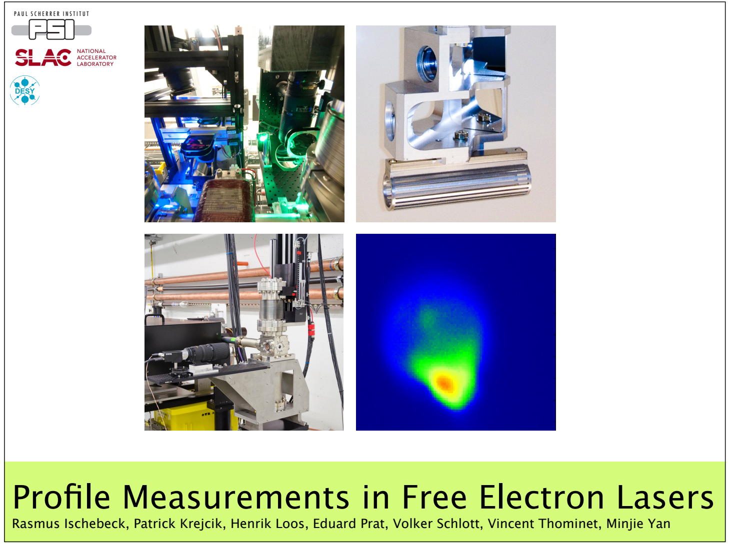
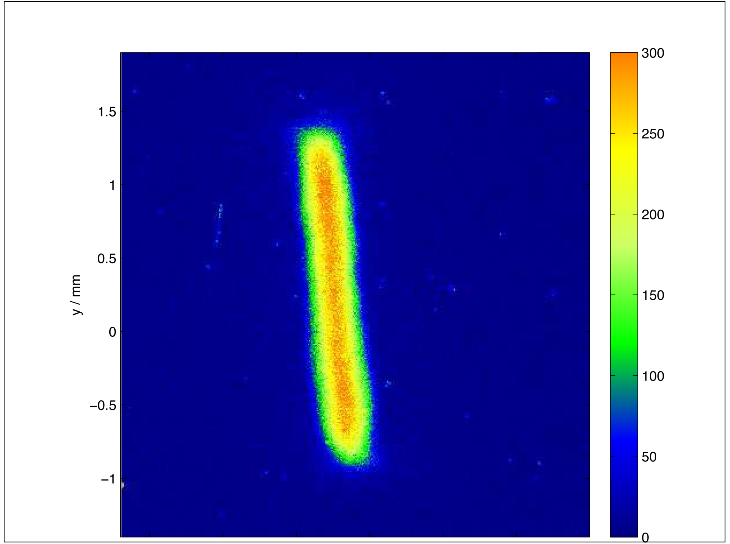


Profile measurements in FELs are basically measurements of beam quality. This includes beam size, but also shape.
Most of the time, we strive for the smallest and the most homogeneous beams, with a few interesting exceptions.
The evolution of the transverse distribution of the electrons along a linac can be described by the beam optics, which can be influenced by magnets, radio frequency structures and self-forces. We use the emittance to characterize the beam quality. The normalized slice emittance is generated in the injector, and is typically degrading from there on.
The importance of the emittance for FELs cannot be overstated: the gain of the FEL depends on the slice emittance, and new FELs such as SwissFEL are basing their entire design on the promise of a good emittance.
We can thus use a lower-energy beam, together with shorter-period undulators to achieve the same wavelength as first-generation FELs at a fraction of the overall facility length.

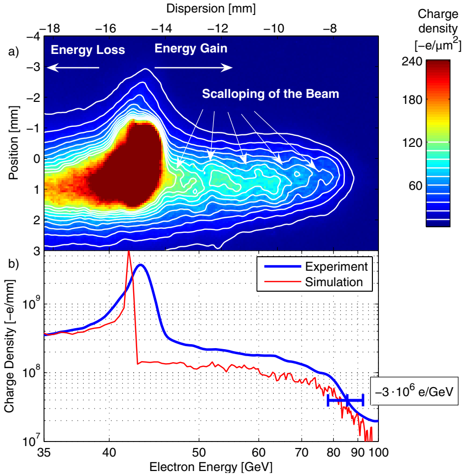
This is why we ask our best physicists to spend endless hours in the control room to optimize the emittance!
The initial emittance is generated in the gun, and it is degraded for example by mis-alignment of the accelerating structures, causing wakefields, and by self-forces during pulse compression.
Back to profile measurements!



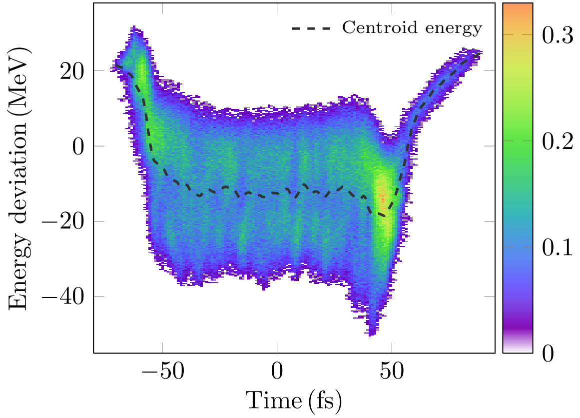
Normally, we treat the x and y planes separately, but there are cases where we are interested in correlations:

> between x and y

We use phase space transformations to swap axes.
Here: electron energy on the horizontal axis.



Blumenfeld, Ian, Christopher E Clayton, Franz-Josef Decker, M J Hogan, C Huang, R Ischebeck, R Iverson, et al. 2007. "Energy Doubling of 42 GeV Electrons in a Metre-Scale Plasma Wakefield Accelerator." Nature 445 (February). doi:10.1038/nature05538.



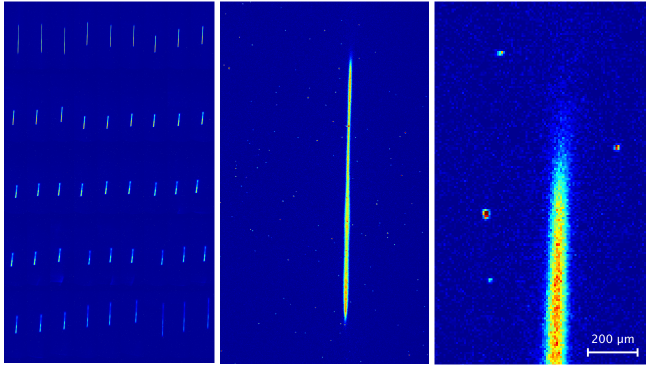
Behrens, Christopher, Franz-Josef Decker, Y Ding, V A Dolgashev, J Frisch, Z Huang, P Krejcik, et al. 2014. “Few-Femtosecond Time-Resolved Measurements of X-Ray Free-Electron Lasers.” Nature Communications 5 (April). Nature Publishing Group: -. doi:10.1038/ncomms4762.

In this case, two phase space transformations:

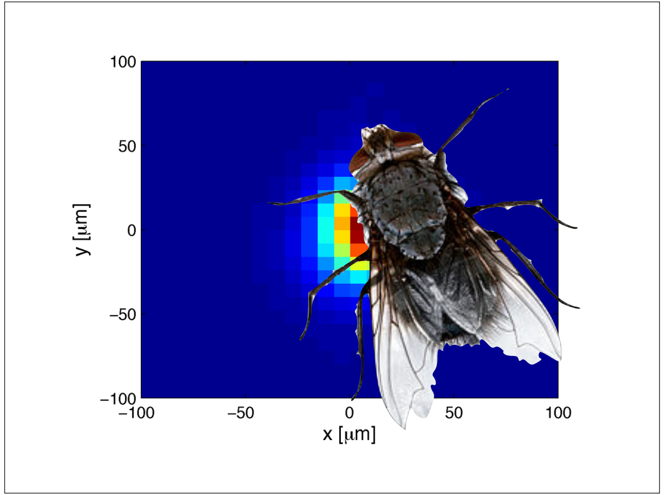
> on the horizontal axis: time

> on the vertical axis: energy

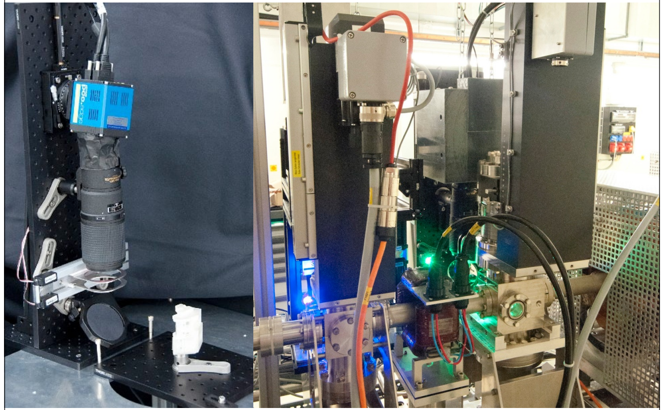
slice emittance measurement:
we look for a correlation between sigma x and y



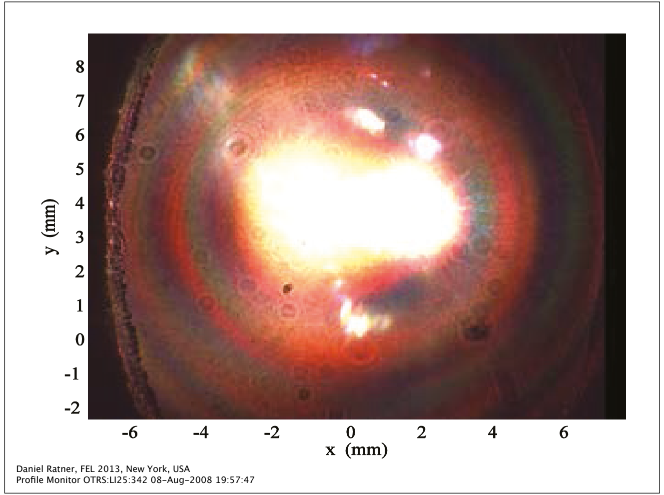
Measurements performed by
Eduard Prat & Marta Divall



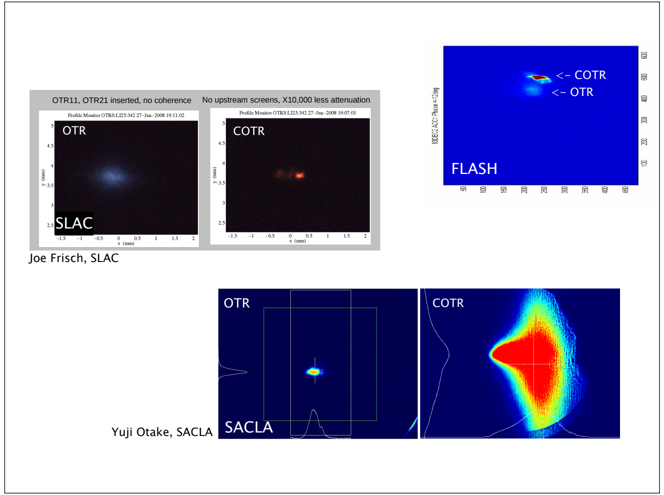
Generation of low-emittance beams has made tremendous progress in recent years, driven by requirements of FELs. As a consequence, the beams are small!



This leads to stringent requirements on profile measurements.
-> this is why my job is fun!

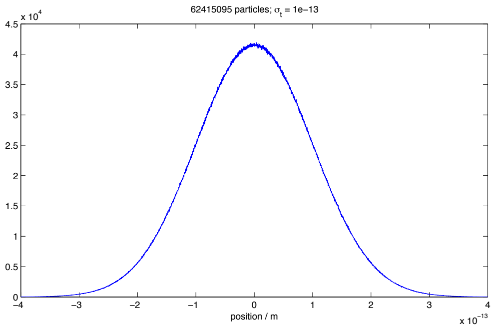


…but now: COTR!
Intense light, has made all the high-energy OTR monitors at LCLS useless

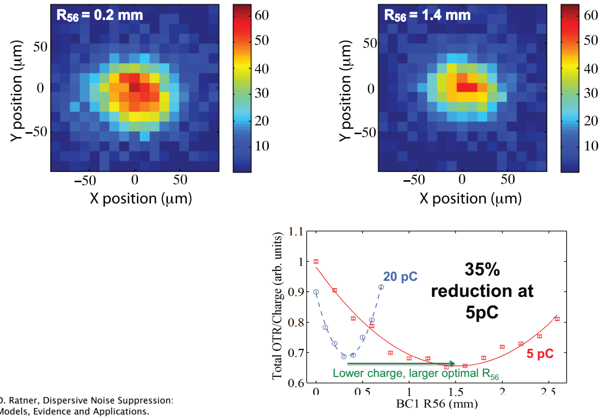


Coherent optical transition radiation, observed at several labs around the world!

$$\frac{dU}{d\omega} = \frac{e^2}{2\pi^2 \varepsilon_0 c}\left(\log(\gamma) + \log 2 - \frac{1}{2}\right)$$



What happens? -> we often make use of optical transition radiation on a metallic surface to generate visible radiation from the electron beam. Our detector (our camera) is sensitive only to a certain wavelength range, e.g. visible light between 400 and 700 nm.
For simplicity, let's first assume that our detector only sees one single wavelength, and let's assume that our bunches are longer than this wavelength.
Now we slice our electron beam in slices that are lambda/2 long.
If we assume Poisson statistics of the electrons in each longitudinal slice of the beam, the variation is proportional to the square root of the number of particles in this slice. The radiated electromagnetic field is proportional to this variation, and the radiated energy is proportional to the square of this, i.e. the number of electrons.
Nice!
Now, what happens if the number of electrons do not obey Poisson statistics?

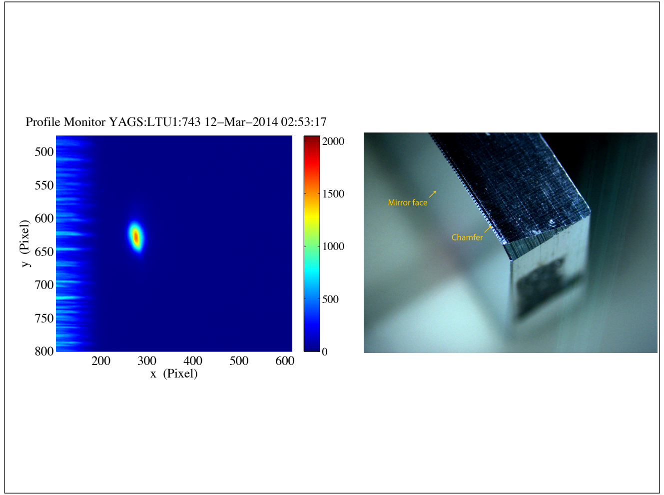


D. Ratner, Dispersive Noise Suppression: Models, Evidence and Applications. FEL 2013, New York, USA

Two cases:

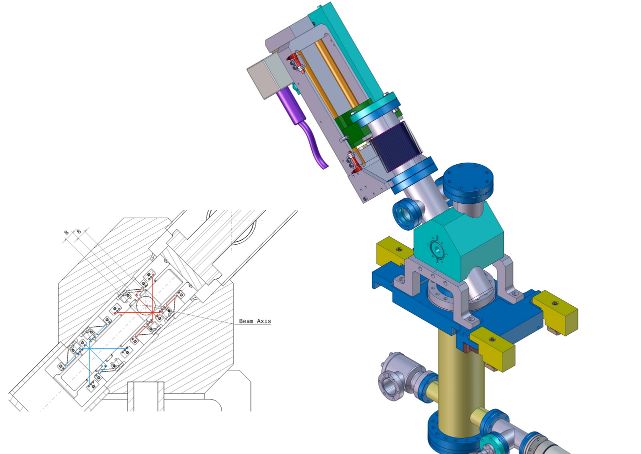
> exceptionally smooth beam ("shot noise suppression")

> exceptionally structured beam ("microbunching")



This COTR can happen:

- on OTR targets
- on mirrors used to image scintillation light
- Coherent Optical Diffraction Radiation (CODR) has even be observed on the chamfer of a mirror!

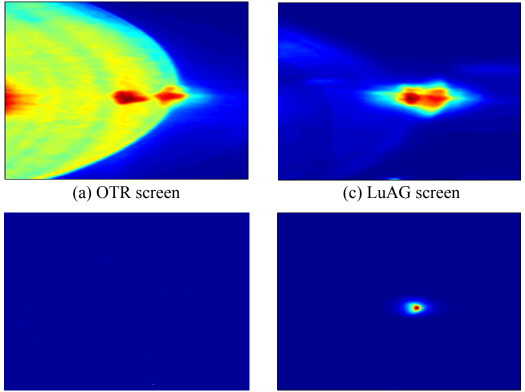


Gian Luca Orlandi: Design and Test of Wire-Scanners for SwissFEL.
FEL 2014, Basel, Switzerland.

Possibilities to overcome COTR effects on the beam profile measurement:

> Geometry
> Temporal separation
> Wire scanners

This is a model of the SwissFEL wire scanner.



(a) OTR screen (c) LuAG screen

(b) OTR screen, +100ns delay (d) LuAG screen, +100ns delay

Minjie Yan et al., DIPAC 2011, Hamburg, Germany

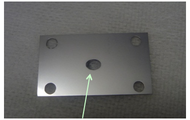
Temporal separation: optical transition radiation is prompt, and thus invisible after a delay of 100 ns. The tail of scintillator radiation is still visible.

This method requires a very fast shutter, accomplished by a microchannel plate

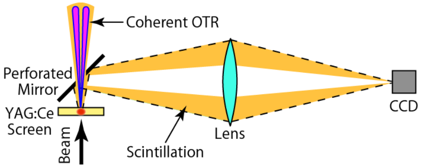
-> expensive setup!

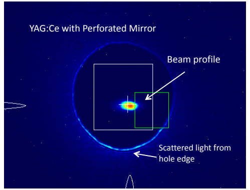
Simpler solution: geometrical separation of (coherent) OTR from scintillation light.

Accomplished at SACLA by using a perforated mirror.



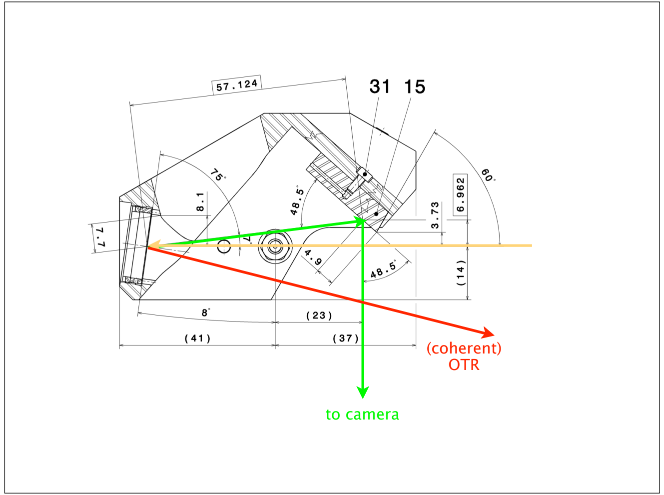
Φ 3 mm





Yuji Otake, SACLA, private communication

S. Matsubara et al., Improvement of Screen Monitor with suppression of Coherent-OTR Effect for SACLA. Proceedings of IBIC2012, KEK, Tsukuba, Japan



SwissFEL geometry allows to

- > direct COTR away from camera
- > large field of view (Scheimpflug imaging condition)
- > good resolution (Snell's law of refraction)

Measurements

>Sensitivity

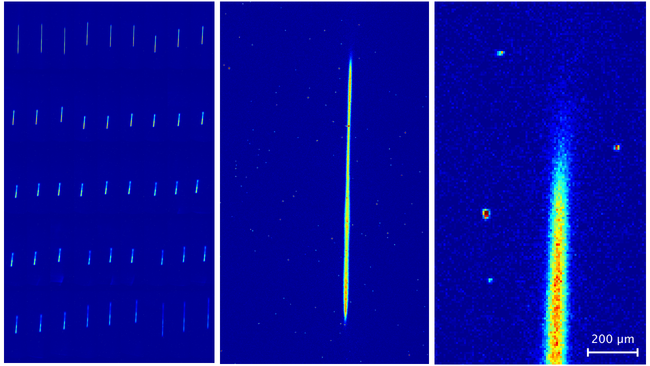
>Resolution

>Field of View

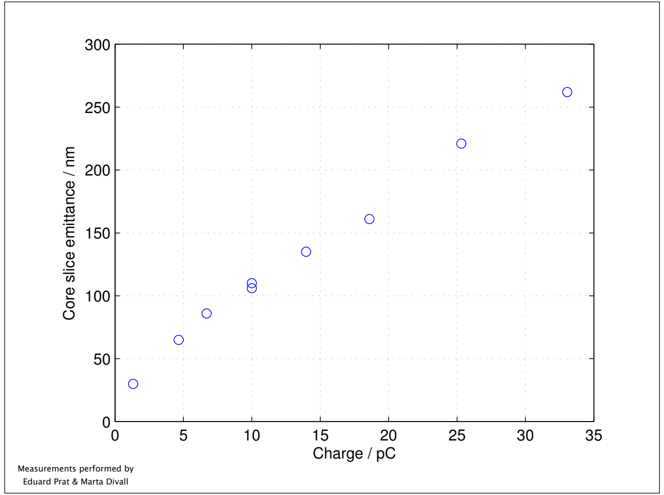
>Saturation

>COTR suppression

Slice emittance measurement of a 1.3 pC beam
Demonstration of excellent resolution (8 μm) over a large field of view (6 x 16 mm)



Measurements performed by
Eduard Prat & Marta Divall

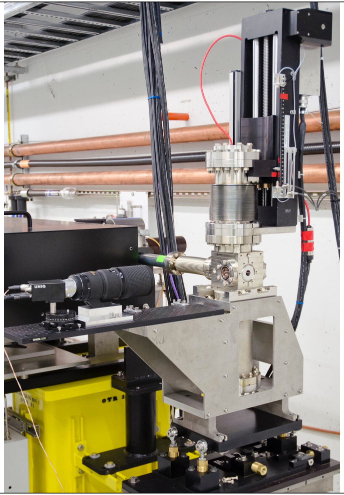


Slice emittance measurement as a function of charge.

What is remarkable:

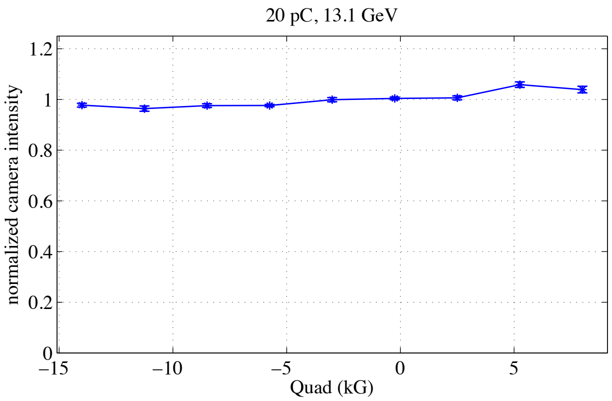
> good sensitivity (down to 1.3 pC)

> good resolution (normalized core slice emittance of 30 nm measured)



Measurements of COTR suppression
LCLS: final energy, final compression
Laser heater on

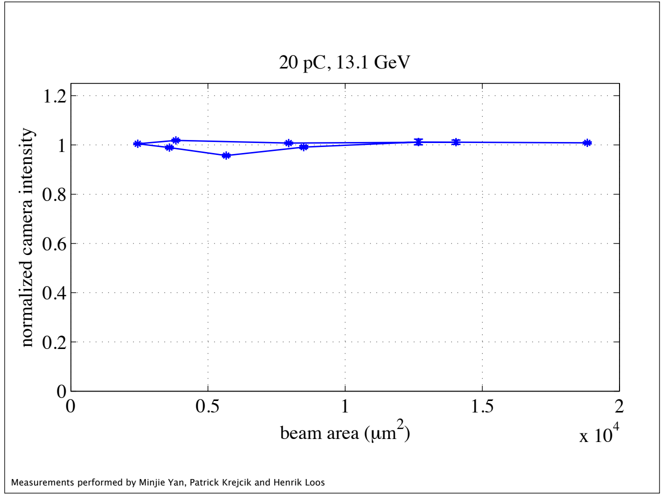
LCLS Linac-to-Undulator Line
Beam energy: up to 14.7 GeV
Bunch charge: 20…250 pC
Bunch length: 3…70 fs
Normalized emittance: 300…1600 nm
Repetition rate: 1…120 Hz



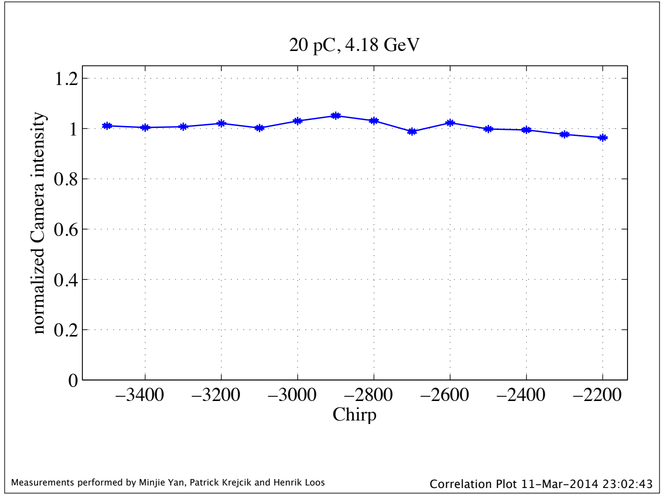
Measurements performed by Minjie Yan, Patrick Krejcik and Henrik Loos

Measurement of Saturation Effects

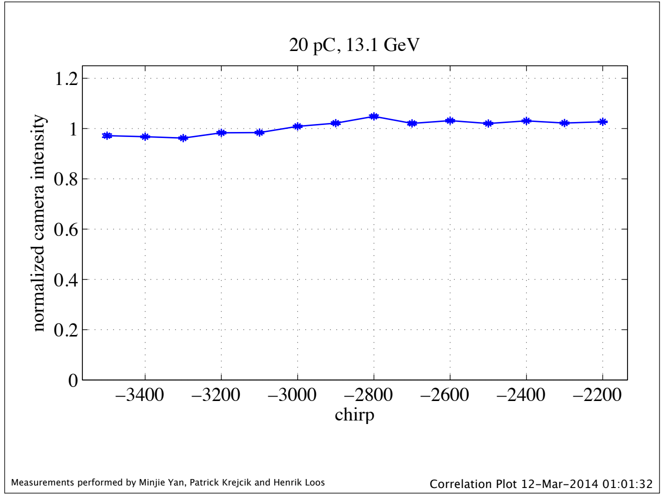
- > Change beam size with quadrupole magnet
- > Saturation: expect a dip in the middle (for smallest beam)



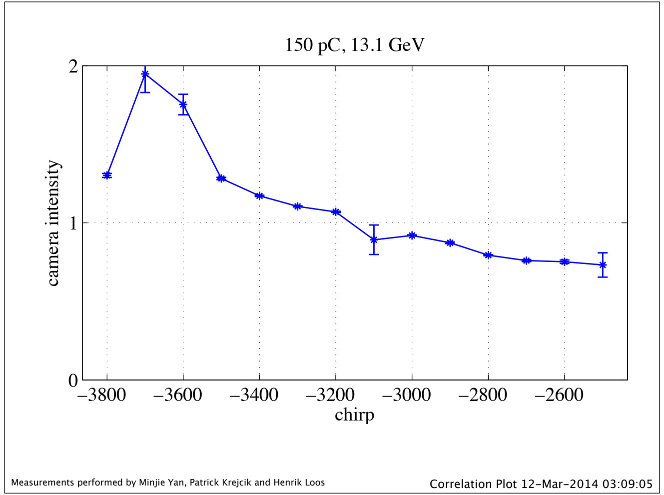
Same measurement, plotted as a function of beam area.
No dependency observed.



Measurement as a function of chirp (i.e. bunch compression): no change observed



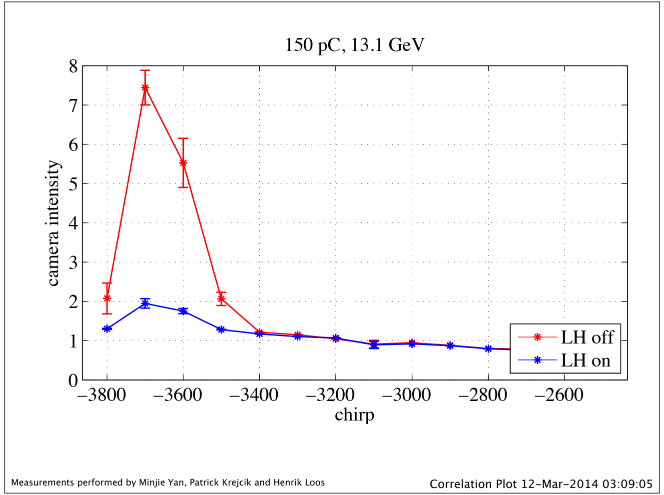
Same thing, at higher energy



Measurement at higher charge, high energy:

> some increase observed

> Factor 2, compared to factor 10’000 in OTR monitors

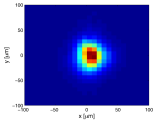


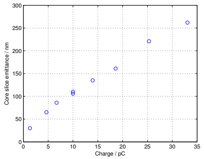
Measurement with laser heater off (this is not the nominal operation mode!)
Increased light output for highest compression

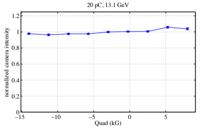
Profile Measurements in Free Electron Lasers

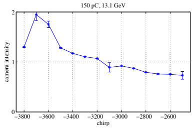
Rasmus Ischebeck, Patrick Krejcik, Henrik Loos, Eduard Prat, Volker Schlott, Vincent Thominet, Minjie Yan

> Demonstration of
  > Sensitivity
  > Resolution
  > Field of View
  > Saturation
  > Immunity to COTR









 Slides available at http://www.ischebeck.net

Rasmus Ischebeck, Patrick Krejcik, Henrik Loos, Eduard Prat, Volker Schlott, Vincent Thominet, Minjie Yan

Thank You!

- Hansueli Walther and Goran Kotrle for the technical design of the SwissFEL profile monitor
- The AMI team at PSI for manufacturing the components
- Markus Baldinger for the assembly
- Gene Kraft for coordinating the installation at LCLS
- The entire SwissFEL Injector Test Facility and LCLS Operations crews
- Joe Frisch for a slide on COTR
- Yuji Otake for a slide on SACLA profile monitors
- Daniel Ratner for an image of COTR and plots on noise suppression
- Gian Luca Orlandi for a slide on the SwissFEL wire scanner

Slides available at http://www.ischebeck.net