Experimental studies on an emittance exchange beamline at the A0 photoinjector

J. C. T. Thangaraj
Fermi National Accelerator Laboratory, Batavia, Illinois

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*

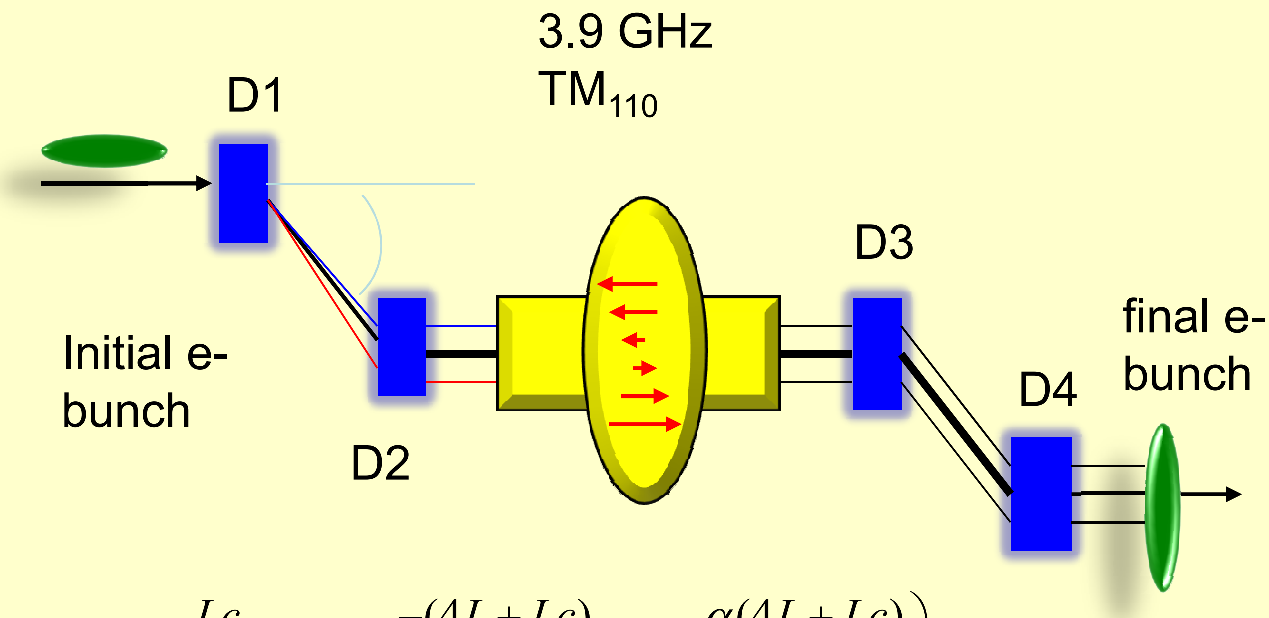
- State-of-the art photo-injectors can generate low 6-D emittance. Typically asymmetric emittances. Emittance exchange can swap transverse with the longitudinal emittance.

- 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



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

α : *Bending angle*

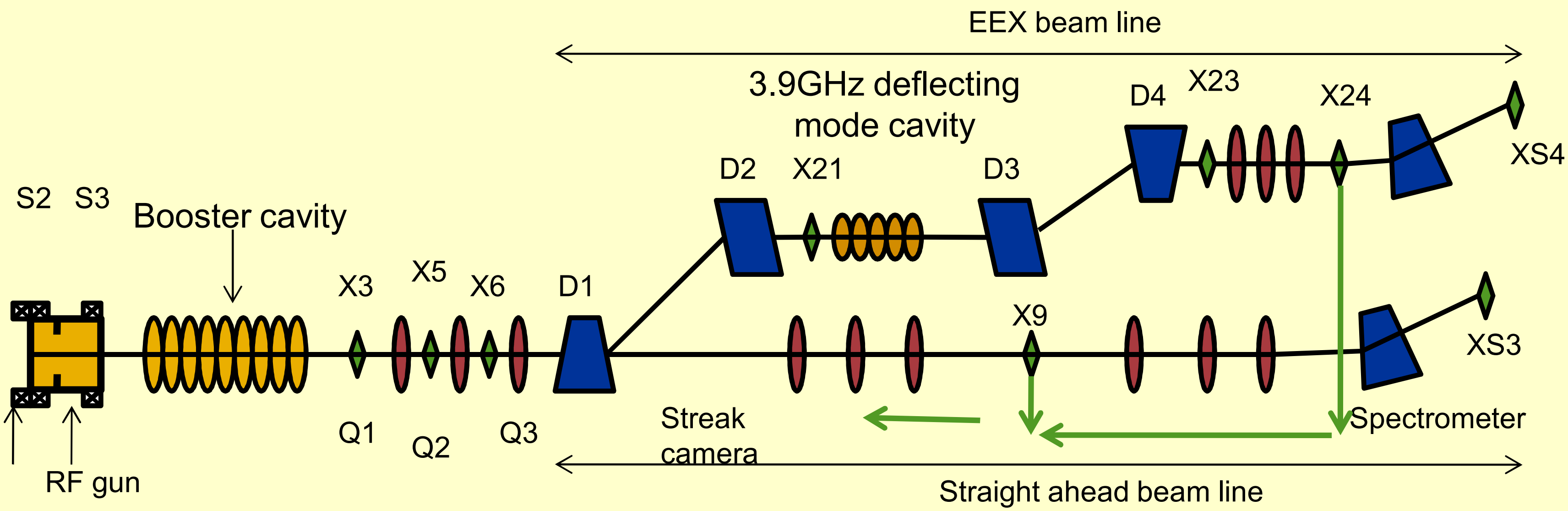
η : *dispersion of dogleg*

L : *Length of the dogleg*

Lc : *Length of the 5-cell*

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

Fermilab A0 photoinjector: Emittance exchange



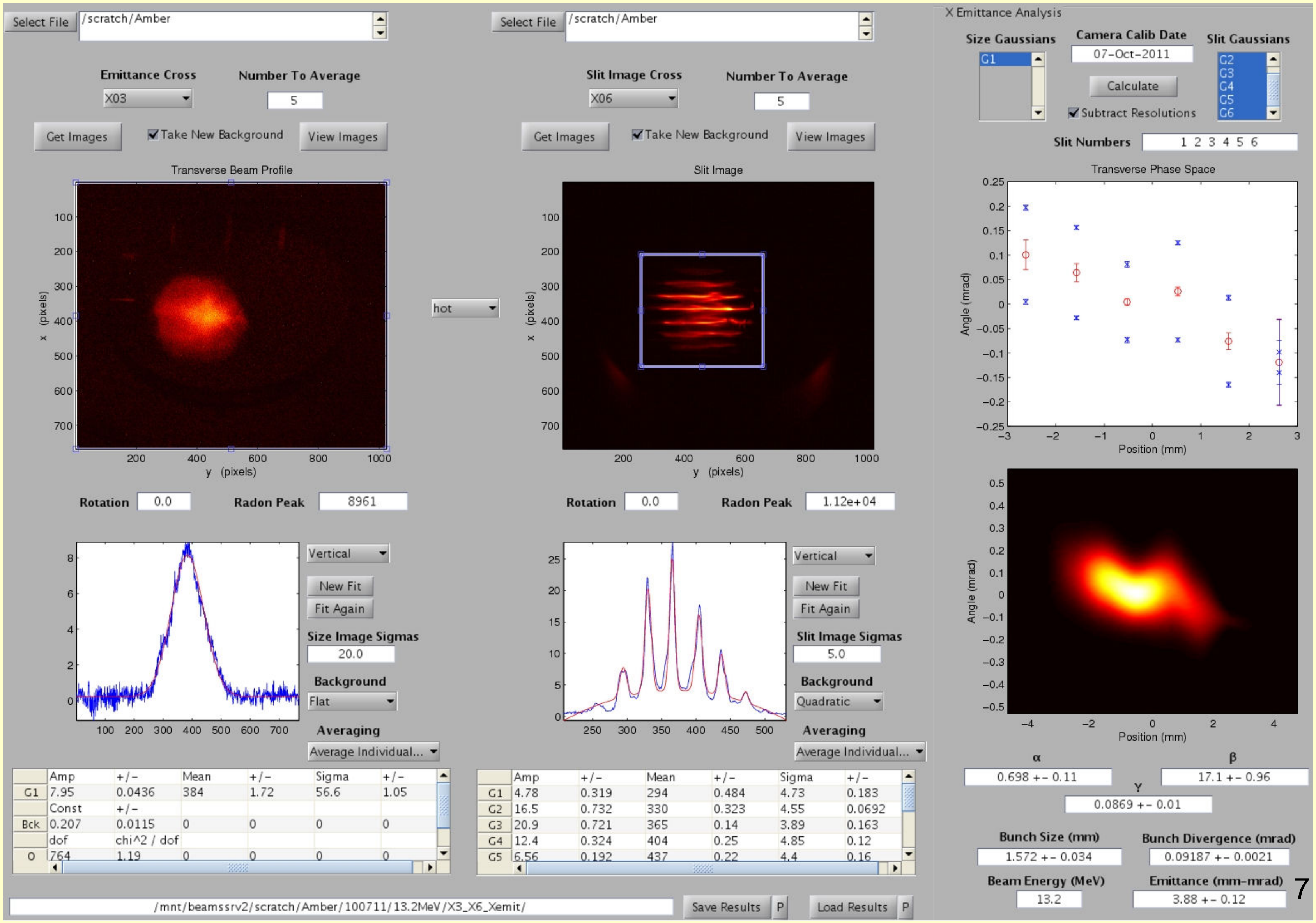
Gun	1.3 GHz NC
Accelerating Cavity	1.3 GHz SC
Deflecting cavity	3.9 GHz NC

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

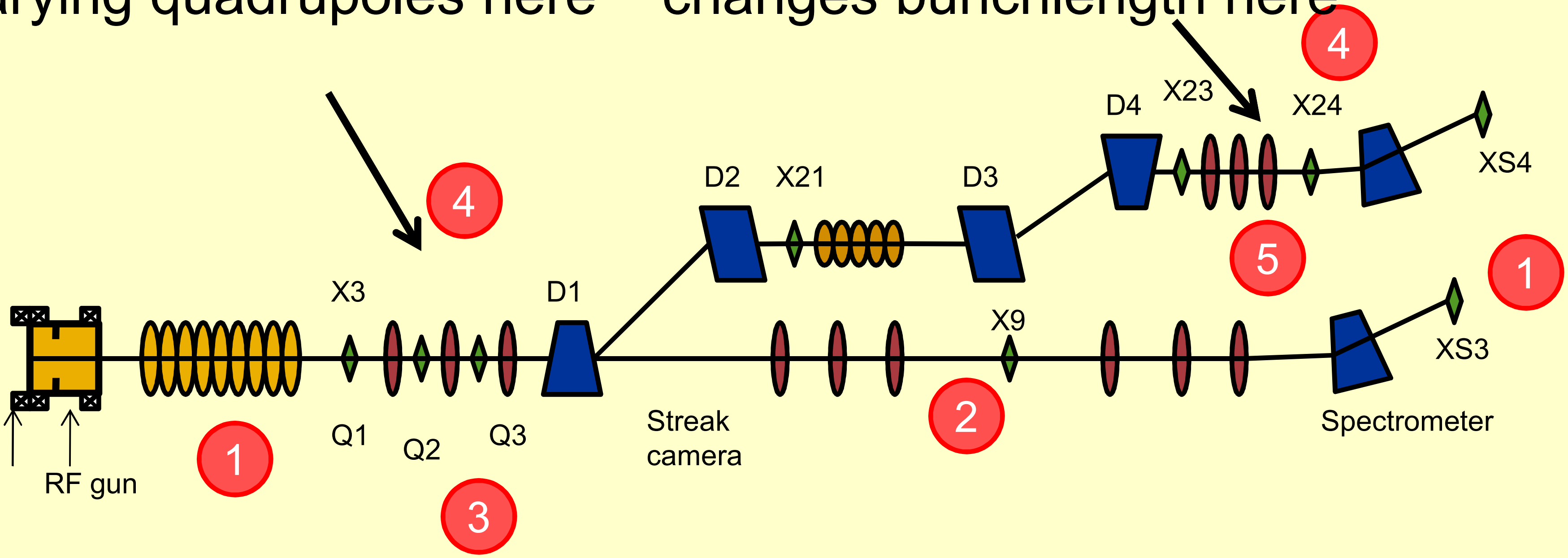


	Amp	+/-	Mean	+/-	Sigma	+/-
G1	7.95	0.0436	384	1.72	56.6	1.05
	Const	+/-				
Bck	0.207	0.0115	0	0	0	0
	dof	chi^2 / dof				
0	764	1.19	0	0	0	0

	Amp	+/-	Mean	+/-	Sigma	+/-
G1	4.78	0.319	294	0.484	4.73	0.183
G2	16.5	0.732	330	0.323	4.55	0.0692
G3	20.9	0.721	365	0.14	3.89	0.163
G4	12.4	0.324	404	0.25	4.85	0.12
G5	6.56	0.192	437	0.22	4.4	0.16

The A0 photoinjector: Machine tuning

Varying quadrupoles here changes bunchlength here



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)

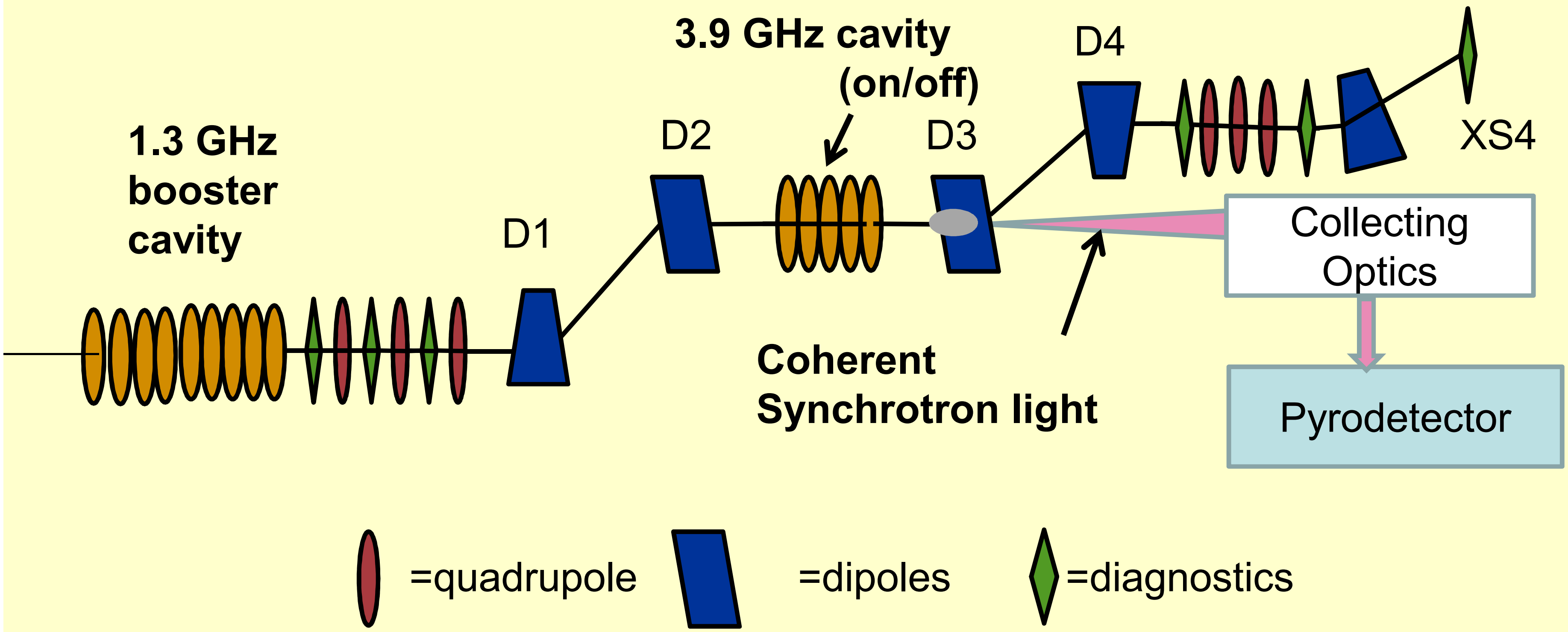
An experimental program to demonstrate a novel phase-space manipulation in which the horizontal and

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 $\lambda >> \sigma_l$

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….

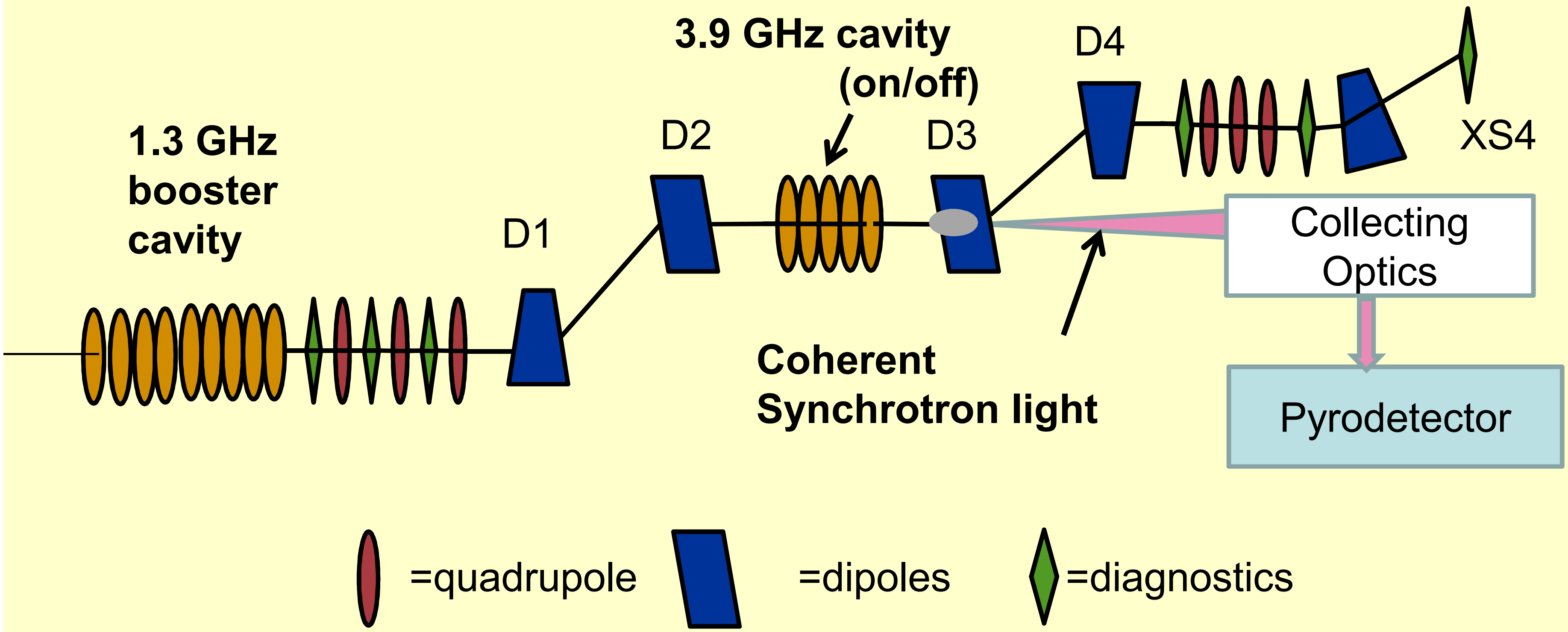
$$\Delta E = 0.35 mc^2 \frac{N_e r_e L_B}{(\rho \sigma_z^2)^{2/3}}$$

r_e Classical electron radius

L_B Length of the bend

N_e Number of *electrons* in the bunch

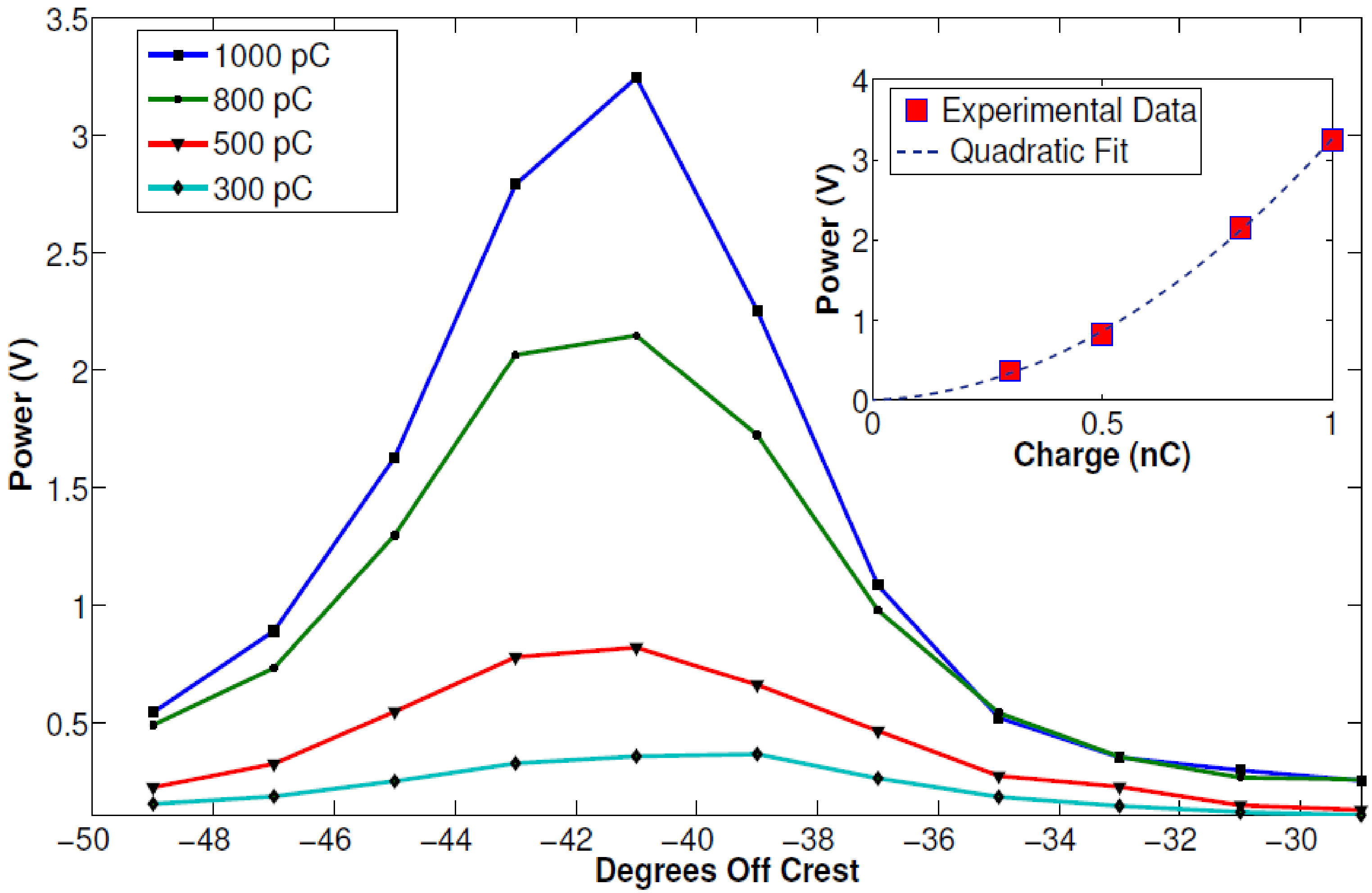
The A0 beamline



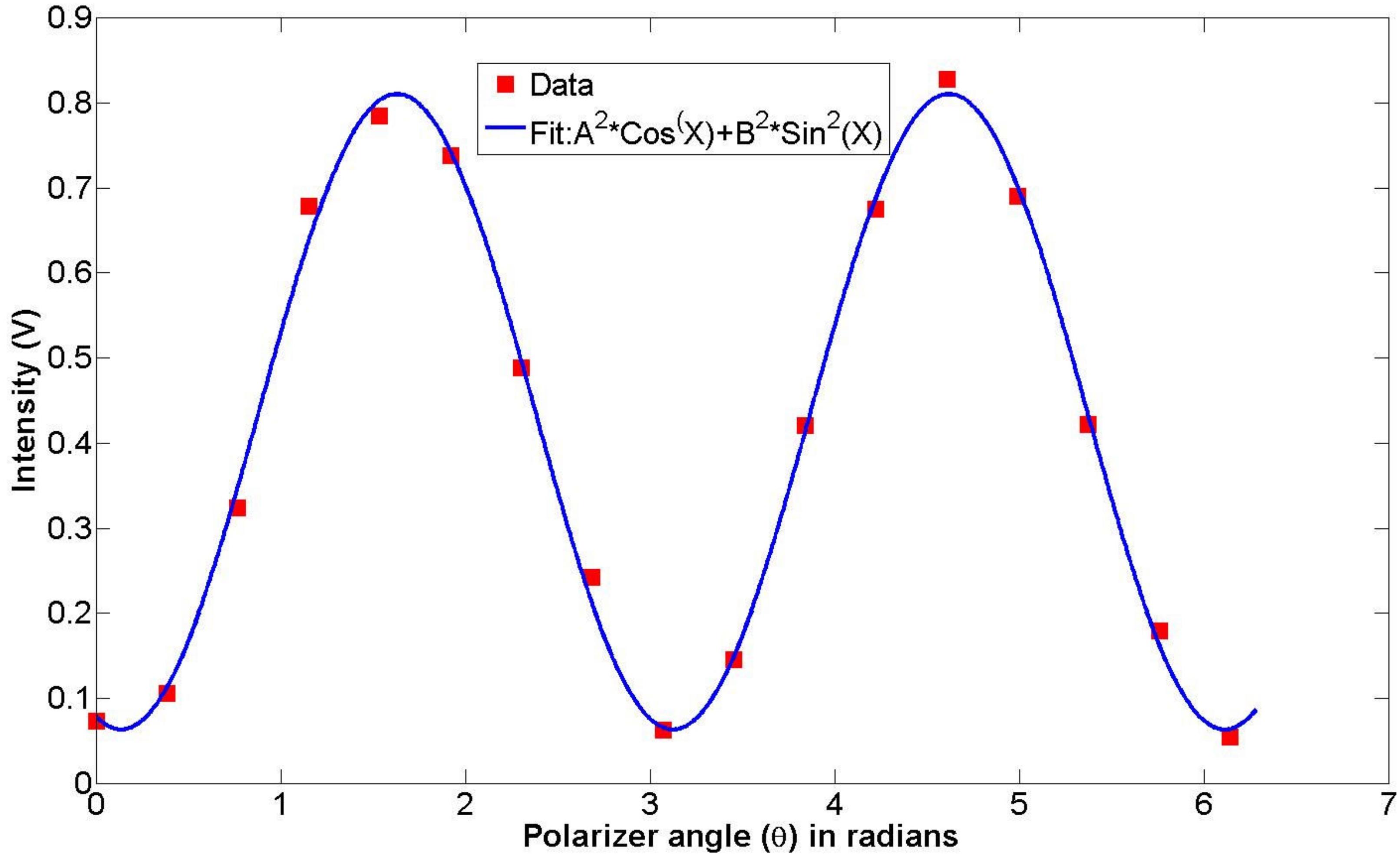
CSR : Measurements

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

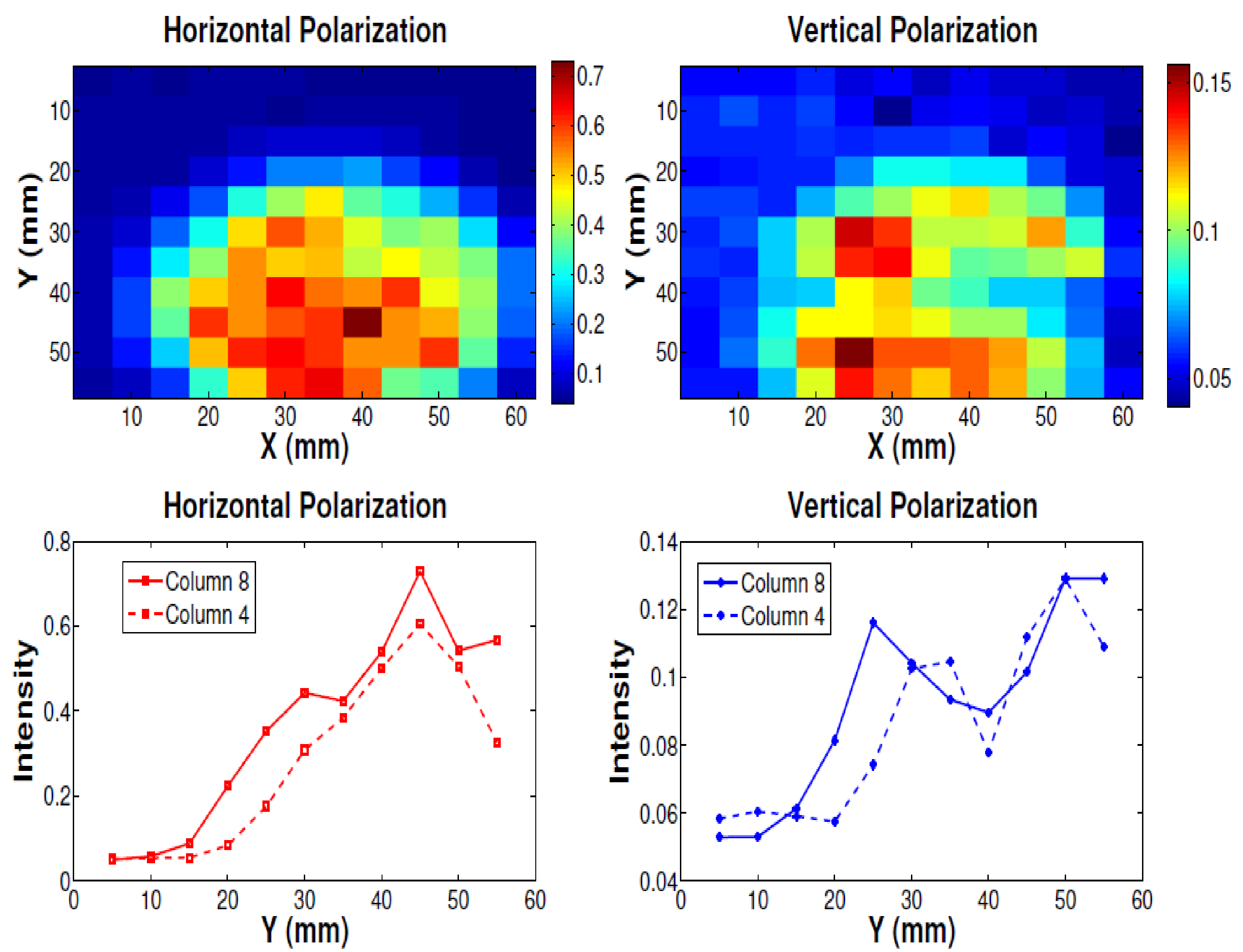
CSR Power Vs RF Phase (bunchlength)



Polarizer angle vs CSR

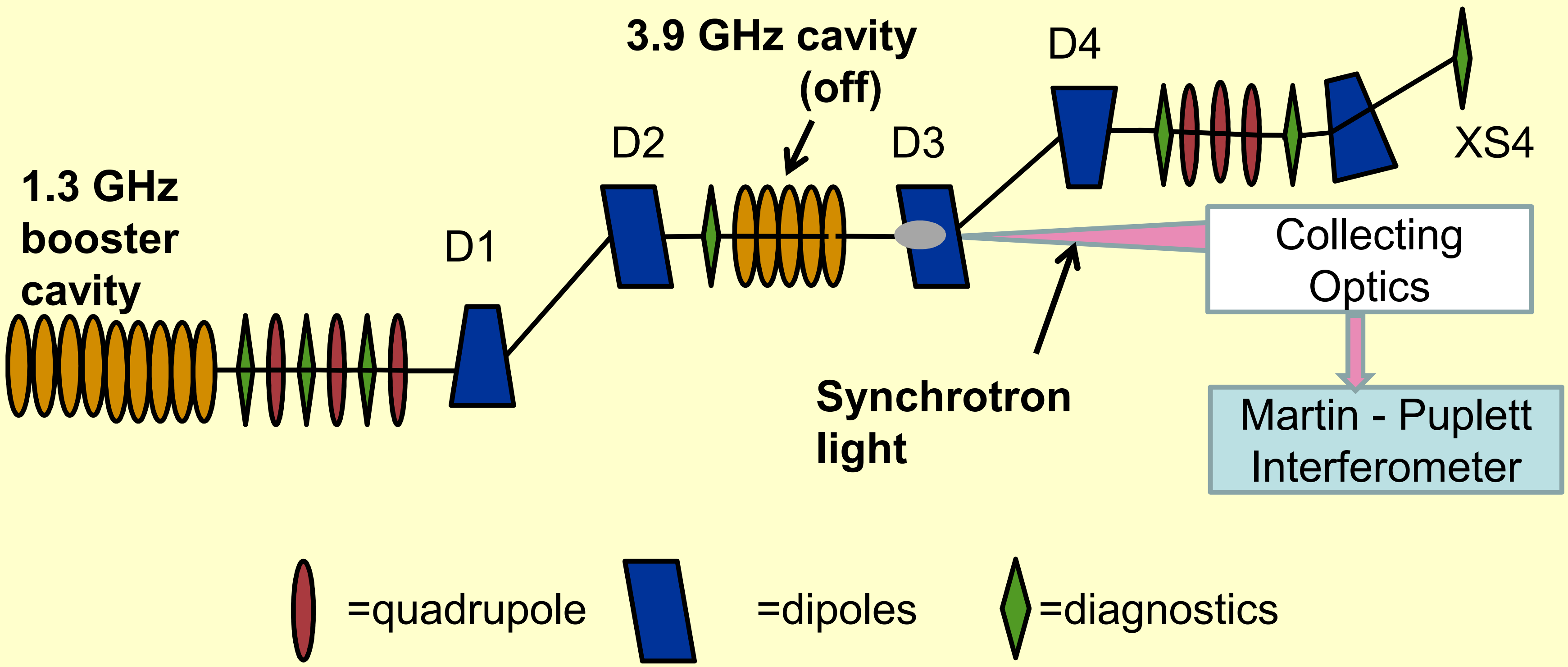


CSR Angular distribution

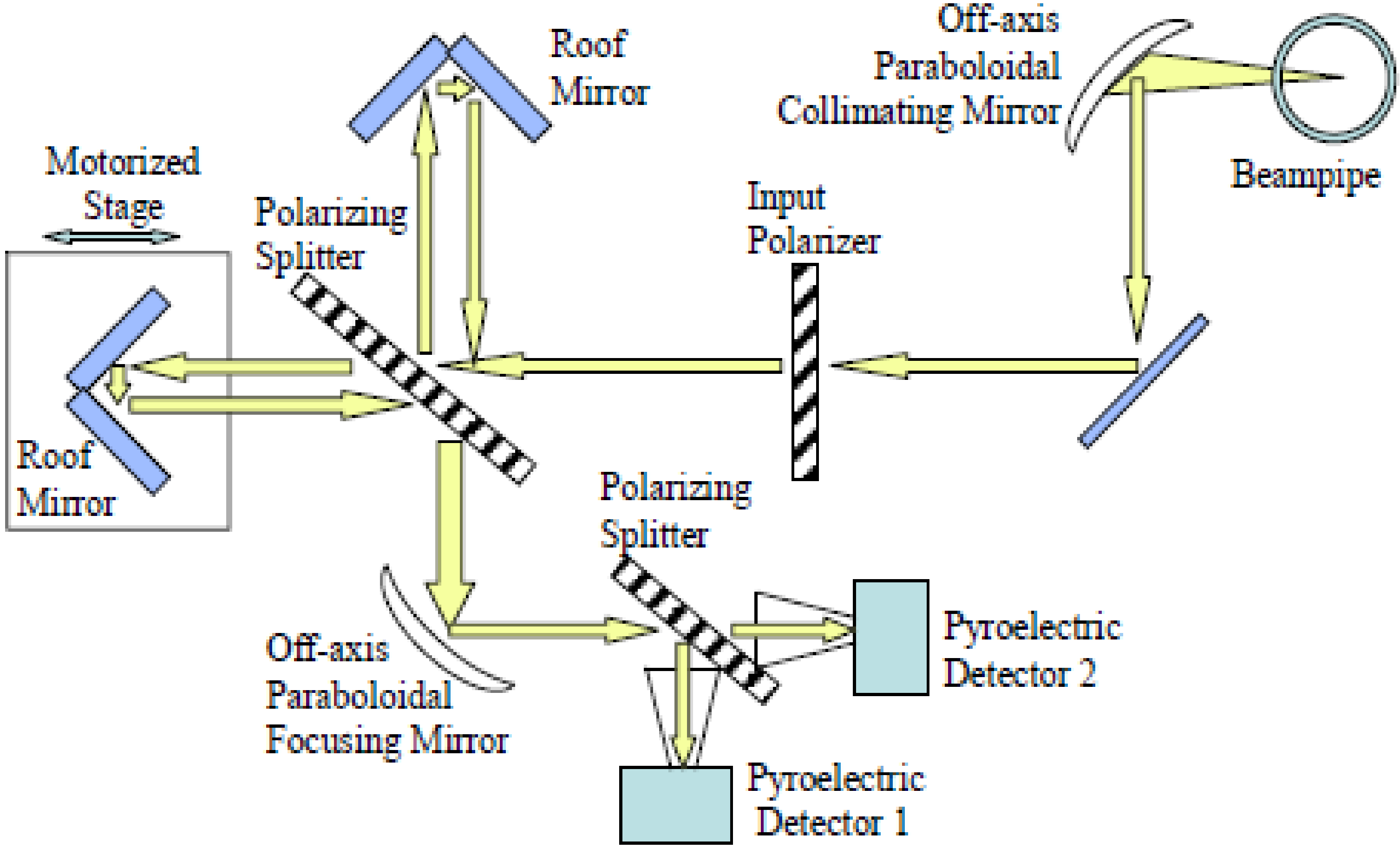


Ratio (Horizontal to vertical) = 4.6

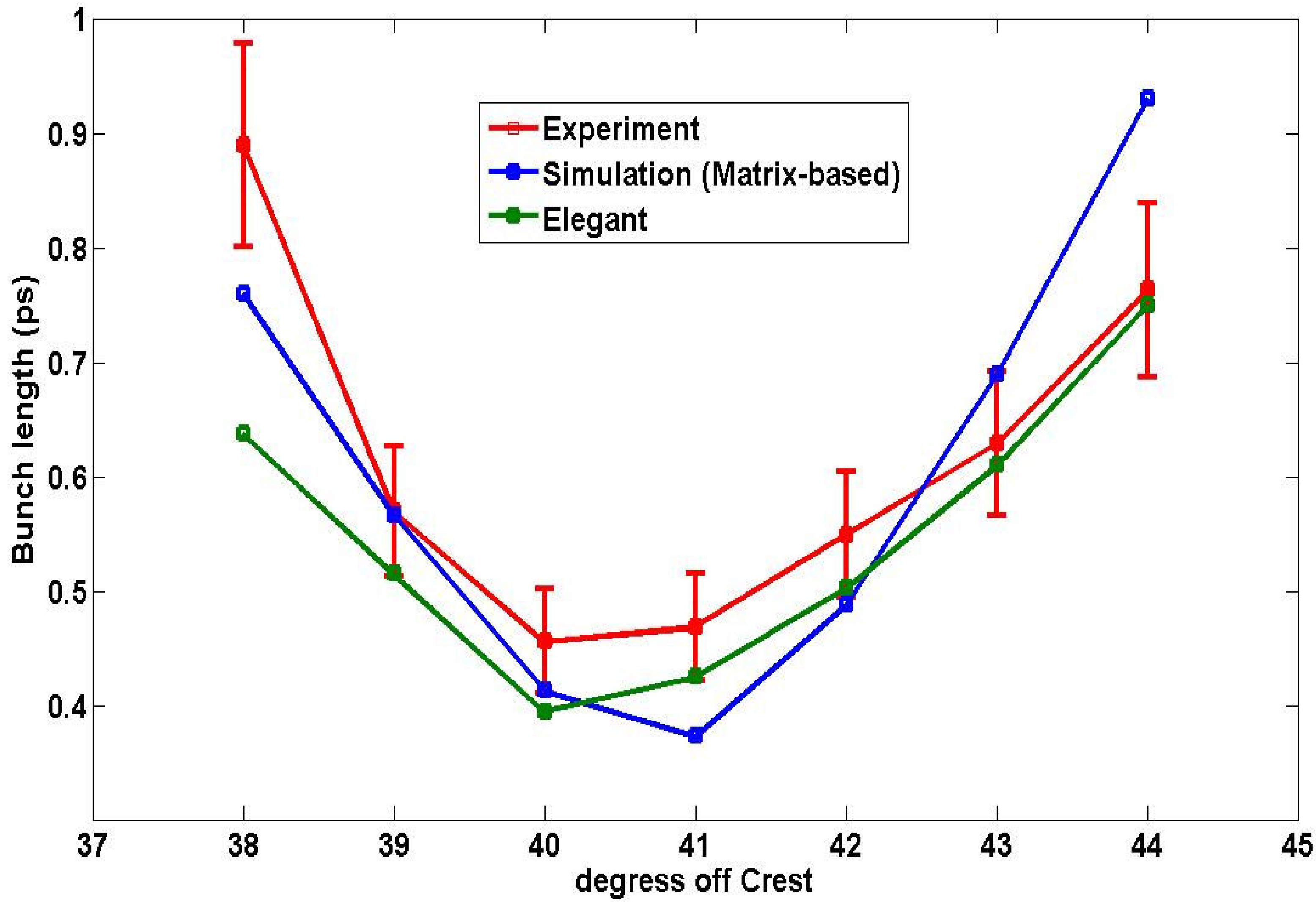
Bunch length measurement: Experimental Setup



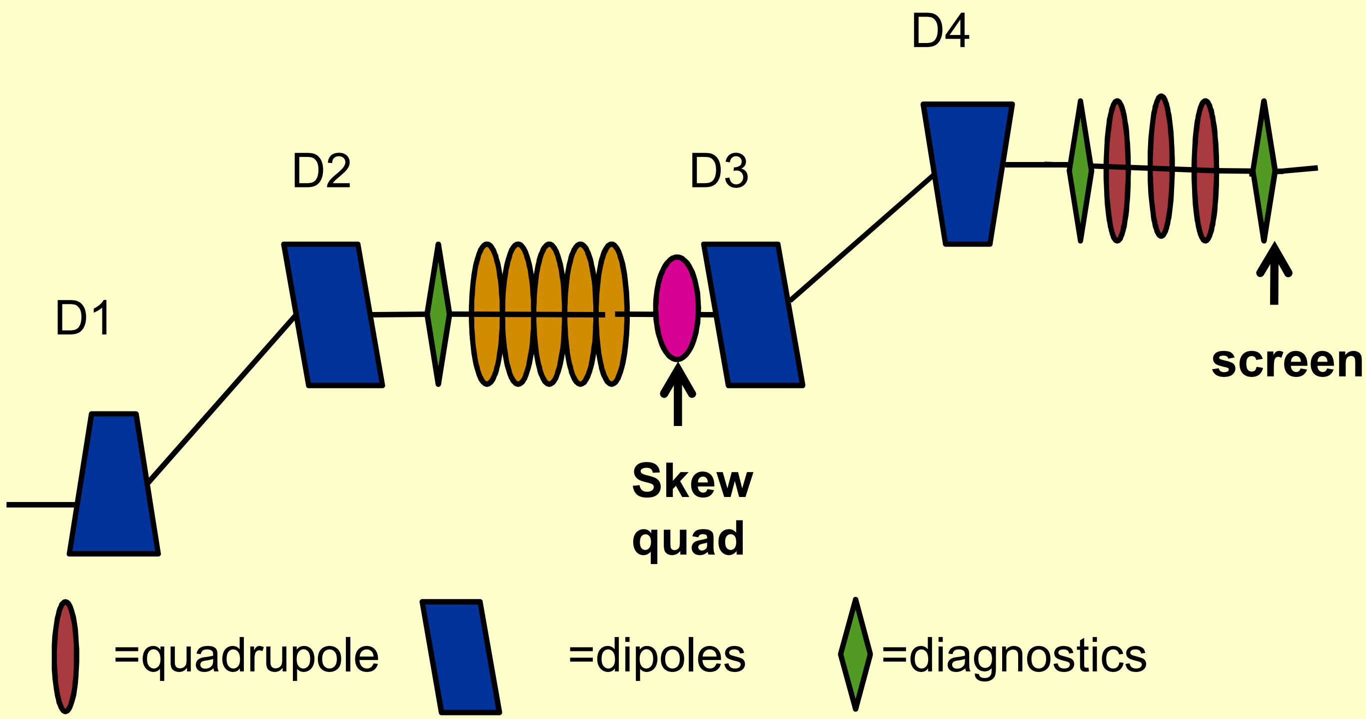
Martin – Puplett interferometer



Bunch length measurement: Simulation Vs Experiment

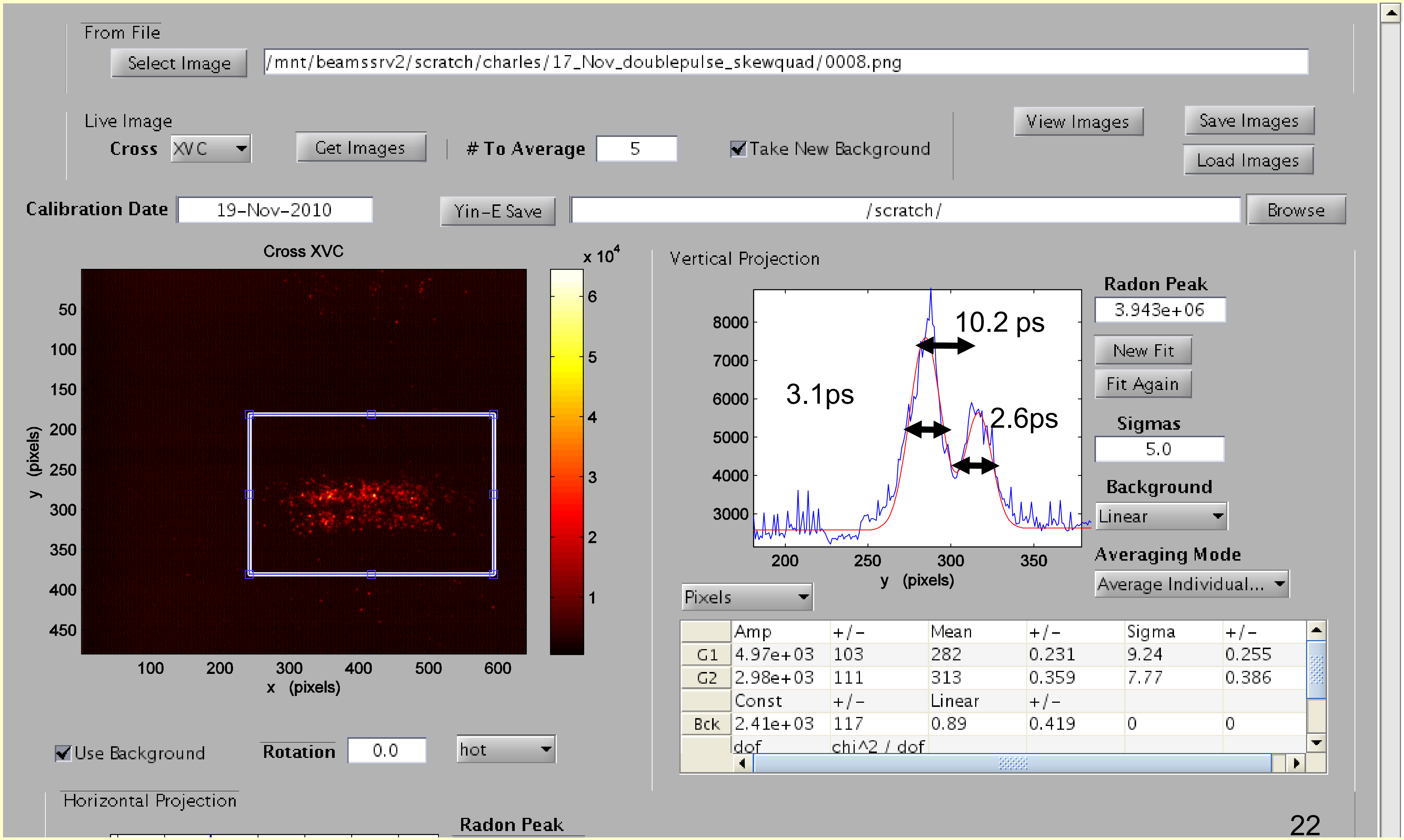


Studying the effects of CSR on the beam*

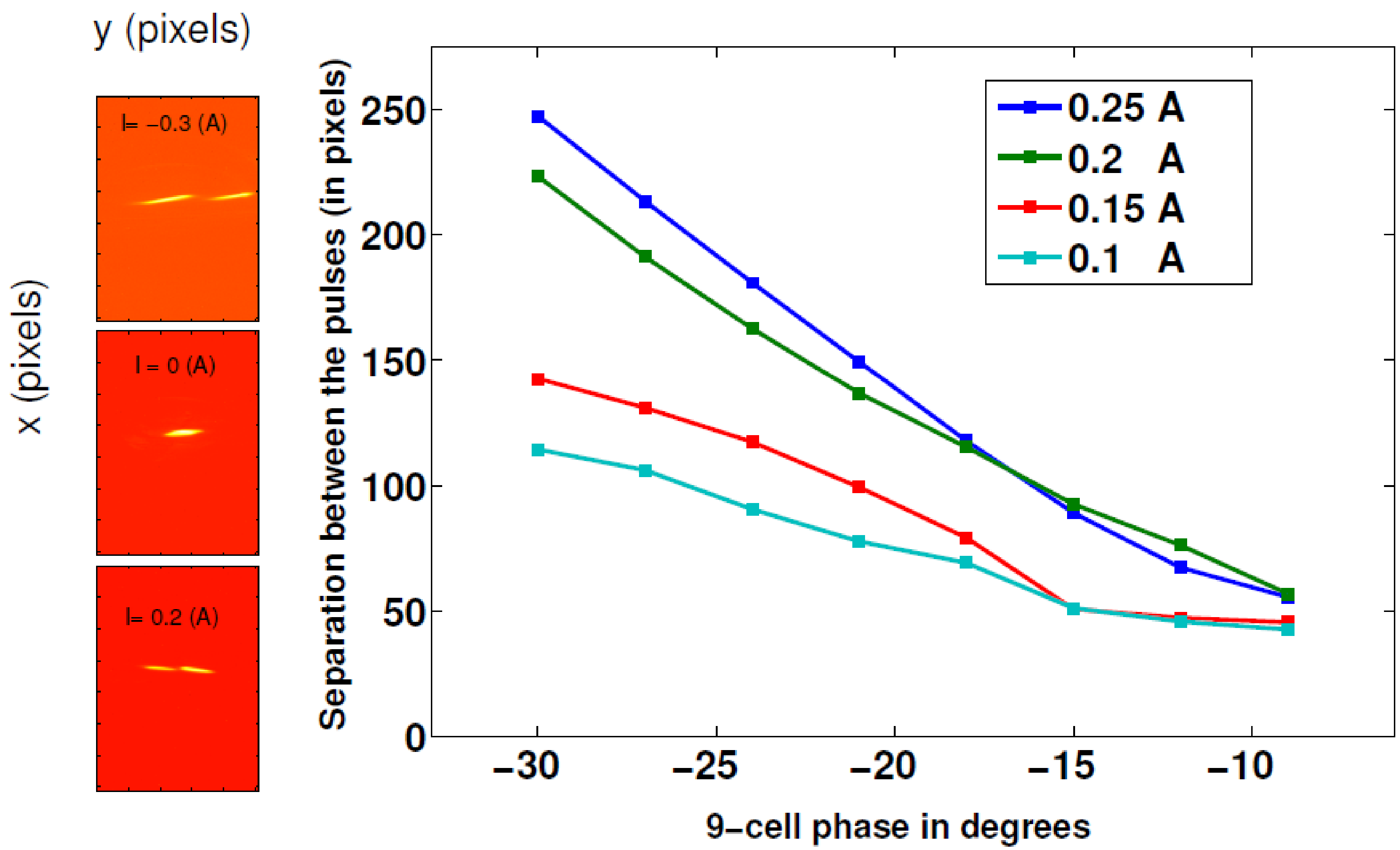


* **Using a Skew Quad in a Chicane to Temporally Resolve the Transverse Effects of CSR – P. Emma (uBI 2010)**

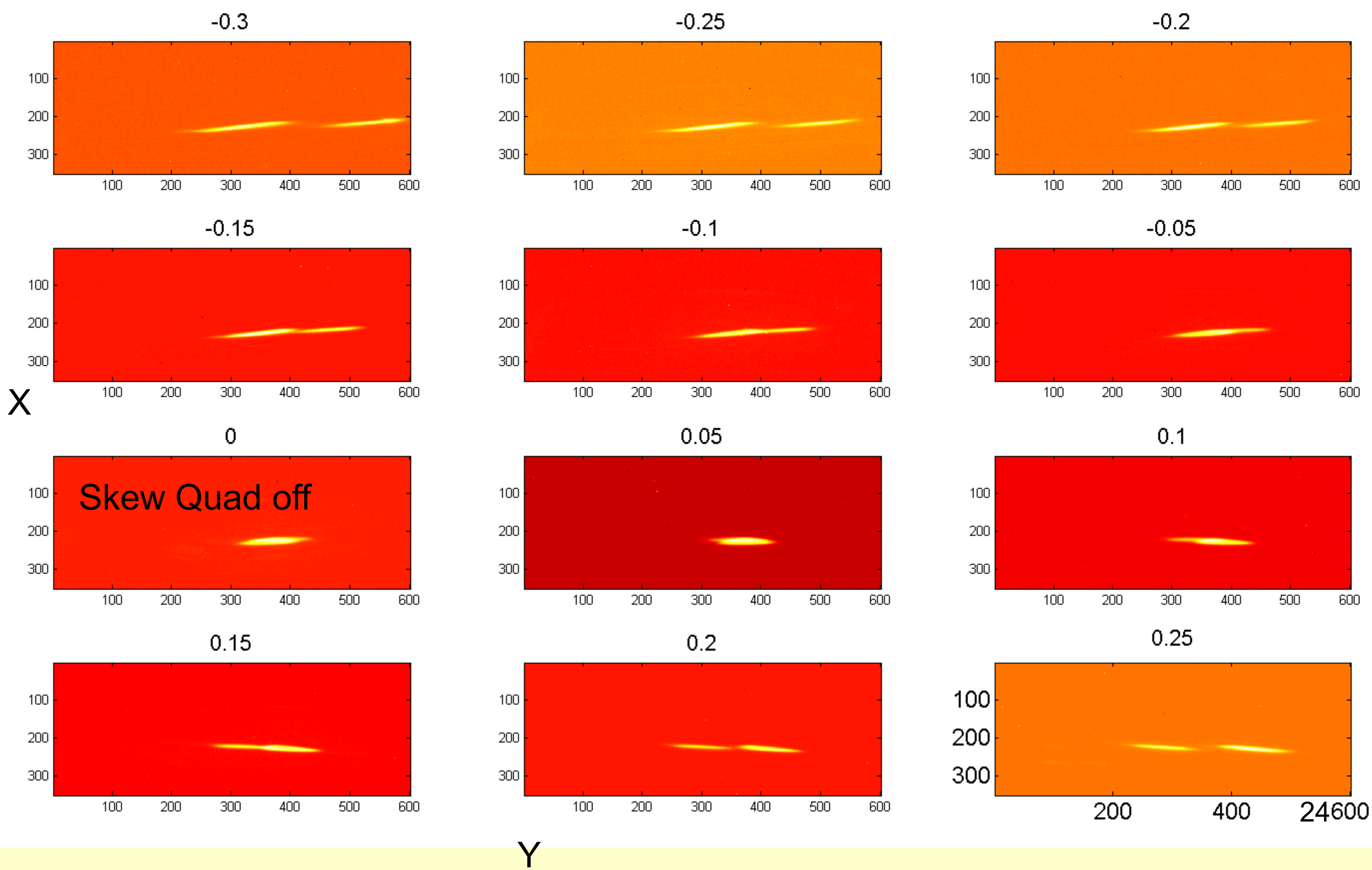
Twin pulse at the cathode



Twin pulse Profile @X24 vs SkewQuad



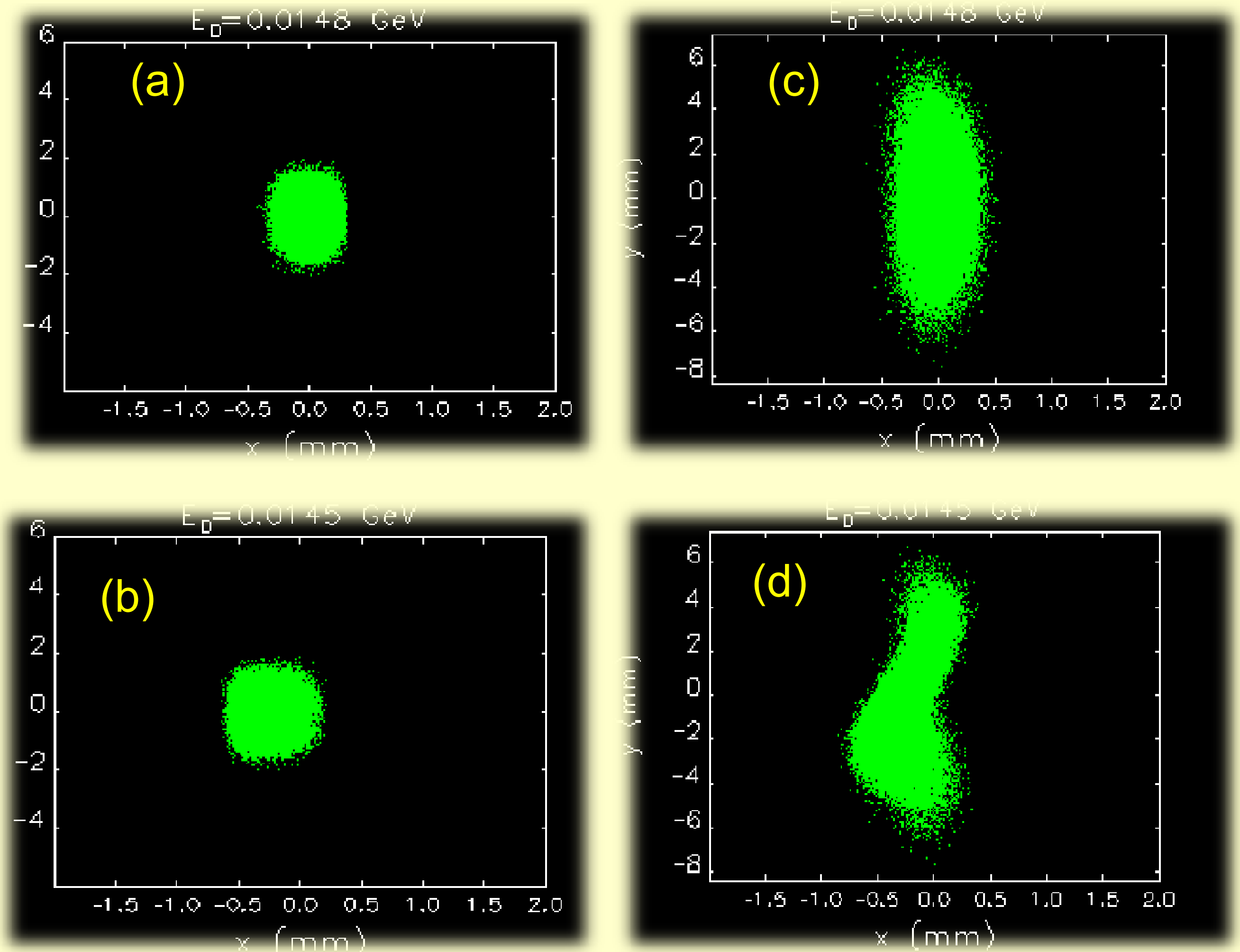
Twin pulse Profile @X24 vs SkewQuad



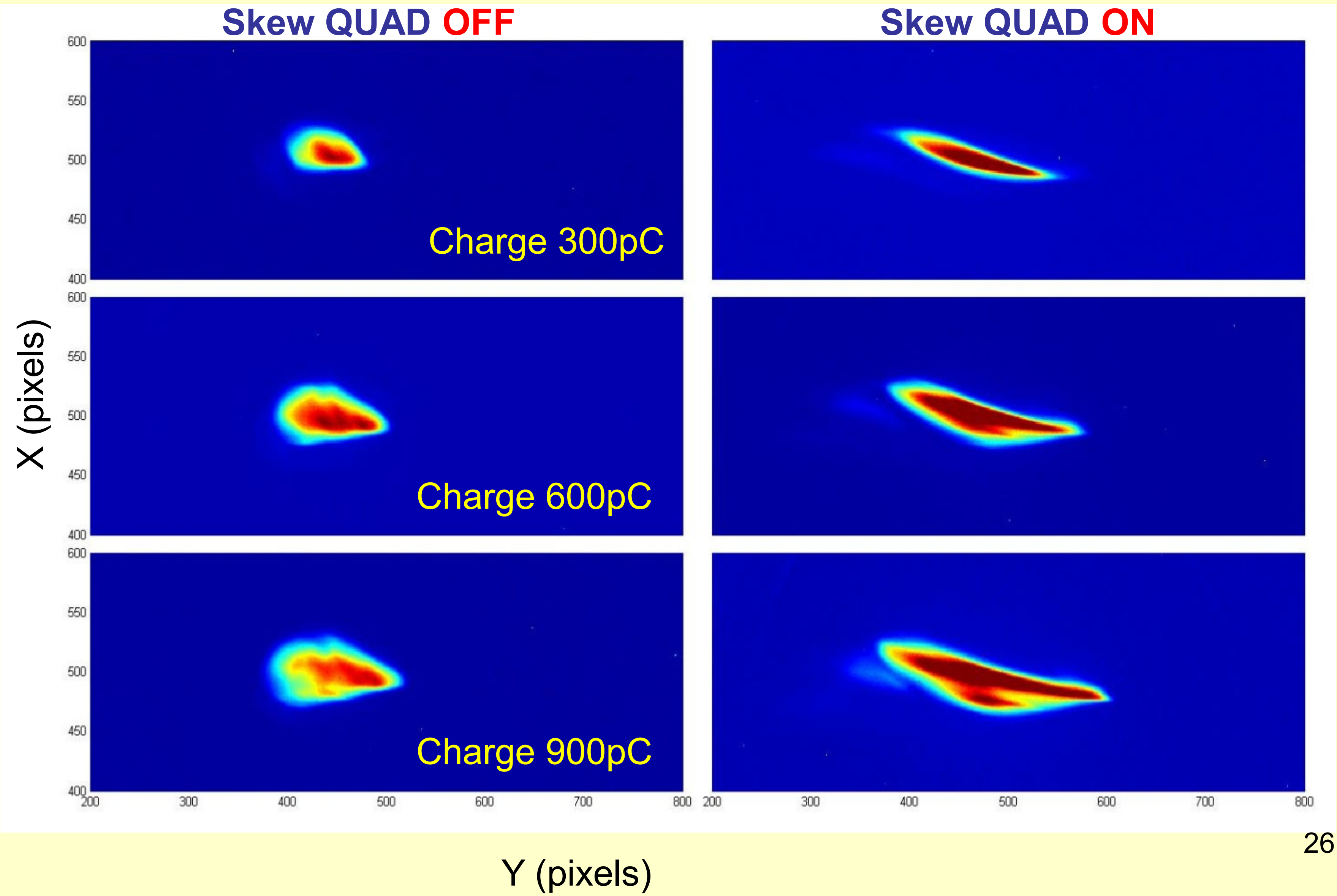
Skew quad diagnostic to resolve CSR effects

Skew QUAD **OFF** | Skew QUAD **ON**

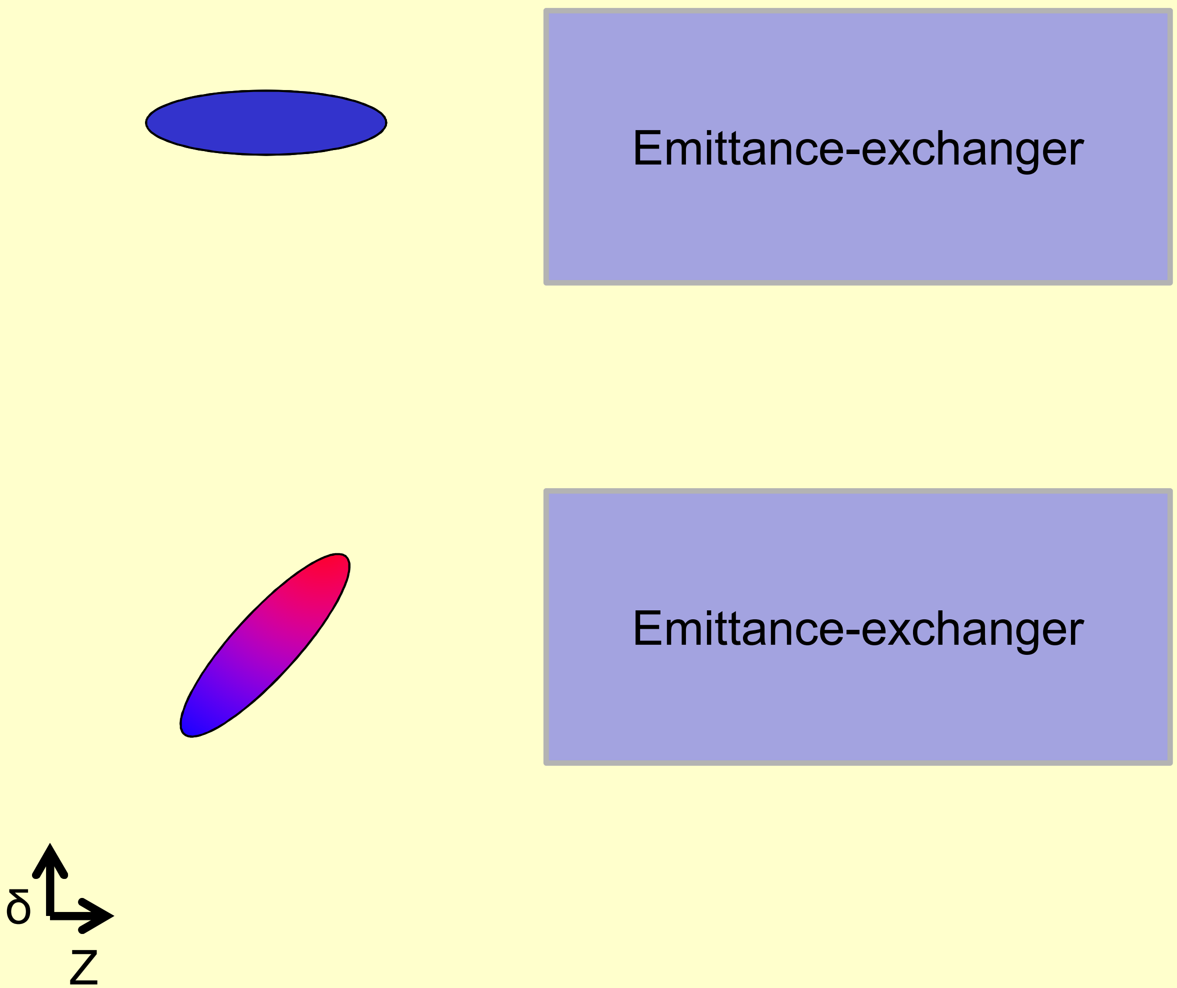
CSR **OFF** / CSR **ON**



Skew quad measurements at X24



Part III: Chirped beam has improved performance



- Improved performance
- Minimizes thick lens effect

How to minimize thick lens effect?*

$$\varepsilon_{x,\mathrm{out}}^2 = \varepsilon_z^2 + \left(\frac{17\lambda^2}{40D}\right)^2 \langle x'^2\rangle[\langle z^2\rangle + \alpha^2 D^2\langle\delta^2\rangle + 2\alpha D\langle z\delta\rangle]$$

$$\varepsilon_{z,\mathrm{out}}^2 = \varepsilon_x^2 + \left(\frac{17\lambda^2}{40D}\right)^2 \langle x'^2\rangle[\langle z^2\rangle + \alpha^2 D^2\langle\delta^2\rangle + 2\alpha D\langle z\delta\rangle]$$

λ : *wavelength of cavity*
x' : *transverse angle*
z : *longitudinal position*
δ : *fractional energy spread*
D : *dispersion of a dogleg*
α : *bending angle*

Minimize this term: $[< z^2 > + \alpha^2 D^2 < \delta^2 > + 2\alpha D < z\delta >]$

Introduce correlation : $\delta = hz$

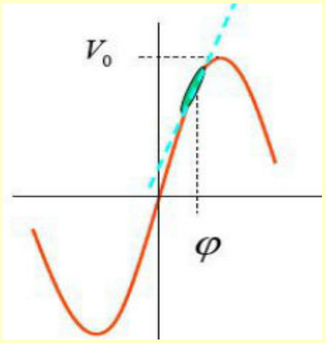
then : $< z^2 > + \alpha^2 D^2 h^2 < z^2 > + 2\alpha h D < z^2 >$

$$=> h = \frac{-1}{\alpha D} \text{ will make this term zero.}$$

In other words, set Chirp to -1/R_{56}

* 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),

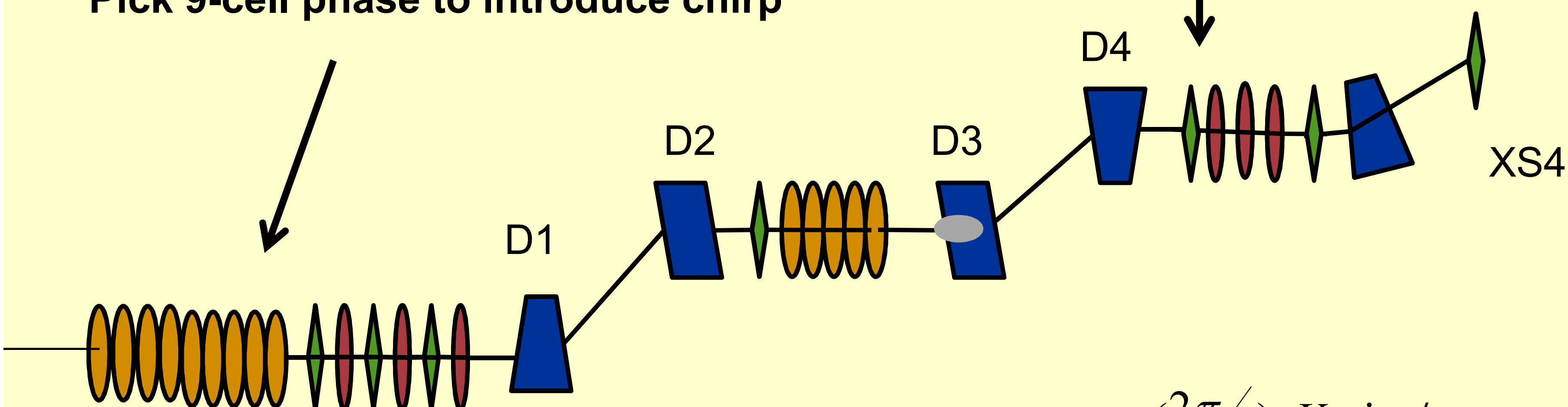
Minimize thick lens effect: Add energy chirp



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)

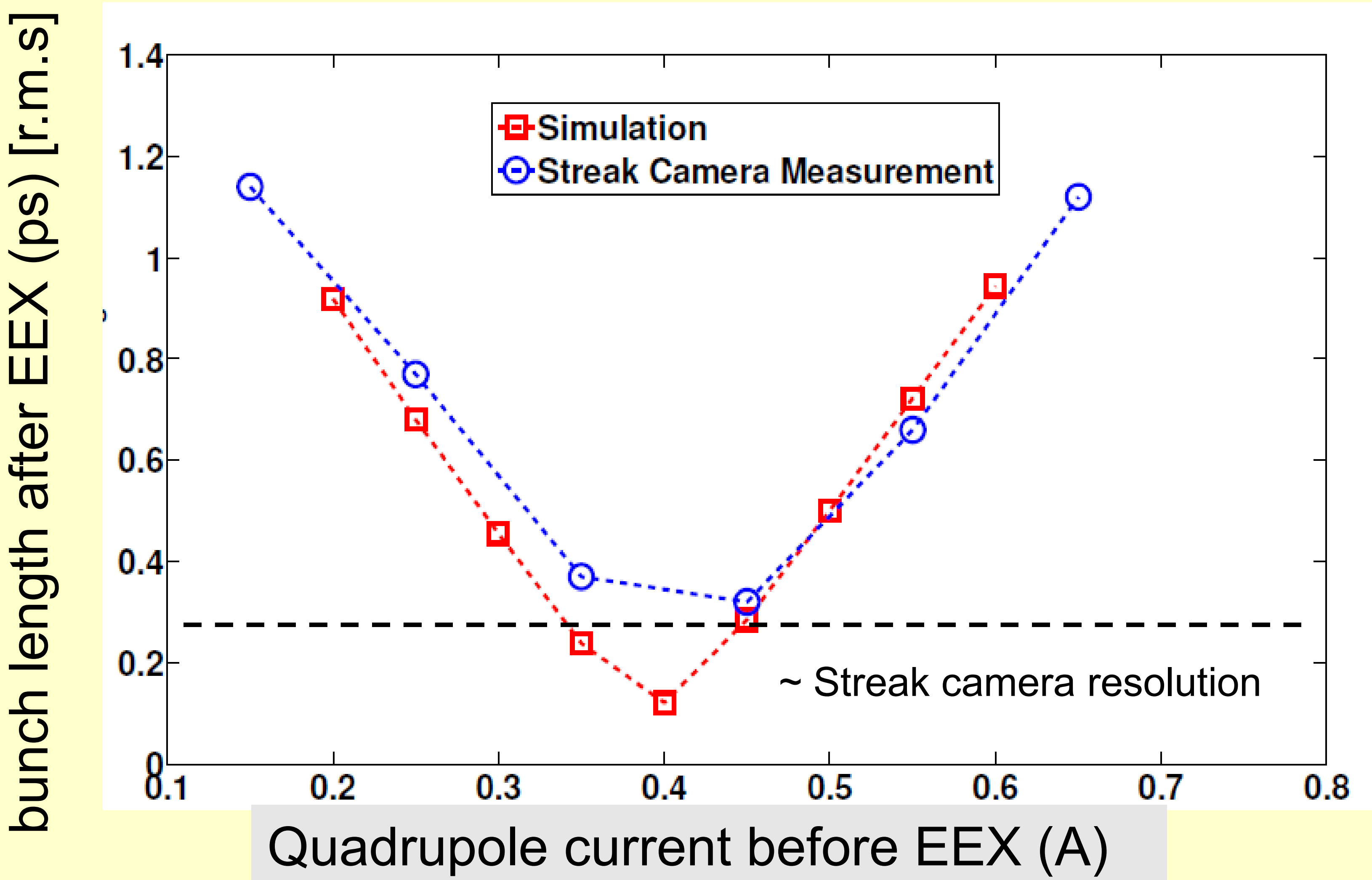
Pick 9-cell phase to introduce chirp



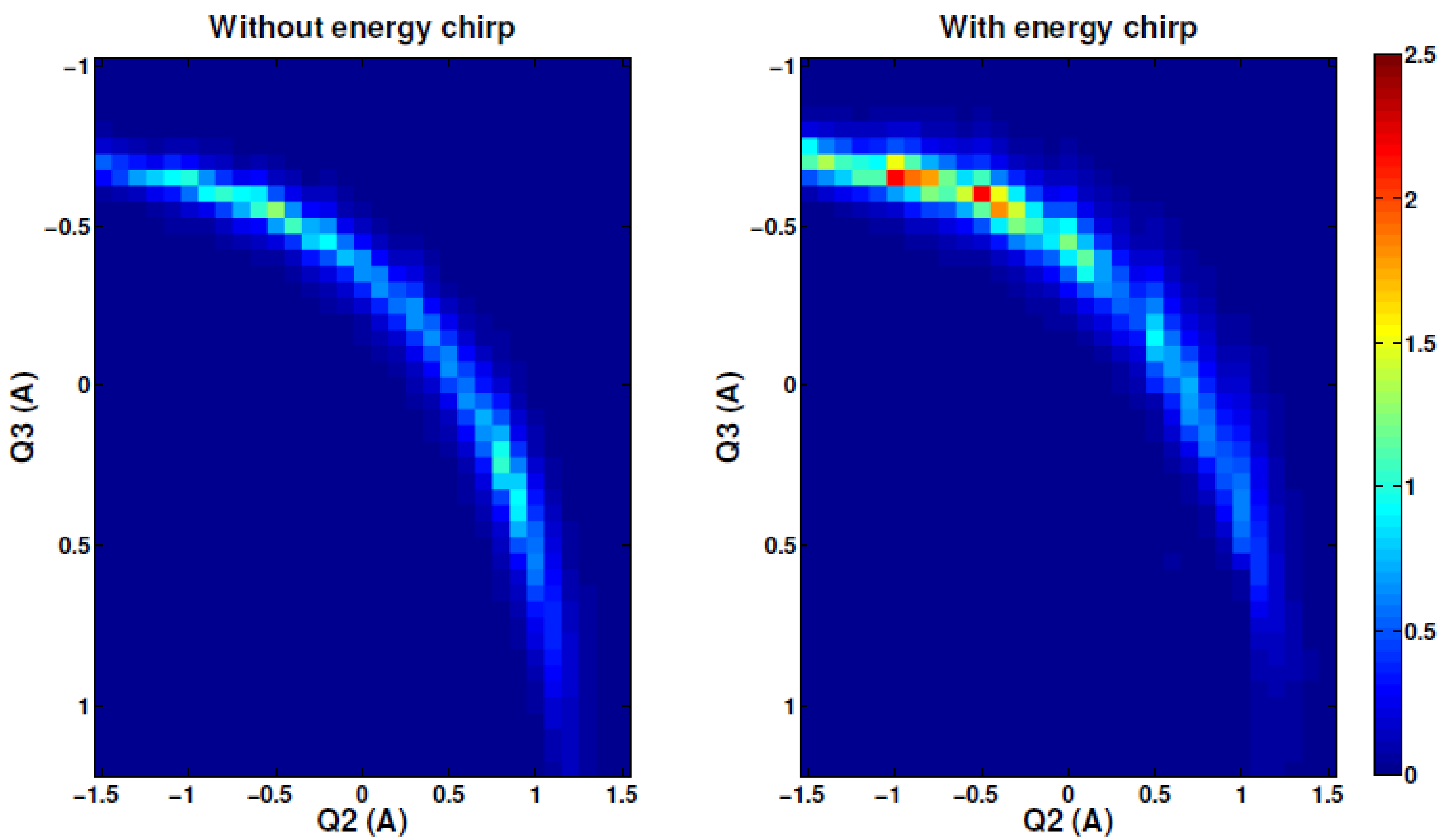
1.3 GHz booster cavity

$$chirp = \frac{d\delta}{dz} = \frac{(2\pi/\lambda) e V_0 \sin\phi}{E_0 + e V_0 \cos\phi}$$

Chirped beam study: Streak camera

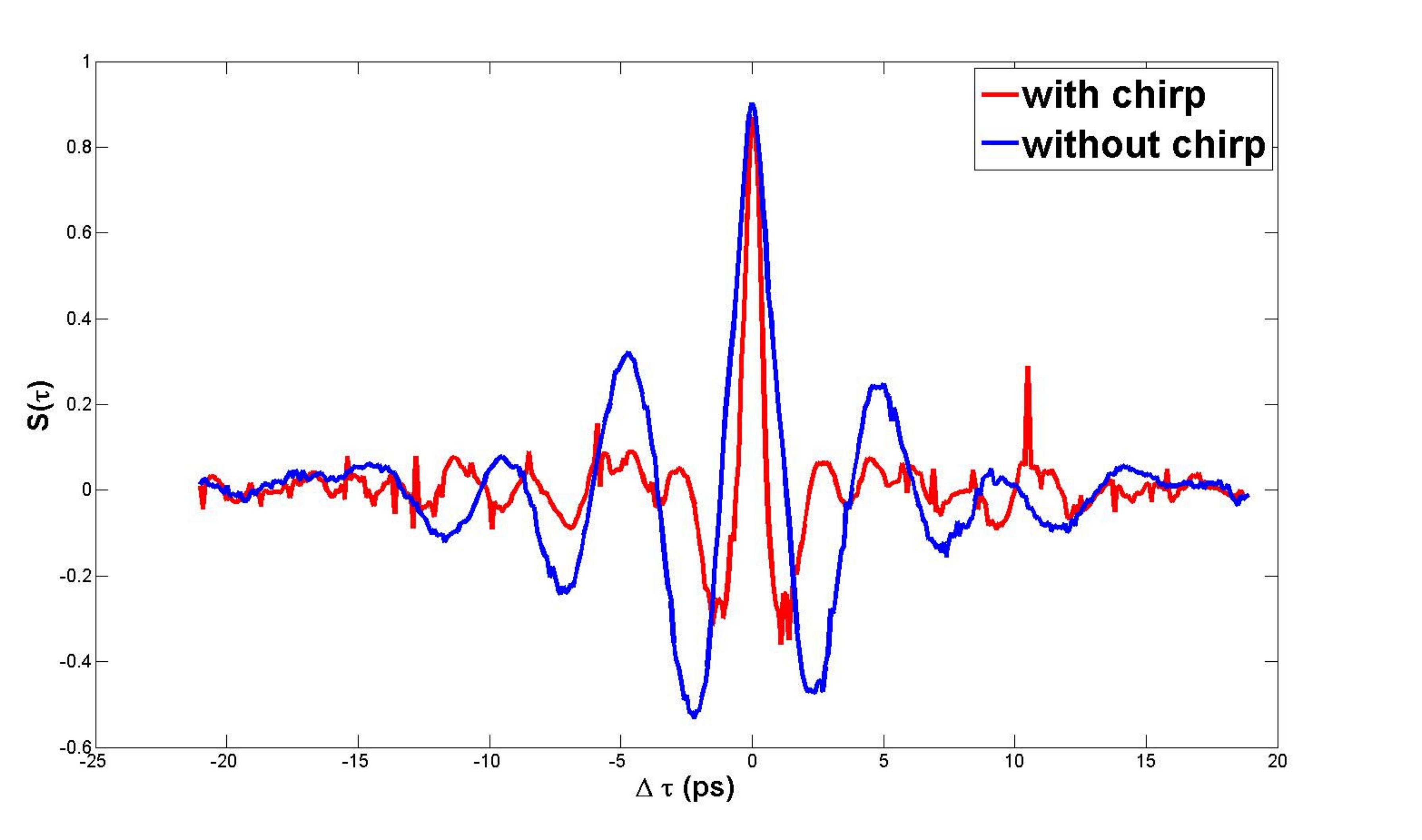


Finer quadrupole scan using interferometer pyros



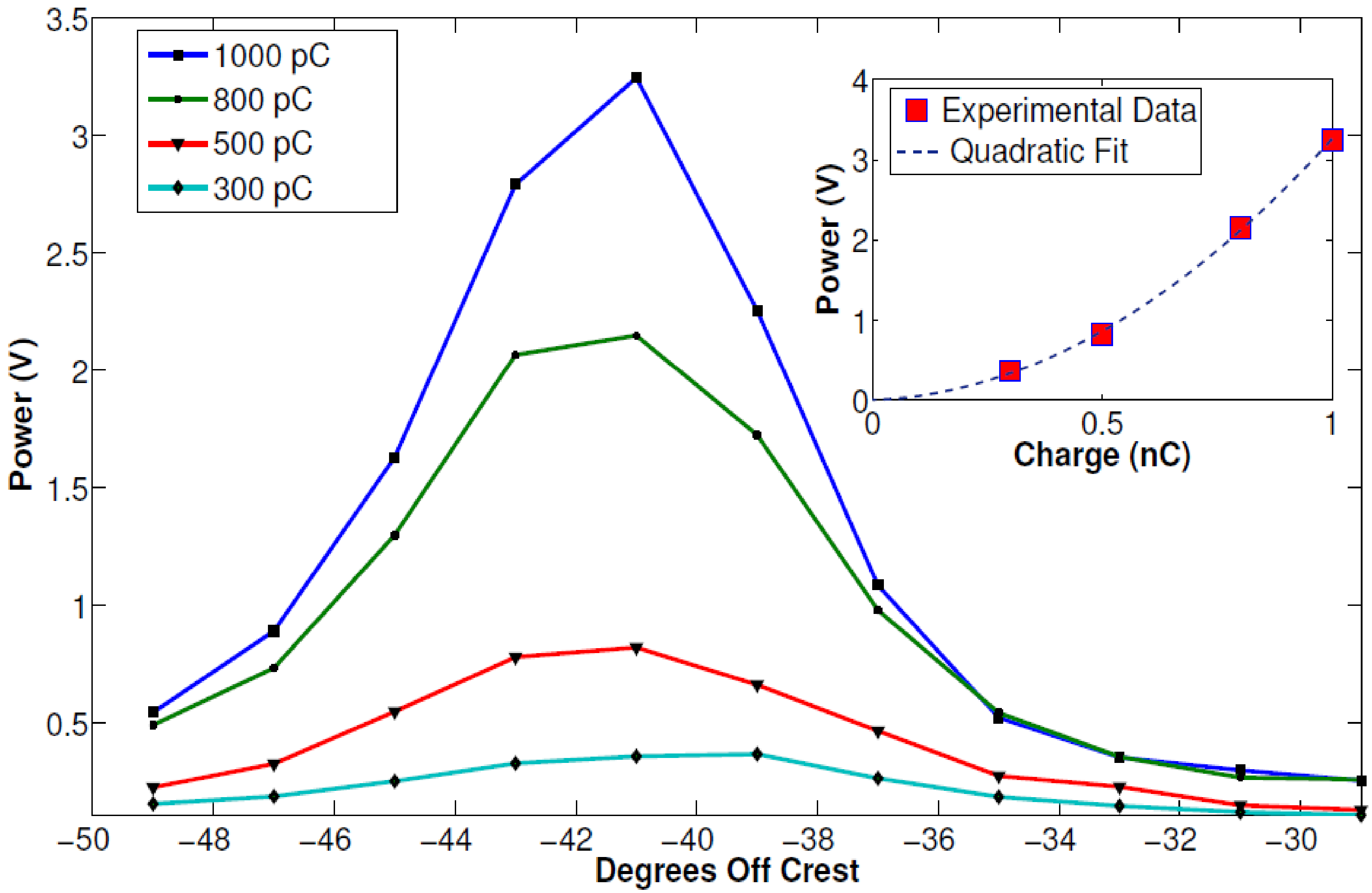
- Pyro signal increases ~ by a factor of 2

Interferometer measurement

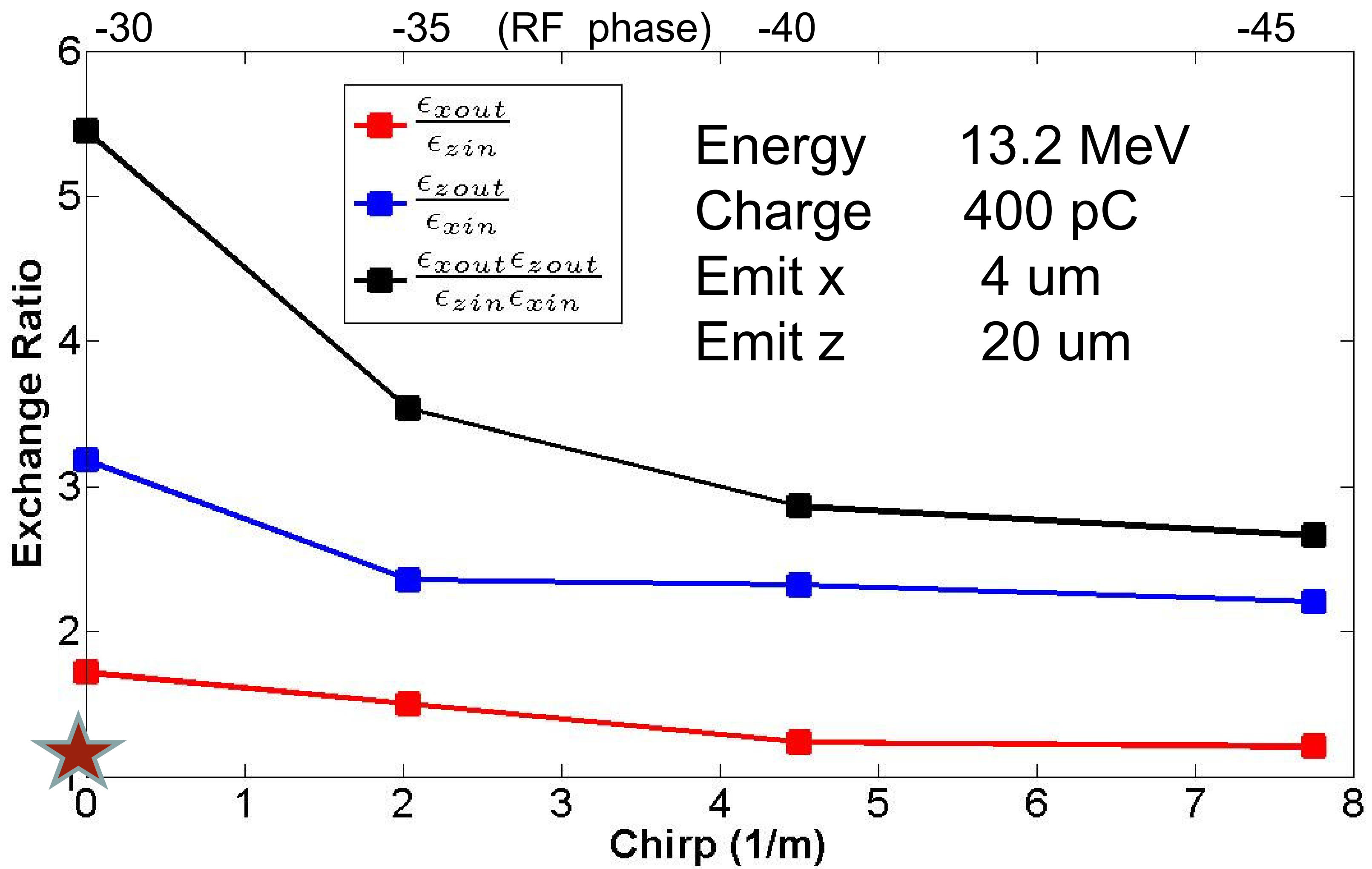


Bunch length reduction ~ 2

CSR Power (pyrometer) Vs RF Phase (bunchlength)

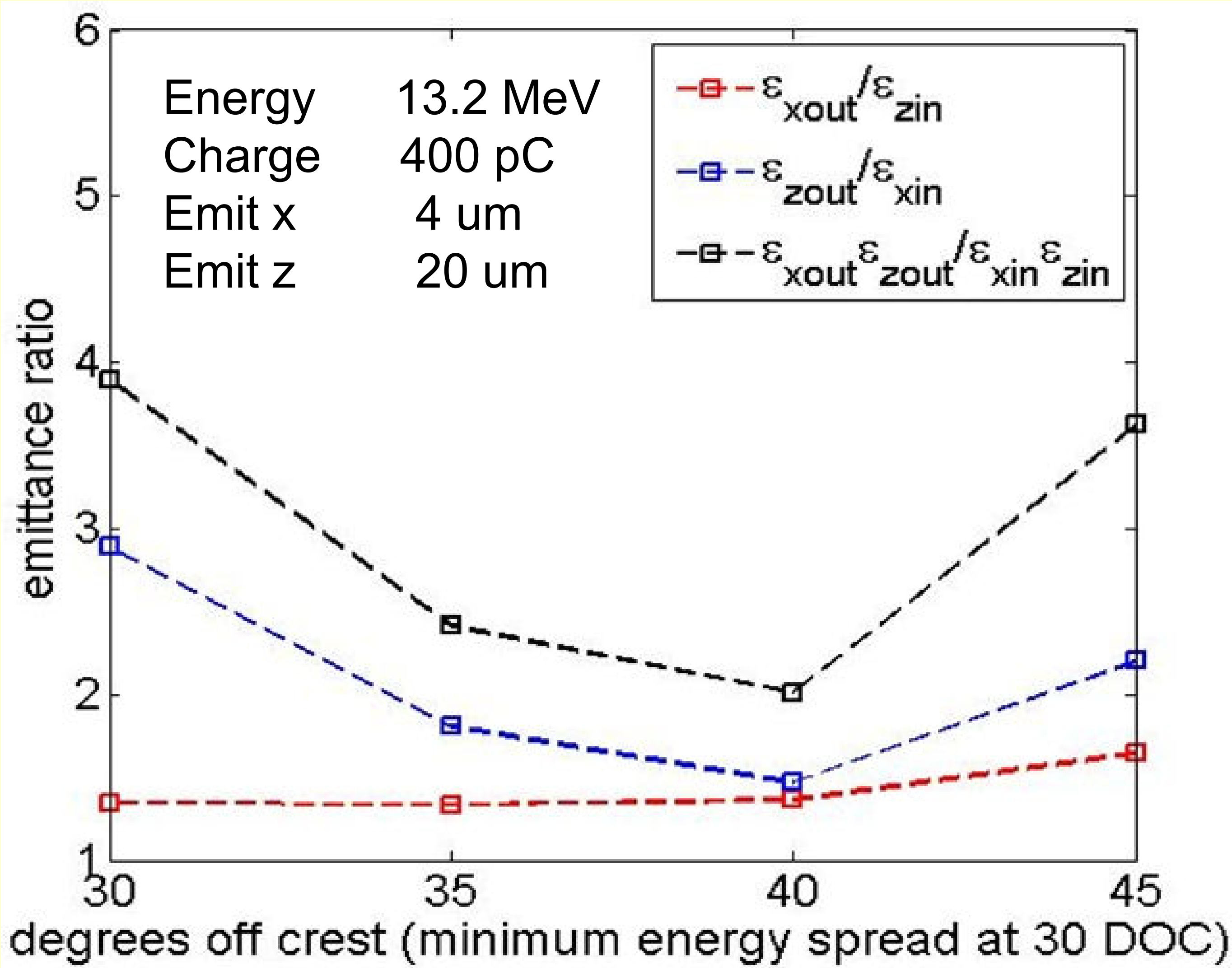


Emittance exchange with chirped beam*

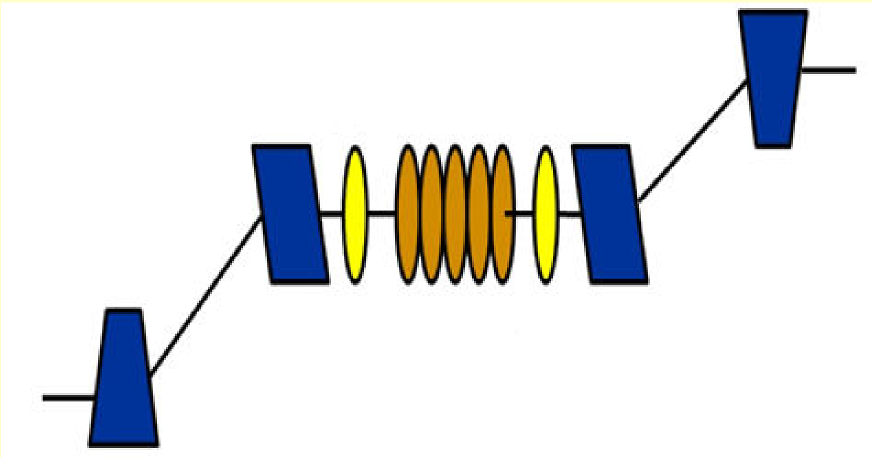


★ 250 pC; PRL 106, 244801 (2011) * IPAC 2012

Emittance exchange simulation with GPT



Next generation EEX: upgraded Classic EEX*



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

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

Next generation EEX : A Negative drift EEX

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

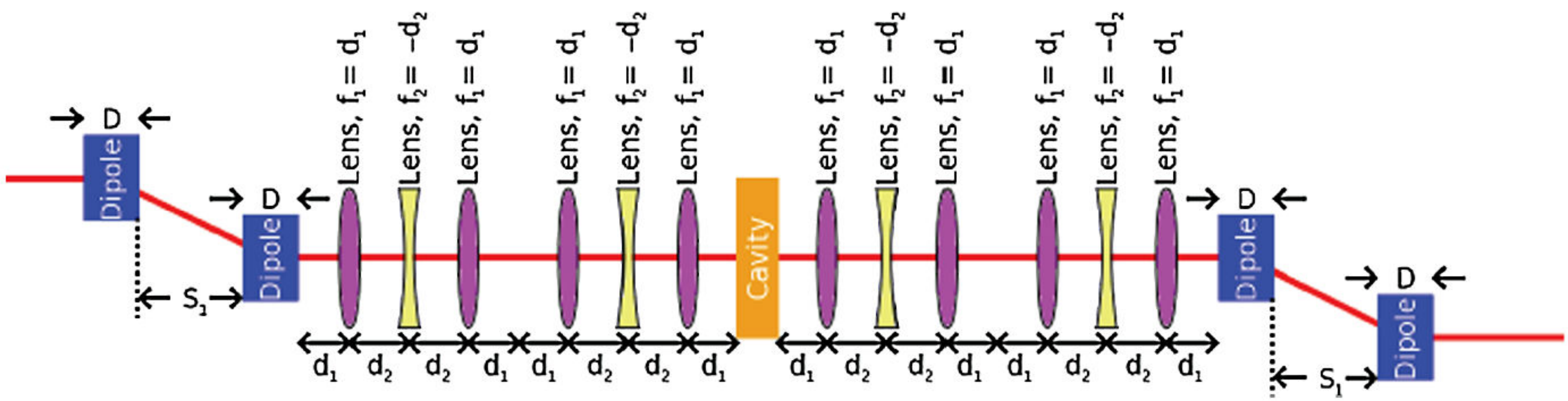


FIG. 13. Transverse-to-longitudinal emittance exchange optic with optics for negative drift lengths between the doglegs.

Next generation EEX : A Chicane style EEX

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

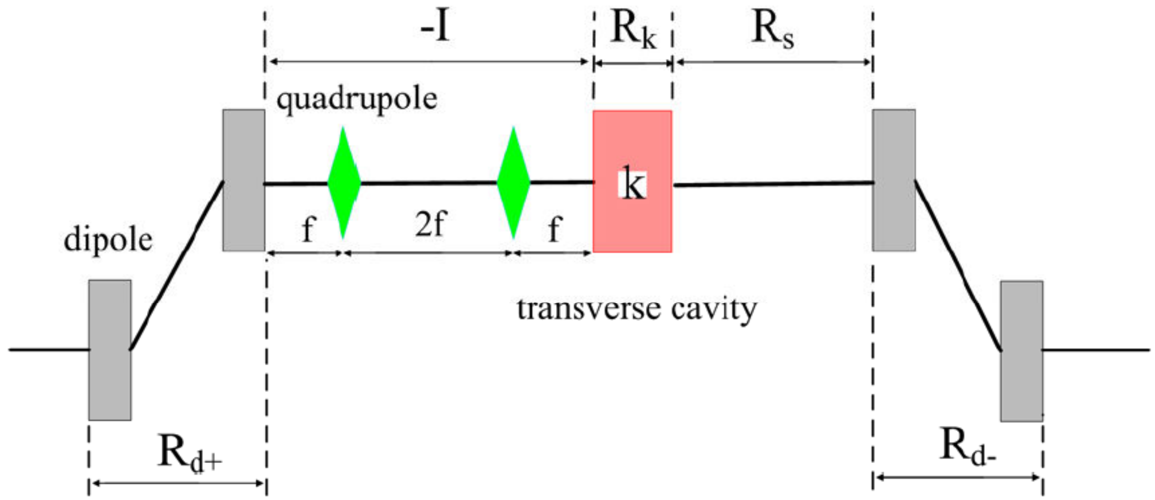
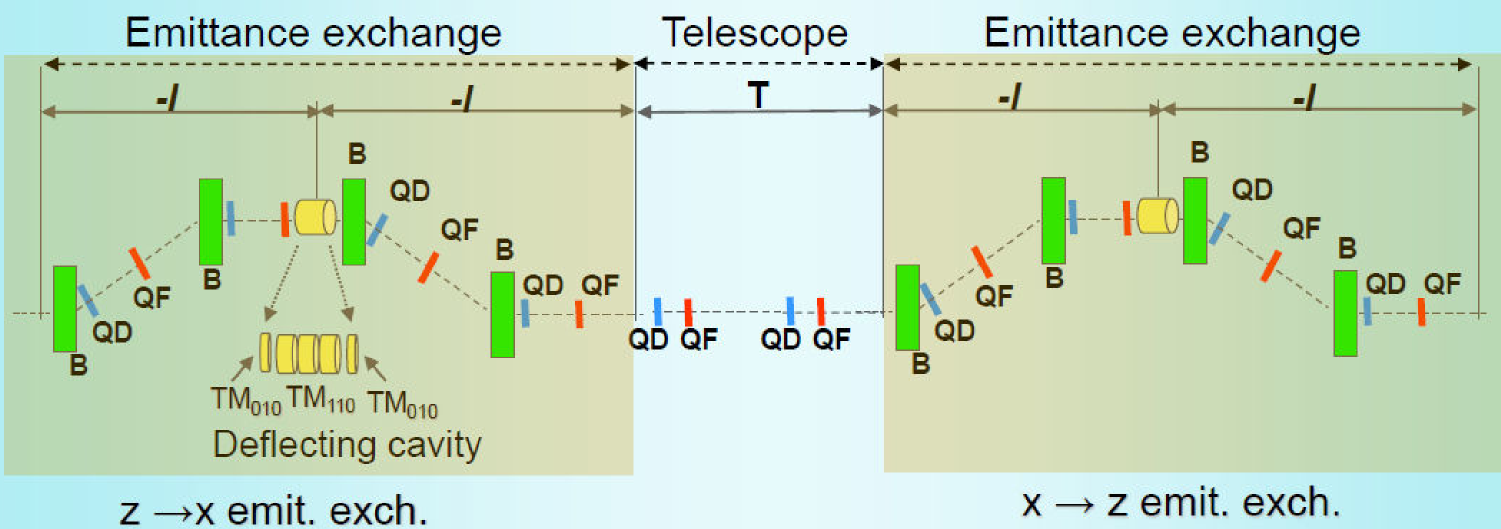


FIG. 2. A chicane-type exact EEX beam line. Two quadrupoles (green diamonds) are put upstream of the transverse cavity to reverse the dispersion.

Next generation EEX : A Double EEX*

A schematic of a proposed bunch compressor



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

A. Zholents & Zolotorev

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)
- Terra incognita ……………………..

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 @ 40 MeV


CCTS-2
CCTS-3