Experimental studies on coherent synchrotron radiation at an emittance exchange beam line

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Outline of the talk

Motivation

I. Emittance exchange beamline

- Diagnostics
- Measurements

II. Coherent synchrotron radiation studies

- Detection and characterization of radiation
- Studies on the electron beam

III. Experimental results of emittance exchange with chirped beam

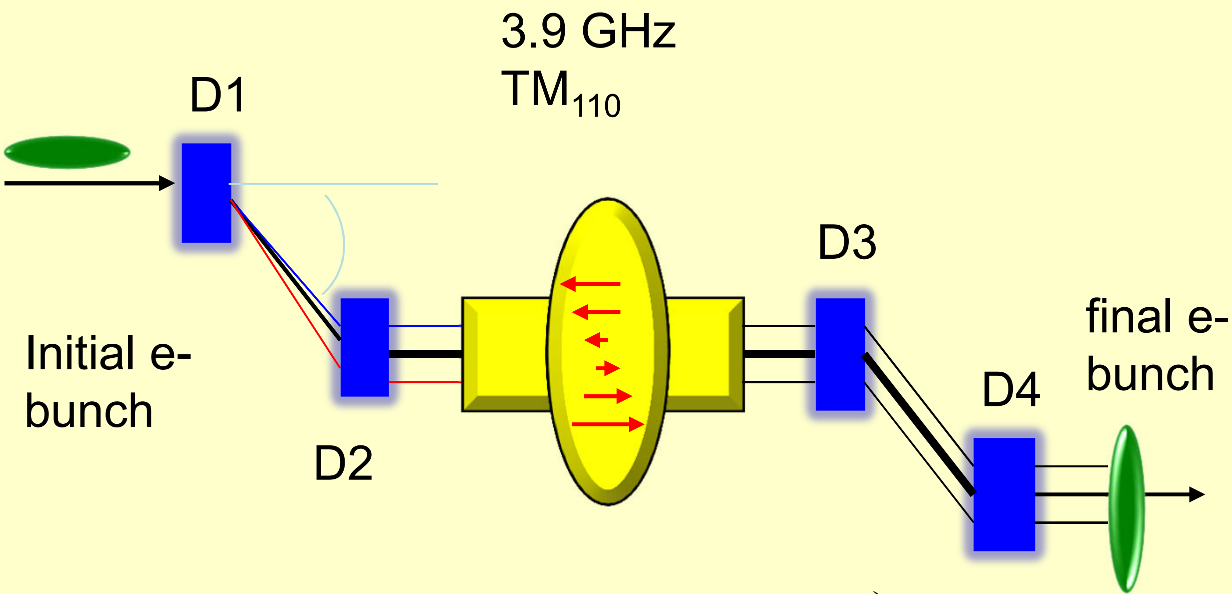
Next-generation emittance exchangers

Motivation

- X-ray FELs demand ultra-low transverse emittance beam*
- State-of-the art photo-injectors can generate low 6-D emittance. Typically asymmetric emittances. Emittance exchange can swap transverse with the longitudinal emittance.
- Allows one to convert transverse modulations to longitudinal modulations : Beam shaping application
- Can also be used to suppress microbunching instability**

**P. Emma et al. , Nature Photonics 4, 641 - 647 (2010) ; **M. Cornacchia and P. Emma, PRSTAB 5, 084001 (2002)*

Emittance exchange beamline



$$R = \begin{pmatrix} 0 & \frac{Lc}{4} & \frac{-(4L+Lc)}{4\eta} & \eta - \frac{\alpha(4L+Lc)}{4} \\ 0 & 0 & \frac{-1}{\eta} & -\alpha \\ -\alpha & \eta - \frac{\alpha(4L+Lc)}{4} & \frac{\alpha Lc}{4\eta} & \frac{\alpha^2 Lc}{4} \\ \frac{-1}{\eta} & \frac{-(4L+Lc)}{4\eta} & \frac{\alpha Lc}{4\eta^2} & \frac{\alpha Lc}{4\eta} \end{pmatrix}$$

$\alpha : Bending\ angle$

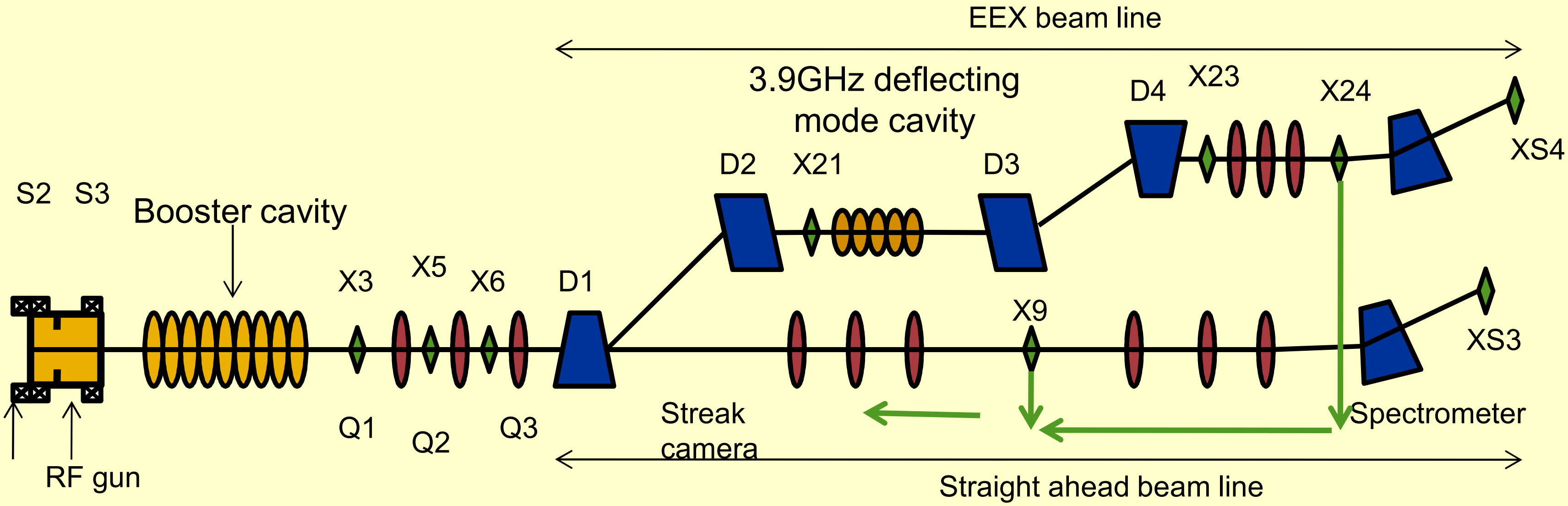
$\eta : dispersion\ of\ dogleg$

$L : Length\ of\ the\ dogleg$

$Lc : Length\ of\ the\ 5-cell$

$\kappa = \frac{-1}{\eta} : Condition\ for\ EEX$

Fermilab A0 photoinjector: Emittance exchange



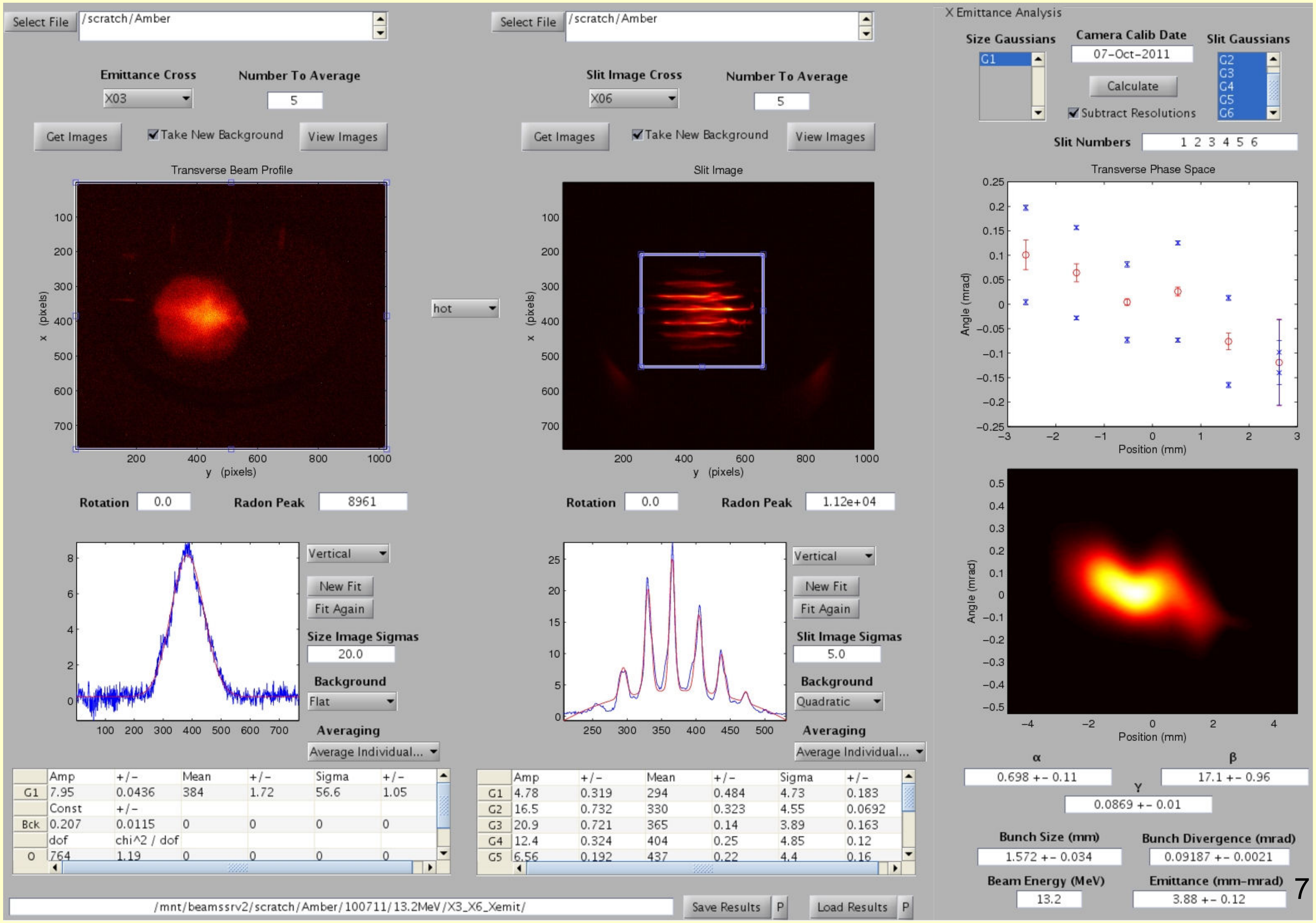
Gun	1.3 GHz NC
Accelerating Cavity	1.3 GHz SC
Deflecting cavity	3.9 GHz NC

Charge per bunch	100 pC – 1 nC
Energy	14.3 MeV
Bunch length (rms)	~ 3 ps
Energy spread (rms)	~ 10 KeV
Rep. rate	1 Hz
Typical number of bunches in a train	~ 100

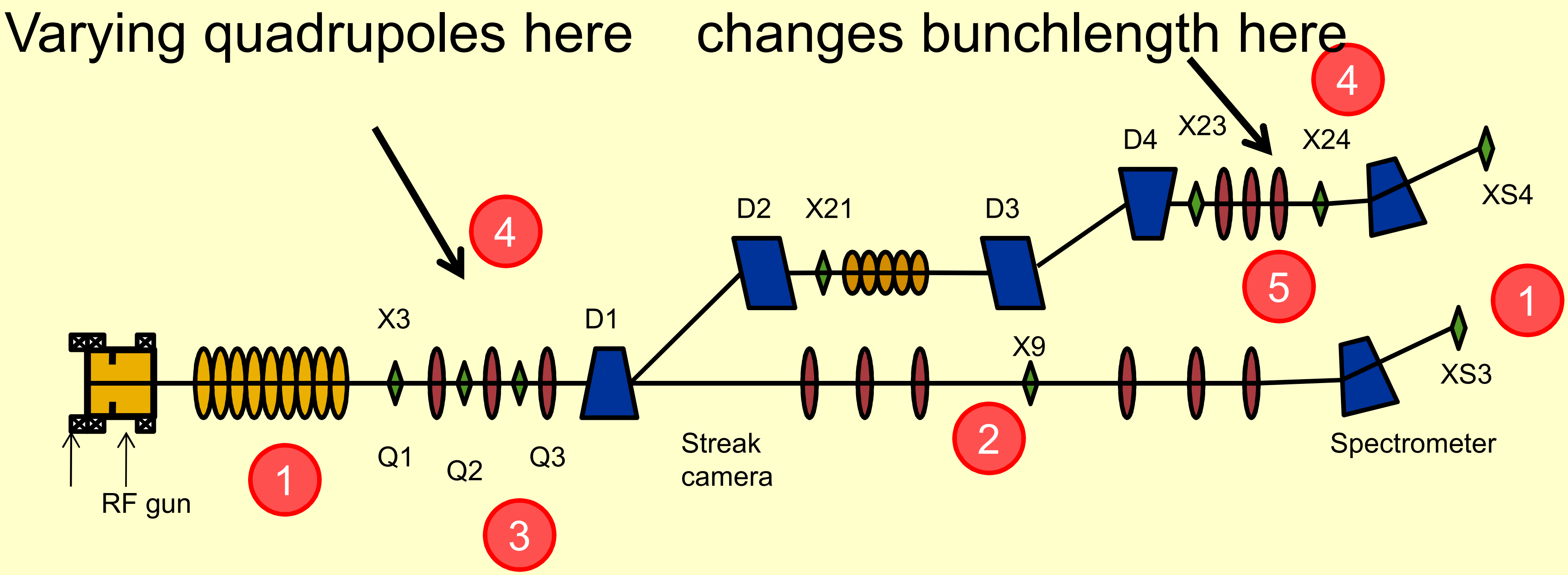
Emittance measurement diagnostics and techniques

- Beam size: OTR and YAG screens
- Bunch length: Streak or Interferometer
- Energy spread: Spectrometer magnet and a screen
- Transverse emittance: Multi-slit method
- Longitudinal emittance: Product of minimum energy spread and bunch length (upper limit)

GUI to extract Courant- Snyder parameters



The A0 photoinjector: Machine tuning



1 RF – scan to locate minimum energy spread i.e. no chirp
2 Streak camera to measure bunch length (Longitudinal emittance)
3 X-Slits and Y-slits to measure the transverse emittances (X3)
4 Tune quadrupoles to maximize CTR radiation thus minimizing the bunchlength. Tune quadrupoles to minimize energy spread at XS4. Finer scan along the minimum values.
5 X-slits and Y-slits to measure outgoing transverse emittance (X23)

First observation of emittance exchange

PRL **106,** 244801 (2011) PHYSICAL REVIEW LETTERS week ending 17 JUNE 2011

First Observation of the Exchange of Transverse and Longitudinal Emittances

J. Ruan, A. S. Johnson, A. H. Lumpkin, R. Thurman-Keup, H. Edwards, R. P. Fliller,* T. W. Koeth,† and Y.-E Sun
Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA
(Received 16 February 2011; published 17 June 2011)

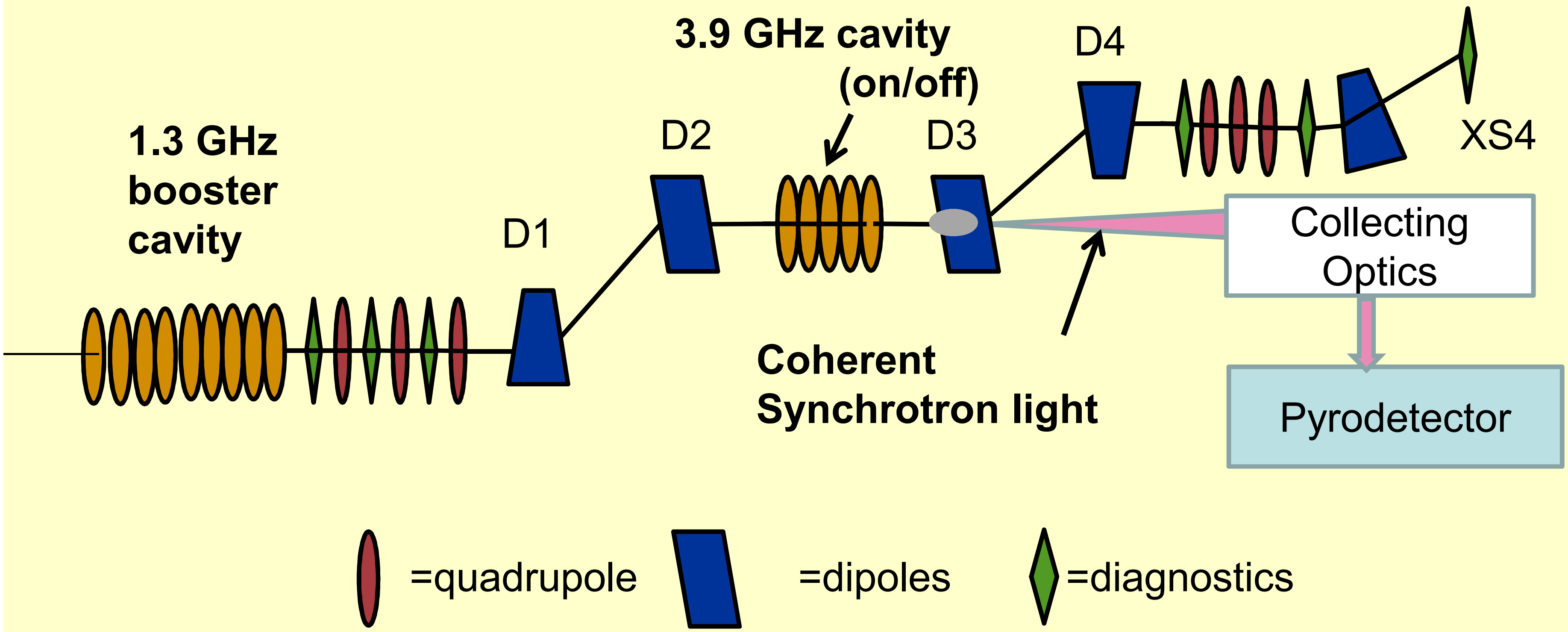
An experimental program to demonstrate a novel phase-space manipulation in which the horizontal and

An Observation of a Transverse to Longitudinal Emittance Exchange at the Fermilab A0 Photoinjector

by Timothy W. Koeth

Ph. D. Dissertation

The A0 beamline: Part II



Coherent Synchrotron Radiation

- Synchrotron radiation is the result of individual electrons that randomly emit photons when passing through a bending magnet.

- Coherent synchrotron radiation (CSR) is produced when a group of electrons collectively emit photons in phase. This occurs when bunch length is shorter than radiation wavelength.

Condition for coherent radiation

Form factor

$$P(\lambda) = p(\lambda) N_e [1 + (N_e - 1) f(\lambda)]$$

$P(\lambda)$ Total power radiated at wavelength λ

$p(\lambda)$ Synchrotron radiation from one electron

N_e Number of electrons in the bunch

$f(\lambda) = 1$ for $\lambda >> \sigma_l$ above λ= 0.3 mm

Long wavelength cutoff due to vacuum chamber

$$\lambda_{cutoff} = 2h\sqrt{\frac{h}{\rho}}$$

h Height of the chamber 1.8 inches

ρ Bending radius 900 mm

λ_{cutoff} 20mm

CSR effect on the bunch is….

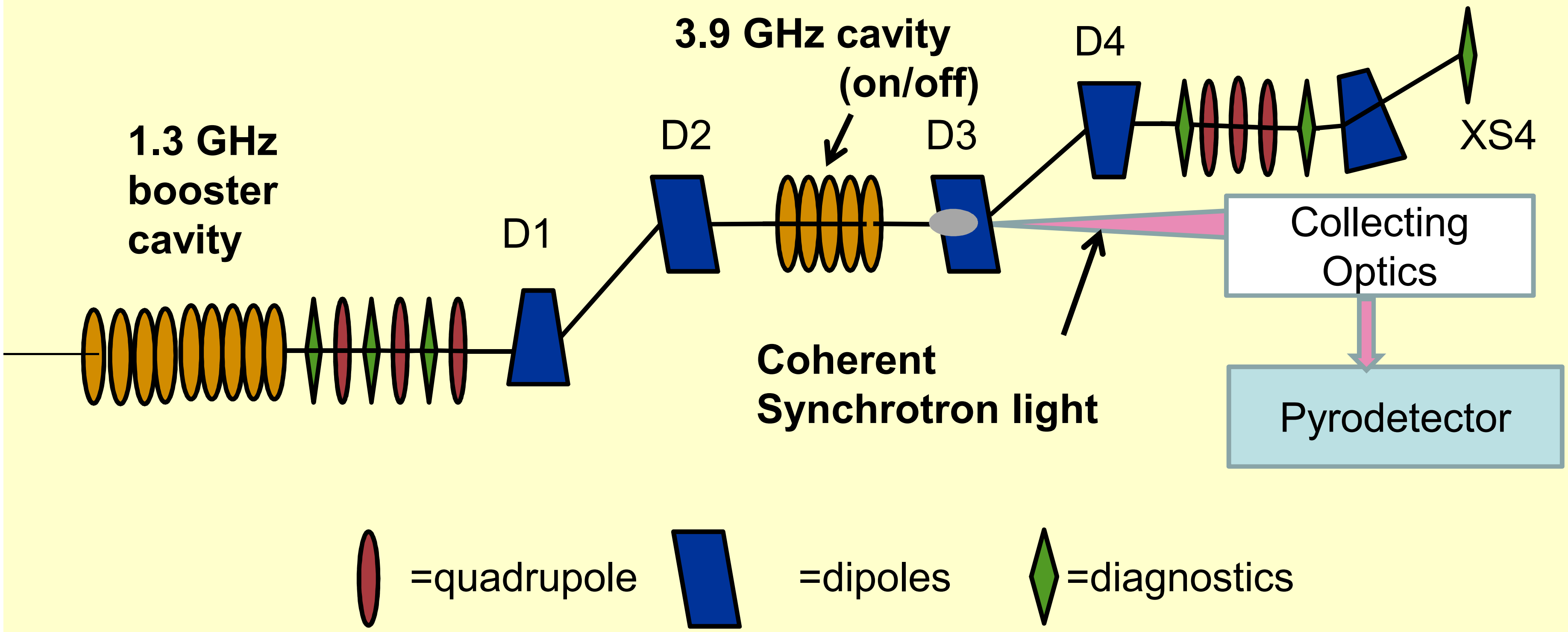
$$\Delta E = 0.35 mc^2 \frac{N_e r_e L_B}{(\rho \sigma_z^2)^{2/3}}$$

r_e Classical electron radius

L_B Length of the bend

N_e Number of *electrons* in the bunch

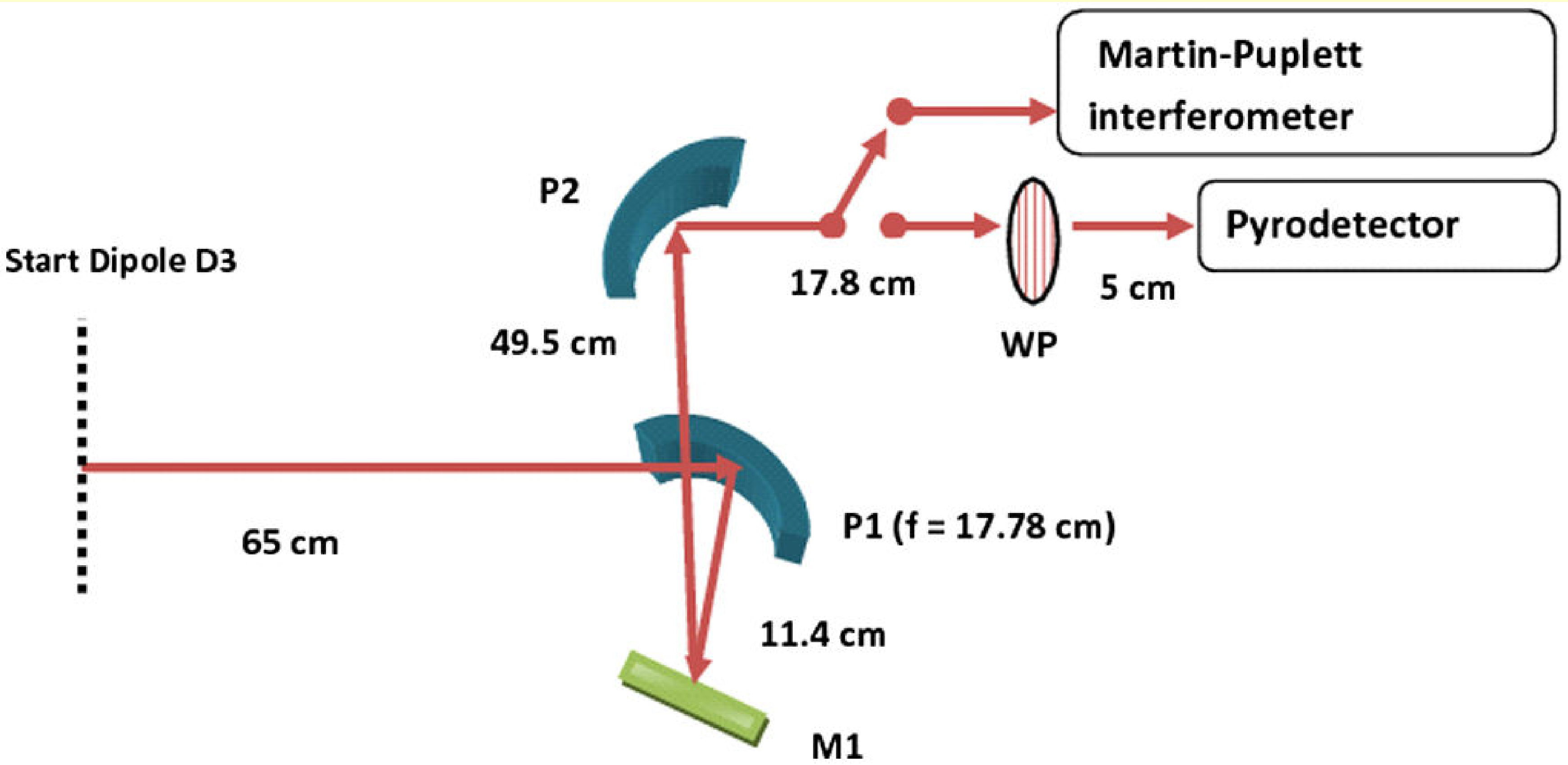
The A0 beamline



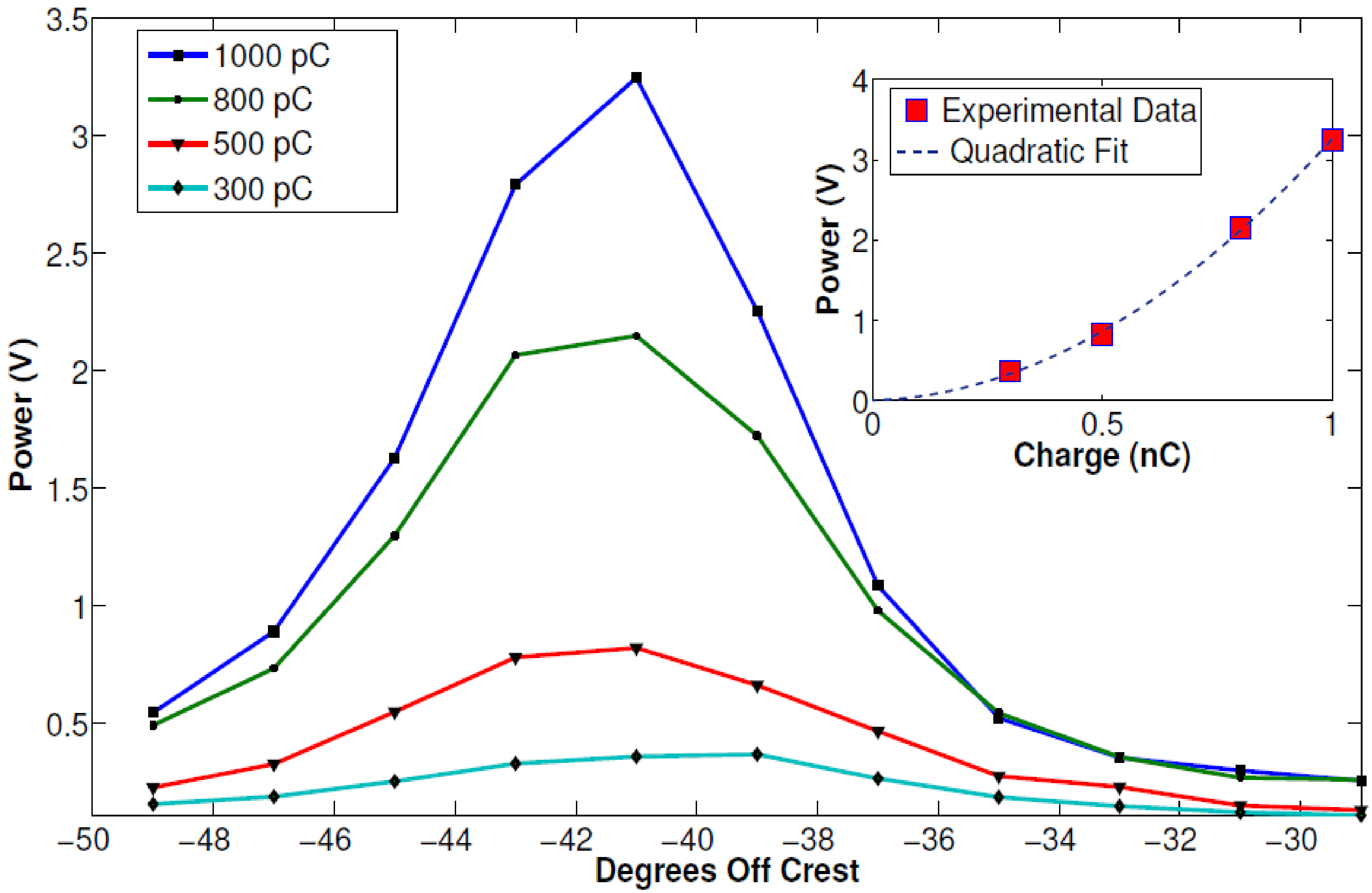
CSR : Measurements

- Power
- Polarization
- Angular Distribution
- Using CSR as a bunchlength monitor

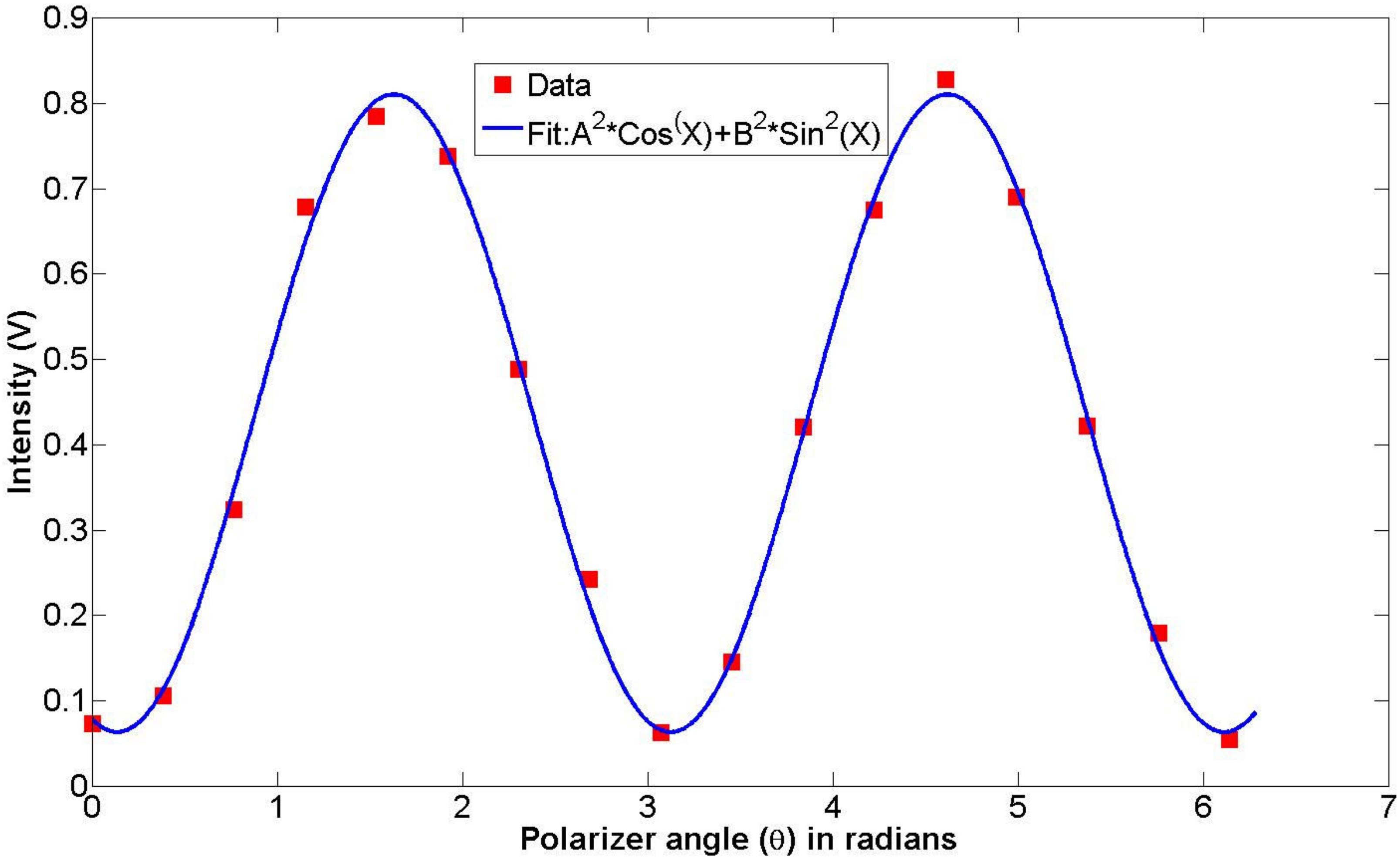
Schematic of the CSR detection optics



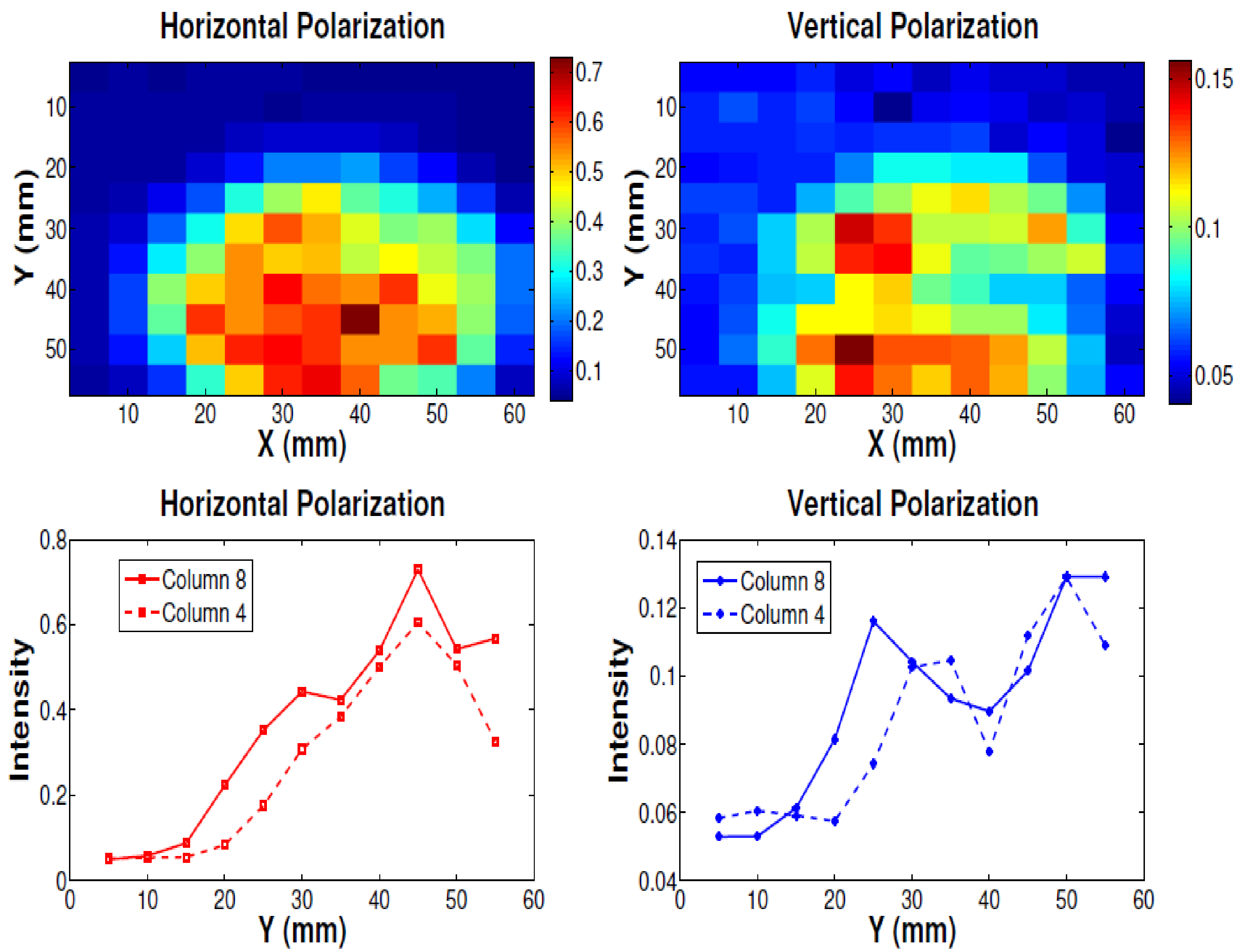
CSR Power Vs RF Phase (bunchlength)



Polarizer angle vs CSR

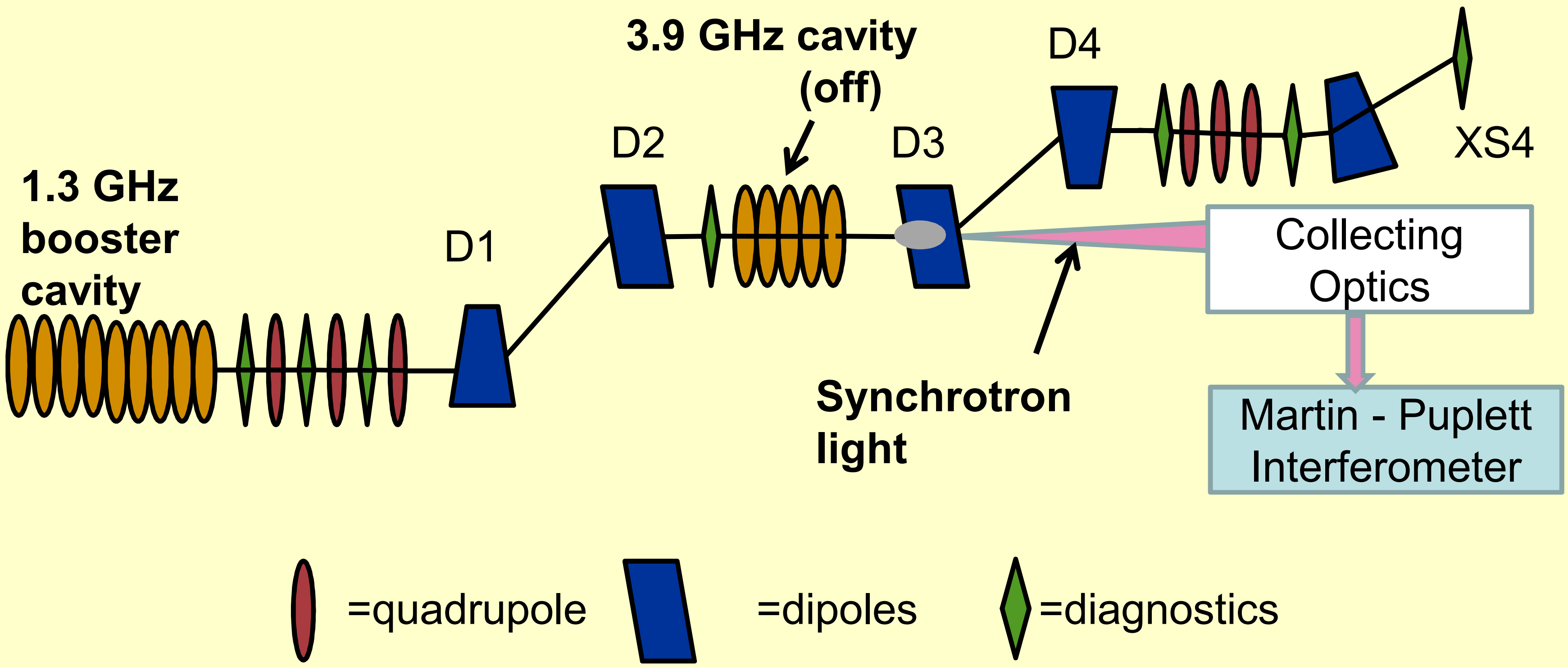


CSR Angular distribution

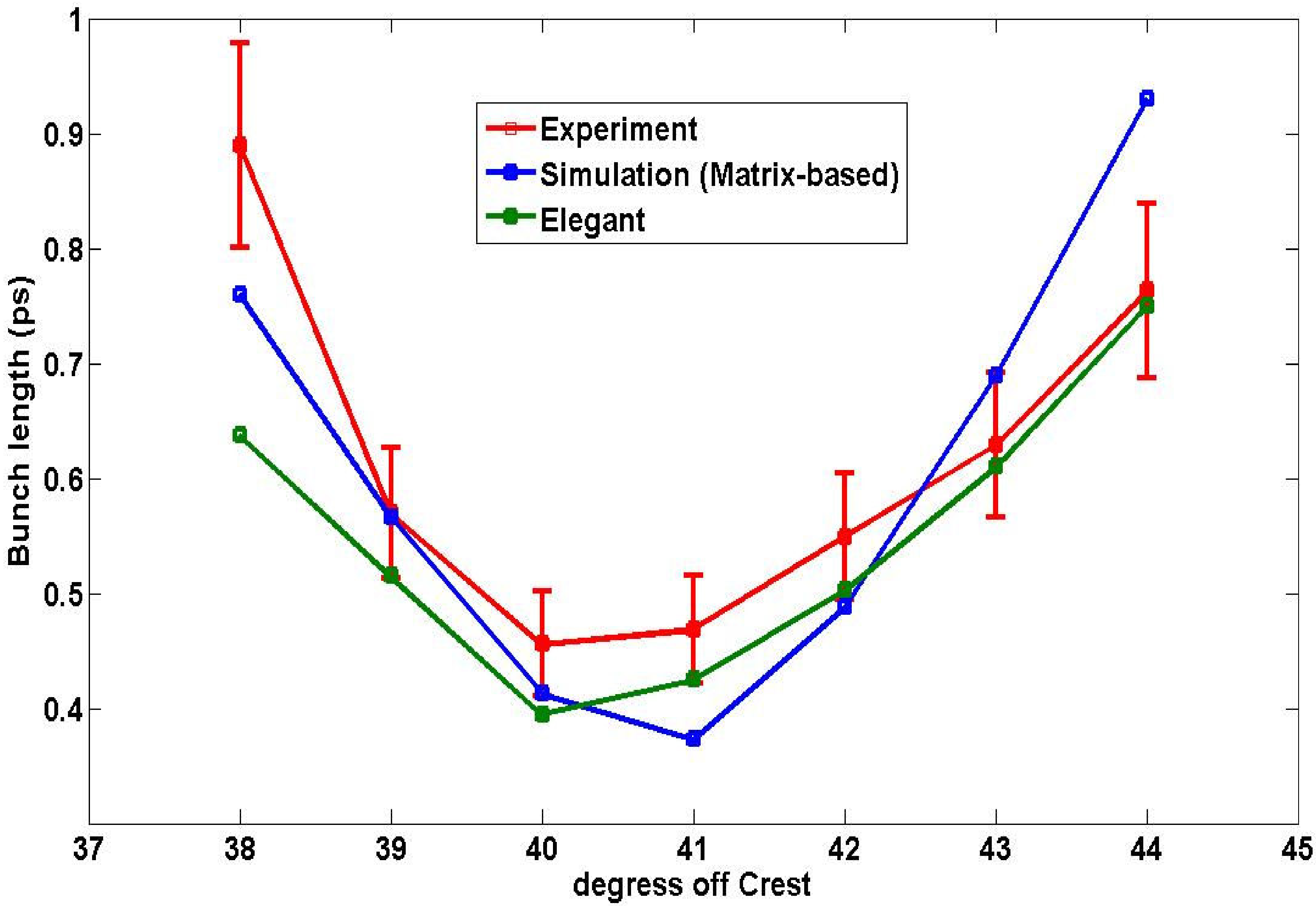


Ratio (Horizontal to vertical) = 4.6

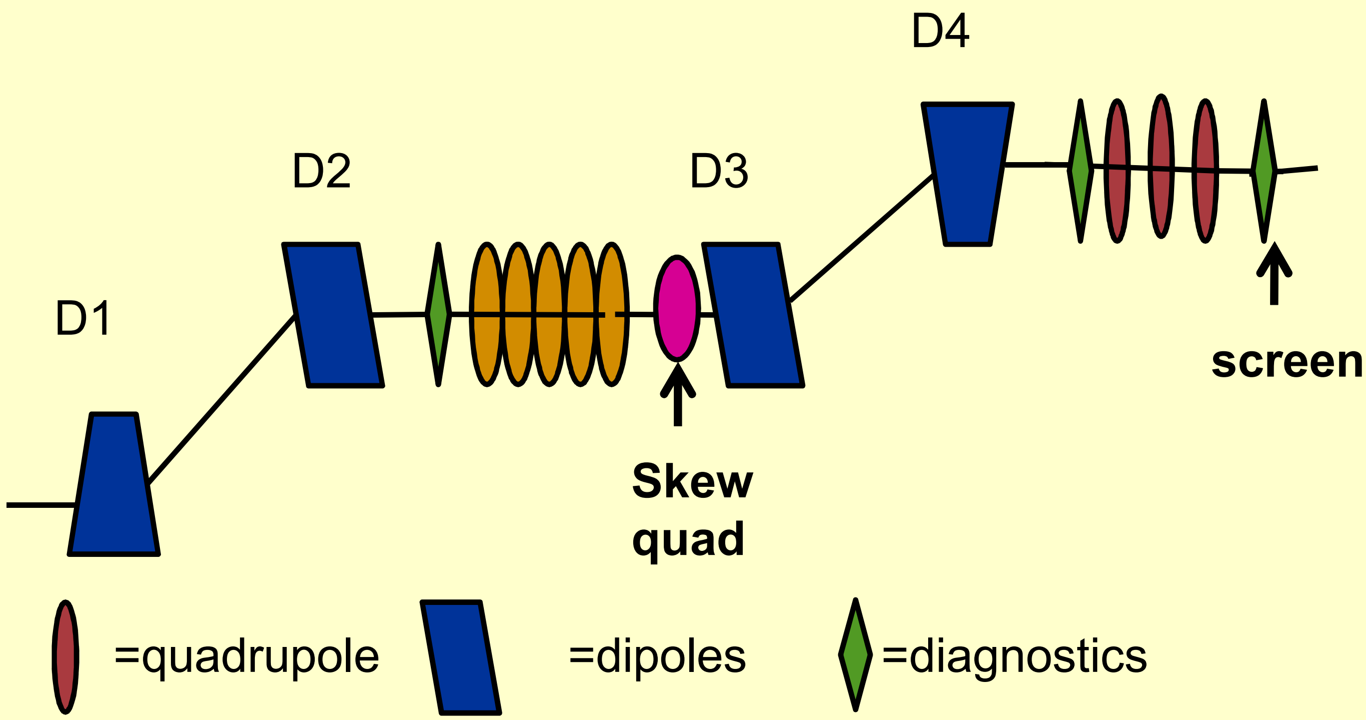
Bunch length measurement: Experimental Setup



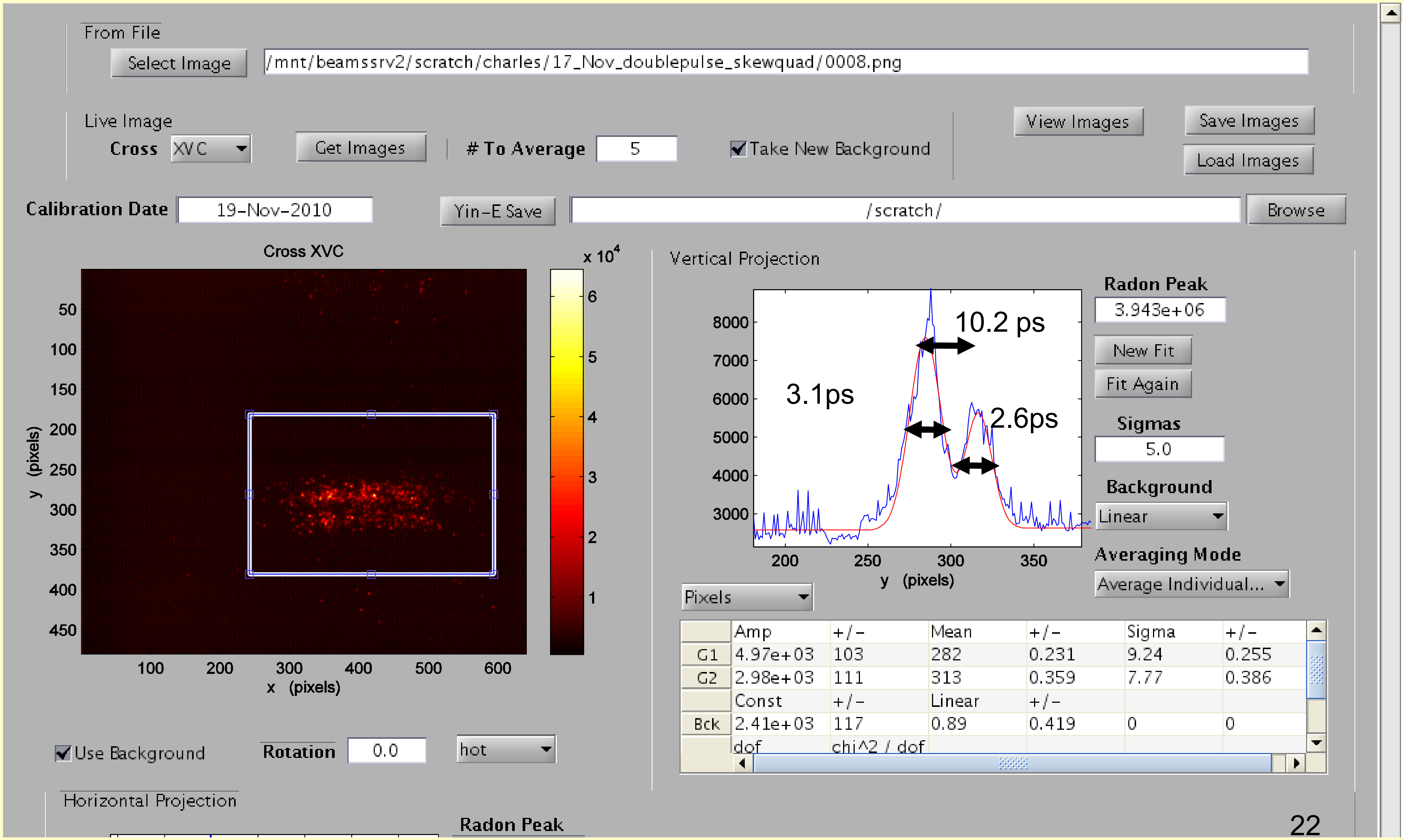
Bunch length measurement: Simulation Vs Experiment



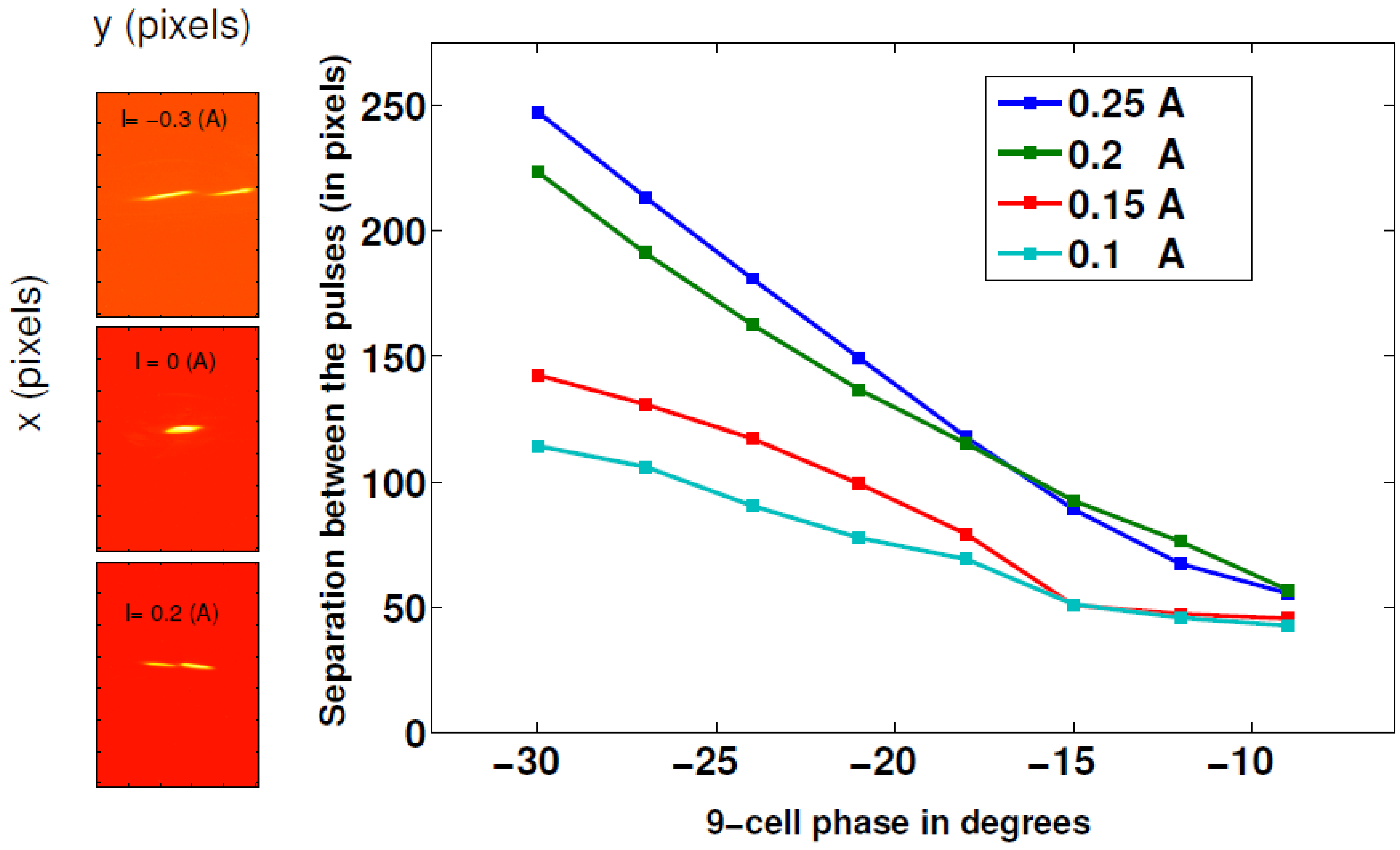
Studying the effects of CSR on the beam



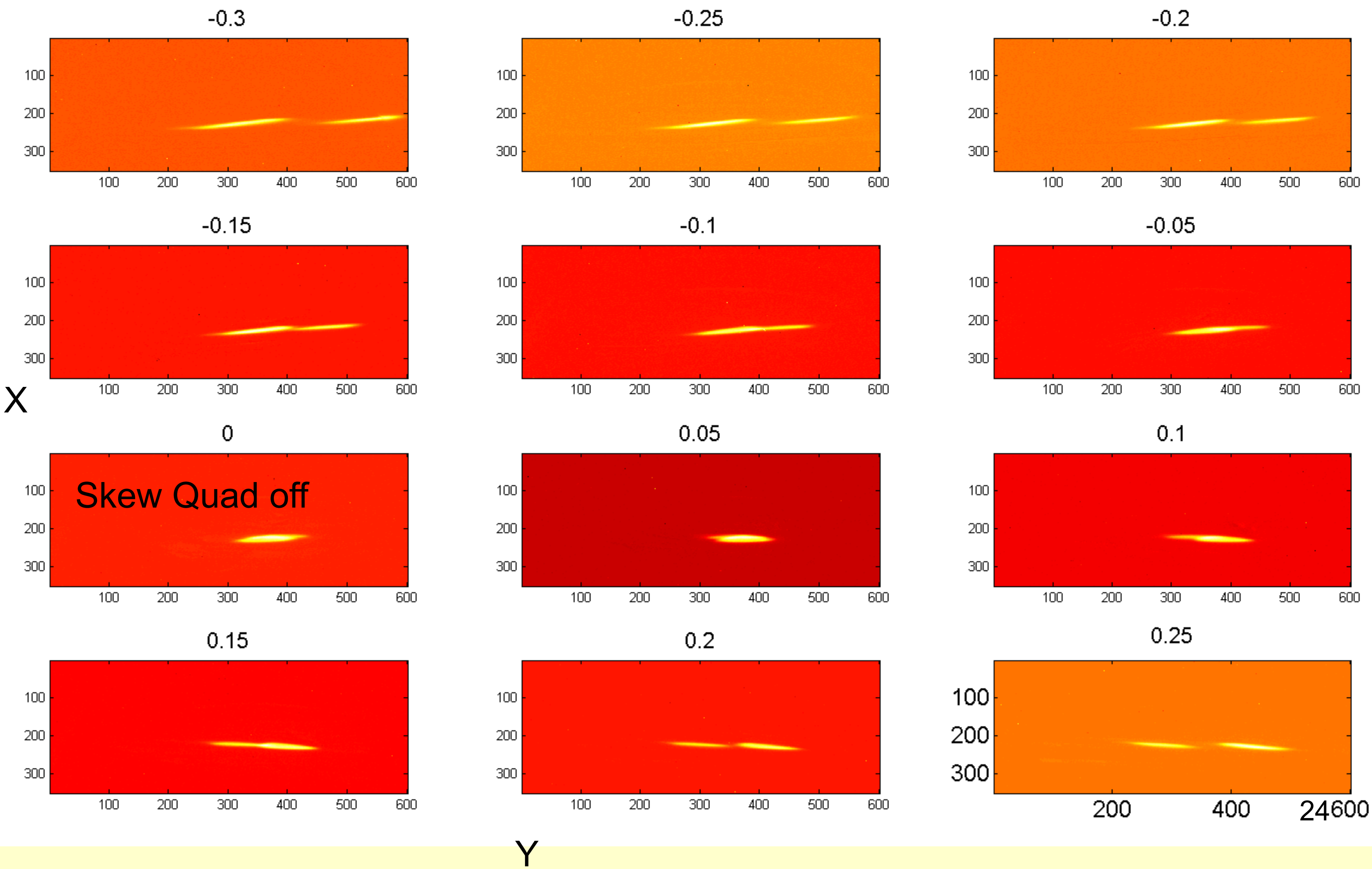
Twin pulse at the cathode



Twin pulse Profile @X24 vs SkewQuad



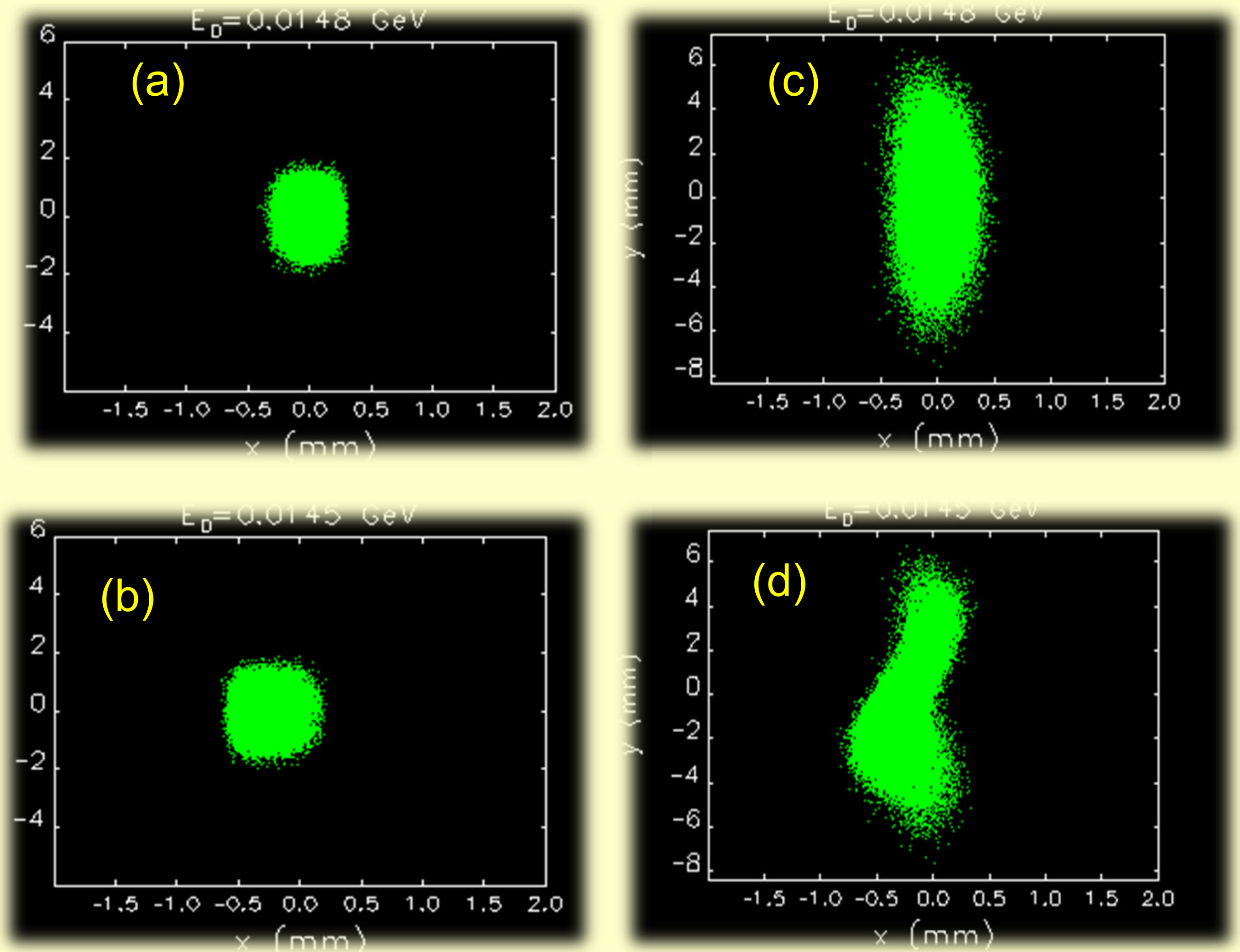
Twin pulse Profile @X24 vs SkewQuad



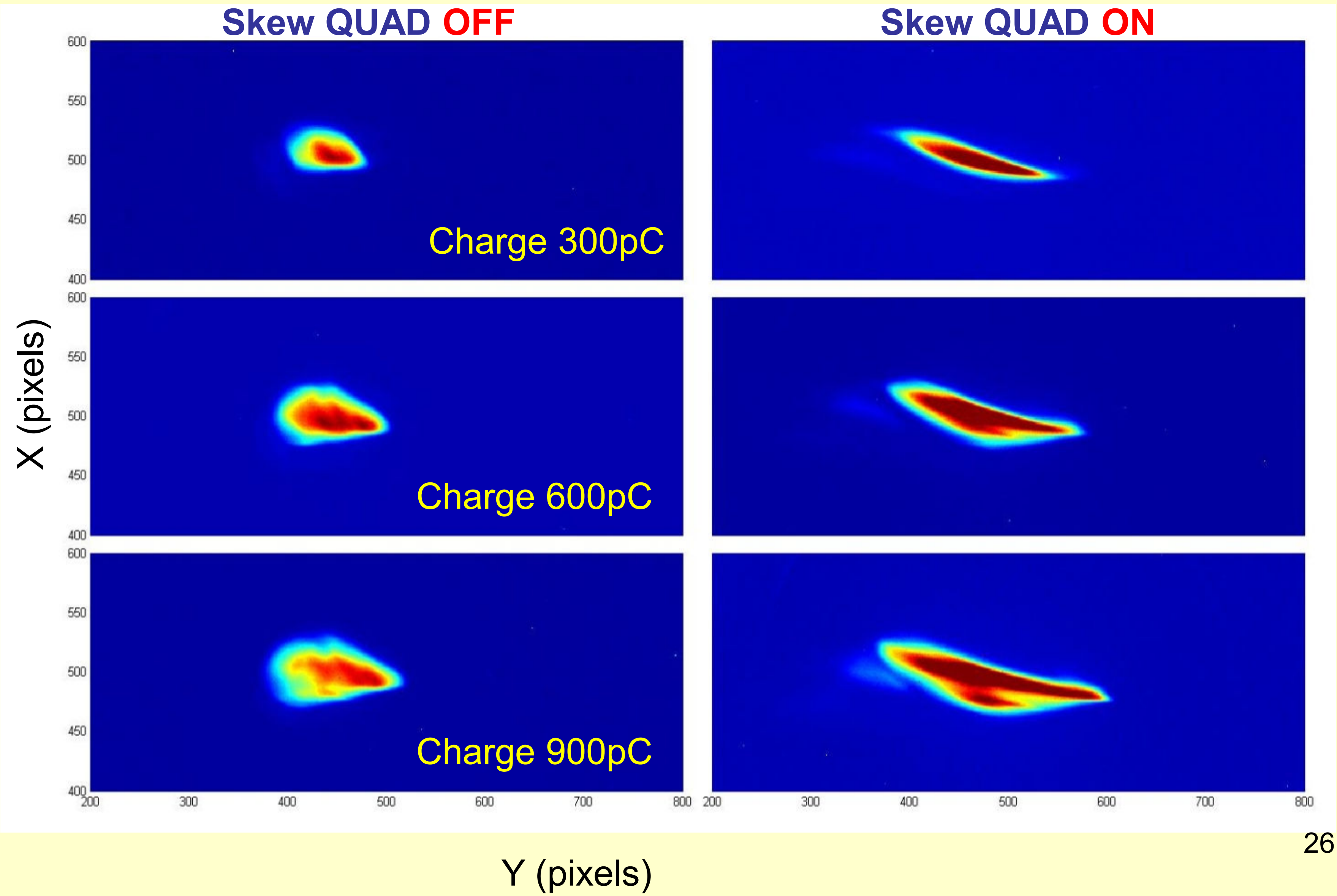
Skew quad diagnostic to resolve CSR effects

Skew QUAD OFF | **Skew QUAD ON**

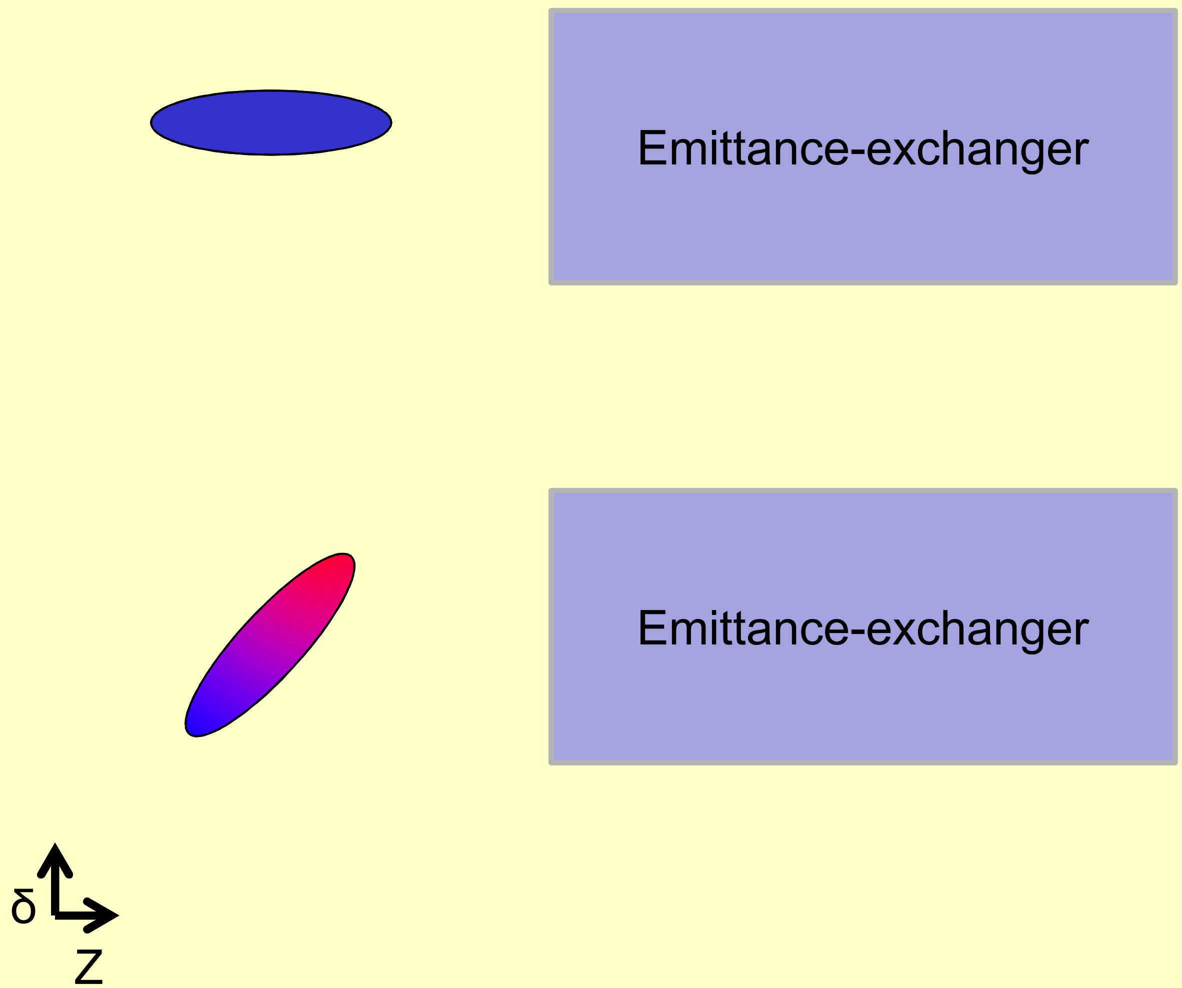
CSR OFF / **CSR ON**



Skew quad measurements at X24

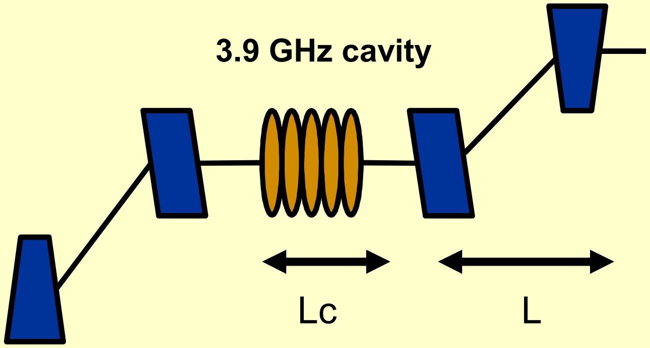


Part III: Chirped beam has improved performance

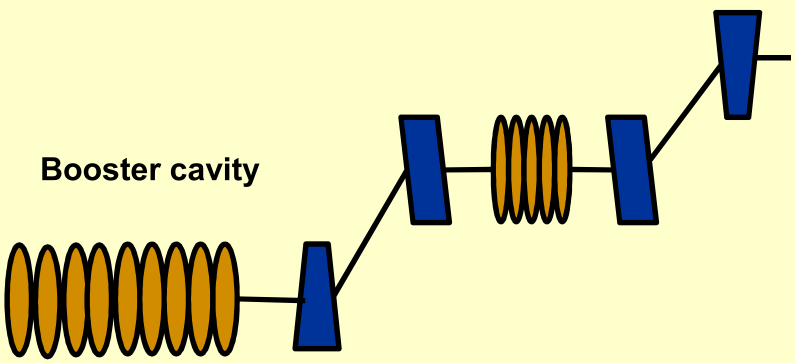


- Improved performance
- Minimizes thick lens effect

How to minimize thick lens effect? Add RF Chirp*



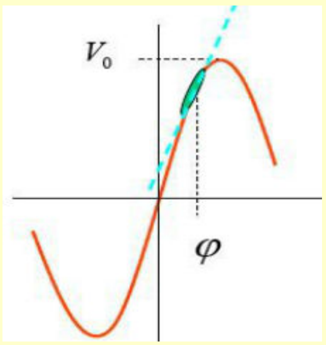
$$R=\begin{pmatrix} 0 & \frac{Lc}{4} & \frac{-(4L+Lc)}{4\eta} & \eta-\frac{\alpha(4L+Lc)}{4} \\ 0 & 0 & \frac{-1}{\eta} & -\alpha \\ -\alpha & \eta-\frac{\alpha(4L+Lc)}{4} & \frac{\alpha Lc}{4\eta} & \frac{\alpha^2 Lc}{4} \\ \frac{-1}{\eta} & \frac{-(4L+Lc)}{4\eta} & \frac{\alpha Lc}{4\eta^2} & \frac{\alpha Lc}{4\eta} \end{pmatrix}$$



$$R=\begin{pmatrix} 0 & \frac{Lc}{4} & \frac{-1}{\alpha} & \eta-\frac{\alpha(4L+Lc)}{4} \\ 0 & 0 & 0 & -\alpha \\ -\alpha & \eta-\frac{\alpha(4L+Lc)}{4} & 0 & \frac{\alpha^2 Lc}{4} \\ \frac{-1}{\eta} & \frac{-(4L+Lc)}{4\eta} & 0 & \frac{\alpha Lc}{4\eta} \end{pmatrix}$$

*** P. Emma, Z. Huang, K. - J. Kim, P. Piot, "Transverse-to-longitudinal emittance exchange to improve performance of high-gain free-electron lasers", Phys. Rev. ST Accel. Beams 9, 100702 (2006),**

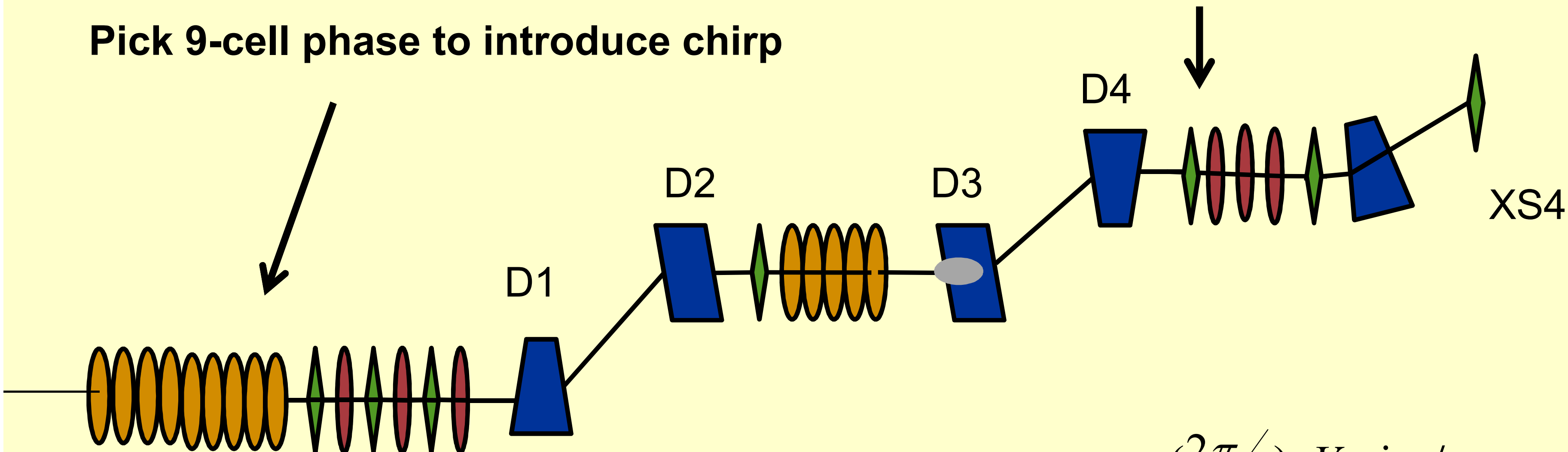
Minimize thick lens effect: Add energy chirp



Chirp	RF-phase
0	-30
2.0	-35
4.5	-40
7.7	-45

Look for bunch length, transverse beam size, emittances (x and z)

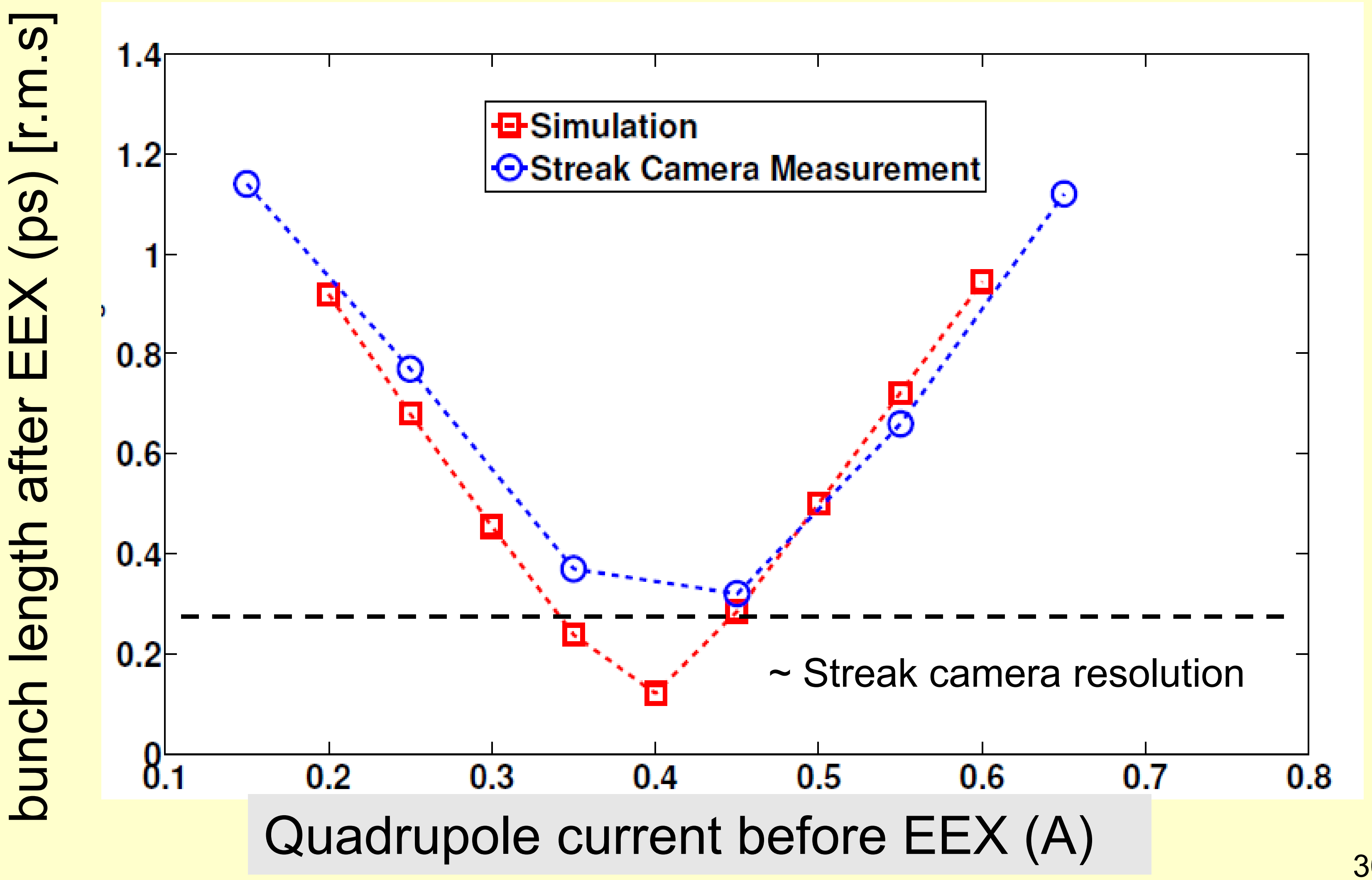
Pick 9-cell phase to introduce chirp



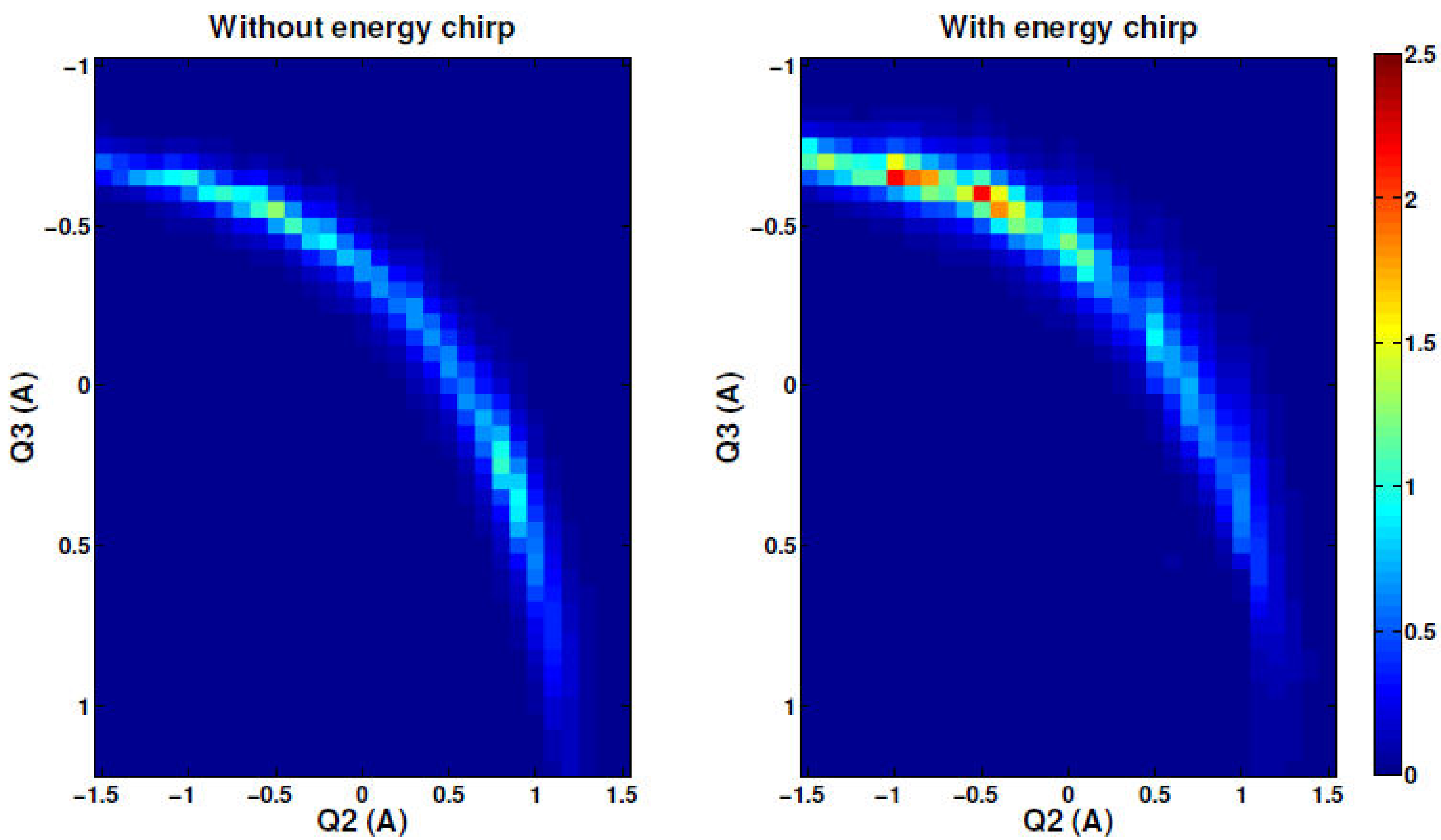
1.3 GHz booster cavity

$$chirp = \frac{d\delta}{dz} = -\frac{(2\pi/\lambda)eV_0\sin\phi}{E_0 + eV_0\cos\phi}$$

Chirped beam study: Streak camera

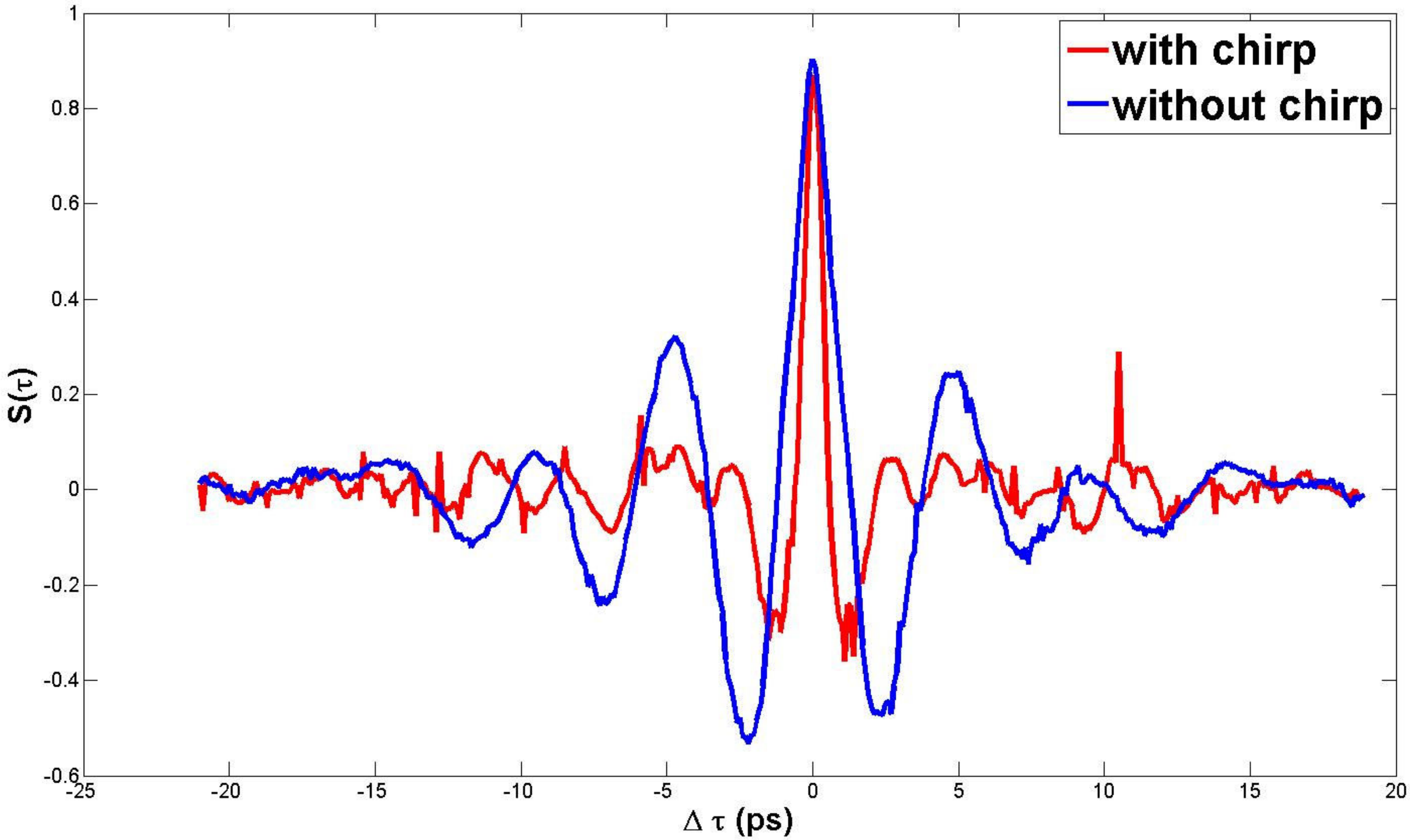


Finer quadrupole scan using interferometer pyros



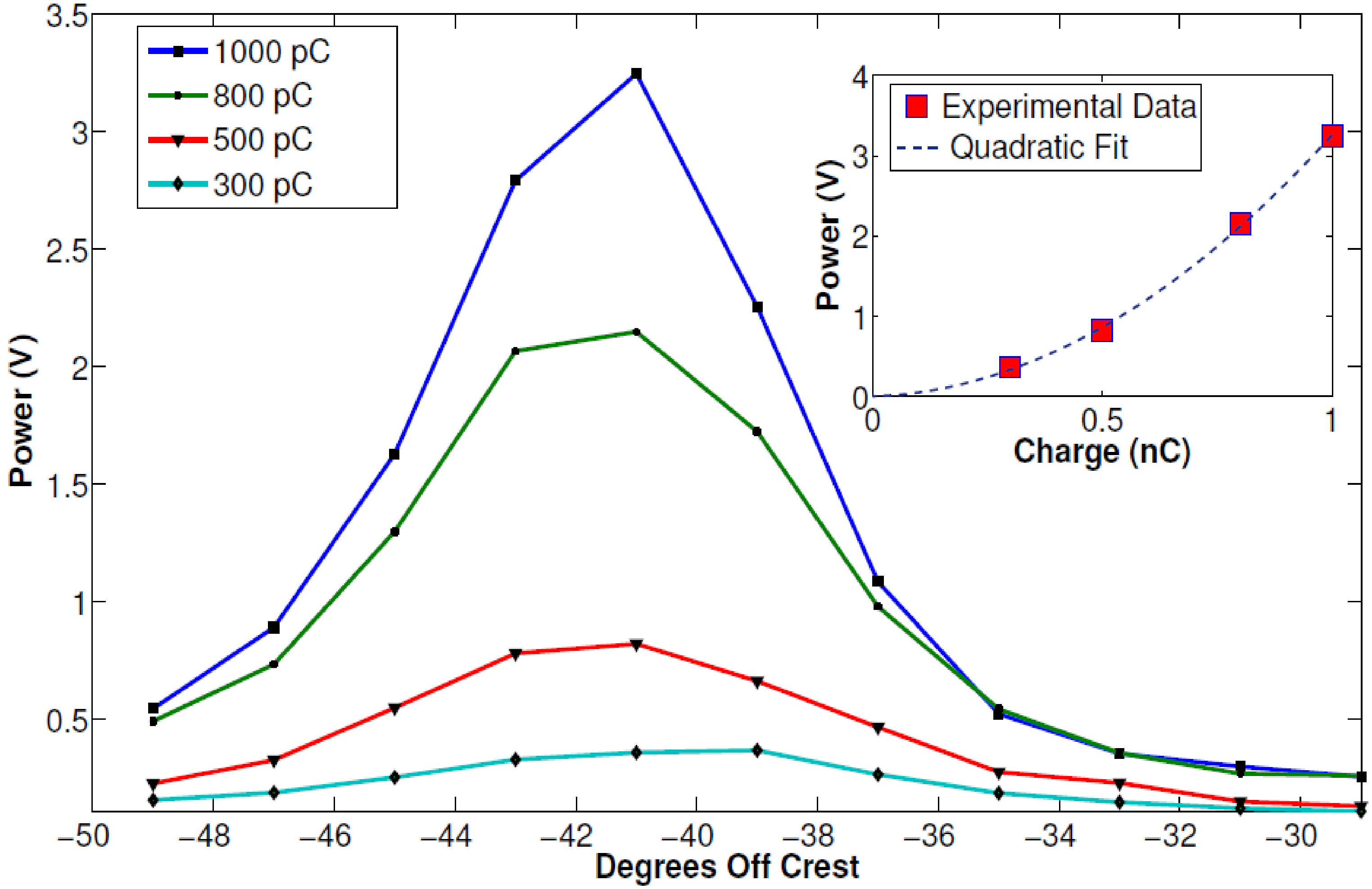
- Pyro signal increases ~ by a factor of 2

Interferometer measurement

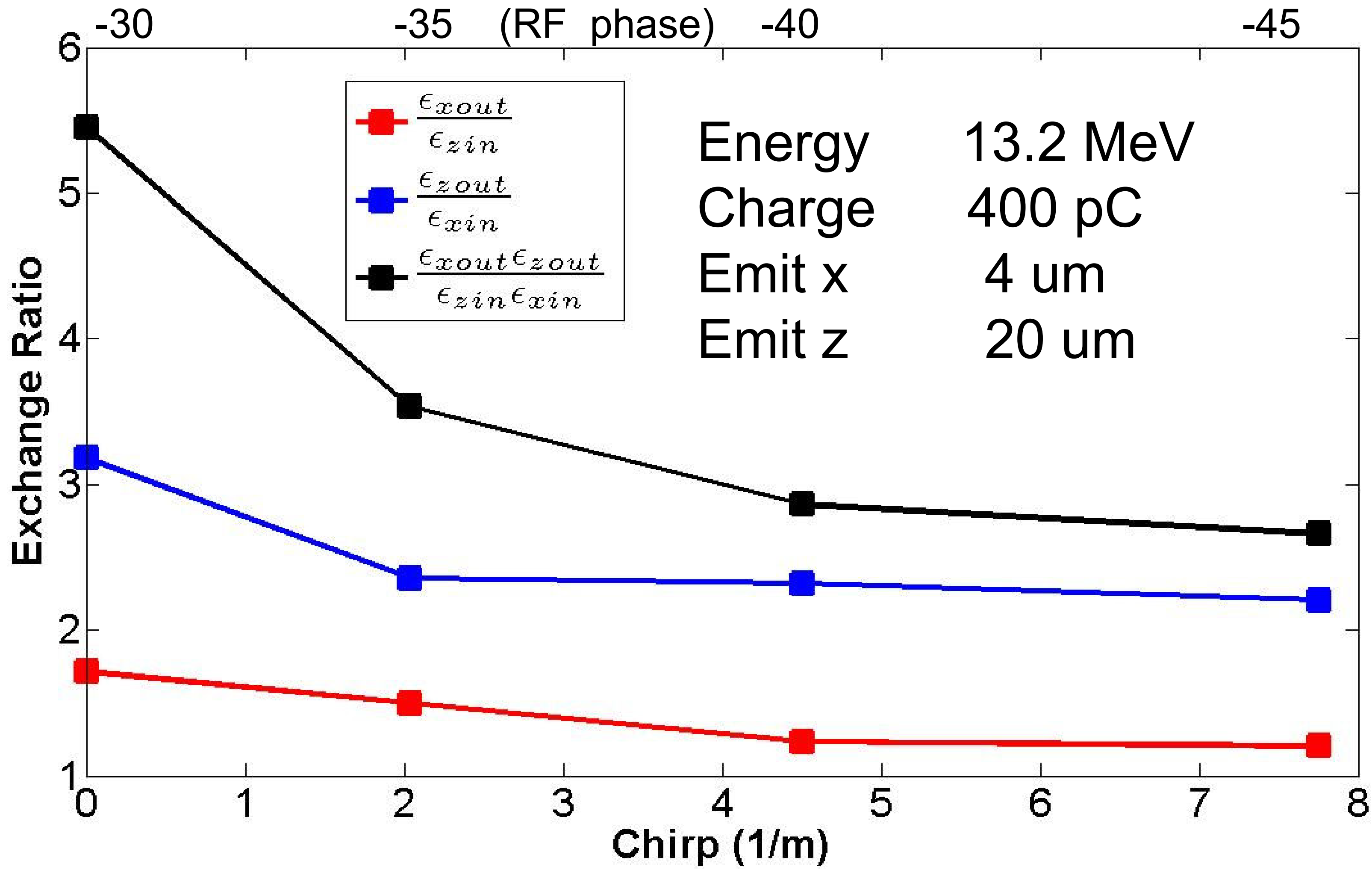


Bunch length reduction ~ 2

CSR Power (pyrometer) Vs RF Phase (bunchlength)

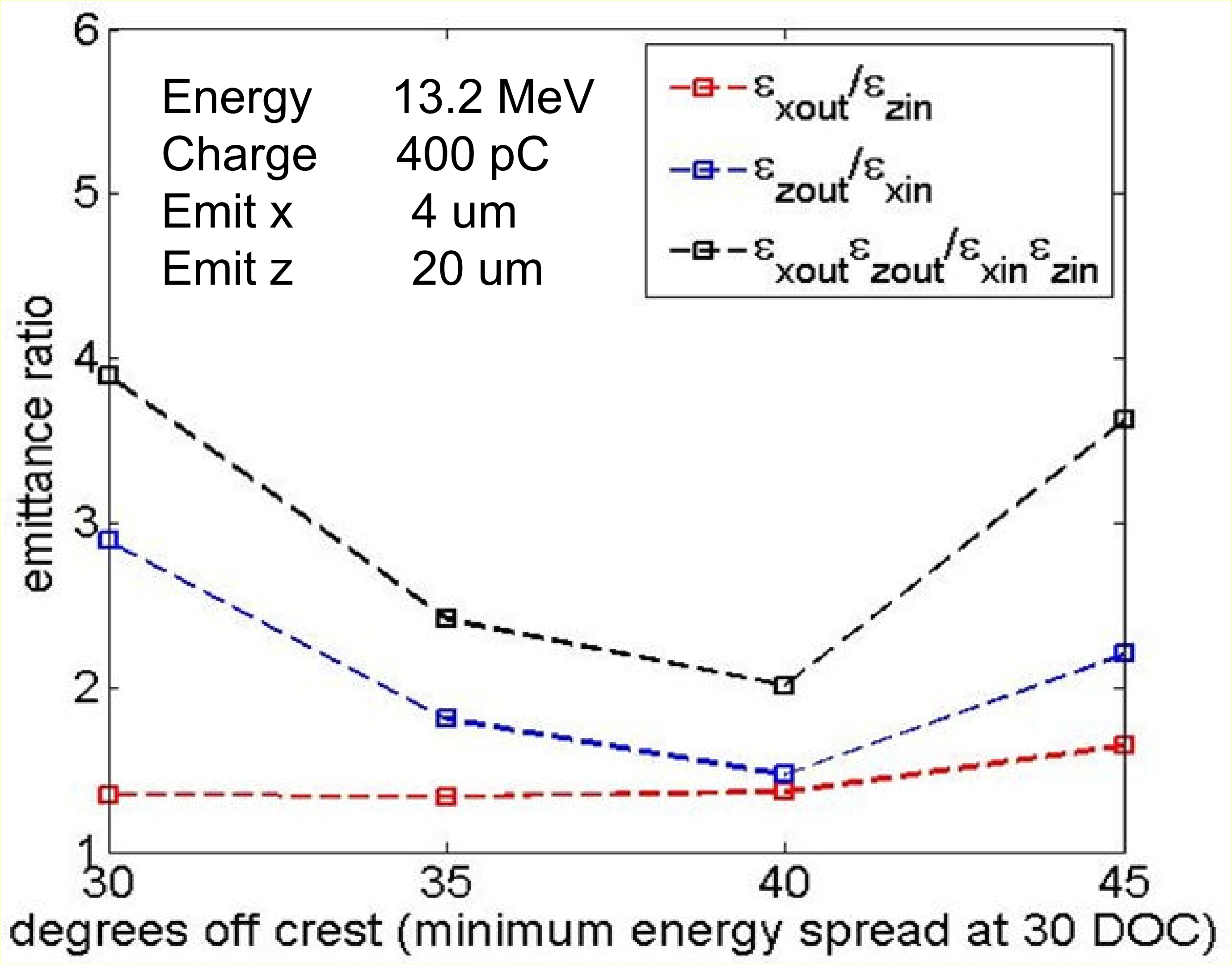


Emittance exchange with chirped beam*

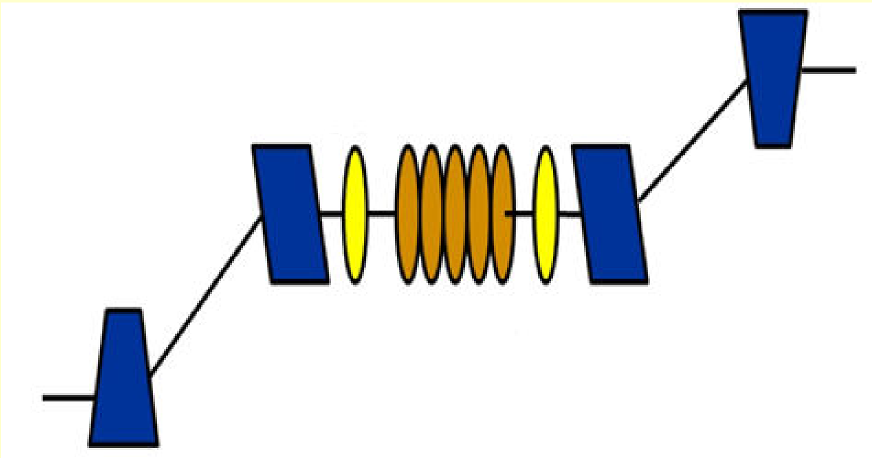


* IPAC 2012

Emittance exchange simulation with GPT



Next generation EEX: upgrade classic EEX



$$\begin{pmatrix} 0 & 0 & -\frac{L+Lc}{\eta} & \eta-\frac{\xi\,(L+Lc)}{\eta} \\ 0 & 0 & -\frac{1}{\eta} & -\frac{\xi}{\eta} \\ -\frac{\xi}{\eta} & \eta-\frac{\xi\,L}{\eta} & 0 & 0 \\ -\frac{1}{\eta} & -\frac{L}{\eta} & 0 & 0 \end{pmatrix}$$

- Use two (or one) more deflecting cavity to compensate thick lens effect
- Use a RF-cavity to compensate thick lens effect

Next generation EEX : A Negative drift EEX

USING AN EMITTANCE EXCHANGER AS A BUNCH . . . Phys. Rev. ST Accel. Beams **14,** 084403 (2011)

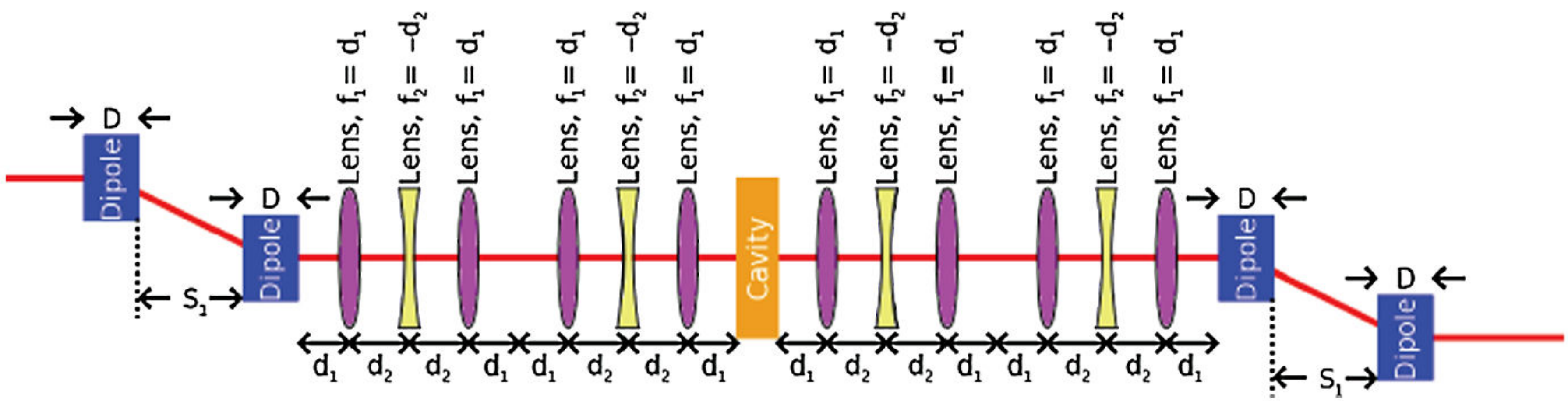


FIG. 13. Transverse-to-longitudinal emittance exchange optic with optics for negative drift lengths between the doglegs.

Next generation EEX : A Chicane style EEX

DAO XIANG *et al.* Phys. Rev. ST Accel. Beams **14,** 114001 (2011)

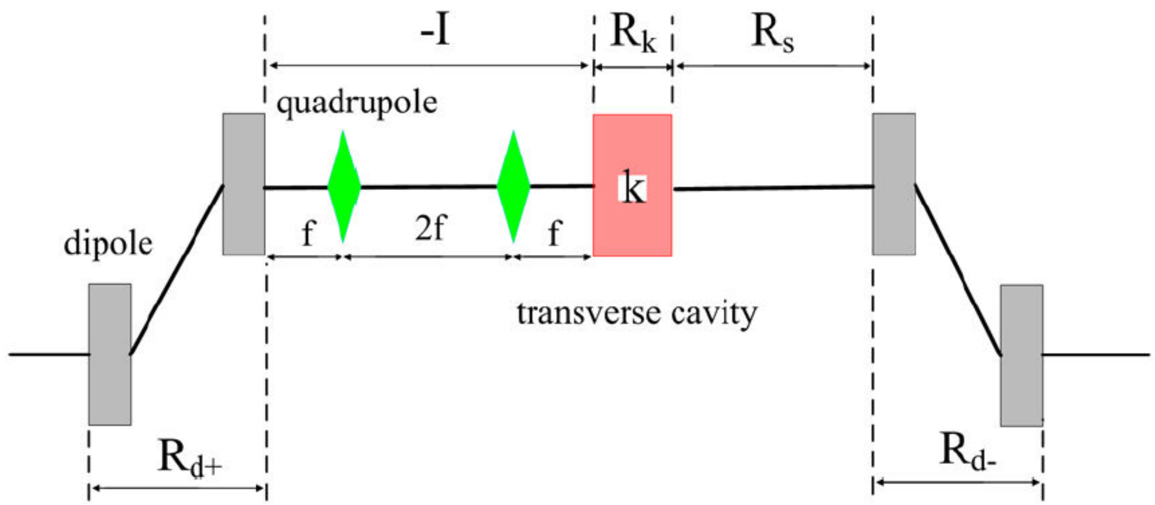
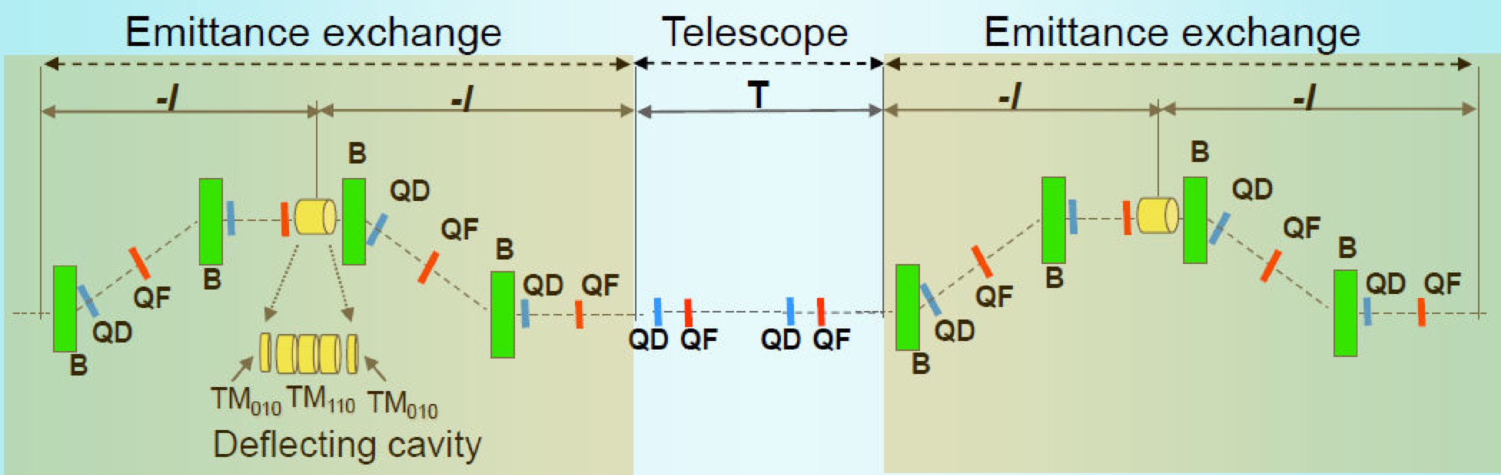


FIG. 2. A chicane-type exact EEX beam line. Two quadrupoles (green diamonds) are put upstream of the transverse cavity to reverse the dispersion.

Next generation EEX : A Double EEX*

A schematic of a proposed bunch compressor



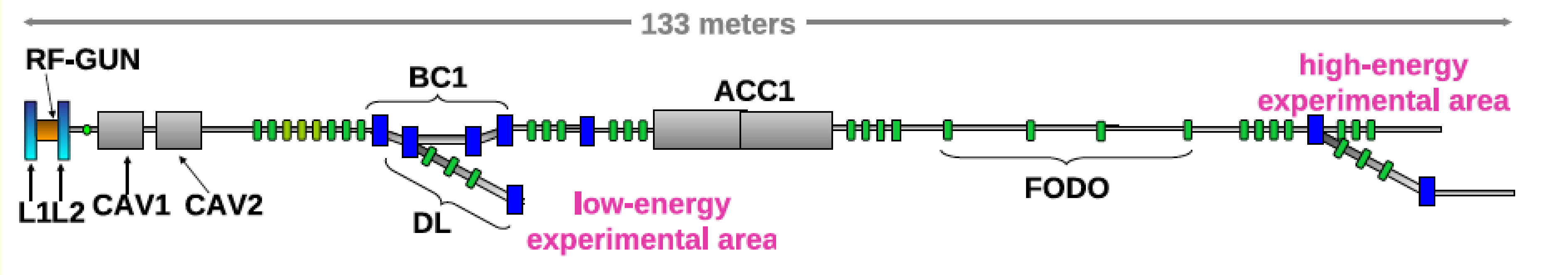
z →x emit. exch.

x → z emit. exch.

Manipulate the longitudinal phase space with ease of manipulation of the transverse phase space

A. Zholents & M. Zolotorev

EEX@ASTA : A Single/Double EEX*



- 50 MeV & 250 MeV design
- Chicane-style
- Dispersion boosted
- 1.3 GHz already in place

* Prokop and Piot (2013) ,THOBB101, IPAC 2013

A brief history of EEX (just a sample)

- Chicane style EEX : Cornacchia and Emma (2002)
- Double dogleg EEX: Kim and Sessler (2005)
- A0 emittance exchange beamline commissioned
- Beam shaping results : Yin-e et. al (2010)
- Emittance exchange result: Jinhao et. al (2010)
- EEX for tailoring current distributions: Piot (2011)
- EEX for HHG: B. Jiang (2011)
- Double EEX proposal : Zholents & Zolotorev (2011)
- Use of EEX as a bunch compressor : Carlsten (2011)
- Chicane style EEX: Xiang and Chao (2012)
- *EEX@ ASTA (double, single): Prokop and Piot (2013)*
- Terra incognita ……………………..

Final thoughts….

- Dogleg design works … 1st generation
- But doglegs are not preferred in a linac .. A chicane would be better
- A chicane, though an improvement ,has an issue that it prevents the use of deflecting mode cavity - an expensive component
- A design that can allow: (i) EEX (ii) Chicane and (iii) use the deflecting mode cavity for operations and diagnostics will be nice
- One solution that will satisfy all these criteria: flipper EEX

Key idea: “Flipper”

Key idea: “flipper”

QD - Quad
QF - Quad
L- Drift length

Transfer matrix

$$flipper[x,z] = \begin{pmatrix} -1 & R12 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

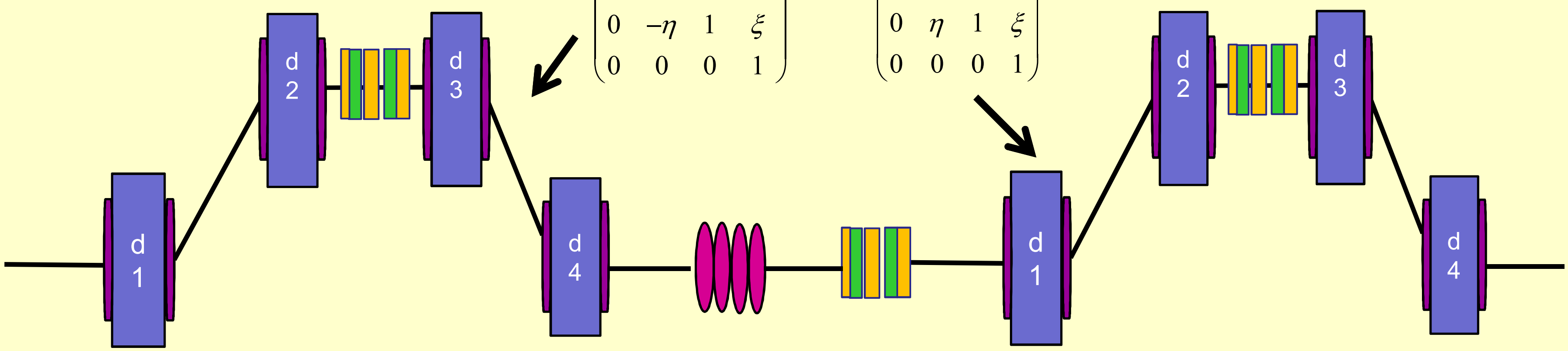
Set focal length QD: L2
Set focal length QF:-L2

R12 could be any constant. I have assumed zero for convenience but it does not change the results if it is a constant

Double-chicane EEX

Key idea: "flipper"

$$\begin{pmatrix} 1 & L & 0 & -\eta \\ 0 & 1 & 0 & 0 \\ 0 & -\eta & 1 & \xi \\ 0 & 0 & 0 & 1 \end{pmatrix} \qquad \begin{pmatrix} 1 & L & 0 & \eta \\ 0 & 1 & 0 & 0 \\ 0 & \eta & 1 & \xi \\ 0 & 0 & 0 & 1 \end{pmatrix}$$



Transfer matrix of the entire beamline is:

$$\begin{pmatrix} 1 & L & 0 & -\eta \\ 0 & 1 & 0 & 0 \\ 0 & -\eta & 1 & \xi \\ 0 & 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & L & 0 & \eta \\ 0 & 1 & 0 & 0 \\ 0 & \eta & 1 & \xi \\ 0 & 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & \alpha_1 & 0 \\ 0 & 0 & 1 & 0 \\ \alpha_1 & 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & L & 0 & -\eta \\ 0 & 1 & 0 & 0 \\ 0 & -\eta & 1 & \xi \\ 0 & 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & L & 0 & \eta \\ 0 & 1 & 0 & 0 \\ 0 & \eta & 1 & \xi \\ 0 & 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} 0 & 0 & \frac{L}{2\eta} & \frac{L\xi}{2\eta} - 2\eta \\ 0 & 0 & \frac{1}{2\eta} & \frac{\xi}{2\eta} \\ \frac{-\xi}{2\eta} & 2\eta - \frac{L\xi}{2\eta} & 0 & 0 \\ \frac{-1}{2\eta} & \frac{-L}{2\eta} & 0 & 0 \end{pmatrix}$$

Set deflecting mode

$$\alpha_1 = \frac{-1}{2\eta}$$

“Flipper” EEX advantages

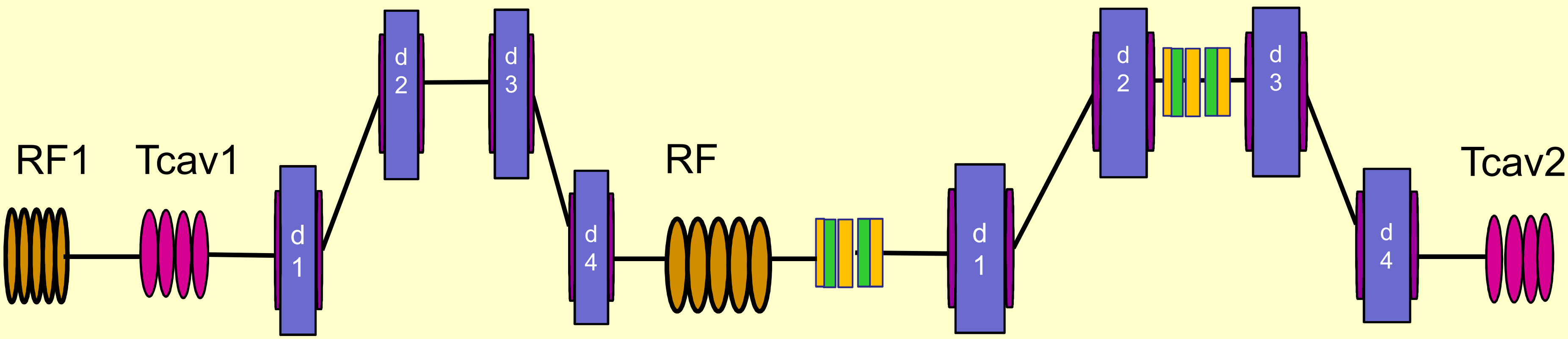
- Could be used as a bunch compressor
- Could be used as a EEX
- Can still use the deflecting mode cavity for measurement diagnostics when EEX is switched off
- Reduction in the required voltage by a factor of 2. Can be reduced still.
- A relatively cheaper extension saves the deflecting cavity for operation
- Limits: (i) How does the optics behave. Work to be done.

  (ii) CSR effect near the last few dipoles could be a problem but this is a problem in all EEX design

  (iii) Larger real estate

Reversible beam heater plus EEX

A beam line that can act as both a reversible beam heater and as an EEX



Transfer matrix of the entire beamline is:

$$\begin{pmatrix} 0 & 0 & 0 & 2\eta \\ 0 & 0 & -\frac{1}{2\eta} & 0 \\ 0 & -2\eta & 0 & 0 \\ \frac{1}{2\eta} & 0 & 0 & 0 \end{pmatrix}$$

Set deflecting mode

$$\alpha_1 = \frac{-1}{2\eta}; \alpha_2 = \frac{1}{2\eta};$$

Set accelerating mode mode

$$h = \frac{-2}{\zeta}; h1 = \frac{-2}{\zeta}$$

"One-to-one EEX"

Summary

- Coherent synchrotron radiation has been studied at the emittance exchange beamline.
- Emittance exchange with an energy-chirped beam shows improved performance. Emittance dilution still exists.
- Next generation EEX has to take into account the thick lens cavity with modification to exchange lattice.
- A chicane-style emittance exchange looks promising and is planned to be tested at the Advanced Superconducting Test Accelerator (ASTA) facility @ 50 MeV
- “Beamnastics” will benefit future accelerators


CCTS-2
CCTS-3