Transverse to Longitudinal Emittance Exchange Results

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ICFA Mini Workshop

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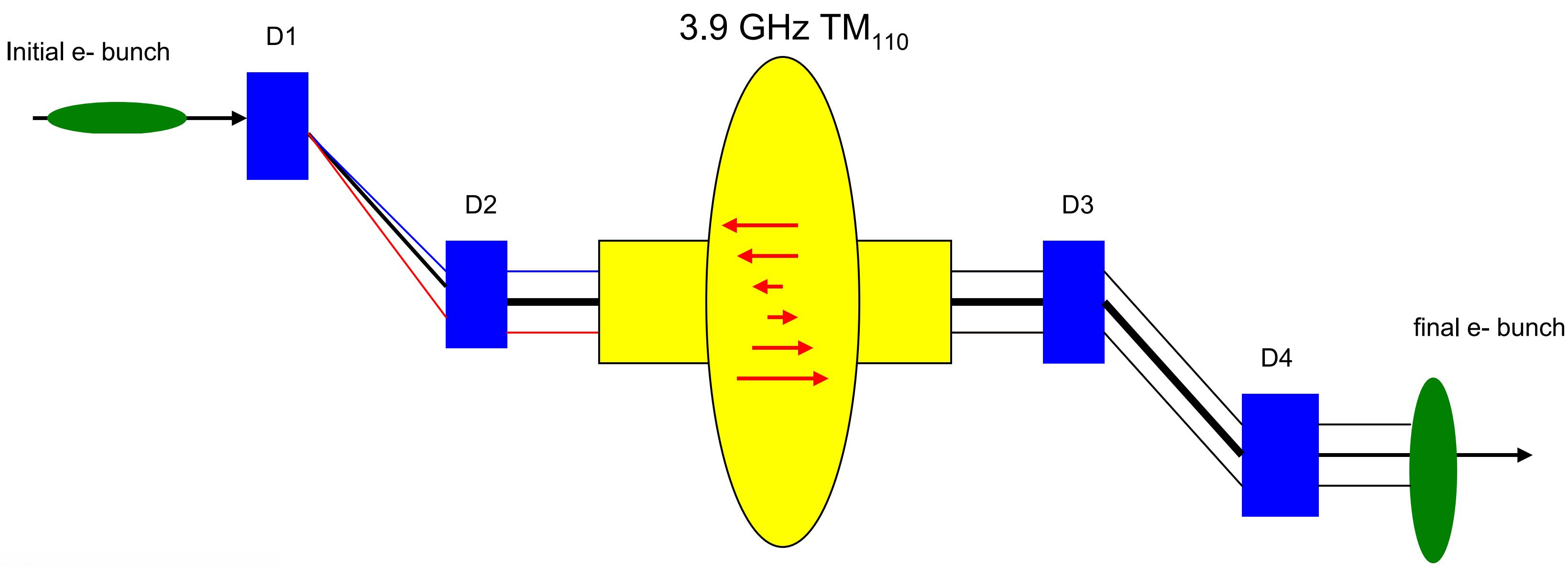
Transverse to Longitudinal Emittance Exchange – How?

- 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?

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

- 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.

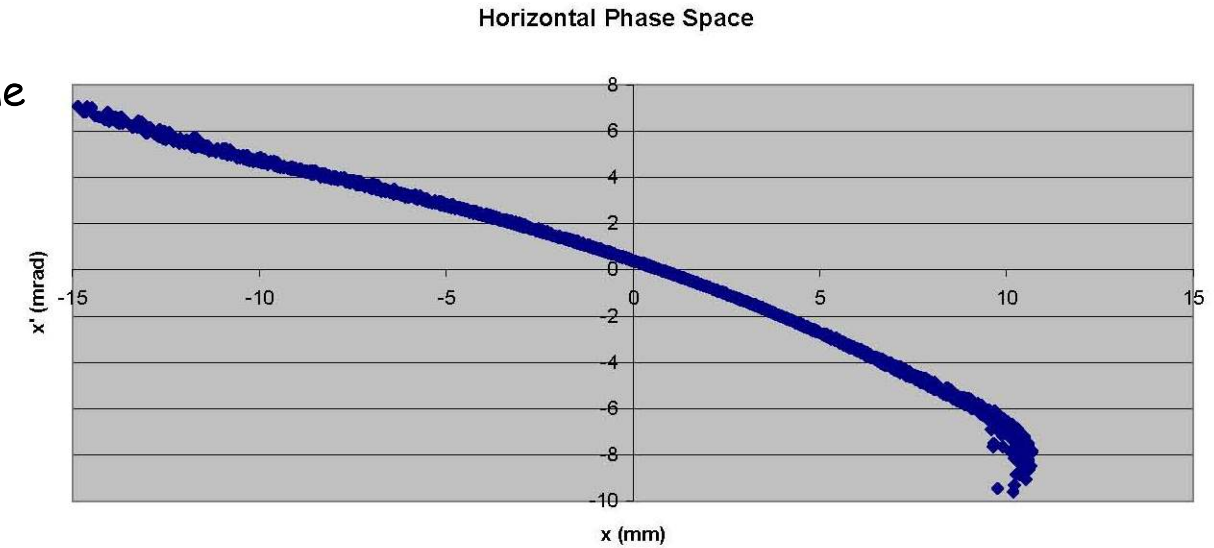
These can be minimized or eliminated by manipulating the incoming beam phase spaces

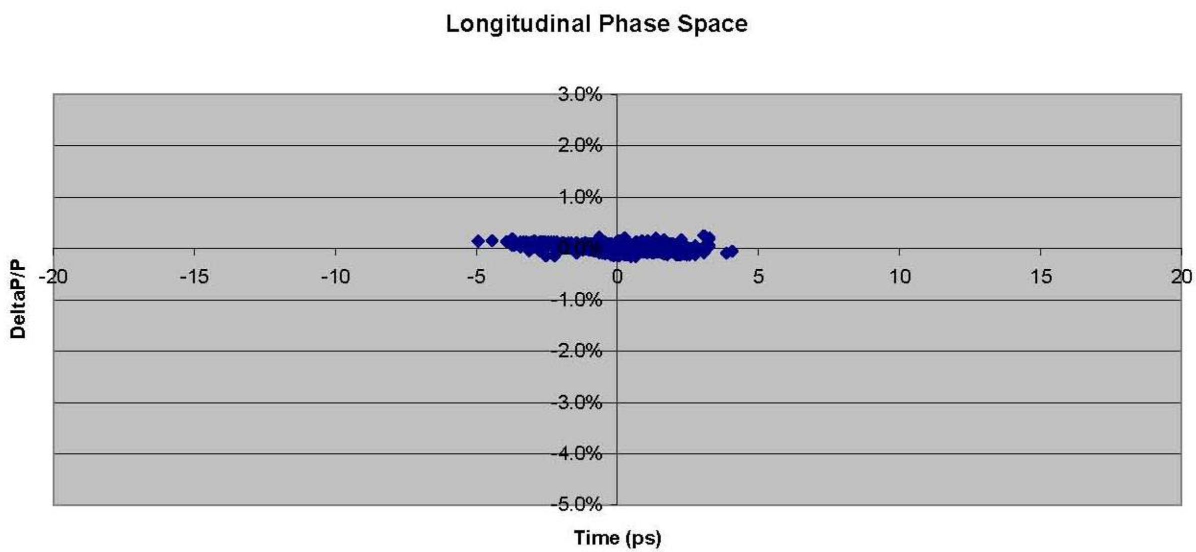
  - Ugly Flies – these can blow up the emittances, possibly washing out the effect of the exchange
    - Space charge
    - Coherent Synchrotron Radiation

    These can be minimized by lowering the beam charge.

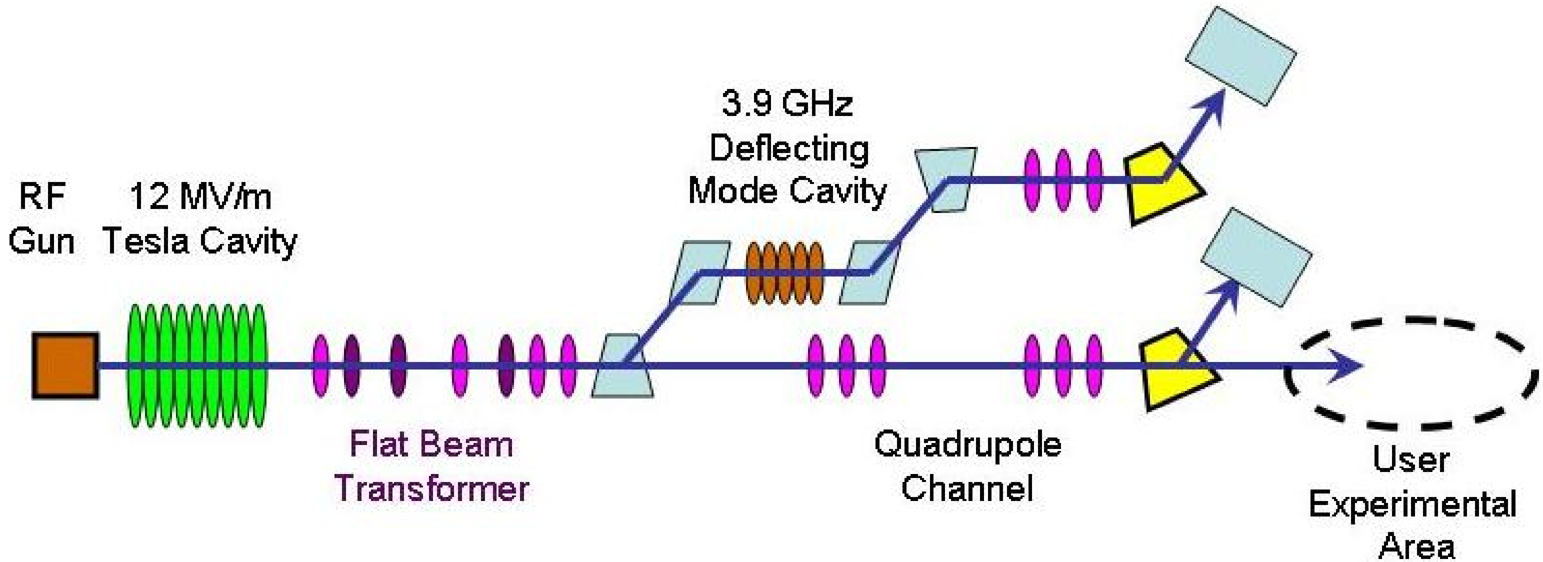
Watching the Exchange – The Fermilab experiment

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





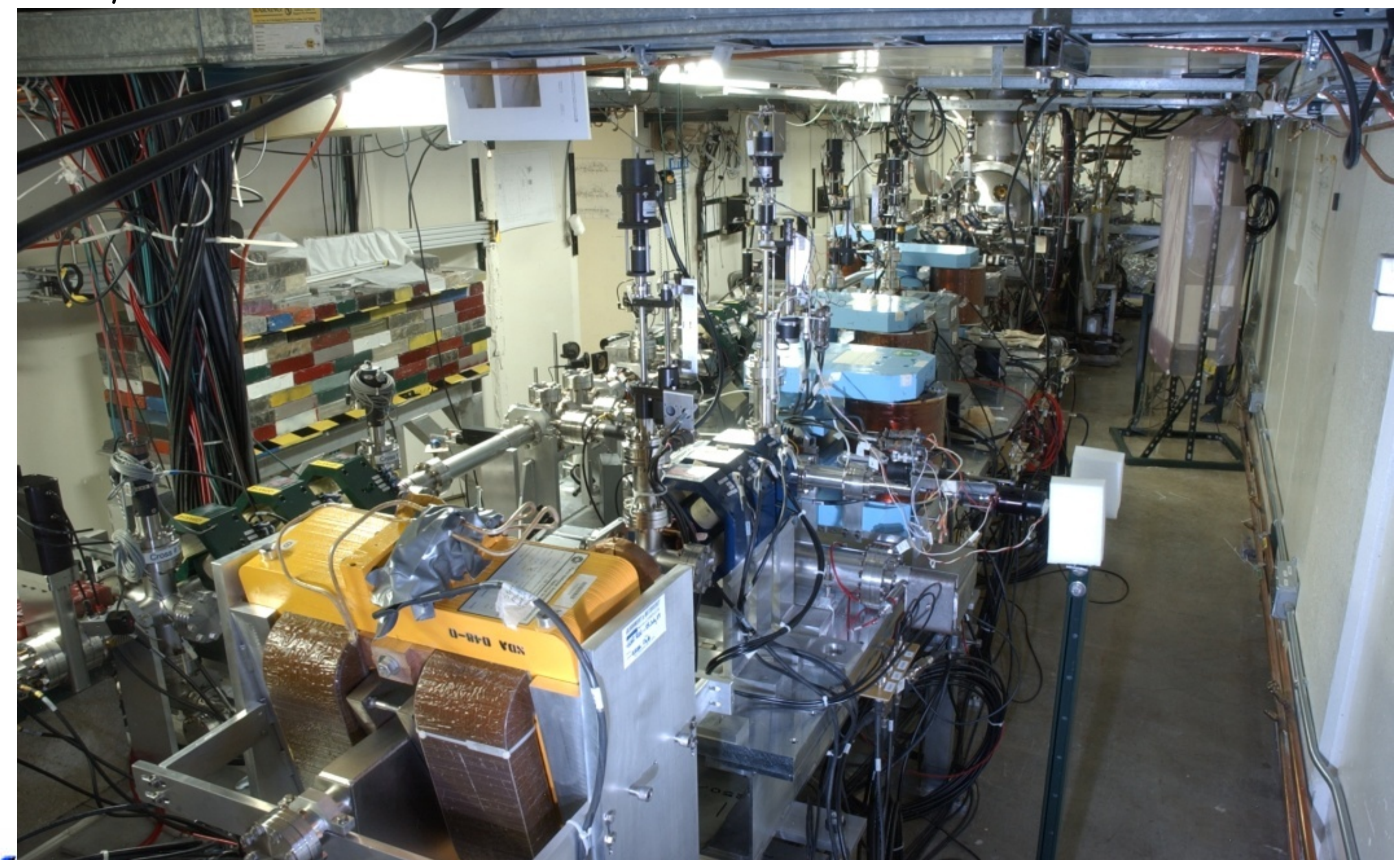
A0 Photoinjector



- 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

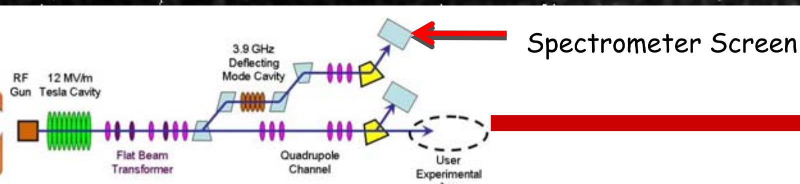
Beam Parameters

- 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)



Early EEX Signature from Spectrometer

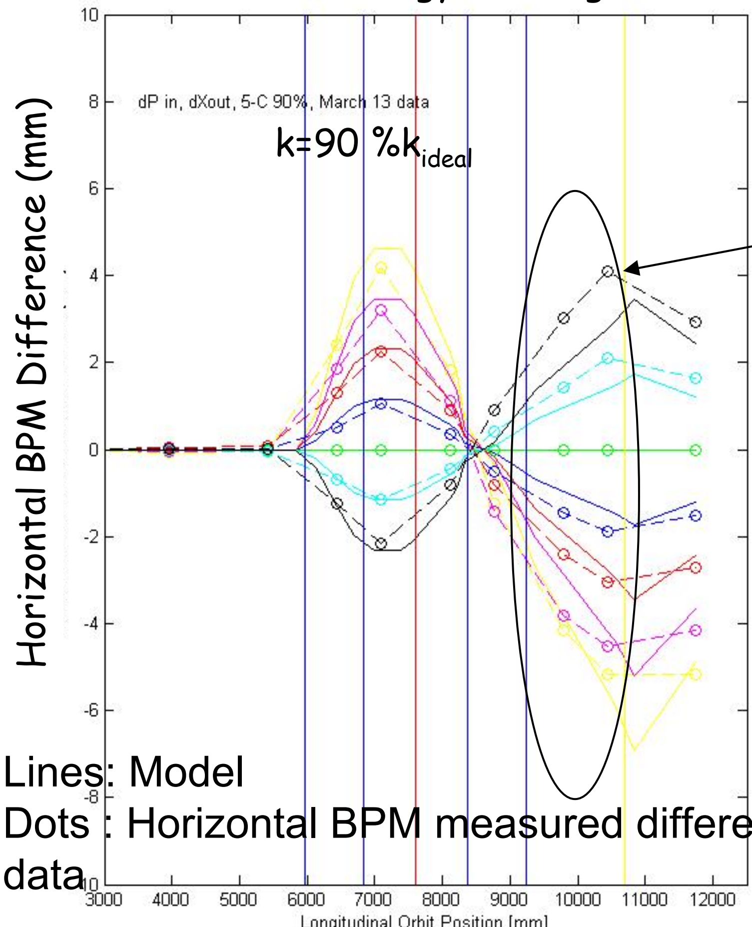
~ 550keV

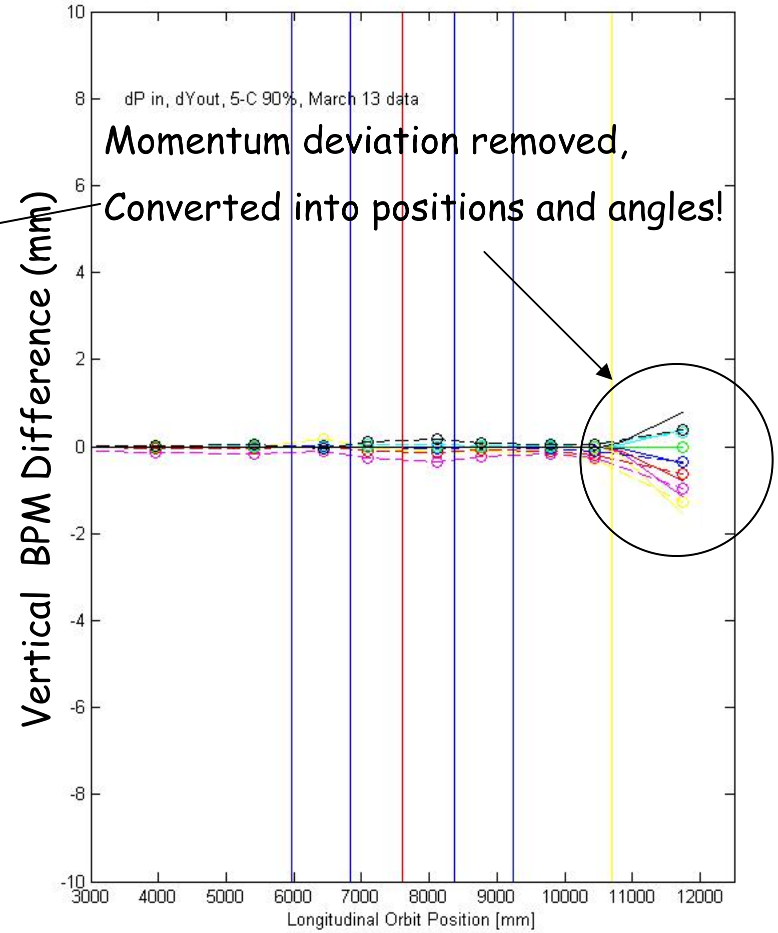


Cavity 100%

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

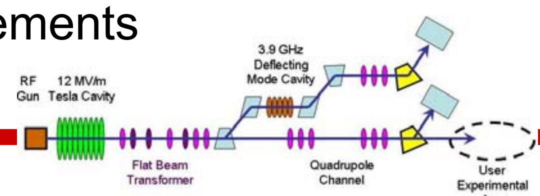
Evolution of the beam trajectory as the cavity strength is increased, and energy is changed





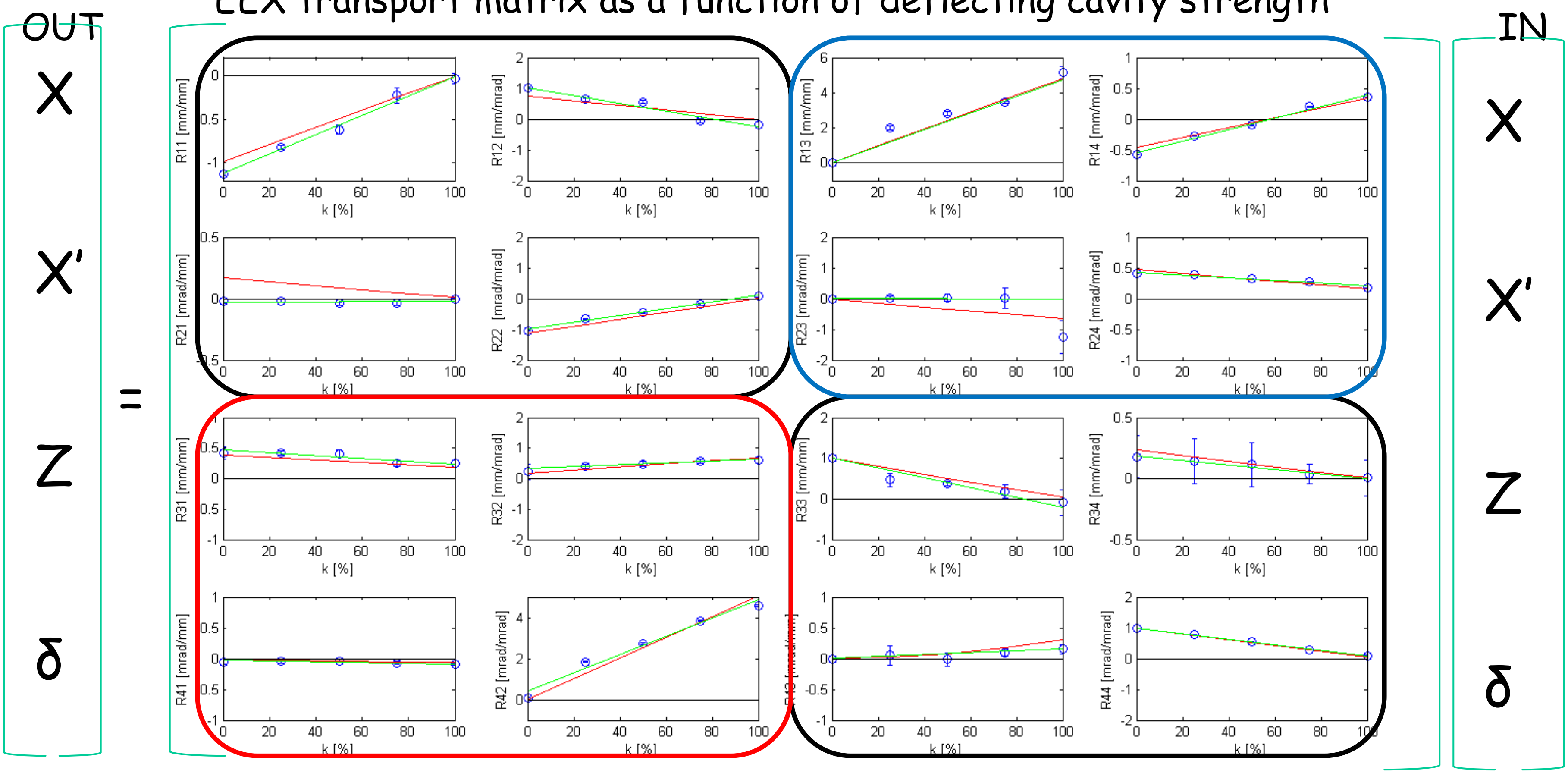
Lines: Model
Dots : Horizontal BPM measured difference data

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



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…

Emittance Exchange Data Sets from A0 - PRELIMINARY!!!

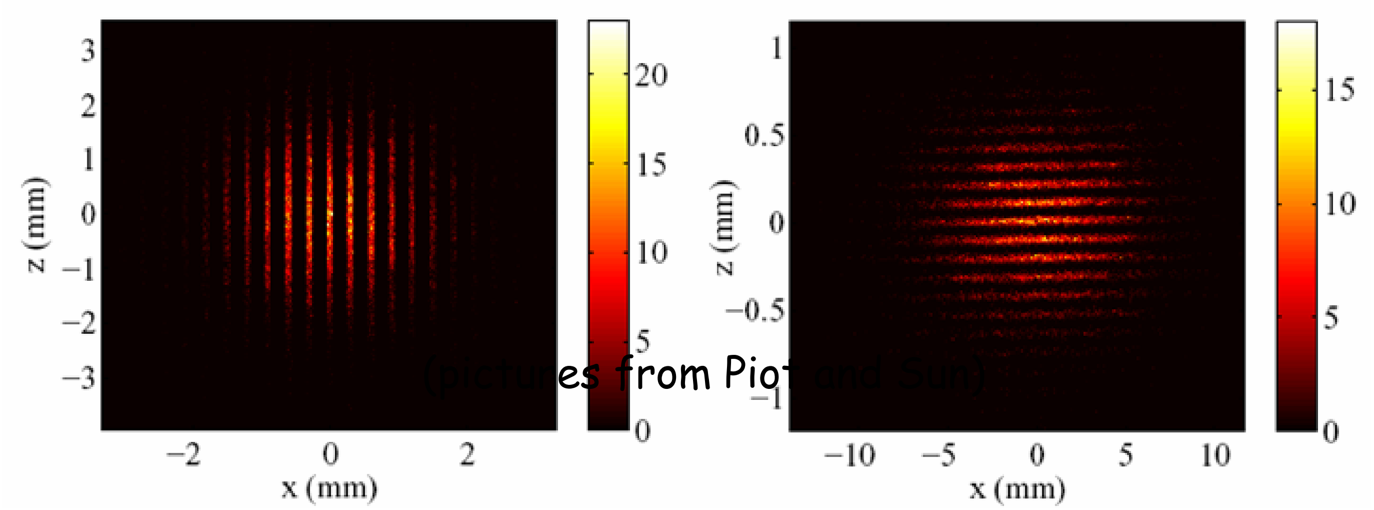
Note: These numbers subject to change

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

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



(pictures from Piot and Sun)

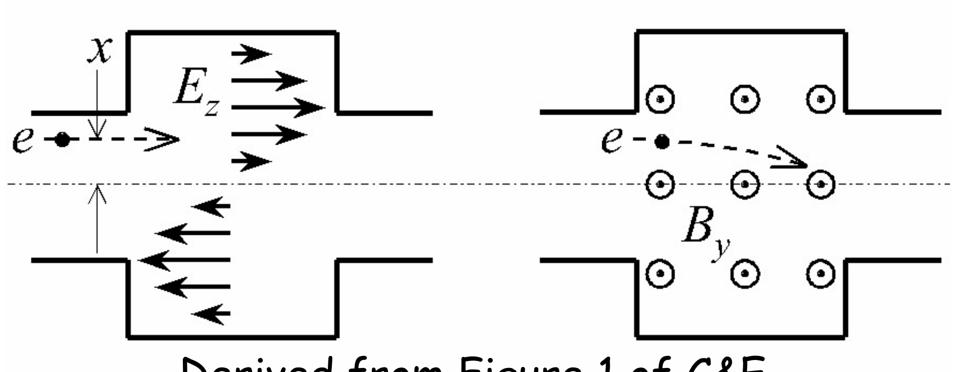
Conclusion

- 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!**

- 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.

Derivation follows C&E