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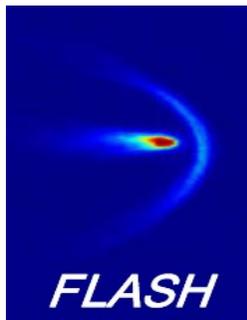
MAC
8-9 Nov 2007
DESY, Hamburg

FLASH
Free-Electron Laser
in Hamburg

Status FLASH

Siegfried Schreiber, DESY

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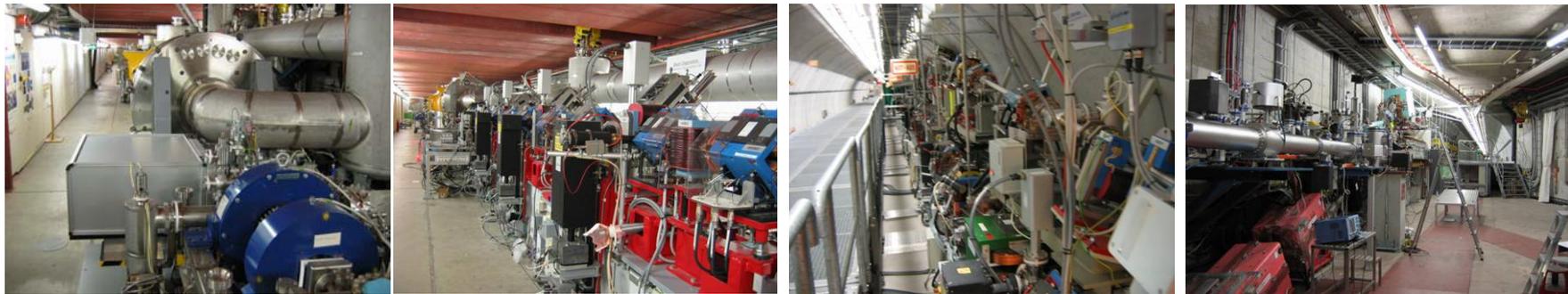
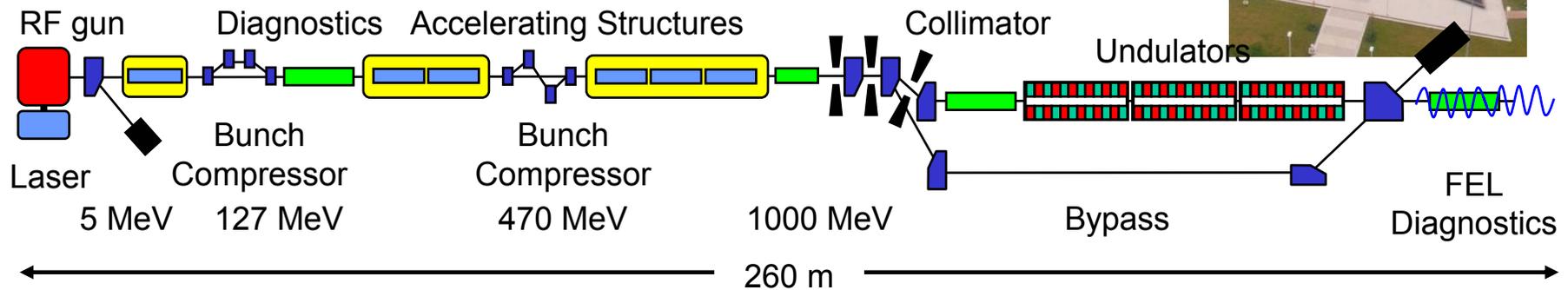
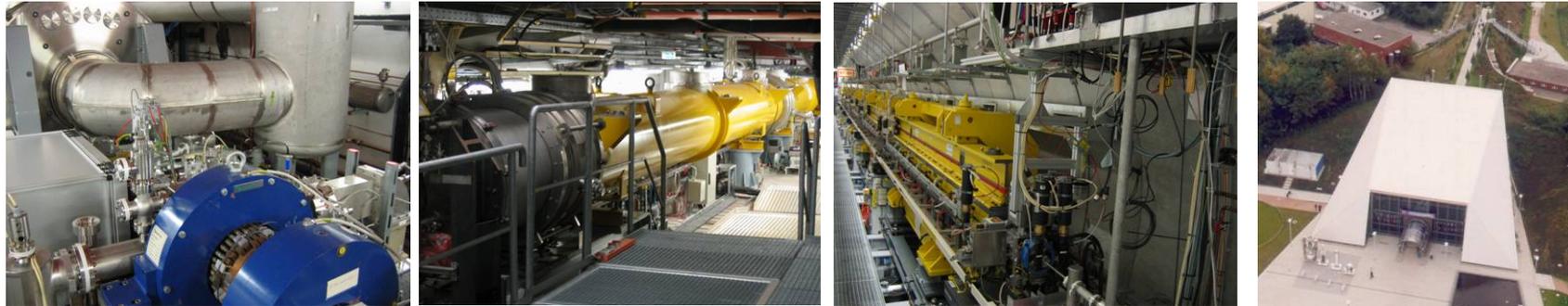
- FLASH – Free Electron Laser User Facility
- VUV/EUV lasing
- Performance and operational issues
- Summary and Outlook



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FLASH Overview

FLASH
Free-Electron Laser
in Hamburg



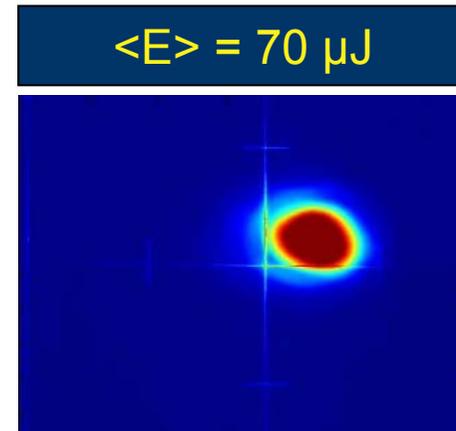
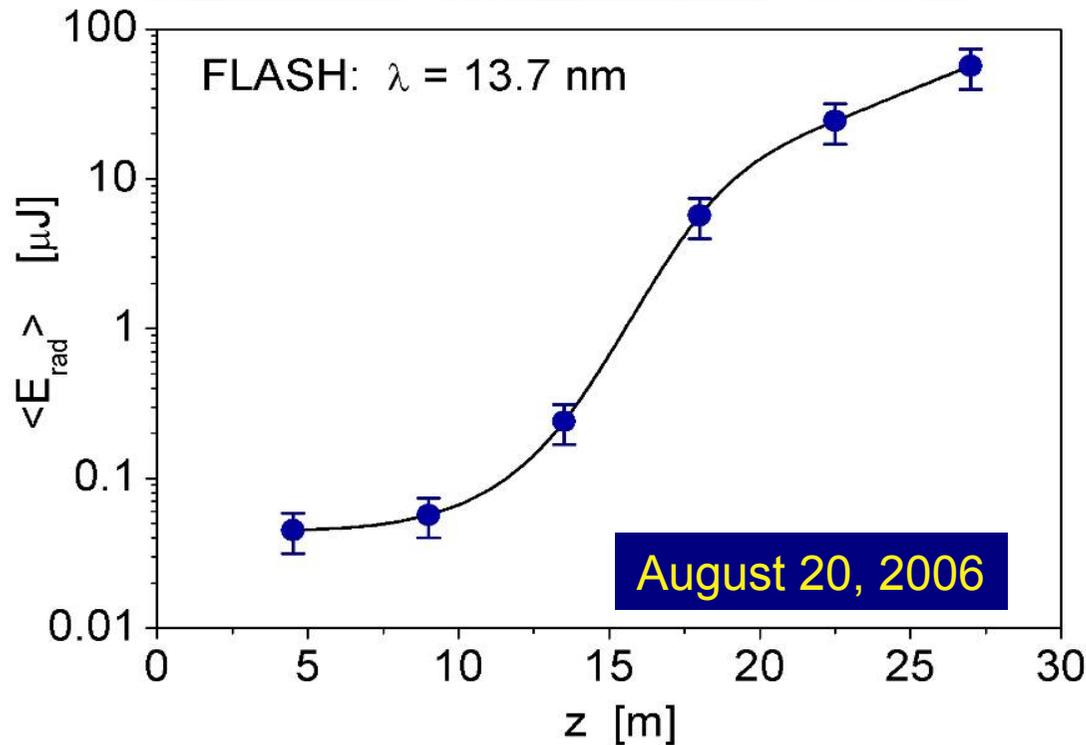
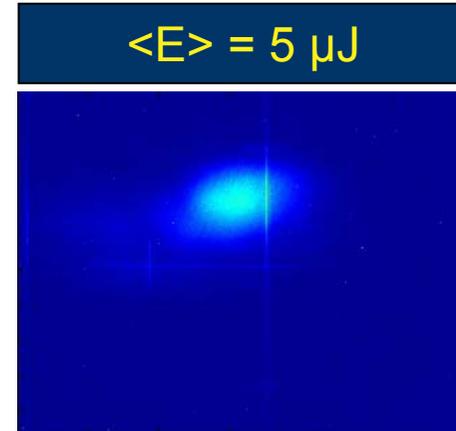
SASE highlights



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From First Lasing at 13 nm to Saturation

FLASH
Free-Electron Laser
in Hamburg



SY, Hamburg

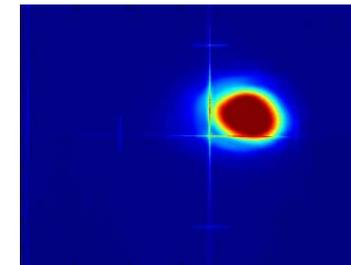
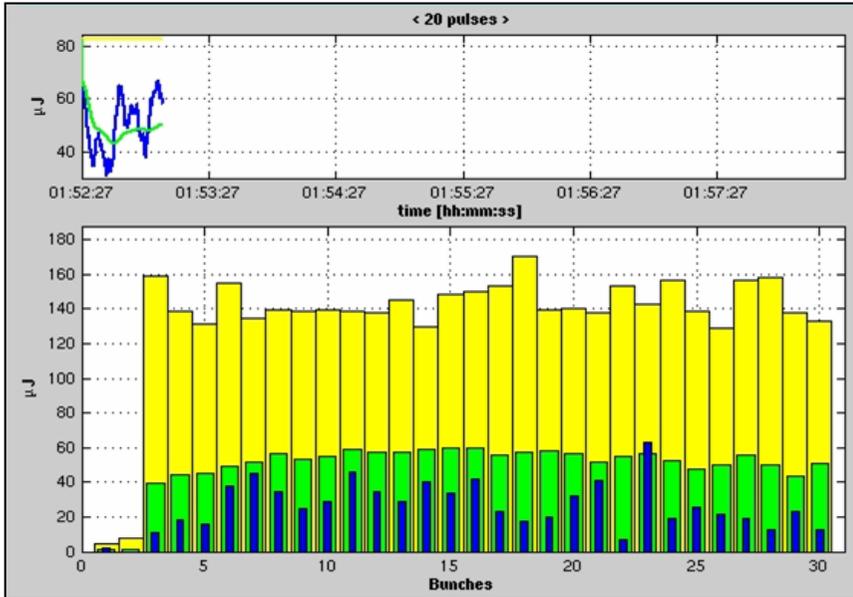


SASE Performance

In saturation at 13.7 nm:

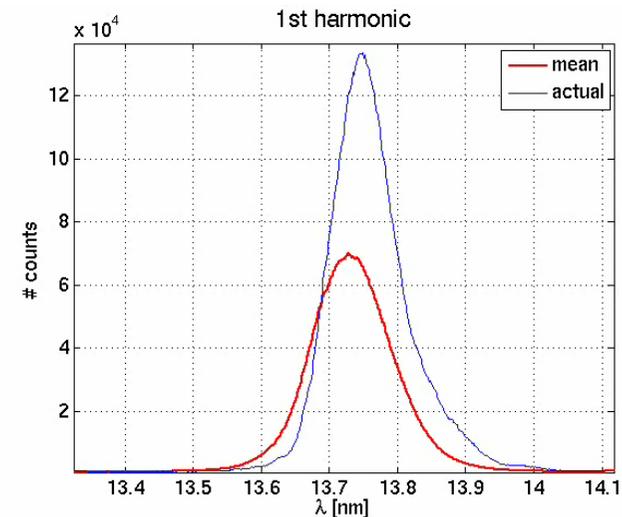
- Average energy: 70 μJ
- Peak energy: 170 μJ
- Pulse duration: 10 fs
- Peak power: >10 GW
- Peak brilliance: $(6 \pm 3) \cdot 10^{29} \text{ B}$

$B = \text{ph/s/mrad}^2/\text{mm}^2/0.1\% \text{bw}$



Normal operation parameters:

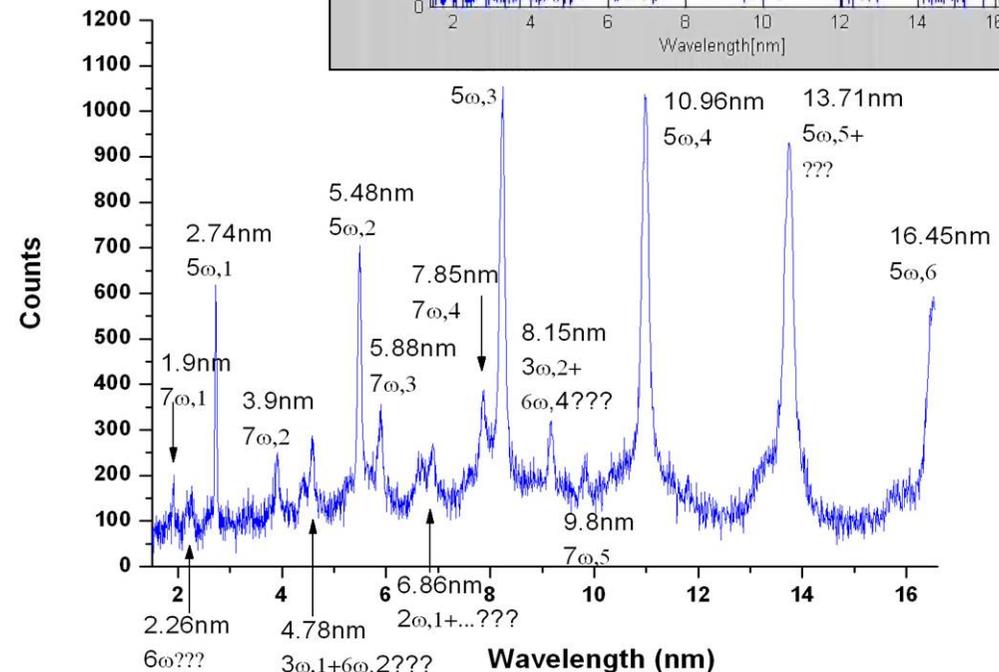
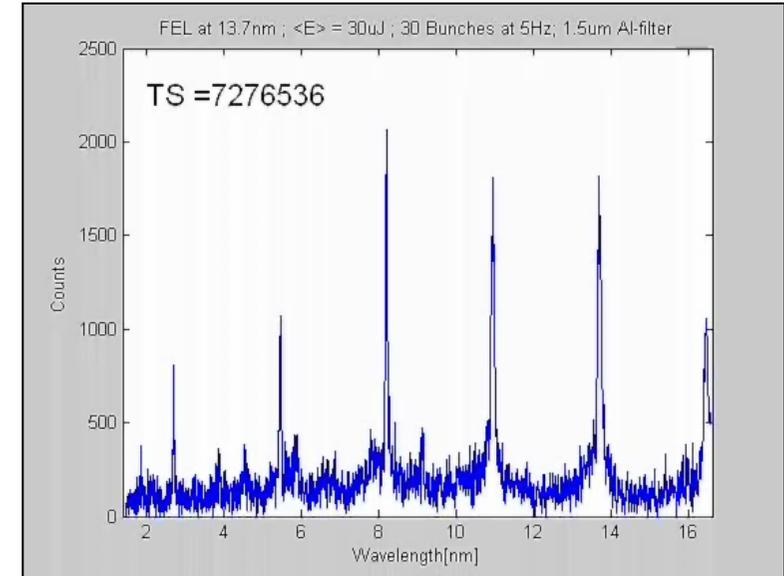
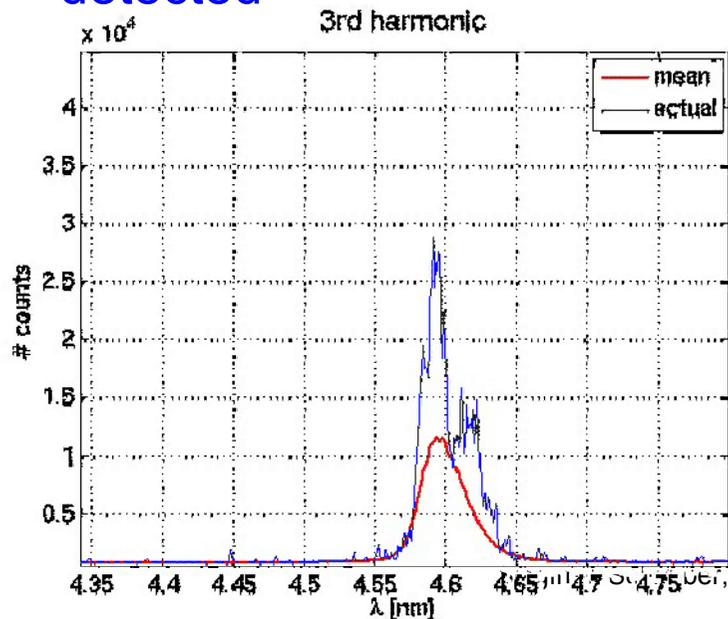
- Wavelength range (fundamental): 13 - 47 nm
- Average single pulse energy: 20 - 30 μJ
- Pulse duration (FWHM): 10 - 25 fs
- Peak power (from av.): $\sim 3 \text{ GW}$
- Average power (700 pulses/sec) $\sim 20 \text{ mW}$
- divergence: 90 μrad
- Spectral width (FWHM): 0.7-1 %
- Brilliance: $\sim 10^{29}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





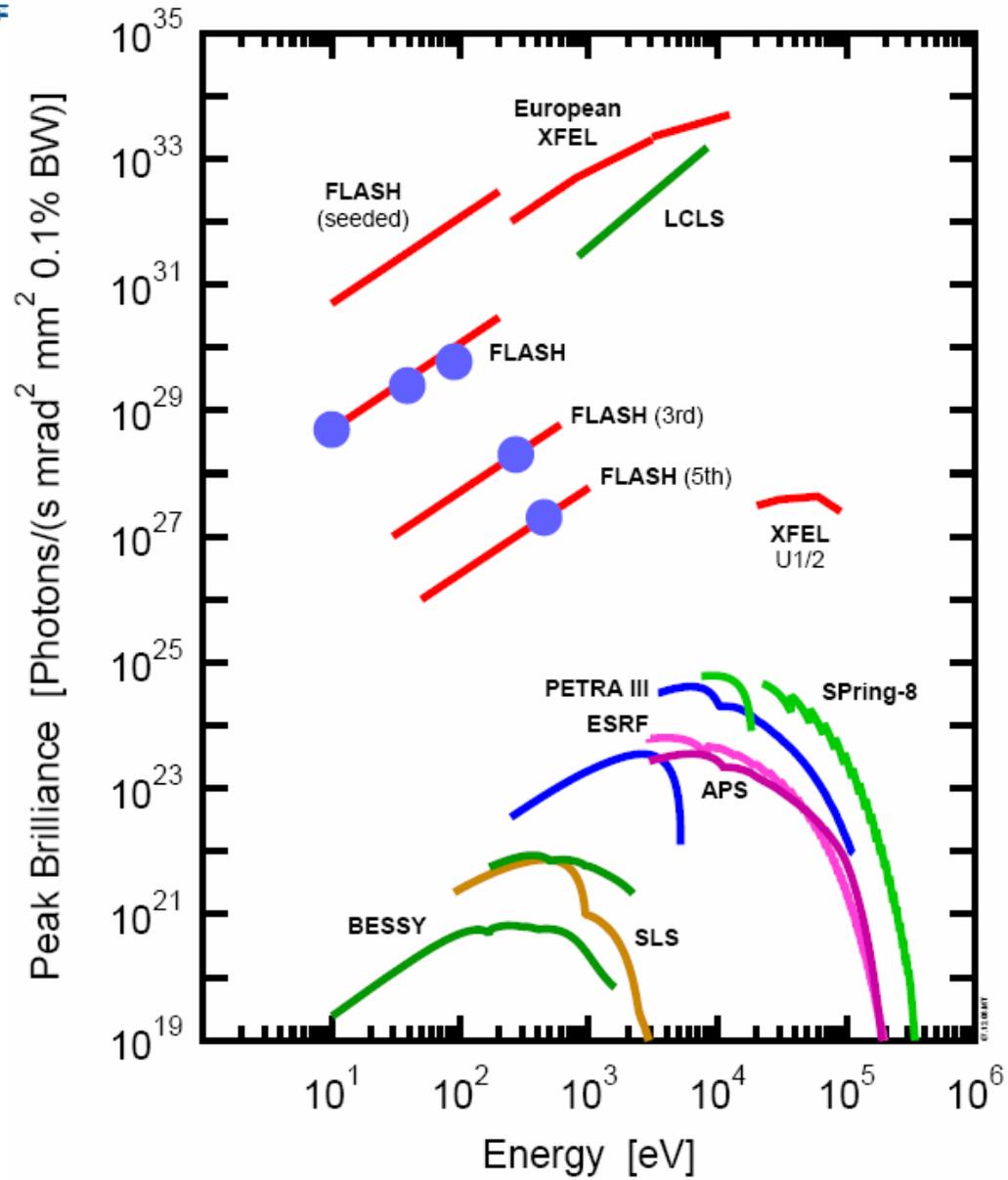
Higher Harmonics

- 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

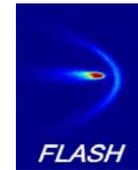




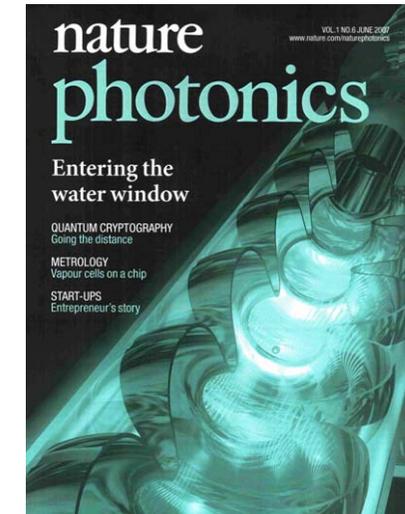
Peak Brilliance



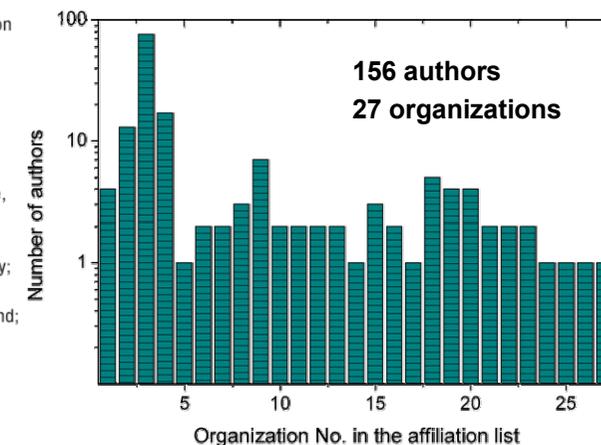
Operation of a free-electron laser from the extreme ultraviolet to the water window



W. ACKERMANN¹, G. ASOVA², V. AYVAZIAN³, A. AZIMA³, N. BABO³, J. BÄHR², V. BALANDIN³, B. BEUTNER⁴, A. BRANDT³, A. BOLZMANN⁵, R. BRINKMANN³, O. I. BROVKO⁶, M. CASTELLANO⁷, P. CASTRO³, L. CATANI⁸, E. CHIADRONI⁹, S. CHORABA³, A. CIANCHI¹⁰, J. T. COSTELLO⁹, D. CUBAYNES¹⁰, J. DARDIS⁹, W. DECKING³, H. DELSIM-HASHEMI⁴, A. DELSERIEYS¹¹, G. DI PIRRO⁷, M. DOHLUS³, S. DÜSTERER³, A. ECKHARDT⁴, H. T. EDWARDS¹², B. FAATZ³, J. FELDHAUS³, K. FLÖTTMANN³, J. FRISCH¹³, L. FRÖHLICH⁴, T. GARVEY¹⁴, U. GENSCHE², CH. GERTH³, M. GÖRLER³, N. GOLUBEVA³, H.-J. GRABOSCH², M. GRECKI¹⁵, O. GRIMM³, K. HACKER^{3,4}, U. HAHN³, J. H. HAN³, K. HONKAVAARA⁴, T. HOTT³, M. HÜNING³, Y. IVANISENKO¹⁶, E. JAESCHKE¹⁷, W. JALMUZNA¹⁸, T. JEZYNSKI¹⁵, R. KAMMERING³, V. KATALEV³, K. KAVANAGH⁹, E. T. KENNEDY⁹, S. KHODYACHYKH², K. KLOSE², V. KOCHARYAN³, M. KÖRFER³, M. KOLLEWE³, W. KOPREK¹⁸, S. KOREPANOV², D. KOSTIN³, M. KRASSILNIKOV², G. KUBE³, M. KUHLMANN³, C. L. S. LEWIS¹¹, L. LILJE³, T. LIMBERG³, D. LIPKA³, F. LÖHL⁴, H. LUNA⁹, M. LUONG¹⁹, M. MARTINS⁴, M. MEYER¹⁰, P. MICHELATO²⁰, V. MILTCHEV⁴, W. D. MÖLLER³, L. MONACO²⁰, W. F. O. MÜLLER¹, O. NAPIERALSKI¹⁵, O. NAPOLY¹⁹, P. NICOLOSI²¹, D. NÖLLE³, T. NUÑEZ³, A. OPPELT², C. PAGANI²⁰, R. PAPARELLA¹⁹, N. PCHALEK^{3,4}, J. PEDREGOSA-GUTIERREZ⁹, B. PETERSEN³, B. PETROSYAN², G. PETROSYAN³, L. PETROSYAN³, J. PFLÜGER³, E. PLÖNJES³, L. POLETTO², K. POZNIAK¹⁸, E. PRAT^{3,4}, D. PROCH³, P. PUCYK¹⁸, P. RADCLIFFE³, H. REDLIN³, K. REHLICH³, M. RICHTER²², M. ROEHRS^{3,4}, J. ROENSCH⁴, R. ROMANIUK¹⁸, M. ROSS¹³, J. ROSSBACH⁴, V. RYBNIKOV³, M. SACHWITZ², E. L. SALDIN³, W. SANDNER²³, H. SCHLARB³, B. SCHMIDT³, M. SCHMITZ³, P. SCHMÜSER⁴, J. R. SCHNEIDER³, E. A. SCHNEIDMILLER³, S. SCHNEPP¹, S. SCHREIBER³, M. SEIDEL^{3,24}, D. SERTORE²⁰, A. V. SHABUNOV⁶, C. SIMON¹⁹, S. SIMROCK³, E. SOMBROWSKI³, A. A. SOROKIN^{25,22}, P. SPANKNEBEL²⁶, R. SPESYVTSYEV¹⁶, L. STAYKOV², B. STEFFEN³, F. STEPHAN², F. STULLE³, H. THOM³, K. TIEDTKE³, M. TISCHER³, S. TOLEIKIS³, R. TREUSCH³, D. TRINES³, I. TSAKOV²⁷, E. VOGEL³, T. WEILAND¹, H. WEISE³, M. WELHÖFER⁴, M. WENDT^{3,12}, I. WILL²³, A. WINTER³, K. WITTENBURG³, W. WURTH⁴, P. YEATES⁹, M. V. YURKOV^{3*}, I. ZAGORODNOV³ AND K. ZAPFE³



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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



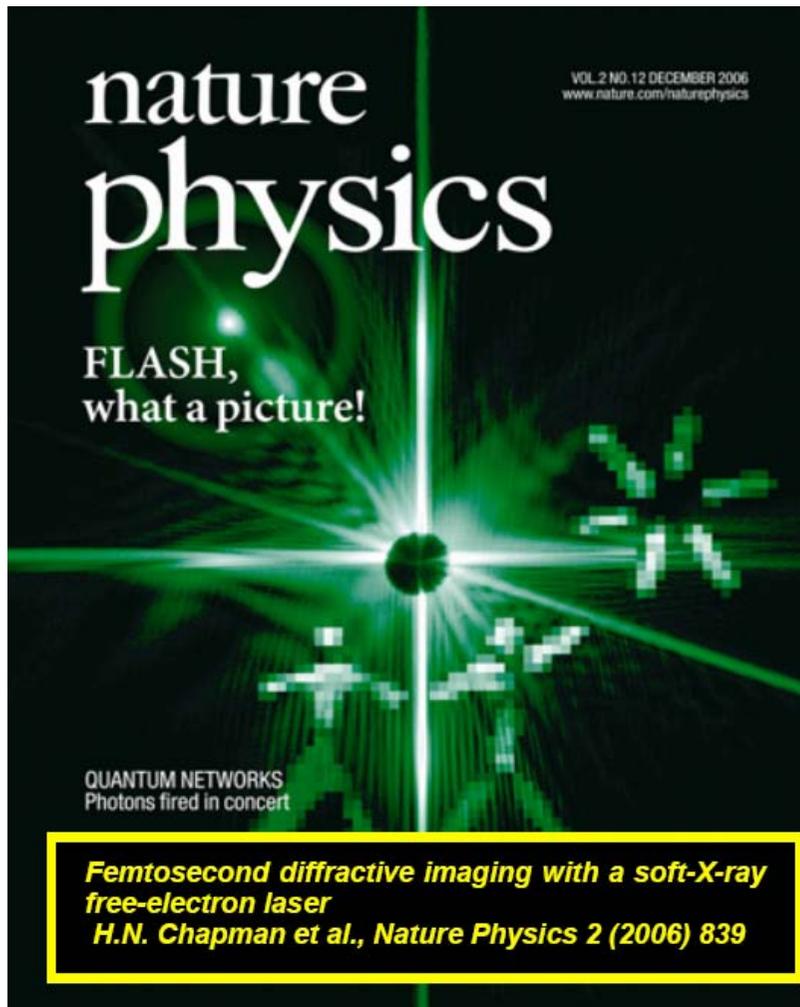


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FLASH,
what a picture!

FLASH
Free-Electron Laser
in Hamburg

1st round of user experiments finished



- **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**



DESY

TELEGRAMM

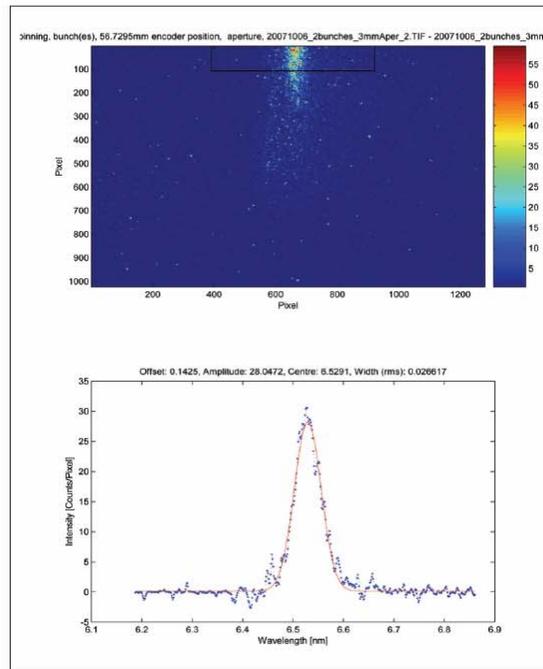
8. Oktober 2007



Wellenlängen-Weltrekord bei FLASH: 6,5 Nanometer!
Geplanter Designwert für die Laserblitze erzielt

Wavelength World Record at FLASH: 6.5 Nanometers!
Design value for laser flashes reached

Zwei Wochen nach dem Erreichen der maximalen Strahlenergie von 1 Giga-elektronenvolt kam aus dem Kontrollraum die Meldung: „Am 4. Oktober haben wir in den Abendstunden zum ersten Mal bei FLASH das Lasen bei einer Wellenlängen von 7 Nanometern (nm) beobachtet.“ Schon 24 Stunden später gelang es dem FLASH-Team, den für die Anlage geplanten Designwert von 6,5 nm zu erzielen. Die in den sechs supraleitenden Modulen auf eine Energie von 986 Megaelektronenvolt beschleunigten Elektronen-



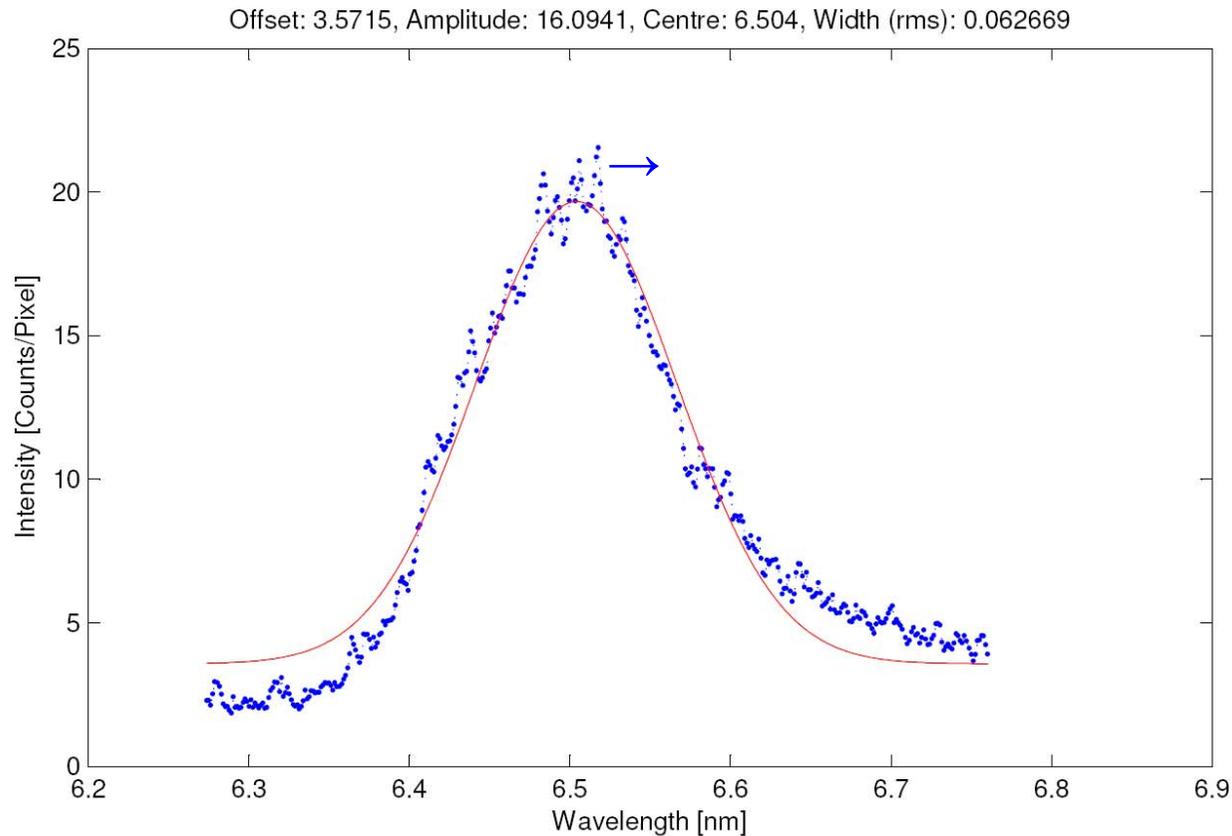
Plot und Zahlen für Experten:
Das Wellenlängenspektrum bei 6,5 nm. Zahl der
Bunche: 2 - Apertur: 3 mm - Wellenlänge: 6.523 nm

Two weeks after the maximum beam energy of 1 gigaelectronvolt was reached, the control room announced another milestone: “On the evening of October 4, we observed lasing at a wavelength of 7 nanometers (nm) at FLASH for the first time.” Only 24 hours later, the FLASH team achieved the facility's design value of 6.5 nm. In FLASH, the electrons are accelerated to an energy of 986 megaelectronvolts in six superconducting modules. On their flight through the undulator, the electrons now demonstrated the desired behavior also at this high energy: the spontaneous radiation they emit amplified itself to form the



Lasing at 6.5 nm

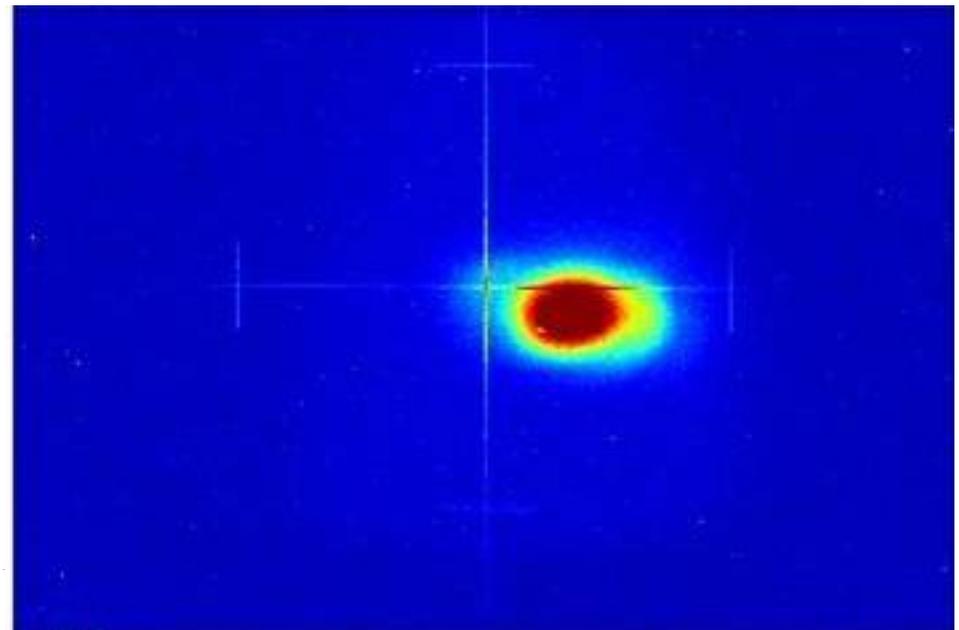
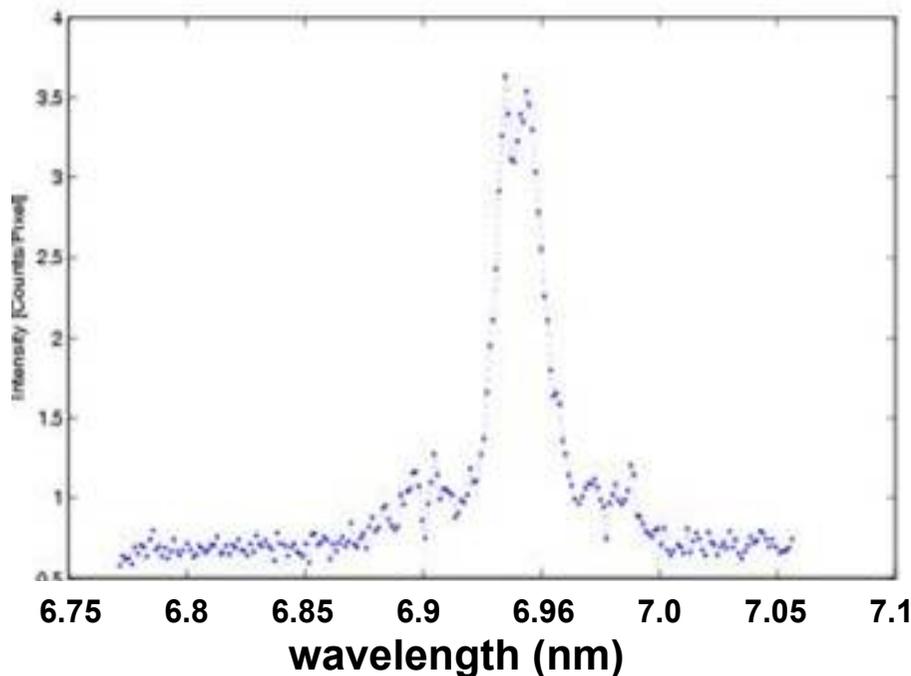
- 1 GeV achieved 21-Sep-2007 00:57 h
- lasing at 6.9 nm 4-Oct-2007 19:25 h
- lasing at 6.5 nm 5-Oct-2007 17:48 h





Preliminary Radiation Properties

- Lasing at 6.5 nm and 6.9 nm, 7 nm requested by users
- estimate 2 μJ level ($\pm 50\%$)
- the single shot spectra show a small number of modes
→ preliminary estimated pulse length: in the 5 fs range
(rough extrapolation from the 13 nm data)

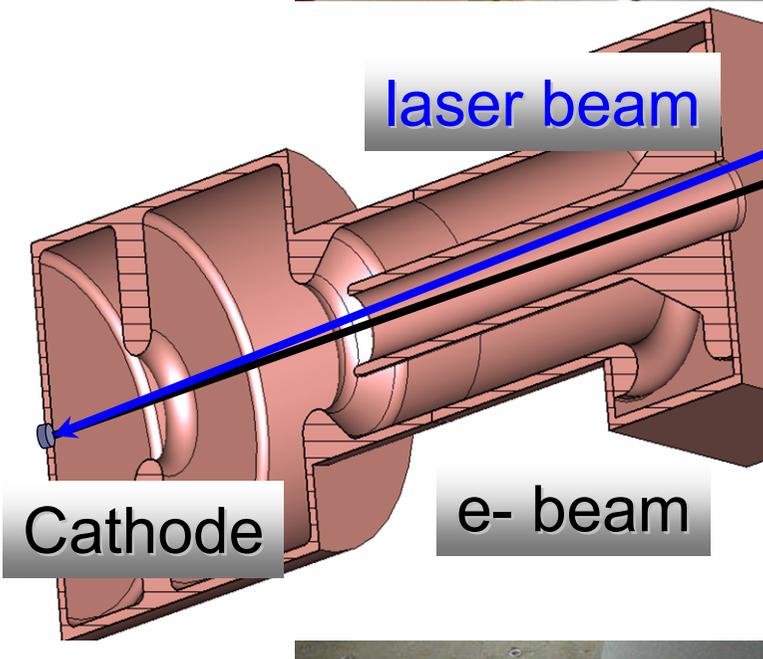
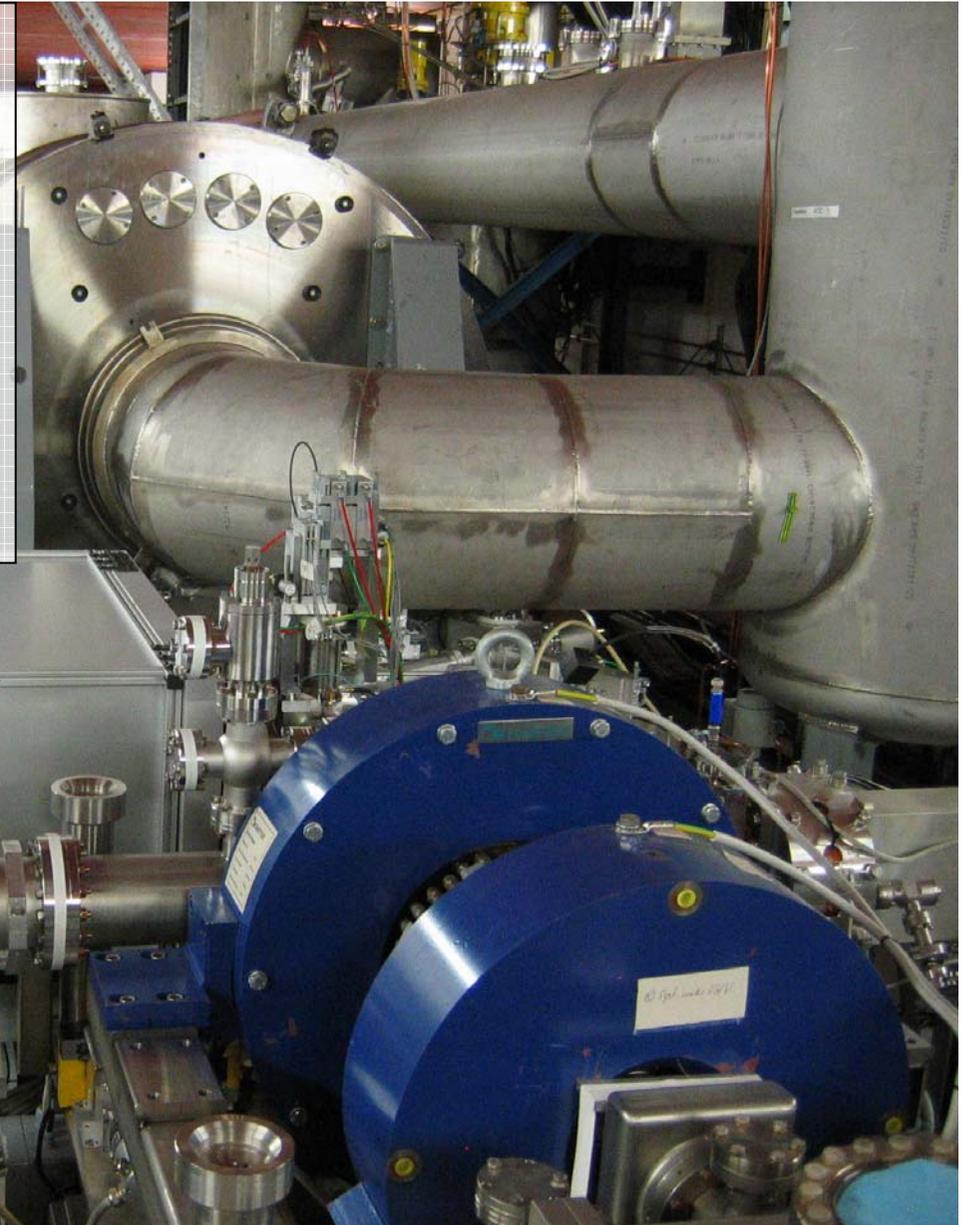


Linac Components



Photoinjector

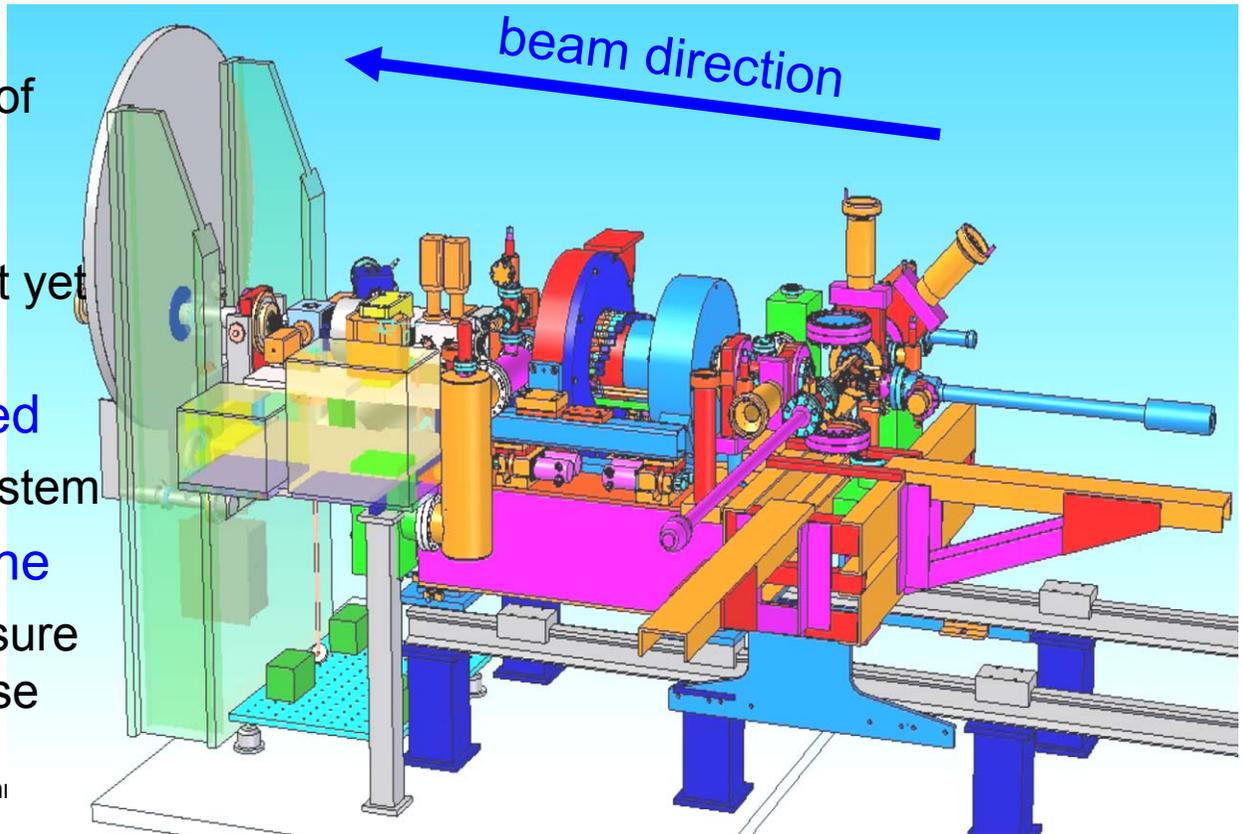
- laser driven RF gun
- L-band 1.3 GHz
- RF power 3.2 MW
- 42 MV/m gradient on cathode
- Pulsed 5 or 10 Hz
- RF pulse length 100 to 900 μ s





RF Gun and Laser upgrades

- 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)
- 2nd laser system installed
 - fully diode pumped system
- Reworked laser beamline
 - gated camera to measure single bunch transverse beam shape



Siegfried Schi



High QE Cs₂Te Cathodes

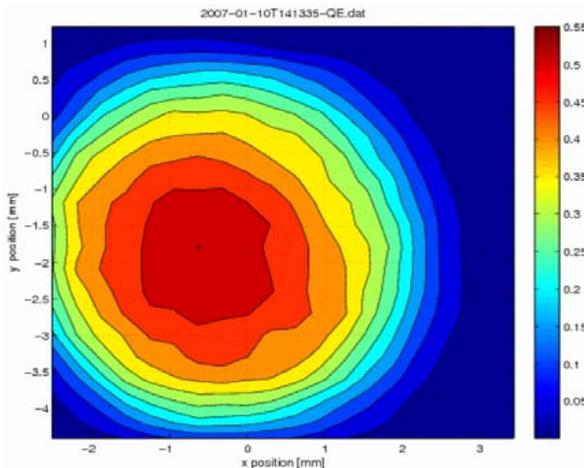
- Quantum efficiency (QE) starts high ~10 % and drops to ~0.5% during a couple of weeks, change of cathodes routine operation
- XPS at BESSY: traces of F and C found, depleted part: metallic Te



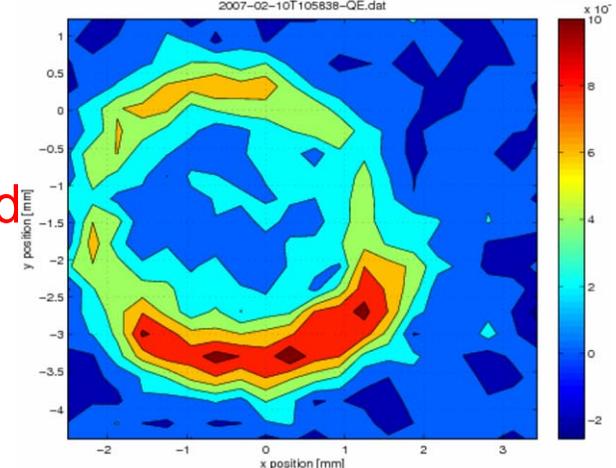
Fresh cathode
12-Dec-2006 Used cathode
7-Feb-2007



- Present understanding:
- Cs reacts with F and leaves metallic Te – more efficient with UV of laser



- F from Teflon washers in the diagnostic cross
- Washers have been removed
- QE stable since then (usual slow drop in QE)

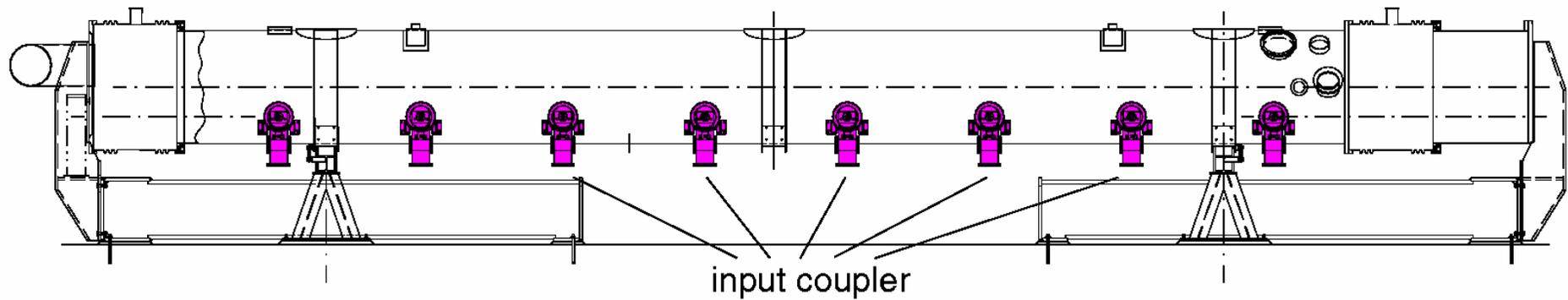
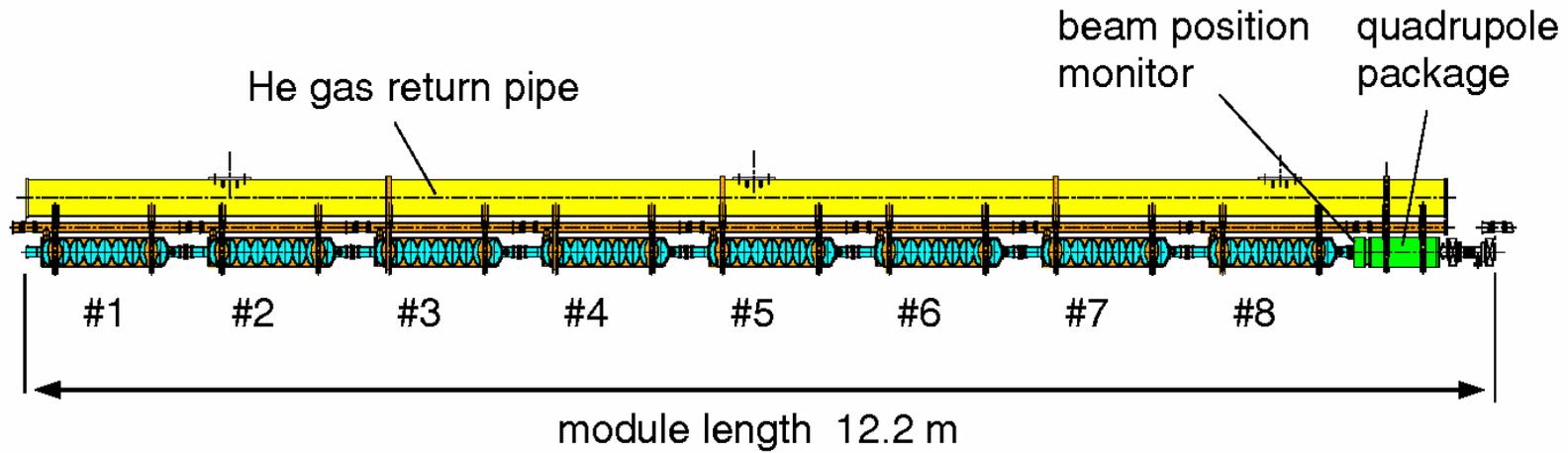




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FLASH uses TESLA Accelerating Modules

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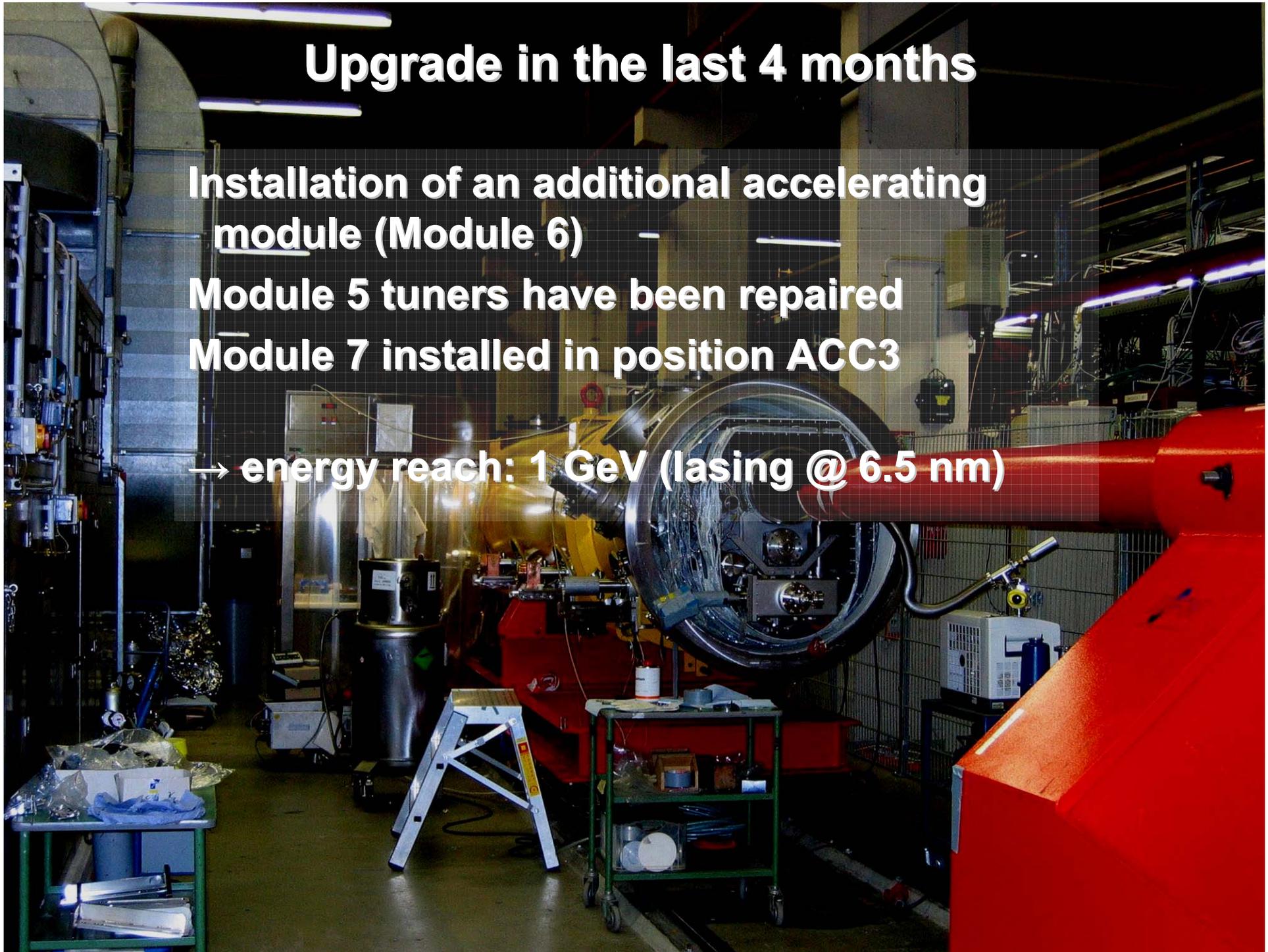
Upgrade in the last 4 months

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)

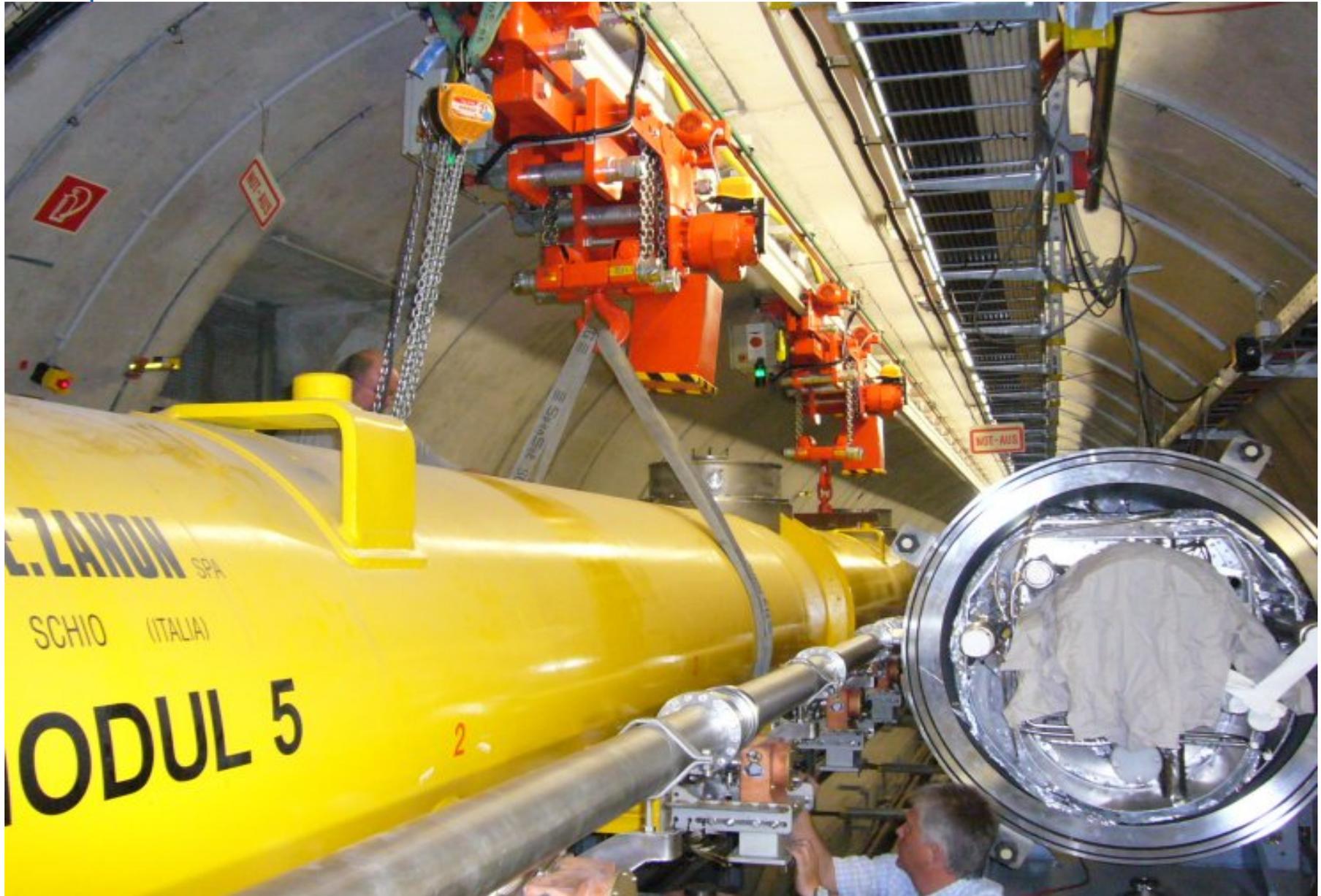




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Dismounting of Module 5 for Repair

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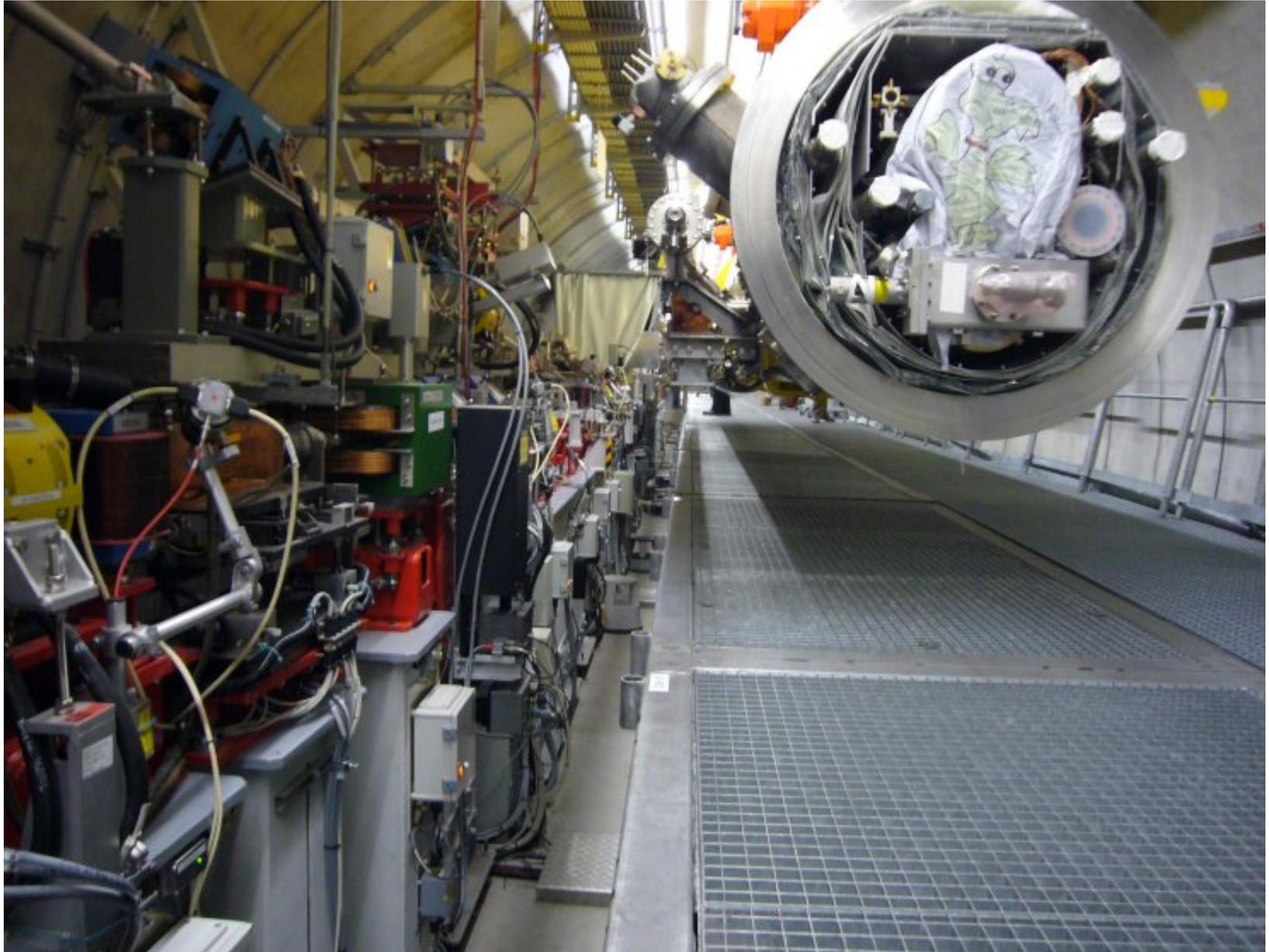




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Dismounting of Module 5 for Repair

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Dismounting of Module 5 for Repair

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Module 6 during Installation

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Module 6 during Installation

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Module 6 during Installation

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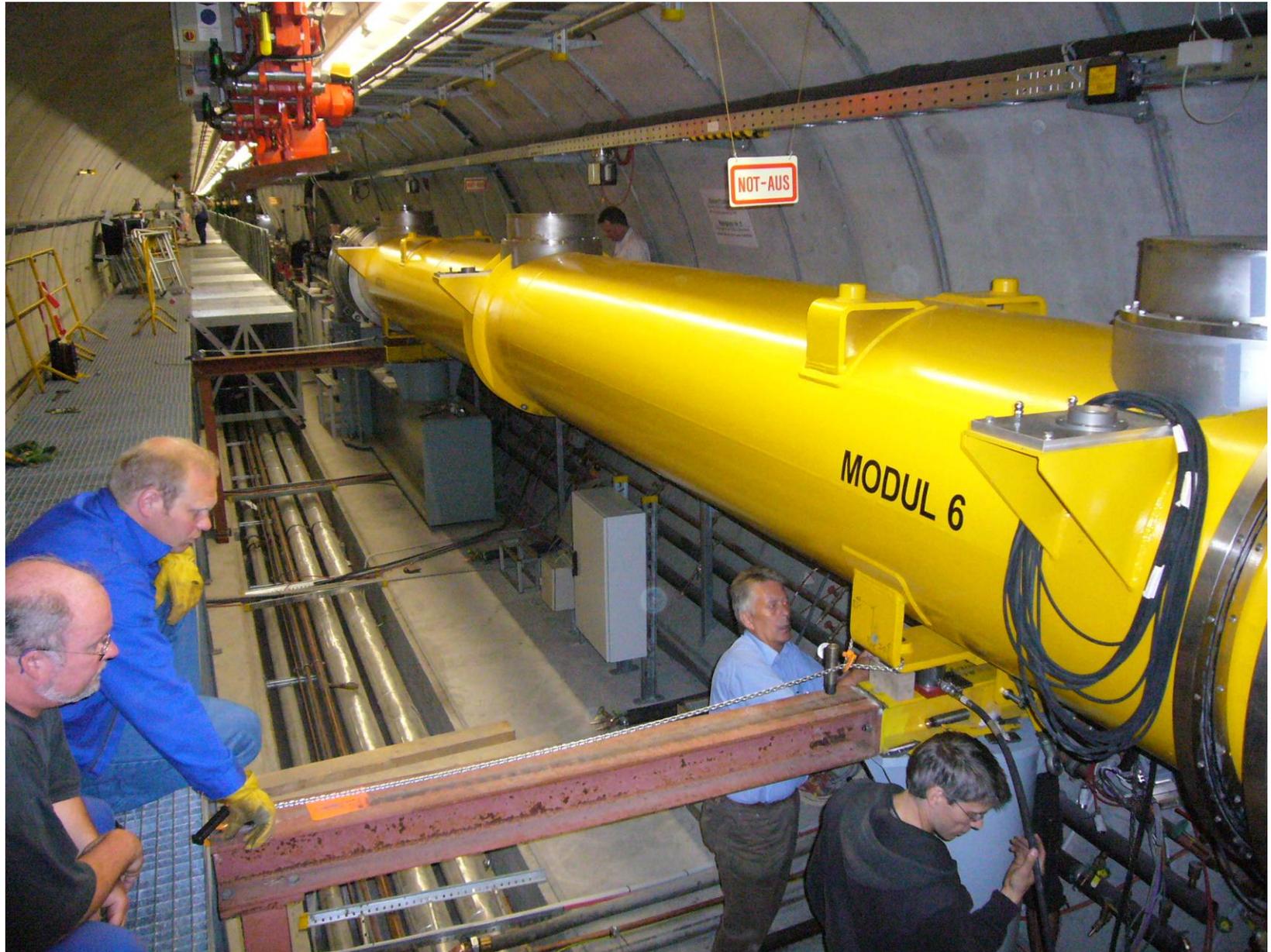
Siegfried Schreiber



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Module 6 during Installation

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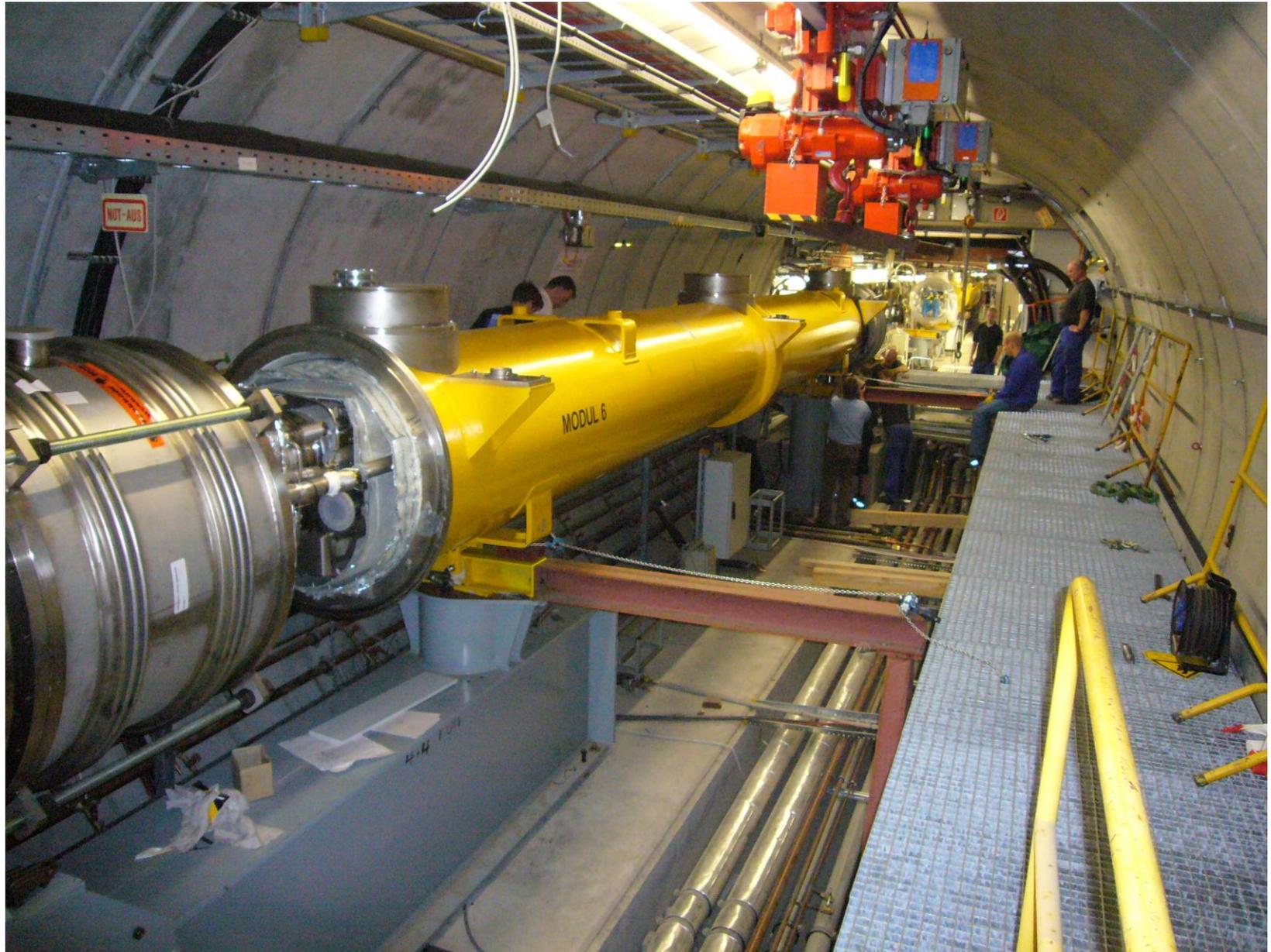




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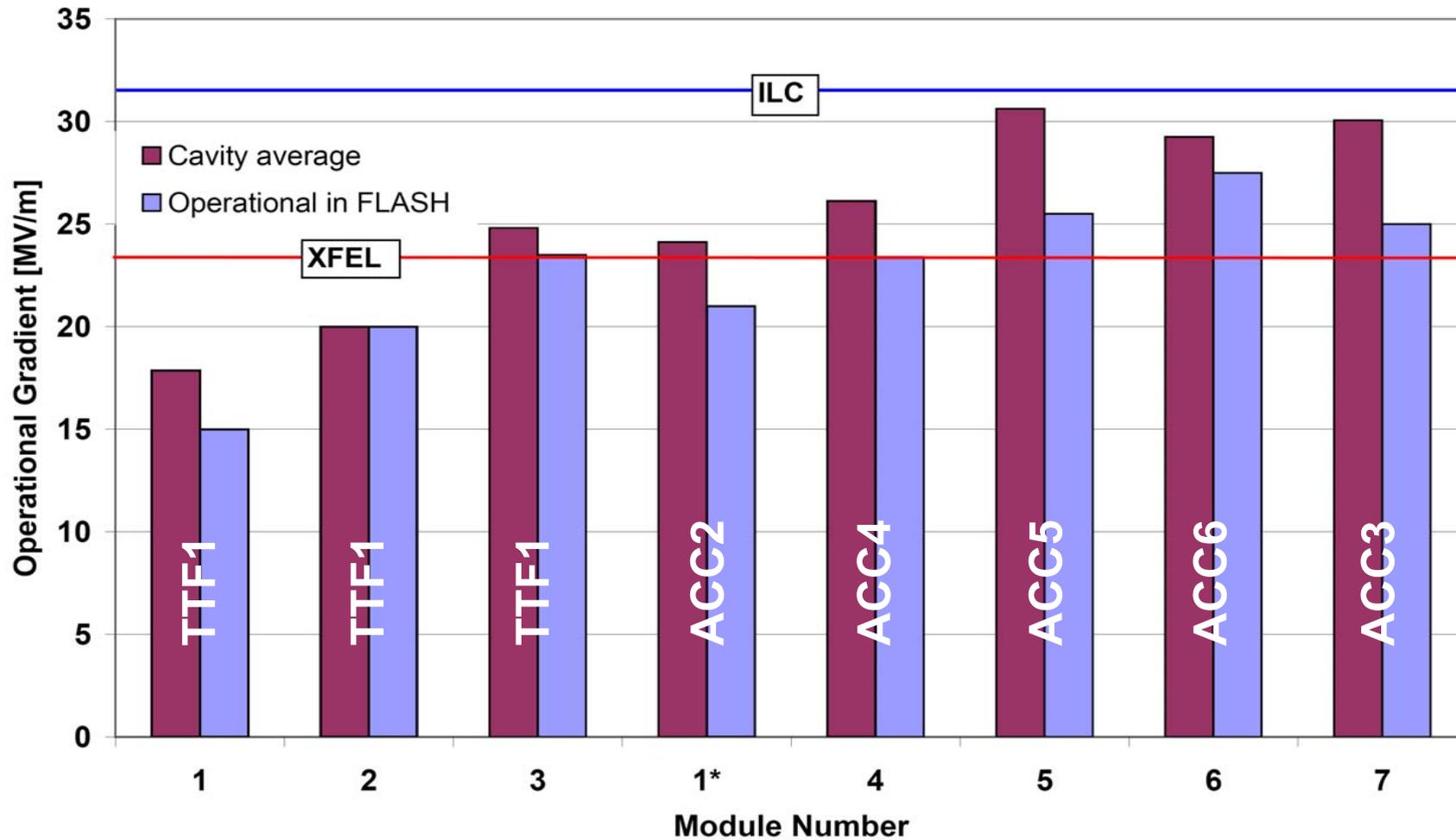
Module 6 during Installation

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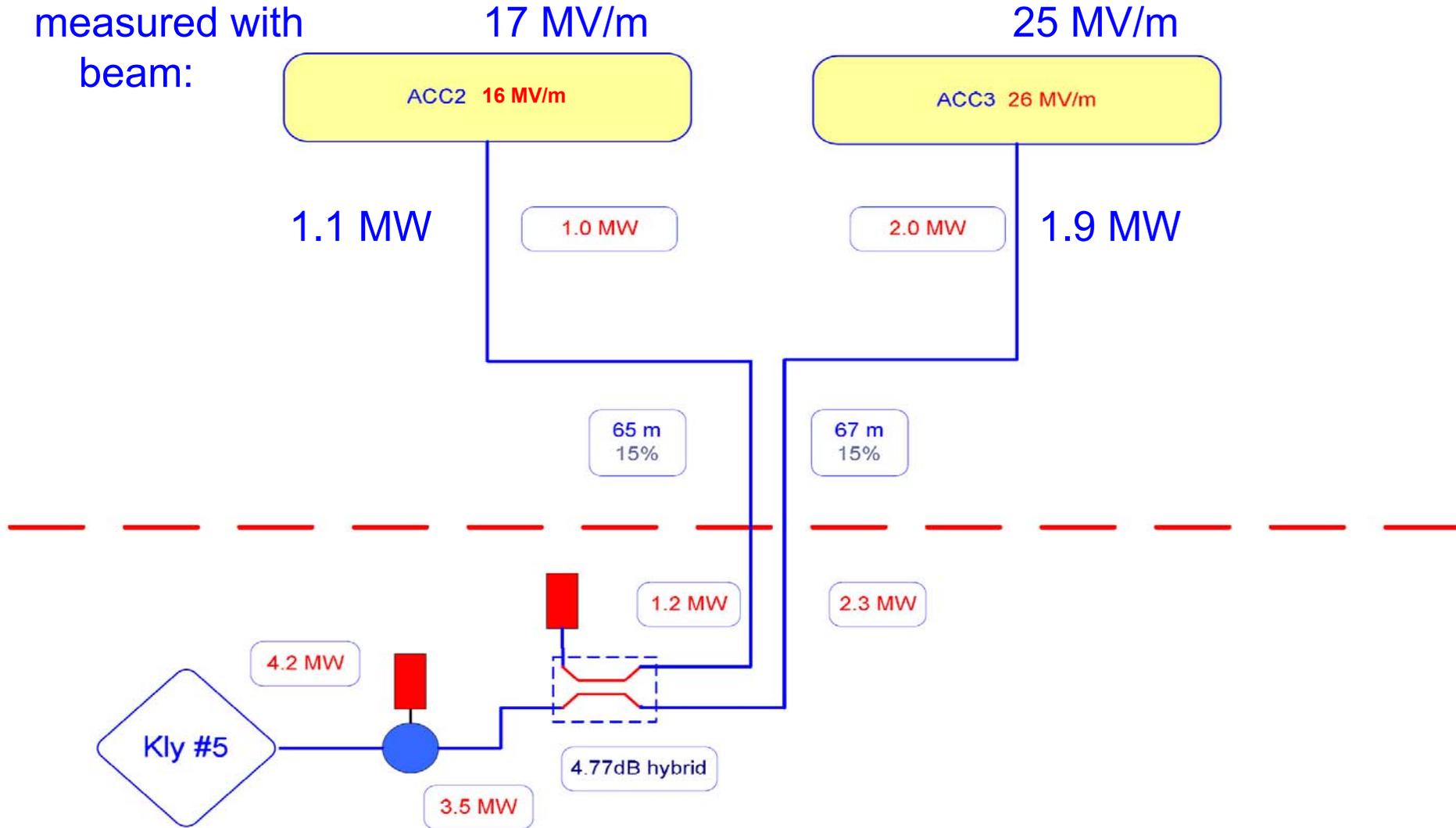
Module Performance





RF Distribution ACC2/3

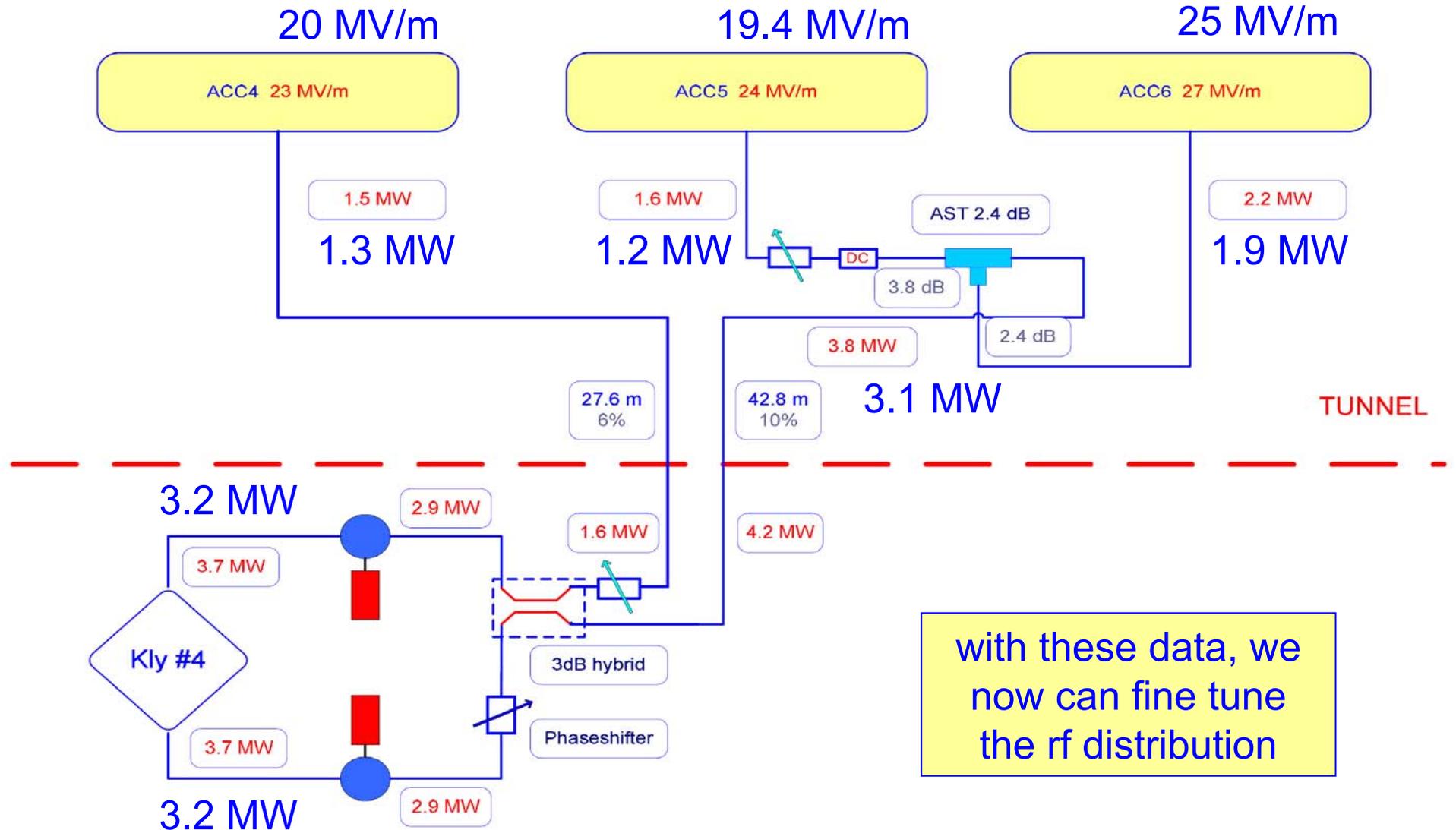
measured with
beam:





RF Distribution ACC4/5/6

measured with beam:

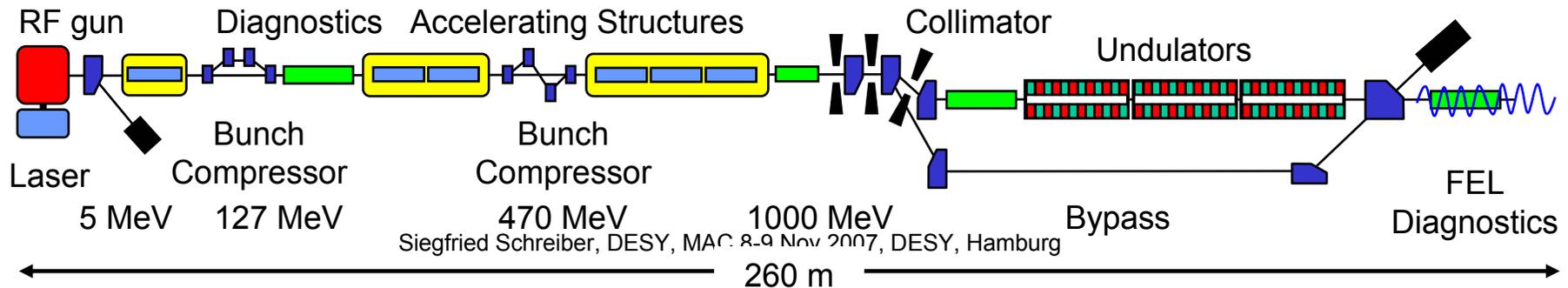




On-Crest Energies from RF Measurements

Energy gain (MeV)	RF Gun	ACC1	ACC2	ACC3	ACC4	ACC5	ACC6
before	5	122	140	101	171	171	
sum		127		370			710
after shutdown	5	124	140	205	166	161	205
sum		129		474			1006

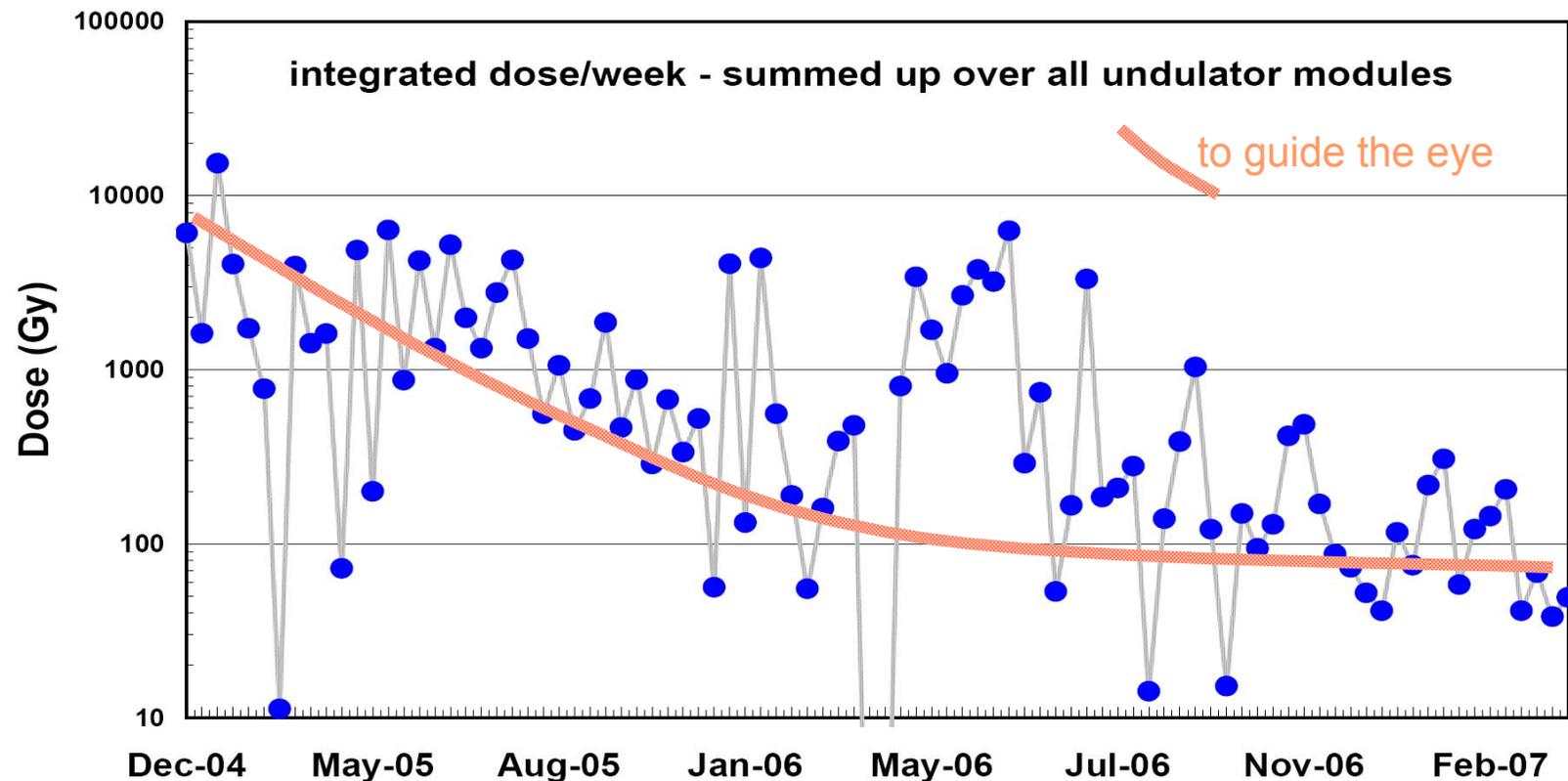
note: off crest with bunch compression, we loose ~ 20 MeV → 980 MeV or 6.5 nm





Radiation Level Undulator Section

- Mainly: **darkcurrent from RF gun** → collimator in GUN section reduces accelerated darkcurrent by 70%
- Also: beam losses during commissioning times
- Level is going down together with better tuning of the orbit and the commissioning of the machine safety system



SASE performance – selected issues

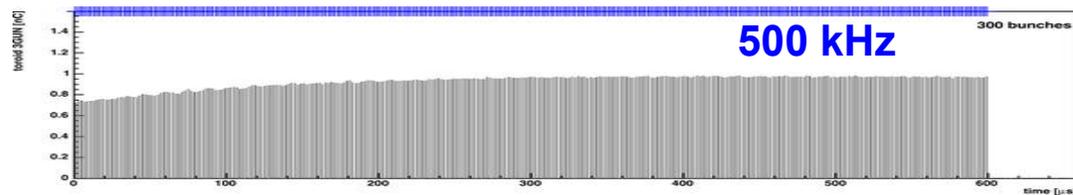
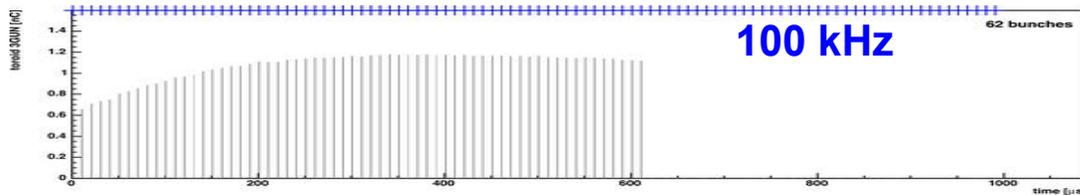
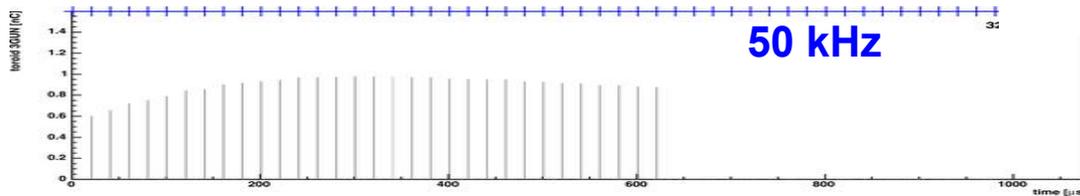
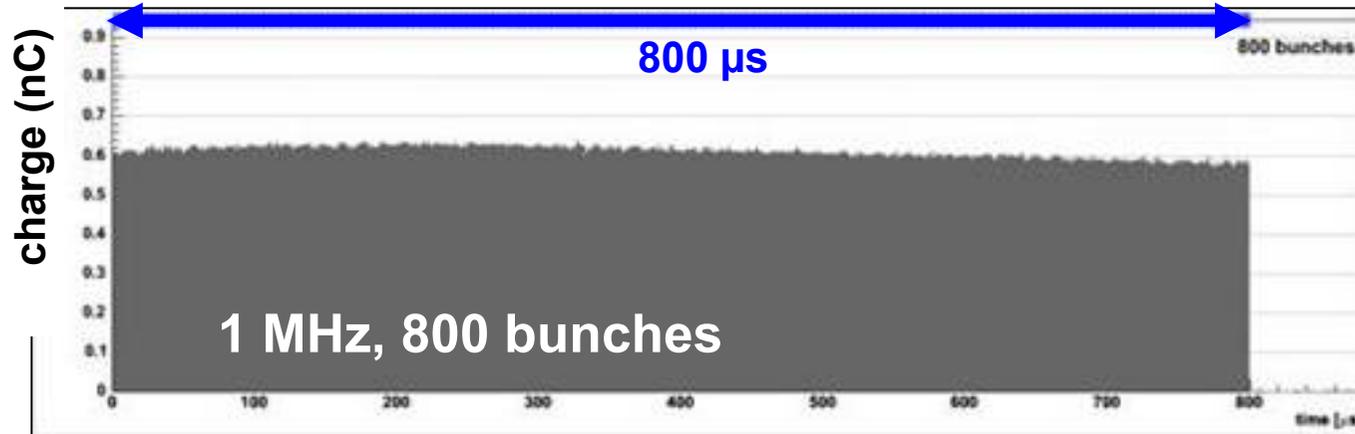
lasing with long bunch trains

lasing with different wavelengths

improvement of stability



Long Bunch Trains



- Transported 800 bunches to beam dump @ 5 Hz
- 1 MHz, 500 kHz, 100 kHz, 50 kHz and others



Lasing with long bunch trains

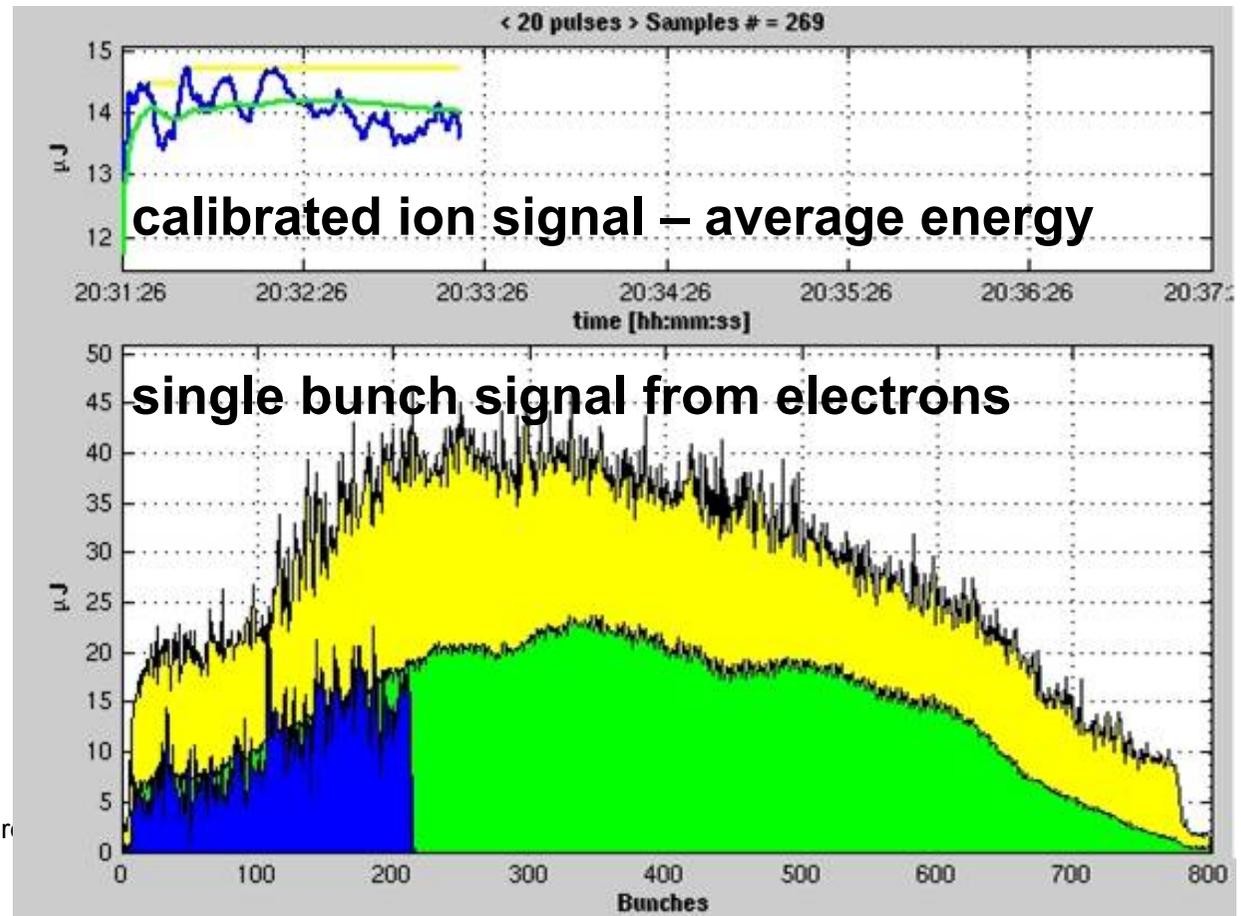
- Lasing with up to 800 bunches, $>10 \mu\text{J}/\text{pulse}$ achieved
- Machine Protection System: fully operational, with minor constraints

GMD – gas monitor detector reading

**800 bunches at
685 MeV**

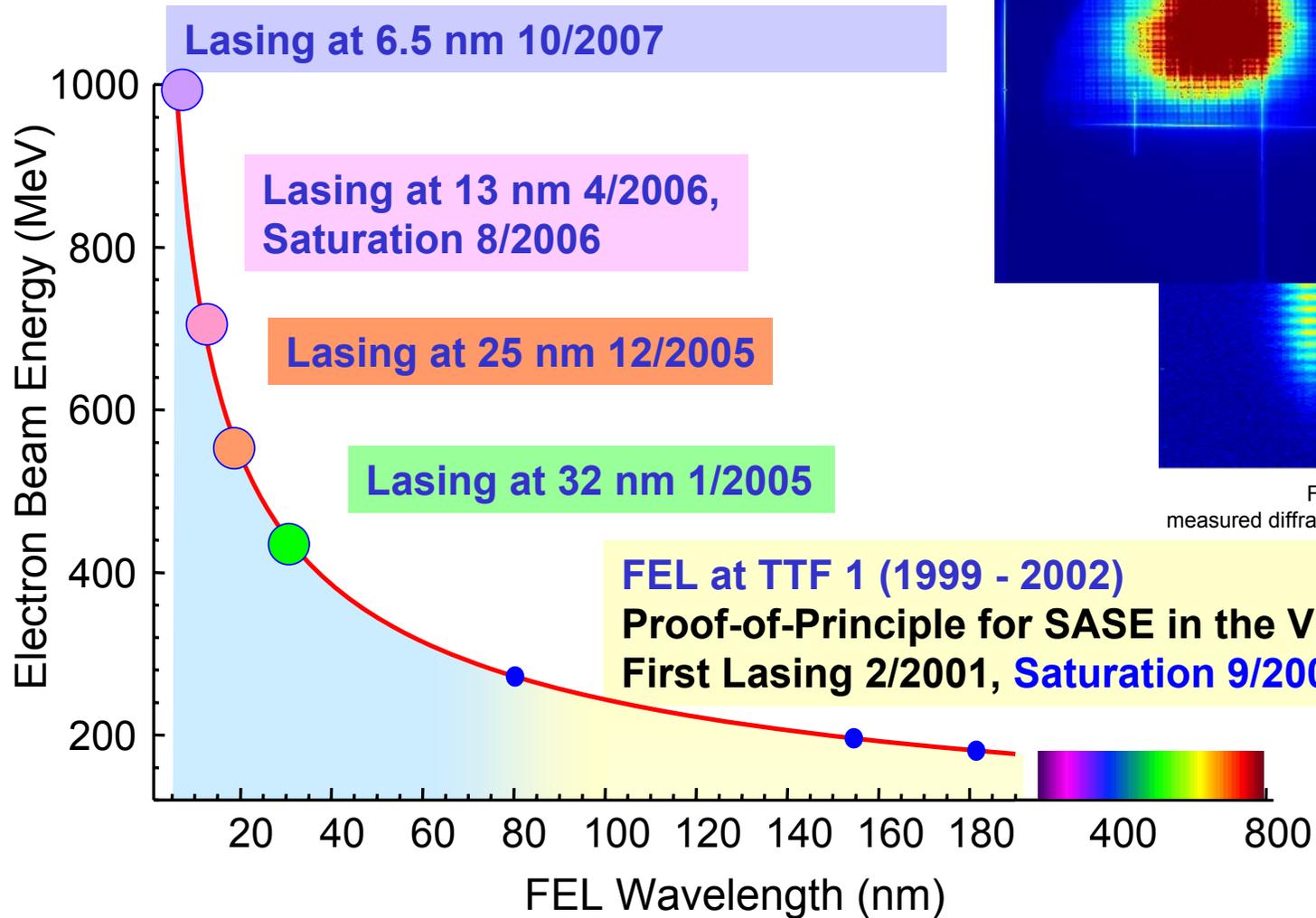
**electron beam:
2.7 kW**

**photon beam:
13.4 nm
56 mW**





Beam Energy and Wavelength





Lasing with different Wavelengths

- Lasing at many different wavelengths
- Slow switch: on shift to shift bases
- Challenge 1
 - each energy requires new tuning, new optics
 - once tuned, reloading of files pretty fast
- Challenge 2
 - hit the right wavelength within 0.1 nm
 - sometimes quite tedious

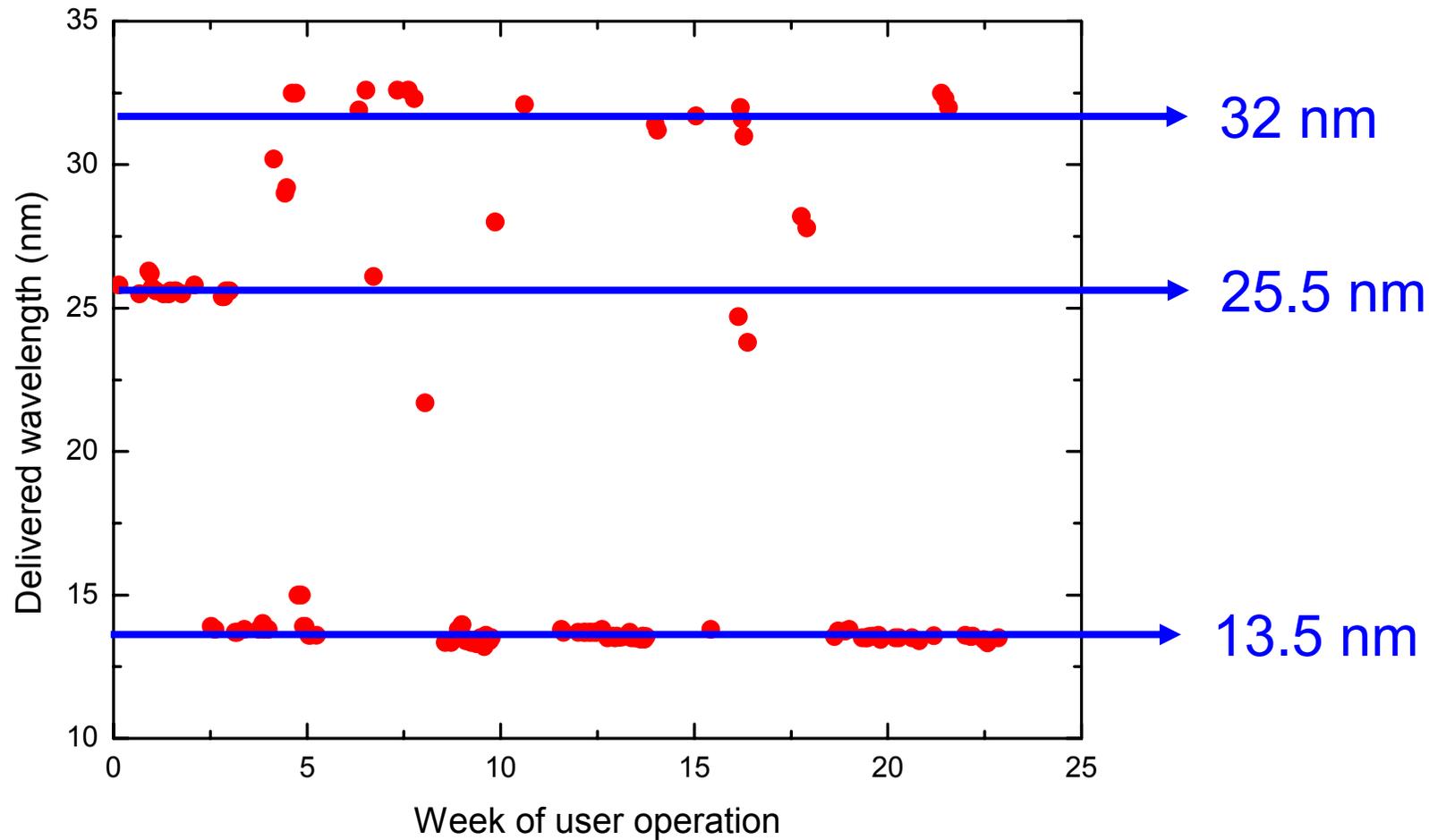
Examples:

achieved wavelength (nm)	Beam Energy (MeV)
6.5	986
6.9	954
13.1	694
13.7	679
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





- 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

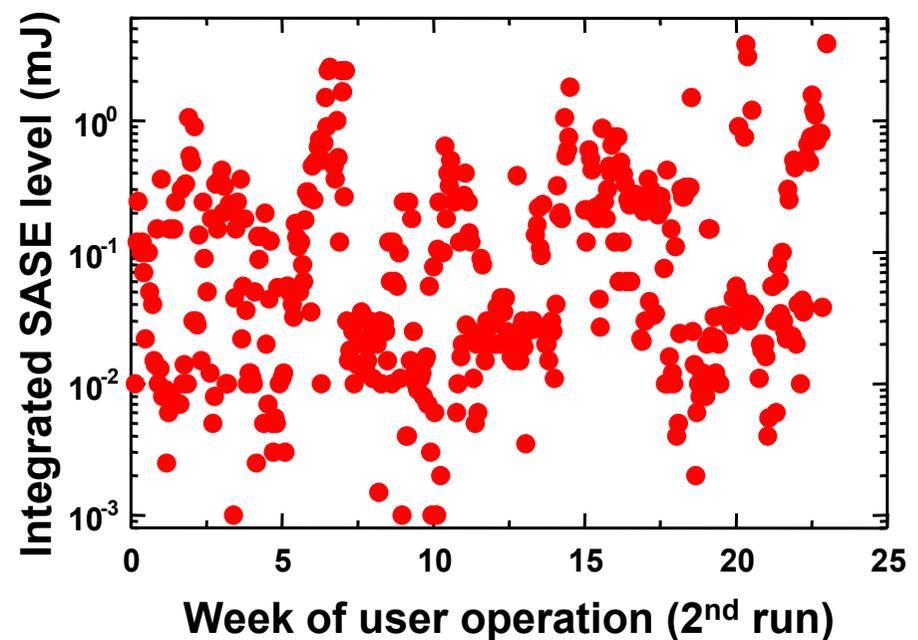
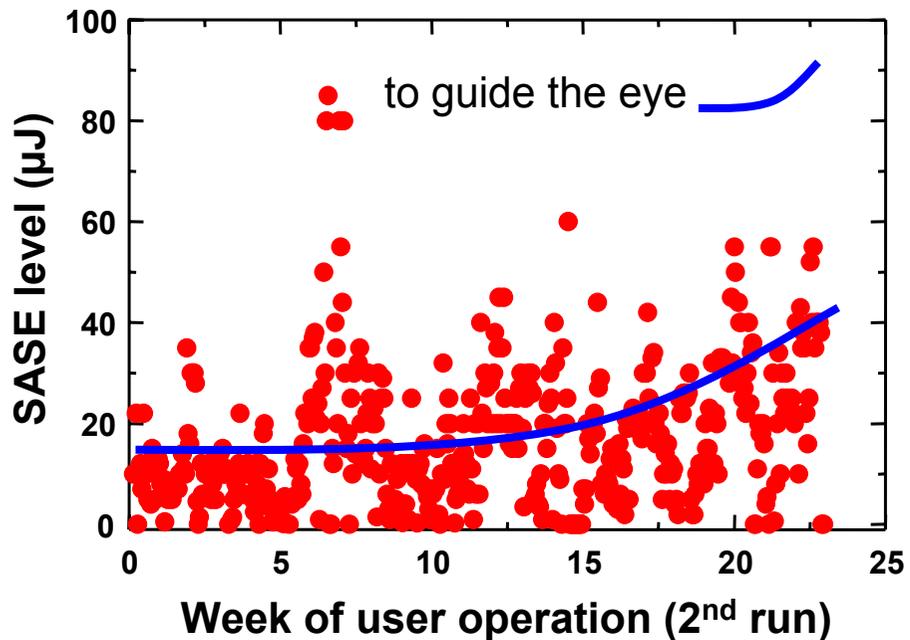


- Many sources of EM interferences have been cured:
 - Low noise power supplies for most magnets
 - New grounding scheme injector area to fight against high currents on earth lines
 - Adequate distribution of main power stations
 - Compensation of PETRA proton ramps
 - and many more
- we have to fight many, mostly small effects
- but in the sum, we improve a lot!



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 photon energy allows collimation of the photon beam \rightarrow improved pointing stability



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**
 - 2007/2008 with 1 long run of 203 days
- We also have study weeks
 - **FEL related machine studies**
preparation of next block of user runs
 - **general accelerator studies**
mostly XFEL and ILC related

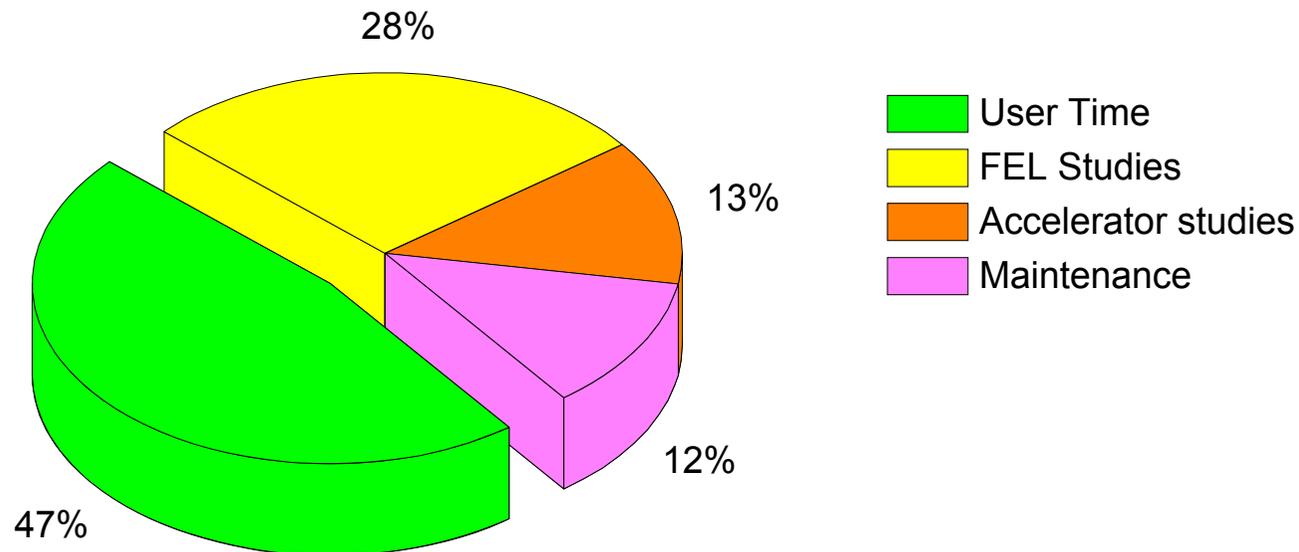
weeks

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%)



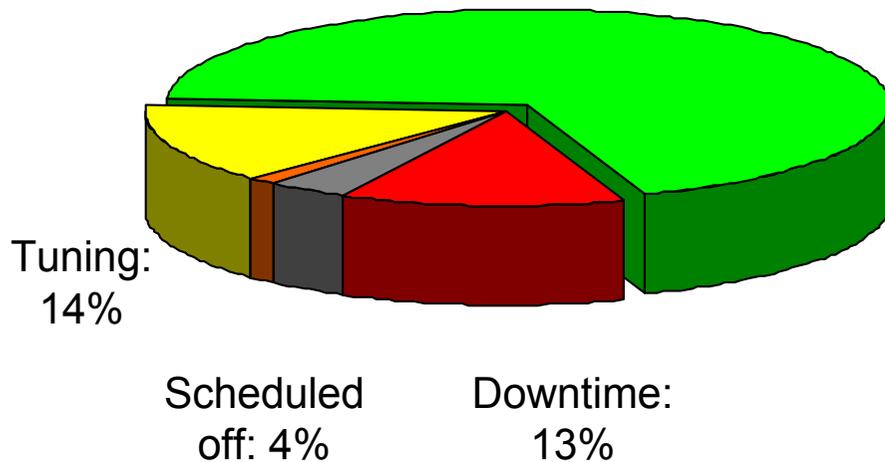


Beam Time Usage User Runs

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

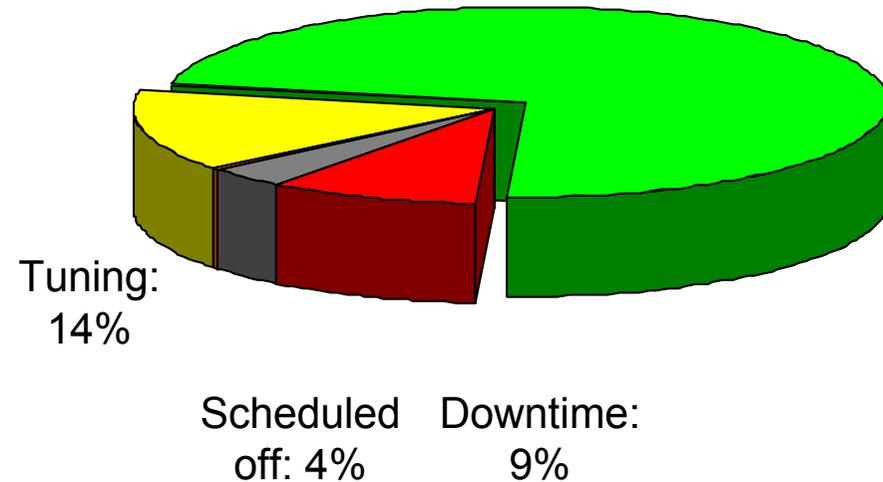
User Run 1

SASE delivery:
69%



User Run 2

SASE delivery:
73%

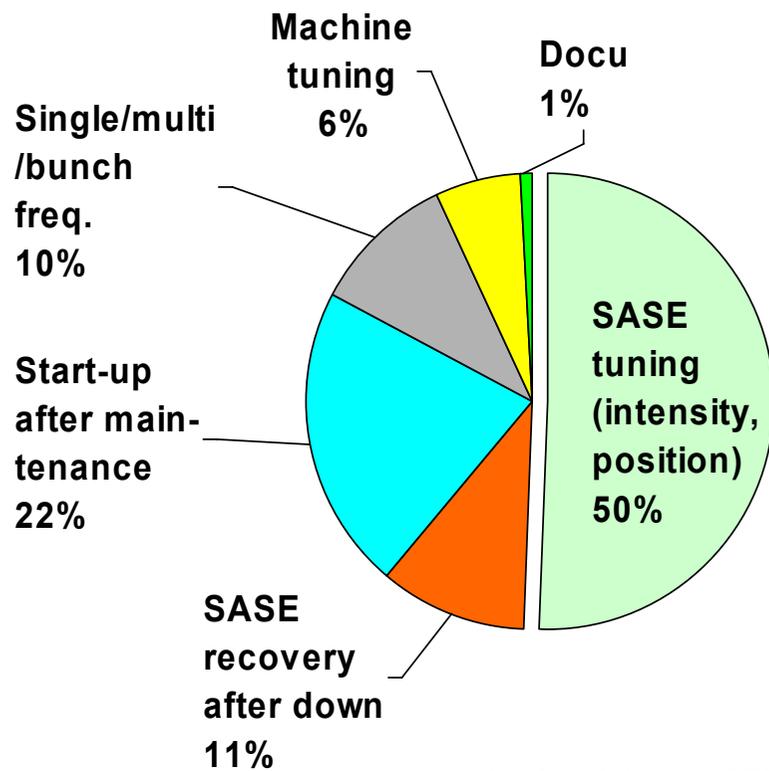




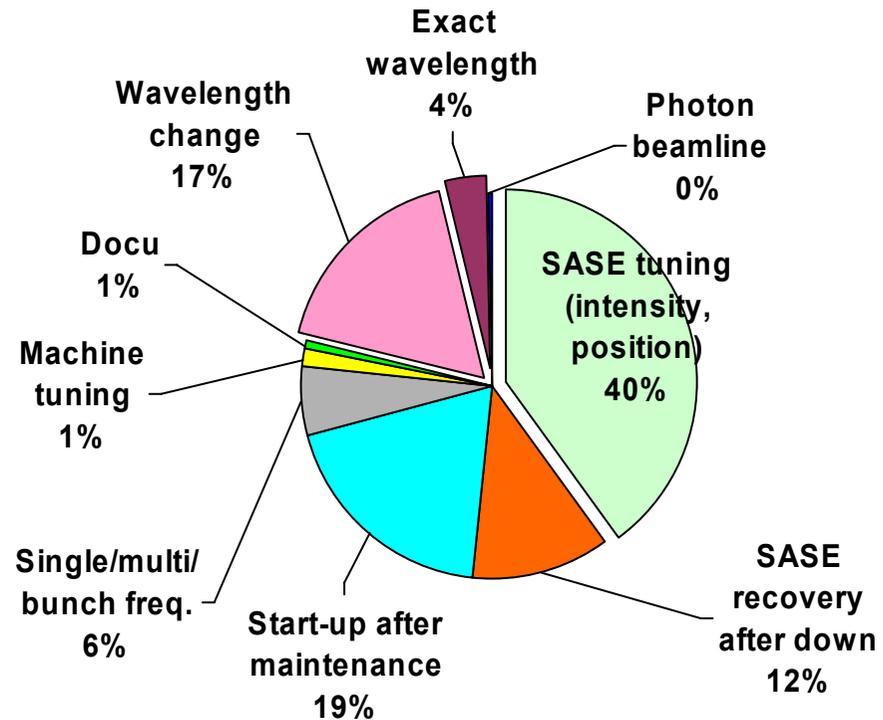
Time Spent on Tuning

- 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

User Run 1



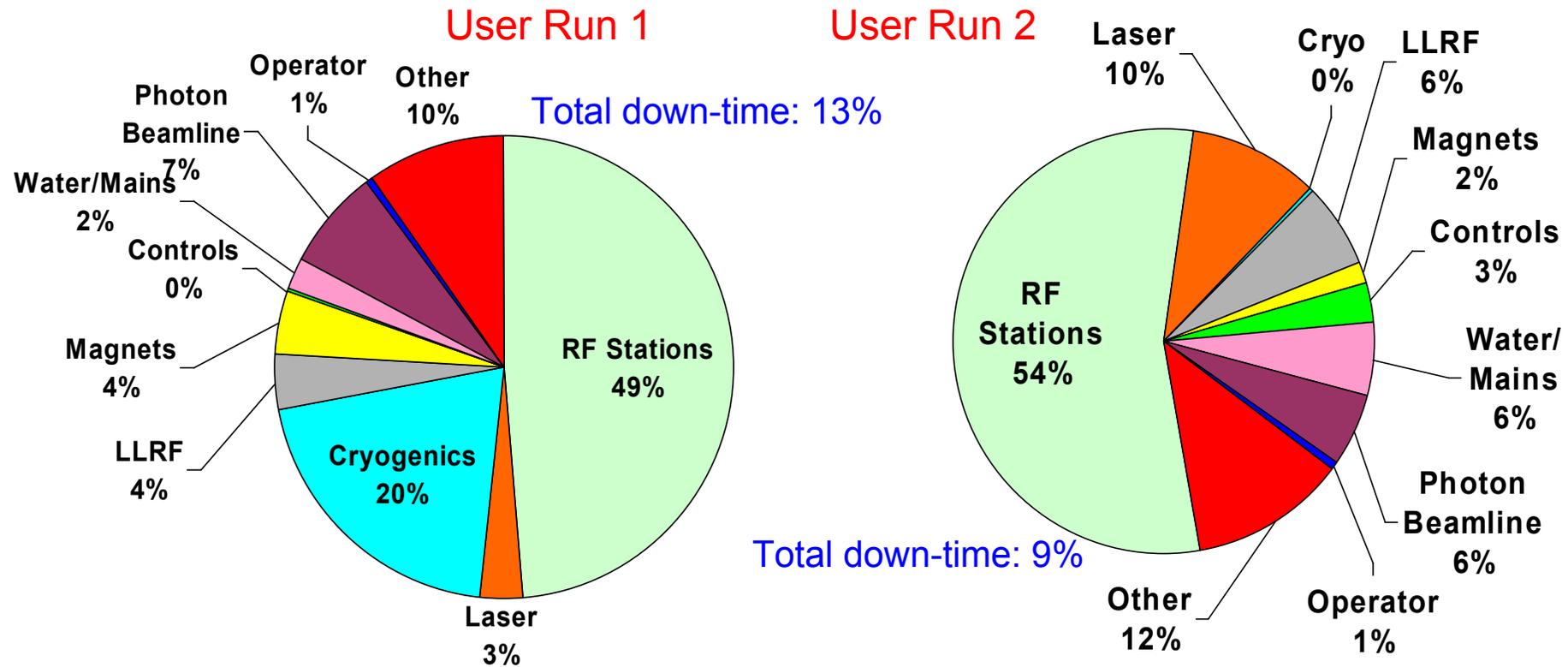
User Run 2





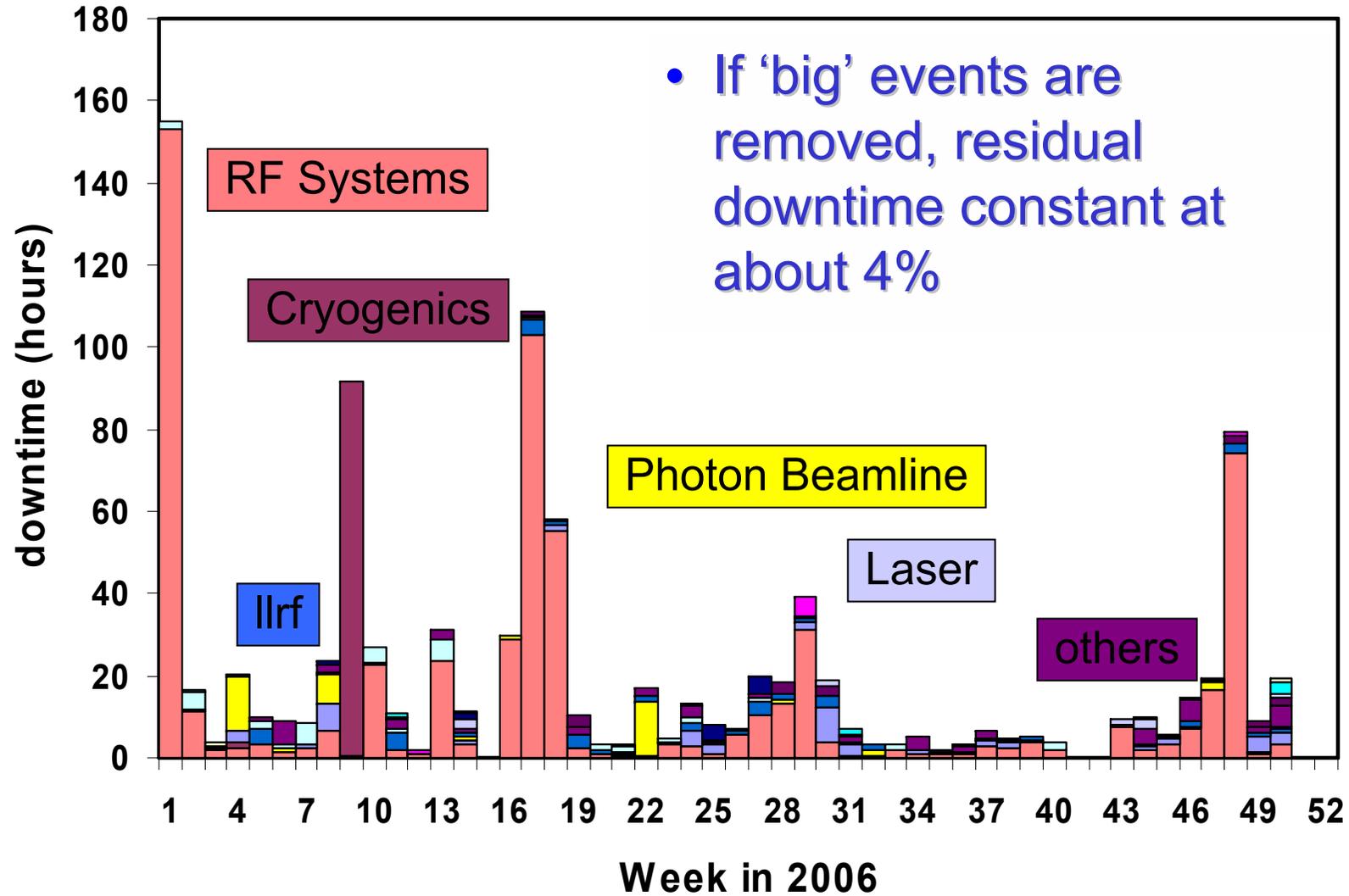
Downtime

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





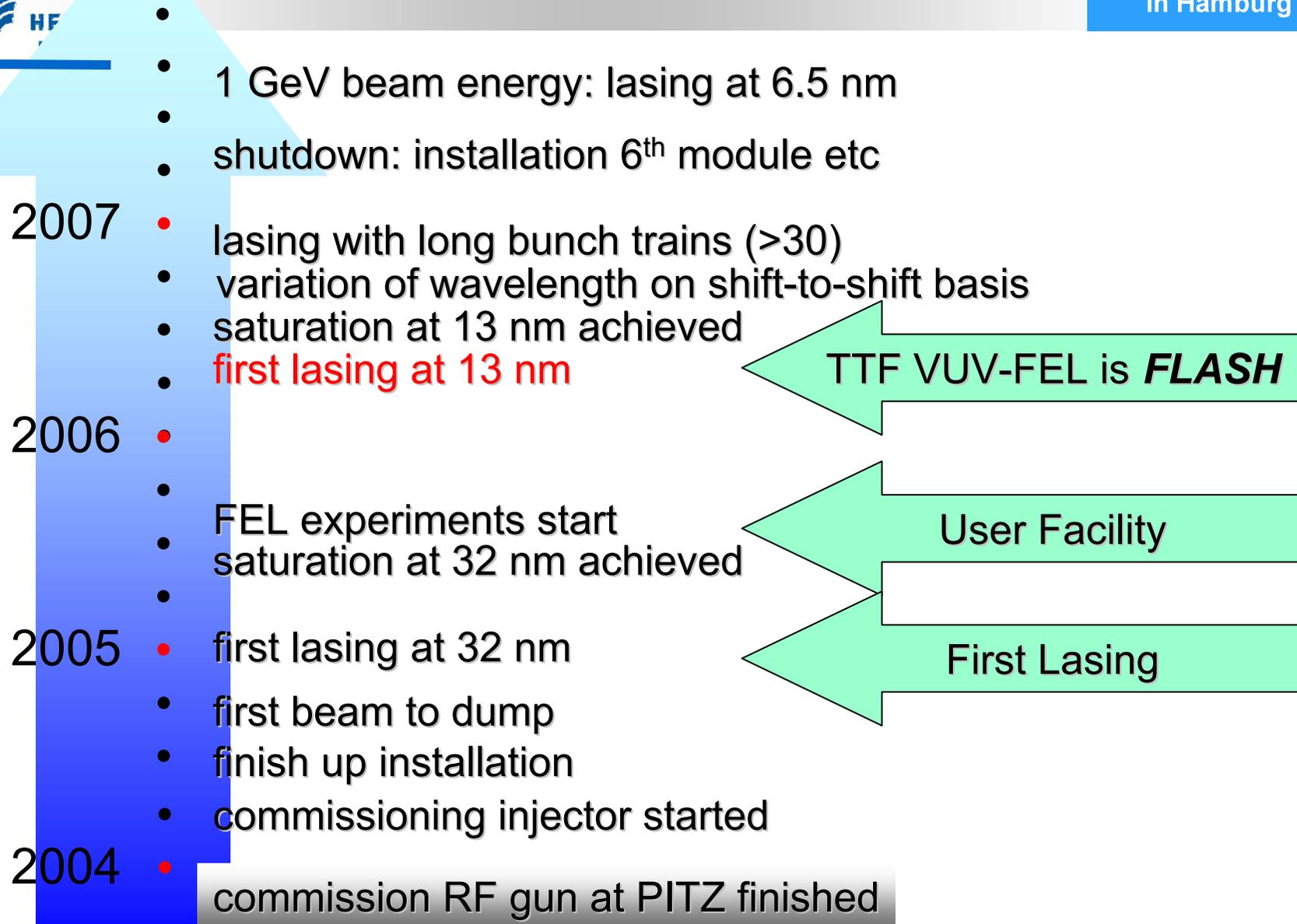
Hardware Failure Evolution in 2006



Schedule



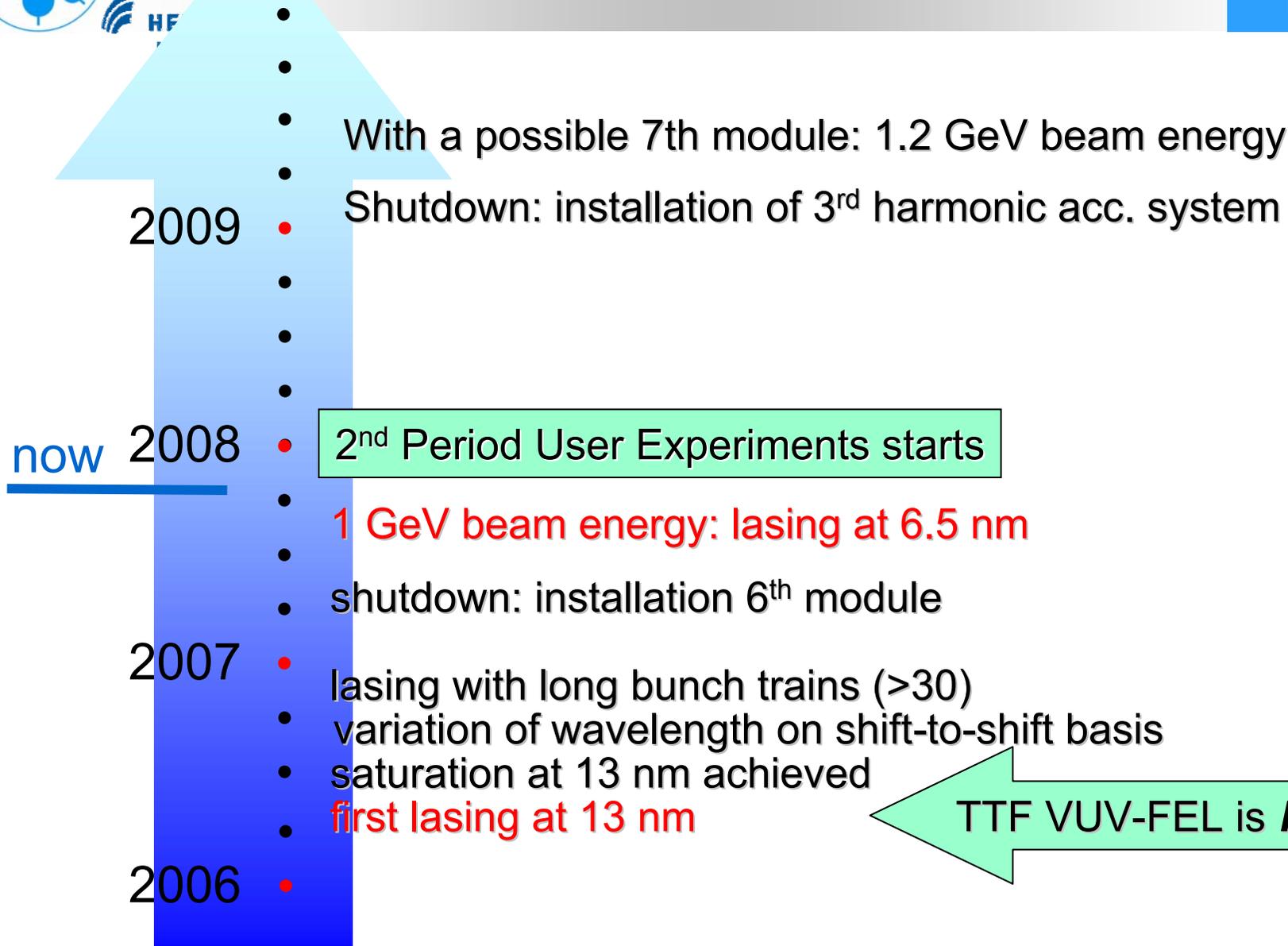
Schedule and Milestones





Schedule and Milestones

FLASH
Free-Electron Laser
in Hamburg



TTF VUV-FEL is **FLASH**



- New experiments have been installed last shutdown
 - IR undulator, optical replica, fast intra-train feedback etc
- New synchronization schemes under development
 - Fiber laser based master oscillator (down to 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
- Harmonic generation experiment (HHG)
 - seeding with external radiation
- self-seeding
- 2nd beamline
 - including XFEL type kicker system



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 6.5 nm - a new record meeting the initial specs of the FEL**
- **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 in one long run starting end Nov 2007 to end 2008