PHOTOINJECTORS

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Linac-Based, High-Gain FELs Working Group

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Charge:

Develop photoinjector model leading to best source parameters (in terms of emittance, charge, pulse length, cathode size, frequency and gradient)

- Very aggressive charge – we will try to provide the basic tools necessary to tackle this charge
- We will try to outline major physics associated with photoinjectors, focusing on emittance growth mechanism, emittance compensation concept, additional emittance minimization ideas, absolutely minimum emittance

First half of talk mostly qualitative

Second half of talk mostly numerical

Photoinjectors are a Mature, Enabling Technology

- Promise of photoinjectors is to produce 1 nC bunch with emittance of 1 mm mrad (peak current of 1 kA desirable, may be possible with higher gradients)

- Experiments have demonstrated emittances as low as 2 mm mrad for 1 nC of charge
  - record is (I think) 1.6 mm mrad (slice 1.3 mm mrad) – AFEL at LANL (Gierman)

- Several simulations show emittances as low a 1 mm mrad for 1 nC of charge, typically higher frequency/gradients

- Emittance has contribution from both space charge fields and rf fields – in general discussions ignore the rf component, but will be important for ultimate emittances

Outline of First Half of Talk

- Discussion on Phase Space/Emittance
  - Thermal Emittance defines Minimum Emittance Possible
- Photoinjector/Compensation Physics
- Other Emittance Reduction Concepts
  - Scraping
  - RF Focusing
  - RF Harmonics

Phase Space and Emittance

Volume of 6D phase space is conserved, we care about 2D projections on $x - x'$ and $y - y'$ axes

There is no conservation law for the 2D projections – can have zero 6D volume, but nonzero N-dimensional surface area ($\mathrm{N} \leq 5$)

We usually describe the beam phase-space area in terms of the rms emittance:

$$\varepsilon_x = \beta\gamma\sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}$$

(I like to use primes for *d/dz* and dots for *d/dt*)

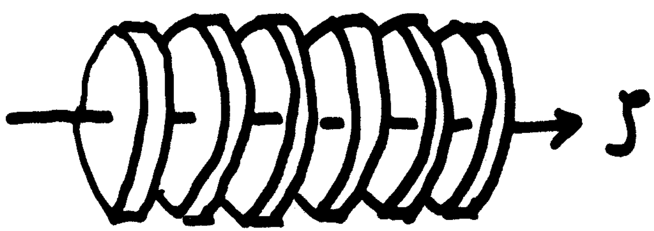
A beam is different than a cloud of charge because the momentum is forward directed (z direction), with a small momentum spread

- We often picture the beam to be a long thin cylinder

We often consider the dynamics in the inertial frame-of-reference of the beam (the beam is essentially nonrelativistic in this frame)

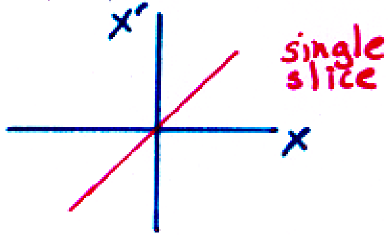
We can divide the beam into slices

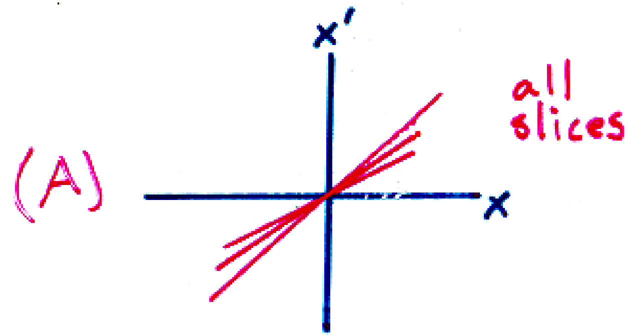
- the emittance where the ensemble average is taken over a single slice is the slice emittance
- slice emittance and full emittance (usually just called the rms emittance) are both important



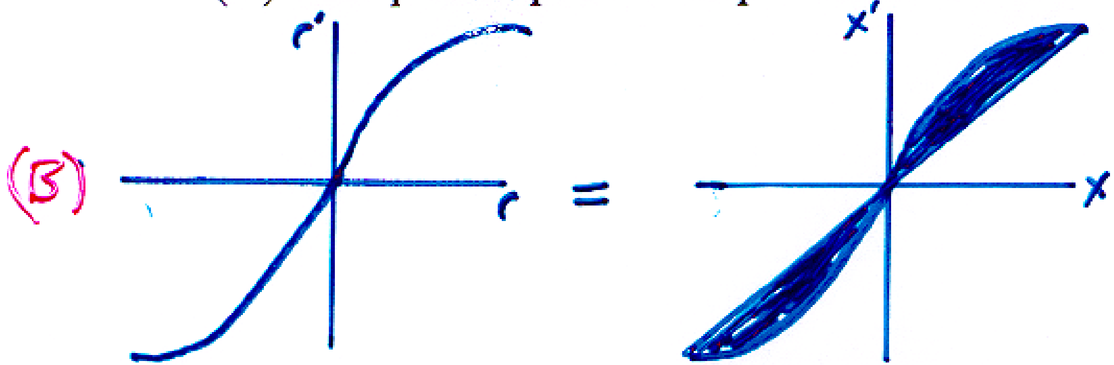
The two basic types of emittance we encounter:

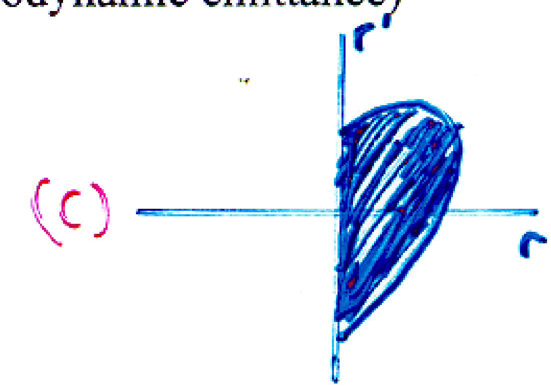
- (A) slice emittance is zero, the rms emittance occurs because of some correlation $\langle xz \rangle$ and/or $\langle x'z \rangle$ (geometric emittance)





- slice emittance is nonzero and equal to the rms emittance
  - (B) slice phase space area is zero (geometric emittance – radial curvature)
  - (C) slice phase space is ellipse with nonzero area (thermodynamic emittance)





Typical case is a combination of (A) and (B), rarely see third case in our regimes

Thermal Emittance Sets a Lower Emittance Limit

- Energy balance: $eV_{emission} = \frac{1}{2}mv^2$

- Normalized emittance is then $\varepsilon_{norm} = \frac{r_{cath}}{4}\sqrt{\frac{2eV_{emission}}{mc^2}}$ (using factor of 2 for equipartioning)

- Excess photon energy is about 1 – 1.5 eV, excess electron emission energy is less, about 0.5 eV

- Using 0.5 eV and 2 mm cathode radius gives thermal emittance of 0.7 mm mrad

Creation of High Phase-Space Density Beams

Photoinjectors (1985) have enabled the generation of high phase-space density beams

- the rms emittance from photoinjectors is not that much less than from thermionic injectors, but the slice emittance (and 6D phase space volume) is much smaller
- the high accelerating field allows "freezing" of the phase space without thermalization

Emittance compensation is key aspect of generating high phase-space density beams from photoinjectors

- Concept was introduced in 1988, experimentally verified in 1993, mechanism experimentally verified in 1996
- S&R (1997) describe effect as coherent transverse plasma oscillations

Start with envelope equation for an axial slice at an axial location within the bunch ζ (no acceleration):

$$\sigma'' + K\sigma - \hat{K}(\zeta)/\sigma = 0$$

(K represents the effect of the uniform focusing, and $\hat{K}(\zeta) = I(\zeta)/2I_A\gamma^3\beta^3$)

The equilibrium slice radius is clearly $\sigma_{eq} = \sqrt{\hat{K}/K}$.

Most (if not all slices) will not be injected at the proper equilibrium radius and will oscillate about the equilibrium radius, which we write as:

$$\sigma(\zeta, z) = \sigma_{eq}(\zeta) + \delta(\zeta, z)$$

where we use ζ to denote which axial slice we are talking about (K is not a function of ζ but $\hat{K}$ is). Using this definition in the envelope equation, we have

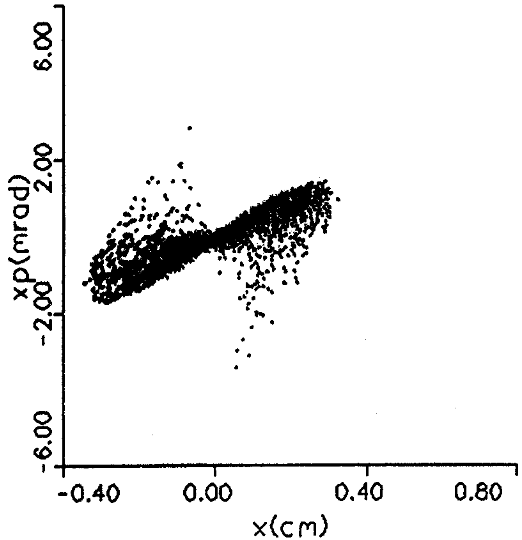
$$\delta'' + K(\sigma_{eq} + \delta) - \frac{\hat{K}}{\sigma_{eq}}\left(1 - \frac{\delta}{\sigma_{eq}} + \left(\frac{\delta}{\sigma_{eq}}\right)^2 + \ldots\right) = 0$$

which becomes (to lowest order):

$$\delta'' + K\delta + \frac{\hat{K}}{\sigma_{eq}^2}\delta - \frac{\hat{K}}{\sigma_{eq}^3}\delta^2 = \delta'' + 2K\delta = 0$$

So the (small amplitude) transverse plasma oscillations stay in phase (the period of the oscillations is independent of the slice current)

Typical phase-space after compensation showing residual emittance caused by a combination of radial curvature in the phase-space plots and different orientations for different slices



BNL experiment (PRL 1996, Qiu et al) showing alignment of ellipses as solenoid strength is varied

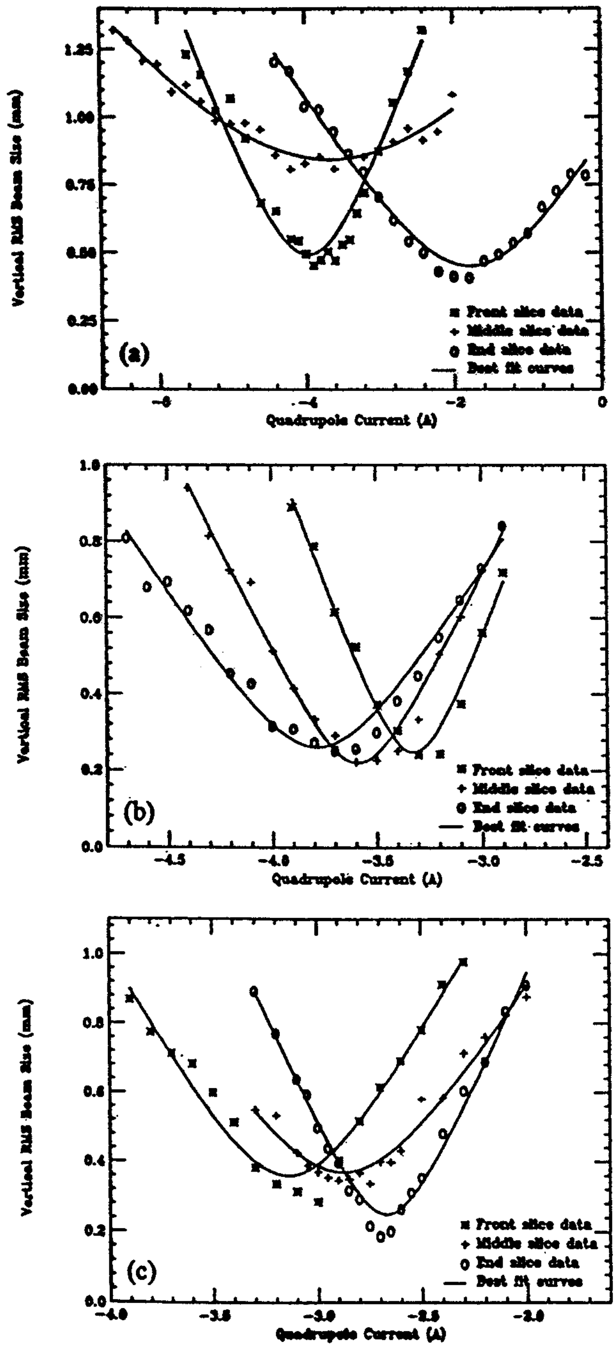


FIG. 3. Slice rms beam size as a function of the quadrupole current for the front, middle, and end slices at various solenoid currents: (a) 102 A, (b) 106 A, and (c) 110 A. The curves represent the best fit to the data points.

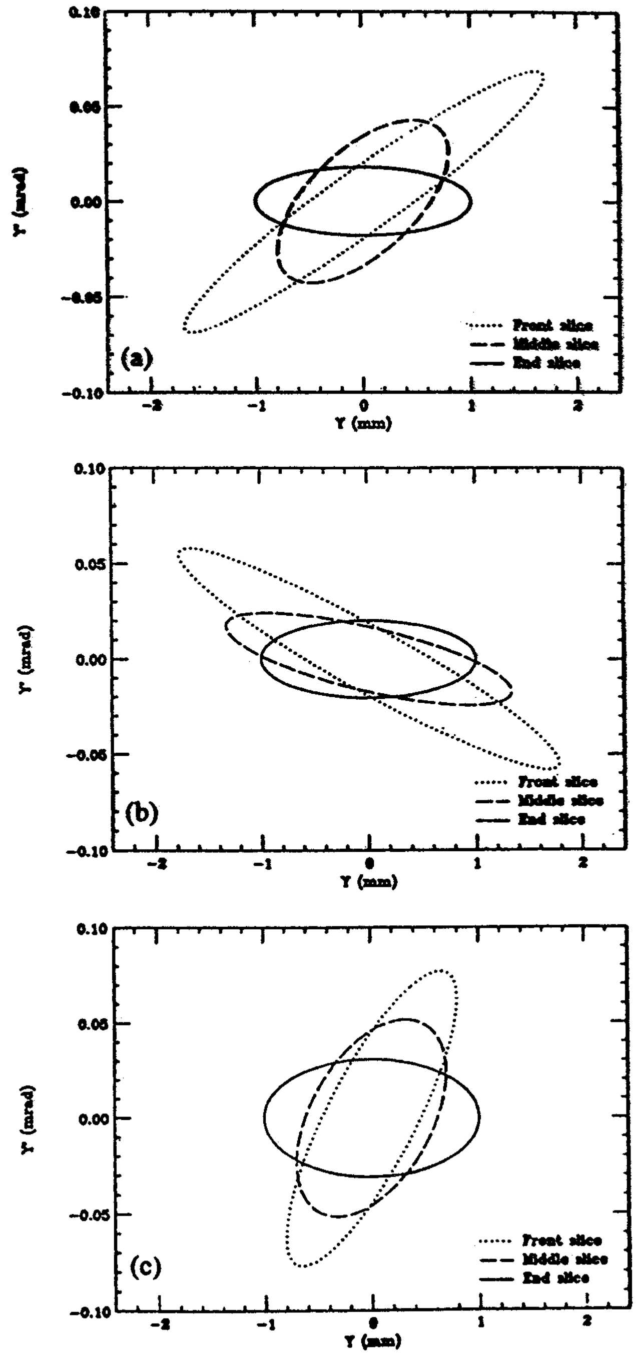


FIG. 4. Plots of the transverse phase space ellipses for each slice. The solenoid currents are (a) 102 A, (b) 106 A, and (c) 110 A.

Scraping

Say a certain emittance is required for a given bunch charge for some application (typical numbers are normalized emittances of 1 mm mrad for 1 nC), and that emittance is not achievable for that bunch charge.

A common argument is that we can produce a bunch of a larger charge (say 2-10 nC), whose center slices have the target emittance. There are two approaches:

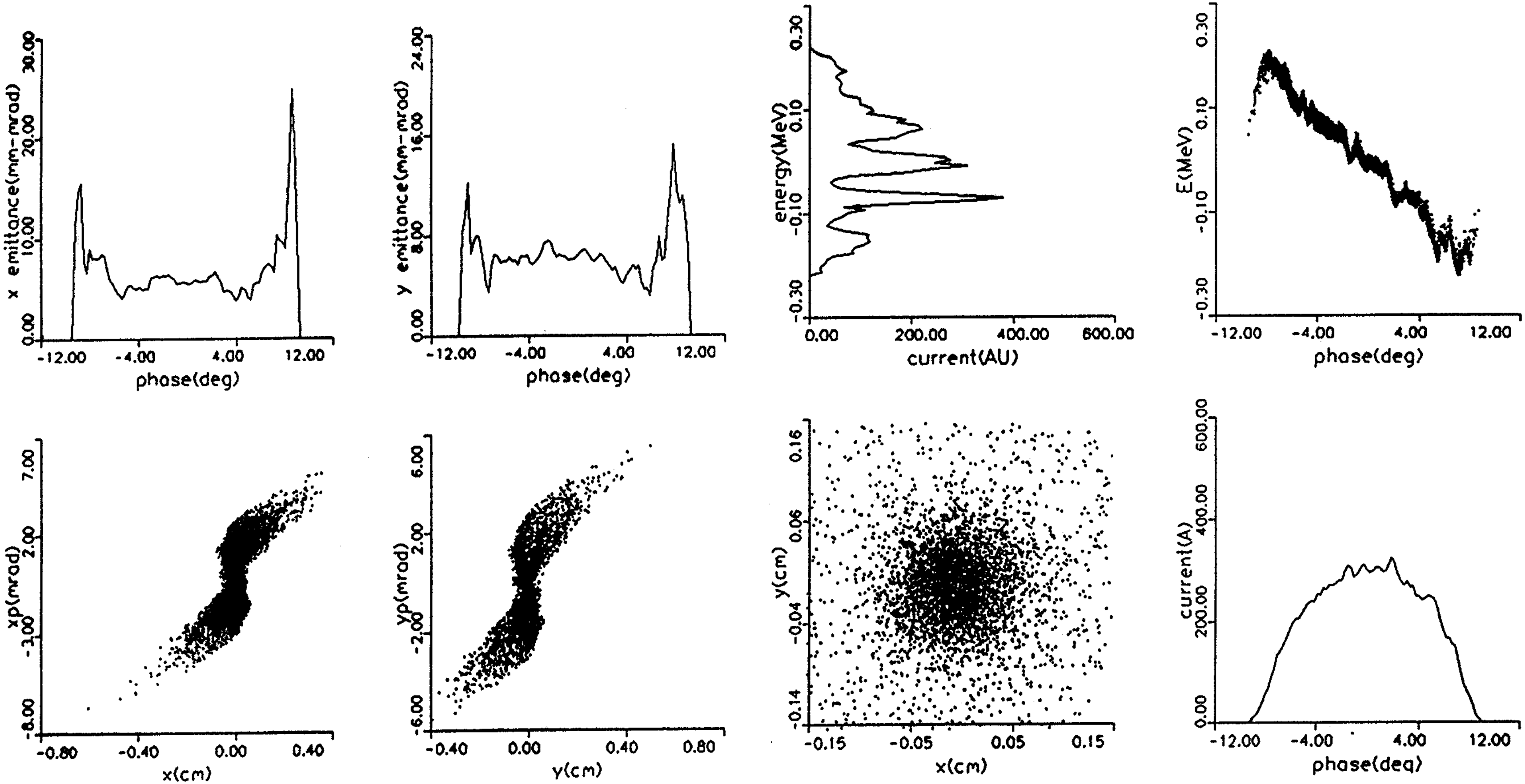
- We can scrape off the tails of the bunch, leading to a smaller bunch with the target emittance
- We ignore the higher emittance tails and accelerate/transport the entire bunch to the application

Scraping is probably more desirable as the actual charge produced becomes a larger and larger factor more than the target charge.

Scraping is not as simple as we like to imagine. The naïve idea of scraping the tails in a dispersive section is very dangerous – longitudinal wakefields destroy the achromaticity – emittance growth is mostly energy independent (geometric)
(LANL experiment 1989 – emittance growth of 200 mm mrad for a 5 nC bunch in a 60 degree achromat).

Scraping is done with an aperture just after the rms beam waist – the central slices are at a waist but the tails are overfocused and get scraped. This is not an especially efficient way to reduce the average emittance/charge ratio.

Phase/Configuration Space At Focus



AFEL example:

Initial charge	Initial emittance [mm mrad]/Q [nC]	Final emittance/Q
1 nC	3.5	1.6
4	3.48	1.27
16	2.47	0.83

If the waist is formed at too low an energy, the beam forms a donut after the waist (bifurcation in phase space – P. Loschialpo's thesis 1985), due to nonlinear space charge fields

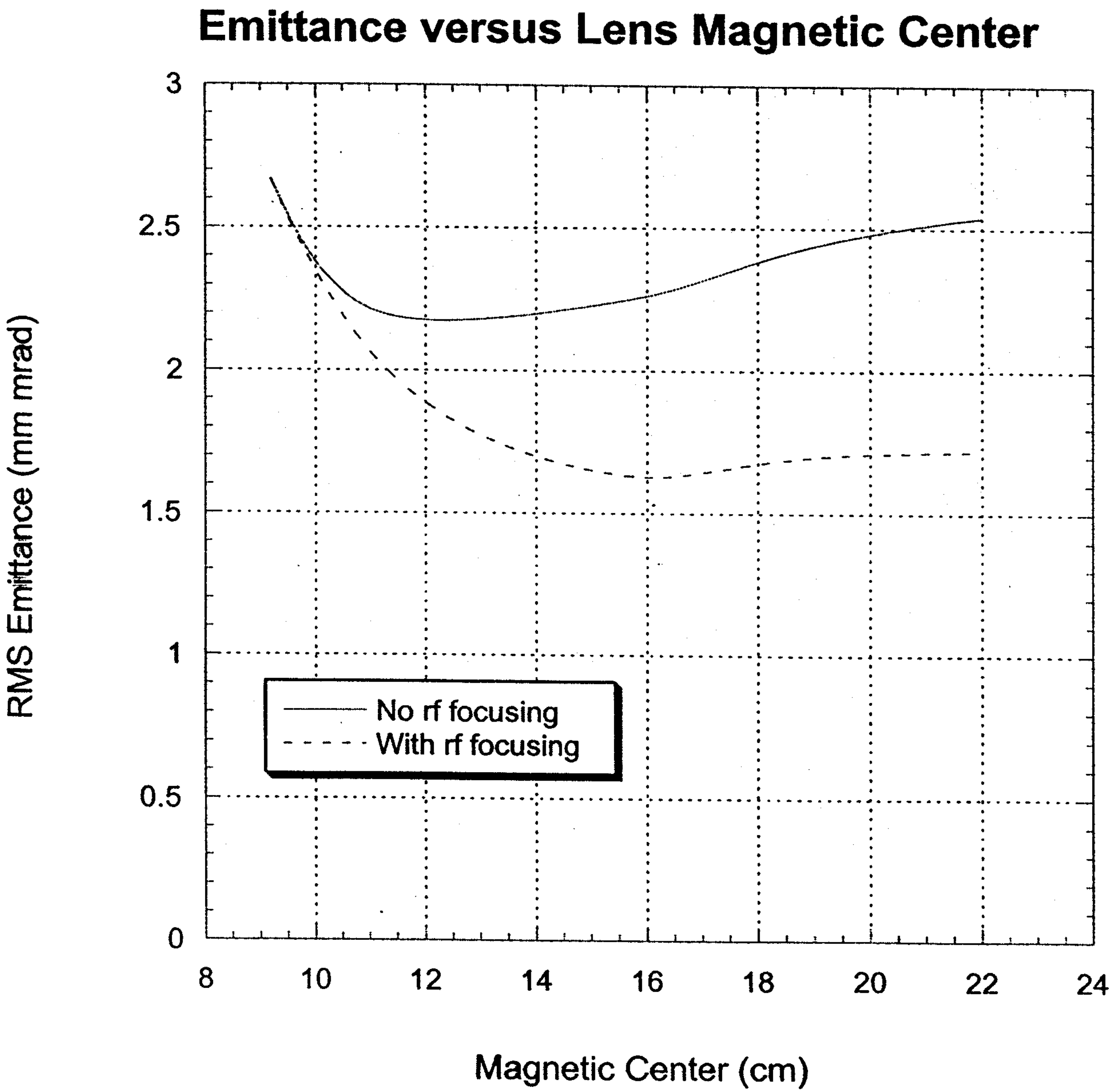
Transverse Plasma Oscillations For An Accelerating Beam Can Be Made More Coherent With RF Focusing

- General transverse equation of motion with acceleration is

$$\sigma'' + \sigma' \frac{\gamma'}{\gamma} + \sigma \Omega^2 \left(\frac{\gamma'}{\gamma} \right)^2 - S \frac{\gamma'^2}{\sigma \gamma^3} = 0 \qquad (S = I(\zeta) / 2 I_A \gamma'^2)$$

  With boundary conditions at cathode, particles at different axial positions ζ within the bunch are in different phases of their transverse plasma oscillations

- Use of transverse focusing rf field in first cavity can adjust effective initial boundary so oscillations of all slices are in phase



Emittance versus Lens Magnetic Center
RMS Emittance (mm mrad)
3
2.5
2
1.5
1
0.5
0
8
10
12
14
16
18
20
22
24
Magnetic Center (cm)
No rf focusing
With rf focusing

Fig 3

Many Other Factors Are Important Also

- Flat-top longitudinal and transverse profiles (opposed to Gaussians)

  Flat-topping reduces nonlinear free energy available for conversion to emittance

- RF harmonics to flatten the rf fields – reduce rf emittance contribution

- Scalings with wavelength and charge can lead to designing optimal systems

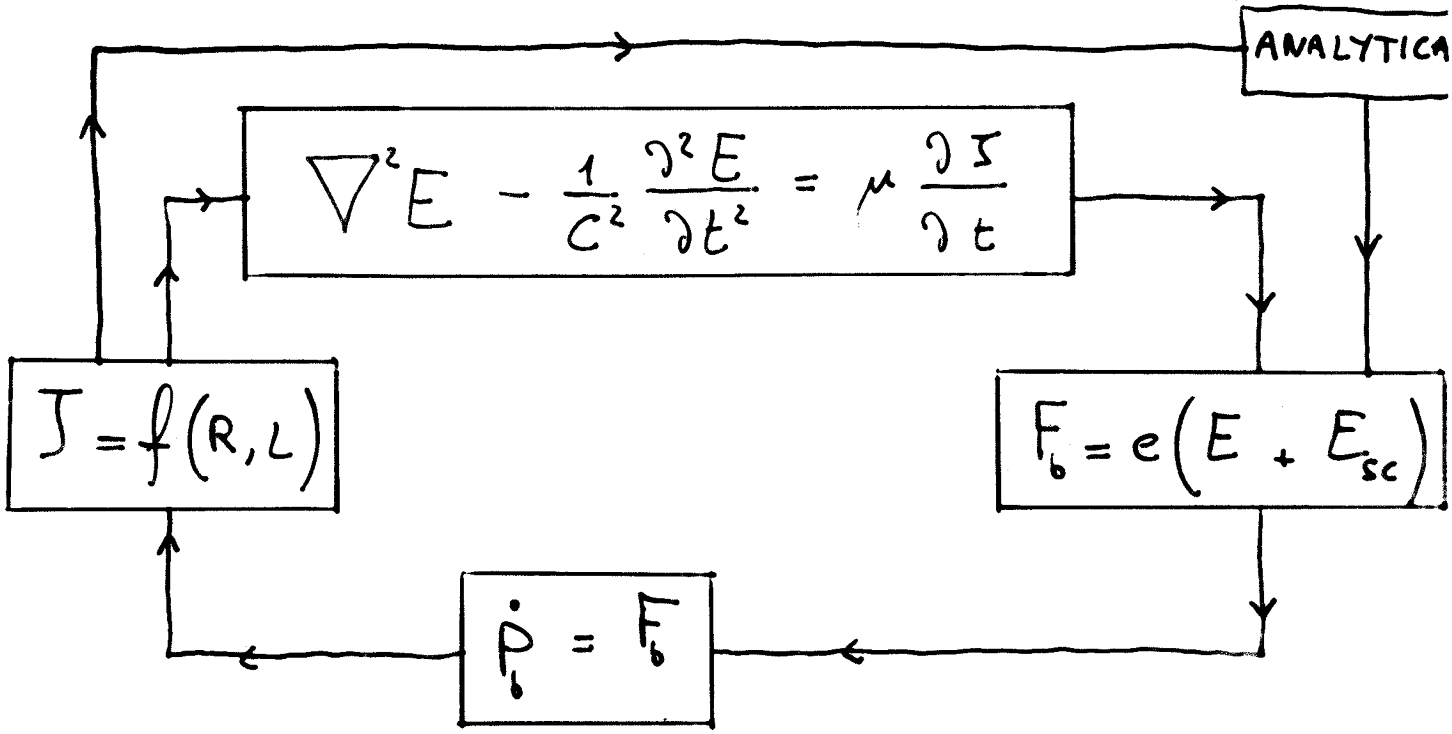
- RF compression in photoinjector

These are topics for our working group

- HOMDYN MODEL
  - COMPARISON WITH ITACA
- SIMULATIONS
  - SPLIT PHOTOINJECTOR
  - INTEGRATED PHOTOINJECTOR
  - PULSED PHOTODIODES

~ SELF CONSISTENT MODEL

LONG TERM (MULTI BUNCH) BEAM - CAVITY INTERACTION

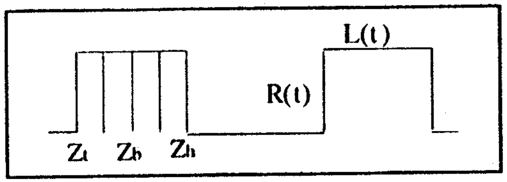


- NORMAL MODES EXPANSION OF CAVITY FIELD
- CURRENT DENSITY DESCRIPTION OF BUNCHES (UNIFORM MULTI-SLICE CHARGED CYLINDER) J_b
- ANALYTICAL COMPUTATION OF SPACE CHARGE FIELD
- $J = J_b + J_g\left(1 - e^{-t/\tau_g}\right)$
- ANALYTICAL COMPUTATION OF FIELDS FROM BUNCH TO BUNCH

$$E_z^{sc}(\tilde z)=\frac{q}{2\pi\varepsilon_o\gamma_b R^2 L}\left(\sqrt{\gamma_b^2(L-\tilde z)^2+R^2}+\gamma_b(2\tilde z-L)-\sqrt{(\gamma_b\tilde z)^2+R^2}\right)$$

$$E_r^{sc}(\tilde z)=\frac{\gamma_b q}{4\pi\varepsilon_o RL}\left\{\frac{\tilde z}{\sqrt{(\gamma_b\tilde z)^2+R^2}}+\frac{(L-\tilde z)}{\sqrt{\gamma_b^2(L-\tilde z)^2+R^2}}\right\}$$

SPACE CHARGE FIELDS



$$\frac{dL}{dt}=c\left(\beta_h-\beta_t\right)$$

$$\ddot R=\frac{2cK^2}{R\beta\gamma^3}G(\zeta,A_r)-\frac{2cK^2}{R\beta\gamma}(1+\beta^2)G(\xi,A_r)-K^{rf}R+\left(\frac{4\varepsilon_n^{TH}}{\gamma}\right)^2\frac{1}{R^3}-\left(\frac{eB_z(z)}{2m_o\gamma}\right)^2R_s-\beta\gamma^2\dot\beta\dot R$$

CURRENT DENSITY DISTRIBUTION

$$\varepsilon_n^{cor}=\frac{\langle\beta\gamma\rangle}{2N}\sqrt{\langle R^2\rangle\langle R'^2\rangle-\langle RR'\rangle^2}$$

$$\varepsilon_n=\sqrt{\left(\varepsilon_n^{th}\right)^2+\left(\varepsilon_n^{cor}\right)^2}$$

RMS NORMALIZED EMITTANCE

HOMDYN

M. Ferrario et al., Part. Acc. 52,

$$\frac{dz_b}{dt}=\beta_b c \qquad \frac{d\beta_b}{dt}=\frac{e}{m_o c\gamma_b^3}E_z(z_b,t)$$

$$\frac{d\gamma_d}{dt}=\frac{e}{m_o c}\beta_d\left[E_z(z_d,t)+E_z^{sc}(d,t)\right]$$

MOTION EQUATIONS

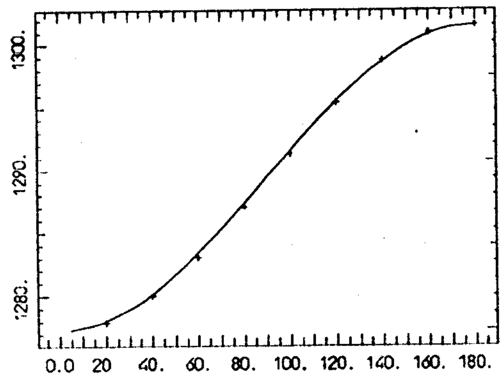
$$\dot\alpha_n+\frac{\omega_n}{2Q_n}\left(1+\frac{i}{2Q_n}\right)\alpha_n=-\frac{1}{2\omega_n\varepsilon_o}\left(1+\frac{i}{2Q_n}\right)\frac{d}{dt}\left[\int J(z,t)\cdot e_n^*(z)\,dz\right]e^-$$

$$J_b(t,z)=\frac{q\beta_{bar}c}{L}\left[\eta(z-z_t)-\eta(z-z_h)\right]$$

$$J_g(t,z_g)=\frac{J_g^0}{2i}\delta(z-z_g)\left(1-e^{-\frac{t}{\tau_g}}\right)e^{i(\omega_1 t+\psi_1)}$$

MODE EQUATIONS

NORMAL MODES EXPANSION



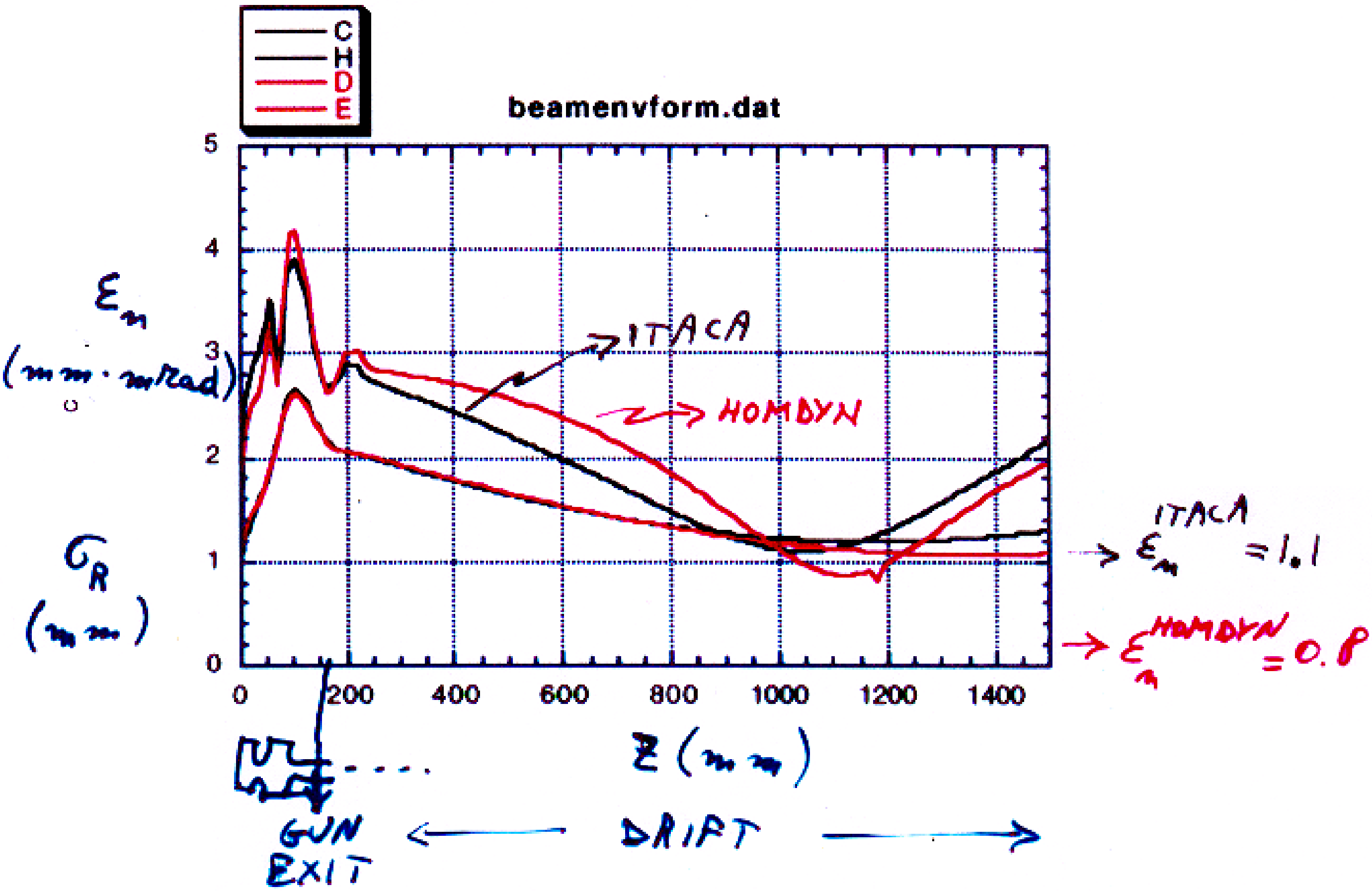
$$\mathbf{E}(\mathbf{r},t)=\sum_n a_n(t)\,e_n(\mathbf{r})\sin(\omega_n t+\phi_n(t))$$

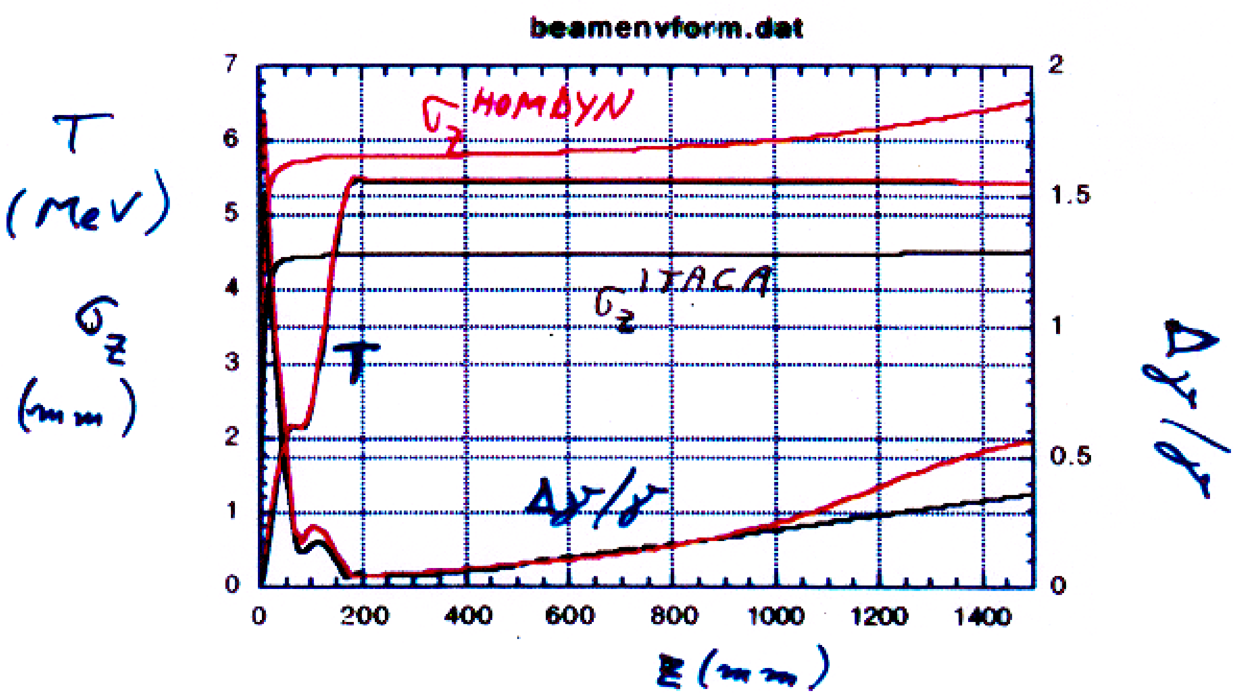
$$=\sum_n\left(\alpha_n(t)\,e_n(\mathbf{r})\,e^{i\omega_n t}+\alpha_n^*(t)\,e_n^*(\mathbf{r})\,e^{-i\omega_n t}\right)$$

TTF-FEL Injector 1.6 cell gun + drift

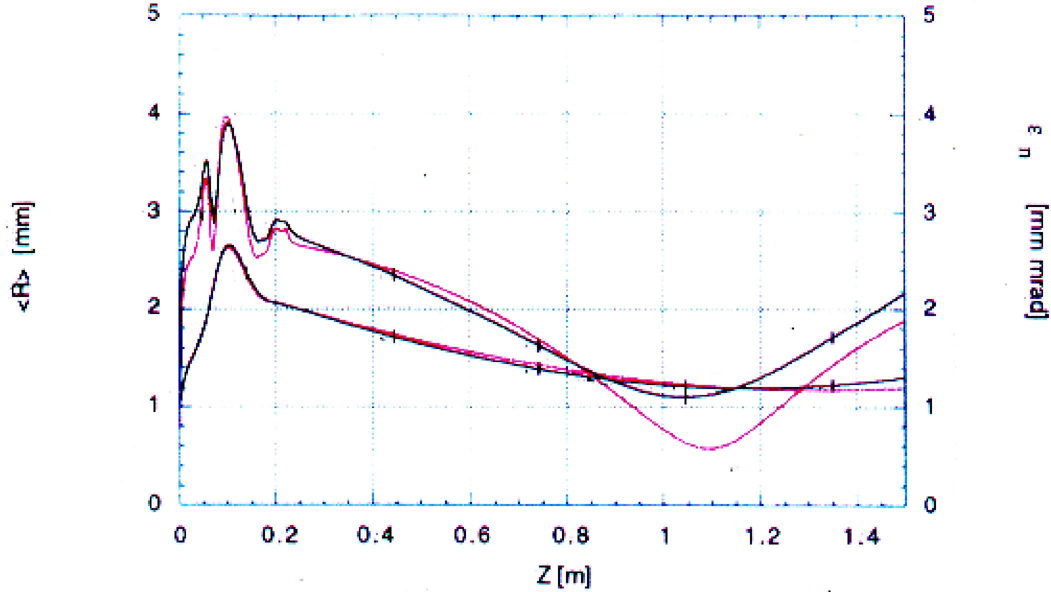
L-band, 50 MV/m, 1 nC, 16 ps (flat top laser), R_{cat} = 1.5 mm

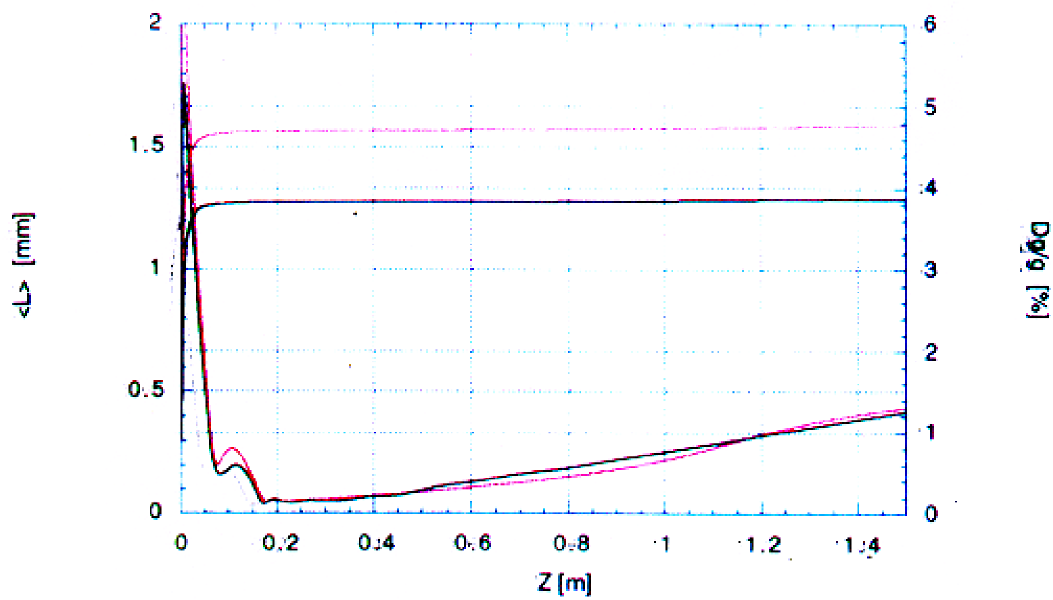
Comparison HOMDYN (red lines) vs ITACA (black lines)



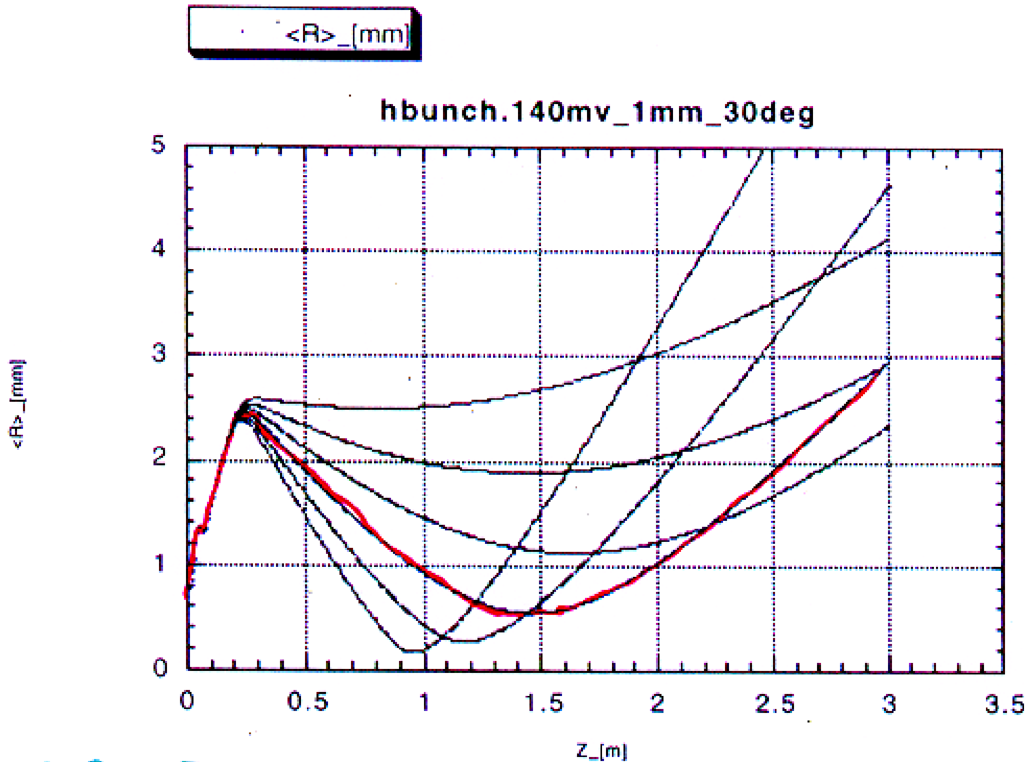


slightly changing (1%) the solenoid setting....

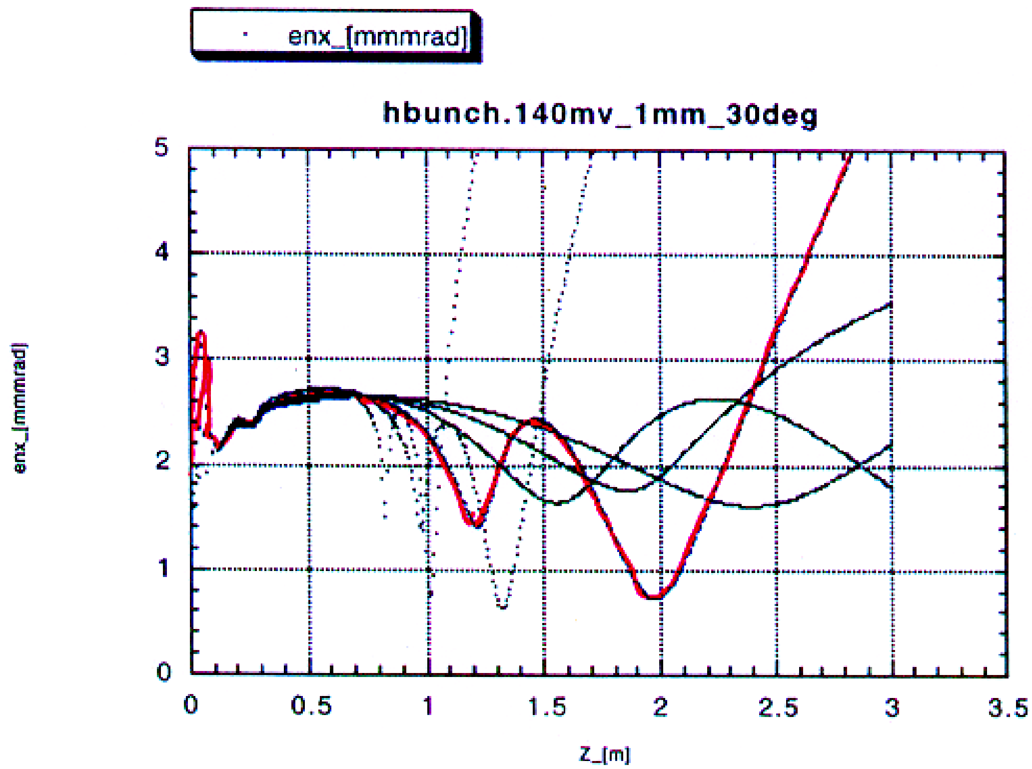




BNL/SLAC/UCLA GUN (1.6 CELL) + DRIFT



SOLENOID SCAN



S-BAND

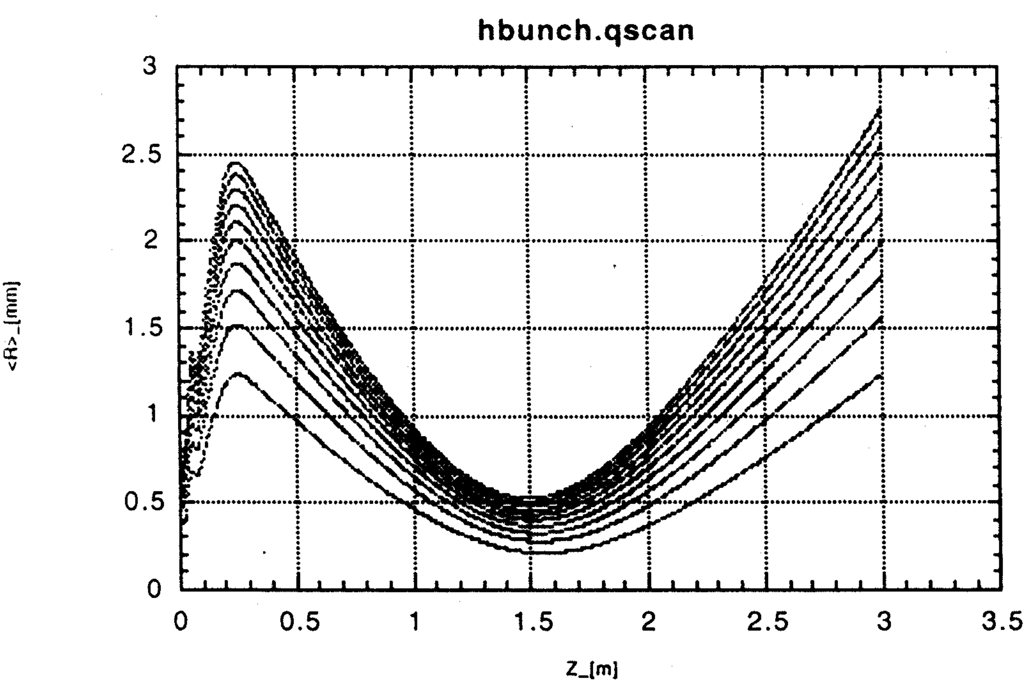
140 MV/m

10ps FLAT TOP LASER

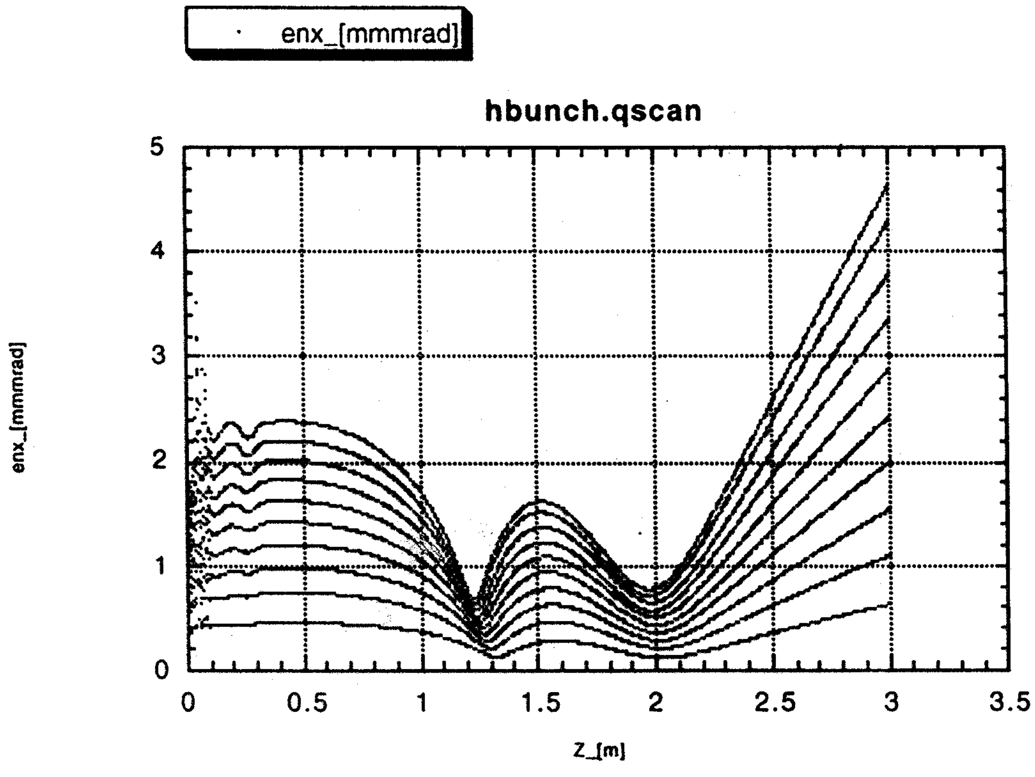
R_{CAT} = 1 mm

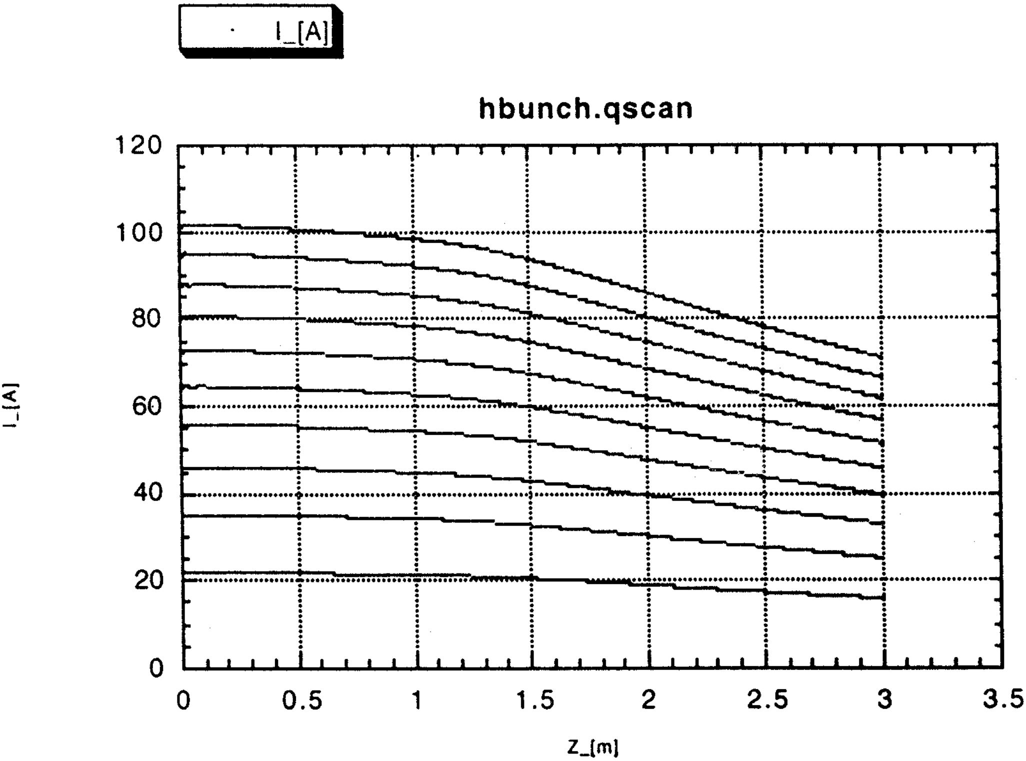
CHARGE SCALING (J.B. Rosenzweig, E. Colby)

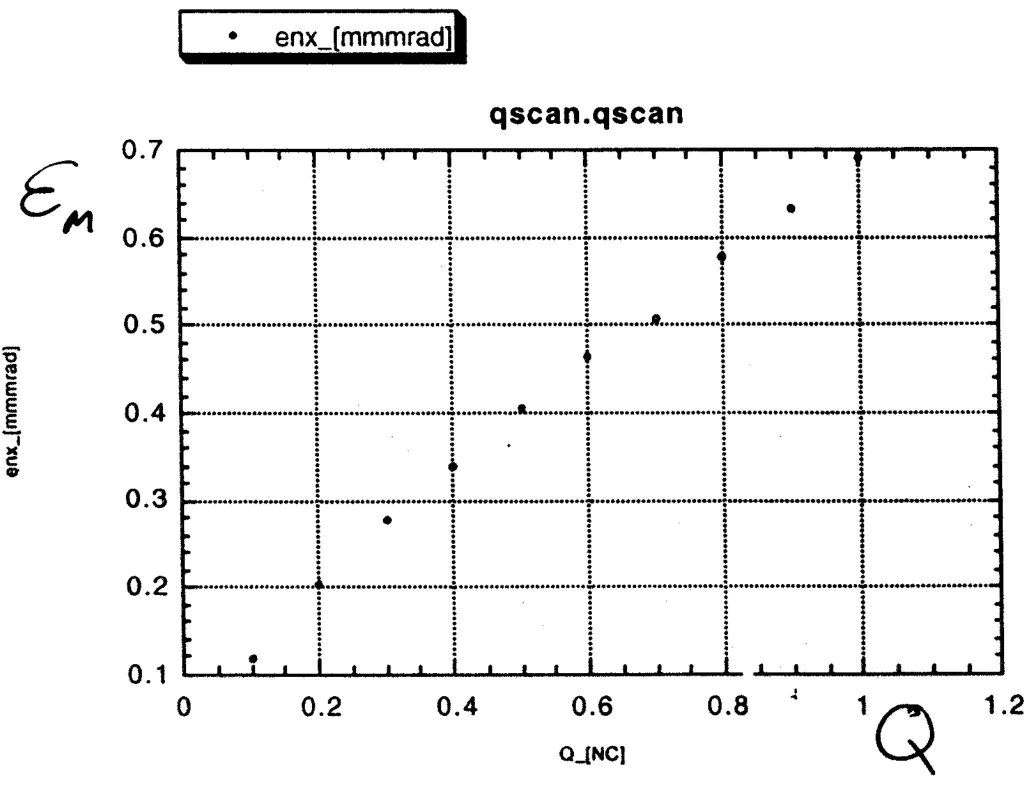
<R>_[mm] $\sigma_{r,z} \div Q^{1/3}$



1 nC
↓
0.1 nC







$$\varepsilon_n \doteq (0.6)\, Q^{2/3}$$

Matching the beam on the Invariant Envelope means:

satisfying at the **laminar waist** (after the gun exit)

$$\sigma_w = \hat{\sigma} = \frac{2}{\gamma'}\sqrt{\frac{\langle I \rangle}{3I_0\gamma}}$$

and

$$\sigma'_w = \hat{\sigma}' + \Delta\sigma'_{RF} = -\frac{\gamma'}{2\gamma}\hat{\sigma} + \frac{\gamma'}{2\gamma}\hat{\sigma} = 0$$

Therefore, the entrance of the booster Linac has to be located at the laminar waist position, with an accelerating gradient set at

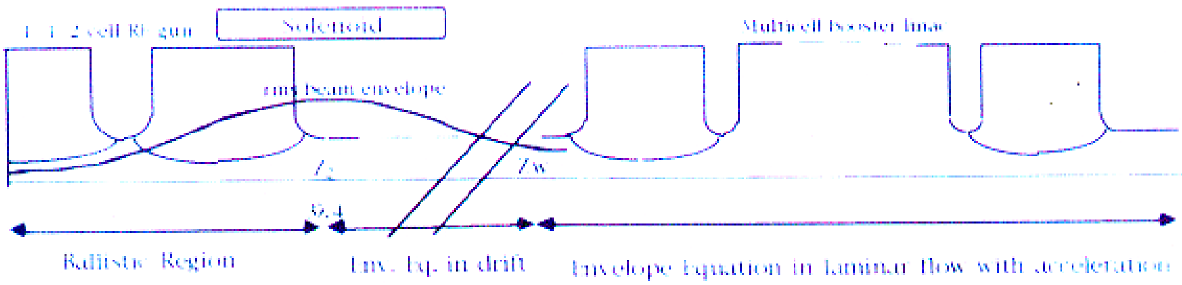
$$\gamma' = \frac{2}{\sigma_w}\sqrt{\frac{\langle I \rangle}{3I_0\gamma_w}}$$

$\langle I \rangle$ rms beam current, σ_w , γ_w beam spot and energy at the waist

We have identified 4 Configurations of Photoinjectors

Split Photo-Injector with matching at the waist

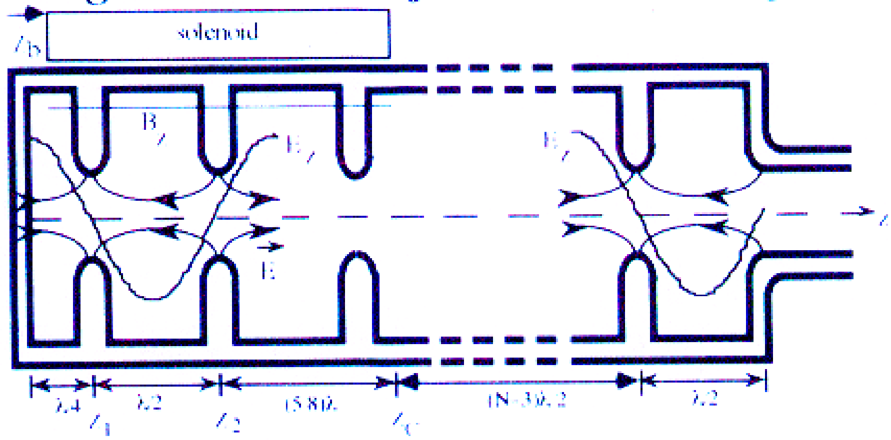
SLAC, BNL, UCLA — A P
D.T. Palmer
G.T.F.-SS.



Integrated PhotoInjector (multi-cell gun)

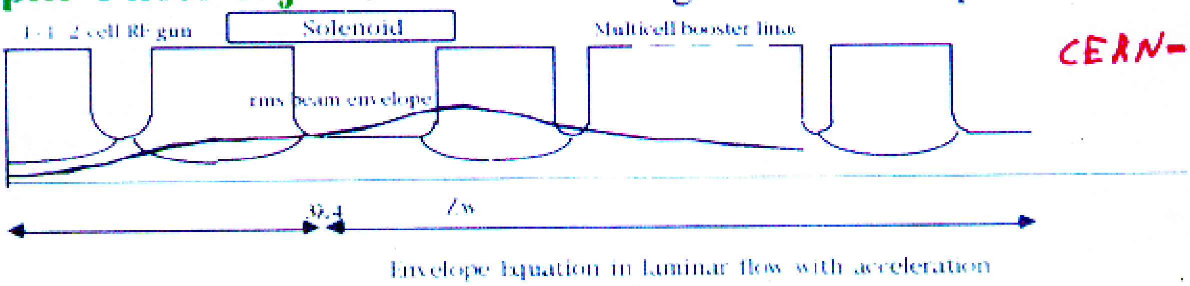
LANL - AFEL
R. Sheffield

UCLA - PWT
J. Rosenzweig



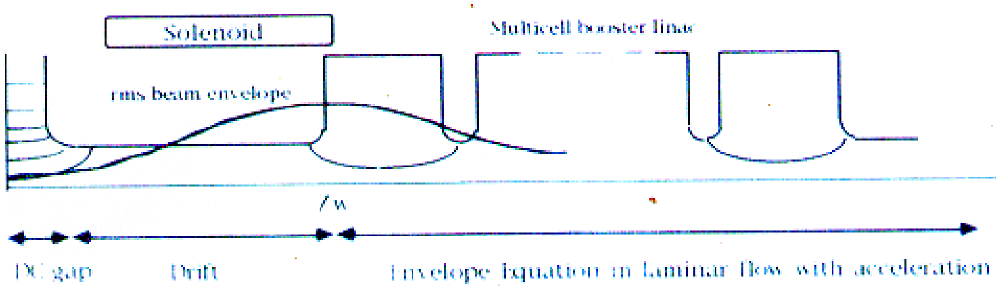
Split Photo-Injector with matching at the envelope maximum

CERN - C.T.F. ?



Pulsed Photo-diode (DC gap) with matching at envel. maximum

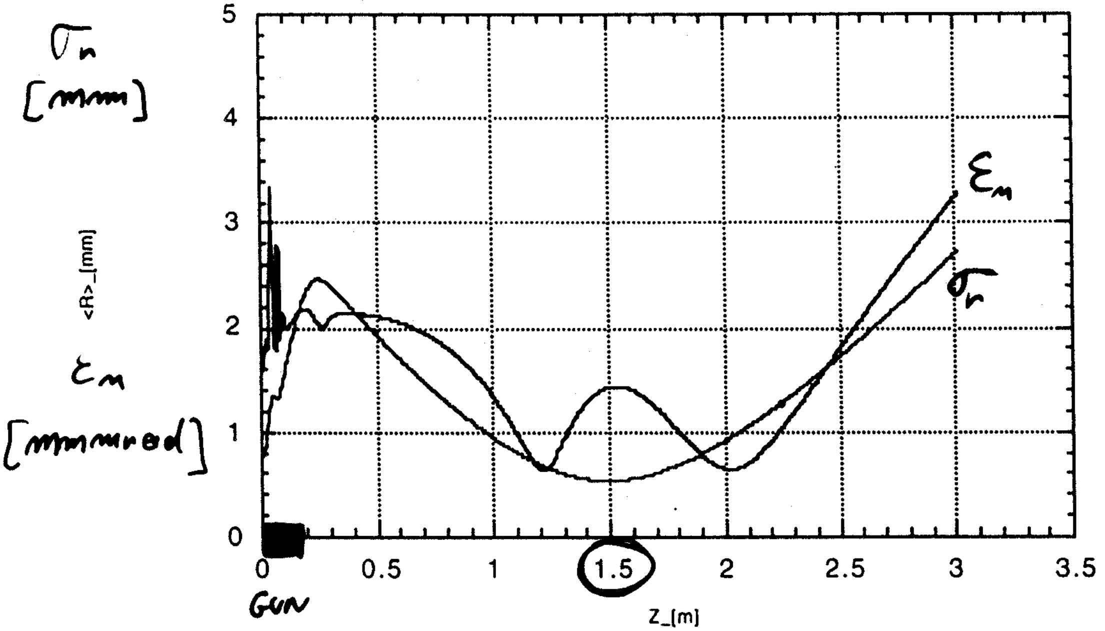
BNL T. Rao, SLAC F. Villa — Pulsed Diode



CONFIGURATION 1

SPLIT PHOTOINJECTOR WITH MATCHING AT THE WAIST

1.6 CELL S-BAND GUN + DRIFT



$Q = 1\,nC$

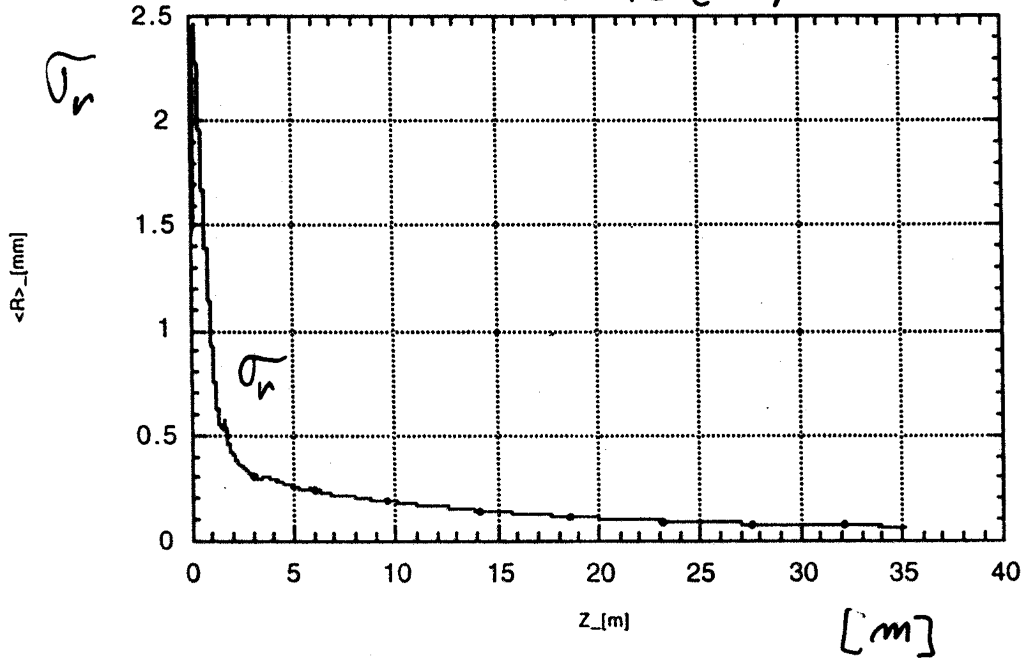
$L = 10\,ps$

$R = 1\,mm$

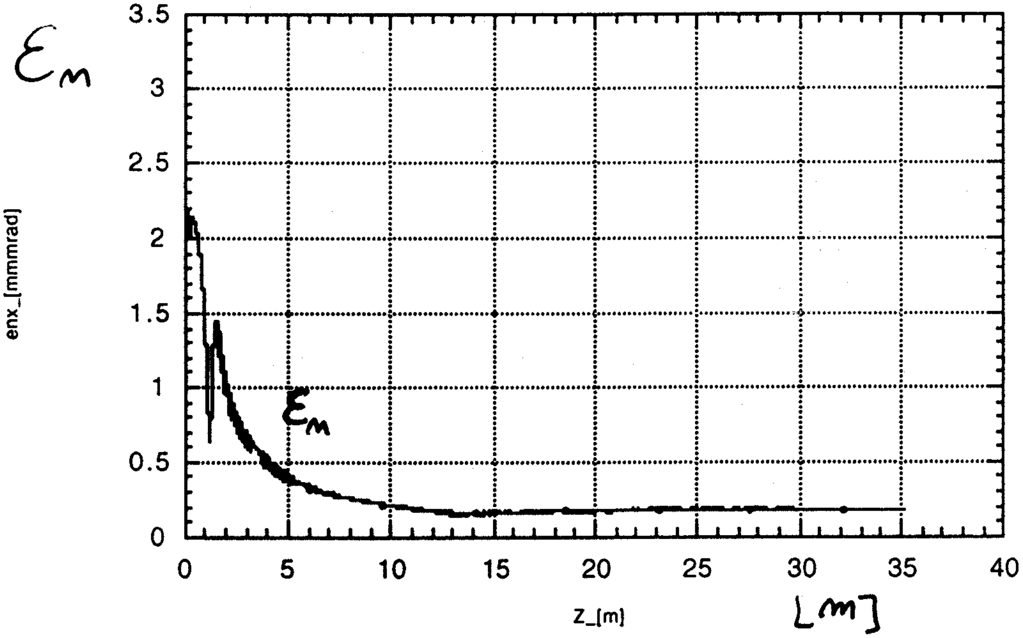
$\hat{E} = 140\,MV/m$

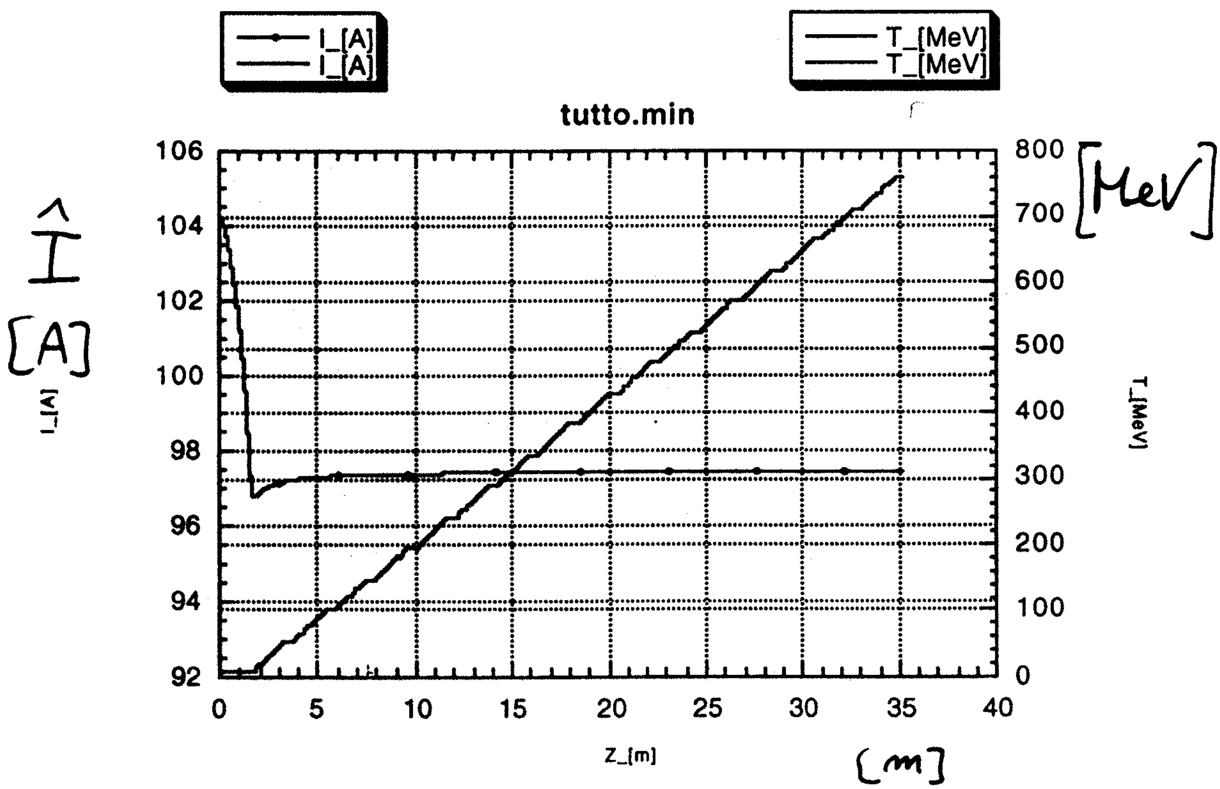
$E = 6\,MeV$

GUN + DRIFT + LINAC (SW)



$E_{acc} = 30\,MV/m$


εn
3.5
3
2.5
2
1.5
1
0.5
0
enx_[mmmrad]
εn
0
5
10
15
20
25
30
35
40
Z_[m]
[m]

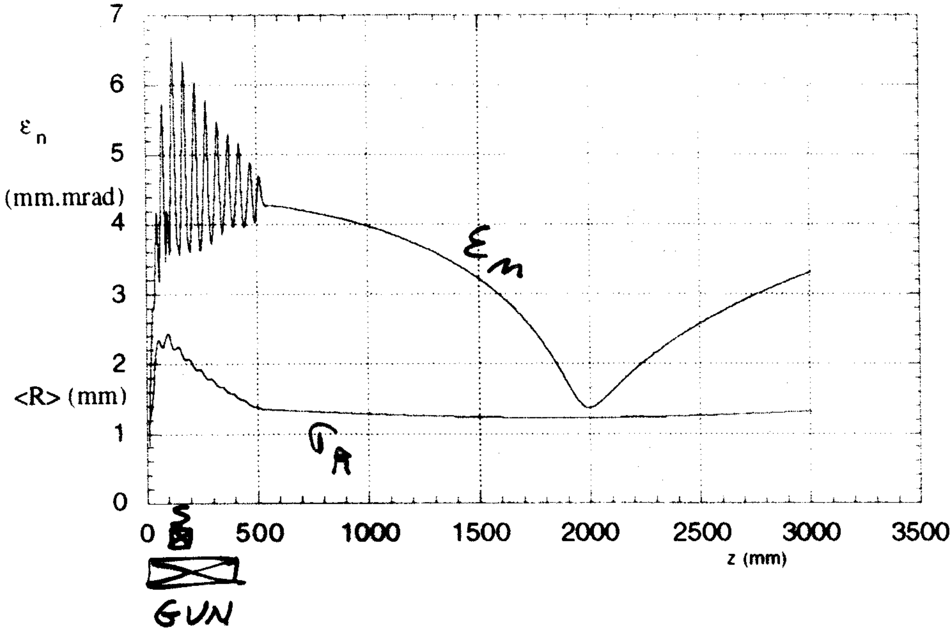

I_[A]
I_[A]
T_[MeV]
T_[MeV]
tutto.min
106
104
102
100
98
96
94
92
Î
[A]
I_[A]
800
700
600
500
400
300
200
100
0
[MeV]
T_[MeV]
0
5
10
15
20
25
30
35
40
Z_[m]
[m]

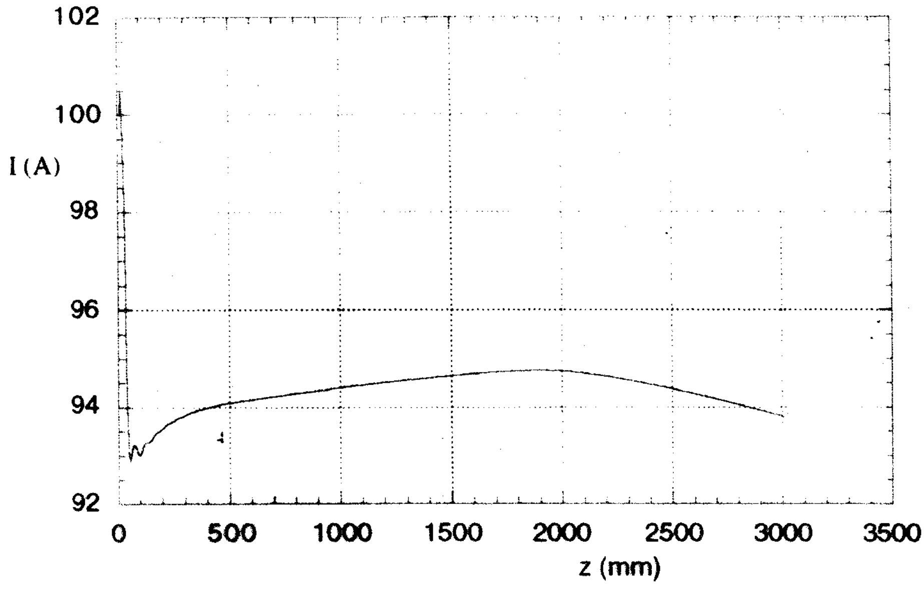
Configuration 2

Integrated Photo-Injector (PWT 1/2+10+1/2 cell at S-band)

60 MV/m, 10 ps flat top laser pulse

16 MeV

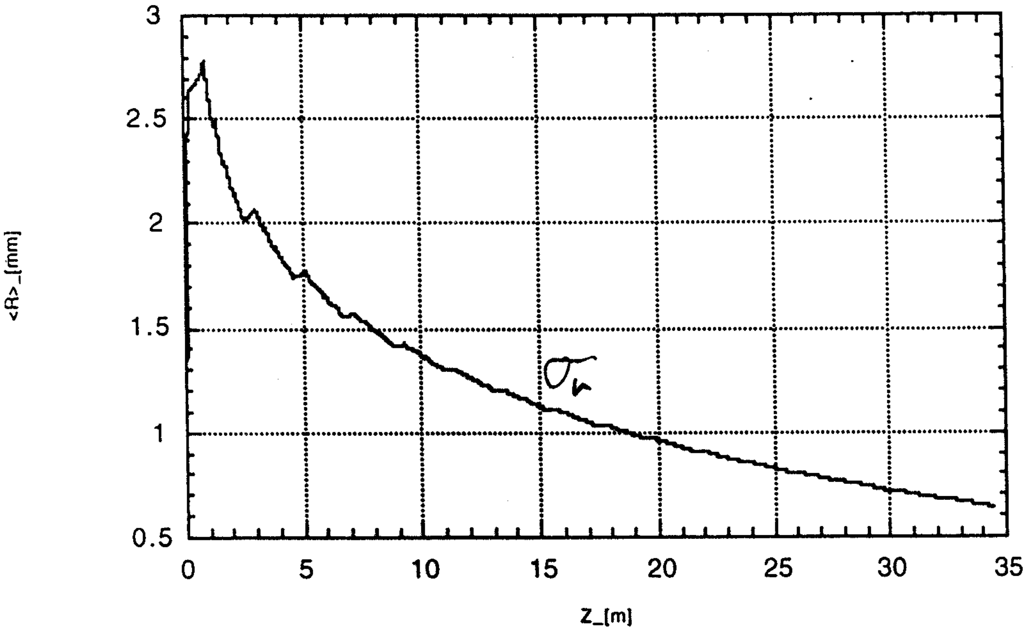


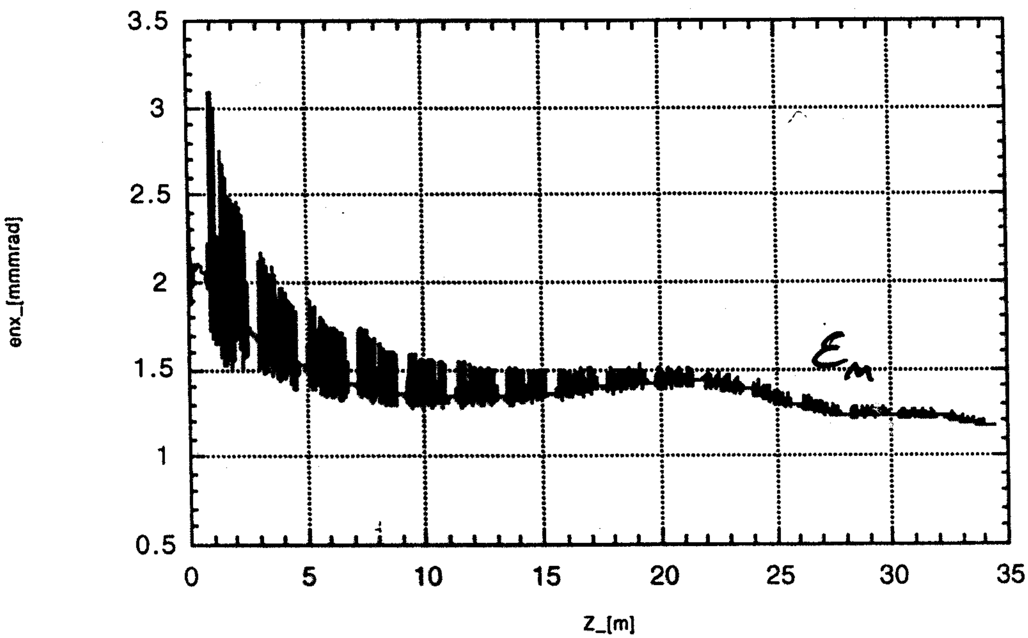


C3

GUN + DRIFT + LINAC

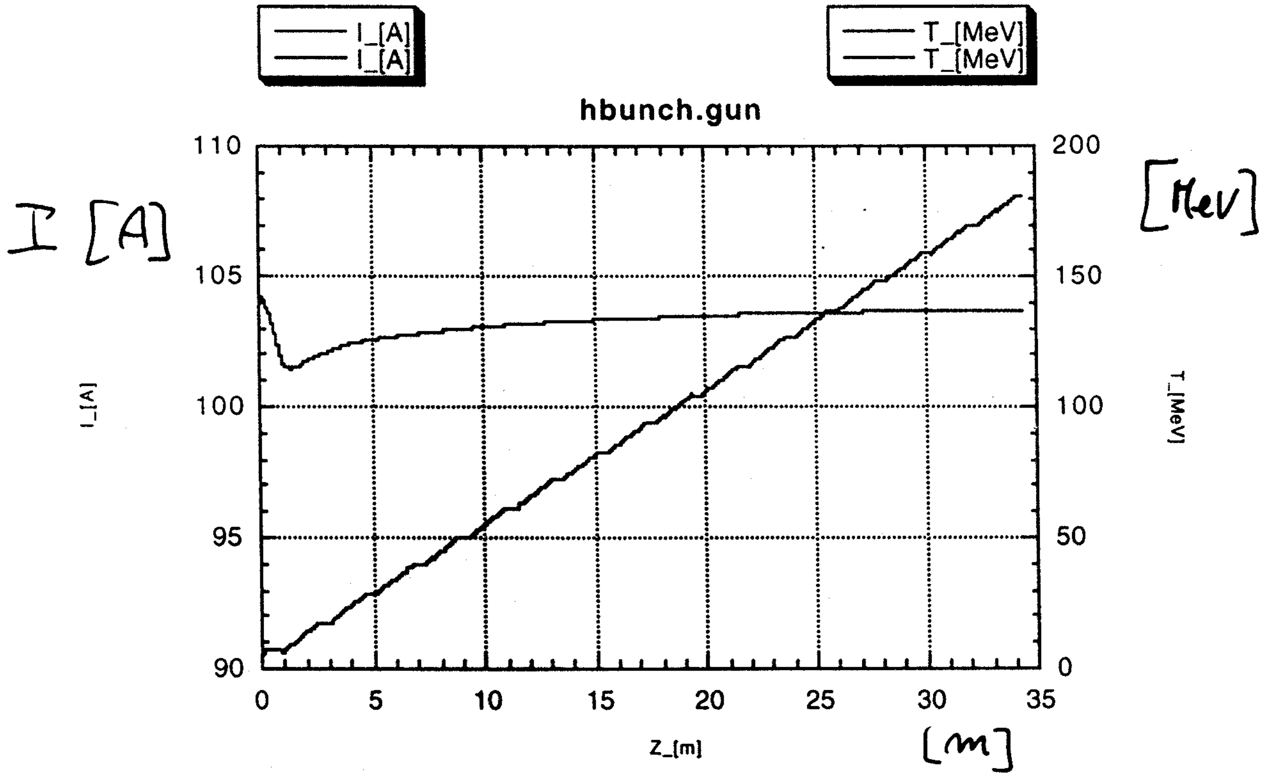
$E_{acc} = 6$ MV/m



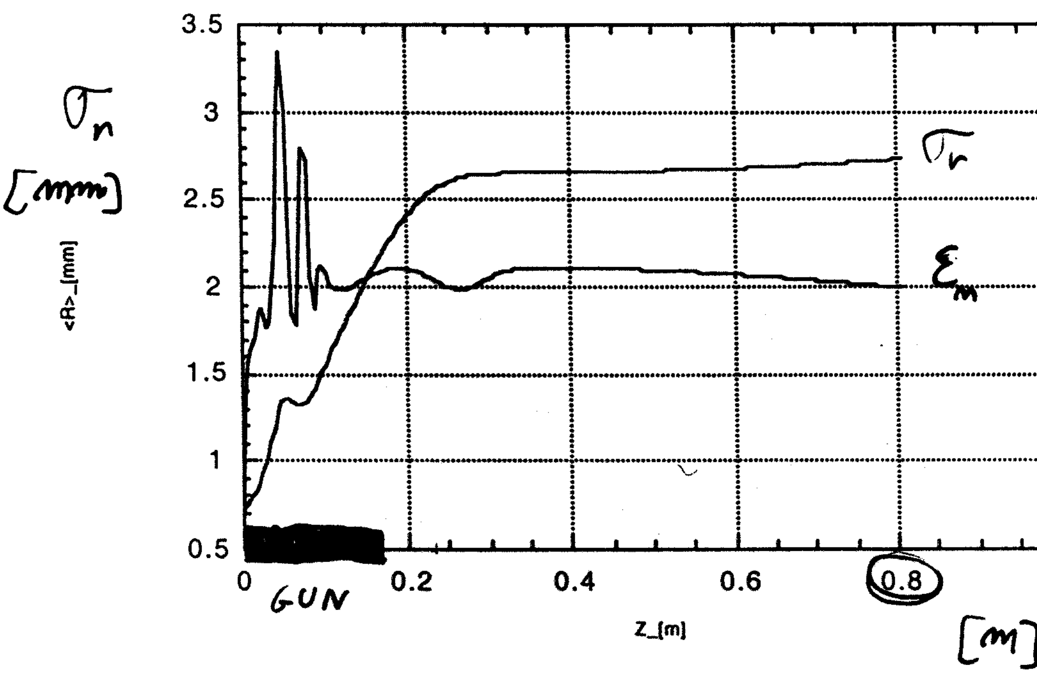


CONFIGURATION 3

SPLIT PHOTOINJECTOR WITH MATCHING AT THE ENVELOP MAXIMUM



GUN + DRIFT



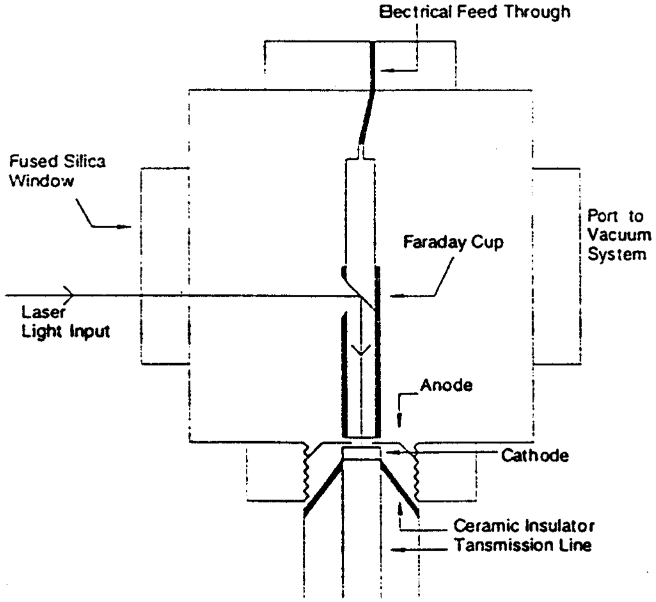


Figure 1. Diode with the Faraday cup inside the vacuum cell

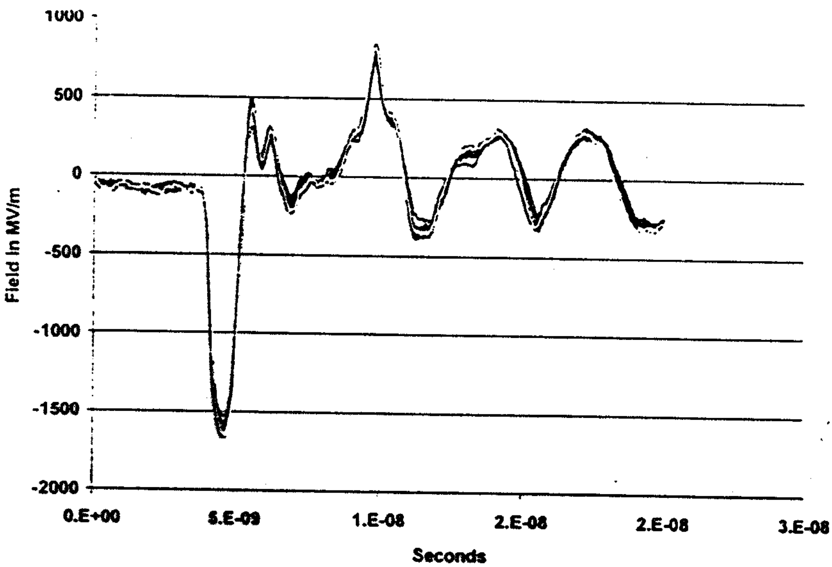


Figure 2 a. The applied field on the cathode, based on the voltage measured at the last probe.

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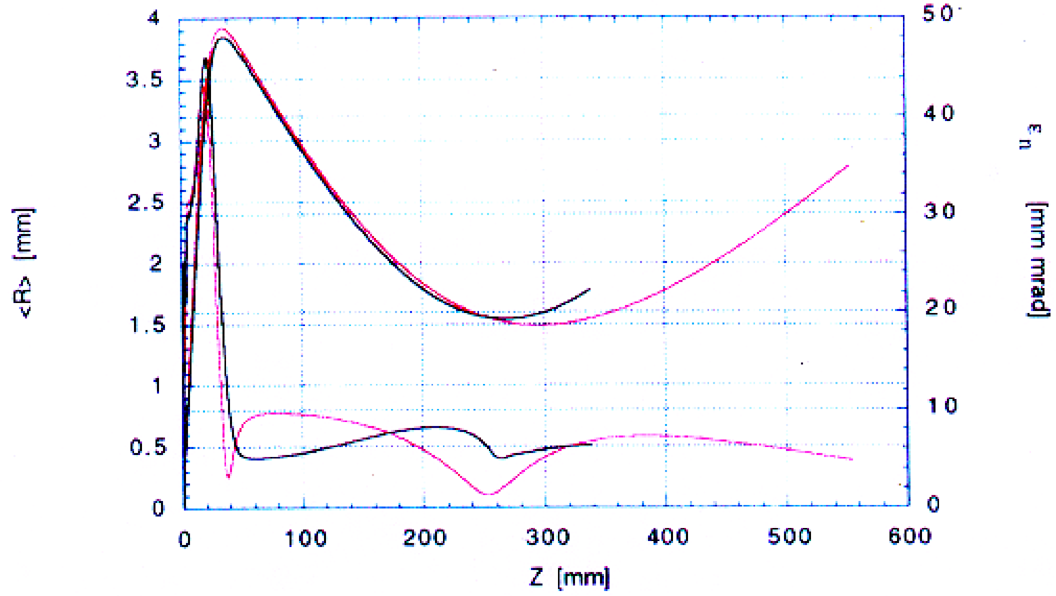
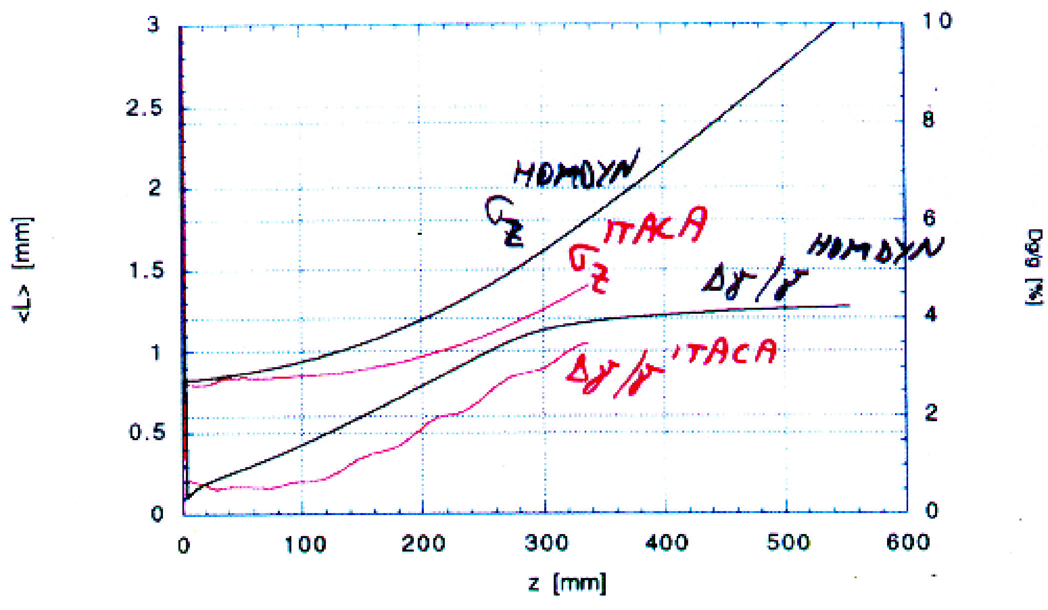
Pulsed Photo-diode (flat cathode - round anode)

1 mm gap, 1 GV/m, 1 nC, 10 ps flat top laser, R_{cat} = 0.5 mm

Comparison HOMDYN (red lines) vs ITACA (black lines)

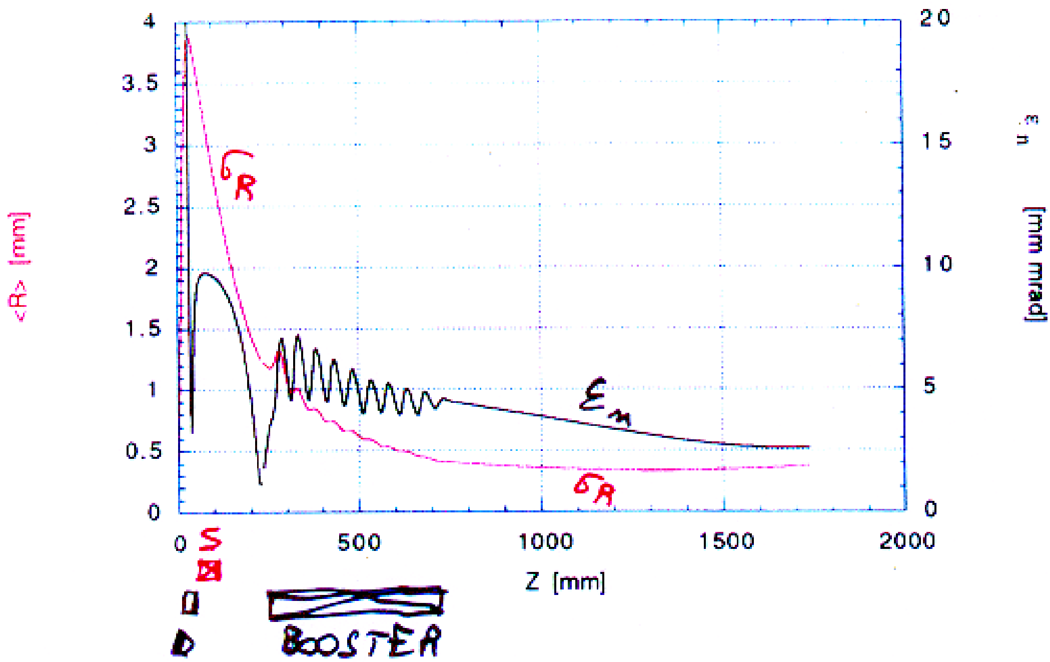


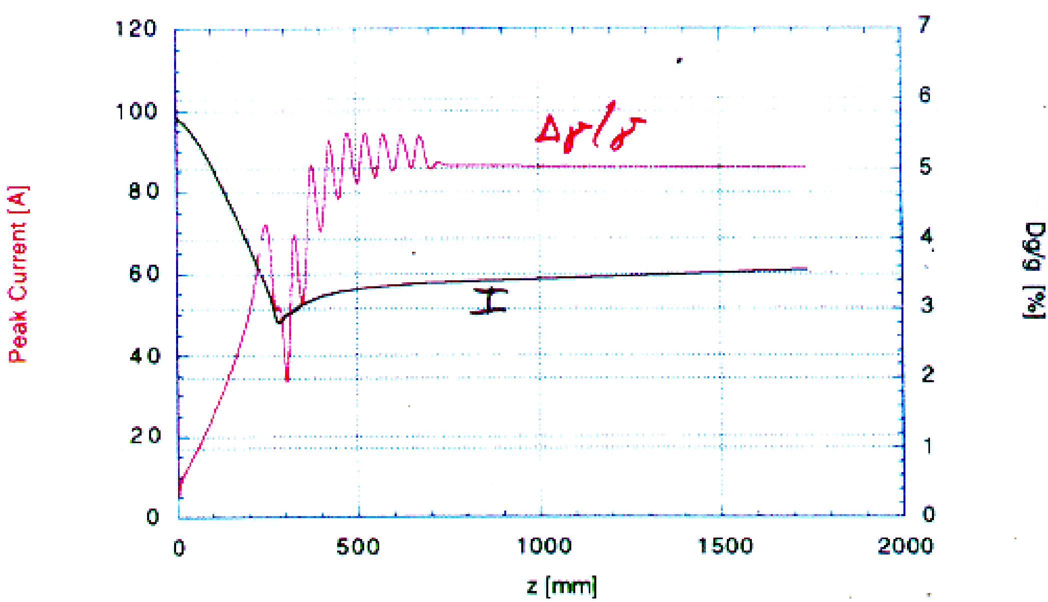


HOMDYN (black lines) vs ITACA (red lines)

Configuration 4a

Pulsed Photo-diode with matching at the waist
(1 mm, 1 GV/m, 10 ps laser, S-band booster @ 21 MV/m)





Configuration 4b

Pulsed Photo-diode with matching at the envelope maximum
S-band booster @ 7 MV/m