# Demonstration of Energy-Chirp Control in Relativistic Electron Bunches at LCLS Using a Corrugated Structure

Karl Bane, 7 April 2017, 加速器物理セミナー, KEK

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

# Introduction

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- At the end of acceleration in an X-ray FEL, the beam may be left with an longitudinal position/energy correlation. The metallic beam pipe with small corrugations—a “dechirper”--was proposed as a passive device to “dechirp” the beam
- The RadiaBeam/LCLS dechirper was installed in the LCLS, to give added flexibility to operations. Device commissioning was performed over the period Oct 2015—Feb 2016
- I will present (i) basic wakefield measurements—energy loss, induced chirp, transverse kick, …—, compare to calculations, and (ii) measurements of their effect on the lasing process
- These are the first measurements of a dechirper at high energies (multi-GeV), short bunch lengths (10’s of μm’s), and in a functioning FEL

# Outline

- Description of RadiaBeam/LCLS dechirper
- Basic wakefield measurements—average energy loss, induced chirp, transverse kick
- Dechirper/FEL interaction
- Conclusions

Will not discuss transverse kick for bunch length measurements—A. Novokhatski et al

Selected references on wake theory of corrugated dechirpers:

K. Bane and G. Stupakov, Nucl Inst Meth A 690, 106 (2012)
A. Novokhatski, Phys. Rev. ST Accel. Beams 18, 104402 (2015)
K. Bane, G. Stupakov, Nucl Inst Meth A 820, 156 (2016)
K. Bane, G. Stupakov, I. Zagorodnov, "Analytical formulas of short bunch wakes in a flat dechirper," SLAC-PUB-16497, March 2016

# Contributors to Dechirper Commissioning Success (effort led by R. Iverson)

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| FEL Physics | Radiabeam Systems | METS | Controls |
|---|---|---|---|
| T. Maxwell | M. Ruelas | A. Cedillos | A. Babbitt |
| P. Krejcik | M. Harrison | M.A. Carrasco | Z. Oven |
| M. Guetg | J. McNevin | G. Gassner | M. Petree |
| J. Zemella | D. Martin | E. Reese | J. Bong |
| Z. Huang | A. Murokh | K. Caban | M. D'Ewart |
| K. Bane | P. Frigola | S. Jansson | S. Hoobler |
| G. Stupakov | | T. Montagne | S. Alverson |
| P. Emma | | J. Garcia | L. Piccoli |
| J. Frisch | | R. Atkinson | |
| H. Loos | | | |
| A. Lutman | | | |
| A. Fisher | | | |
| A. Novokhatski | | | |
| R. Iverson | | | |

We especially thank RadiaBeam for building the dechirper and collaborating on the commissioning

# Linac Coherent Light Source (LCLS)

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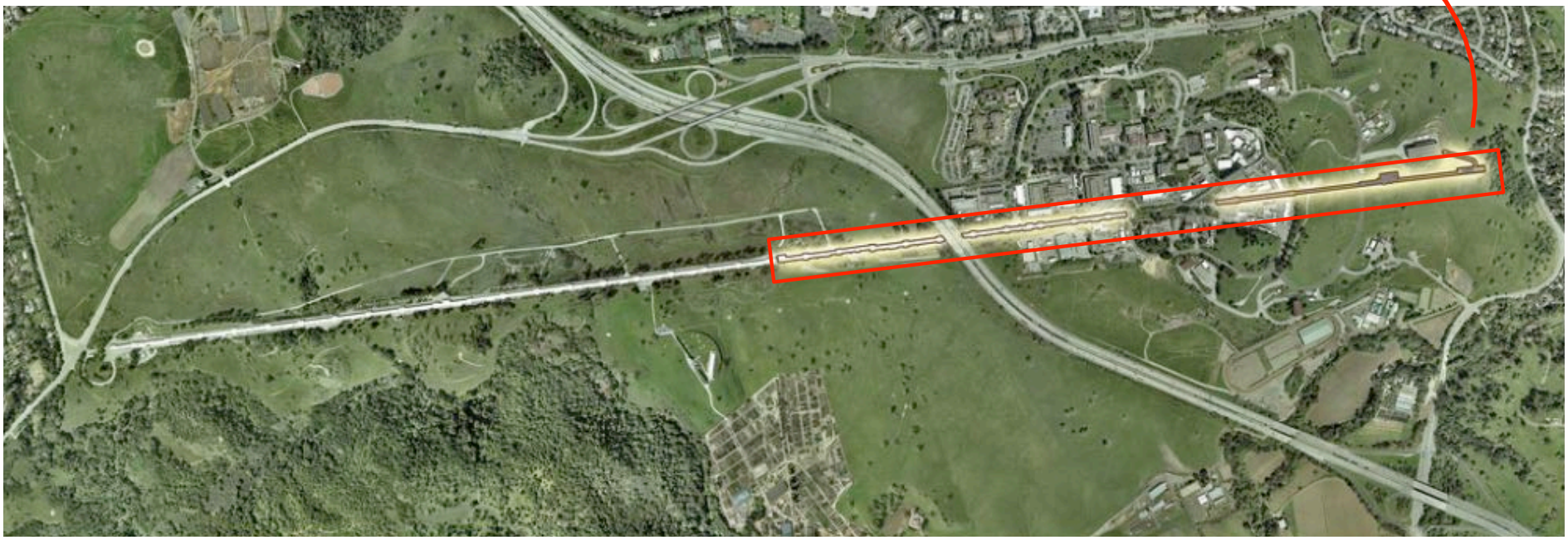
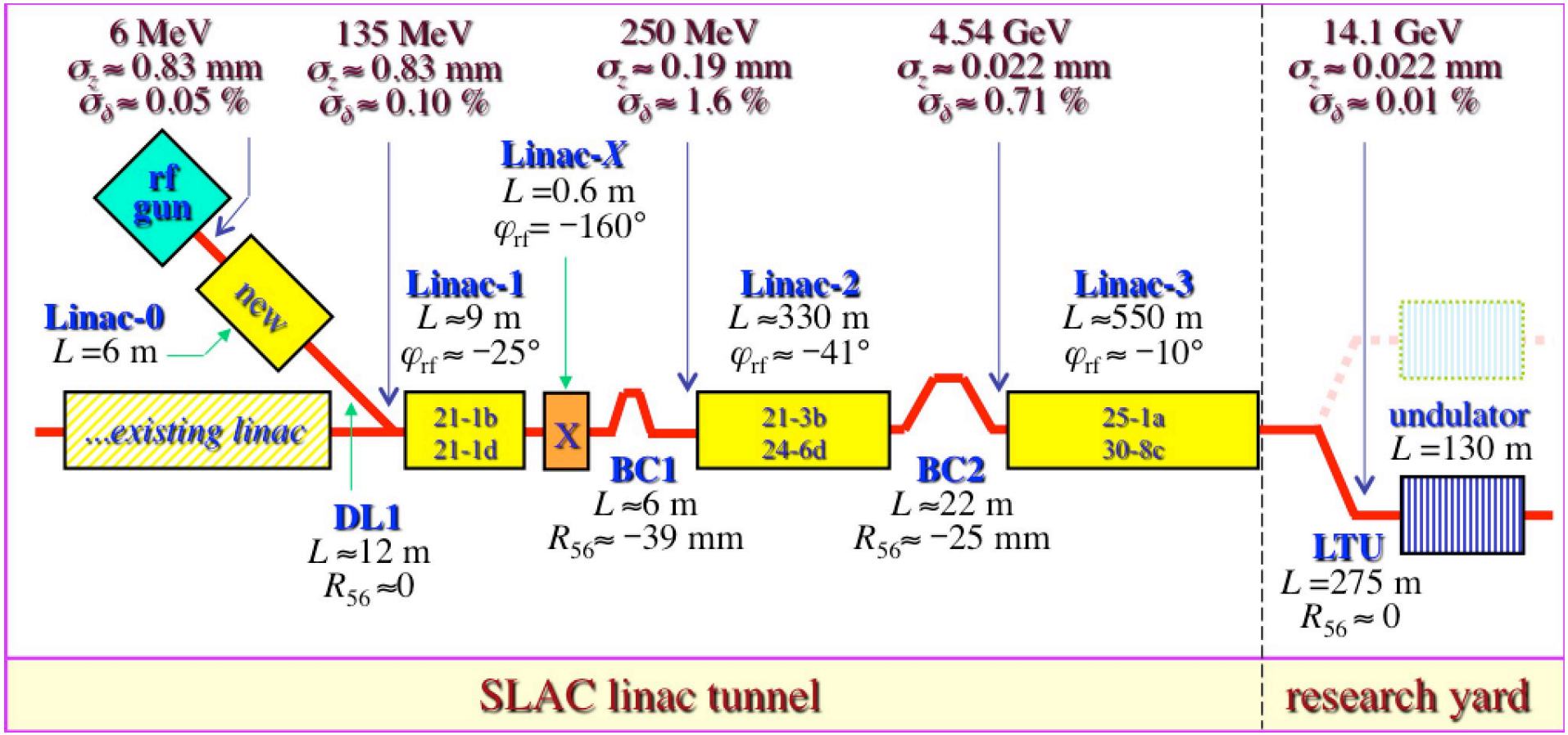
Electron Energy : 14.3 GeV
Light Wavelength : 0.15 nm
Peak Brillance : 2.0 x $10^{33}$
Light Flashes : 120 per sec.
Facility Length : 3 km
Undulators : 1
Experiment Stations : 1

--LCLS-II: $10^{9}$$ upgrade; install superconducting RF, run at 1 MHz repetition

# LCLS Schematic



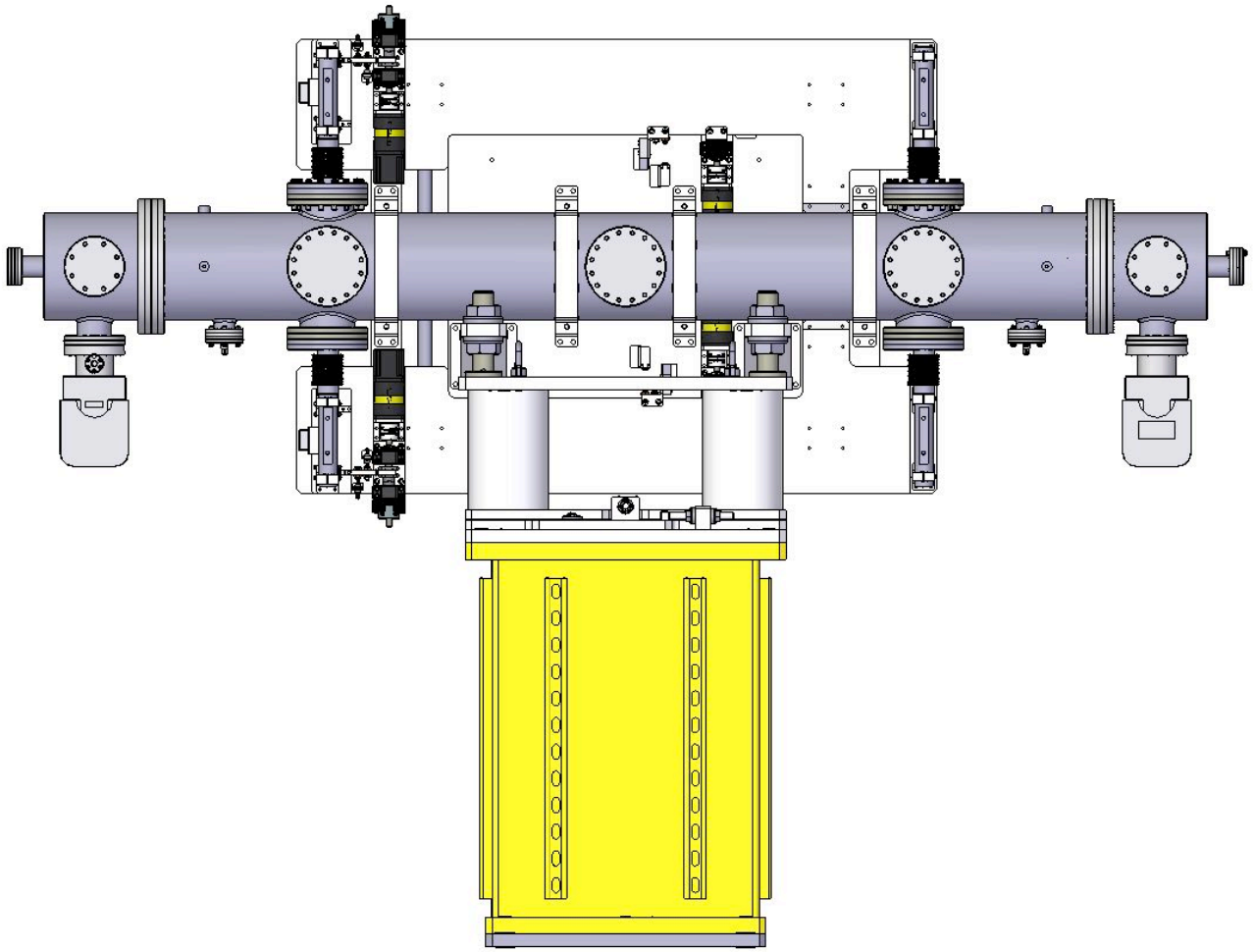

(P. Emma)

# RadiaBeam/LCLS Dechirper Installed in the LCLS


RadiaBeam SLAC Dechirper (photo pkr)

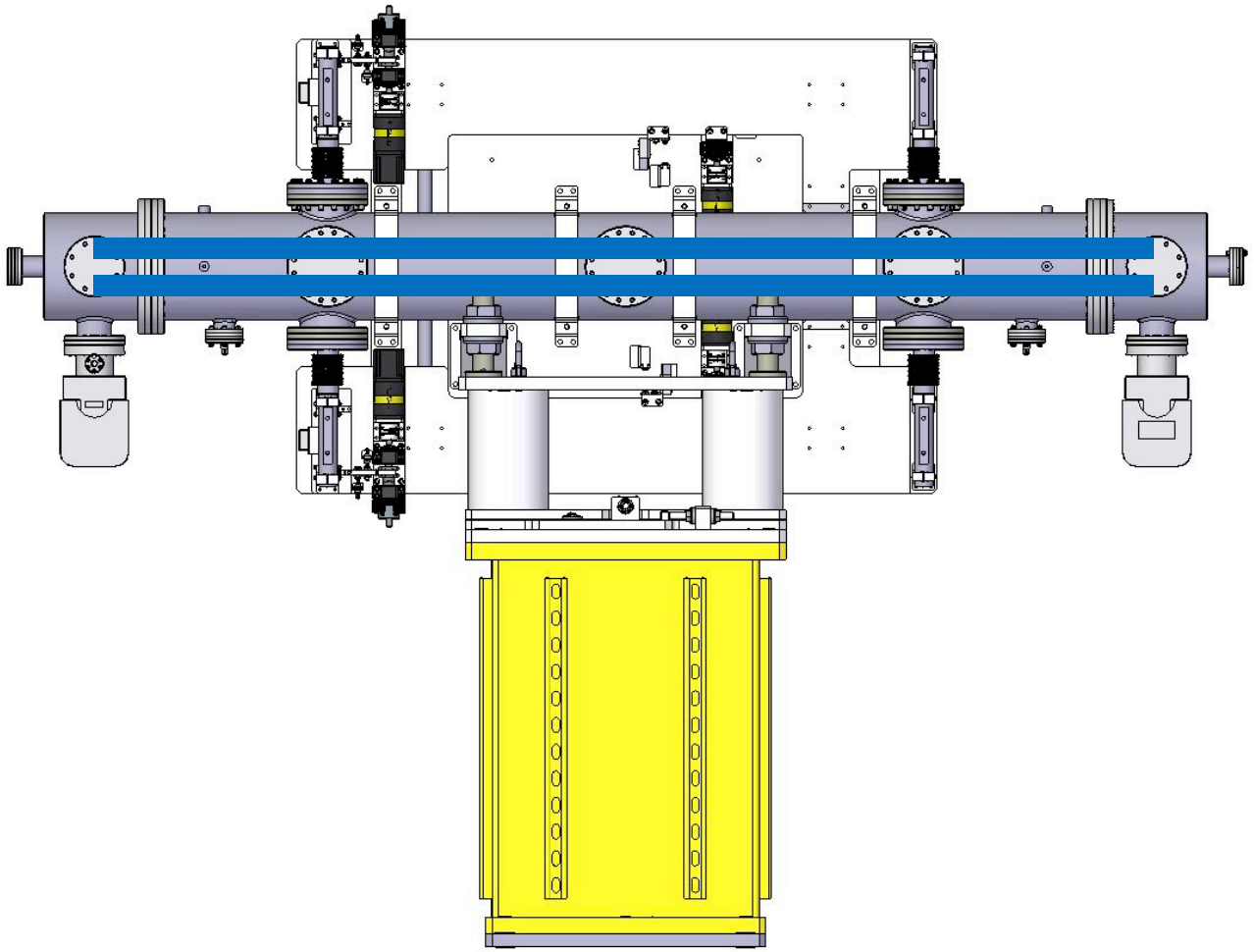
25 um precision over 2 m (P. Krejcik)

# Vertical Dechirper Module - Actuation



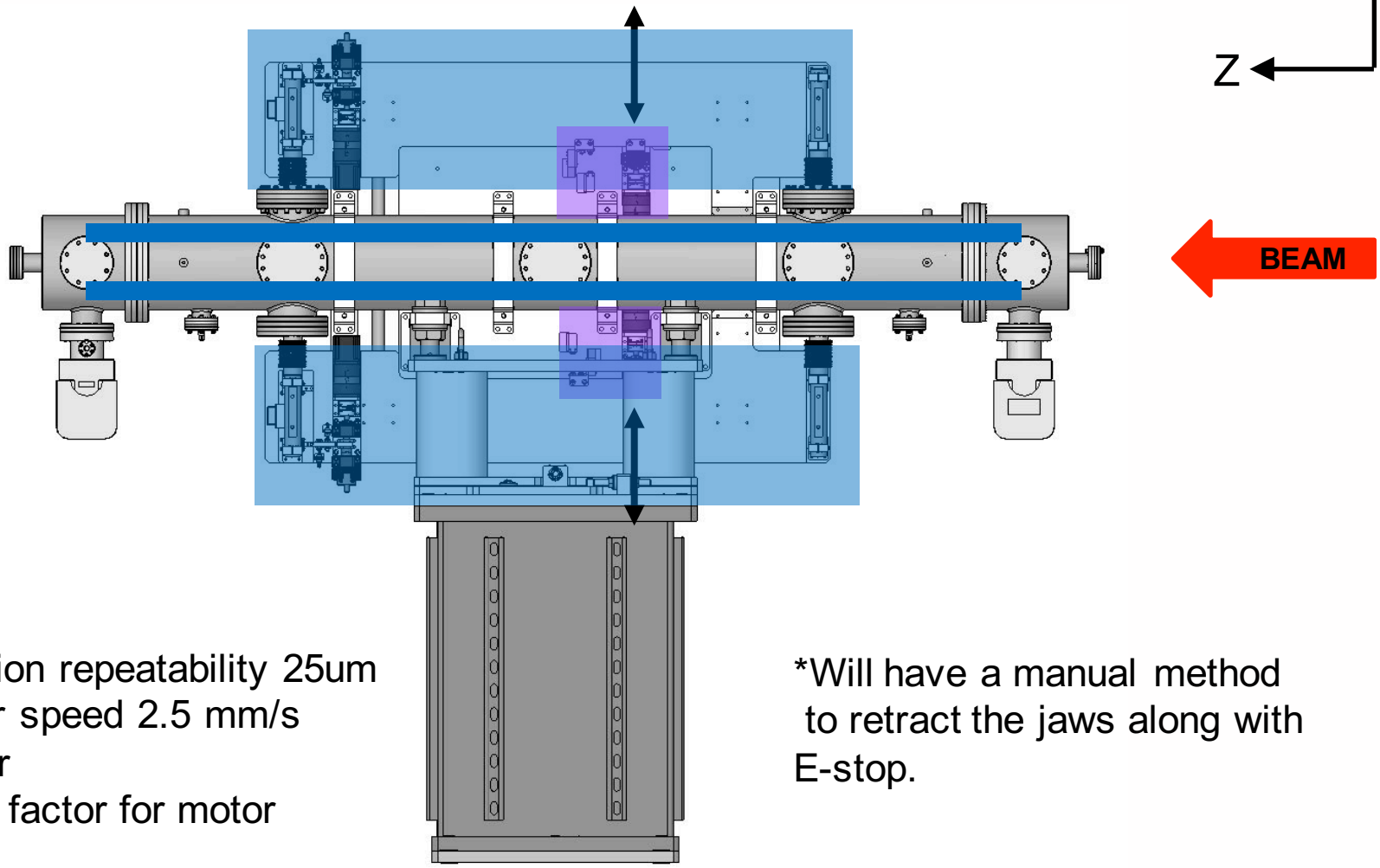

(A. Cedillos)

# Vertical Dechirper Module - Actuation




(A. Cedillos)

# Vertical Dechirper Module – Insertion/Retraction

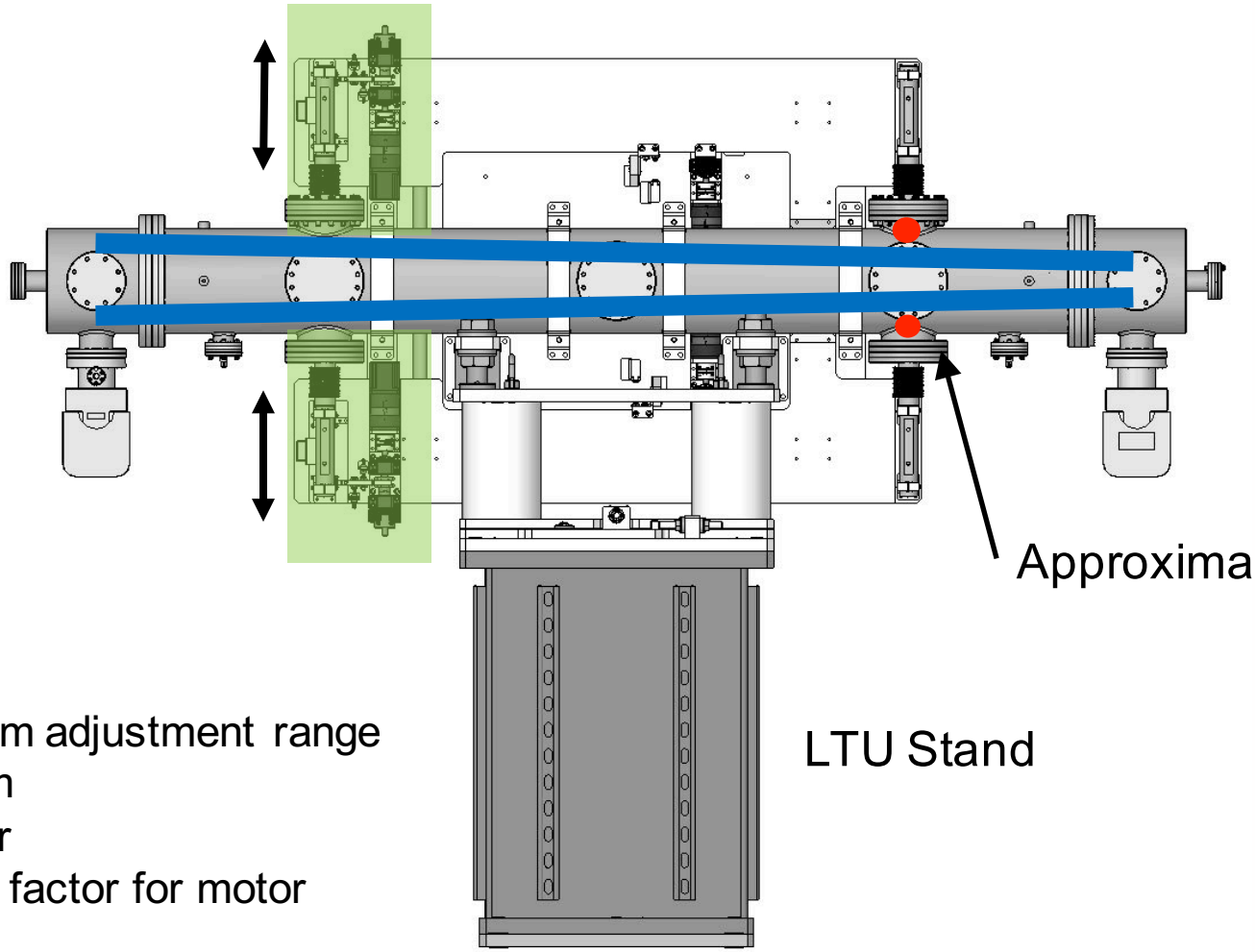



- Carrier position repeatability 25um
- Carrier linear speed 2.5 mm/s
- Gear reducer
- Large safety factor for motor

*Will have a manual method to retract the jaws along with E-stop.

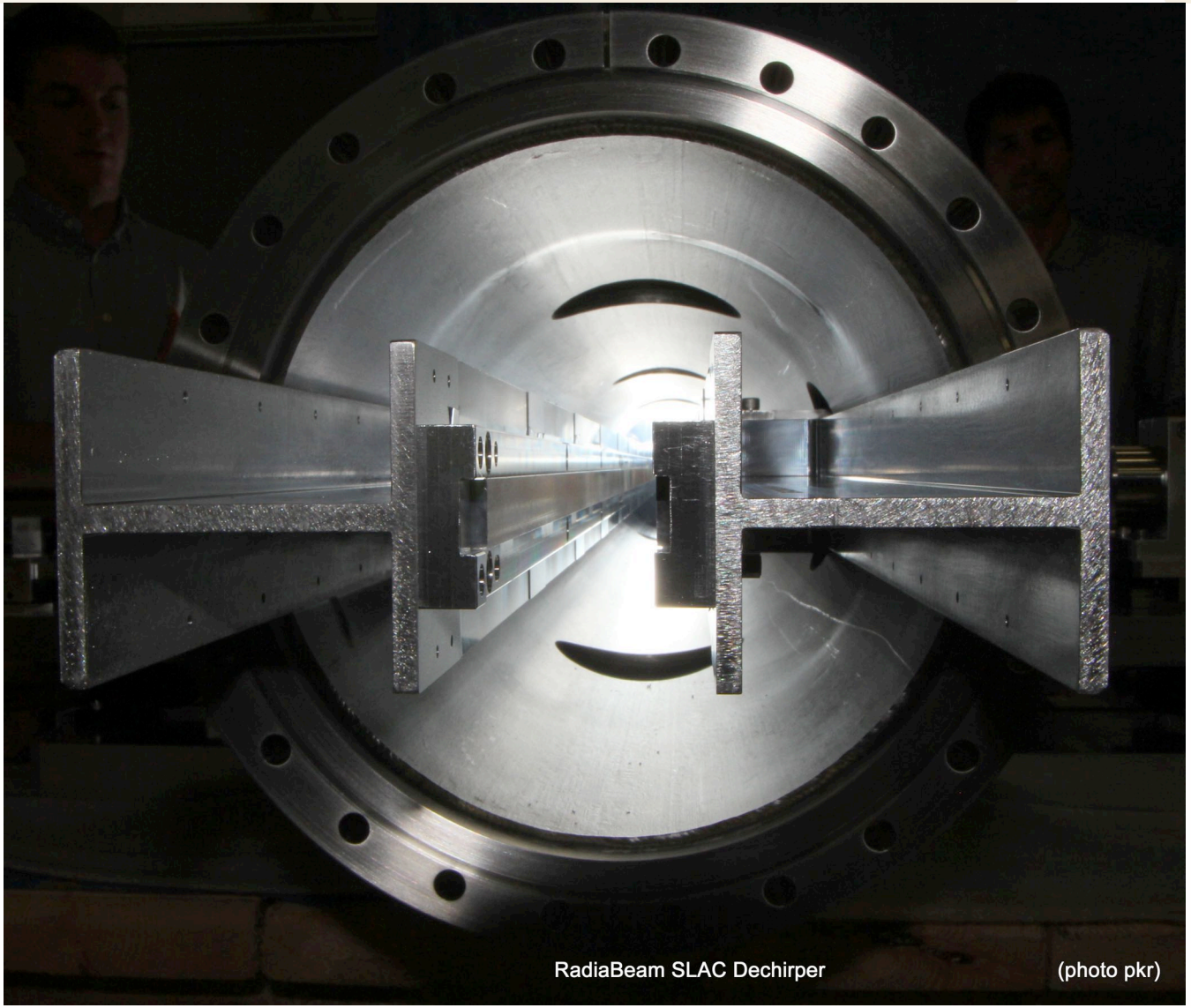
(A. Cedillos)

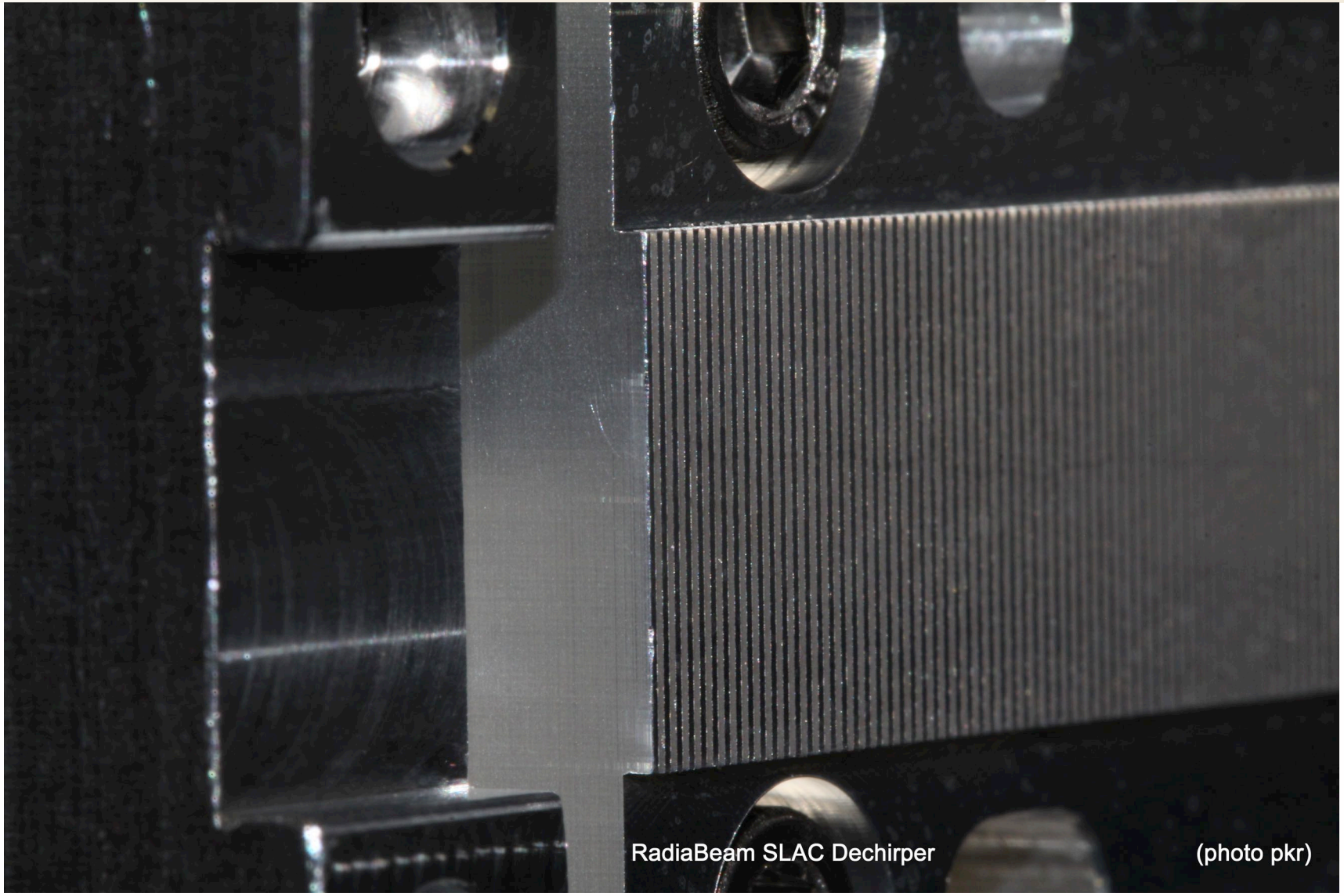
# Vertical Dechirper Module – Trim Actuation



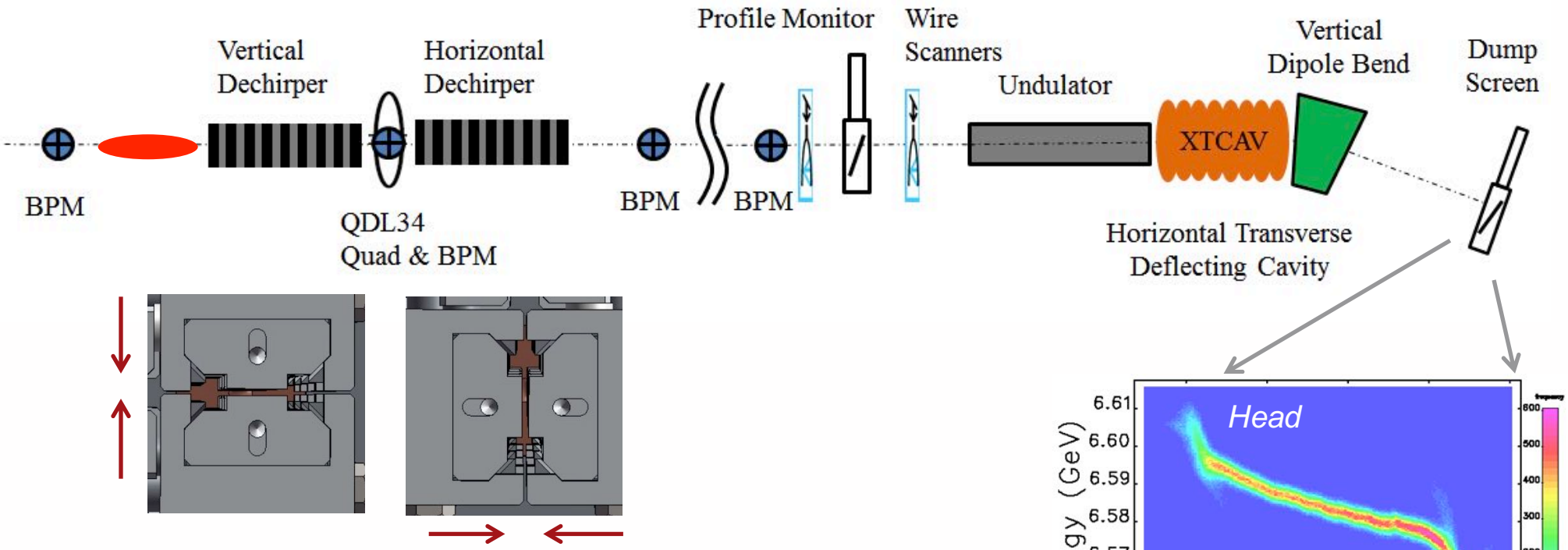

- Carrier tip trim adjustment range
  - +/- 1mm
- Gear reducer
- Large safety factor for motor

(A. Cedillos)


RadiaBeam SLAC Dechirper
(photo pkr)


RadiaBeam SLAC Dechirper
(photo pkr)

# Dechirper at LCLS




Note: on dump screen *x* is proportional to time and *y* to energy

Simulation by Z. Zhang

(R. Iverson)

# RadiaBeam/LCLS Dechirper

- The dechirper unit consists of 2 m of a vertical dechirper followed by 2 m of a horizontal one

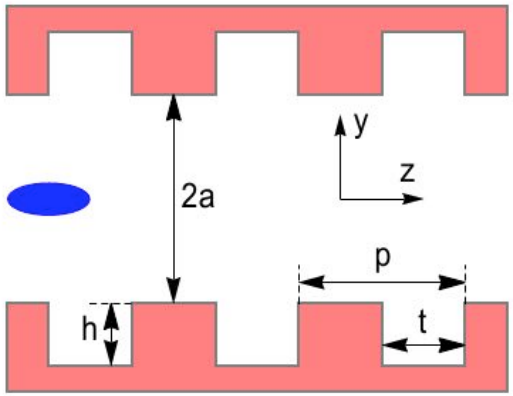
- This configuration was chosen to partially cancel the unavoidable quad wake mismatch at the tail of the bunch

- *h*, *p* not << *a* => not in perturbation regime. Wakes have a droop, and dechirp in a uniform bunch is not quite as strong, not completely linear

Note: a dechirper based on dielectric-lined, metallic plates will behave similarly

| Parameter | Value | Units |
|---|---|---|
| Full gap 2a | 1.4/2.0 | mm |
| Period p | 0.5 | mm |
| Depth h | 0.5 | mm |
| Slit width t | 0.25 | mm |
| Fin width w | 12 | mm |
| Total length L | 4* | m |

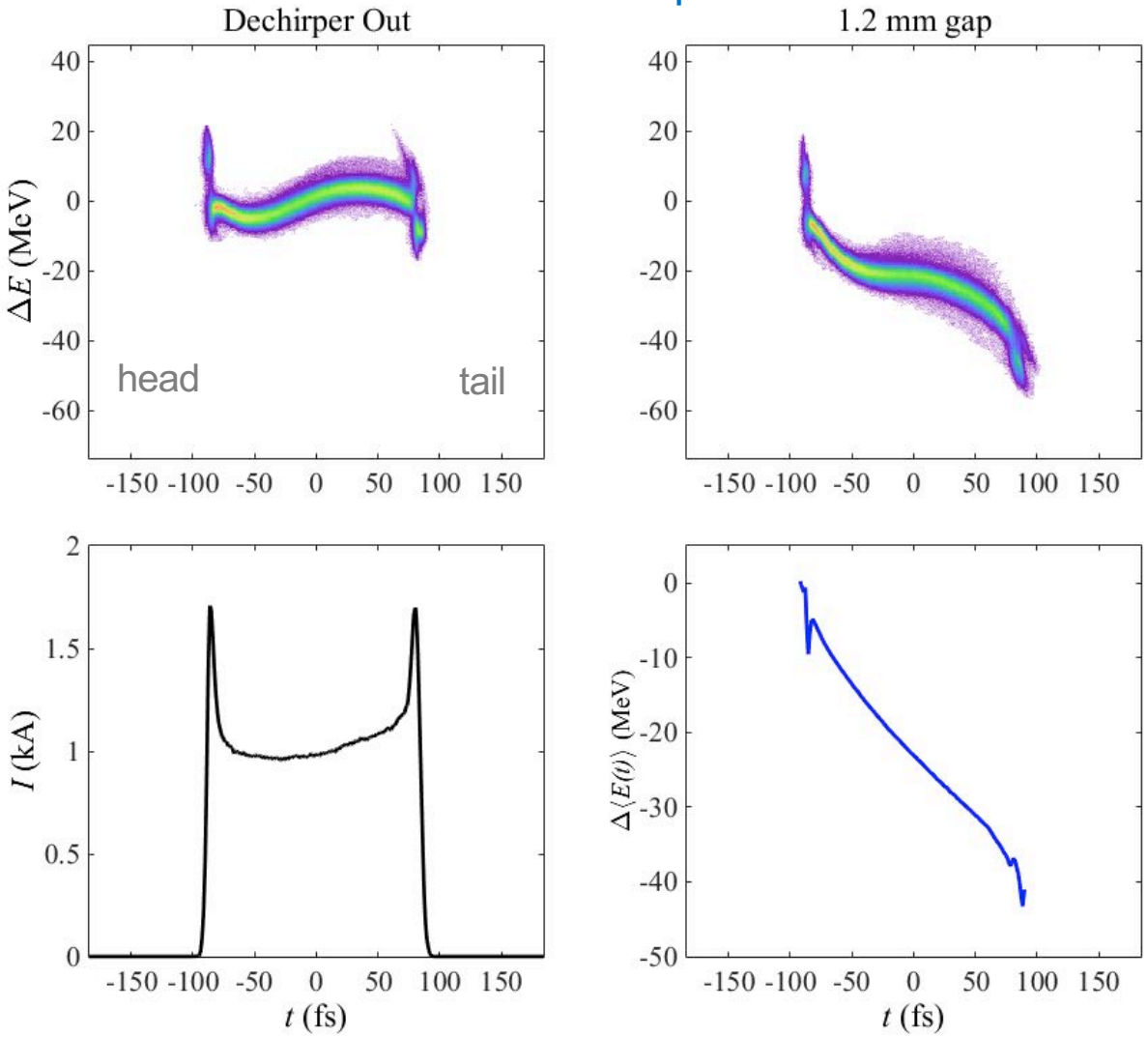
*The Dechirper is composed of two modules 2m each.

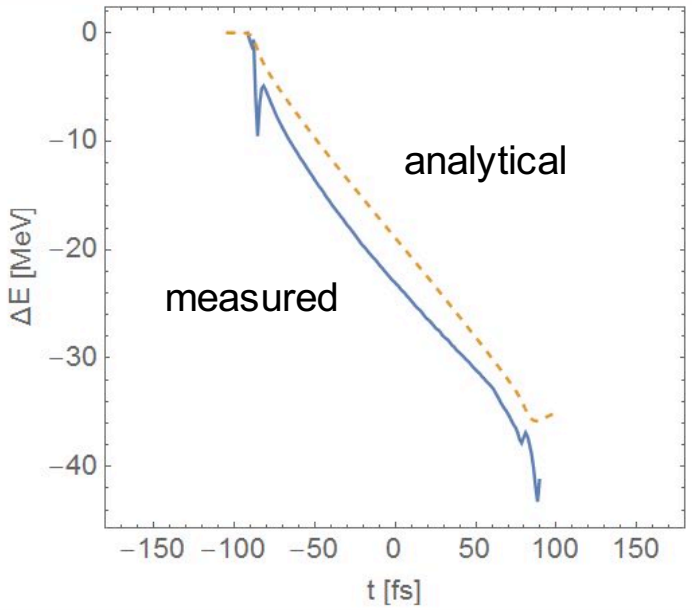



*Three periods of the vertical dechirper*

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

Data from dump screen




Clear, ~linear additional chirp observed

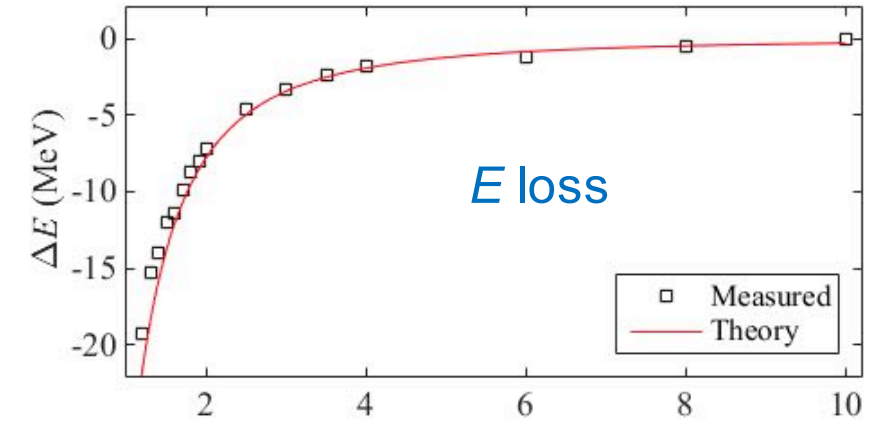
Using both dechirpers (L= 4 m)

Obtained from data from dump screen

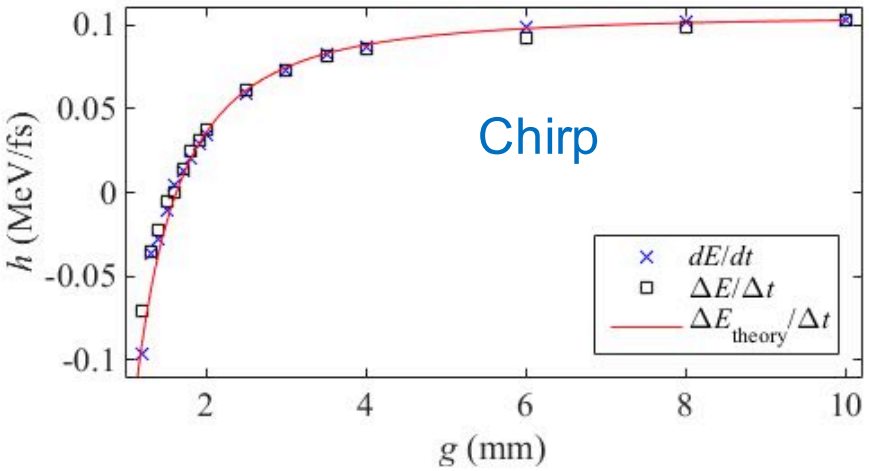
(T. Maxwell)

# Measurements @ 4.4 GeV / 180 pC / 1 kA

for uniform bunch, average loss $\Delta E = \frac{\pi Z_0 c Q L}{8 g^2}$

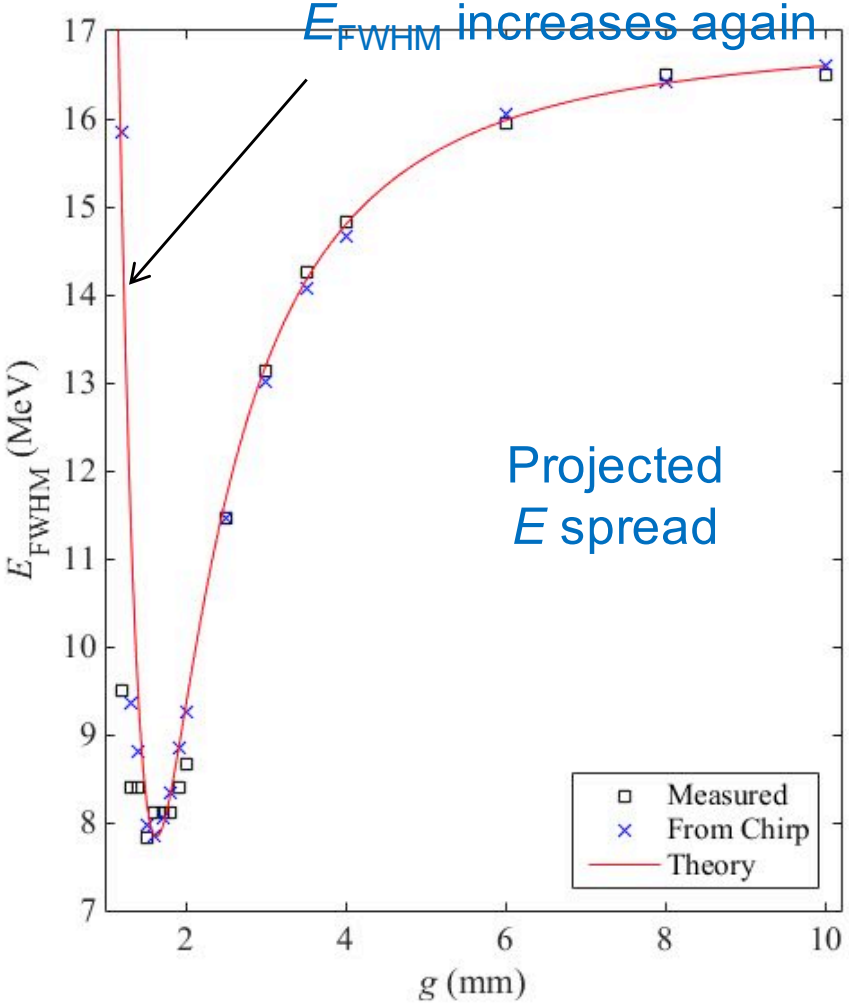



*E* loss




Chirp

As gap becomes smaller here $E_{FWHM}$ increases again

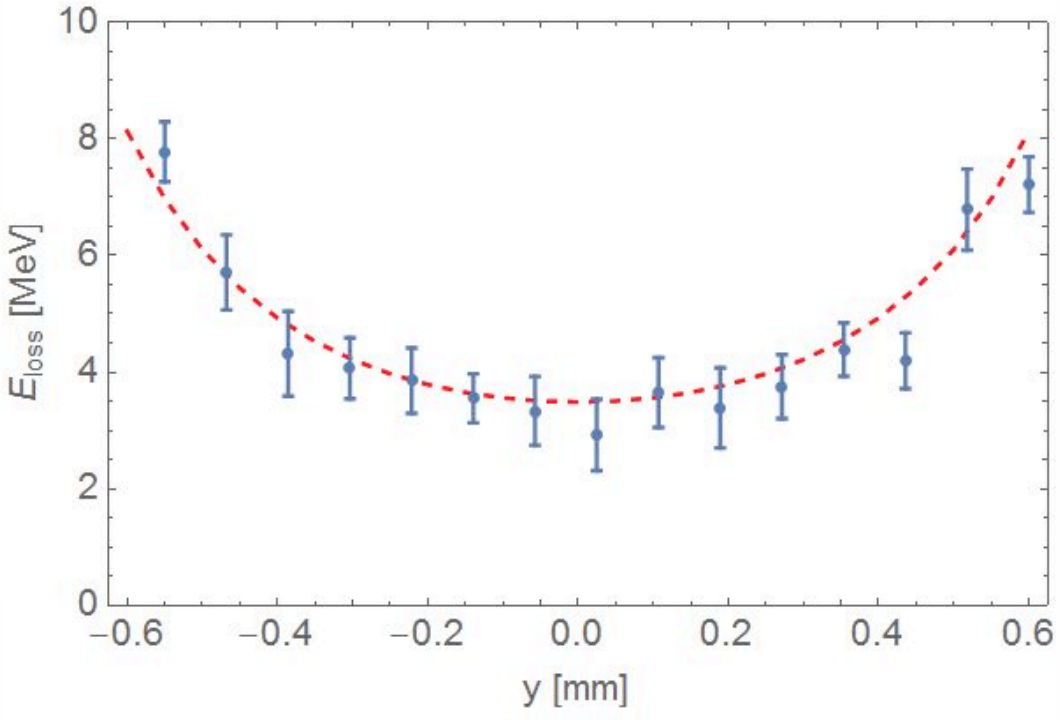



Projected *E* spread

(T. Maxwell)

# Average $E_{loss}$ vs. Bunch Offset

$$E_{loss} \sim \frac{QL}{g^2} \sec^2 \frac{\pi y}{g}$$




*g*= 2*a*= 2.2 mm

*I*= 1 kA
*Q*= 190 pC
*E*= 4.425 GeV

Single dechiper
*L*= 2 *m*

Measured using BPMs in dispersive region, averaged over many shots; dashes show analytical function

To obtain this agreement, a slight adjustment, *g* -> 2.1 mm, was made

# Transverse Kick vs Bunch Offset from Axis

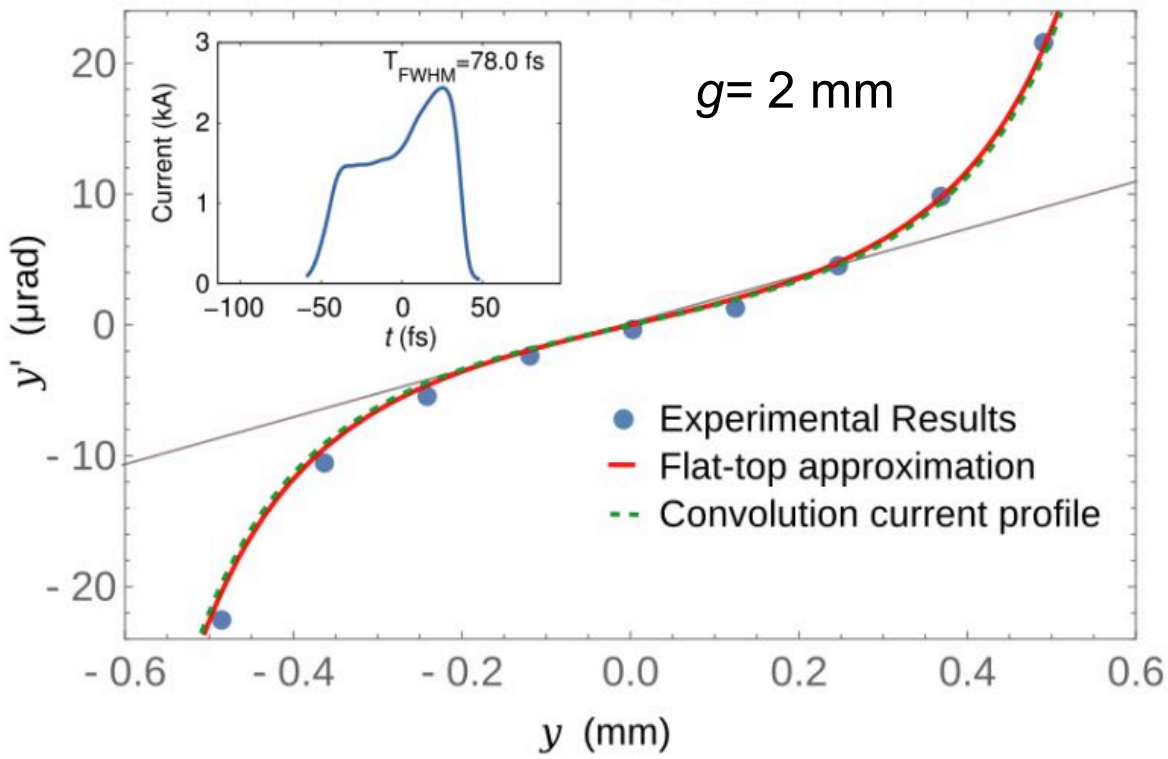
For uniform bunch:

near axis

$$\langle V_y \rangle \sim Z_0 \frac{I\ell^2 L y}{g^4}$$

away from axis

$$\langle V_y \rangle \sim Z_0 \frac{I\ell^2 L}{g^3} \sec^2 \frac{\pi y}{g} \tan \frac{\pi y}{g}$$




*I*- current
*g*- gap
*ell*- bunch length
*L*- structure length
*y*- bunch offset

Deflection angle as function of center position in one dechirper module. The gap of the simulations was reduced from *g*= 2.0 mm to 1.8 mm to fit the experimental data

# Transverse Kick vs Bunch Offset from Single Plate

The agreement is very good for both plots

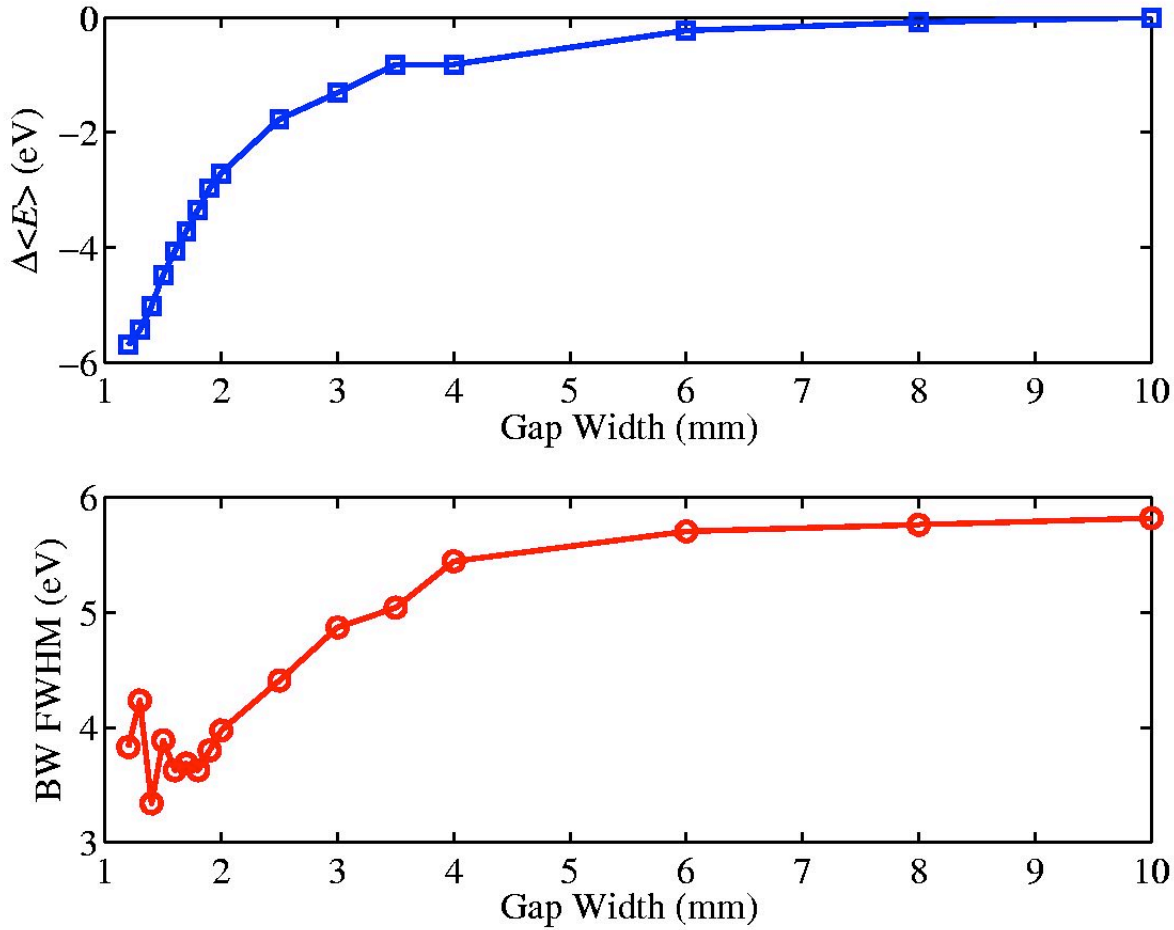
(A. Novokhatski, M. Guetg)

For the beam passing by a single dechirper plate: the average wake energy loss $<U_w>$ (left) and transverse kick $<y_w'>$ (right) *vs*. beam offset from plate, *b,* as measured (plotting symbols) and according to theory (red curve). For the fit, the measured points were shifted in *b* by −126 μm and −135 μm, respectively

- Absolute values of $<U_w>$, $<y_w'>$, *b* not known; constant offsets were fit for

# Translates directly to measured X-ray spectra

From SXR spectrometer @ 870 eV



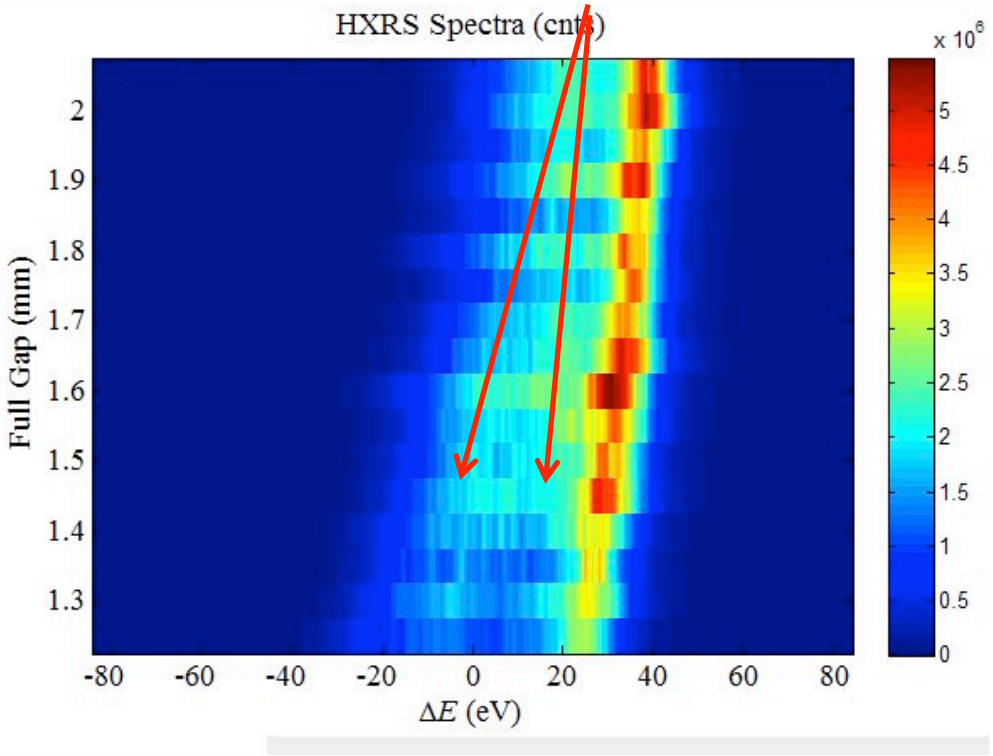

Near nominal setting ($g$= 1.4 mm) does not degrade FEL performance (T. Maxwell)

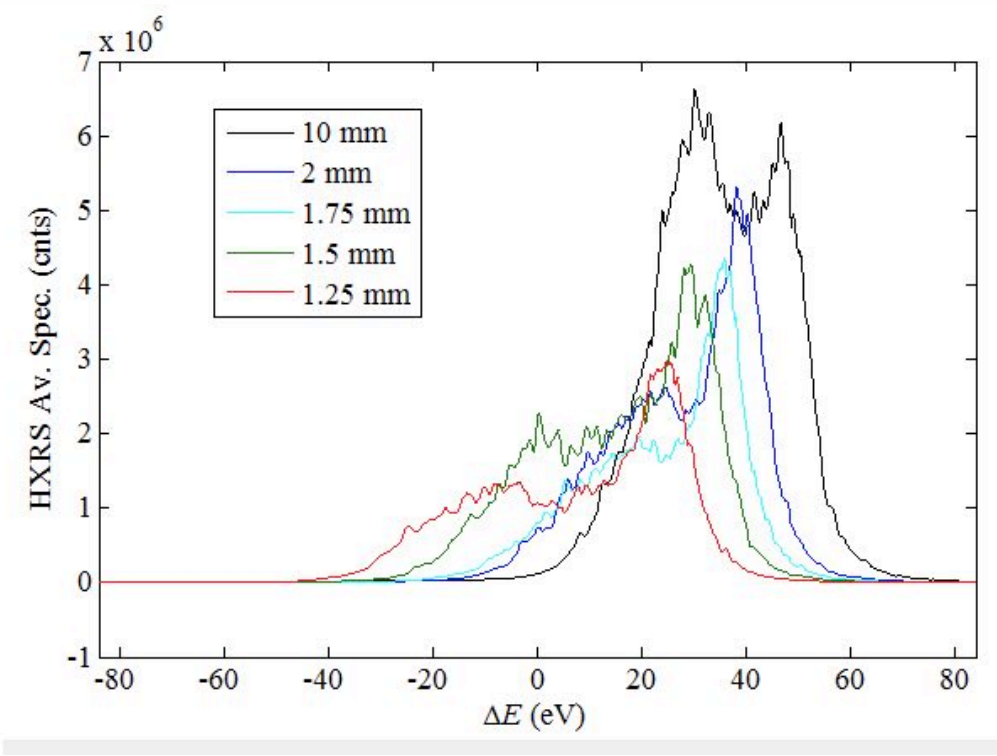
# Adding Chirped Hard X-ray Bandwidth

Just as effective at high energy:

Observe center downshift / BW increase on FEE HXRS

Can increase chirp for over-compressed bunch—desirable for some experiments

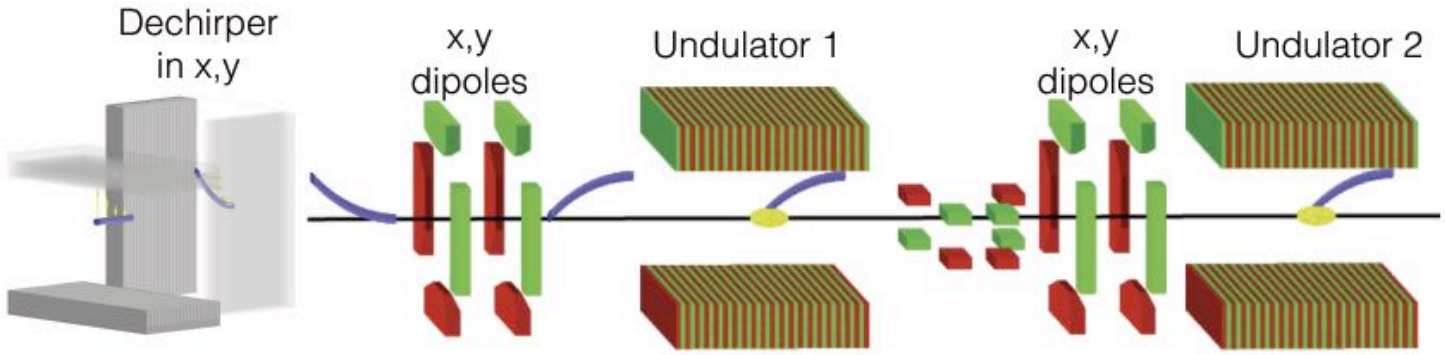


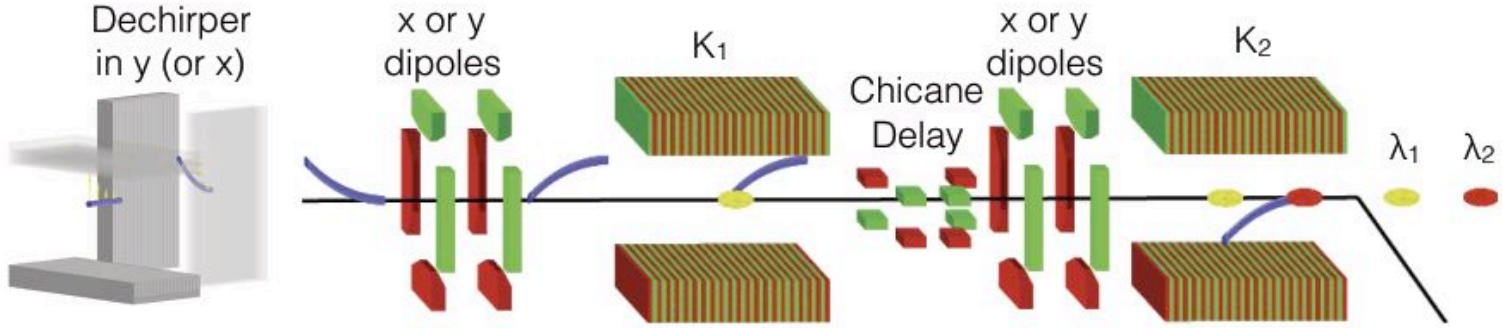

(T. Maxwell)

# Dechirper as a fast passive kicker: experimental uses

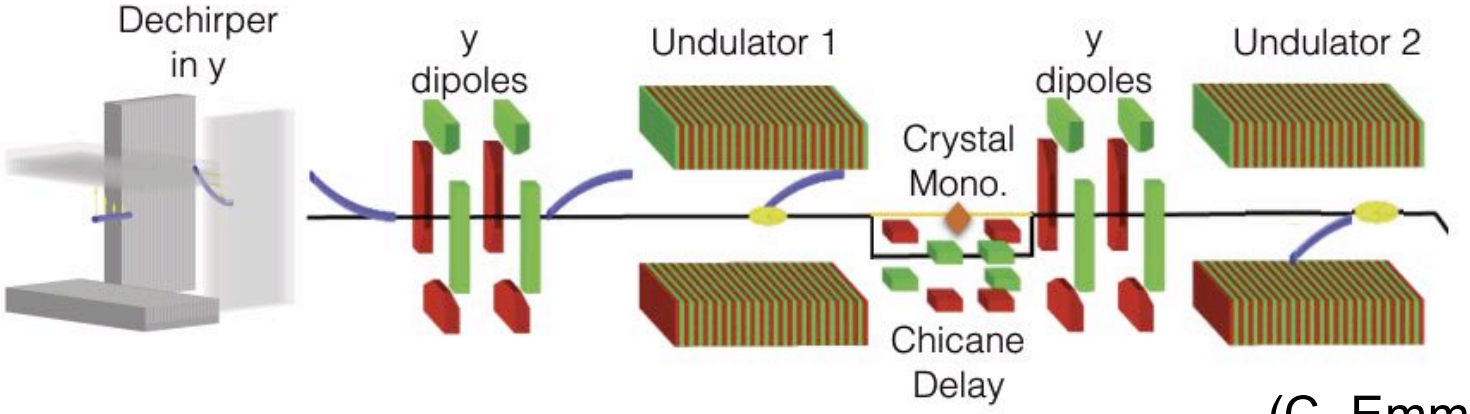
1) Fresh slice SASE for control of pulse duration




2) Two-color fresh slice SASE with polarization control

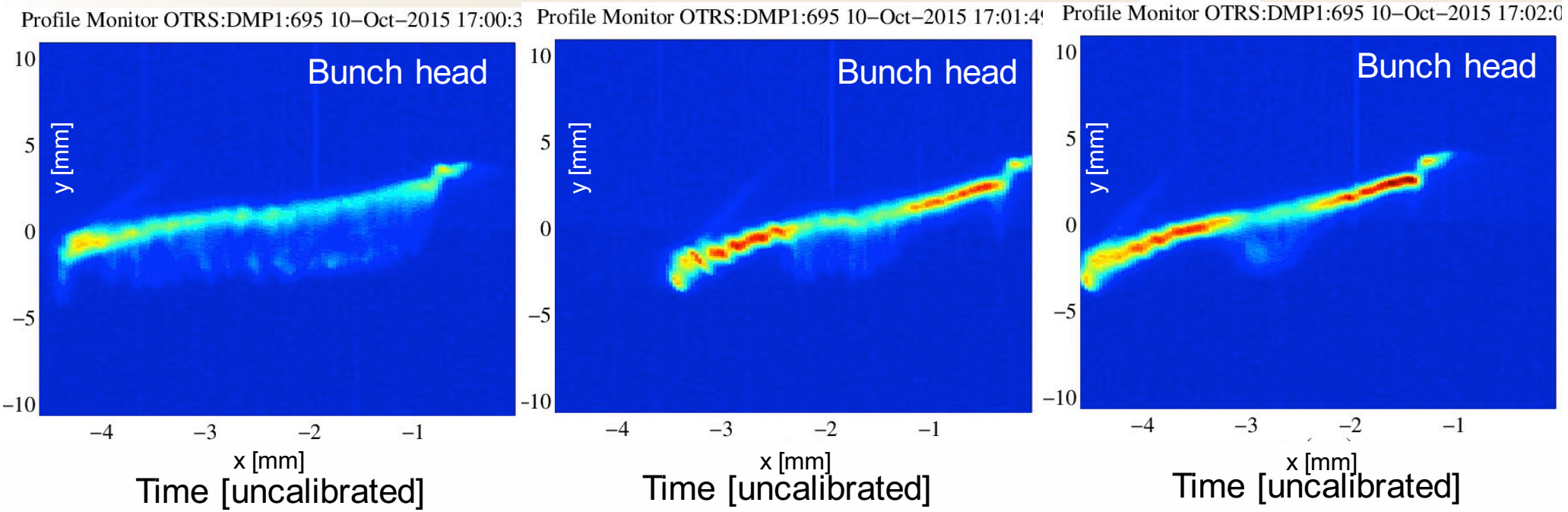



3) Fresh bunch self-seeding with high intensity short seeded pulses




(C. Emma)

# First evidence of lasing suppression with the dechirper 10 October 2015




- Larger kick was given by closing more the gap (instead of changing the structure offset), evidently the beam was travelling slightly off-axis from the structure
- Trajectory feedbacks keep the center of mass of the electron beam on the straight trajectory
- Larger kicks yield a shorter lasing slice

(A. Lutman)

# Fresh-slice double-pulses:
# Two color scheme, with color separation and tail lasing first

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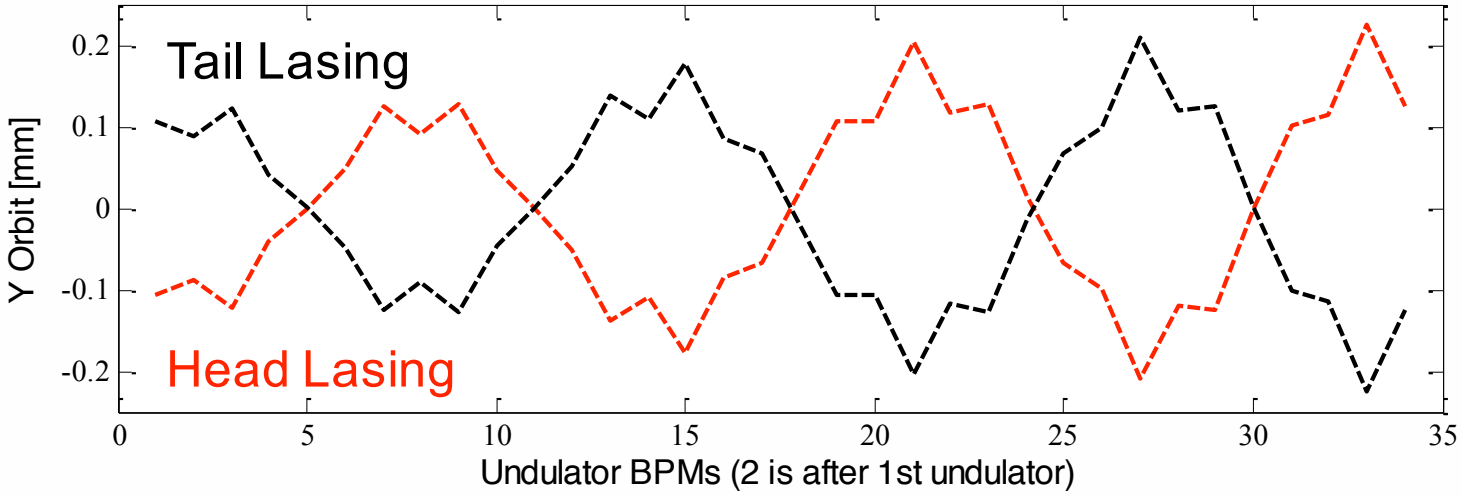
| Dechirper Configuration | Gap | Offset |
|---|---|---|
| Vertical | 3.5 mm | 0.8 mm |
| Horizontal | OUT | / |

| Undulator Configuration | Status | K value |
|---|---|---|
| 1-8 | IN | K~3.455, Strong Saturation taper from Und #6 |
| 10-25 | OUT | / |
| 26-33 | IN | K~3.505 Variable Taper (Regular/Reverse) |




(A. Lutman)

# Fresh-slice double-pulses:
# Two color scheme, with color separation and tail lasing first

(A. Lutman)

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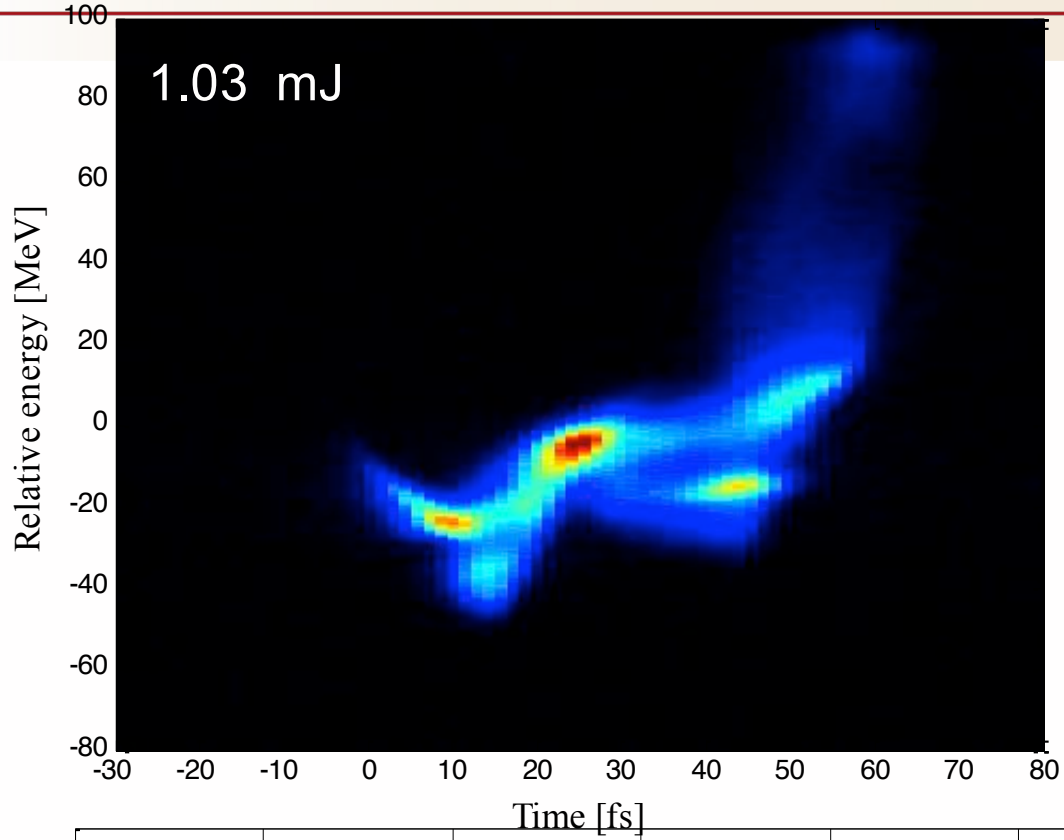
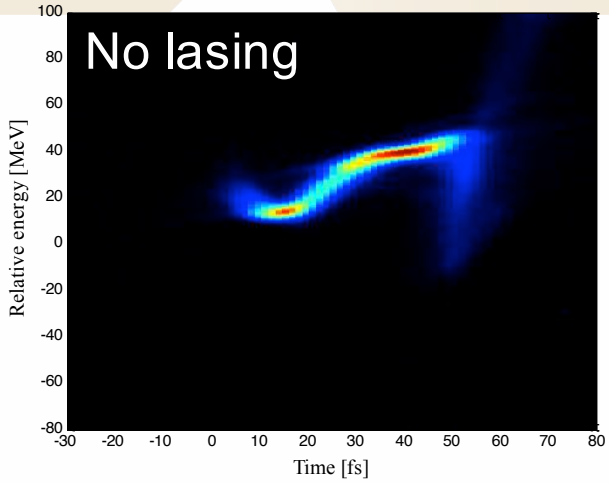
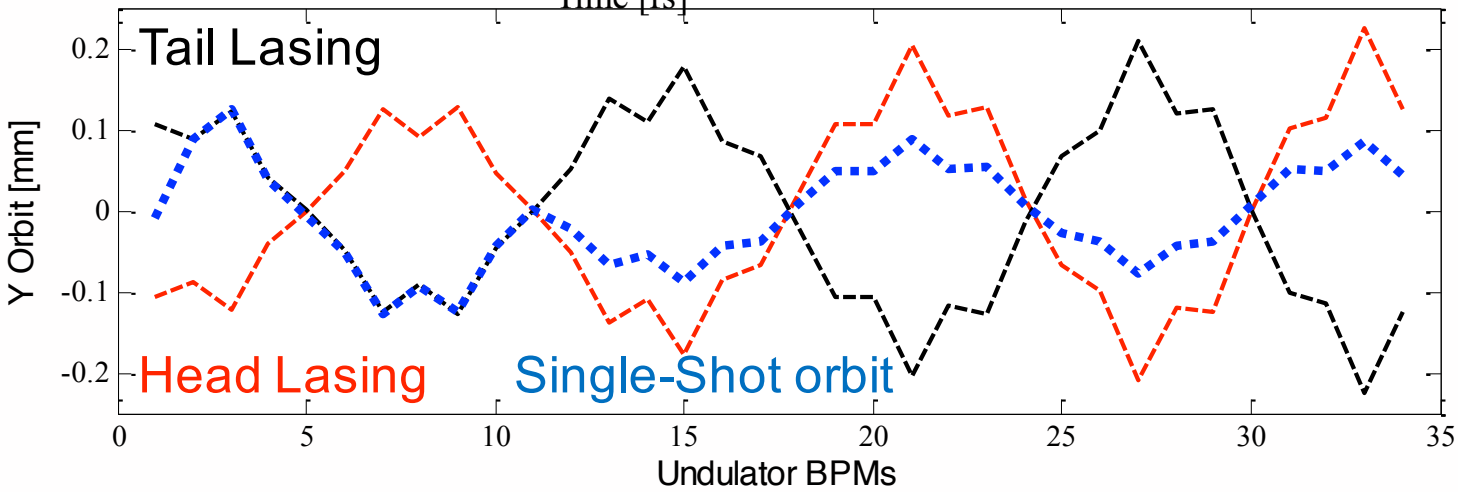



FEL Statistics:
746 +/- 125 μJ




Regular Taper
Delta in circular polarization

first color: ~250 μJ
second color: ~ 500 μJ

first color: ~8 fs
second color: ~ 15 fs

# Conclusions

- Large-scale dechirper system has been realized for high-energy (GeV) short bunch (10s of um) bandwidth control at the LCLS

It is a precision instrument fully integrated into the LCLS. The vanes are straight and settings are reproducible to 25 um over 2 m

- Wake measurements—energy loss, chirp, transverse kick—agree well with theory; also for single plate
- The fast kicker capability of the dechirper is being applied for two-color and self-seeding applications; delivering improved two-color radiation to users
- An improved dechirper unit (horizontal part only) is being designed and built by RadiaBeam for use in LCLS-II for use as fast kicker (not needed as dechirper). With 1 MHz bunch rate cooling is needed. The Joule heating has been studied, and the cooling requirements are not severe (~200 W/m at max)

# Some of the Contributors