Emittance Compensation in High Brightness RF Photo-Injectors: an introduction (to the SPARC project)

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Transverse Brightness of Electron Beams

$$B_n = \frac{2I}{\varepsilon_{nx}\varepsilon_{ny}} \quad \left[\frac{A}{m^2 rad^2}\right]$$

I = peak current

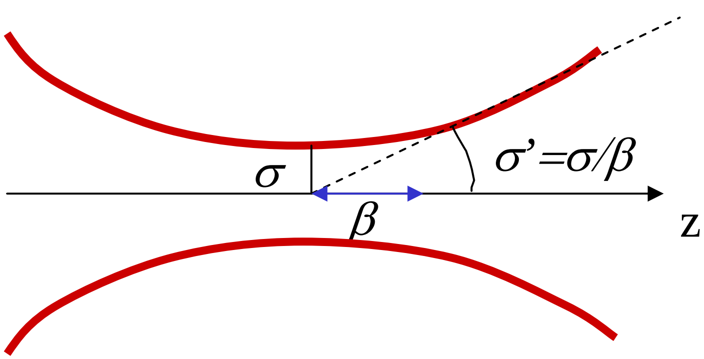
ε_{nx} = rms normalized transverse emittance

Quality Factor : beam peak current density normalized to the rms beam divergence angle

Round Beam : $\varepsilon_{nx} = \varepsilon_{ny}$, $J = I/\sigma^2$ $\Rightarrow$

$$B_n = \frac{2J}{(\sigma'\gamma)^2} = \frac{2J\sigma^2}{\varepsilon_n^2}$$

$$\sigma = \sqrt{\varepsilon_n \beta/\gamma}$$



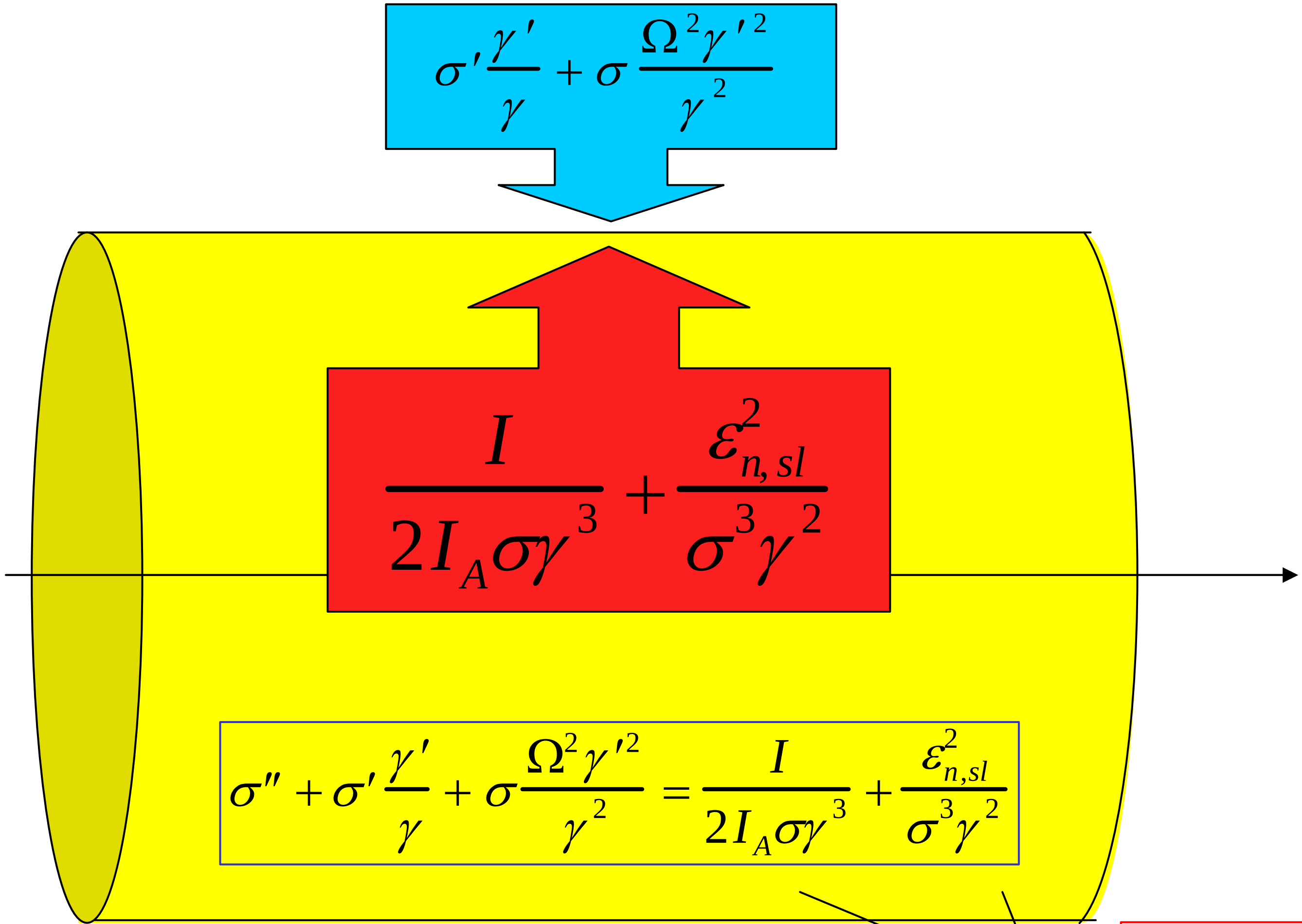
SASE-FEL Scaling Laws

$$\lambda_r^{MIN} \propto \frac{\varepsilon_n}{K}\left(\frac{\delta\gamma}{\gamma}\right)\sqrt{\frac{\left(1+K^2/2\right)}{I\gamma}} \propto \left(\frac{\delta\gamma}{\gamma}\right)\sqrt{\frac{\left(1+K^2/2\right)}{\gamma B_n K^2}}$$

$$L_g \propto \frac{\varepsilon_n \gamma^{3/2}}{K\sqrt{I\left(1+K^2/2\right)}} \propto \frac{\gamma^{3/2}}{K\sqrt{B_n\left(1+K^2/2\right)}}$$

R. Saldin et al. in *Conceptual Design of a 500 GeV e+e- Linear Collider with Integrated X-ray Laser Facility*, DESY-1997-048

Schematic View of the Envelope Equations



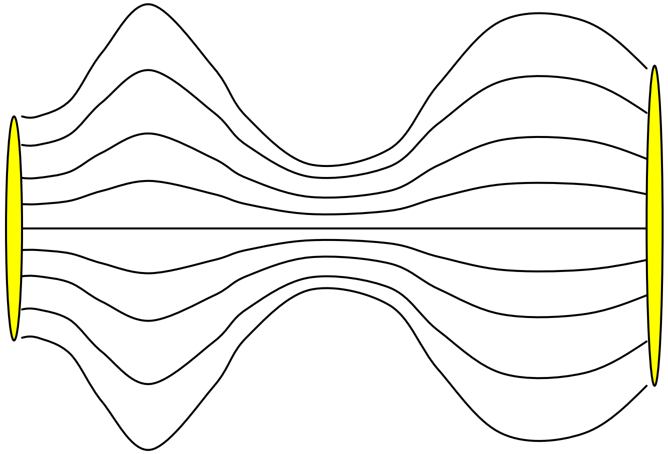
Laminarity Parameter ==> $\rho = \frac{I\sigma^2}{2\gamma I_A \varepsilon_n^2}$

The beam undergoes *two regimes* along the accelerator:

ρ>>1

$$\sigma'' + \sigma'\frac{\gamma'}{\gamma} + \sigma\frac{\Omega^2\gamma'^2}{\gamma^2} = \frac{I}{2I_A\sigma\gamma^3} + \frac{\varepsilon_{n,sl}^2}{\sigma^3\gamma^2}$$

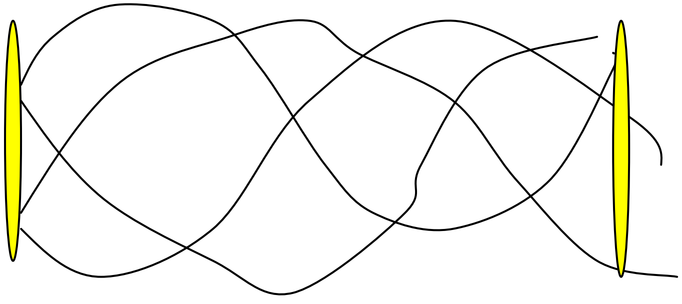
Laminar Beam



ρ<<1

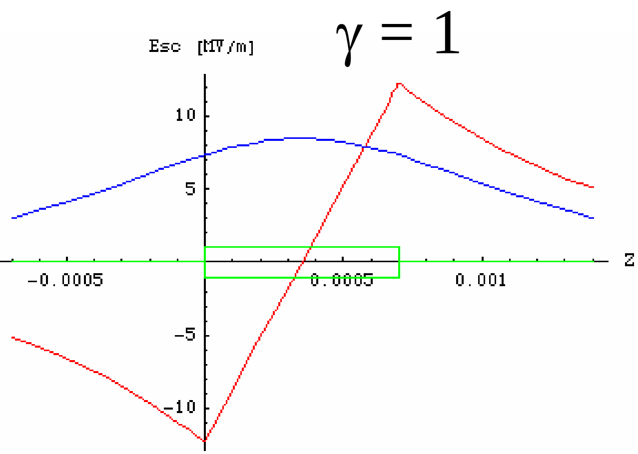
$$\sigma'' + \sigma'\frac{\gamma'}{\gamma} + \sigma\frac{\Omega^2\gamma'^2}{\gamma^2} = \frac{I}{2I_A\sigma\gamma^3} + \frac{\varepsilon_{n,sl}^2}{\sigma^3\gamma^2}$$

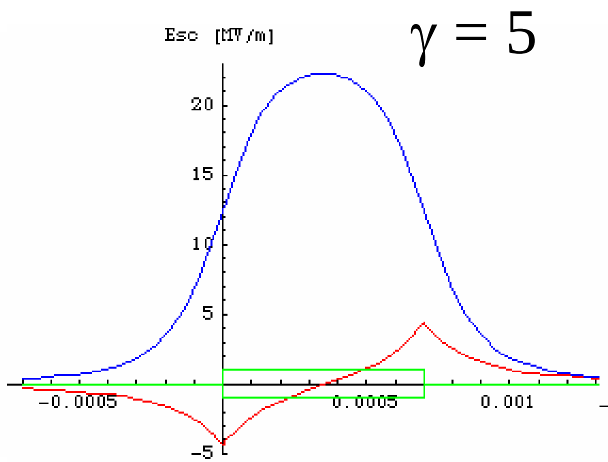
Thermal Beam

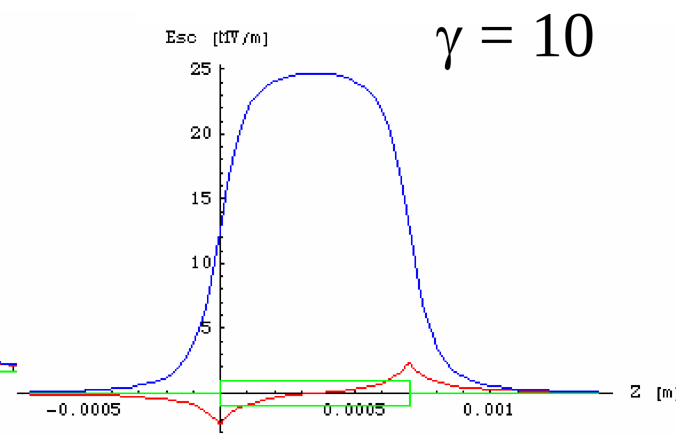


Laminar Beam-Transverse Space charge Field

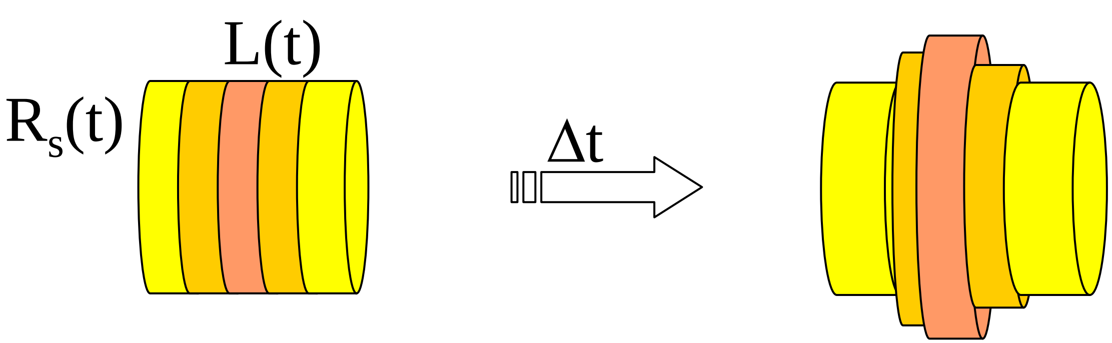
$$E_r^{sc}(\zeta_s)=\frac{Q}{4\pi\varepsilon_o R_s L}\left(\frac{1-\zeta_s/L}{\sqrt{(1-\zeta_s/L)^2+A_{r,s}^2}}+\frac{\zeta_s/L}{\sqrt{(\zeta_s/L)^2+A_{r,s}^2}}\right)=\frac{Q}{4\pi\varepsilon_o R_s L}g(\zeta_s,A_{r,s})$$



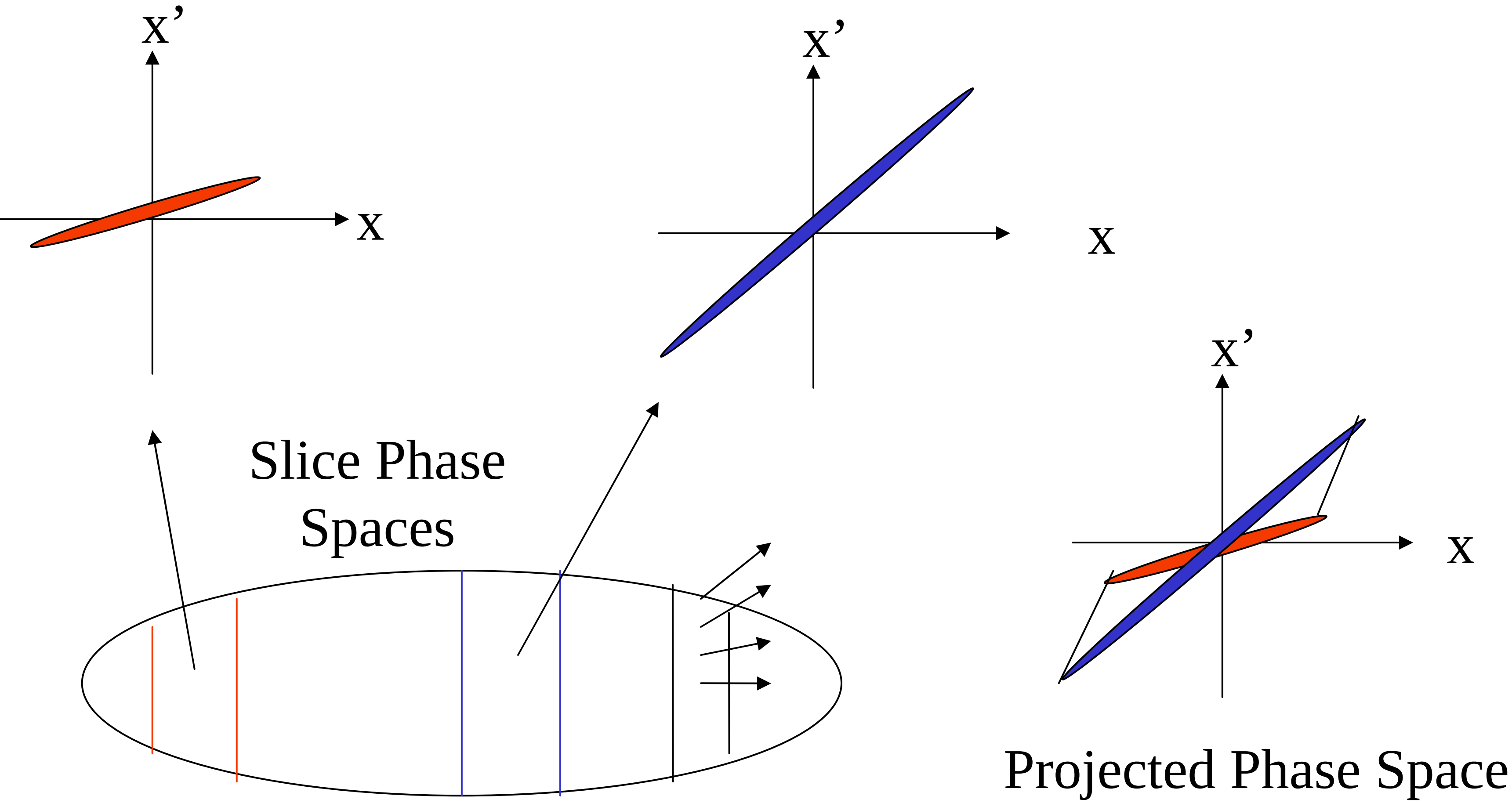




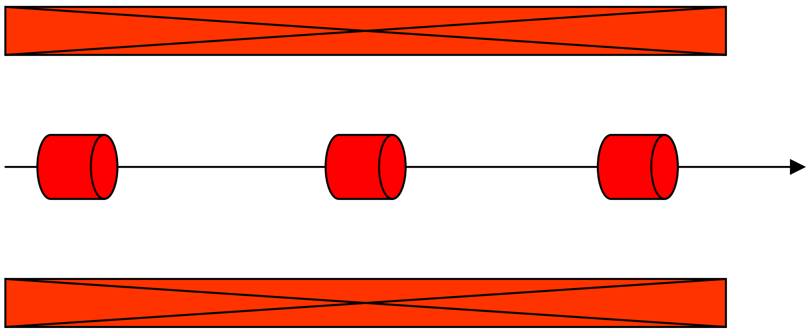
$$A_{r,s}\equiv R_s/(\gamma_s L)$$



Emittance Oscillations and Growth are driven by space charge differential defocusing in core and tails of the beam



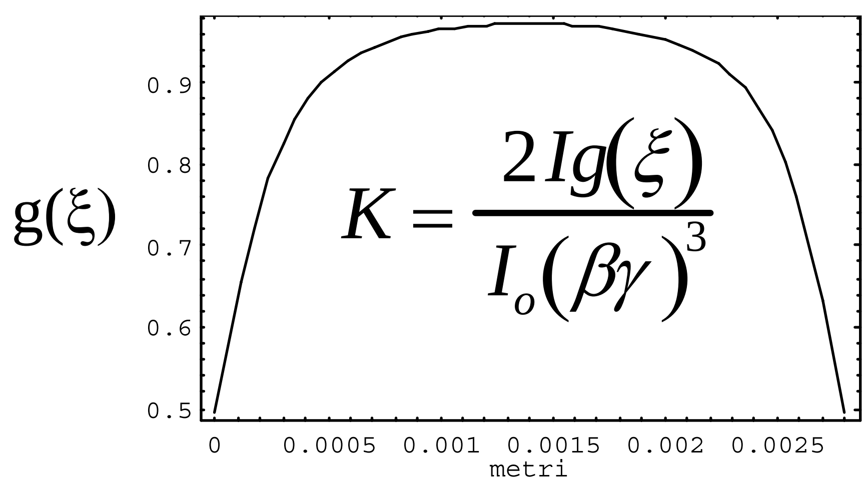
Simple Case: Transport in a Long Solenoid



$$\sigma'' + k_s^2 \sigma = \frac{K}{\sigma}$$

$\sigma'' = 0$ ==> Equilibrium solution ? ==> $$\sigma_{eq}(\xi) = \frac{\sqrt{K(\xi)}}{k_s}$$

$$k_s = \frac{qB}{2mc\beta\gamma}$$



$$K = \frac{2Ig(\xi)}{I_o(\beta\gamma)^3}$$

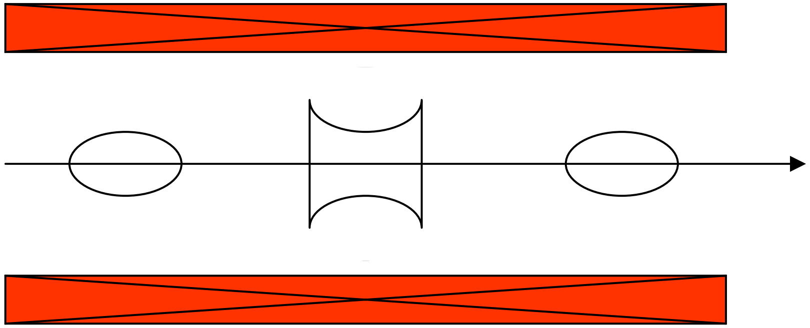
Small perturbations around the equilibrium solution

$$\sigma = \sigma_{eq} + \delta\sigma$$

$$\delta\sigma'' + 2k_s^2\delta\sigma = 0$$

$$\sigma(\xi) = \sigma_{eq}(\xi) + \left(\sigma(\xi) - \sigma_{eq}(\xi)\right)\cos\left(\sqrt{2}k_s z\right)$$

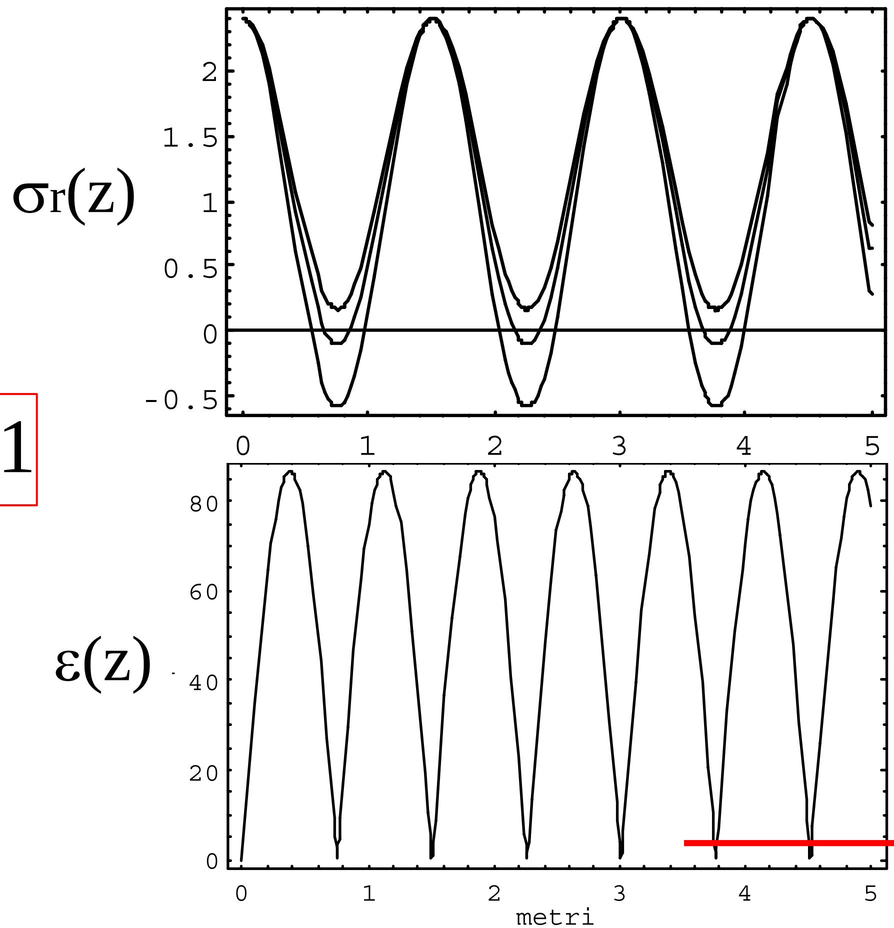
$$\sigma'(\xi) = -\sqrt{2}k_s\left(\sigma(\xi) - \sigma_{eq}(\xi)\right)\sin\left(\sqrt{2}k_s z\right)$$



Plasma frequency

Envelope oscillations drive Emittance oscillations

$$0.5 \le g(\xi) \le 1$$

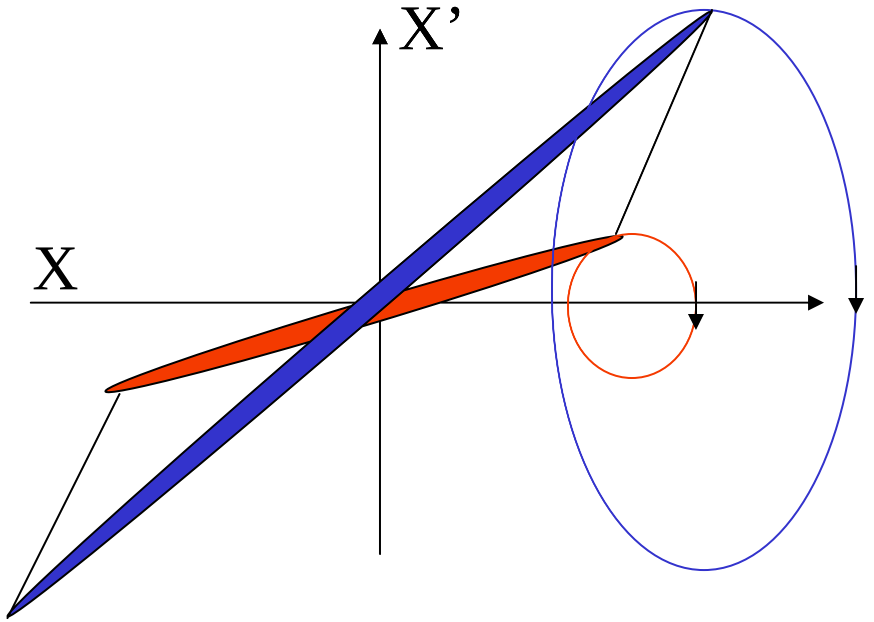


$$\frac{\delta\gamma}{\gamma} = 0$$

$$\sigma' = 0$$

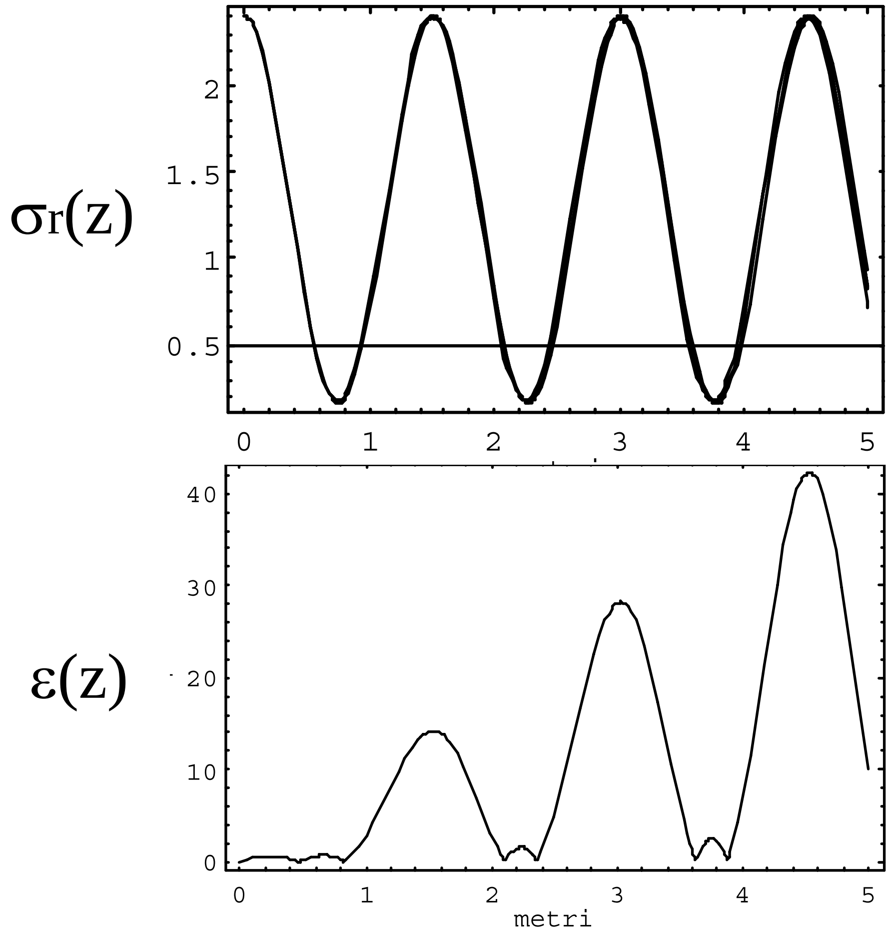
$$\varepsilon(z) = \sqrt{\langle \sigma_r^2 \rangle \langle \sigma_r'^2 \rangle - \langle \sigma_r \sigma_r' \rangle^2} \div \left| \sin\left(\sqrt{2} k_s z\right) \right|$$

Perturbed trajectories oscillate with the same frequency but with different amplitudes



A Spread in Plasma Frequencies drives a Beating in Emittance Oscillations

$$g(\xi) = 1$$



$$\frac{\delta\gamma}{\gamma} = 1\%$$

Beam subject to strong acceleration

$$\sigma'' + \sigma' \frac{\gamma'}{\gamma} + \sigma \frac{\Omega^2 \gamma'^2}{\gamma^2} = \frac{I}{2 I_A \sigma \gamma^3} + \frac{\varepsilon_{n,sl}^2}{\sigma^3 \gamma^2}$$

where

$$\gamma = \gamma_0 + \gamma' z$$

$$\gamma' \equiv \frac{E_{acc}}{mc^2}$$

$$\Omega^2 = \left(\frac{eB_{sol}}{mc\gamma'} \right)^2 + \begin{Bmatrix} \approx 1/8 \;\; SW \\ \approx 0 \;\;\; TW \end{Bmatrix}$$

Normalized focusing gradient (solenoid +RF foc.)

PHYSICAL REVIEW E VOLUME 55, NUMBER 6 JUNE 1997

Envelope analysis of intense relativistic quasilaminar beams in rf photoinjectors: A theory of emittance compensation

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(Received 11 November 1996)

Cauchy Transformation: $z ==> y = \ln \frac{\gamma}{\gamma_o}$

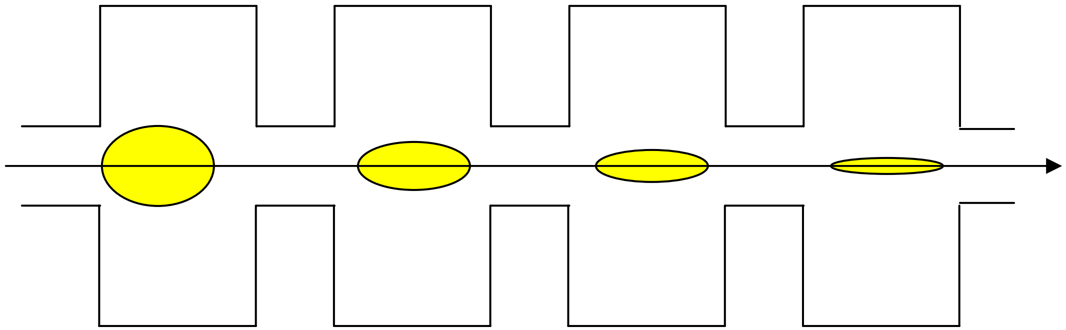
$$\frac{d^2\sigma}{d\sigma^2} + \Omega^2 \sigma = \frac{S(\xi)}{\sigma} e^{-y}$$

Dimensionless quantity: $\tau = \frac{\sigma}{\sqrt{S}}$

$$\frac{d^2\tau}{dy^2} + \Omega^2 \tau = \frac{1}{\tau} e^{-y}$$

Particular Solution: $\tau = 2\sqrt{\frac{e^{-y}}{1 + 4\Omega^2}}$

Back to Real World: Invariant Envelope Solution



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

This solution represents a beam equilibrium mode that turns out to be the transport mode for achieving minimum emittance at the end of the emittance correction process (L.S and J.B.R., *PRE* **55** (1997) 7565)

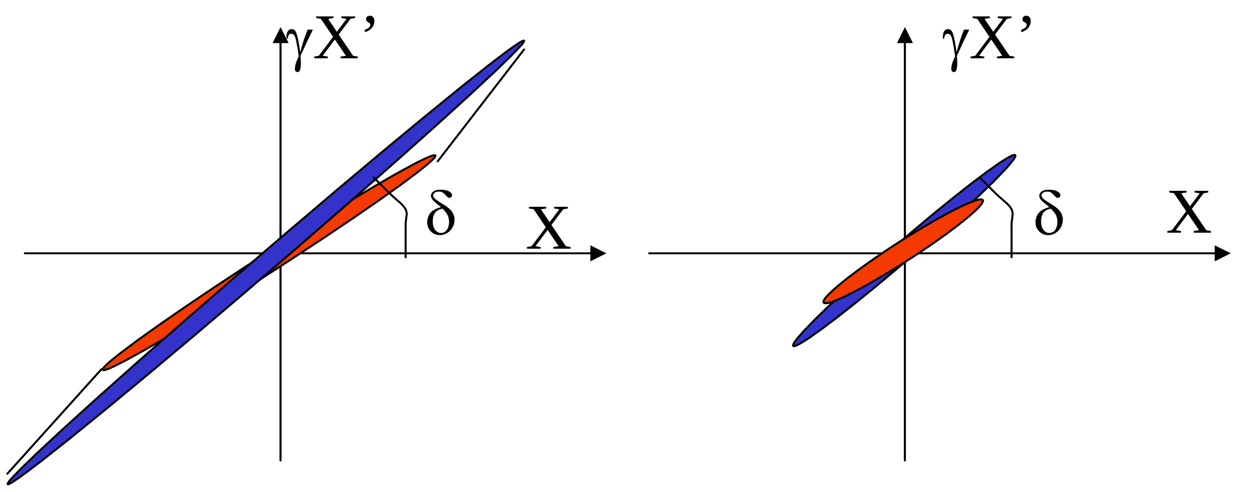
An inportant property of the Invariant Envelope

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

$$\sigma'_{inv} = \frac{1}{\gamma'}\sqrt{\frac{I(\zeta)}{2I_A\left(1+4\Omega^2\right)\gamma_o^{3/2}}}$$

Constant phase space angle:

$$\delta = \frac{\gamma\sigma'_{inv}}{\sigma_{inv}} = -\frac{\gamma'}{2}$$



Small perturbations around the equilibrium solution

$$\delta\sigma = \delta\sigma_o \cos(\psi) + \sqrt{2}\,\frac{\gamma_o}{\gamma'}\,\delta\sigma_o' \sin(\psi)$$

$$\delta\sigma' = -\frac{1}{\sqrt{2}}\frac{\gamma'}{\gamma}\,\delta\sigma_o \sin(\psi) + \delta\sigma_o' \frac{\gamma_o}{\gamma}\cos(\psi)$$

$$\psi = \frac{1}{\sqrt{2}}\ln\left(\frac{\gamma}{\gamma_o}\right) \qquad \delta\sigma_o = \sigma_o - \sigma_{INV}$$

Emittance Oscillations

$$\Delta\varepsilon_n(z) \cong \frac{\delta\sigma_0}{\gamma'}\sqrt{\frac{I/I_0}{2\gamma}}\left|\cos(\psi)-\sqrt{2}\sin(\psi)\right|$$

Envelope Oscillations drive emittance oscillations $\Delta\varepsilon_n \propto \frac{\delta\sigma}{\sqrt{\gamma}}$

and are dumped by acceleration $\psi = \frac{1}{\sqrt{2}}\ln\left(\frac{\gamma}{\gamma_o}\right)$

Laminarity Parameter

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

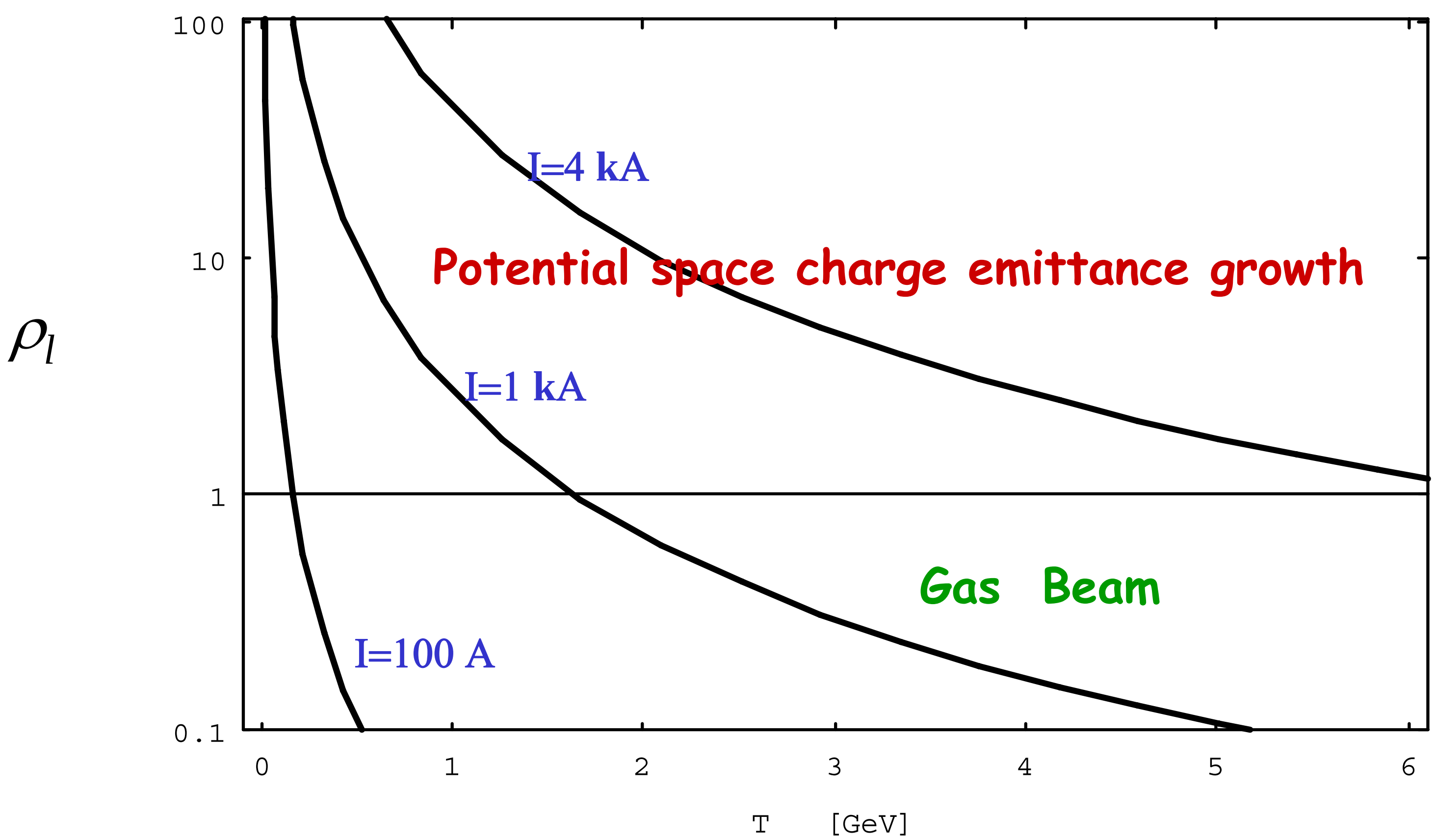
$$\rho = \frac{I\sigma^2}{2\gamma I_A \varepsilon_n^2} = \left(\frac{I}{2\gamma I_A \varepsilon_n}\frac{1}{\gamma'\sqrt{1/4+\Omega^2}}\right)^2$$

Typical X-FEL Beam

$$If \quad \varepsilon_{nth} = 0.3 \;\; mm.mrad \;\; @ \; 1 \;\; nC$$

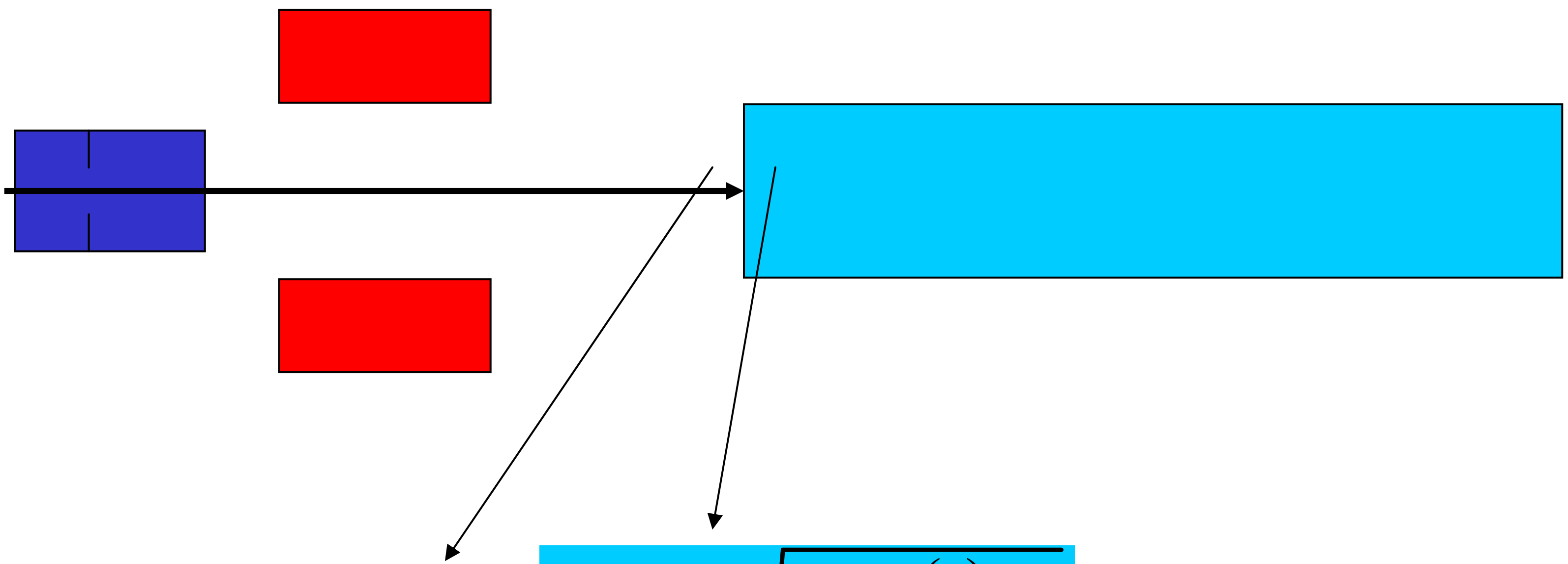
$$I_0 = 17 \;\; kA \qquad \Omega^2 \cong 1/8 \;\; (SW \;\; acc. \;\; str.)$$

$$\gamma' = 50 \;\; m^{-1} \;\; \Leftrightarrow \;\; E_{acc} = 25 \;\; MV/m$$



The New working Point
for a Split RF Photoinjector

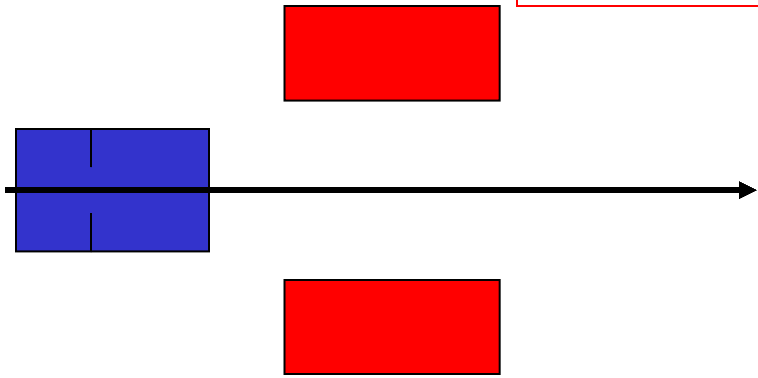
Adopted by LCLS, TESLA-XFEL, ORION, SPARC,...

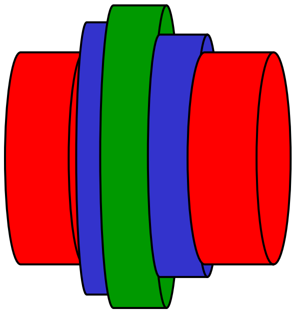


$$\sigma' = 0$$

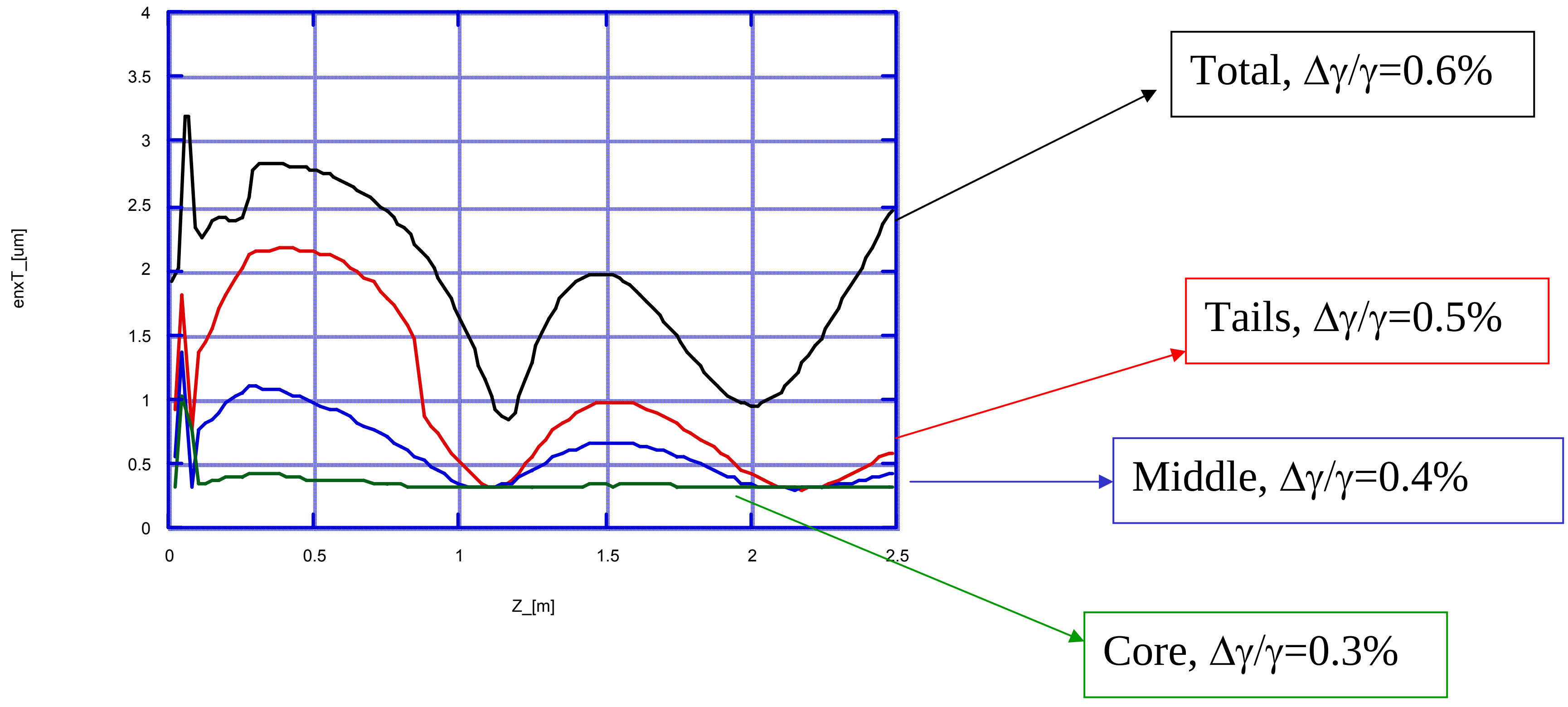
$$\gamma' = \frac{1}{\sigma_{INV}} \sqrt{\frac{2I(\zeta)}{I_A\left(1+4\Omega^2\right)\gamma}}$$

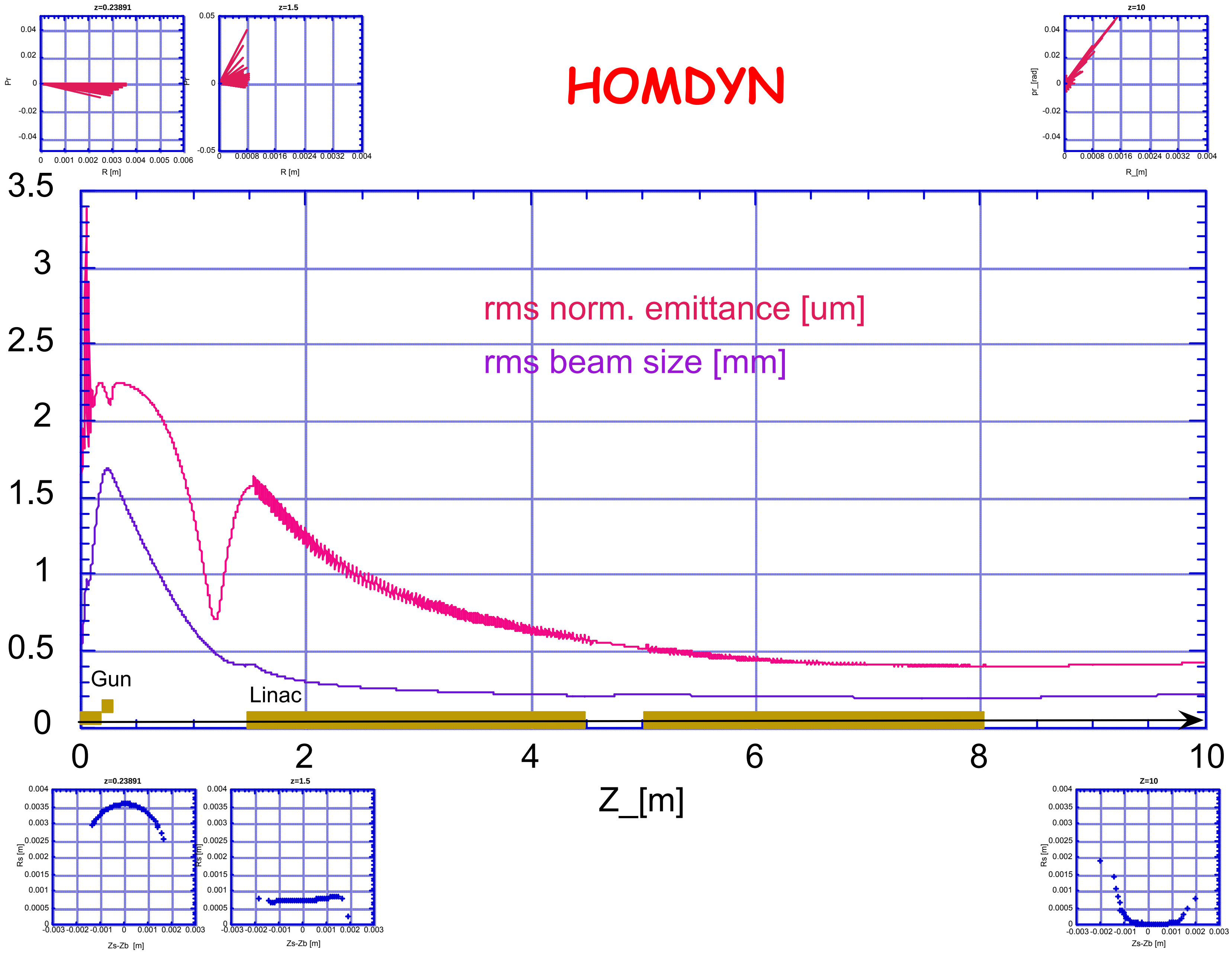
Realistic Case





Slice emittance

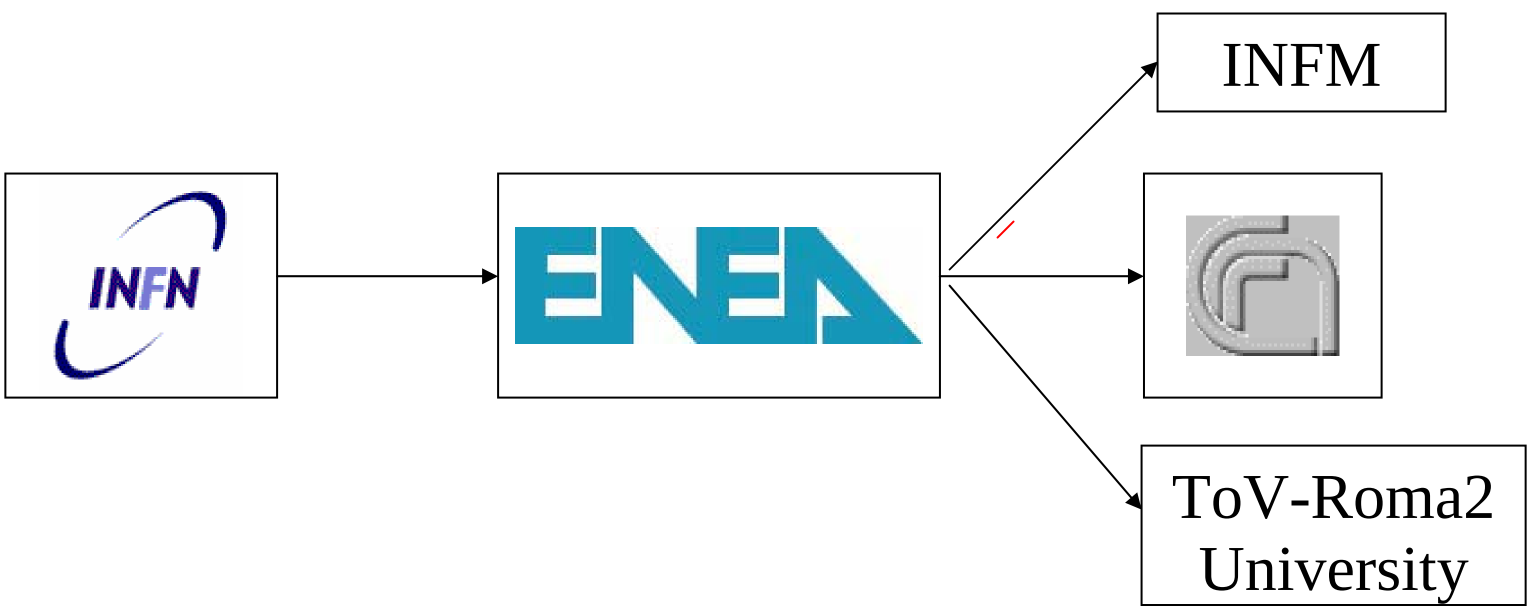




HOMDYN
rms norm. emittance [um]
rms beam size [mm]
Gun
Linac
Z_[m]
z=0.23891
z=1.5
z=10
R [m]
R_[m]
Pr
pr_[rad]
Rs [m]
Zs-Zb [m]

The SPARC FEL Project

On behalf of the SPARC study group



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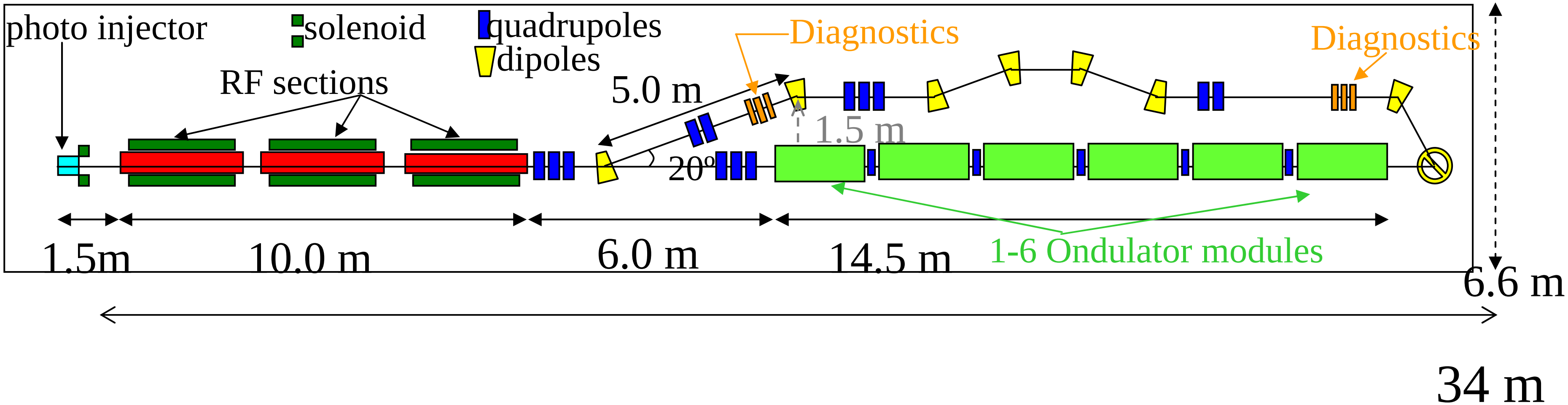
150 MeV Photo-injector R&D Project to investigate High Brightness e⁻ Beam Production for SASE-FEL experiments



Frequency: 2856 MHz	Normal Conducting
GUN PARAMETERS	LINAC PARAMETERS
Peak Field: 120-140 MV/m (15 MW)	Accelerating Field: 25-30 MV/m (50 MW)
Solenoid Field: 0.3 Tesla	Solenoid Field: 0.1 Tesla
Charge: 1 nC	Beam Energy: 150 MeV
Laser: 10 ps x 1 mm (Flat Top)	

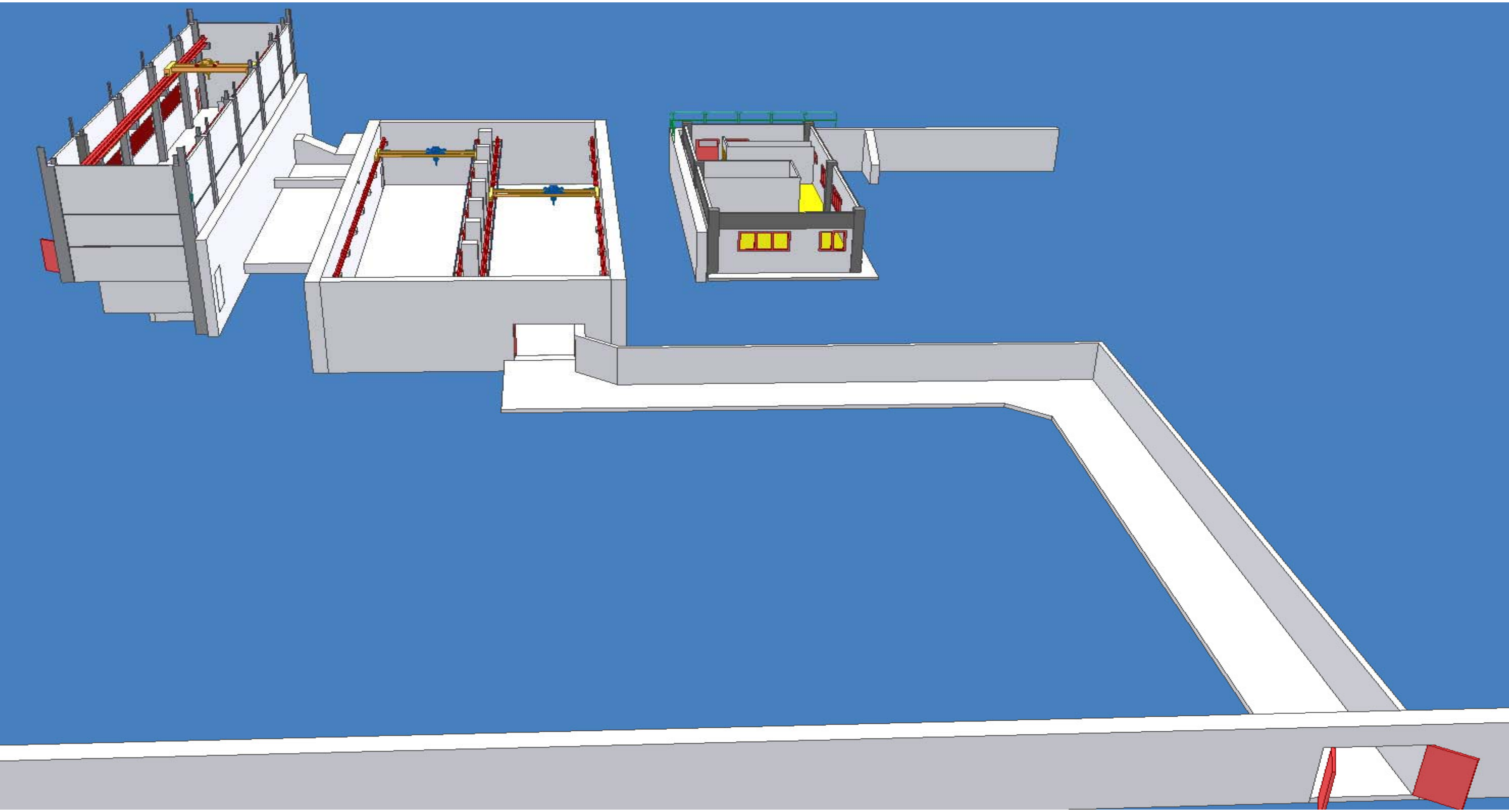
SPARC Linac: the Time Table

Ź	1^{st} year				2^{nd} year				3^{rd} year			
1.1 Laser	Ź	Ź	Ź	Ź	Ź	Ź	Ź	Ź	Ź	Ź	Ź	Ź
1.2 RF Gun	Ź	Ź	Ź	Ź	Ź	Ź	Ź	Ź		Ź	Ź	Ź
1.3 Linac	Ź	Ź	Ź	Ź	Ź	Ź		Ź	Ź	Ź	Ź	Ź
1.4 Diagn.-contr.	Ź	Ź	Ź	Ź	Ź	Ź	Ź	Ź	Ź	Ź	Ź	Ź
1.5 Commiss.	Ź	Ź	Ź	Ź	Ź	Ź	Ź	Ź	Ź	Ź	Ź	Ź

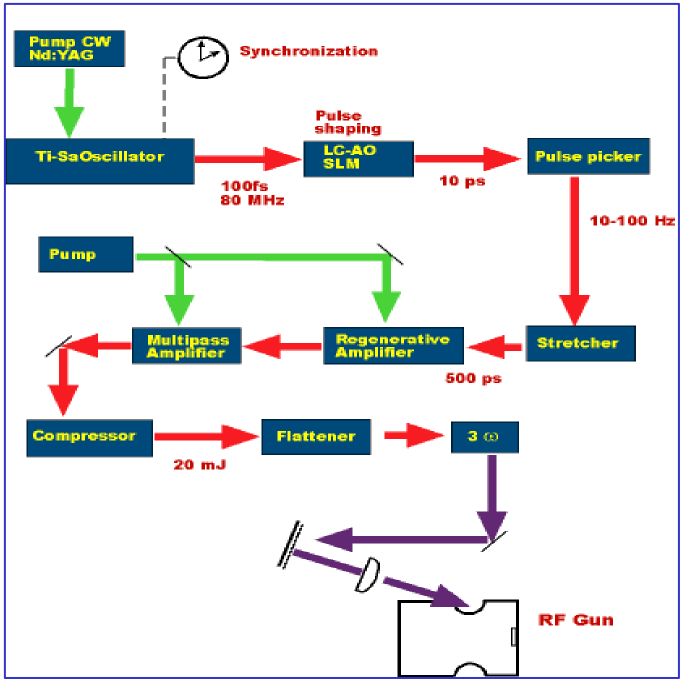
design	acquisition	assembling	test

We are waiting for delivery of the funding to our Institutions: released by a Techn. Committee of the Res. Department (MIUR)

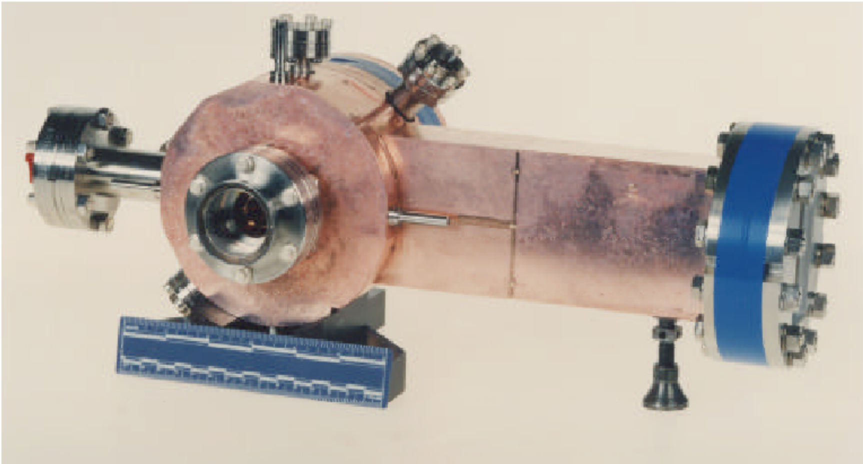
A view of the complex with Shielding Ground and building roof removed

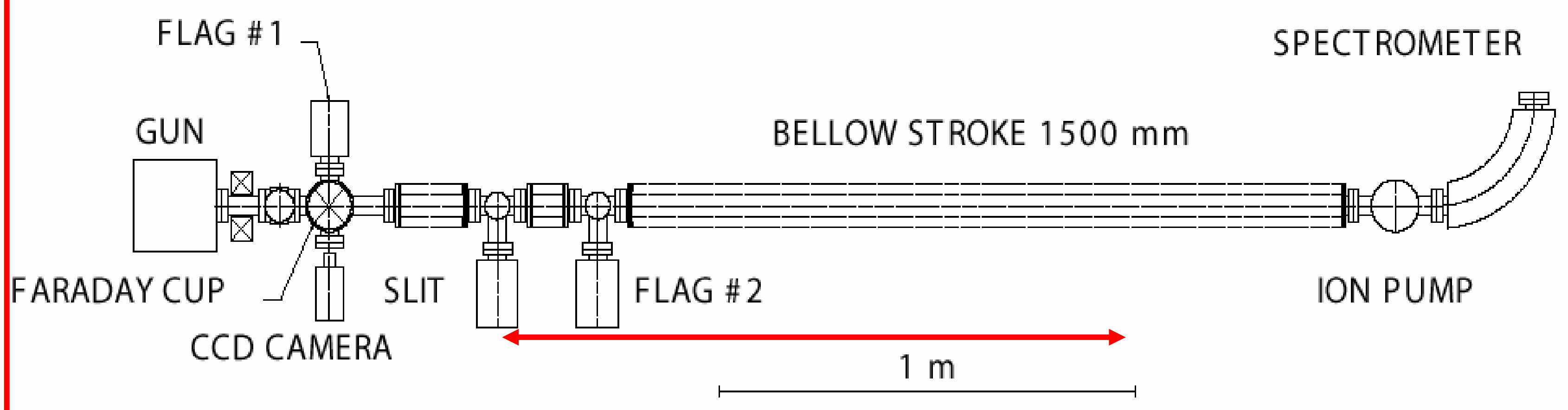


SPARC-Phase 1

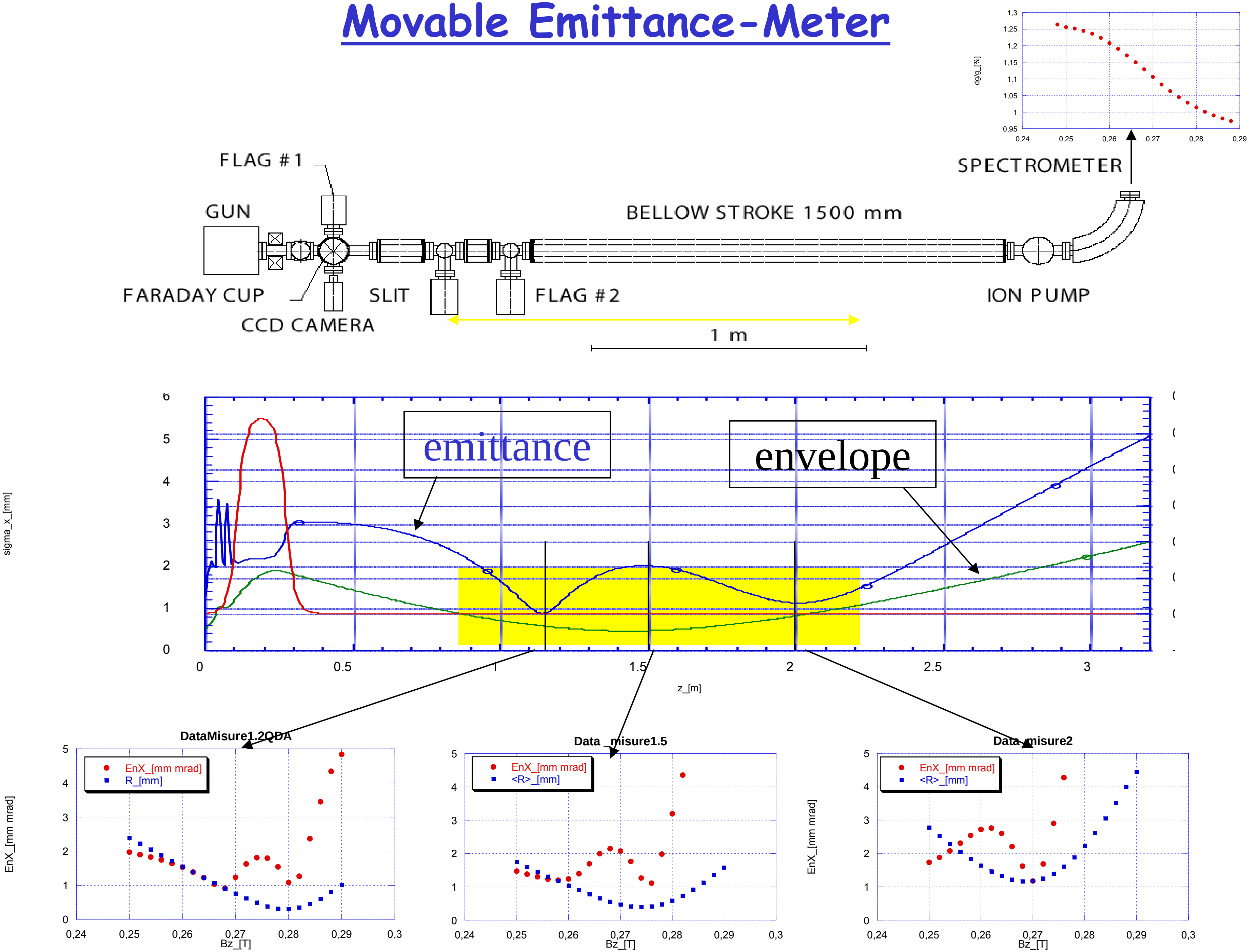


BNL/SLAC/UCLA 1.6 cell S-Band RF GUN

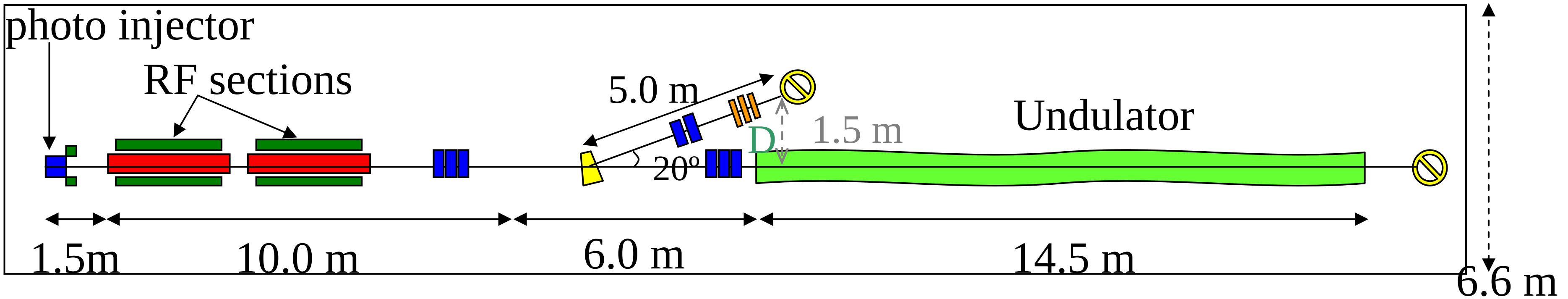




Movable Emittance-Meter

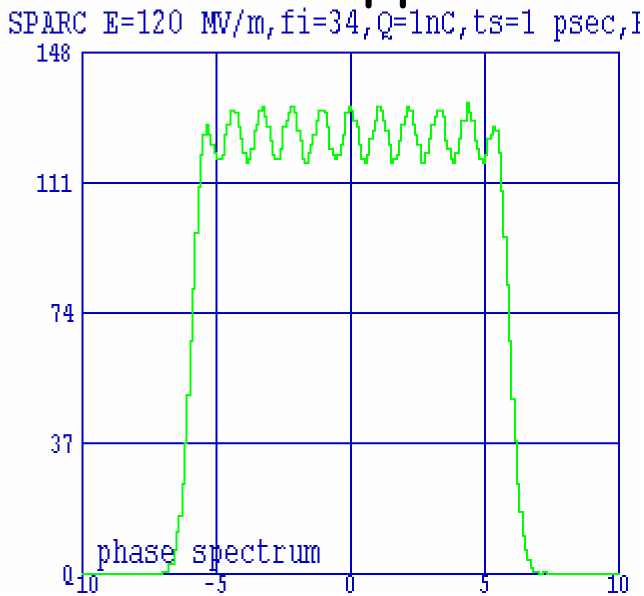


SPARC-Phase 2

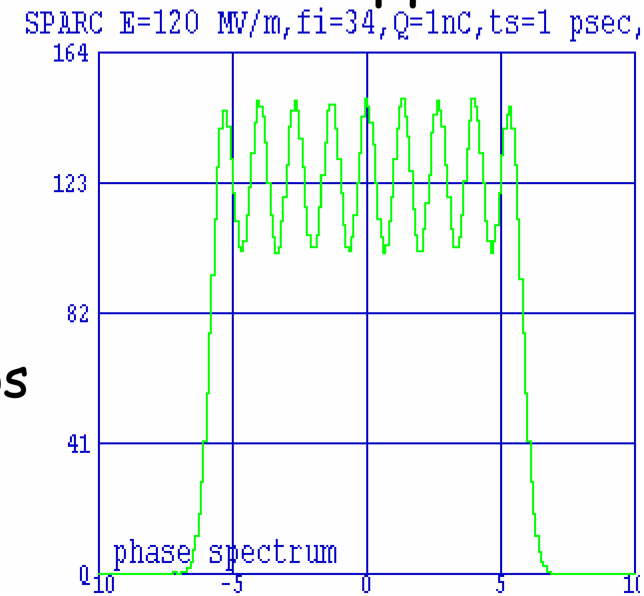


Boscolo/Ronsivalle PARMELA

10% Ripple

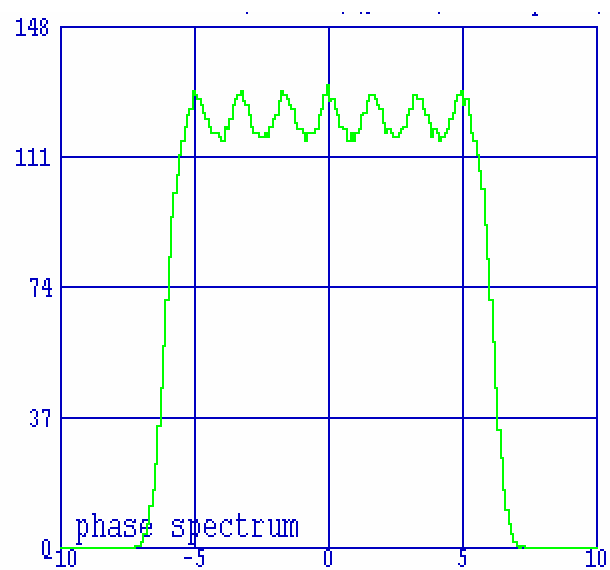


30% Ripple



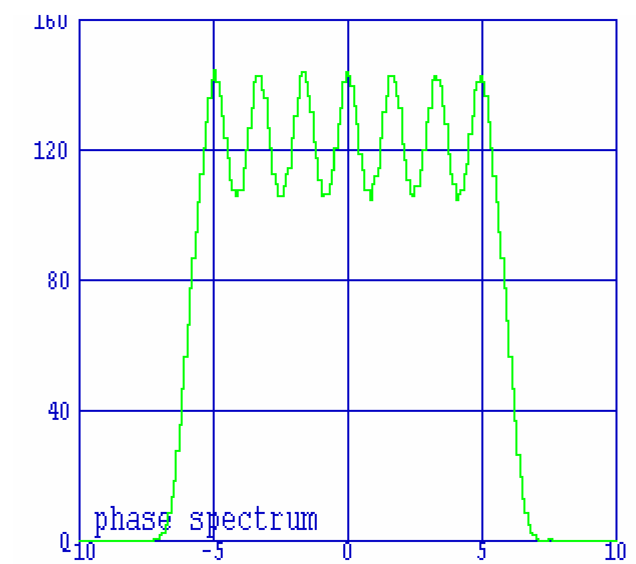
(A)

Rise time<1ps



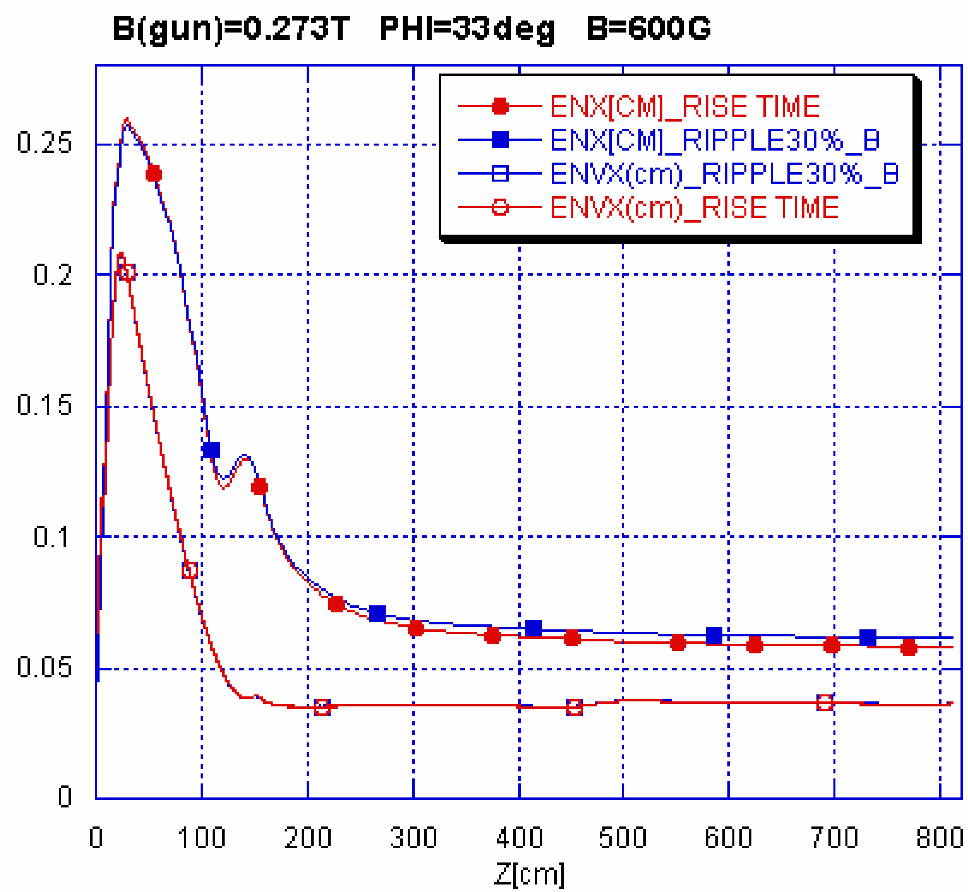
(B)

Rise time=1ps



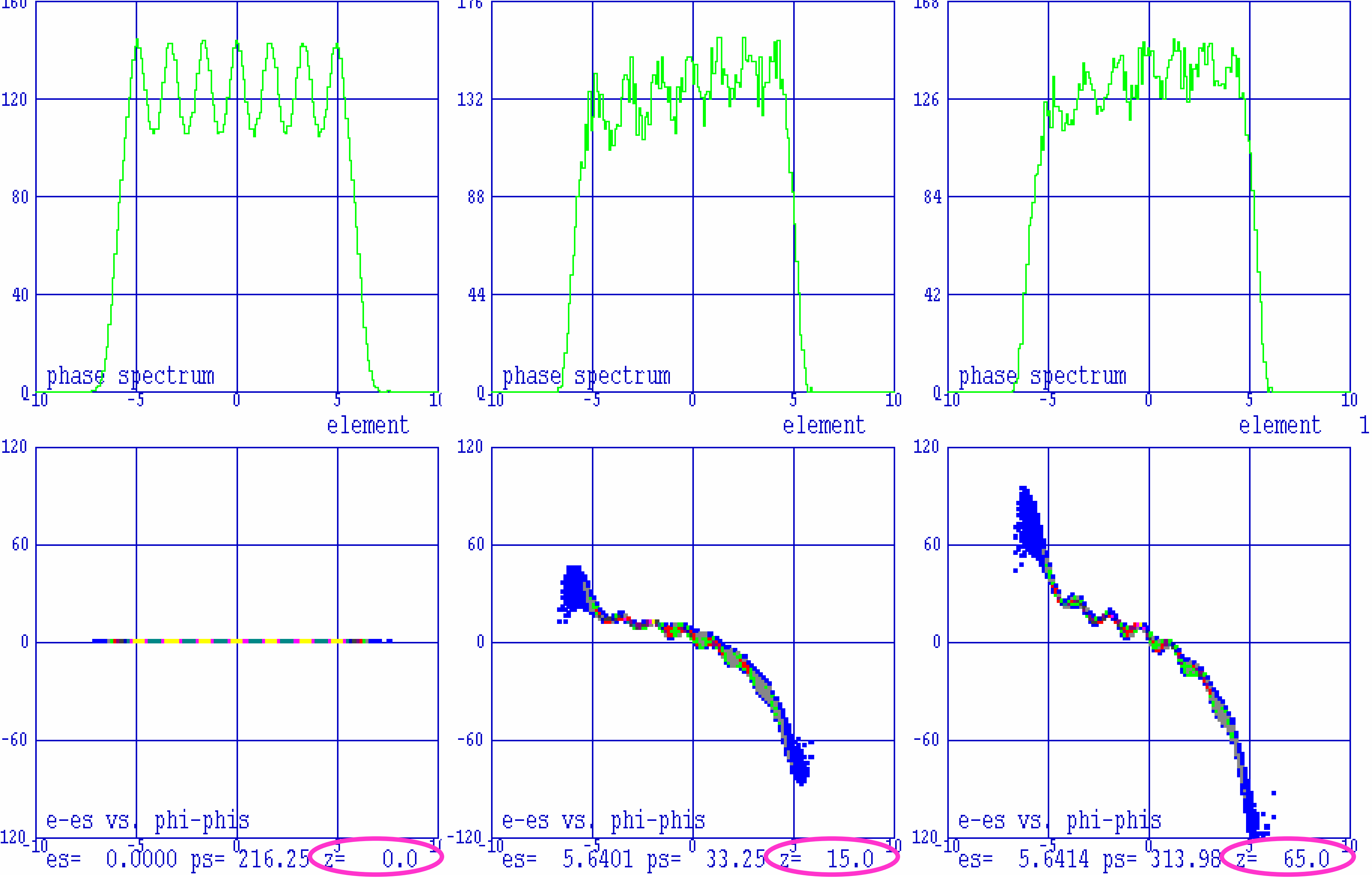
Gun-end linac simulations

B(first linac section)= stack of 11
Helmoltz coils- Sanelli



beam distribution	ε [mm mrad]
Rise time 1ps	0.58
30% ripple	0.62
10% ripple	0.58

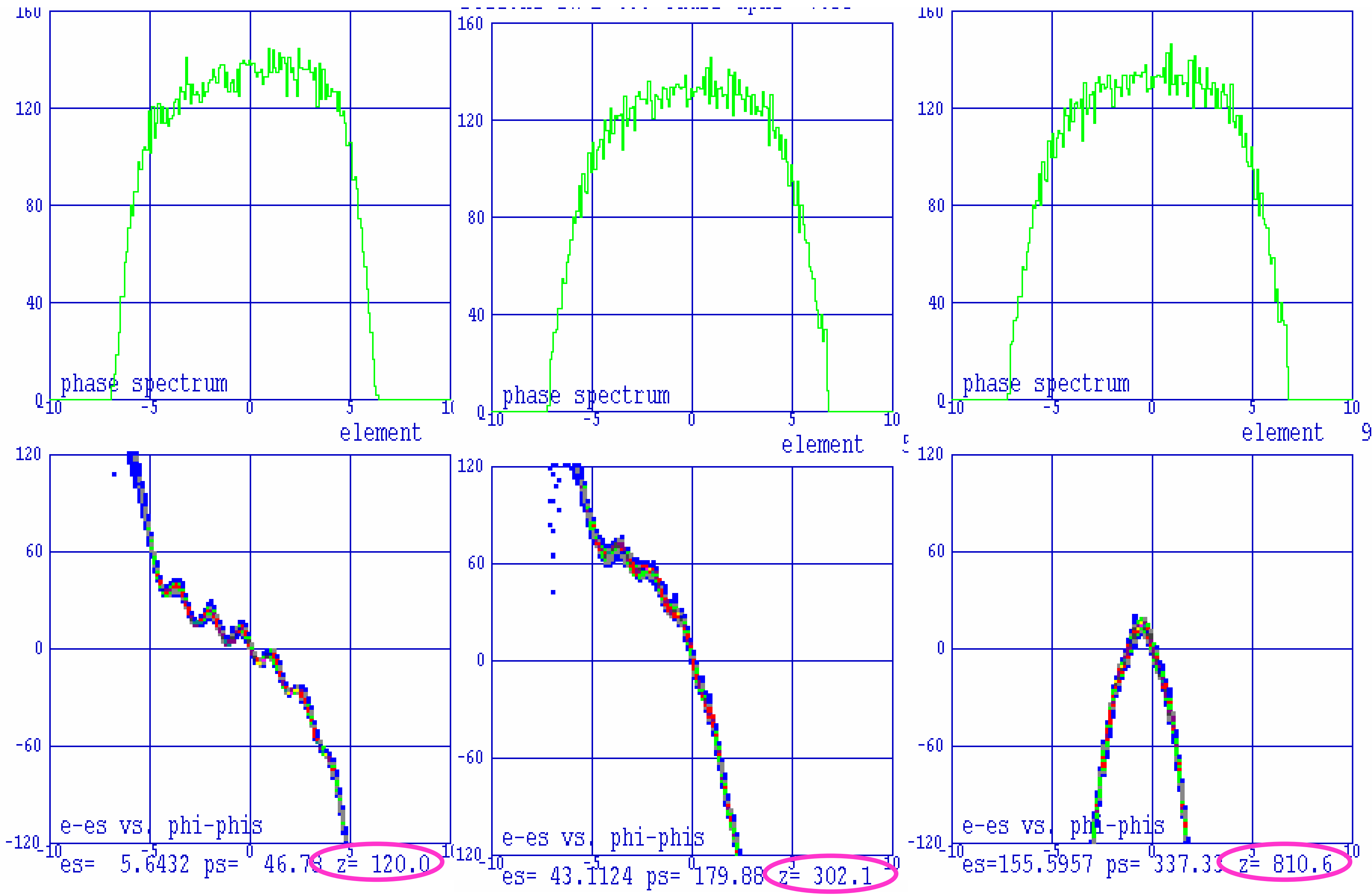
Beam distribution with ripple ➡ NOT expected significant changes!



z=0 @cathode

z=15cm end gun

z=65cm



z=1.2 m start linac   z=3.0m   z=8.1 m end linac

JOURNAL OF APPLIED PHYSICS VOLUME 92, NUMBER 3

Low-emittance electron-beam generation with laser pulse shaping in photocathode radio-frequency gun

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(Received 17 December 2001; accepted for publication 26 April 2002)

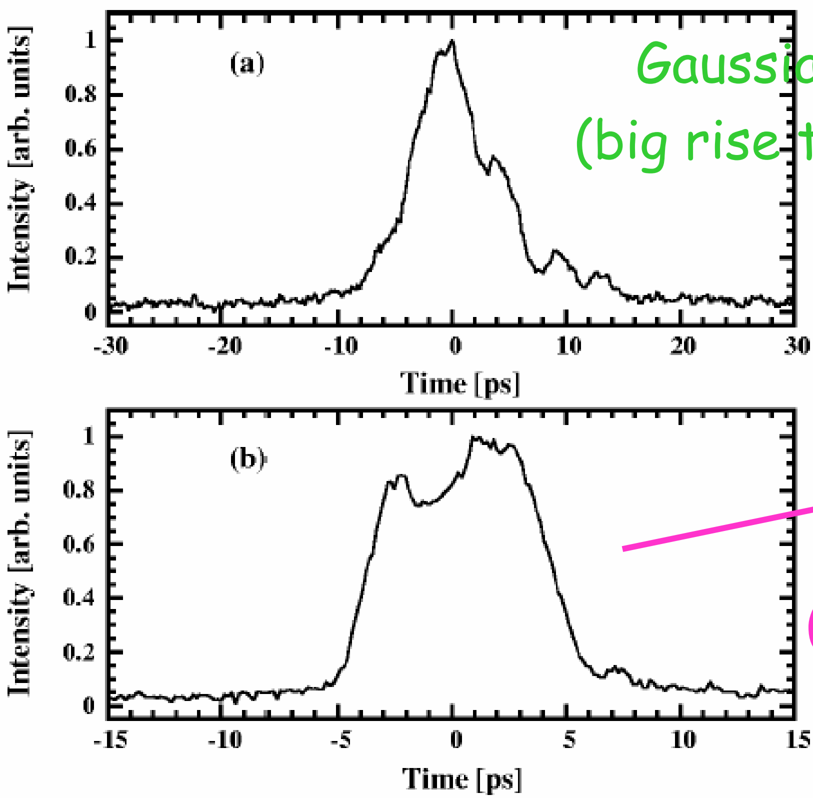


FIG. 2. The temporal distributions of shaped gaussian (a) and square (b) UV laser pulses with a pulse length of 9 ps FWHM.

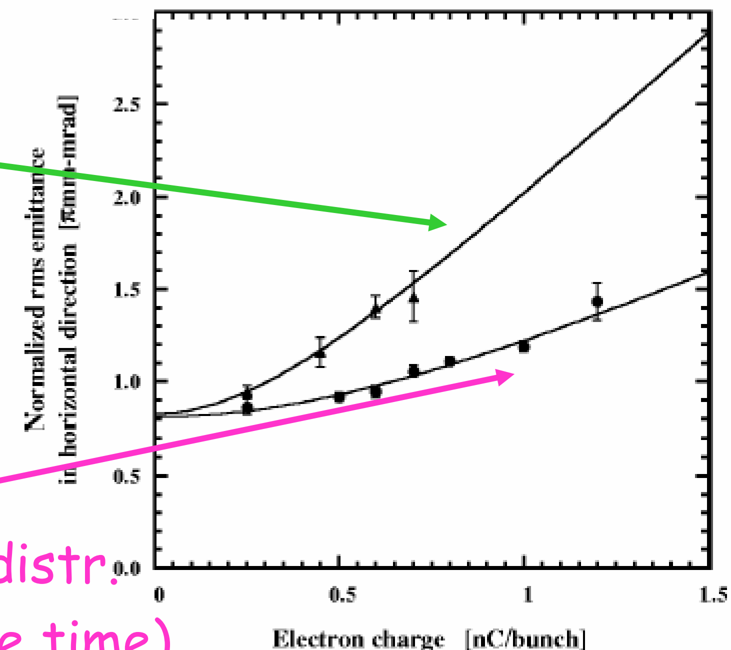
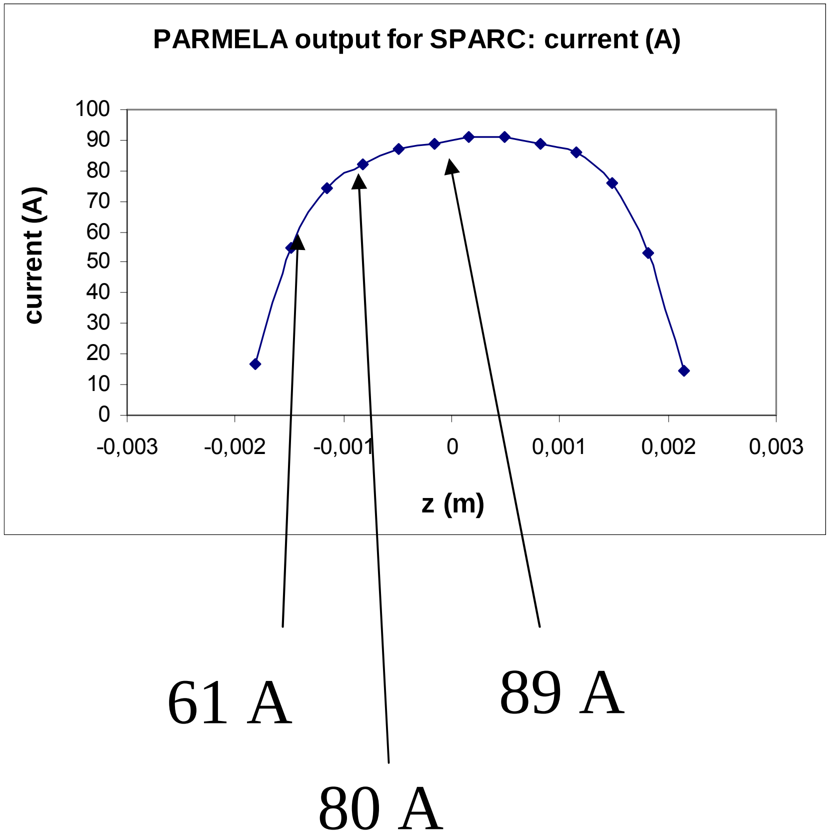
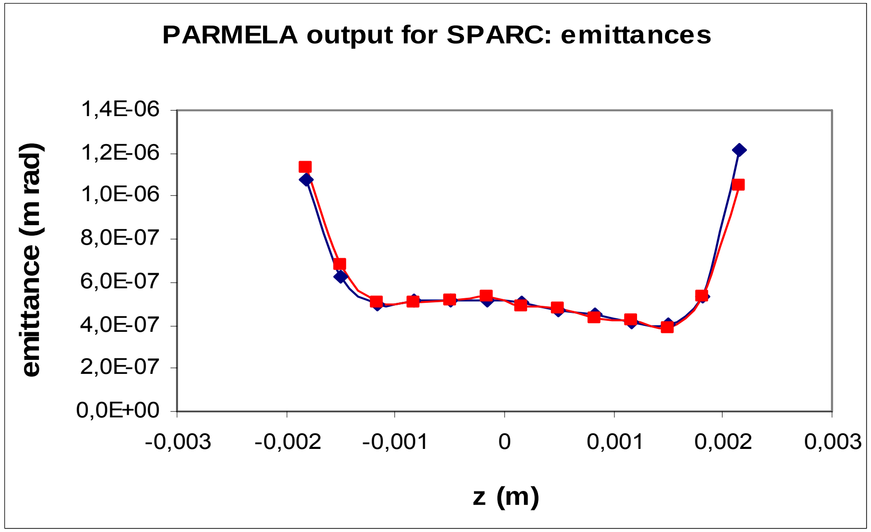


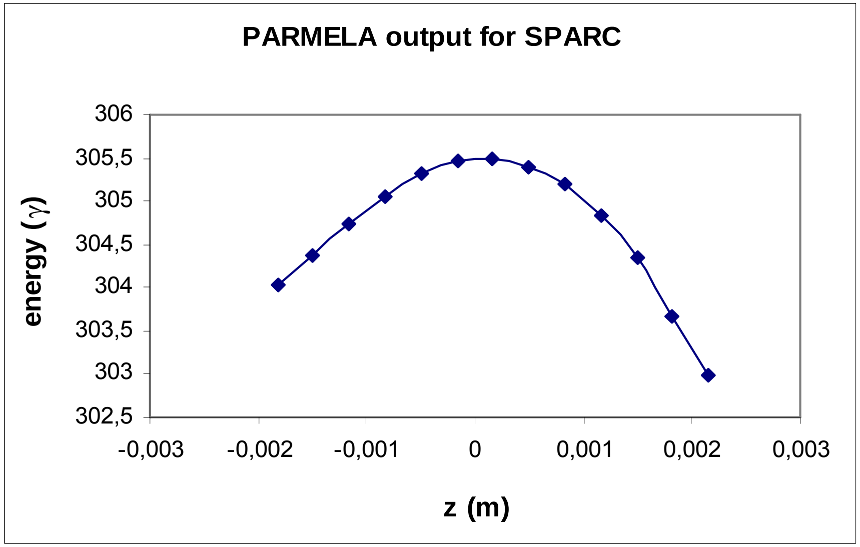
FIG. 6. The normalized rms horizontal emittance measured as a function of the electron charge with the gaussian (uptriangle) and square (circle) temporal pulse shape with a pulse length of 9 ps FWHM. The fit is plotted as solid lines with Eq. (2).

PARMELA output for SPARC

3 groups of “GENESIS slices” were chosen at different current



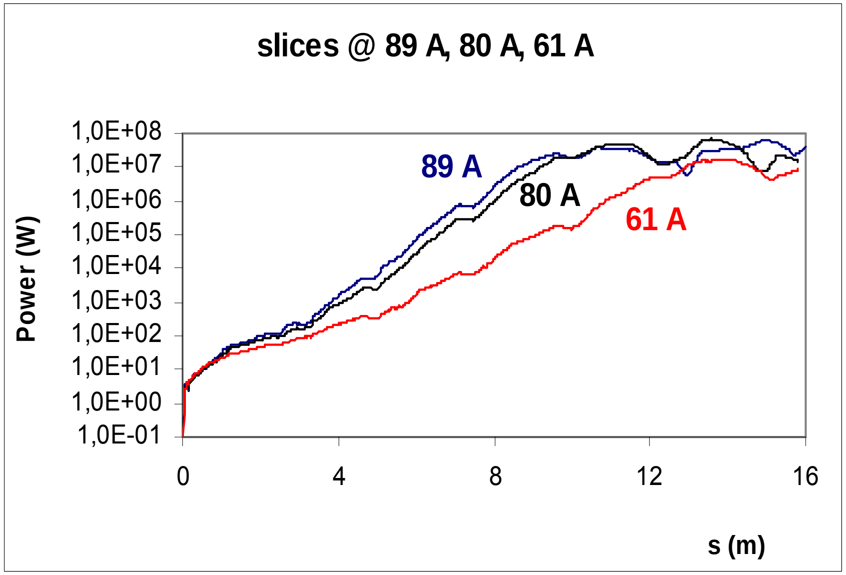


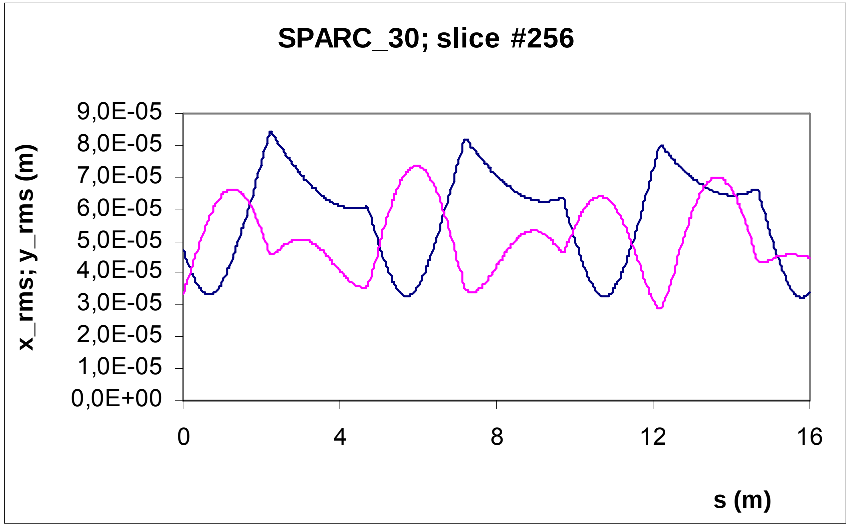


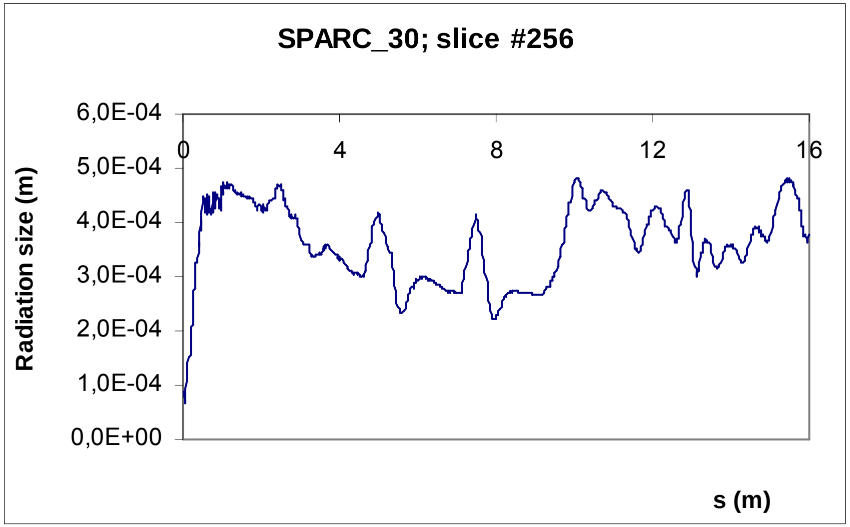
(L. Giannessi-R. Bartolini)

SPARC time – dependent GENESIS simulations;

λ = 485.5 nm; Lsat = 11.0 m







@ 89 A

$\varepsilon = 0.5 \cdot 10^{-6}$ m rad

$\sigma_\varepsilon = 10^{-4}$

$\alpha_x = 1.06$

$\alpha_y = -0.57$

$\rho = 7.2 \cdot 10^{-3}$

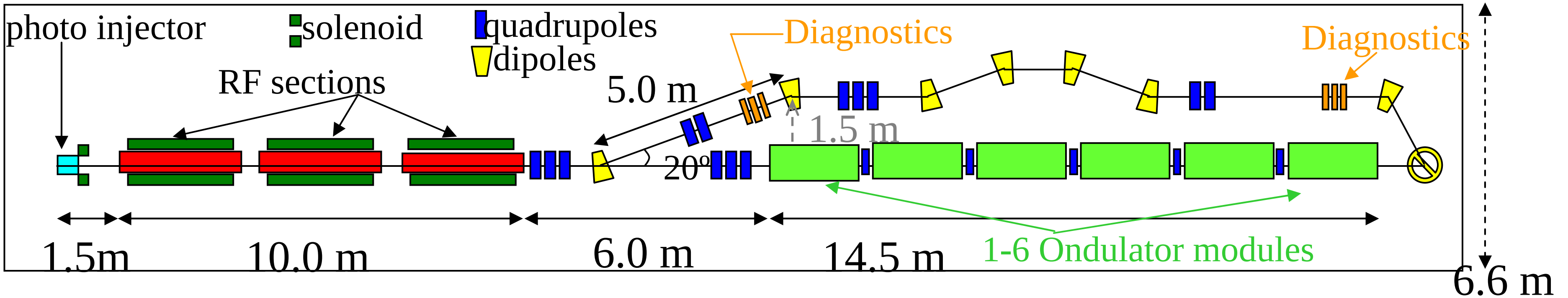
$\lambda_w = 3.3$ cm

$k_w = 1.88$

$\alpha_x = 0.76$

$\alpha_y = -0.59$

SPARC-Phase 3



Velocity Bunching in Photoinjectors i.e. Compression during Acceleration

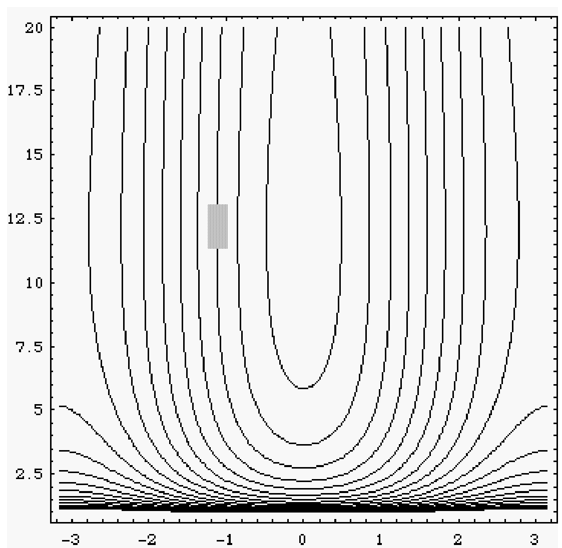
- Alternative option of **bunch compression** $\Rightarrow$ high brightness sub-ps beams (as needed by X-Ray SASE Fel's)

- Compression is rectilinear (no Coherent Synch. Radiation effects), based on *longitudinal focusing* in **slow RF waves**

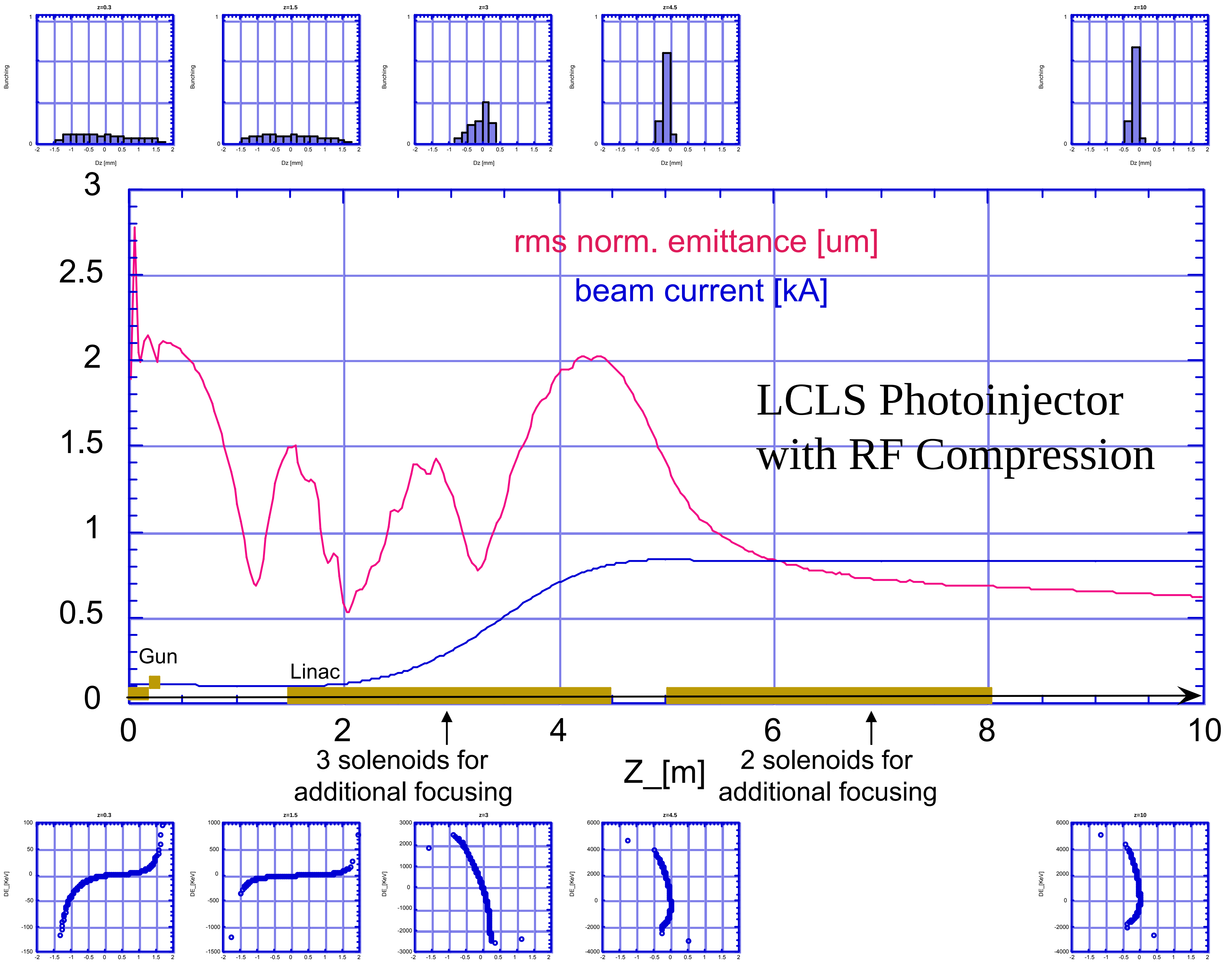
- Performed at low energy (10-80 MeV), fully integrated into the emittance correction process (for maximum brightness)

A quarter synchrotron oscillation gives phase compression

- By *Injecting* at $\gamma = \gamma_r$ and *extracting* at $\xi = 0°$ we perform an energy spread enhancement associated to a phase spread reduction



Zoom-in of the diagram plotted in previous transp. corresponding to $\gamma \leq 20$.



LCLS Photoinjector
with RF Compression
rms norm. emittance [um]
beam current [kA]
Gun
Linac
3 solenoids for
additional focusing
2 solenoids for
additional focusing
Z_[m]
z=0.3
z=1.5
z=3
z=4.5
z=10
Bunching
Dz [mm]
DE_[KeV]
DZ_[mm]

Transverse Dynamics of a laminar plasma-beam subject to Velocity Bunching

- Assuming a **current growing** at the same rate as the beam energy the envelope equation becomes

$$I = \frac{I_0 \gamma}{\gamma_0}$$

$$\sigma'' + \sigma' \frac{\gamma'}{\gamma} + \sigma \frac{\Omega^2 \gamma'^2}{\gamma^2} - \frac{I_0}{2 I_A \sigma \gamma_0 \gamma^2} = 0$$

- and the *new (exact) solution* is

$$\sigma_{RFC} = \frac{1}{\Omega \gamma'} \sqrt{\frac{I_0}{2 I_A \gamma_0}}$$

RF Compression Invariant Envelope

- with same plasma frequency as the IE

No beam confin. without external focusing

$$k_p^{RFC} = \frac{\Omega \gamma'}{\sqrt{2}\gamma}$$

Three Conditions to preserve emittance while bunching

- **current growing** at the same rate as the beam energy (velocity bunching !, not ballistic)

$$\frac{I}{\gamma} = const.$$

- *(additional external focusing to match onto a parallel envelope (I.E. RFC solution)*

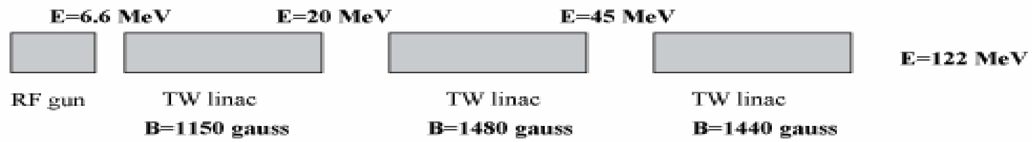
$$\sigma_{RFC} = \frac{1}{\Omega\gamma'}\sqrt{\frac{I_0}{2I_A\gamma_0}}$$

- RF compressor accelerating section longer than a plasma wavelength (2-3 m)

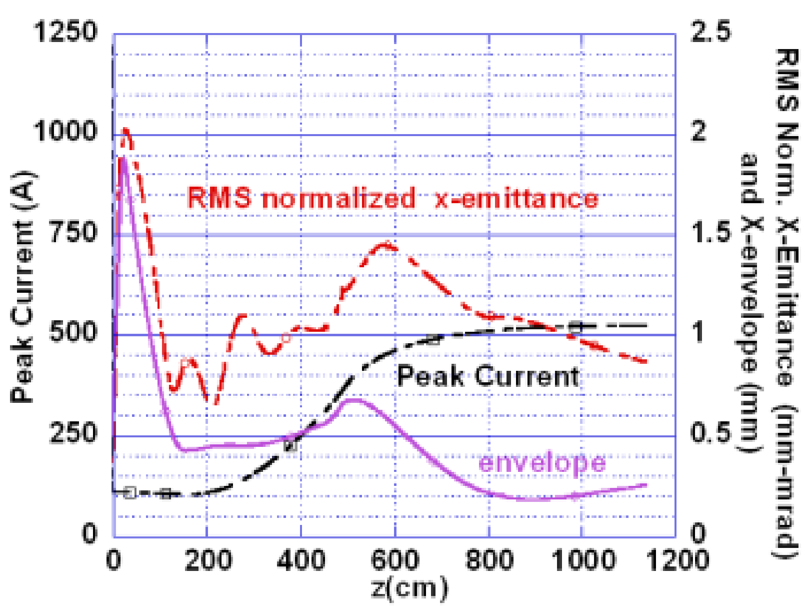
$$k_p^{RFC} = \frac{\Omega\gamma'}{\sqrt{2}\gamma}$$

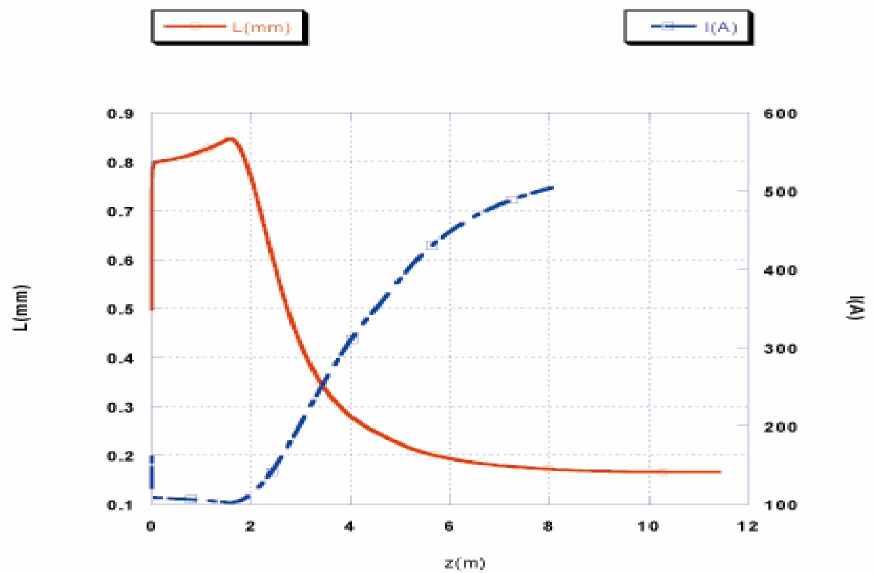
First PARMELA Simulation of RF Compressor

PRELIMINARY LAYOUT



Ipeak=500 A
En=0.6 π mm mrad
ΔE/E= ± 2.25%

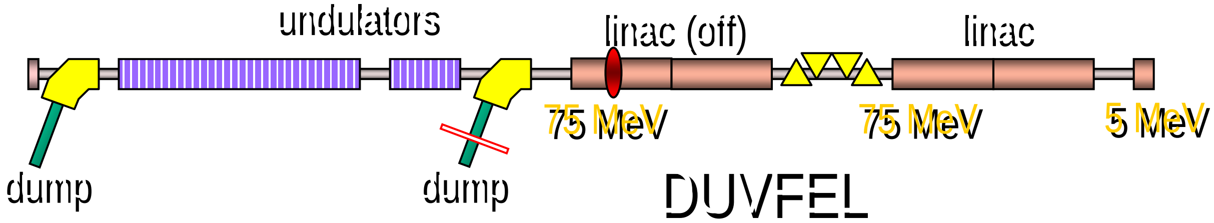


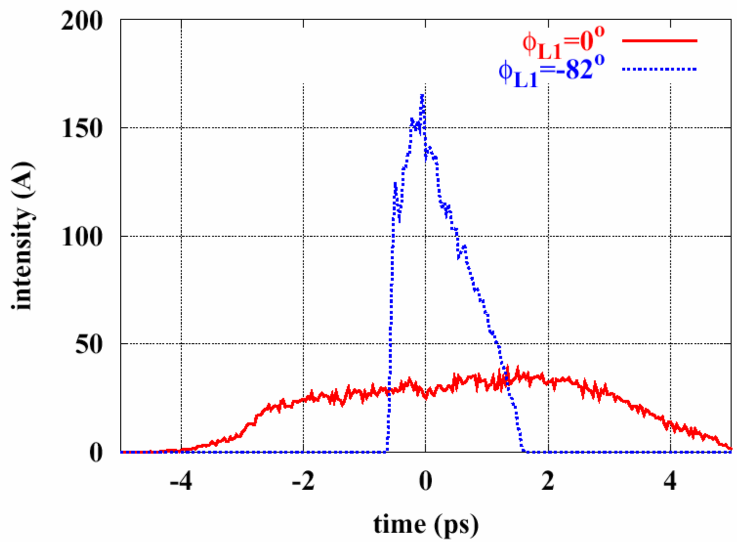


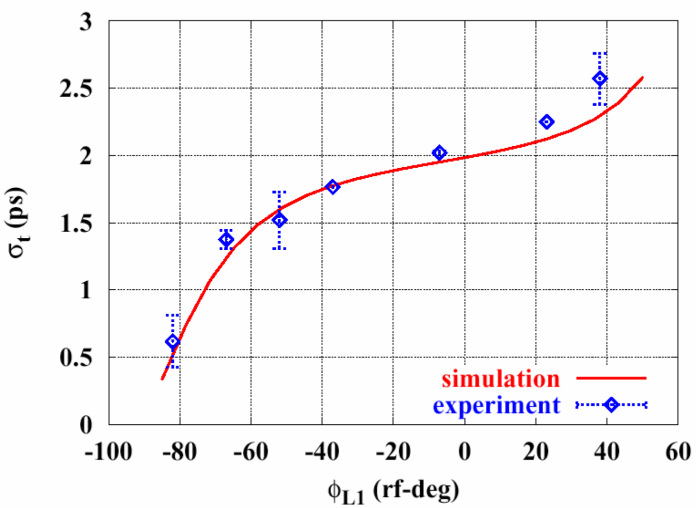
C. Ronsivalle

RF Compression at DUVFEL

(B. Graves & Ph. Piot)

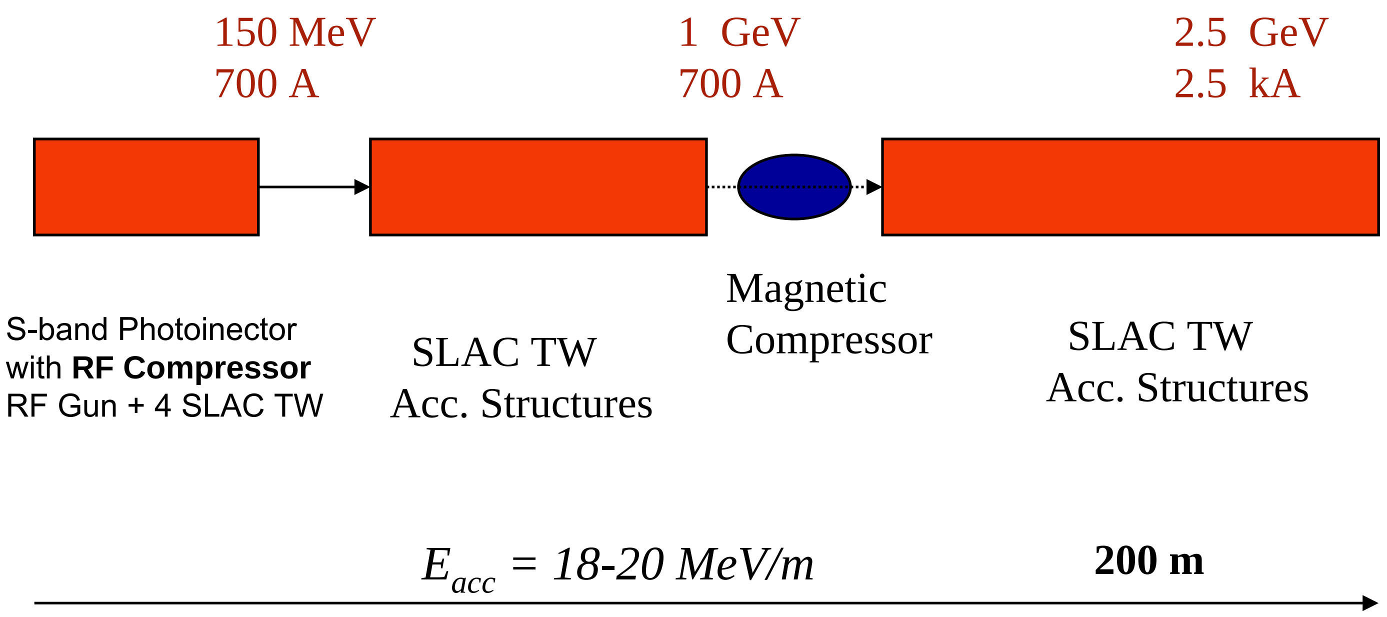




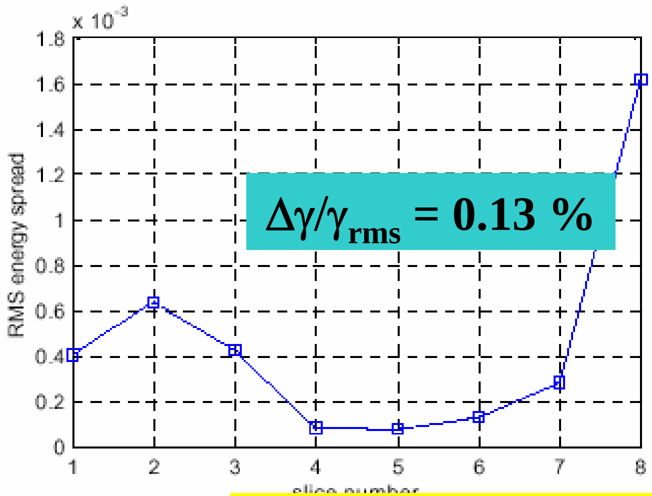


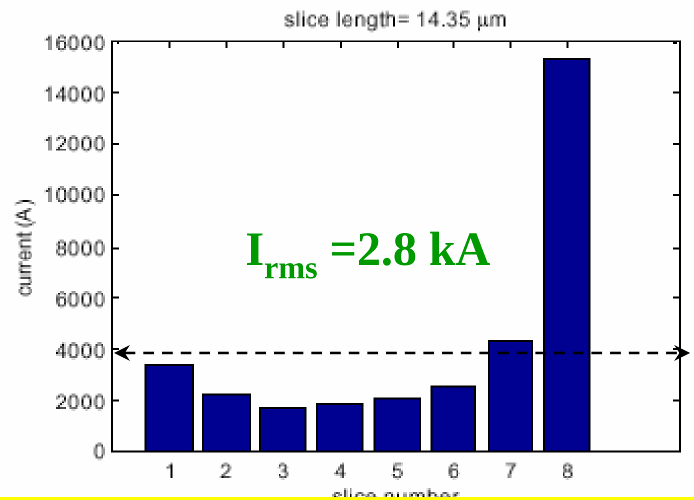
Examined two solutions:
S-band normal conducting and L-band SC

S-band Room-Temperature

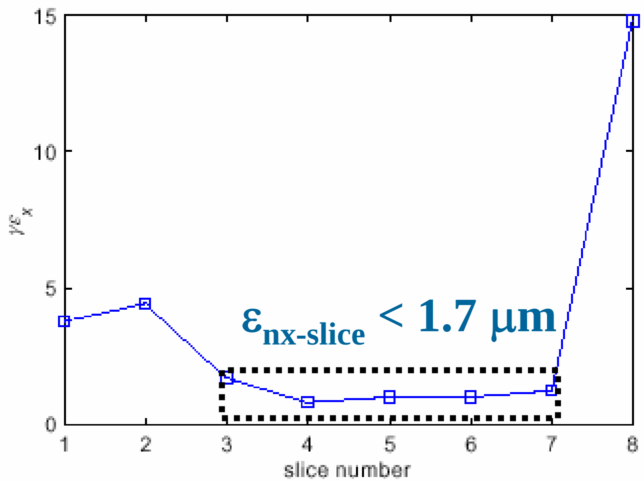


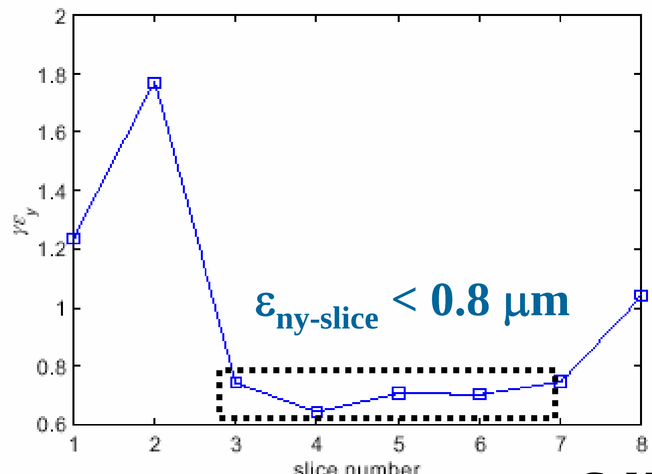
Start-to-End Simulations (First with RF Compressor!)
Slice Analysis at Linac End. (T=2.5 GeV)





Specs for FEL operation satisfied over 60% of bunch slices





C. Vaccarezza

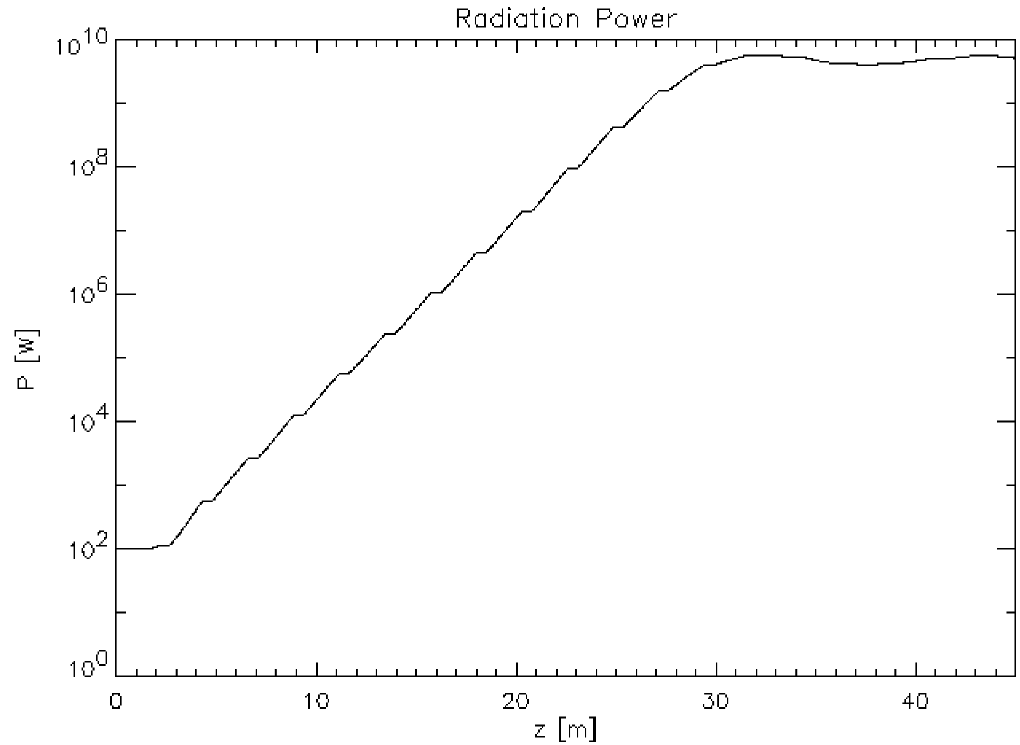
3D simulation with GENESIS @ 1.5 nm

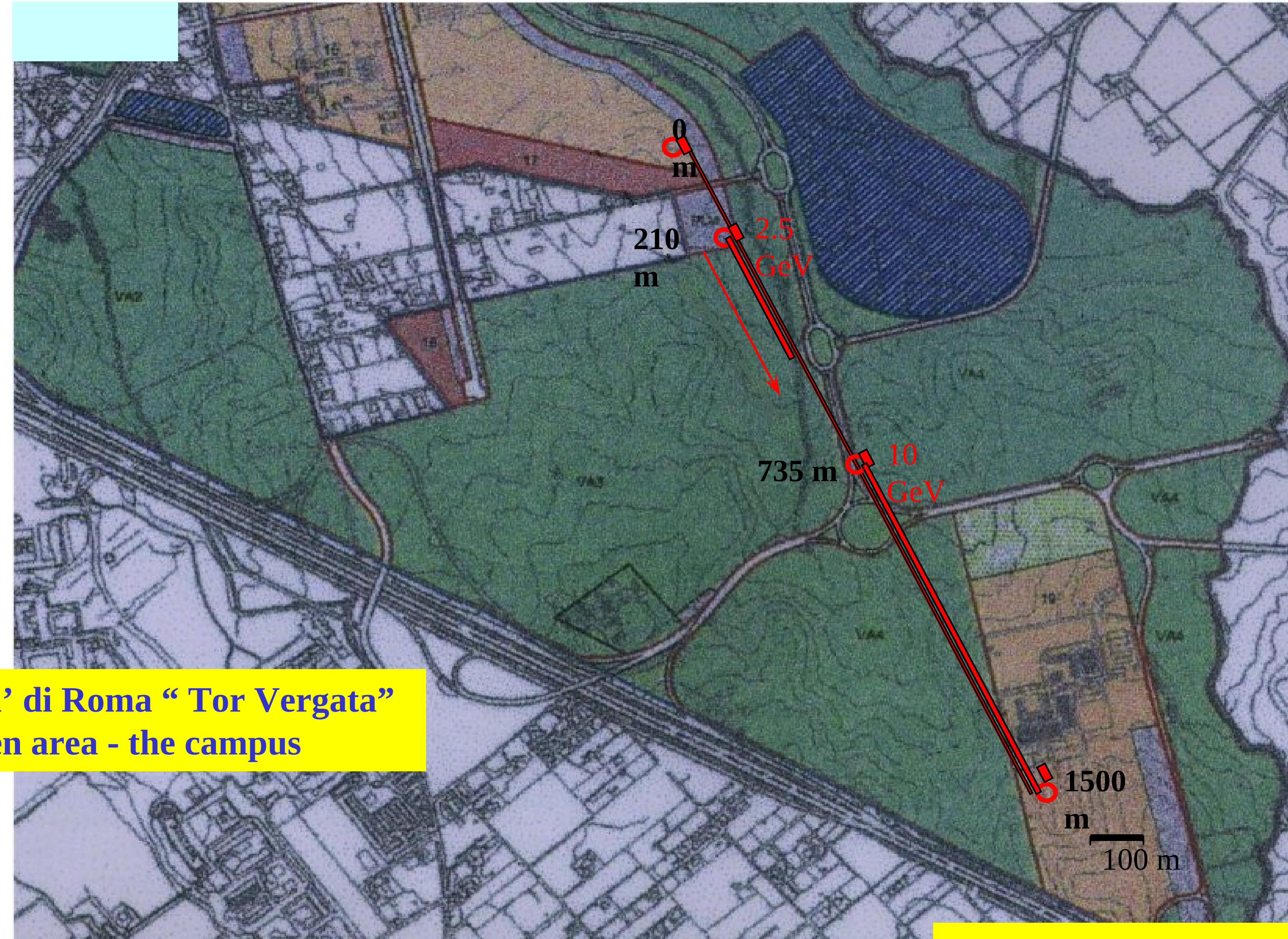
Tab. 3: Undulators characteristics

	Undulator 1 @1.5 nm	Undulator 2 @13.5 nm
Type	Halbach	Halbach
Period	3 cm	5 cm
K	1.67	4.88
Gap	12.67 mm	12.16 mm
Residual Field	1.25 T	1.25 T

Tab. 4: FEL-SASE expected performances

Wavelength (λ)	1.5 nm	13.5 nm
Saturation length	24.5 m	14.5 m
Peak Power	10^{10} W	4 10^{10} W
Peak Power 3 harm.	2 10^{8} W	5 10^{9} W
Peak Power 5 harm.	3 10^{7} W	2 10^{8} W
Brilliance	1.8 10^{31}	2 10^{32}
Brilliance 3 harm.	10^{29}	10^{31}
Brilliance 5 harm.	9 10^{28}	3 10^{29}





Universita' di Roma " Tor Vergata"
green area - the campus

Frascati INFN & ENEA
Laboratories

2 mile off map