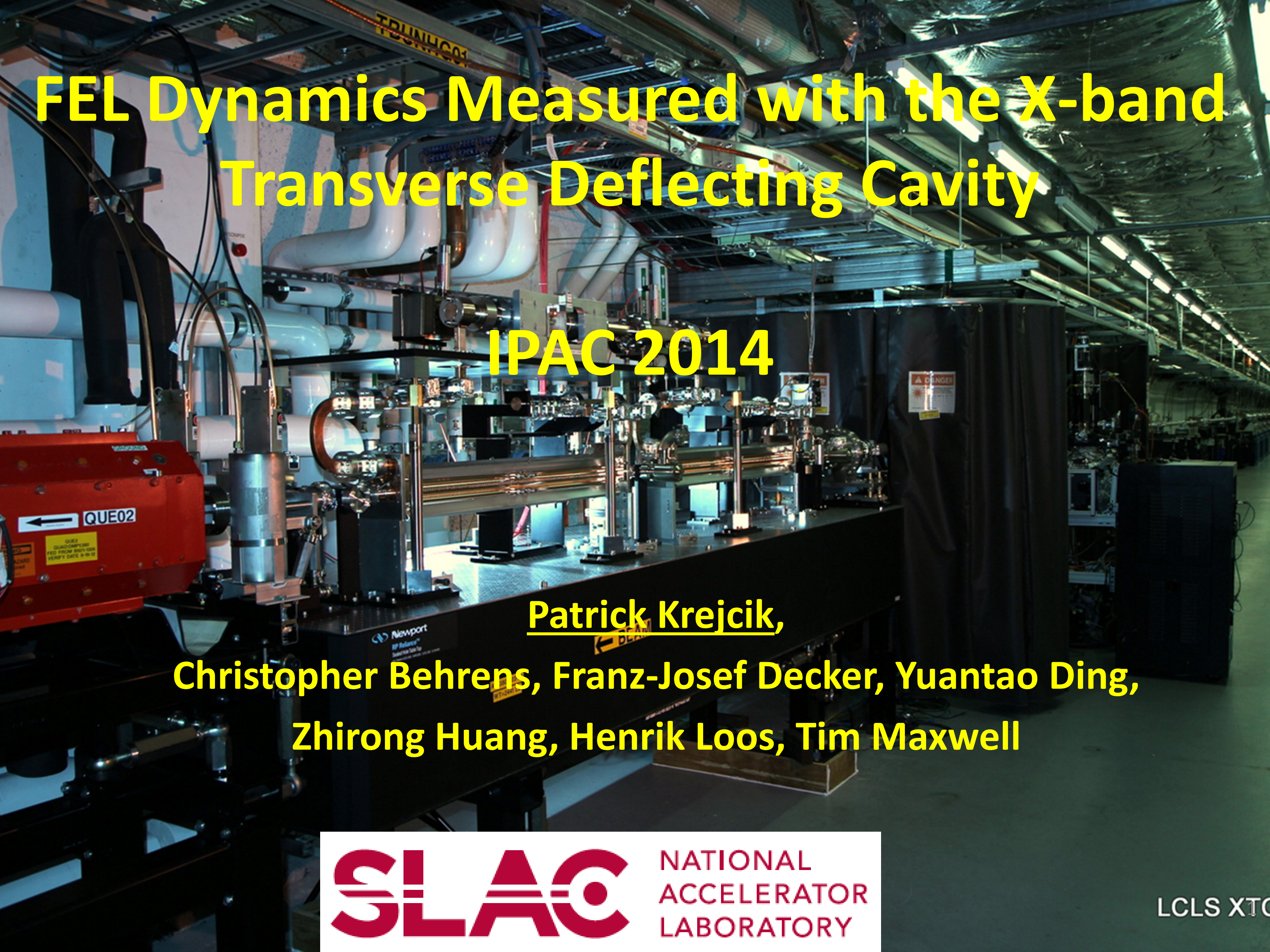


FEL Dynamics Measured with the X-band Transverse Deflecting Cavity

IPAC 2014

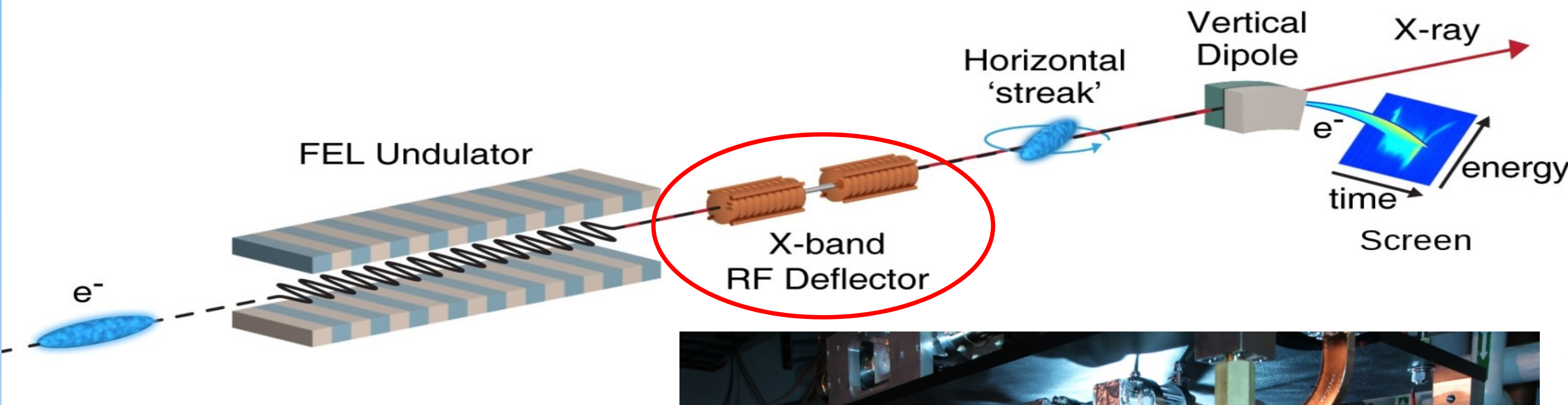
Patrick Krejcik,

Christopher Behrens, Franz-Josef Decker, Yuantao Ding,

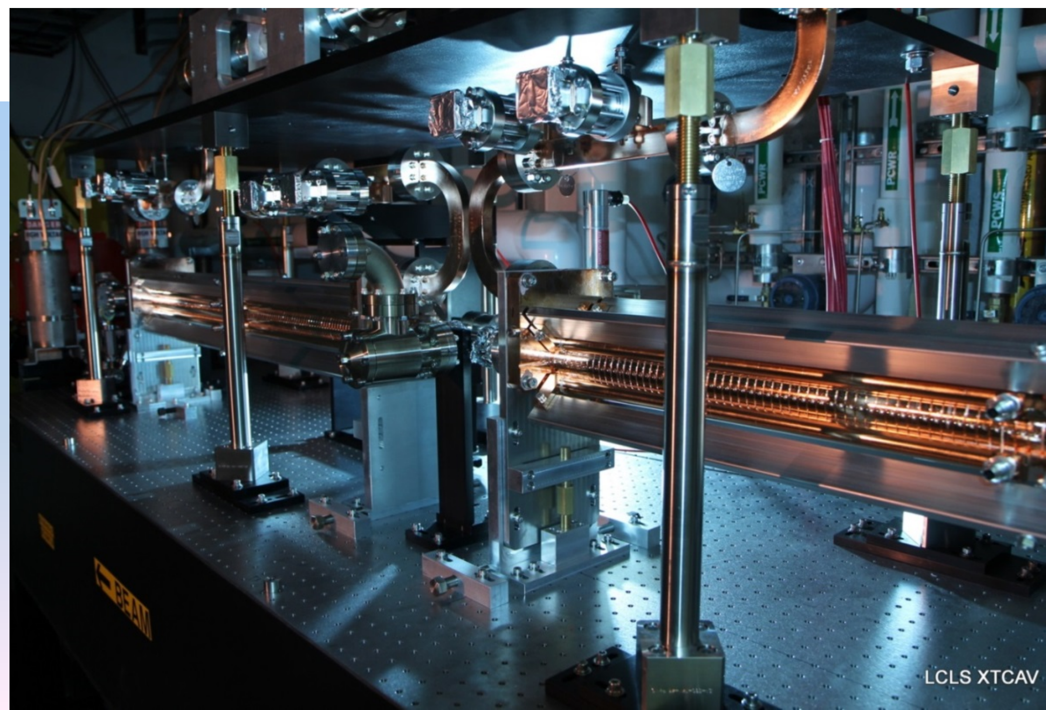
Zhirong Huang, Henrik Loos, Tim Maxwell

SLAC NATIONAL ACCELERATOR LABORATORY

- Image the temporal profile of the beam by streaking with an <u>RF deflecting cavity</u> and measure time-dependent energy



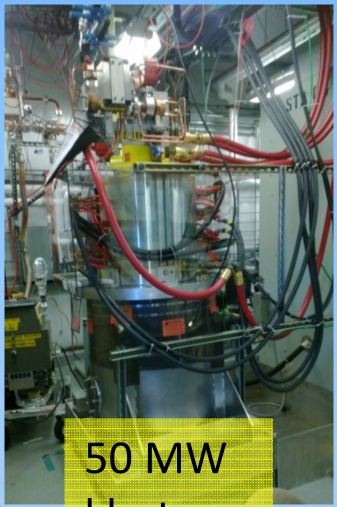
- RF deflecting structure is a well-established method to measure longitudinal phase space, so what is different here …



XTCAV offers 3 new Important Features

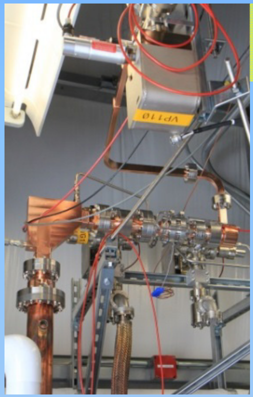
- Operates at 11.424 GHz and gives 8 times better temporal resolution
  - Factor 4 from shorter wavelength and twice the voltage gradient
- Located downstream of the undulator and cannot interfere with photon operation
  - Continuous <u>noninvasive</u> operation at 120 Hz
- Reconstruct the temporal profile of the x-ray beam from the energy loss profile of the electrons
  - Compare the FEL off and FEL on images

Installation Details - Operating since May 2013

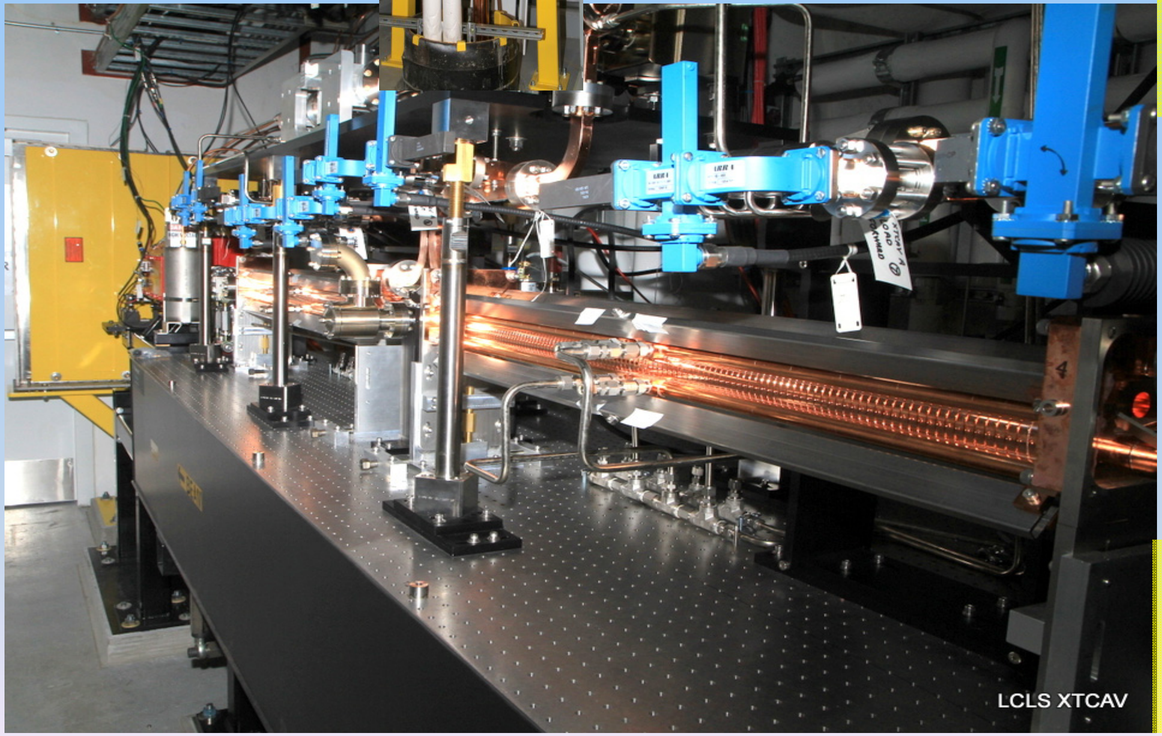


50 MW klystron

430 kV modulator



waveguide

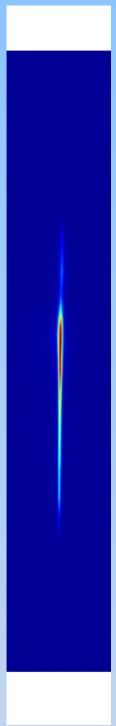


Controls:
PAC, PADS, MKSU

LLRF Drive:
TWTA, klystron
Mag. Suppl.

Measurement examples: 4.7GeV, 150pC (1keV)

Three Images at the e-dump spectrometer screen

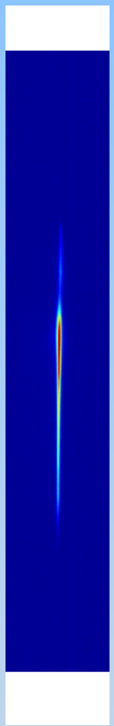


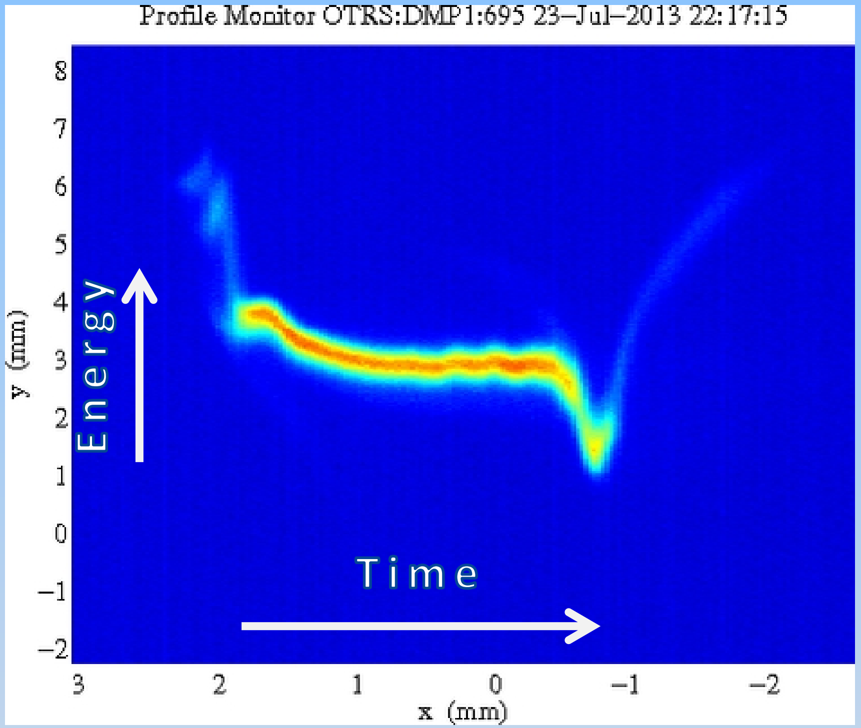
Vertical dispersion reveals energy distribution of the electron bunch

XTCAV
Off

Measurement examples: 4.7GeV, 150pC (1keV)

Three Images at the e-dump spectrometer screen





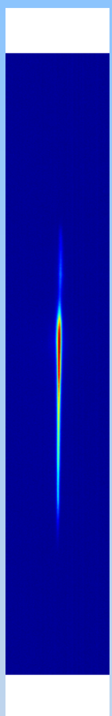
Vertical dispersion is now resolved in time showing energy distribution along the length of the bunch

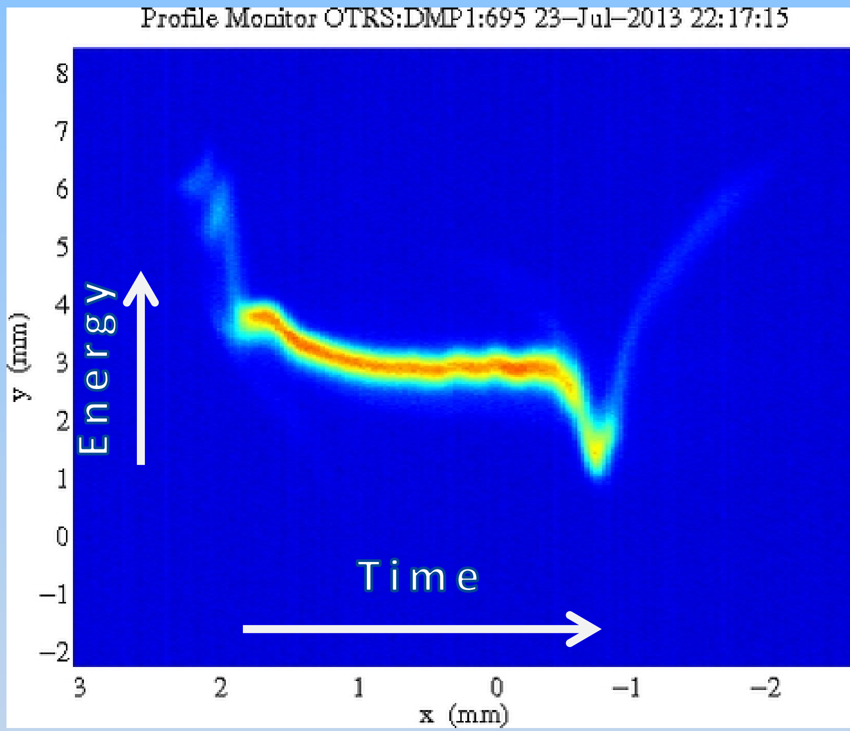
XTCAV Off

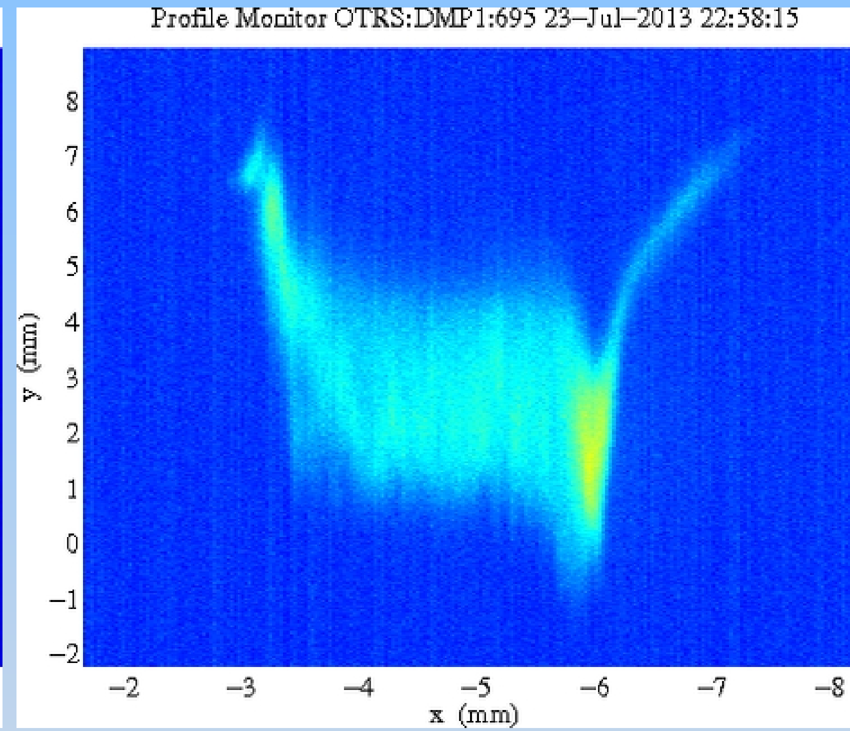
XTCAV On
FEL Supressed
(baseline)

Measurement examples: 4.7GeV, 150pC (1keV)

Three Images at the e-dump spectrometer screen





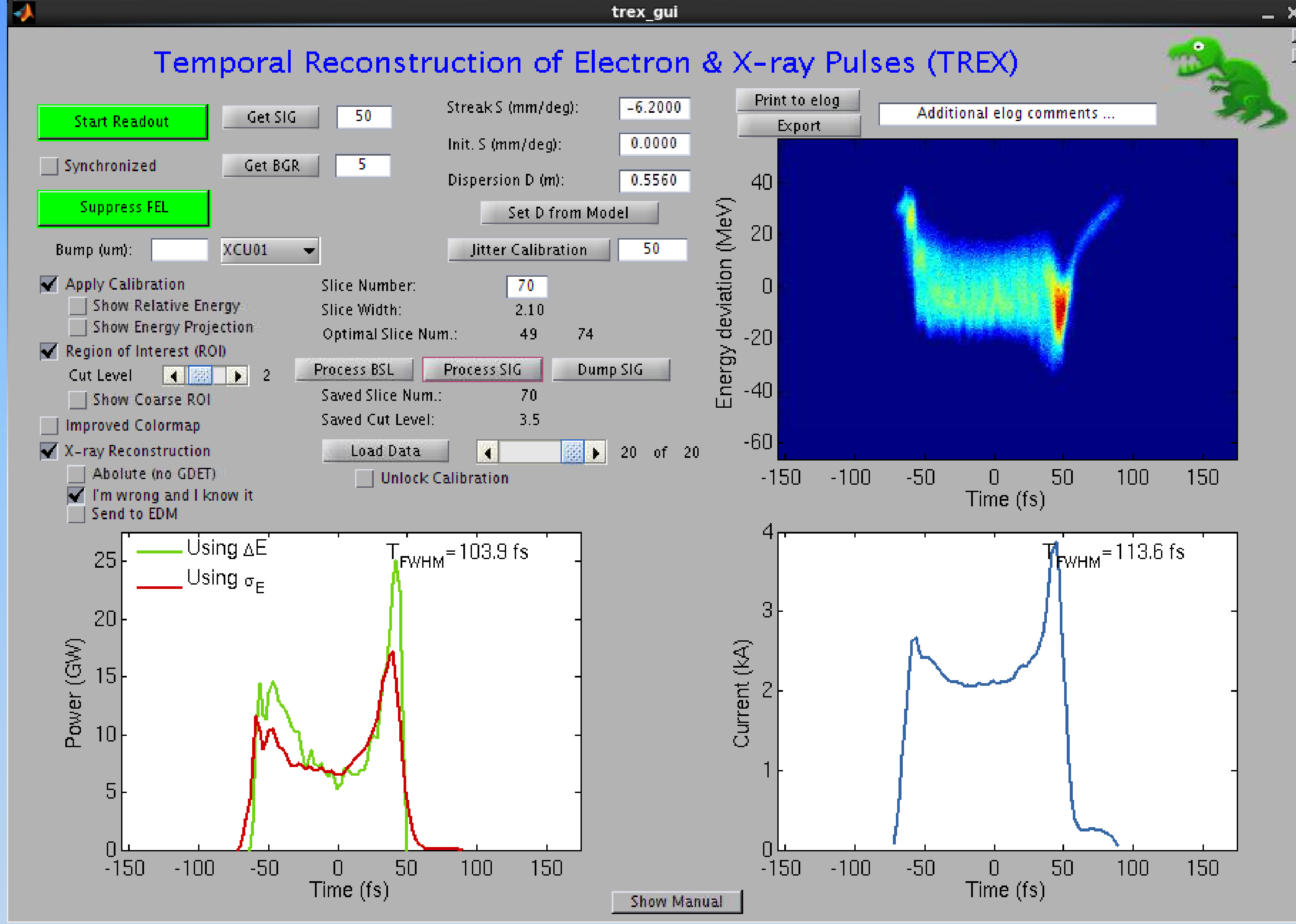


XTCAV
Off

XTCAV On
FEL Supressed
(baseline)

XTCAV On
FEL On
~1mJ FEL pulse energy
Transfer of energy to photons causes e- energy loss and spread

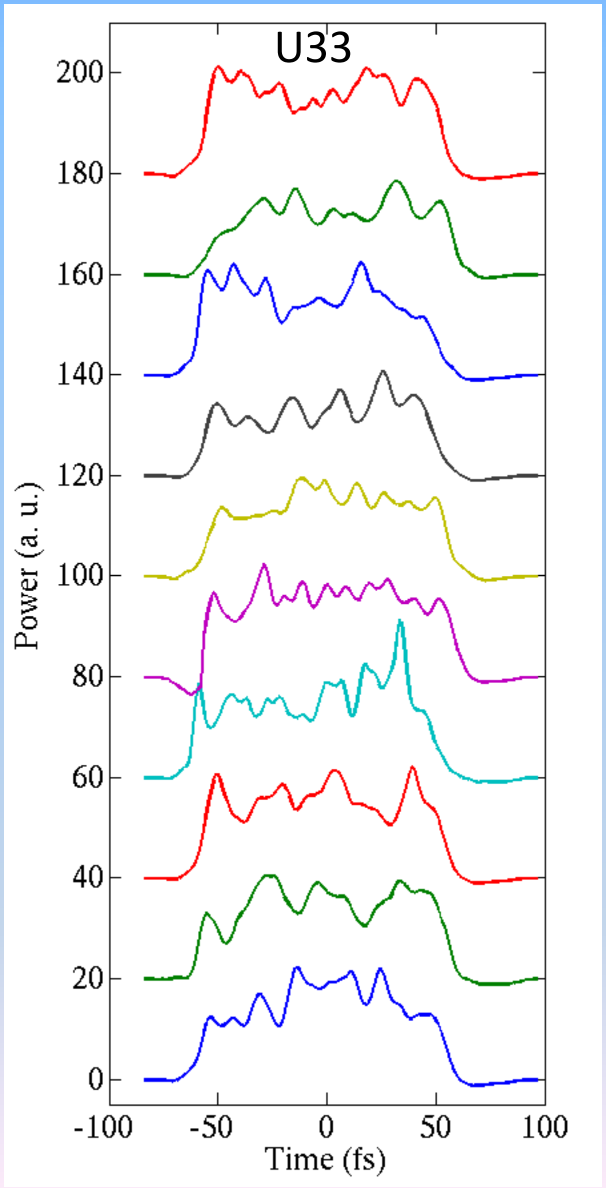
Single shot data processing

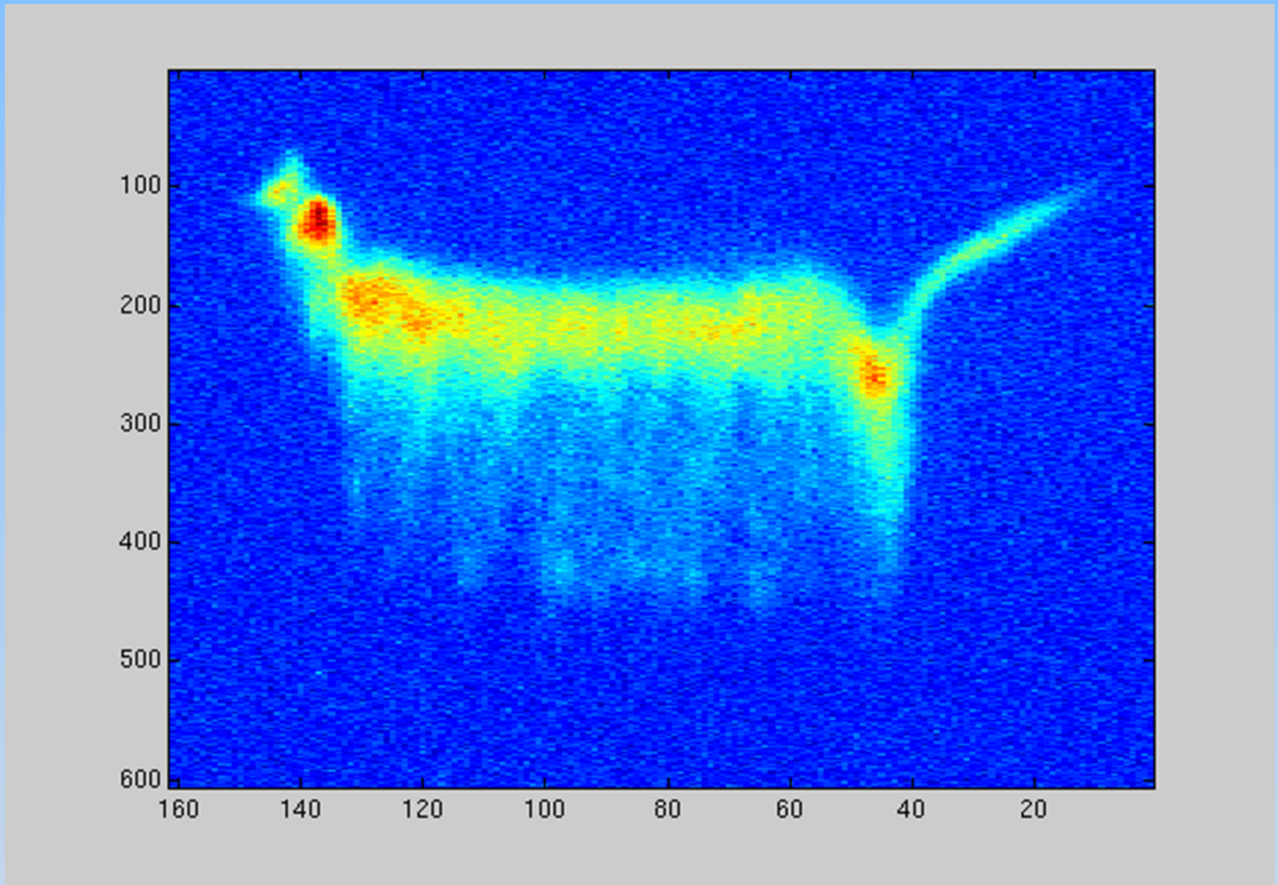


(successful DESY collaboration- C. Behrens)

- Calibration;
  - Record baseline images (FEL-off);
  - Image processing, slicing and averaging baseline data;
- Take single-short image (FEL-on) and other beam parameters;
  - Reconstruct electron and x-ray temporal profile from peak current in each slice and energy change in each slice

10 consecutive shots (1keV, 150pC)

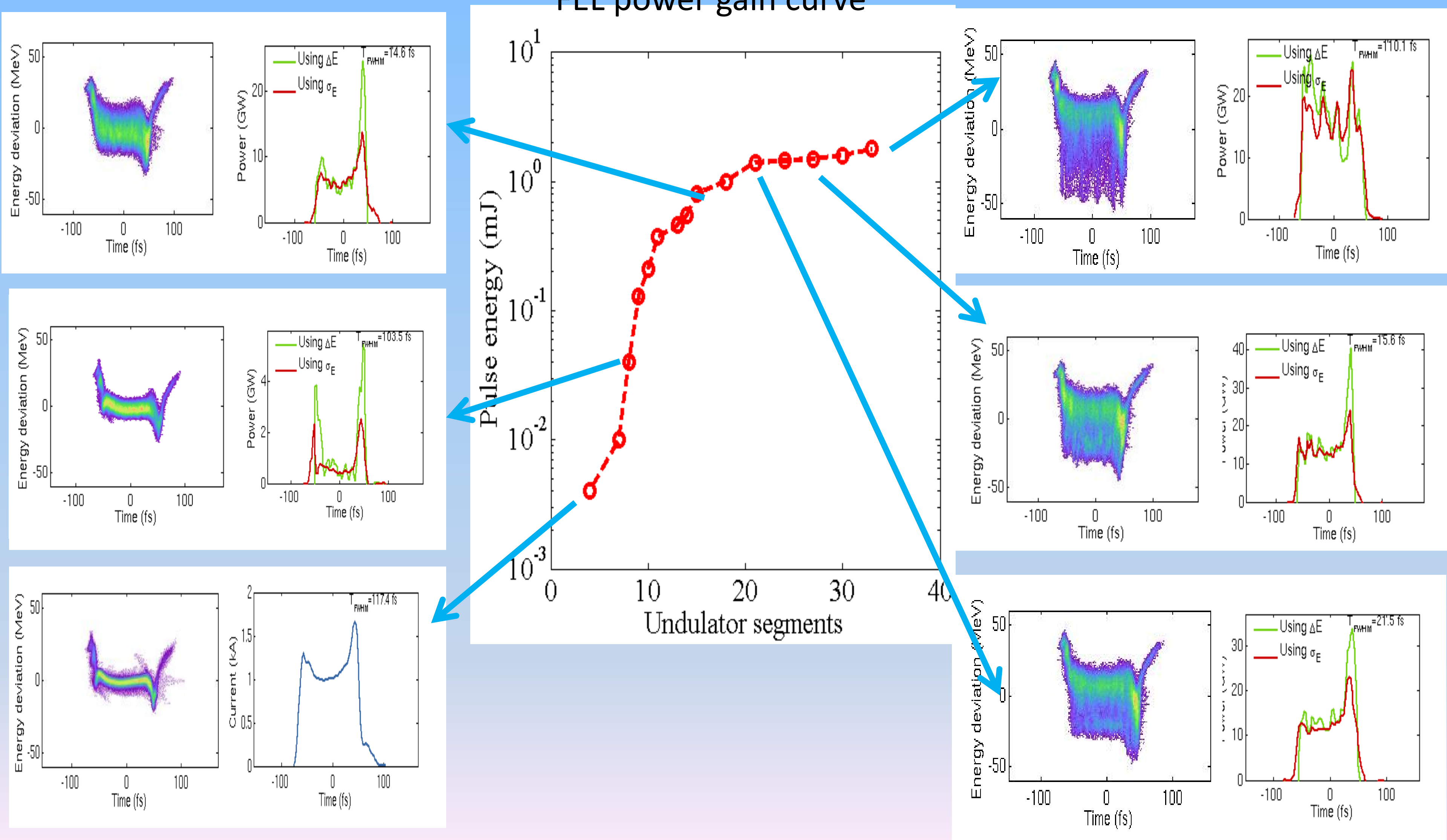




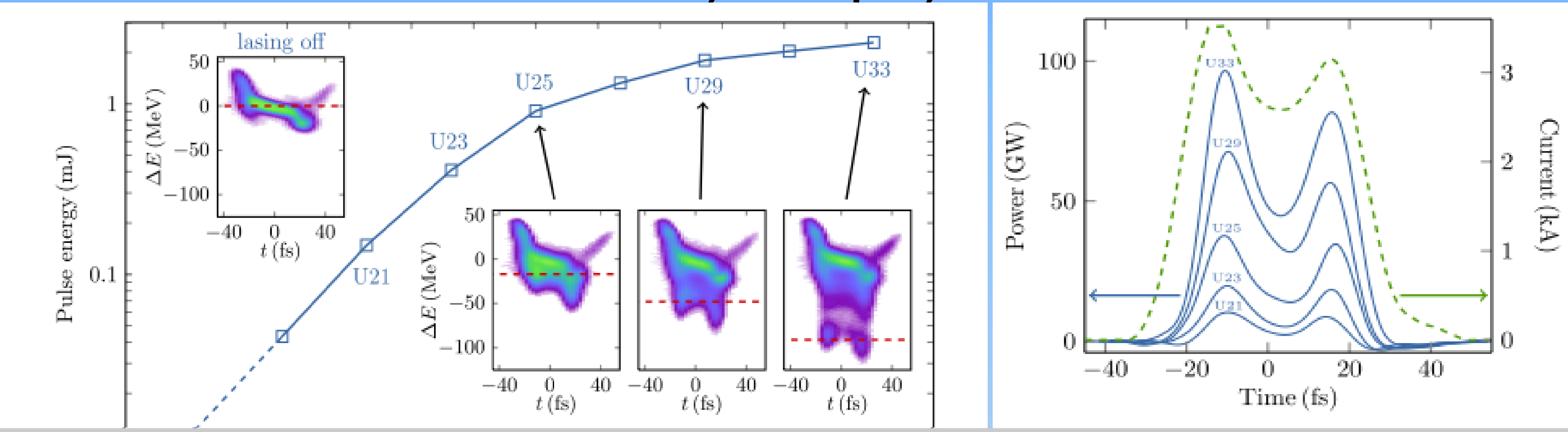
It is important to analyze every shot at 120 Hz.

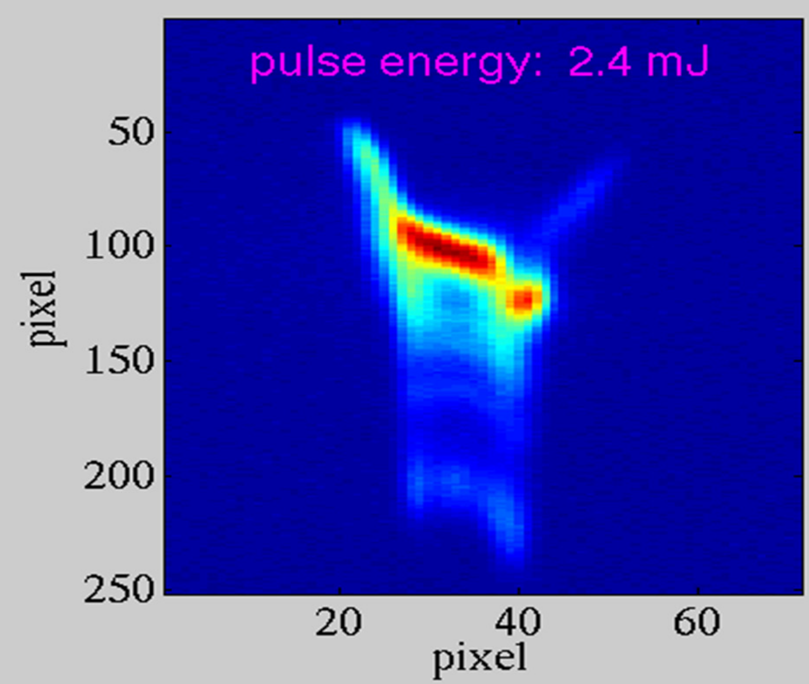
Evolution of SASE along the Gain Curve at 4.7GeV, 150pC (1keV)

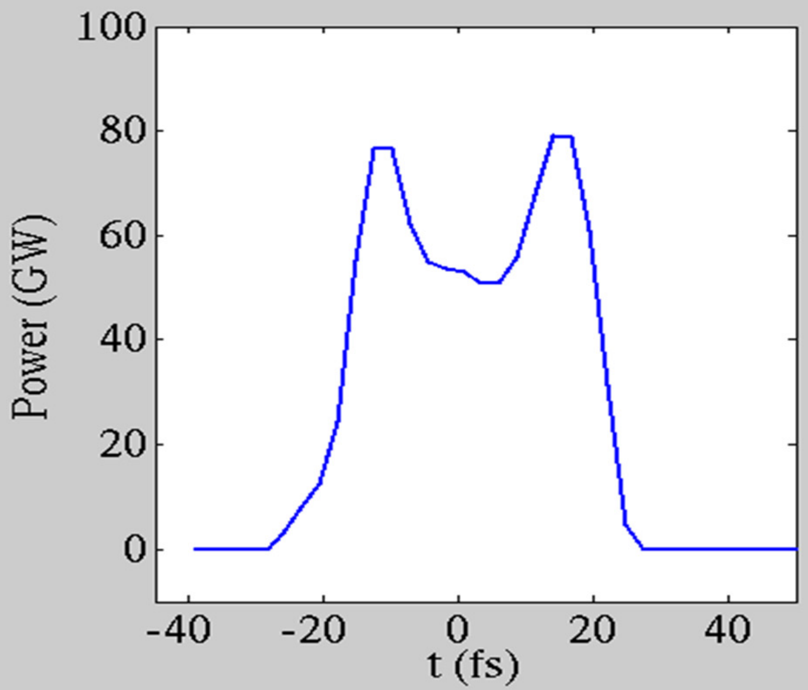
FEL power gain curve



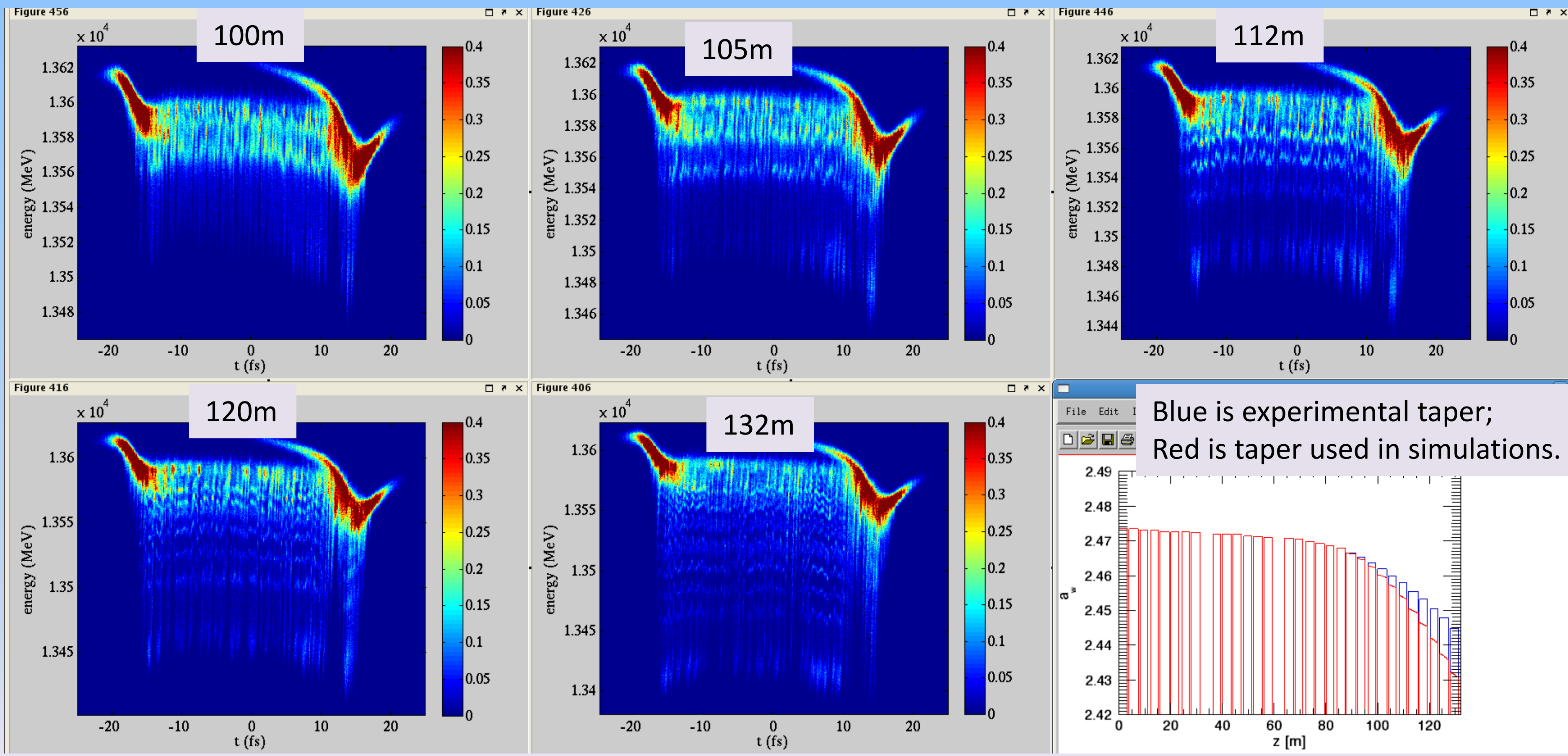
Taper optimization and resonant trapping at 15.2GeV, 150pC, 10.2keV







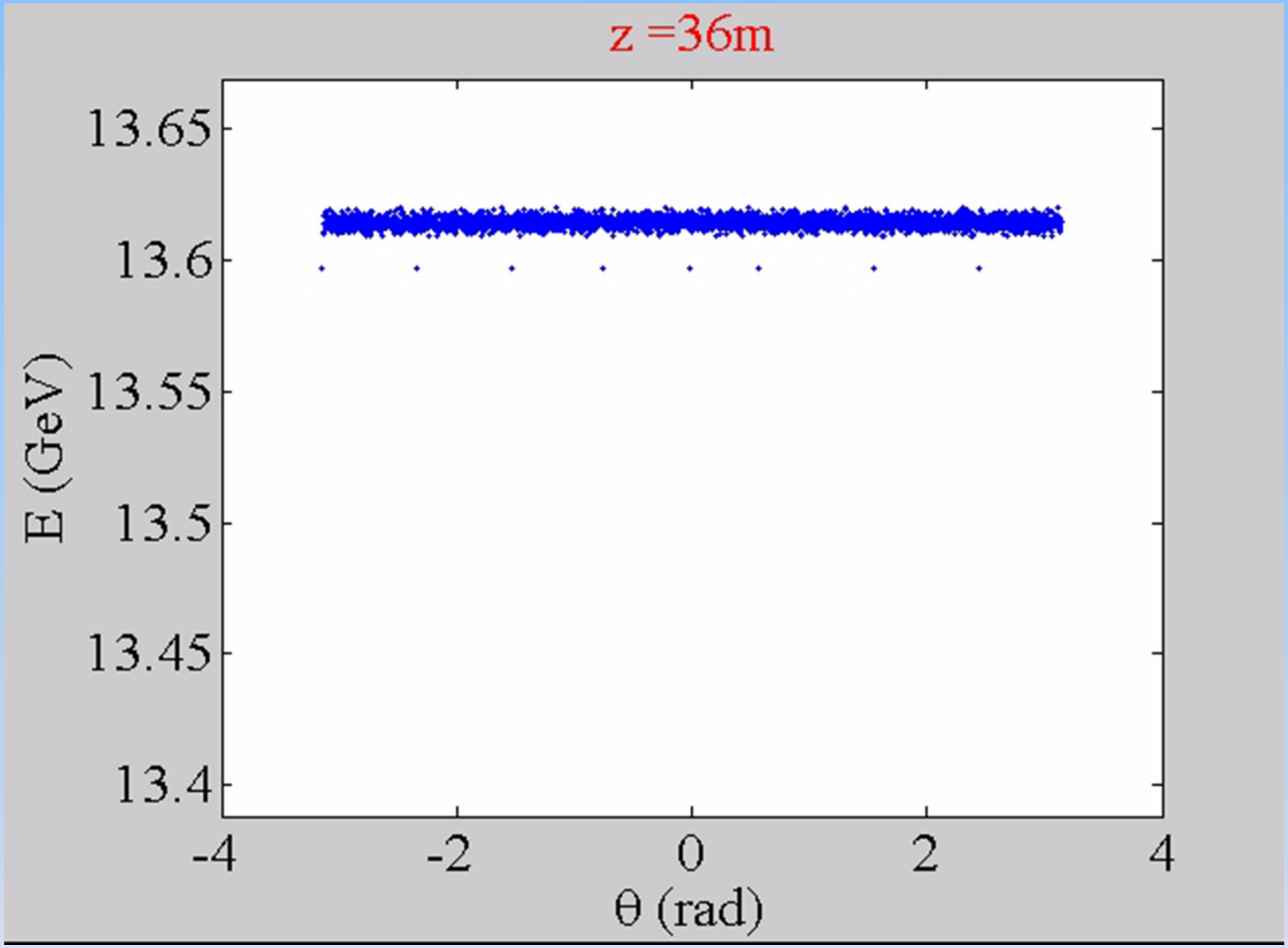
HXR 150pC, 8keV. simulations



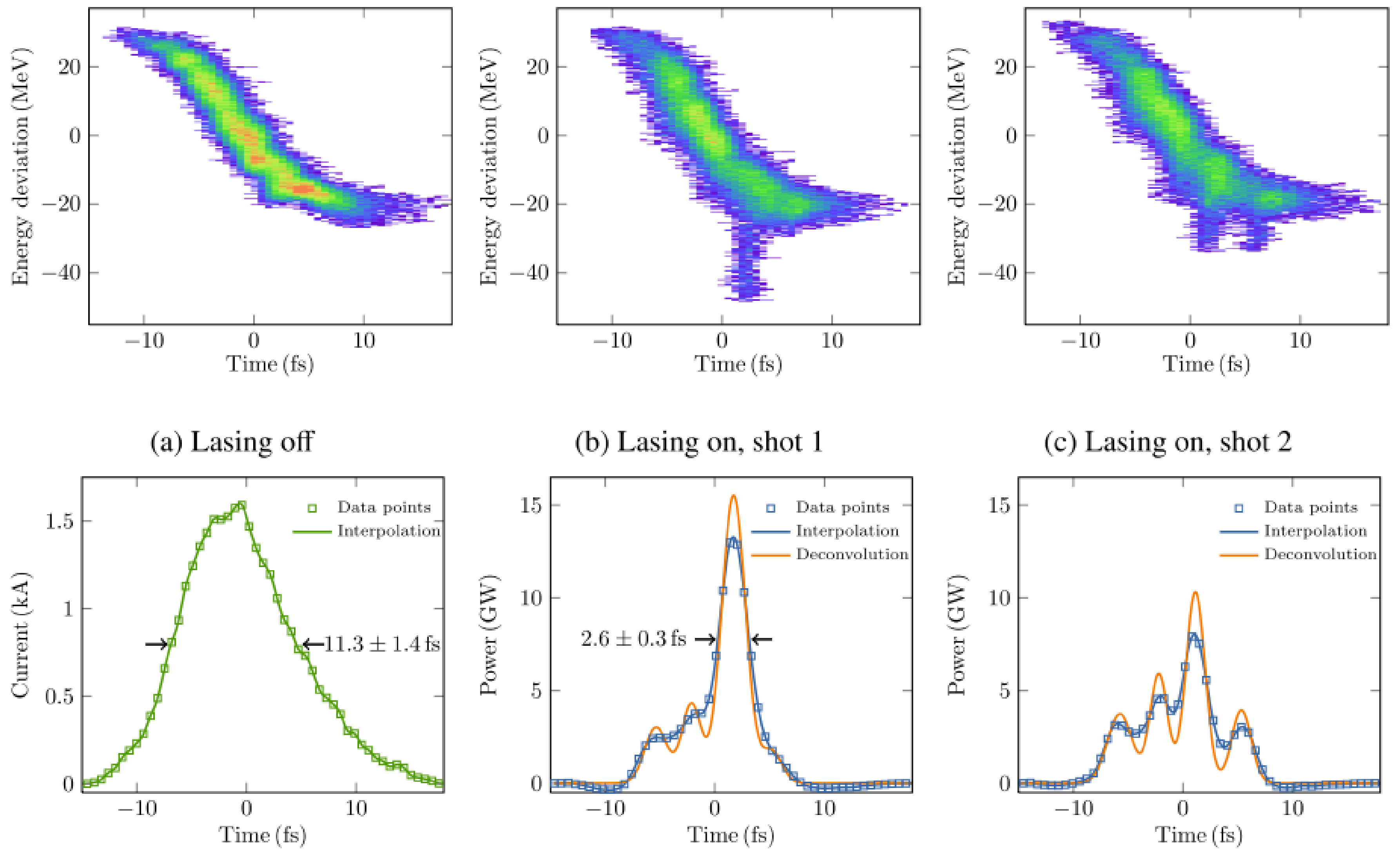
Genesis particle simulation of electron trapping in the FEL – Y. Ding

Energy versus Phase
for

8 keV Hard X-Rays
150pC bunch charge



Short pulse -- 20pC, 1keV examples



(a) Lasing off

(b) Lasing on, shot 1

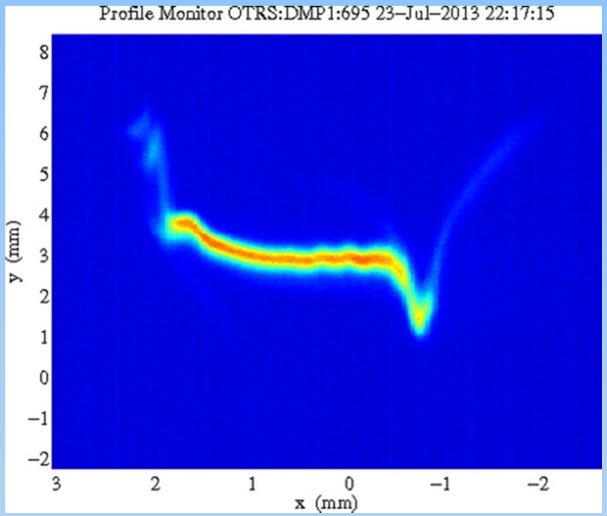
(c) Lasing on, shot 2

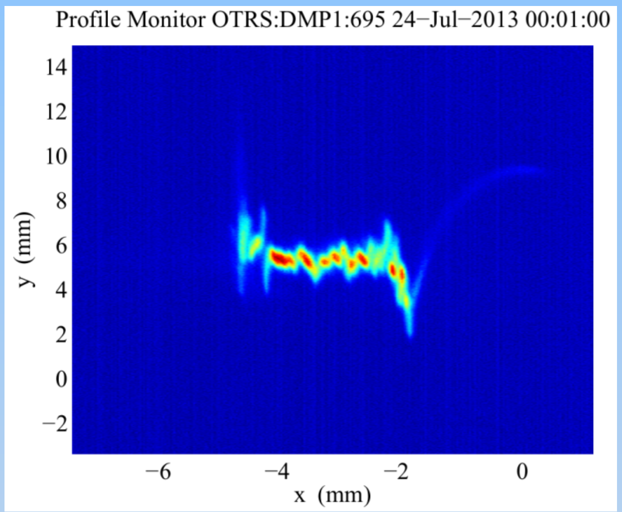
(d) Electron current

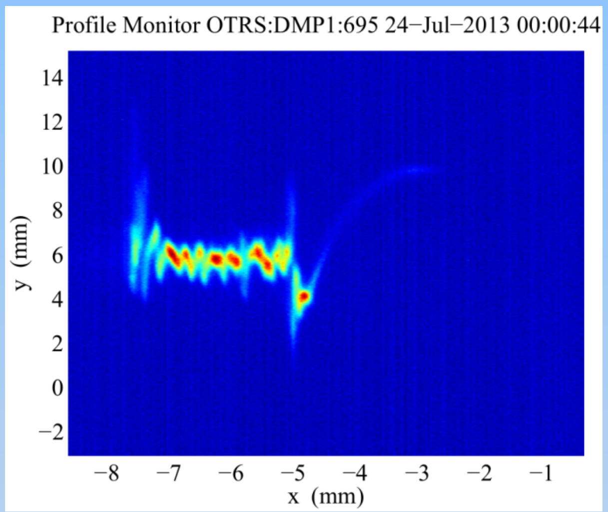
(e) X-ray power, shot 1

(f) X-ray power, shot 2

Direct Observation of Microbunching Instability







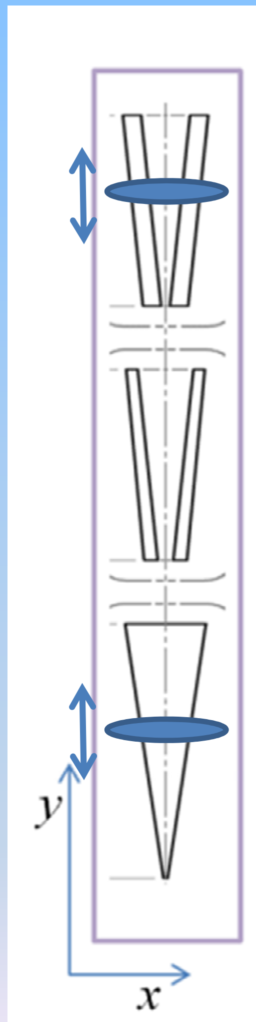
Decreasing gain on the Laser Heater

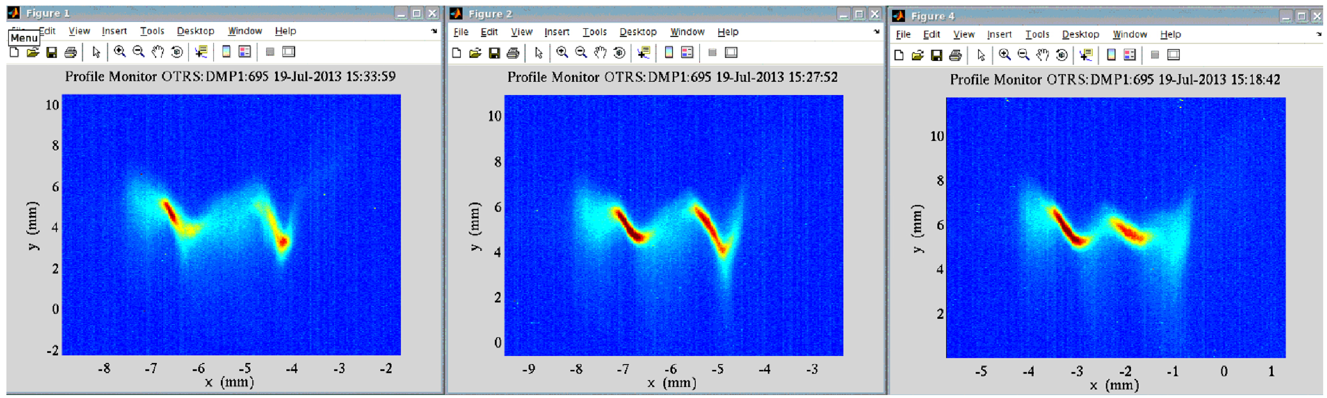
Slotted-foil examples (lasing off)

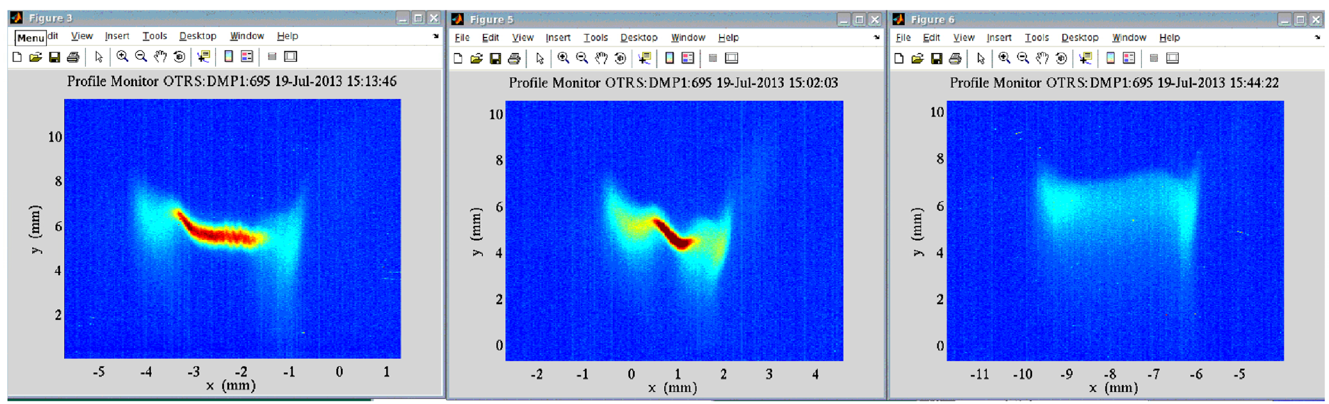
shows clearly the unspoiled beam region

Double Slit

Single Slit

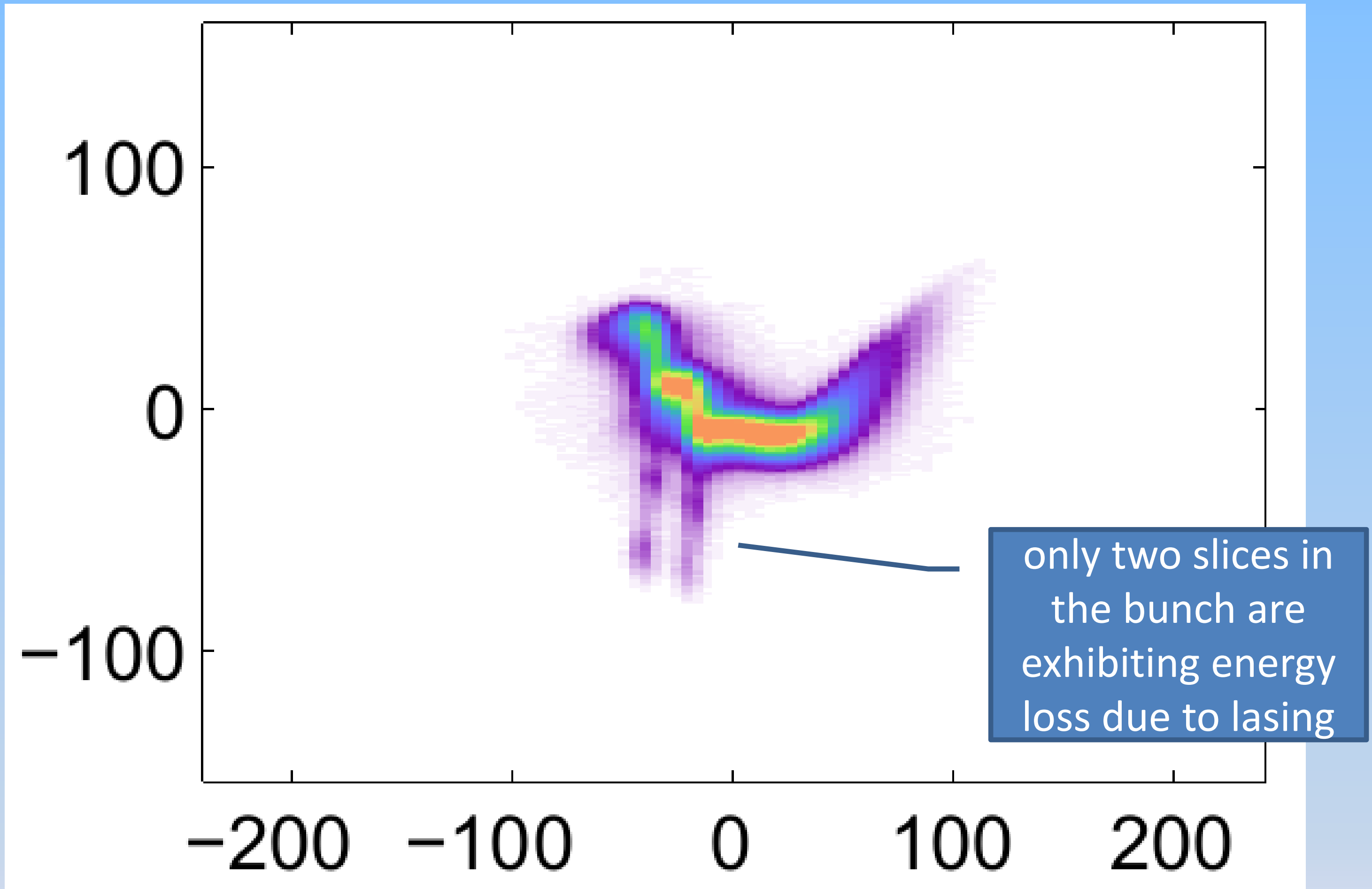






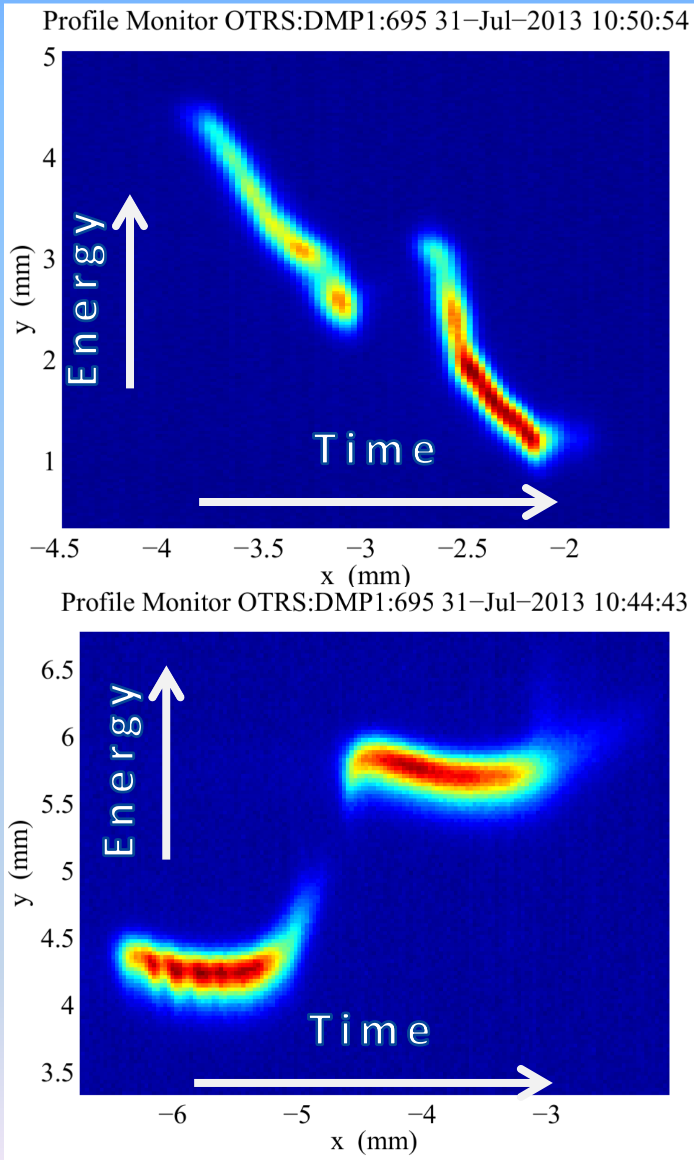
4.7GeV, 150 pC

Lasing with double-slotted foil



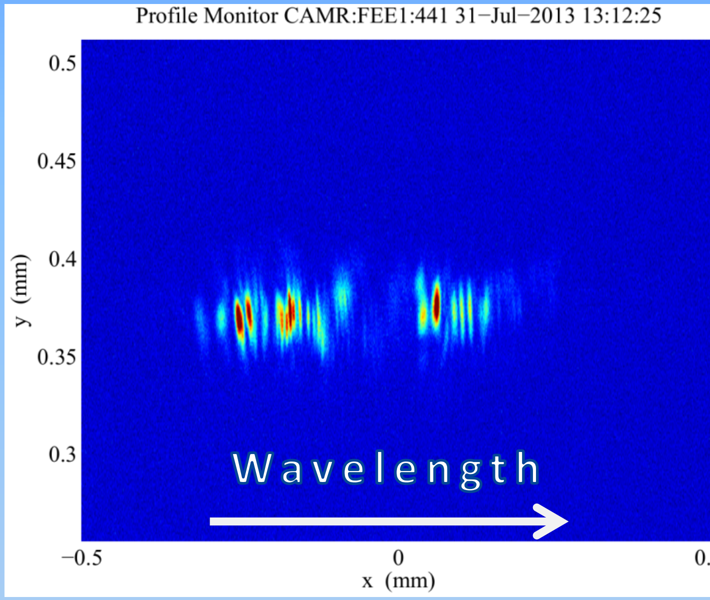
XTCAV Diagnostics During Pulse Stacking Experiments

- Laser pulses are stacked at the LCLS Photo-Injector to produce multiple electron bunches within one RF bucket
- XTCAV gives clear view of bunch separation and orientation in longitudinal phase space

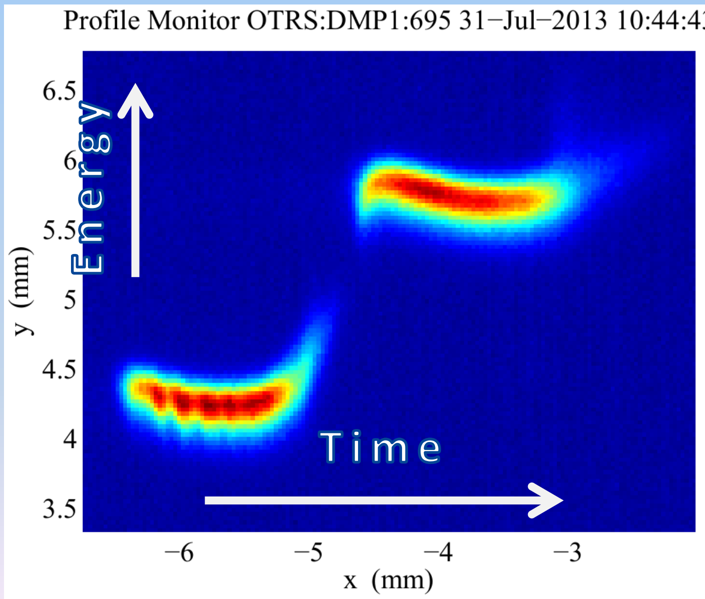


Two Color Experiment with Stacked Bunches
A. Marinelli et al

- Single shot X-ray spectrometer
  - Y. Feng et al



- Single shot XTCAV time resolved image

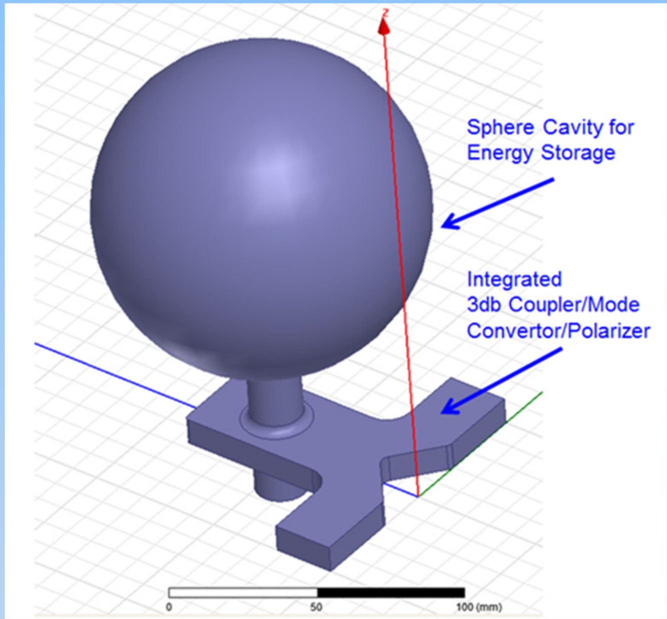


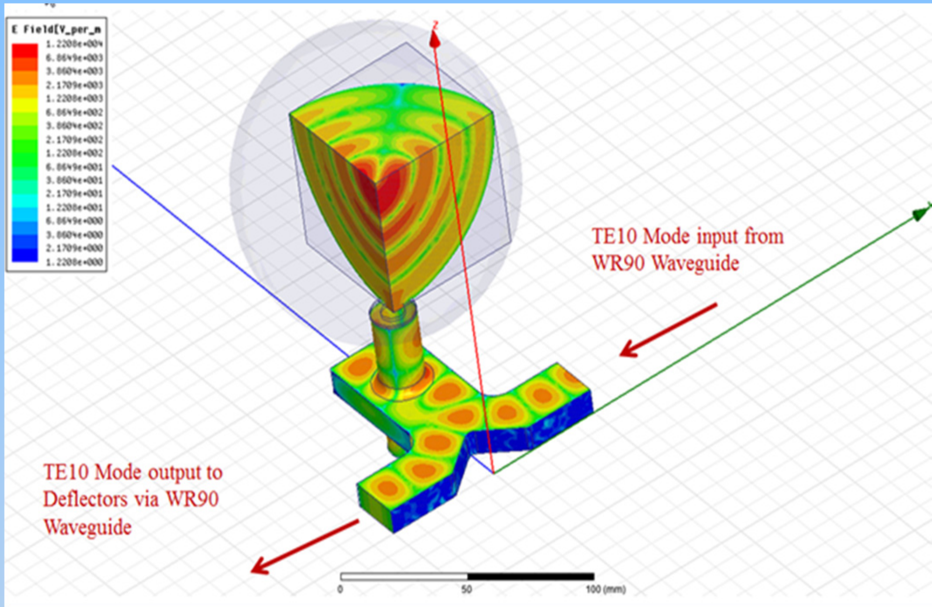
XTCAV System Improvements

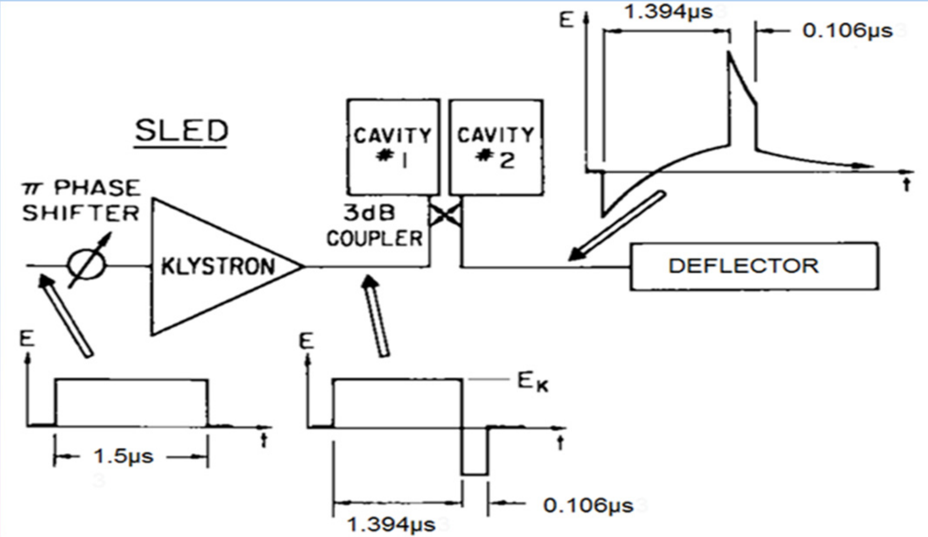
- **120 Hz camera** installed so that images can be captured at full beam rate
  - Raw images are written to photon experiment DAQ in real-time
  - Real time processing of x-ray slice profiles (TREX) is underway
- **Doubling the temporal resolution** by raising the RF power by factor 4 is being proposed

X-SLED RF Pulse Compression

- An elegant new scheme proposed by
  J. Wang, S. Tantawi, X. Chen



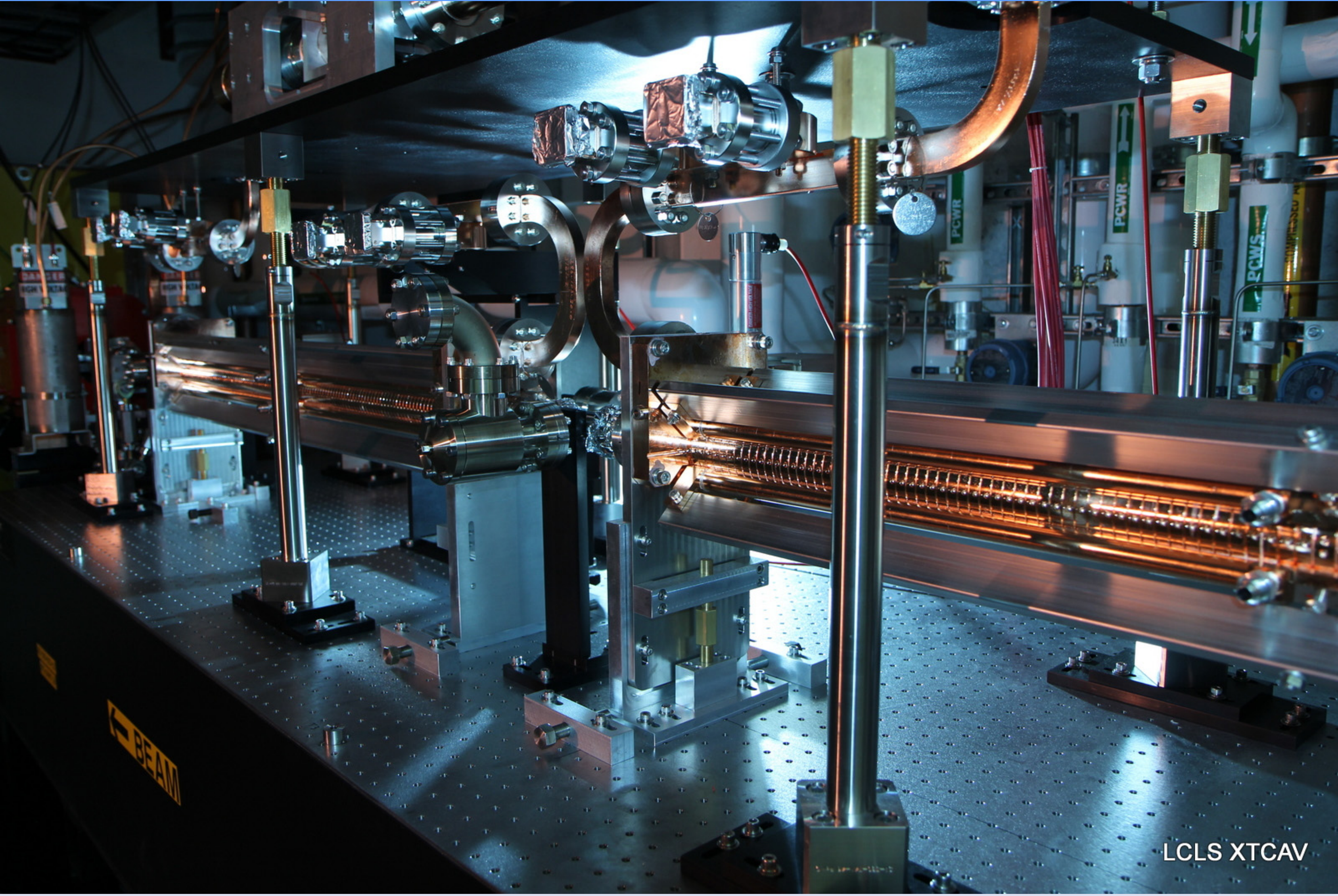




- Peak power increase **x5**

Summary and outlook

- Demonstrated resolution of 0.8 ±0.2 fs
- XTCAV provides non-invasive monitoring of longitudinal phase space at 120 Hz
  - quantitative measurement,
  - absolute calibration
- Directly observed
  - SASE evolution
  - Chirp and bunch compression dynamics
  - Microbunching
  - Slotted foil
  - Multi-bunch, Two-color, Selfseeding …
- Upgrade data acquisition to stream 120 Hz measurements to photon users
- Upgrade RF power for enhanced resolution

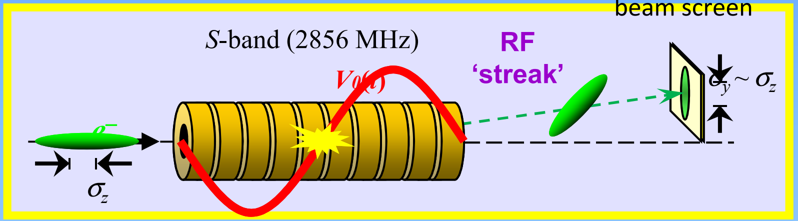


Thanks to the many engineers and physicists at SLAC !

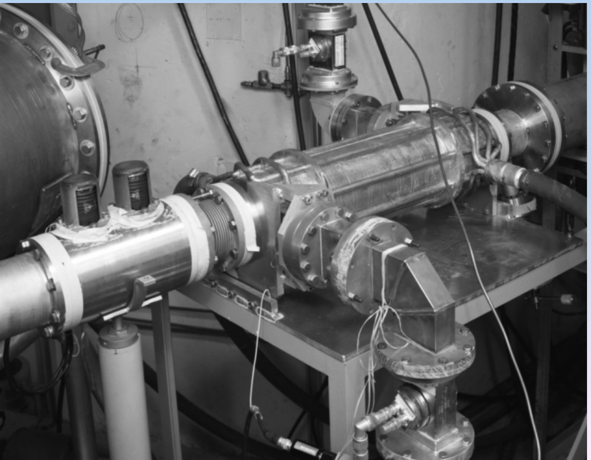
BONUS MATERIAL

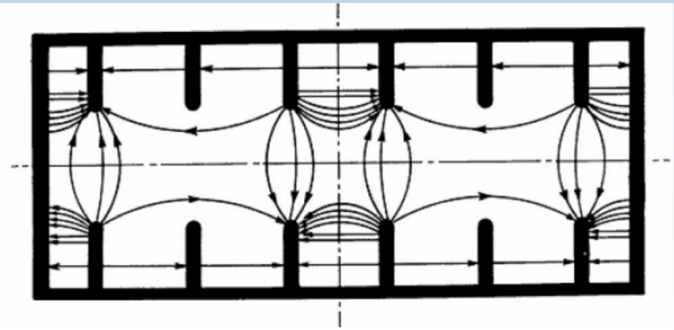
Parameter	Value	Unit
RF frequency	11.424	GHz
Structure type	2π/3 backward wave	
Structure orientation	Horizontal	
Effective structure length	1	m
Total flange-flange length	118.8	cm
Number of structures	2	
Number of regular cells per structure	113	
Aperture 2a	10	mm
Cavity diameter 2b	29.77	mm
Cell length d	8.7475	mm
Quality factor Q	6320	
Kick factor k	2.849×10^{16}	V/C/m/m
Transverse shunt impedance	41.9	MΩ/m
Filling time	106	ns
Attenuation factor	0.62	Neper
Nominal power required at structure input	40	MW
Nominal transverse kick (on crest) @40MW	48	MeV/c

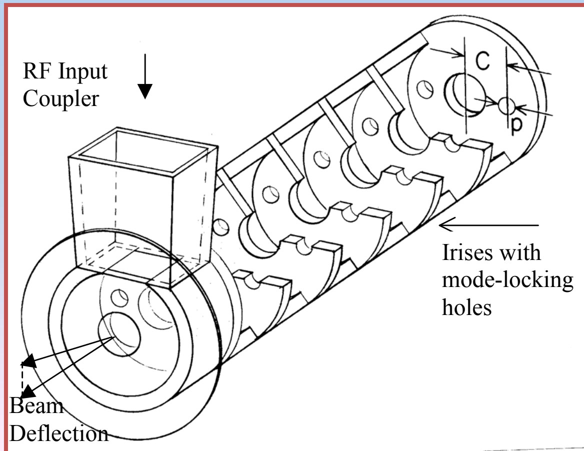
Transverse Deflecting Structures



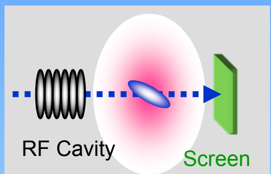
- Well-established technique at SLAC to measure bunch length.
- Use a time-varying transverse electric field to "streak" the beam across a monitor screen.
- 3 m long S-band 2856 MHz structures built in the 1960's
- Installed in the LCLS linac, but are invasive to operation for photon users.

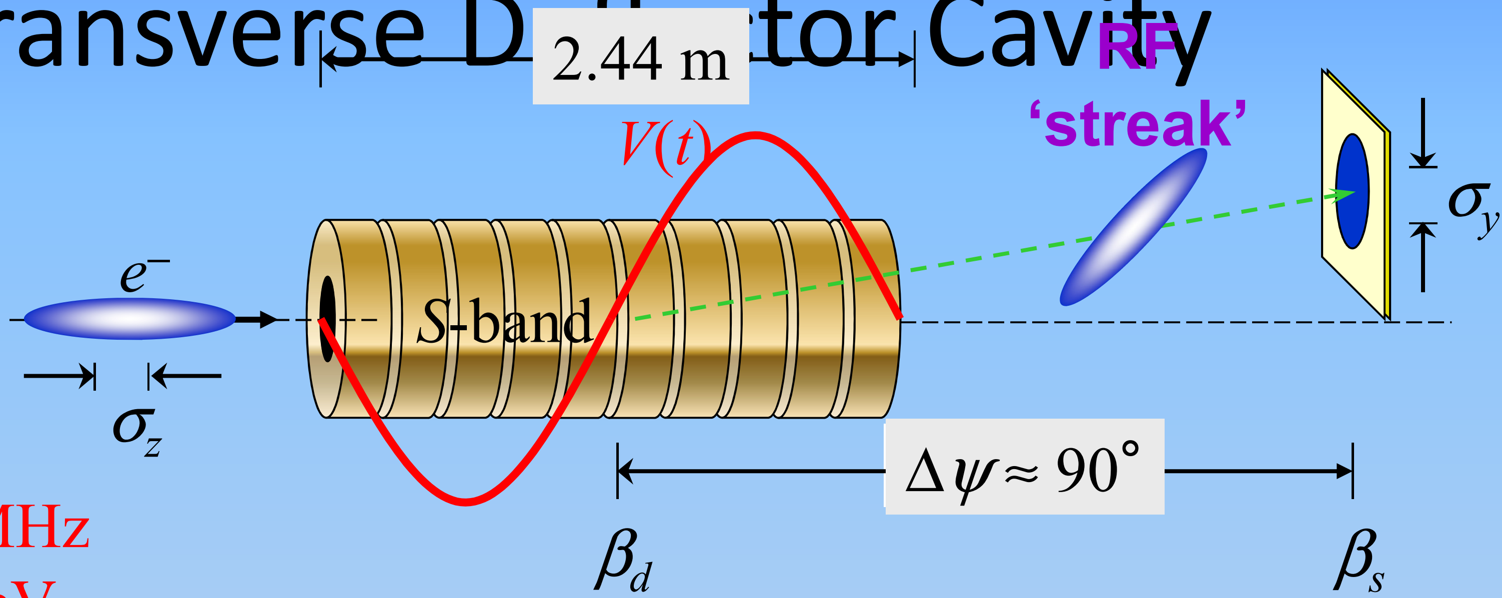




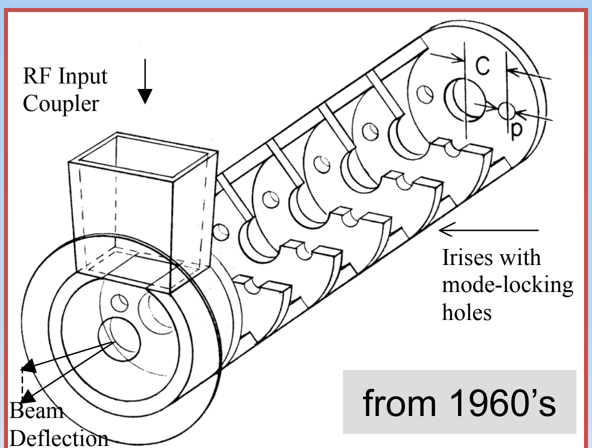


Transverse Deflector Cavity





$V_0 > 20$ MV
$f_{RF} = 2856$ MHz
$E_S = 13.6$ GeV

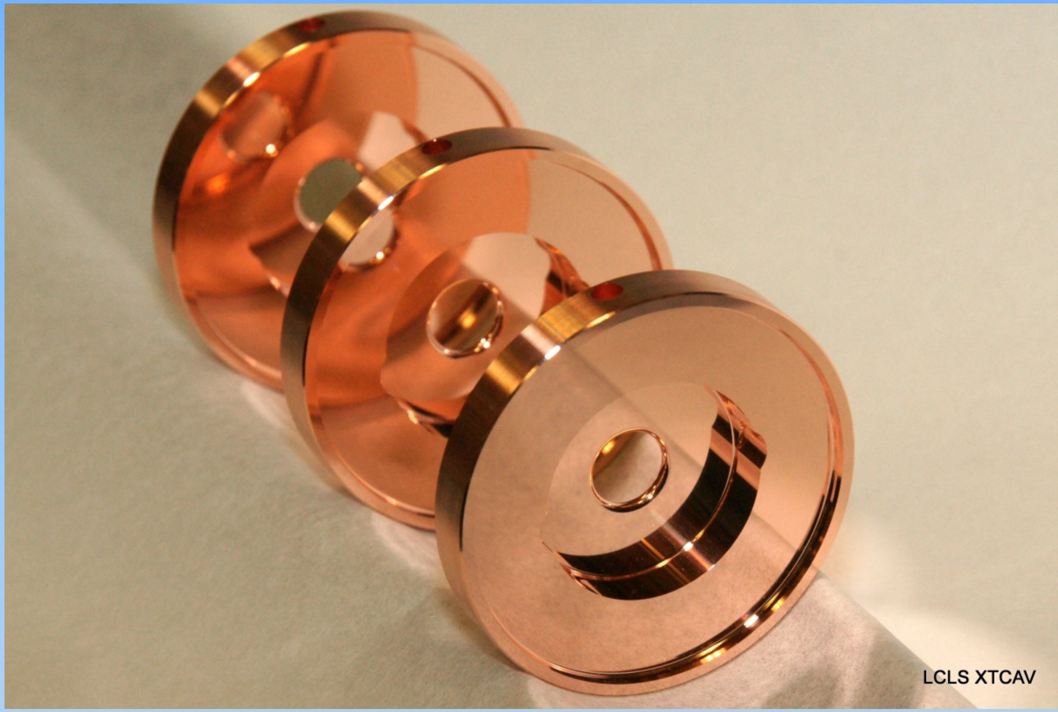


$$\sigma_y^2 = \sigma_{y0}^2 + \beta_d \beta_s \sigma_z^2 \left(\frac{k_{RF} e V_0}{E_s} \sin\Delta\psi \cos\phi \right)^2$$

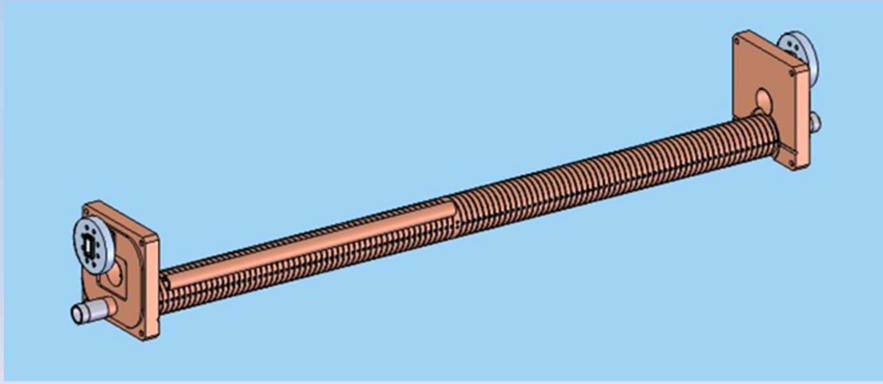
- Map time axis onto transverse coordinate
- Simple calibration by scan of cavity phase

The Challenges

- The x-band microwave structure is made up of copper “cups” diamond machined to micron precision and diffusion bonded into 1 m long structures



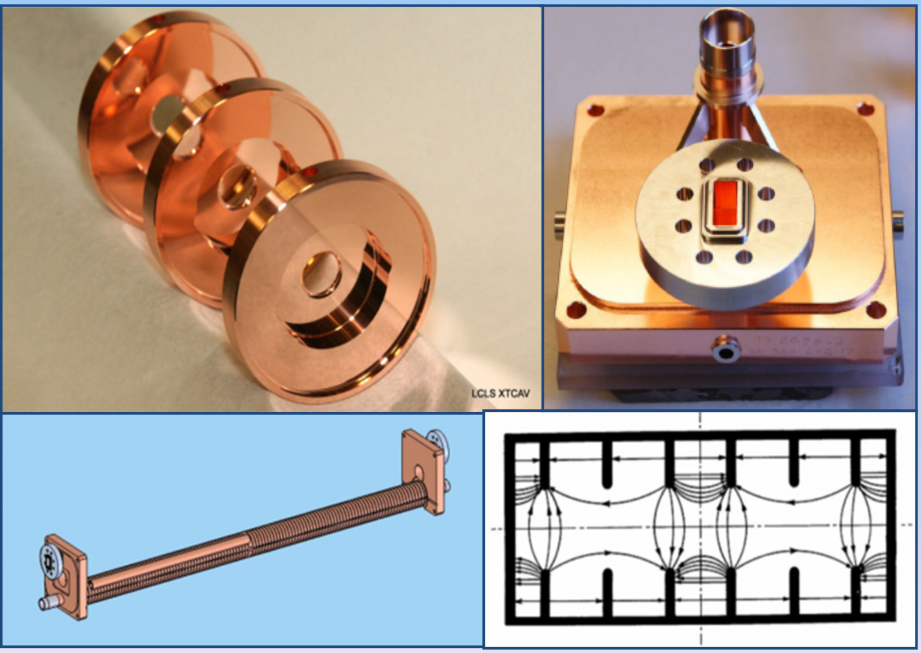
- Each of the **113 cells** is RF tuned at the tunnel operating temp. of 20 ° C

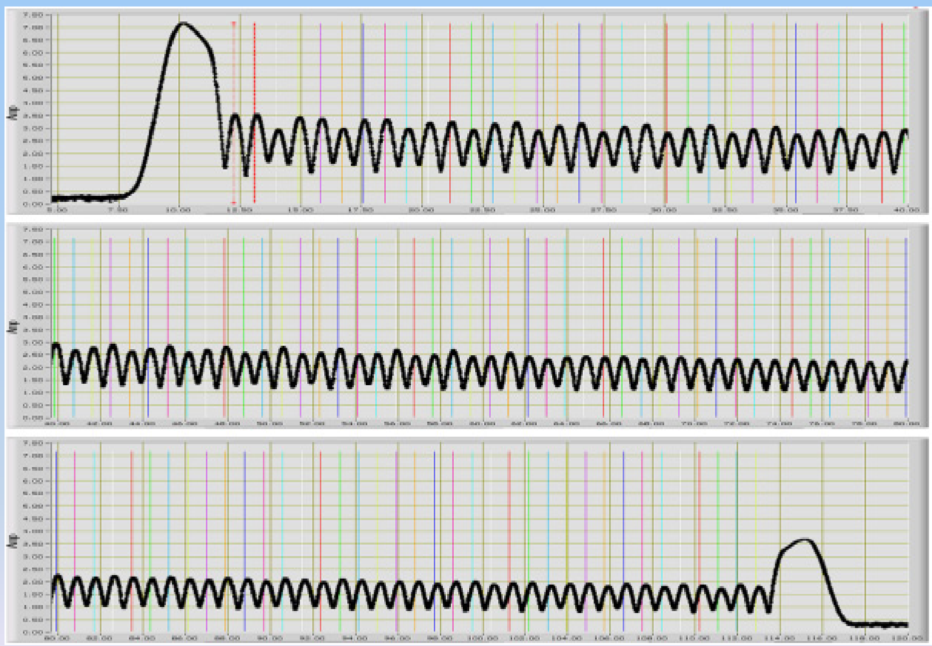


- The structures were pre-assembled on an optical bench and aligned to 50 um

Structure Tuning

- Low power tuning was performed after fabrication using a nodal shift method with a metal rod passed vertically through the structure.

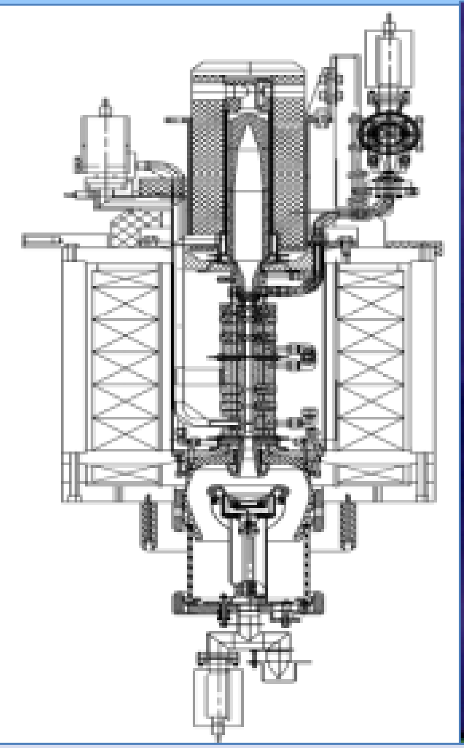
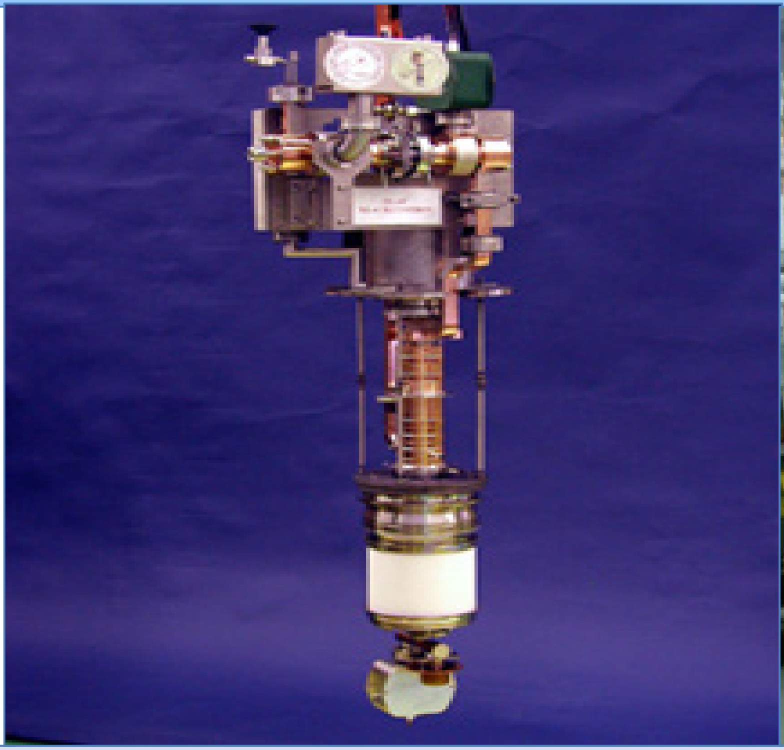




Pre-Assembly and Alignment on an Optical Bench

SLAC X-Band Klystron

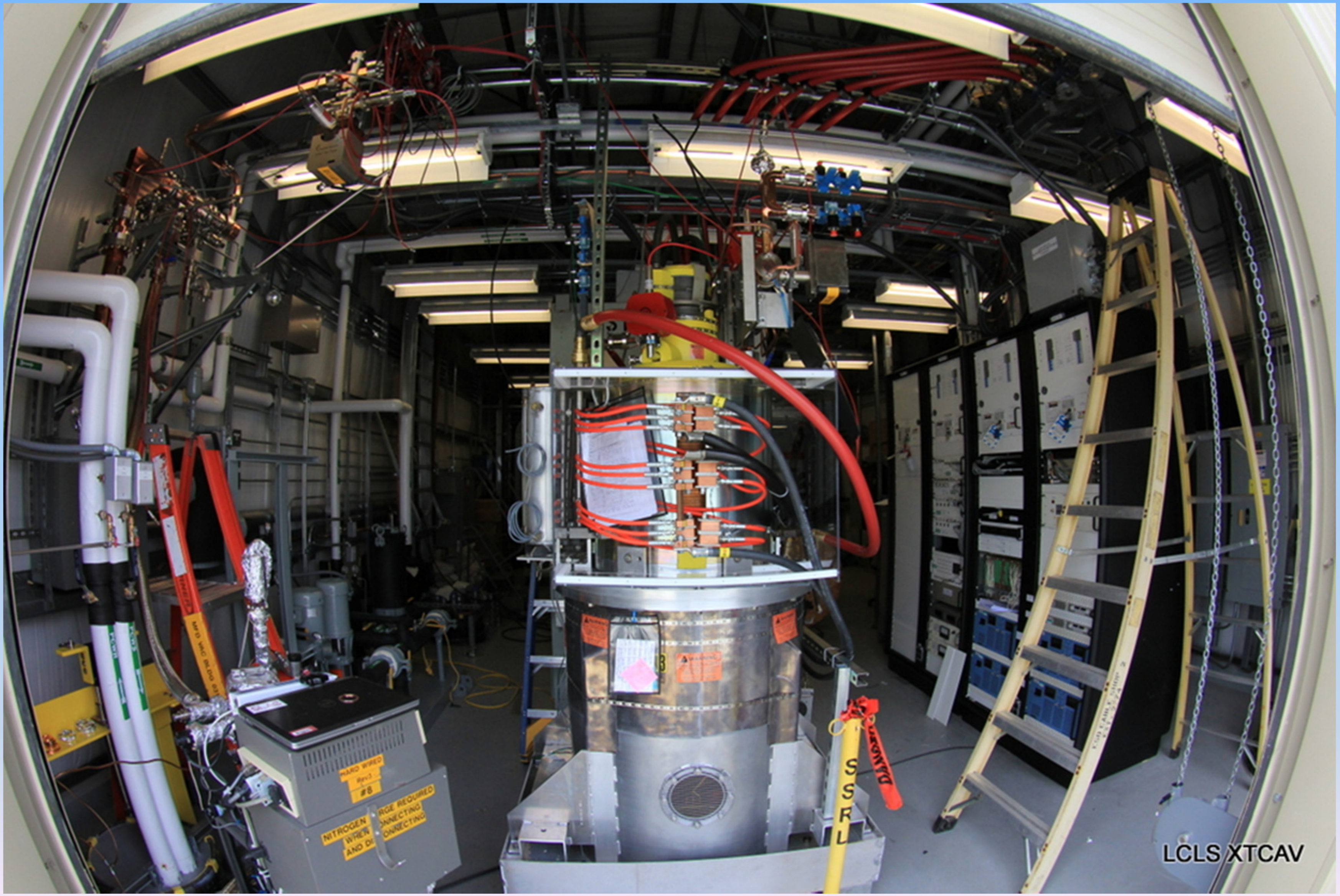
- 50 MW XL4 tube
- 120 Hz, 0.2 us pulse length


Klystron Modulator

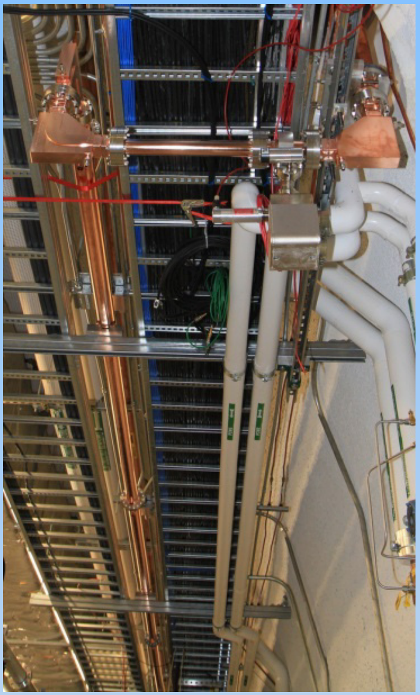
- Use an existing linac modulator
- Upgrade to 430 kV, 80 ppm stability

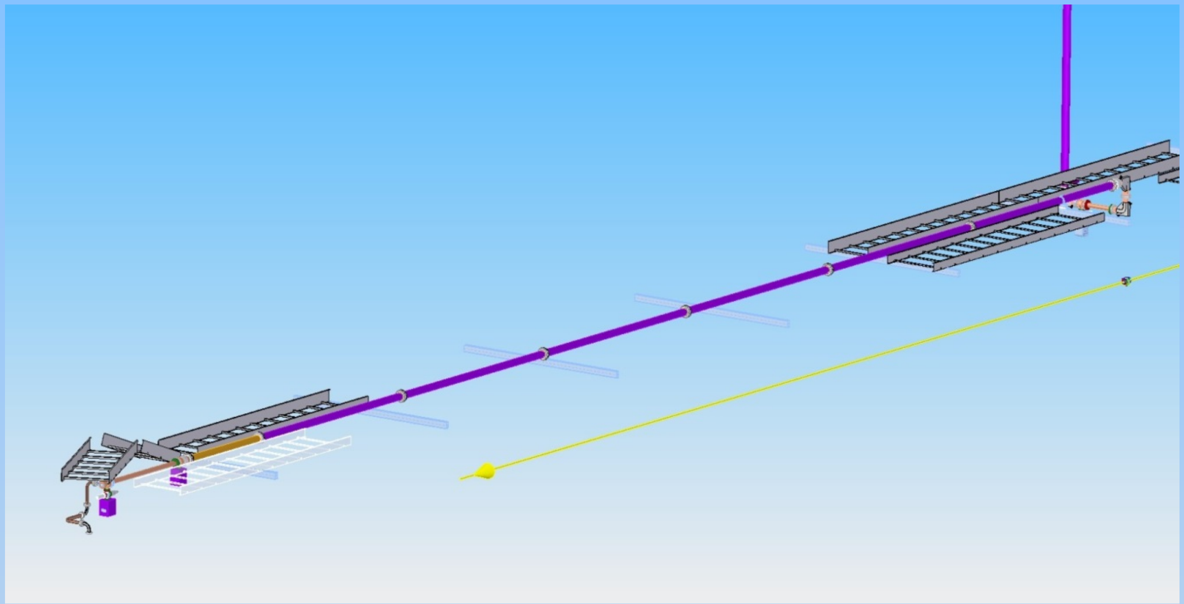
Klystron Support Building



Waveguide System

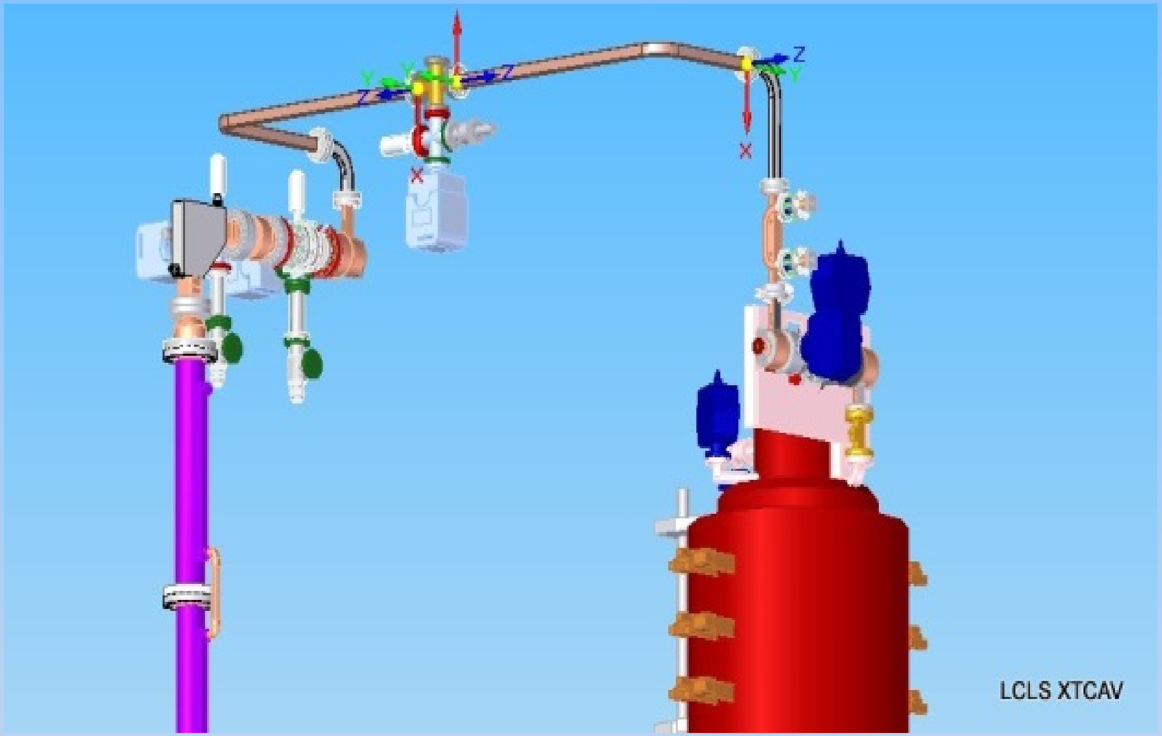
1 dB loss from100’ of over-moded circular waveguide

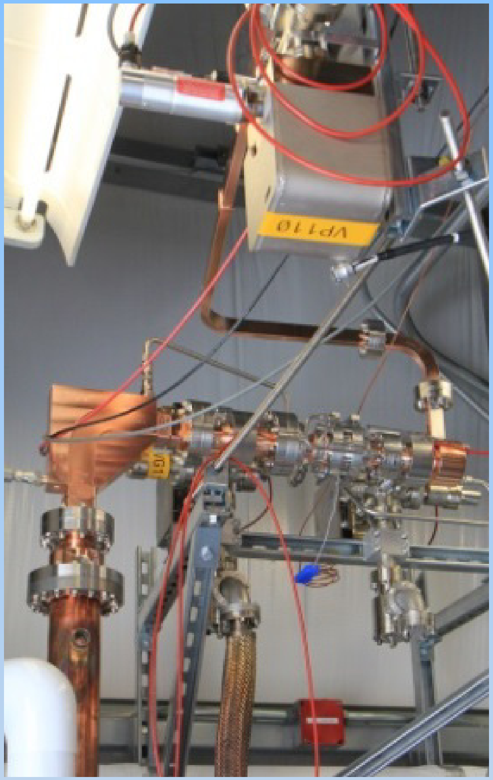




Waveguide System

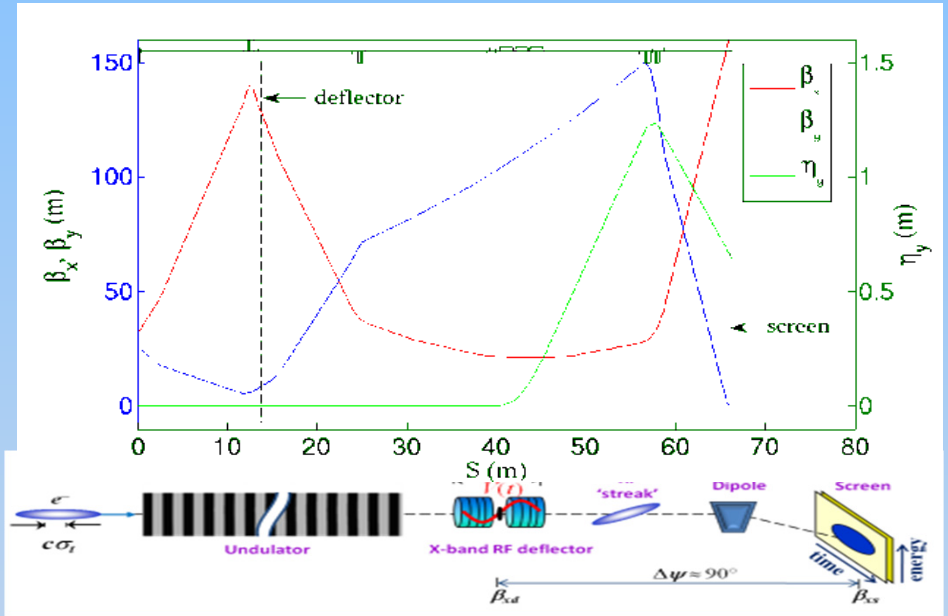
plus another 1 dB loss from 10' of WR90 x-band waveguide





Beam Line Optics

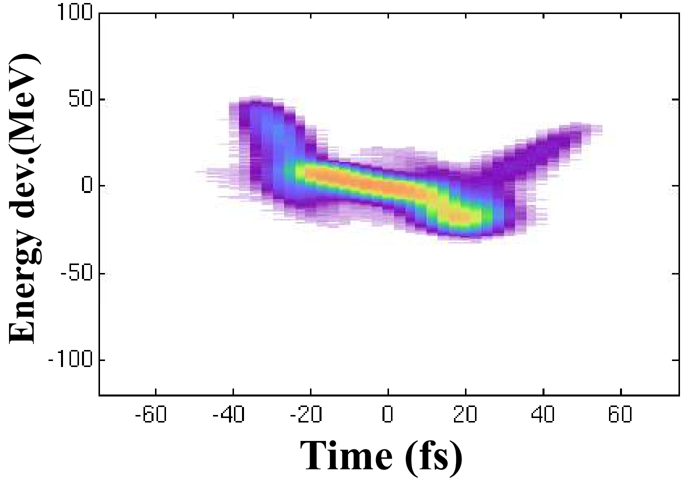
- Modified lattice to optimize phase advance between deflector and screen, plus beta at the deflector



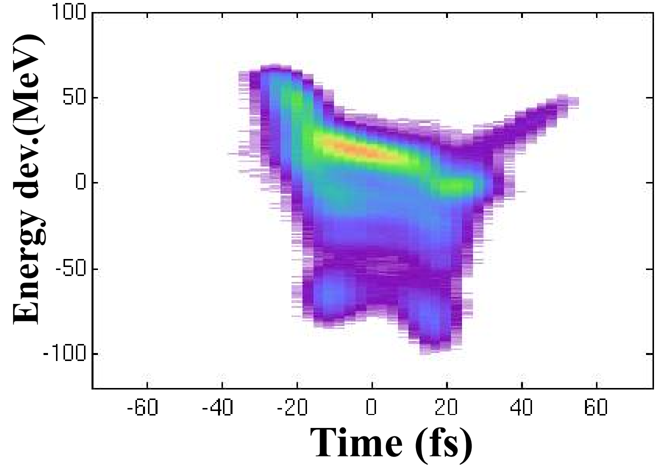
$$\sigma_{t,R} = \frac{\sigma_{y0}}{S} = \sqrt{\frac{\varepsilon_{N,y}}{\gamma\beta_d}}\frac{\lambda_{rf}E_e}{2\pi|eV_0\sin\Delta\psi|} \qquad \sigma_{E,r} = \frac{E_0}{\eta_{yS}}\sqrt{\frac{\beta_{yS}\varepsilon_n}{\gamma}+\sigma^2_{screen}}$$

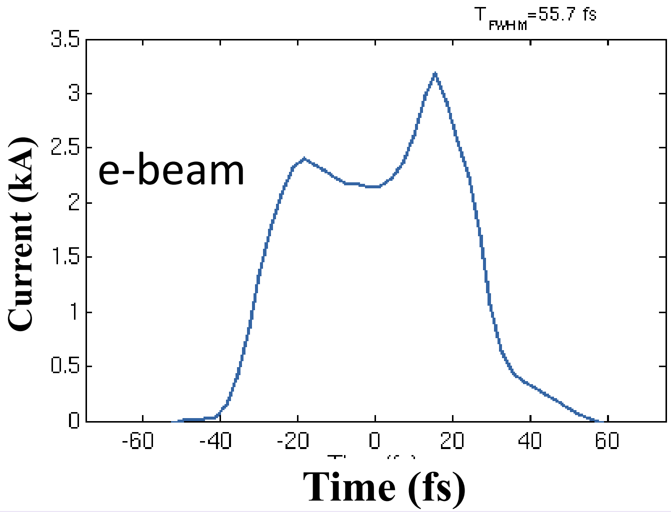
HXR examples at 15.2GeV, 150pC, 10.2keV

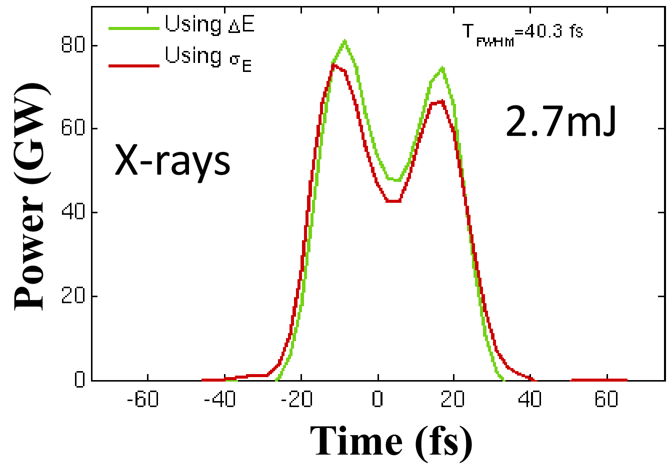
Lasing off



Full lasing

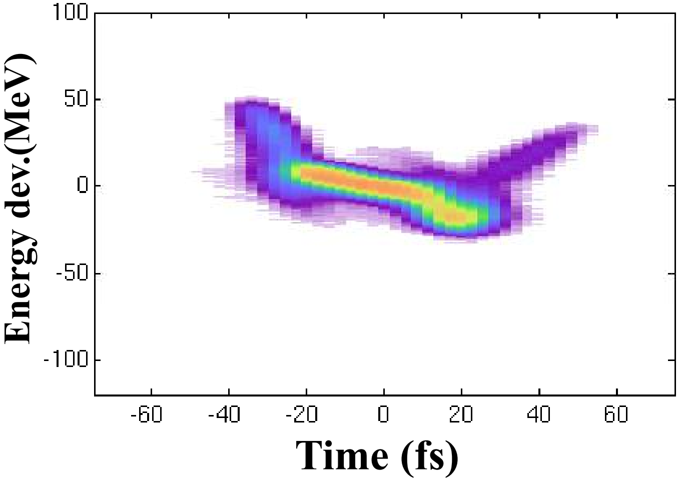




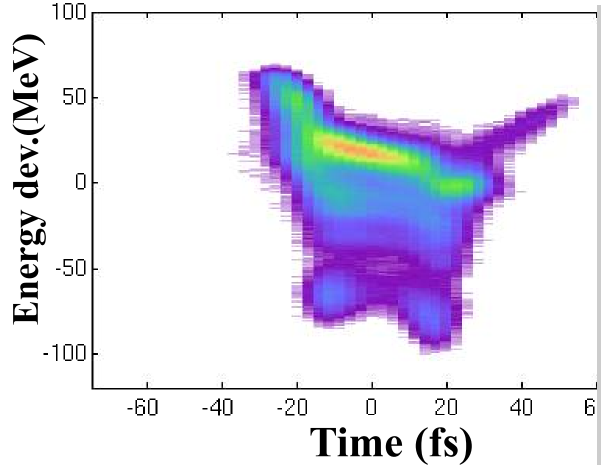


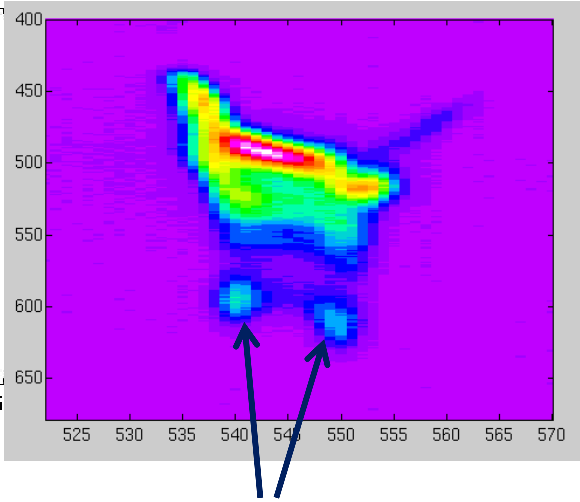
HXR examples at 15.2GeV, 150pC, 10.2keV

Lasing off

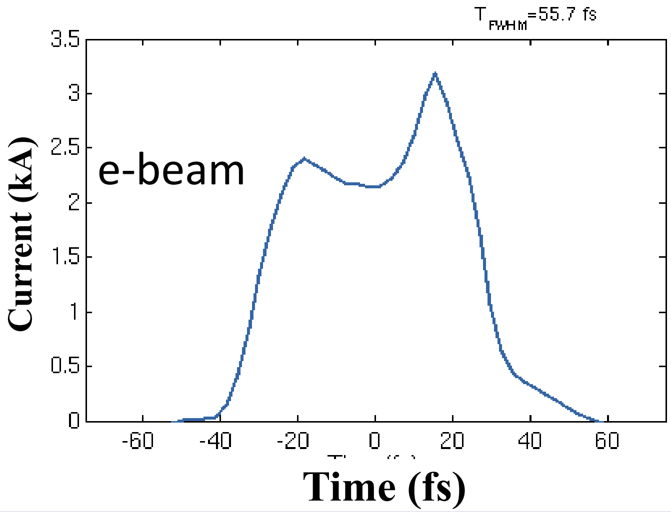


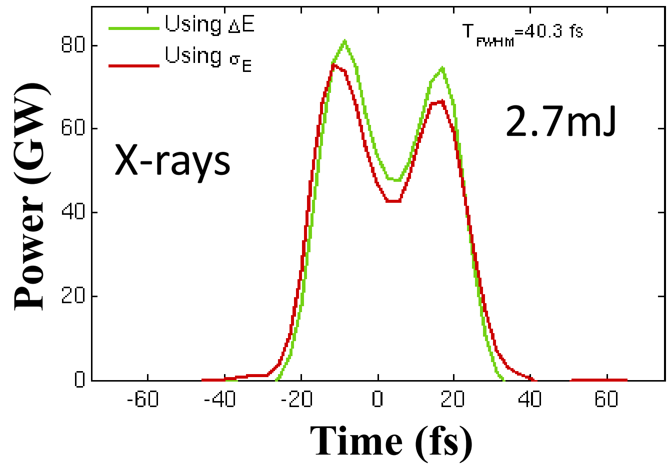
Full lasing





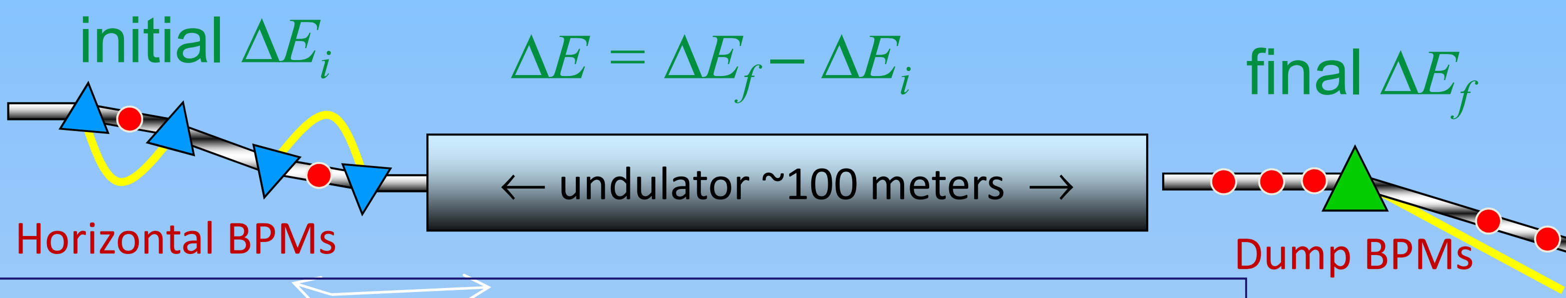
Trapped electrons after saturation.



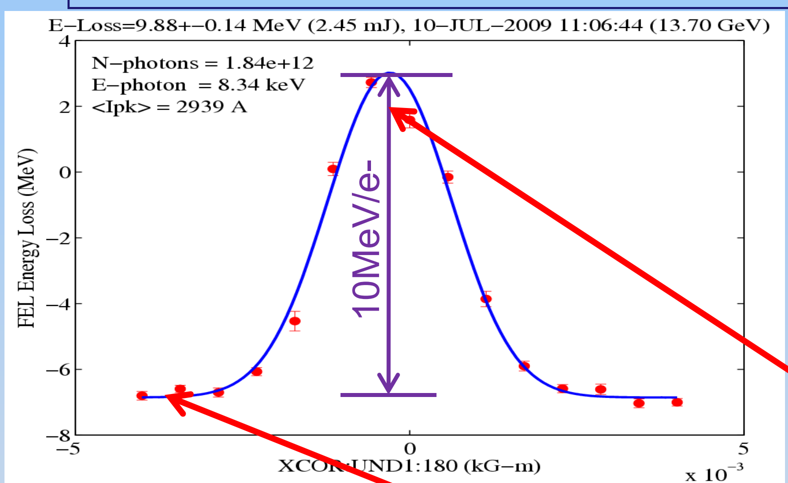


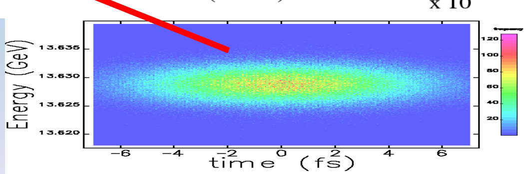
How to retrieve x-ray temporal profile?

- The E-loss scan for measuring x-ray pulse energy:

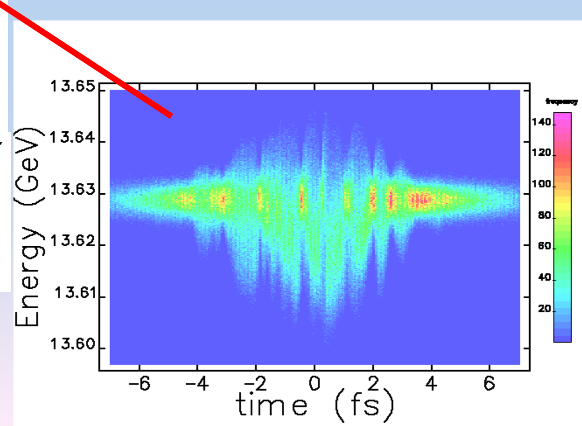


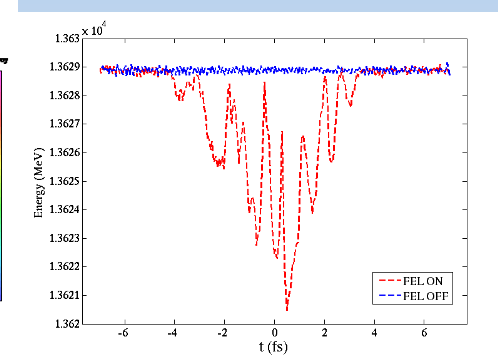
vary FEL power with oscillations & record e⁻ energy loss





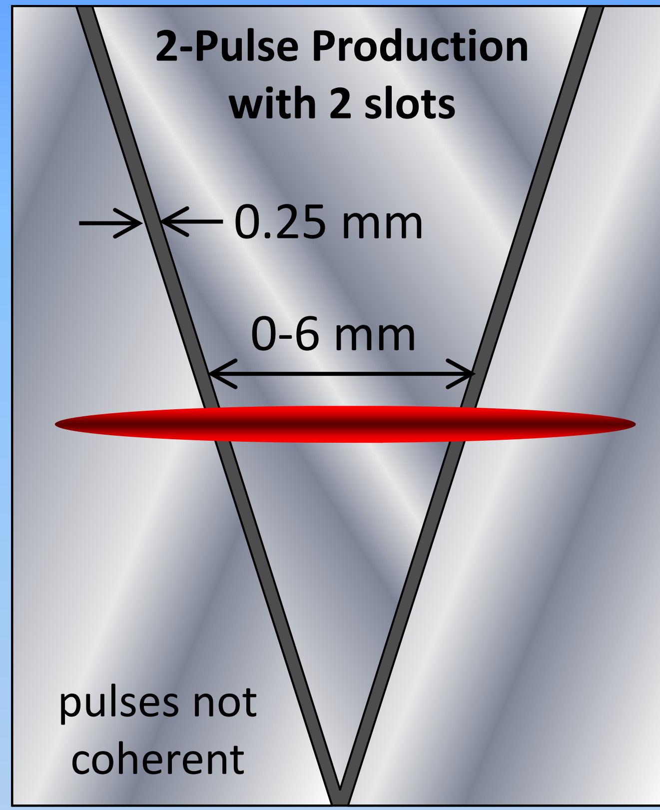
→ to measure the ***time-resolved*** lasing effect ("footprint") left on the electron bunch. (**Ding et al., PRSTAB2011**)

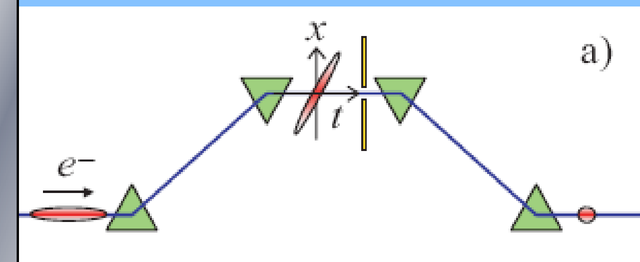


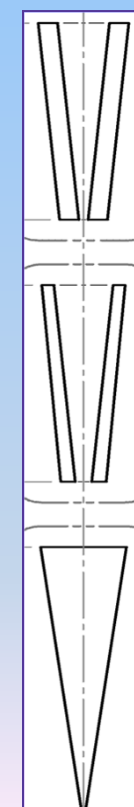


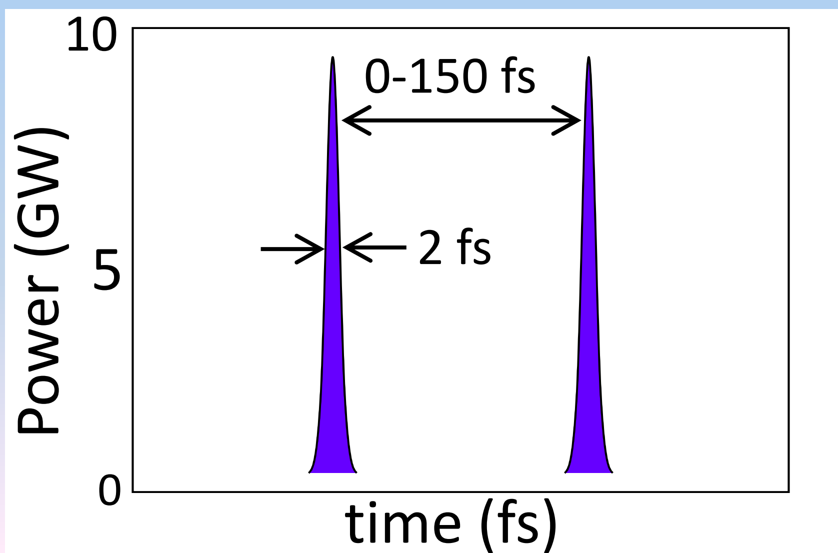
Short pulse--

Double X-Ray Pulses from a Double-Slotted Foil





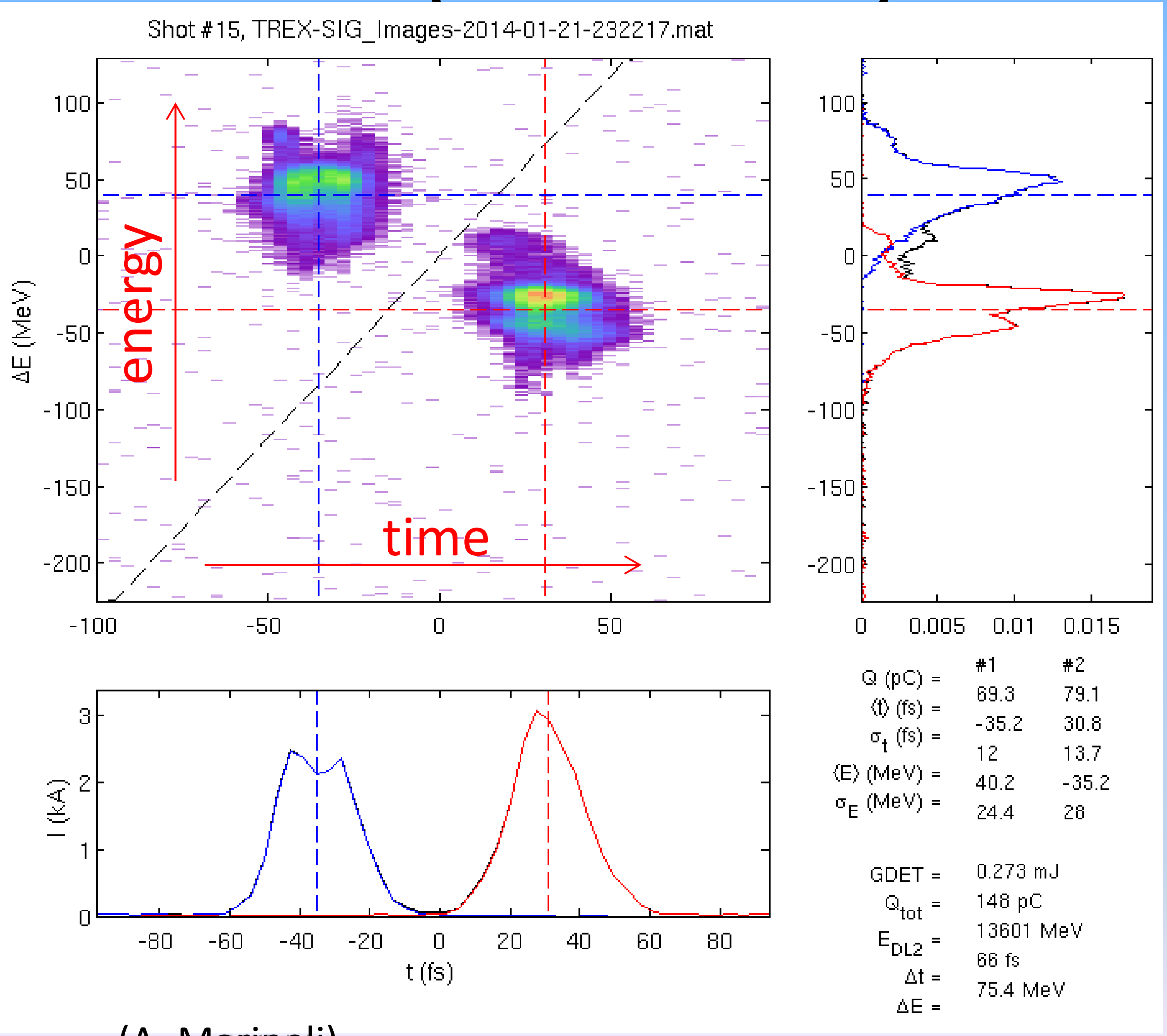




Emma et al., PRL 92, 074801;
Ding et al., PRL 109, 254802.

Courtesy P. Emma

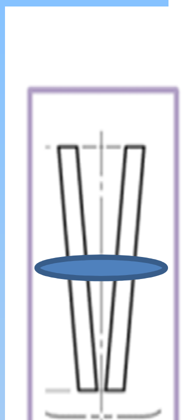
Double-bunch (two-color) example

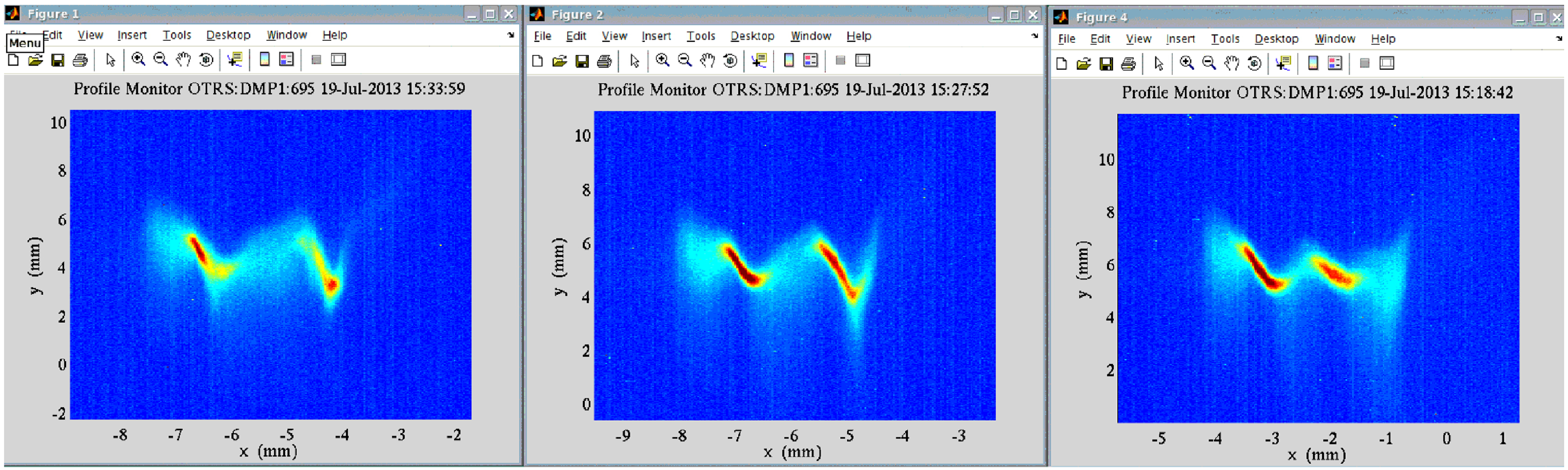


(A. Marineli)

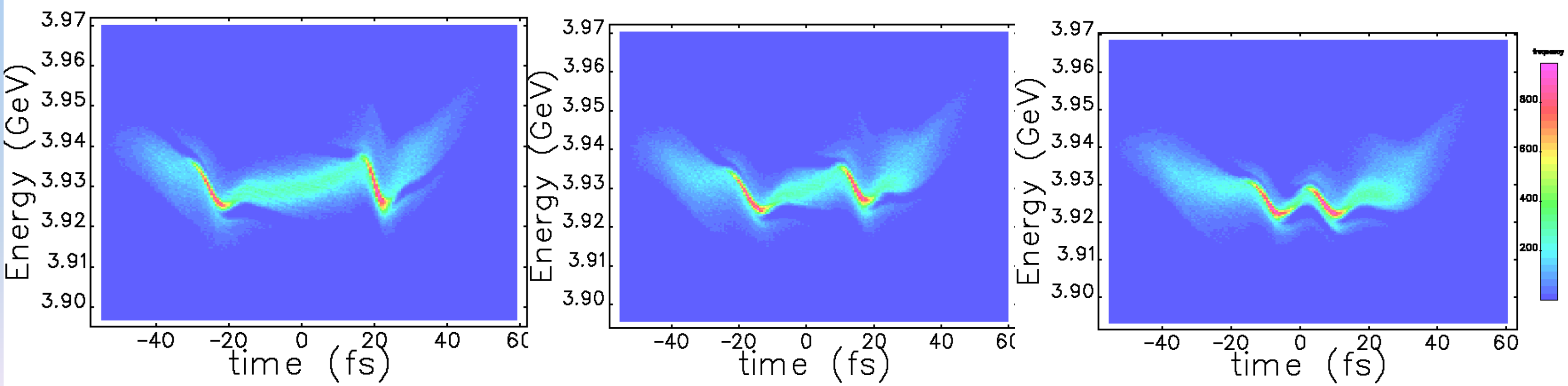
Slotted-foil comparison with simulation

measurements

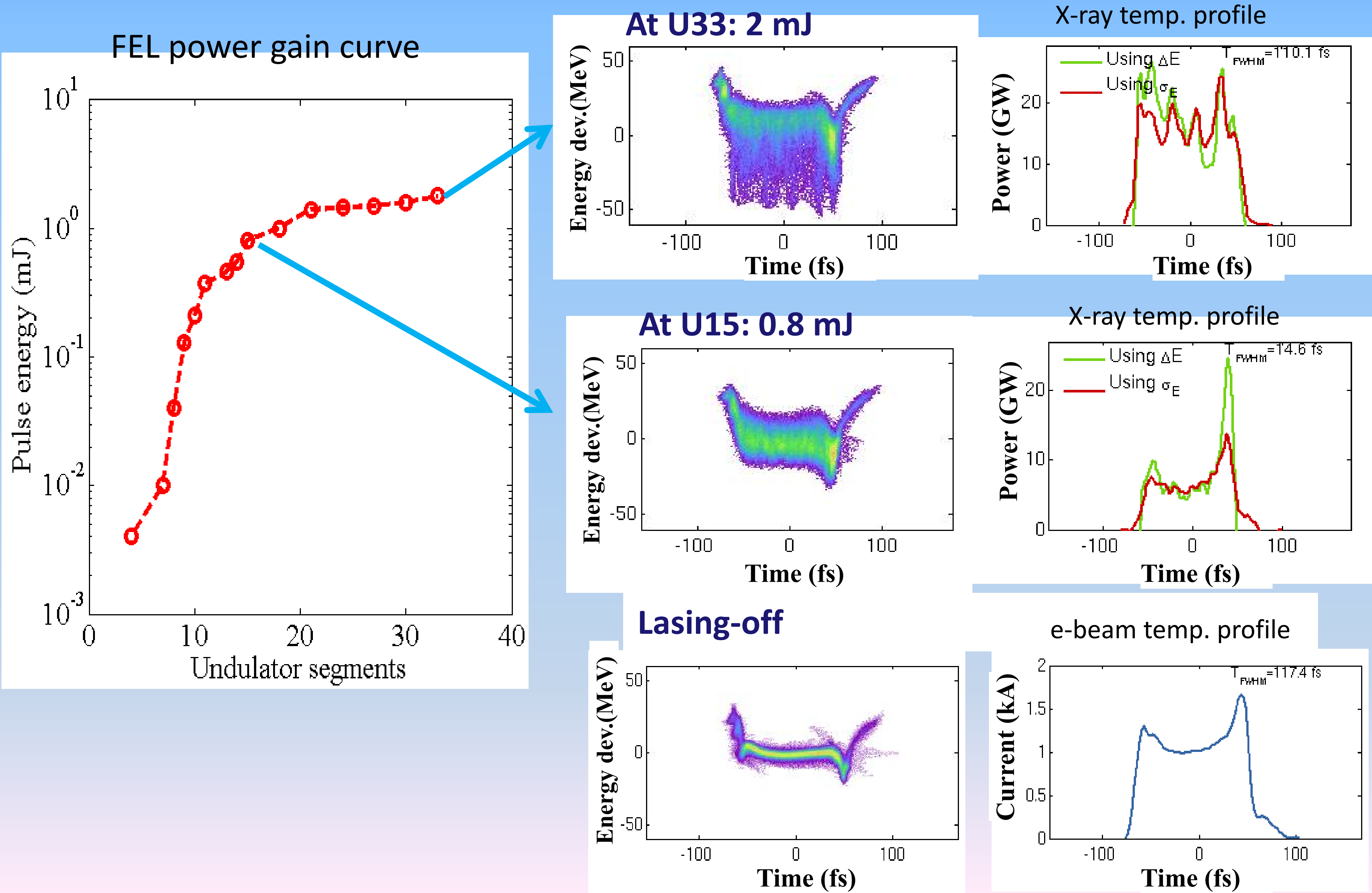




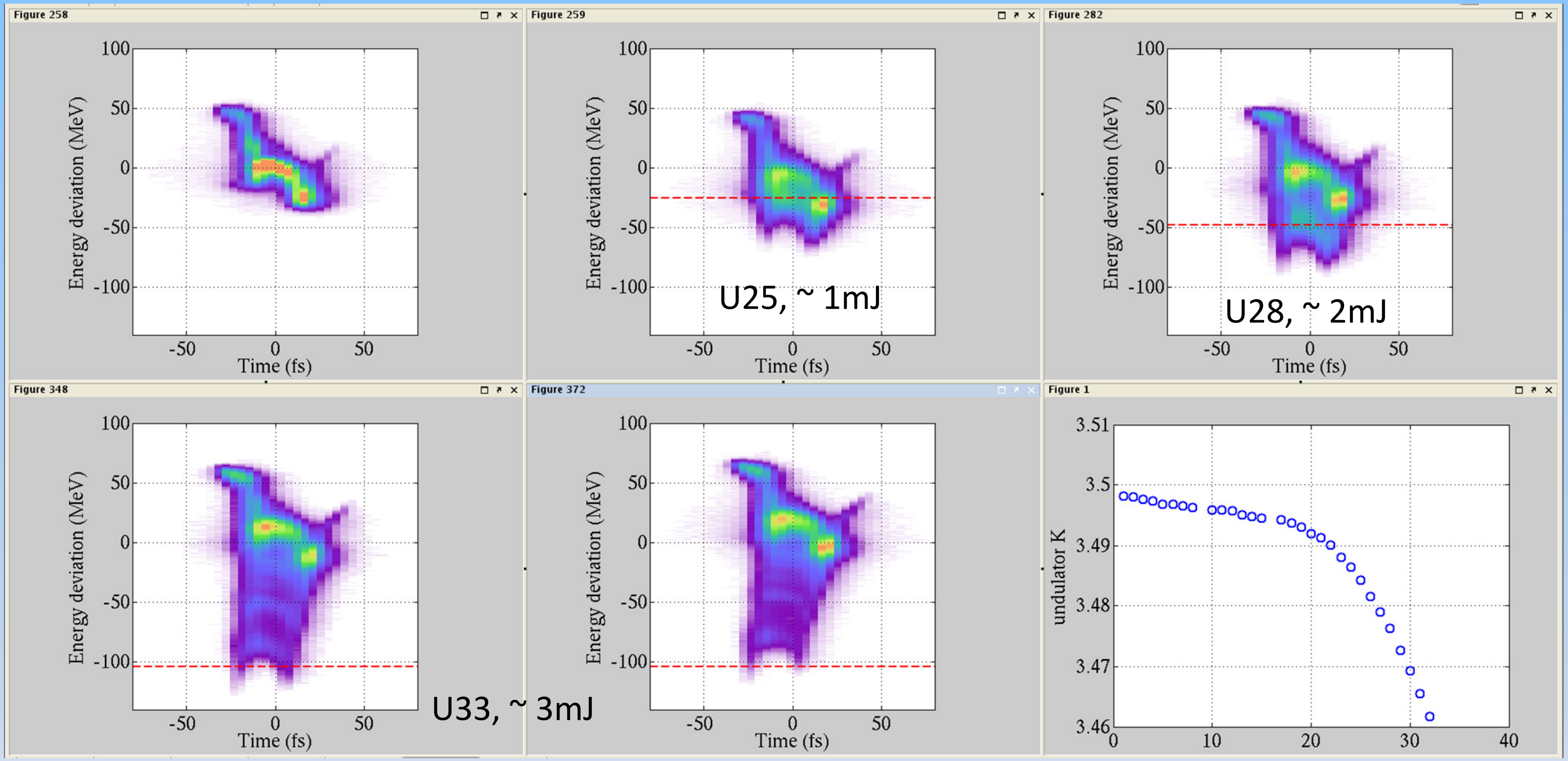
simulations

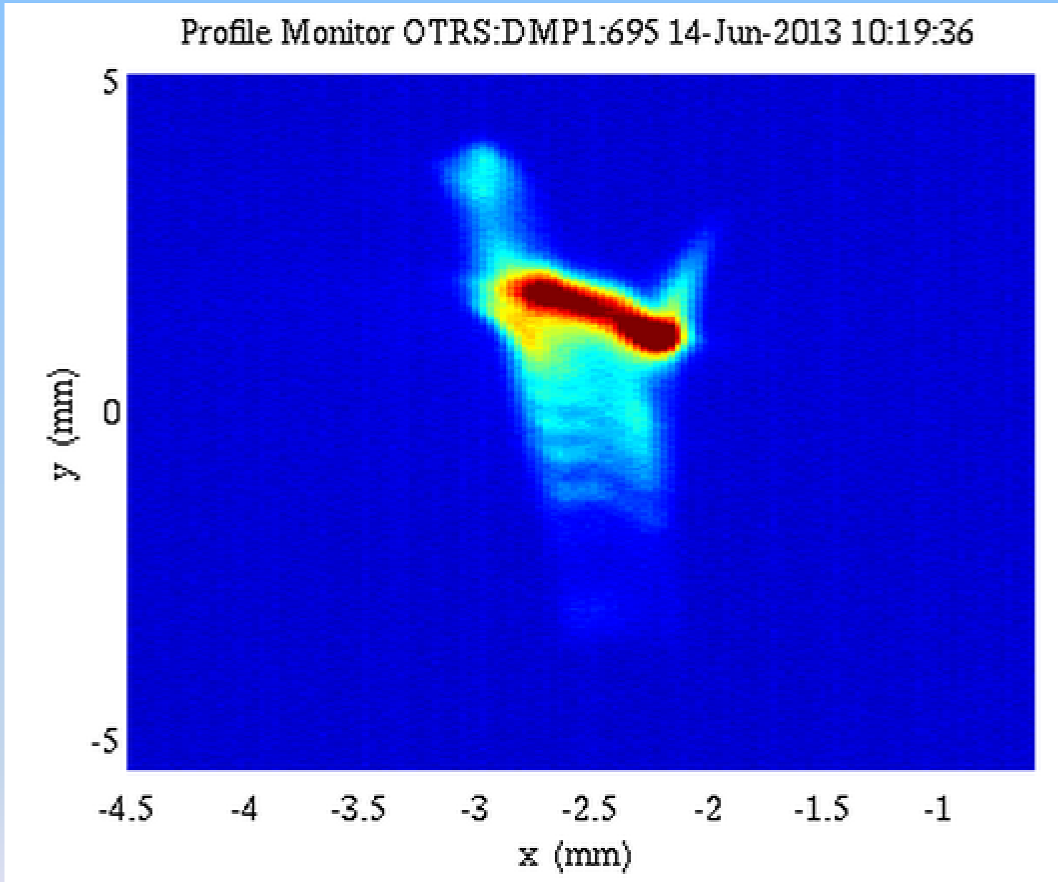


SXR Examples at 4.7GeV, 150pC (1keV)



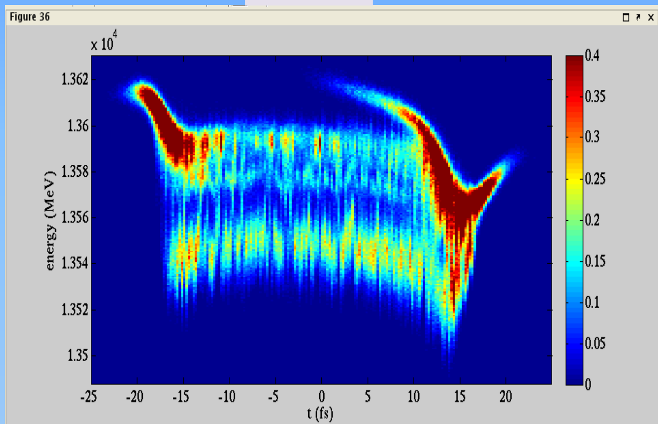
HXR 150pC, 8keV, measured on 2014/2/4



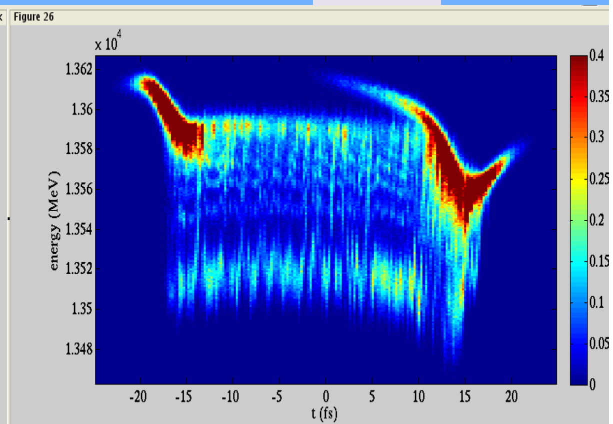

Profile Monitor OTRS:DMP1:695 14-Jun-2013 10:19:36
5
0
-5
y (mm)
-4.5
-4
-3.5
-3
-2.5
-2
-1.5
-1
x (mm)

HXR 150pC, simulations, experimental taper (2/4/2014)

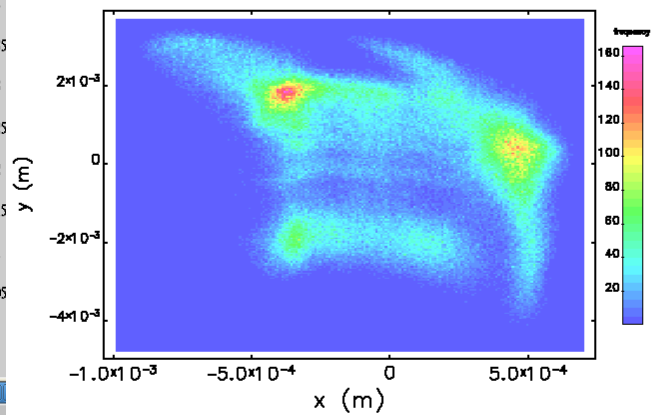
110m



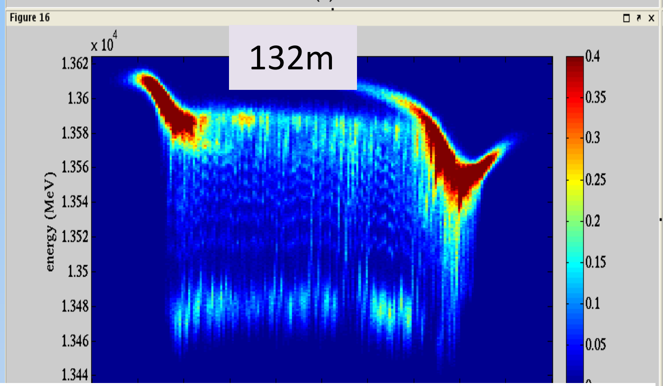
120m

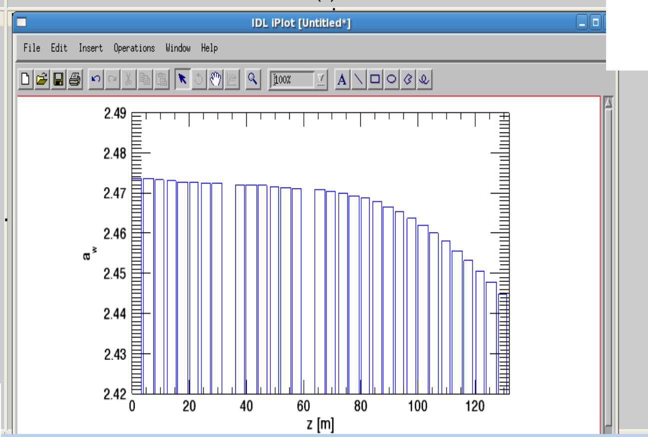


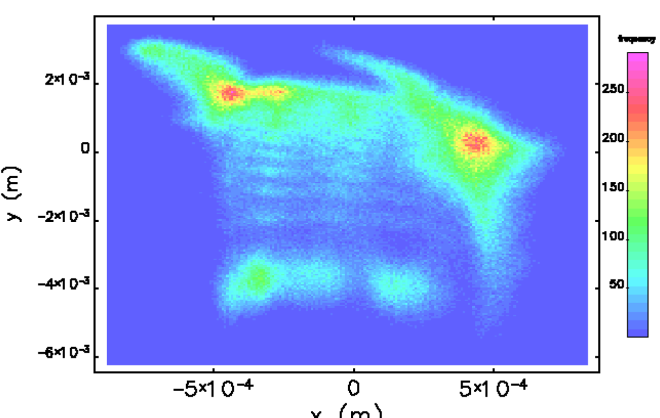
Simulated xtcav images:
120m



132m

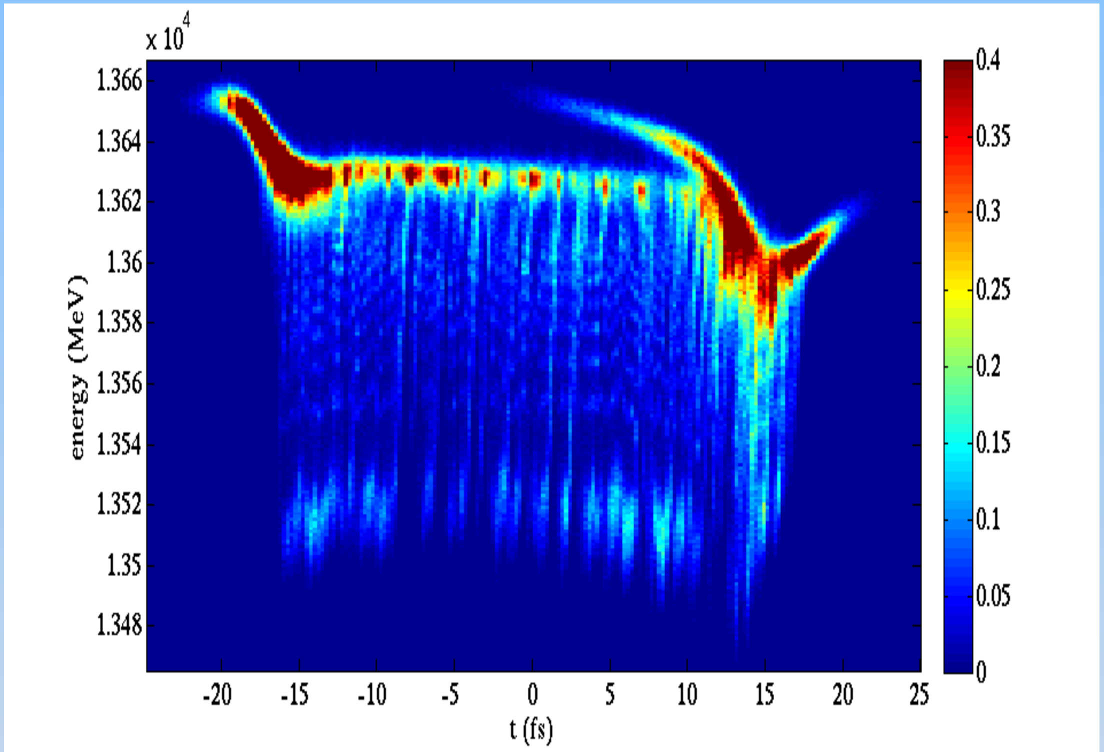






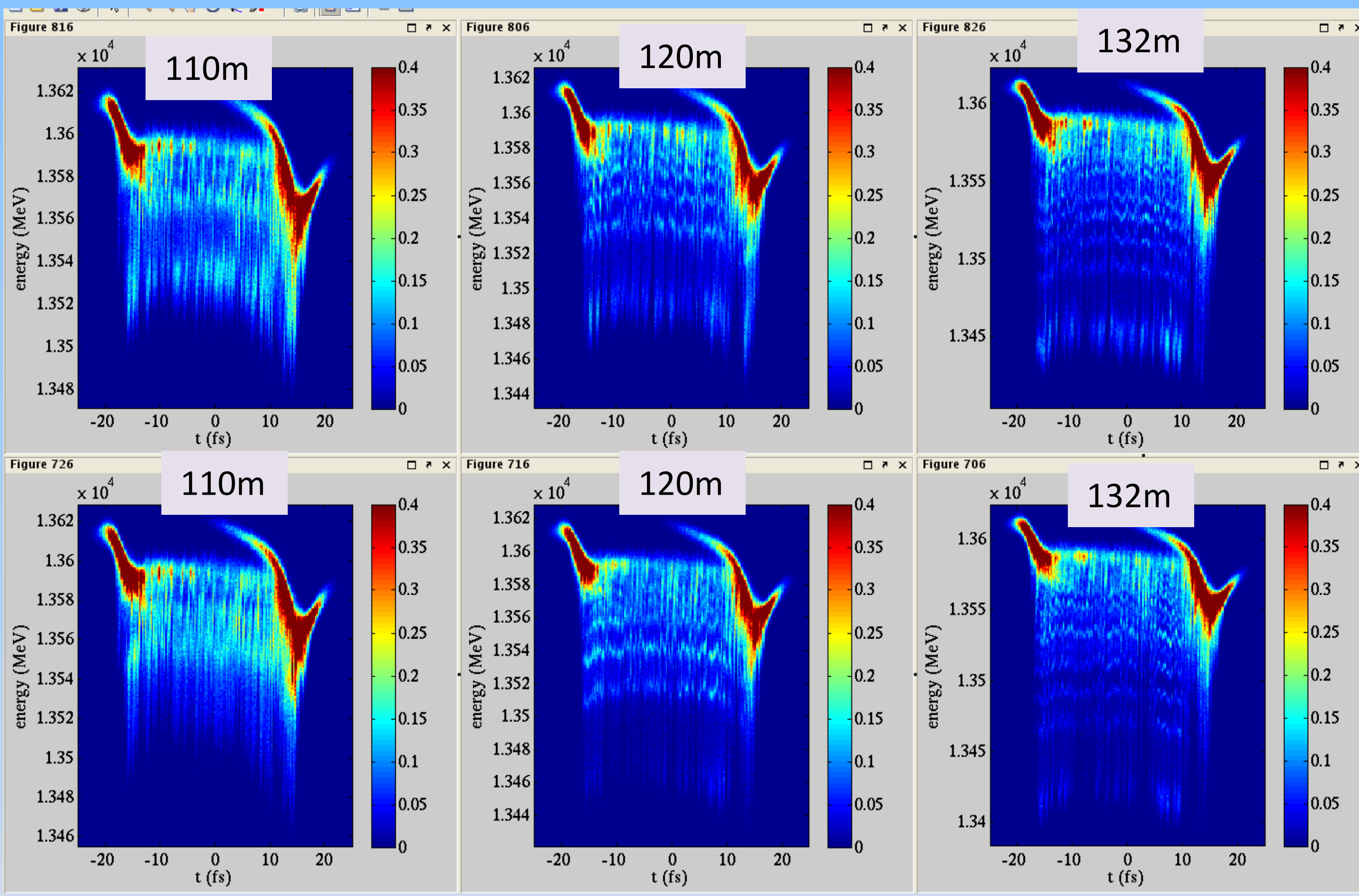
Simulated xtcav images:
132m

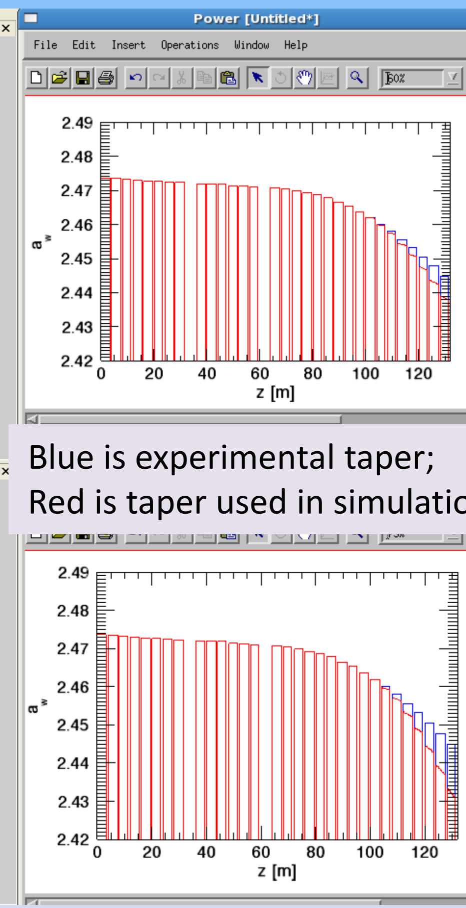
Continuous taper, 132m



To compare with p4 at 132m.

HXR 150pC, 8keV. simulations





Blue is experimental taper;
Red is taper used in simulations.