FEL2007
Aug 26-31, 2007, Budker INP,
Новосибирск, Russia

FLASH
Free-Electron Laser in Hamburg

Operational Experience with FLASH

Siegfried Schreiber, DESY

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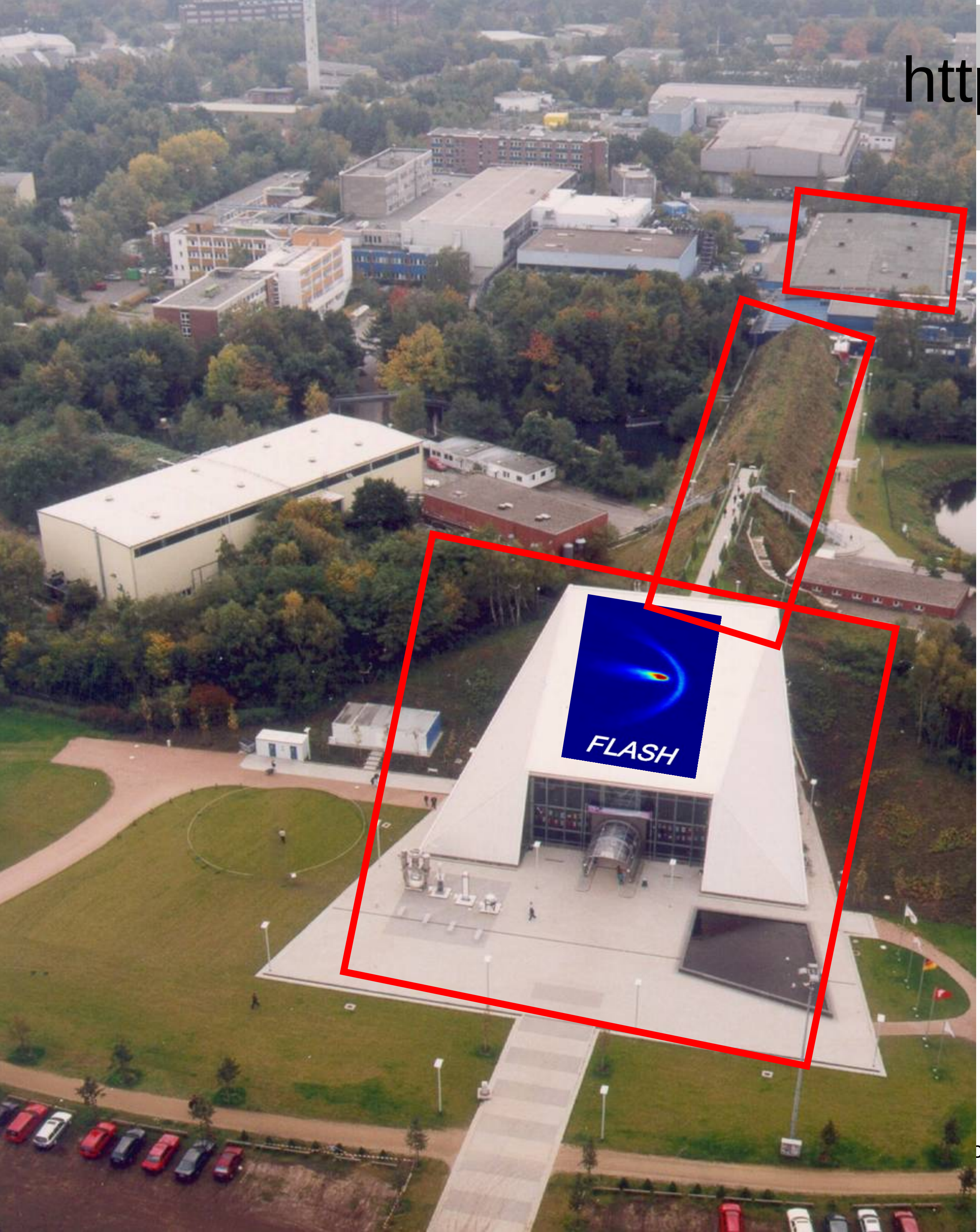
- FLASH – Free Electron Laser User Facility
- VUV/EUV lasing
- Performance and operational issues
- Summary and Outlook

DESY Hamburg, Germany

http://flash.desy.de/



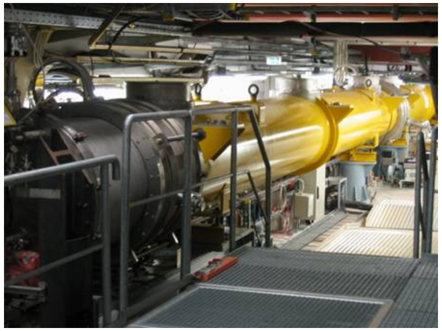
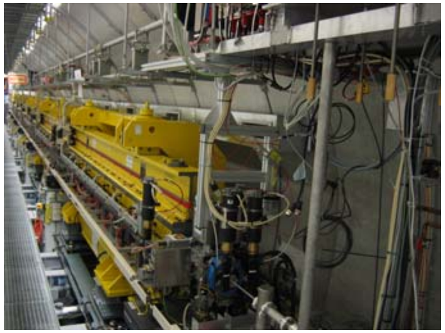
TESLA Test Facility, FLASH Injector + acceleration + bunch compression

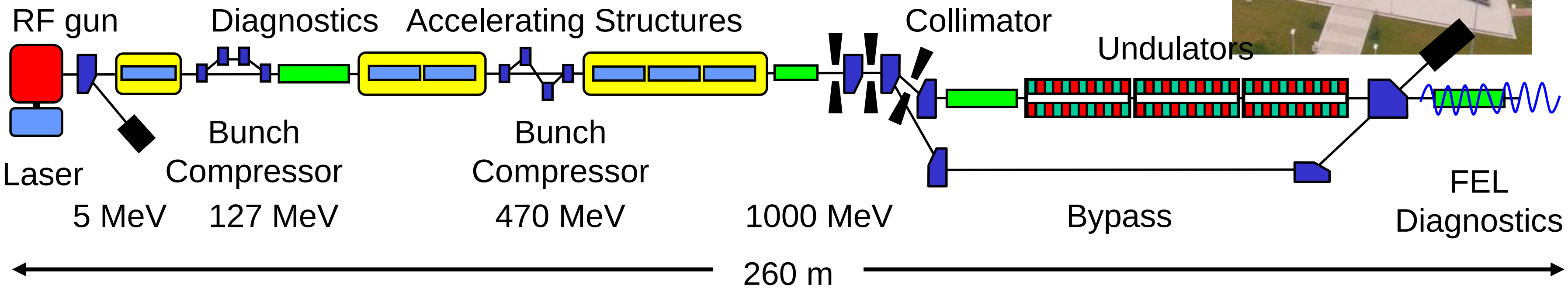
Tunnel with acceleration + undulators

experimental hall

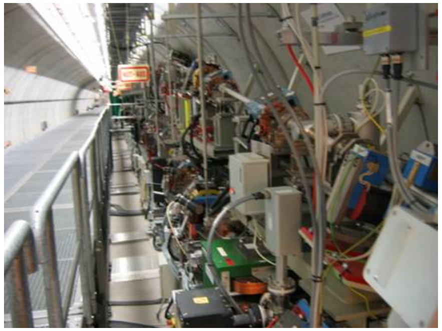
First lasing
108 nm Feb-2000
32 nm in Jan-2005
13 nm in Apr-2006

FLASH Overview

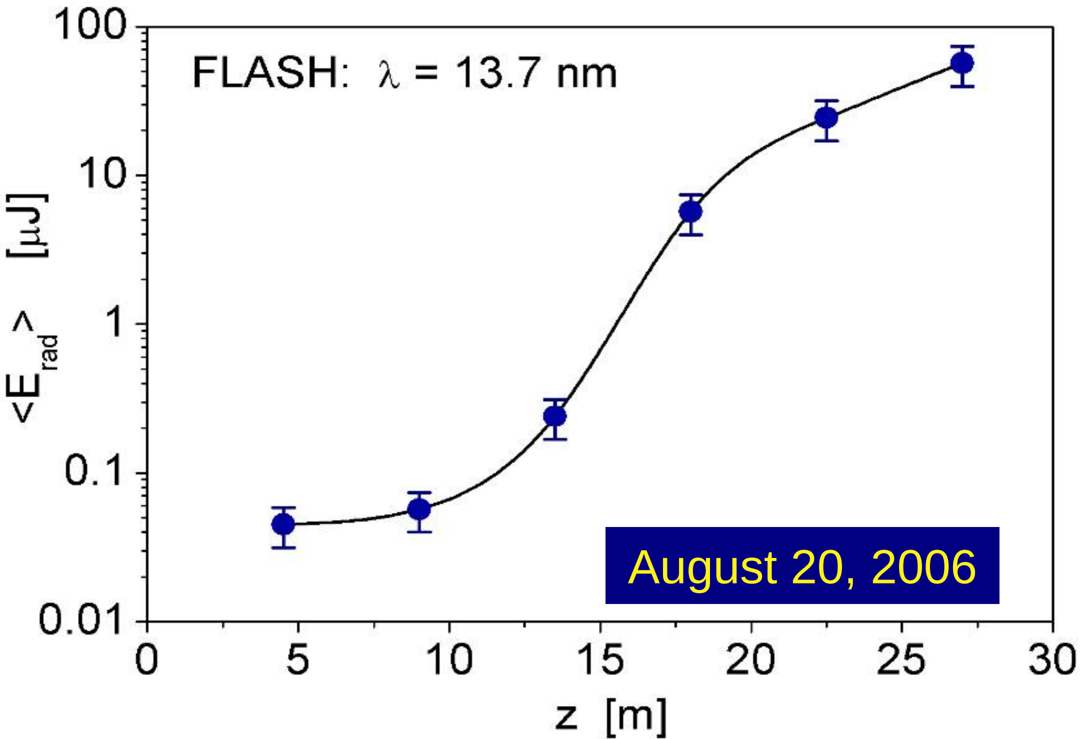





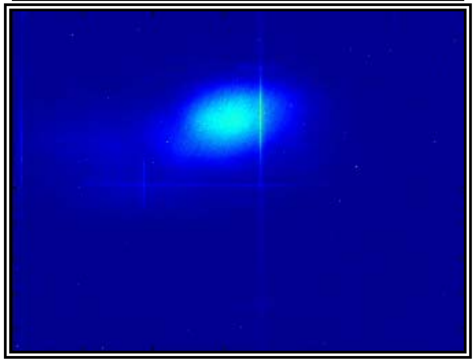



SASE highlights

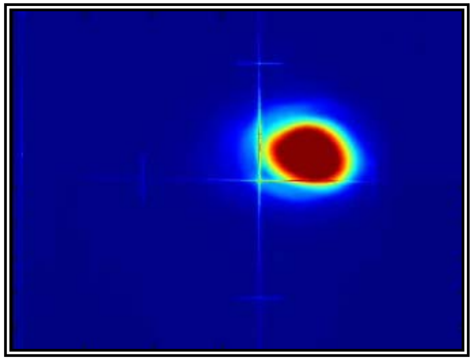
From First Lasing at 13 nm to Saturation



<E> = 5 μJ



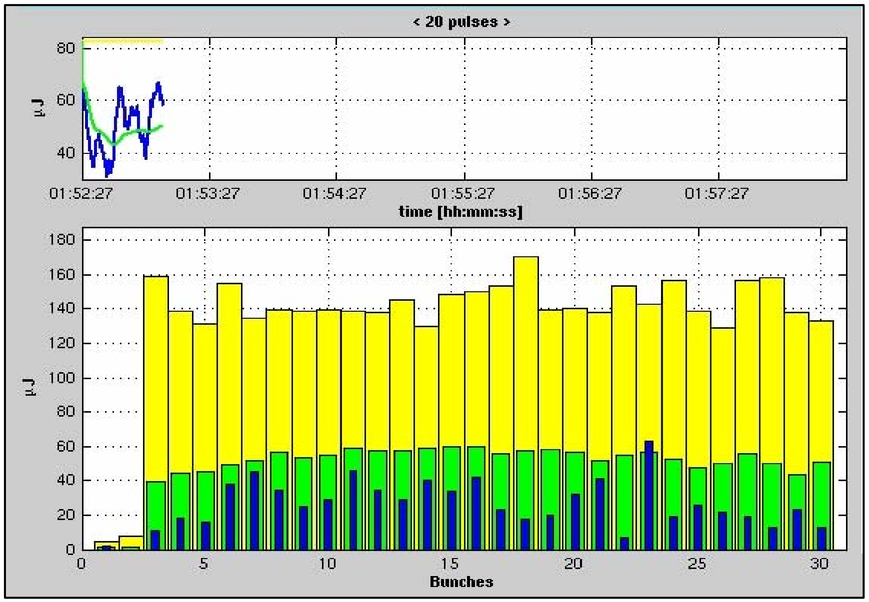
<E> = 70 μJ



lovosibirsk, Russia

SASE Performance

HELMHOLTZ GEMEINSCHAFT



Multibunch SASE signal (µJ) recorded with MCP detector

max

single

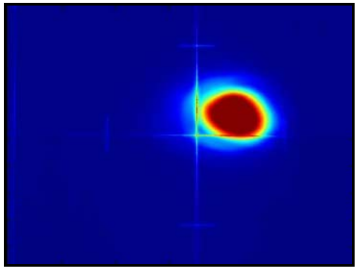
average

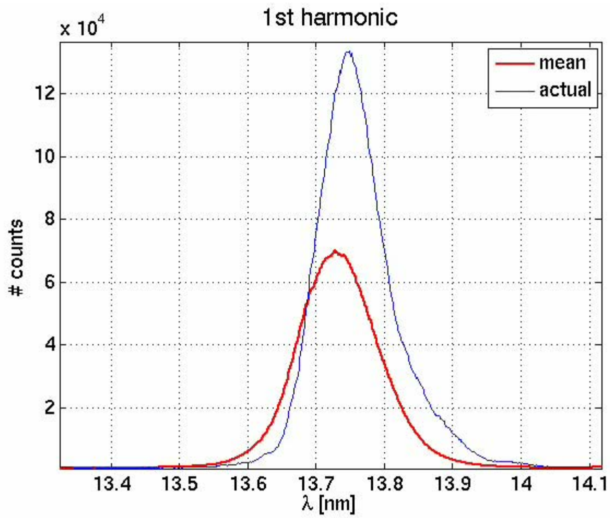
In saturation at 13.7 nm:

- Average energy: 70 µJ
- Peak energy: 170 µJ
- Pulse duration: 10 fs
- Peak power: >10 GW
- Peak brilliance: (6 ± 3) 10^{29} B

B=ph/s/mrad^2/mm^2/0.1%bw

FLASH





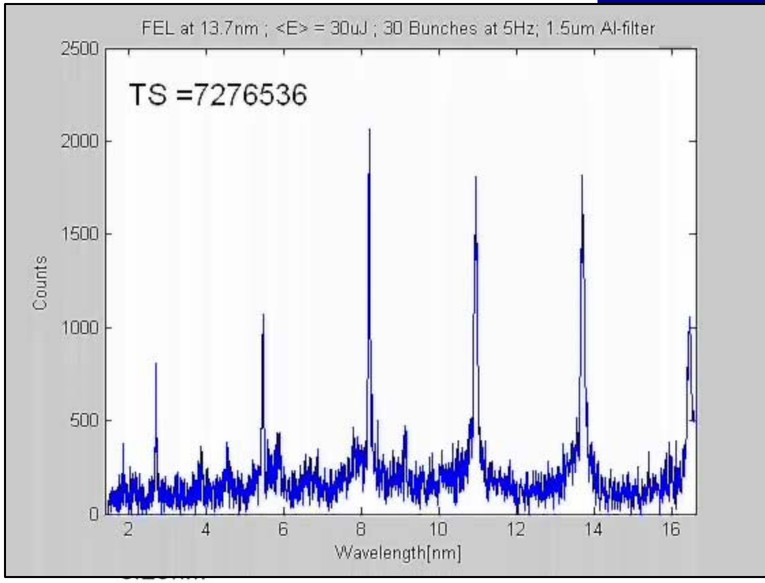
Normal operation parameters:

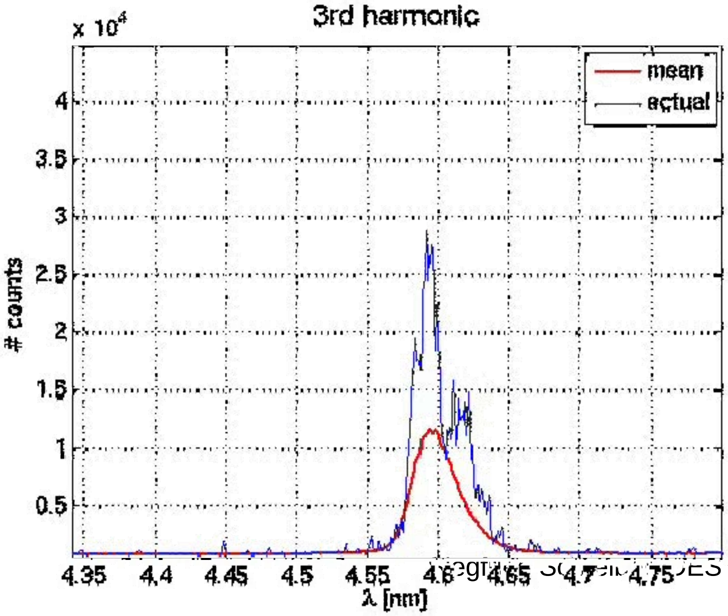
- Wavelength range (fundamental): 13 - 47 nm
- Average single pulse energy: 20 - 30 µJ
- Pulse duration (FWHM): 10 - 25 fs
- Peak power (from av.): ~ 3 GW
- Average power (700 pulses/sec) ~20 mW
- divergence: 90 urad
- Spectral width (FWHM): 0.7-1 %
- Brilliance: ~10^{29} B

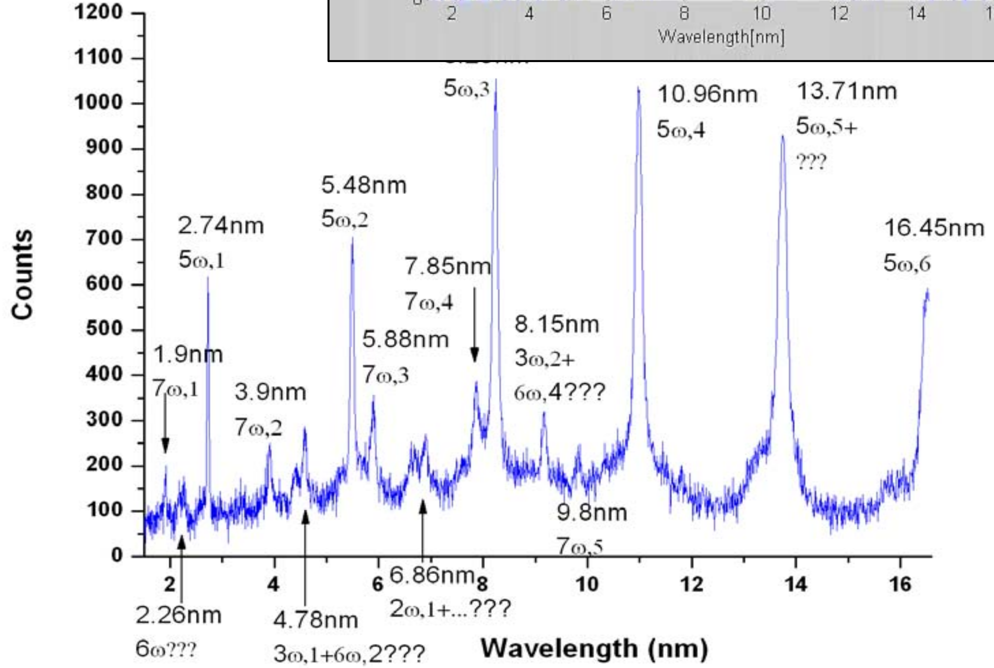
Novosibi

Higher Harmonics

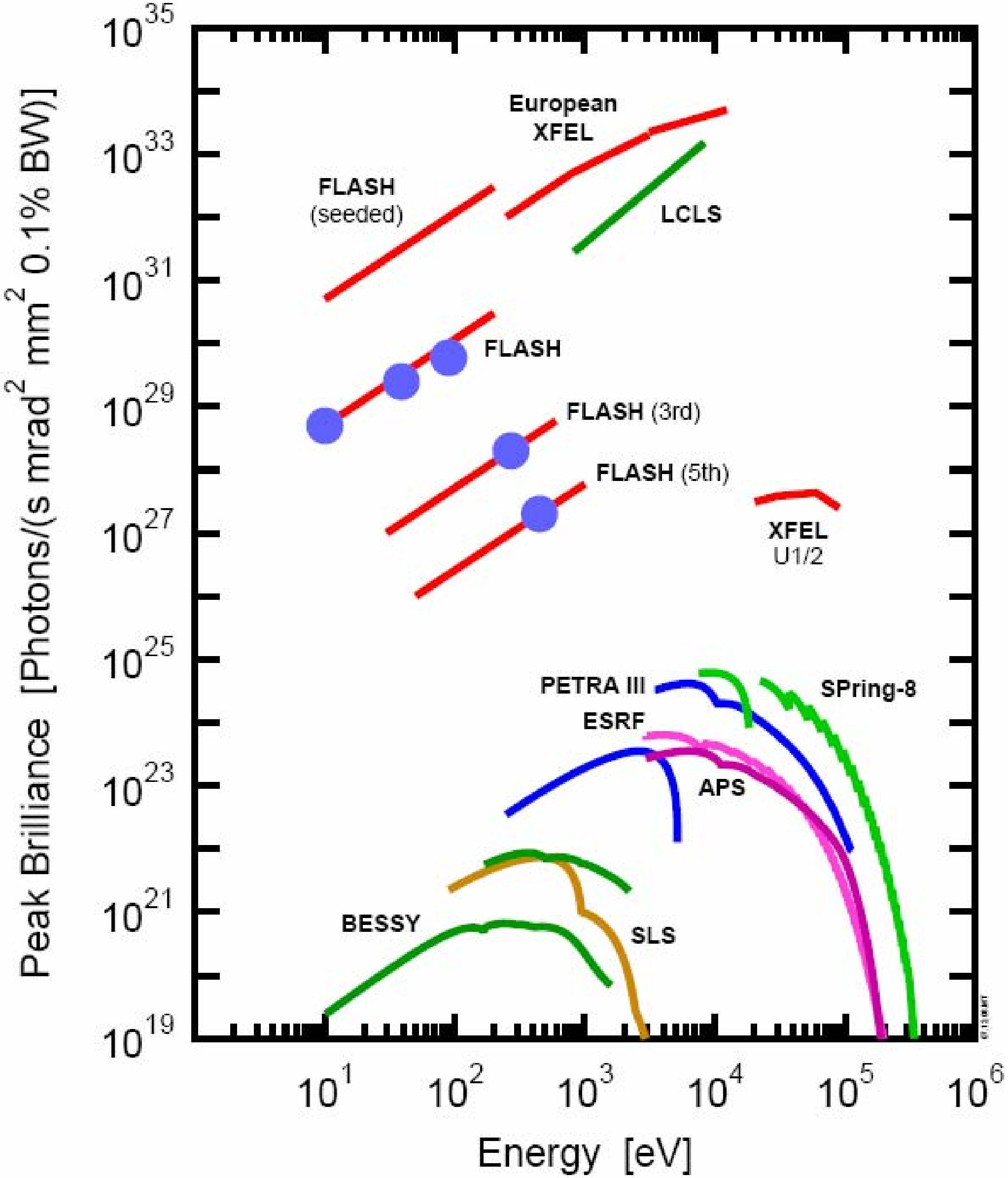
- Saturation: radiation contains mainly odd harmonics
- 3rd harmonic: 4.6 nm (270 eV), 250 nJ, 40 MW peak power
- 5th harmonic: 2.7 nm (450 eV), 10 nJ, 2 MW peak power
- 7th harmonic: 1.9 nm (630 eV) is clearly detected





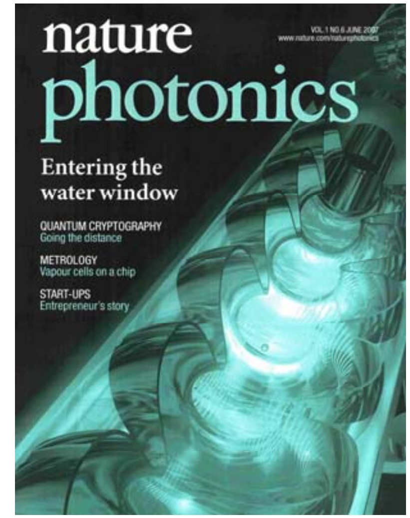


Peak Brilliance



Operation of a free-electron laser from the extreme ultraviolet to the water window

W. ACKERMANN[1], G. ASOVA[2], V. AYVAZYAN[3], A. AZIMA[3], N. BABOI[3], J. BÄHR[2], V. BALANDIN[3], B. BEUTNER[4], A. BRANDT[3], A. BOLZMANN[5], R. BRINKMANN[3], O. I. BROVKO[6], M. CASTELLANO[7], P. CASTRO[3], L. CATANI[8], E. CHIADRONI[8], S. CHOROBA[3], A. CIANCHI[8], J. T. COSTELLO[9], D. CUBAYNES[10], J. DARDIS[9], W. DECKING[3], H. DELSIM-HASHEMI[4], A. DELSERIEYS[11], G. DI PIRRO[7], M. DOHLUS[3], S. DÜSTERER[3], A. ECKHARDT[4], H. T. EDWARDS[12], B. FAATZ[3], J. FELDHAUS[3], K. FLÖTTMANN[3], J. FRISCH[13], L. FRÖHLICH[4], T. GARVEY[14], U. GENSCH[2], CH. GERTH[3], M. GÖRLER[3], N. GOLUBEVA[3], H.-J. GRABOSCH[2], M. GRECKI[15], O. GRIMM[3], K. HACKER[3,4], U. HAHN[3], J. H. HAN[3], K. HONKAVAARA[4], T. HOTT[3], M. HÜNING[3], Y. IVANISENKO[16], E. JAESCHKE[17], W. JALMUZNA[18], T. JEZYNSKI[15], R. KAMMERING[3], V. KATALEV[3], K. KAVANAGH[9], E. T. KENNEDY[9], S. KHODYACHYKH[2], K. KLOSE[2], V. KOCHARYAN[3], M. KÖRFER[3], M. KOLLEWE[3], W. KOPREK[18], S. KOREPANOV[2], D. KOSTIN[3], M. KRASSILNIKOV[2], G. KUBE[3], M. KUHLMANN[3], C. L. S. LEWIS[11], L. LILJE[3], T. LIMBERG[3], D. LIPKA[3], F. LÖHL[4], H. LUNA[9], M. LUONG[19], M. MARTINS[4], M. MEYER[10], P. MICHELATO[20], V. MILTCHEV[4], W. D. MÖLLER[3], L. MONACO[20], W. F. O. MÜLLER[1], O. NAPIERALSKI[15], O. NAPOLY[19], P. NICOLOSI[21], D. NÖLLE[3], T. NUÑEZ[3], A. OPPELT[2], C. PAGANI[20], R. PAPARELLA[19], N. PCHALEK[3,4], J. PEDREGOSA-GUTIERREZ[9], B. PETERSEN[3], B. PETROSYAN[2], G. PETROSYAN[3], L. PETROSYAN[3], J. PFLÜGER[3], E. PLÖNJES[3], L. POLETTO[2], K. POZNIAK[18], E. PRAT[3,4], D. PROCH[3], P. PUCYK[18], P. RADCLIFFE[3], H. REDLIN[3], K. REHLICH[3], M. RICHTER[22], M. ROEHRS[3,4], J. ROENSCH[4], R. ROMANIUK[18], M. ROSS[13], J. ROSSBACH[4], V. RYBNIKOV[3], M. SACHWITZ[2], E. L. SALDIN[3], W. SANDNER[23], H. SCHLARB[3], B. SCHMIDT[3], M. SCHMITZ[3], P. SCHMÜSER[4], J. R. SCHNEIDER[3], E. A. SCHNEIDMILLER[3], S. SCHNEPP[1], S. SCHREIBER[3], M. SEIDEL[3,24], D. SERTORE[20], A. V. SHABUNOV[6], C. SIMON[19], S. SIMROCK[3], E. SOMBROWSKI[3], A. A. SOROKIN[25,22], P. SPANKNEBEL[26], R. SPESYVTSEV[16], L. STAYKOV[2], B. STEFFEN[3], F. STEPHAN[2], F. STULLE[3], H. THOM[3], K. TIEDTKE[3], M. TISCHER[3], S. TOLEIKIS[3], R. TREUSCH[3], D. TRINES[3], I. TSAKOV[27], E. VOGEL[3], T. WEILAND[1], H. WEISE[3], M. WELLHÖFER[4], M. WENDT[3,12], I. WILL[23], A. WINTER[3], K. WITTENBURG[3], W. WURTH[4], P. YEATES[9], M. V. YURKOV[3]*, I. ZAGORODNOV[3] AND K. ZAPFE[3]



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FLASH.

The Free-Electron Laser
in Hamburg

New technologies for new science: Soon X-ray free-electron lasers will enable us to probe ultrafast physical, chemical and biochemical processes at atomic resolution, opening new frontiers for science and technology. At long last we may see, and not just model, how molecular machines really work.

http://flash.desy.de/

Accelerators | Photon Science | Particle Physics

Deutsches Elektronen-Synchrotron
Member of the Helmholtz Association

DESY

1st round of user experiments

Femtosecond diffractive imaging with a soft-X-ray free-electron laser
H.N. Chapman et al., Nature Physics 2 (2006) 839

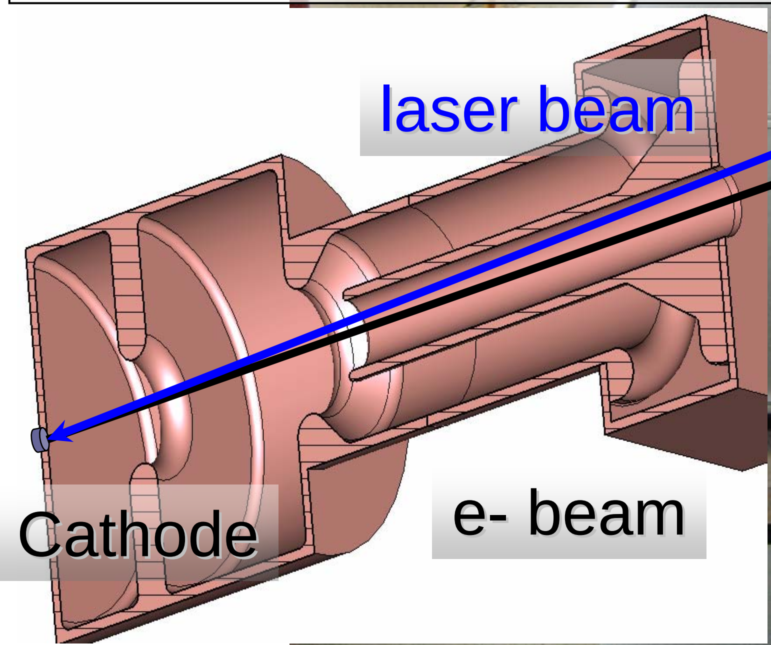
- **30 proposals submitted in 2002**
  - **29 proposals approved in Sept. 2002**
  - **200 scientists involved from**
  - **60 institutes and 11 countries**
- **11 proposals were combined in a joint project ("peak brightness collaboration")**
- **2 proposals were combined into a project on biological samples**
- **18 projects had beamtime in two campaigns:**
  - **Aug. 2005 – Feb. 2006 & May 2006 – March 2007 1st Round of First User Experiments**

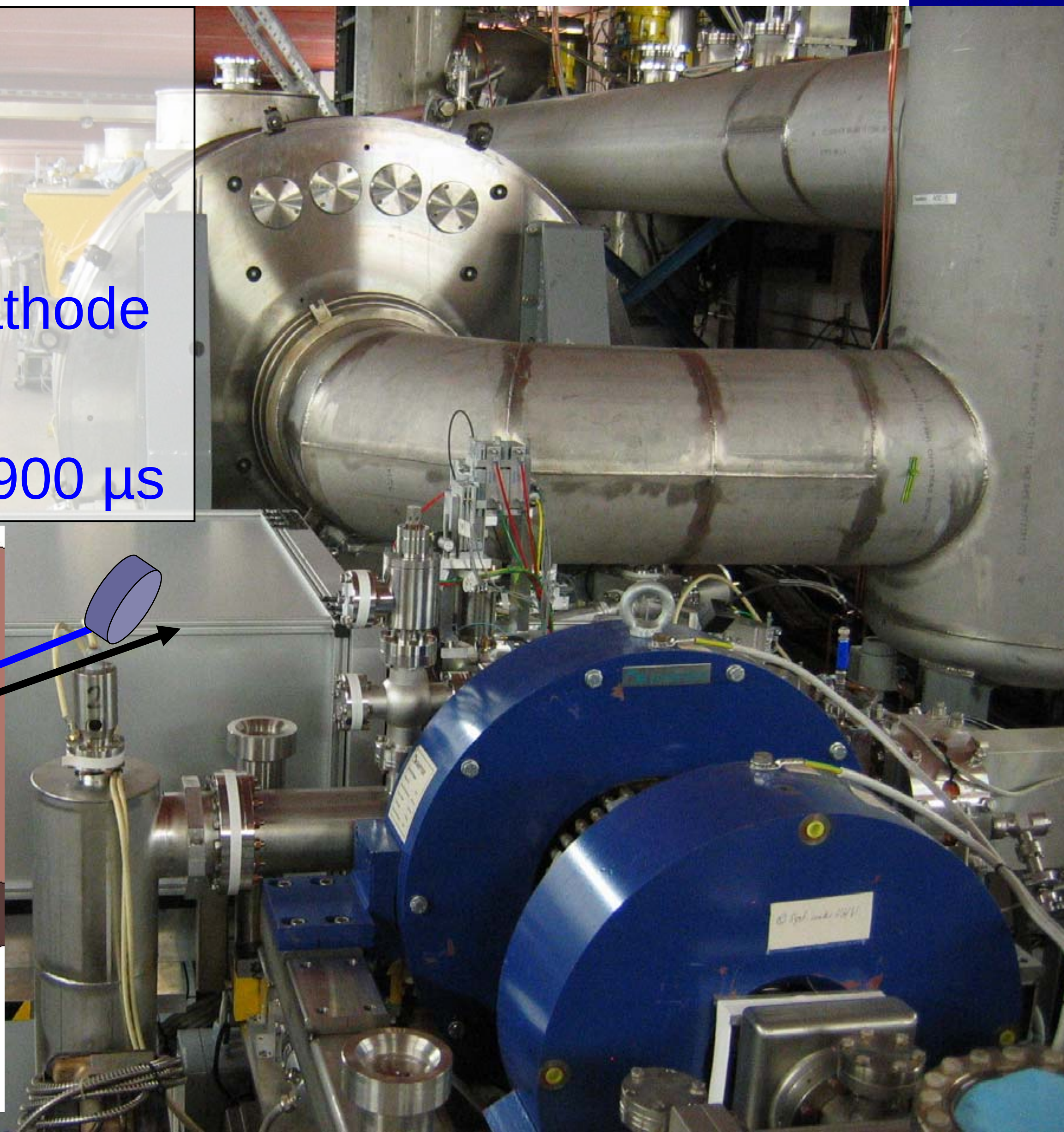
→ R. Treusch: "Research Highlights from FLASH" – next session

Linac Components

Photoinjector

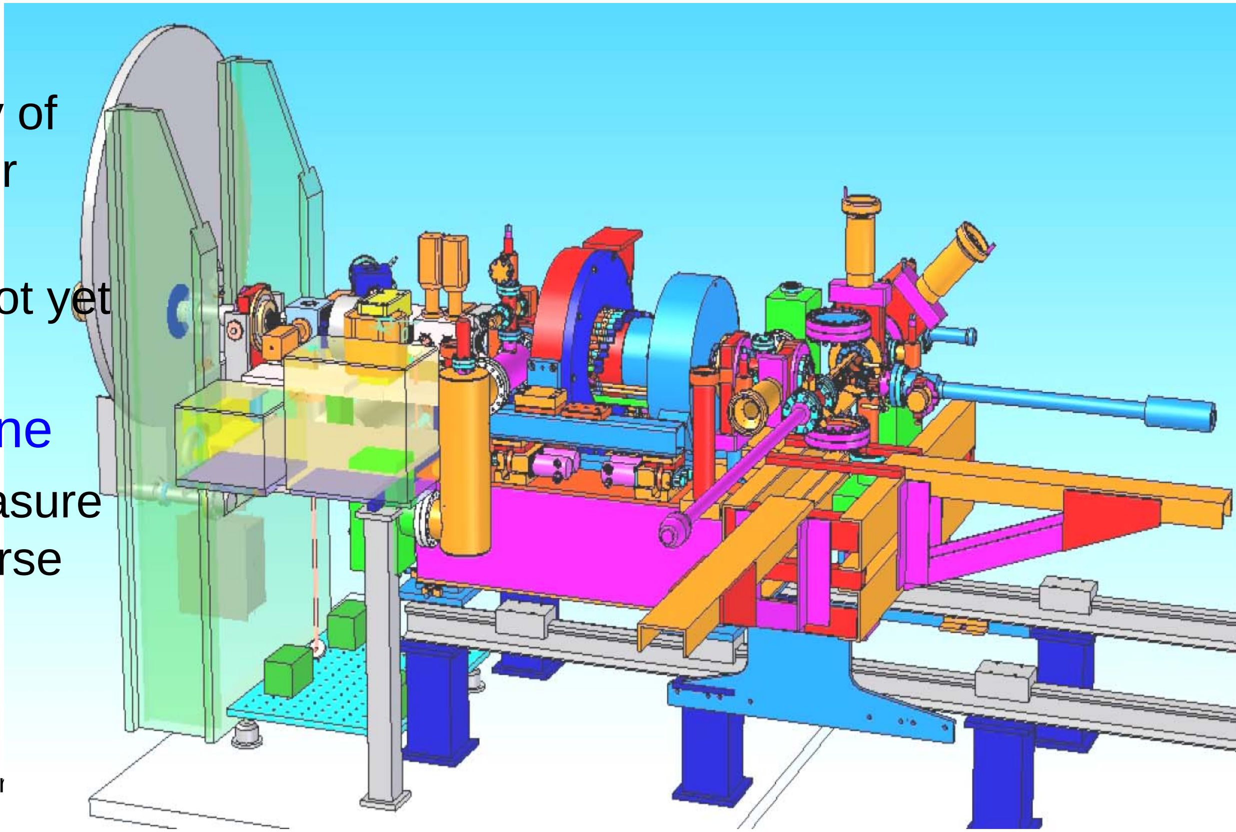
- laser driven RF gun
- L-band 1.3 GHz
- RF power 3.2 MW
- 42 MV/m gradient on cathode
- Pulsed 5 or 10 Hz
- RF pulse length 100 to 900 µs





New RF Gun diagnostic section installed

- New diagnostic cross design with reduced wakefield
  - Easier alignment of elements in the section
  - dipole with larger gap
- RF gun is moved upstream by 30 cm
  - to increase efficiency of darkcurrent collimator
  - to make place for a darkcurrent kicker (not yet installed)
- reworked laser beamline
  - gated camera to measure single bunch transverse beam shape

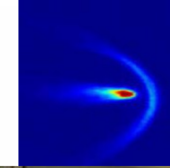


Photoinjector Laser

- Nd:YLF based laser
- designed for long pulse trains of up to 800 µs @ 10 Hz
- 10 kHz to 1 MHz within train
- average power in the Watt range
- single UV pulse energy some µJ
- requires high QE cathode (Cs_2Te)
- 2nd, fully diode pumped laser installed (laser 2)
- laser 1 has been running since 1997, the upgraded oscillator since Feb. 2004

In cooperation DESY –
Max-Born-Institute, Berlin

Photoinjector Laser



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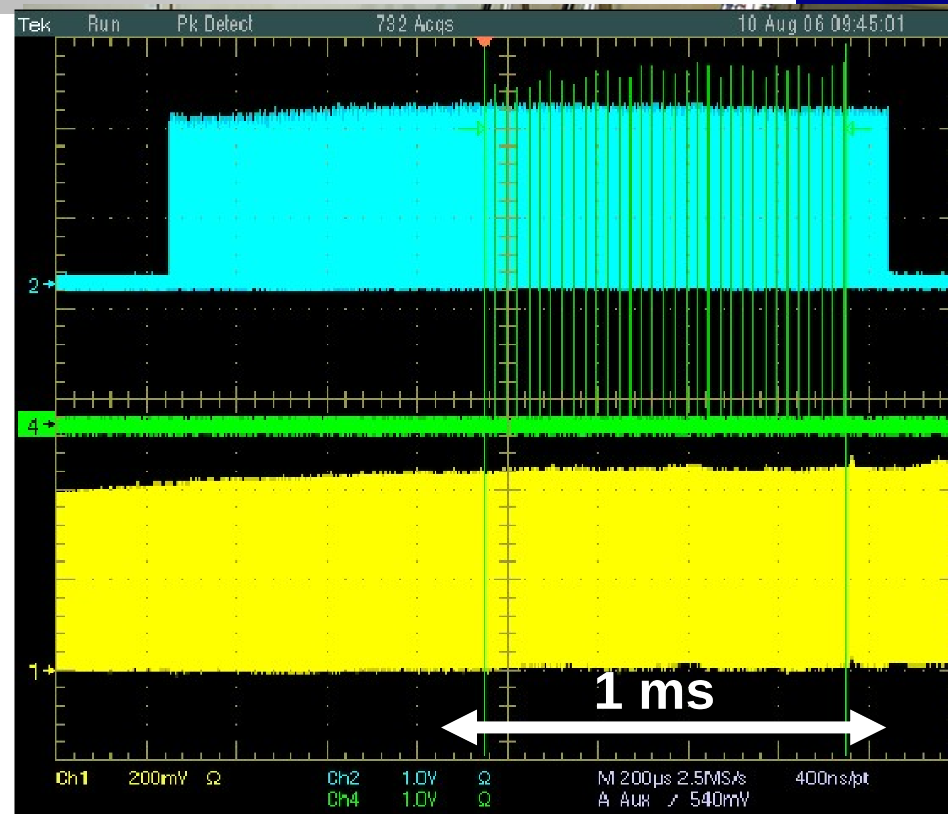
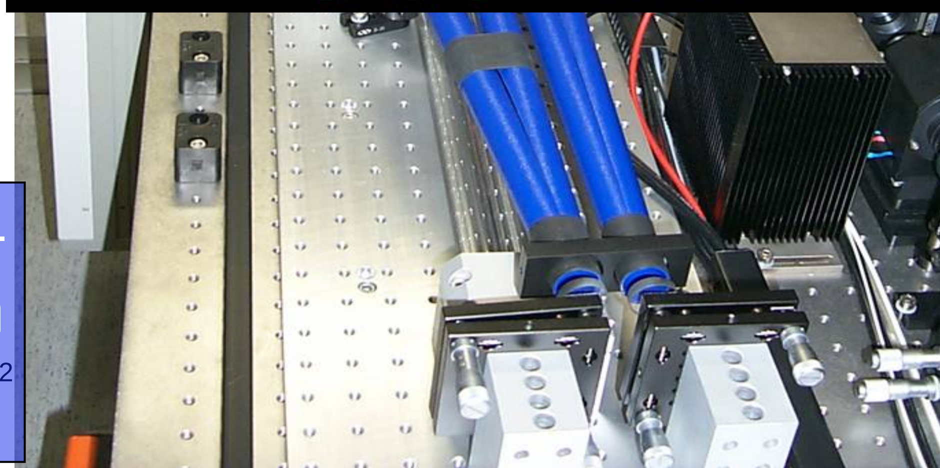
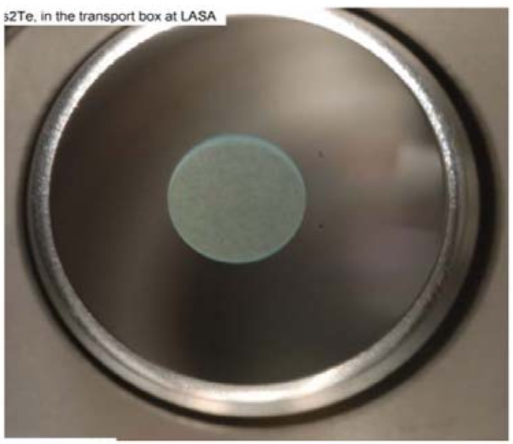




In cooperation DESY – Max-Born-Institute, Berlin

High QE Cs_2Te Cathodes

- Quantum efficiency (QE) starts high ~10 % and drops to ~0.5% during a couple of weeks, change of cathodes routine operation
- XPS at BESSY: traces of F and C found, depleted part: metallic Te

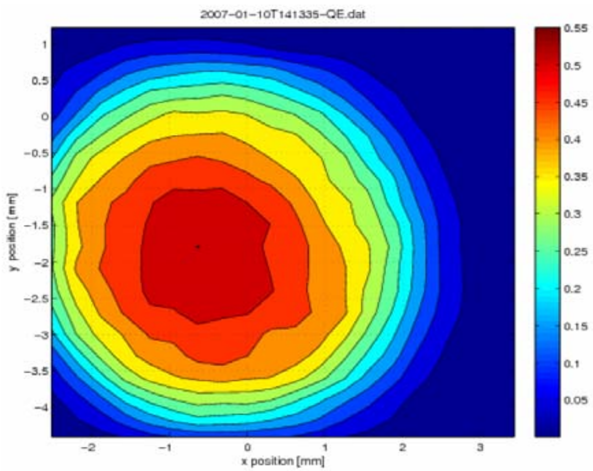


Fresh cathode

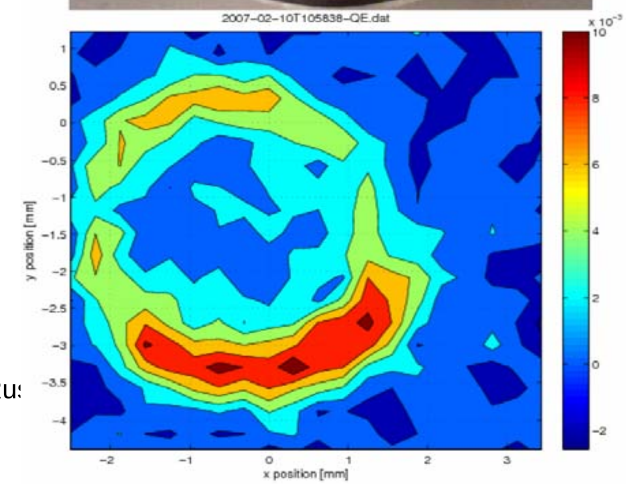
12-Dec-2006

Used cathode

7-Feb-2007

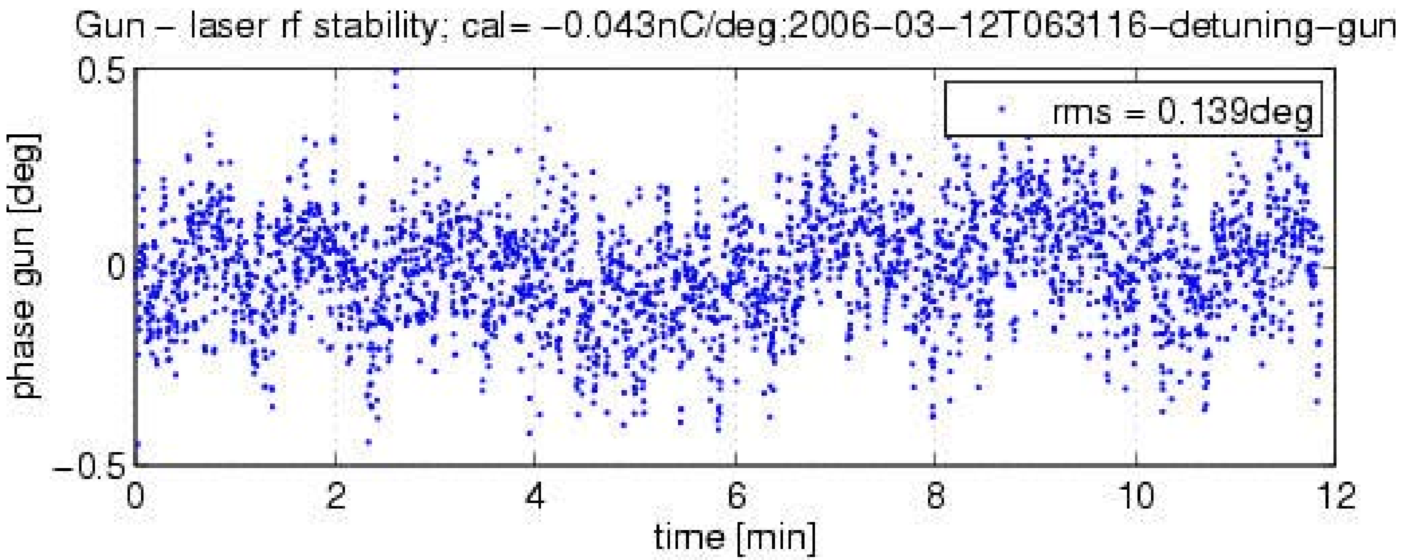


→ Poster:
S. Lederer
WEPPH048



RF Gun low level rf control

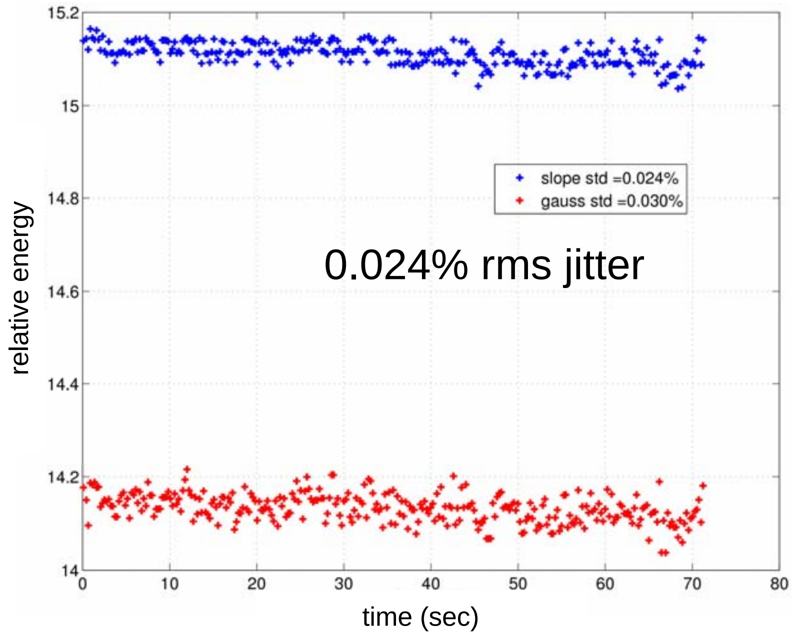
- Amplitude and phase regulation by calculating the vector sum of forward and reflected power
- FPGA based controller (latency reduced to 150 ns)
- Phase stability of 0.14 dg of 1.3 GHz or 300 fs achieved



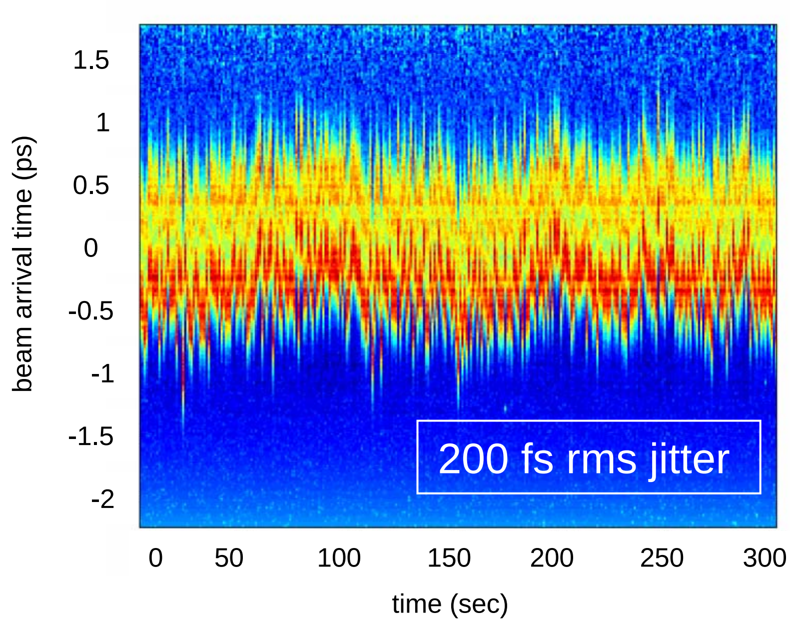
Energy and Arrival Time Stability

- dE/E = 2.4 10^{-4} measured at 127 MeV
- Electron and FEL beam arrival time jitter 200 fs rms

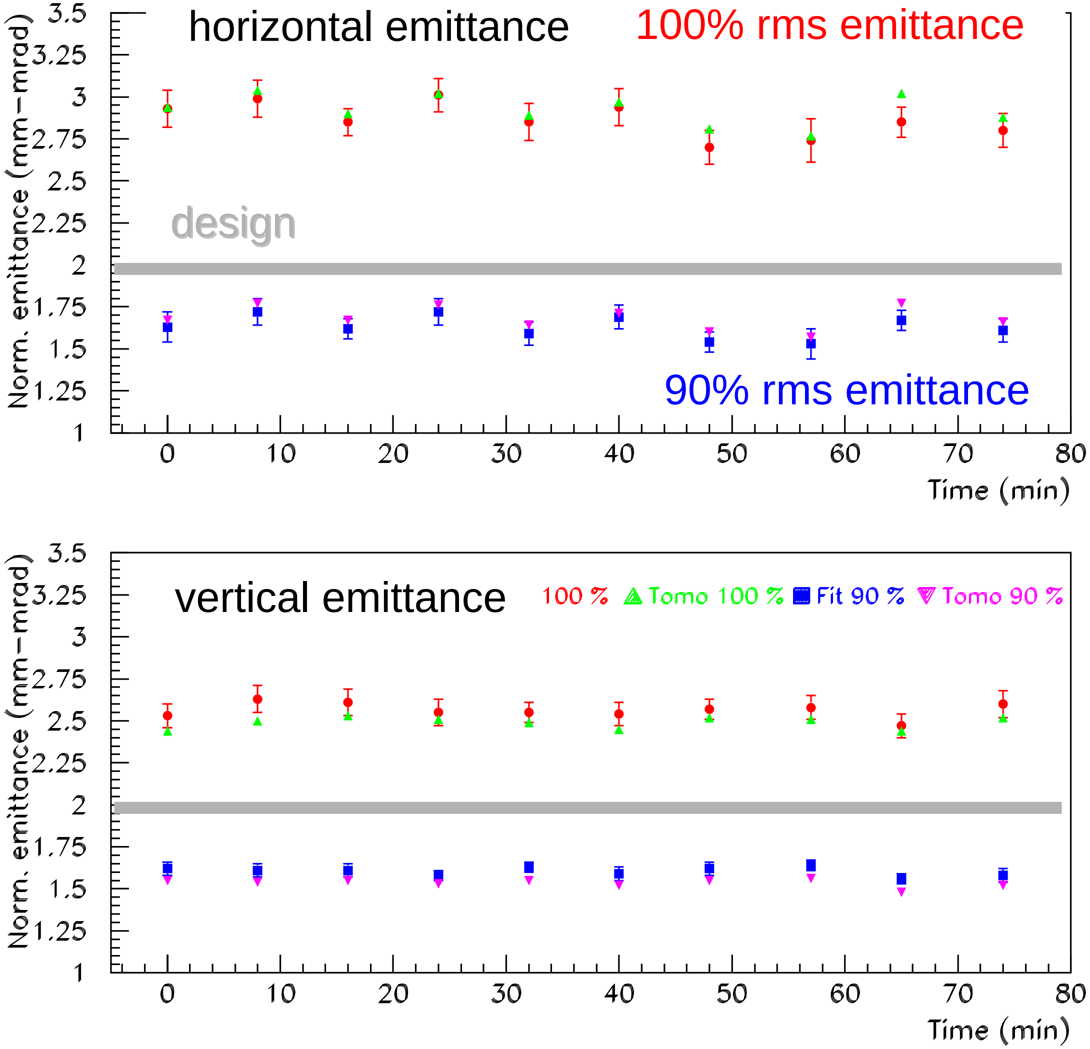
Energy jitter measured with synchrotron radiation monitor



Beam arrival time measure with electro-optical decoding



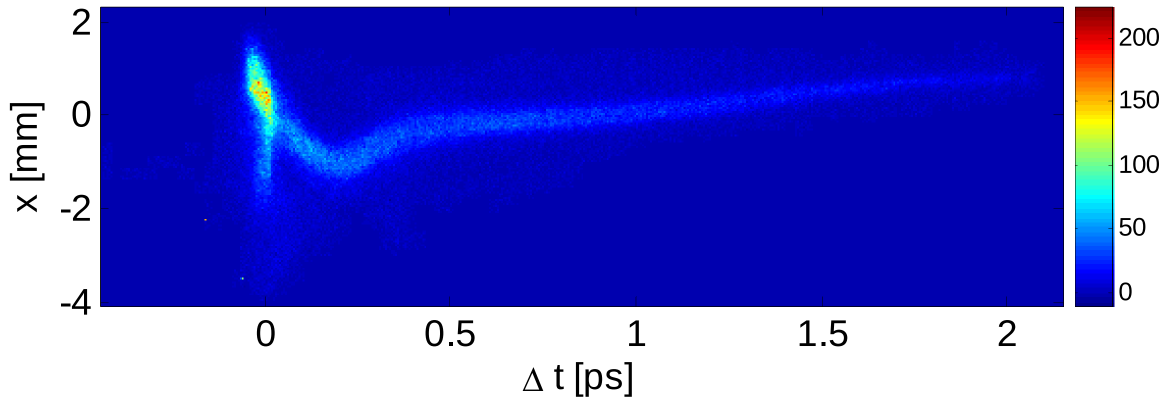
Transverse Projected Emittance



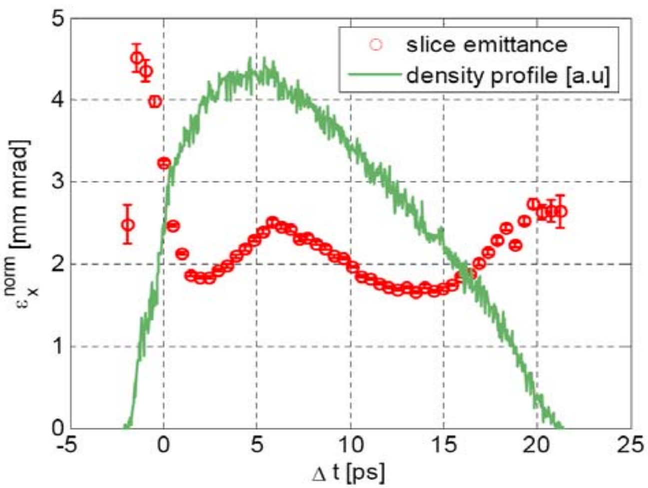
- Projected normalized rms emittance (90% core) = 1.6 mm mrad
- Jitter 2 - 3 % (rms)
- the projected emittance (on crest) is preserved along the linac
- lasing slice emittance in the undulator estimated from SASE radiation properties to be 1 to 1.5 mm mrad

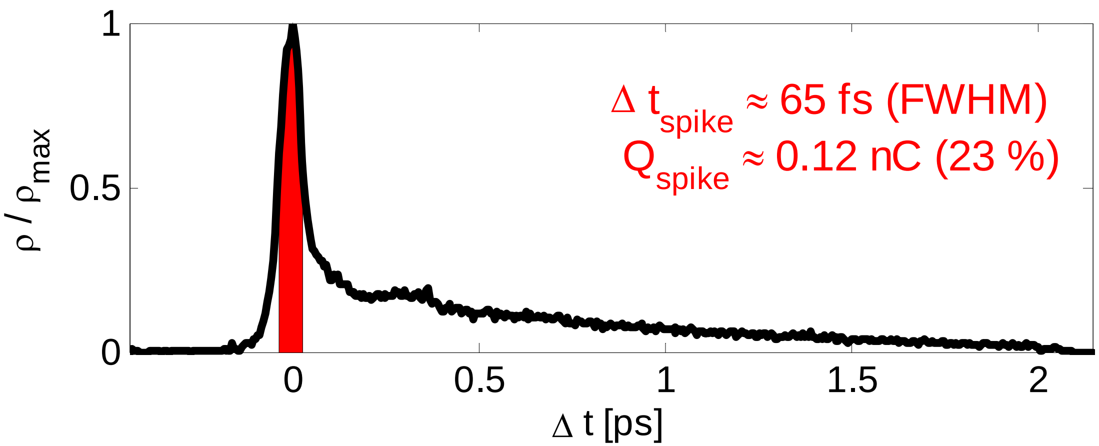
Longitudinal Bunch Shape

- Measured with LOLA – S-band deflecting cavity
- resolution 10 to 50 µm



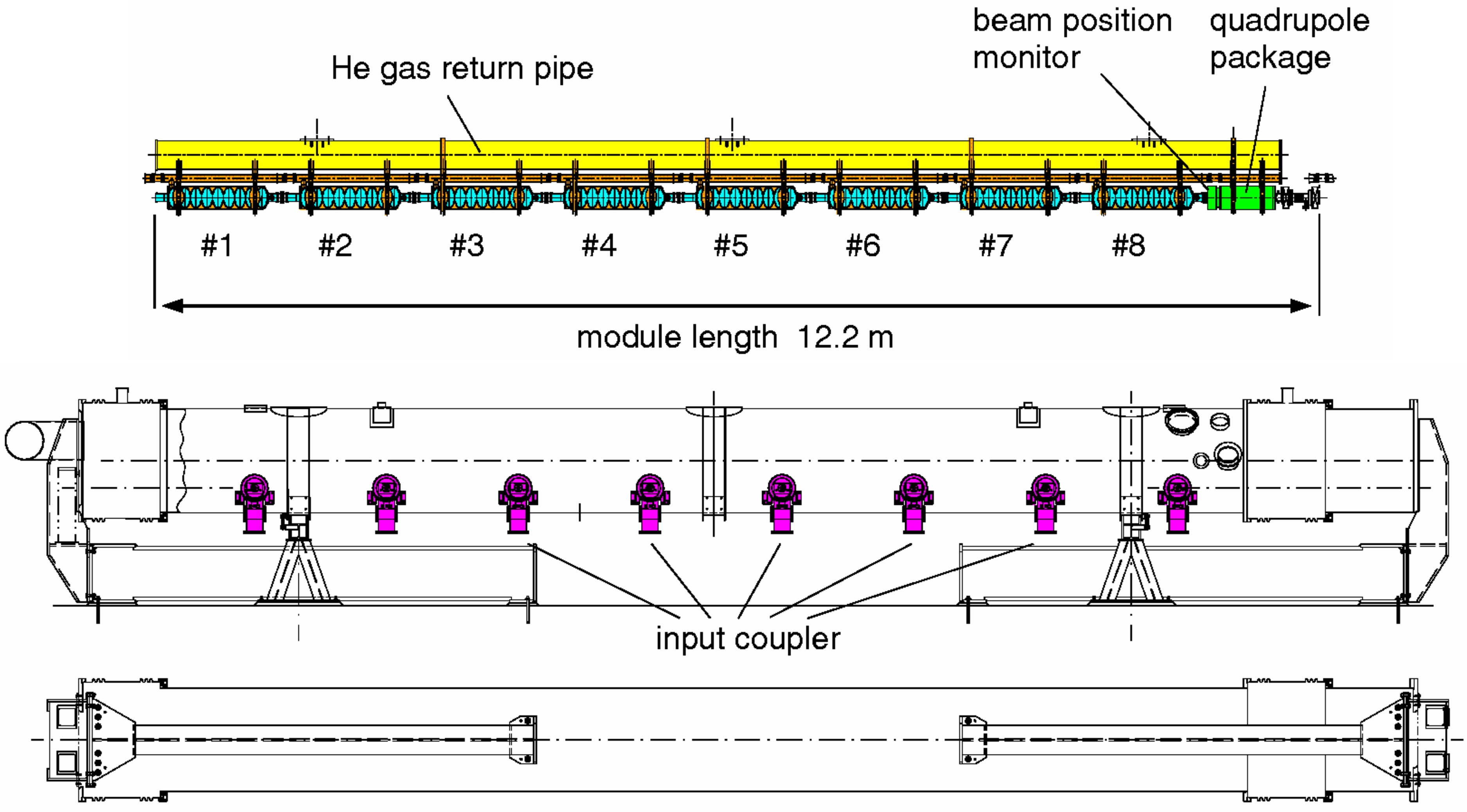
- First results on slice emittance measurements with LOLA





→ **B. Steffen: “Single-Shot Longitudinal Bunch Profile Measurements at FLASH” – We sessio**

FLASH uses TESLA Accelerating Modules



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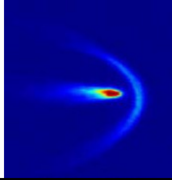
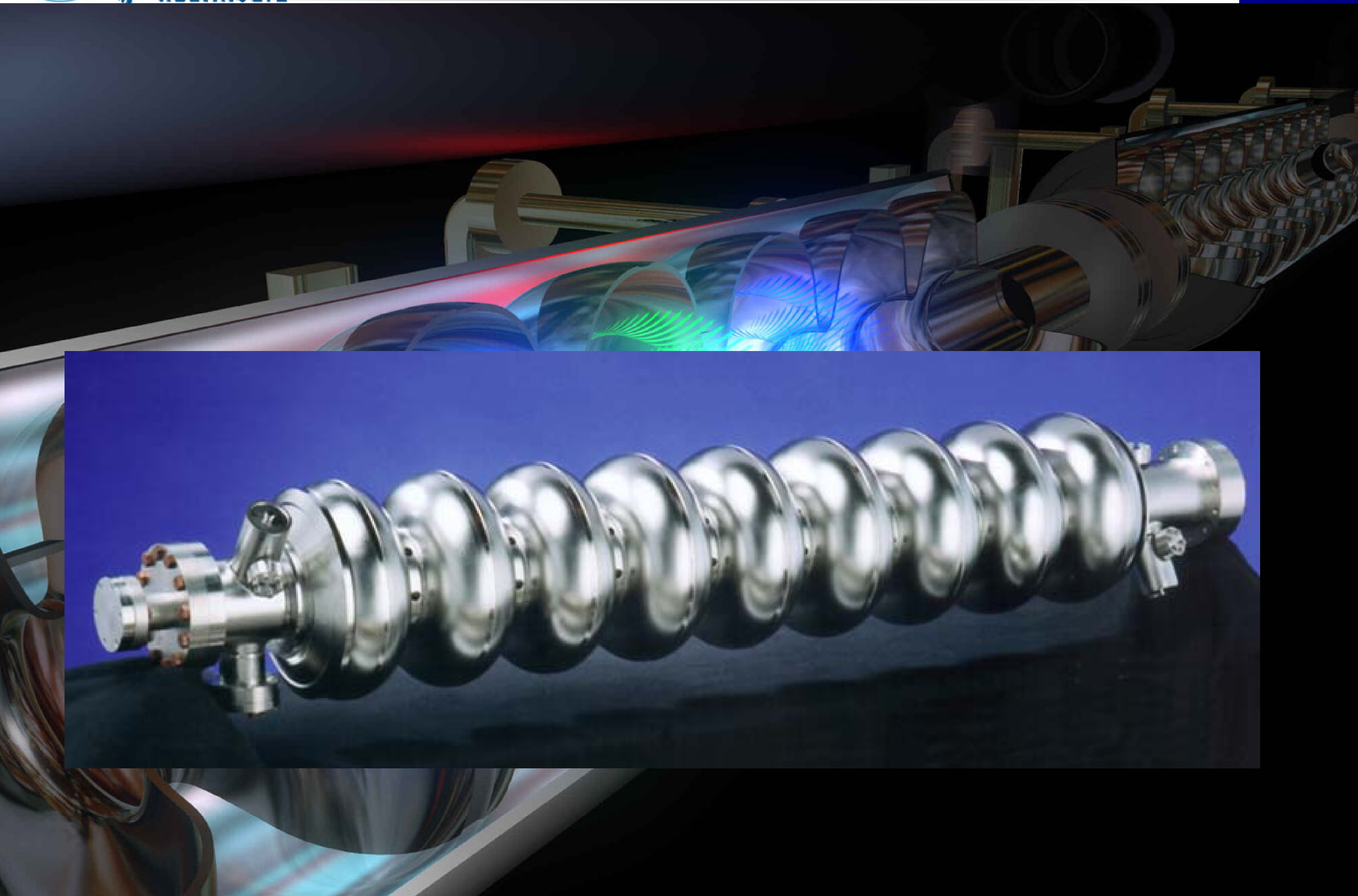
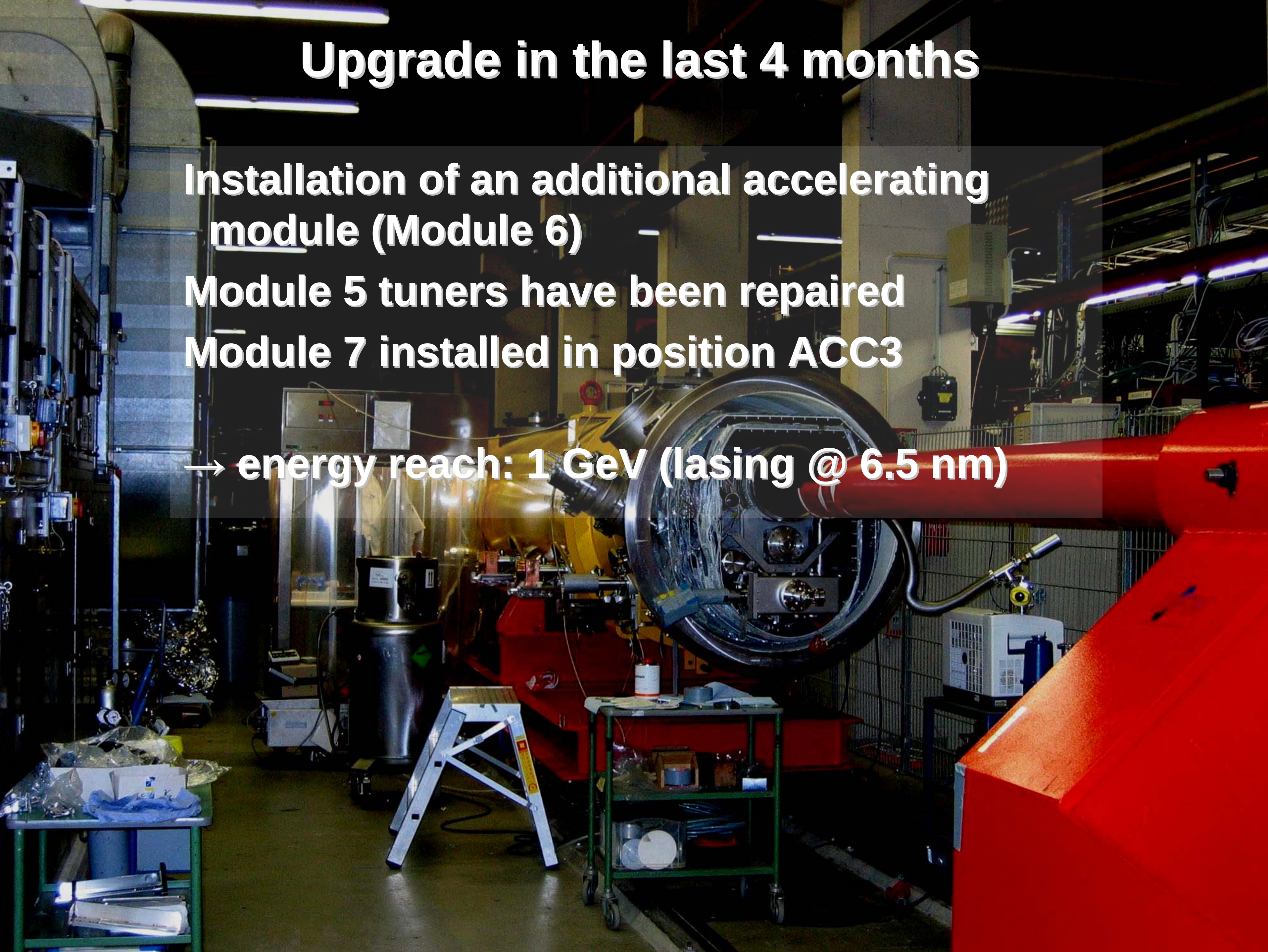




Upgrade in the last 4 months

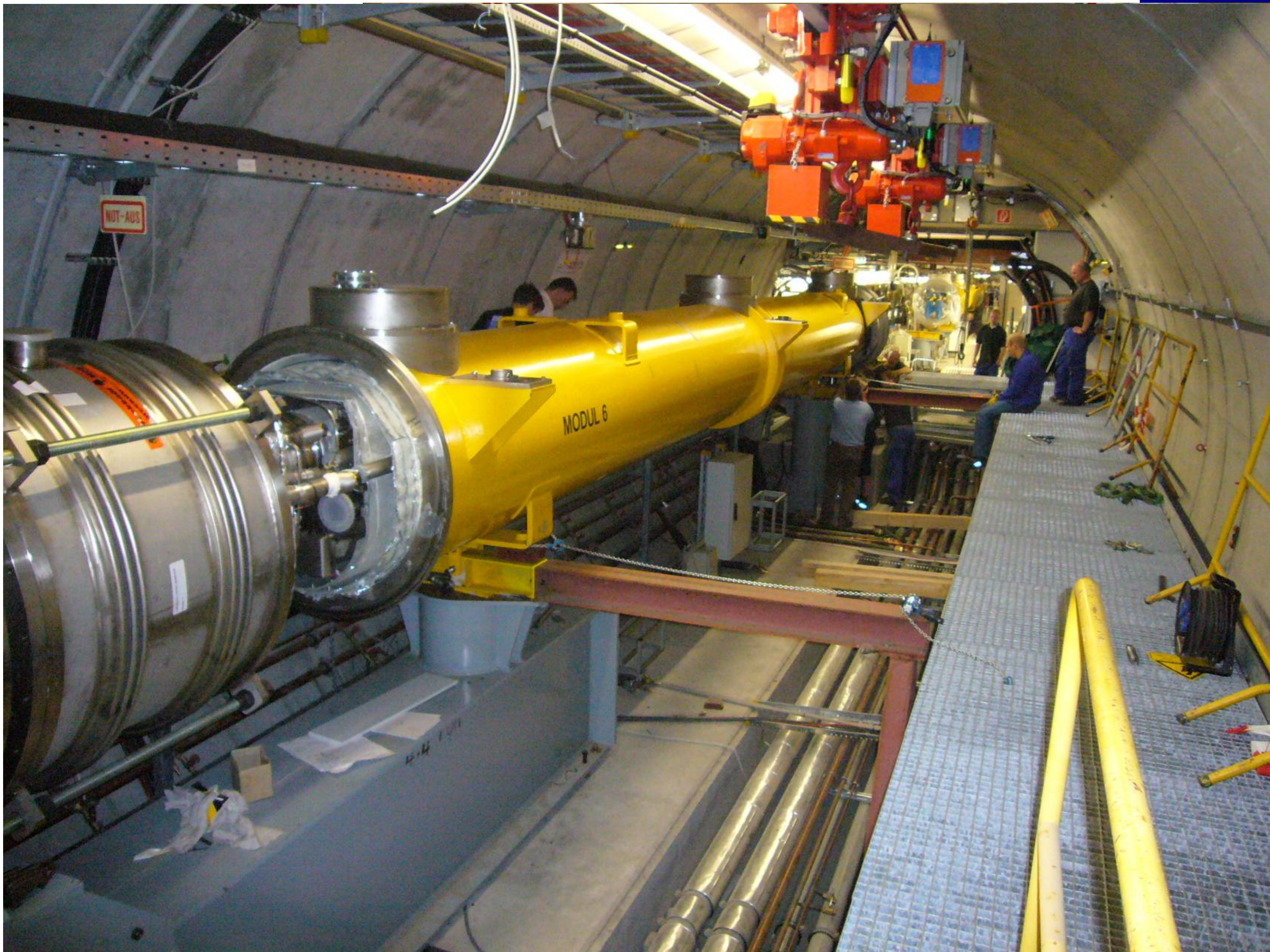
- Installation of an additional accelerating module (Module 6)
- Module 5 tuners have been repaired
- Module 7 installed in position ACC3

→ energy reach: 1 GeV (lasing @ 6.5 nm)



Dismounting of Module 5 for Repair

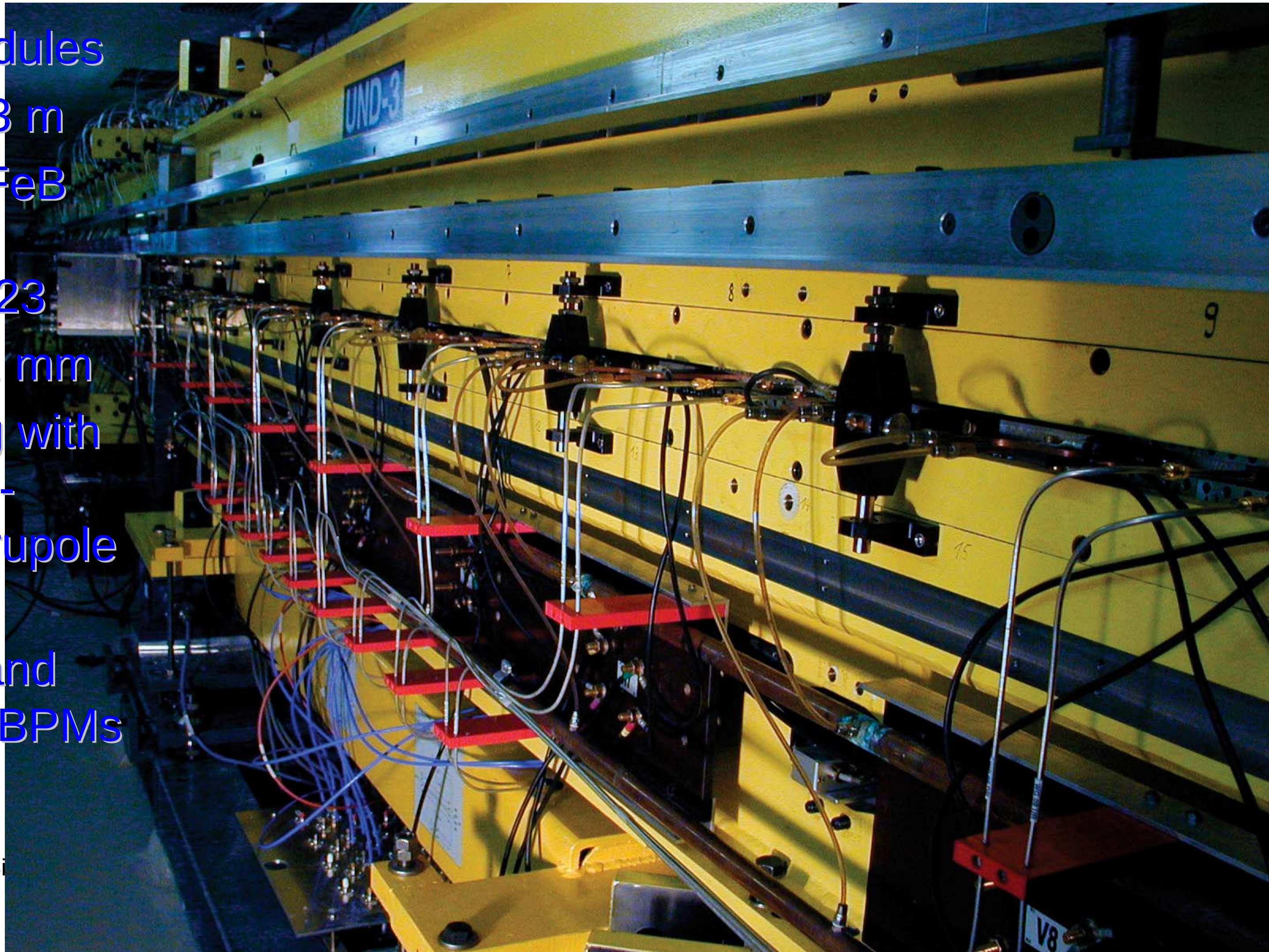
Module 6 during Installation



Undulators

Single pass high gain FEL operating in the SASE mode (self amplified spontaneous emission)

- 6 undulator modules
- total length 27.3 m
- Permanent NdFeB magnets
  B=0.48 T, K=1.23
- Fixed gap of 12 mm
- Strong focusing with external electro-magnetic quadrupole duplets
- Wirescanners and high resolution BPMs (20 µm)

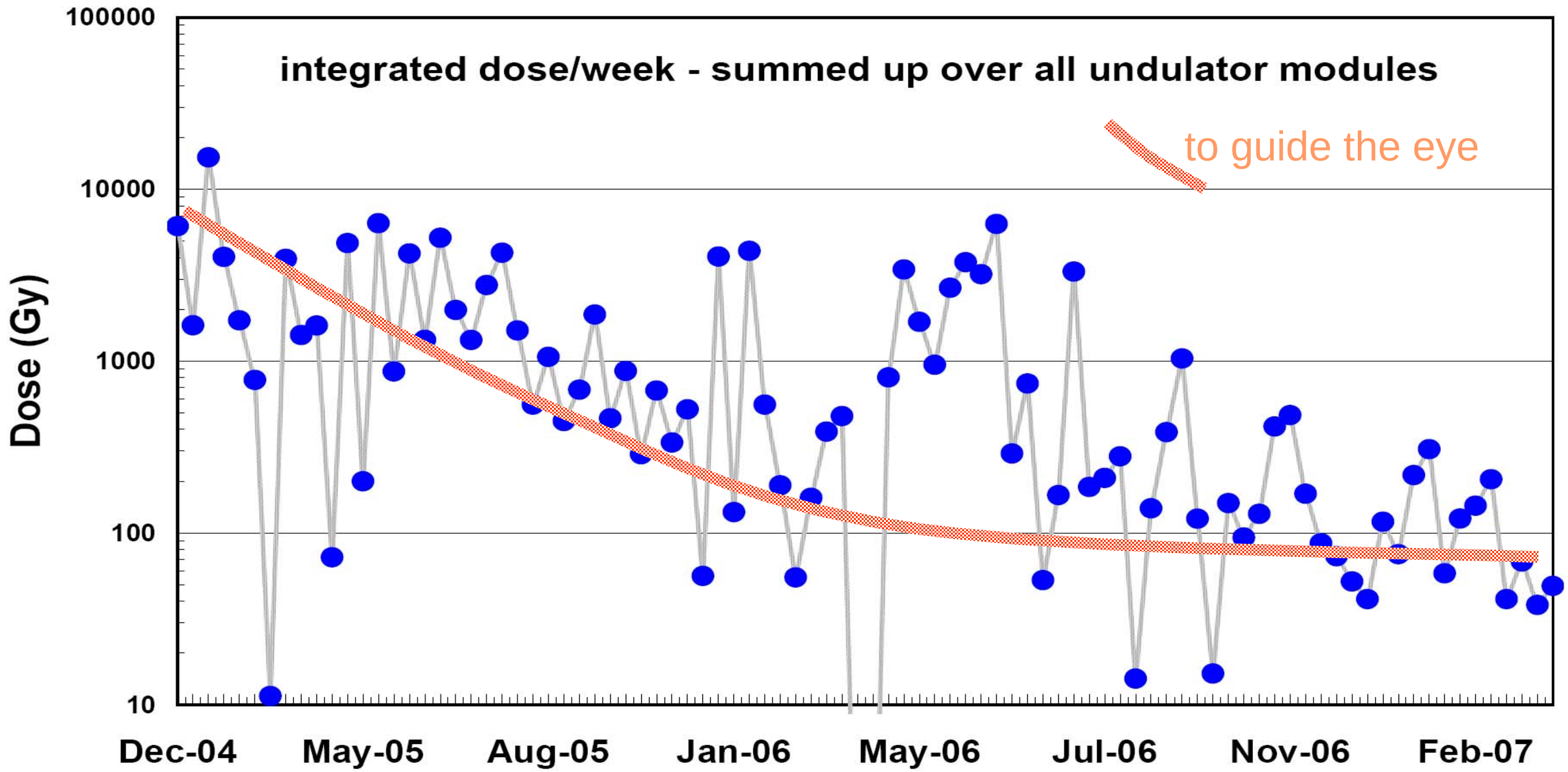


Radiation Level Undulator Section

- Mainly: darkcurrent from the RF gun
- Also: beam losses during commissioning times

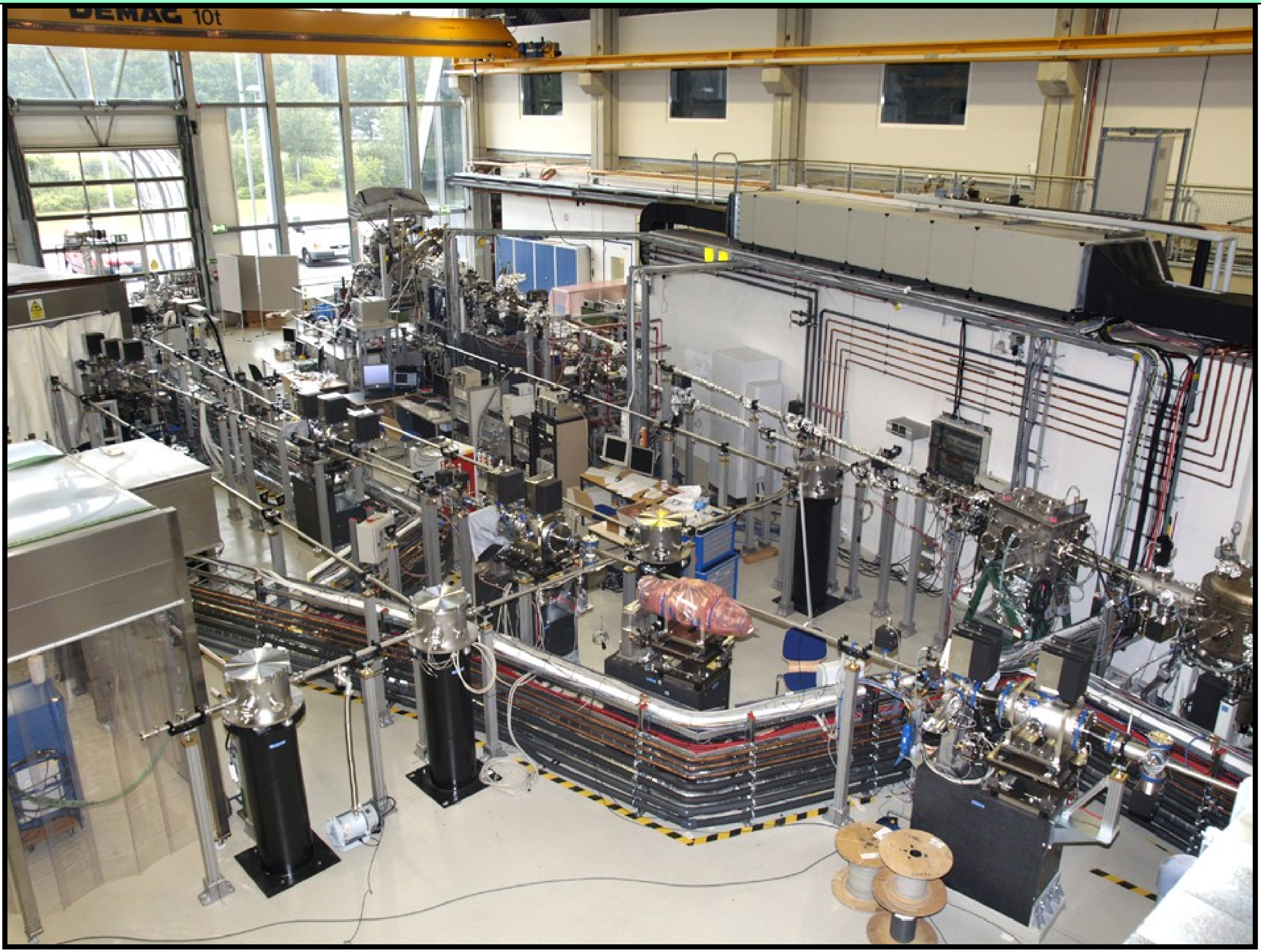
→ may result in high radiation doses in the undulator modules

- Level is going down together with better tuning of the orbit and the commissioning of the machine safety system



FLASH Experimental Hall

→ R. Treusch: “Research Highlights from FLASH” – next session



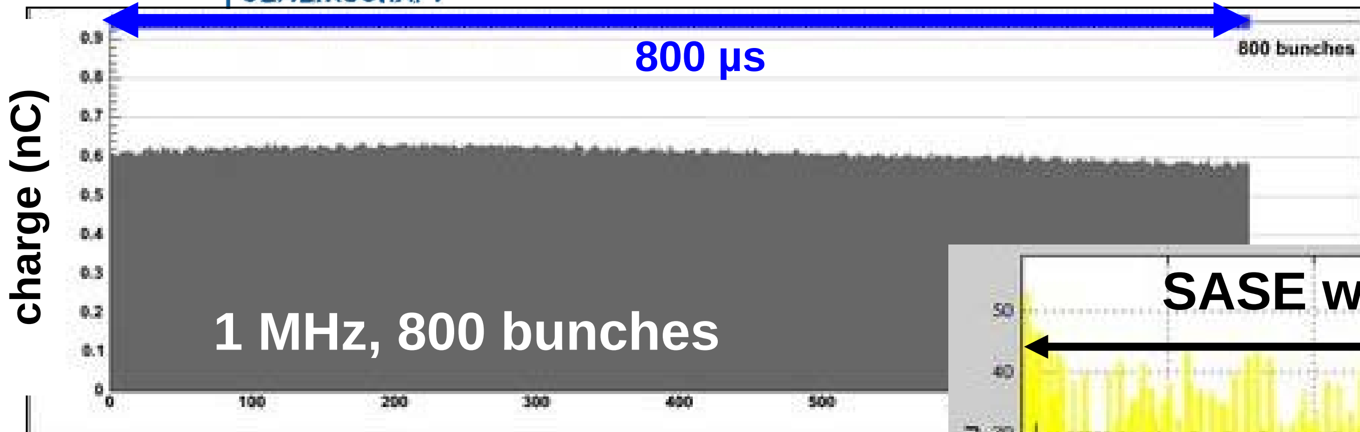
SASE performance – selected issues

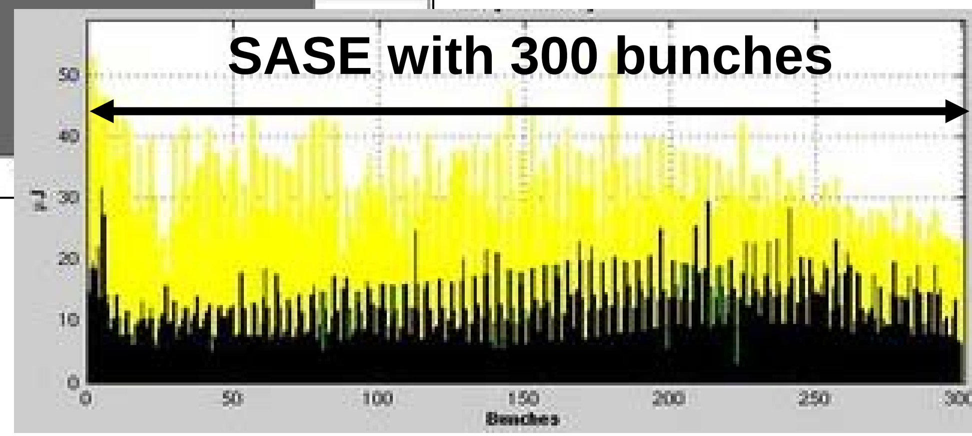
lasing with long bunch trains

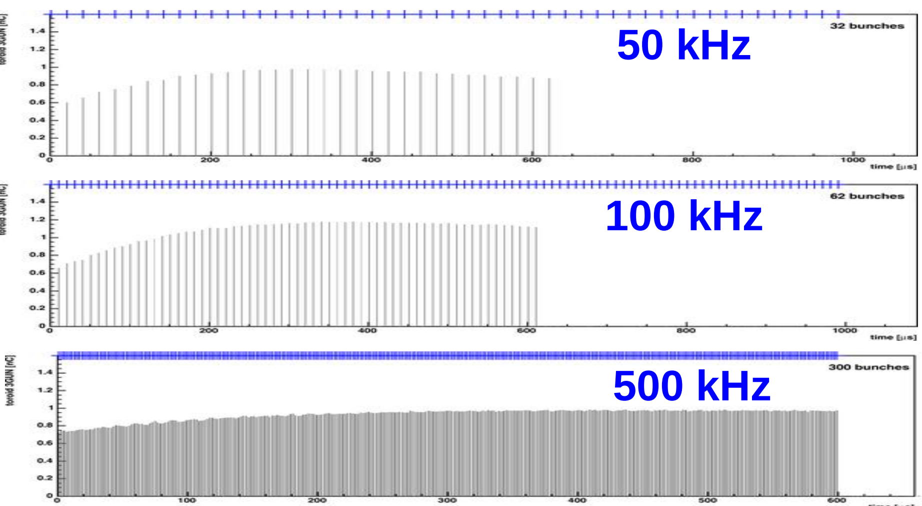
lasing at shortest wavelength

lasing with different wavelengths

Lasing with long bunch trains





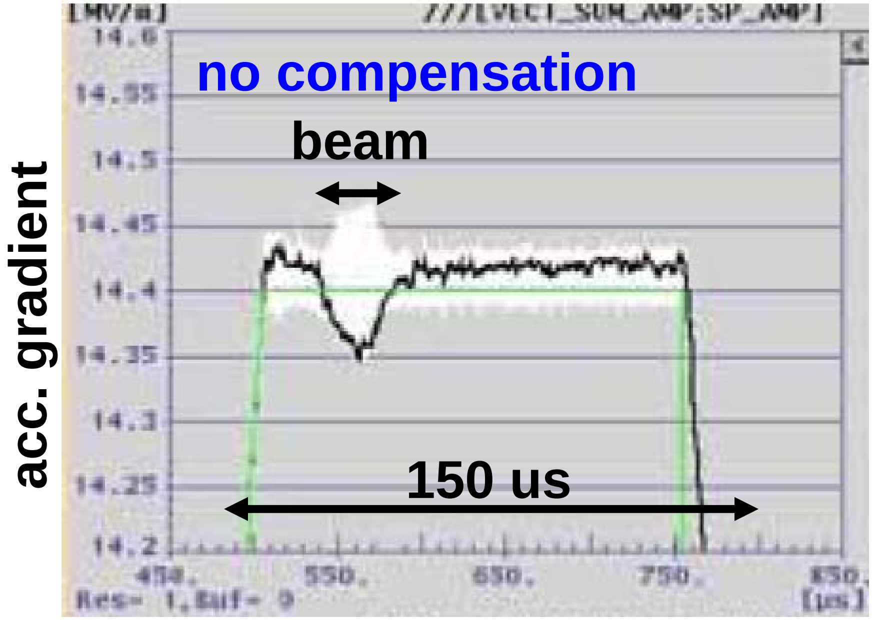


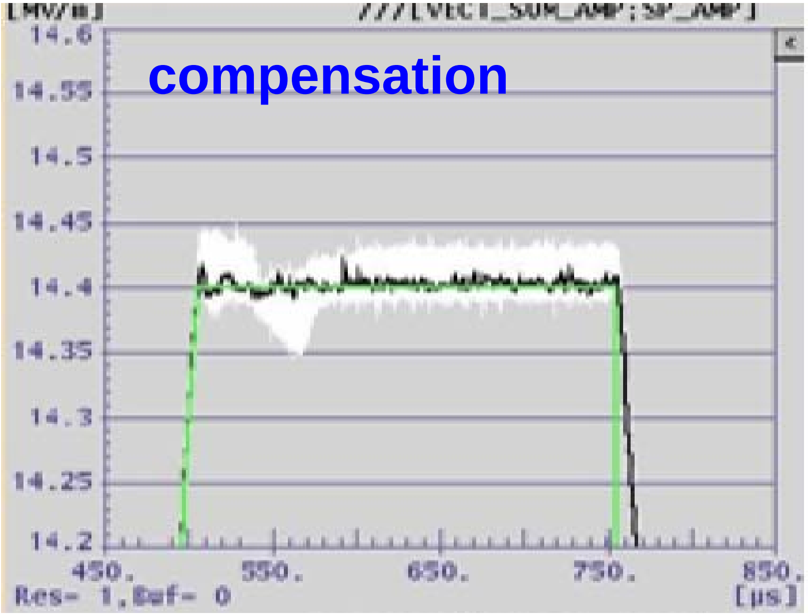
- Transported 800 bunches to beam dump @ 5 Hz
- 1 MHz, 500 kHz, 100 kHz, and 50 kHz
- Lasing with > 450 bunches @ levels up to 70 to 80 µJ av.

Lasing with Long Pulse Trains

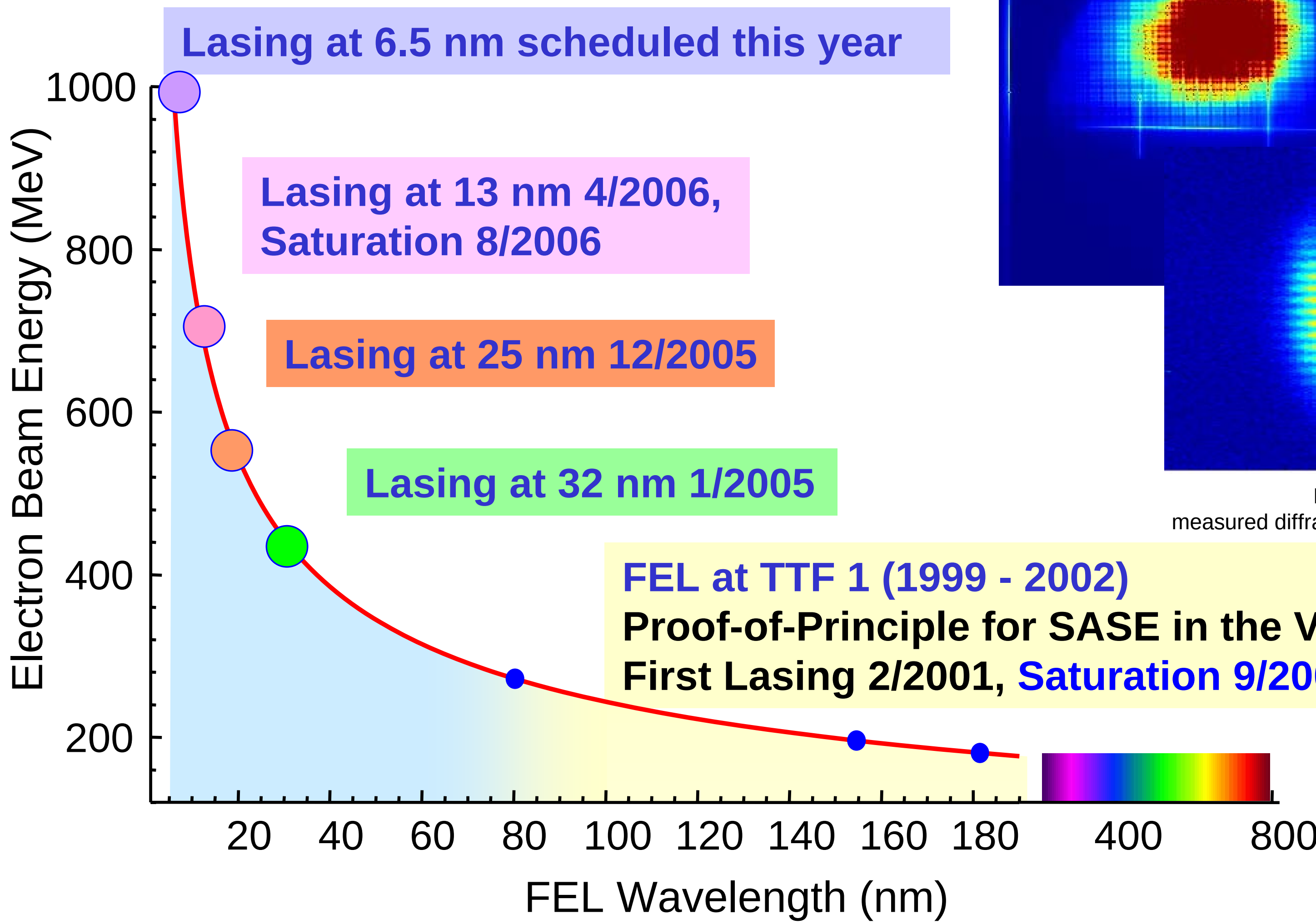
- Big step forward in long pulse train lasing
- Adaptive feed forward to compensate beam loading
- Large phase slopes during the train as observed earlier reduced now to some dg/800 us

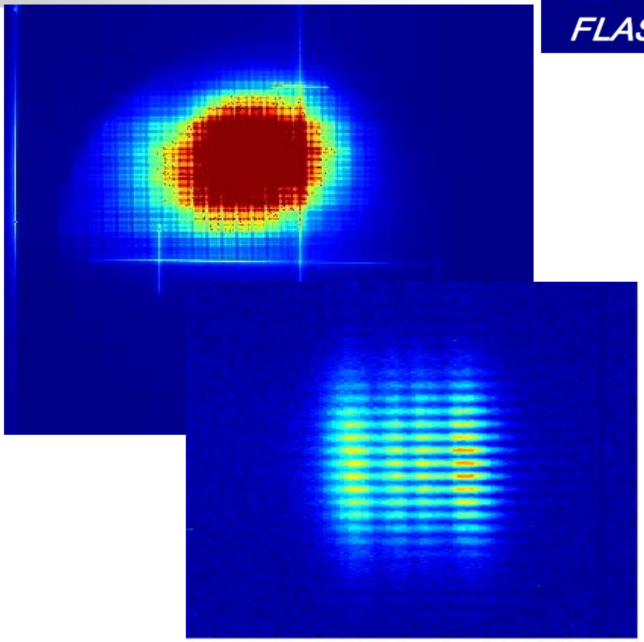
example of beam loading compensation:





Beam Energy and Wavelength





FEL radiation:
measured diffraction pattern of a double slit

Lasing with different Wavelengths

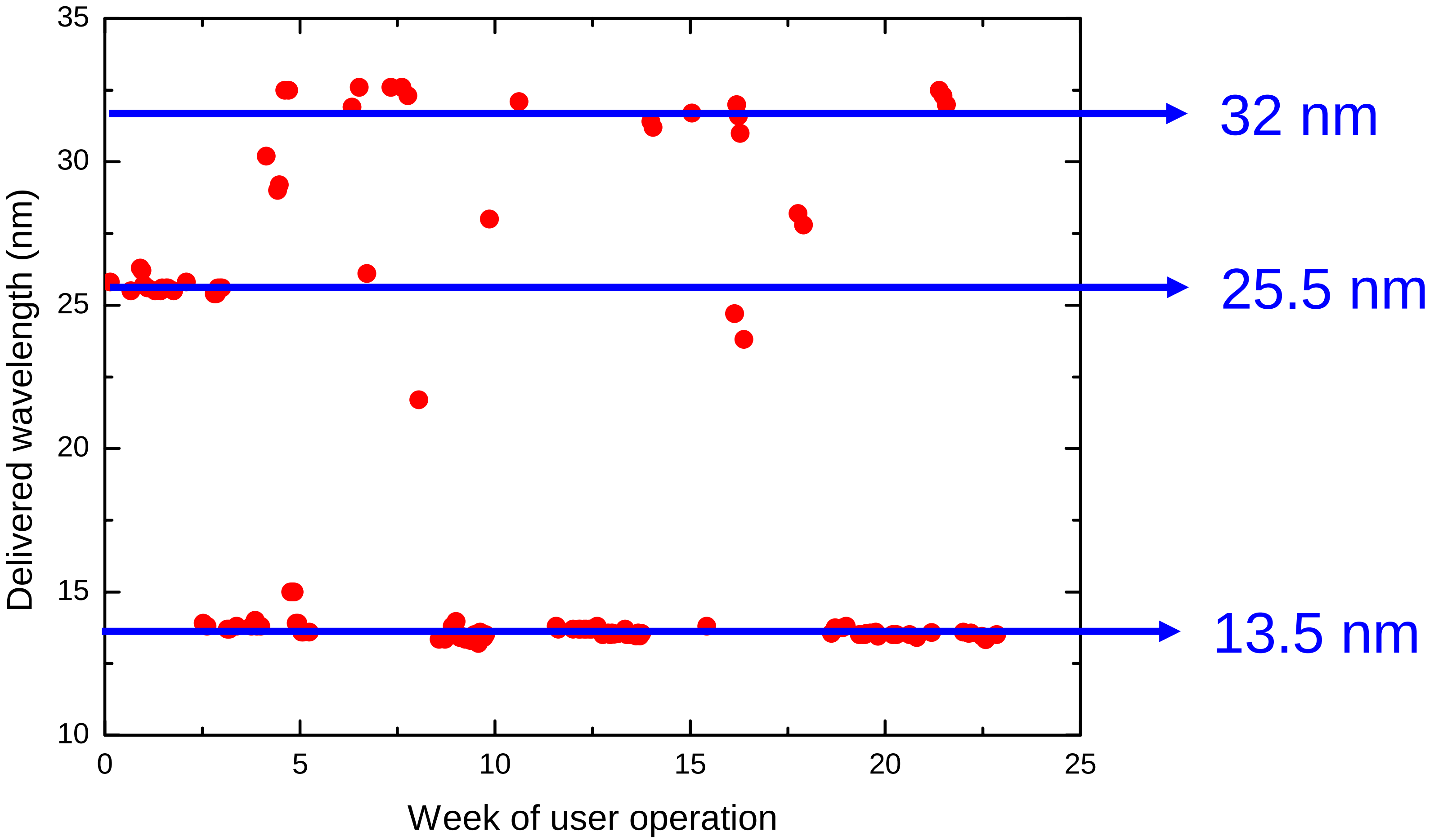
- Lasing at different wavelengths
- Switch on shift to shift bases
- Lasing with >14 wavelengths achieved
- Challenge 1
  - each energy requires new tuning
  - once tuned, reloading of files pretty fast
- Challenge 2
  - hit the right wavelength within 0.1 nm
  - sometimes quite tedious

Examples of wavelengths achieved:

achieved wavelength (nm)	Beam Energy (MeV)
13.1	680
13.7	680
15.1	650
16.9	610
20	576
18.9	580
20.9	550
25.5	500
28.6	478
32.5	465
32.5	445
35.1	428
38	407
40.4	397
47	374

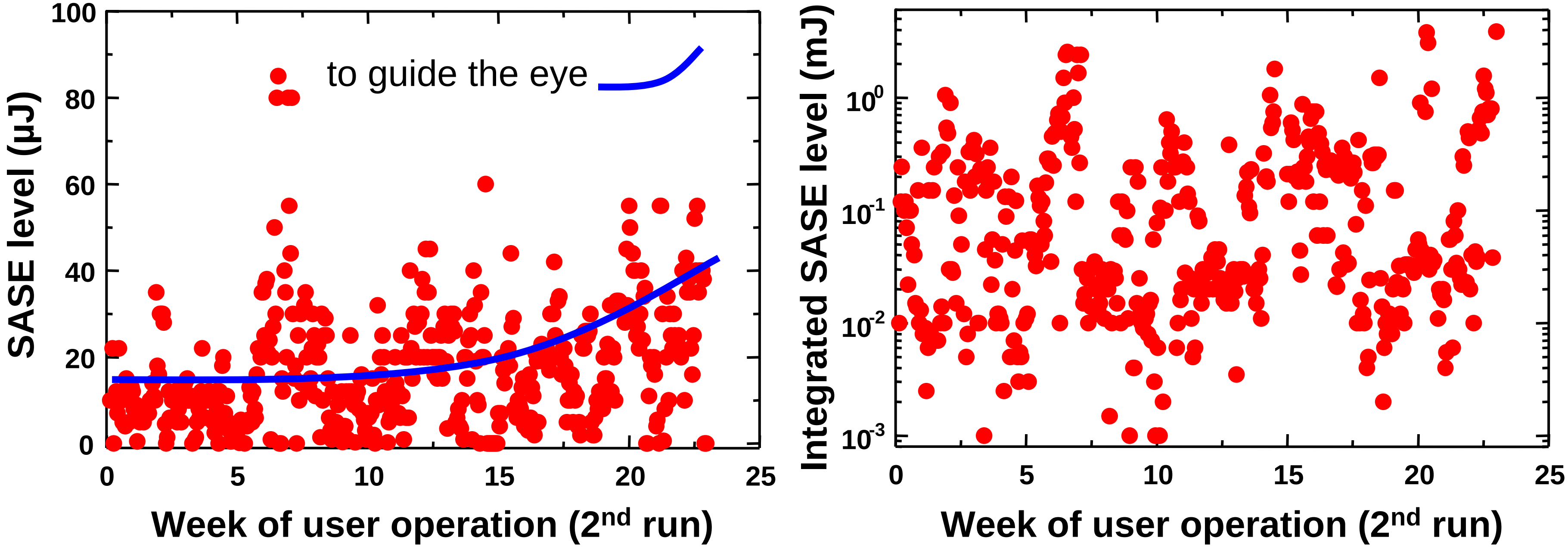
Wavelengths requested

- User's favorites 13.5, 25.5 and 32 nm



SASE radiation energy

- During the 1st run: 1 to 5 µJ average single pulse energy
- During the 2nd run: 20 to 30 µJ average
- The high energy allows collimation of the photon beam
  → improved pointing stability



Stability

- Main issue for the last 2 years: improve stability
  - Injection: stability of laser profile, alignment injector section
  - Low level rf: improve rf feedbacks and stability (new hardware for rf gun and 1st acc. module with improved precision and reduced latency, stabilize ambient temperatures)
  - Slow feedbacks to reduce drifts: charge, compression, orbit
  - Beam optics: new optics, less sensitive to quad errors
  - Dispersion corrections
  - Beam based alignment undulator section with improved diagnostics
  - Better understanding of non-linear beam dynamics
  - Investigation and fixing external noise sources

Electro-magnetic interferences

- Many sources of EM interferences have been cured:
  - Low noise power supplies for most magnets
  - New grounding scheme injector area to fight against high currents on earth lines
  - Adequate distribution of main power stations
  - Compensation of PETRA ramps
  - and many more details

→ we have to fight many mostly small effects

→ but in the sum, we improve a lot!

Statistics

and Run Time Distribution

Distribution of Run Time

- User period 1 had two runs:

→ run 1 in 2005/2006 with 119 days

→ run 2 in 2006/2007 with 160 days

- Next user period 2 will start end 2007/2008 with 1 long run and 203 days

- we also have study weeks

→ FEL related machine studies

preparation of next block of user runs

→ general accelerator studies (XFEL, ILC etc)

weeks

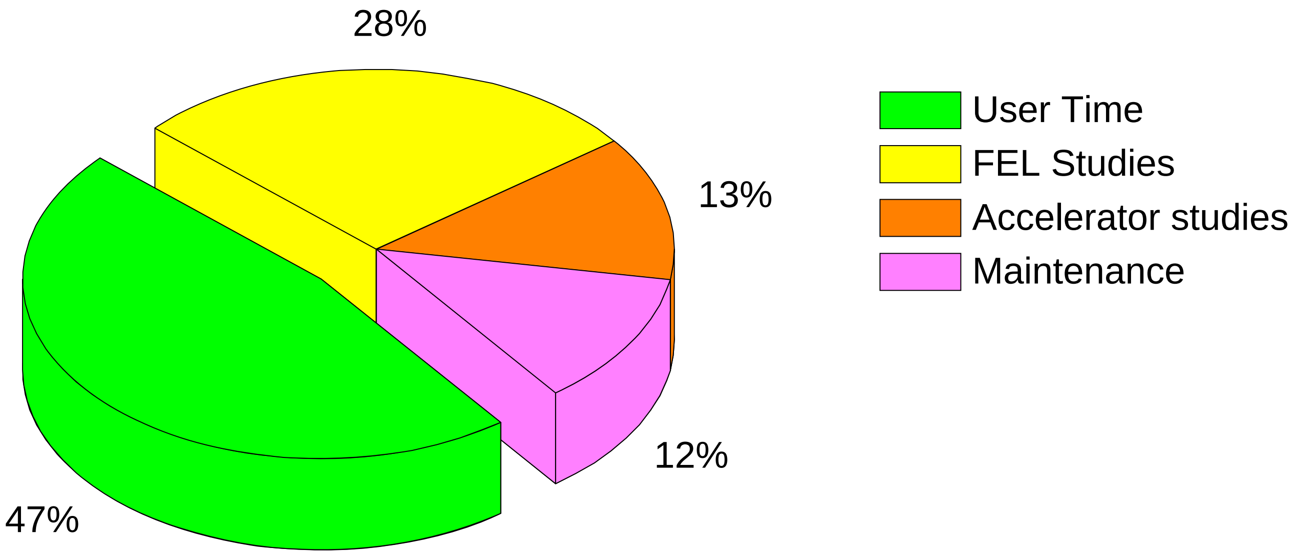
7	
6	
5	
4	User Experiments
3	User run preparation
2	
1	FEL related Studies
7	
6	
5	
4	User Experiments
3	User run preparation
2	
1	FEL related Studies
4	
3	
2	
1	Accelerator Studies

Beam Time Distribution

- Run 2: May-2006 to Mar-2007

→ 45 weeks or 7728 h

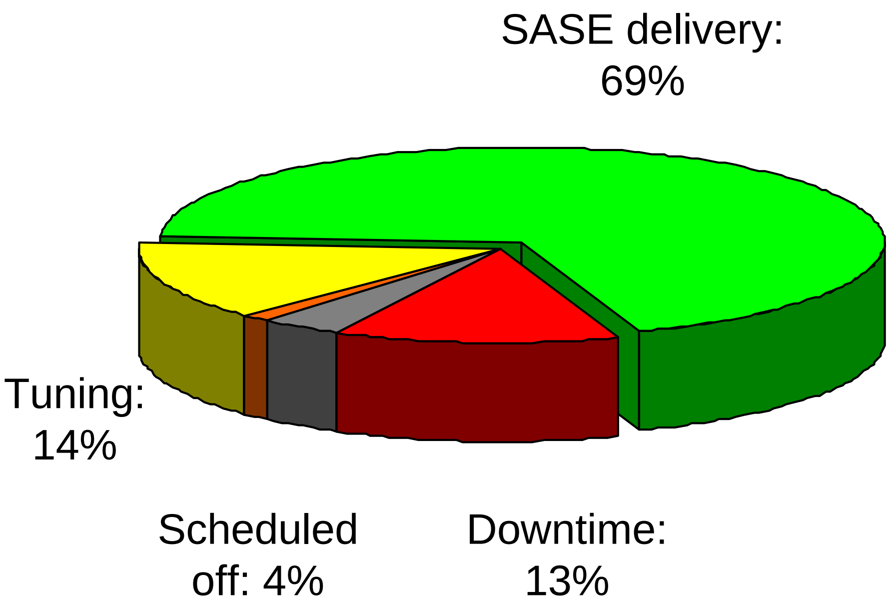
- User experiments had 3840 h of beam time (47 %)
- with 2798 h of actual beam delivery (73%)



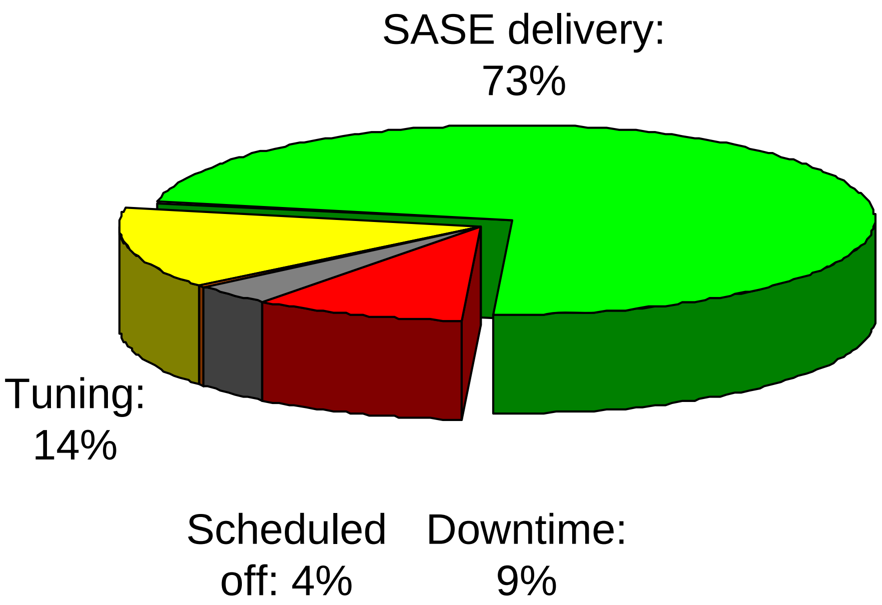
Beam Time Usage User Runs

- ~70 % of the beam time is actually beam delivery
- slight improvement from run 1 to run 2 by 4 %

User Run 1

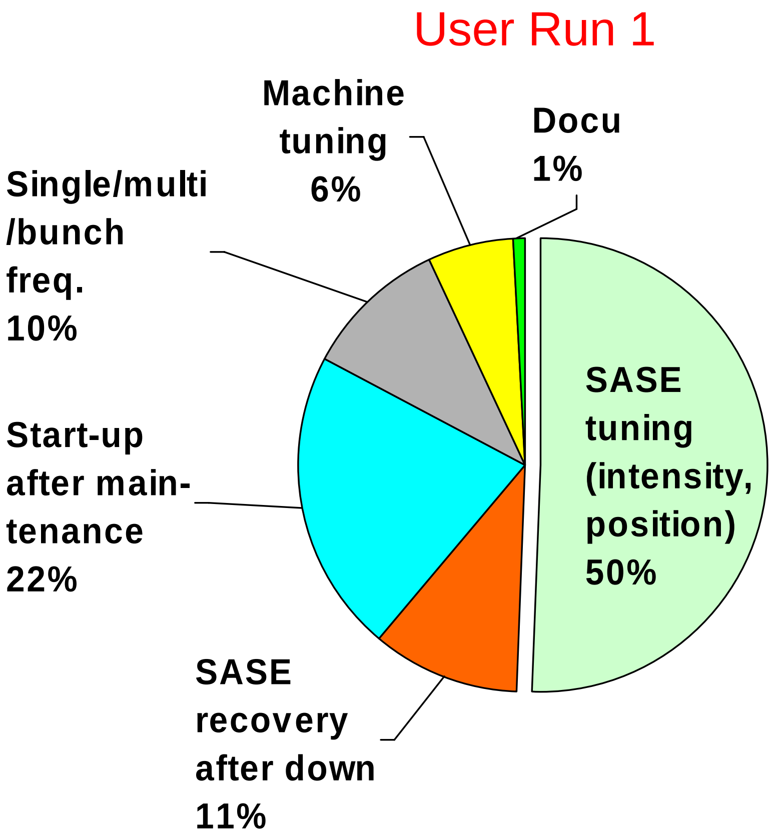


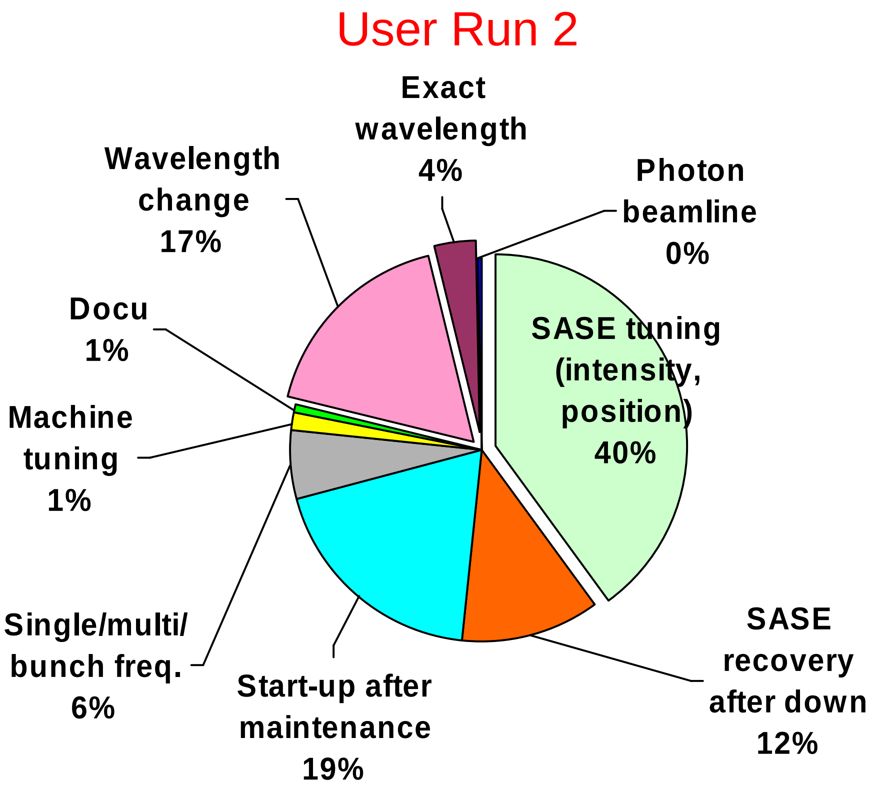
User Run 2



Time Spent on Tuning

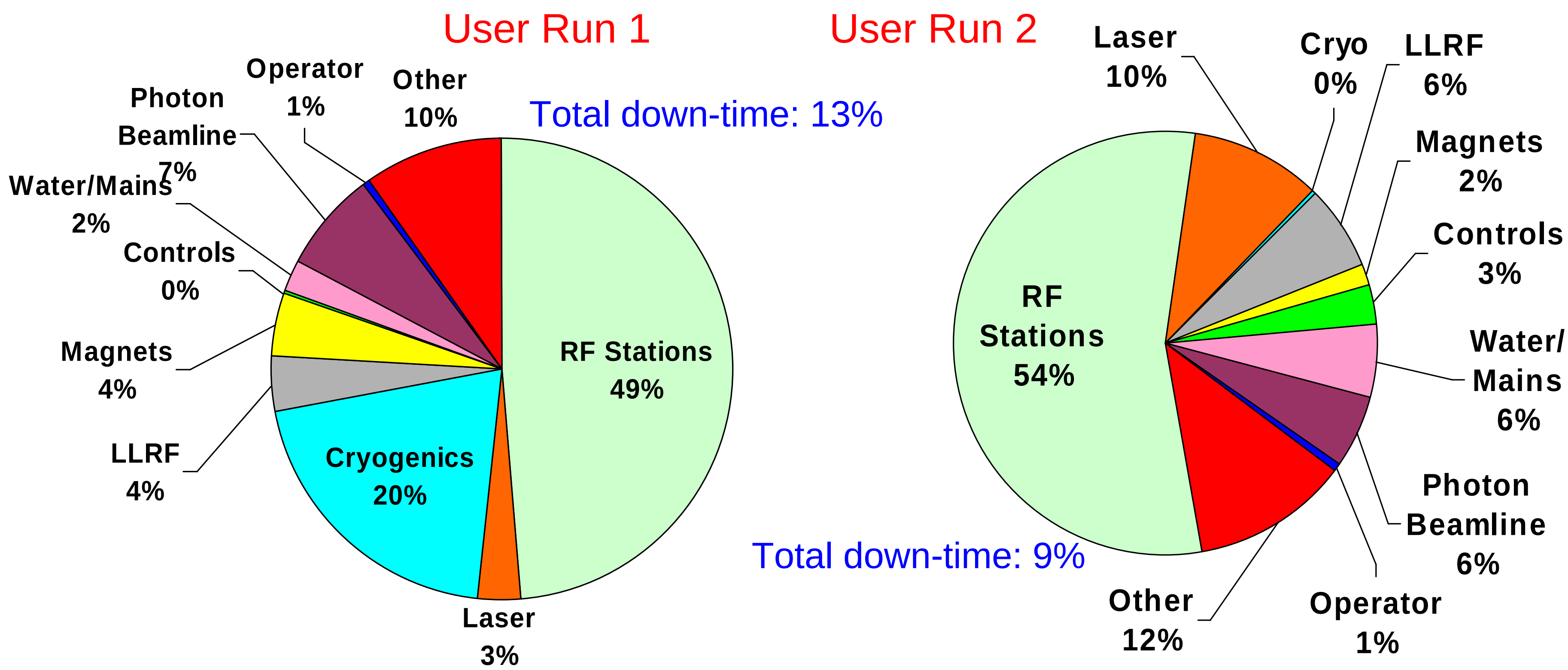
- Beam delivery to users requires tuning
- mostly tuning of SASE performance and start-up/recovery after maintenance or downtimes
- In run 2, wavelength tuning came up in addition



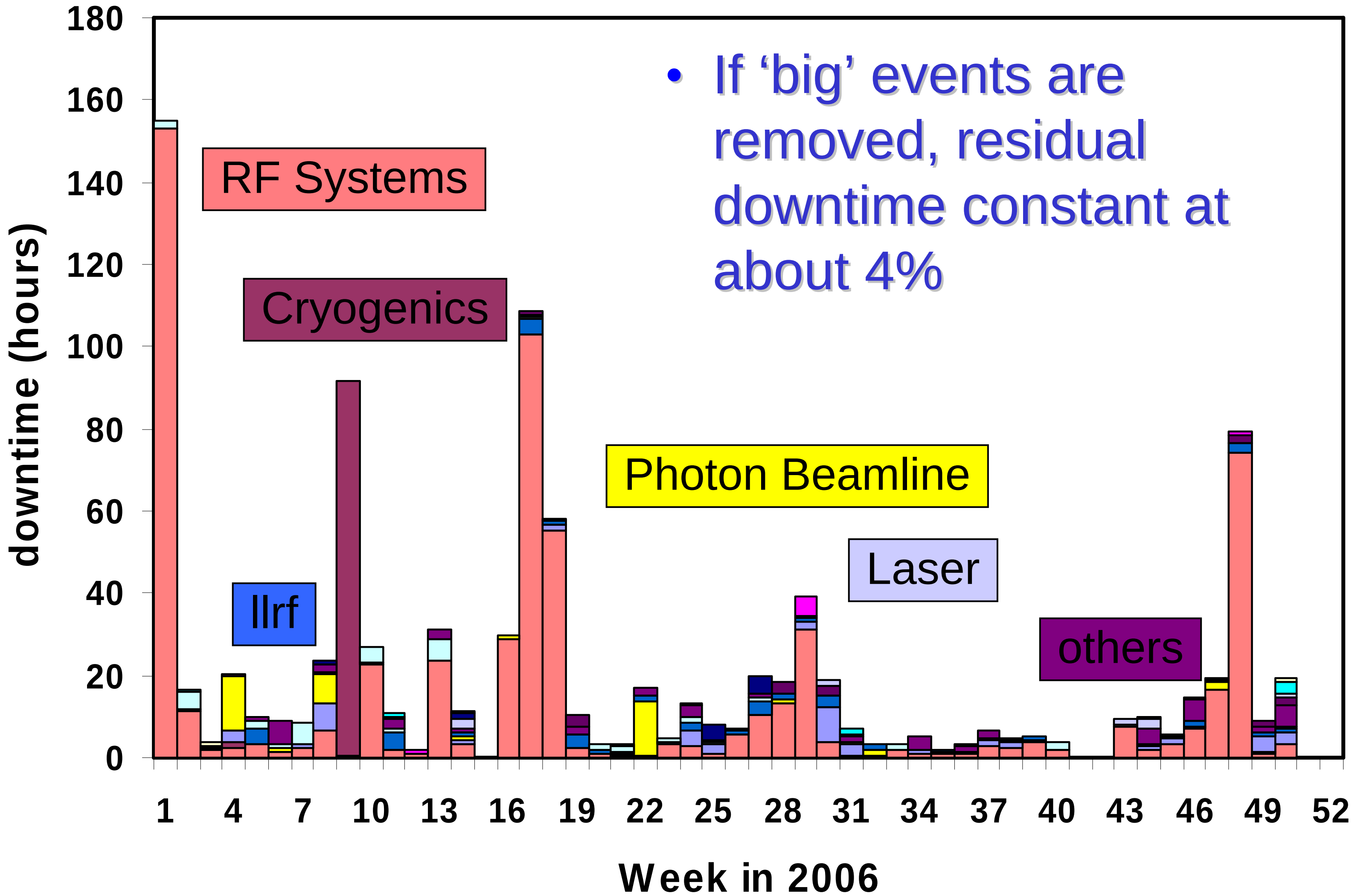


Downtime

- Downtime mainly due to RF stations
- a few 'big' events (cryo/rf stations)
- otherwise lots of little problems with downtimes ~4%



Hardware Failure Evolution in 2006



- If 'big' events are removed, residual downtime constant at about 4%

Schedule

Schedule and Milestones

now

- 1 GeV beam energy: lasing at 6 nm
- shutdown: installation 6th module etc

2007

- lasing with long bunch trains (>30)
- variation of wavelength on shift-to-shift basis
- saturation at 13 nm achieved
- first lasing at 13 nm

TTF VUV-FEL is ***FLASH***

2006

- FEL experiments start
- saturation at 32 nm achieved

User Facility

2005

- first lasing at 32 nm

First Lasing

- first beam to dump
- finish up installation
- commissioning injector started

2004

- commission RF gun at PITZ finished

Schedule and Milestones

With a possible 7th module: 1.2 GeV beam energy

Shutdown: installation of 3rd harmonic acc. system

2009

2008

2nd Period User Experiments starts

now

1 GeV beam energy: lasing at 6 nm

shutdown: installation 6th module

2007

lasing with long bunch trains (>30)
variation of wavelength on shift-to-shift basis
saturation at 13 nm achieved
first lasing at 13 nm

TTF VUV-FEL is ***FLASH***

2006

Major Mid and Long Term Projects

- New experiments have been installed last months
  - IR undulator, optical replica, fast intra-train feedback etc
- New synchronization schemes under development
  - Fiber laser based master oscillator
  - for synchronization down to the 10 fs level
- Install 3rd harmonic accelerating cavity in injector
  - to flatten E-z phase space before compression
- Install 7th module, replace older modules
  - to reach 1.2 (perhaps 1.3 GeV) and lasing at 4.4 (3.7) nm
- Install darkcurrent kicker ds RF gun
  - reduction of accelerated darkcurrent
- Harmonic generation experiment

→ H. Schlarb: "FLASH upgraded – Preparation for the European XFEL" – session last Tu

Last Updated: Tuesday, 5 June 2007, 16:47 GMT 17:47 UK

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BBC NEWS

Green light for flash fantastic

By Jonathan Amos
Science reporter, BBC News

A major new particle accelerator is to be built at Hamburg, Germany, that is capable of producing super-brilliant, ultra-short flashes of X-ray light.

The XFEL will start in a
than 30m underground

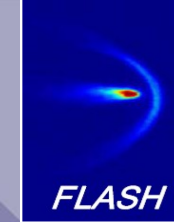
The intense beam made in the 3.4km-long (2.1 miles) machine will probe how matter is pieced together atom by atom.

The properties of the X-ray Free-Electron Lase
should make it possible, for example, to film t
mome

Const
later

It will be placed underground. The XFEL will b
DESY (Deutsches Elektronen-Synchrotron) sit
Hamburg and then run north-west, fanning ou
experimental stations close to the neighbourir
Schenefeld.

5-Jun-2007
Official launch of the European X-ray Laser Facility XFEL.



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German Research Minister launches XFEL

On Tuesday 5 June, the German Federal Minister of Education and Research Annette Schavan officially launched the European X-ray laser facility XFEL. Using essentially the same uperconducting accelerator technology that is planned for the ILC, the 3.4-kilometre XFEL (for X-ray free-electron laser) will produce high-intensity ultra-short X-ray flashes with the properties of laser light. This will open up a whole range of new perspectives for fundamental research and for industrial users.

Summary

- First period of user experiments with 2 runs successfully finished - 1st user run 2005/6 with 119 days of FEL beam, 2nd run ended March 2007 with 160 days of beam time
- Lasing at 13.1 nm - a new record
- Saturation and full characterization of lasing at 13.7 nm
- Lasing has been achieved for many wavelengths and long pulse trains
- Wavelength change on a shift by shift basis
- Stability and performance in the last year has much improved compared to 2005:
  we provide 20 to 30 µJ average single pulse energy now
- Many user experiments have been successfully performed
- Next user period is 3 times overbooked:
  FLASH – a unique facility proving excellent opportunities for experiments