Summary: Topical Session C
RF Photocathode Beam Dynamics

K. Flöttmann

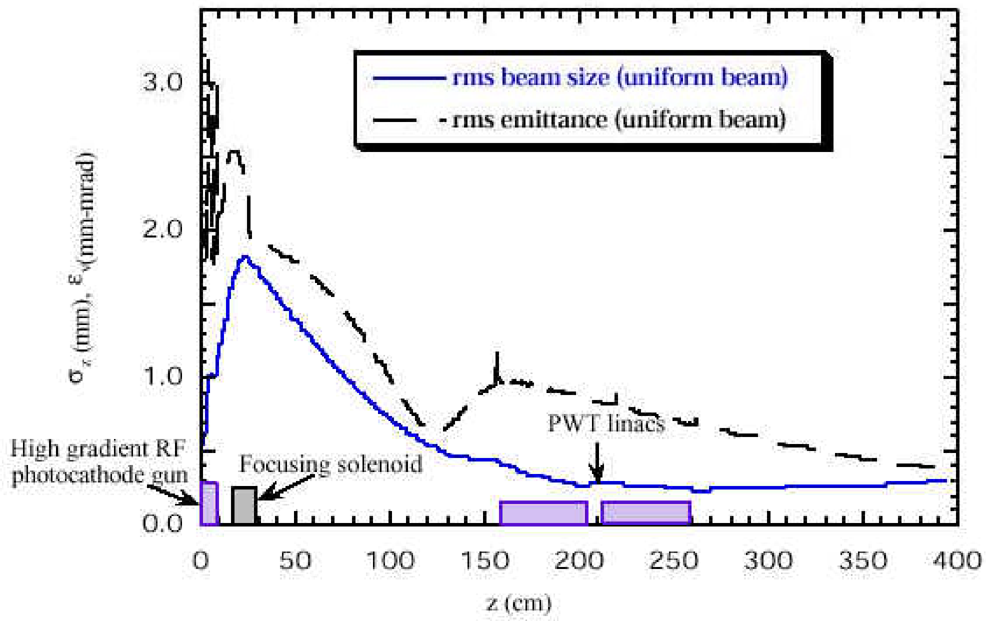
J. Lewellen

Program:

Emittance Compensation Overview	B. Carlsten
Beam Dynamics in Photocathode RF Gun	M. Ferrario
DUVFEL Experimental Results	W. Graves
Longitudinal Emittance / Virtual Cathodes Effects	D. Dowell
Longitudinal Space Charge instability	C. Limborg
Beam dynamics in combined cavity – solenoid sections	K. Flöttmann
Discussion	

Plasma Oscillations Dominate Emittance Evolution

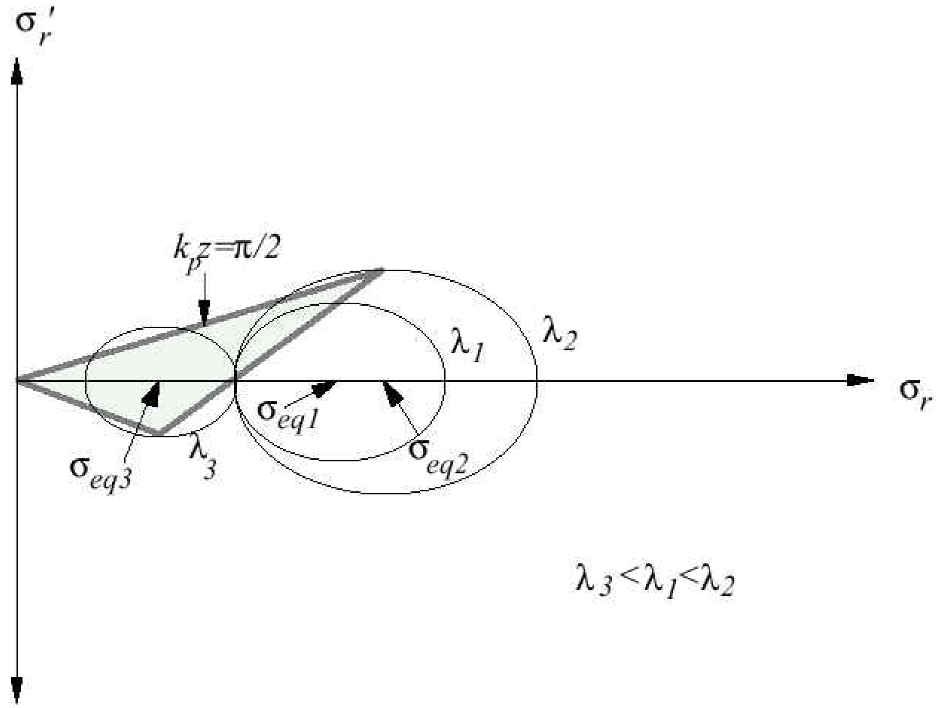
Major features common for many rf gun designs:



Typical emittance evolution profile for rf linac with photocathode gun (UCLA design), emittance minimum at full plasma period (S. G. Anderson and J. B. Rosenzweig, Phys. Rev. ST Accel. Beams **3**, 094201 (2000))

B. Carlsten

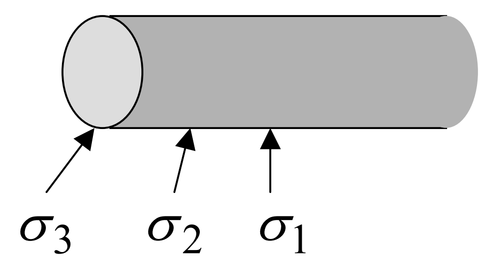
Emittance Oscillations Tied To Plasma Oscillations



$$\sigma'' + K\sigma - K_s / \sigma = 0$$

$$K_s = 2I(r) / I_A \gamma^3 \beta^3$$

$$\sigma_{eq} = \sqrt{K_s / K}$$



Bow-tie phase space distribution forms during the plasma oscillations of particles with different equilibrium radii

B. Carlsten

DARHT Is The Next-Generation U.S. Facility For Radiographic Hydrodynamics Testing

Aerial view of DARHT

A "hydrotest" on the operational first axis of DARHT

- **Flash radiography measurements require 3 essential capabilities :**

    1. *high-resolution*
    2. *multiple-views (3D reconstruction)*
    3. *multiple times (dynamic code benchmarking)*

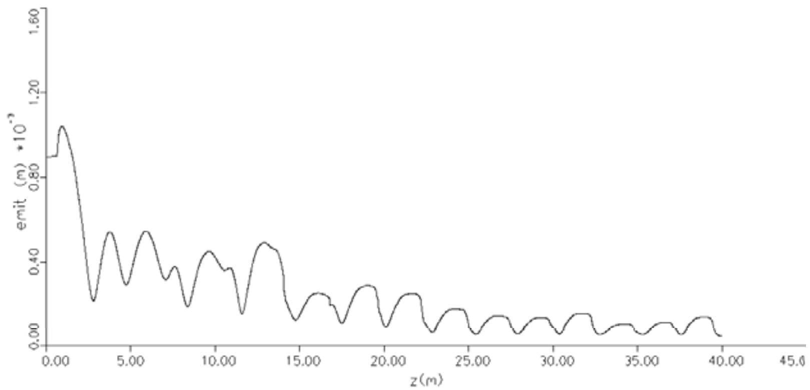
- **DARHT is the first U.S. facility that begins to provide these capabilities :**

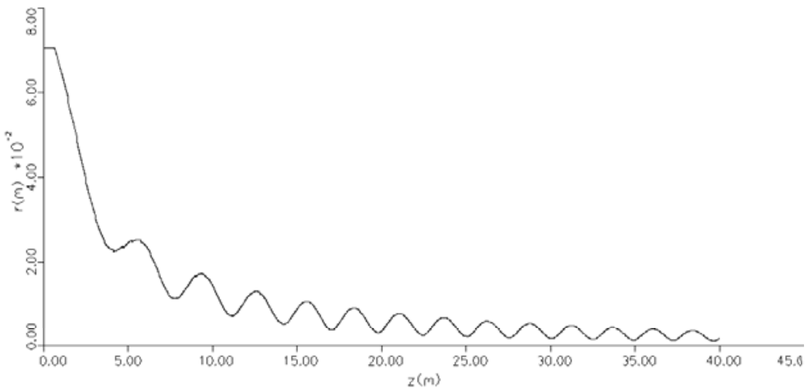
    1. *high-resolution (0.2-mm - 0.5-mm rms edge location)*
    2. *multiple-views (2-axes, can be simultaneously viewed)*
    3. *multiple-times (single-pulse 1st axis, 4-pulse in 2-μsec 2nd axis)*

B. Carlsten

Emittance Oscillations In DARHT Lead To Additional Insights

Control of emittance oscillations important for high-brightness induction linacs like DARHT:



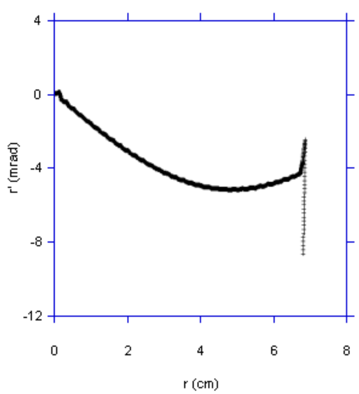


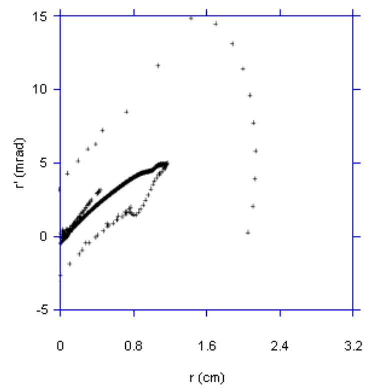
Three key physics issues - (1) diode nonlinearities initiate emittance oscillations (which are out of phase), (2) nonlinear forces due to the potential depression of the beam curve the phase space and *lead to the emittance decreasing*, (3) wave breaking can lead to uncontrollable thermalization and breakdown of the emittance oscillations

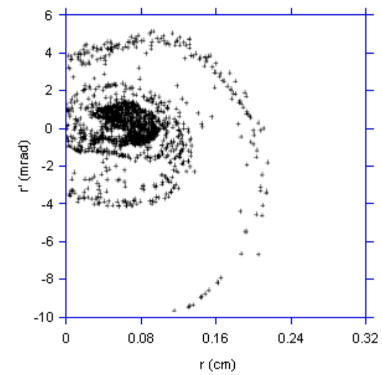
B. Carlsten

Wave Breaking Leads To Final Emittance

Wave breaking dominates final DARHT emittance:







Wave breaking particles passing through the beam core forming a halo early on, and final evolved distribution consists of wave breaking particles spiraling about the 2:1 resonance

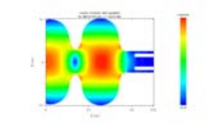
B. Carlsten

Beam Dynamics in RF photocathode Gun

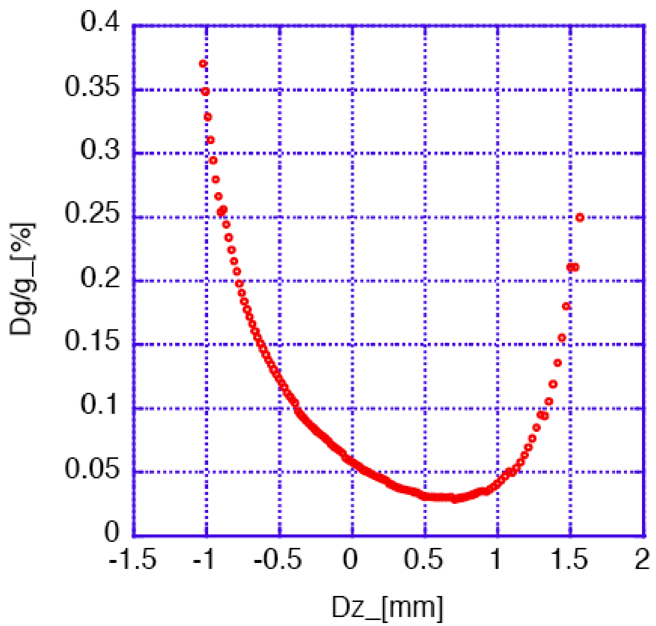
M. Ferrario

- Chromatic Effect in the Gun Solenoid

- Towards a Superconducting High Brightness Photoinjector

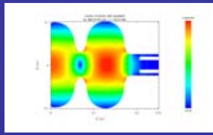


The head and tail slices carry the most pronounced energy spread

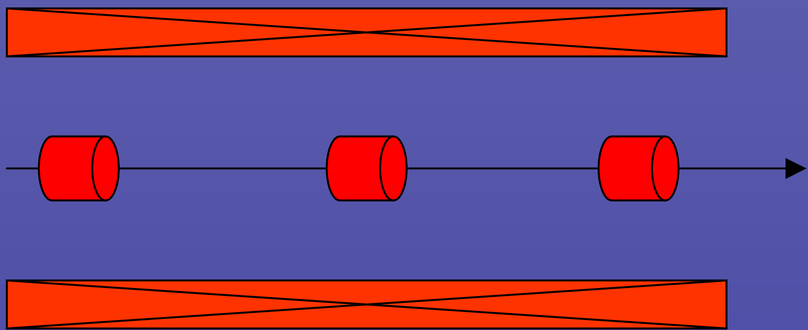


Energy deviation along the bunch at z=0.2 (solenoid centre) computed for a 400 μm long slice centered at Dz.

M. Ferrario



Simple Case: Transport in a Long Solenoid

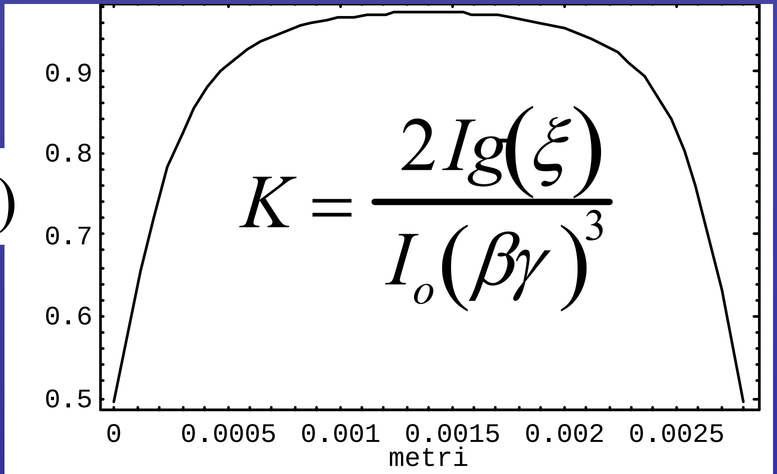


$$\sigma'' + k_s^2 \sigma = \frac{K}{\sigma}$$

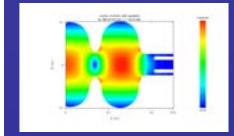
$\sigma'' = 0$ ==> Equilibrium solution ? ==>

$$\sigma_{eq}(\xi) = \frac{\sqrt{K(\xi)}}{k_s}$$

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



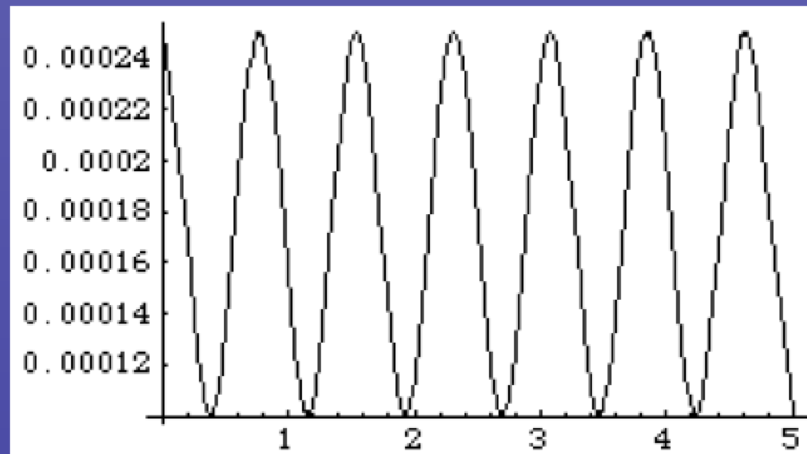
$$K = \frac{2Ig(\xi)}{I_o(\beta\gamma)^3}$$



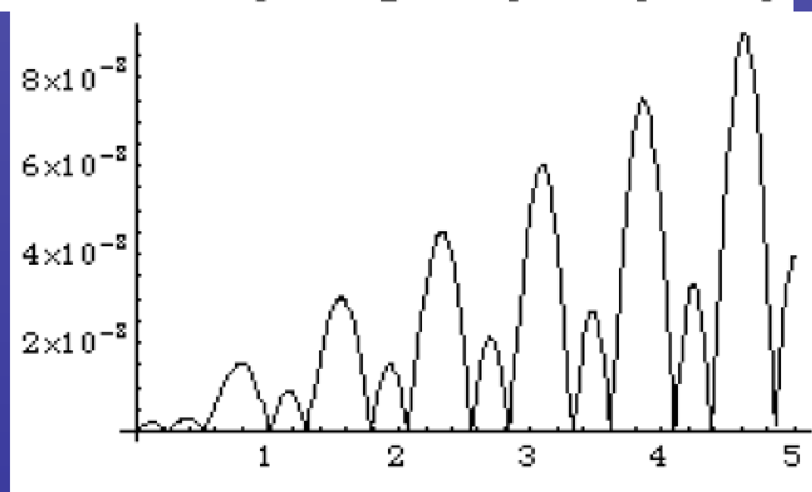
M. Ferrario

A Spread in Plasma Frequencies drives a Beating in Emittance Oscillations

$$\delta\sigma_o = \sigma_c - \sigma_{eqo}$$



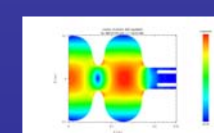
$$\langle k \rangle = \frac{1}{\sqrt{2}}\left(k_+ + k_-\right) = \sqrt{2}k_o$$



$$\Delta k = \sqrt{2}\left(k_- - k_+\right) = 2\sqrt{2}k_o\delta_\gamma$$

M. Ferrario

$$\varepsilon_n = \frac{\gamma}{\sqrt{2}}k_o\left|\sigma_{eqo}\left(2\delta\sigma_o + \delta_\gamma\right)\sin\left(\frac{\Delta k}{2}z\right)\cos\left(\langle k \rangle z\right) + \delta\sigma_o^2\sin\left(\Delta kz\right)\right|$$



Towards a Superconducting High Brightness RF Photoinjector

Main Questions/Concerns

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

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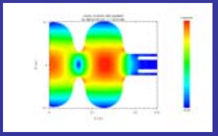
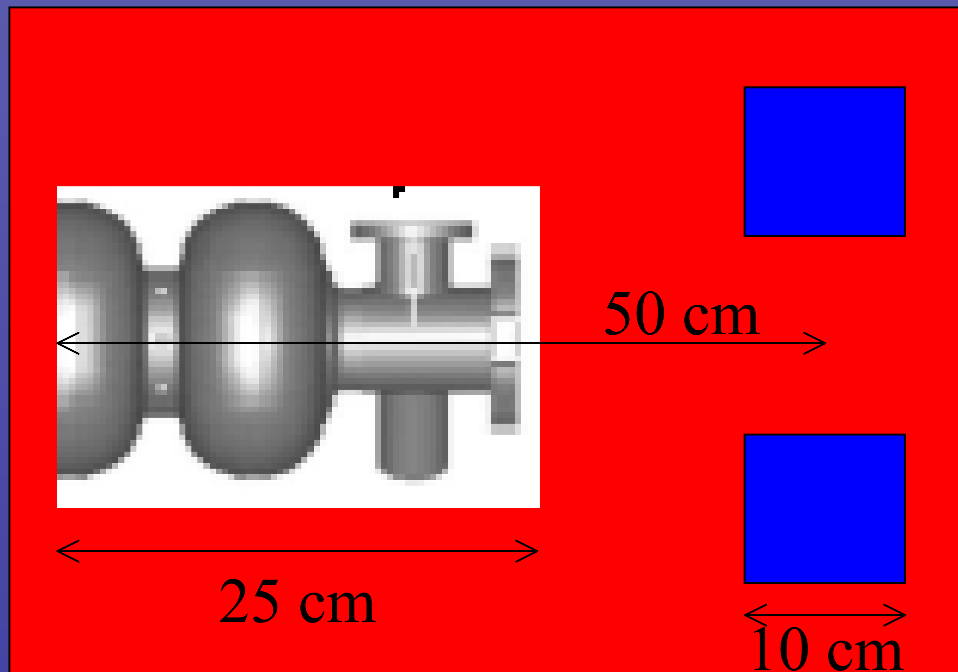
Laboratori Nazionali di Frascati

M. Ferrario



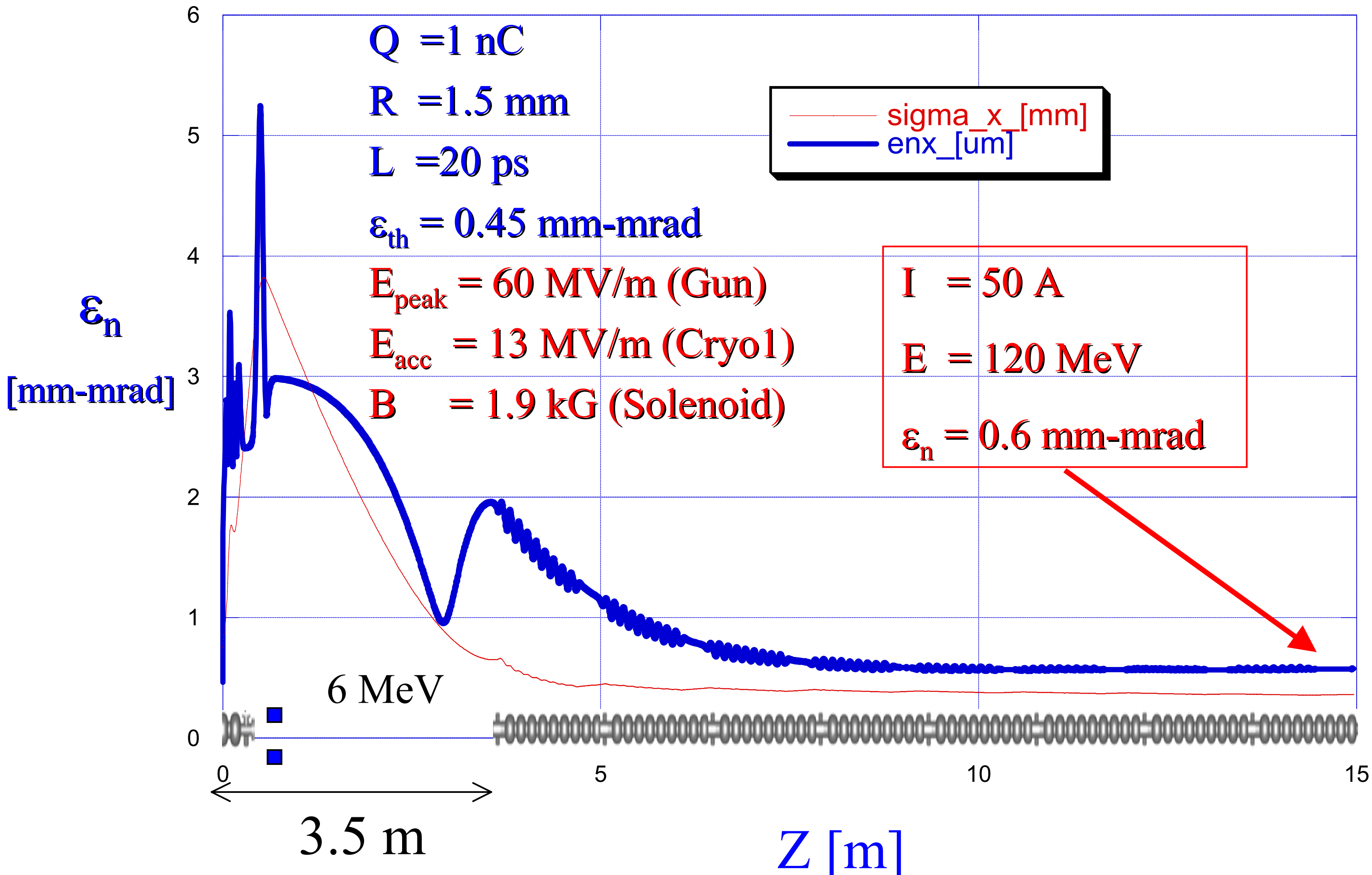
Splitting Acceleration and Focusing



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

M. Ferrario

HOMDYN Simulation



M. Ferrario

scaling laws for Q and E_{peak} available

DUVFEL Experimental Results

W. Graves

Sorry, no slides available

- FEL Cost vs. Wavelength, Energy & Emittance
- Measurement and Simulation of slice and projected emittance agree if all initial conditions are well known and applied in the simulation
  - field balance, hot spots…

Longitudinal Emittance

Old and New Results

David H. Dowell
SLAC

Definition of Phase Space Parameters, Including Correlations

Longitudinal Beam Ellipse:

$$\gamma\Delta t^2 + 2\alpha\Delta t\Delta E + \beta\Delta E^2 = \frac{\varepsilon_\ell}{\pi}$$

Longitudinal Beam Matrix:

$$\tau = \begin{pmatrix} \tau_{11} & \tau_{12} \\ \tau_{12} & \tau_{22} \end{pmatrix} = \varepsilon_\ell \begin{pmatrix} \beta & \alpha \\ \alpha & \gamma \end{pmatrix}$$

$\sqrt{\tau_{11}} =$ **Uncorrelated Bunch Length**

$\sqrt{\tau_{22}} =$ **Uncorrelated Energy Spread**

Include correlated emittance by distorting the ellipse boundary using quadratic and cubic terms:

$$\Delta E = -\frac{\alpha}{\beta}\Delta t \pm \sqrt{\left(\frac{\alpha}{\beta}\Delta t\right)^2 - \frac{\gamma\Delta t^2 - \frac{\varepsilon_\ell}{\pi}}{\beta}} + a\Delta t^2 + b\Delta t^3$$

Randomly populate and ray-trace down the 433 MHz accelerator:

$$\Delta E_1 = \Delta E_0 + E_{433}(\cos(\phi_{433} + \Delta t_0) - \cos(\phi_{433})) \quad ; \quad \Delta t_1 = \Delta t_0$$

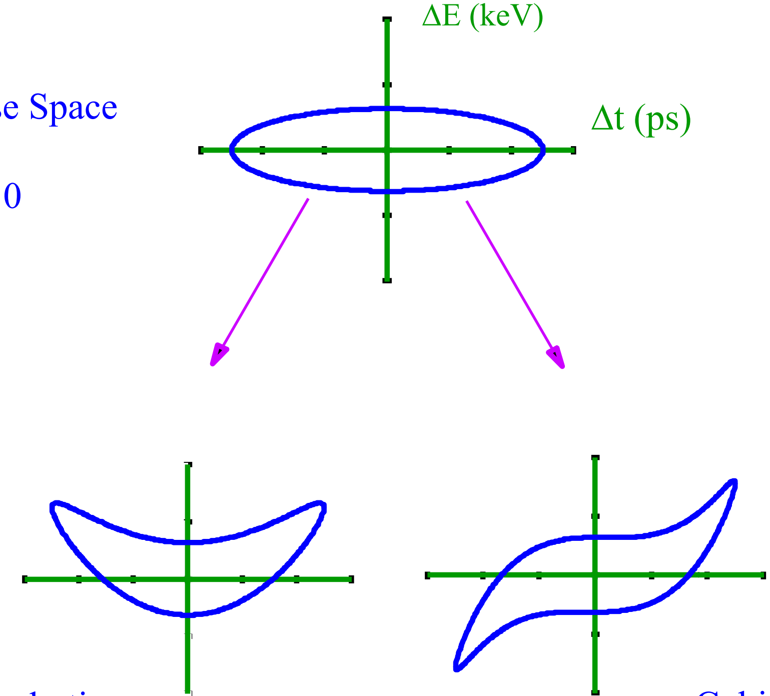
And continue ray-tracing around the Demi-Tour:

$$\Delta E_2 = \Delta E_1 \quad ; \quad \Delta t_2 = \Delta t_1 + R_{56}\Delta E_1$$

D. Dowell

Distortions of the Longitudinal Phase Space Ellipse

Undistorted Phase Space
$\tau_{12} = 0$
$a = 0, \; b = 0$

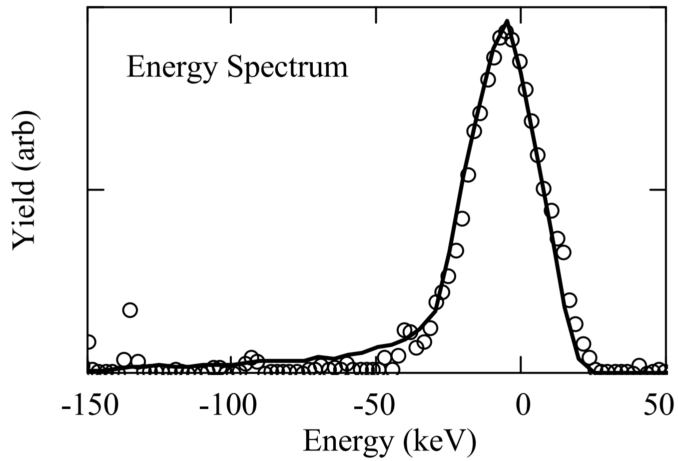


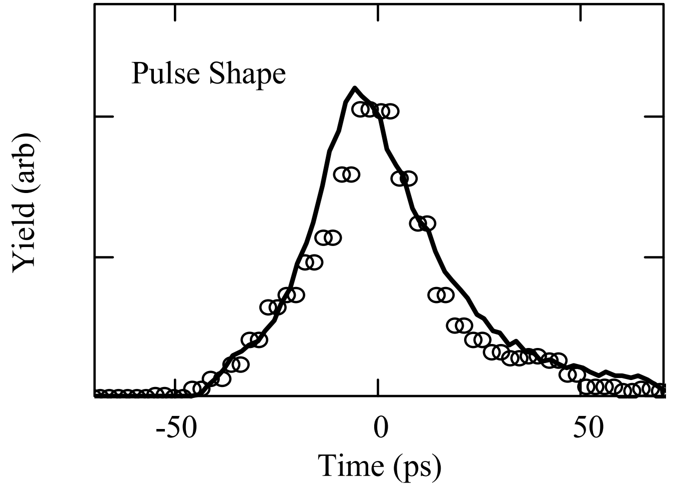
Quadratic
Distortion
$\tau_{12} = 0$
$a > 0, \; b = 0$

Cubic
Distortion
$\tau_{12} = 0$
$a = 0, \; b > 0$

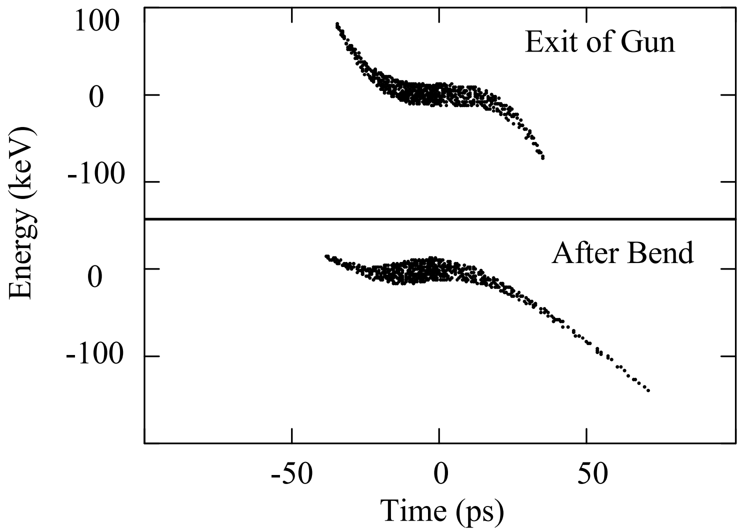
D. Dowell

Fits to 1 nC per Microbunch Data





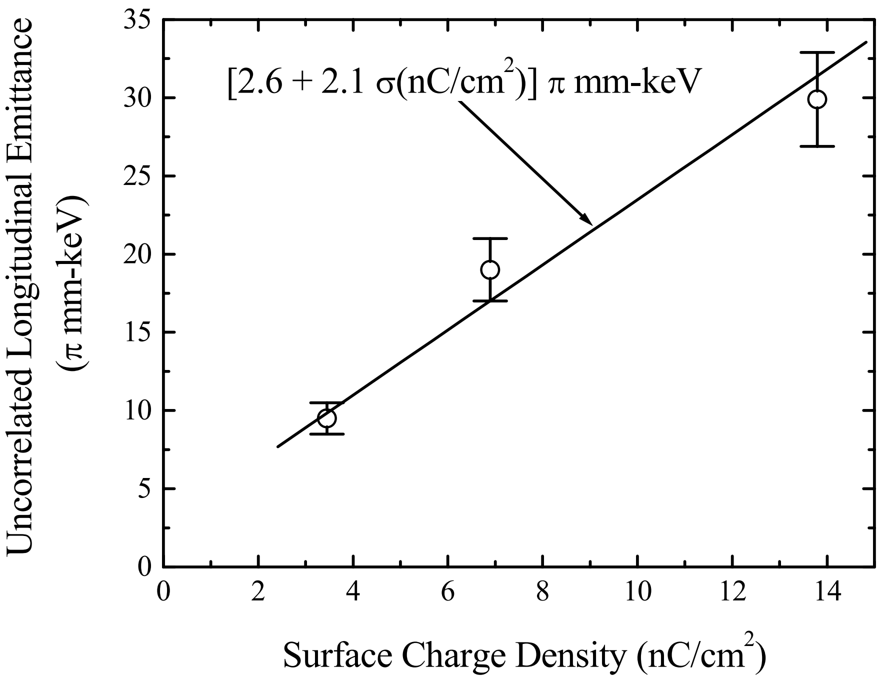
Longitudinal Phase Space Distributions Obtained from the Data Analysis



Ref: S. Joly et al.,...

D. Dowell

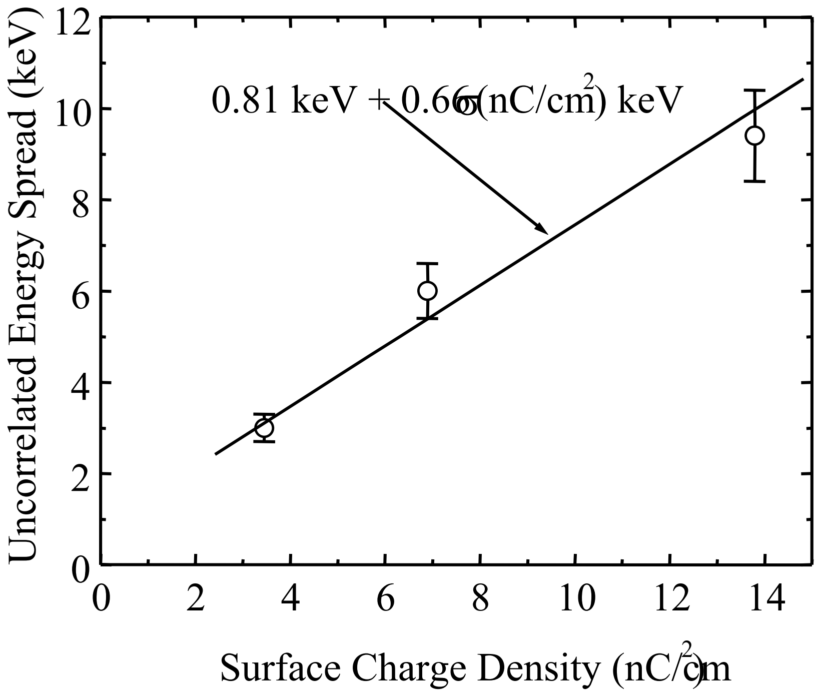
The Uncorrelated Emittance Grows Linearly with Surface Charge Densities Below the Space Charge Limit



Pulse length a constant 11 ps(rms)

10 nC/cm² corresponds to 11 MV/m

In These Experiments Most of the Emittance Growth Was due to Increased Energy Spread



Ref: D.H. Dowell et al., PAC97.

D. Dowell

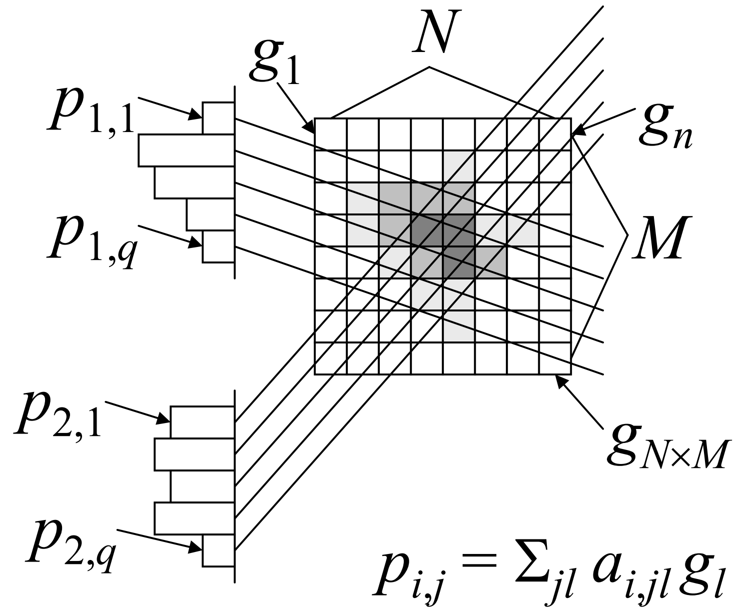
Algebraic Reconstruction Technique

- Many different transformations of an image g generate a set of histograms or projections p_i.
- Find the transport matrix a_i, so that $p_{i,j} = \Sigma_{jl}\, a_{i,jl}\, g_l$.
- The algorithm iterates an initial guess $g^{(0)}$ for each projection i according to

$$g_q^{(k+1)} = g_q^{(k)} + \Sigma_j \left[a_{i,jq}\,(p_{i,j} - \Sigma_l\, a_{i,jl}\, g_l^{(k)}) \,/\, \Sigma_{nl}\, a_{i,nl}^{\;2}\right]$$

until each projection has been used.

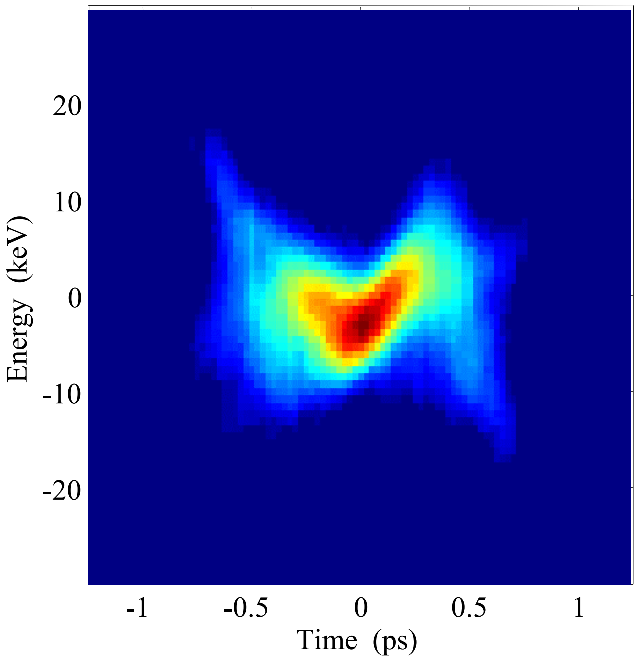
- Repeat until convergence achieved.

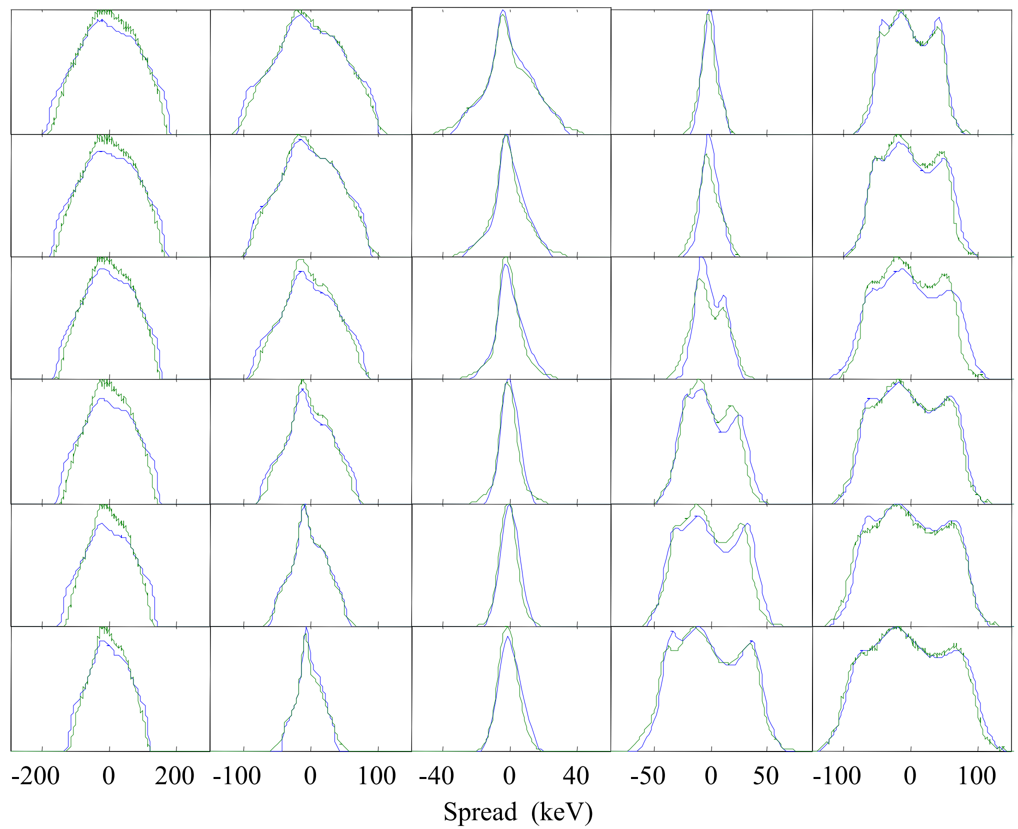


Slide compliments of H. Loos, BNL

D. Dowell

Reconstruction for 15 pC





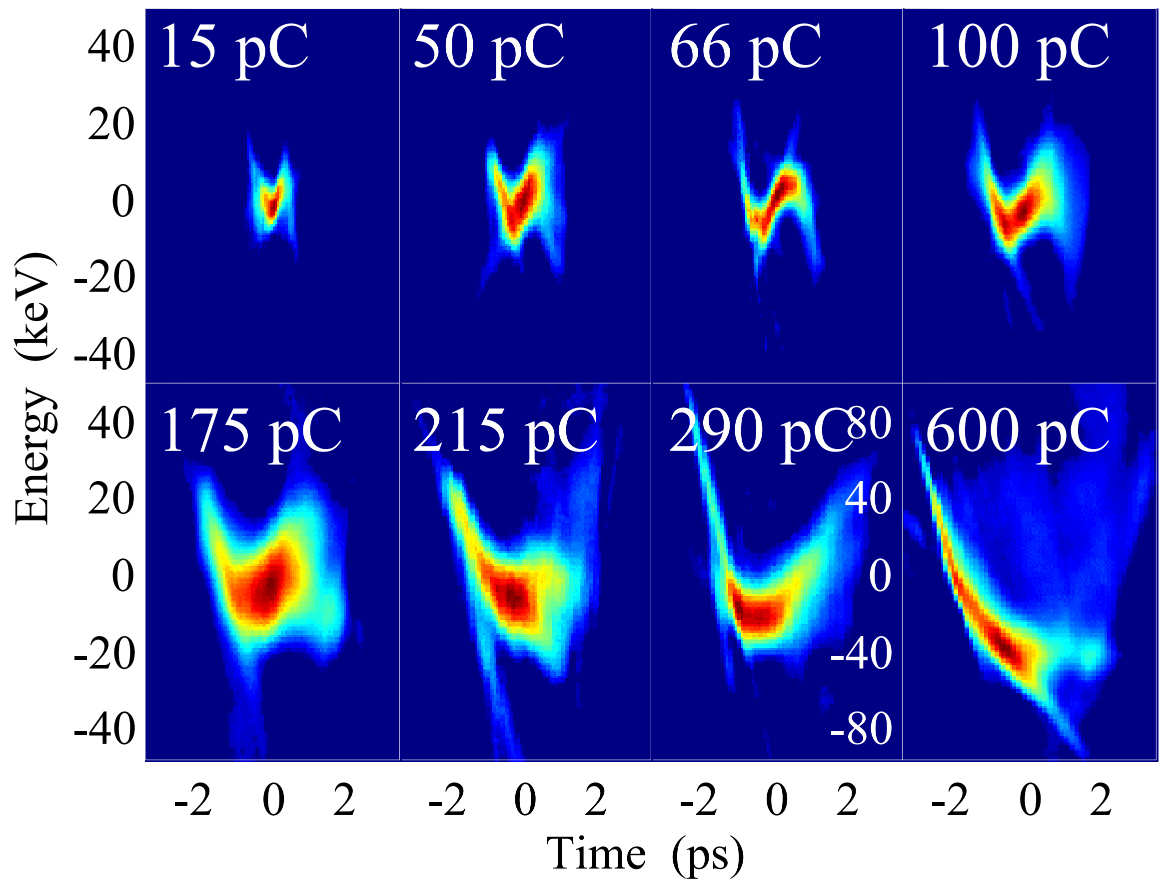
Reconstruct phase space w/o initial chirp to minimize rectangular phase space area.

Slide compliments of H. Loos, BNL

D. Dowell

Reconstructed Phase Spaces

- Artifacts due to linac phase and amplitude drifts.
- Removal of 'streak' artifacts with 7% floor cut.
- Slice energy spread grows with charge
- Energy spread higher in bunch tail for higher charges.



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Virtual Cathode Effects

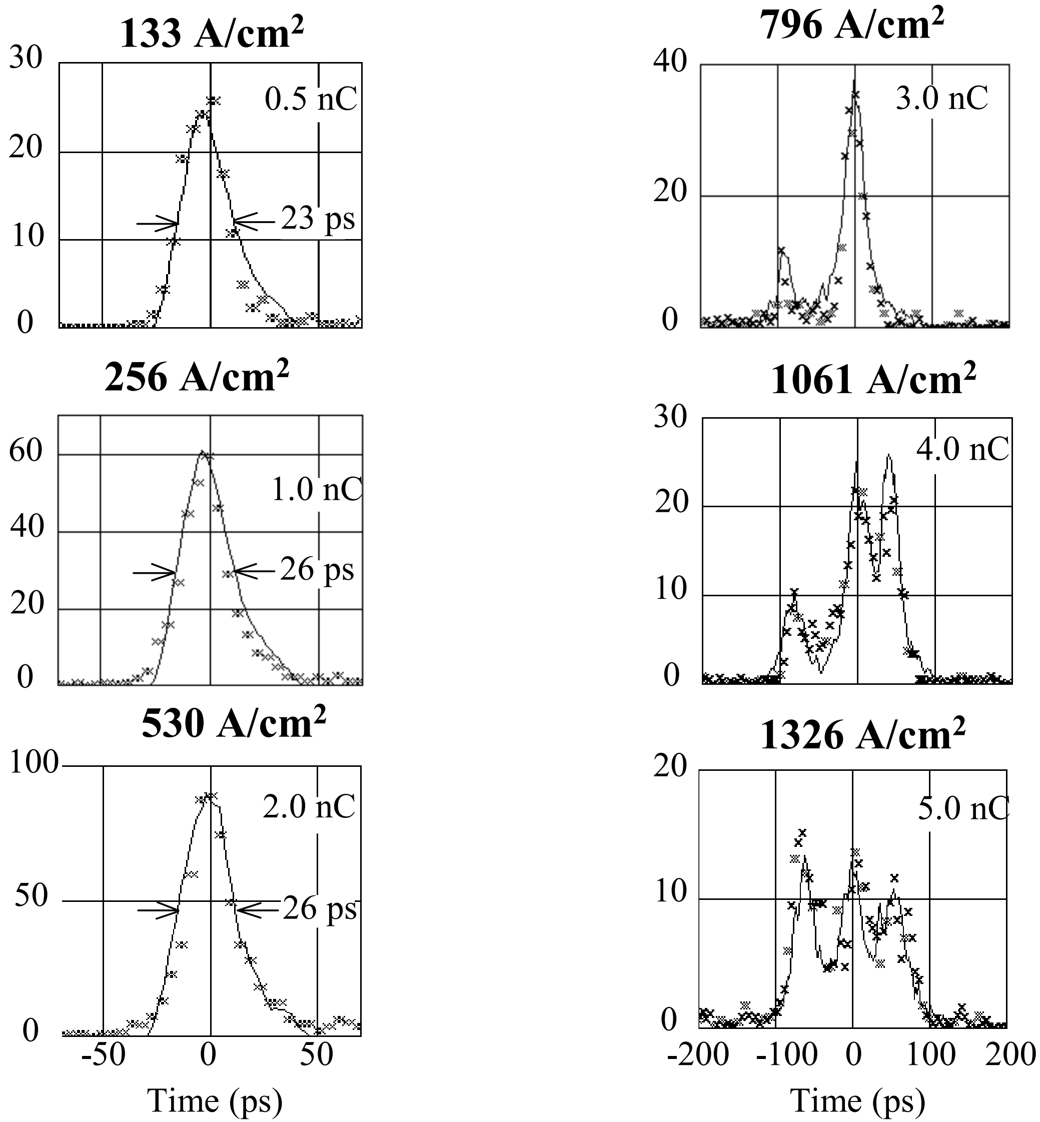
D.H. Dowell
SLAC

The 'Old', Circa. 1993

CEA, Bruyeres-le-Chatel, France:
S. Joly
A. Loulergue
G. Haouat
J.P. de Brion

D.H. Dowell, S. Joly, A. Loulergue, J.P. deBrion and G. Haouat, Phys. Plasmas 4, 3369(1997)

Streak Camera Measurements Showing Onset of Virtual Cathode



Cathode Peak Field 21 MV/m
Launch Phase ~ 60 degrees
Space Charge Limit:
Child's Law ~250 A/cm²

$$J_{Childs} = 2.33\times10^{-2}\,\frac{V_0^{3/2}}{d^2} \quad [\mathrm{A/cm^2}]$$

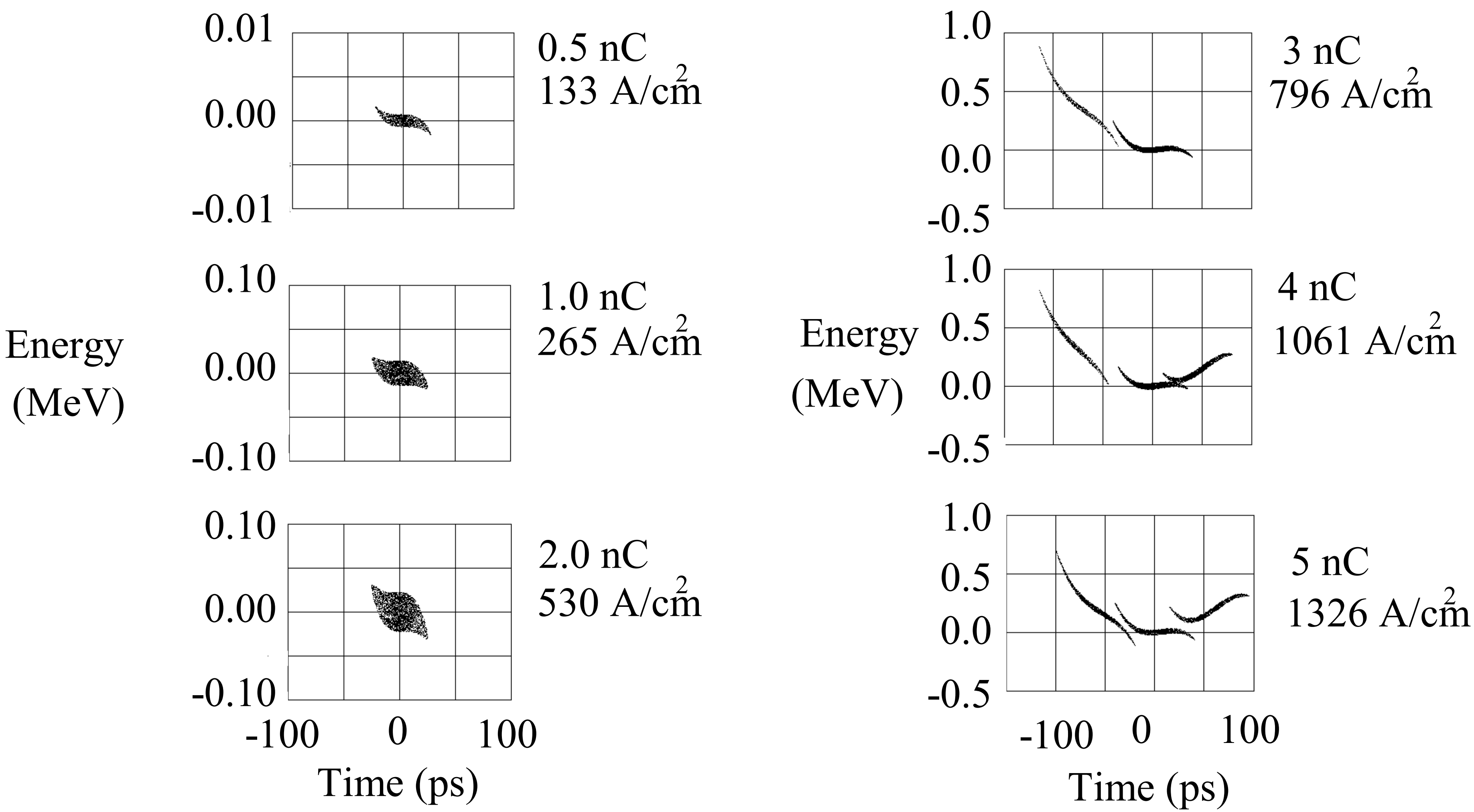
V_0 is the voltage across gap d

See Reiser, "Theory and Design of Particle Beams"

D. Dowell

Fits to Parameterized Phase Space Distributions

Space Charge Limit: Child's Law ~250 A/cm^2



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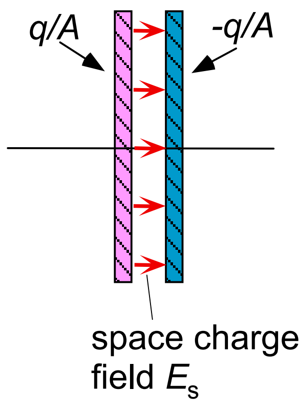
SIMPLE

MODEL

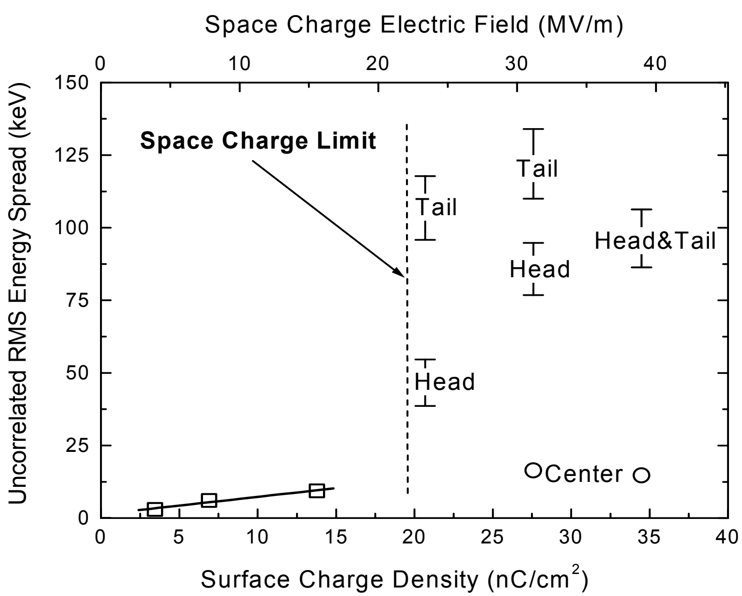


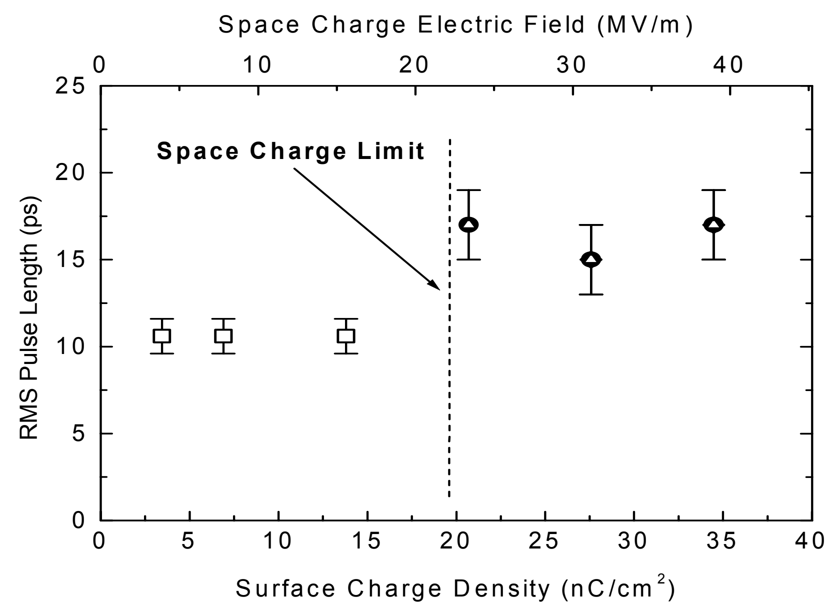
- Space charge field E_s increases as charge is photo-emitted from cathode surface

$$E_s = \frac{q}{A\varepsilon_o}$$

- Emission shuts off when it neutralizes the RF field E_o
- Maximum extractable charge is therefore

$$q_{mx} = \varepsilon_o E_o A = \frac{\pi \varepsilon_o E_o d^2}{4} = .2\ d^2 \frac{\text{nC}}{\text{mm}^2}$$





D. Dowell

Longitudinal Space Charge Instability

C. Limborg

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- small perturbations in the current density can be amplified in a linear accelerator
- the gain of this instability can be very high (up to 6000 for LCLS)
- the dynamics in the gun tends to wash out current perturbations for short wavelength, but momentum perturbations arise. This is difficult to simulate!

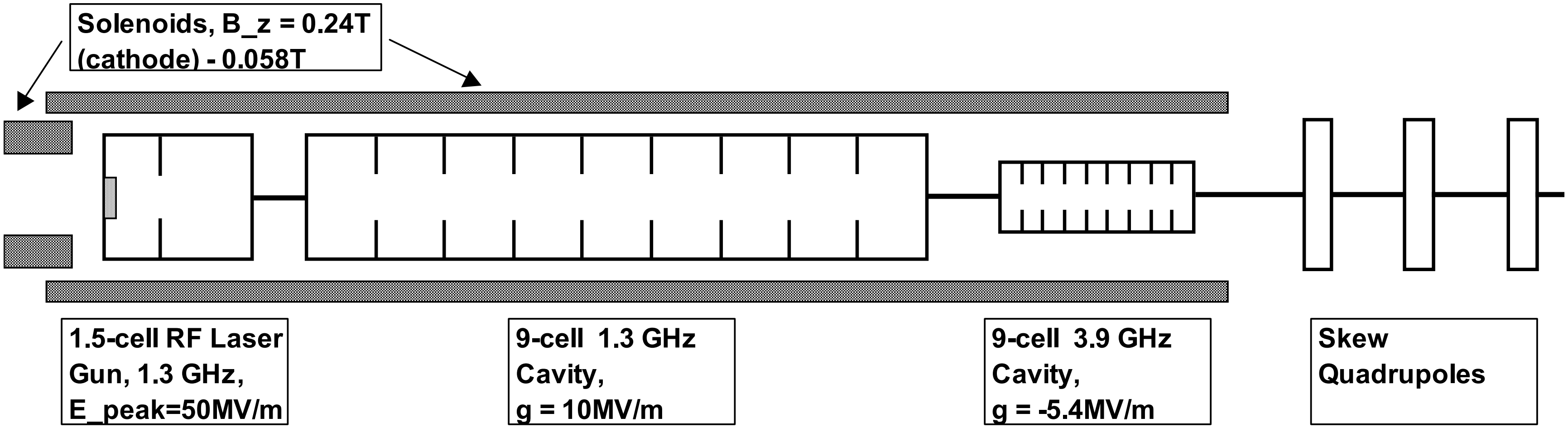
Beam dynamics in combined cavity – solenoid sections

K. Flöttmann

ANL Theory Institute on Production of Bright Electron Beams

Sept. 22-26, 2003

Simulation study for a Flat-beam Injector



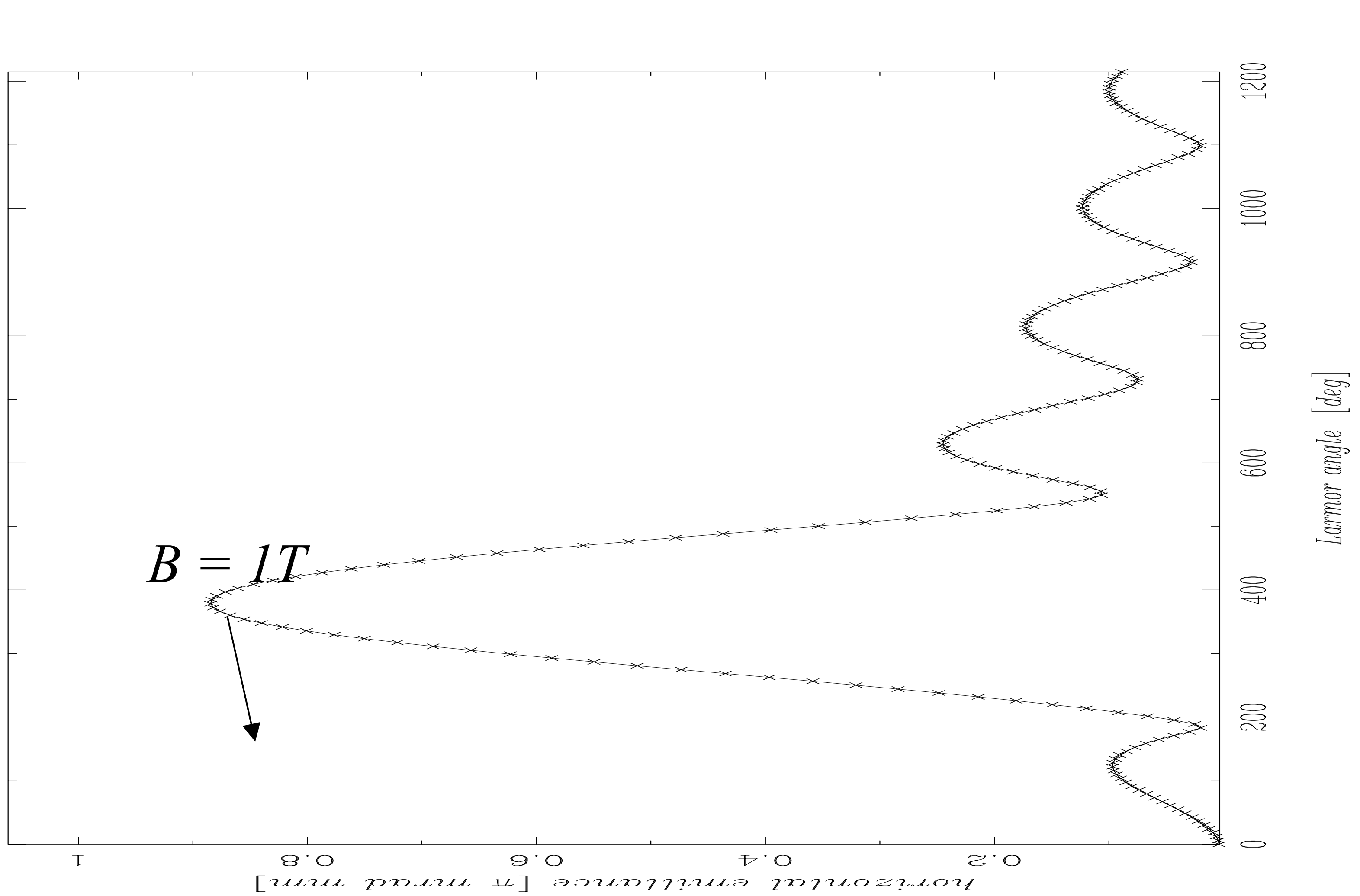
$\varepsilon_x = 1.1 \cdot 10^{-5}$ m $\qquad \varepsilon_x / \varepsilon_y = 370$

$\varepsilon_y = \quad 3 \cdot 10^{-8}$ m

PRSTAB Issue 5, May 2001

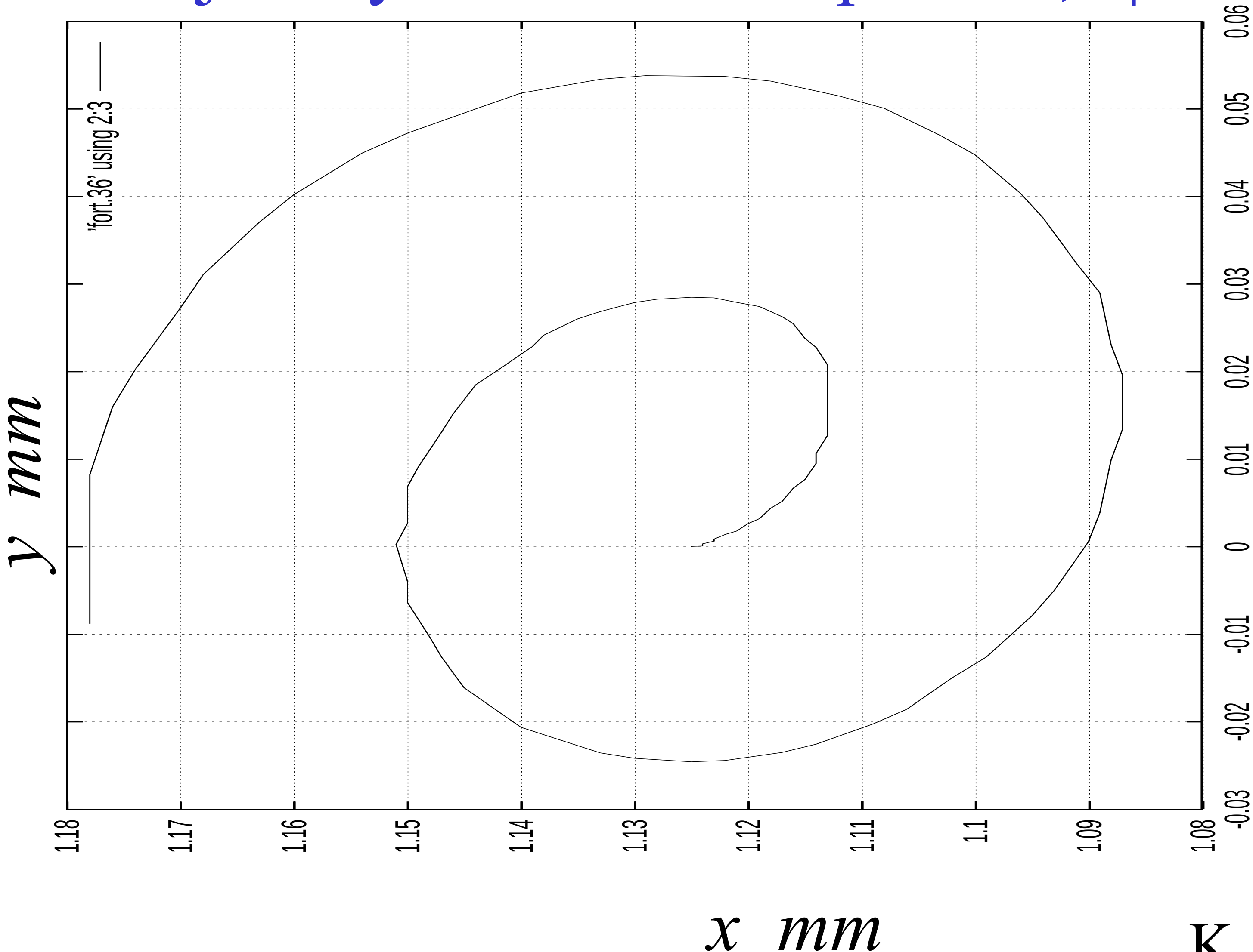
K. Flöttmann

Emittance growth of a ‘magnetized’ bunch passing a two cell cavity embedded in a solenoid



K. Flöttmann

Trajectory of an off-axis particle, $\varphi = 360^o$



K. Flöttmann

Discussion: *Session C Wants / Needs / What should come next?*

- Theory
  - Improved understanding and theoretical solution of wavebreaking effects / filamentation. Experiments need to be done concurrently.
  - Include coupling of longitudinal and transverse dynamics emittance compensation theory.
  - Only academic interest in virtual cathode (D. Dowell)?!
  - Explore concept of using optical feedback, ala stochastic feedback schemes, to remove harmful effects & correlations.
  - Kwang-Je will perform detailed, complete calculations of the solenoid-RF interaction.

Discussion: *Session C Wants / Needs / What should come next?*

- Simulation codes
  - More flexible simulation codes.
  - Simulation codes need 3 – 4 orders of magnitude increase in available particle count (1 virtual = 1 real particle), or some clever ideas to make the sims more accurate and faster. Funding for the algorithm and code development? Multiphysics support? Self-similar code to allow same code to perform both exploration and design tasks?
  - General beamline description language.

Discussion: *Session C Wants / Needs / What should come next?*

- Parameter optimization
  - Deeper exploration of parameter space? Incl. sensitivity effects.
  - What is the limit on compression ratios for beam currents? Are there alternatives to help reduce CSR effects?
  - Explore working in non-space charge-compensation regime (2f gun, Emma compensation scheme). Possibility of multi-beam combination techniques?
  - Compare emittance compensation techniques (solenoid vs. rf). Novel cavity design to improve either process?

Discussion: *Session C Wants / Needs / What should come next?*

- Experiments
  - Experiments on microbunching instability.
- Diagnostics
  - Development of analysis (esp. tomographic) techniques & combine them with improved diagnostics and instrumentation … also need to log enough data to allow the diagnostic data to be properly filtered or combed.
  - Need a design for a high-resolution temporal diagnostic that can operate at low to medium beam energies; should be part of a general diagnostics program?
  - How does one measure various correlations in phase space (e.g. conditioning (pz vs r), radial energy spread (pr vs r), etc.?

Discussion: *Session C Wants / Needs / What should come next?*

- General
  - General expansion of research and development activities across many facilities; optimal distribution of resources and tasks?
  - More money.
  - Development of techniques to introduce correlations in phase space in the injector.