Transverse to Longitudinal Emittance Exchange Results

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Acknowledgements

- This work is really the work of many people at two national laboratories and NIU

Fermilab

- Helen Edwards
- Ray Fliller (now at BNL)
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•Chunguang Jing

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•Philippe Piot
•Marwan Rihaoui (provided slides for AWA experiment)

If I forgot your name - please accept my apologies!

EEX Papers at this conference

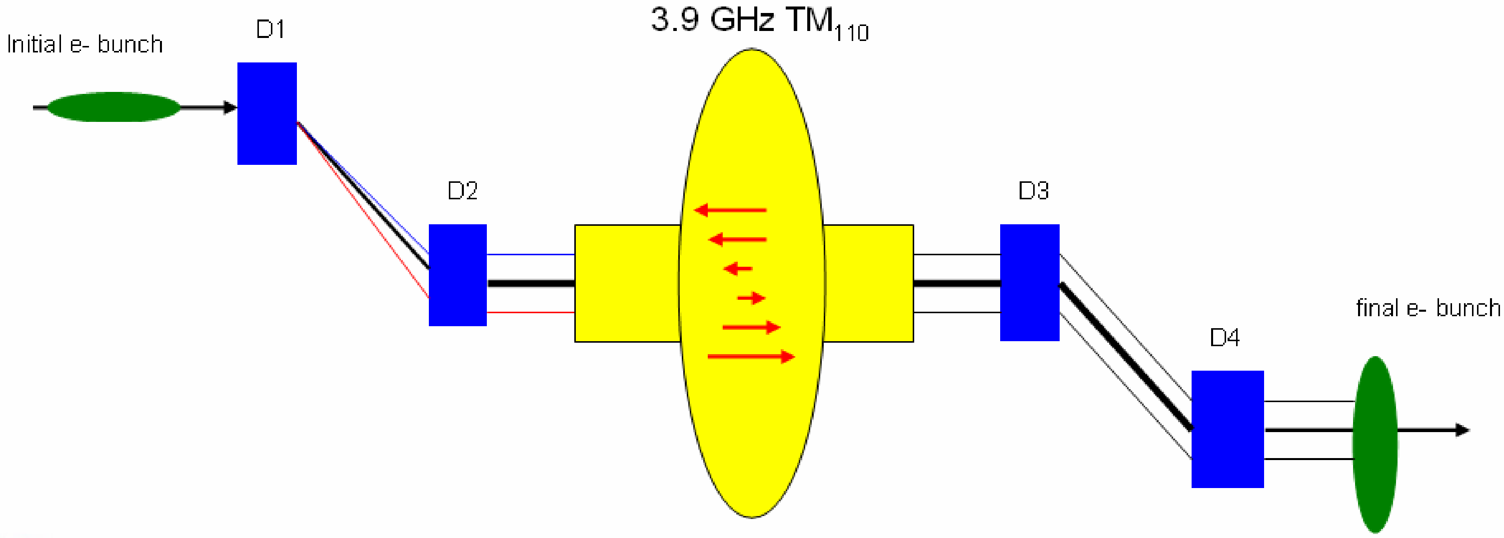
- Fermilab
  - **FR5PFP020** - Emittance Exchange at the A0 Photoinjector
  - **TH5RFP042** -Bunch Length Monitoring at the A0 Photoinjector Using a Quasi-Optical Schottky Detector
- ANL
  - **TH5RFP005** - Measurement of the 4D Transverse Phase Space Distribution from an RF Photoinjector at the AWA
- NIU
  - **TH6PFP087** - Limiting Effects in the Transverse-to-Longitudinal Emittance Exchange for Low Energy Relativistic Electron Beams
  - **FR5PFP039** - Verification of the AWA Photoinjector Beam Parameters Required for a Transverse-to-Longitudinal Emittance Exchange Experiment
- Others
  - **TH5PFP036** - Conceptual Design of a 20 GeV Electron Accelerator for a 50 keV X-Ray Free-Electron Laser Using Emittance Exchange Optics and a Crystallographic Mask
  - **TH5RFP040** - Resonant-Cavity Diagnostics for an Emittance Exchange Experiment

Transverse to Longitudinal Emittance Exchange -What and Why?

- The idea of Transverse to Longitudinal Emittance Exchange (EEX) is simple. Take a beam with emittances (ε_x, ε_y, ε_z) and make a beam with emittances (ε_z, ε_y, ε_x) .
- Why?
  - Basic and unique beam dynamics manipulation
  - FEL's
    - Possibility of a smaller transverse emittances gives a shorter gain length.
    - Larger longitudinal emittance might stabilize against instabilities
  - This phase space manipulation could have application in a linear collider
    - Possibly can combine EEX with a flat beam transform to produce the proper beam at the main linac entrance without an electron damping ring.

Transverse to Longitudinal Emittance Exchange - How?

- There have been two proposals for EEX in a linac
  1. Use a deflecting cavity in the middle of a chicane (Cornacchia and Emma, 2002)
  2. Use a deflecting cavity in the middle of two doglegs (Kim and Sessler, 2006)
     1. Emma, et.al. in 2006 combined this scheme with a round to flat beam transformer as well.
- Both FNAL and ANL use the Kim and Sessler scheme.
- Incoming beam is manipulated to have the appropriate transverse and longitudinal phase ellipses
- First dogleg provides dispersion at DMC.
- The deflecting cavity gives a longitudinal position dependant transverse kick and a transverse position dependant momentum kick.
- The second dogleg couples the remaining correlations to finish the exchange.



How does the exchange work??

- The transverse - longitudinal transport matrix R, and beam matrix σ look like (in 2x2 block mode)

$$R = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \qquad \sigma_1 = \begin{pmatrix} \sigma_x & 0 \\ 0 & \sigma_z \end{pmatrix}$$

- The beam matrix after the transport is given by

$$\sigma_2 = R\sigma_1 R^T$$

- If the R matrix can be made to look like

$$R = \begin{pmatrix} 0 & B \\ C & 0 \end{pmatrix}$$

- Then the beam matrix looks like

$$\sigma_2 = \begin{pmatrix} B\sigma_z B^T & 0 \\ 0 & C\sigma_x C^T \end{pmatrix}$$

New Horizontal Emittance is the old longitudinal emittance

New Longitudinal Emittance is the old Horizontal emittance

How does the exchange work??

- Assume that the beamline consists of a before cavity section, a DMC, and an after cavity section.

$$R = M^{ac} M^{cav} M^{bc}$$

- Assume that the before cavity section produces some dispersion, η, with a slope η'.
- Assume that the cavity is a zero length element
  - What does the cavity strength need to be?

$$k = \frac{eV_0\omega}{Ec} = -\,{}^{1}\!/_{\eta}$$

  - What are the needed properties for the after cavity section?

$$\begin{pmatrix} M^{ac}_{16} \\ M^{ac}_{26} \end{pmatrix} = \begin{pmatrix} M^{ac}_{11} & M^{ac}_{12} \\ M^{ac}_{21} & M^{ac}_{22} \end{pmatrix} \begin{pmatrix} \eta \\ \eta' \end{pmatrix}$$

- These equations come out of nothing more than the symplectic condition and the condition that the A and D blocks of the R matrix are all zeros.
- **Note: The vertical emittance is unaffected by the transformation.**

Fly's in the Ointment

- There are many effects that may leave residual coupling, dilute, or obscure the emittance exchange.
  - Linear Flies – can lead to residual coupling of the emittances, leading to an emittance increase
    - I've assumed an infinitely thin cavity, a finite length cavity will leave residual coupling
    - Building an imperfect beamline such as using a chicane vs. a double dogleg as Cornacchia and Emma pointed out.
    - Incorrect cavity strength – too strong is as bad as too weak.

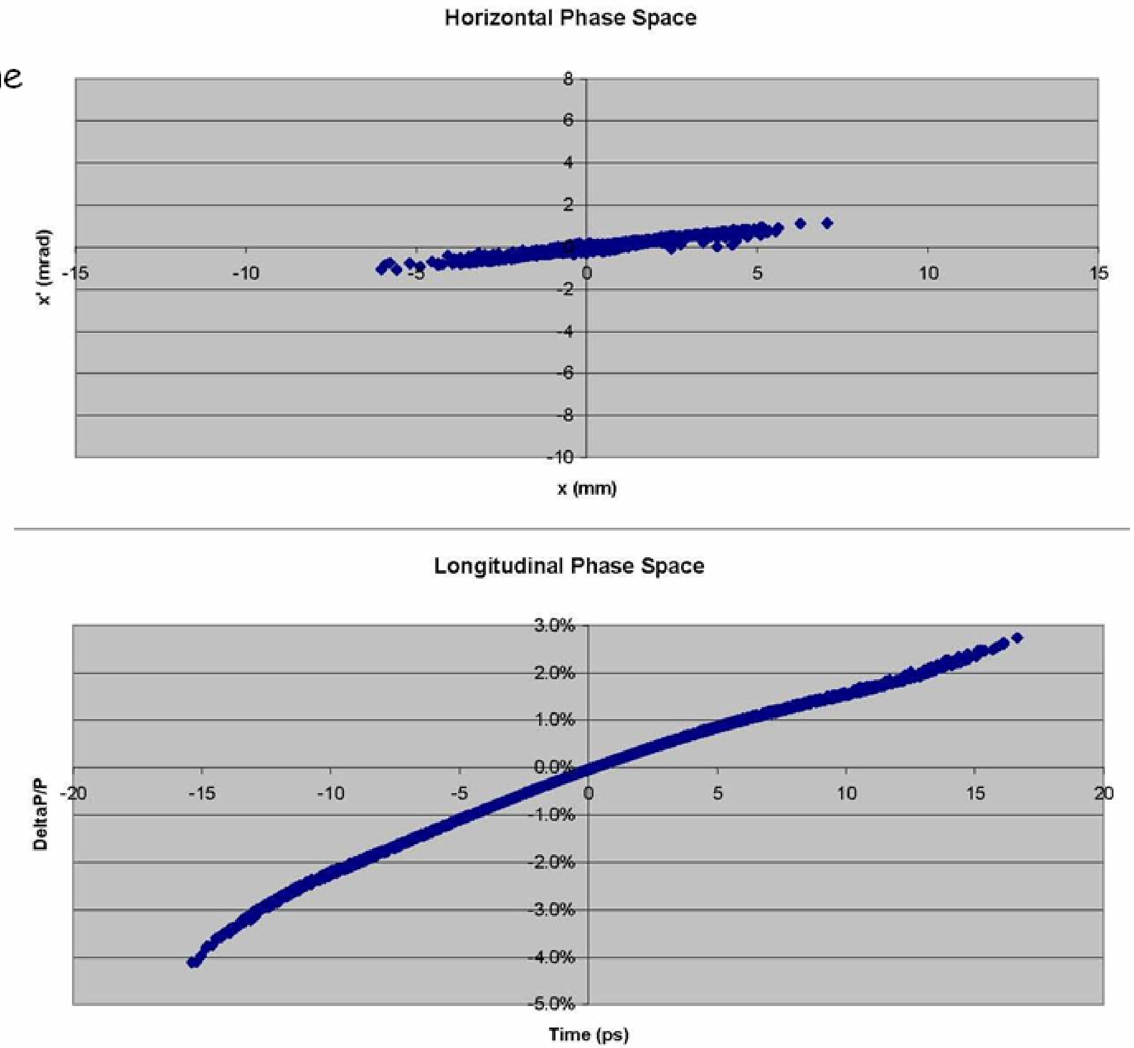
These can be minimized or eliminated by manipulating the incoming beam phase spaces

  - Ugly Flies – these can blow up the emittances, possibly washing out the effect of the exchange
    - Space charge
    - Coherent Synchrotron Radiation

    These can be minimized by lowering the beam charge.

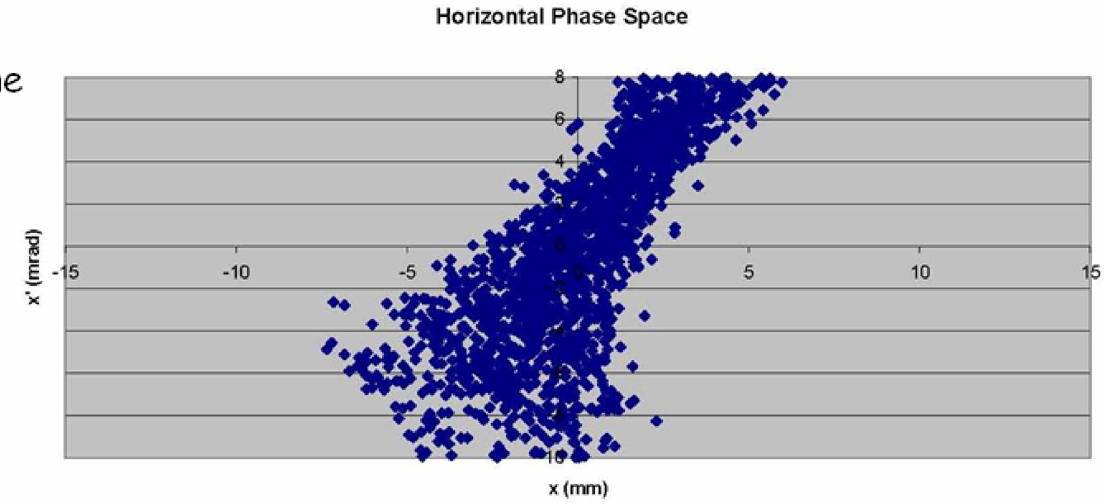
Watching the Exchange - The Fermilab experiment

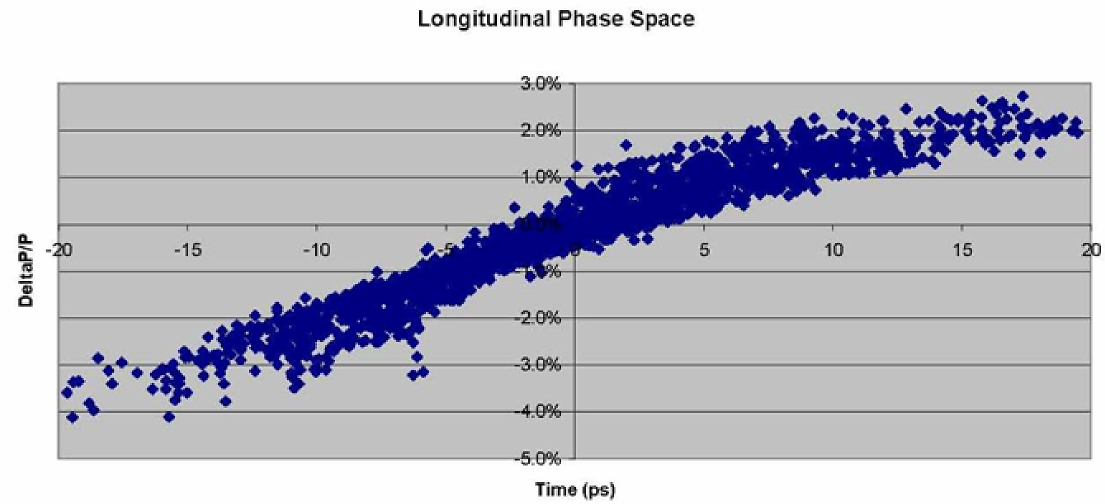
Input to the EEX line



Watching the Exchange - The Fermilab experiment

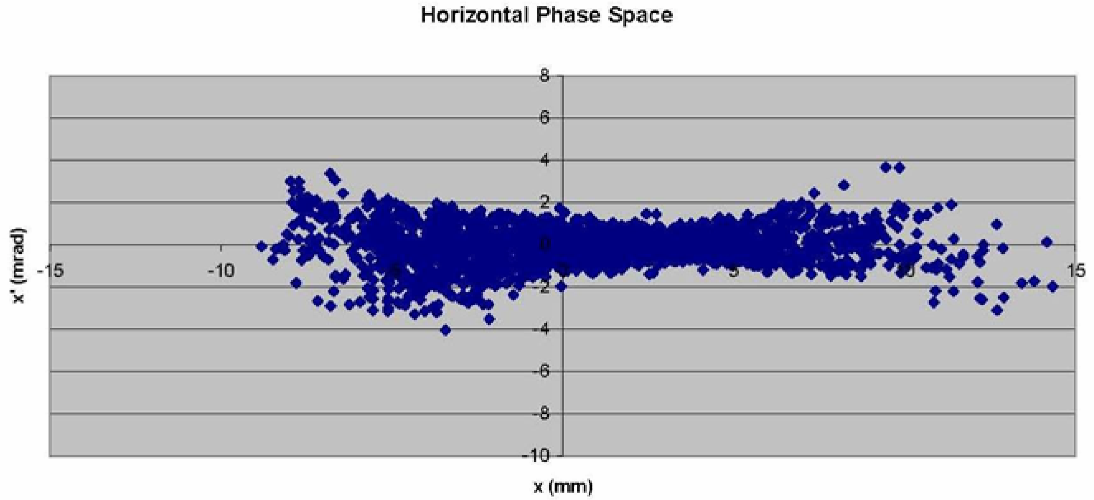
Input to the EEX line
Before Dipole 2

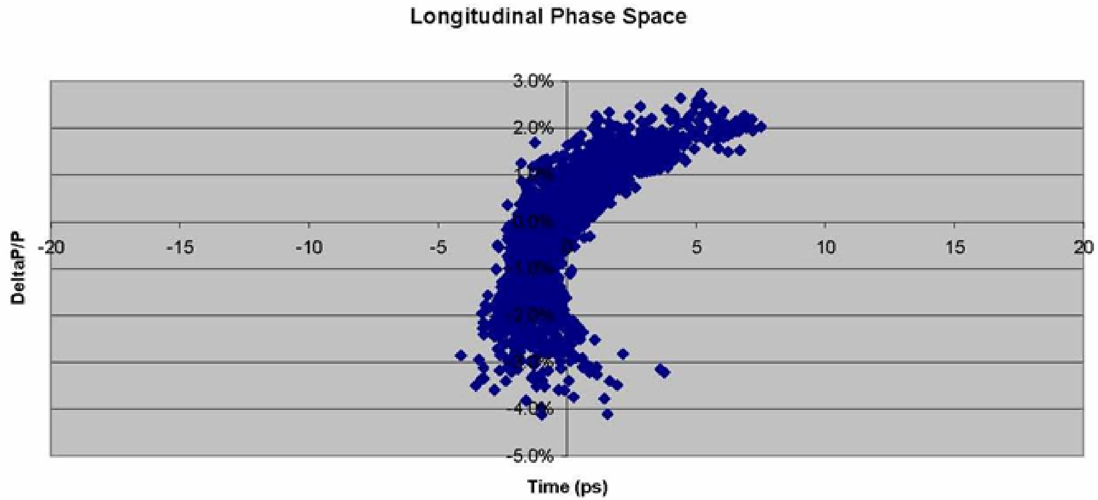




Watching the Exchange - The Fermilab experiment

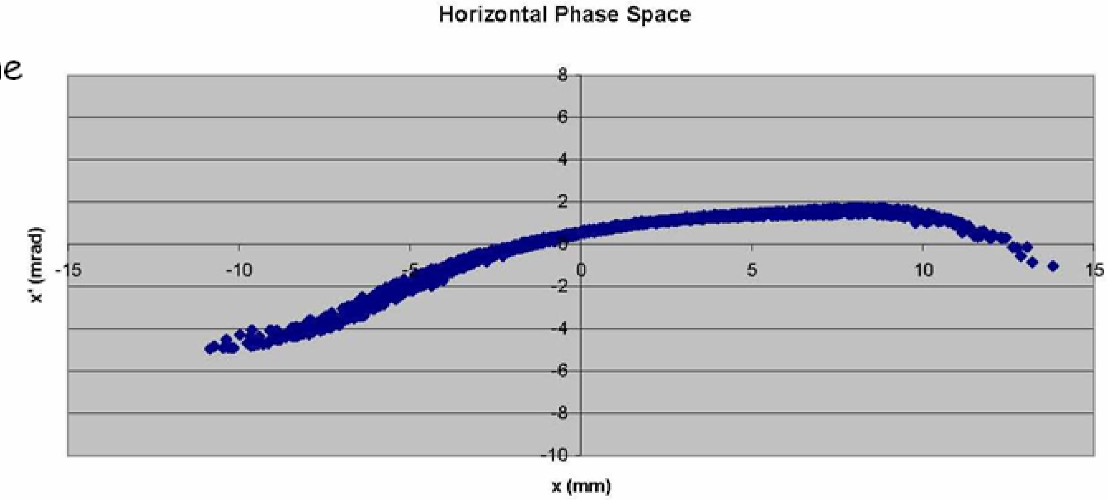
Input to the EEX line
Before Dipole 2
Before DMC

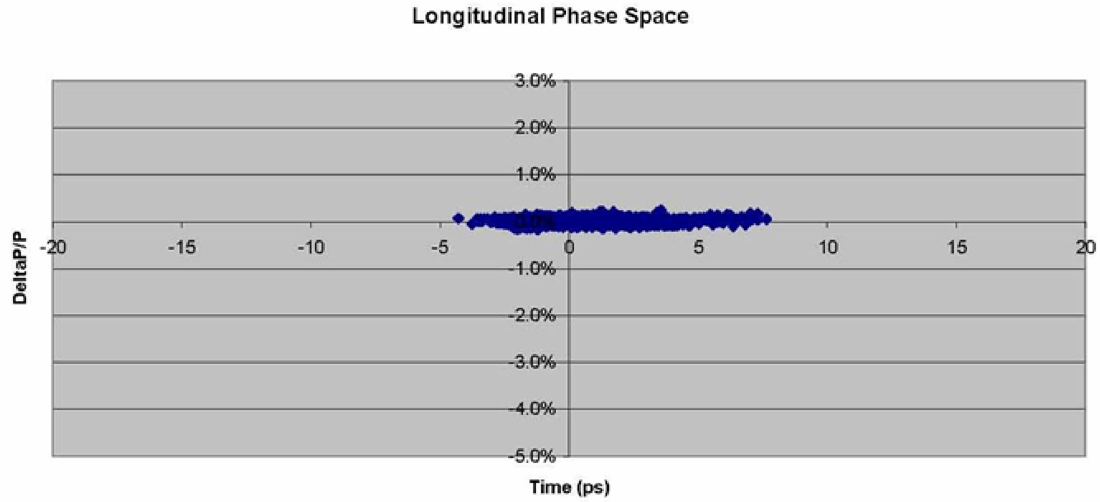




Watching the Exchange - The Fermilab experiment

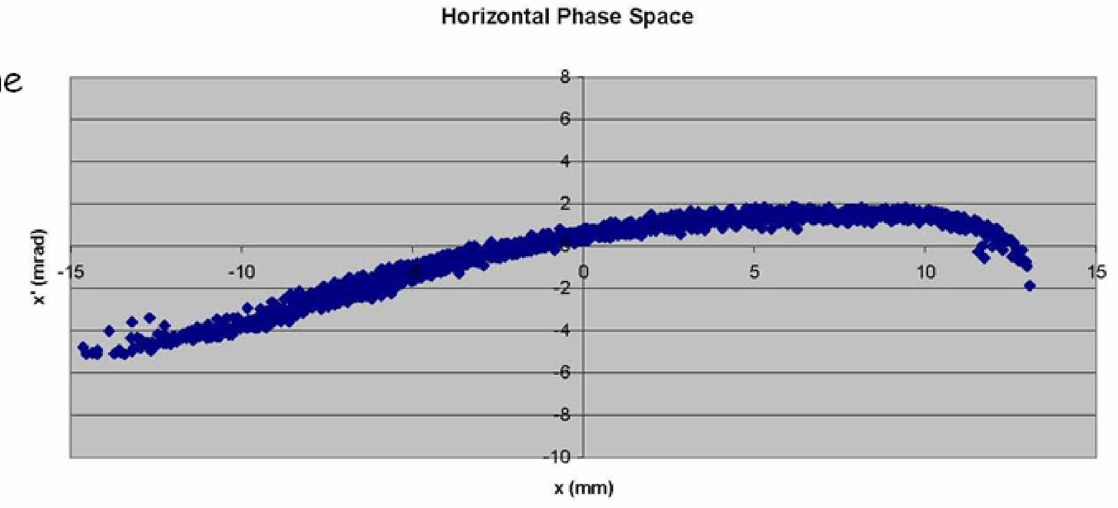
Input to the EEX line
Before Dipole 2
Before DMC
After DMC

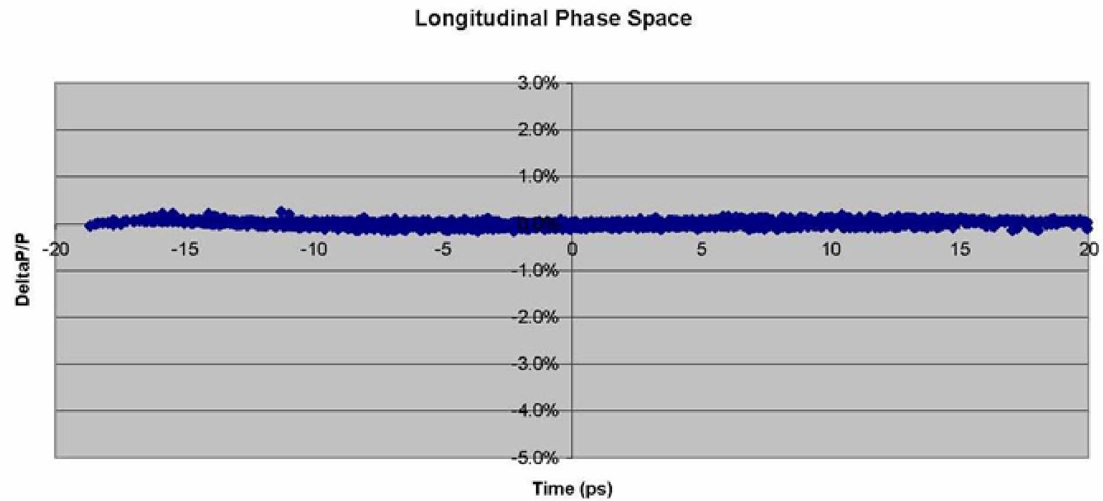




Watching the Exchange - The Fermilab experiment

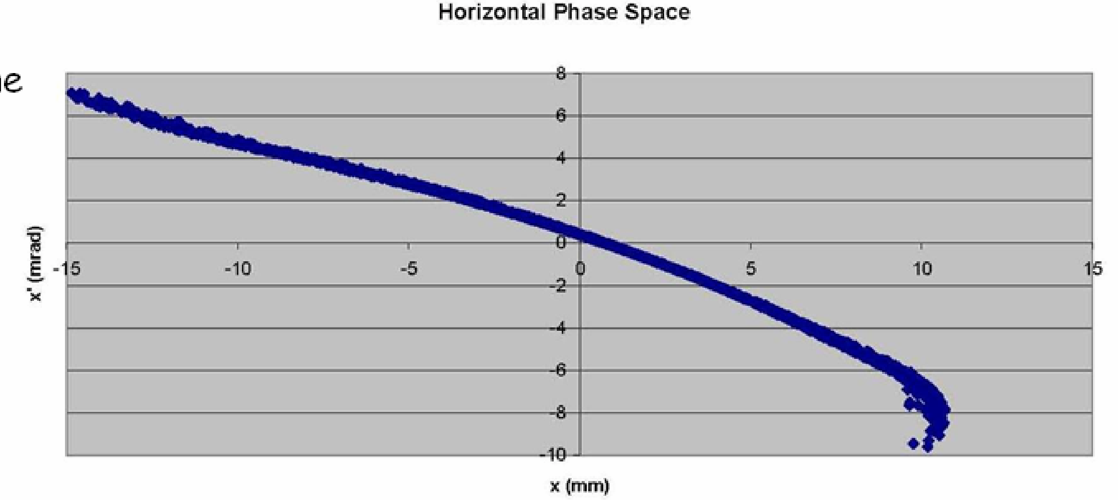
Input to the EEX line
Before Dipole 2
Before DMC
After DMC
Before Dipole 4

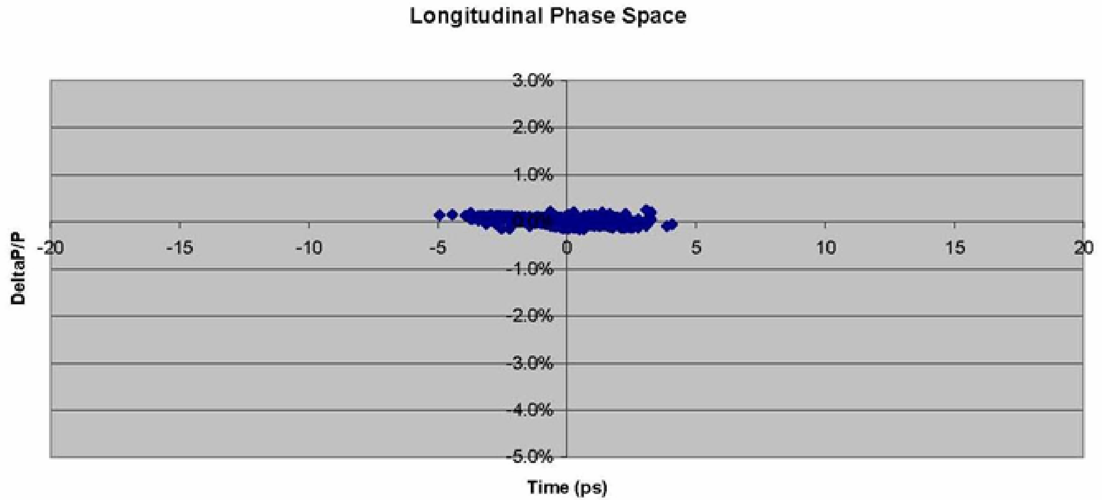




Watching the Exchange - The Fermilab experiment

Input to the EEX line
Before Dipole 2
Before DMC
After DMC
Before Dipole 4
Exchange Complete



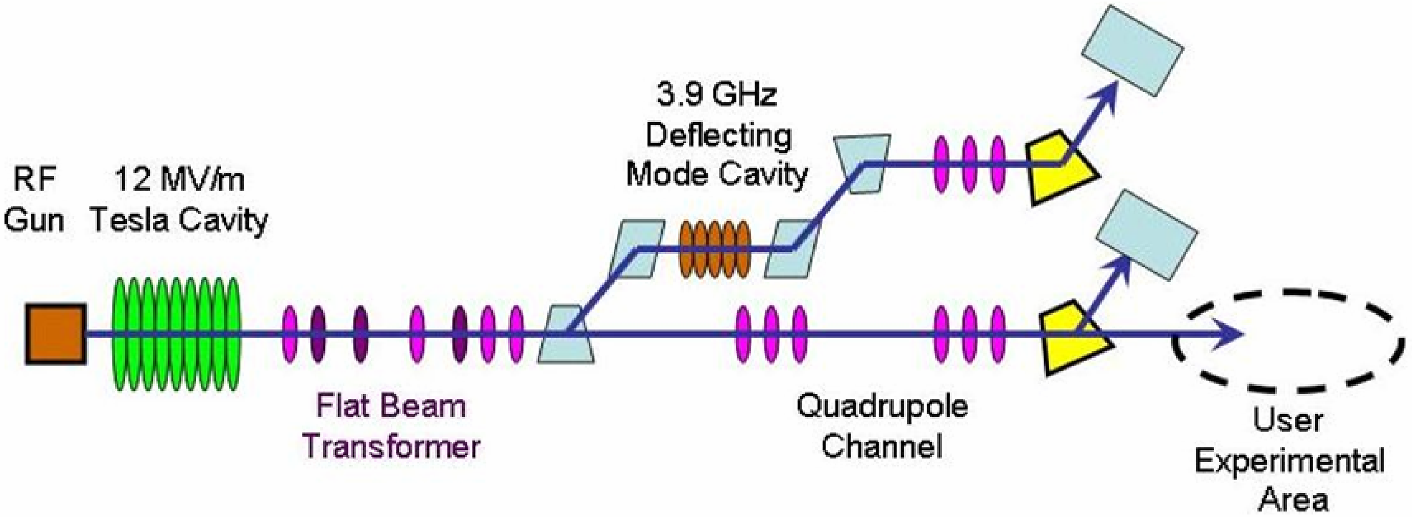


The Experiments

- Fermilab
  - Fermilab's A0 Photoinjector is exchanging a large longitudinal emittance with a small transverse emittance
- ANL
  - Argonne's AWA is exchanging a small longitudinal emittance with a large transverse emittance.

Fermilab's A0 Photoinjector

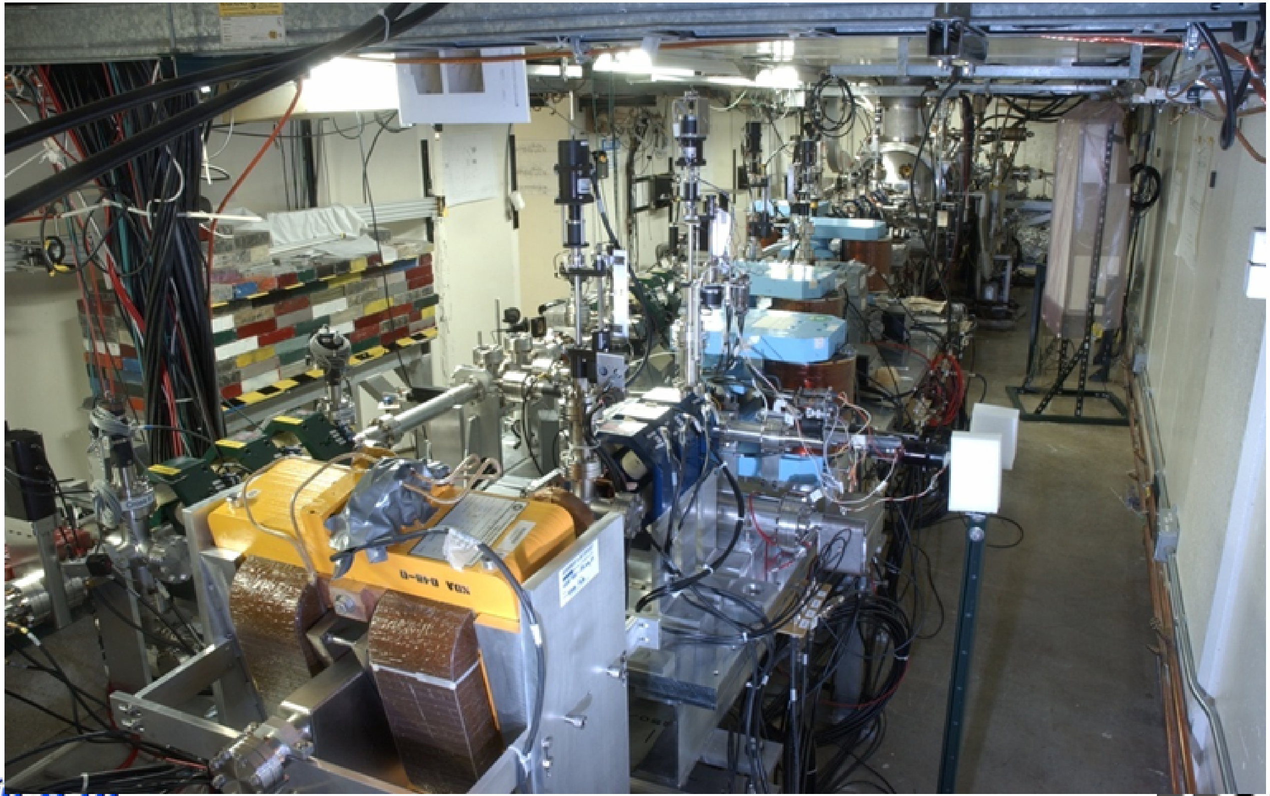
A0 Photoinjector



- L band 1.5 cell NC RF gun with Cs_2Te photocathode
  - 35 MV/m maximum cathode gradient
- TESLA technology accelerating cavity
  - 12 MV/m accelerating gradient
- Round to Flat beam transformer
- Transverse to Longitudinal Emittance Exchange Beamline
- Quadrupole transport channel
- User experimental area

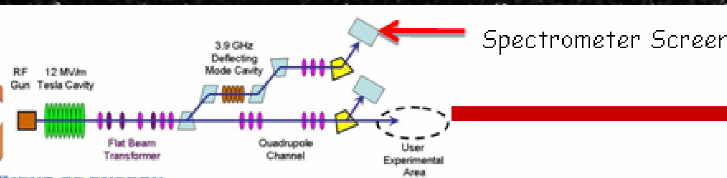
Beam Parameters

- 16 MeV total energy
- $\Delta p/p \approx 0.1\%$@ 16MeV (250 pC)
- Bunch length ≈ 0.75 mm (250 pC)
- $\gamma\varepsilon_z \approx 20$ mm-mrad (RMS @ 250 pC)
- $\gamma\varepsilon_x, \gamma\varepsilon_y \approx 5$ mm-mrad (RMS @ 250 pC)



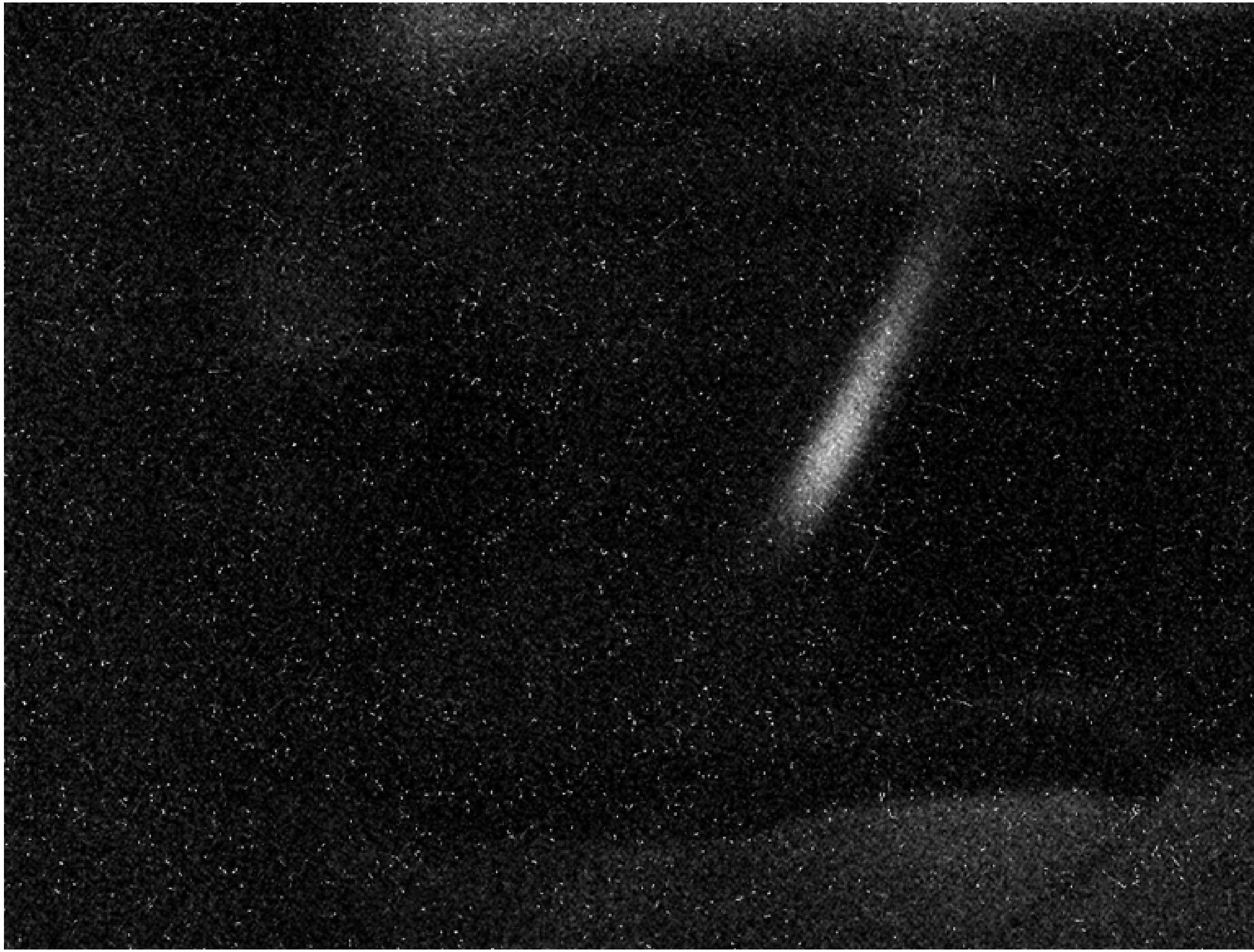
- Preliminary investigations showed encouraging results. For instance, as we increased the TM_{110} cavity strength we saw a reduction in momentum spread…

Early EEX Signature from Spectrometer

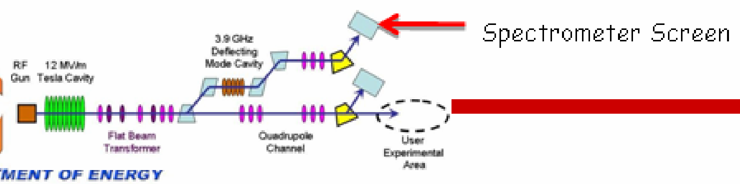


Cavity: OFF

Early EEX Signature from Spectrometer

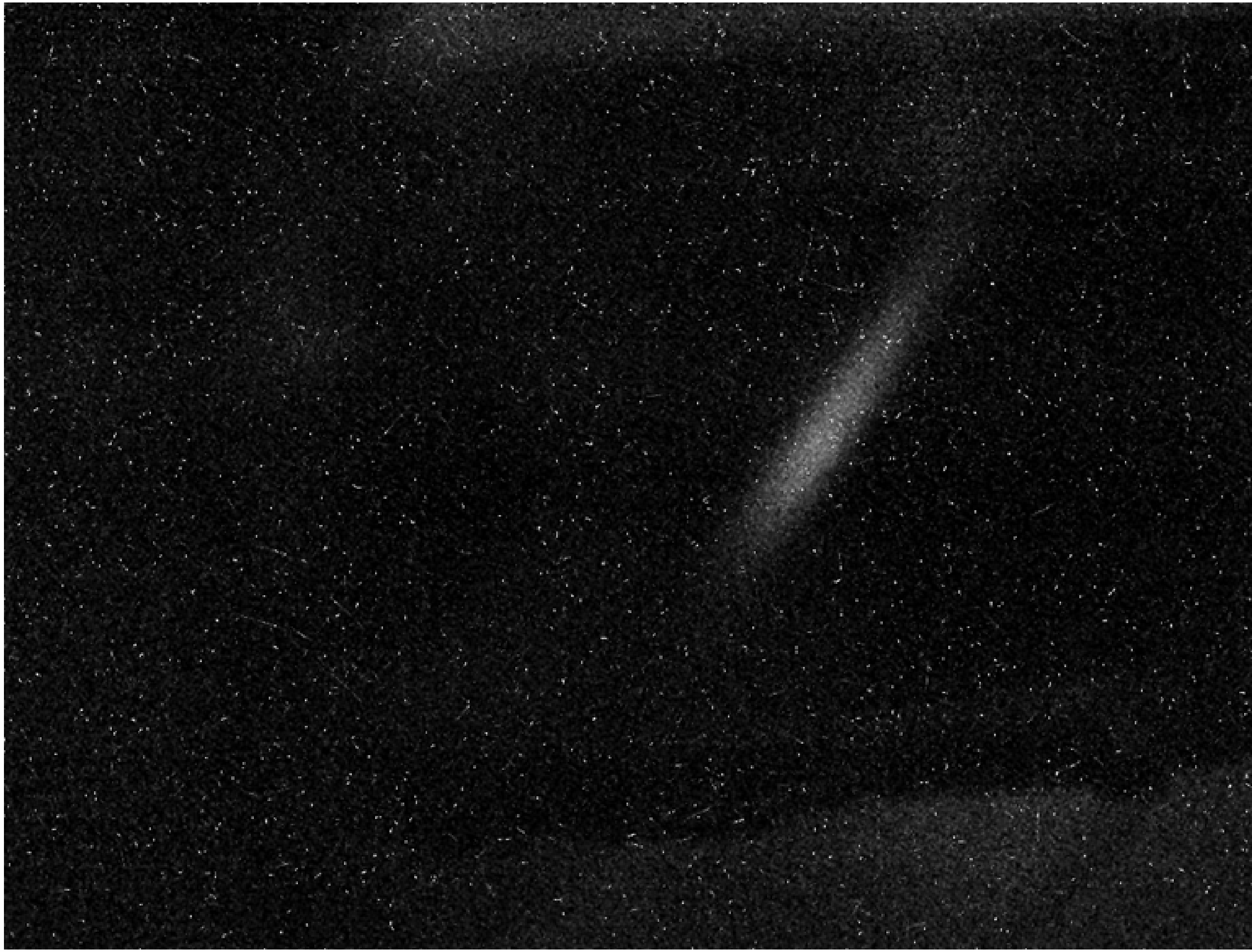


~ 550keV

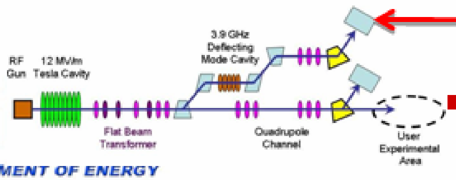


Cavity 10%

Early EEX Signature from Spectrometer

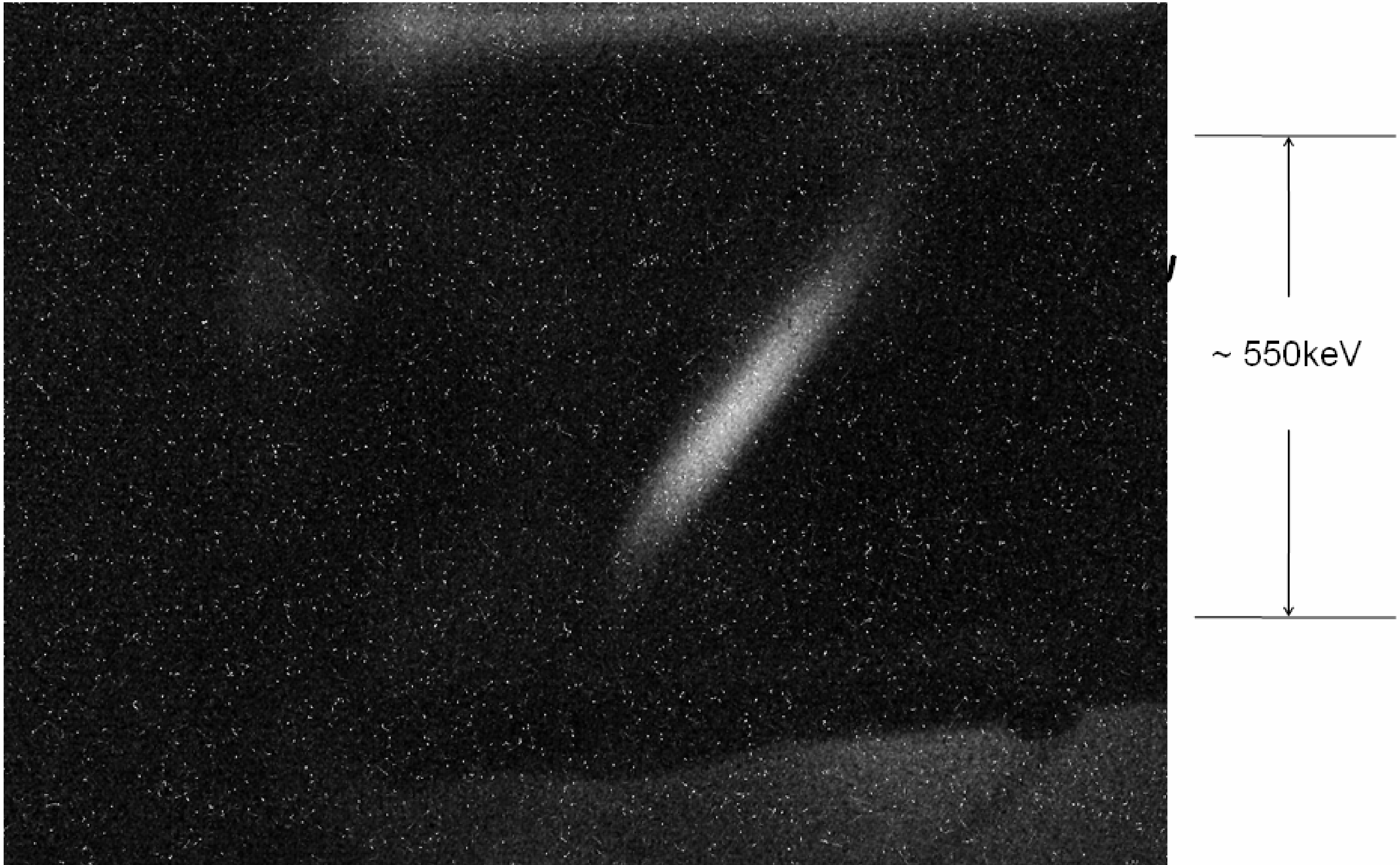


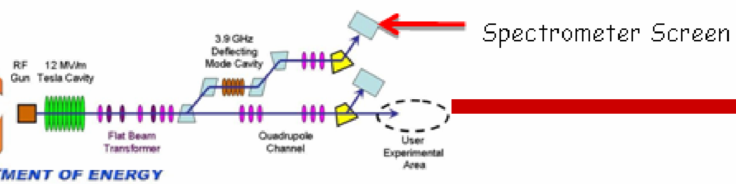
~ 550keV



Cavity 20%

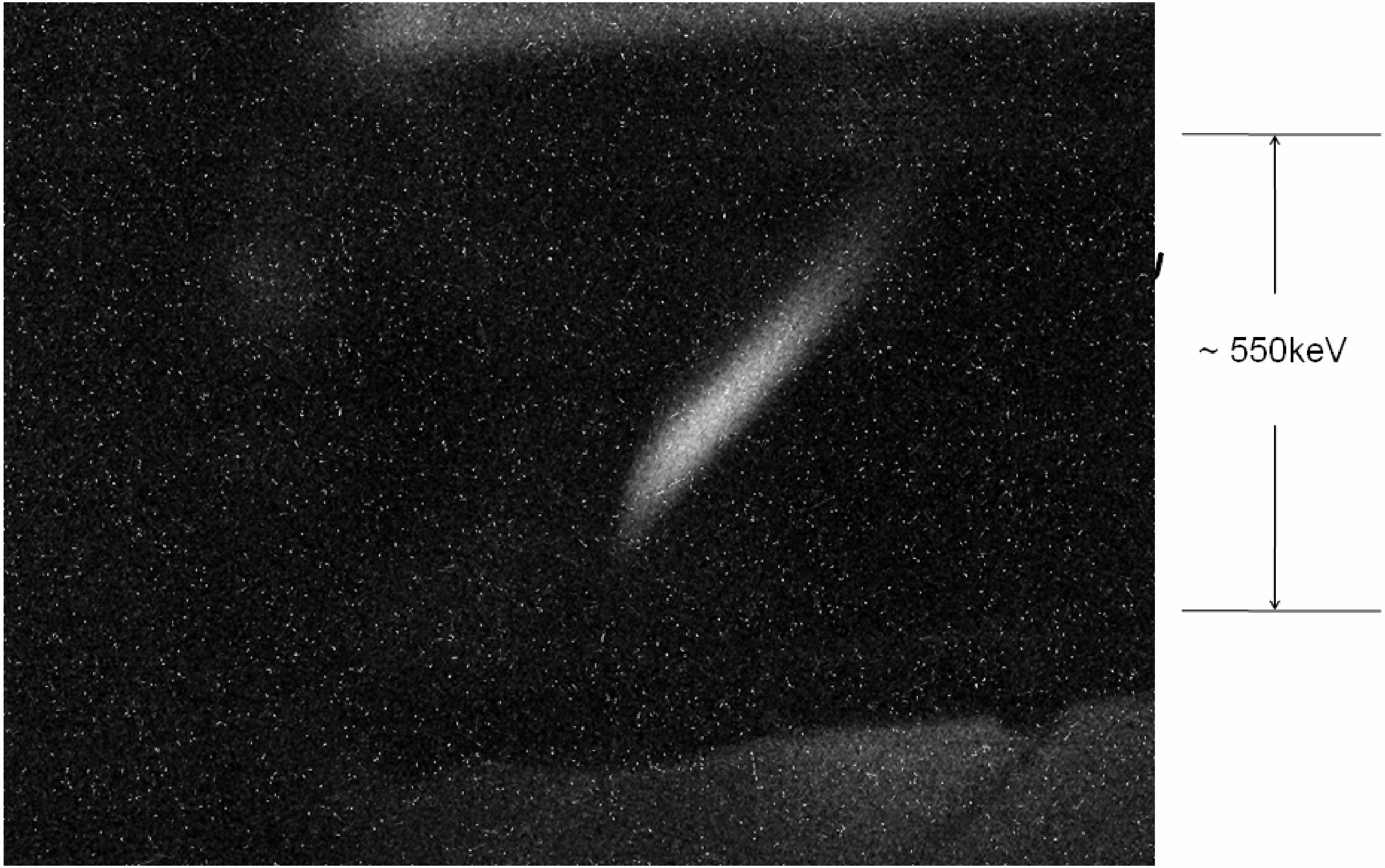
Early EEX Signature from Spectrometer

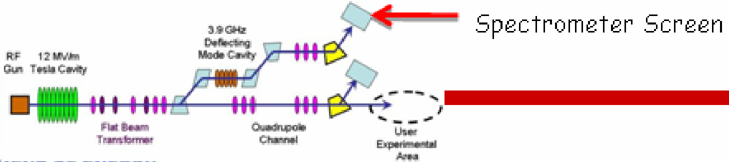




Cavity 30%

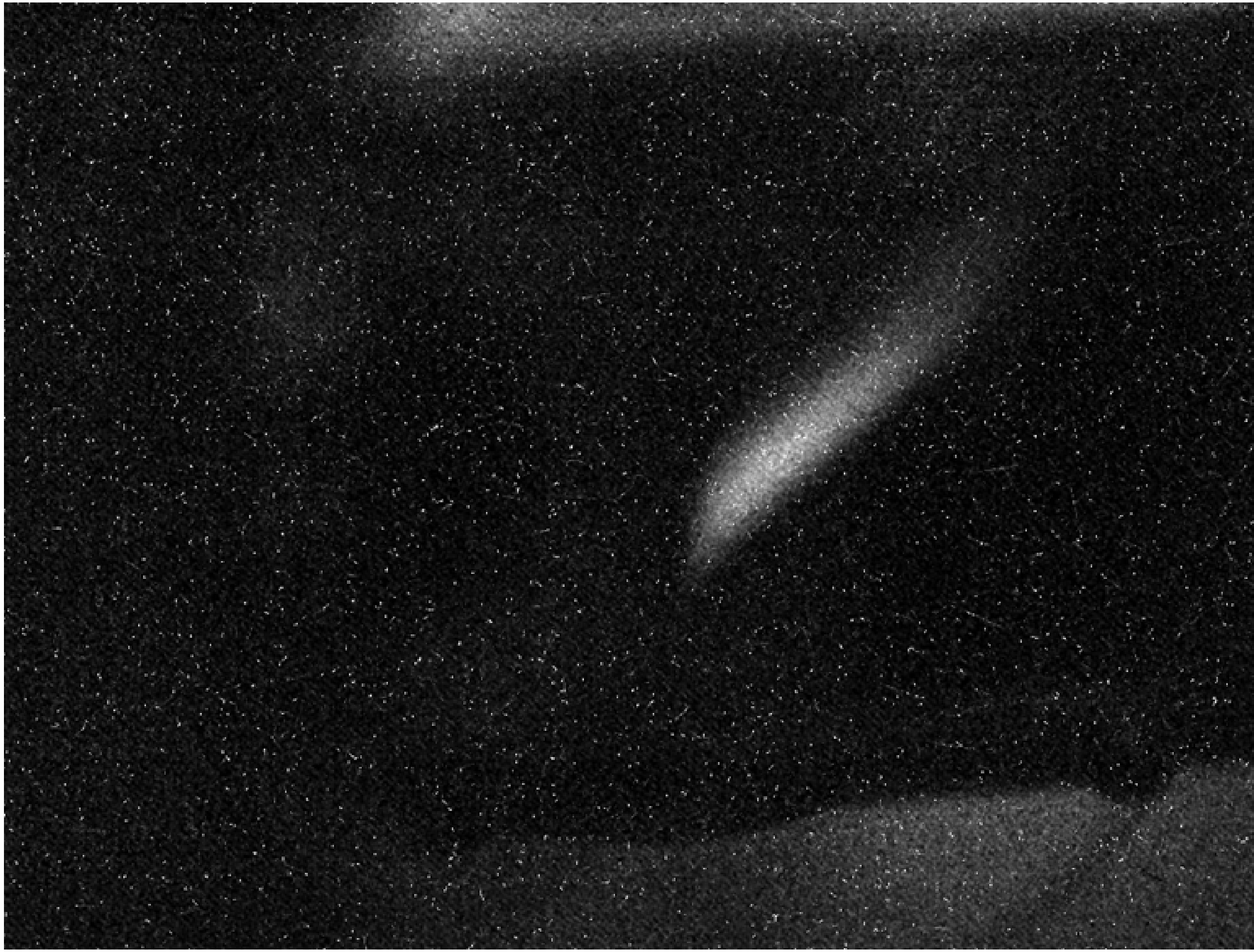
Early EEX Signature from Spectrometer



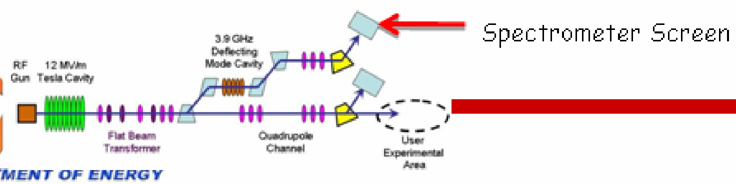


Cavity 40%

Early EEX Signature from Spectrometer

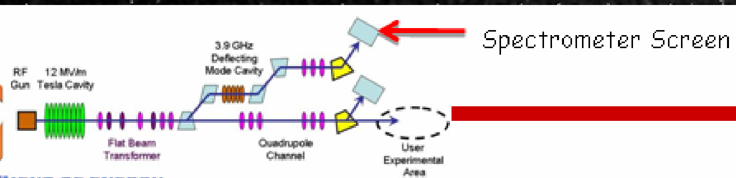


~ 550keV



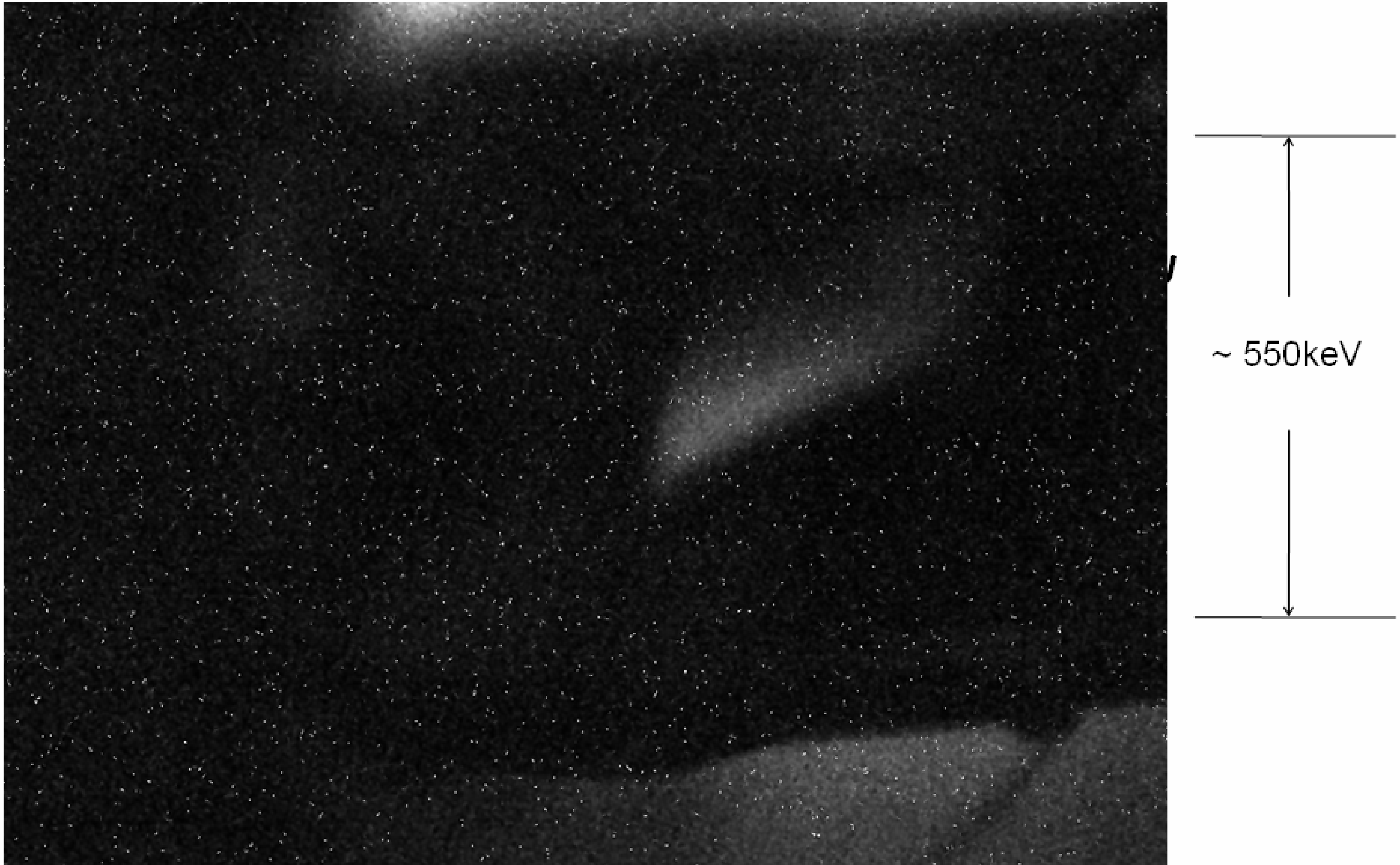
Cavity 50%

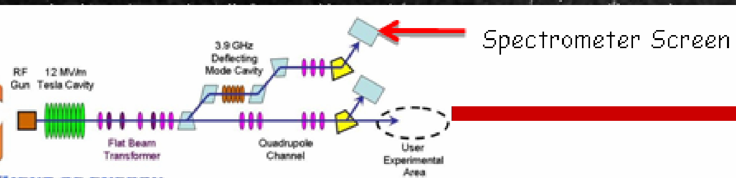
Early EEX Signature from Spectrometer



Cavity 60%

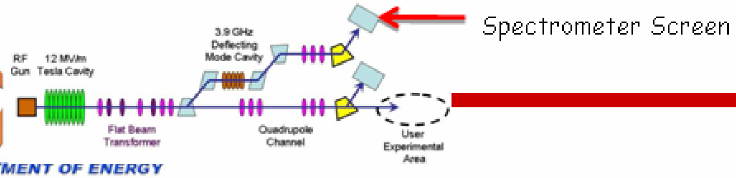
Early EEX Signature from Spectrometer





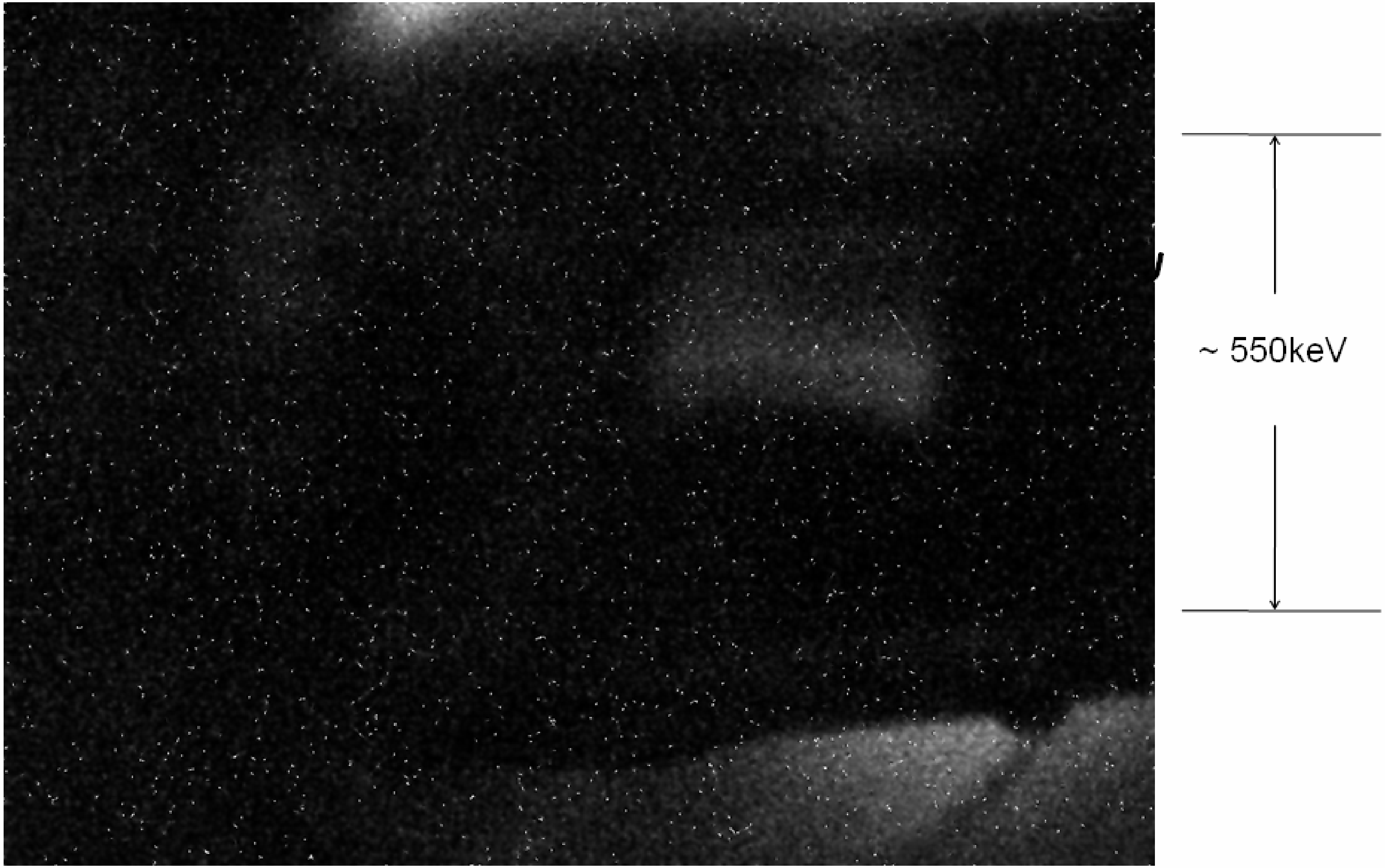
Cavity 70%

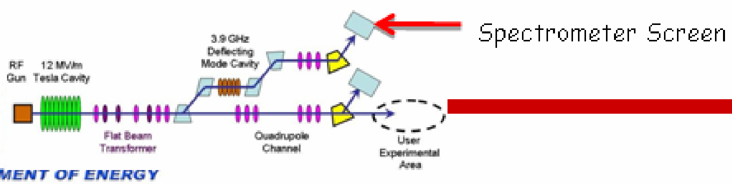
Early EEX Signature from Spectrometer



Cavity 80%

Early EEX Signature from Spectrometer

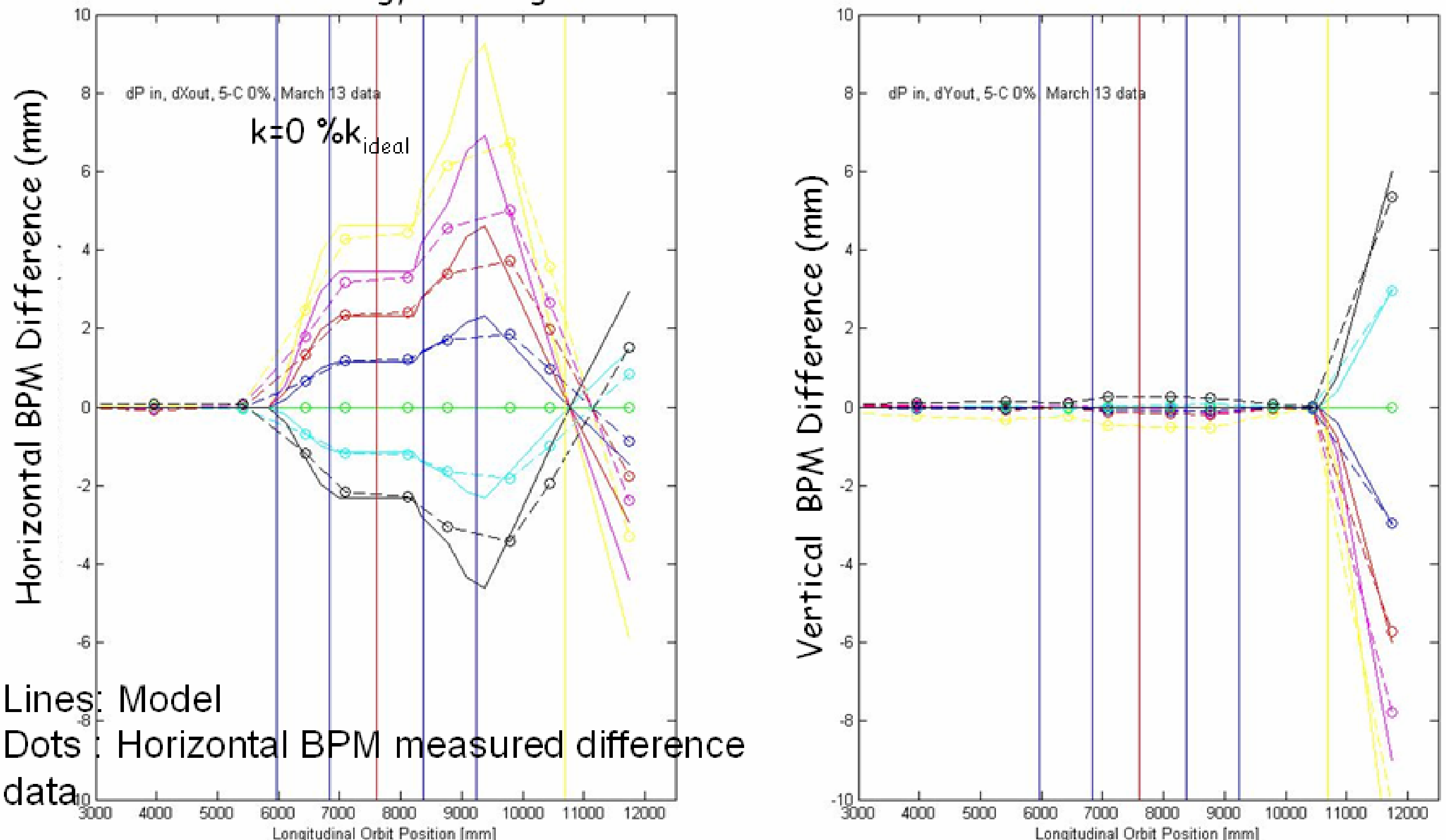




Cavity 100%

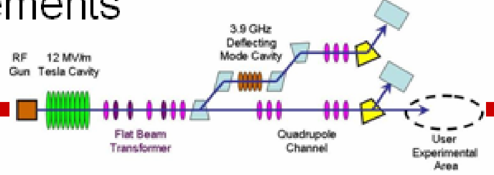
Measuring the R_{14} and R_{34} through the EEX line

Evolution of the beam trajectory as the cavity strength is increased, and energy is changed



Lines: Model
Dots : Horizontal BPM measured difference data

$\delta P = \pm 1.05$ % in 0.35 % increments



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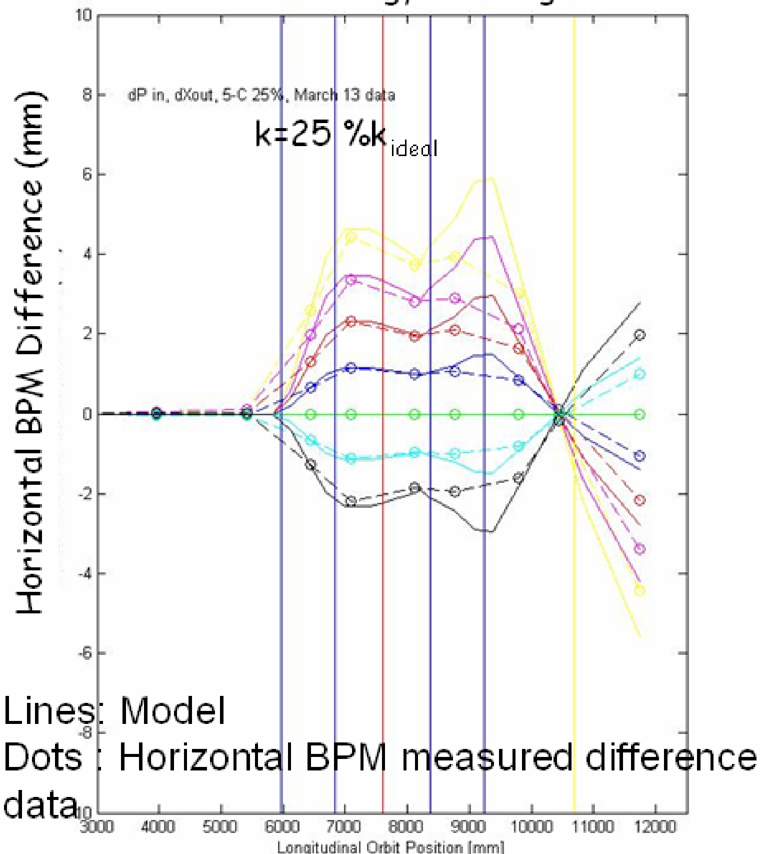
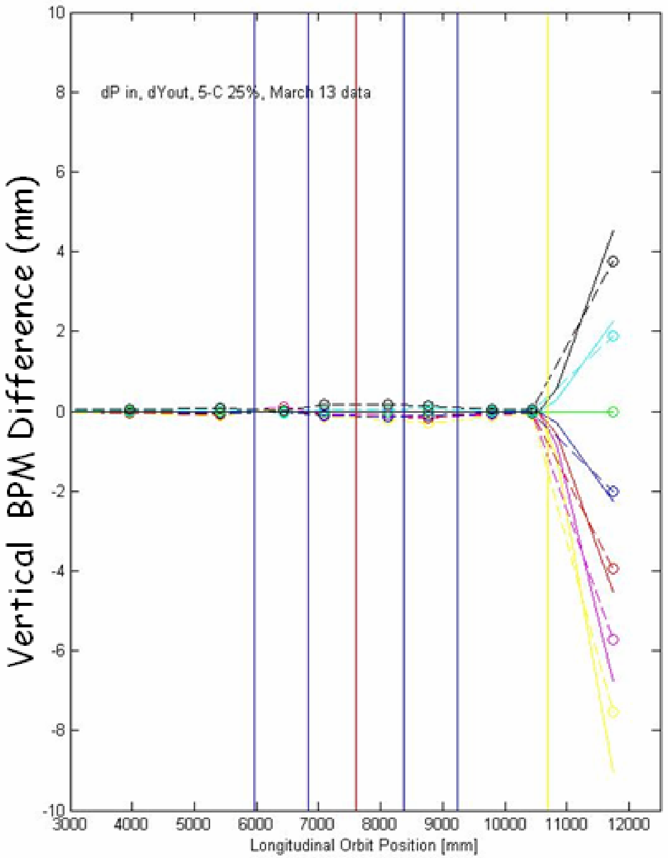
Evolution of the beam trajectory as the cavity strength is increased, and energy is changed





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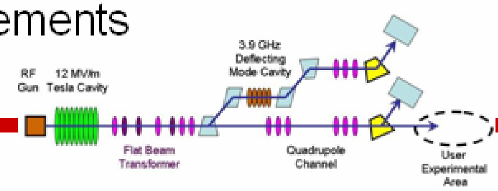

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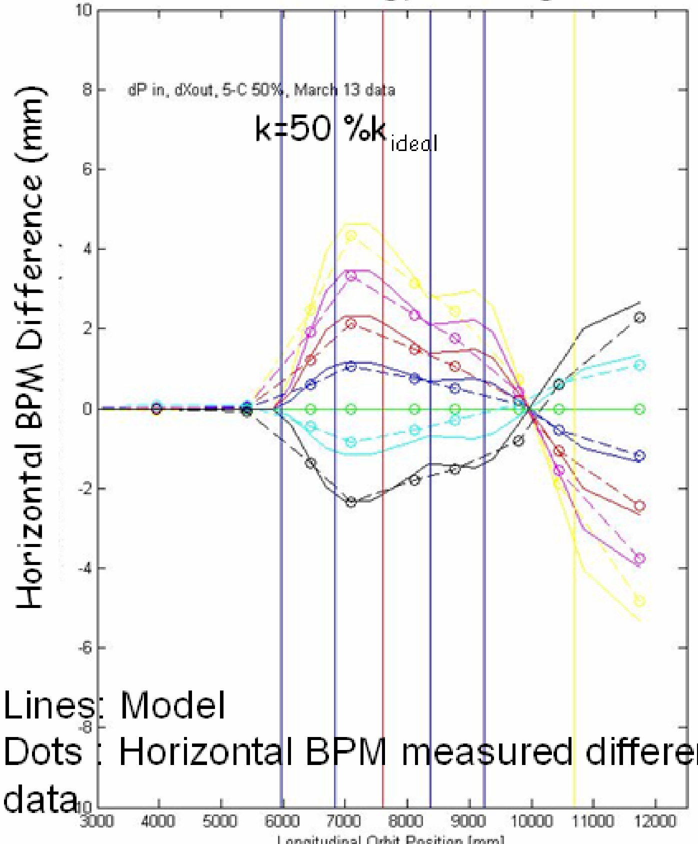
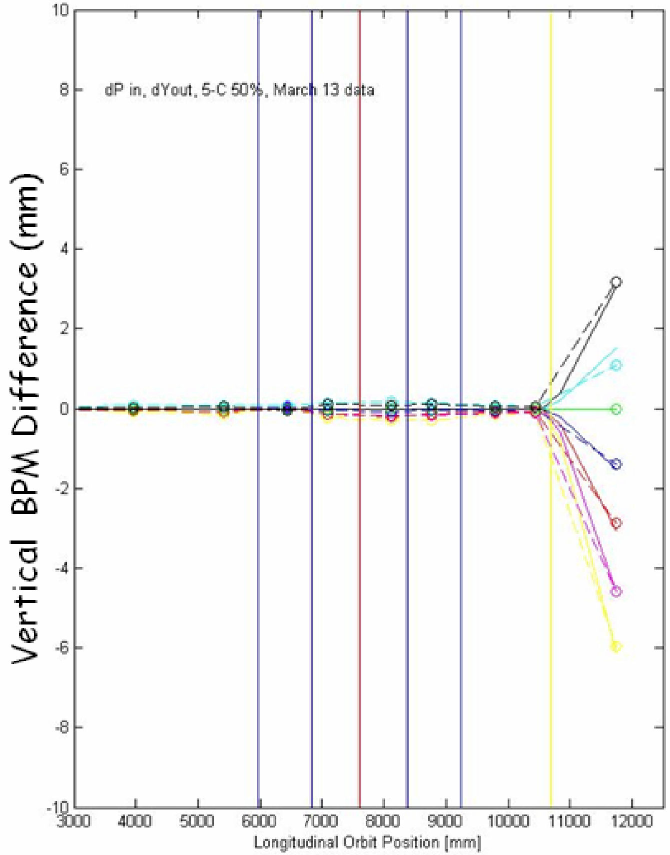
Evolution of the beam trajectory as the cavity strength is increased, and energy is changed





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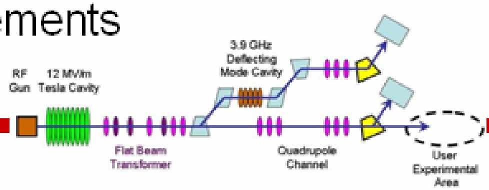

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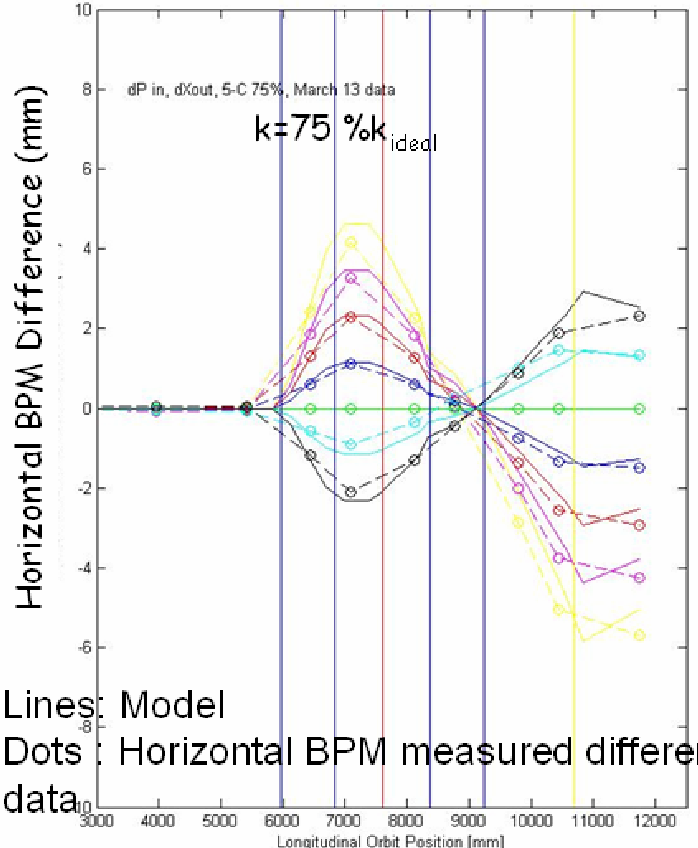

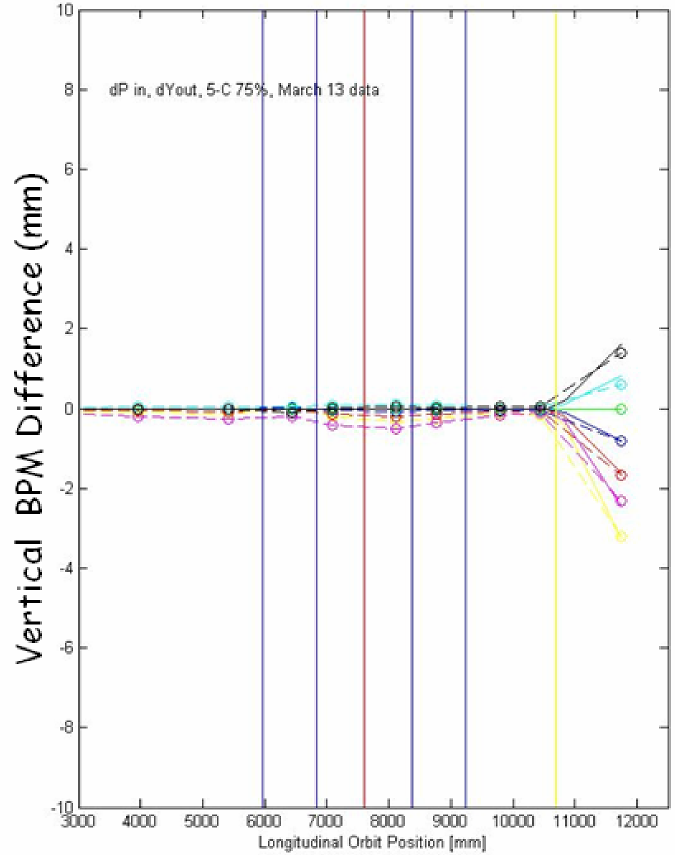

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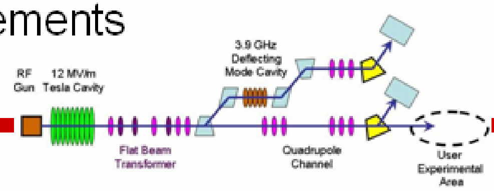
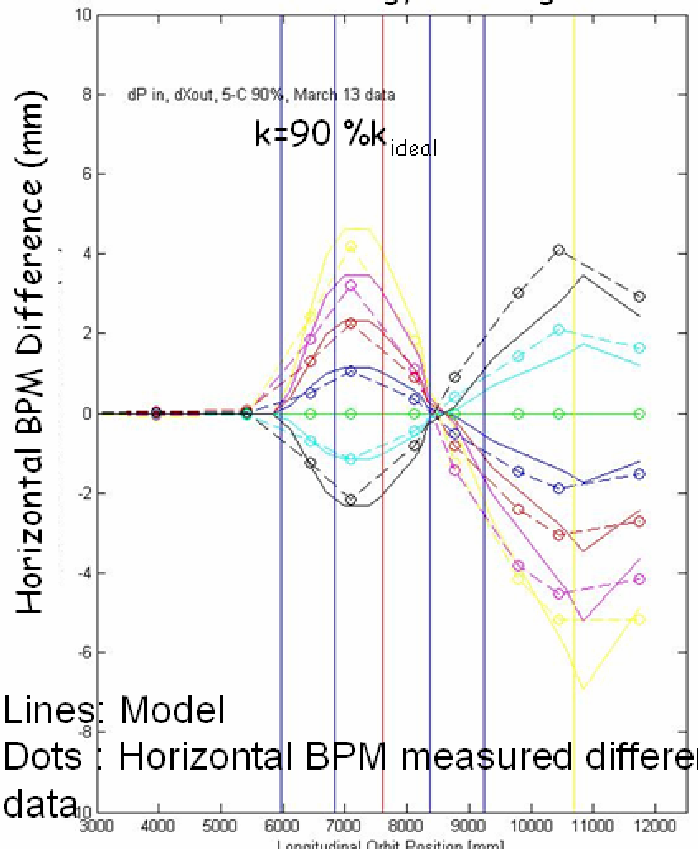


Measuring the R_{14} and R_{34} through the EEX line

Evolution of the beam trajectory as the cavity strength is increased, and energy is changed



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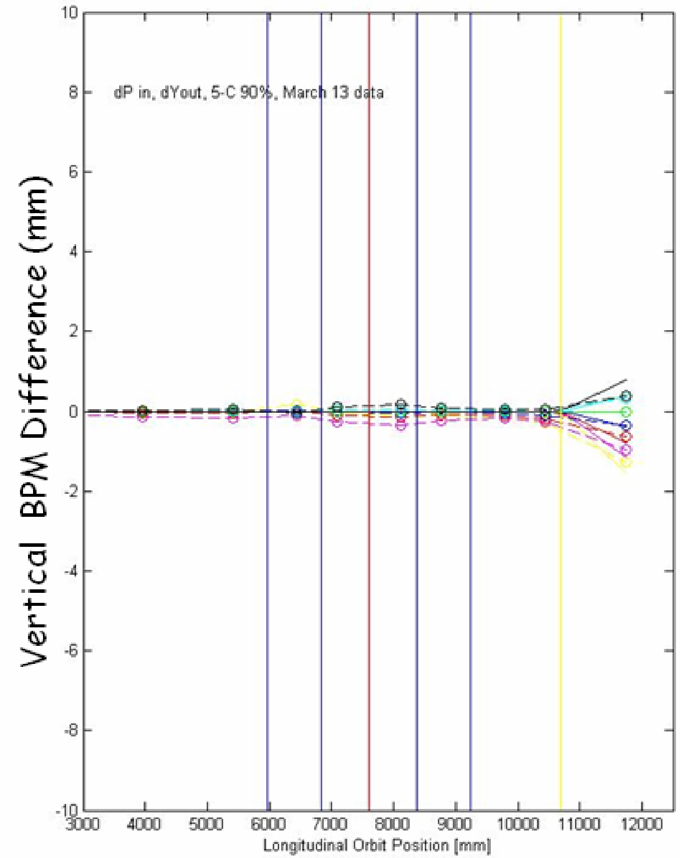

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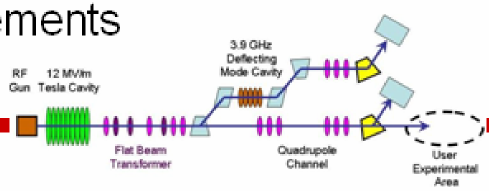

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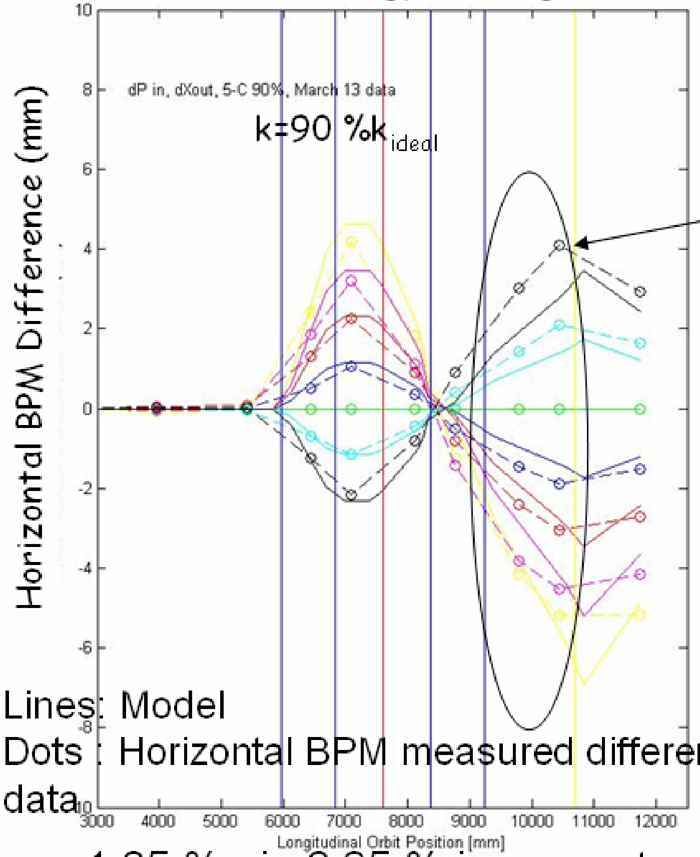

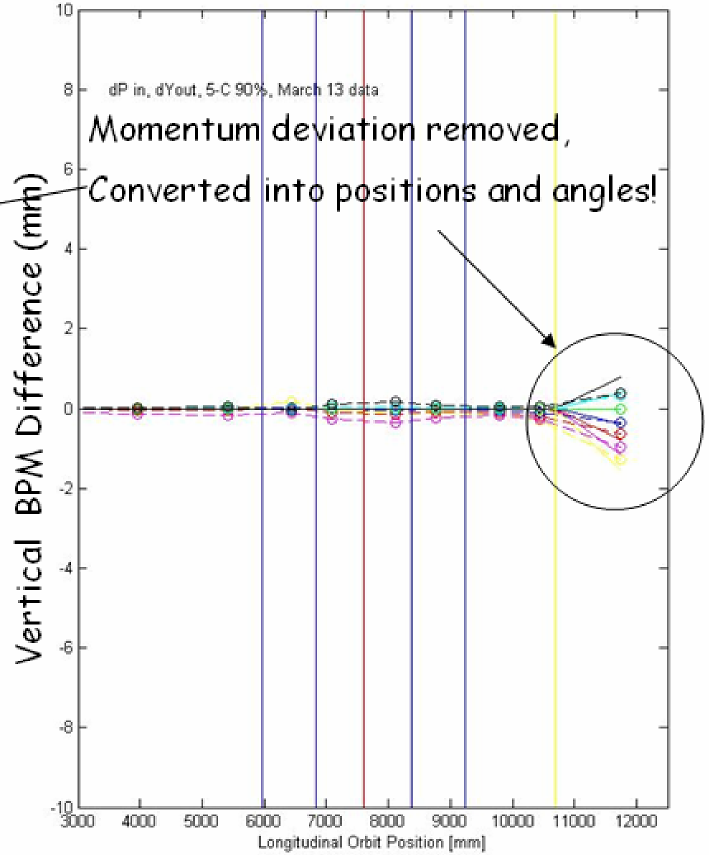

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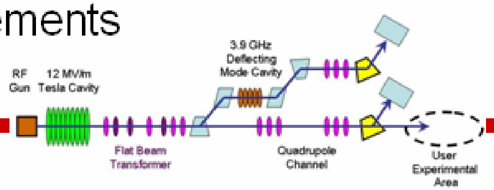
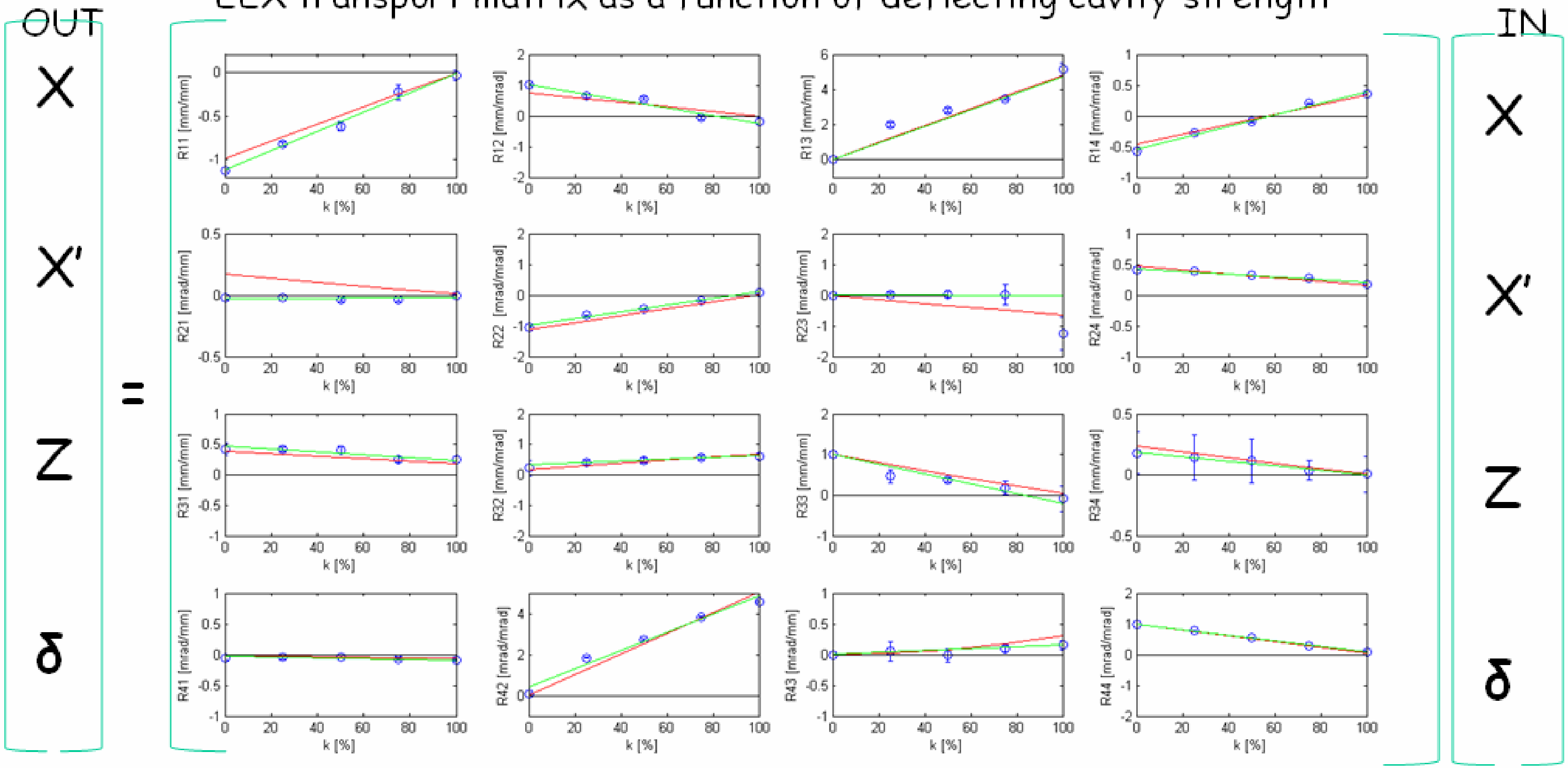


Measured EEX Transport Matrix FR5PFP020

EEX transport matrix as a function of deflecting cavity strength



Circles are measurements, green lines are a weighted linear fit

Red lines are calculated expected values

Measured full 6 x 6; the vertical plane is unaffected by the cavity status...

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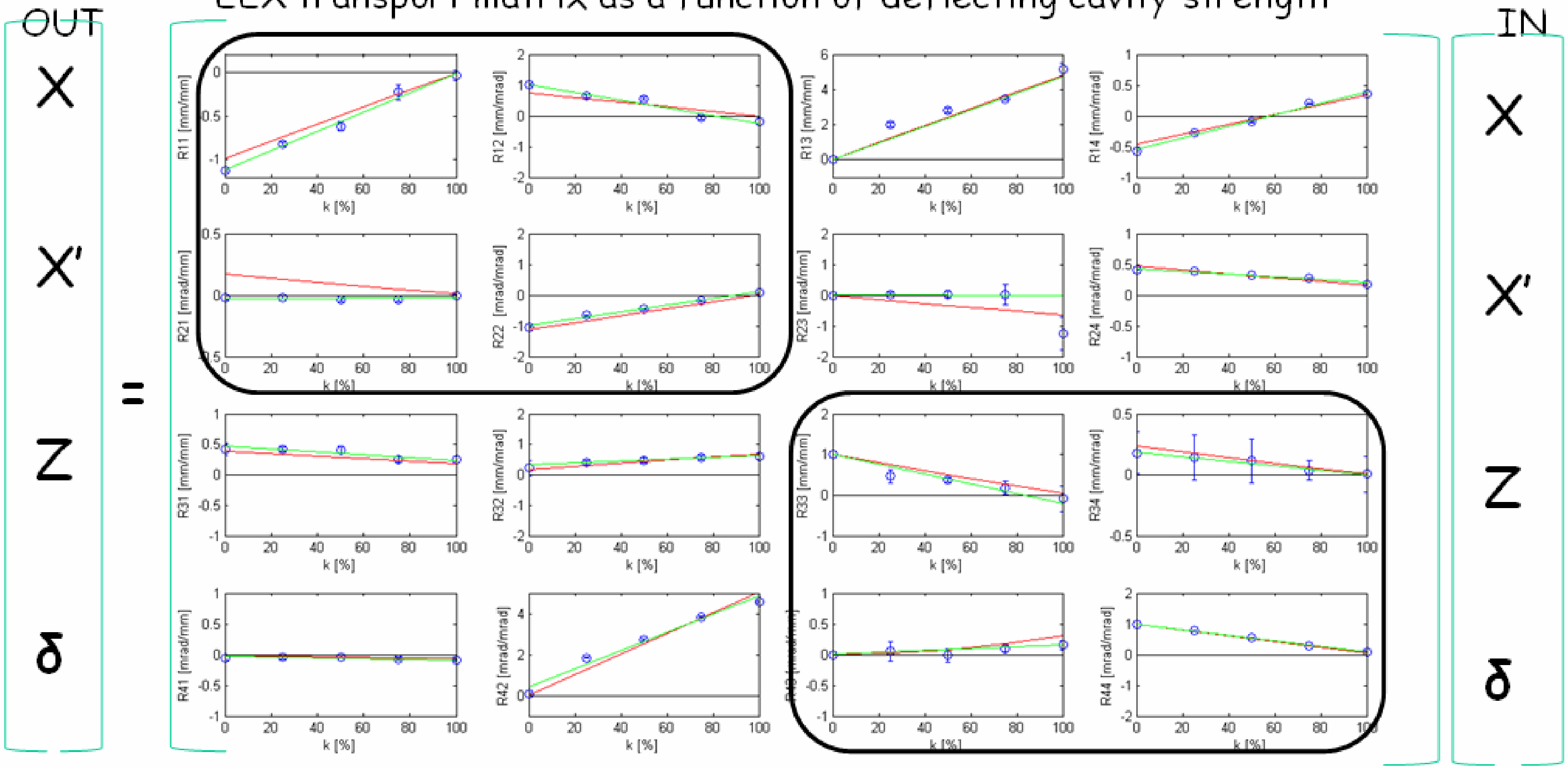

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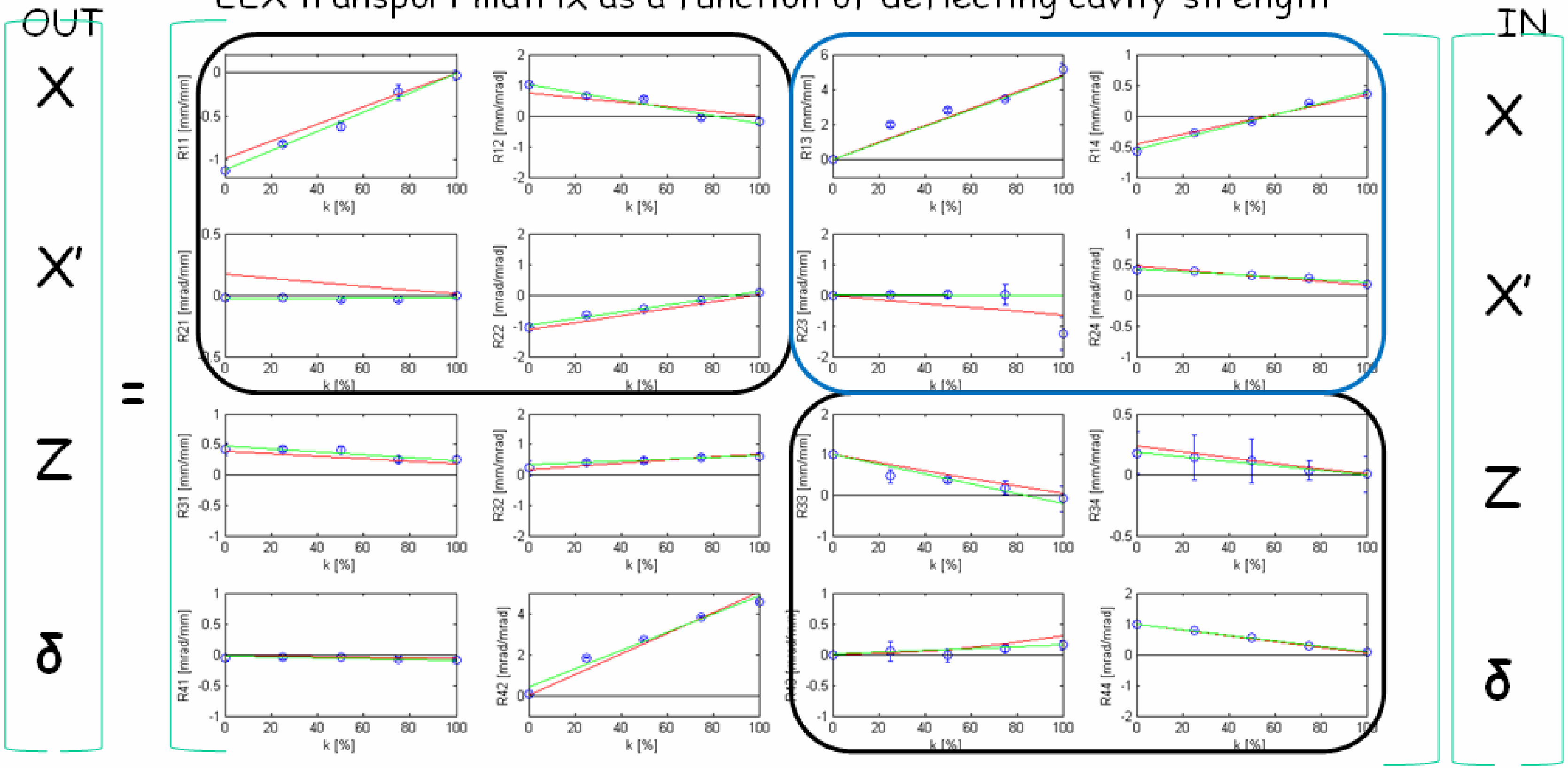
Measured EEX Transport Matrix FR5PFP020

EEX transport matrix as a function of deflecting cavity strength



Circles are measurements, green lines are a weighted linear fit

Red lines are calculated expected values

Measured full 6 x 6; the vertical plane is unaffected by the cavity status...

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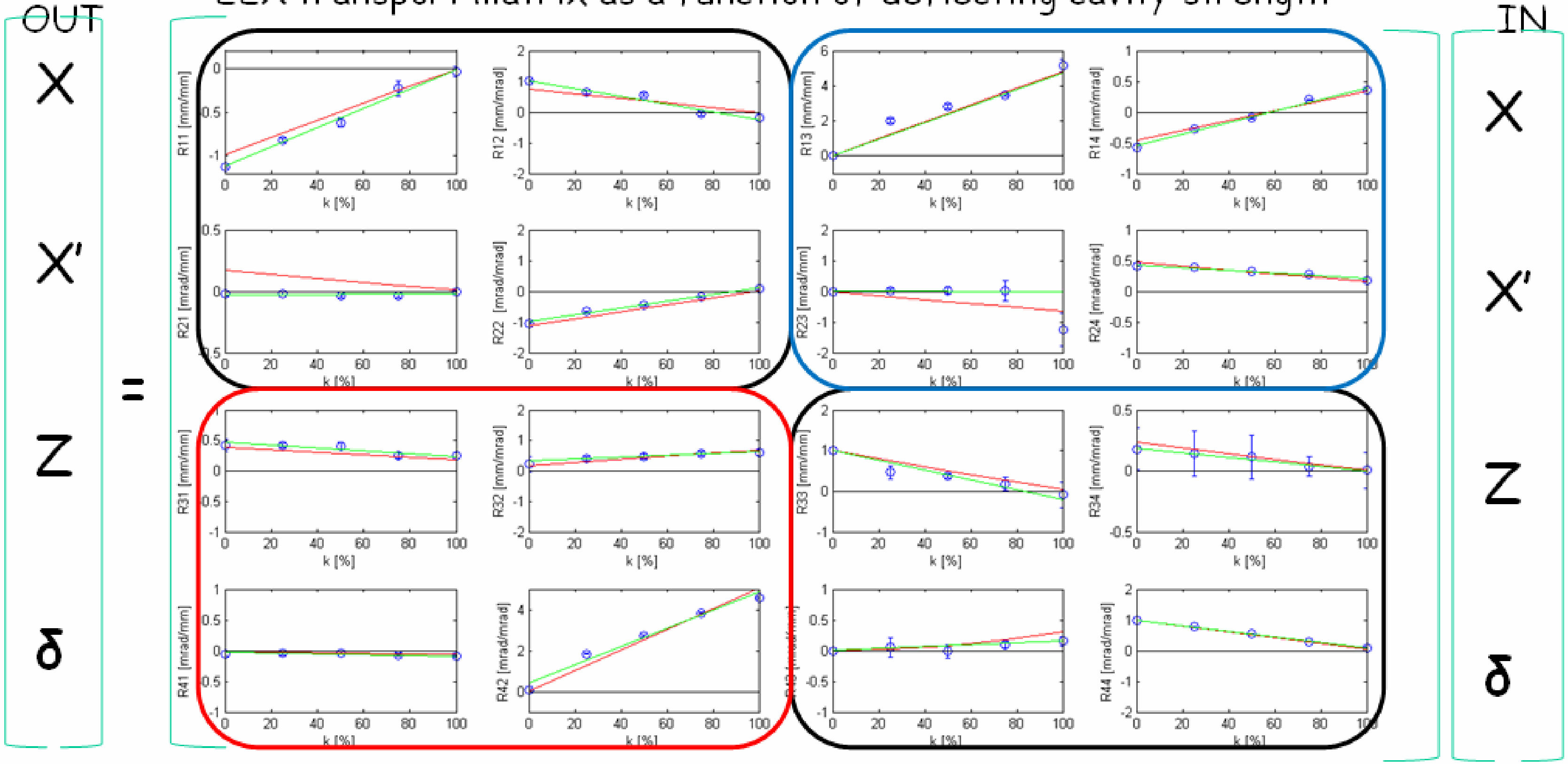

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Measured full 6 x 6; the vertical plane is unaffected by the cavity status...

Emittance Exchange Data Sets from A0

FR5PFP020

Plane	ε[mm-mrad] input	ε[mm-mrad] output
Horizontal	4.7	20
Vertical	5.1	6.0
Longitudinal	21	7.0

Successful exchange of horizontal and longitudinal emittances!!!

Future of AOPI EEX Program

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- Re-measure R_{23} and R_{43} element

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- Space Charge Studies

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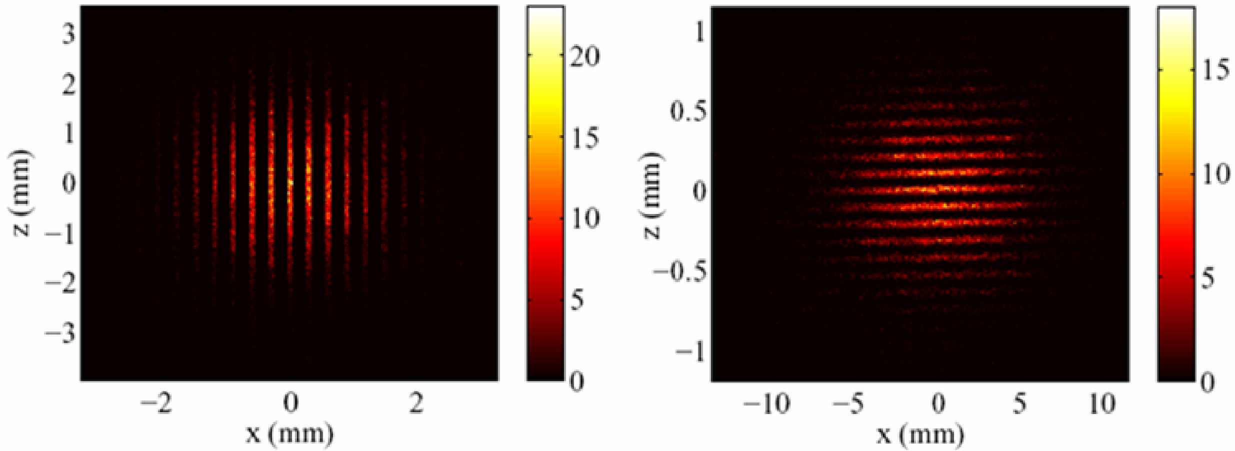
- Re-measure R_{23} and R_{43} element
- Space Charge Studies
- transverse-modulation → temporal Modulation



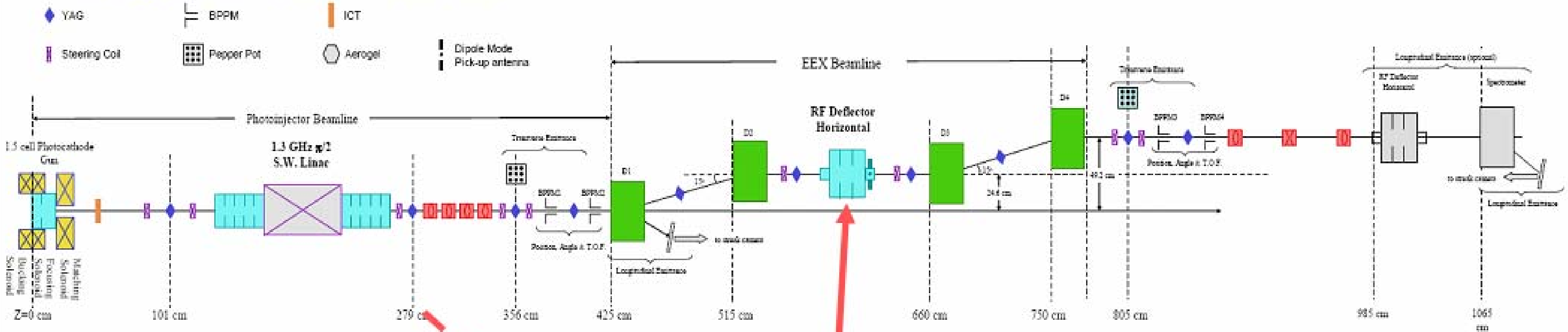
(pictures from Piot and Sun)

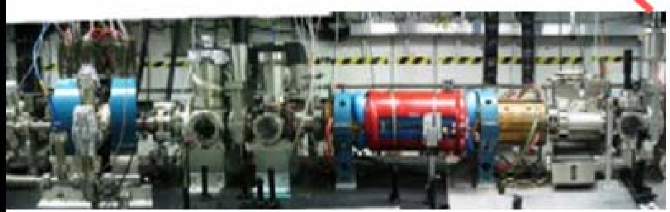
ANL's
Argonne Wakefield Accelerator

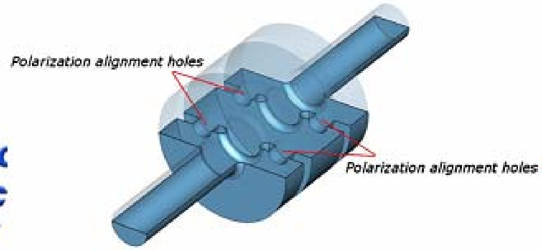
EX@AWA: overview/goals

FR5PFP039

- Exchange incoming emittance from $(\varepsilon_x,\varepsilon_z)=(22,3)$ μm to $(3,22)$ μm
- Exchanger beamline includes a $\frac{1}{2}+1+\frac{1}{2}$ cells deflecting cavity
- Possibly perform parametric study with varying incoming emittance partition, e.g., using a flat beam transform





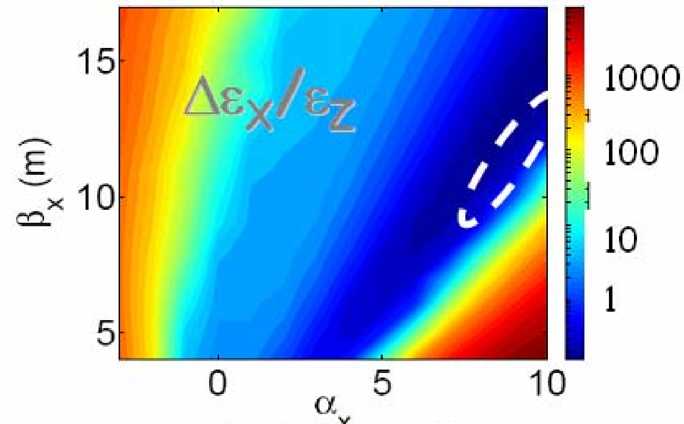


parameters	Value	units
Charge	100	pC
ε_x	22.3	μm
ε_z	2.90	μm
Energy	12.1	MeV

Incoming beam parameters after numerical optimization

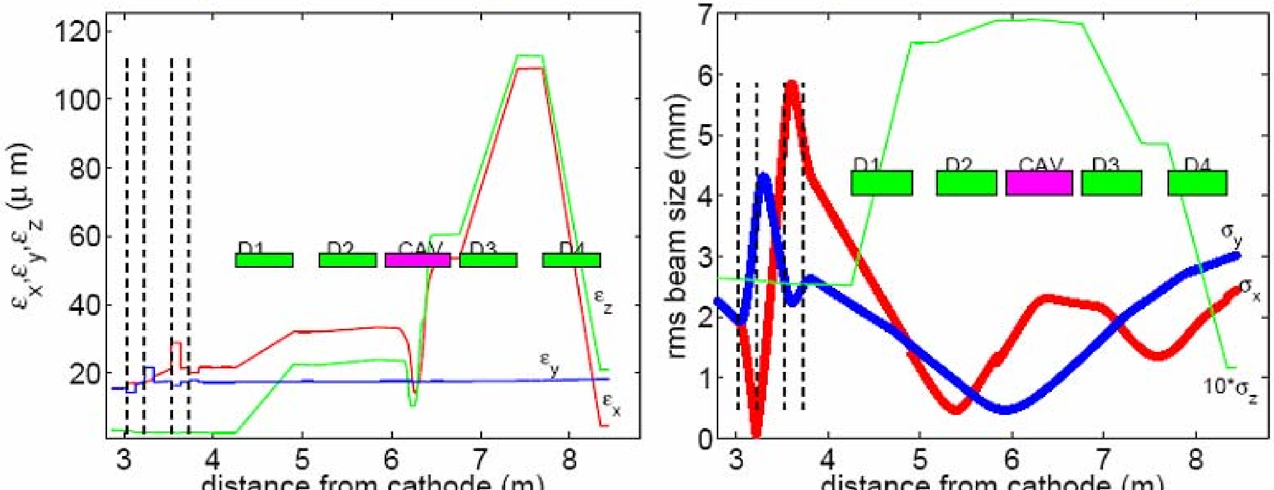
EX@AWA: modeling

- Explored and optimized the emittance exchange scheme at low energy [taking into account collective effects (space charge)]
- Emittance exchange very sensitive to incoming transverse Courant-Snyder parameters
- Best exchange numerically achieved so-far:



Space Charge	ϵ_{xi}	ϵ_{zi}	ϵ_{xf}	ϵ_{zf}	units
OFF	22.3	2.90	4.4	22.67	μm
ON	21.58	2.54	4.7	20.90	μm

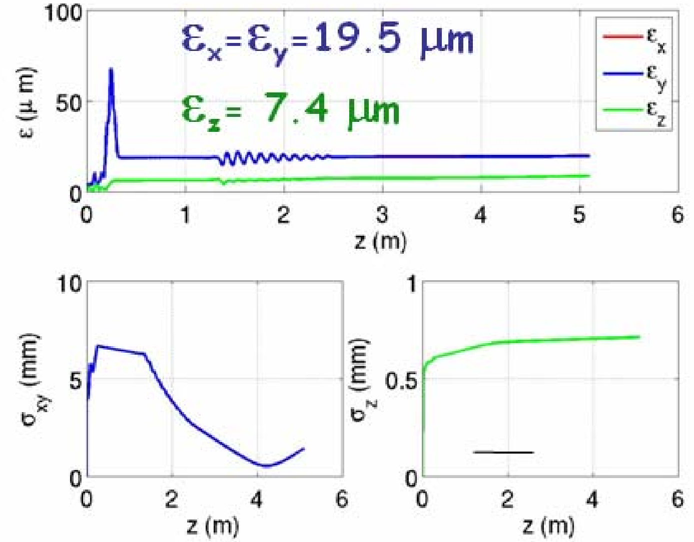
Emittances (left) and beam size (right) evolution along the EX-beamline (PIC simulations performed with Impact-T from LBNL)



EX@AWA: experimental progress

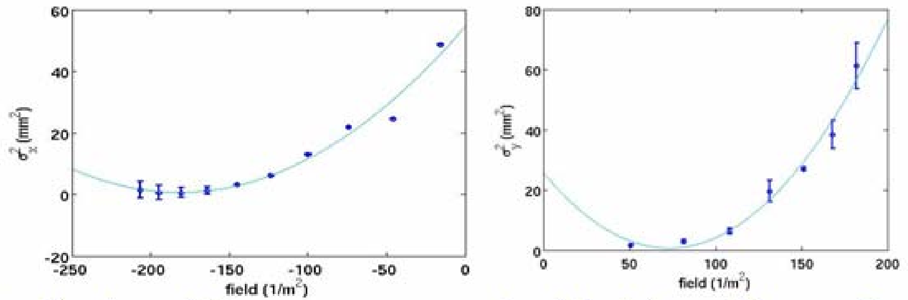
- To date measured the achievable emittance partition downstream of the linac (before EX)
- The emittance-exchanging beamline will be installed this summer

Simulations FR5PFP039

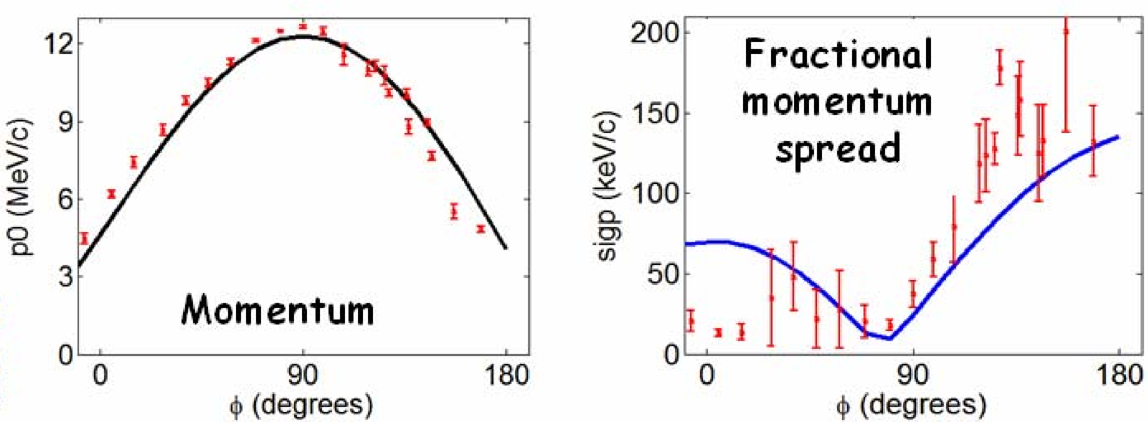


Transverse emittance measured with quadrupole scan

$\varepsilon_x=18.4+/-2$ µm $\varepsilon_y=21.2+/-$ 2 µm



Longitudinal emittance measured with Linac Phase Scan



Longitudinal emittance from ImpactT simulatio

ε_z=6.5 µm

U.S. DEP.

BROOKHAVEN NATIONAL LABORATORY
BROOKHAVEN SCIENCE ASSOCIATES

Conclusion

•The A0 Photoinjector has constructed a transverse to longitudinal emittance exchange beamline to swap a small transverse emittance with a large longitudinal emittance.

- **•A0 Photoinjector has successfully shown an emittance exchange!**

•AWA is also persuing an emittance exchange experiment. They will swap a large transverse emittance with a small longitudinal emittance.

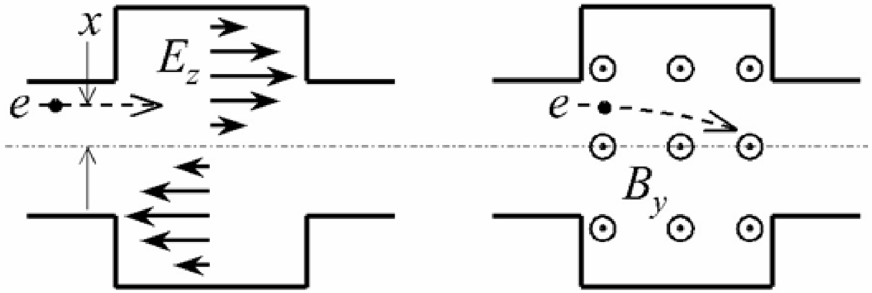
- •Hardware is in hand
- •Installation will begin this summer
- •Work continues on simulations and understanding the input beam parameters

•Other ideas of how to use these manipulations are also around.

- •Couple with a round to flat beam transformer
- •Making a microbunch train

Thanks for your attention

TM_{110} Deflecting Mode Cavity (DMC)



Derived from Figure 1 of C&E.
Electric field at synchronous phase.
Magnetic field a quarter period later.

- No longitudinal electric field on axis.
- Electric field imparts an energy kick proportional to distance off axis.
- Electro-magnetic field provides deflection as a function of arrival time.
- This type of cavity can be used as a crab cavity or for bunch length measurement.

$$M_{Thin-Cav} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & k & 0 \\ 0 & 0 & 1 & 0 \\ k & 0 & 0 & 1 \end{pmatrix}$$

$$k = \frac{eV_0\omega}{Ec}$$

k is the integrated transverse kick normalized to the beam energy *E*.

Making an Emittance Exchange - Part I

- The 4x4 emittance matrix at two points in an accelerator are related by:

$$\sigma_1 = \begin{pmatrix} \sigma_x^2 & \sigma_{xx'} & 0 & 0 \\ \sigma_{xx'} & \sigma_{x'}^2 & 0 & 0 \\ 0 & 0 & \sigma_z^2 & \sigma_{z\delta} \\ 0 & 0 & \sigma_{z\delta} & \sigma_\delta^2 \end{pmatrix} \qquad \sigma_2 = R\sigma_1 R^T$$

- R is the 4x4 transport matrix between these points

$$R = \begin{pmatrix} A & B \\ C & D \end{pmatrix}$$

- B and C typically have zero determinant and couple transverse and longitudinal emittances through dispersion.
- The emittances after the transport line are given by:

$$\varepsilon_{x2}^{\ 2} = |A|^2 \varepsilon_{x1}^{\ 2} + |B|^2 \varepsilon_{z1}^{\ 2} + \lambda^2 \varepsilon_{x1}\varepsilon_{z1}$$

$$\varepsilon_{z2}^{\ 2} = |C|^2 \varepsilon_{x1}^{\ 2} + |D|^2 \varepsilon_{z1}^{\ 2} + \lambda^2 \varepsilon_{x1}\varepsilon_{z1}$$

$$\lambda^2 \varepsilon_{x1}\varepsilon_{z1} = tr\left[\left(A\sigma_{x1}A^T\right)^a B\sigma_{z1}B^T\right] = tr\left[\left(C\sigma_{x1}C^T\right)^a D\sigma_{z1}D^T\right]$$

Derivation follows C&E

Making an Emittance Exchange - Part II

- These equations show that for perfect exchange we need:

$$|A| = |D| = 0$$

$$|B| = |C| = 1$$

Follows from the symplectic condition

$$\lambda^2 = 0$$

- How to get $\lambda^2=0$?

$$A_{ij} = D_{ij} = 0$$

- If $\lambda^2 \neq 0$ the emittances are coupled.
  - Proper adjustment of the σ matrix can reduce or remove the coupling.