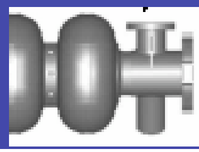
Emittance Compensation in High Brightness RF Photoinjectors: an introduction with some application

M.Ferrario

INFN-LNF



* CASA Seminar 23 May 2003 *

- e^- Brightness & SASE FEL
- Emittance Compensation Theory
- Split RF Photoinjector Working Point
- Towards a SCRF Photoinjector Design

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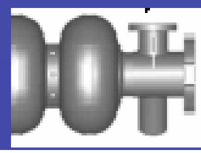


Transverse Brightness of Electron Beams

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

I = peak current

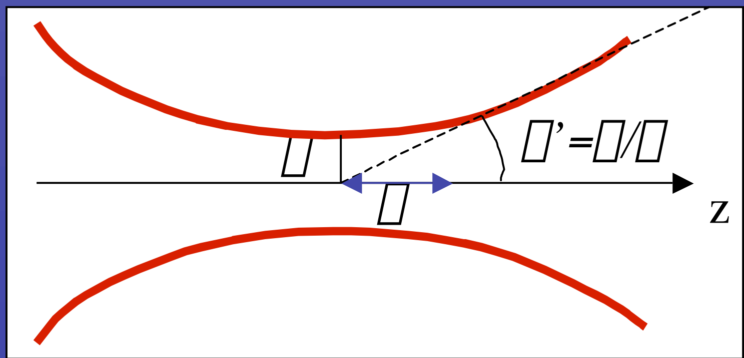
ε_{nx} = rms normalized transverse emittance

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

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

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

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



SASE FEL Electron Beam Requirements: High Brightness B_n

$$\lambda_r^{MIN} \quad \sigma_{\gamma} \sqrt{\frac{\left(1+K^2/2\right)}{\gamma B_n K^2}}$$

minimum radiation wavelength

energy spread

undulator parameter

$$B_n = \frac{2I}{\varepsilon_n^2}$$

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

gain length

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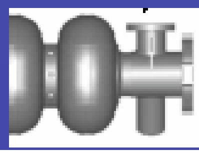
R. Saldin et al. in *Conceptual Design of a 500 GeV e+e- Linear Collider with Integrated X-ray Laser Facility*, DESY-1997-048

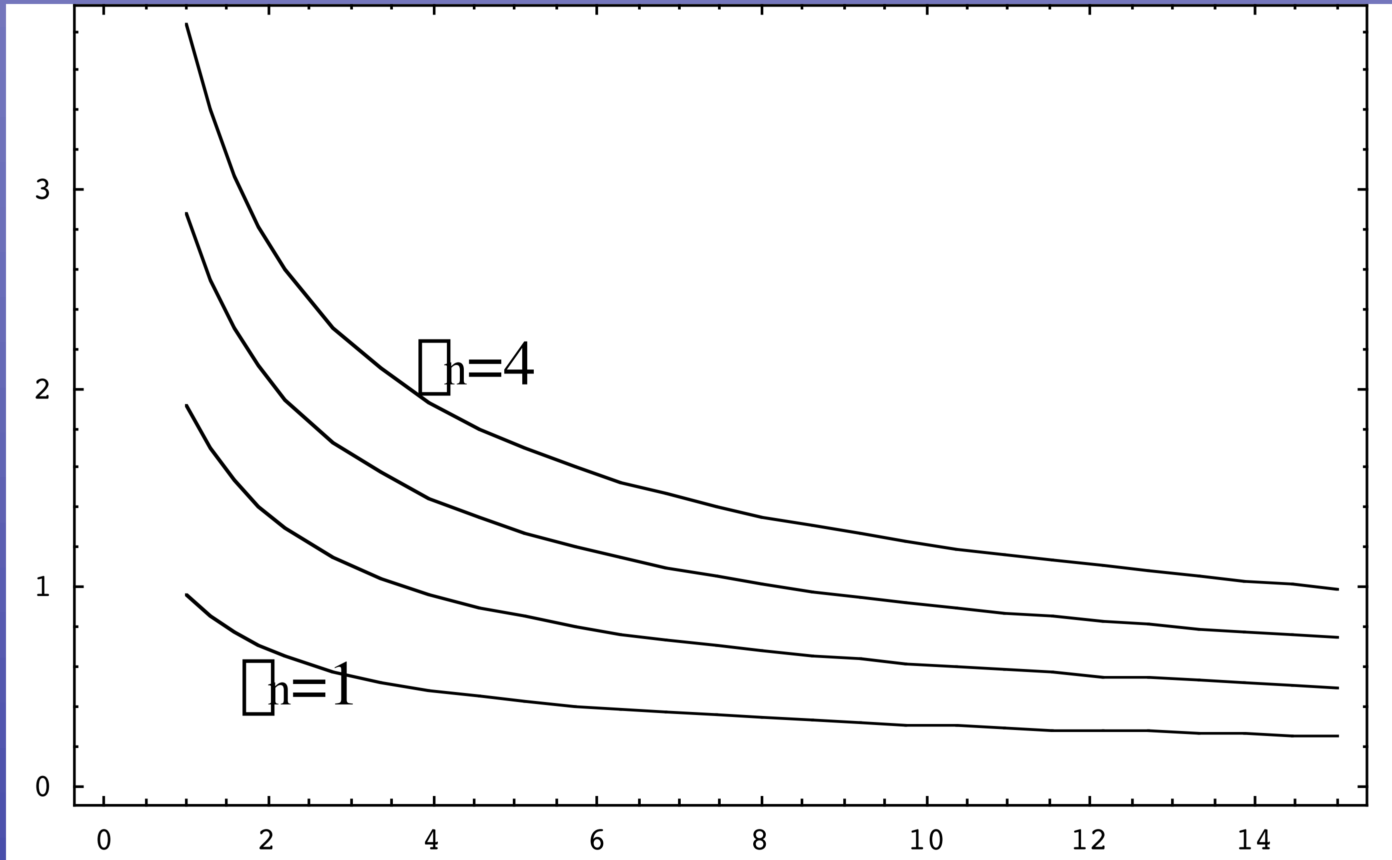


I=2.5kA

K=5

$\square_e$=0.0002

$\square$cr [nm]



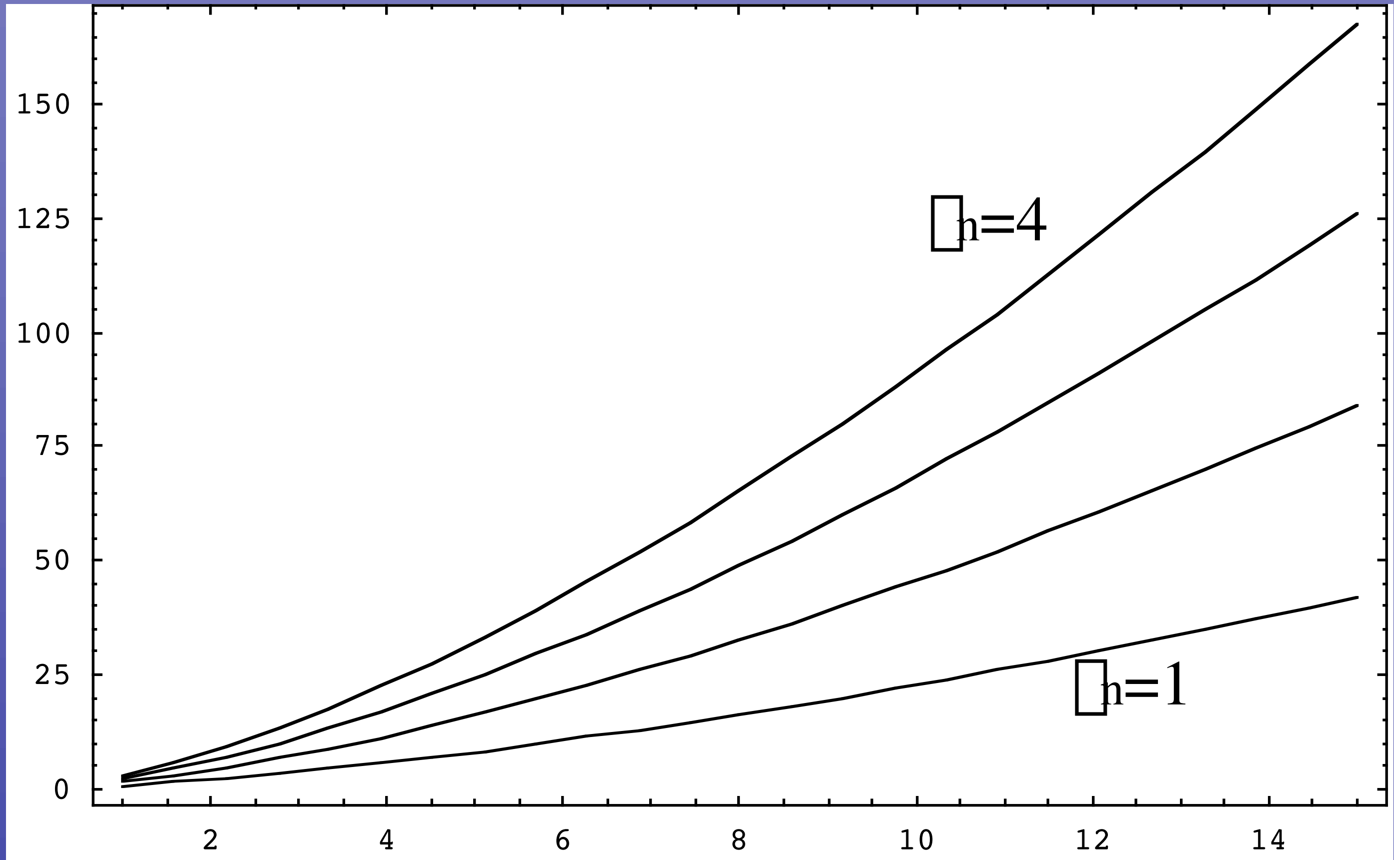
Energy [GeV]

I=2.5kA

K=5

$\square_e$=0.0002

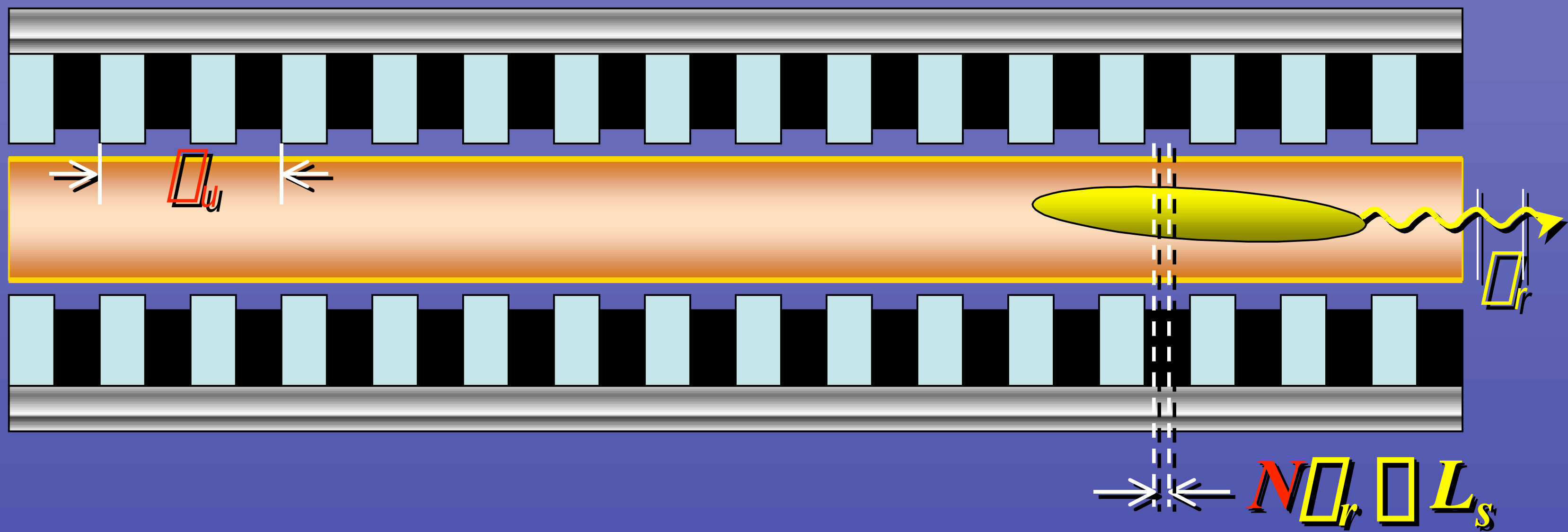
Lsat [m]



Energy [GeV]

We need high peak current low emittance and maintain small energy spread all simultaneously ……….BUT………..

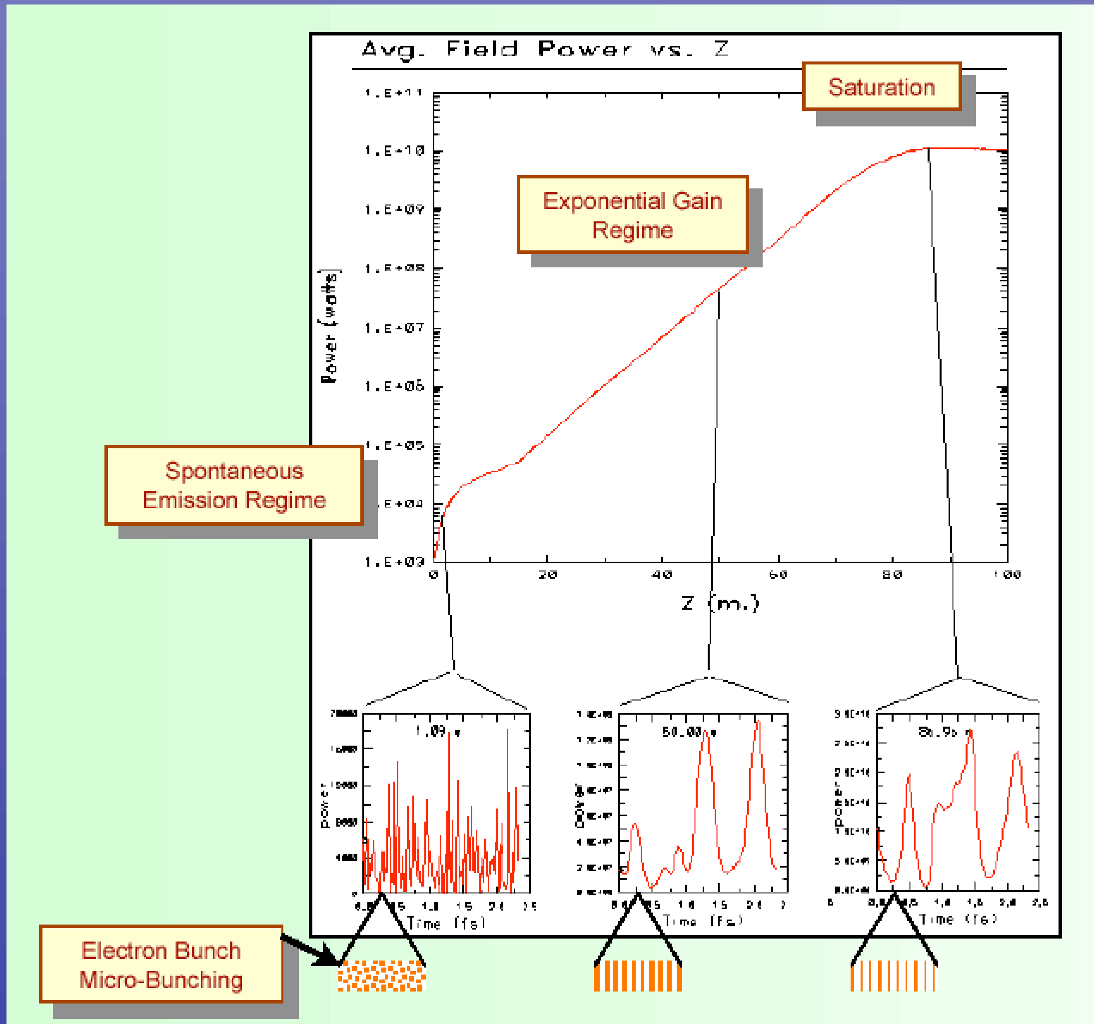
e^- slips back in phase w.r.t. photons by λ_r per period



FEL integrates over slippage length L_s :

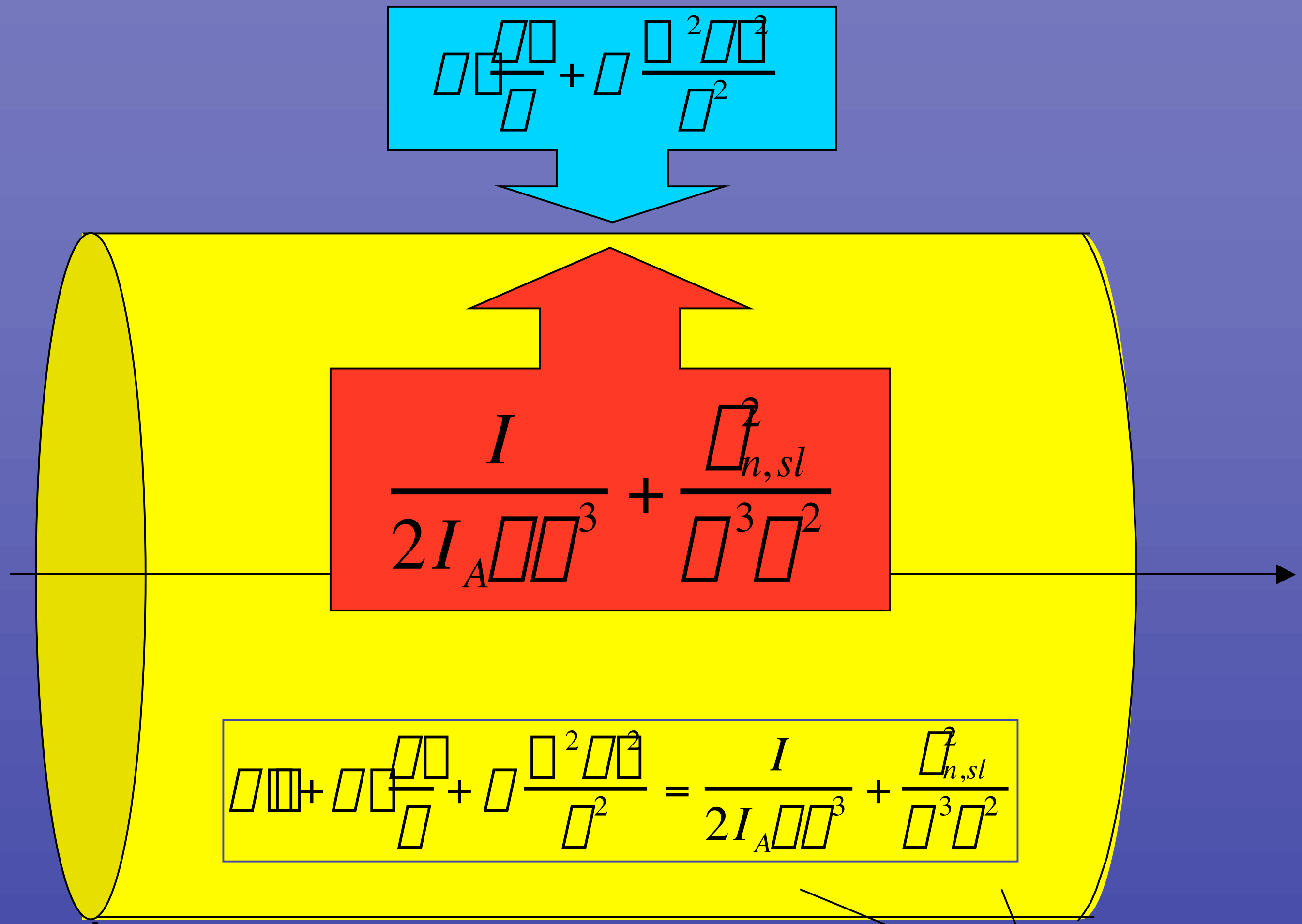
'slice' parameters are important

==> Radiation Spikes



Emittance Compensation Theory

Schematic View of the Envelope Equations



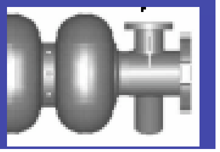
$$\sigma\frac{\gamma'}{\gamma}+\Omega^2\frac{\gamma'^2}{\gamma^2}\sigma$$

$$\frac{I}{2I_A\sigma\gamma^3}+\frac{\varepsilon^2_{n,sl}}{\sigma^3\gamma^2}$$

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

Laminarity Parameter ==>

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

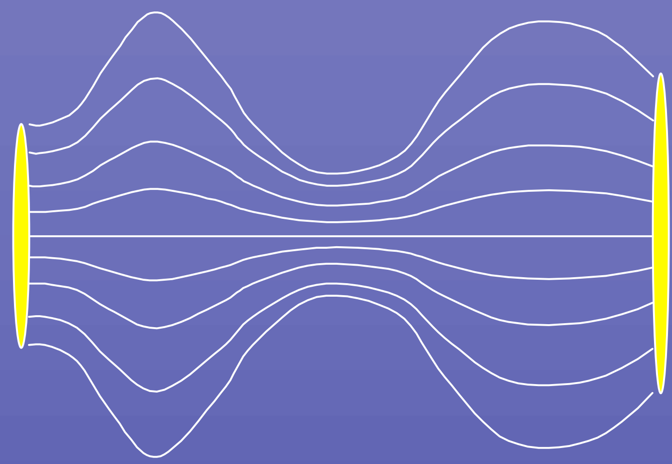


The beam undergoes *two regimes* along the accelerator:

$\rho >> 1$

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

(last term crossed out)

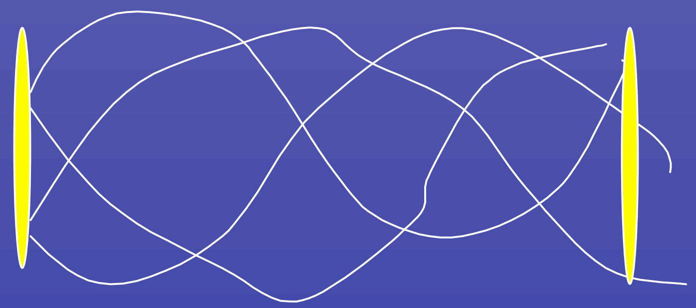


Laminar Beam

$\rho << 1$

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

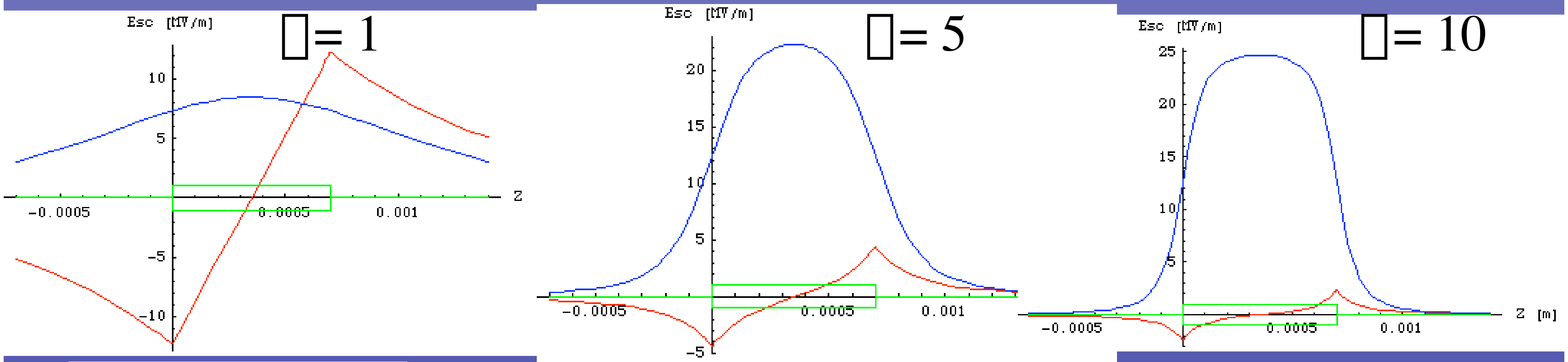
(space-charge term $\frac{I}{2I_A\sigma\gamma^3}$ crossed out)



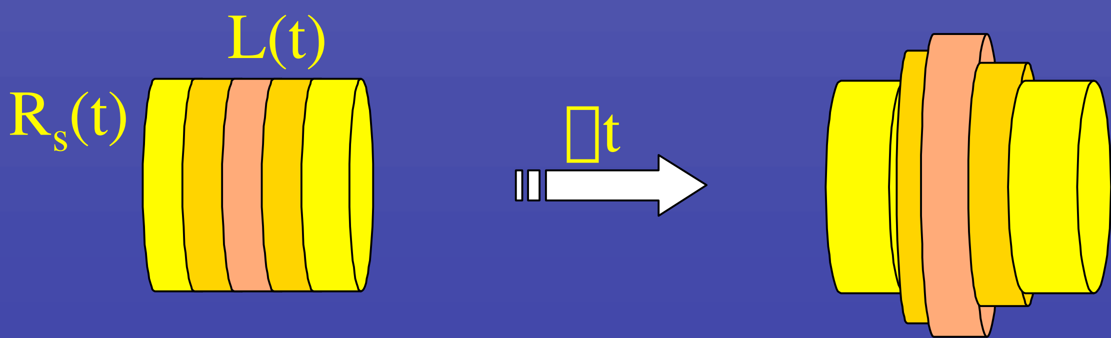
Thermal Beam

Laminar Beam-Transverse Space charge Field

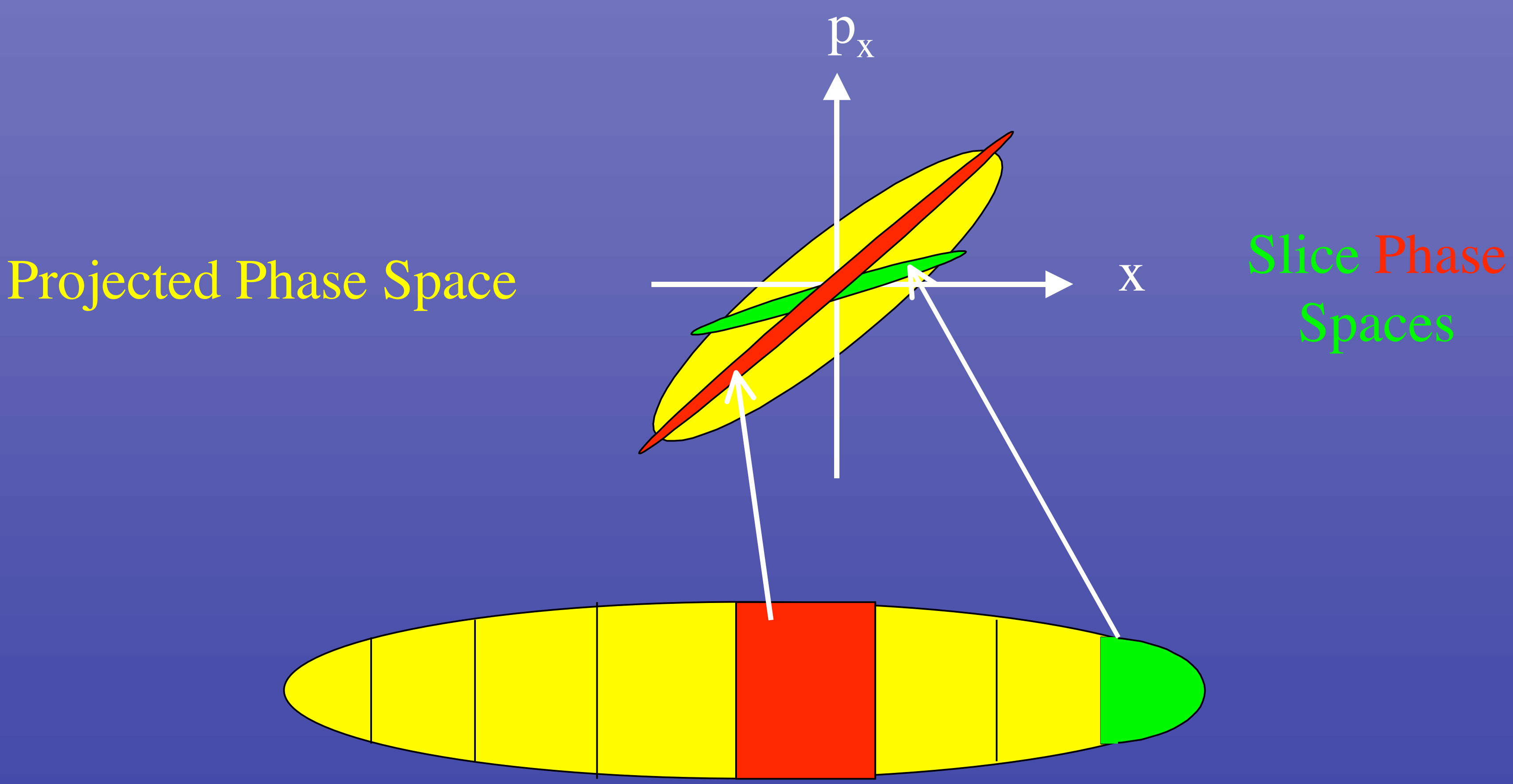
$$E_r^{sc}(\zeta_s) = \frac{Q}{4\pi\varepsilon_o R_s L}\left[\frac{1-\zeta_s/L}{\sqrt{(1-\zeta_s/L)^2 + A_{r,s}^2}} + \frac{\zeta_s/L}{\sqrt{(\zeta_s/L)^2 + A_{r,s}^2}}\right] = \frac{Q}{4\pi\varepsilon_o R_s L}\, g(\zeta_s, A_{r,s})$$



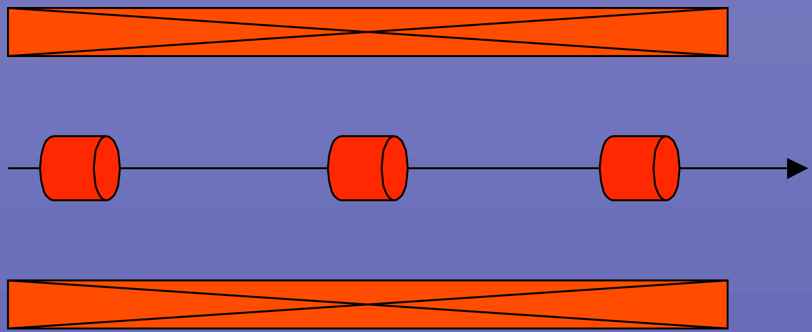
$$A_{r,s} \equiv R_s / (\gamma_s L)$$



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



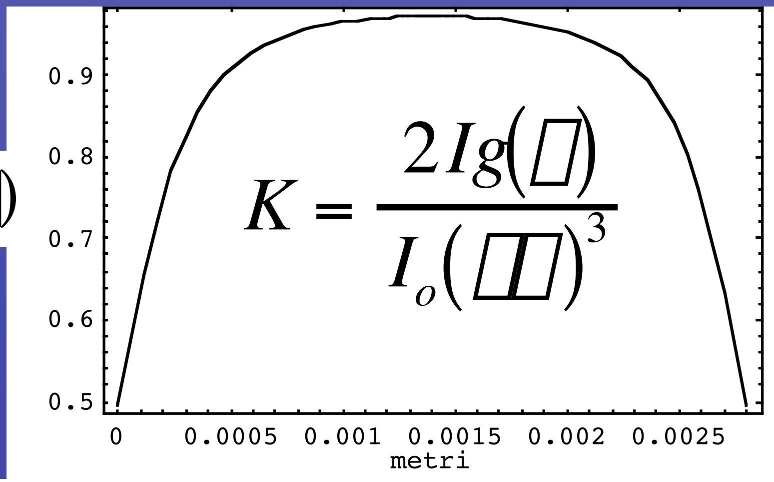
Simple Case: Transport in a Long Solenoid



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

$\Box'' = 0$ ==> Equilibrium solution ? ==> $\Box_{eq}(\Box) = \frac{\sqrt{K(\Box)}}{k_s}$

$$k_s = \frac{qB}{2mc\Box\Box}$$



$$K = \frac{2Ig(\Box)}{I_o(\Box\Box)^3}$$

Small perturbations around the equilibrium solution

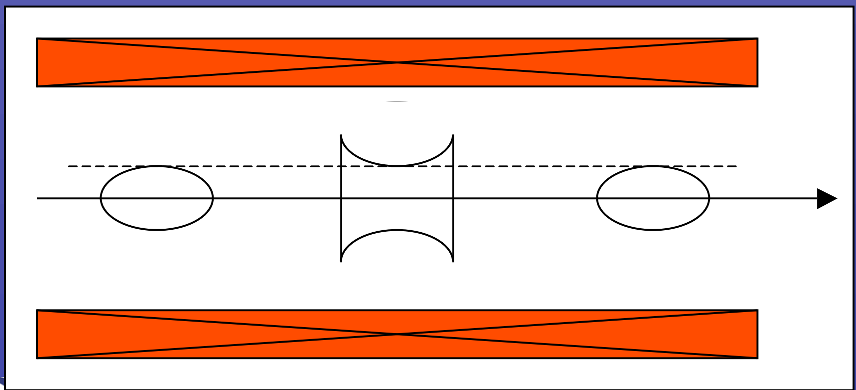
$$\square = \square_{eq} + \square\square$$

$$\square\square'' + 2k_s^2\square\square = 0$$

$$\square(\square) = \square_{eq}(\square) + \left(\square(\square)\ \square\ \square_{eq}(\square)\right)\cos\left(\sqrt{2}k_s z\right)$$

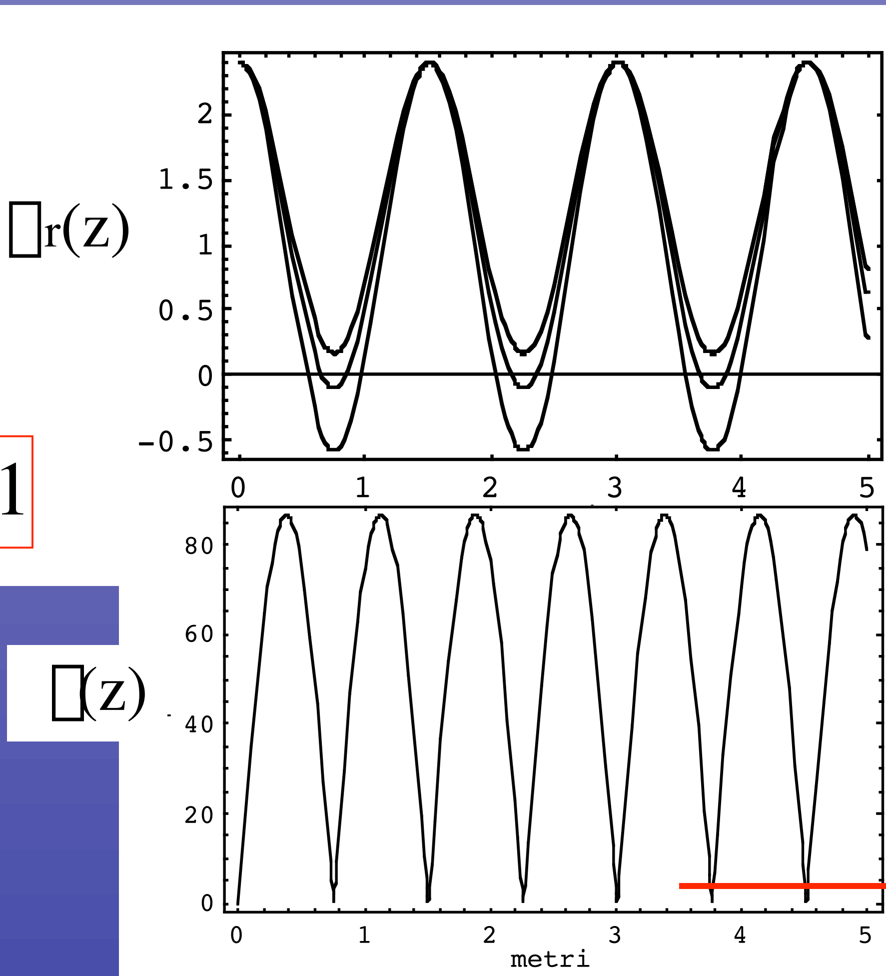
$$\square'(\square) = \square\sqrt{2}k_s\left(\square(\square)\ \square\square_{eq}(\square)\right)\sin\left(\sqrt{2}k_s z\right)$$

Plasma frequency



Envelope oscillations drive Emittance oscillations

$0.5 \,\square\, g(\square) \,\square\, 1$

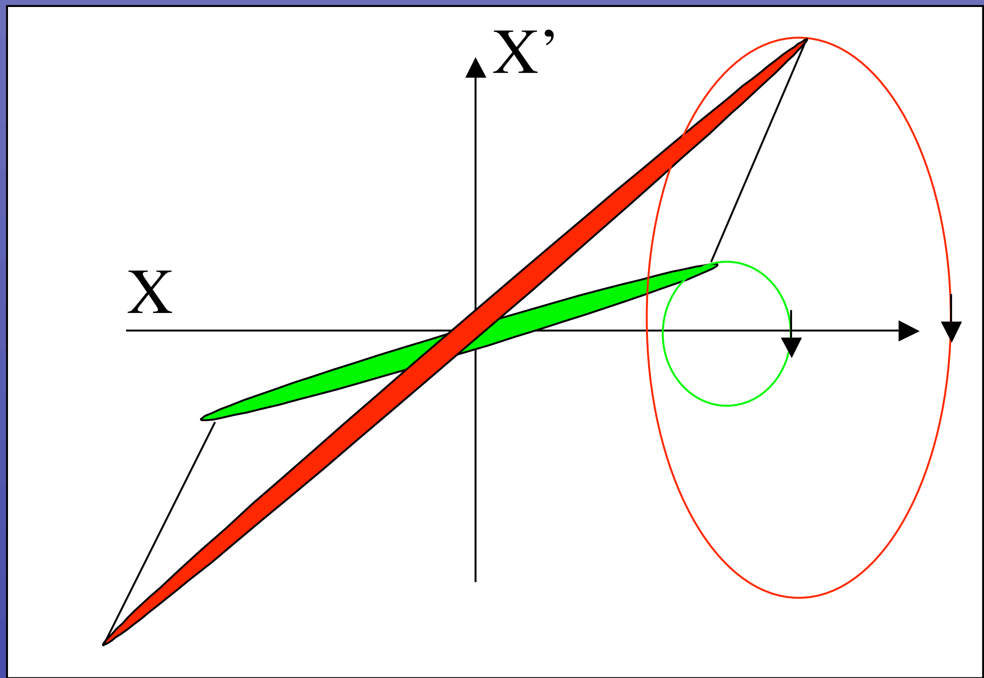


$\frac{\square\square}{\square} = 0$

$\square\square = 0$

$$\square(z) = \sqrt{\langle \square_r^2 \rangle \langle \square_r'^2 \rangle \,\square\, \langle \square_r \square_r' \rangle^2} \div \left|\sin\left(\sqrt{2}\,k_s z\right)\right|$$

Perturbed trajectories oscillate around the equilibrium with the same frequency but with different amplitudes

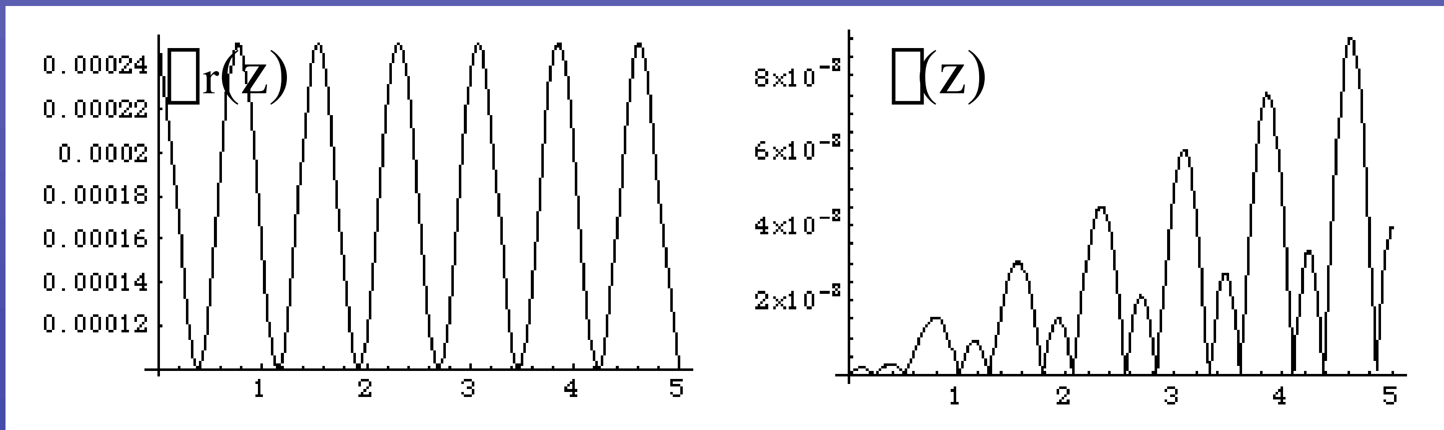


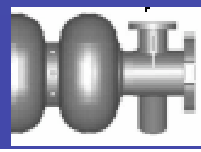
A Spread in Plasma Frequencies drives a Beating in Emittance Oscillations

$$\square_{\square} = \frac{\square\square}{\square_o}$$

$$g(\square) = 1$$

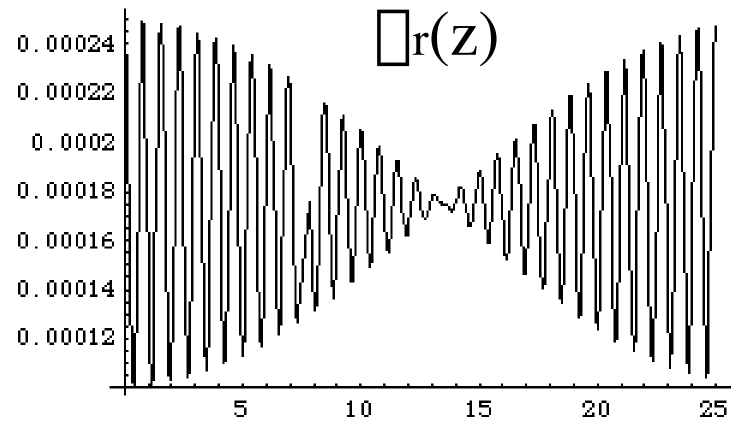
$$\square\square_o = \square_c \; \square\square_{eqo}$$

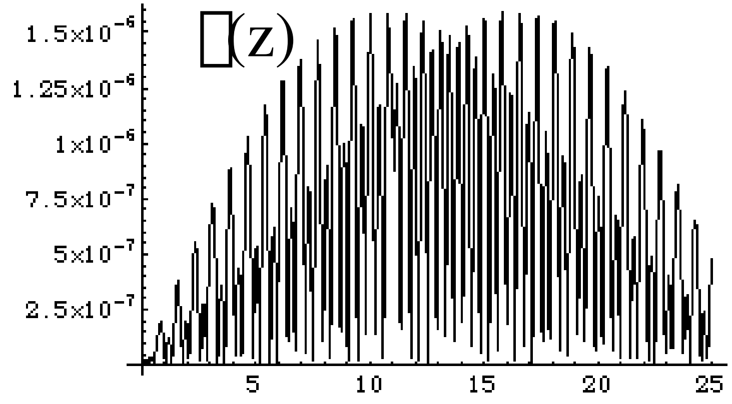




M. Ferrario et al., **Recent Advances And Novel Ideas For High Brightness Electron Beam Production Based On Photo-Injectors, LNF-03-06**

On a longer time scale





$$\square_n = \frac{\square}{\sqrt{2}} k_o \left| \square_{eqo} \left(2\square\square_o + \square_\square\right) \sin\left(\frac{\square k}{2} z\right) \cos\left(\langle k\rangle z\right) + \square\square_o^2 \sin\left(\square k z\right) \right|$$

$$\langle k\rangle = \frac{1}{\sqrt{2}}\left(k_+ + k_\square\right) = \sqrt{2}\, k_o$$

$$\square k = \sqrt{2}\left(k_\square \square k_+\right) = 2\sqrt{2}\, k_o \square_\square$$

Beam subject to strong acceleration

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

where

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

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

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

Normalized focusing gradient (solenoid +RF foc.)

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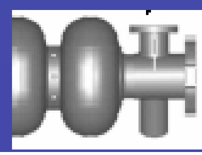

PHYSICAL REVIEW E VOLUME 55, NUMBER 6 JUNE 1997

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:

$$z \Longrightarrow y = \ln\frac{\gamma}{\gamma_o}$$

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

Dimensionless quantity:

$$\rho = \frac{\sigma}{\sqrt{S}}$$

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

Particular Solution:

$$\rho = 2\sqrt{\frac{e^{-y}}{1+4\Omega^2}}$$

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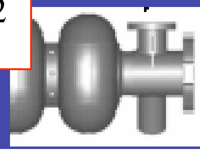
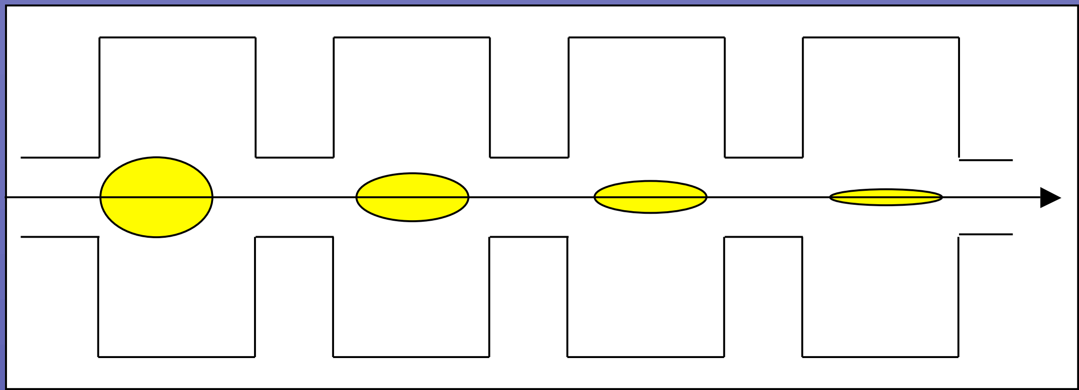


Back to Real World: Invariant Envelope Solution



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

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

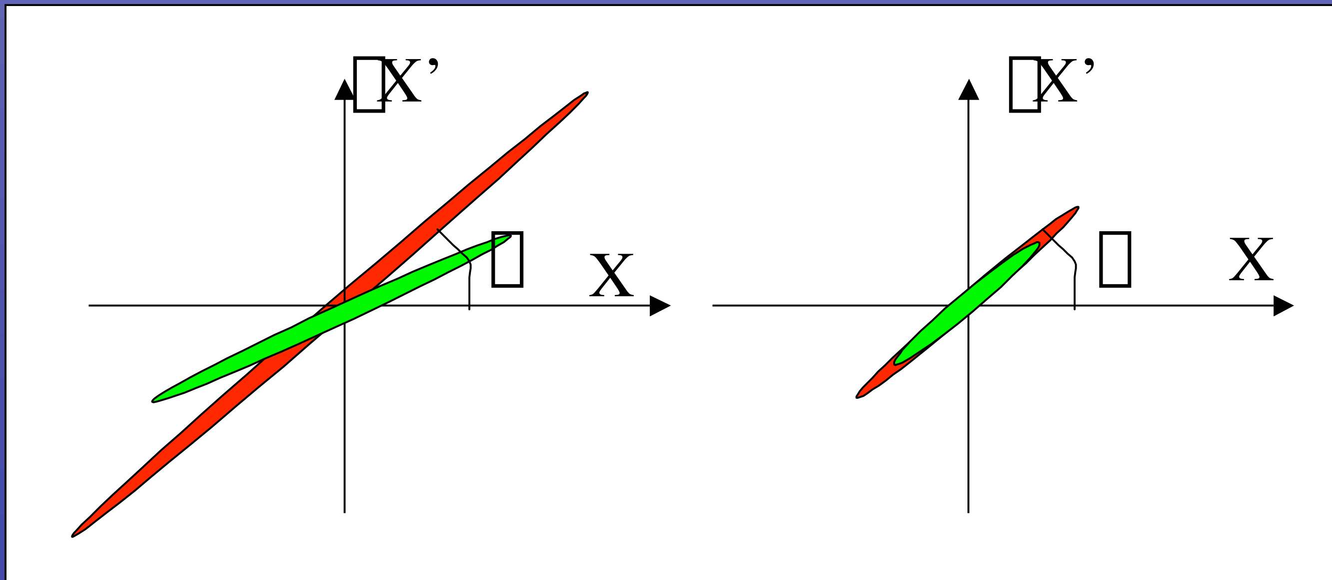
An important property of the Invariant Envelope

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

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

Constant phase space angle:

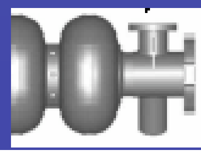
$$\theta = \frac{\sigma'_{inv}}{\sigma_{inv}} = -\frac{\gamma'}{2\gamma}$$



Laminarity Parameter

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

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

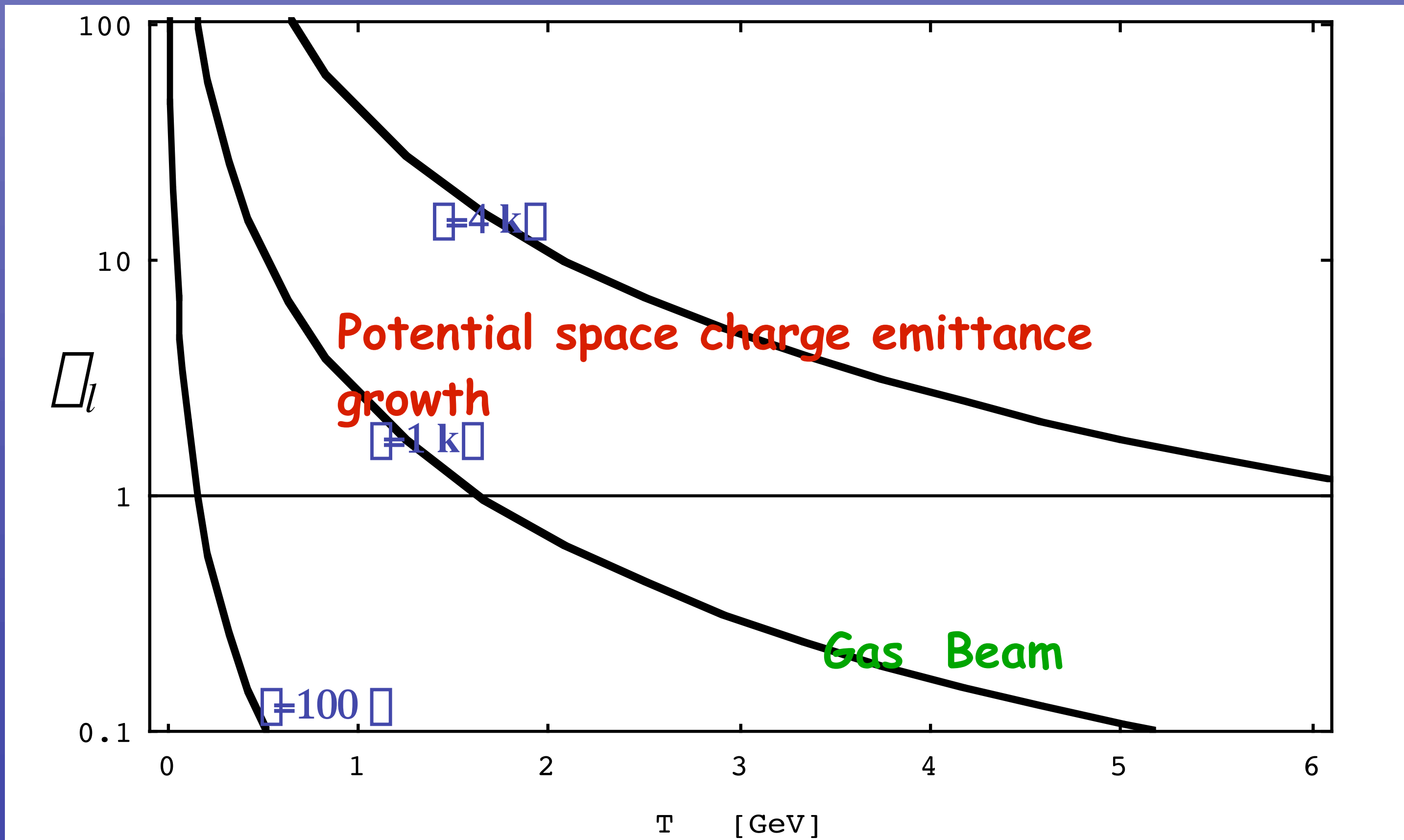


Typical X-FEL Beam

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

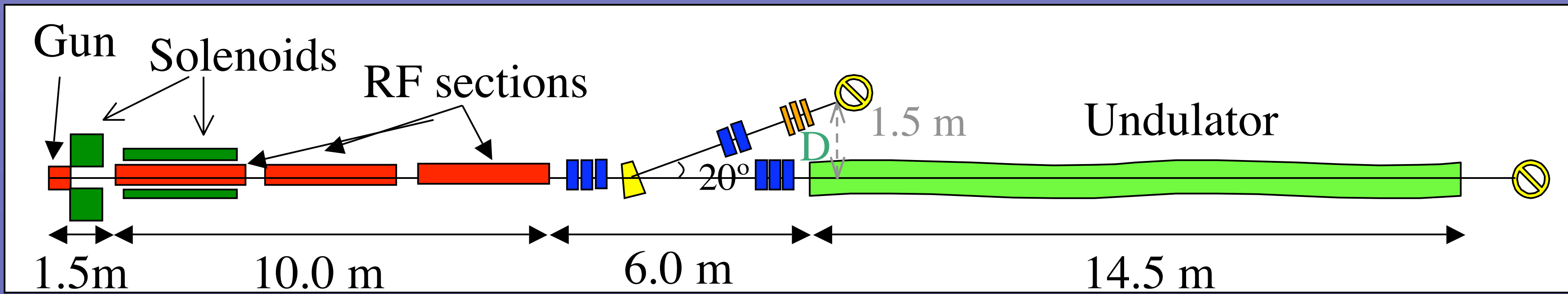
$I_0 = 17\ kA \quad \eta^2 \approx 1/8\ (SW\ \ acc.\ \ str.)$

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



•Split RF Photoinjector Working Point

SPARC Working Point



GUN PARAMETERS

Frequency: 2856 MHz

Peak Field: 120 MV/m

Solenoid Field: 0.27 Tesla

Beam Energy: 5.6 MeV

Charge: 1 nC

Laser: 11.5 ps x 1 mm (Flat Top with <1 ps rise time)

Thermal emittance 0.3 μm

LINAC PARAMETERS

Frequency: 2856 MHz

Accelerating Field: 25-12.5-12.5 MV/m

Solenoid Field: 0.1 Tesla

Beam Energy: 155 MeV

FEL PARAMETERS

Wavelength: 530 nm

Coop. Length: 300 μm

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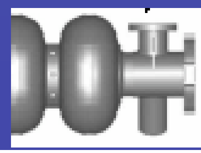
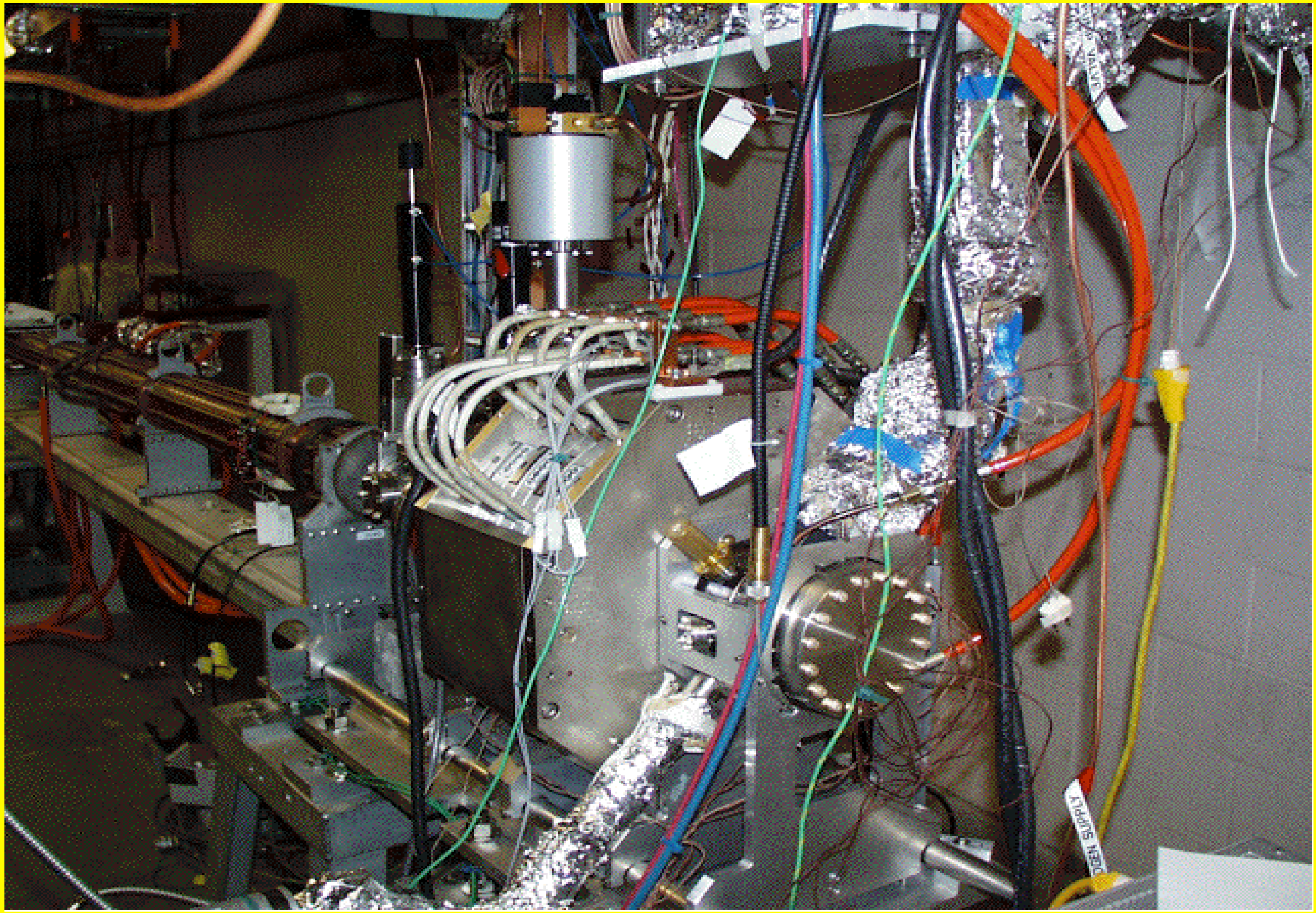
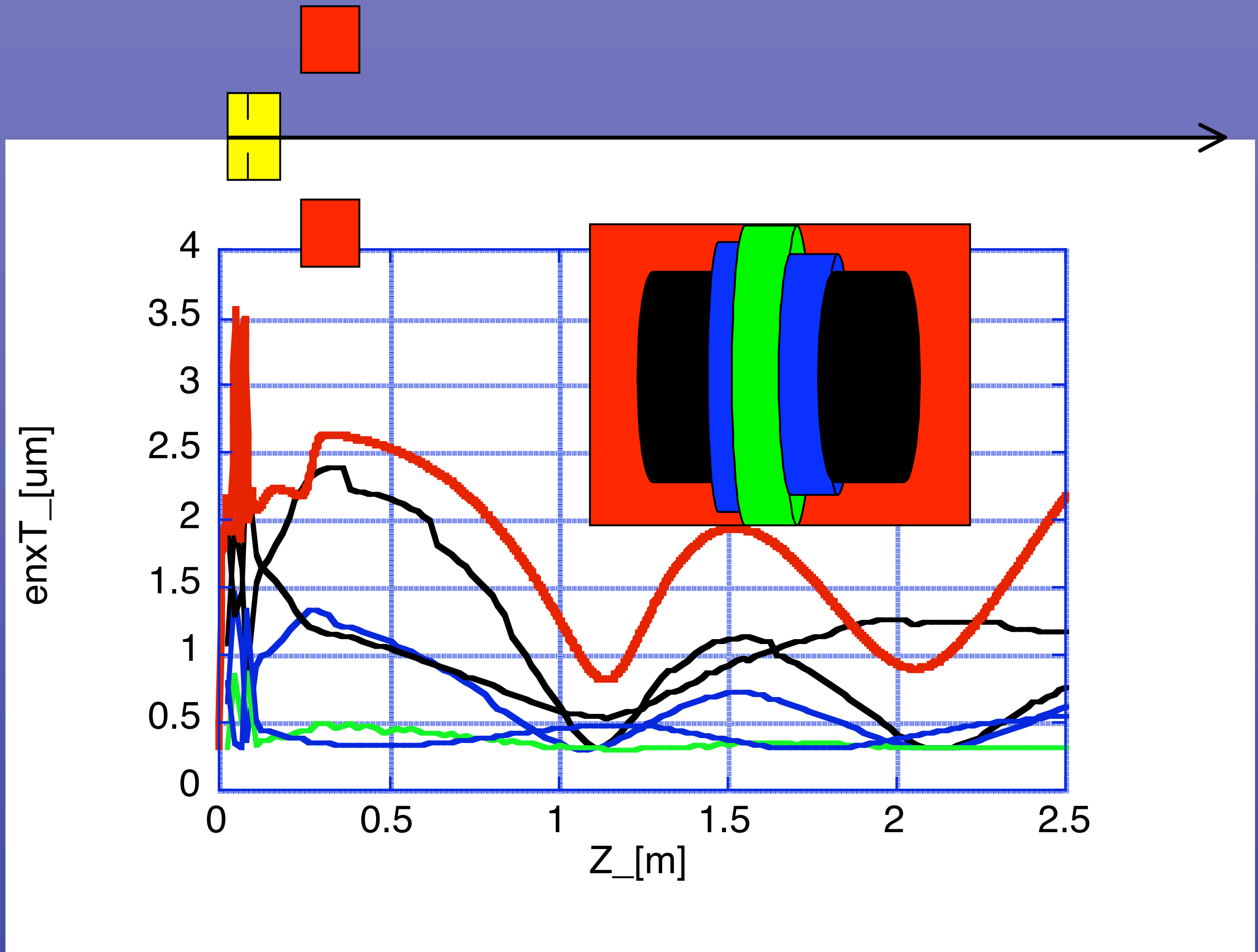


SLAC GUN TEST FACILITY



Gun Working Point

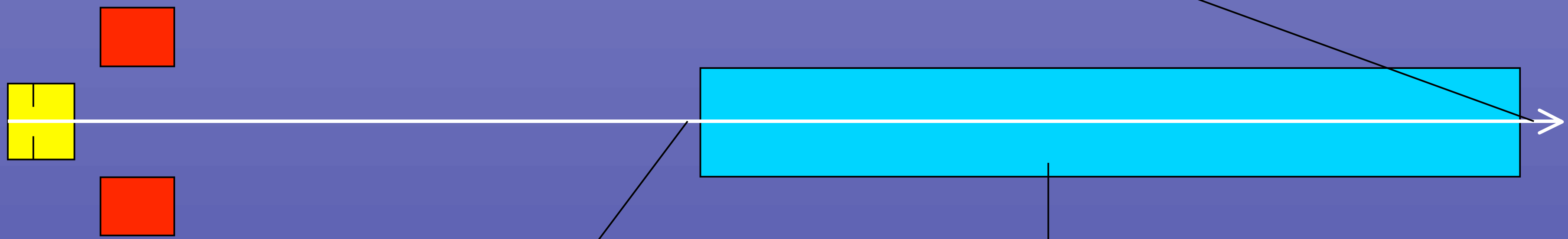


M. Ferrario et al., **HOMDYN study for the LCLS RF photoinjector, LNF-00-004**

Matching Conditions with the Linac

$$\square = \sqrt{\frac{8}{3}}\,\frac{\hat{I}}{2 I_o \square_{th} \square}$$

150 MeV



$$\square' = 0$$

$$\square\square = \frac{2}{\square_w}\sqrt{\frac{\hat{\square}}{2 I_0 \square}}$$

25 MV/m

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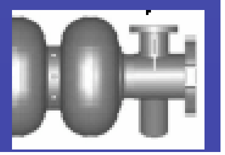
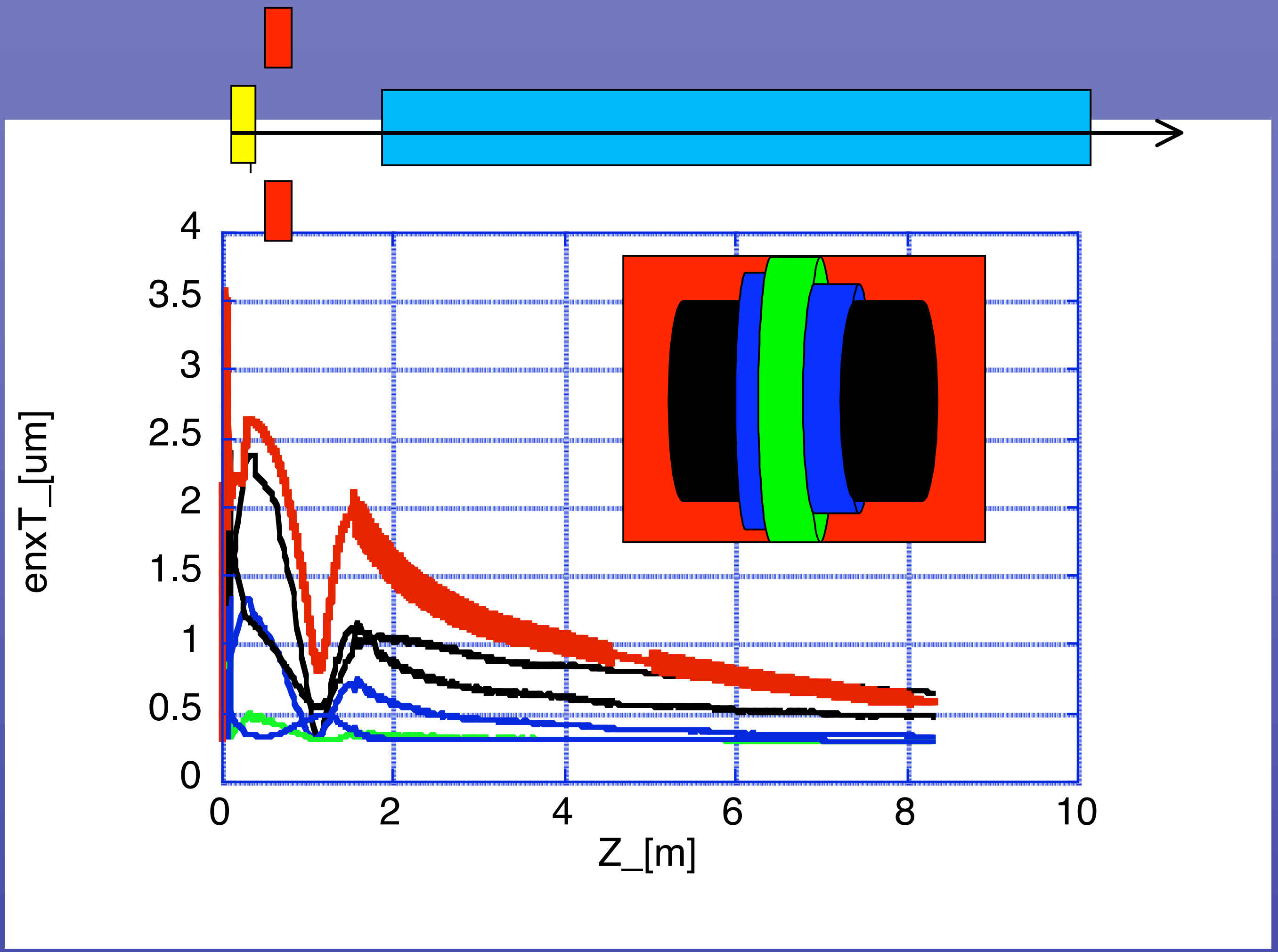
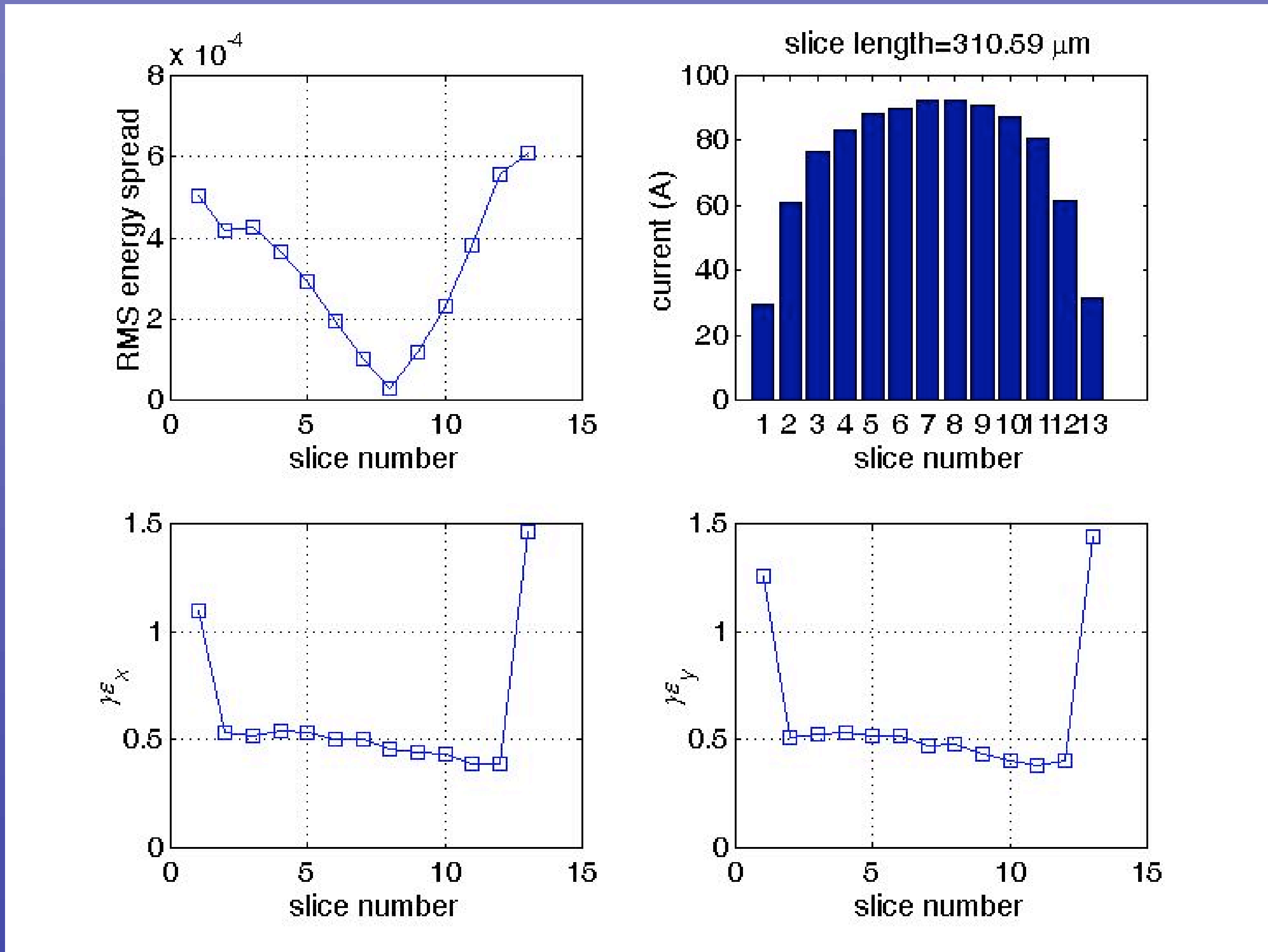


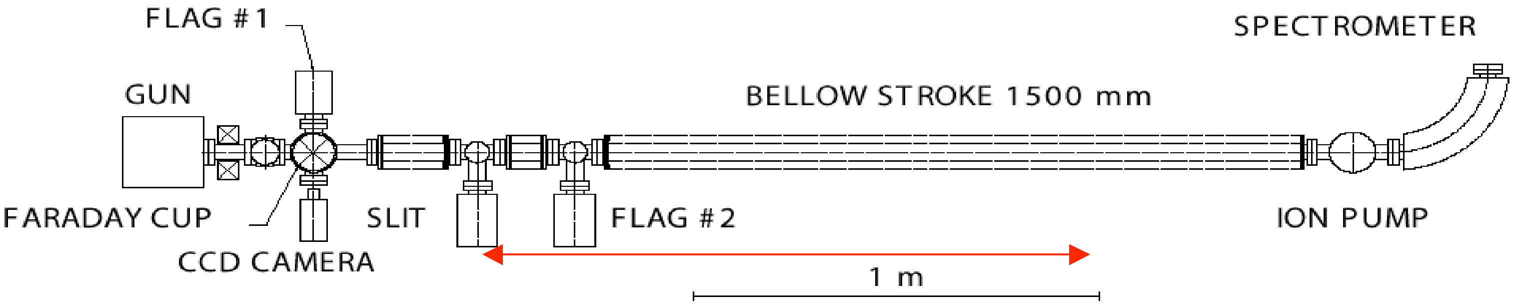
Linac Working Point

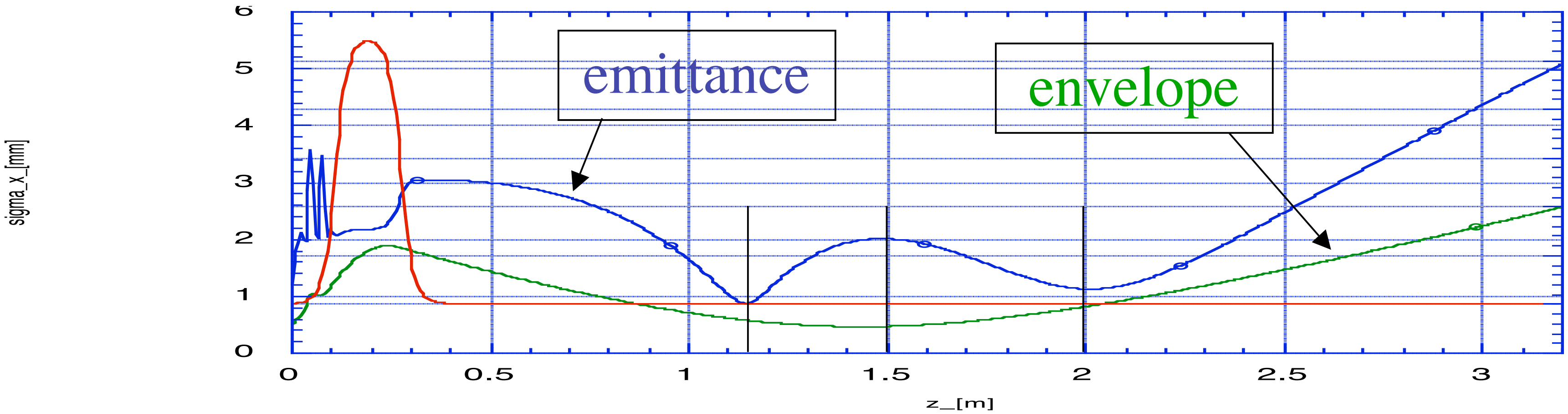


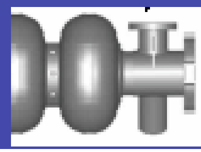
Slice analysis of beam properties at the undulator entrance



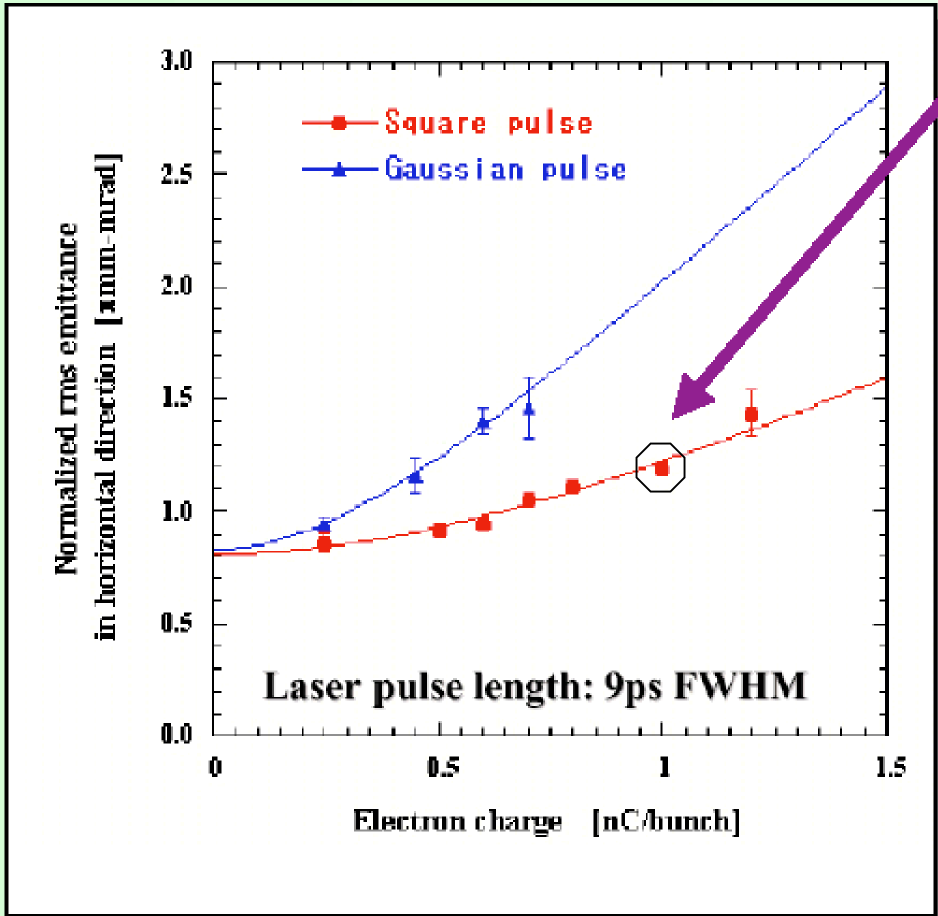
Movable Emittance-Meter Experiment







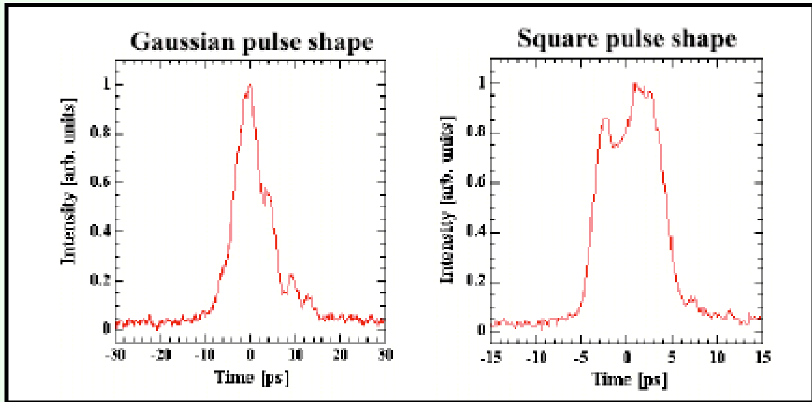
Sumitomo Spring 2002



1nC

ε_p = 1.2 mm.mrad

with "LCLS type" Gun



Frequency domain pulse shaping

Courtesy of J.Yang FESTA

Sumitomo Heavy Industries, Ltd.

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Towards a High Brightness L-Band Superconducting RF Photoinjector Design

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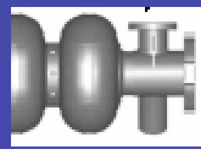

Main Questions/Concerns

- RF Focusing vs Magnetic focusing ?
- High Peak Field on Cathode ?
- Cathode Materials and QE ?
- Q degradation due to Magnetic Field ?

ELSEVIER Nuclear Instruments and Methods in Physics Research A 452 (2000) 34–43
Section A
www.elsevier.nl/locate/nima

RF focussing – an instrument for beam quality improvement in superconducting RF guns

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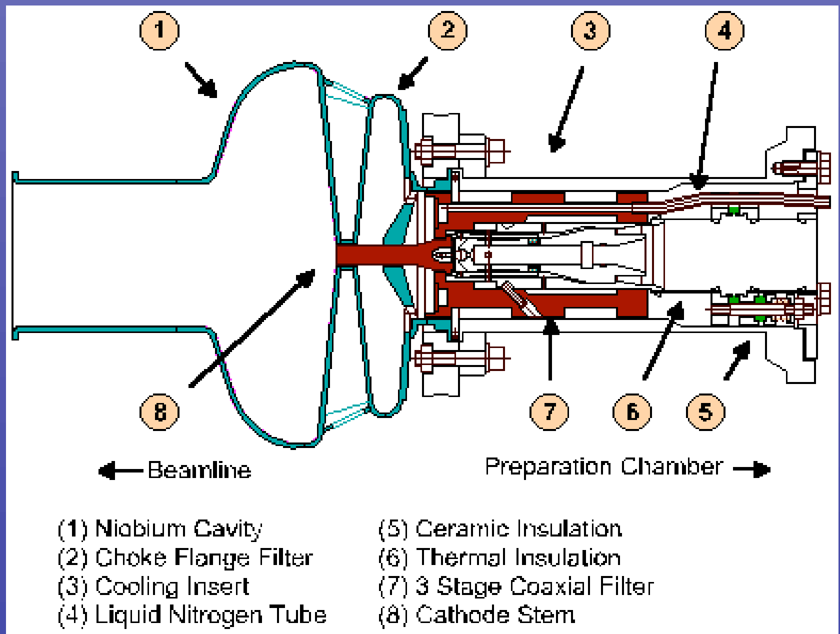
[a]FZ Rossendorf Zentralabteilung, Postfach 51 01 19, D-01314 Dresden, Germany
[b]Budker INP, 630090, Lavrentev Avenue, 11, Novosibirsk, Russia



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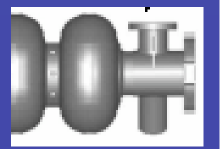

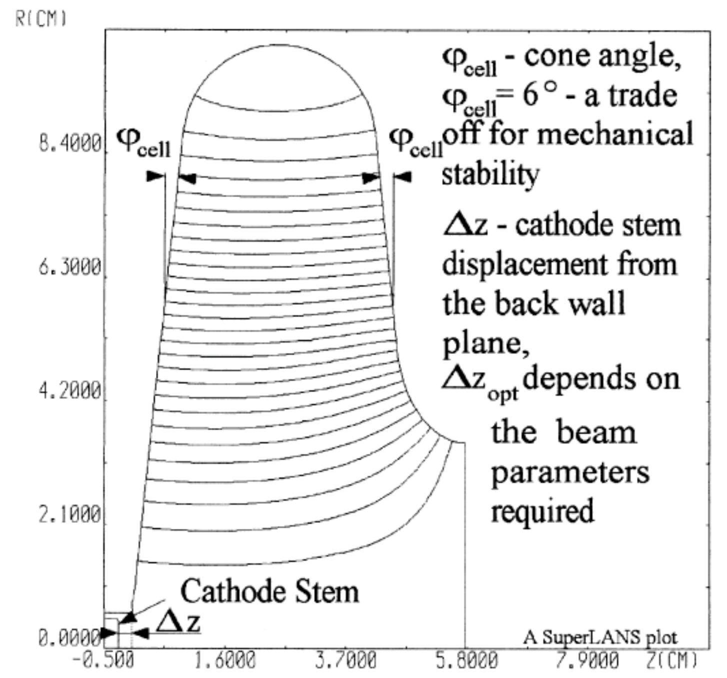

Fig. 2. Geometry and the field pattern of the first cell.

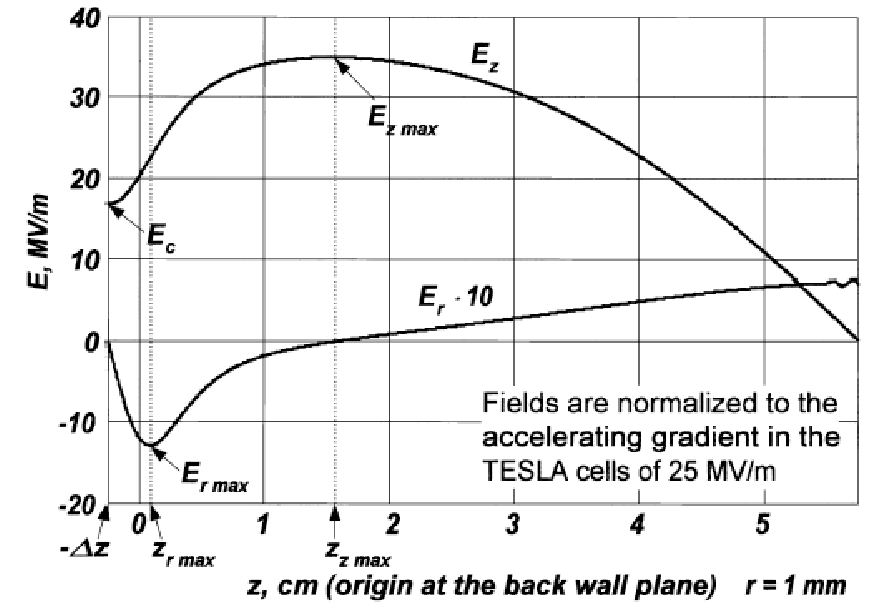

Fig. 4. Electric field components in the first cell of the 1.3 GHz RF gun cavity.

No flexible and independent tuning of accelerating field and RF focusing effects

$$E_r \approx -\frac{r}{2}\frac{\partial}{\partial z}E_z(z,0)+\ldots\ldots$$

Transverse non linearities

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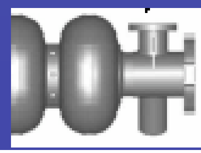


Recent results allow us to look for a simpler design

DEVELOPMENT OF ELECTROPOLSHING TECHNOLOGY FOR SUPERCONDUCTING CAVITIES

K.Saito#, KEK, 1-1 Oho, Tsukuba-shi, Ibaraki-ken, Japan

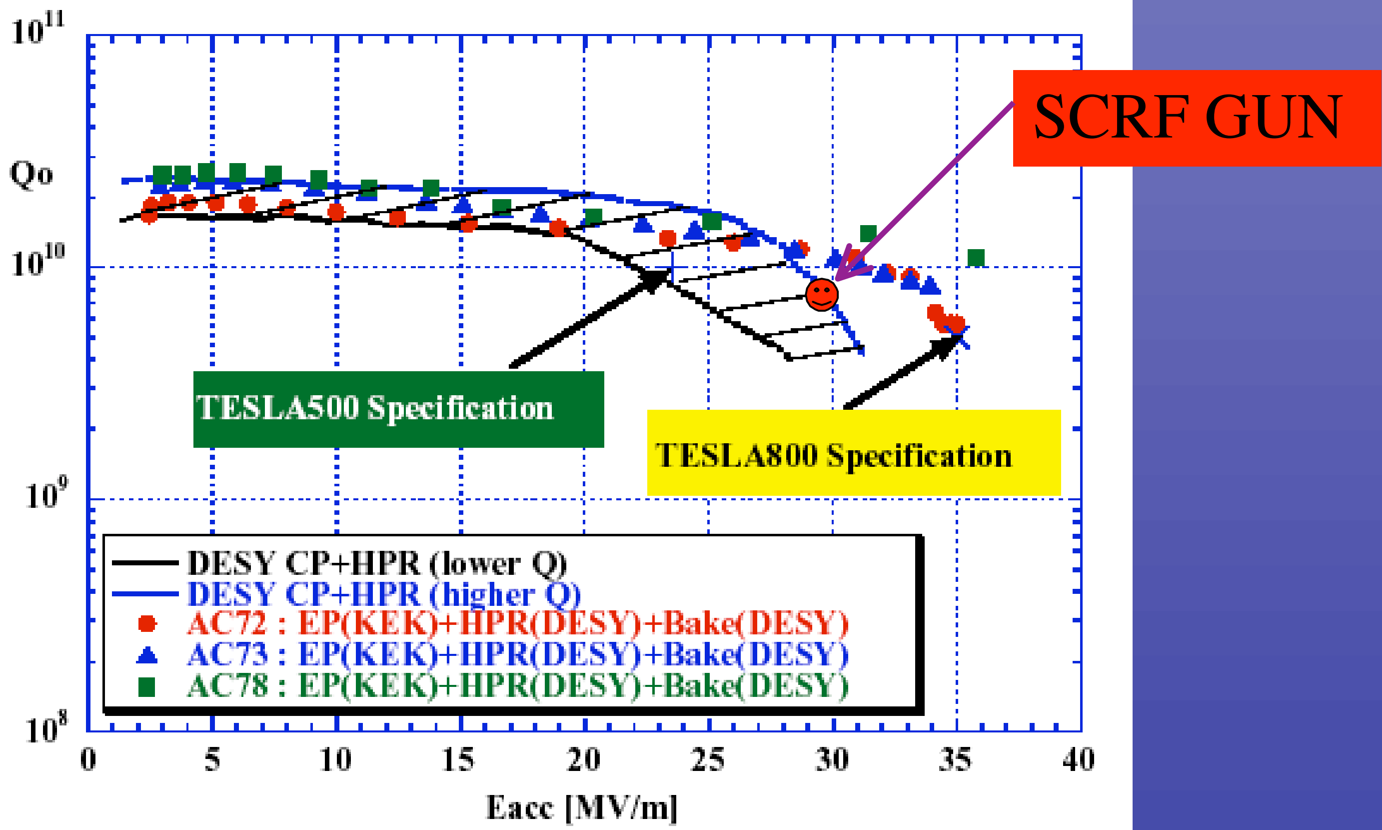
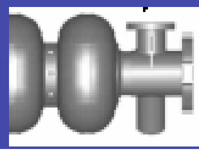


Figure 8: Results of electropolished TTF cavities.



TESTS OF NIOBIUM CATHODE FOR THE SUPERCONDUCTING RADIO FREQUENCY GUN

Qiang Zhao, Triveni Srinivasan-Rao, BNL, Upton, NY 11973, USA
Mike Cole, Advanced Energy Systems, Medford, NY 11763, USA

Laser Cleaning

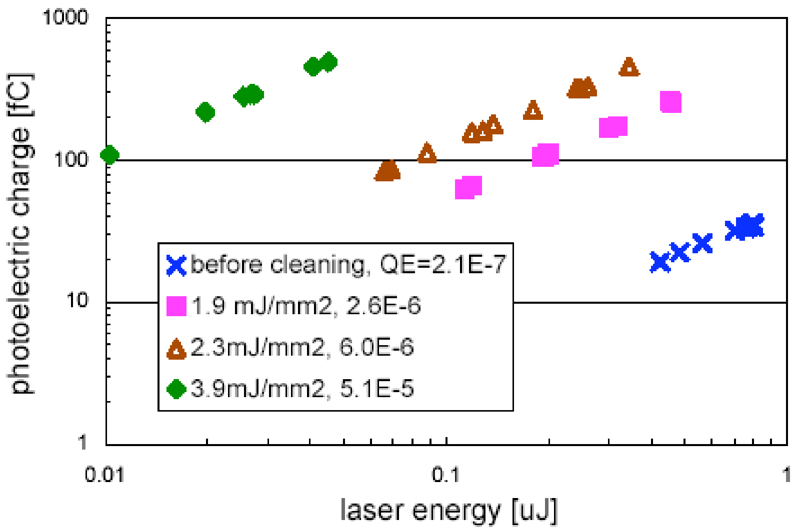


Figure 3: QE of BCP Niobium sample cleaned by 248nm, measured by 266nm

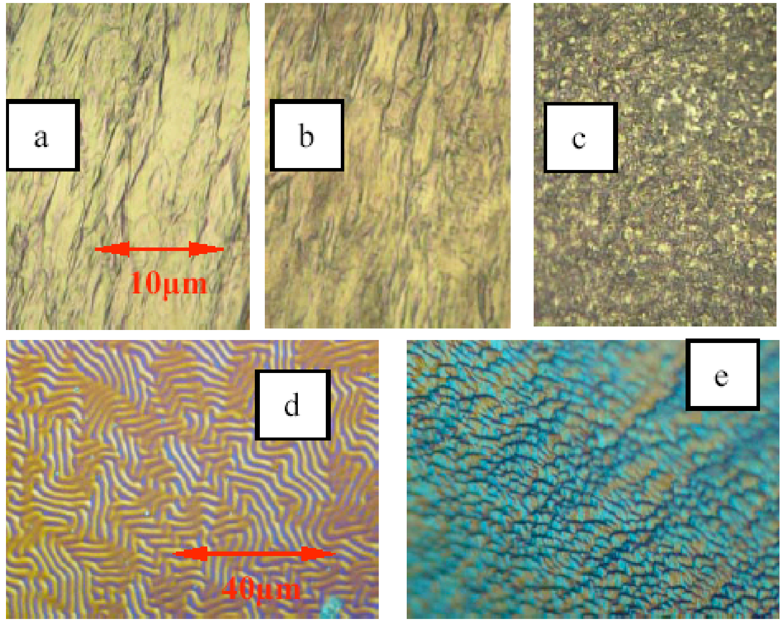
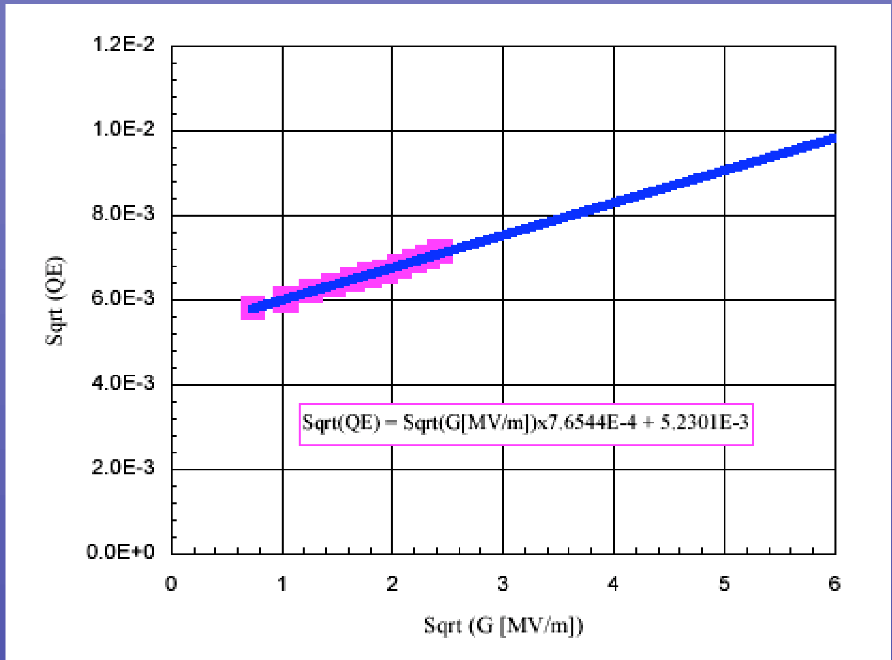


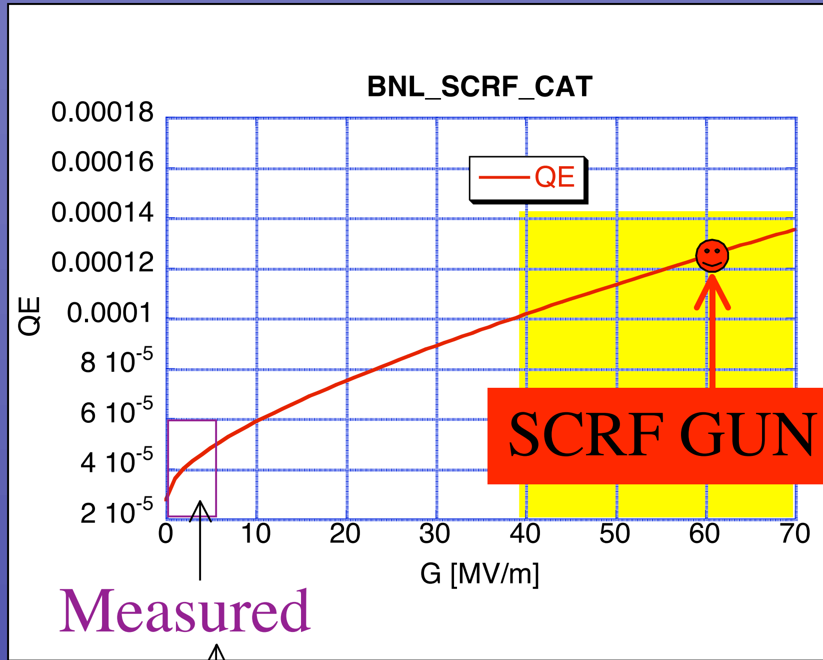
Figure 2: Niobium surfaces cleaned with different ps-YAG laser energy densities, observed under optical microscope. BCP sample: a) before laser cleaning, b) laser energy density 0.25mJ/mm^2, c) laser energy density 0.67mJ/mm^2 EP sample: d) before cleaning; e) laser energy density 0.45mJ/mm^2

QE limited by surface morphology degradation

Measurements at room T on a dedicated DC system

Extrapolation to Higher Field





$$\eta = K\left(h\nu - \phi_o + \sqrt{\tfrac{e}{4\pi\varepsilon_0}}\sqrt{E_s}\right)^2$$

$\eta = QuantumEfficiency$

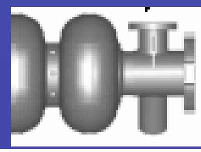
$h\nu = PhotonEnergy$

$\phi_o = ElectronWorkFunction$

$K = Const.$

$E_s = AppliedElectricField$

Limited by the available voltage



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DESIGN, CONSTRUCTION AND STATUS OF ALL NIOBIUM SUPERCONDUCTING PHOTOINJECTOR AT BNL

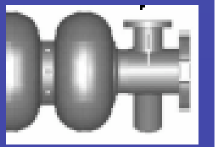
T. Srinivasan-Rao, I. Ben-Zvi, A. Burrill, G. Citver, A. Hershcovitz, D. Pate, A. Reuter, J. Scaduto, Q. Zhao, Y. Zhao, BNL, Upton, NY, USA

J. Delayen, P. Kneisel, TJNAF, Newport News, VA, USA

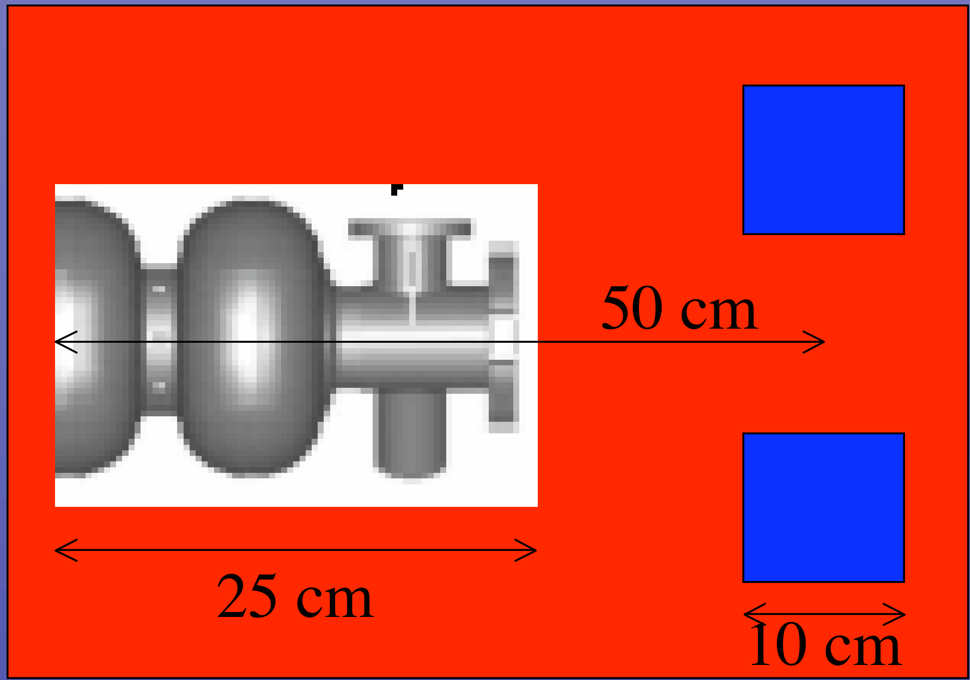
H. Bluem, M. Cole, A. Favale, J. Rathke, T. Schultheiss, Advanced Energy Systems, Medford, USA

Figure 4: Photograph of ½ cell Nb cavity

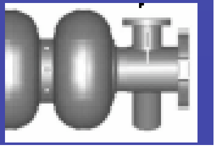
Ready for cold test: QE? Thermal Effects?

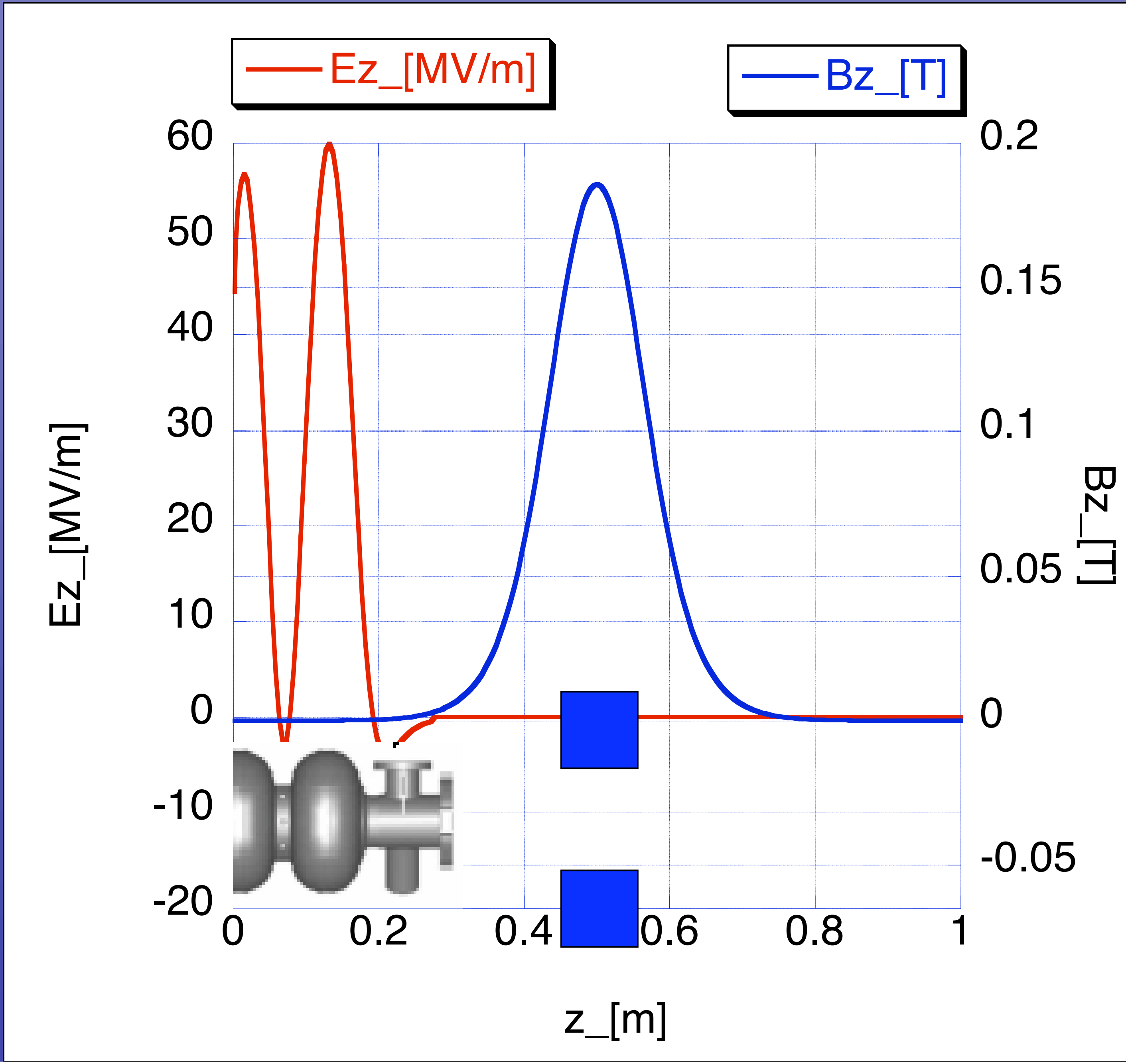


Splitting Acceleration and Focusing



- The Solenoid can be placed at the exit of the cavity
- Switching on the solenoid when the cavity is cold prevent any trapped magnetic field





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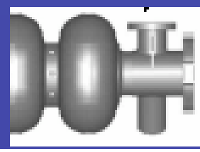
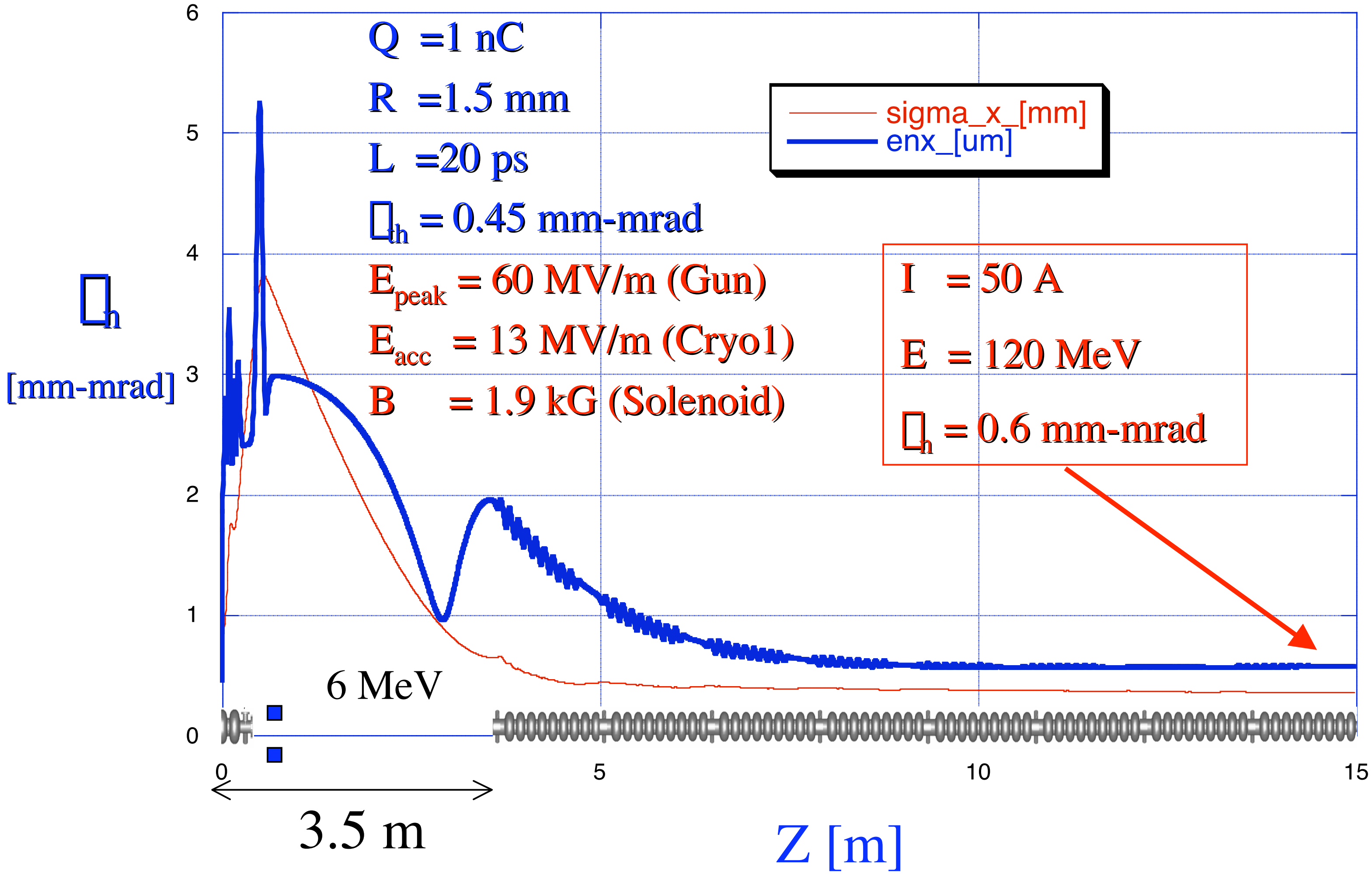


HOMDYN Simulation



scaling laws for Q and E_{peak} available

CONCLUSIONS

- RF focusing is not necessary
- 60 MV/m peak field in SC cavity have been already demonstrated
- Work in progress @ BNL to demonstrate Nb QE ~ 10^{-4} @ 60 MV/m
- The new working point for a Split Photoinjector can be easily adopted by a SCRF gun