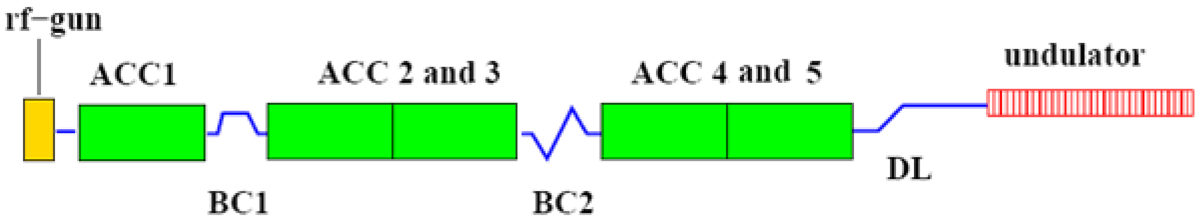
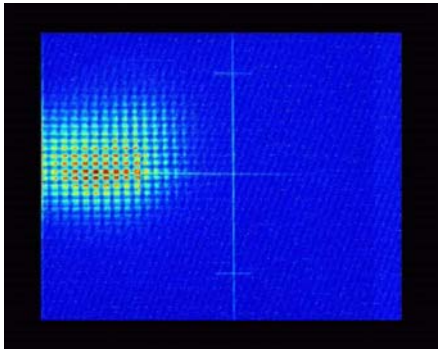
# Recent results from FLASH
## (VUV FEL at DESY)

*E. Saldin, E. Schneidmiller and M. Yurkov for FLASH team*

*June 27, 2006*

- Milestones
- Parameters of FEL radiation
- Beam dynamics: consequences for machine operation
- Tuning SASE: tools and general remarks
- Main problems
- Lasing at 13 nm
- Saturation



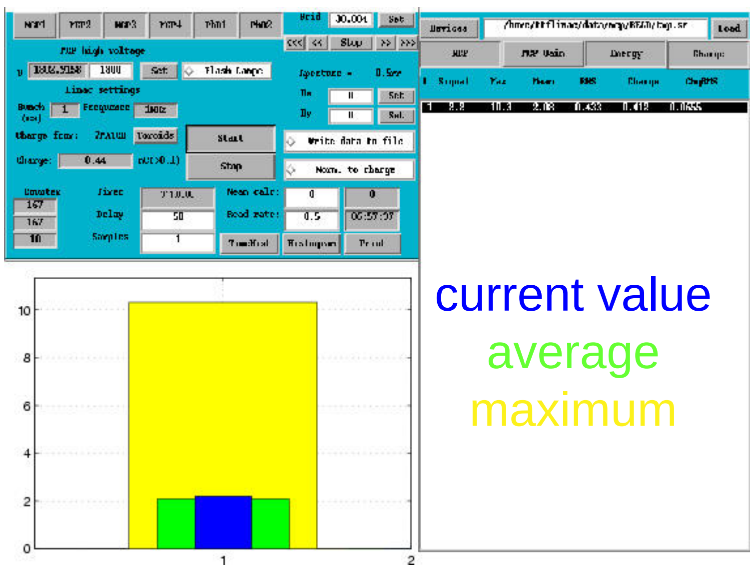



*14-29.01.2005*

# Milestones

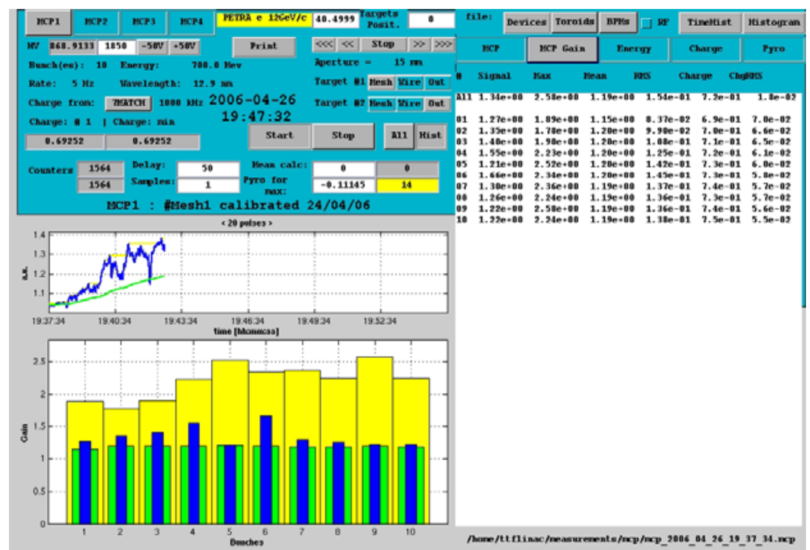
- December 2004: beam through the undulator
- January 2005: first lasing (32 nm)
- June 2005: nonlinear regime, harmonics, stable operation
- August 2005: begin of regular user runs
- November 2005: tunability 25-45 nm
- April 2006: lasing at 13 nm
- June 2006: 25 uJ av. @13 nm, 65 uJ av. @ 26 nm

14.01.2005




32 nm

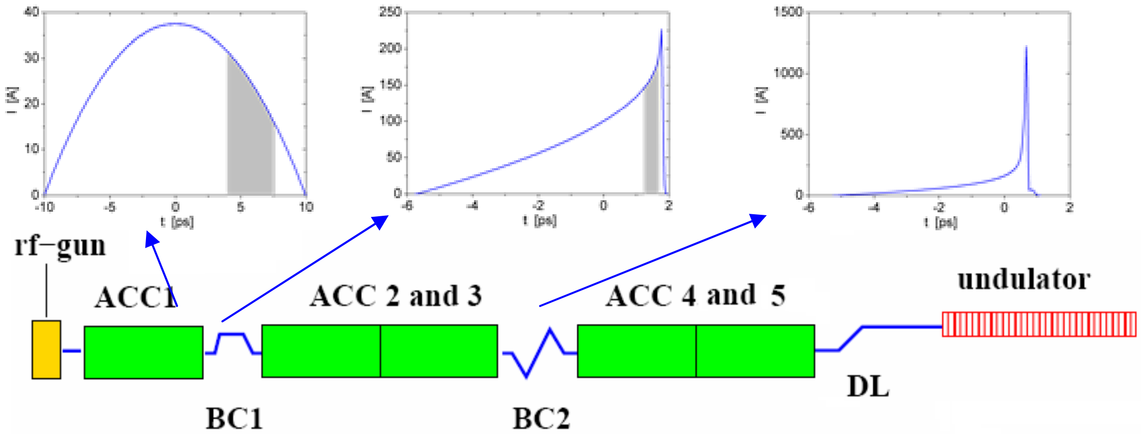
26.04.2006



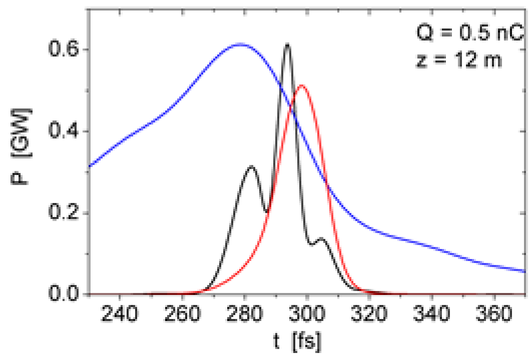

13 nm

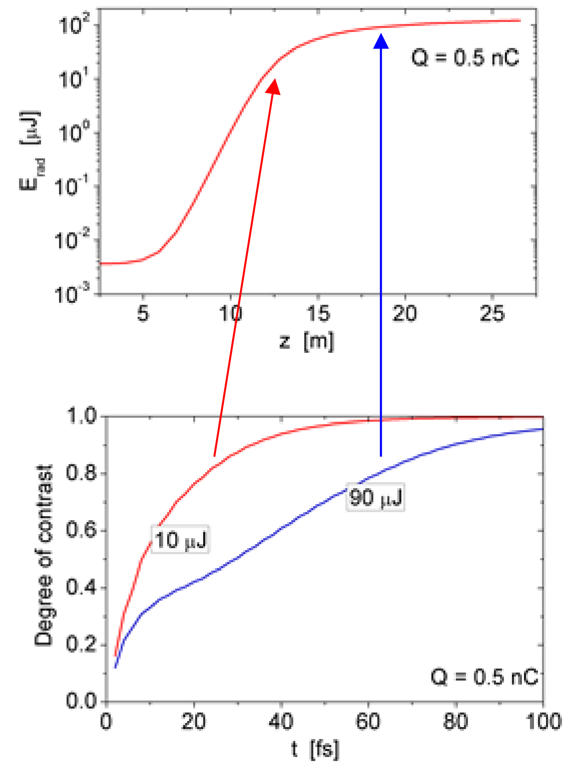
# Production of ultra-short radiation pulses in the VUV FEL

An ultra-short current spike (50-100 fs FWHM) with peak current 1-2 kA is formed in the nonlinear bunch formation system of the VUV FEL




Strong energy chirp along current spike leads to significant shortening of the radiation pulse. Minimum pulse length occurs in the end of the linear regime.

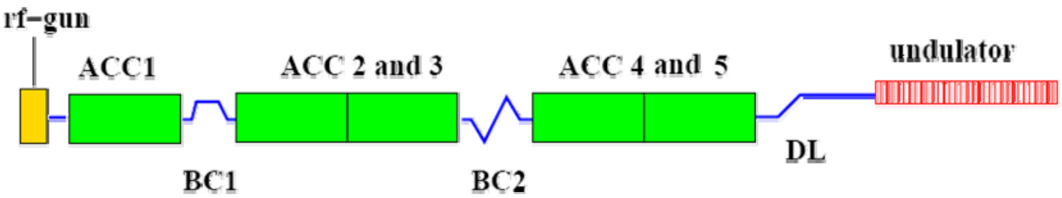


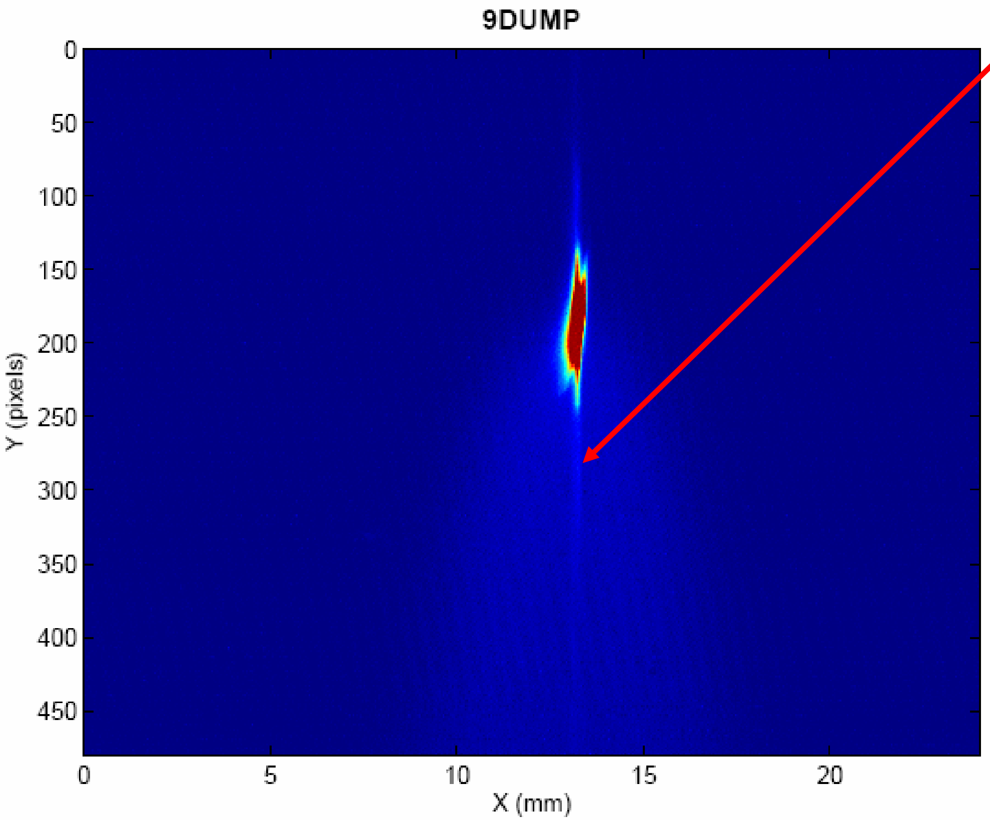

The VUV FEL is capable to produce short, down to 20 fs radiation pulses with GW-level peak power and degree of contrast 80 %:

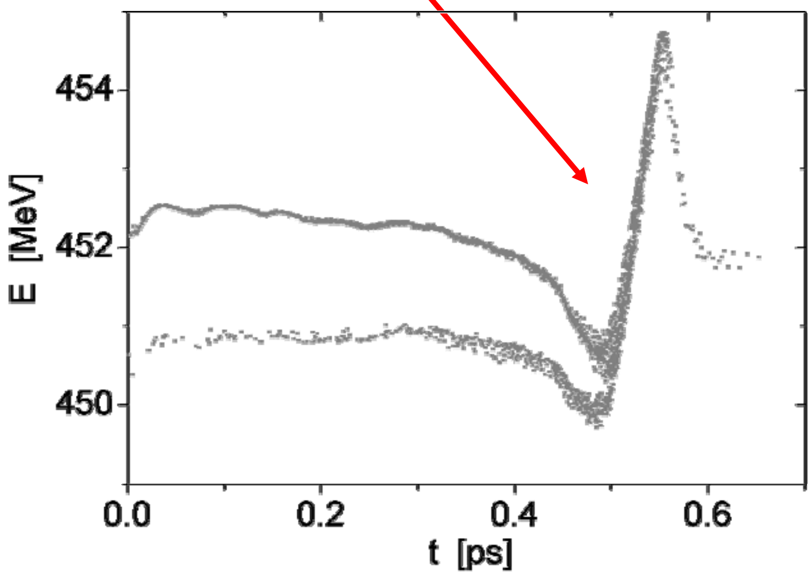
$$C(\tau) = \frac{\int_{-\tau/2}^{\tau/2} P(t)\,\mathrm{d}\,t}{\int_{-\infty}^{\infty} P(t)\,\mathrm{d}\,t}\ .$$

# Electron beam shape after bending magnet under lasing conditions




Tails are due to collective effects (space charge)



# Main problems

One can distinguish between two levels:

•Zero-order: no compression, single-particle dynamics (except for injector part), standard work on accelerator performance using standard diagnostics

We still have a lot to do at this level

•Making beam for SASE: compression, strong collective effects, unprecedented beam parameters, poor diagnostics

Main method: multi-knob empirical tuning

# Main problems

## Undulator orbit

no working procedures but empirical tuning; suspicion of stray fields; suspicion of season drifts; work in progress

## Losses in the undulator (mainly dark current)

radiation dose; sometimes a compromise between losses and FEL performance; difficult to play with orbit; fast kicker to be commissioned

## Laser/RF phase stability: jitters and slow drifts

reduces average intensity and stability of SASE; complicates tuning; improved since first lasing, to be improved further

### Dispersion, dogleg

…

# Main problems

Commissioning 445-MeV optics for the TTF2 linac: Effect of the collimator dogleg on the longitudinal phase space distribution of the beam.

V. Balandin, N. Golubeva

March 3, 2005

## 4 Beam with chirp in energy (compression of nominal beam)

The 6D tracking of particles were performed using a beam with chirp in energy, which gives the compression of the nominal beam in the collimator dogleg. Beam parameters (rms) used at the dogleg entrance were the following (green points in figure 10):

- Normalized emittances: $\varepsilon_{nx,ny} = 3\,mm \cdot mrad$.
- Bunch length: $\sigma_z = 7\,\mu m$.
- Chirp in energy :

  $\Delta E/E_0 = 3 \cdot 10^{-3}$ (correlated energy spread).

  $\alpha_z = -10$ (compression in dogleg, particles in the head of the bunch have larger energy than particles in the tail).

With such energy chirp the beam gets an additional longitudinal compression during the dogleg passage. And though this effect is small for the perfect beam, the variations of the beam energy or/and the variations of the beam transverse positions at the dogleg entrance could change the situation considerably, and the amount of this changes strongly depends on sextupole settings. Figures 9 - 16 show the examples.

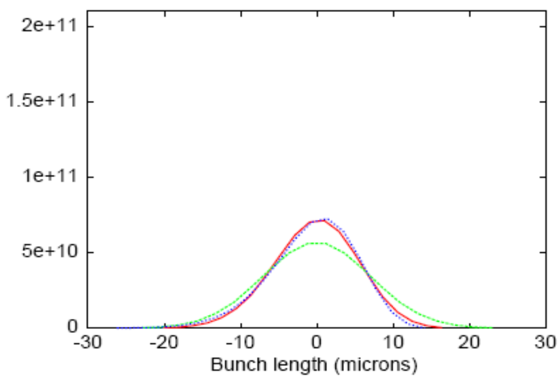



Figure 9: Beam with energy chirp (compression). Profiles of longitudinal beam density (arbitrary units) at the exit of the dogleg with sextupoles off (blue) and with sextupoles on (red). For comparison, green curve shows the density profile of the perfect beam without chirp in energy.

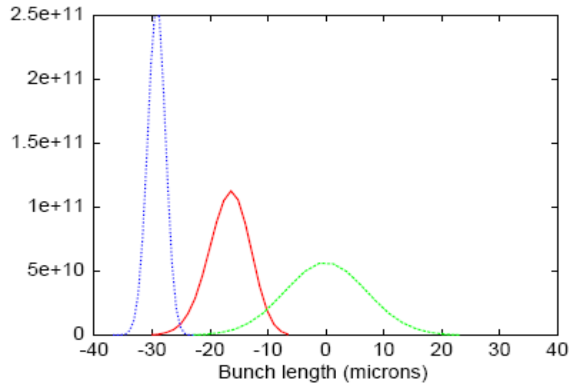



Figure 15: Beam with energy chirp (compression). Effect of the beam energy deviation at the dogleg entrance ($\Delta E/E_0 = +2\%$). Profiles of longitudinal beam density (arbitrary units) at the exit of the dogleg with sextupoles off (blue) and with sextupoles on (red) are shown. For comparison, green curve shows the density profile of the perfect beam without chirp in energy.

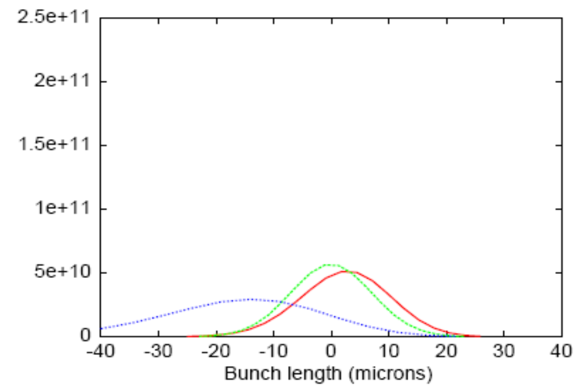
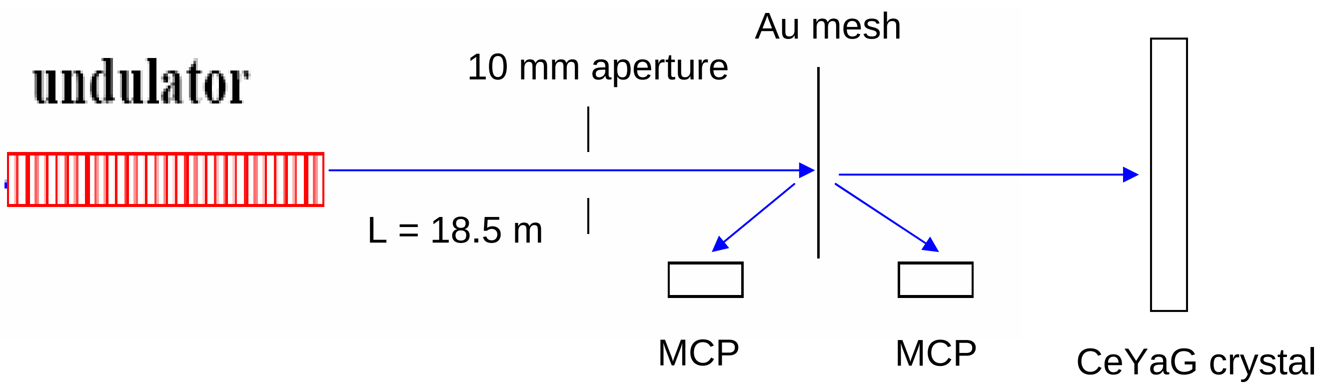


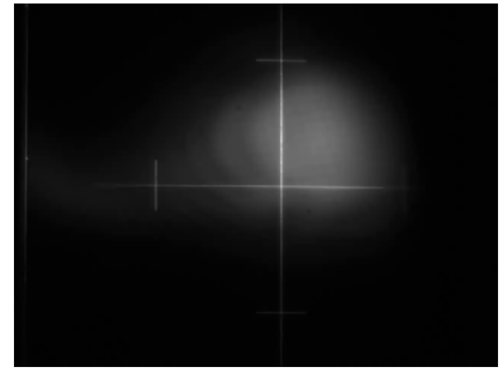

Figure 13: Beam with energy chirp (compression). Effect of the beam energy deviation at the dogleg entrance ($\Delta E/E_0 = -2\%$). Profiles of longitudinal beam density (arbitrary units) at the exit of the dogleg with sextupoles off (blue) and with sextupoles on (red) are shown. For comparison, green curve shows the density profile of the perfect beam without chirp in energy.

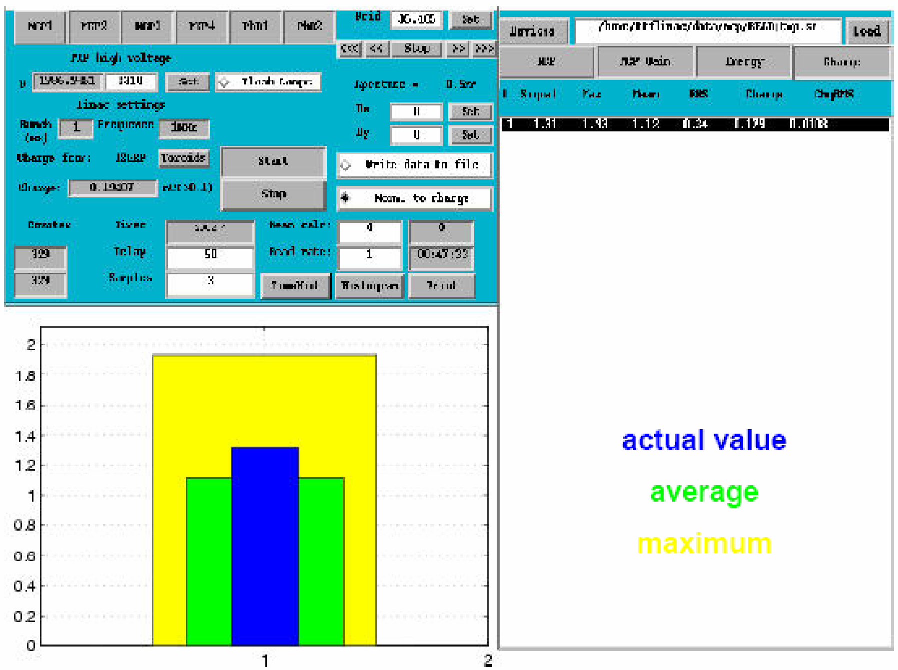
*Uncontrolled compaction factor + energy chirp ➔ dogleg can work as compressor/decompressor ➔ high sensitivity to energy changes ➔ significant complication for wavelength tuneability of the radiation*

*For an ideal dogleg R56~0.5 mm (sign opposite to that of chicane). For an energy chirp (due to space charge) ~1% over 20-30 um one gets 20-30 % compression. If transverse dispersion is not closed, the R56 can effectively be much larger, can also change sign. Thus, peak current and spike widths after the dogleg depend on energy, dogleg settings, misalignment, incoming orbit etc.*

# Main tools for SASE search and optimization



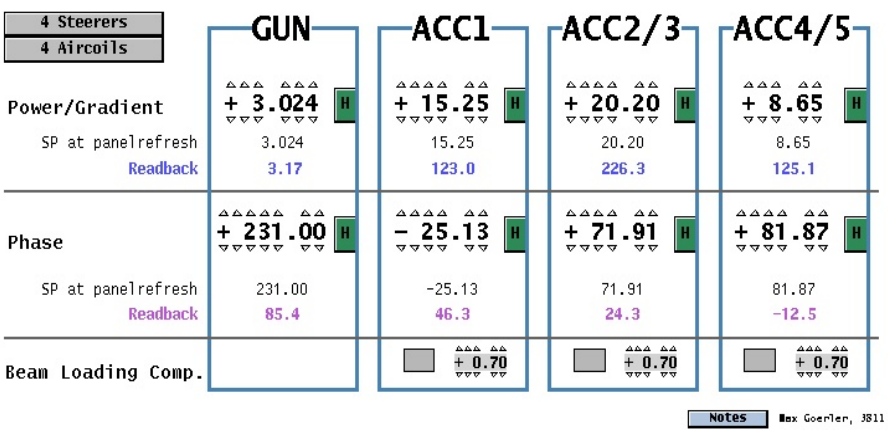


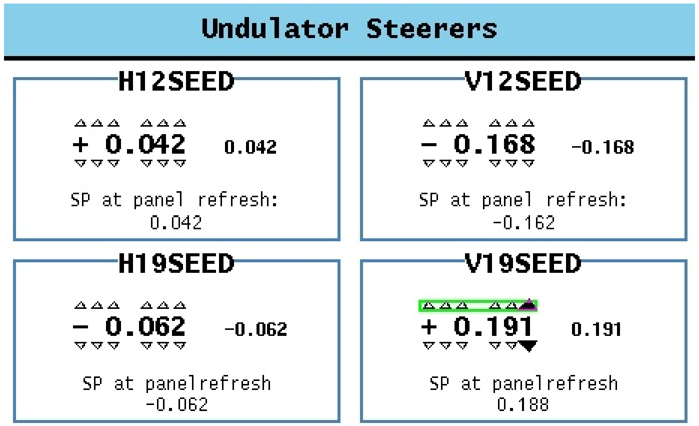

## Micro-channel plate (MCP) detector

- Low electronic noise ( about 1 mV)
- Low radiation background (about 1 mV)
- High level of signal (above 100 mV)
- Large dynamic range
- Normalization of MCP signal to bunch charge
- Reliable detection of amplification just above spontaneous emission level

# How do we tune SASE?

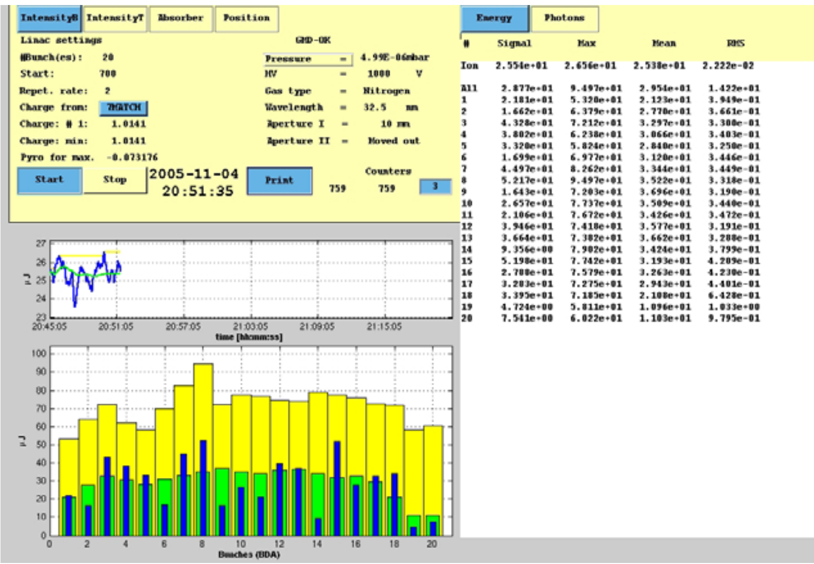
- Starting from scratch (after shutdown, new wavelength etc.): sometimes easy, but often a complicated task; extensive scan of parameter space, many subjective (sometimes intuitive) decisions to be taken
- Fine tuning (keep/improve) during user operation: not so many knobs involved (RF settings + 4 steerers), now relatively easy for every operator

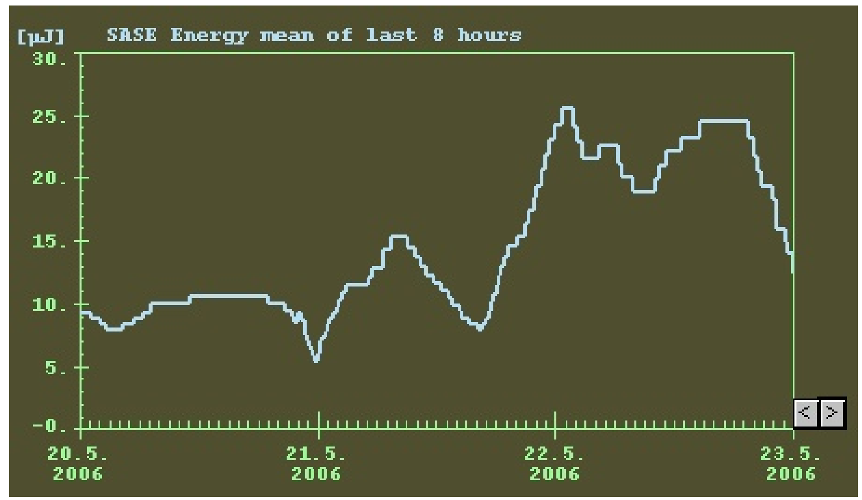


# Intensity monitoring during user operation

Gas monitor detector (GMD): non-destructive intensity measurement




Experience of the FLASH team has grown significantly: smooth user runs as a result

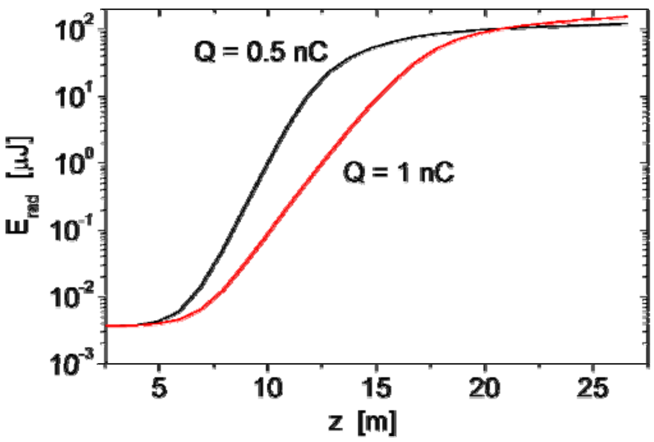
# Where we are now?

- *The VUV FEL works.* At the moment we operate unique user facility providing photon beams with ultimate peak brilliance, 100 millions times above the best SR storage rings. *Users are happy:*

***10.02.2006: Summary from FEL users*** We loved those 15 microJ pulses! Today we measured time-delay holograms of exploding latex spheres (pump-probe, using a multilayer mirror to reflect the pulse back onto the particle). Will post picture in logbook. Thanks for all the photons. (H.Chapman et al., BL2)*

***18.02.2006: Summary from FEL users*** WHAT AN EXCELLENT RUN!!! We really enjoyed the 15-22 microJ average and were able to complement our previous cluster data with higher pulse energies. This shift with higher energies was very valuable to us. Hopefully we can get similar intensities tomorrow...*
** Christoph Bostedt, TU Berlin*

## How far is the limit for radiation intensity?

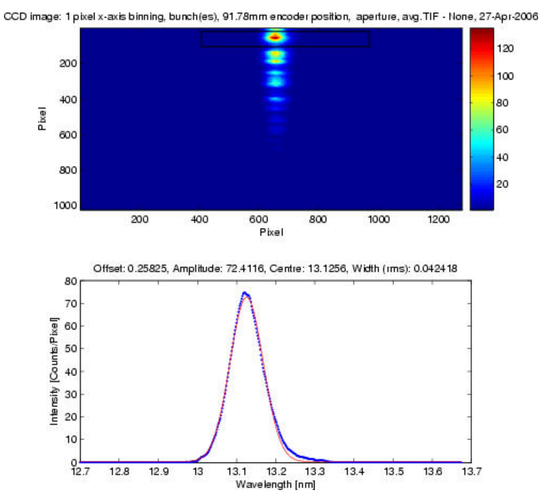


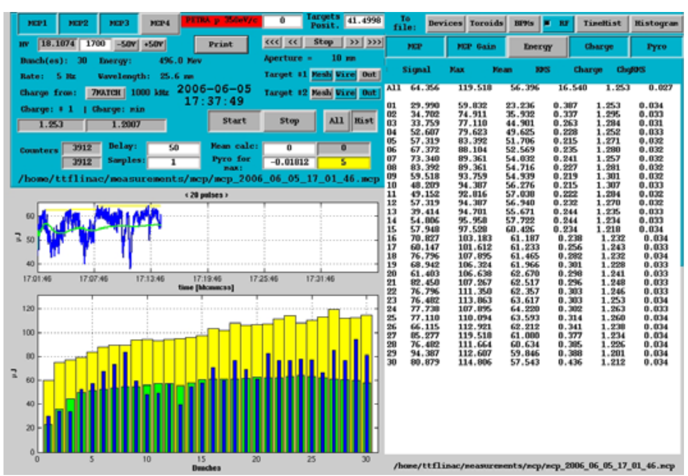

For an „ideal“ machine limit for average energy in the radiation pulse is 100-150 uJ

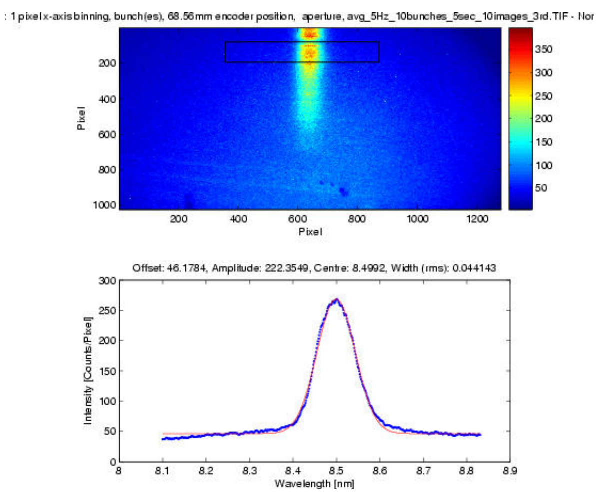
(TESLA FEL 2004-06)

# Experimental results for main parameters of the FEL radiation

- Wavelength range (fundamental): 13-48 nm
- FEL third harmonic: 8.5 nm
- Pulse energy: up to 65 uJ (aver.), 120 uJ (peak)
- Peak power: > 1 GW
- Average power: up to 10 mW
- Pulse duration (FWHM): 20-50 fs
- Spectral width (FWHM): 0.5-1 %
- Peak brilliance: up to $5\times10^{29}$

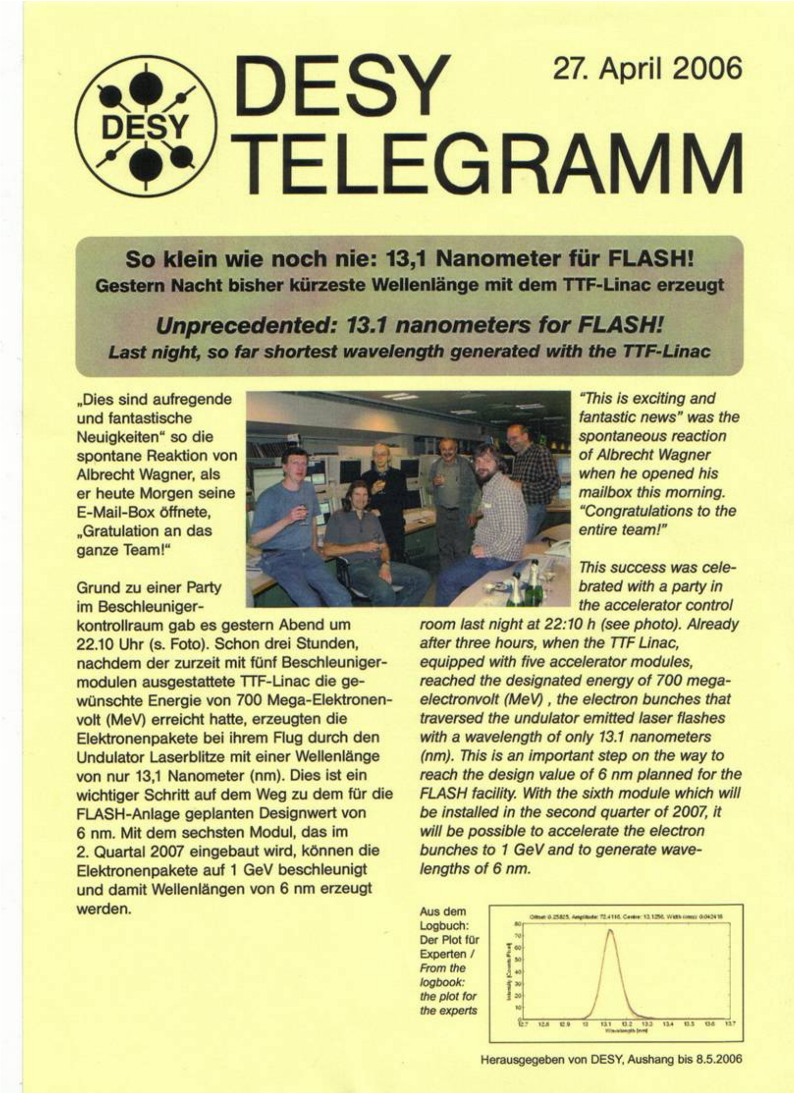





13.1 nm (1st harm.) average power up to 10 mW 8.5 nm (3rd harm.)

# First lasing at 13 nm



DESY TELEGRAMM

27. April 2006

**So klein wie noch nie: 13,1 Nanometer für FLASH!**
**Gestern Nacht bisher kürzeste Wellenlänge mit dem TTF-Linac erzeugt**

***Unprecedented: 13.1 nanometers for FLASH!***
***Last night, so far shortest wavelength generated with the TTF-Linac***

„Dies sind aufregende und fantastische Neuigkeiten“ so die spontane Reaktion von Albrecht Wagner, als er heute Morgen seine E-Mail-Box öffnete, „Gratulation an das ganze Team!“

Grund zu einer Party im Beschleuniger-kontrollraum gab es gestern Abend um 22.10 Uhr (s. Foto). Schon drei Stunden, nachdem der zurzeit mit fünf Beschleuniger-modulen ausgestattete TTF-Linac die gewünschte Energie von 700 Mega-Elektronen-volt (MeV) erreicht hatte, erzeugten die Elektronenpakete bei ihrem Flug durch den Undulator Laserblitze mit einer Wellenlänge von nur 13,1 Nanometer (nm). Dies ist ein wichtiger Schritt auf dem Weg zu dem für die FLASH-Anlage geplanten Designwert von 6 nm. Mit dem sechsten Modul, das im 2. Quartal 2007 eingebaut wird, können die Elektronenpakete auf 1 GeV beschleunigt und damit Wellenlängen von 6 nm erzeugt werden.

*"This is exciting and fantastic news" was the spontaneous reaction of Albrecht Wagner when he opened his mailbox this morning. "Congratulations to the entire team!"*

*This success was celebrated with a party in the accelerator control room last night at 22:10 h (see photo). Already after three hours, when the TTF Linac, equipped with five accelerator modules, reached the designated energy of 700 mega-electronvolt (MeV), the electron bunches that traversed the undulator emitted laser flashes with a wavelength of only 13.1 nanometers (nm). This is an important step on the way to reach the design value of 6 nm planned for the FLASH facility. With the sixth module which will be installed in the second quarter of 2007, it will be possible to accelerate the electron bunches to 1 GeV and to generate wavelengths of 6 nm.*

Aus dem Logbuch: Der Plot für Experten / *From the logbook: the plot for the experts*

Herausgegeben von DESY, Aushang bis 8.5.2006

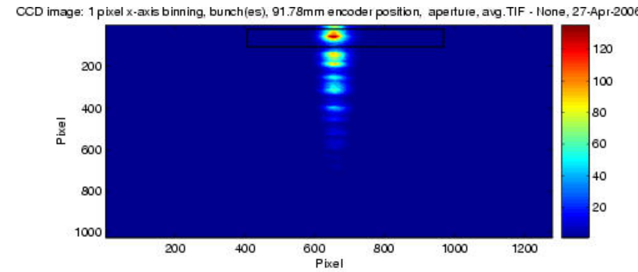
## Quick and easy lasing:

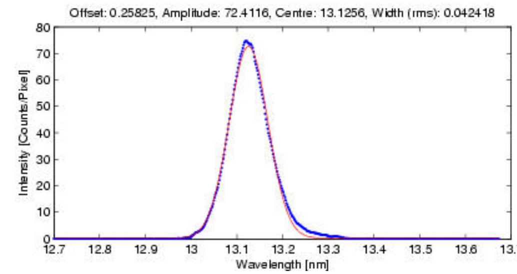
- Machine was relatively well prepared (optics, undulator BPMs)
- It was stable
- As expected, operation at higher energy was easier (SC effects less important)
- Experience also helped

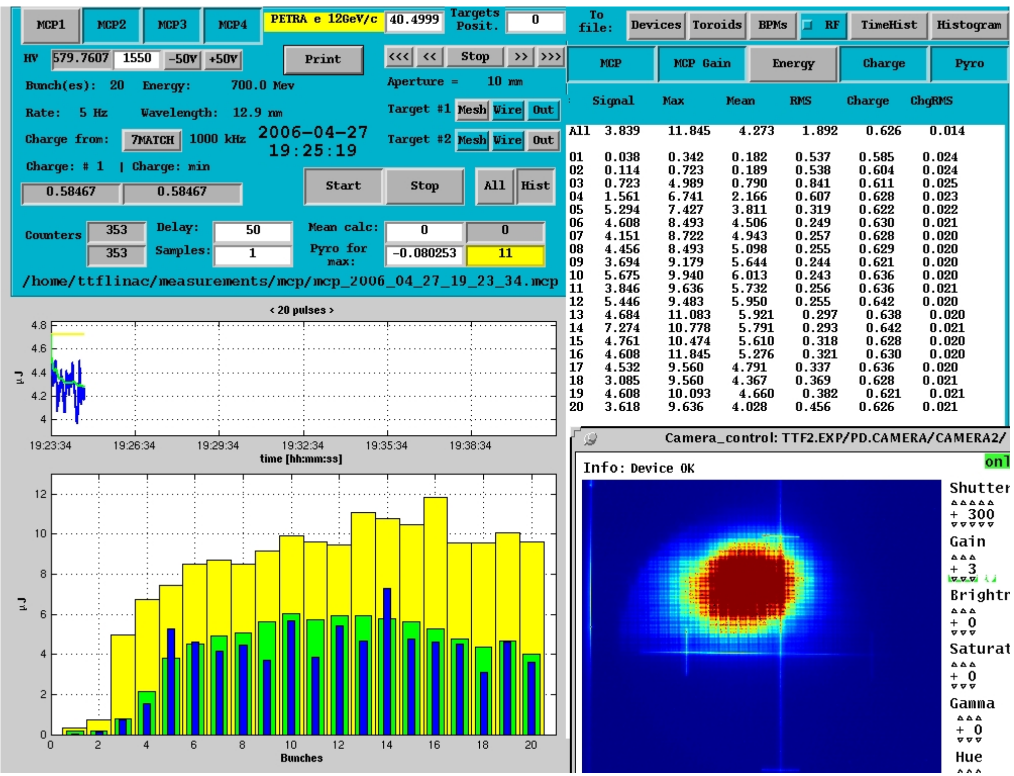
# First lasing at 13 nm

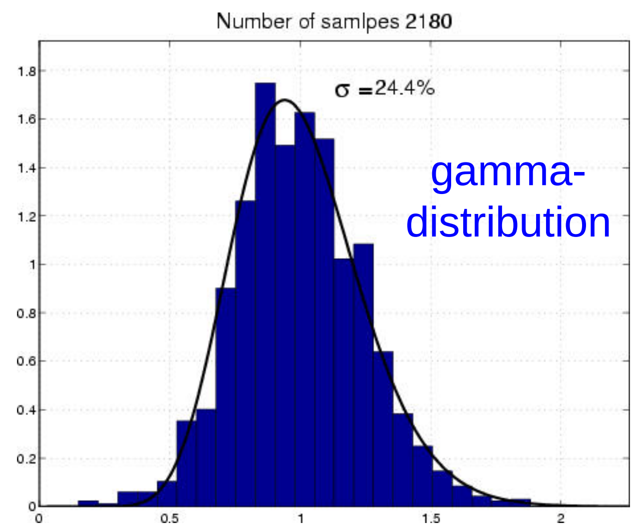
## Next day: after some tuning

~5 uJ (average)



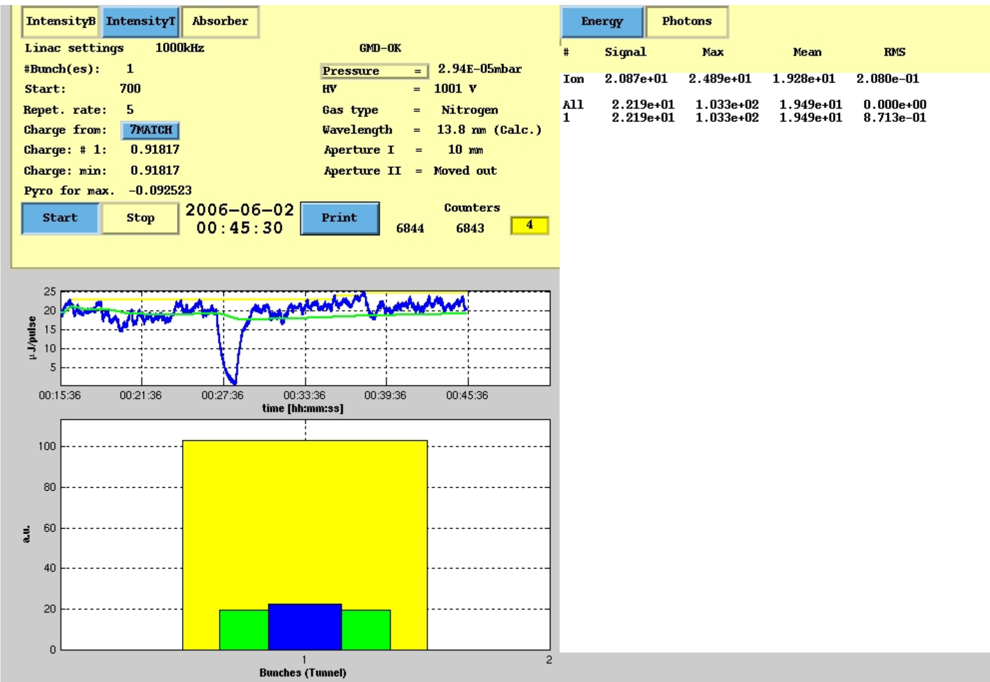



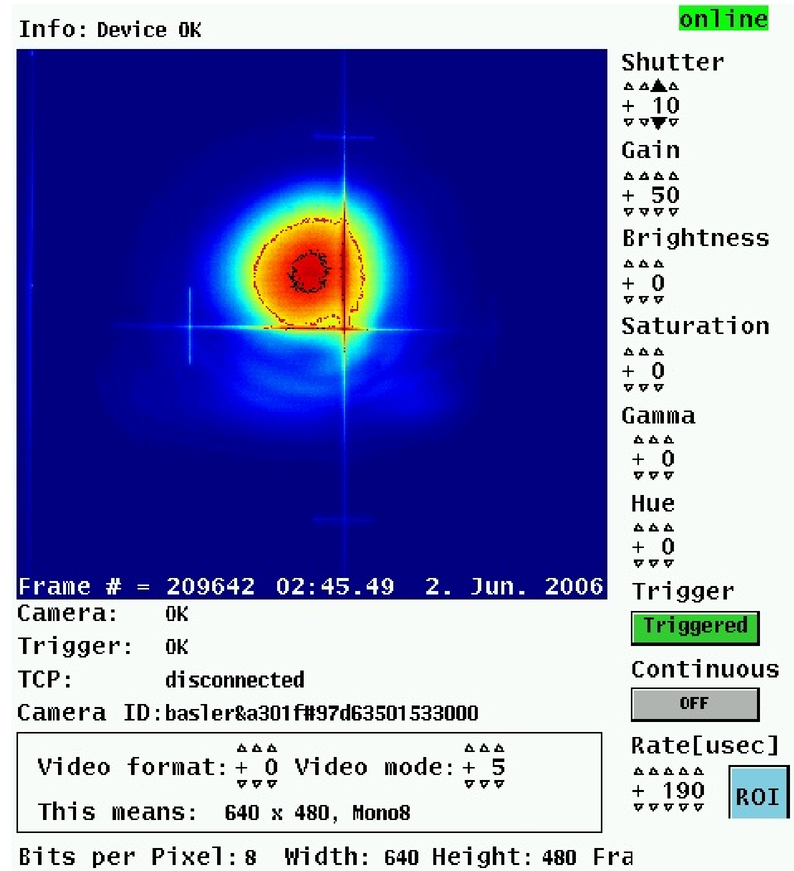



# 13.8nm: 25 uJ average

02.06.2006 00:45ttflinac**/tmp/GMD_DAQTool.jpg**

SASE during user operation. SASE drop around 0:30 is due to switching on absorber.

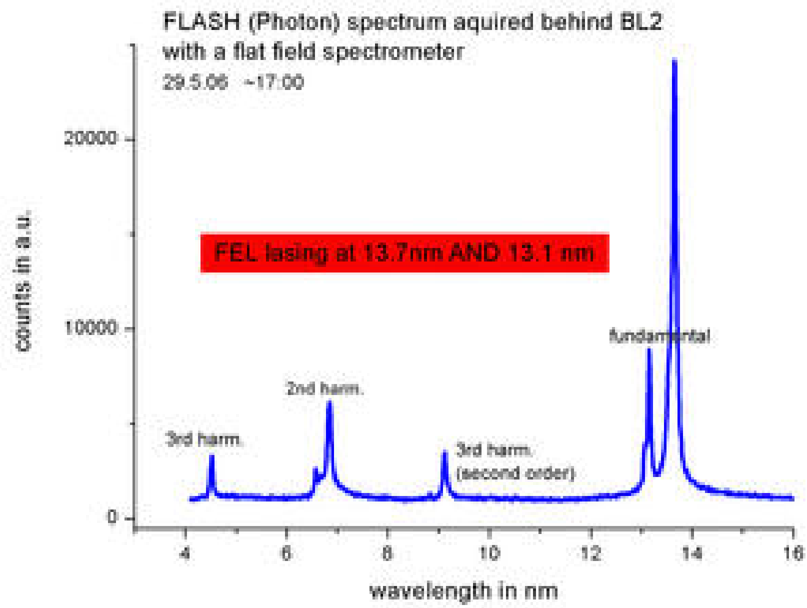


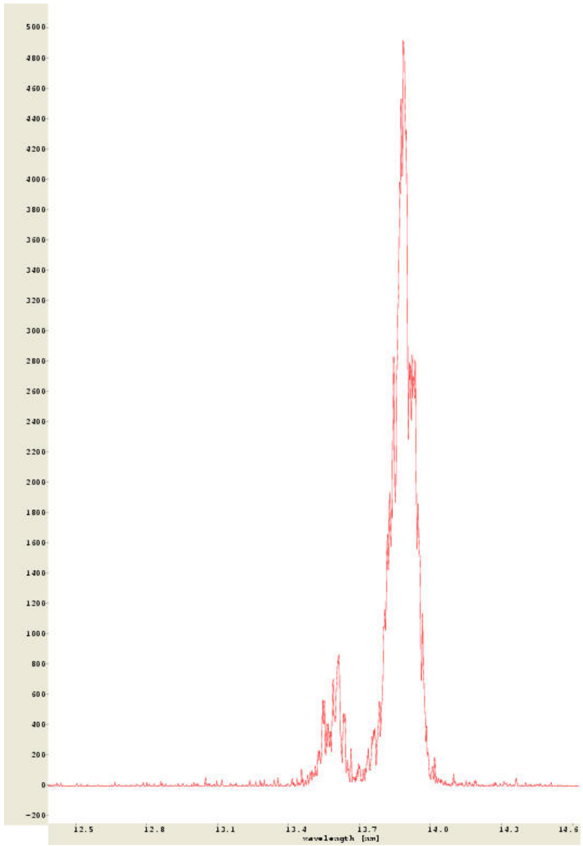
# 13.8nm: two-colour mode of operation

30.05.2006 18:15 PP team

**FEL spectrum at BL2 when 2 wavelength are lasing**

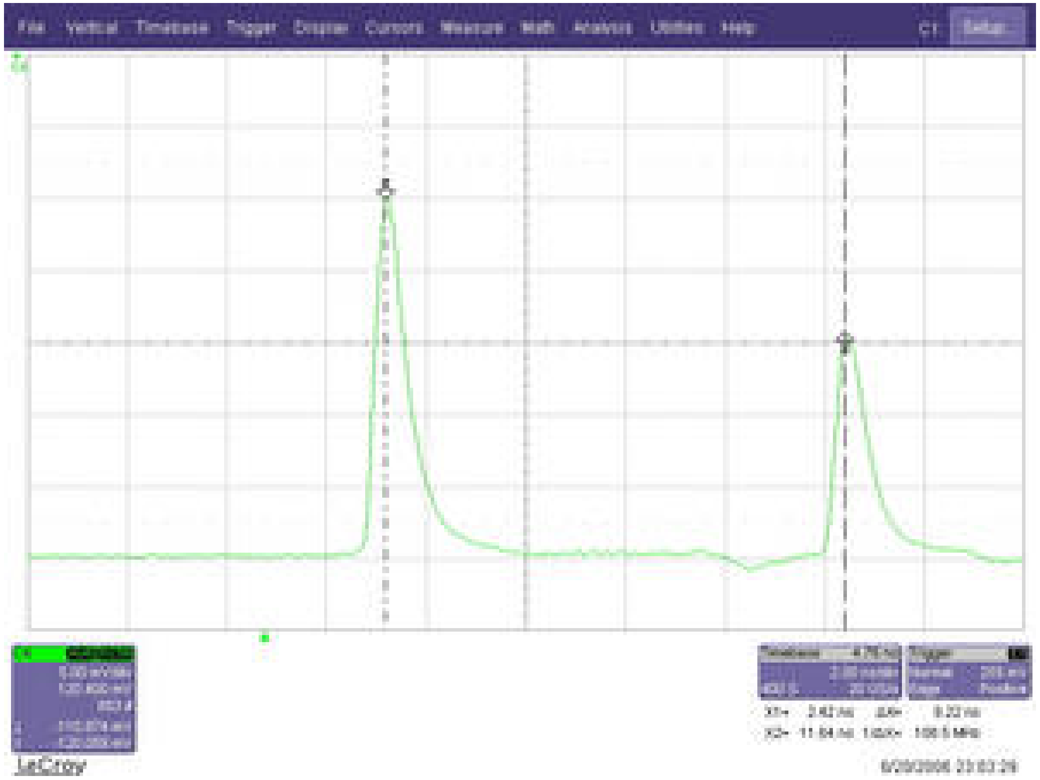



**02.06.2006 15:22 profile of singleshot**



# Lasing with double electron pulses

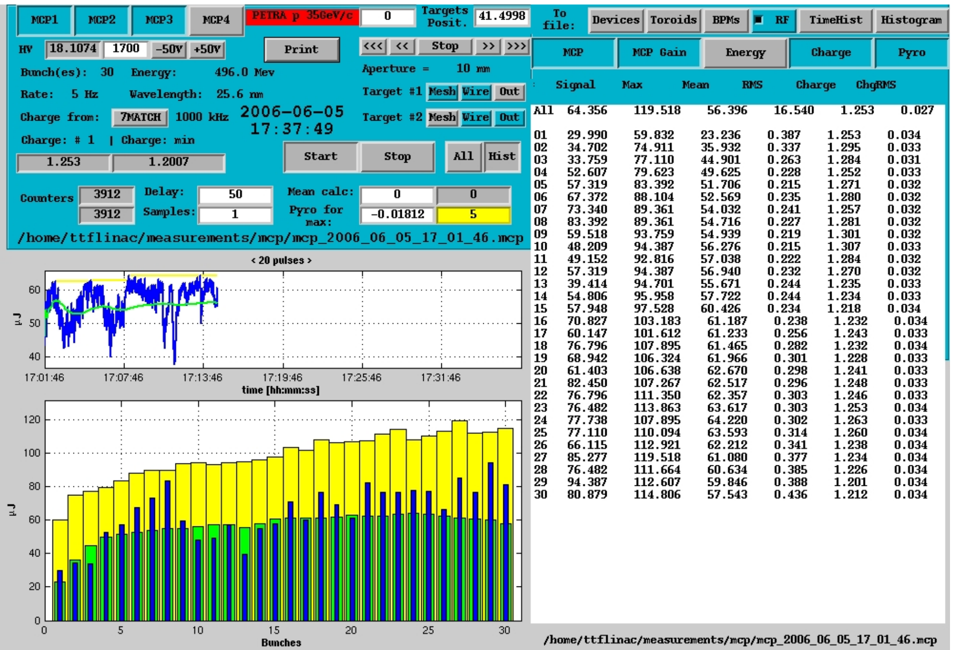
**20.06.2006 23:45**
**Double pulses at 32 nm wavelength**




**Photoinjector laser produces doubled pulses separated by 9.2 ns (12 rf periods of 1.3 GHZ). Then double electron pulses produce SASE**

# 25.7 nm: 65 uJ average

05.06.2006 17:37ttflinac/**tmp/MCPTool.jpg**




| | Signal | Max | Mean | RMS | Charge | ChgRMS |
|---|---|---|---|---|---|---|
| All | 64.356 | 119.518 | 56.396 | 16.540 | 1.253 | 0.027 |
| 01 | 29.990 | 59.832 | 23.236 | 0.387 | 1.253 | 0.034 |
| 02 | 34.702 | 74.911 | 35.932 | 0.337 | 1.295 | 0.033 |
| 03 | 33.759 | 77.110 | 44.901 | 0.263 | 1.284 | 0.031 |
| 04 | 52.607 | 79.623 | 49.625 | 0.228 | 1.252 | 0.033 |
| 05 | 57.319 | 83.392 | 51.706 | 0.215 | 1.271 | 0.032 |
| 06 | 67.372 | 88.104 | 52.569 | 0.235 | 1.280 | 0.032 |
| 07 | 73.340 | 89.361 | 54.032 | 0.241 | 1.257 | 0.032 |
| 08 | 83.392 | 89.361 | 54.716 | 0.227 | 1.281 | 0.032 |
| 09 | 59.518 | 93.759 | 54.939 | 0.219 | 1.301 | 0.032 |
| 10 | 48.209 | 94.387 | 56.276 | 0.215 | 1.307 | 0.033 |
| 11 | 49.152 | 92.816 | 57.038 | 0.222 | 1.284 | 0.032 |
| 12 | 57.319 | 94.387 | 56.940 | 0.232 | 1.270 | 0.032 |
| 13 | 39.414 | 94.701 | 55.671 | 0.244 | 1.235 | 0.033 |
| 14 | 54.806 | 95.958 | 57.722 | 0.244 | 1.234 | 0.033 |
| 15 | 57.948 | 97.528 | 60.426 | 0.234 | 1.218 | 0.034 |
| 16 | 70.827 | 103.183 | 61.187 | 0.238 | 1.232 | 0.034 |
| 17 | 60.147 | 101.612 | 61.233 | 0.256 | 1.243 | 0.033 |
| 18 | 76.796 | 107.895 | 61.465 | 0.282 | 1.232 | 0.034 |
| 19 | 68.942 | 106.324 | 61.966 | 0.301 | 1.228 | 0.033 |
| 20 | 61.403 | 106.638 | 62.670 | 0.298 | 1.241 | 0.033 |
| 21 | 82.450 | 107.267 | 62.517 | 0.296 | 1.248 | 0.033 |
| 22 | 76.796 | 111.350 | 62.357 | 0.303 | 1.246 | 0.033 |
| 23 | 76.482 | 113.863 | 63.617 | 0.303 | 1.253 | 0.034 |
| 24 | 77.738 | 107.895 | 64.220 | 0.302 | 1.263 | 0.033 |
| 25 | 77.110 | 110.094 | 63.593 | 0.314 | 1.260 | 0.034 |
| 26 | 66.115 | 112.921 | 62.212 | 0.341 | 1.238 | 0.034 |
| 27 | 85.277 | 119.518 | 61.080 | 0.377 | 1.234 | 0.034 |
| 28 | 76.482 | 111.664 | 60.634 | 0.385 | 1.226 | 0.034 |
| 29 | 94.387 | 112.607 | 59.846 | 0.388 | 1.201 | 0.034 |
| 30 | 80.879 | 114.806 | 57.543 | 0.436 | 1.212 | 0.034 |

05.06.2006 21:52

1. SASE regime tuned in the morning shift was stable during whole shift which allowed to take statistical measurements. Significant fraction of the shift has been disturbed by PETRA/HERA activity,
and this will complicate a lot data analysis.
2. Bad news is that UND6 does not produce radiation at all. We failed to find mover positions to align trajectory for lasing in UND6. May be we did not have enough time and luck. However, this looks to be suspicious if we remember high radiation level measured last weeks in UND6. One needs to check what may happen. There can be nasty things like shortcut in quad, or something else.

---

07.06.2006 20:23 MKK shift, Castro and Polzin went to the tunnel.

We have measured the voltage difference at the quadrupoles:

| | Q6 | Q5 |
|---|---|---|
| UND1 | 247 | 270 |
| UND2 | 244 | 268 |
| UND3 | 242 | 266 |
| UND4 | 247 | 266 |
| UND5 | 43 | 274 |

all values in mV

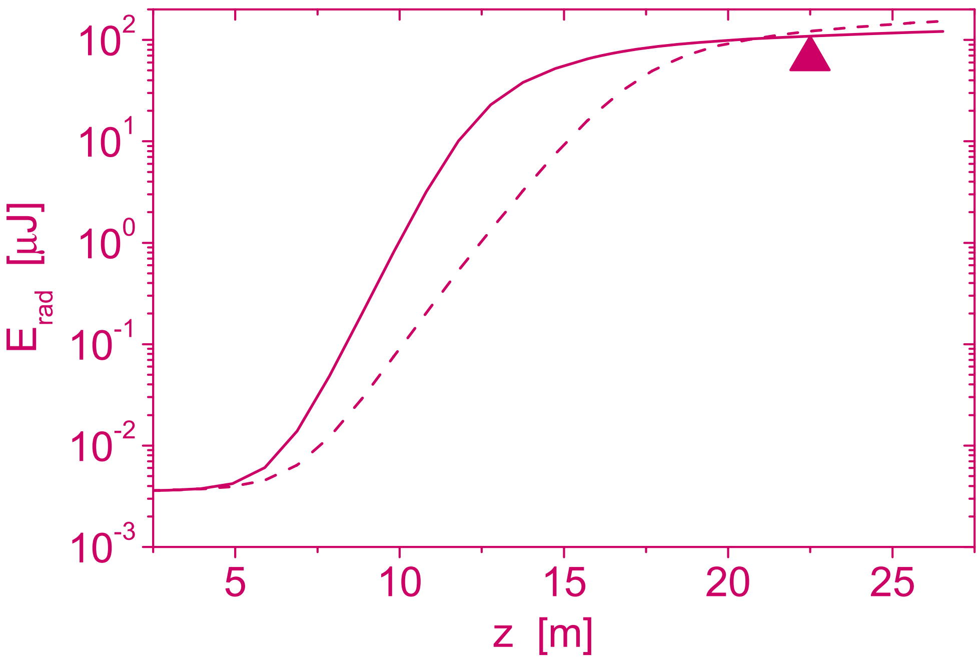
after MKK repaired the shortcut in Q6UND5
we have measured 246 mV

We have informed the run-coordinators.

This shortcut is the best explanation for the vertical big beam size and the losses in UND6.

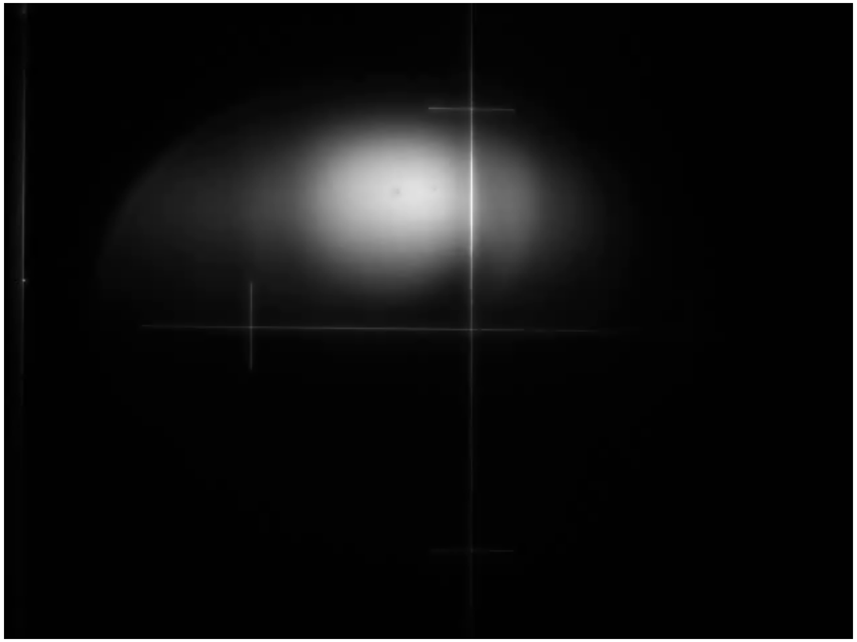
Only 5 modules contributed to SASE

# 25.7 nm: average energy

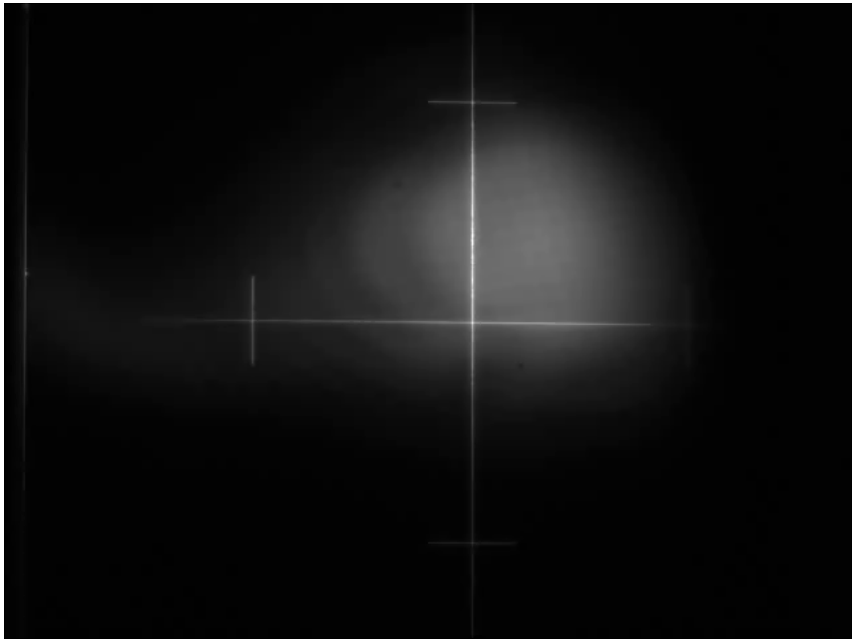



Average radiation energy (TESLA FEL 2004-06).
Triangle: measurements on 05.06.2006.

# Angular divergence: nearly diffraction limited

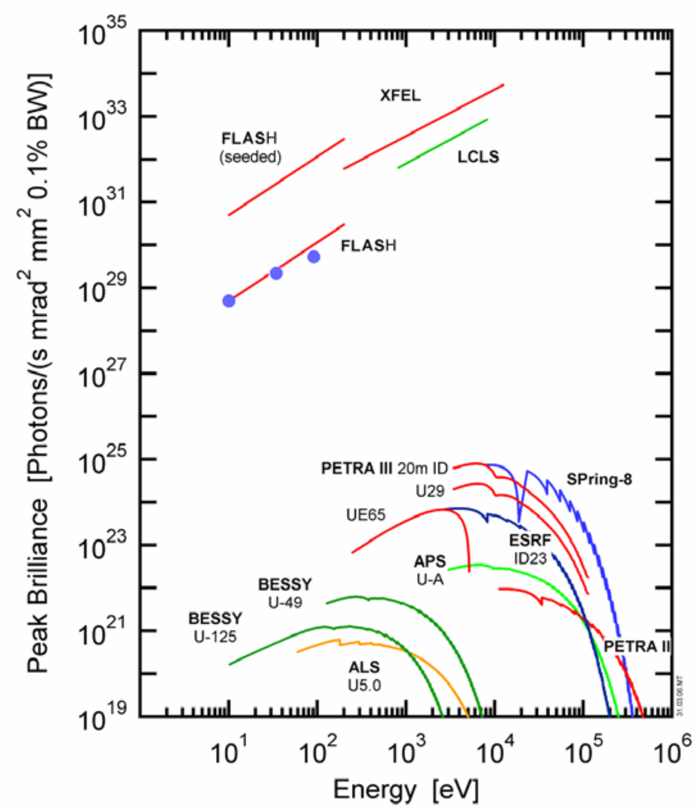


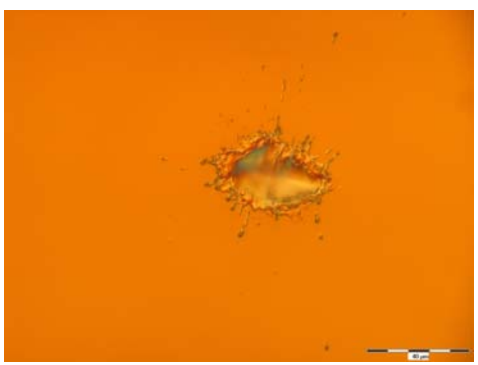
13.8 nm



25.7 nm

# Summary



•The first VUV FEL user facility works. At the moment we operate unique user facility providing photon beams with ultimate peak brilliance, 100 millions times above the best SR storage rings.

• Lasing at FLASH has been demonstrated in the range of wavelengths from 13.1 to 45 nm.

•The best performance of FLASH has been obtained in the end of user run in June 2006. At the wavelength of 25.7 nm average energy in the radiation pulse was 65 uJ, and peak values were up to 120 uJ . At the wavelength of 13.9 nm average energy in the radiation pulse was up to 25 uJ. With these numbers peak brilliance is $1.5 \times 10^{29}$ and $5 \times 10^{29}$ photons/(s mrad$^2$ mm$^2$ (0.1 % bandwidth)) for the wavelengths 25.7 and 13.9 nm, respectively.

•Design goals for the present machine configuration are reached in both aspects, minimum wavelength (which is limited with present energy of accelerator) and maximum output power: FLASH currently produces GW-level, laser-like VUV radiation pulses on a sub-50 fs scale in a good agreement with theoretical predictions .