Transverse-to-longitudinal emittance-exchange with an energy chirped beam

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Outline of the talk

Motivation

Emittance exchange beamline

- Diagnostics
- Measurements

Experimental results of emittance exchange

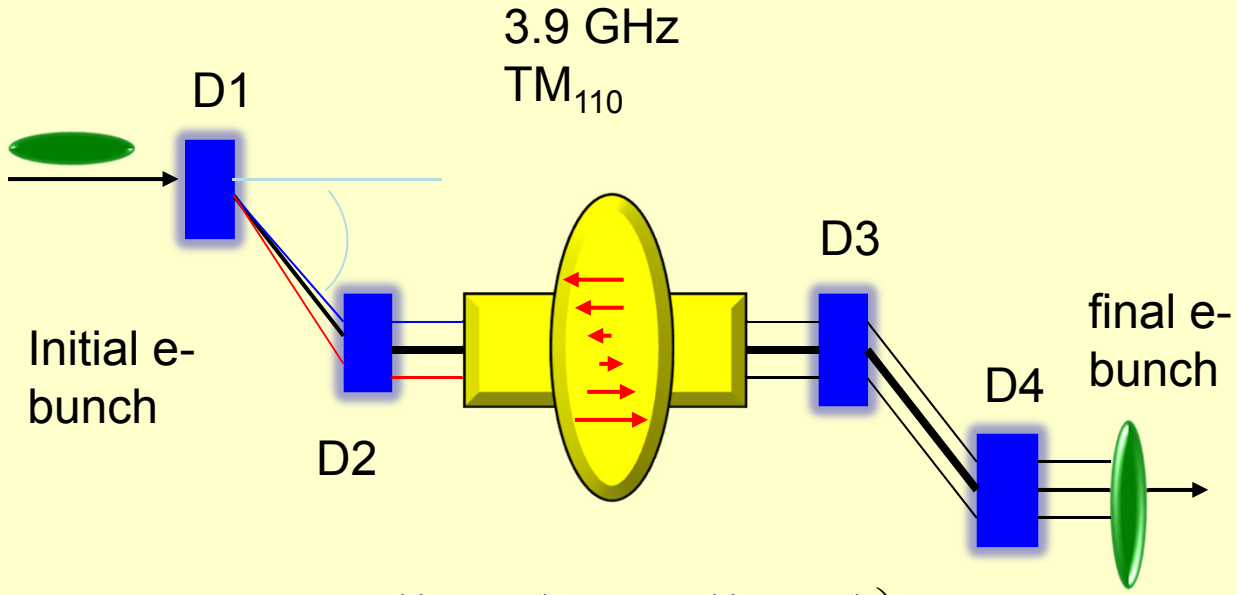
- Energy-chirped beam

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: Concept



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

α : *Bending angle*

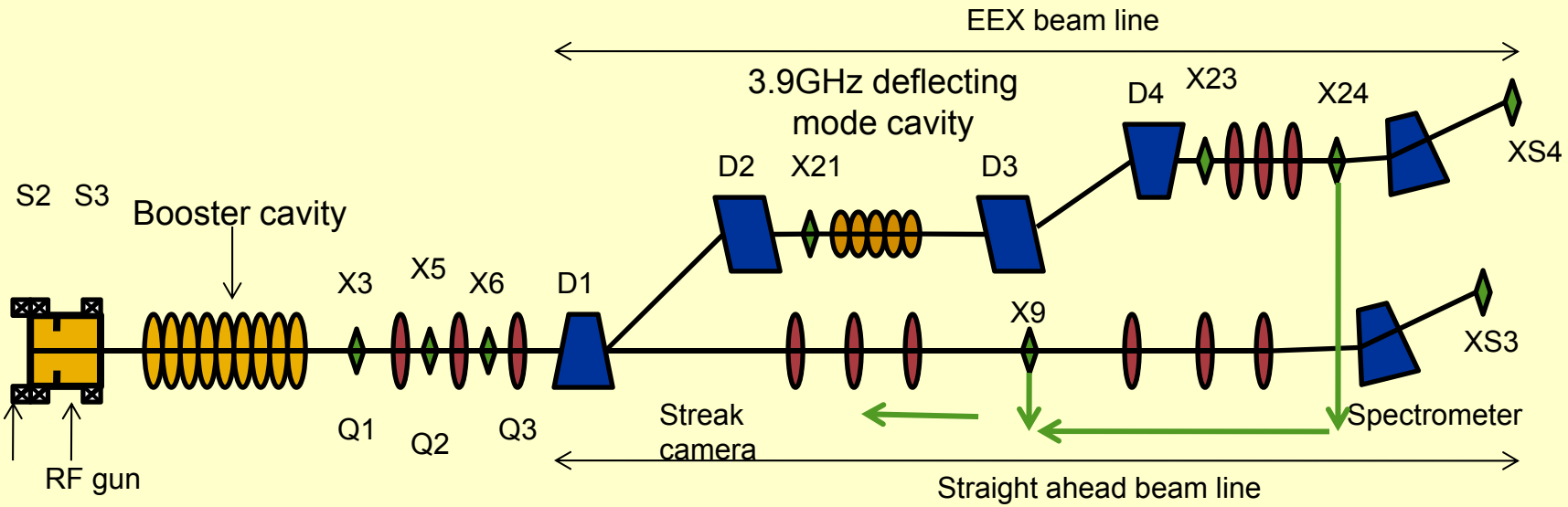
η : *dispersion of dogleg*

L : *Length of the dogleg*

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

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

Fermilab A0 photoinjector: Emittance exchange



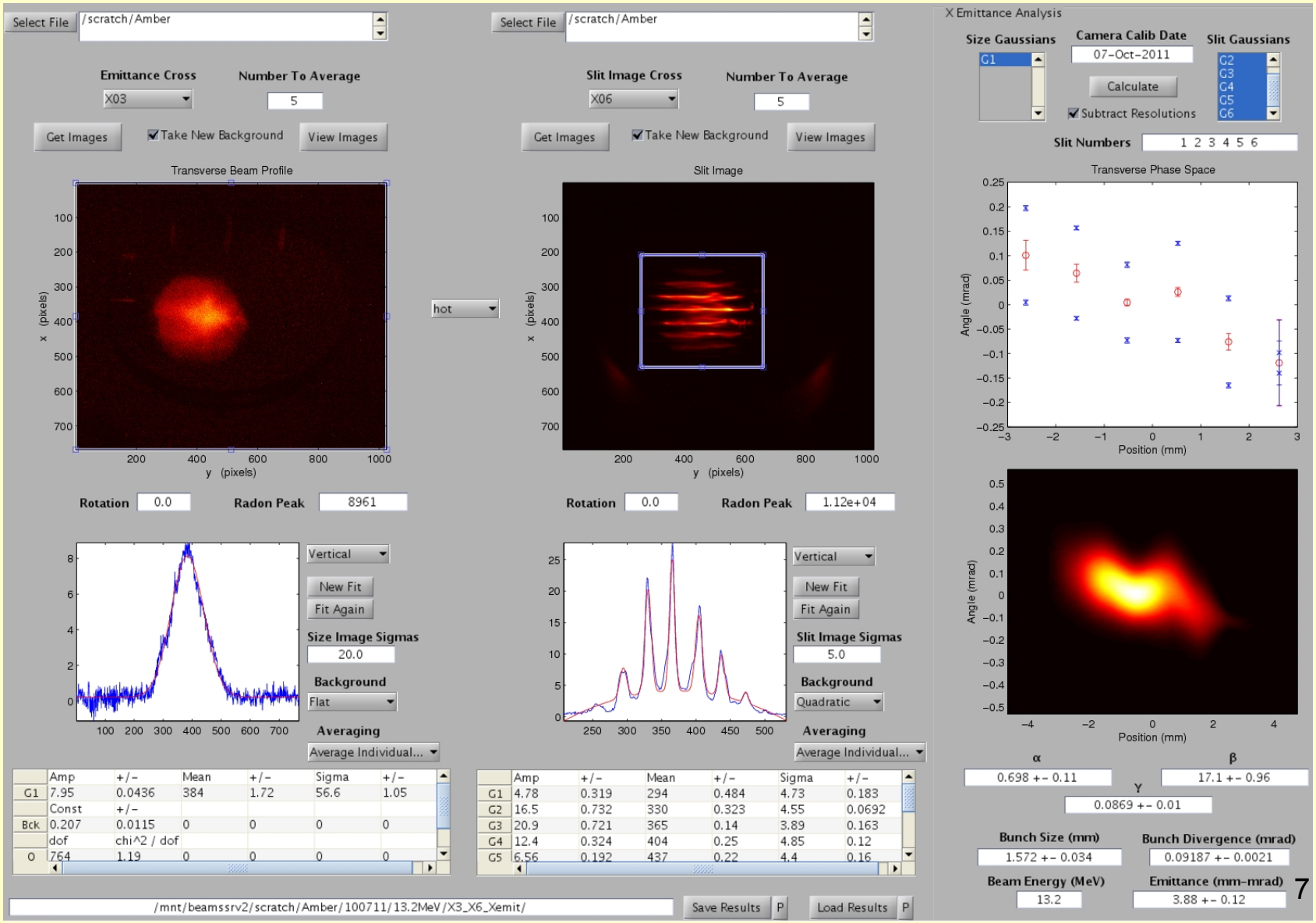
Gun	1.3 GHz NC
Accelerating Cavity	1.3 GHz SC
Deflecting cavity	3.9 GHz NC

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

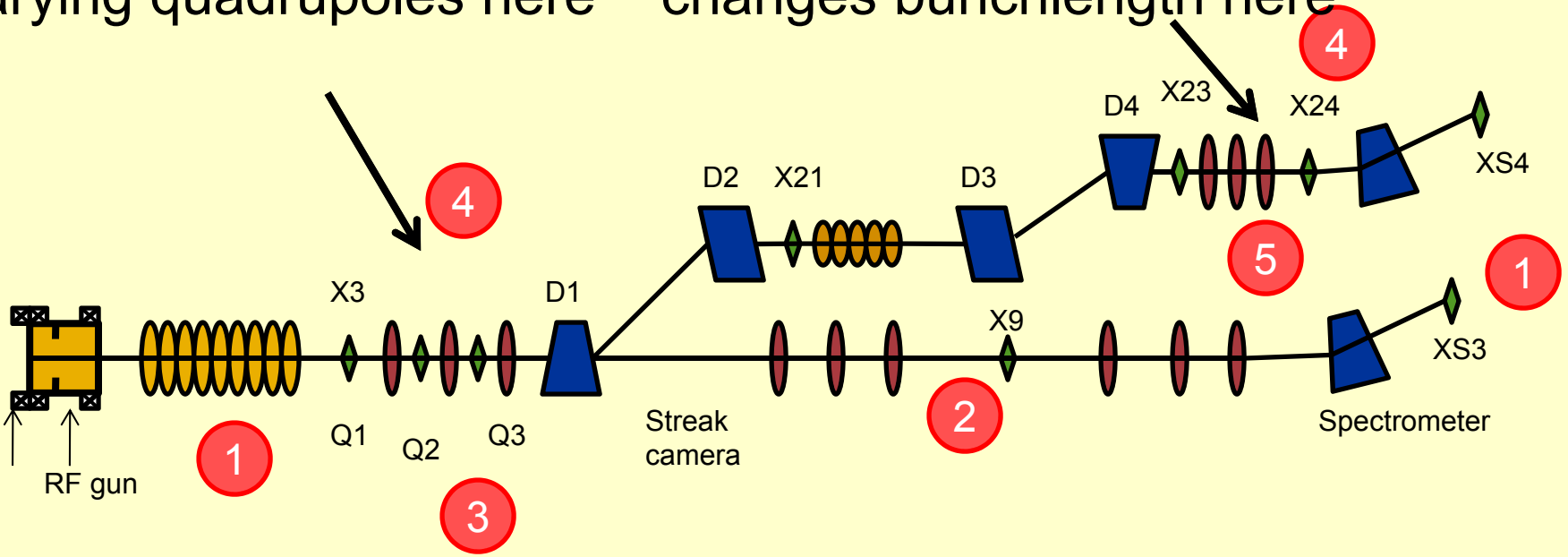
- Beam size: OTR and YAG screens
- Bunch length: Streak or Interferometer
- Energy spread: Spectrometer magnet and a screen
- Transverse emittance: Multi-slit method
- Longitudinal emittance: Product of minimum energy spread and bunch length (upper limit)

GUI to extract Courant- Snyder parameters



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

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(Received 16 February 2011; published 17 June 2011)

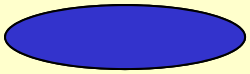
An experimental program to demonstrate a novel phase-space manipulation in which the horizontal and

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

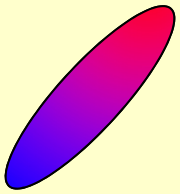
by Timothy W. Koeth

Ph. D. Dissertation

Message: Chirped beam has improved performance



Emittance-exchanger



Emittance-exchanger

- 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 : $\delta = hz$

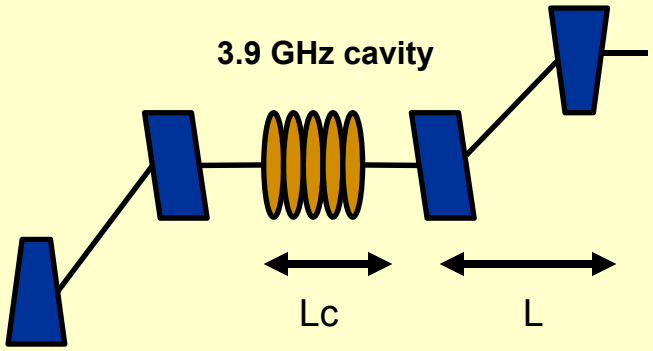
then : $< z^2 > +\alpha^2 D^2 h^2 < z^2 > +2\alpha h D < z^2 >$

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

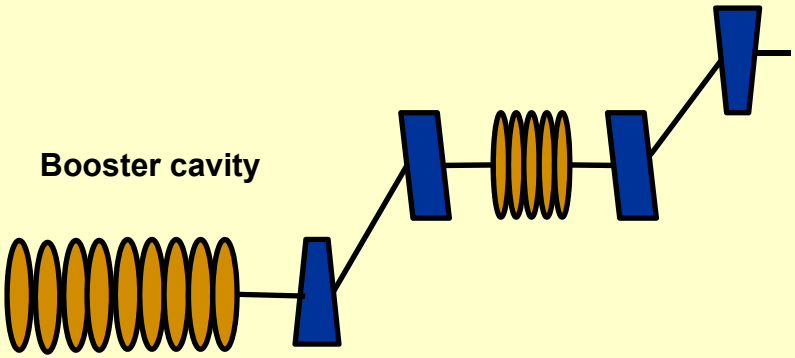
In other words, set Chirp to $-1/R_{56}$

*** 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),**

Effect of chirp on the R-matrix

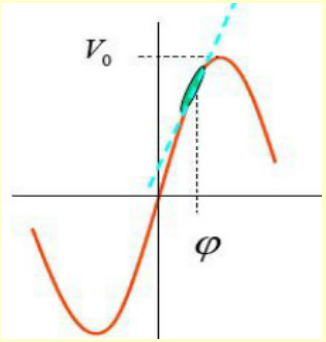


$$R = \begin{pmatrix} 0 & \frac{Lc}{4} & \frac{-(4L+Lc)}{4\eta} & \eta - \frac{\alpha(4L+Lc)}{4} \\ 0 & 0 & \frac{-1}{\eta} & -\alpha \\ -\alpha & \eta - \frac{\alpha(4L+Lc)}{4} & \frac{\alpha Lc}{4\eta} & \frac{\alpha^2 Lc}{4} \\ \frac{-1}{\eta} & \frac{-(4L+Lc)}{4\eta} & \frac{\alpha Lc}{4\eta^2} &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



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

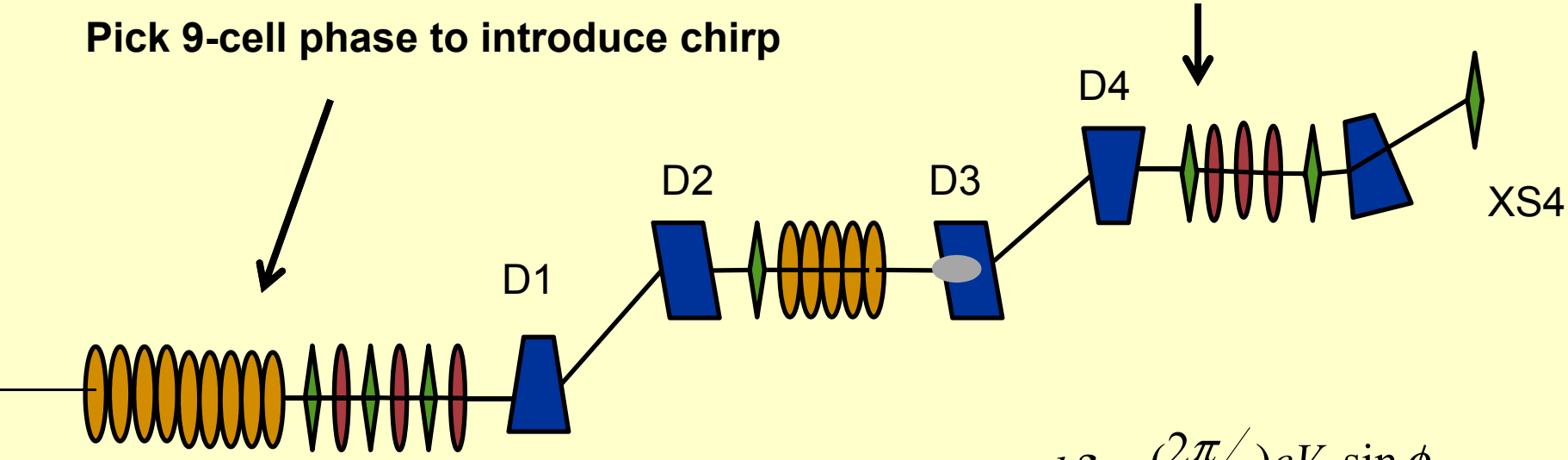
Minimize thick lens effect: Add energy chirp



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)

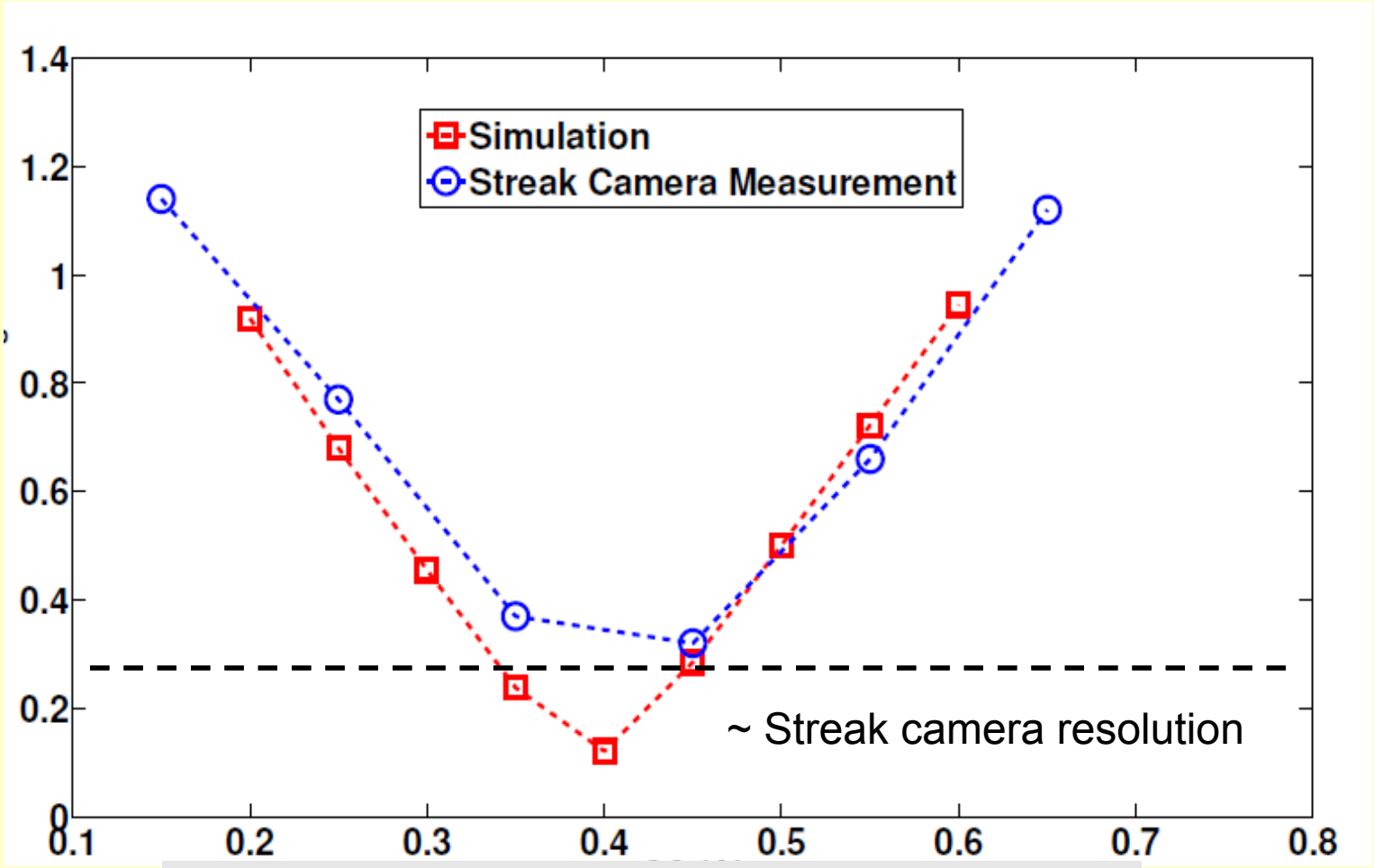
Pick 9-cell phase to introduce chirp



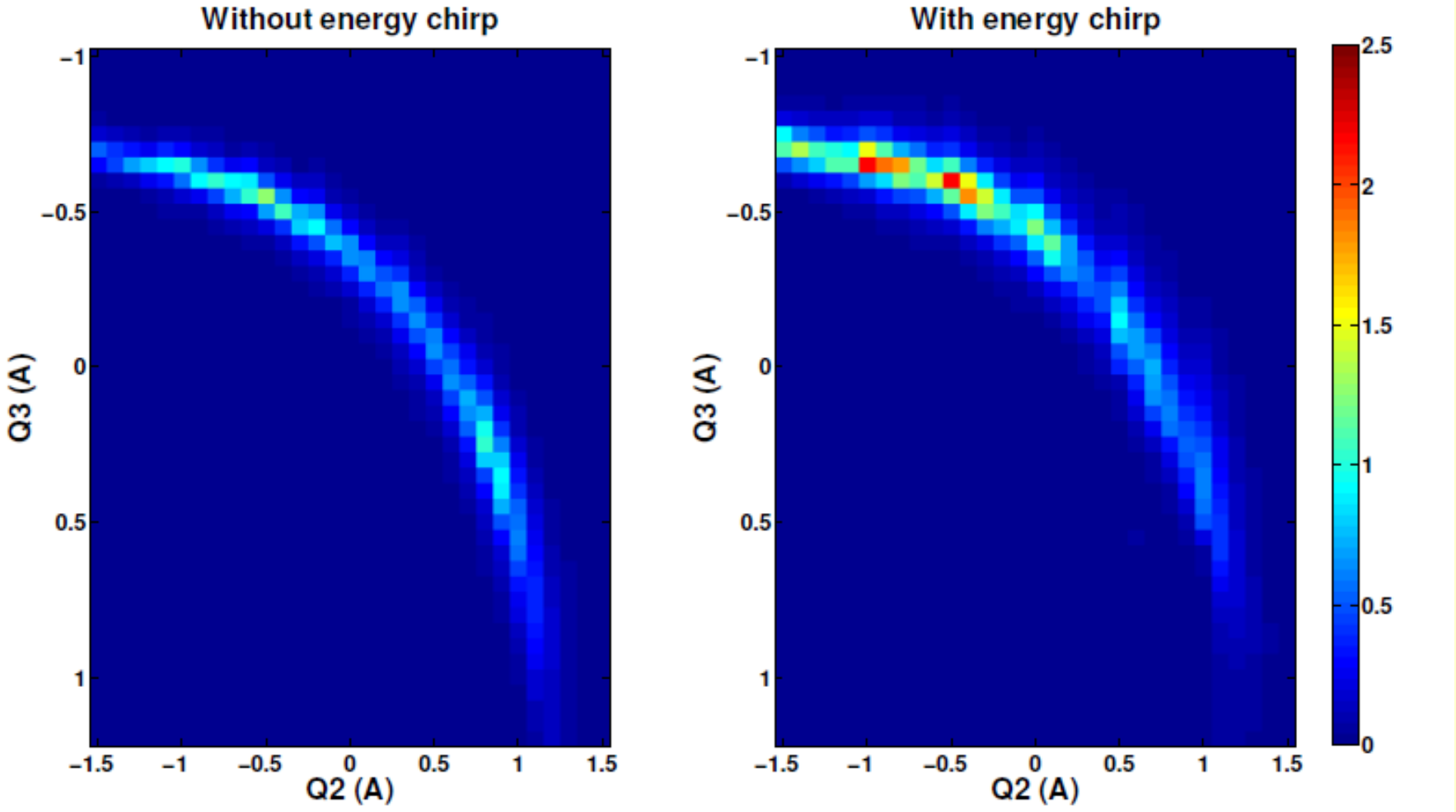
1.3 GHz booster cavity

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

Chirped beam study: Streak camera

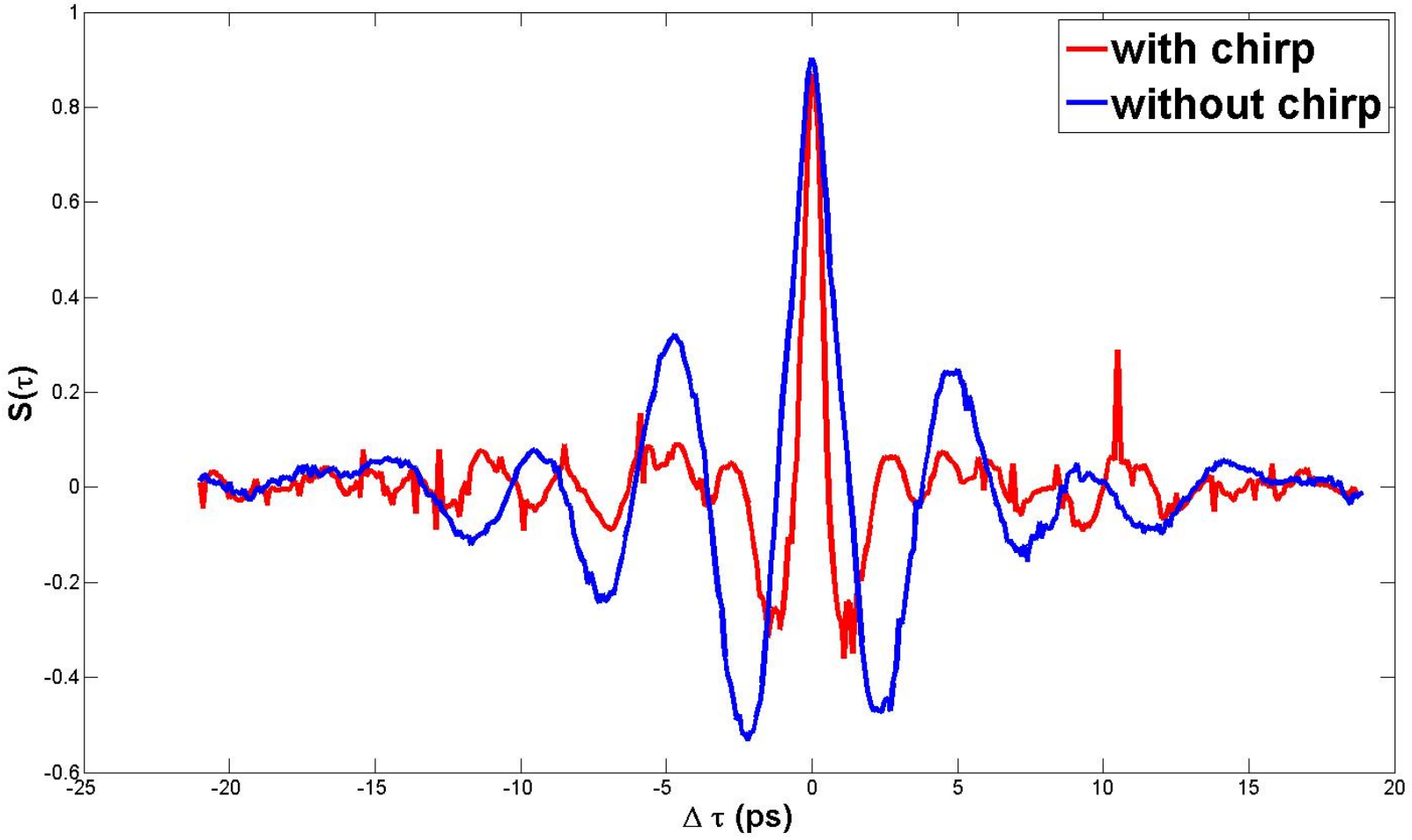


Finer quadrupole scan using interferometer pyros



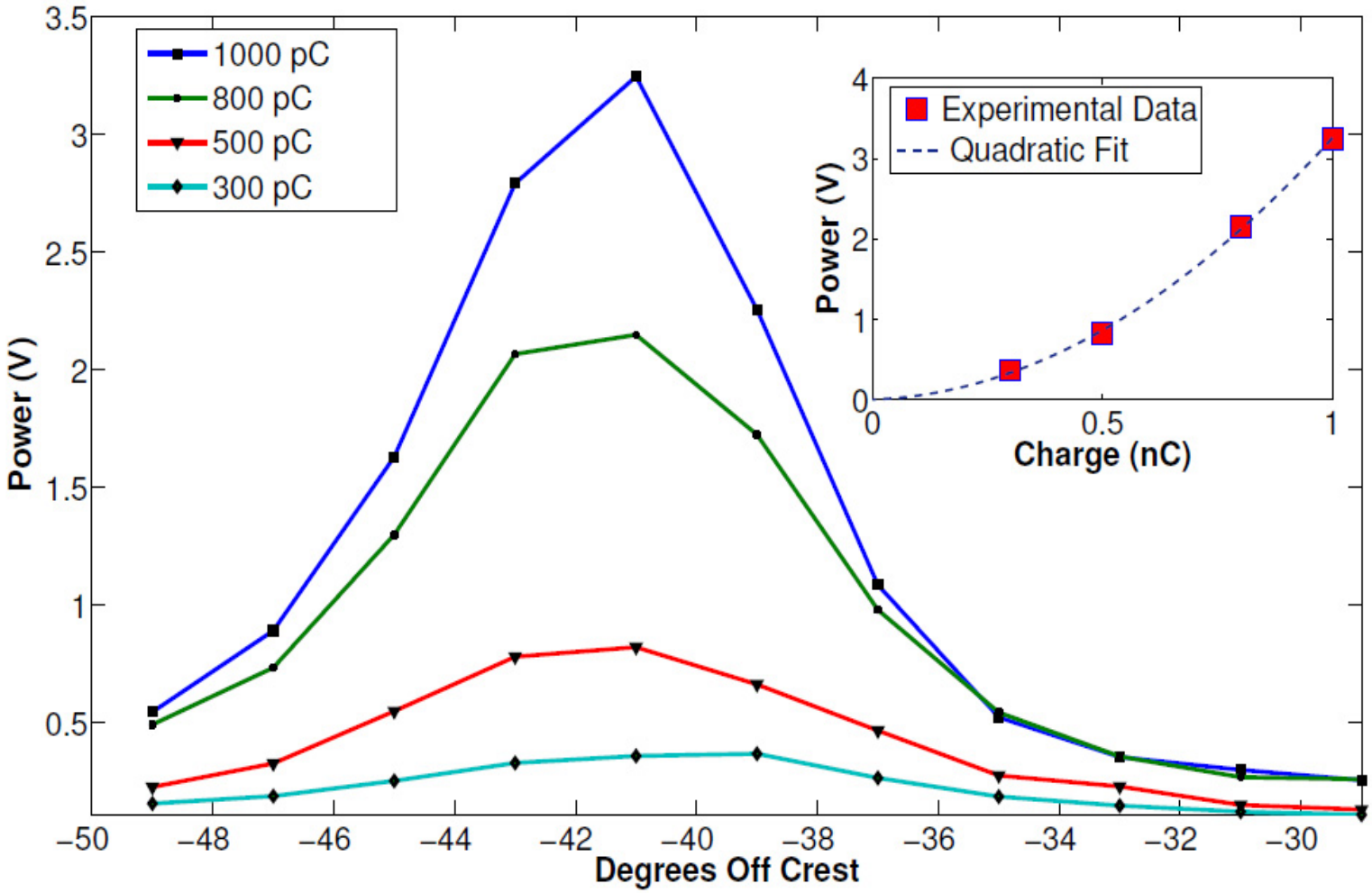
- Pyro signal increases ~ by a factor of 2

Interferometer measurement

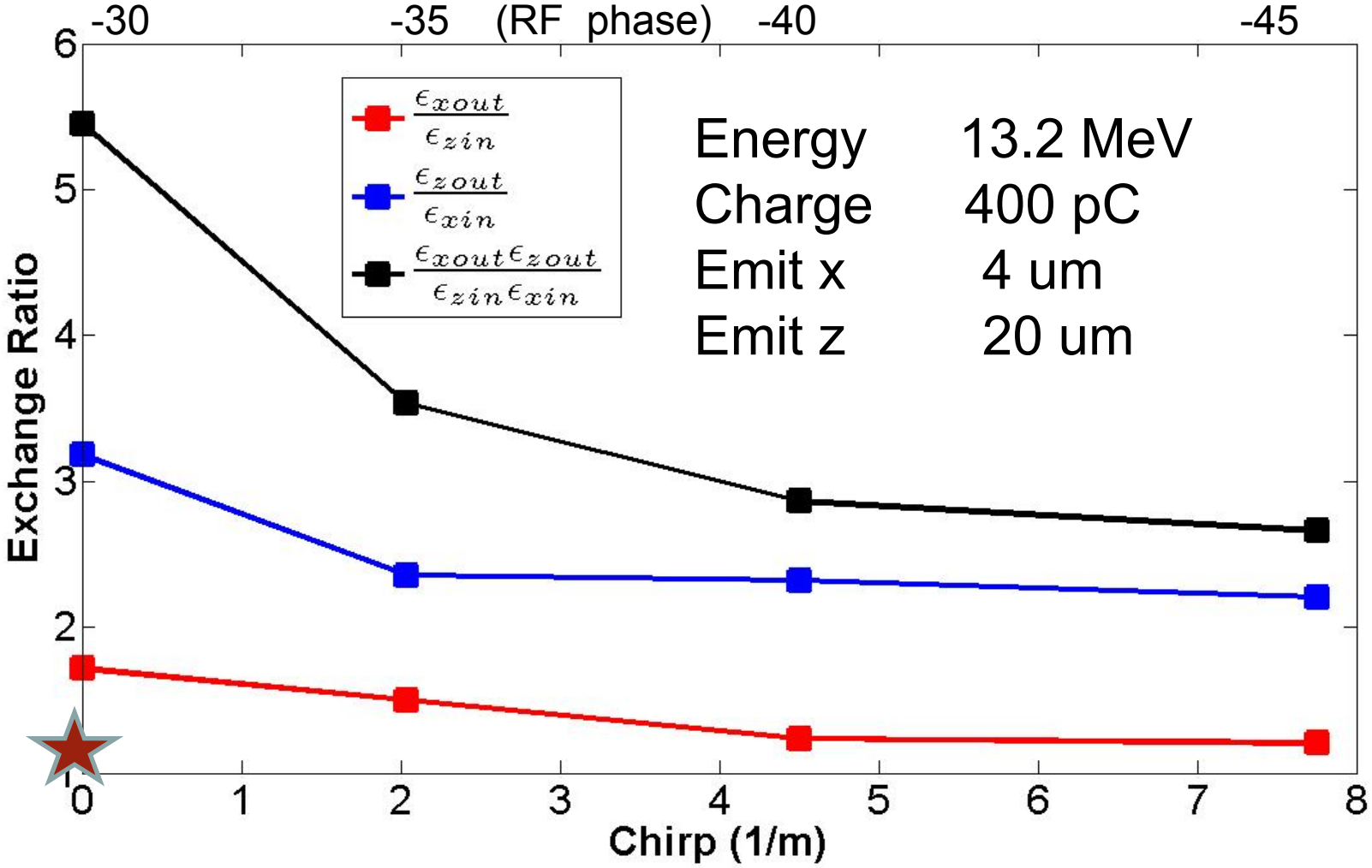


Bunch length reduction ~ 2

CSR Power (pyrometer) Vs RF Phase (bunchlength)

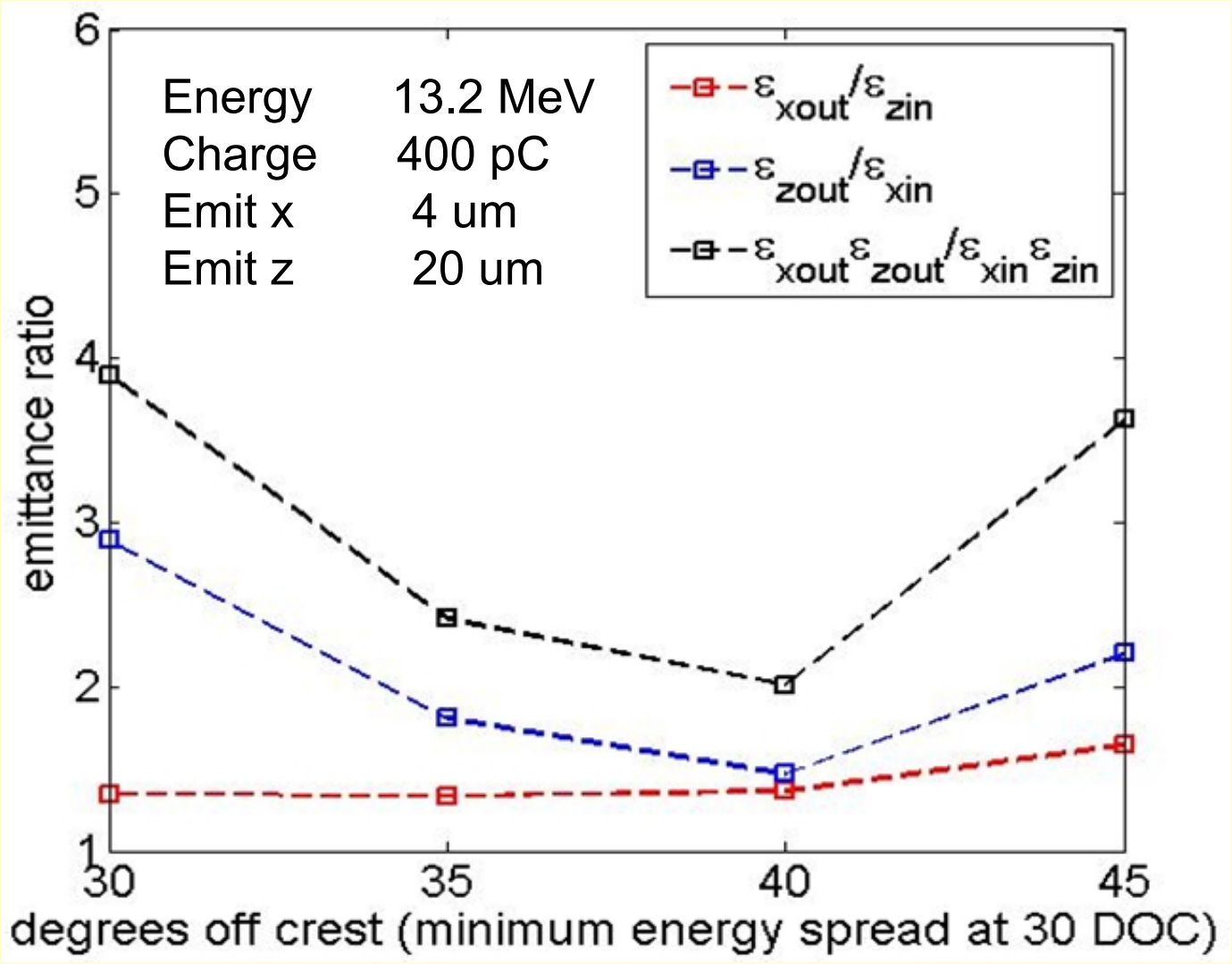


Emittance exchange with chirped beam

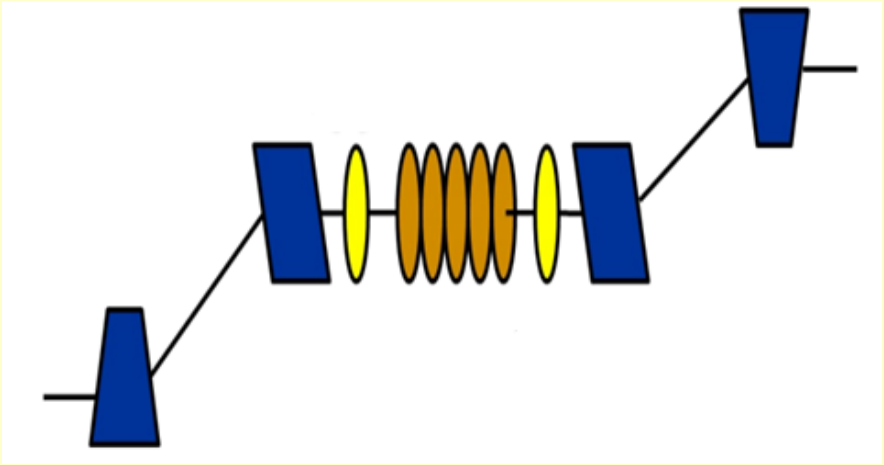


250 pC; PRL 106, 244801 (2011)

Emittance exchange simulation with GPT



Alternative schemes to 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 deflecting cavity to compensate thick lens effect

- Can also use single accelerating cavity to compensate the thick lens effect (A. Zholents APS Note LS 327)

- Chicane style possible with some modifications to the doglegs
  (D. Xiang Phys. Rev. ST Accel. Beams 14, 114001**)**

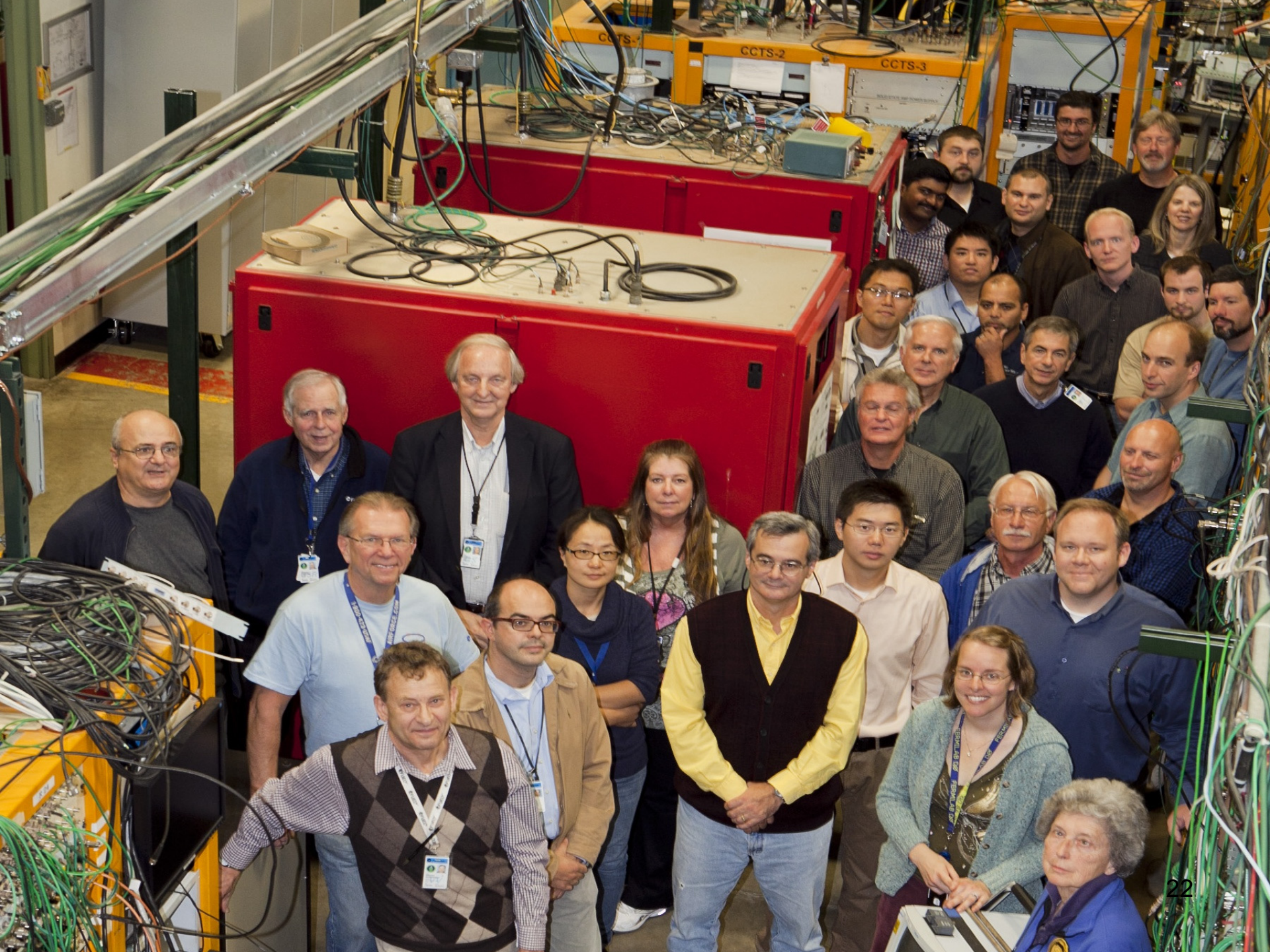
•. Being pursued for Advanced Superconducting Test Accelerator (ASTA) facility at 40 MeV.

Summary

- 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.

- Simulations are being done for studying a chicane-style emittance exchange at the Advanced Superconducting Test Accelerator (ASTA) facility @ 40 MeV.


CCTS-2
CCTS-3