RadiaBeam/SLAC Dechirper

Dechirper Design and Experimental Results

Tim Maxwell, K.L.F. Bane, A.S. Fisher, M. Guetg, M.A. Harrison, Z. Huang, R. Iverson, P. Krejcik, A.A. Lutman, J.D. McNevin, A. Novokhatski, M. Ruelas, G. Stupakov, J. Zemella, Z. Zhang…

Sept. 22nd, 2017

NOCE 2017

U.S. DEPARTMENT OF ENERGY
Office of Science

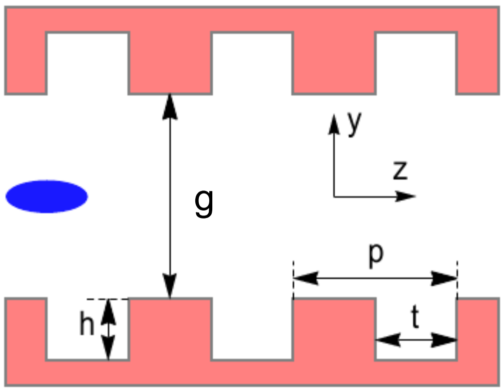
radiabeam SYSTEMS

SLAC NATIONAL ACCELERATOR LABORATORY

Overview

- Review of the corrugated structure (CS) dechirper
- Design challenges on hard X-ray FEL linac scale
- LCLS installation, commissioning and results
- Novel applications beyond chirp control

Theory of CS Wakes



3 periods of long CS

Description of the short-range wakefield of a beam between periodically grooved metal rails

K. Bane, G. Stupakov, I. Zagorodonov

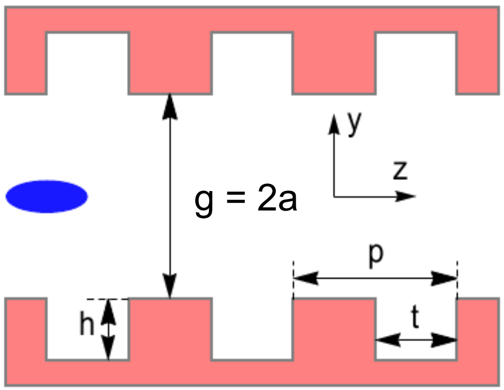
0th Wakefield for rectangular geometry, PRST-AB, **6**, 024401 (2003).

0th Corrugated pipe as a beam dechirper, NIMA, **690**, 106 (2012)

0th Transverse wake for flat geometry, PRST-AB, **18**, 010702 (2015)

1st Analytical formulas, PRST-AB, **19**, 084401 (2016)

Theory of CS Wakes



3 periods of long CS

Point response wakefield [$E_{loss}(z)$] from dominant longitudinal mode (perturbative approach):

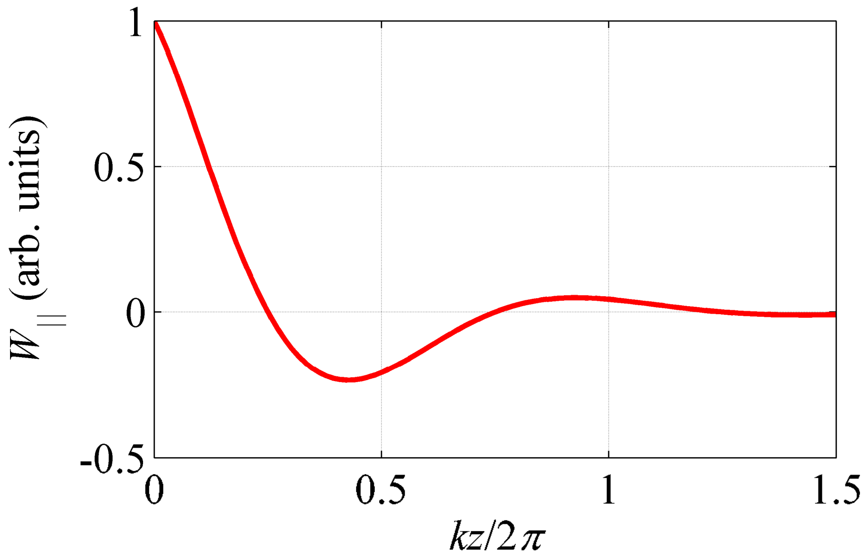
$$W_{\|}(z) = \frac{\pi^2}{16}\frac{Z_0 c}{\pi a^2} F H(z) e^{-\frac{kz}{2Q}} \cos(kz)$$

$$k = \sqrt{2p/ght}$$

Assuming $p = 2t < h, g$ and rectangular current $I(z)$ with bunch length $\Delta z << 2\pi/k$

$$E_{loss}(z) = \int_0^z W_{\|}(z) I(z' - z) dz'$$

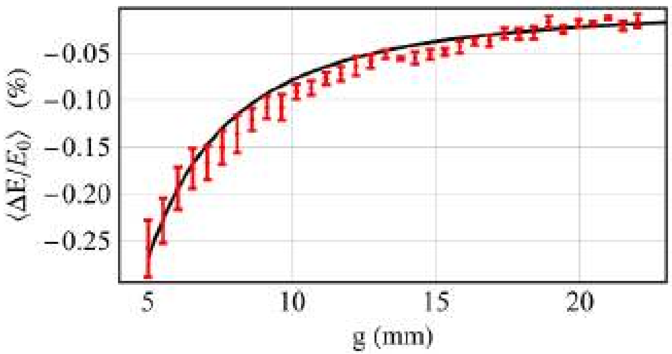
$$\approx \frac{\pi Z_0 c Q L}{4 g^2 \Delta z} z$$



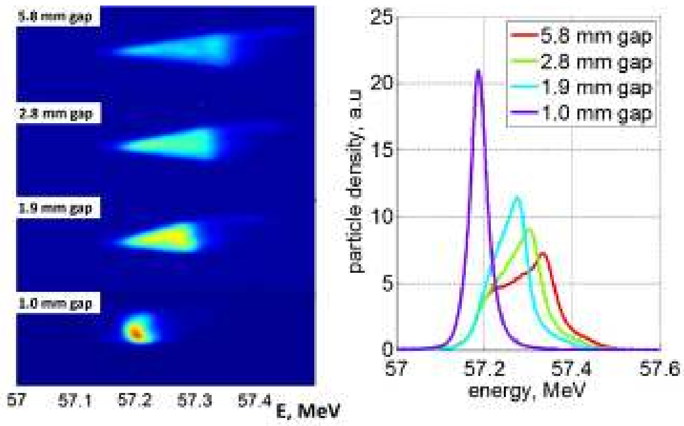
CS Dechirper Demonstrations

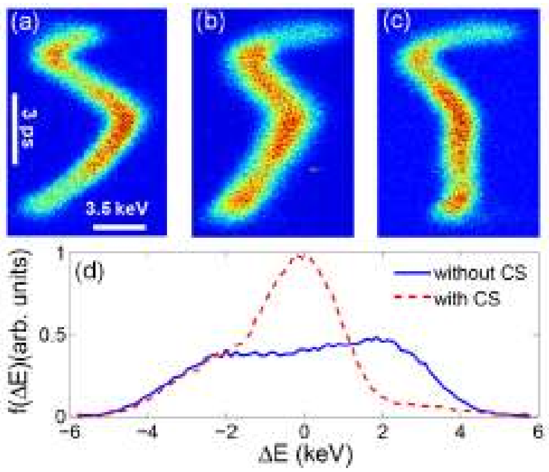
Prior demos: ~10 cm-long devices with 10 MeV, 100 pC beams (keV slice energy spreads), few mm gap

- LBNL/Pohang/SLAC
- BNL/RadiaBeam
- Shanghai collaboration



P. Emma *et al.,* PRL **112**, 034801 (2014)





S. Antipov, *et al.*, PRL **112**, 114801 (2014)
M. Harrison *et al., Proc. of NAPAC 2013*

Feichao Fu, *et al.*, PRL **114**, 114801 (2015)

Hard X-ray FEL Dechirper system

Hard X-ray FEL beam requirements:

- High GeV energy, kA peak current
- Preserve low E spread / emittance

FEL bandwidth control requires $E_{\text{loss,Dech}} > E_{\text{slice}} \sim E_{\text{beam}}\,\rho_{\text{FEL}}$ (1 MeV)

$$\langle E_{loss} \rangle = \frac{\pi Z_0 c Q L}{8 g^2}$$

Can't go much smaller than ~mm!

Have to go longer…

…Much longer. A few meters long with sub-mm, in-vacuum positioning.

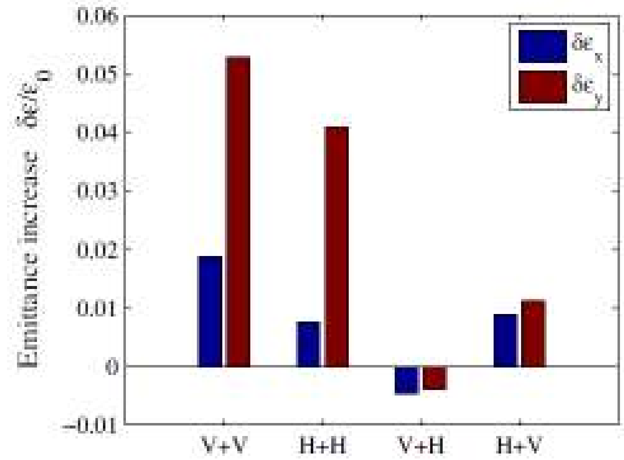
The RadiaBeam / SLAC Dechirper System

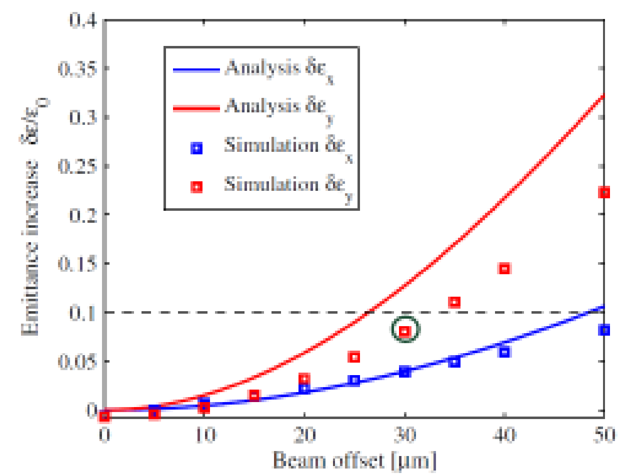
Mechanical, vacuum, and instrumenting by RadiaBeam (Phase II SBIR) in partnership with SLAC under a Cooperative Research And Development Agreement

Prototype LCLS Dechirper Design Parameters

- 2 x 2 m modules
  - One horiz., one vertical
  - Quadrupole wake cancellation

Fin period	0.5 mm
Fin depth	0.5 mm
Nominal gap	1.4 mm
Min. gap	0.7 mm
Peak-to-peak flatness	50 um
Motion Repeatability	25 um





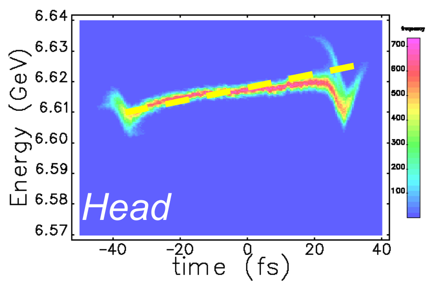
Z. Zhang, PRST-AB, **18**, 010702 (2015)

Prototype LCLS Dechirper Parameters

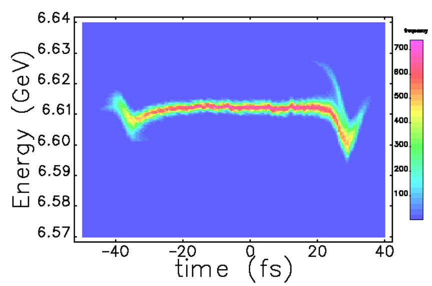
After dechirper

Simulations
by Z. Zhang

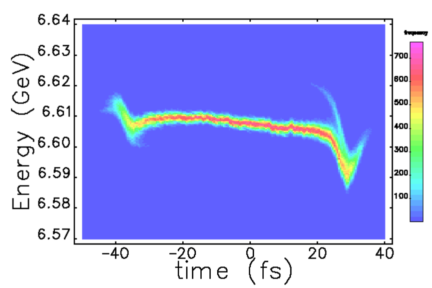
$g = \infty$



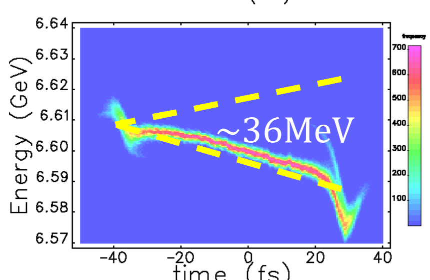
$g = 2.0\text{mm}$

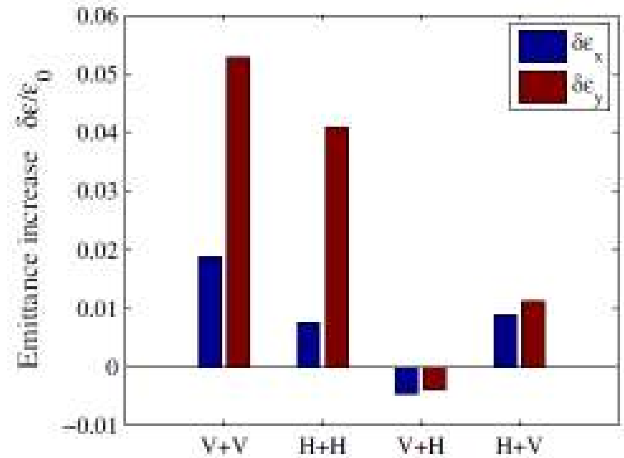


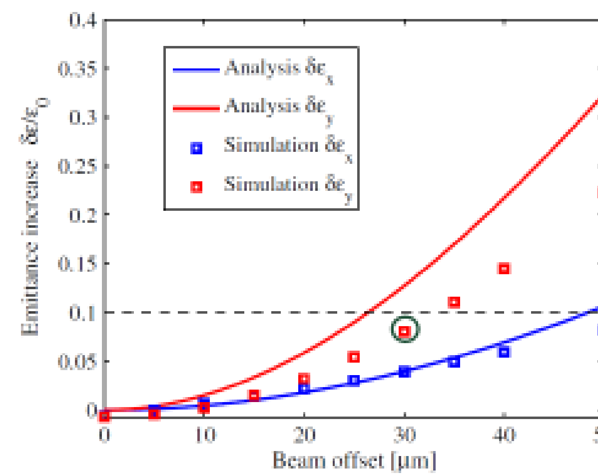
$g = 1.4\text{mm}$



$g = 1.0\text{mm}$
$W(0^+) = 60\ \text{MV/nC/m}$





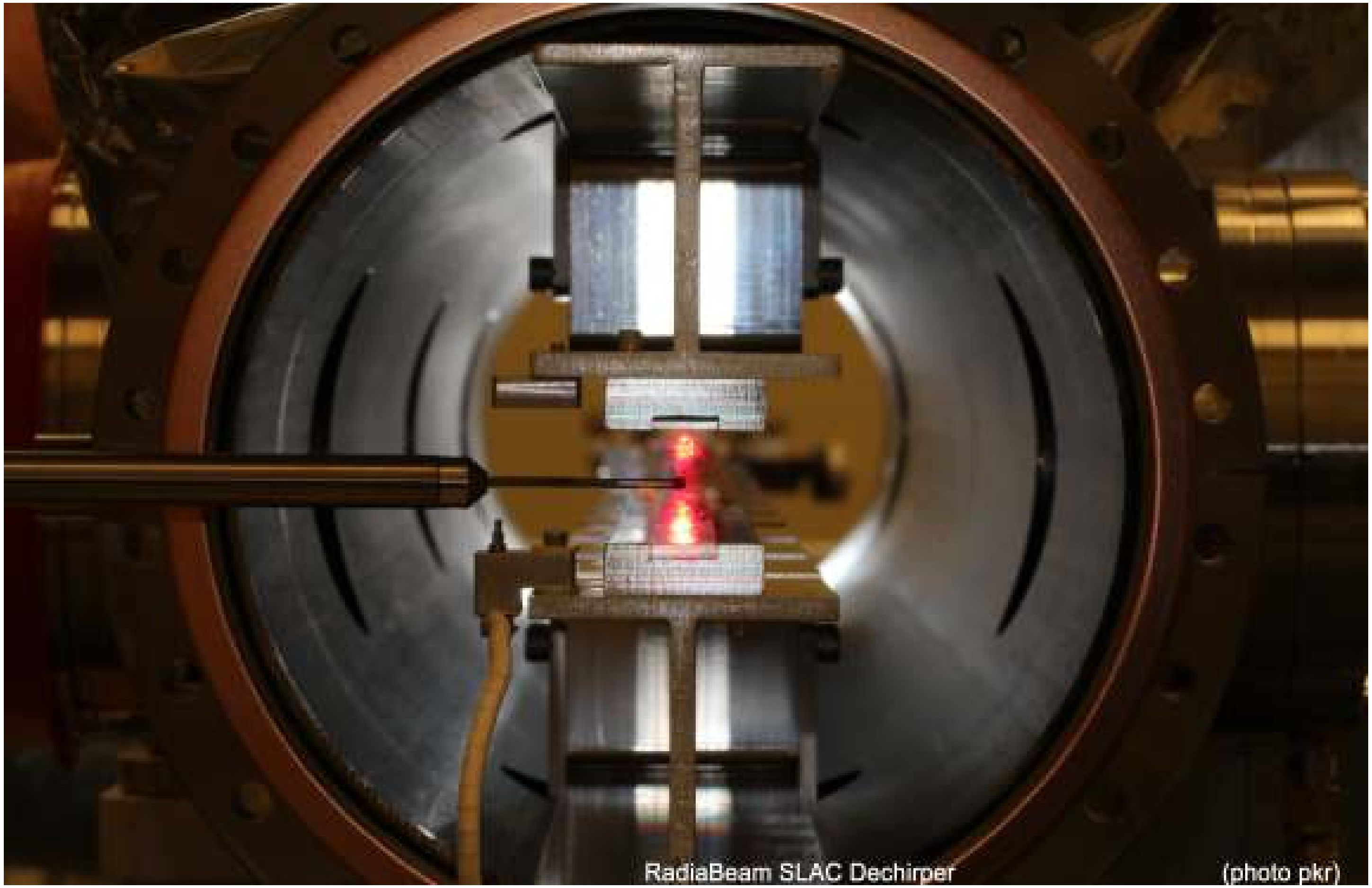


Z. Zhang, PRST-AB, **18**, 010702 (2015)

Dechirper on SLAC Coordinate Measuring Machine

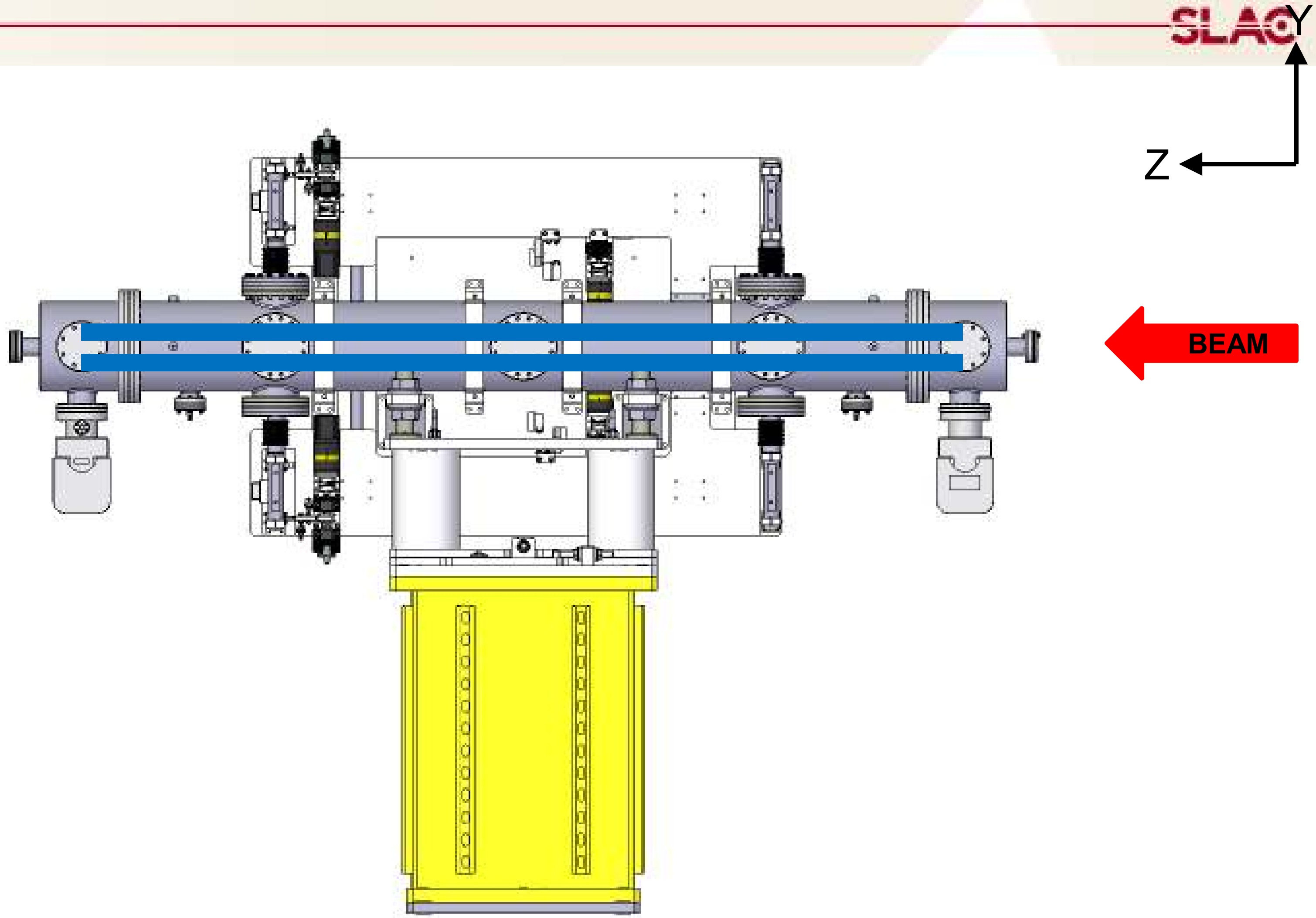
Global jaw flatness < 50 μm after rail shimming

50 μm backlash on carriage motion



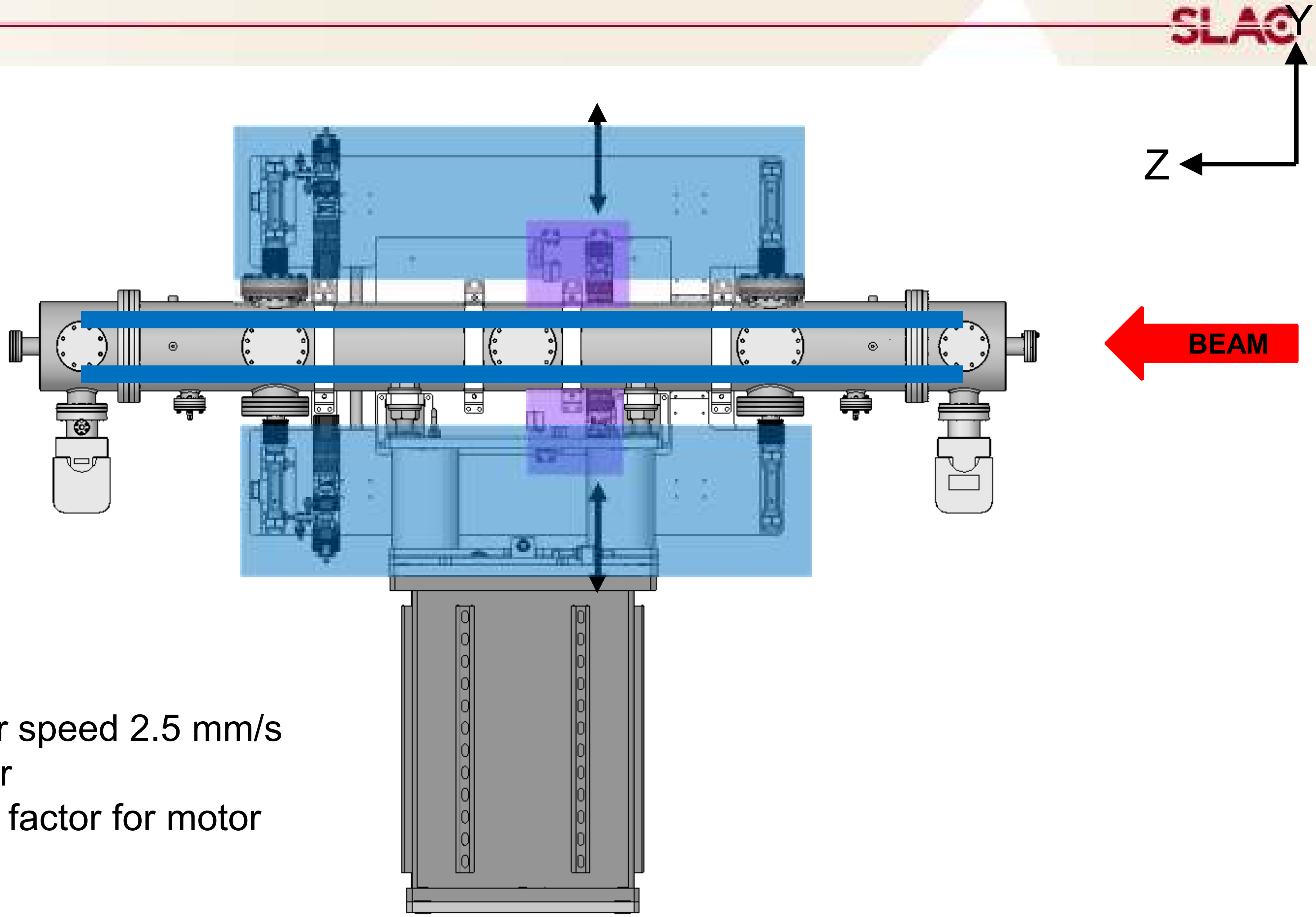
Dechirper Installation October 7, 2015

Vertical Dechirper Module - Actuation



(A. Cedillos)

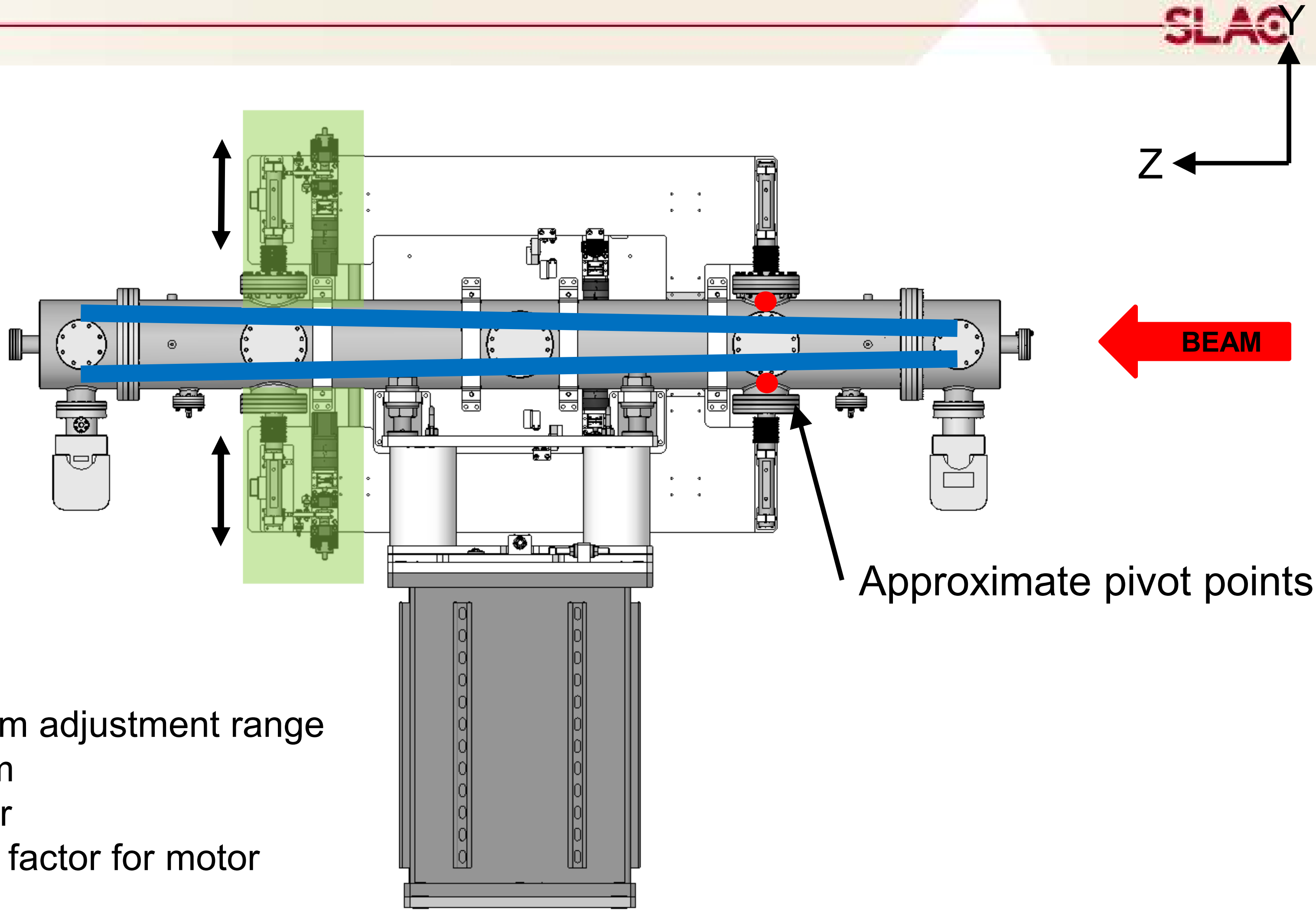
Vertical Dechirper Module – Insertion/Retraction



- Carrier linear speed 2.5 mm/s
- Gear reducer
- Large safety factor for motor

(A. Cedillos)

Vertical Dechirper Module – Trim Actuation

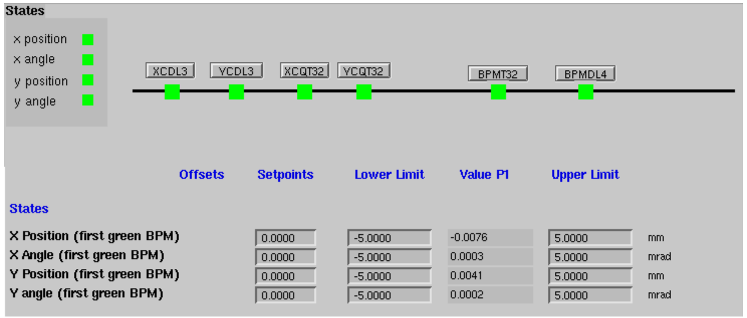


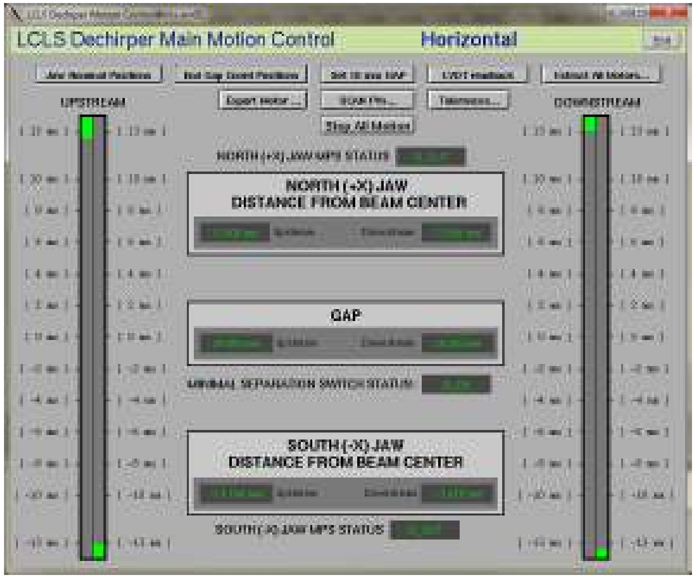
- Carrier tip trim adjustment range
  - +/- 1mm
- Gear reducer
- Large safety factor for motor

(A. Cedillos)

Additional controls

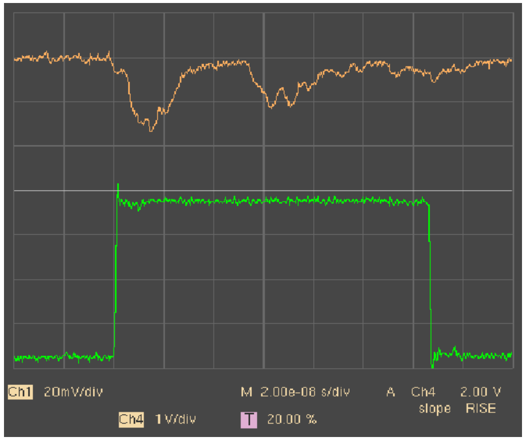
New position/angle orbit feedback
through Dechirper modules
(R. Iverson, L. Piccoli)



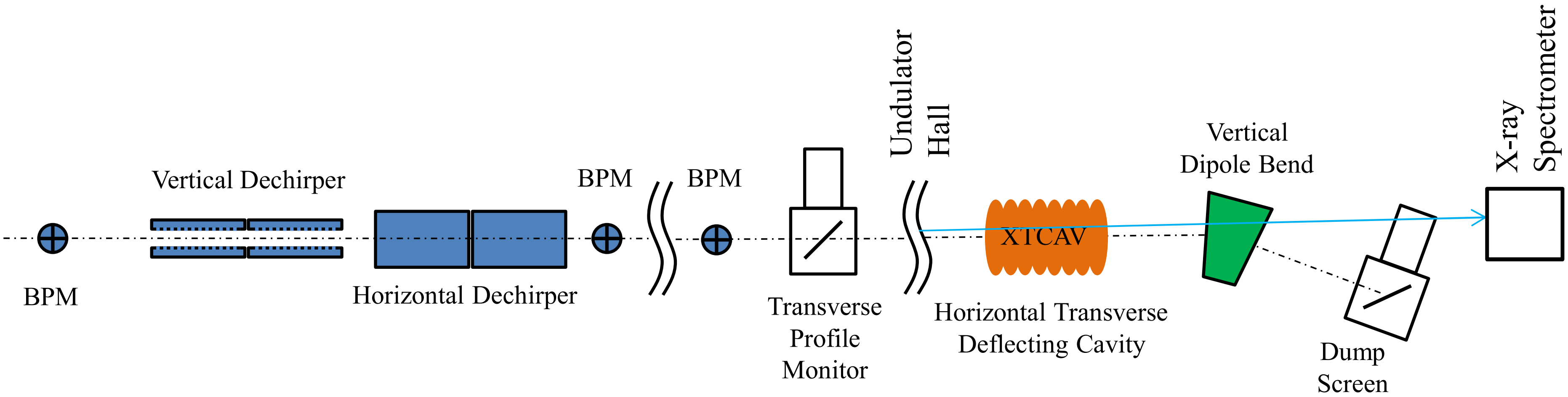


EPICS-level motion control of Dechirper
US/DS gaps and/or rail *ends*
- 8 motors
- 8 independent position encoders
(Z. Oven, A. Babbitt)

New beam loss fiber – losses at beginning & end
E-beam parameters: 6.6 GeV, 150pC, gap = 1.1mm
(A. Fisher)



Diagnostic layout

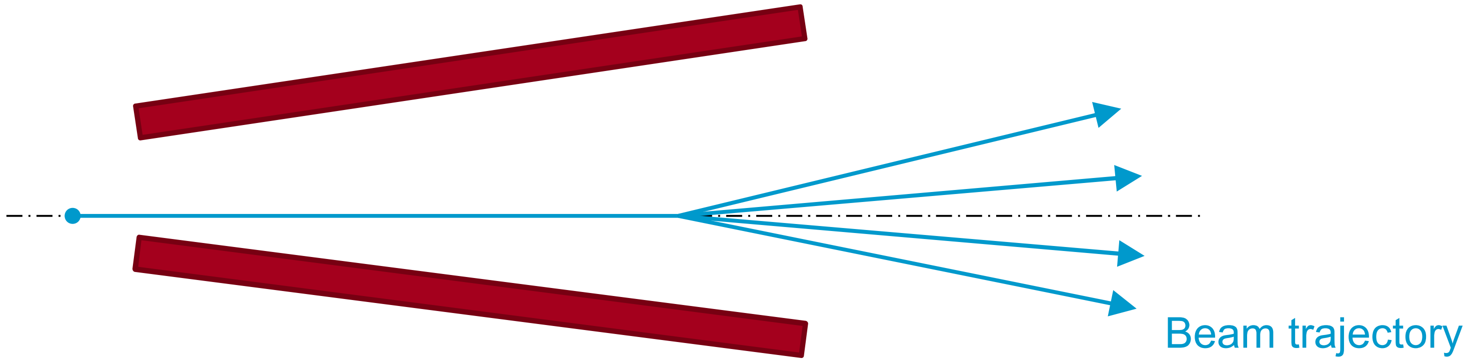


- BPMs (beam-based alignment)
- Transverse profile monitor & wire scanners
- X-band deflector, spectro. bend, & screen (*t-E* space)
- Hard/soft X-ray spectrometers (X-ray BW)

Beam-based alignment procedure

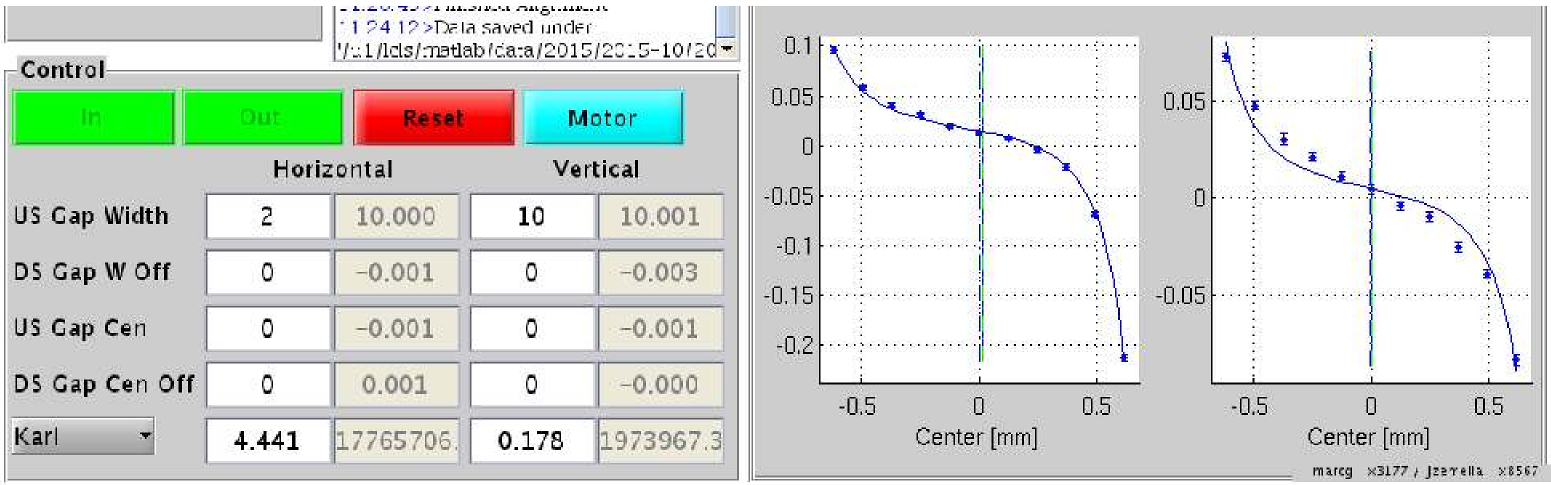
- *Off-axis* beam also experiences a *dipole* wake
- Gap at each end well calibrated from metrology, end-to-end angle to beam less well known

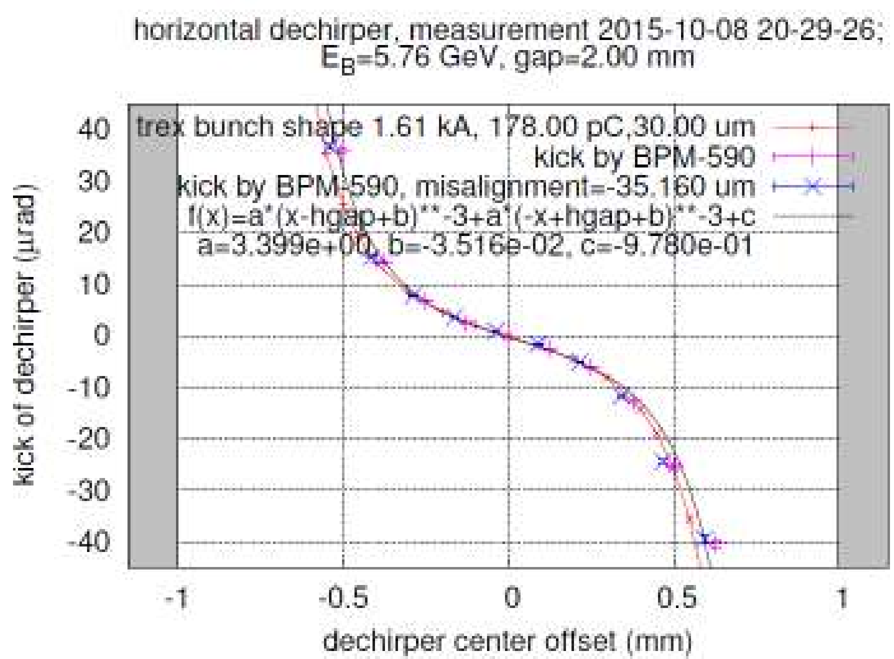
- BBA: Scan single dechirper across beam with strong taper and orbit feedbacks off, measure change in orbit downstream, repeat 4x



Beam-based alignment procedure

SLAC



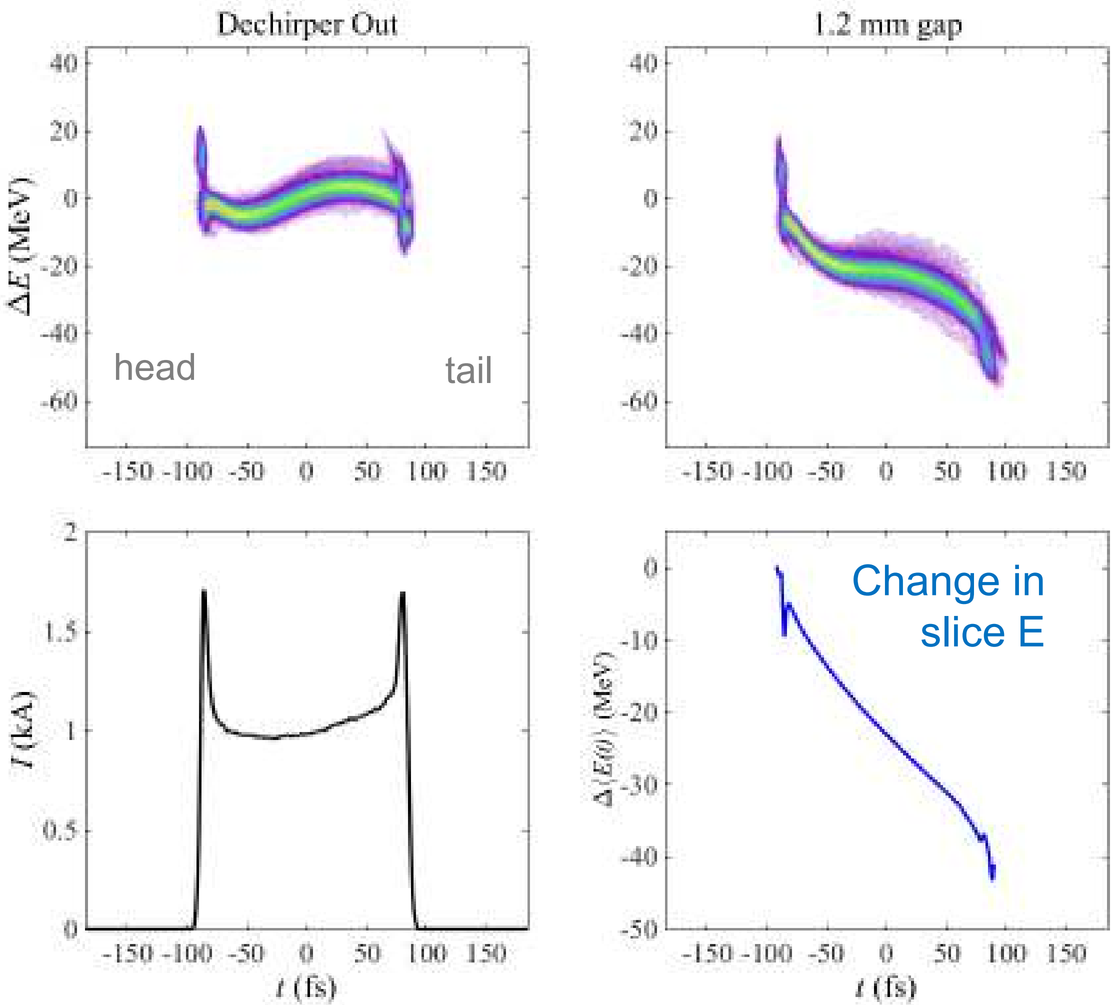


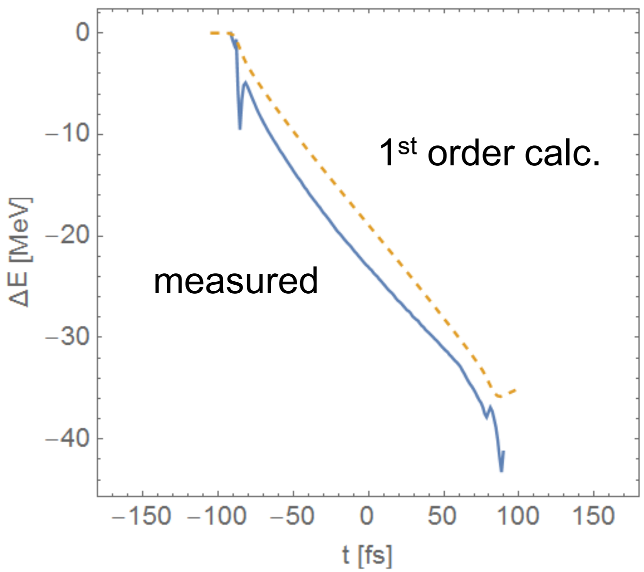
New Dechirper GUI

1. manage all procedural setup
2. run all 4 scans
3. do all (cubic or analytical) fits to find/set offsets

(J. Zemella, M. Guetg)

Single X-band deflector measurement: @ 4.4 GeV / 180 pC / 1 kA

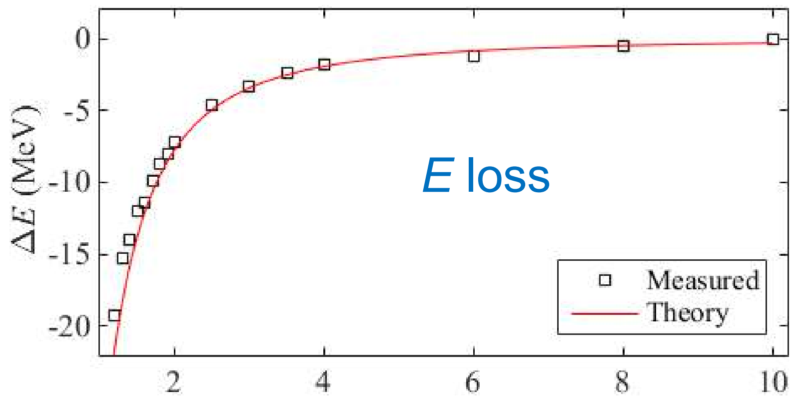


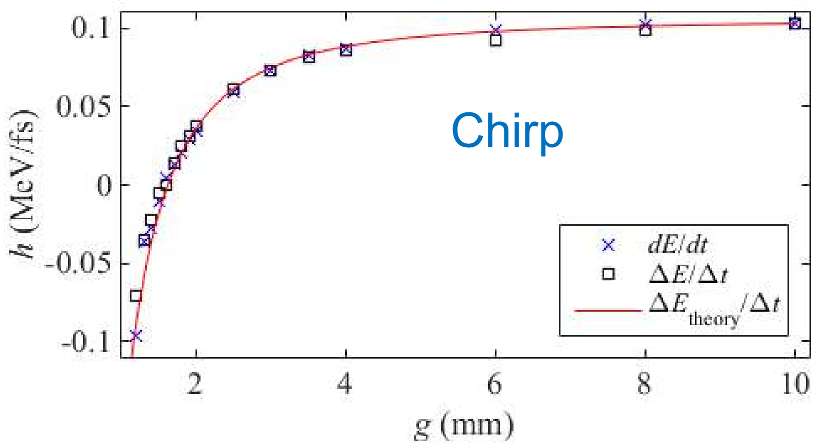


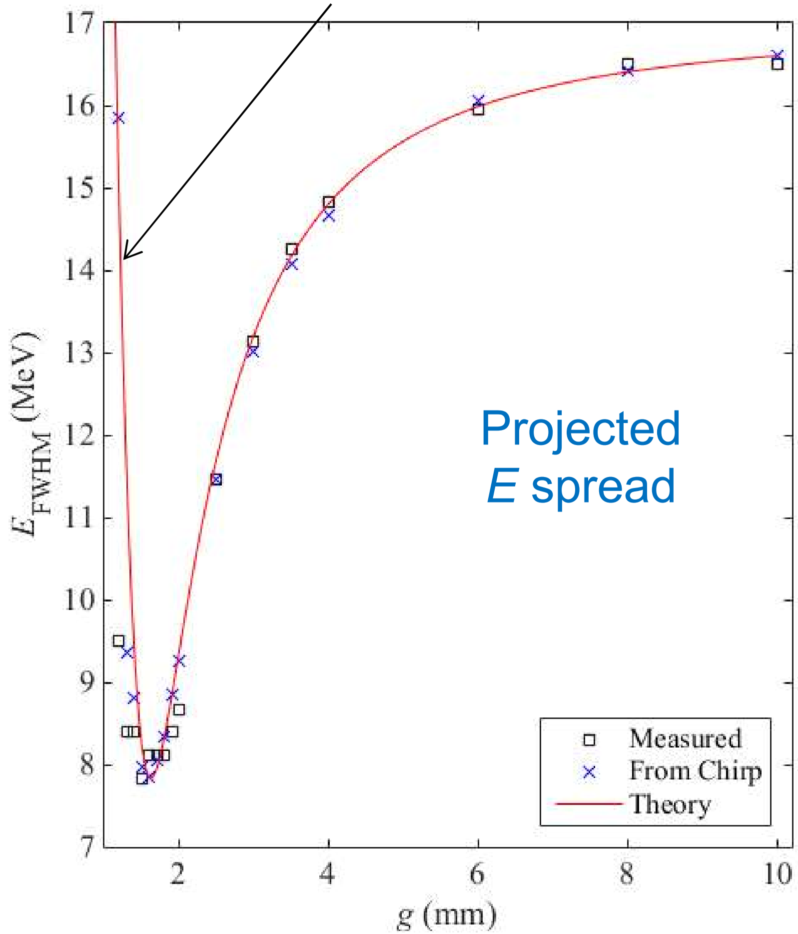
Measurements @ 4.4 GeV / 180 pC / 1 kA

Average loss $\Delta E = \dfrac{\pi Z_0 c Q L}{8 g^2}$

For very small gap, becomes "over dechirped," *E* spread grows

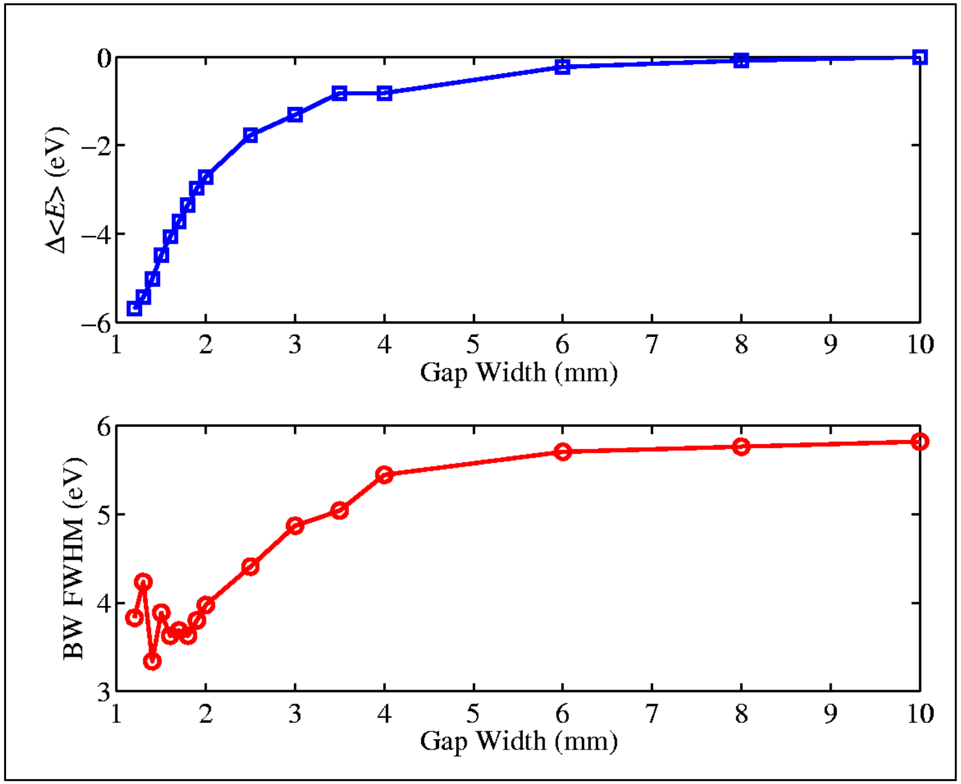




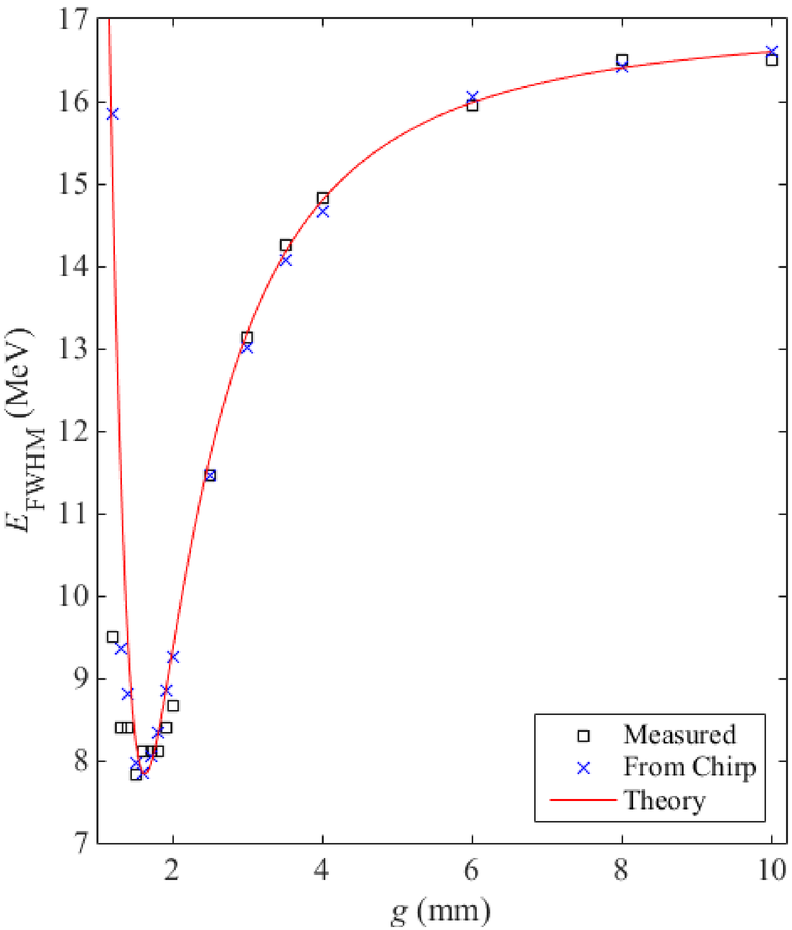


Measurements @ 4.4 GeV / 180 pC / 1 kA

Translates directly to
measured X-ray spectra



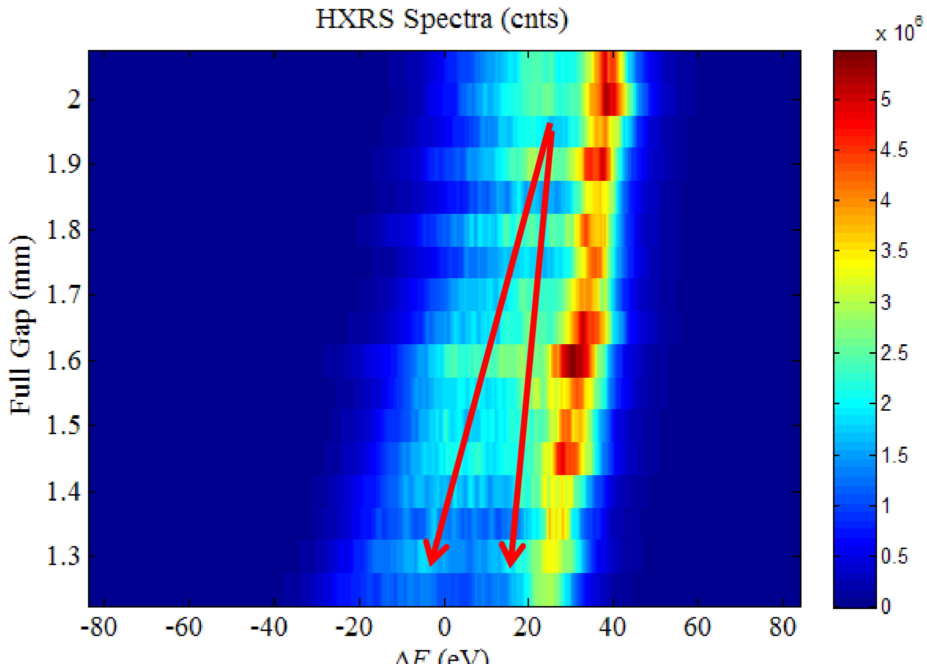
From SXR
spectrometer @ 870 eV

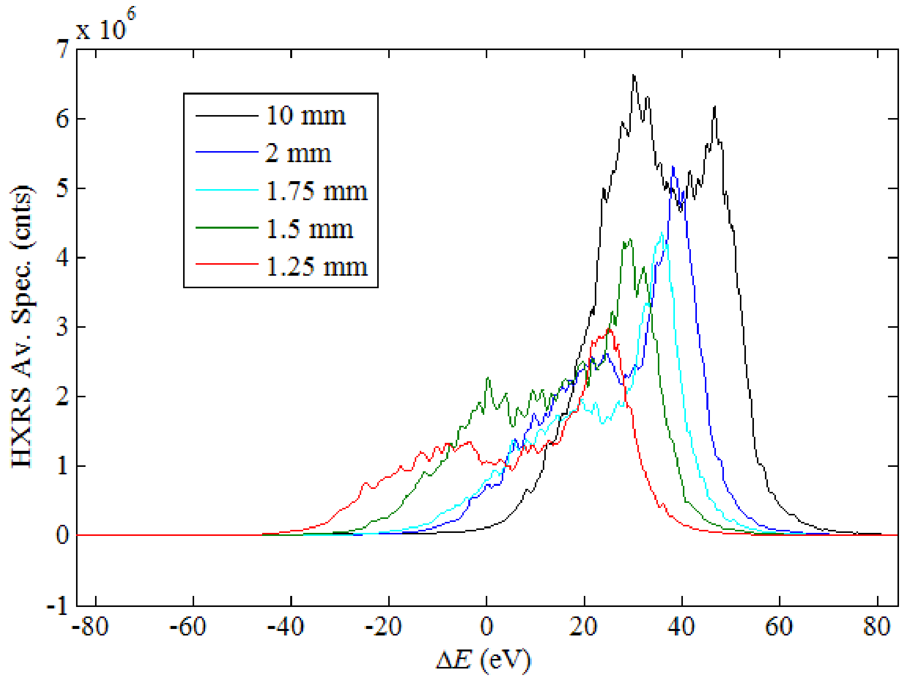


Adding Chirped Hard X-ray Bandwidth

Just as effective at high energy:

Observe red shift / BW increase on hard X-ray spectrometer

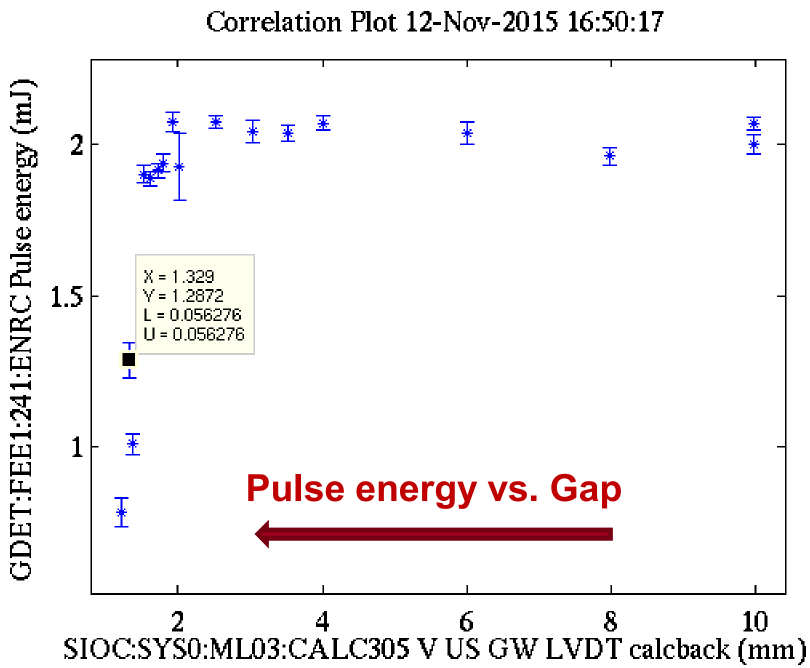


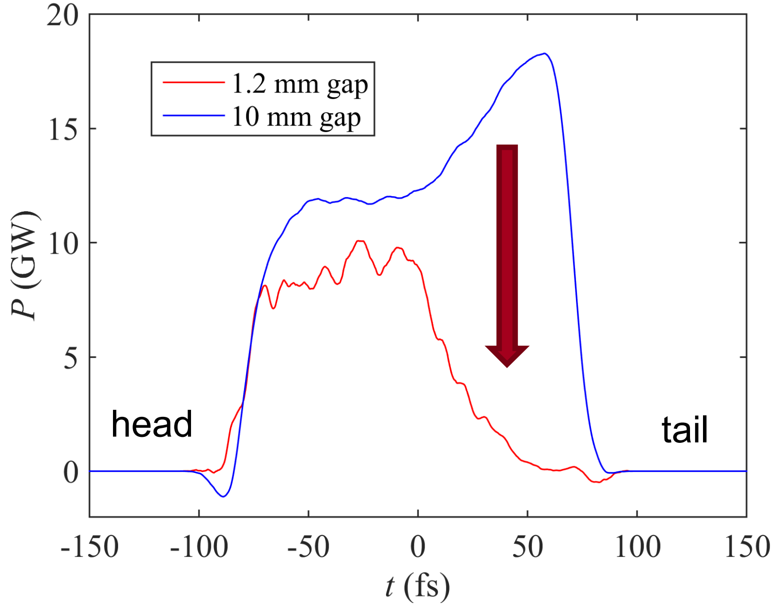


Can increase BW for over-compressed bunch (where desirable)

Steep Slope < 1.4 mm Full Gap

Early days: FEL degrades for gap < 1.4 mm





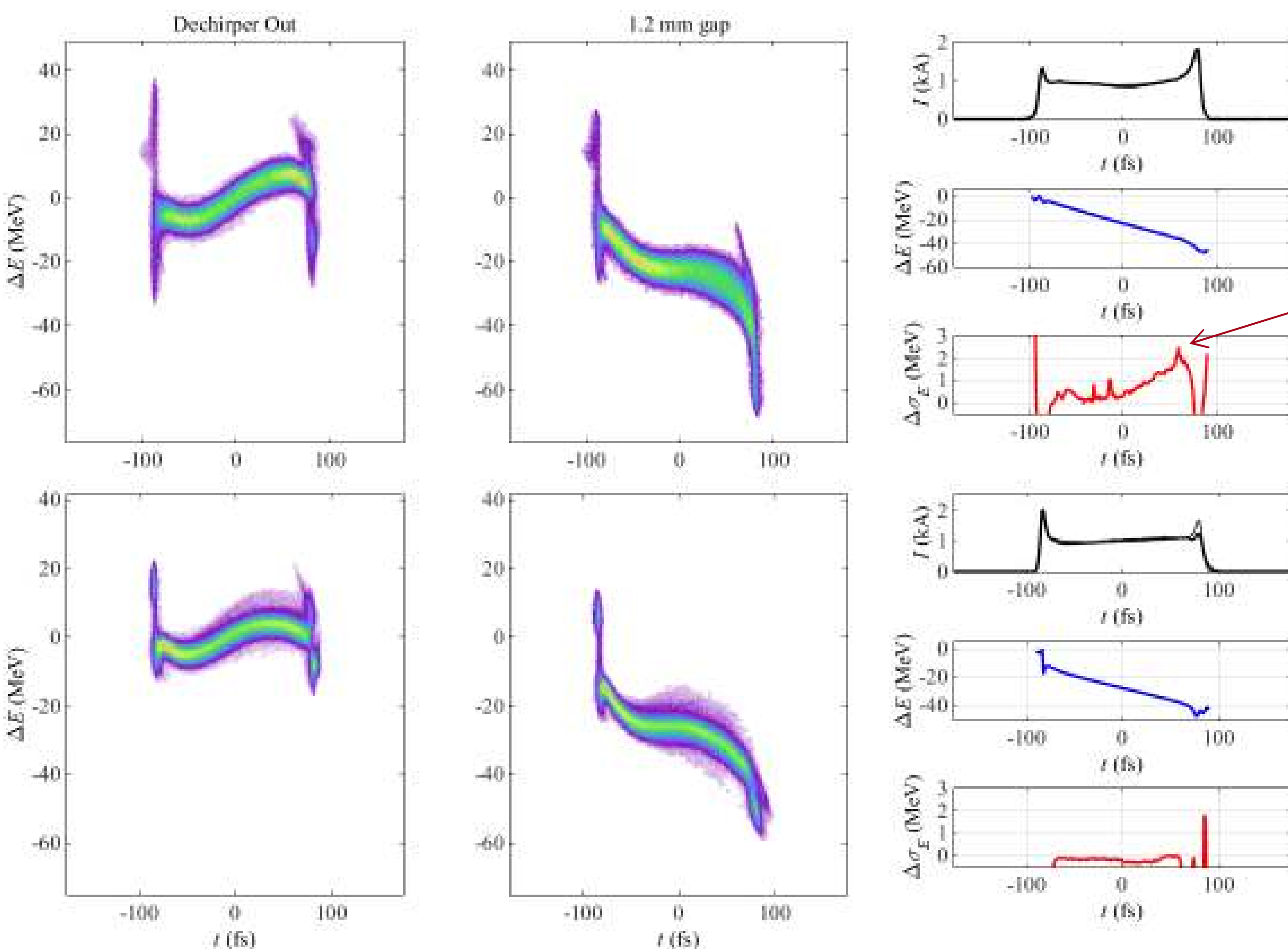
X-ray pulse reconstruction with XTCAV shows tail stops lasing

Steep Slope < 1.4 mm Full Gap

Seen on tail slice energy spread (no lasing). Repeatedly moving dechirper in/out to same location eliminates this growth. With FEL, also restores full intensity.

Nov. 2015

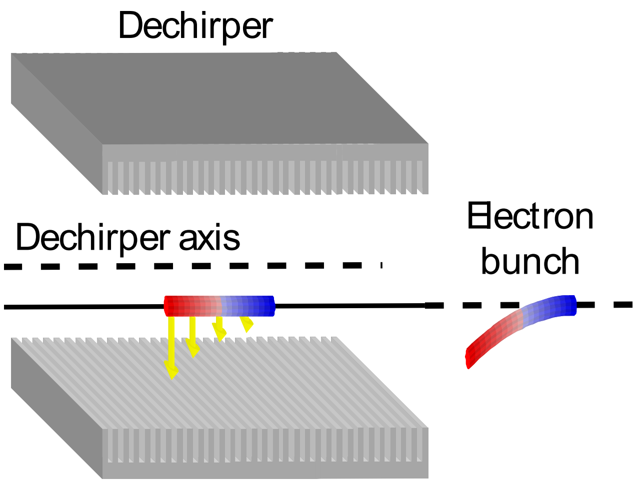
Feb 2016



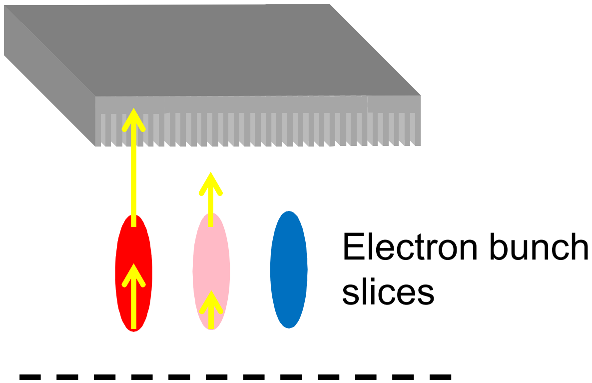
On-axis, *E* spread should be < 100 keV on tail

Transverse wakes

Dipole: time-correlated transverse kick



Quad: time-correlated focusing



(A. Lutman)

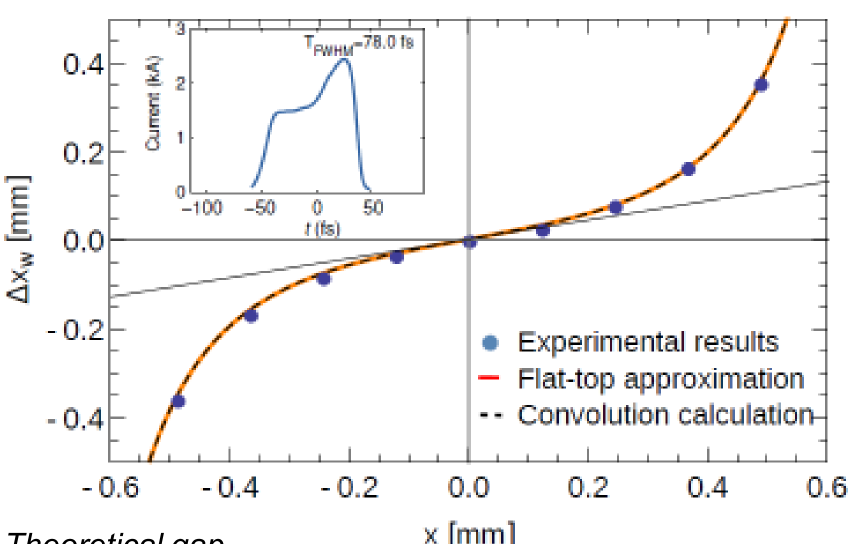
Average dipole wake studies: Single jaw position scans

$$w_x(s) = \left(\frac{Z_0 c}{4\pi}\right) A s_{0x} \left[1 - \left(1 + \sqrt{s/s_{0x}}\right) e^{-\sqrt{s/s_{0x}}}\right]$$

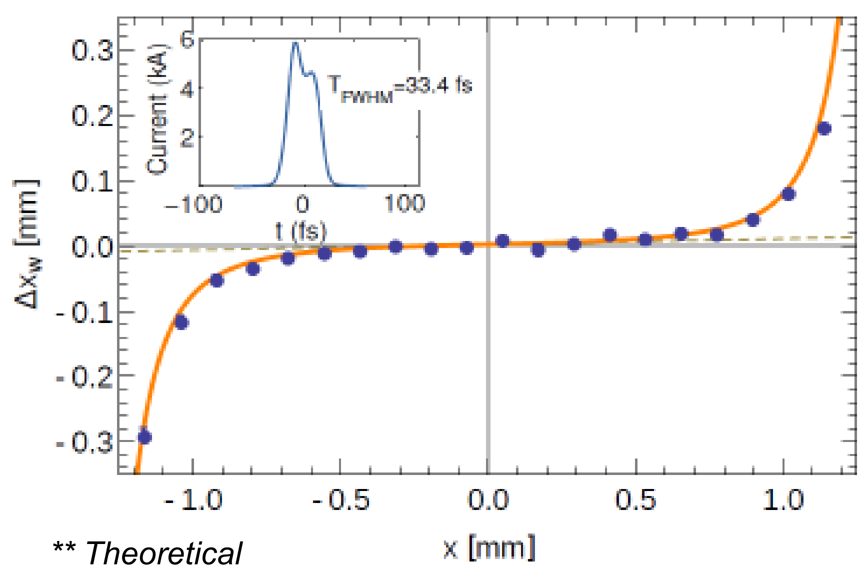
$$A_d = \frac{\pi^3}{4a^3} \sec^2\left(\frac{\pi x}{2a}\right) \tan\left(\frac{\pi x}{2a}\right), \quad s_{0r} = \frac{a^2 t}{2\pi\alpha^2 (t/p) p^2}$$

$$s_{0xd} = 4 s_{0r} \left[\frac{3}{2} + \frac{\pi x}{a} \csc\left(\frac{\pi x}{a}\right) - \frac{\pi x}{2a} \cot\left(\frac{\pi x}{a}\right)\right]^{-2}$$

6.6 GeV, 150 pC, 2 mm full gap*



13 GeV, 180 pC, 3.1 mm full gap**



** Theoretical gap reduced 11%*

*** Theoretical gap reduced 6%*

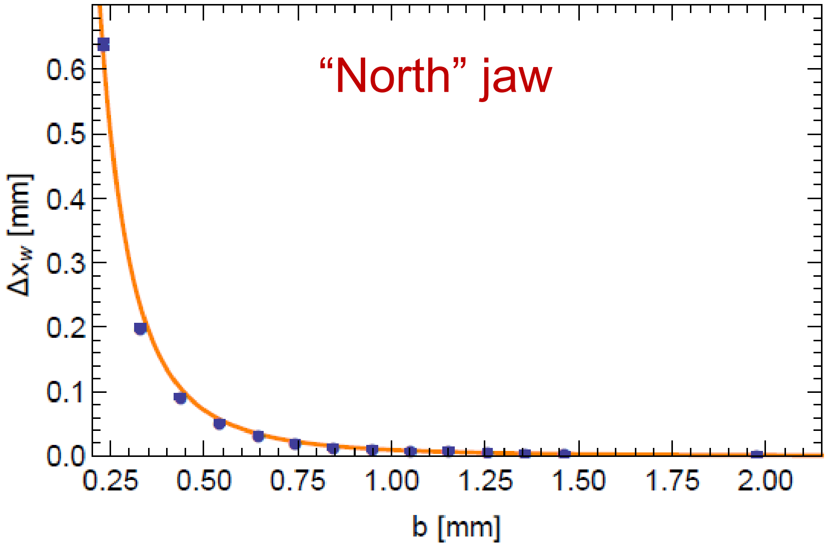
Average dipole wake studies: Two jaws, scan gap center

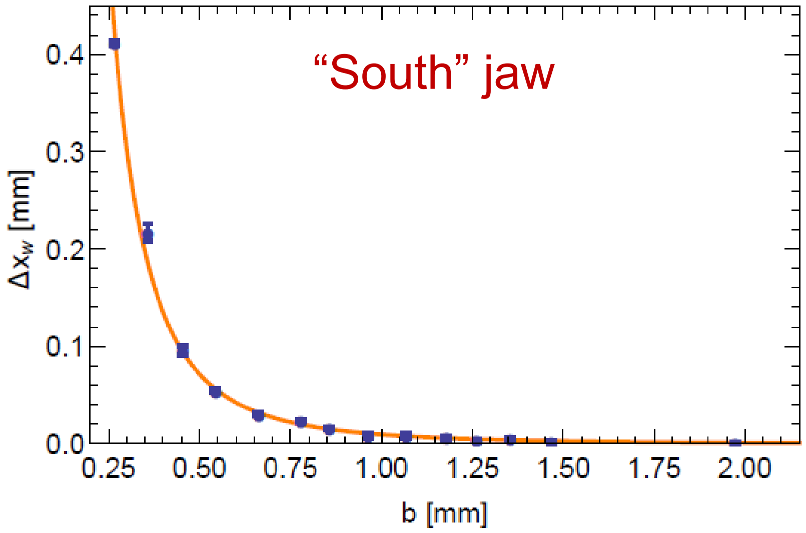
J. Zemella, *et. al*, PRAB (submitted)

$$w_x(s) = \left(\frac{Z_0 c}{4\pi}\right) A s_{0x} \left[1 - \left(1 + \sqrt{s/s_{0x}}\right) e^{-\sqrt{s/s_{0x}}}\right]$$

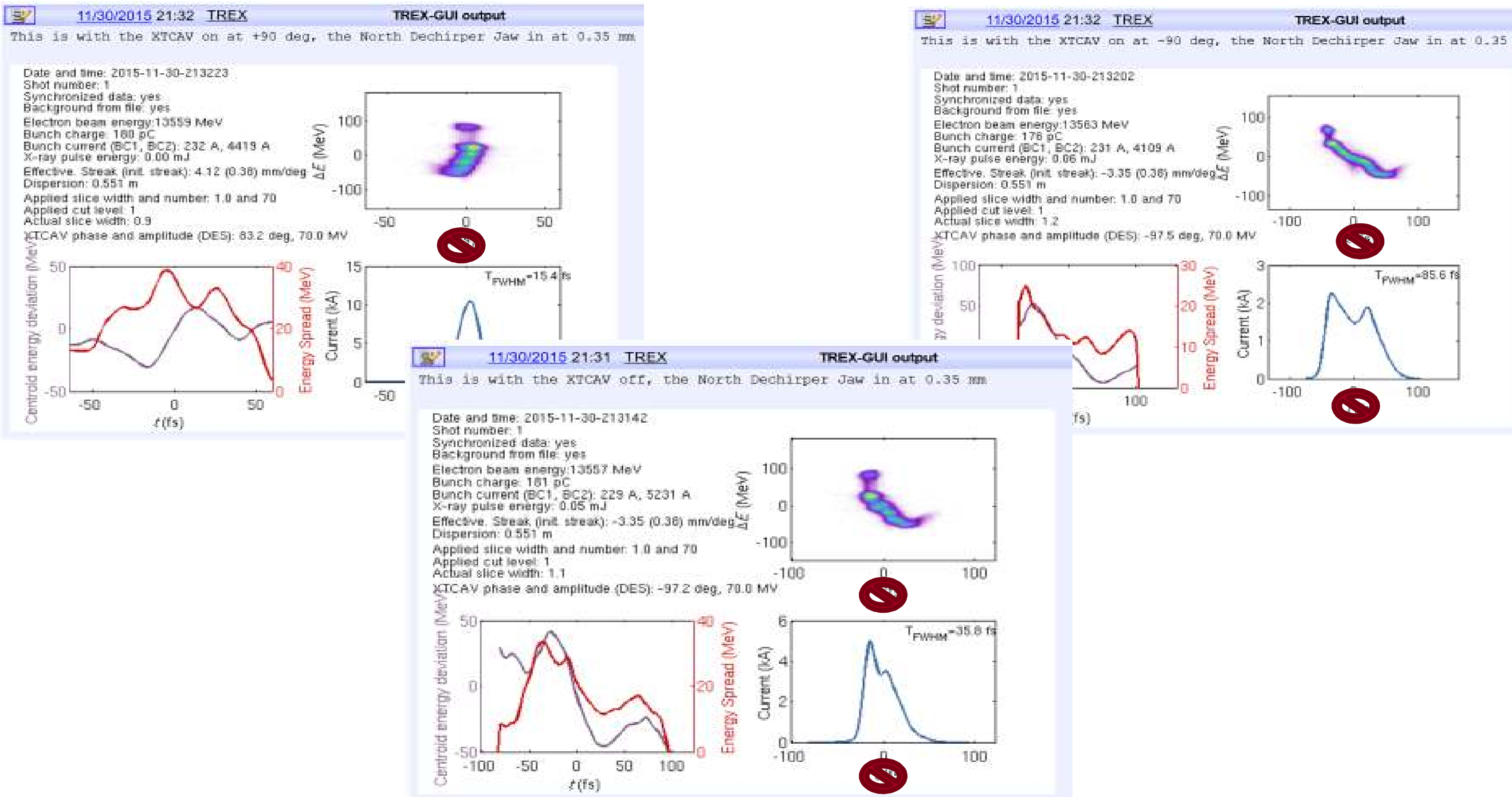
$$A_s = \frac{2}{b^3}\ , \qquad s_{0xs} = \frac{8b^2 t}{9\pi\alpha^2 p^2}$$

13 GeV, 180 pC, 3.5 kA





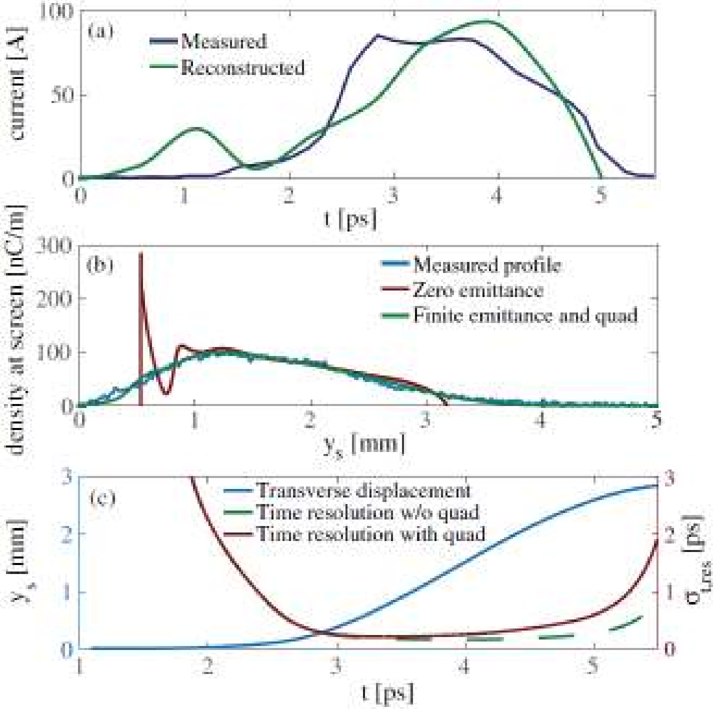
Strong effect, once incidentally equivalent to XTCAV…



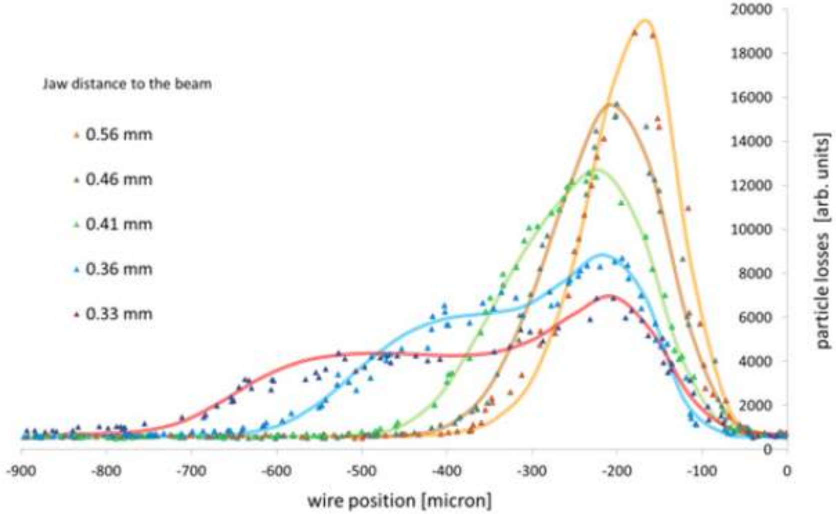
Passive streaker

- Proposals from A. Novokhatski, S. Bettoni, P. Craievich, A. Lutman
- PSI Demo [S. Bettoni, PRAB **19**, (2016)]
- First SLAC demo [A. Novokhatski, *IPAC 2016*, MOPOW046 (2016)]

PSI measurements



SLAC measurements

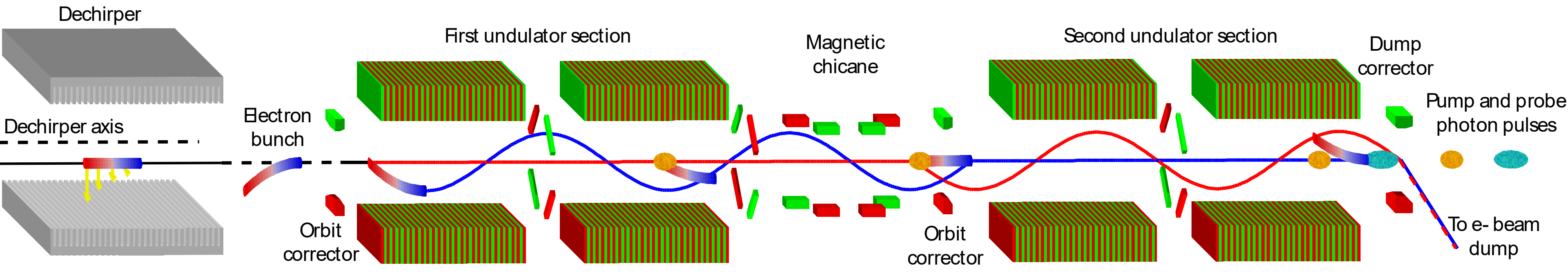


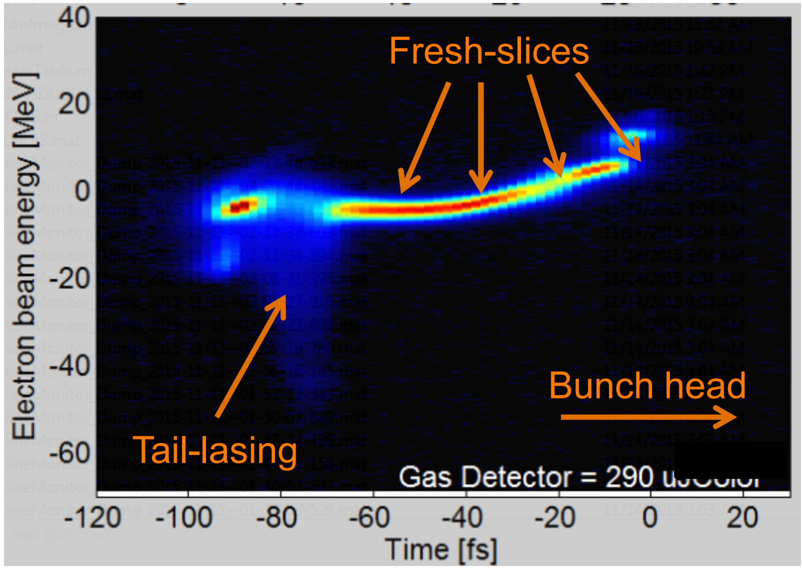
Requires algorithmic reconstruction *but,* self-synchronized/highly stable (vs. TDS)

< 1 fs resolution feasible

Fresh-slice X-ray free-electron lasers

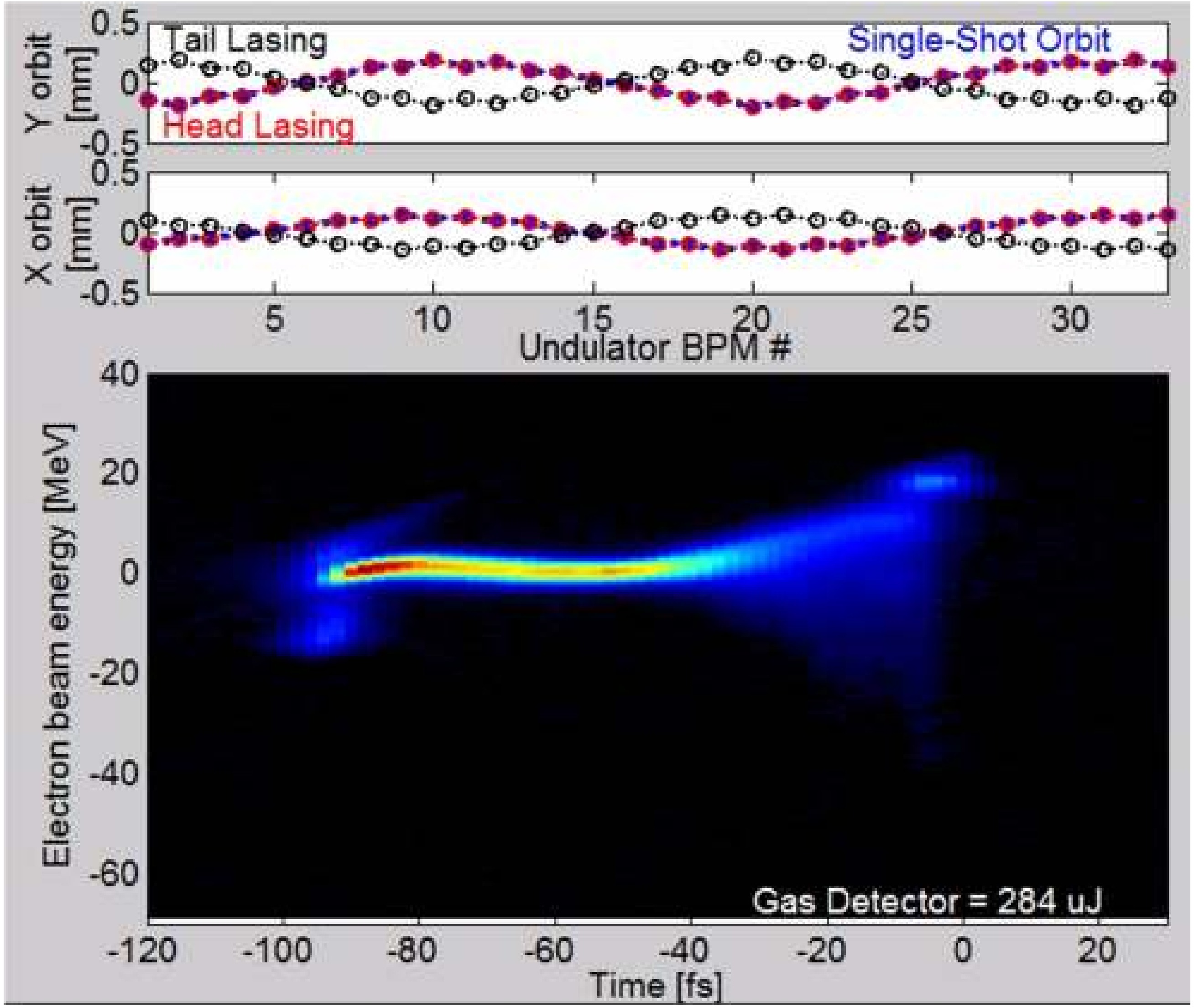
- Tail of bunch undergoes betatron oscillations, head slice lases
- Only one temporal slice lases





(A. Lutman)

Slice and pulse duration control



Both X and Y dechiper used

Recorded BPM orbits

1.8 keV photons

XTCAV images: electron bunch after lasing in undulator

Bunch head →

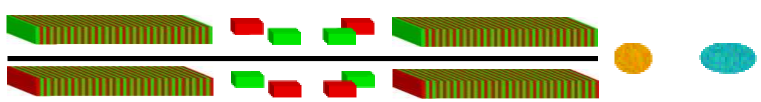
Two-color, variable delay X-ray pulses

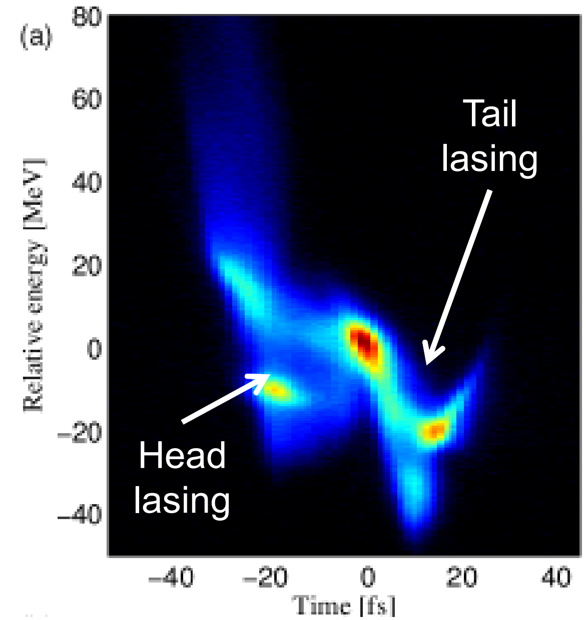
SLAC

nature photonics
ARTICLES
PUBLISHED ONLINE: 17 OCTOBER 2016 | DOI: 10.1038/NPHOTON.2016.201

Fresh-slice multicolour X-ray free-electron lasers

Alberto A. Lutman[1]*, Timothy J. Maxwell[1], James P. MacArthur[1], Marc W. Guetg[1], Nora Berrah[2], Ryan N. Coffee[1,3], Yuantao Ding[1], Zhirong Huang[1,3], Agostino Marinelli[1], Stefan Moeller[1] and Johann C. U. Zemella[1,4]





Fresh slice features:

+ Easy to setup and stable
+ Fully saturated short pulses
+ Delay controlled by chicane
+ Color controlled by undulator K's
+ Scan through zero delay if tail lases first
+ Independent pointing in each section
+ Polarization control with Delta
+ And so much more! ***(Ref C. Emma's talk TUB3CO03)***

	Tail Pulse	Head Pulse
Energy [μJ]	248 ± 83	484 ± 91
Duration	~ 5 fs	~ 17 fs
Wavelength	715 eV	699 eV
Undulators	U1-U8, K~3.455	U26-U33, K~3.505

(A. Lutman)

Outlook

- A pair of crossed, 2 m, all-metal, variable-gap CS dechirpers have been built and designed for X-ray FEL applications
- Chirp control for correlated BW tuning of the LCLS has been demonstrated with excellent agreement to theory
- Lessons learned for improving motion repeatability
- Additional applications for the controlled dipole wakefield to sub-fs passive streaking and advanced, fresh-slice lasing techniques
- Not directly interceptive, application to future high-rate, high-power X-ray FEL linacs remains to be explored

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