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Phase Space Manipulation in High-Brightness Electron Beams

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Lawrence Berkeley National Laboratory Seminar

NGLS talk

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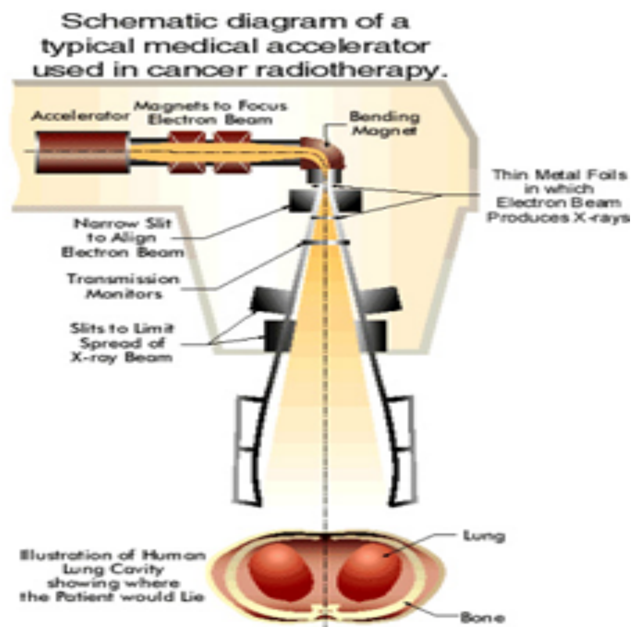
Outline

- Introduction/Motivation.
- The Argonne Wakefield Accelerator.
- “Multi-beam” control of electron beam.
- Phase space exchange between two degrees of freedom.
- Development of a single-shot longitudinal phase space diagnostics.
- Production of a train of picosecond relativistic electron bunches.
- Future plans.

Introduction

- Particle accelerators produce and accelerate charged-particles beams up to relativistic energies.

- Accelerators applications include
  - Material sciences (electron microscopy and X-ray in accelerator-based light sources),
  - Medical application,
  - Nuclear and high-energy physics.



Beam & Phase Space: definitions

- A particle is identify by its coordinate and momentum in a 6D phase.

$$P_i \equiv \{x_i, p_{xi}; y_i; p_{yi}; z_i, p_{zi}\}$$

- A beam is a collection of particle confined in space $p_z >> p_x, p_y$

- Separate to 2D sub-phase space

Transverse space $\{x_i, p_{xi}\}\ \{y_i, p_{yi}\}$ Longitudinal space $\{z_i, p_{zi}\}$

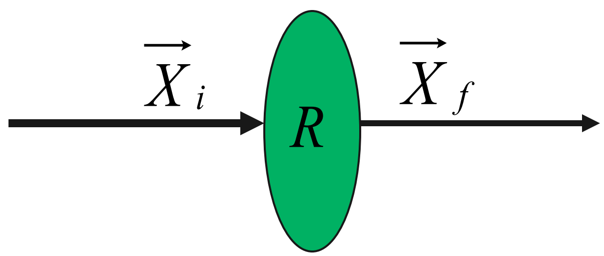
- Trace space coordinates:

$$\vec{X}_i \equiv (x_i, x_i'; y_i, y_i', z_i, \delta_i) \quad \text{with} \quad (x', y') \equiv \frac{p_{(x,y)}}{p_z} \quad \text{and} \quad \delta \equiv \frac{p_z - p_{z,REF}}{p_z}$$

- Trace space coordinates of a particle downstream of an element can be obtained via

$$\vec{X}_f = R\vec{X}_i$$

R: transfer matrix of the element



Statistical representation of a beam

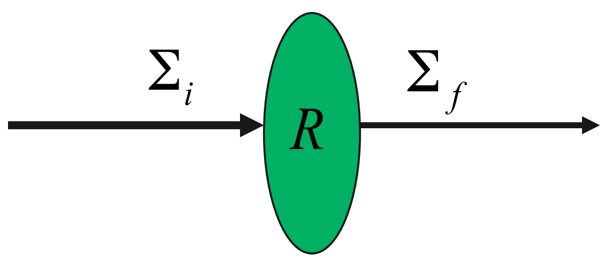
- A beam can be represented by its second-order moments arranged as a covariance matrix or “ beam matrix”

$$X = \begin{pmatrix} x \\ x' \\ y \\ y' \\ z \\ \delta \end{pmatrix} \qquad \Sigma = \langle X\tilde{X} \rangle = \begin{pmatrix} \langle x^2 \rangle & \langle xx' \rangle & \langle xy \rangle & \langle xy' \rangle & \langle xz \rangle & \langle x\delta \rangle \\ \langle x'x \rangle & \langle x'^2 \rangle & \langle x'y \rangle & \langle x'y' \rangle & \langle x'z \rangle & \langle x\delta \rangle \\ \langle yx \rangle & \langle yx' \rangle & \langle y^2 \rangle & \langle yy' \rangle & \langle yz \rangle & \langle y\delta \rangle \\ \langle y'x \rangle & \langle y'x' \rangle & \langle y'y \rangle & \langle y'^2 \rangle & \langle y'z \rangle & \langle y'\delta \rangle \\ \langle zx \rangle & \langle zx' \rangle & \langle zy \rangle & \langle zy' \rangle & \langle z^2 \rangle & \langle z\delta \rangle \\ \langle z'x \rangle & \langle z'x' \rangle & \langle z'y \rangle & \langle z'y' \rangle & \langle z'z \rangle & \langle \delta^2 \rangle \end{pmatrix}$$

- Uncoupled 2D phase spaces $\Rightarrow$ beam matrix is block diagonal. $\sum = \begin{bmatrix} A & & \\ & B & \\ & & C \end{bmatrix}$

- The beam matrix can be propagated using the transfer matrix formalism

$$\sum{}_f = R \sum{}_i R^T$$



Emittance and Brightness: figure of merit of a beam

- Canonical emittance:

$$\varepsilon_x = \frac{1}{m_e c}\sqrt{\langle x^2\rangle\langle p_x{}^2\rangle - \langle x p_x\rangle^2}$$

- Trace-space emittance (experimentally measurable)

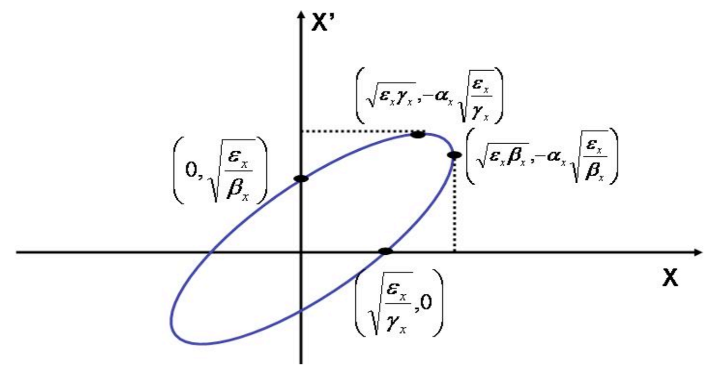
$$\tilde{\varepsilon}_x = \sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle x x'\rangle^2}$$

- Normalized Brightness

$$B = \frac{Q}{\Gamma} = \frac{Q}{\varepsilon_x \varepsilon_y \varepsilon_z}$$

Beam charge

- Beam's moment used to parametrize the beam



$$\beta x'^2 + \gamma x^2 + 2\alpha x x' = \tilde{\varepsilon}_x$$

- Courant-Snyder parameters

$$\beta = \frac{\langle x^2\rangle}{\tilde{\varepsilon}_x}, \alpha = -\frac{\langle x x'\rangle}{\tilde{\varepsilon}_x}, \gamma = \frac{\langle x'^2\rangle}{\tilde{\varepsilon}_x}$$

Goals of research work

- Explore phase space manipulations.
- Multi-beam control of the transverse beam parameters.
- Investigate phase space exchange between two degrees of freedom.
- Develop a single shot longitudinal phase space diagnostics and produce a train of picoseconds electron bunches.

Importance of phase space manipulation: next generation e+/e- linear collider

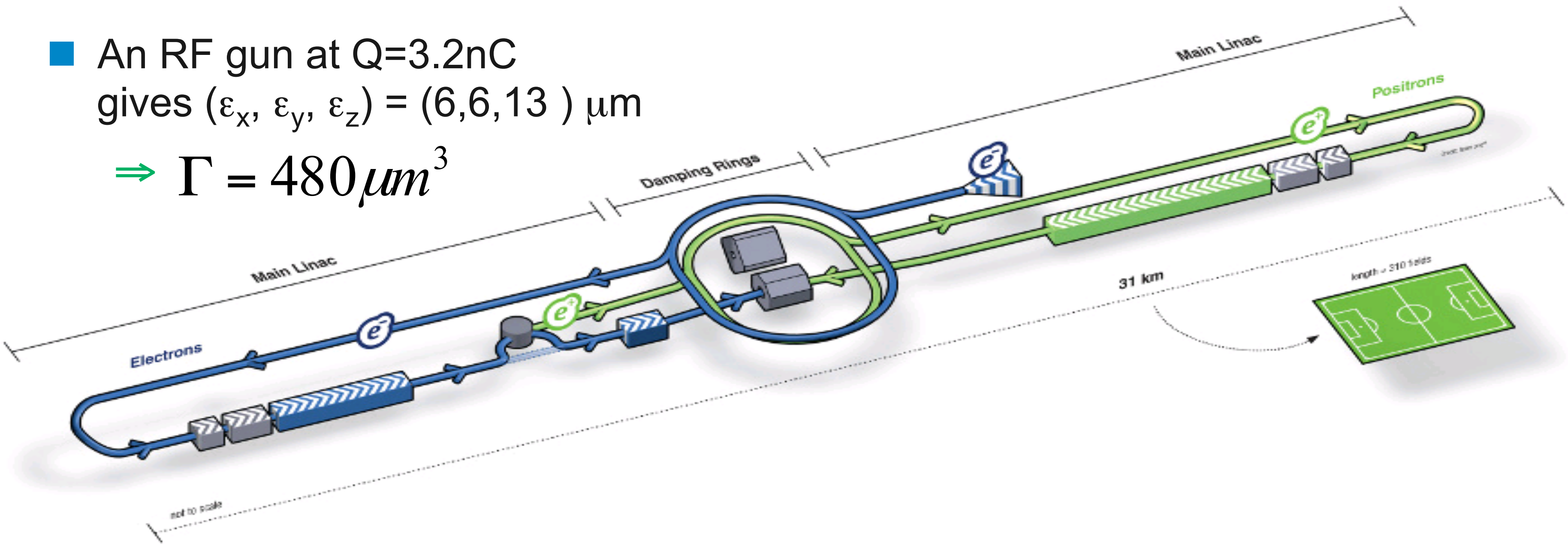
- International Linear Collider requirement →(ε_x, ε_y, ε_z) = (8, 0.02, 3000) μm

$$L = \frac{f_R N_+ N_-}{4\pi\varepsilon\sqrt{\beta_x \beta_y}}$$

f_R is the repetition frequency. β_x and β_y are the twiss parameters . Assume $\varepsilon = \varepsilon_x = \varepsilon_z$

- An RF gun at Q=3.2nC gives (ε_x, ε_y, ε_z) = (6,6,13) μm

$$\Rightarrow \ \Gamma = 480\mu m^3$$



- Redistributing the beam emittances within the 3 degrees of freedom
  ⇒ suppression of the damping ring (a 3 km circumference ring!)

Importance of phase space manipulation: reducing the size of accelerator-based light sources

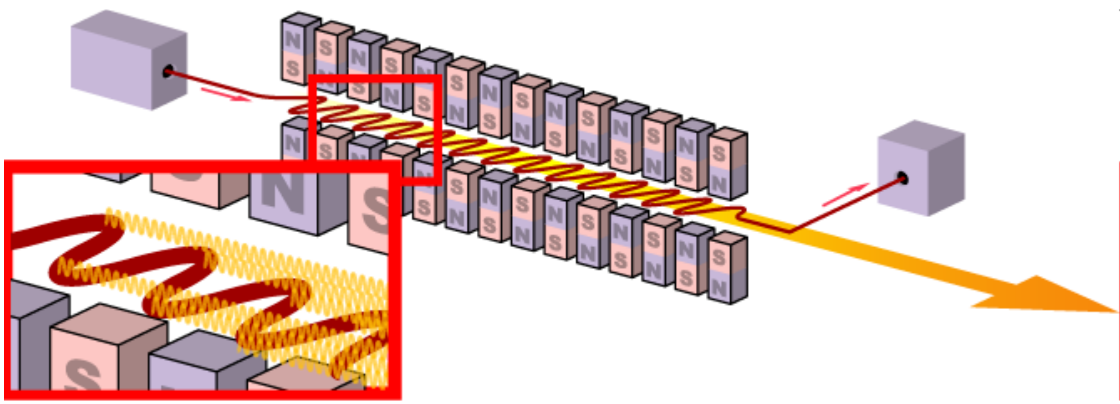
- Compact (5 GeV) short-wavelength (λ=1 Å), x-ray free-electron lasers require

$$\varepsilon_{x,y} \le \frac{1}{4\pi}\gamma\lambda$$

or $(\varepsilon_x, \varepsilon_y, \varepsilon_z) = (0.1, 0.1, 10)\ \mu m$

- An RF gun at Q=1 nC gives $(\varepsilon_x, \varepsilon_y, \varepsilon_z)$ = (1,1,0.1) μm

$$\Rightarrow \quad \Gamma = 0.1 \mu m^3$$

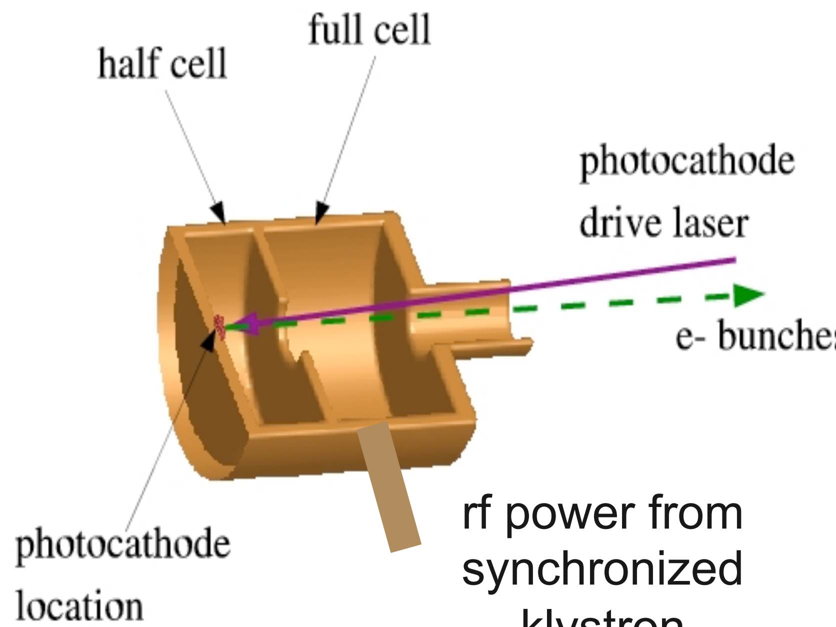


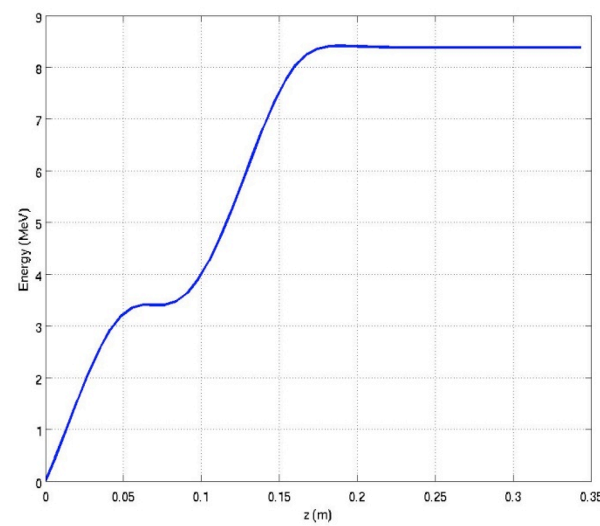
- Only x-ray FEL (LCLS at SLAC) so far operates at 25 GeV

Source of high-quality electron beams: the photoinjectors

- Principle of operation:
  - 1+1/2 cell cavity resonating on TM_{010},π mode
  - Laser illuminate photocathode on back plate
  - Laser synchronized with e.m. field

- Capabilities
  - e- beam is naturally bunch,
  - e- bunch shape controlled by laser parameters,
  - emittances, charge, size are variable





Beam dynamics simulations using Particle-in-Cell codes

- Beam is represented by ensemble of macroparticles.

External field

$$\frac{dP}{dt} = F_{ext} + F_{sc}$$

- To compute space charge force (F_{sc}) we use the quasi-static approach.

  1- Lorentz transformation to rest frame

  2- Deposit the charge on 2D or 3D grid

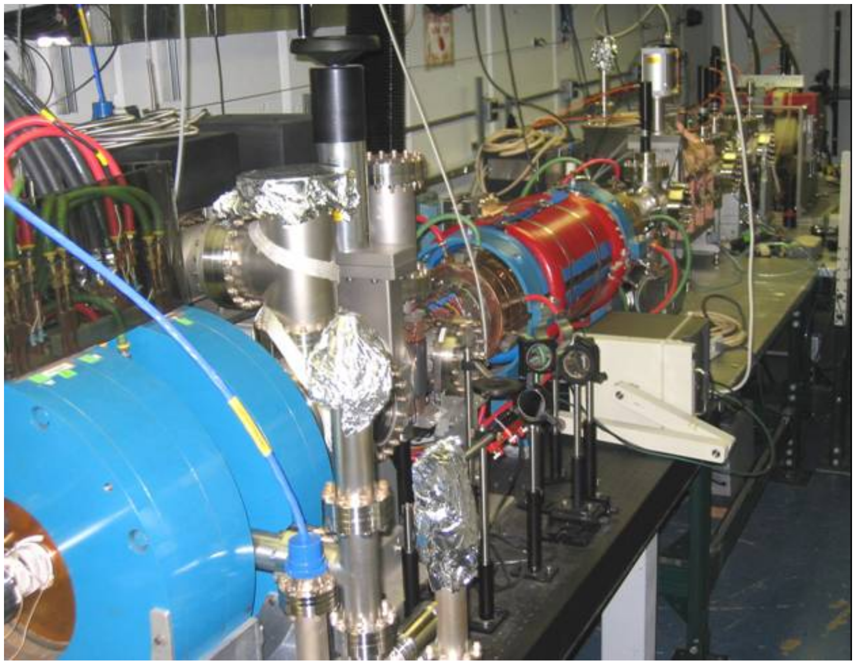
  3- Solve Poisson equation $\Rightarrow$ electric field.

  4- Inverse Lorentz transformation to Laboratory frame $\Rightarrow$ B and E fields.

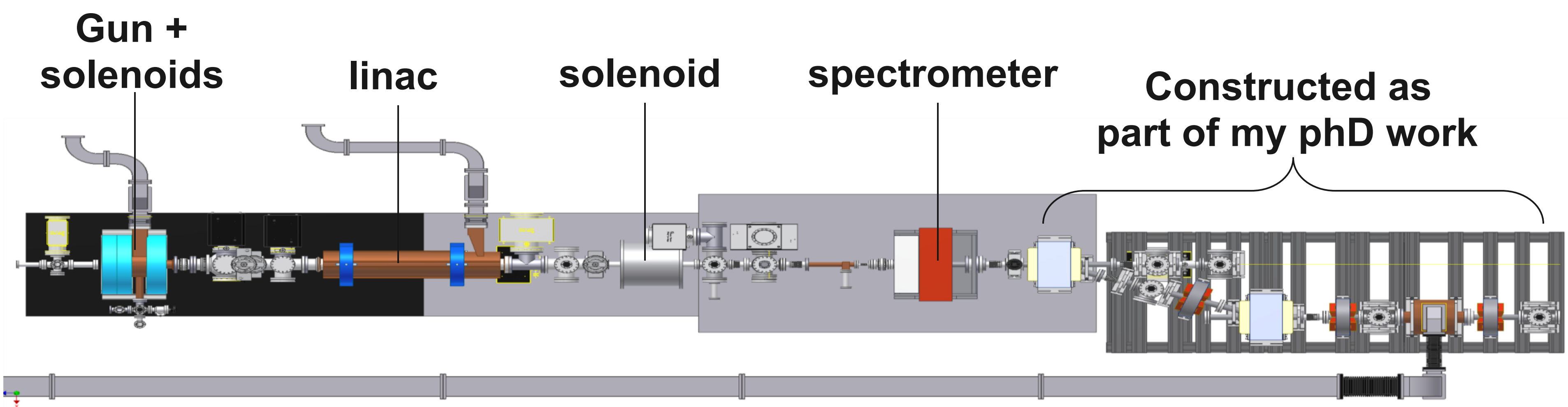
  5- Interpolate E and B field for each of the macro particle position

- ASTRA for 2D cylindrically symmetrical beam low number of macroparticles (between 2000 and 5000).
- IMPACT-T: a fully 3D tracking code, can be run on cluster computers allowing a large number of macroparticles (~ 200,000).

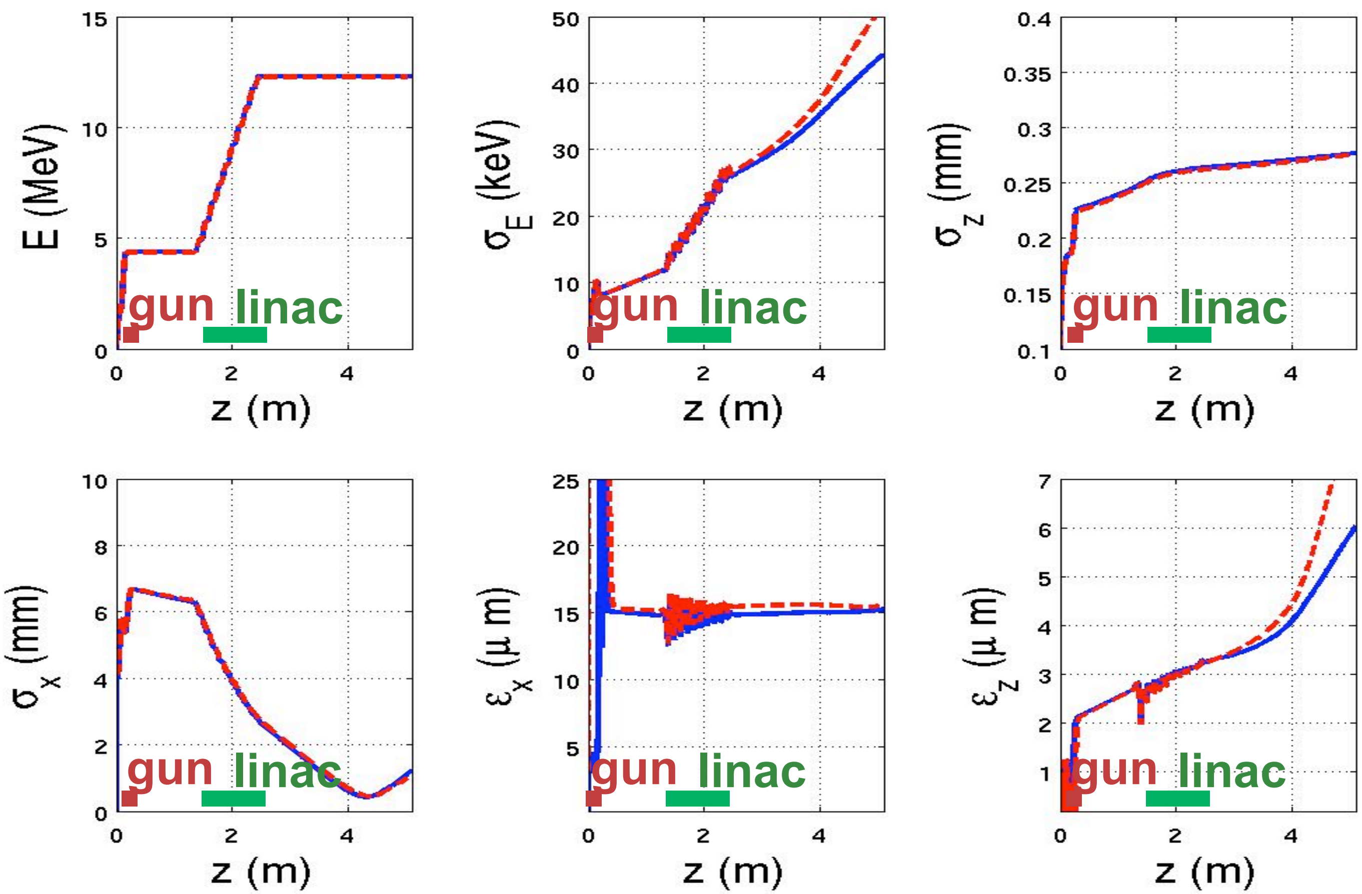
An example of high-brightness photoinjector
The Argonne Wakefield Accelerator (AWA)



- Support advanced accelerator science experiments
- Availability to external user (e.g. NIU)
- Chosen for its versatility
- Overview
  - 5-8 MeV rf gun
  - Linac with 8 MV accelerating voltage
  - Extensive diagnostics



Simulation of AWA nominal setup

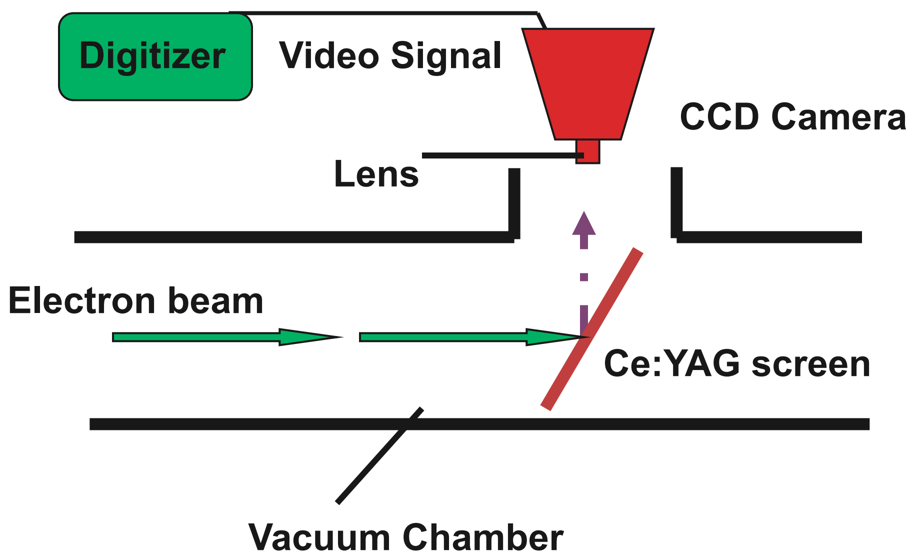


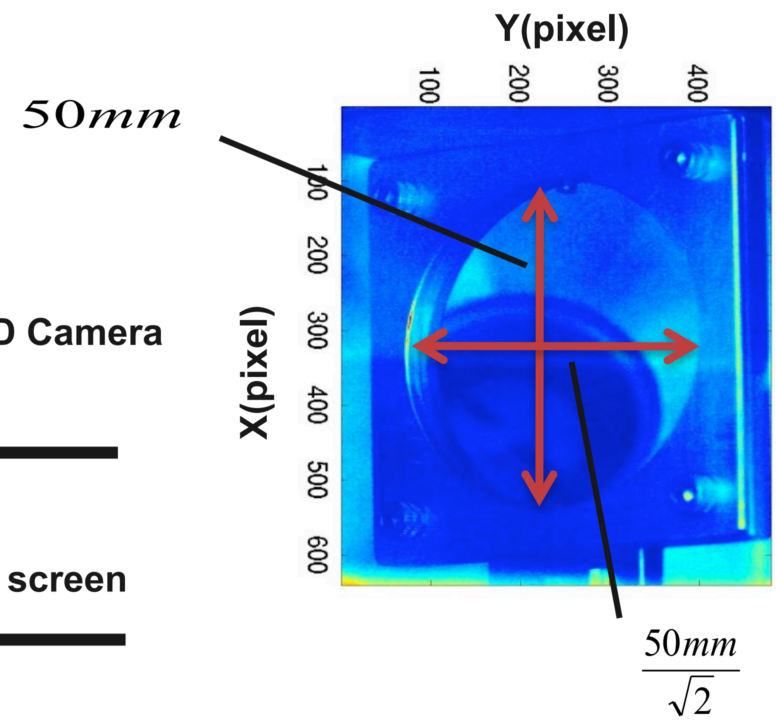
Astra (**blue**) VS Impact-T (**red**)

Q=1nC

Generic beam diagnostics at AWA

- Transverse beam density monitor

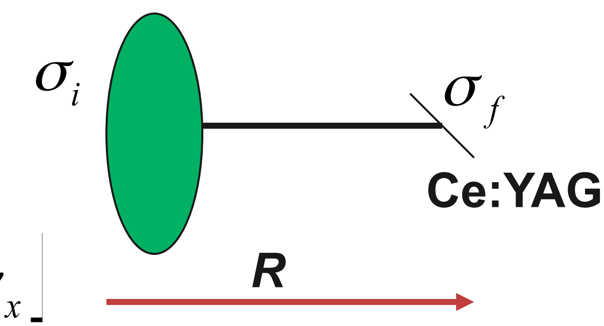




- Integrating Current Monitor: Measure beam charge
- Virtual Cathode: Get laser distribution on the photocathode

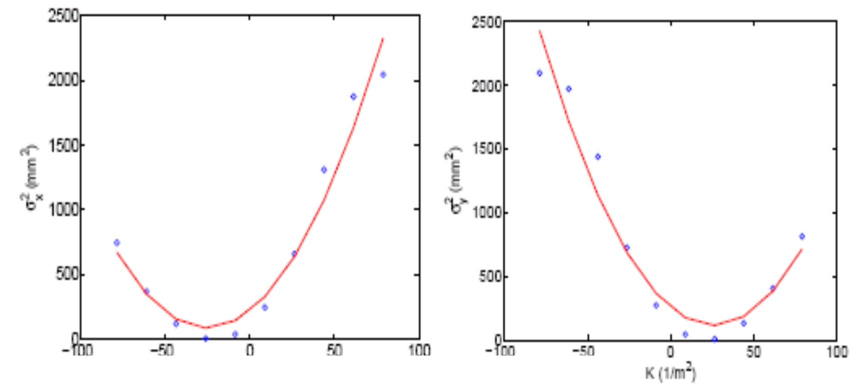
Generic beam diagnostics at AWA (cont)

- Quadruple Scan Measure emittance
  - Vary quadrupole
  - Measure spot size downstream

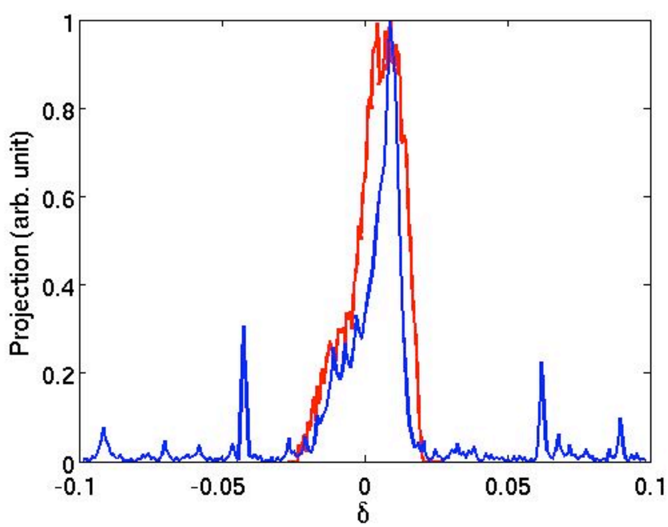


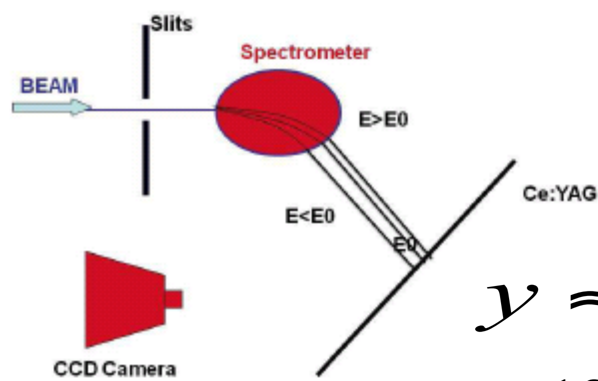
$$\sigma_f^2 = \tilde{\varepsilon}\left[R_{11}^2(k)\beta_x - 2R_{11}(k)R_{12}(k)\alpha_x + R_{12}^2(k)\gamma_x\right]$$

  - Simulated measurements retrieved 22.75/26.37 vs 23.18/25.55 μm



- Spectrometer: Measure beam energy





$$y \approx \eta \frac{\delta p}{p}$$

$$\eta = 18.4cm$$

“Multi-beam” control of electron beam

- Experiment reveals some interesting physics.
- Interaction of multiple beams can be used to shape/control the parameters of a “main” beam

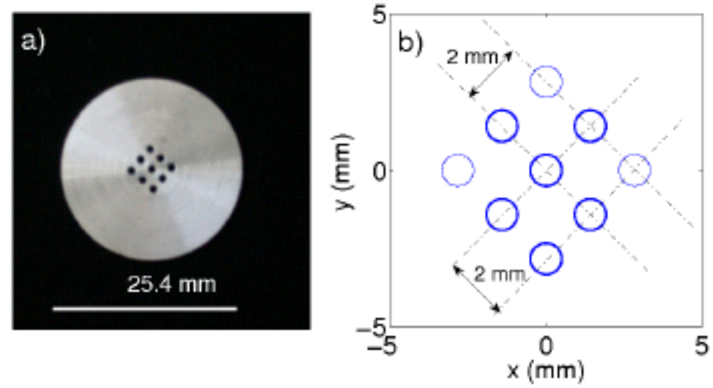
- Multibeams also provide intricate distribution for precisely benchmarking multi-particle simulation algorithms.

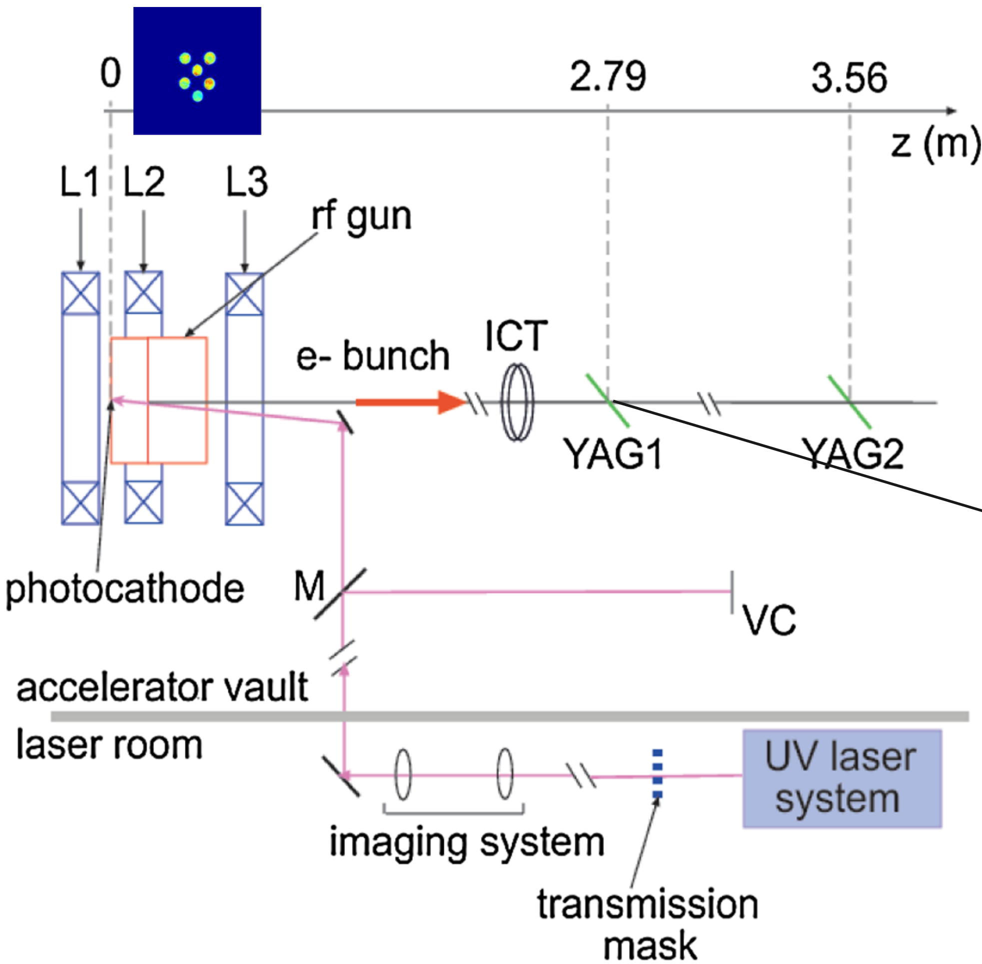
- Potential Applications
  - Beam focusing.
  - Multi-beam-based manipulation of a beam
  - Mimicking and optimizing field-array emitter patterns.

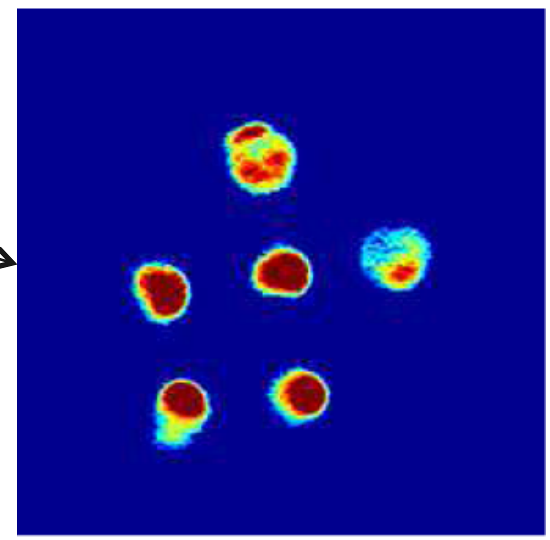
- Recent example:
  - Halo removal at Tevatron,
  - Electron lens at Tevatron.

How to generate a multi-beam electron bunch in a photoinjector?

- mask in the laser path ⇒ **generation of a multibeamlet distribution**



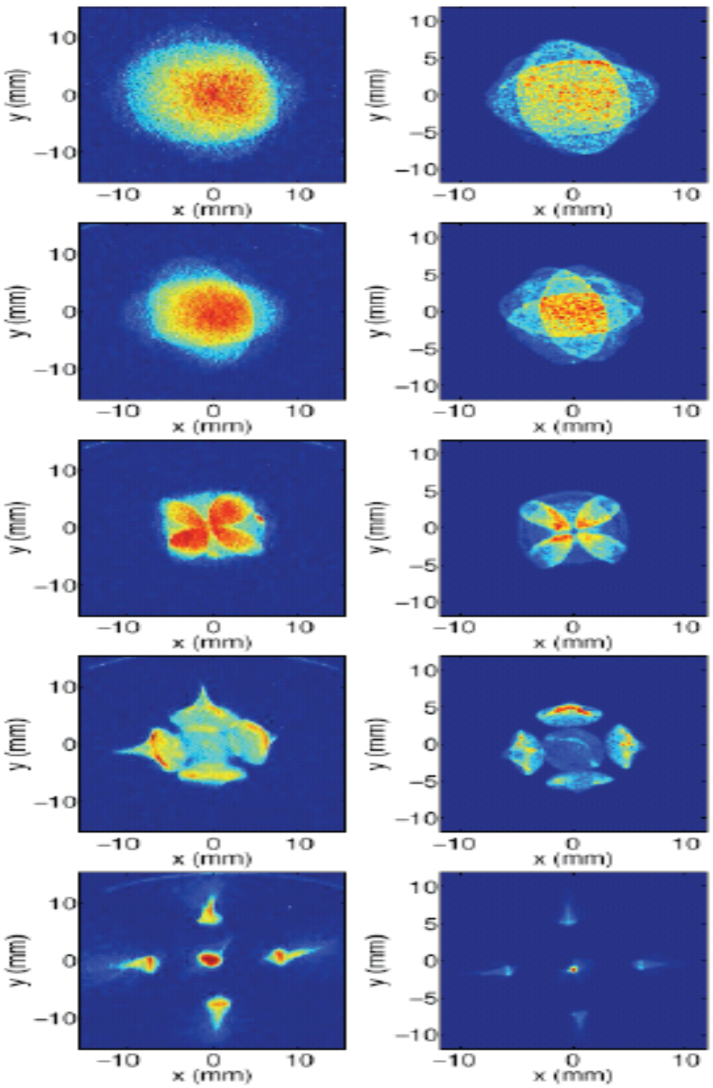




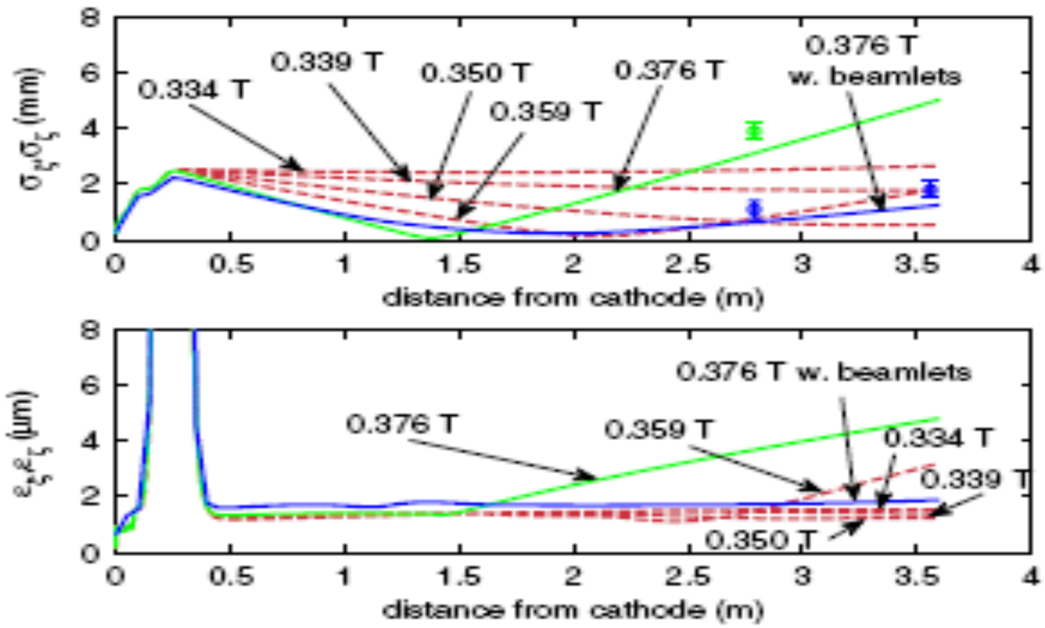
low charge 20 pC

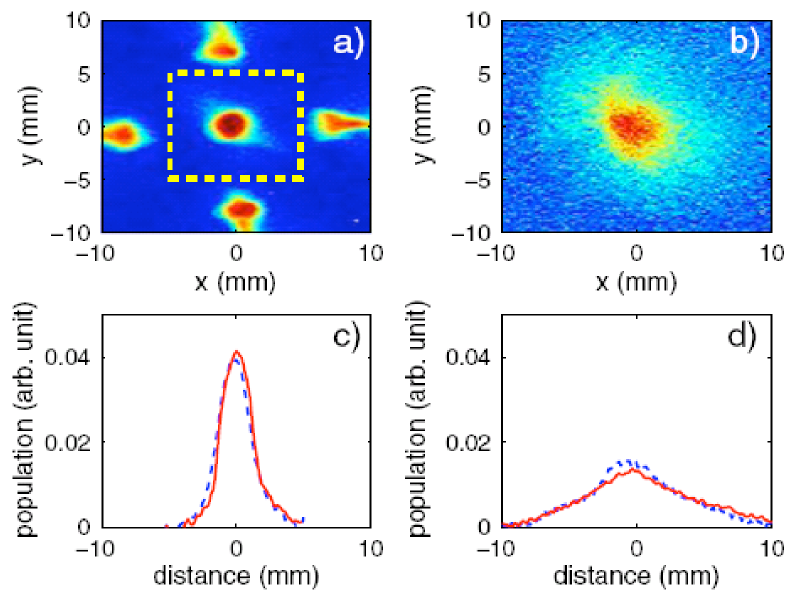
Comparison simulation/experiments

experiment **simulation**



Increasing B-field

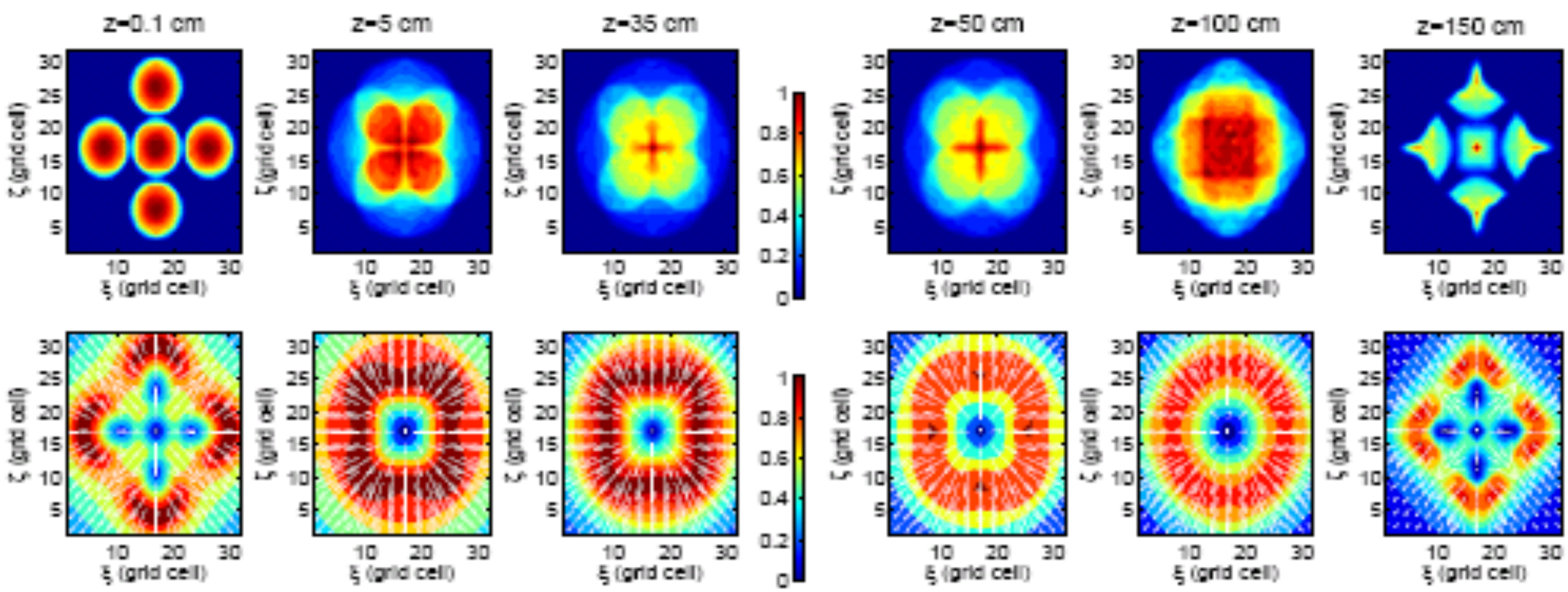




Q=1nC

Insights from simulations

- Lorentz force integrated over the longitudinal bunch distribution along beamline.
- Most of beam-beam interaction occurs within 5 cm from the cathode surface.



Emittance Exchange Concept

$$\sigma_f = M_{EX}\sigma_0 M_{EX}^T$$

Initial state → **EEX** → **Final State**

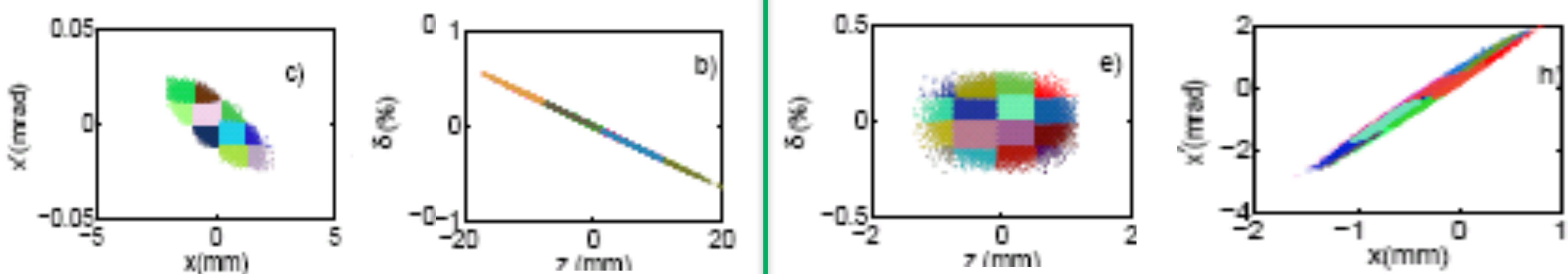
$$\boxed{M_{EX} = \begin{pmatrix} 0 & B \\ C & 0 \end{pmatrix}}$$

$$\sigma_0 = \begin{pmatrix} \varepsilon_{x0}T_{x0} & 0 \\ 0 & \varepsilon_{z0}T_{z0} \end{pmatrix} \qquad \sigma_f = \begin{pmatrix} \varepsilon_{z0}T_{z0}BB^T & 0 \\ 0 & \varepsilon_{x0}T_{x0}CC^T \end{pmatrix}$$

$$T_{u0} = \begin{pmatrix} \beta_{u0} & -\alpha_{u0} \\ -\alpha_{u0} & \gamma_{u0} \end{pmatrix}$$

$$\varepsilon_x^2 = \det(\sigma_{xx}) = \langle x^2\rangle\langle x'^2\rangle - \langle x'x\rangle^2$$
$$\varepsilon_z^2 = \det(\sigma_{z\delta}) = \langle z^2\rangle\langle \delta^2\rangle - \langle z\delta\rangle^2$$

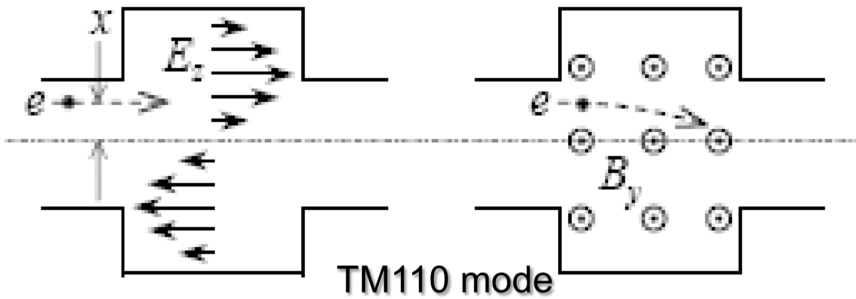
- Need M_{EX} ➔ $\varepsilon_{xf}=\varepsilon_{z0}$ & $\varepsilon_{zf}=\varepsilon_{x0}$

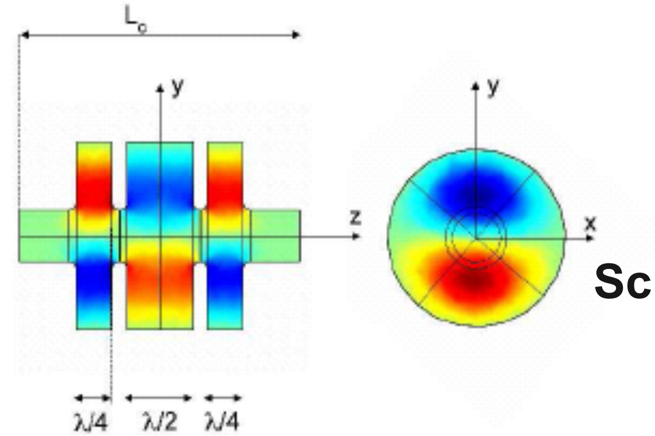


- Coordinates swap between transverse and longitudinal spaces.
- From now on, we use 4D notations

Deflector Cavity Design and modeling

- Key element in phase space exchange





- Field in a pillbox cylindrical cavity at zero-crossing

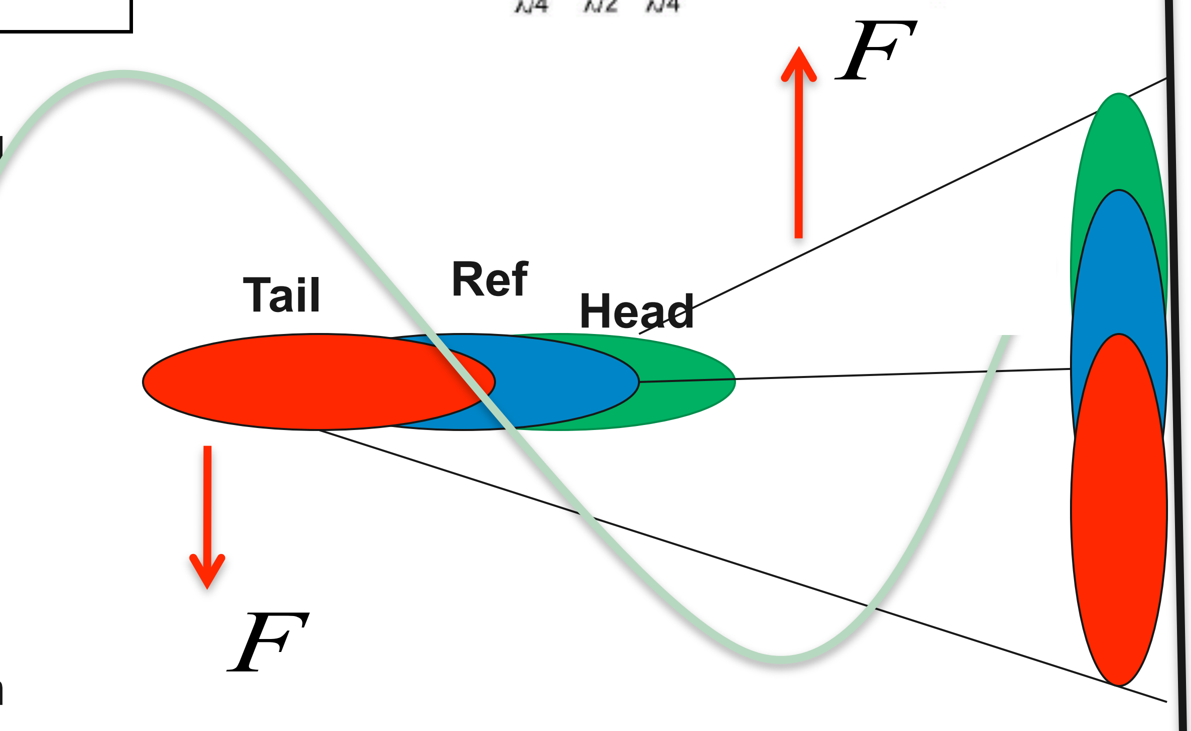
$$E_z = E_0 kxe^{-i\omega t} \approx E_0 kx$$

$$cB_y = iE_0 e^{-i\omega t} \approx E_0 kz$$

$$\delta = \kappa x \quad \Delta x' = \kappa z$$

- Cavity normalized strength

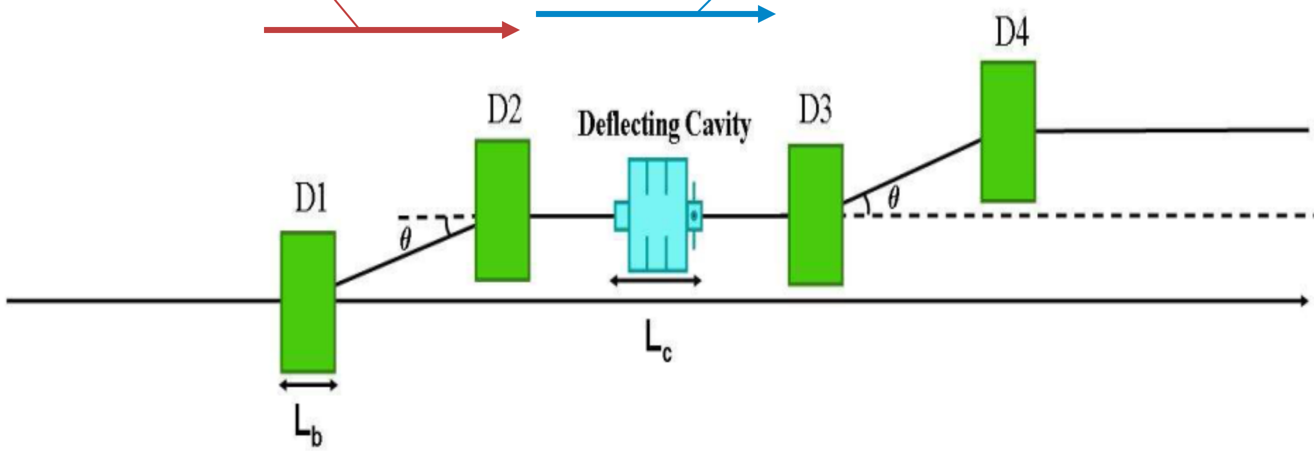
$$\kappa = \frac{2\pi e V_0}{\lambda E}$$



Phase space exchange theory

$$M_{DL} = \begin{bmatrix} 1 & L & 0 & \eta \\ 0 & 1 & 0 & 0 \\ 0 & \eta & 1 & \xi \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$M_{cav} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & \kappa & 0 \\ 0 & 0 & 1 & 0 \\ \kappa & 0 & 0 & 1 \end{bmatrix}$$



- Total transport matrix of the exchanger is

$$\begin{bmatrix} 1+\eta\kappa & 2L(1+\eta\kappa) & L\kappa & 2\eta+LR_{56}\kappa+\eta^2\kappa \\ 0 & 1+\eta\kappa & \kappa & R_{56}\kappa \\ R_{56}\kappa & 2\eta+LR_{56}\kappa+\eta^2\kappa & 1+\eta\kappa & 2R_{56}(1+\eta\kappa) \\ \kappa & L\kappa & 0 & 1+\eta\kappa \end{bmatrix} \xrightarrow{\boxed{\kappa = -\frac{1}{\eta}}} \begin{bmatrix} 0 & 0 & \frac{-L}{\eta} & \eta-\frac{L}{\eta}R_{56} \\ 0 & 0 & \frac{-1}{\eta} & \frac{-R_{56}}{\eta} \\ \frac{-R_{56}}{\eta} & \eta-\frac{L}{\eta}R_{56} & 0 & 0 \\ \frac{-1}{\eta} & \frac{-L}{\eta} & 0 & 0 \end{bmatrix},$$

Limitations for exact emittance exchange

- Exchanger matrix:

$$M = \begin{bmatrix} 0 & \frac{23\lambda}{128} & -\frac{128L+64L_c-23\lambda}{128\eta} & \eta - \frac{R_{56}(128L+64L_c-23\lambda)}{128\eta} \\ 0 & 0 & \frac{-1}{\eta} & -\frac{R_{56}}{\eta} \\ \frac{-R_{56}}{\eta} & \eta + \frac{R_{56}}{\eta}\left(\frac{23\lambda}{128} - L - \frac{L_c}{2}\right) & \frac{23R_{56}\lambda}{128\eta^2} & \frac{23R_{56}{}^2\lambda}{128\eta^2} \\ \frac{-1}{\eta} & -\frac{128L+64L_c-23\lambda}{128\eta} & \frac{23\lambda}{128\eta^2} & \frac{23R_{56}\lambda}{128\eta^2} \end{bmatrix}$$

- Emittance not perfectly exchanged

$$\varepsilon_x{}^2 = \varepsilon_{z0}{}^2 + \boxed{\Lambda^2}\varepsilon_{x0}\varepsilon_{z0}$$

$$\varepsilon_z{}^2 = \varepsilon_{x0}{}^2 + \boxed{\Lambda^2}\varepsilon_{x0}\varepsilon_{z0}$$

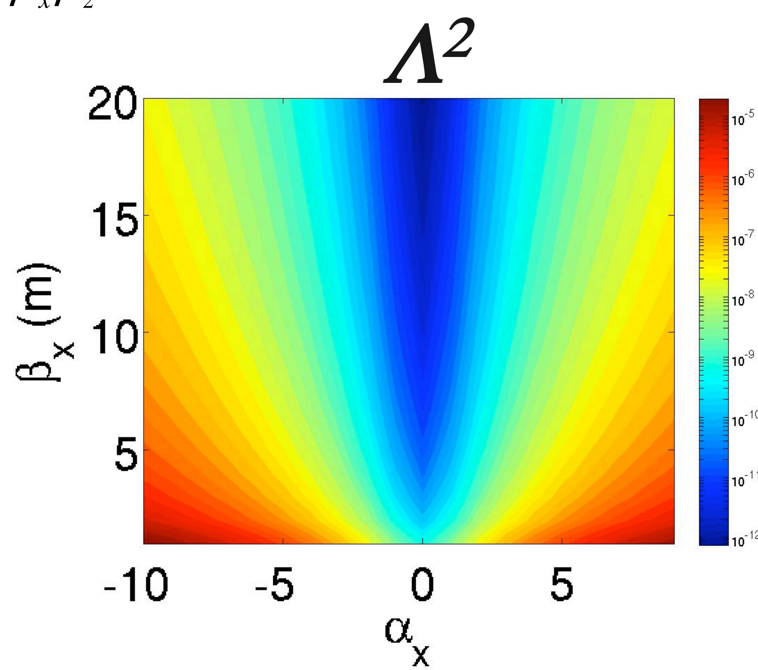
$$\Lambda^2 = \frac{529\lambda_c{}^2(1+\alpha_x{}^2)}{16384\eta^2\beta_x\beta_z}\left(R_{56}{}^2(1+\alpha_z{}^2) - 2R_{56}\alpha_z\beta_z + \beta_z{}^2\right)$$

- Coupling Terms, can minimized with respect to chirp:

$$\Lambda^2 = \frac{529\lambda_c{}^2 R_{56}{}^2(1+\alpha_x{}^2)}{16384\eta^2\beta_x\beta_z} \quad \text{for} \quad \alpha_z \equiv -\frac{\langle z\delta\rangle}{\varepsilon_z}$$

Dispersion

Deflecting Cavity wavelength



- We need a quadrupole magnets upstream of the exchanger

Limitations for exact emittance exchange

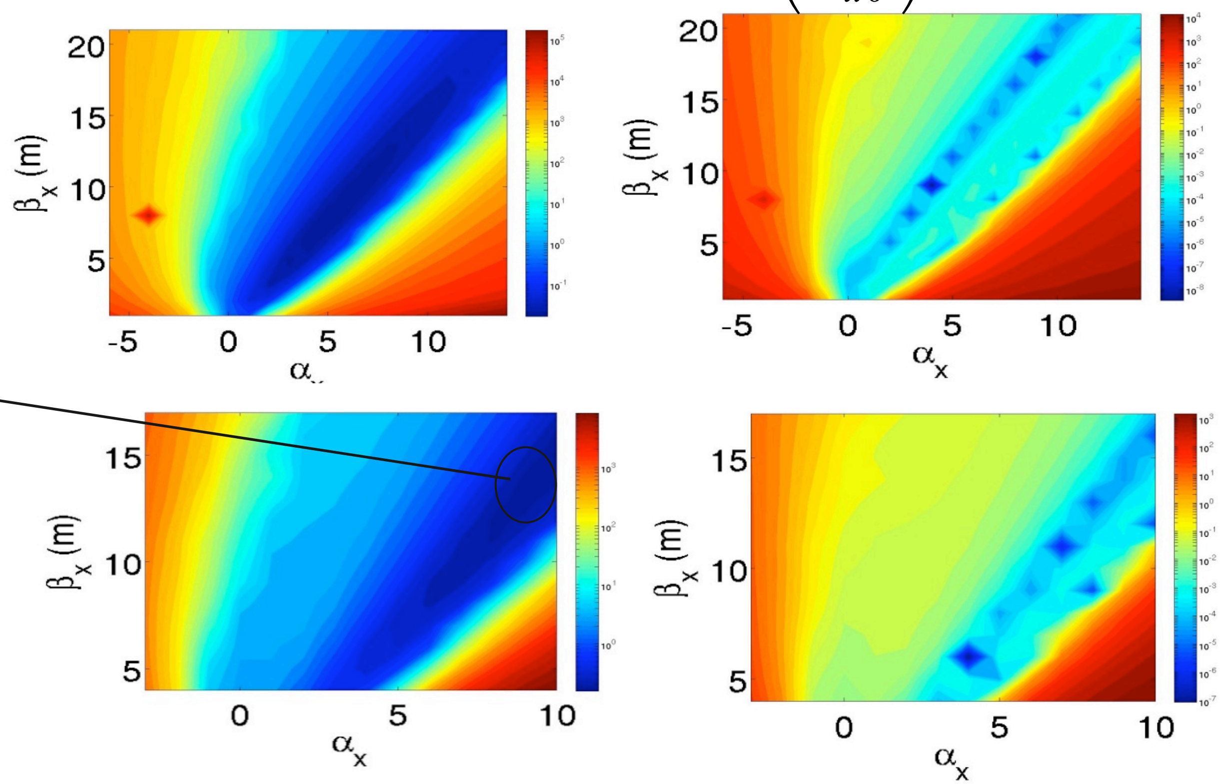
- Real particle distribution with incoming emittance (e_x,e_z) = (15.9,3.75)mm

$$\Delta_x = \left(\frac{\varepsilon_x}{\varepsilon_{z0}}\right) - 1 \qquad \Delta_z = \left(\frac{\varepsilon_z}{\varepsilon_{x0}}\right) - 1$$

No space charge

Choose this region

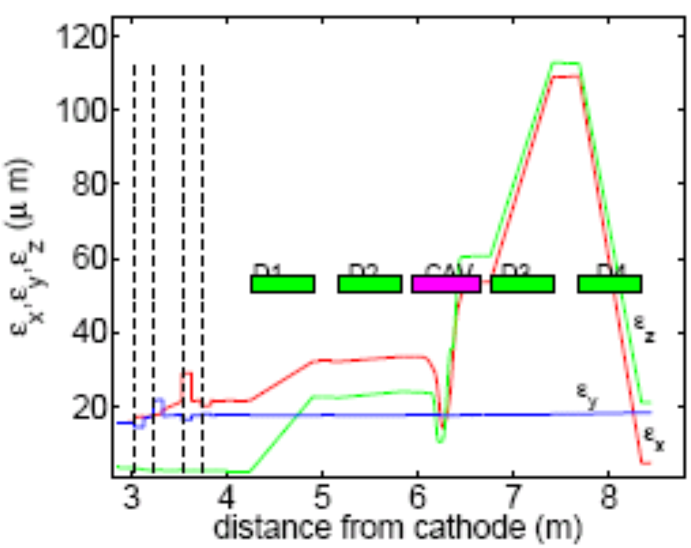
Q = 100pC

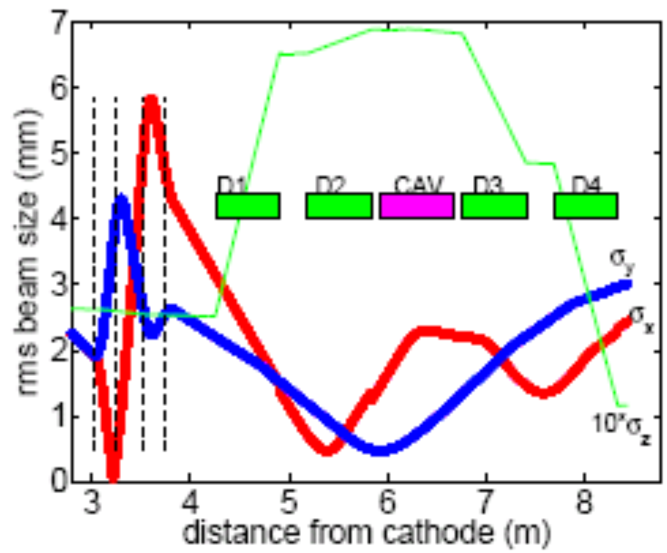


- Space charge does not prevent the minimization of emittance dilution

Investigation of emittance exchange via start-to-end simulation of AWA

- Cathode to exchanger entrance modeled with ASTRA output passed to IMPACT-T for simulation of exchanger beamline





- Optimized C-S parameters (space charge on)

$$\alpha_x = 10.2; \beta_x = 13.54\,\mathrm{m}$$

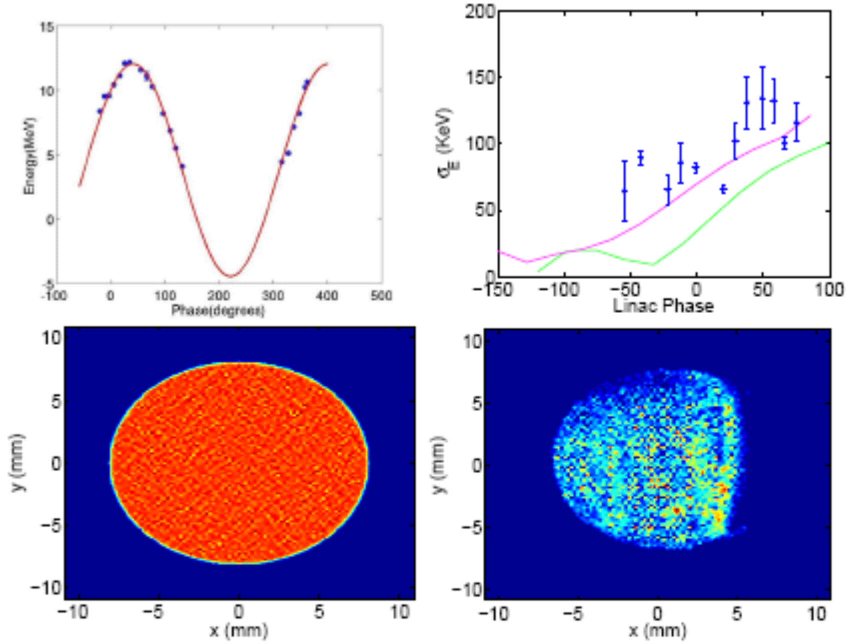
- Summary of emittance dilutions

Space Charge	$\epsilon_{xi}(\mu m)$	$\epsilon_{zi}(\mu m)$	$\epsilon_{xf}(\mu m)$	$\epsilon_{zf}(\mu m)$	$\Delta_x(\%)$	$\Delta_z(\%)$
OFF	22.30	2.90	4.4	22.67	51%	16%
ON	21.58	2.54	4.7	20.90	85%	−4%

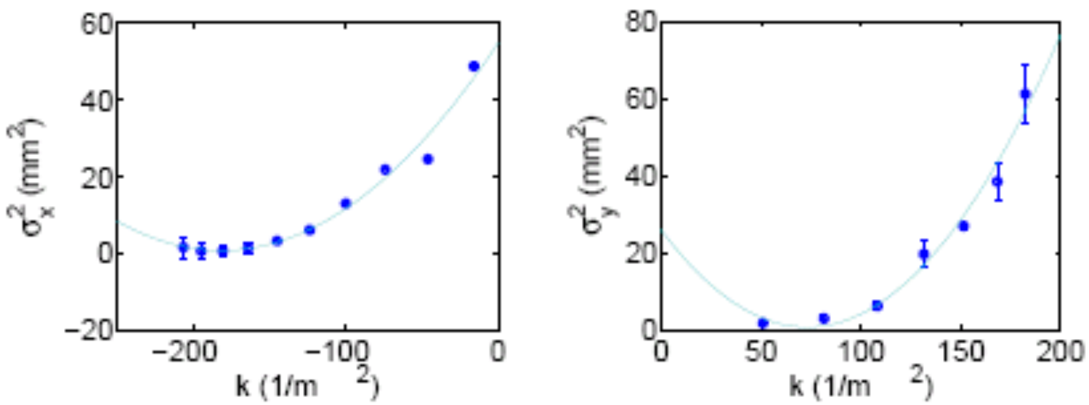
Measured initial emittance partition

Symbol (unit)	ASTRA	Experiment
Q (pC)	100	100 ± 10
laser σ_t (ps)	1.95	1.85 ± 0.2
rms laser size (mm)	4.0	4.0
gun field (MV/m)	43.92	47 ± 2
gun phase (deg.)	65	60 ± 5
booster field (MV/m)	15.75	15.5 ± 1
booster phase (deg.)	50.35	52 ± 4
L1 peak B-field (T)	0.062	0.0618 ± 0.0031
L2 peak B-field (T)	-0.062	-0.0626 ± 0.003
L3 peak B-field (T)	-0.228	-0.228 ± 0.0114
ε_x (μm)	19.5	18.5 ± 2
ε_y (μm)	19.5	16.2 ± 2
ε_z (μm)	7.40	-

Longitudinal emittance is inferred from the energy spread measurement~8mm



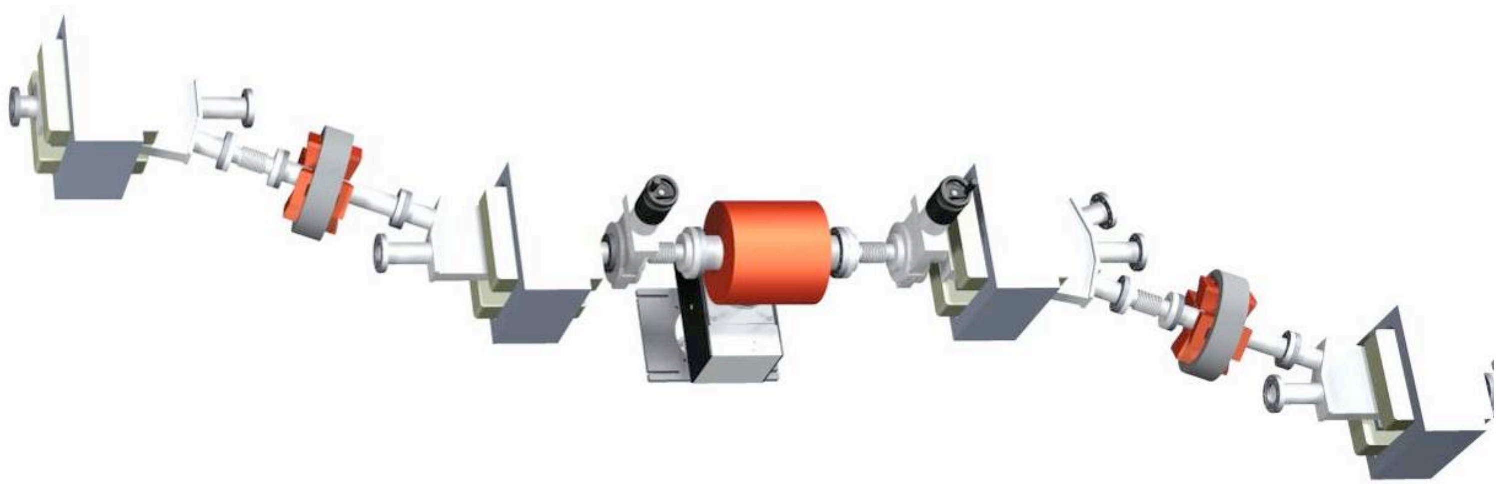
Transverse emittance measured using Quadrupole scan technique



Phase space exchange: experimental plans

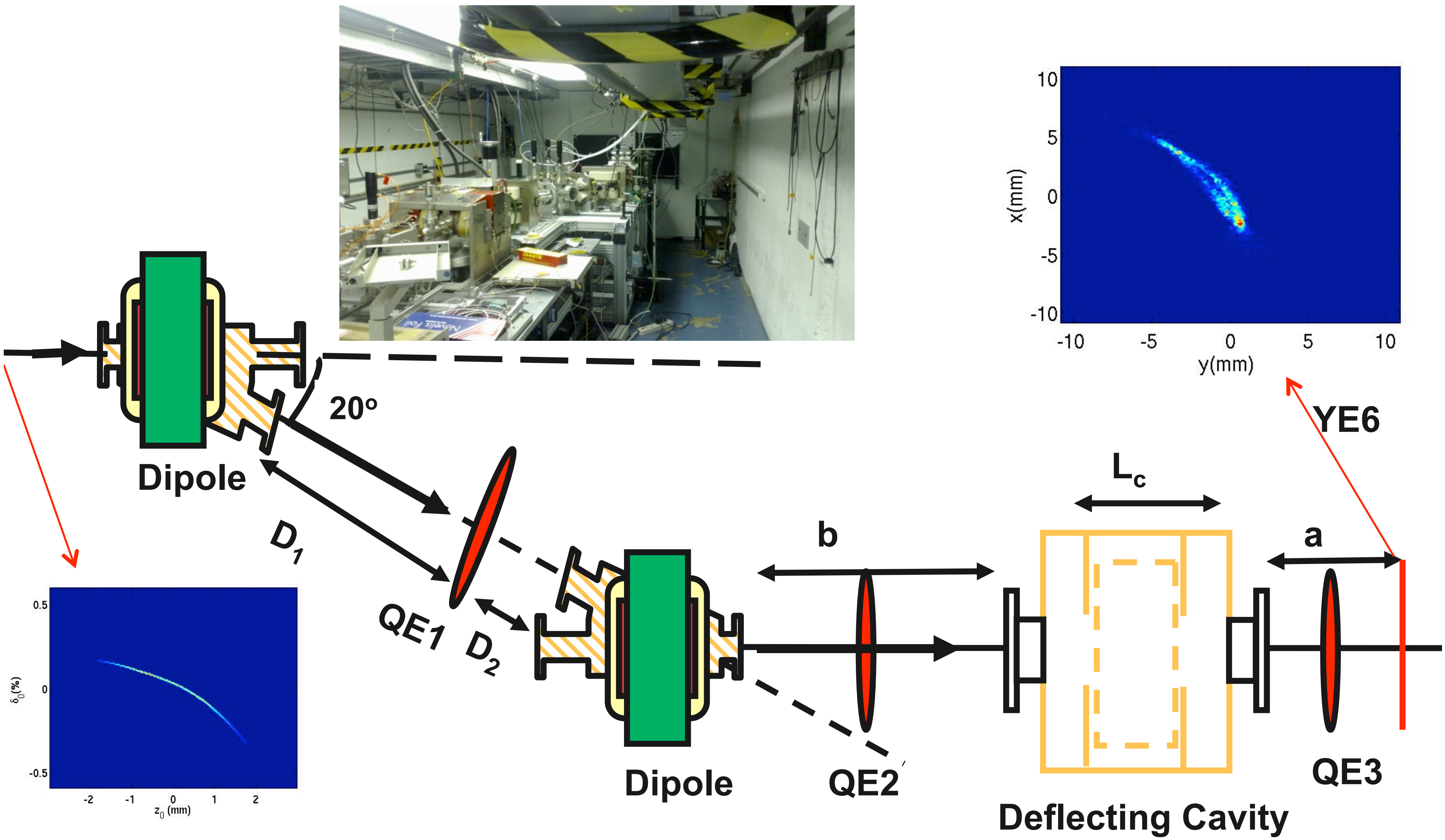
- AWA can achieved an interesting emittance partition $\varepsilon_z < \varepsilon_x$

- Next step was to design and construct a phase space exchange beamline
  - Not possible due to space and time constraints.
  - Construct simpler beamline to commission the hardware especially the deflecting cavity
  - **Configure the beamline for other purpose: a single-shot longitudinal phase space diagnostics**

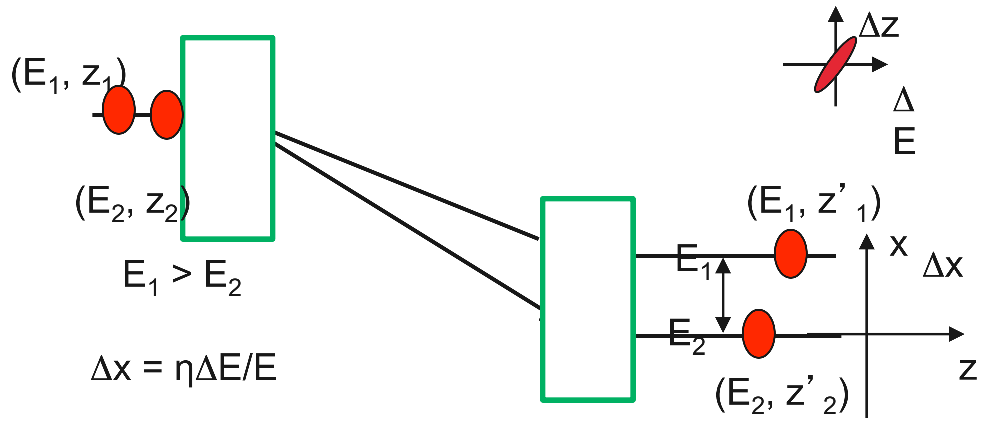


Single-shot longitudinal phase space measurement

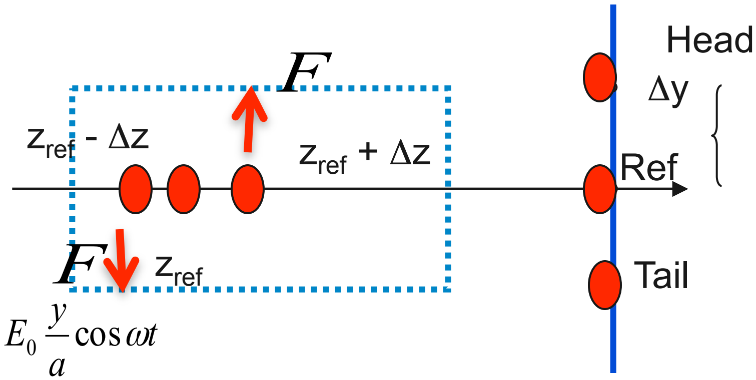
- Map initial (*z, d) longitudinal phase space to the* transverse plane (*x,y)*



Theoretical background



$\Delta x = \eta \Delta E/E$



$$E_z = E_0 \frac{y}{a} \cos \omega t$$

Typically ΔE/E = a few mrad $\Longrightarrow$ Δx = a few mm's

$$B_x = \frac{E_0}{\omega a} \sin \omega t \Longrightarrow F_y \neq 0 \Longrightarrow \Delta y = \kappa \cdot \Delta z$$

$\Delta z \approx R_{56} \Delta E/E$ $\qquad$ $\Delta z \equiv (z_2' - z_1') - (z_2 - z_1)$

To preserve the relative distance between particles $\Longrightarrow$ $\Delta z = 0$ $\Longrightarrow$ $R_{56} = 0$ $\Longrightarrow$ *QE1 inserted between dipoles*

Higher order terms

Determine the resolution

- Goal to map longitudinal phase space to screen

$$\left.\begin{aligned} x &= \eta\delta_0 + h_x \\ y &= \kappa z_0 + h_y + \cancel{R_{56}}^{=0}\delta_0\kappa \end{aligned}\right\} \varepsilon_z^{\,2} = \left(\frac{\beta\gamma}{\eta\kappa}\right)^2 \left(\langle x^2\rangle\langle y^2\rangle - \langle xy\rangle^2 + H_{xy}\right)$$

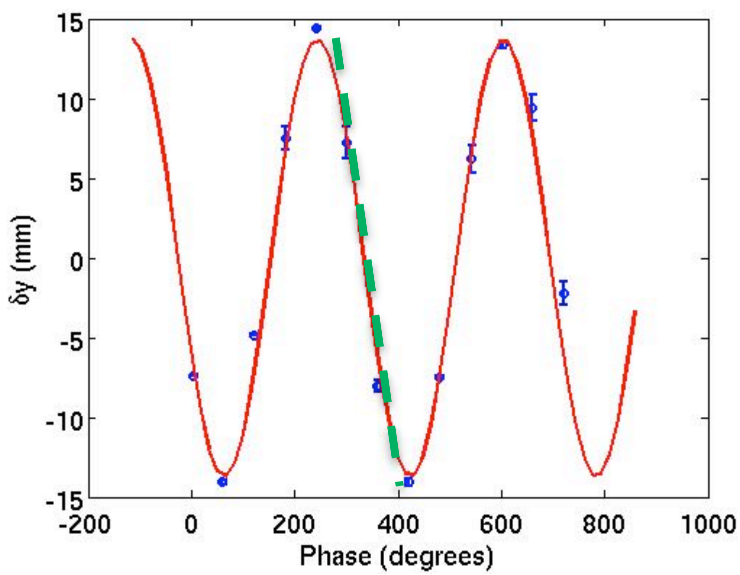
$$\beta = \left(1 - \frac{1}{\gamma^2}\right)^{1/2}$$

$$H_{xy} = h_x^{\,2}\langle x^2\rangle + h_y^{\,2}\langle y^2\rangle - 2h_x h_y \langle xy\rangle$$

Commissioning of the deflecting cavity

- Developed beam-based calibration procedure to determine cavity deflecting strength

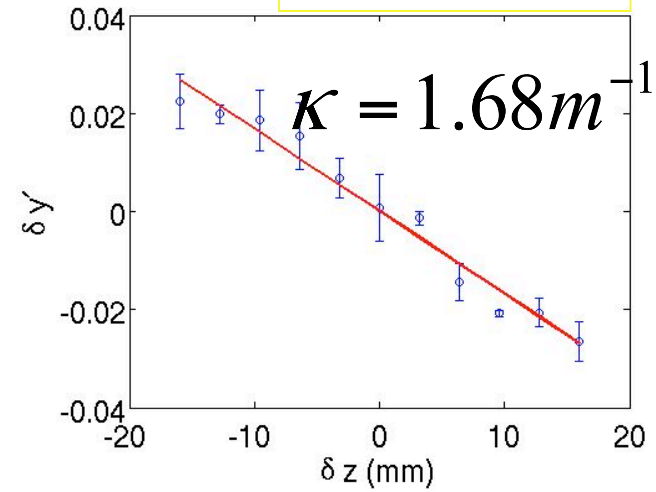
Vertical displacement on screen versus phase of TDC



$$\delta y = 13.75\sin(\varphi - 153.1) + 0.47$$

Calibration procedure for TDC strength

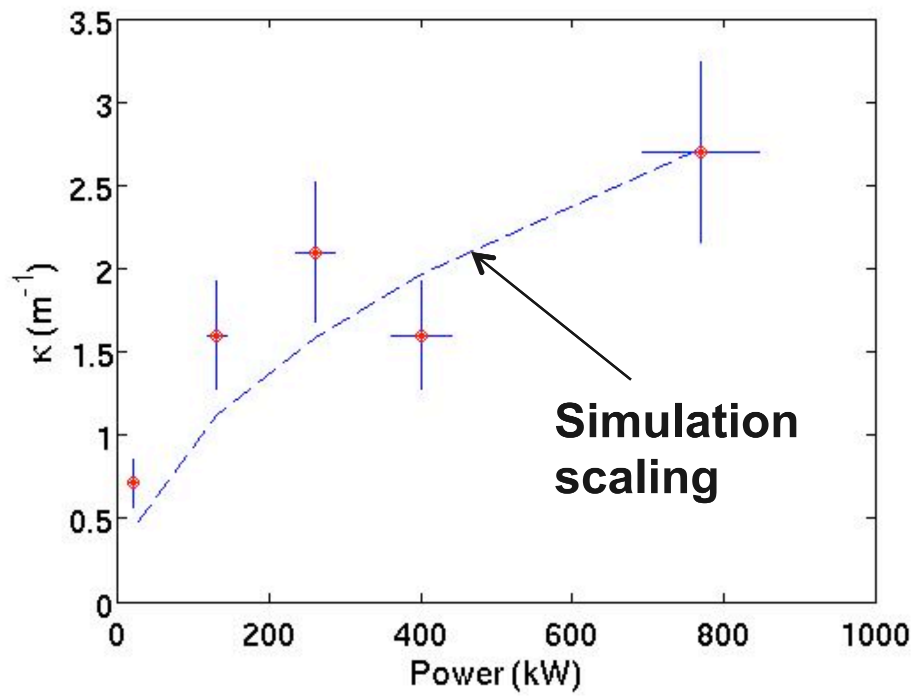
P= 40 kW

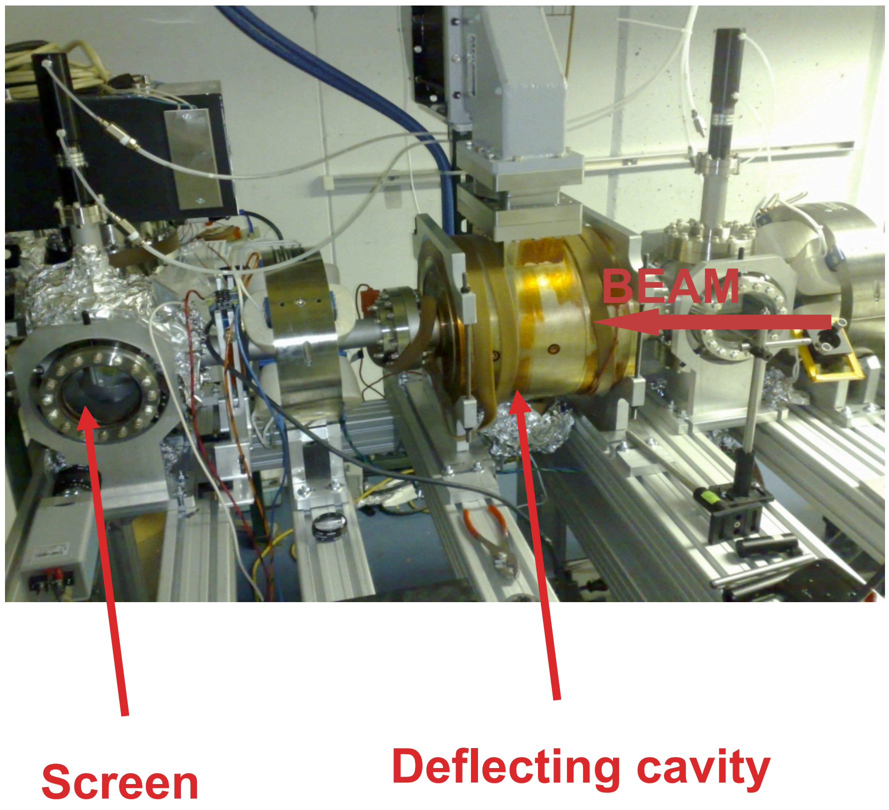


$$\delta z = \Delta\phi\left(\frac{230}{360}\right)$$

Commissioning of the deflecting cavity (cont)

- Measured deflecting k as a function of input power is in good agreement with numerical simulations.
- The cavity was operated up to 800 kW but conditioned to its nominal 2.3 MW power without problem.

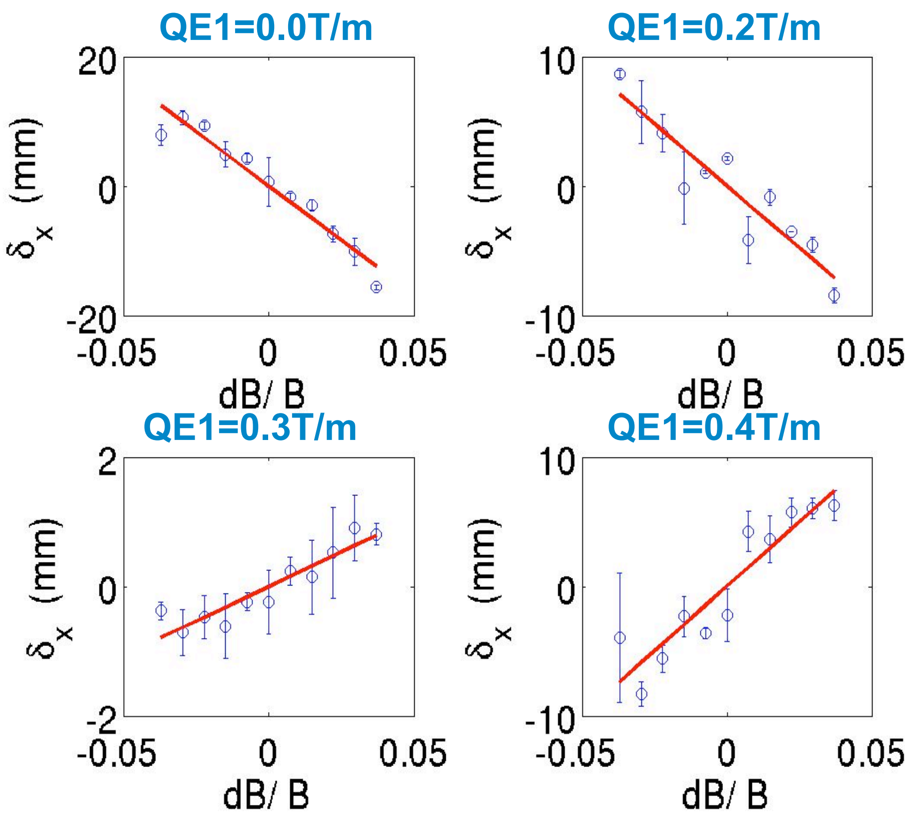




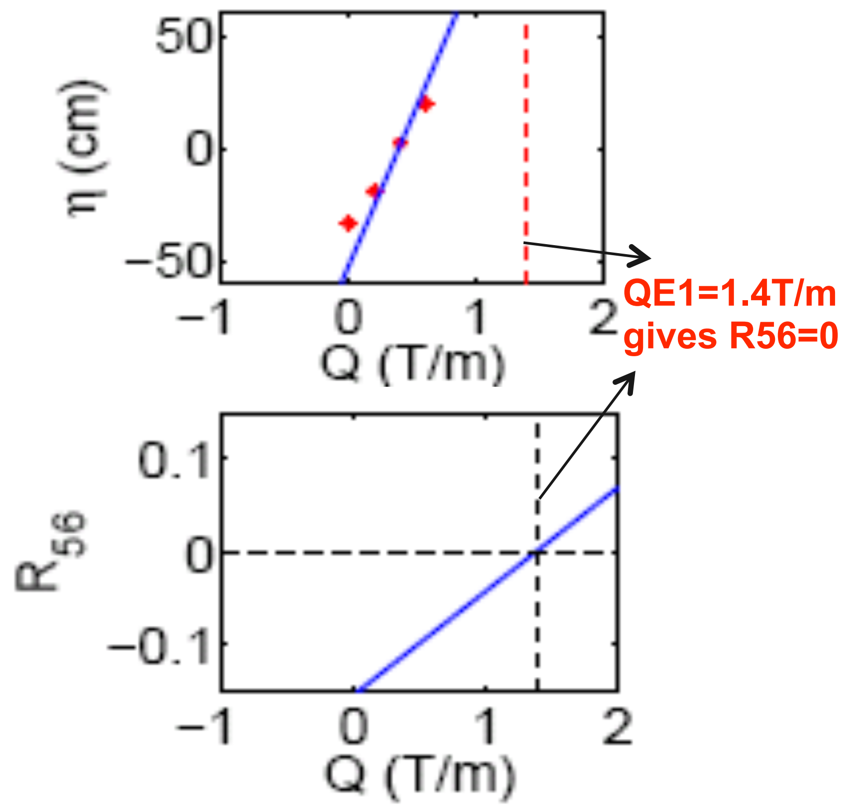
Dispersion measurements

- Beam Based measurement of dispersion is used in order to indirectly tune the R56

Dispersion measurement at YE6 for different QE1 strength

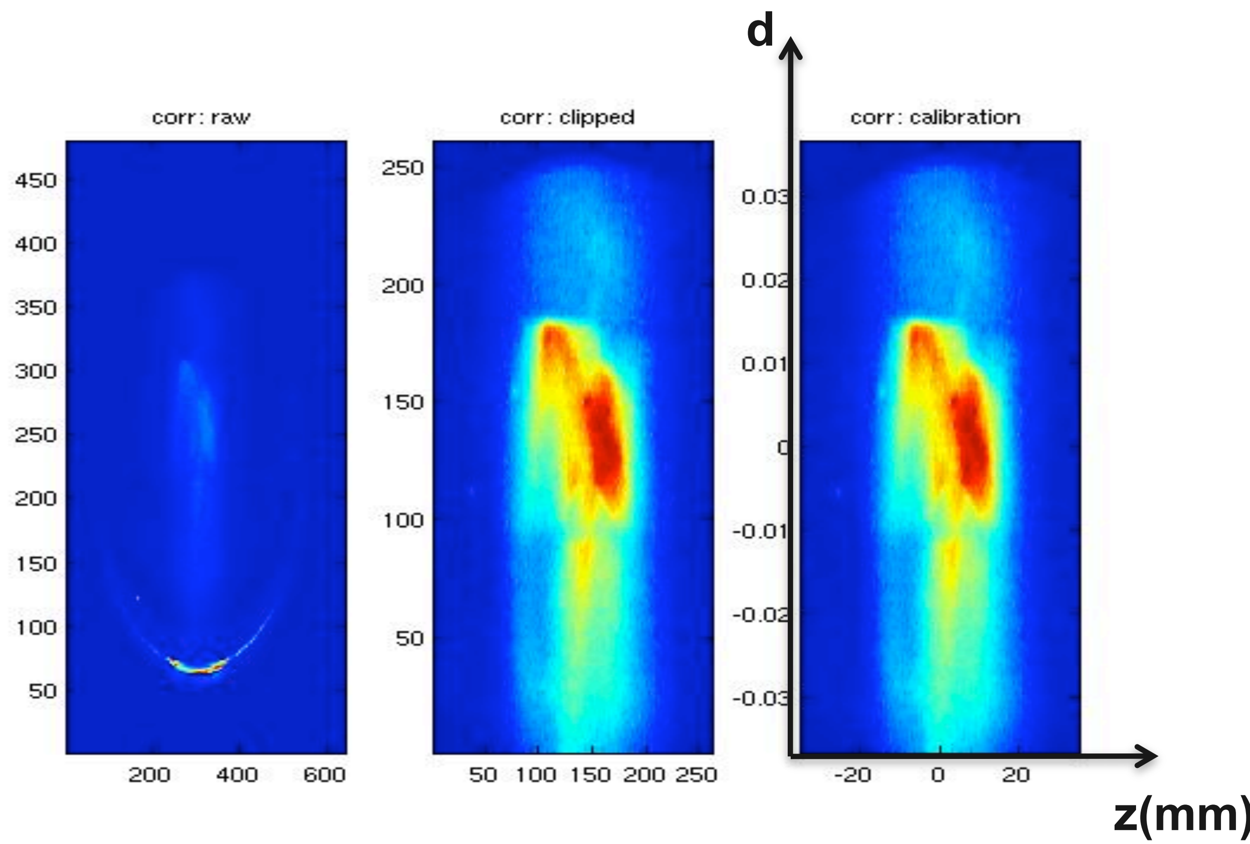


Dispersion versus QE1 strength



Single shot measurement of the LPS

- Using calibration procedure, we can convert the configuration space coordinates into longitudinal coordinate and fractional momentum spread.



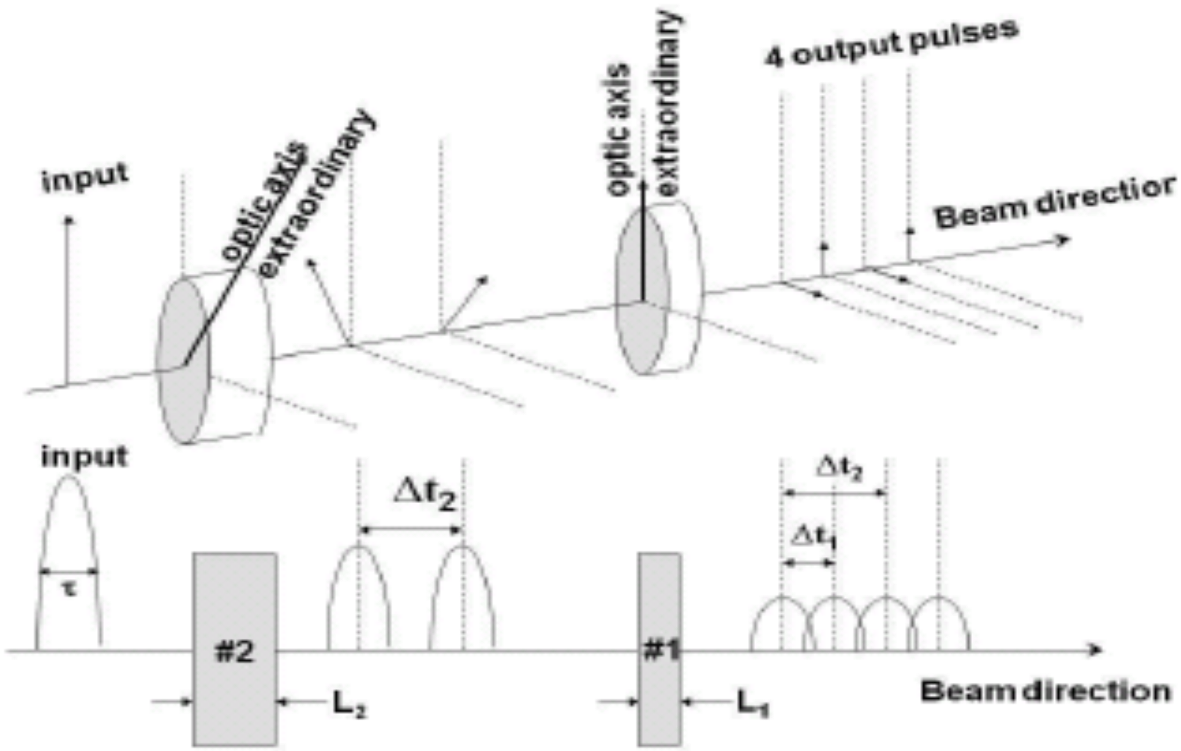
Q=1.5nC
E =14.6 MeV

$$\eta = 0.4m$$

$$\kappa = 1.7m^{-1}$$

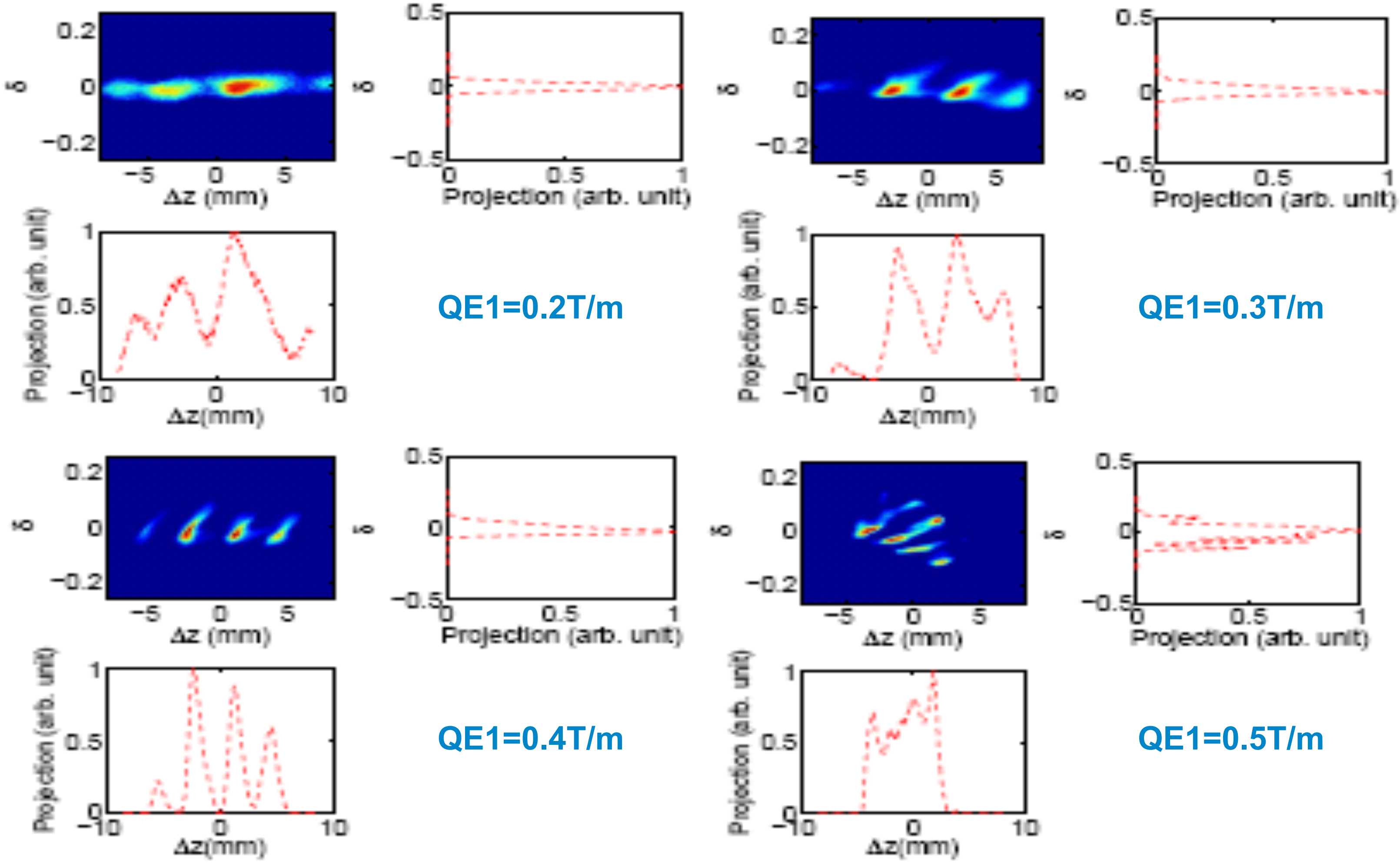
Generation of train of bunches

- Generate bunch with tunable spacing. 4 pulses generated using a-BBO crystal .



Generation of train of bunches measurement

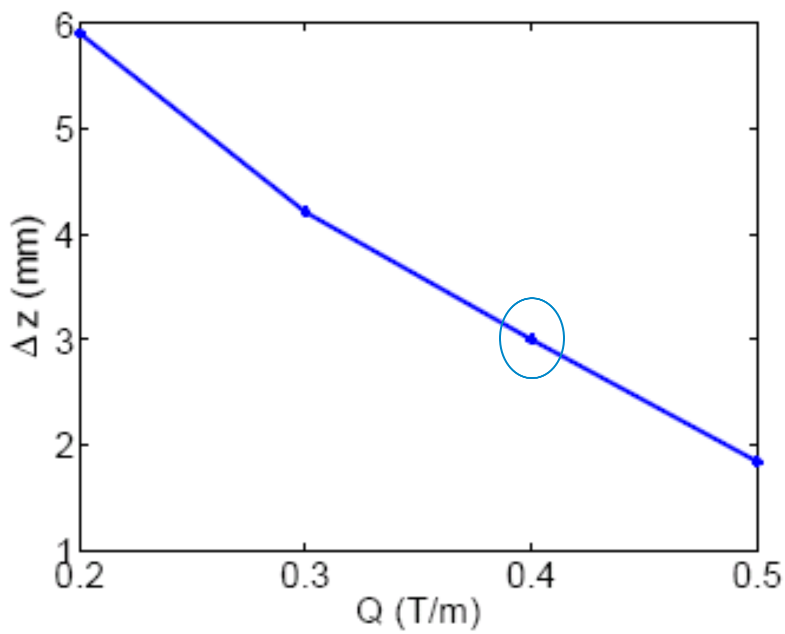
- Evolution of the longitudinal phase space associated to a train of four bunches as a function of the quadrupole QE1.



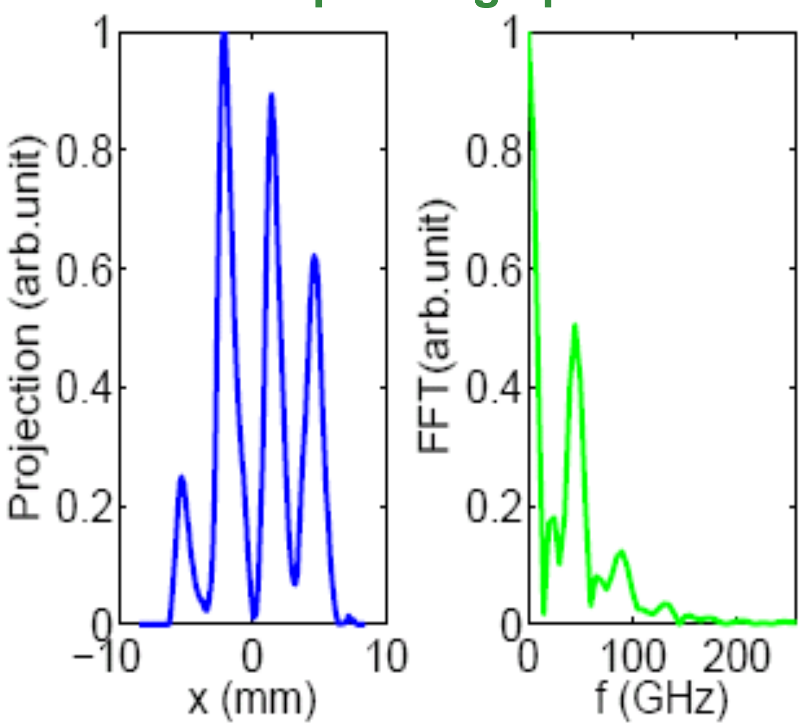
Generation of train of bunches: applications

- Resonant excitation wakefield in dielectric-loaded waveguides
- Production of narrow-band radiation in the Terahertz (THz) regime

z-spacing vs. quadrupole strength



Modulated distribution and corresponding spectrum



Summary of achievement and future plans

- Advanced beam controls in a photoinjector:
  - Developed and tested a technique to use a multi-beam arrangement to control the beam properties via “multi-beam” interaction.
- Emittance Exchange:
  - Designed a emittance exchanger beamline and explore limiting effects,
  - *Installed and commissioned key components of the exchanger*
  - *Verified initial emittance partitions of AWA*
- Longitudinal phase space diagnostics:
  - Designed, build a single-shot longitudinal phase space diagnostics
  - Use the beamline to produce a train of ps electron bunches
- Future Plans:
  - Developed longitudinal phase space diagnostics to
    - *Explore velocity bunching in photoinjector*
    - *Beam dynamic in beam-driven wakefield accelerators*
  - Designed exchanger beamline will be installed at AWA
    - *Current shaping for enhancing performance of beam-drive wakefield acceleration*

Thank you

List of publications published or submitted

- P. Piot, Y. E. Sun, J. G. Power and M. Rihaoui, “**Generation of Relativistic Electron Bunches with Arbitrary Current Distribution via Transverse-to-Longitudinal Phase Space Exchange**”. *Phys. Rev. ST Accel. Beams 14, 022801 (2009) (2011)*
- M. Rihaoui, P. Piot, J.G. Power, W. Gai, “**Verification of the AWA photoinjector beam parameters required for a transverse-to-longitudinal emittance exchange experiment**”. *In the Proceeding of Particle Accelerator Conference (PAC’09), Vancouver, Canada (May 2009)*
- M. Rihaoui, P. Piot, J.G. Power, W. Gai, “**Limiting Effects in the Transverse-to-Longitudinal Emittance Exchange for Low Energy Relativistic Electron Beams**”. *Proceeding of Particle Accelerator Conference (PAC’09), Vancouver, Canada (May 2009)*
- M. Rihaoui, W. Gai, P.Piot, J.G. Power, Z.Yusof, “**Measurement and Simulation of Space Charge Effects in a Multi-Beam Electron Bunch from an RF Photoinjector**”. *Proceeding of Particle Accelerator Conference (PAC’09), Vancouver, Canada (May 2009)*

List of publications published or submitted

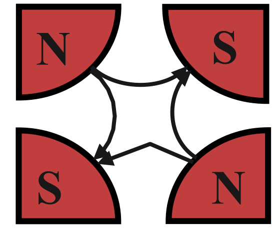
- P. Piot, V. Demir, T. Maxwell, M. Rihaoui, J.G. Power, C. Jing, Longitudinal Beam "**Diagnostics for the ILC Injectors and Bunch Compressors**". *Proceeding of Particle Accelerator Conference (PAC'09), Vancouver, Canada (May 2009)*
- M. Rihaoui, P. Piot, J. G. Power, Z. Yusof and W. Gai, "**Observation And Simulation Of Space- Charge Effects In A Radio-Frequency Photoinjector Using A Transverse Multi-Beamlet Distribution**". *Phys. Rev. ST Accel. Beams 12, 124201 (2009)*
- M. Rihaoui, W. Gai, K. J. Kim, P. Piot, J. G. Power and Y. E. Sun, "**Beam Dynamics Simulations Of The Transverse-To-Longitudinal Emittance Exchange Proof-Of-Principle Experiment At The Argonne Wakefield Accelerator**". *AIP Conf. Proc. 1086, 279 (2009)*
- P. Piot, Y. E. Sun and M. Rihaoui, "**Production of relativistic electron bunch with tunable current distribution**". *AIP Conf. Proc. 1086, 677 (2009)*
- M. Rihaoui, W. Gai, P. Piot, J. G. Power and Z. Yusof, "**Observation Of Transverse Space Charge Effects In A Multi-Beamlet Electron Bunch Produced In A Photo-Emission Electron Source**". *AIP Conf. Proc. 1086, 671 (2009)*

List of publications published or submitted

- M. Rihaoui, C. L. Bohn, P. Piot and J. G. Power, "**Impact of transverse irregularities at the photo- cathode on the production of high-charge electron bunches**". *In the Proceedings of Particle Accelerator Conference (PAC 07), Albuquerque, New Mexico, 25-29 Jun 2007, pp 4027*
- Y.-E Sun, J. G. Power, K.-J. Kim, P. Piot, M. M. Rihaoui, "**Design study of a transverse-to- longitudinal emittance exchange proof-of-principle**". *Proceedings of the 22nd Particle Accelerator Conference (PAC'07), Albuquerque, New Mexico (25-29 June, 2007)*
- G. Power, M. E. Conde, W. Gai, F. Gao, R. Konecny, W. Liu, Z. Yusof, P. Piot, M. Rihaoui, "**Pepper-pot based emittance measurement of the AWA photoinjector**". *Proceedings of the 22nd Particle Accelerator Conference (PAC'07), Albuquerque, New Mexico (2007)*

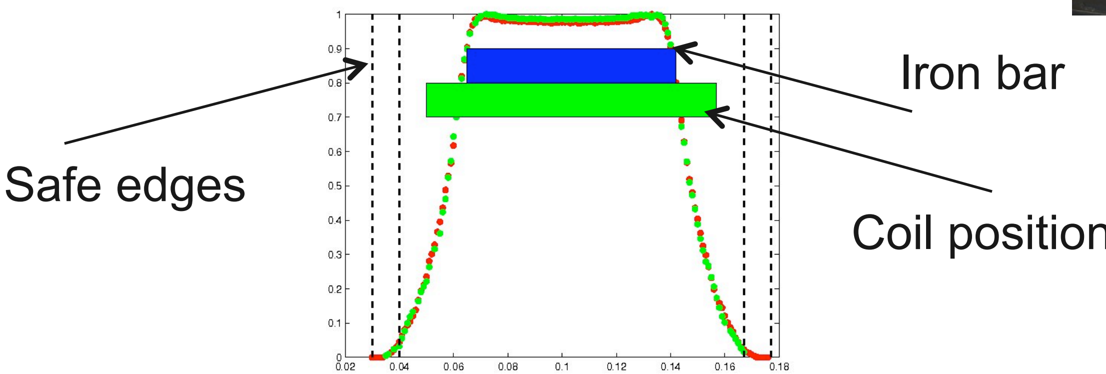
Backup slides

Magnets modeling

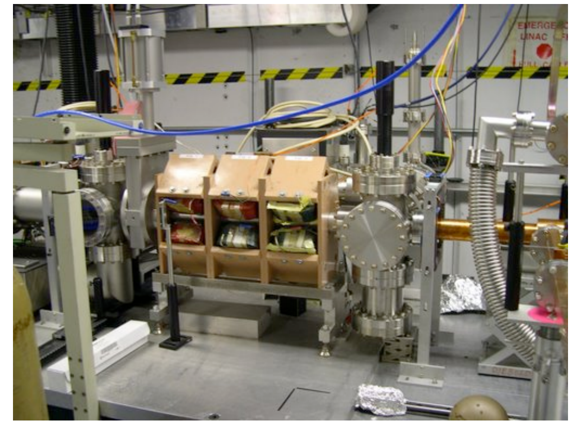


Magnetic Quadrapoles:

Perform measurements of B field for the AWA quads



Quad Bz field measurements

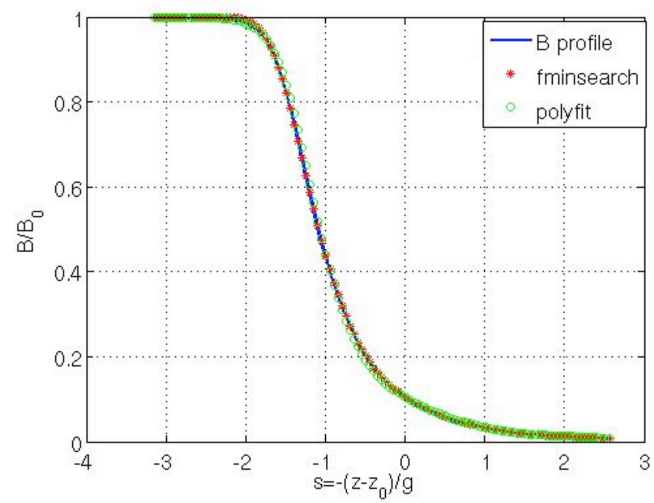


Magnetic dipole:

- *Magnetic field profile and magnets are from RadiaBe*
- *Ideal magnetic dipole have hard edge model. We mo dipoles with fringe fields using Enge Coefficients*

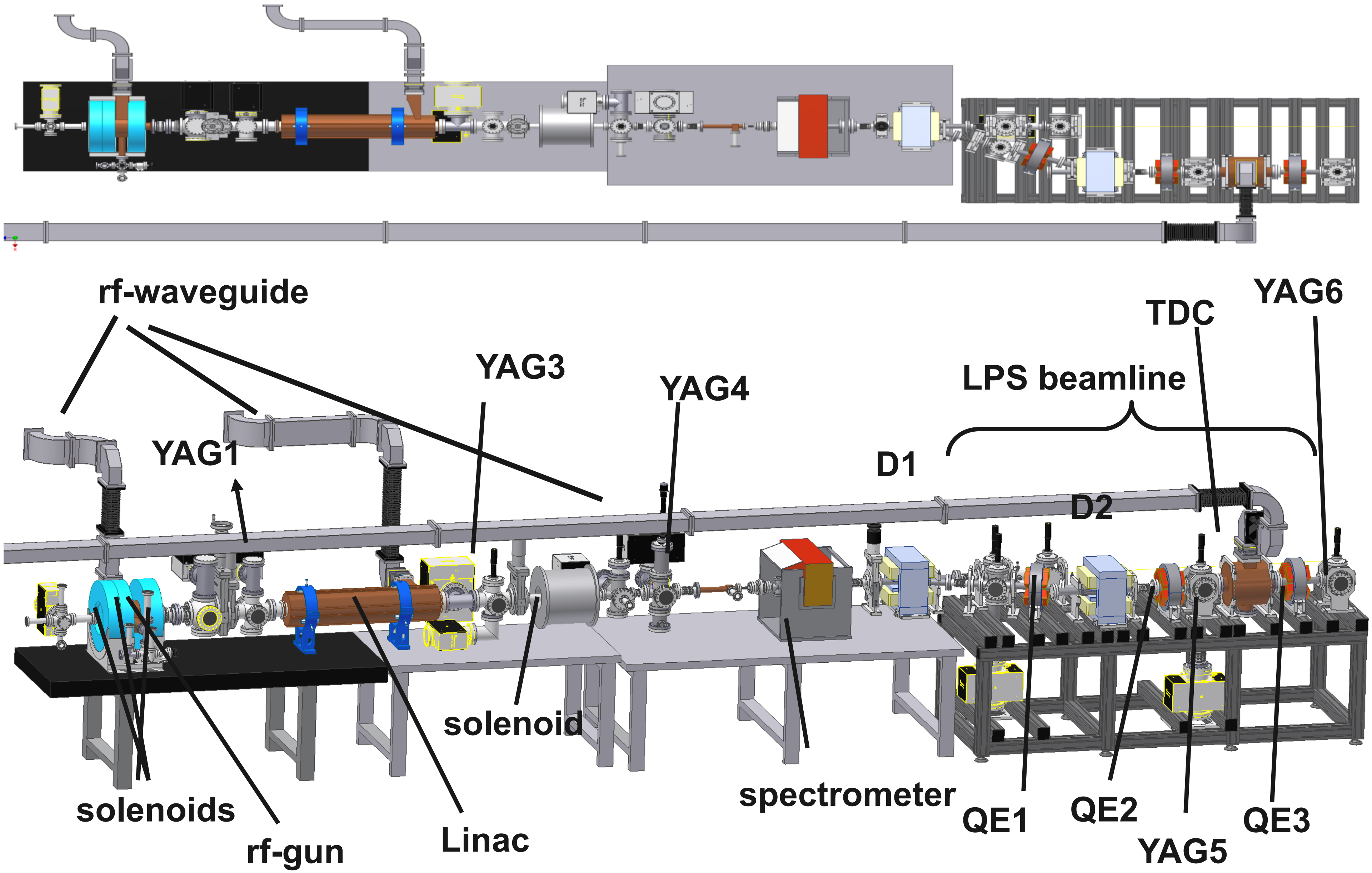
$$\frac{B_y}{B_{y0}} = \frac{1}{1+\exp(c_i s^{i-1})}, i = 1, \cdots, 8$$

$$s \equiv -\frac{z-z0}{g}$$



Enge Coefficients fit

Argonne Wakefield Accelerator



Transfer matrix of a realistic system

•*Use a realistic model to test for the exchanger validation.*

•*Generate Initial particle distribution of 6 particles with offset in position and momentum with a reference particle X = 0.*

- *to get the six phase space R transfer matrix*

$$X = \vec{0}$$ **Reference particle**

$$X_i = \alpha_i \hat{e}_i$$ **Probe particles**

$$X \xrightarrow{R} Y = RX$$ **Ref**

$$X_i \xrightarrow{R} Y_i = RX_i$$ **Probe**

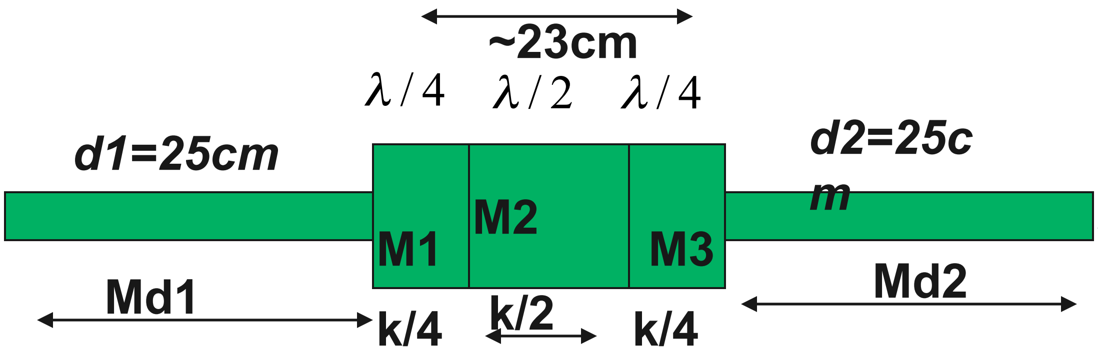
$$\delta_i Y_i \equiv Y_i - Y = R[X_i - X]$$

Differece orbit

$$\delta_i Y_i = RX_i = \alpha_i R \hat{e}_i = \alpha_i \hat{e}_i \begin{bmatrix} R_{1i} \\ . \\ . \\ . \\ . \\ R_{6i} \end{bmatrix} \Rightarrow$$

$$\begin{bmatrix} R_{1i} \\ . \\ . \\ . \\ . \\ R_{6i} \end{bmatrix} = \frac{\delta_i Y}{\alpha_i}$$

RF deflecting Cavity



*From Don Edwards notes**
The transfer matrix for one cell deflecting cavity using pillbox model is:

$$M_i = \begin{bmatrix} 1 & L_i & \frac{\kappa L_i}{2} & 0 \\ 0 & 1 & \kappa & 0 \\ 0 & 0 & 1 & 0 \\ \kappa & \frac{\kappa L_i}{2} & \frac{\kappa^2 L_i}{4} & 1 \end{bmatrix}$$

$$M_{cav} = \begin{bmatrix} 1 & 0.7294 & 1.4262 & 0 \\ 0 & 0.9974 & 3.909 & 0 \\ 0 & 0 & 0.9956 & 0 \\ 3.91 & 1.426 & 0.732 & 1.003 \end{bmatrix}$$

$$L_c = d_1 + \lambda + d_2$$

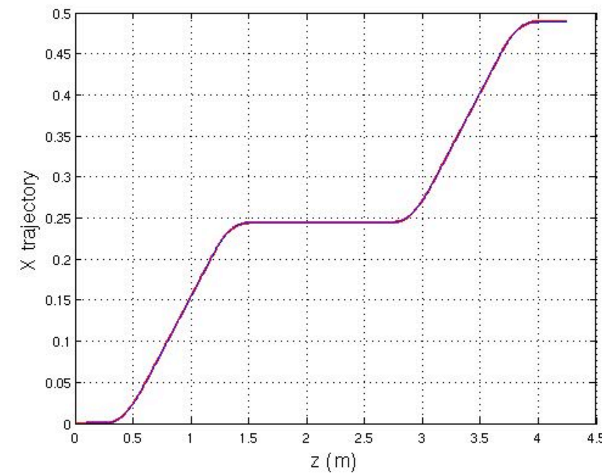
$$M_{theory} = M_{d2} M_3 M_2 M_1 M_{d1} = \begin{bmatrix} 1 & L_c & \kappa\frac{L_c}{2} & 0 \\ 0 & 1 & \kappa & 0 \\ 0 & 0 & 1 & 0 \\ \kappa & \kappa\frac{L_c}{2} & \frac{23}{128}\left(\kappa^2\lambda\right) & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0.73 & 1.427 & 0 \\ 0 & 1 & 3.909 & 0 \\ 0 & 0 & 1 & 0 \\ 3.909 & 1.427 & 0.631 & 1 \end{bmatrix}$$

**Note on rf deflecting cavity can be found at:*
http://www.nicadd.niu.edu/aard/emittance_exchange/

Transfer matrix of a realistic emittance-exchanger beamline

- *Matrix inferred from particle tracking*

$$M_{DL-CAV-DL} = \begin{bmatrix} -0.0010 & 0.0858 & 8.4 & -0.266 \\ -0.0015 & 0.015 & 3.896 & 0.2355 \\ 0.2387 & 0.2471 & 0.0233 & 0.0022 \\ 3.896 & 8.409 & 0.745 & 0.0436 \end{bmatrix}$$

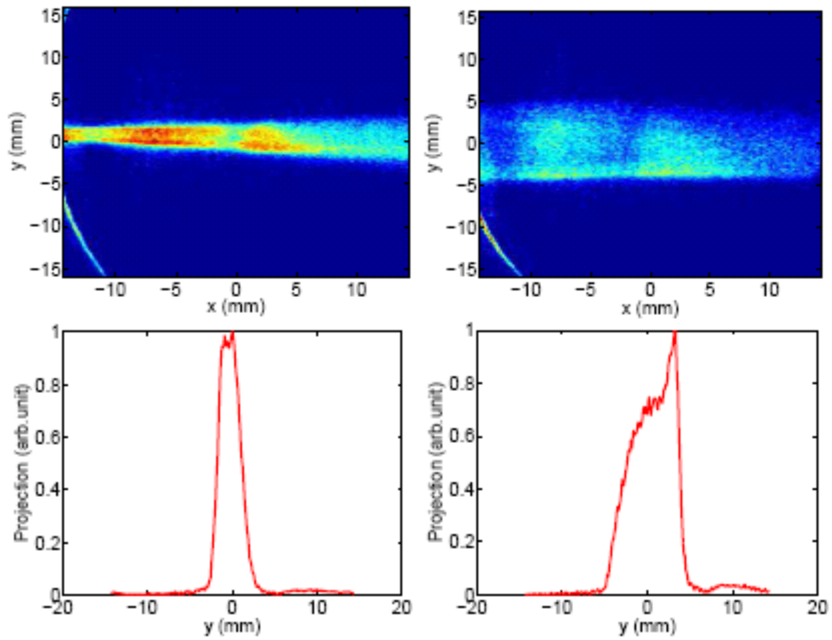


- *Matrix analytically derived and evaluated for* $\kappa = \dfrac{-1}{\eta}$

$$M = \begin{bmatrix} 0 & \dfrac{23\lambda}{128} & -\dfrac{128L+64L_c-23\lambda}{128\eta} & \eta - \dfrac{R_{56}\left(128L+64L_c-23\lambda\right)}{128\eta} \\ 0 & 0 & \dfrac{-1}{\eta} & -\dfrac{R_{56}}{\eta} \\ \dfrac{-R_{56}}{\eta} & \eta + \dfrac{R_{56}}{\eta}\left(\dfrac{23\lambda}{128} - L - \dfrac{L_c}{2}\right) & \dfrac{23R_{56}\lambda}{128\eta^2} & \dfrac{23R_{56}{}^2\lambda}{128\eta^2} \\ \dfrac{-1}{\eta} & -\dfrac{128L+64L_c-23\lambda}{128\eta} & \dfrac{23\lambda}{128\eta^2} & \dfrac{23R_{56}\lambda}{128\eta^2} \end{bmatrix} = \begin{bmatrix} 0 & 0.041 & 8.3 & 0.2456 \\ 0 & 0 & 3.909 & 0.236 \\ 0.236 & 0.2456 & 0.038 & 0.002 \\ 3.909 & 8.3 & 0.631 & 0.038 \end{bmatrix}$$

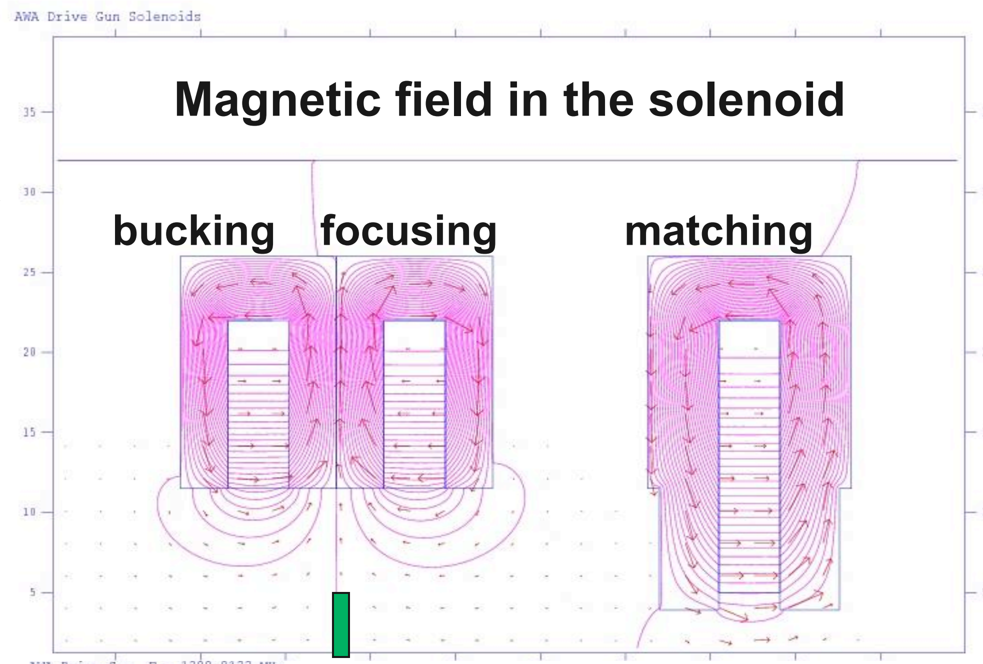
- *Realistic model reproduce the matrix analytically derived using hard-edge elements*

Cavity off **Cavity on**



Simulations Tools cont…

POISSON used to generate B field



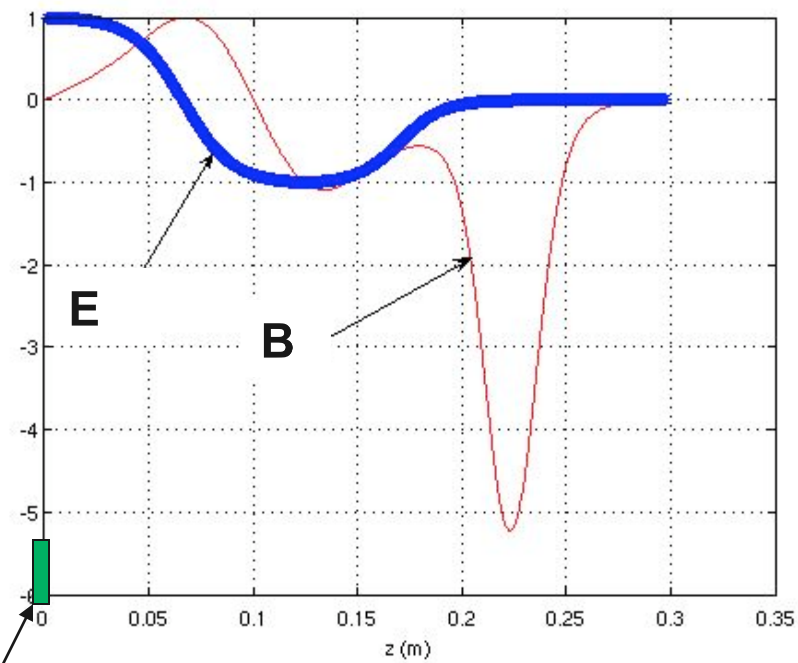
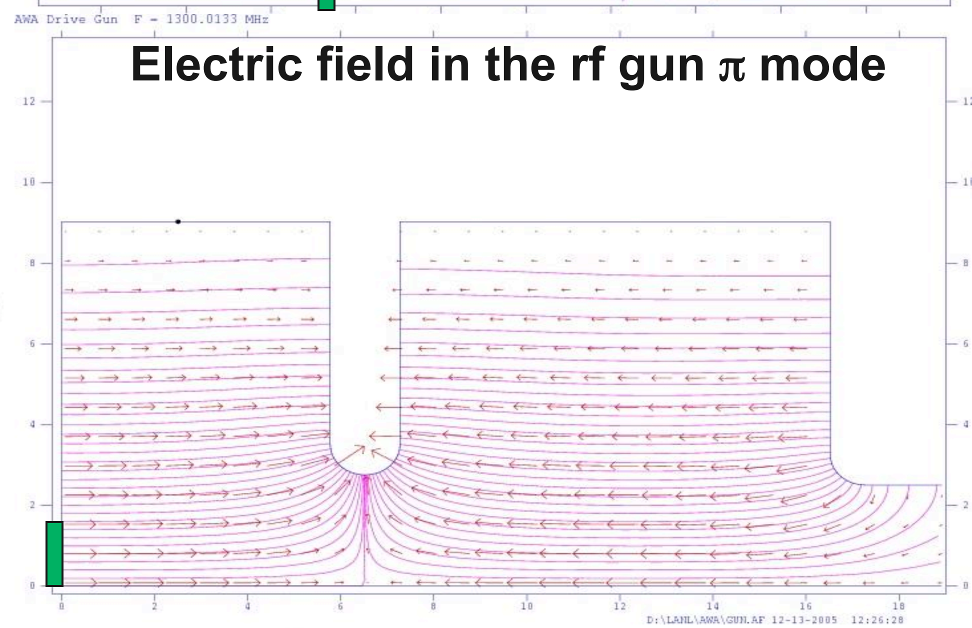
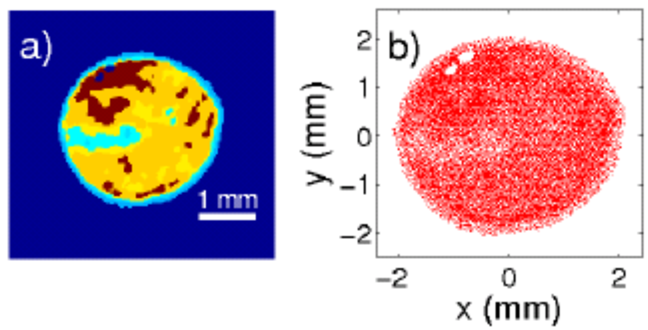


Photo cathode(B = 0)

SUPERFISH used to generate E field



NORTHERN ILLINOIS UNIVERSITY


a)
1 mm
b)
2
1
0
−1
−2
y (mm)
−2
0
2
x (mm)