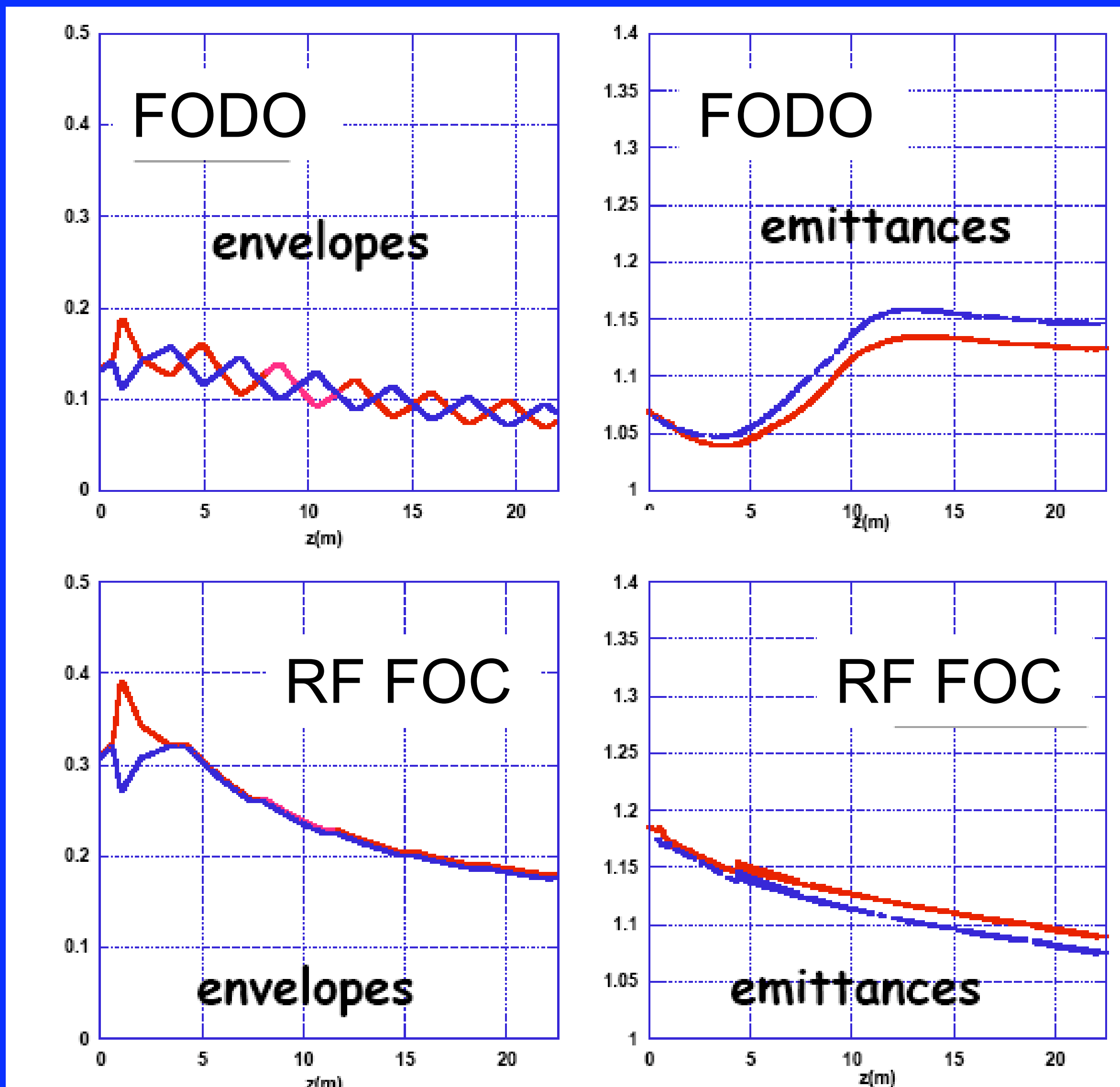
∀ HB Linac behaves like a HB Photoinjector up to the transition energy

•propagation close to the equilibrium solution allows control of emittance oscillation "phase"

•external focusing not necessary (no quads)



PARMELA computations in L1



Advantages of the matching based on the invariant envelope regime:

- **no need of quads**
- **better control of emittance**

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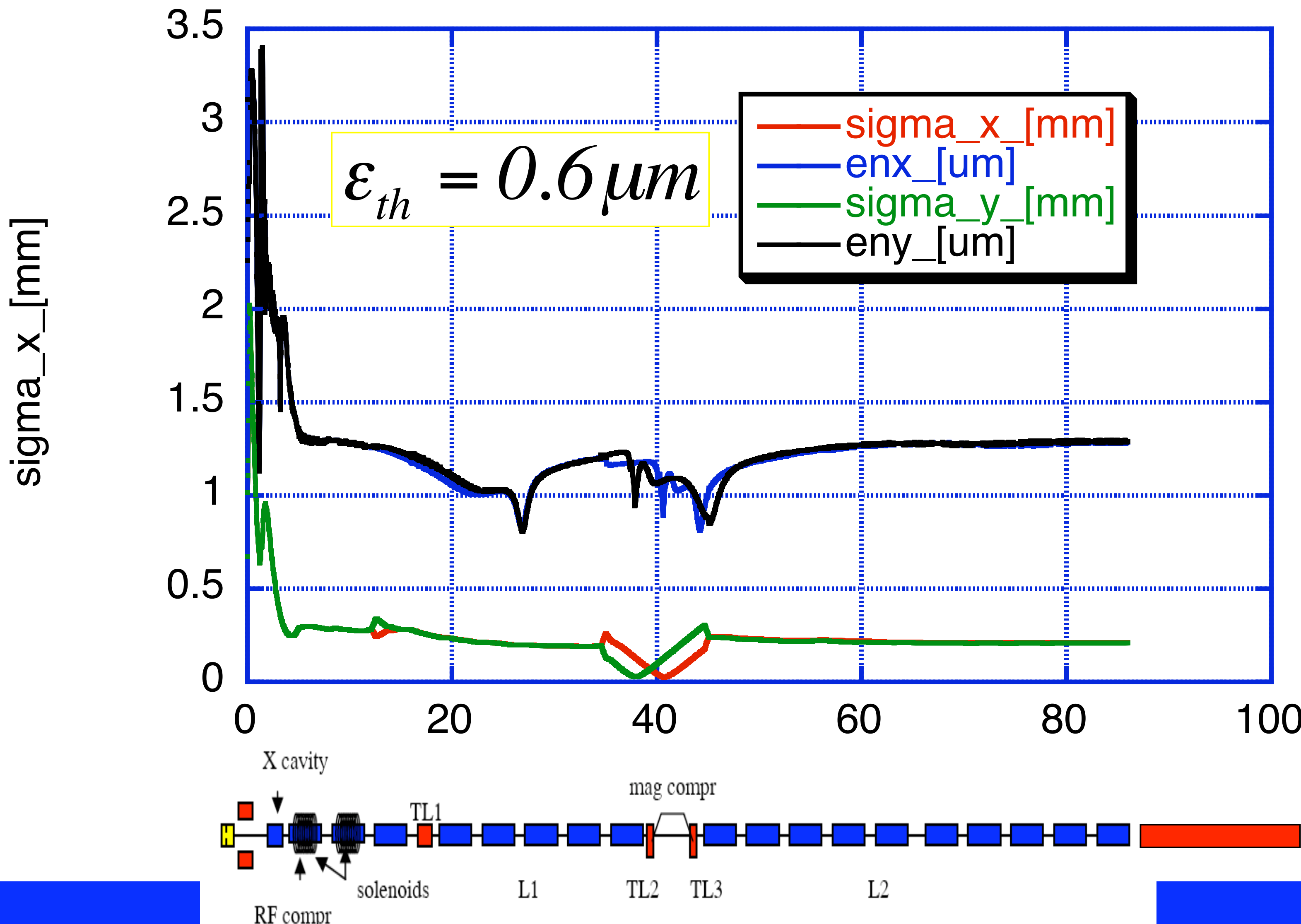
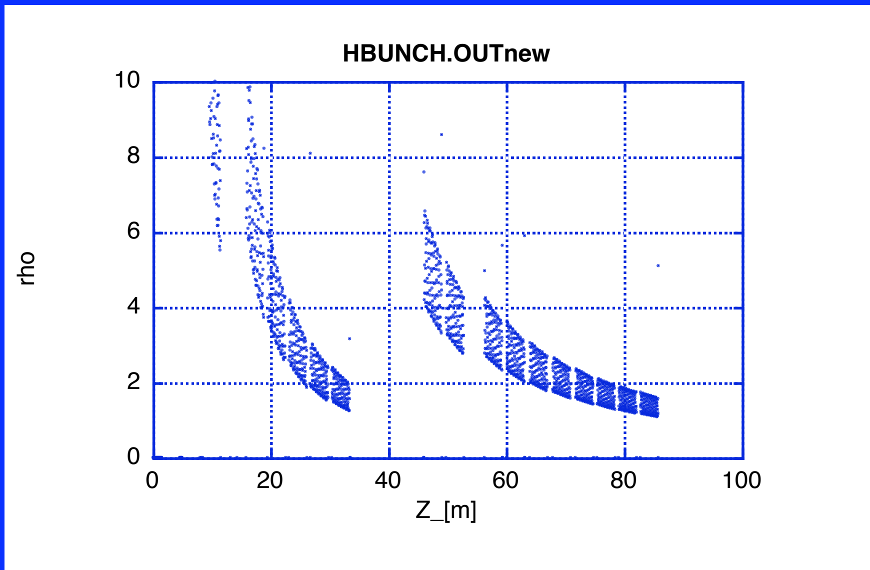
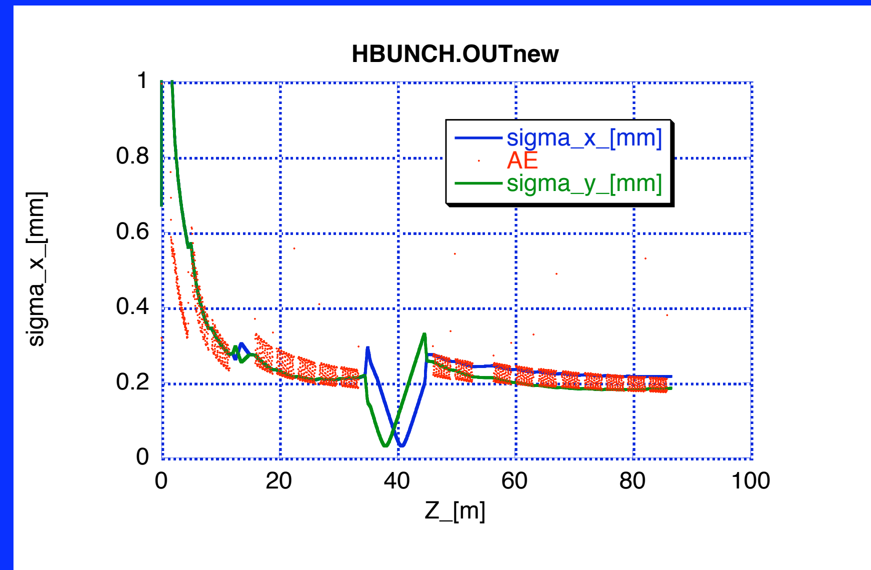
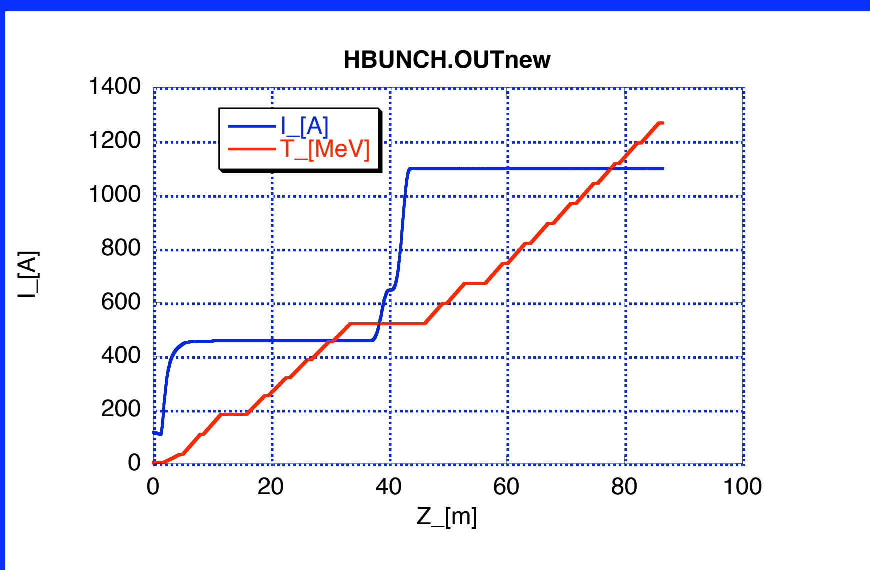
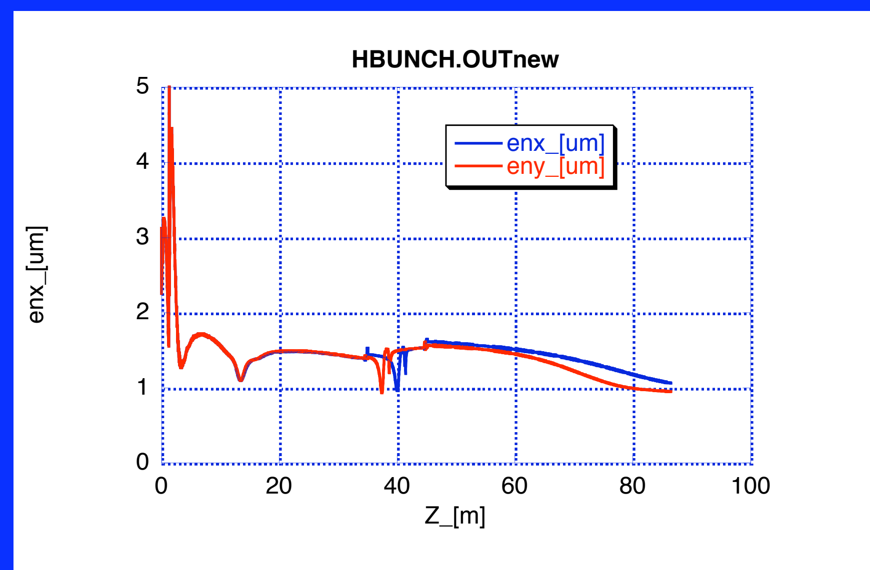



HBUNCH.OUTnew
rho
0
2
4
6
8
10
0
20
40
60
80
100
Z_[m]


HBUNCH.OUTnew
sigma_x_[mm]
0
0.2
0.4
0.6
0.8
1
0
20
40
60
80
100
Z_[m]
sigma_x_[mm]
AE
sigma_y_[mm]


HBUNCH.OUTnew
I_[A]
0
200
400
600
800
1000
1200
1400
0
20
40
60
80
100
Z_[m]
I_[A]
T_[MeV]

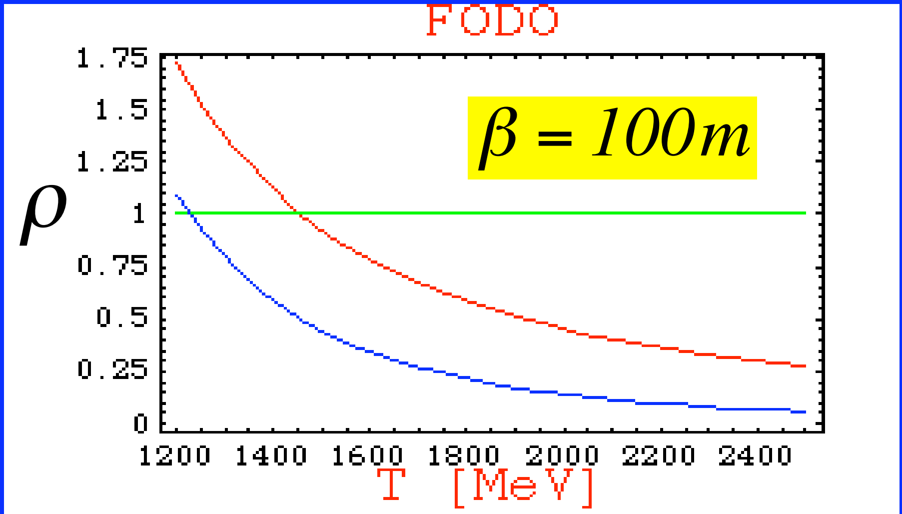

HBUNCH.OUTnew
enx_[um]
0
1
2
3
4
5
0
20
40
60
80
100
Z_[m]
enx_[um]
eny_[um]

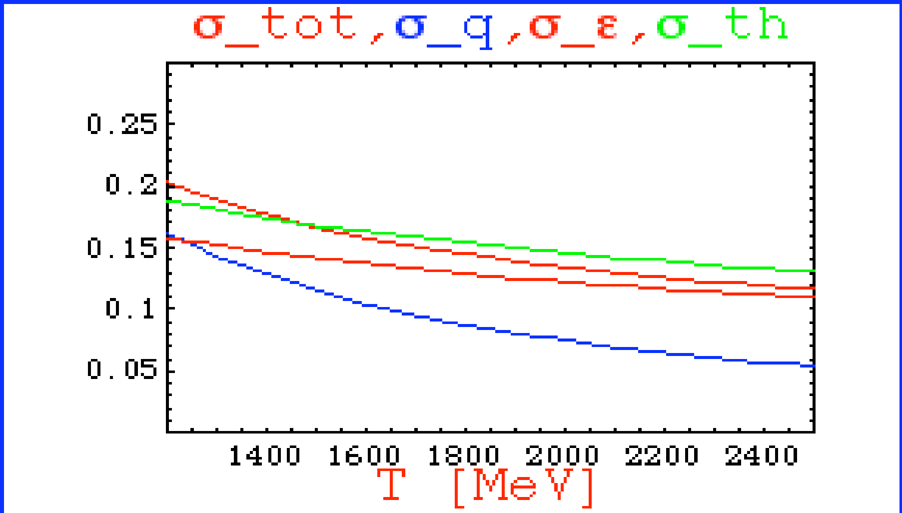
What about transport to the undulator?

$$\overline{\sigma}_q = \sqrt{\frac{I\beta^2}{2I_A\gamma^3}}$$

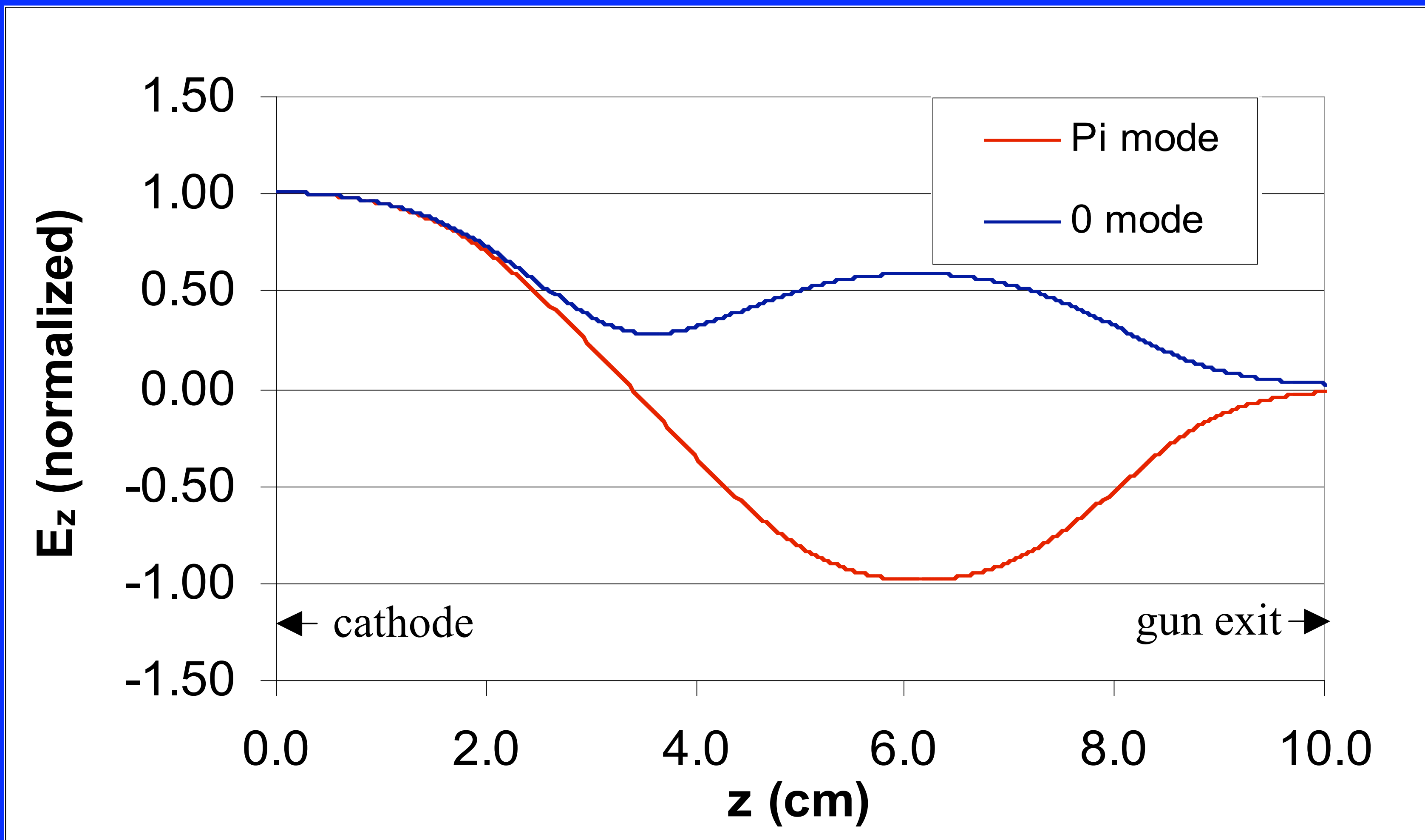
$$\overline{\sigma}_\varepsilon = \sqrt{\frac{\beta\varepsilon_n}{\gamma}}$$

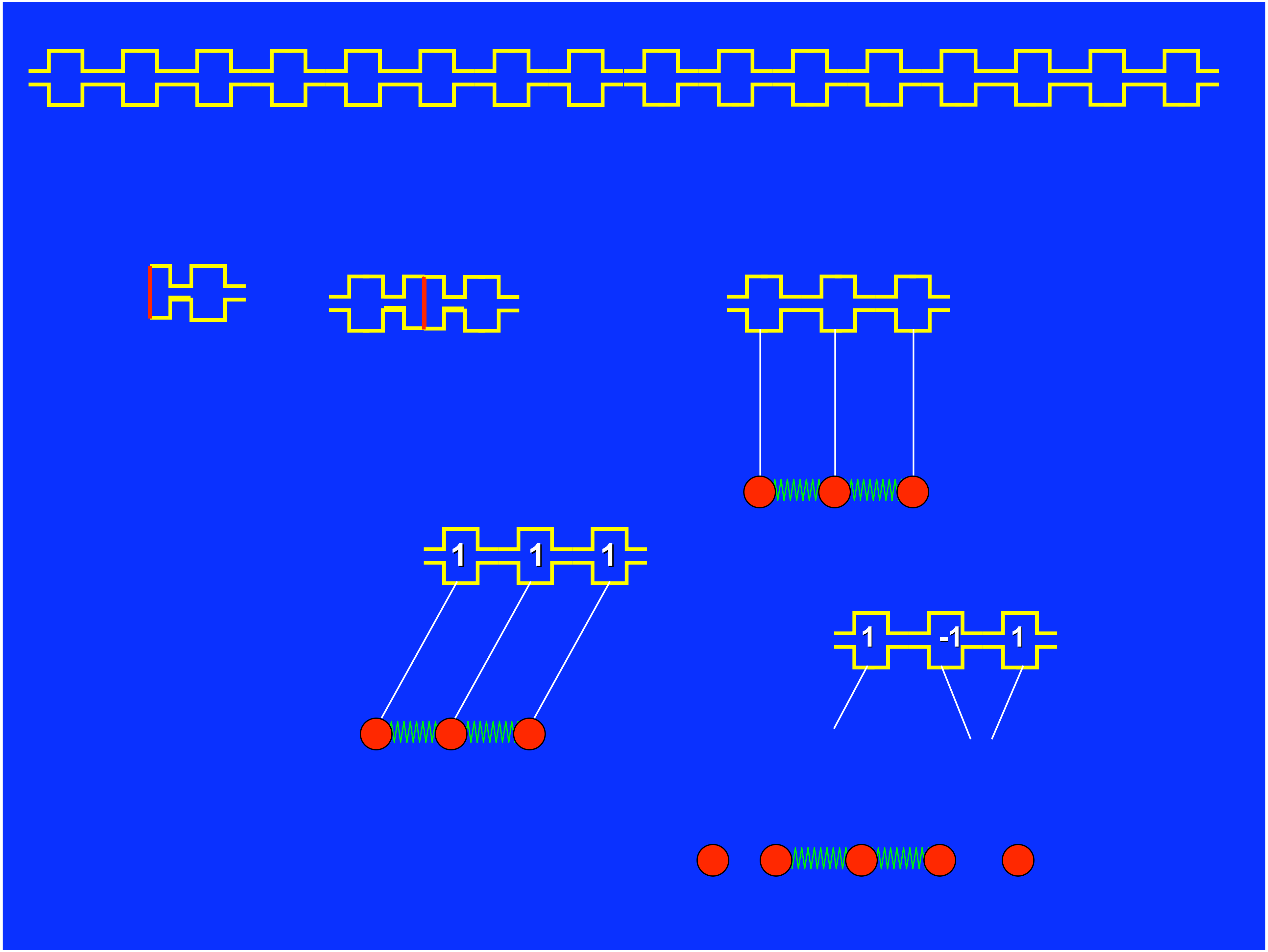
$$\overline{\sigma}_T = \sqrt{\frac{1}{2}\left(\overline{\sigma}_q^2 + \sqrt{\overline{\sigma}_q^4 + 4\overline{\sigma}_\varepsilon^4}\right)}$$



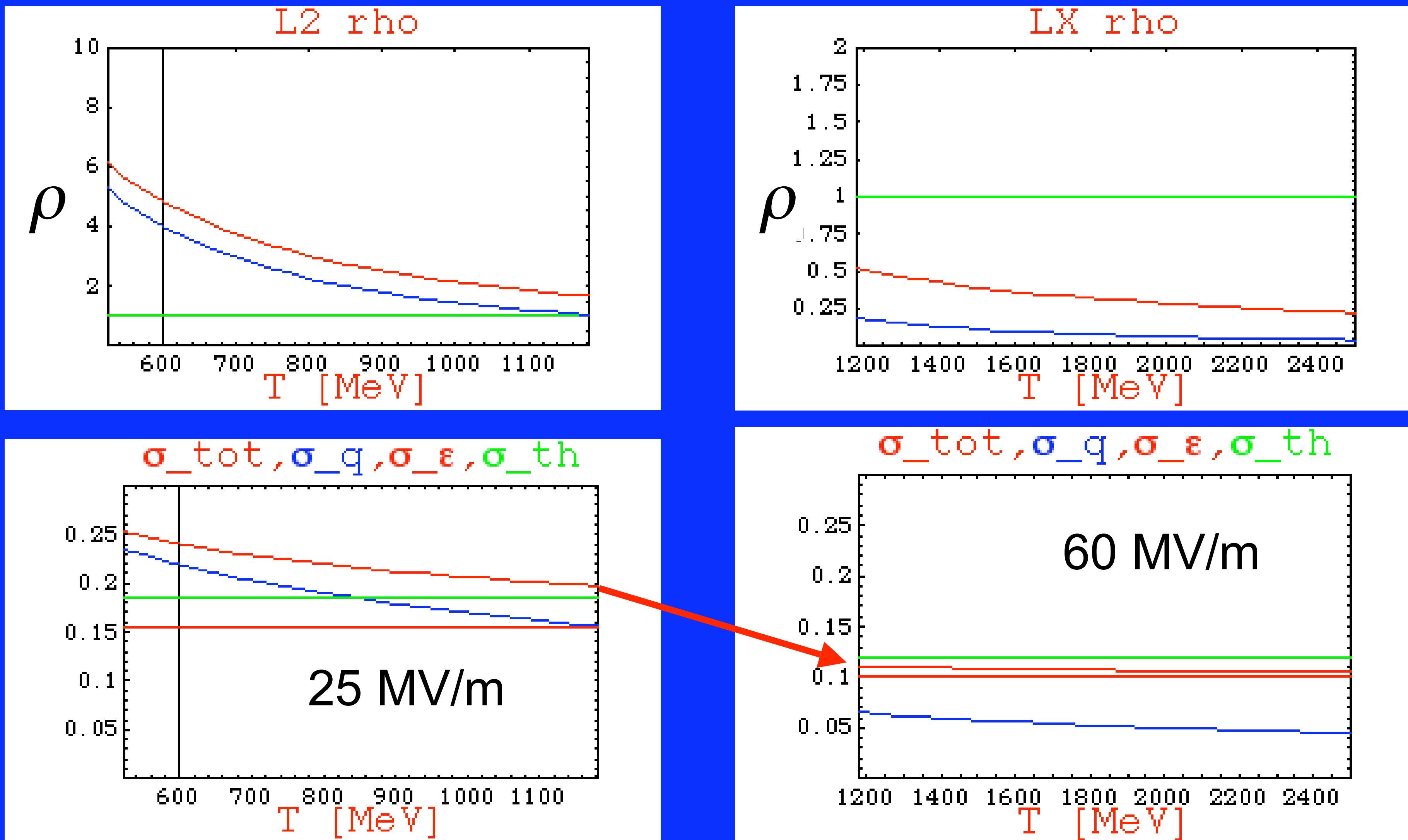


π and 0 mode vs position




1
1
1
1
-1
1

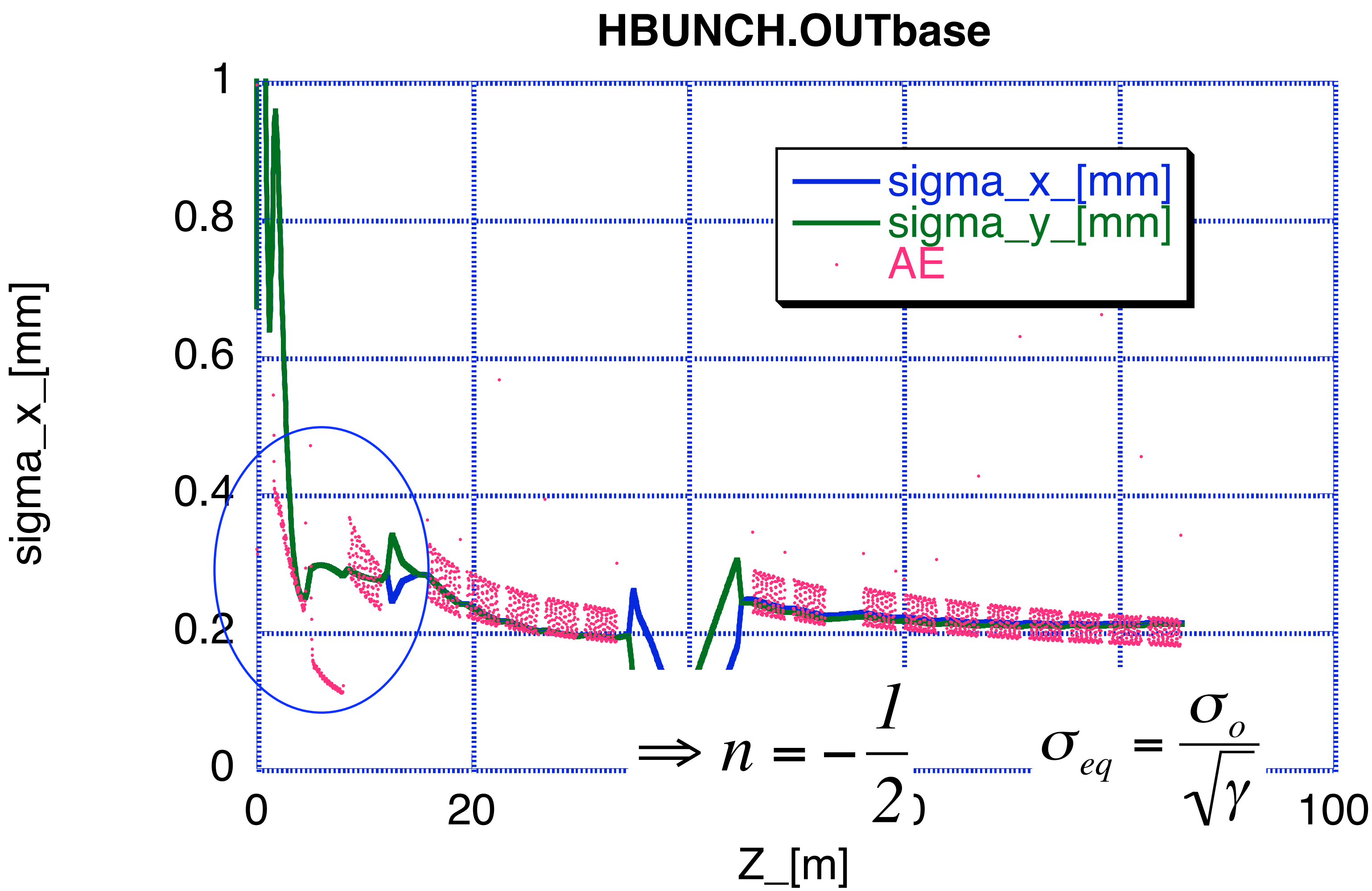
Transfer line from S-band to X-band linac required for proper matching



$$\sigma'' + \frac{\gamma'}{\beta^2\gamma}\sigma' + K_r\,\sigma - \frac{\kappa_s}{\beta^3\gamma^3\,\sigma} - \frac{\epsilon_n^2}{\beta^2\gamma^2\,\sigma^3} = 0$$

$$K_r = \left(\frac{\gamma'}{\gamma}\right)^2\Omega^2\ , \qquad \Omega^2 = \frac{1}{\sin^2\phi}\left[\frac{\eta}{8} + \left(\frac{B_z c}{E_0}\right)^2\right]\ , \qquad \kappa_s = Ig(\zeta)/2I_0$$

$\eta = 1$



$$\Rightarrow n = -\frac{1}{2}$$

$$\sigma_{eq} = \frac{\sigma_o}{\sqrt{\gamma}}$$