Review of DESY FEL Activities

Jörg Rossbach

University of Hamburg & DESY, Germany

- FEL Basics
- Strategy
- FLASH
- The European XFEL project

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FEL Basics: Radiation of a moving oscillating charge

$$P = \frac{Q^2 a^2}{4\pi\varepsilon_0 3c^3}\gamma^4\omega^4$$

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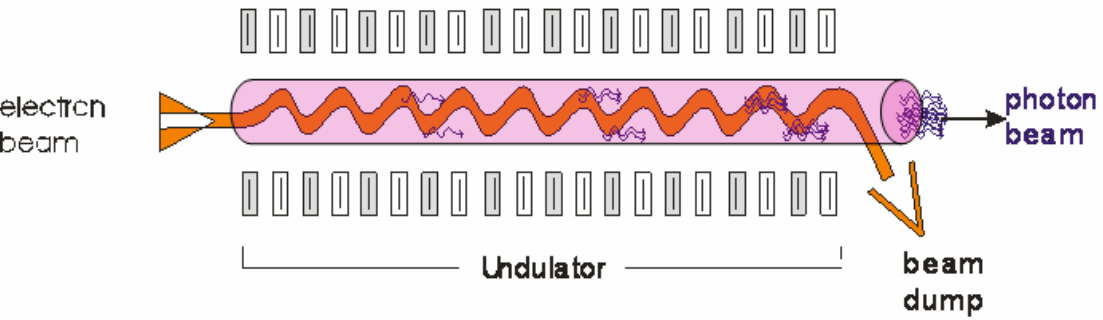
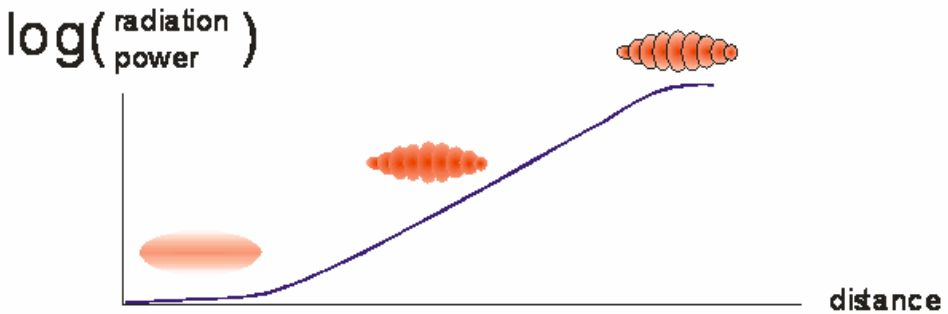
Special version starting from noise:

Self-Amplified Spontaneous Emission (SASE)





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Narrow-band amplifier with resonance wavelength:

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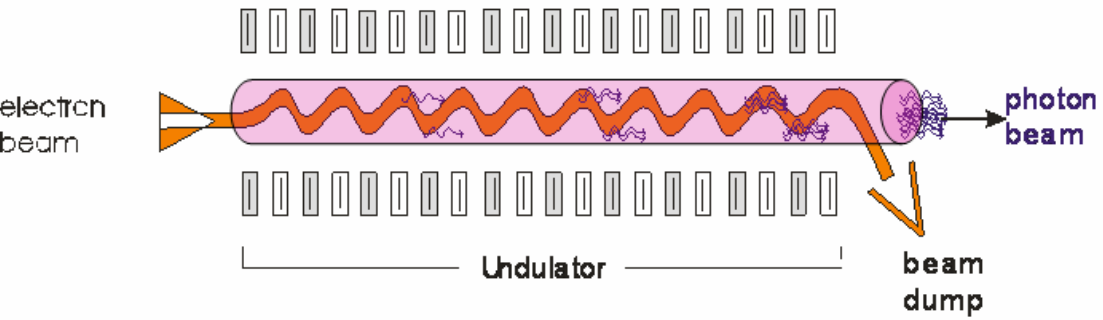
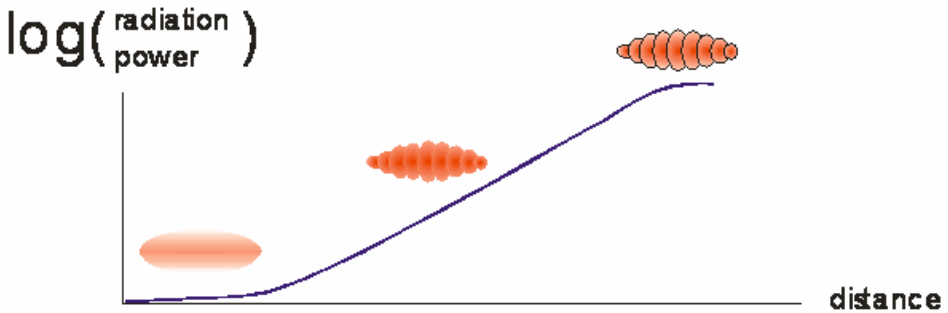
Undulator parameter ≈ 1





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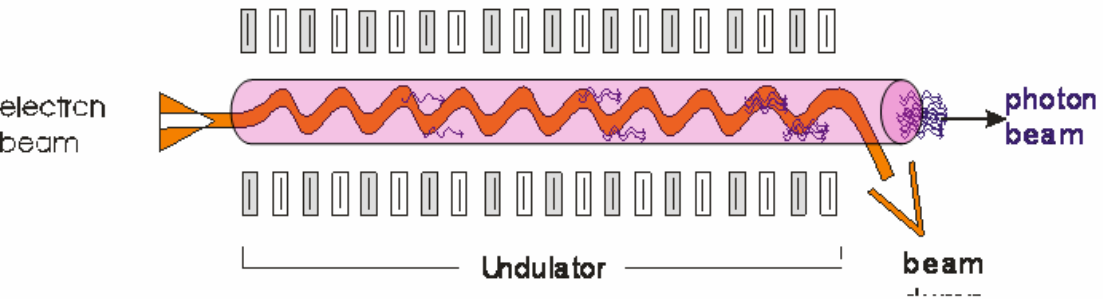
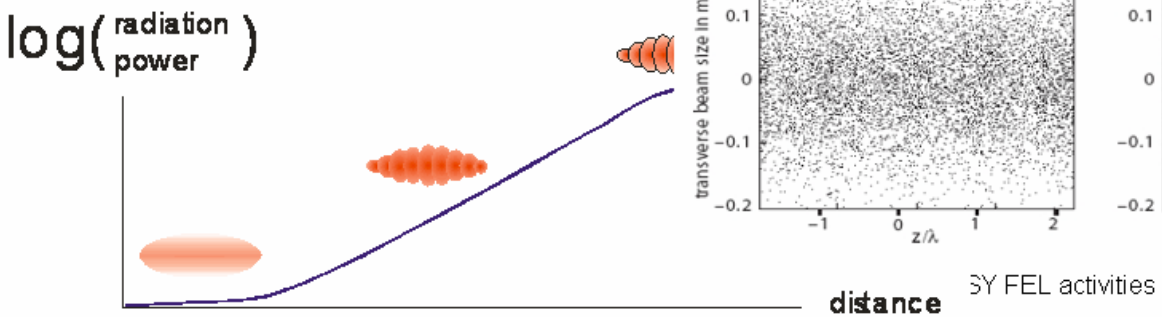
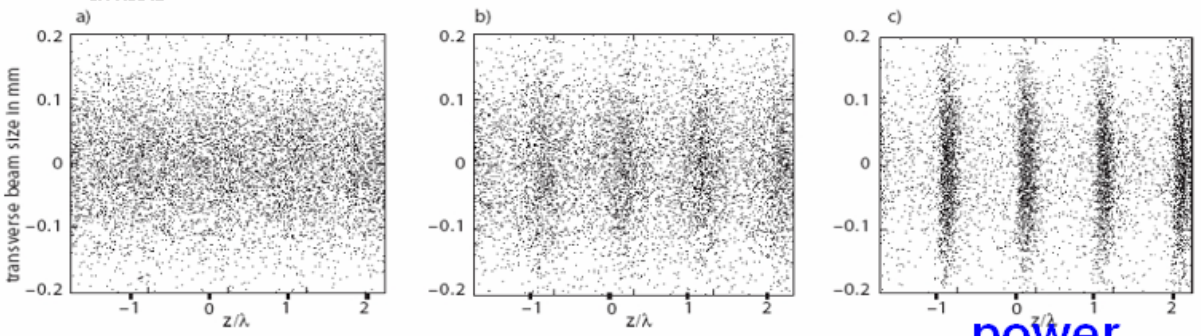


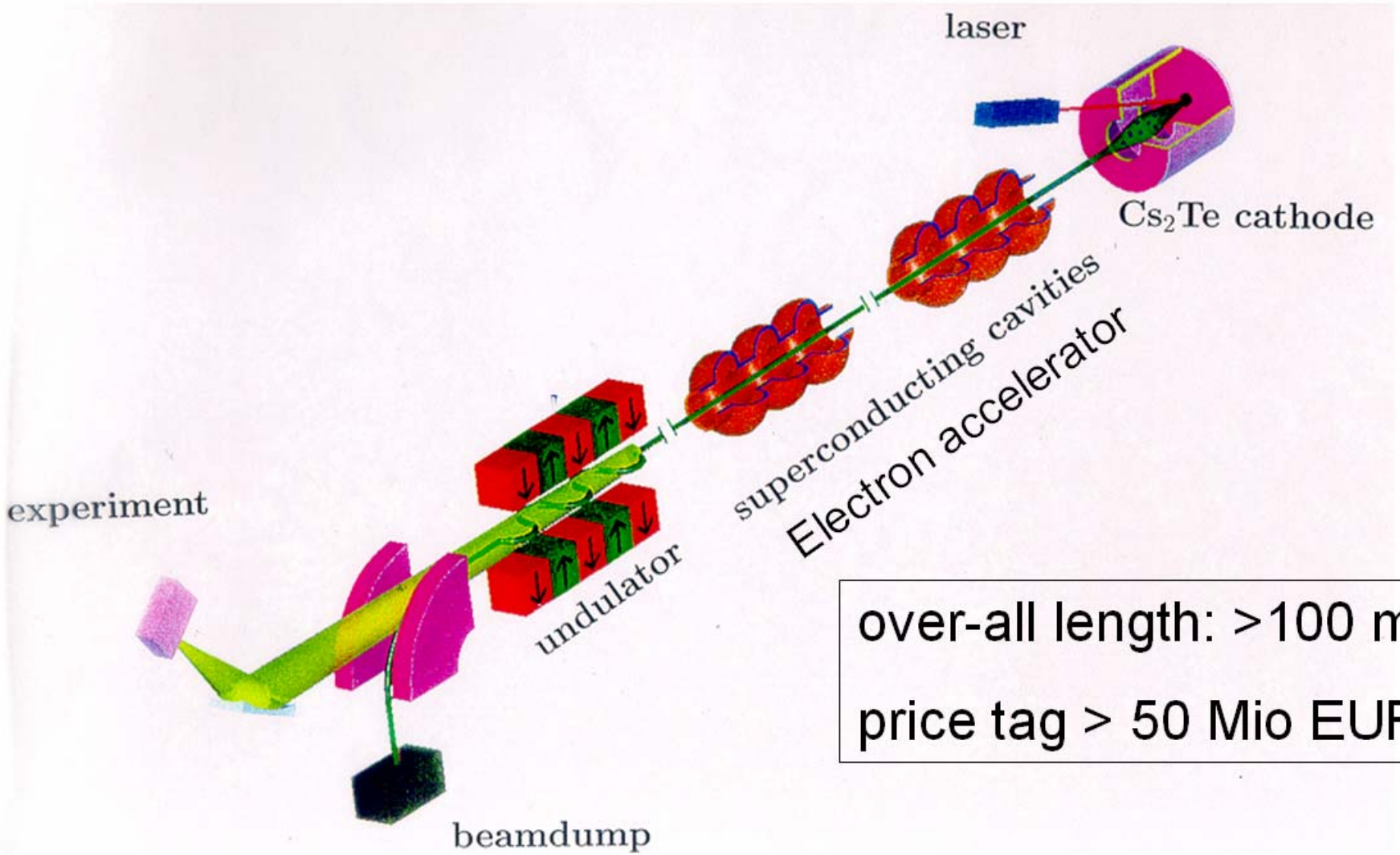




SY FEL activities

power saturation

Schematic of a high-gain Free-Electron Laser (FEL)



over-all length: >100 m

price tag > 50 Mio EUR

Why SASE FELs?

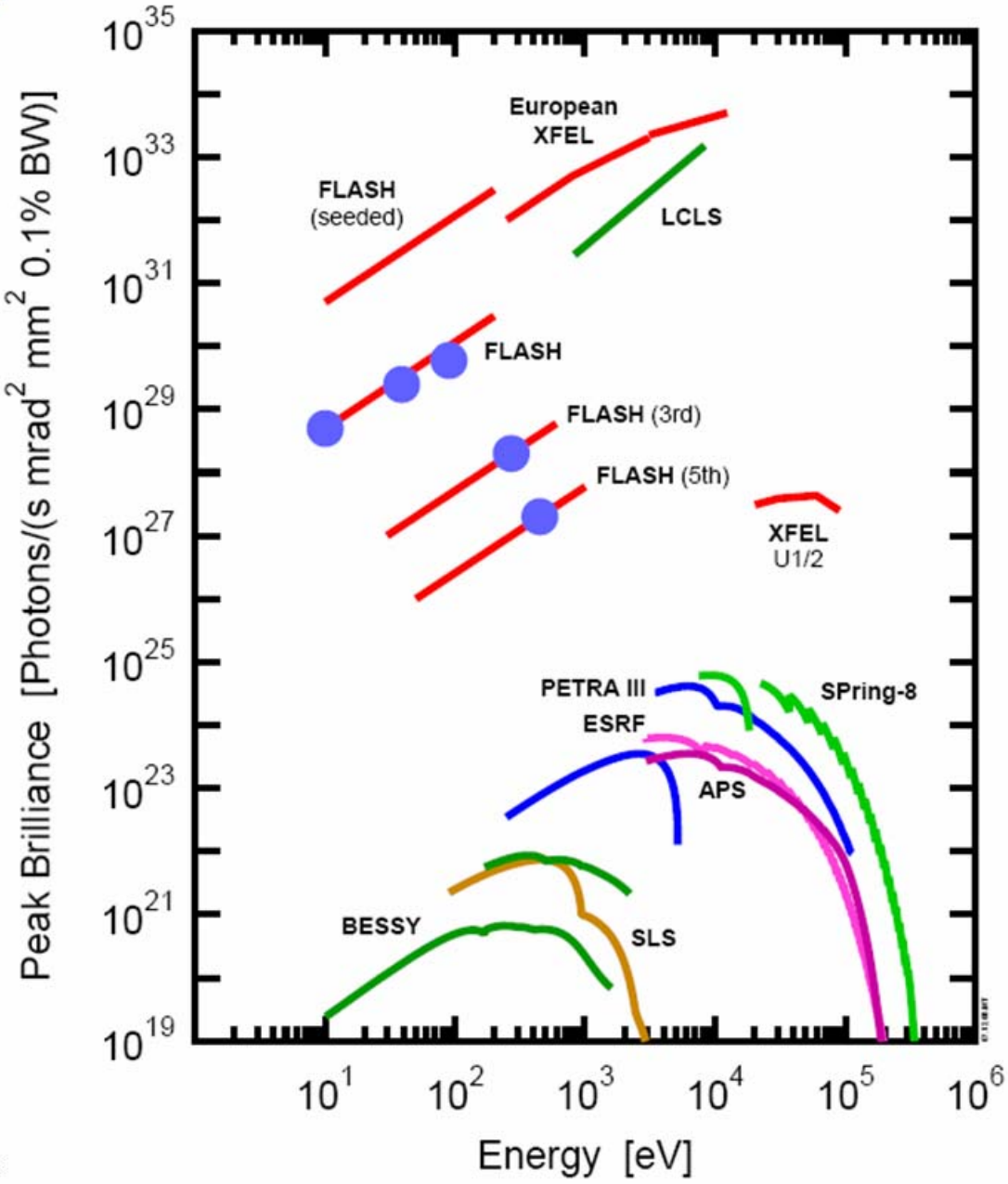
Figure of merit for all experiments involving

- **diffraction**
- **very fast processes**

Brilliance:

No. of photons

- per second
- per cross section of the radiating source
- per opening angle of radiation
- per spectral bandwidth



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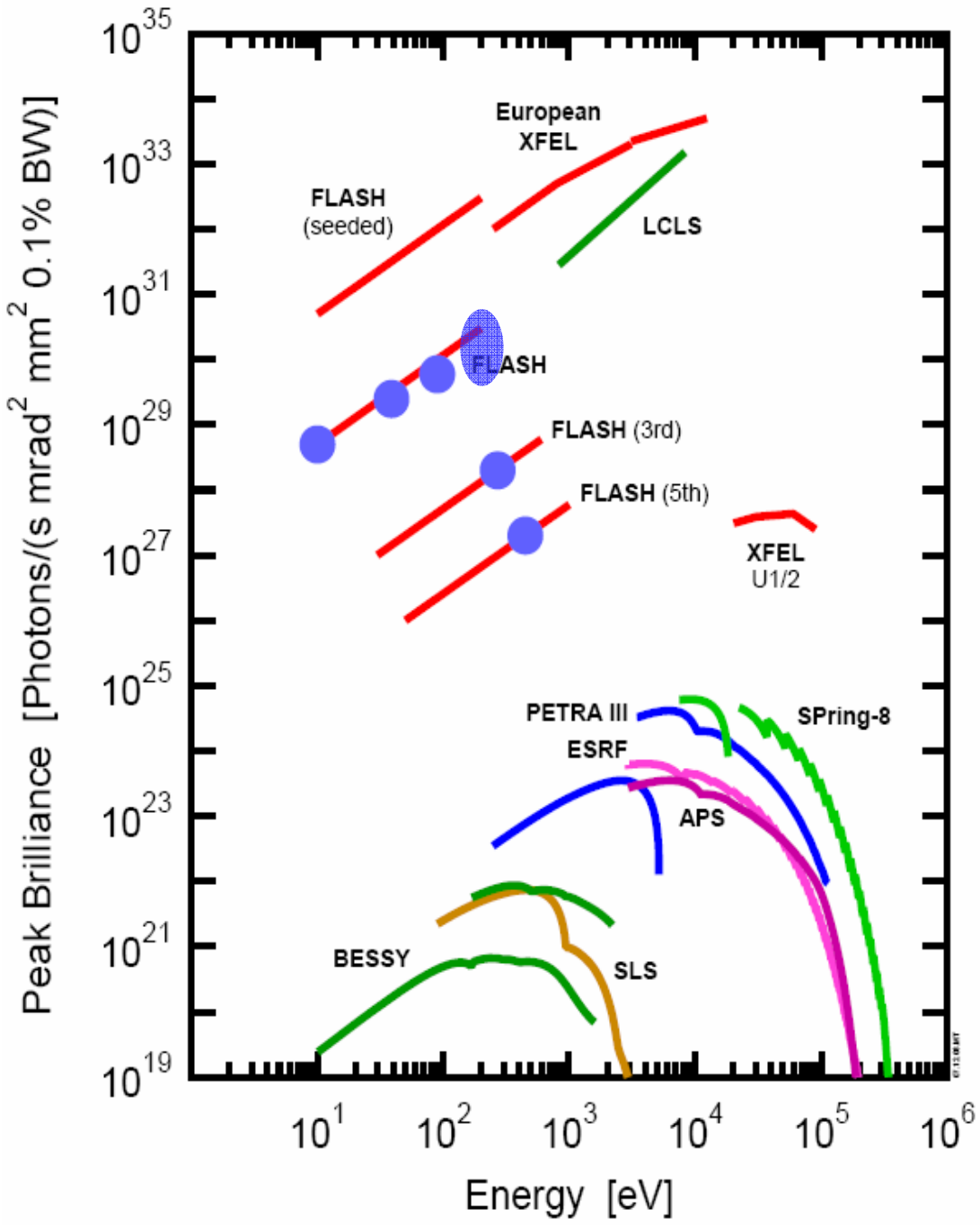


DESY's strategy towards 1 Å

- Proceed in stages (starting 1994):

  TTF1 (100 nm), FLASH (6.5 nm), XFEL (0.1 nm)

- Maintain key components if successful.
- Go for superconducting accelerator:

  excellent stability

  large number of bunches per sec.

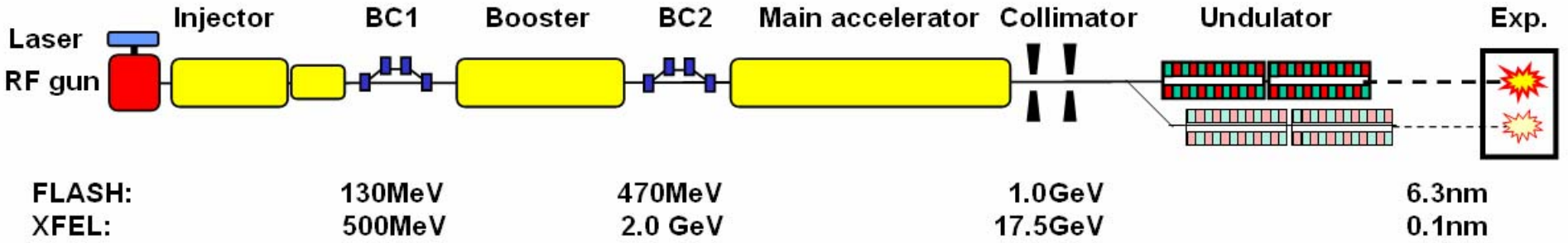
  several beamlines

  multi-user facility

- Run FLASH as a user facility as soon as possible.

FLASH/European XFEL technology

- FLASH and European XFEL are basically very similar machines:



Based on same SRF technology
Only small differences in beam parameter (except E)

⇒ High Level RF & RF controls
⇒ Beam dynamics issue
⇒ Diagnostics development
⇒ Test of utility systems

Can almost all be carried out at FLASH!

Para.	FLASH	XFEL
$\varepsilon_{x,y}$	2 µm	1.4 µm
I_{peak}	2.5 kA	5 kA
f_{rep}	1 (9)MHz	5 MHz
Q	1 nC	1 nC
E	1 GeV	17.5 GeV
RF	1.3/3.9GHz	1.3/3.9GHz
Δt	800µs	650µs
$\Delta x/\Delta y$	5µm	3µm

FLASH @ DESY Hamburg, Germany

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Acc. Module 6 installed → 1 GeV/6.5 nm

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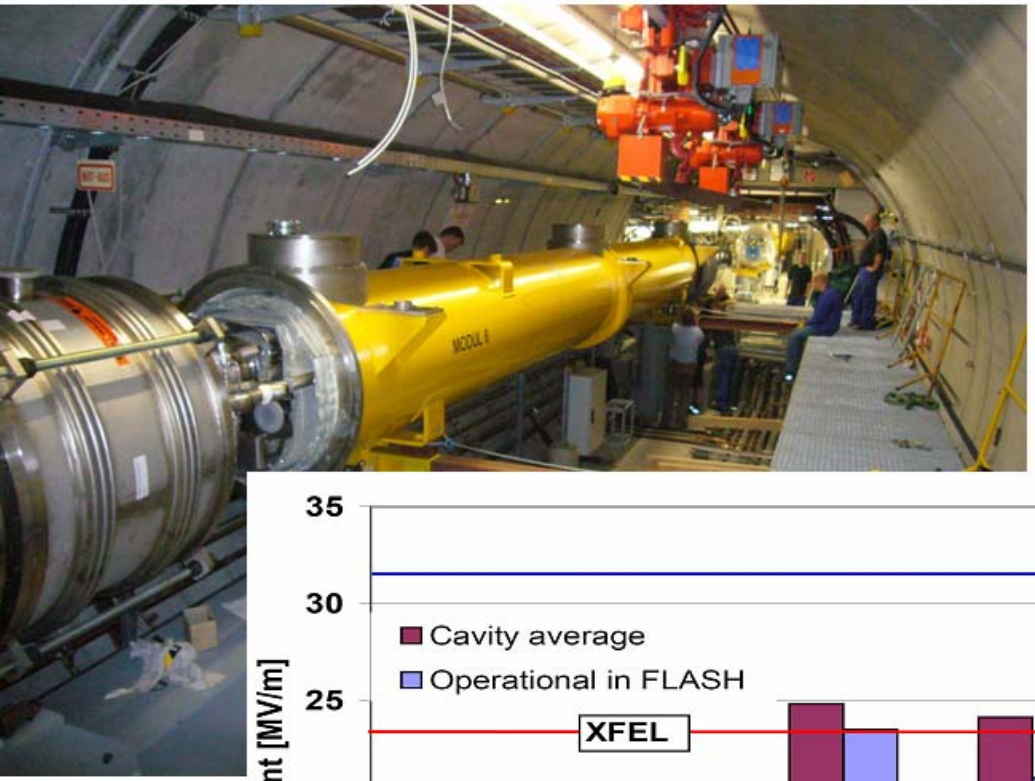
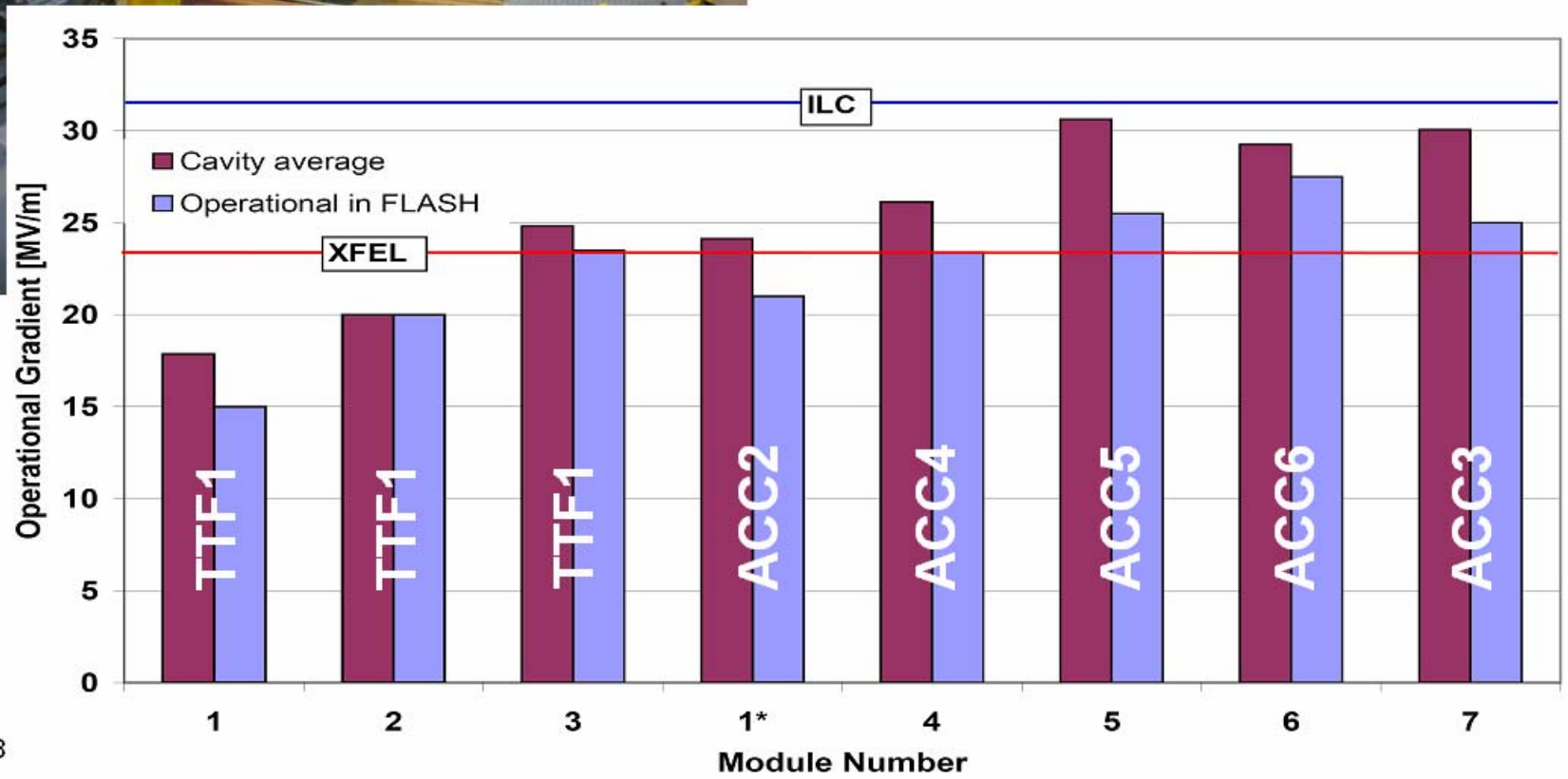
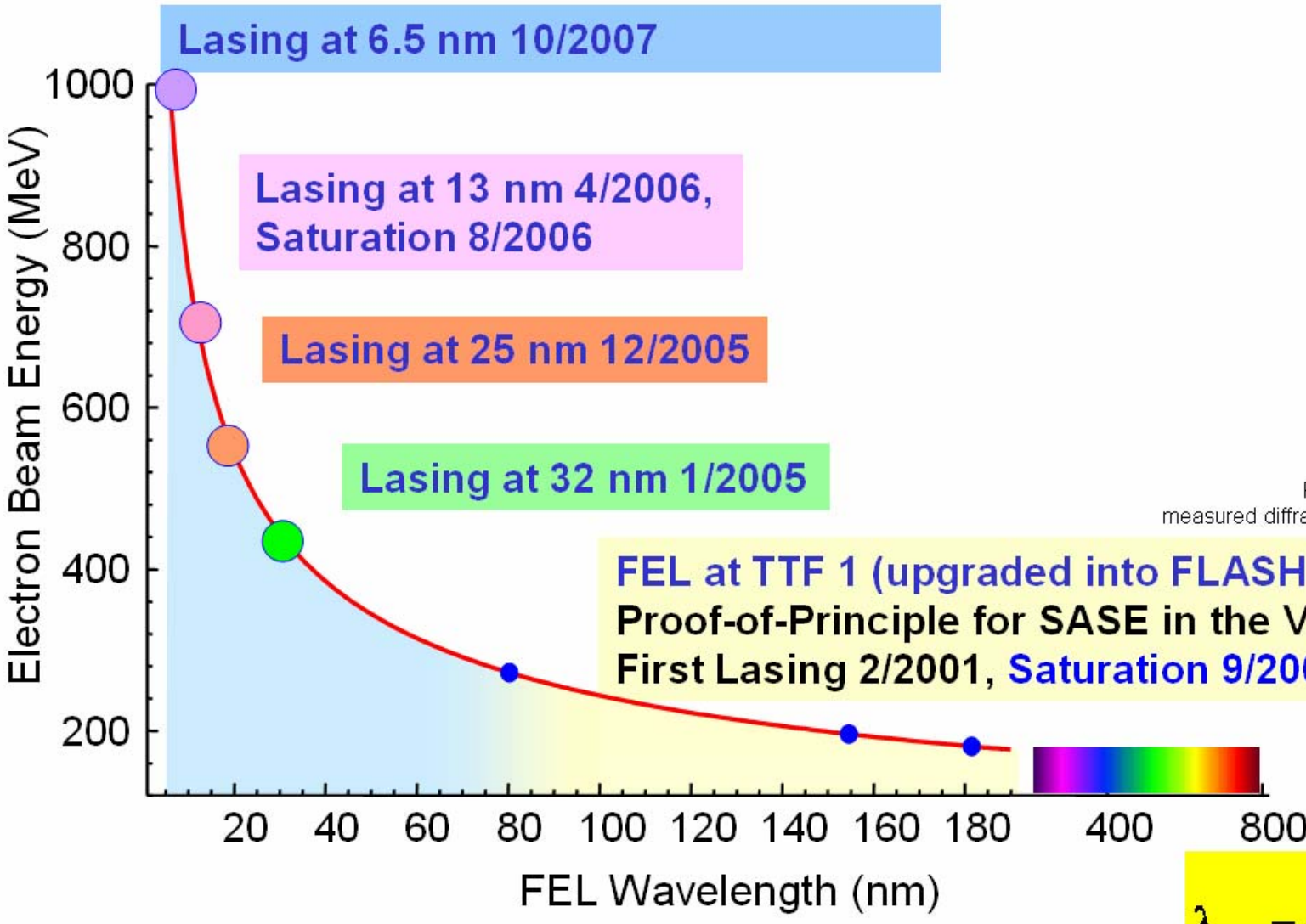




Beam Energy and Wavelength



FEL radiation:
measured diffraction pattern of a double slit

FEL at TTF 1 (upgraded into FLASH 2002)
Proof-of-Principle for SASE in the VUV
First Lasing 2/2001, Saturation 9/2002

$$\lambda_{ph} = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

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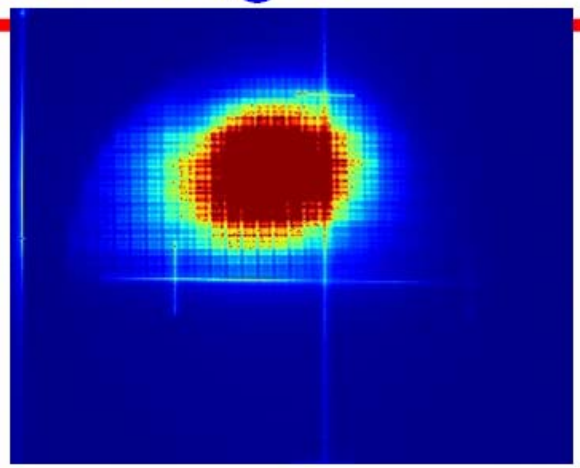

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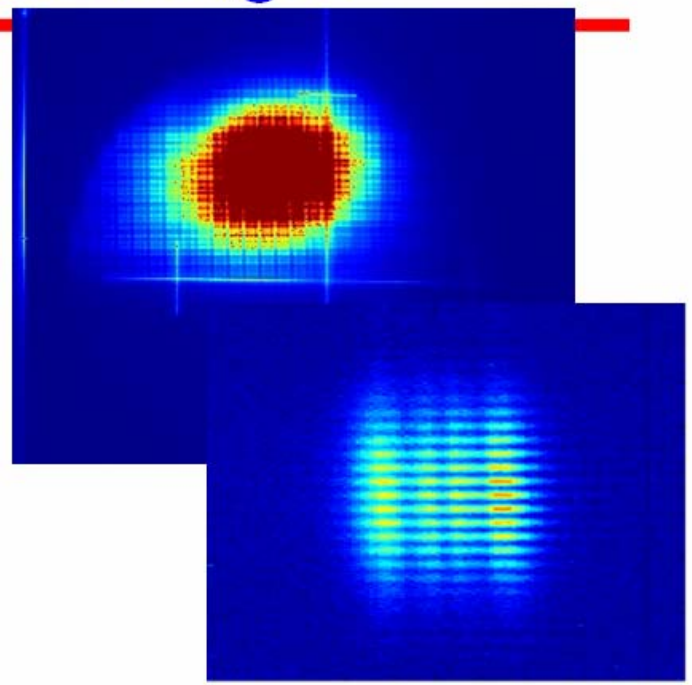


FEL radiation:
measured diffraction pattern of a double slit

Lasing at 6.5 nm 10/2007

Lasing at 13 nm 4/2006,
Saturation 8/2006

Lasing at 25 nm 12/2005

Lasing at 32 nm 1/2005

FEL at TTF 1 (upgraded into FLASH 2002)
Proof-of-Principle for SASE in the VUV
First Lasing 2/2001, Saturation 9/2002

Electron Beam Energy (MeV)

1000
800
600
400
200

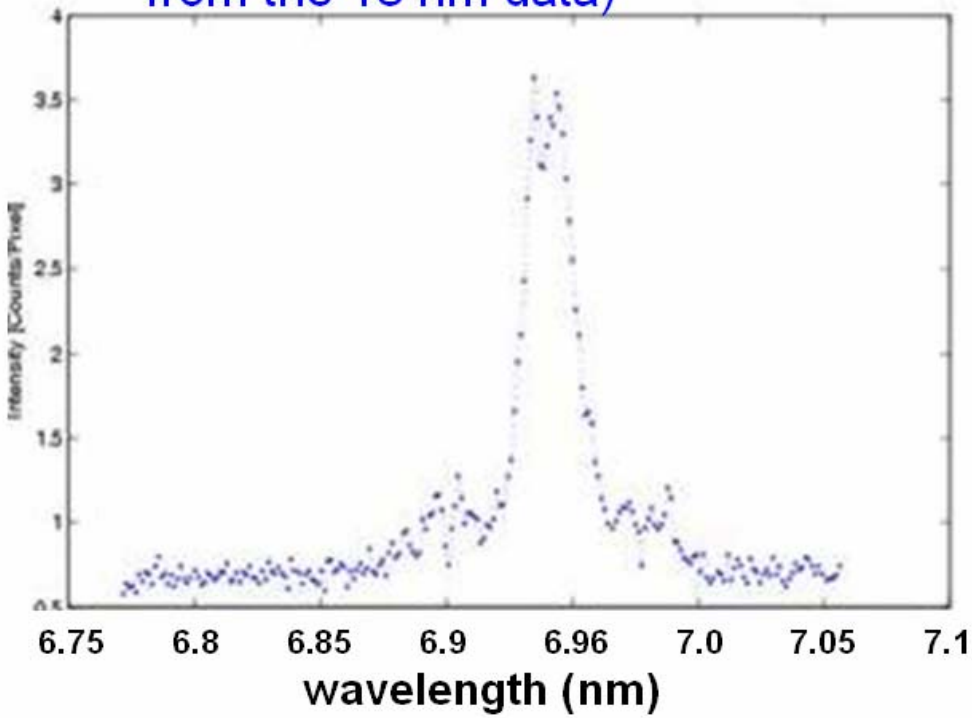
20 40 60 80 100 120 140 160 180 400 800

FEL Wavelength (nm)

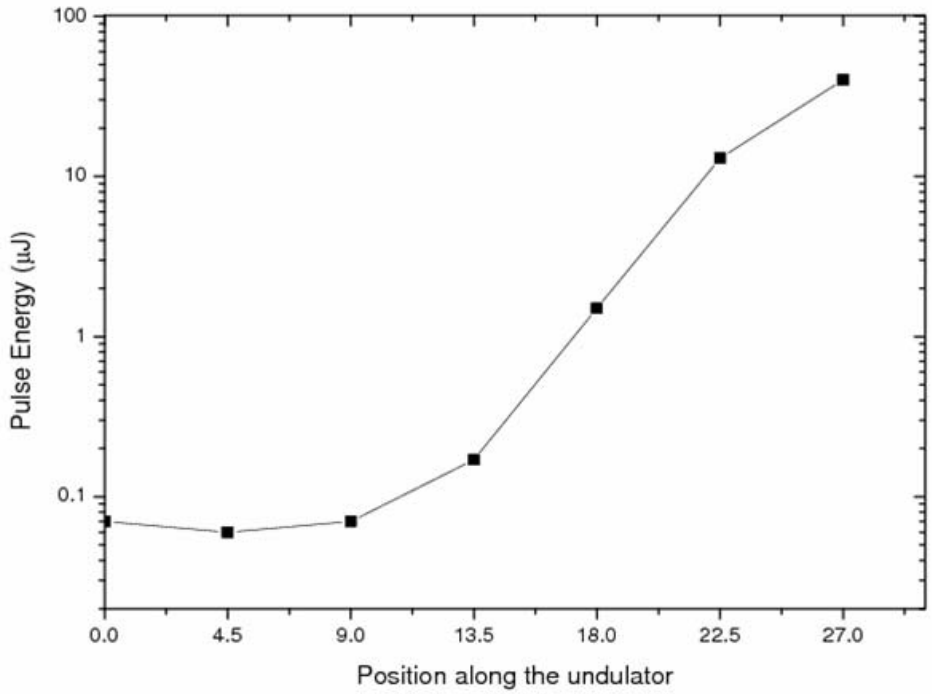
$$\lambda_{ph} = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$

Preliminary Radiation Properties @ 6.9 nm

- Lasing at 6.5 nm and 6.9 nm, 7 nm delivered to users
- single shot spectra show a small number of modes → preliminary
  estimated pulse length: in the 5-10 fs range (rough extrapolation from the 13 nm data)

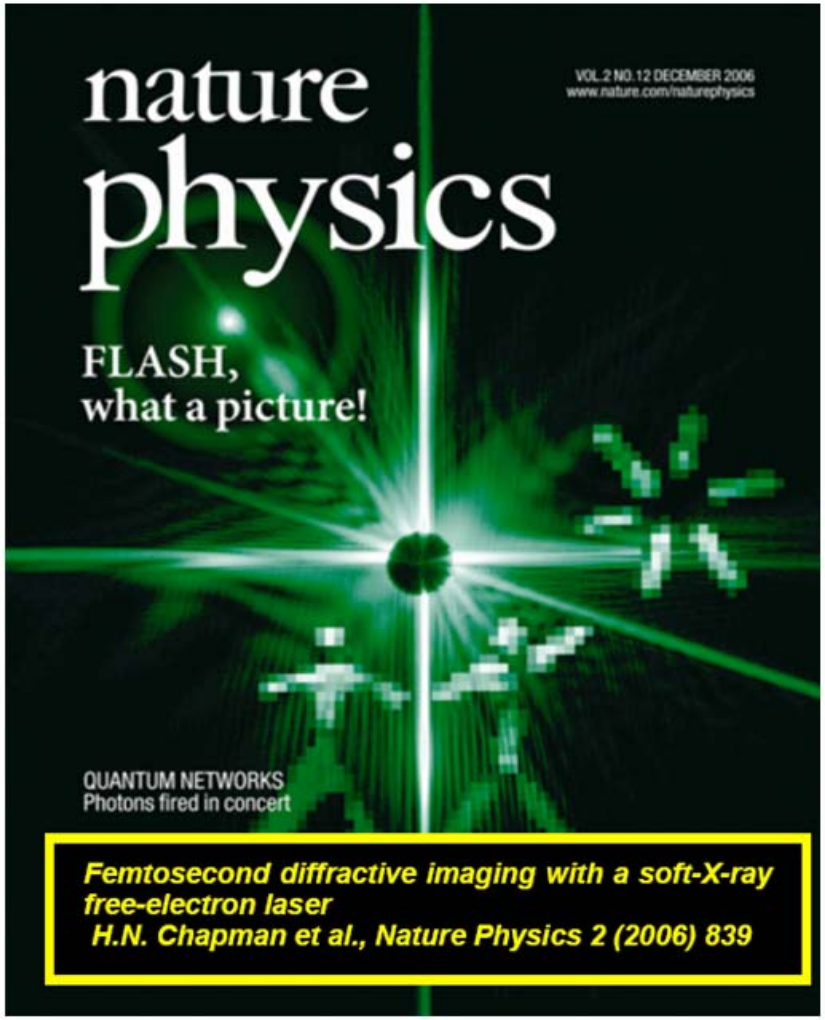


Gain curve @6.9 nm (preliminary)



FLASH, what a picture!

1st Round of User Experiments ended 3/2007



18 projects received beamtime
>200 scientists
60 institutes, 11 countries

> 25 publications already,
many more to come

- 4 PRL
- 6 APL
- 1 Nature,
- 1 Nature Physics
- 1 Nature Photonics
- ...

See, e.g.,
http://hasylab.desy.de/facilities/flash/publications

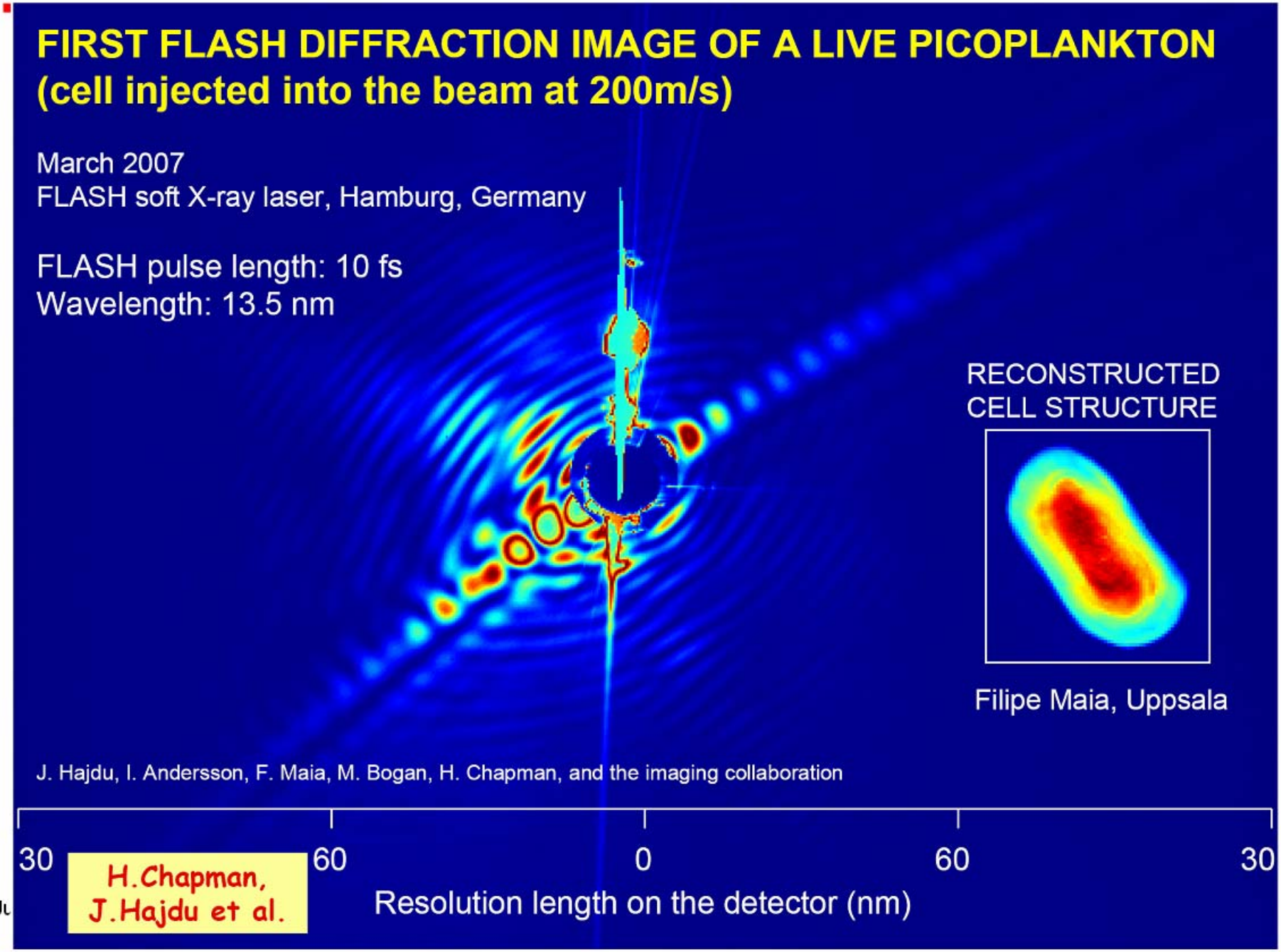
2nd Round of User Experiments

total of 45 proposals, 13 rejected

377 twelve hour user shifts available in 18 months,
316 shifts allocated + ≥10% management contingency ≈ 350 shifts

Research fields	Number of 12 hour shifts		Percentage
	Requested (all 45 prop.)	Allocated	
Atoms, Molecules, Ions	247	61	25
Clusters	71	36	50
Imaging, Diffraction	90	53	59
Plasma physics / Warm dense matter	194	56	29
Solids, Surfaces	214	46	21
Methods/ Technology	157	64	41

As an example …



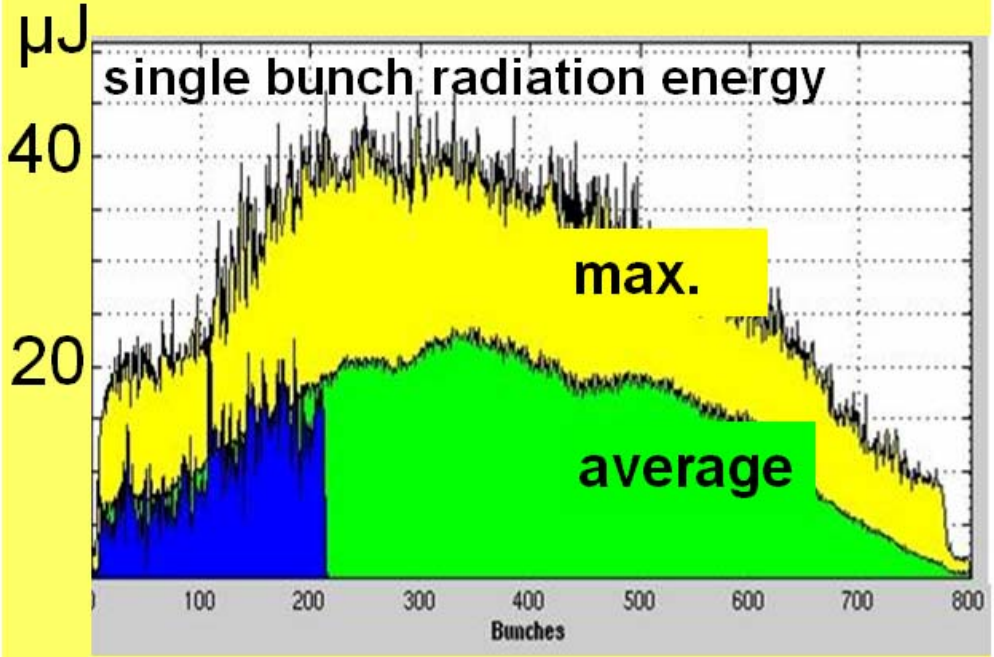
Lasing with long bunch trains

- Lasing with up to 800 bunches, >10 µJ/pulse achieved
- Machine Protection System: fully operational, with minor constraints

800 bunches, 685 MeV, 13 nm

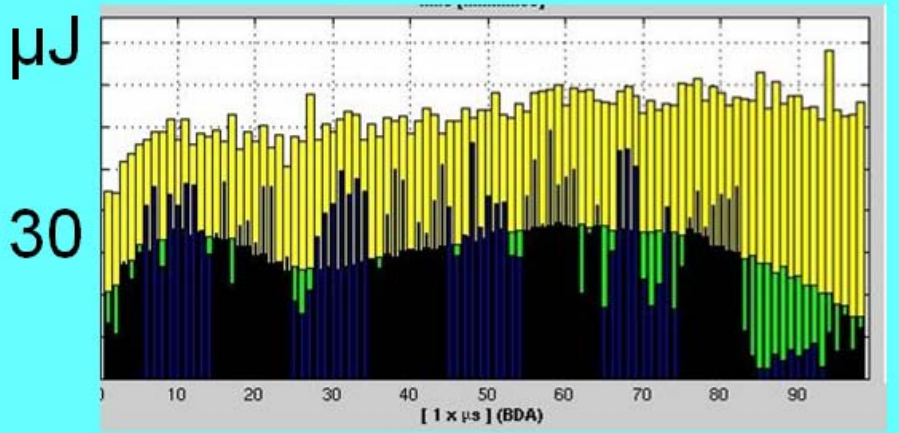
<electron beam power> : 2.7 kW

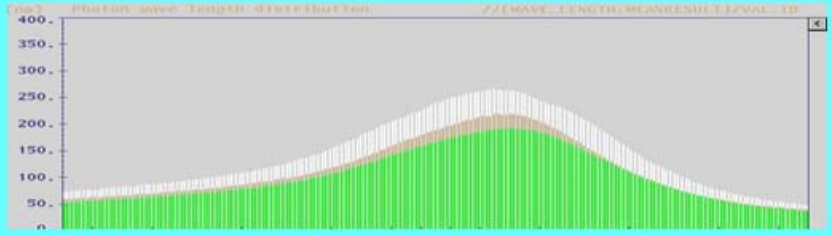
<photon power>: 56 mW



100 bunches, 960 MeV, 7 nm

<photon power>: 14 mW



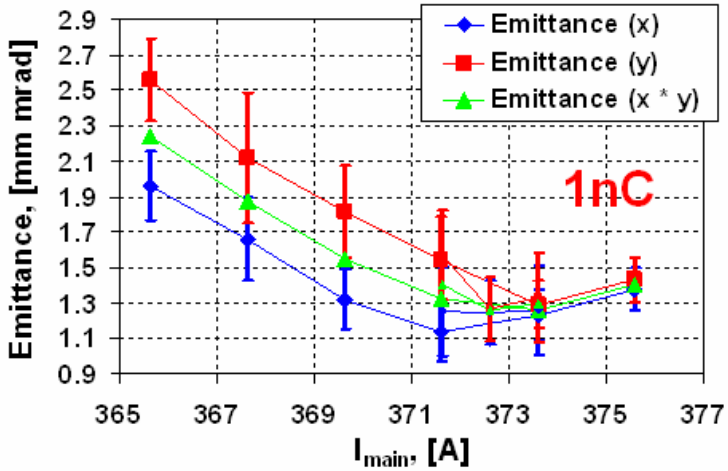


7.0 7.1 λ/nm

single bunch

RF gun development @ PITZ/DESY-Zeuthen

	Oct. 2006	2007
Gun gradient	43 MV/m	60 MV/m
Momentum	12.8 MeV/c	14.5 MeV/c
$\varepsilon_{x,norm}$/mrad mm	1.32 ± 0.11	1.25 ± 0.19
$\varepsilon_{y,norm}$/mrad mm	1.43 ± 0.17	1.27 ± 0.18

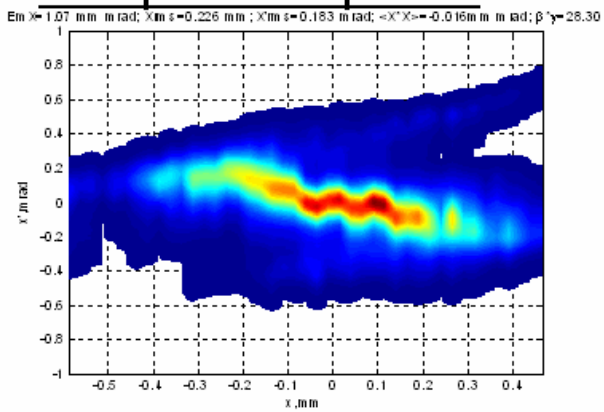


good agreement with ASTRA code

This is:

- Projected rms emittance
- Total beam (100 %)

x-x' phase space:



Cut 5% of charge → $\varepsilon_{x,y,norm}$ ≈ 0.8 mrad mm (95%) → OK for XFEL

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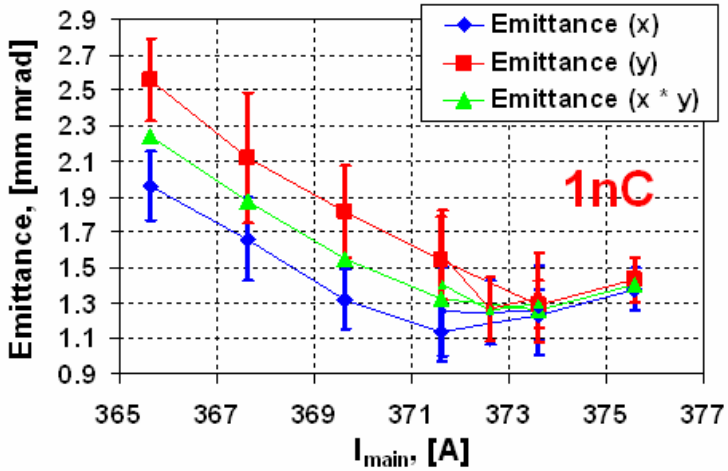

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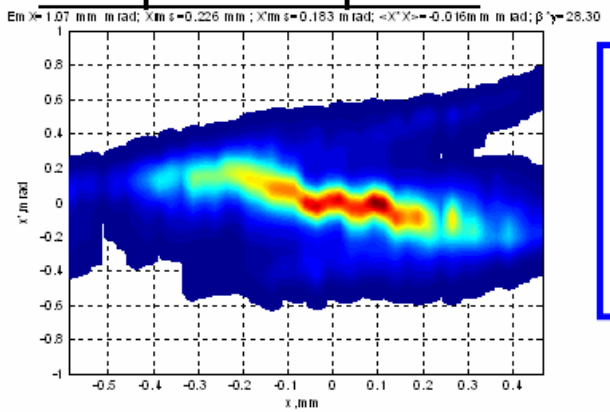

Dark current largely reduced by CO_2 cleaning

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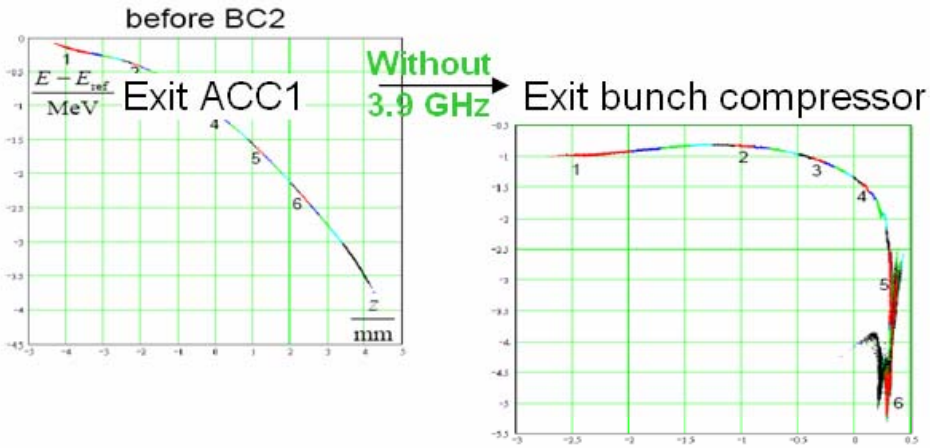
MOPC002, MOPC019, MOPC078N, TUPC002,TUPP034

Third harmonic cavity (3.9 GHz)

- Linearization of long. phase space



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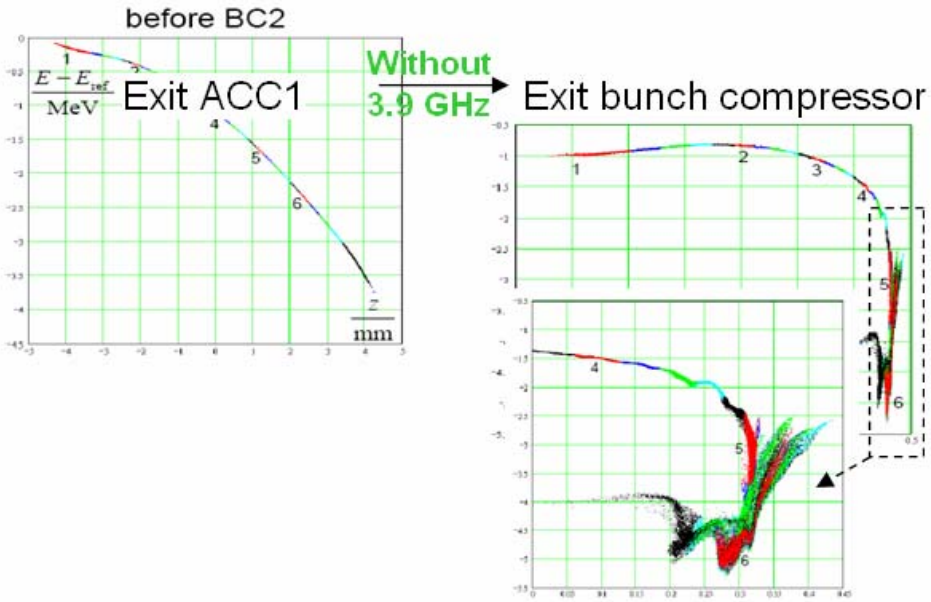

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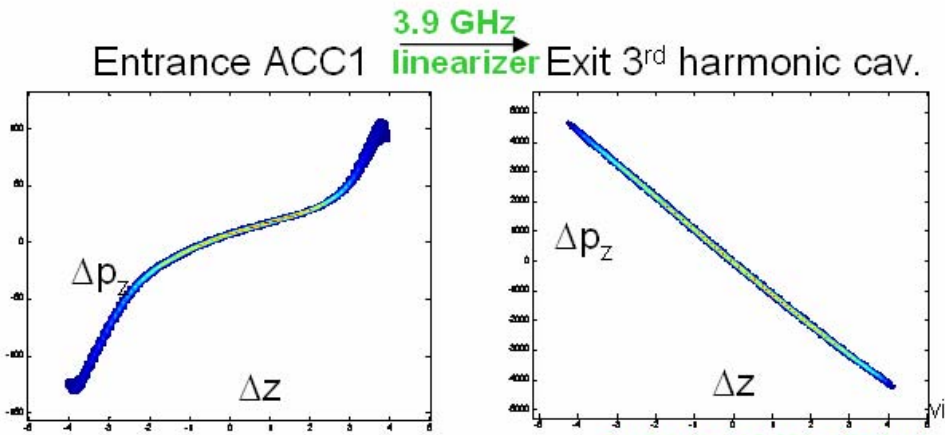

Courtesy: M. Krasilnikov

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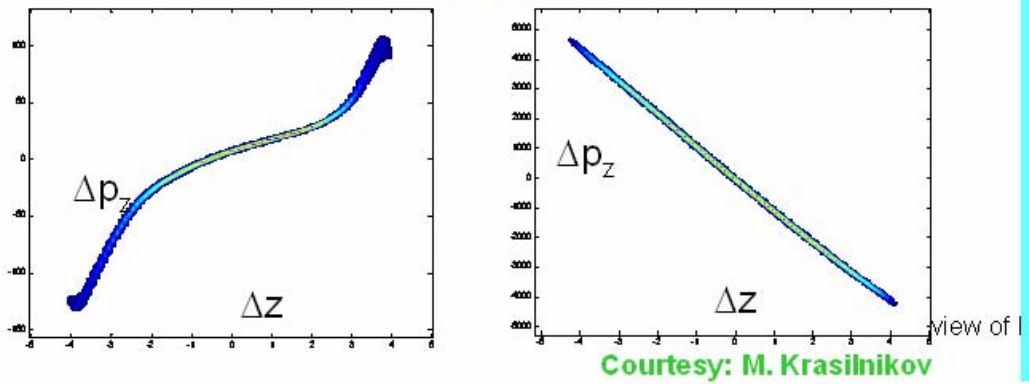
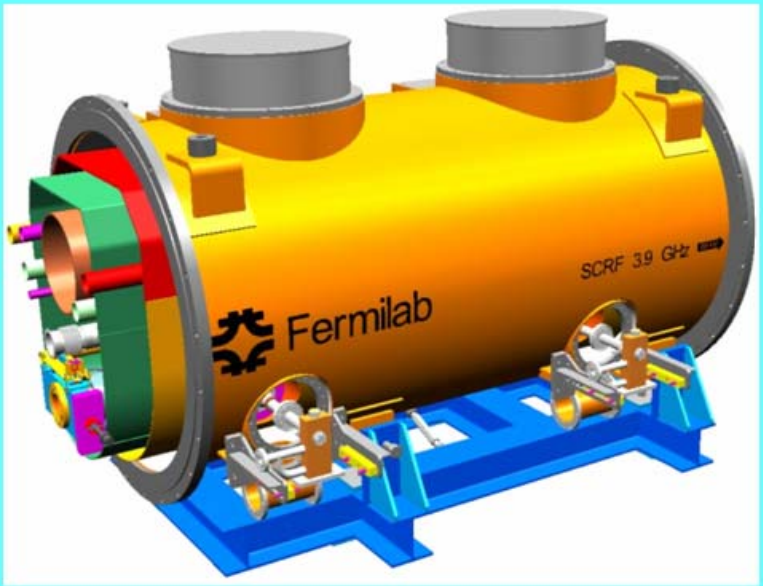


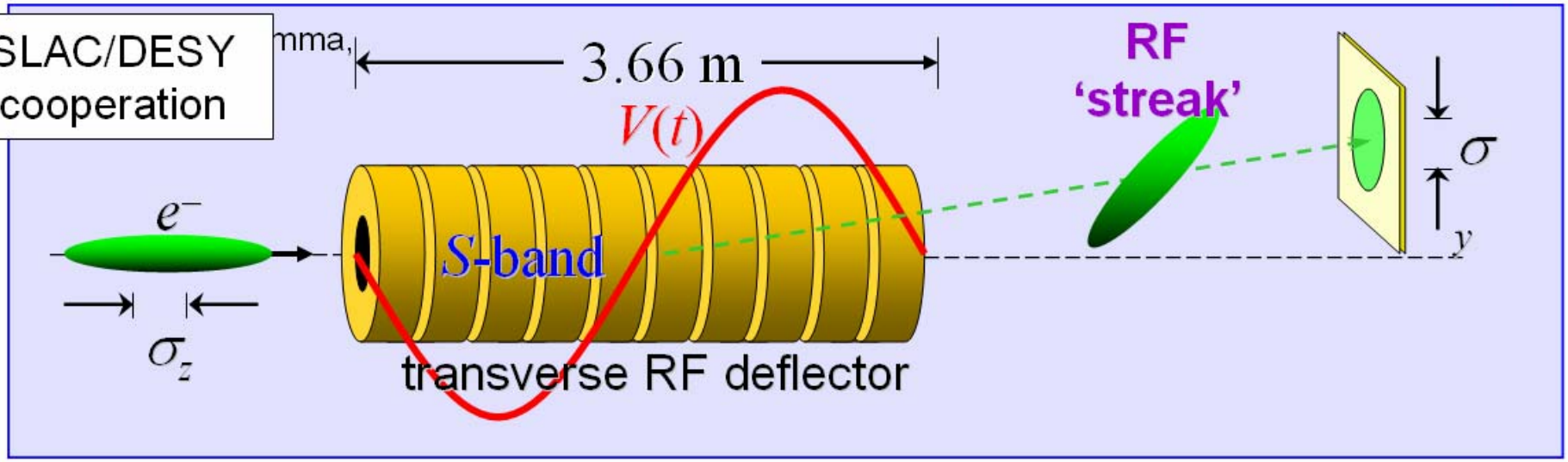
- Complete cryomodule delivered by FNAL
- Installation after ACC1 scheduled for 2009

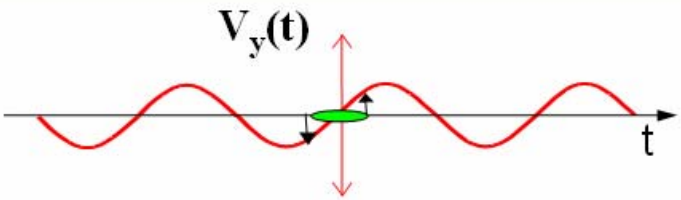


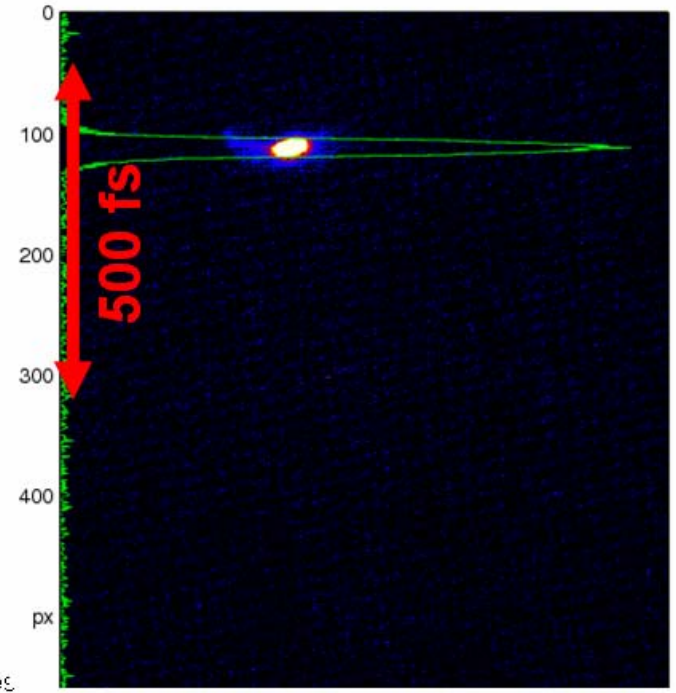
- module with four nine cell cavities
- fits type 2 TESLA module
- XFEL will use three 6 m long modules

MOPP135

Bunch Length Measurement: LOLA



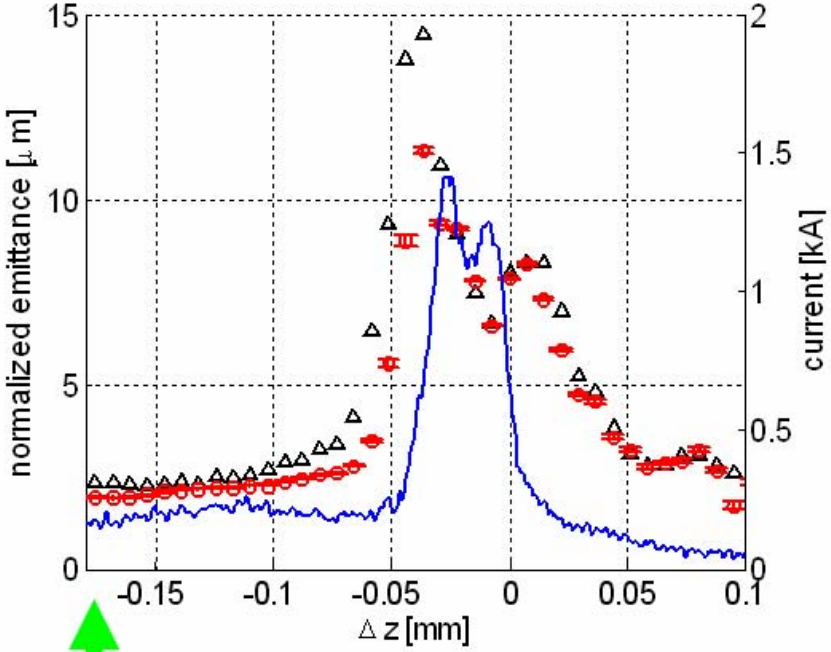




- Deflecting RF structure (S-band) from SLAC is used as a 'streak camera'
- Resolution ~ 10 µm

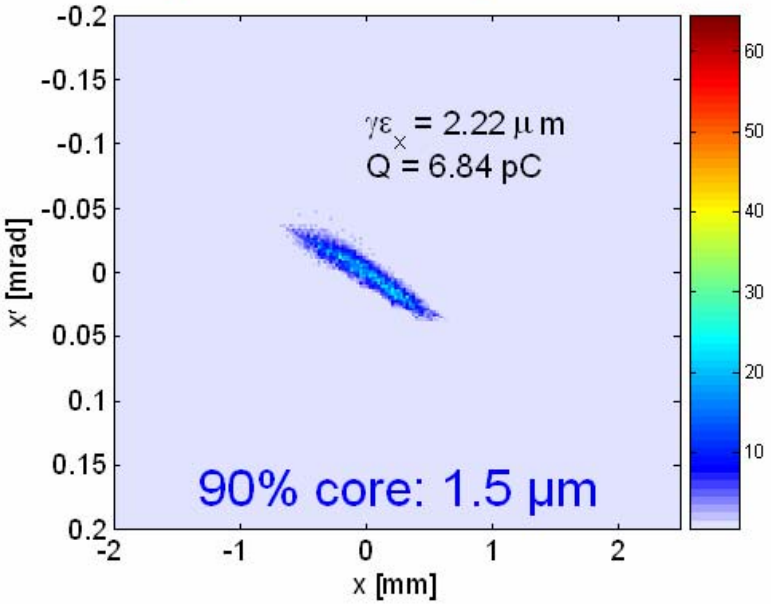
Horizontal phase space slice resolved

Slice emittance and current:



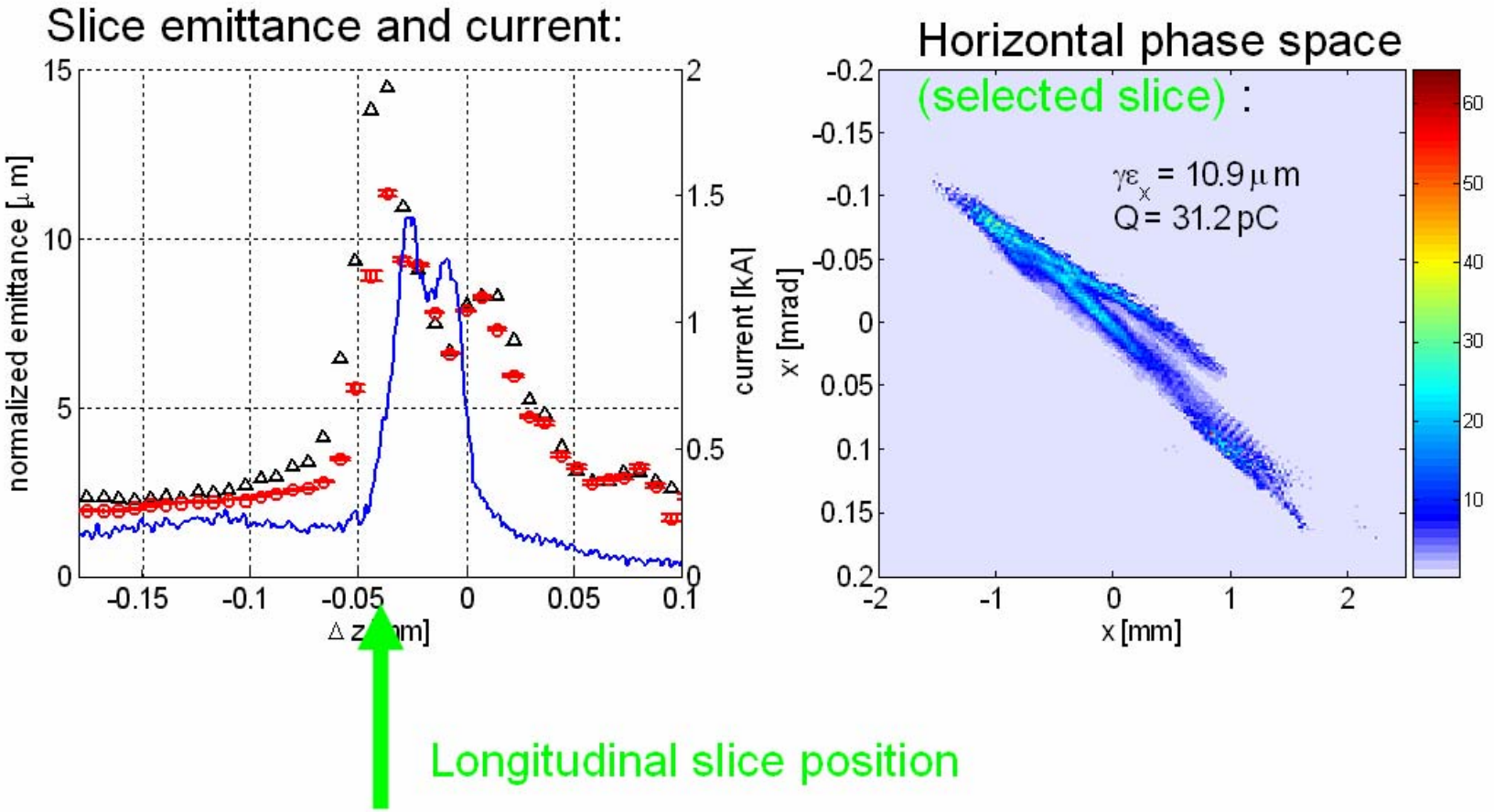
Longitudinal slice position

Horizontal phase space
(selected slice) :



TUPP017,
TUPP018

Horizontal phase space slice resolved



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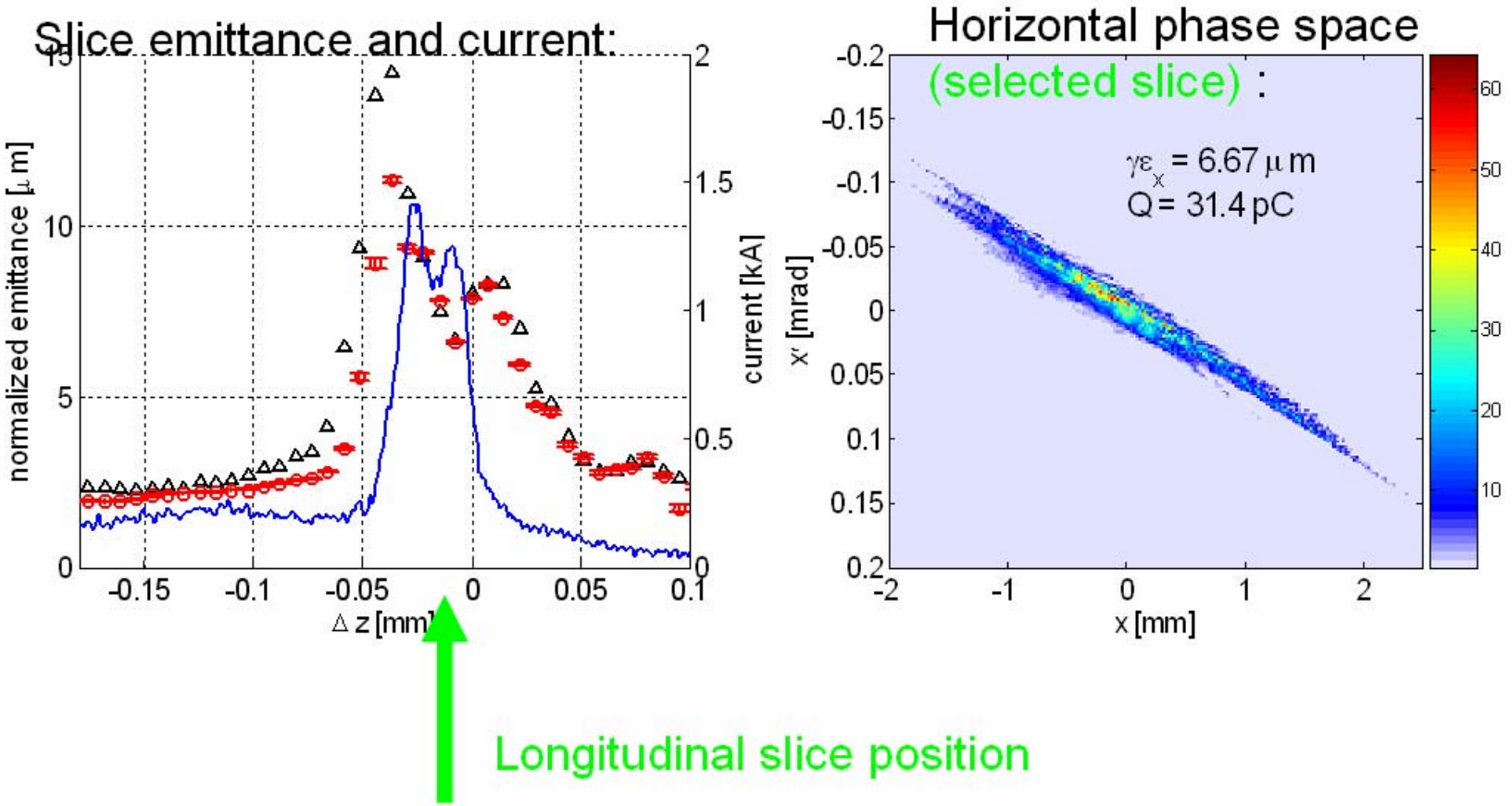
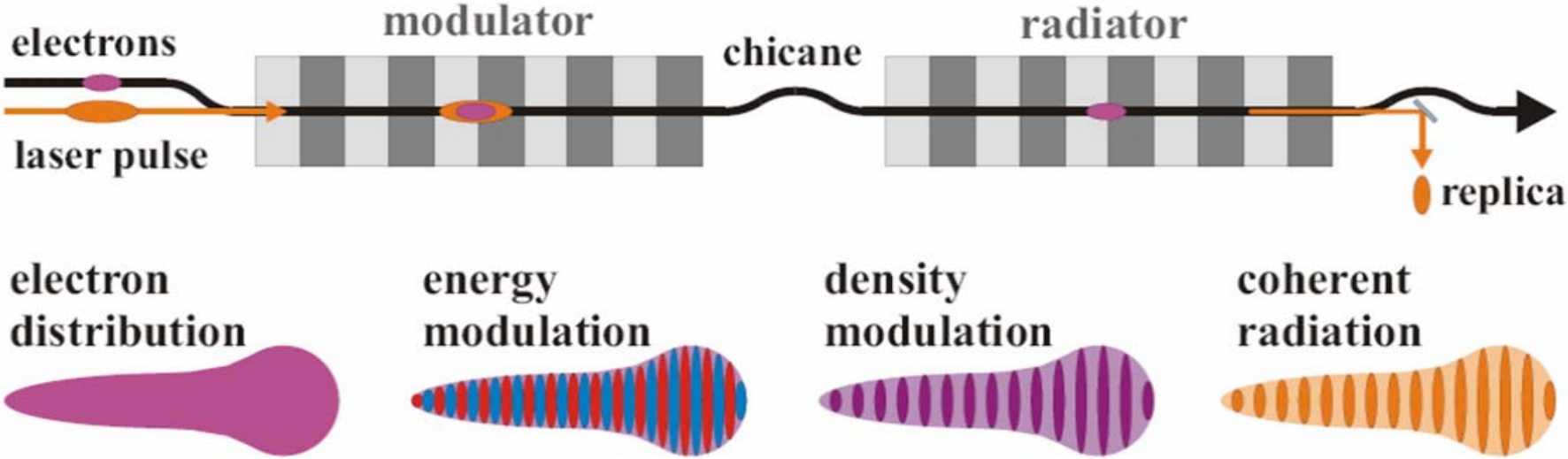


Bunch Length Measurement: ORS

- Optical replica synthesizer (ORS)

Uppsala Uni.,
Stockholm Uni.
Uni. Hamburg
BESSY
DESY

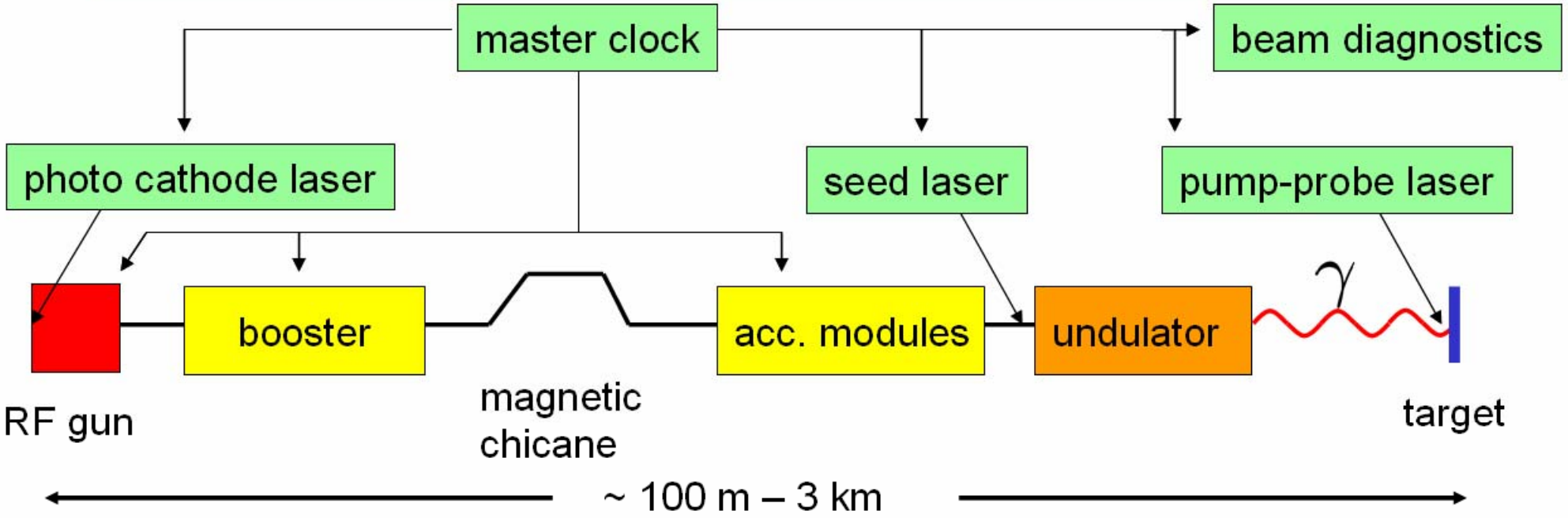
SSY: Nucl. Inst. and Methods A 539 (2005) 499.



→ Parasitic, high resolution (10fs), single shot, longitudinal bunch profiling
→Valuable experience for laser heater design
→Presently being commissioned, first signals observed

TUPC155

Synchronization needed in a FEL facility



Many sources for changes of arrival-time of the FEL radiation !

Key Problem:

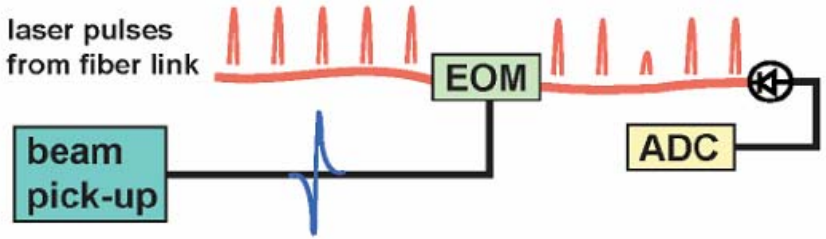
rf microwave oscillator is excellent master clock, but long-distance distribution of rf signals with cables is impossible at fs stability !

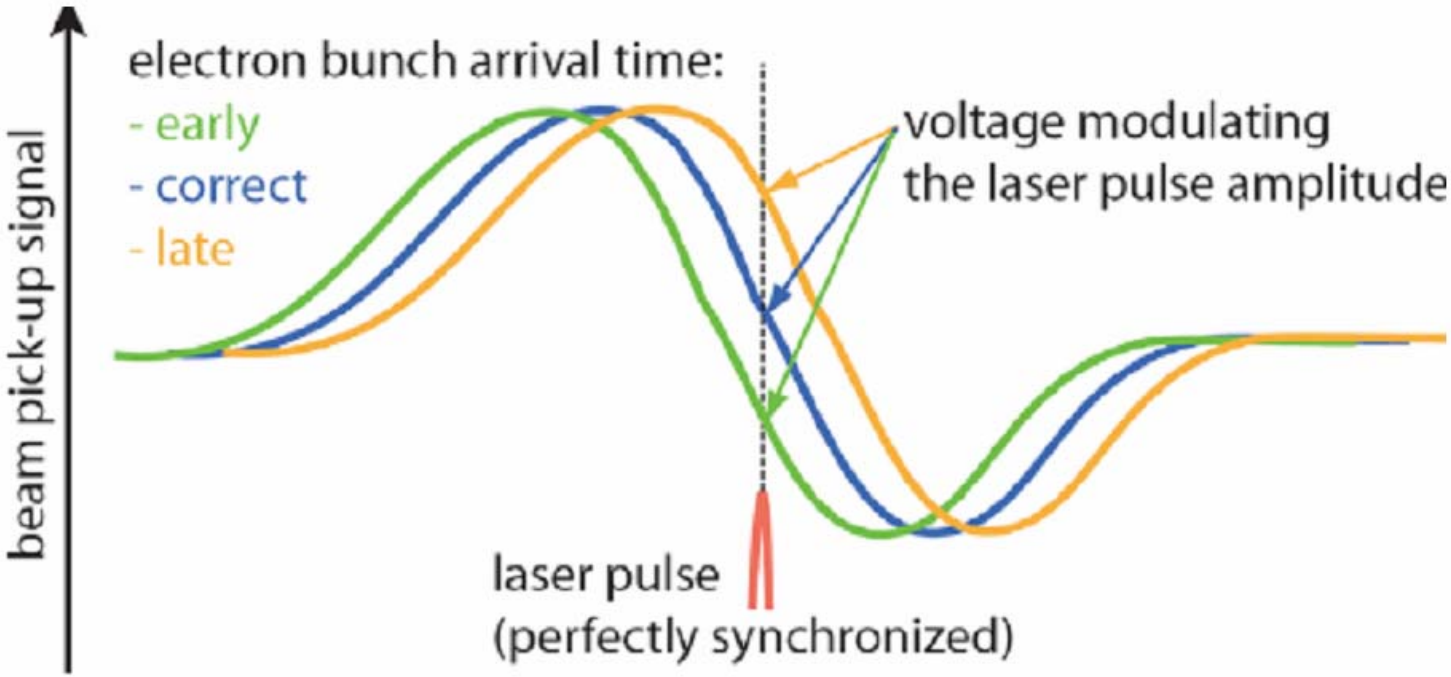
→ Work on an all-optical synchronization system

Key Component: *Beam Arrival Monitor (BAM)*

Timing information of electron bunch is transferred into a laser amplitude modulation →

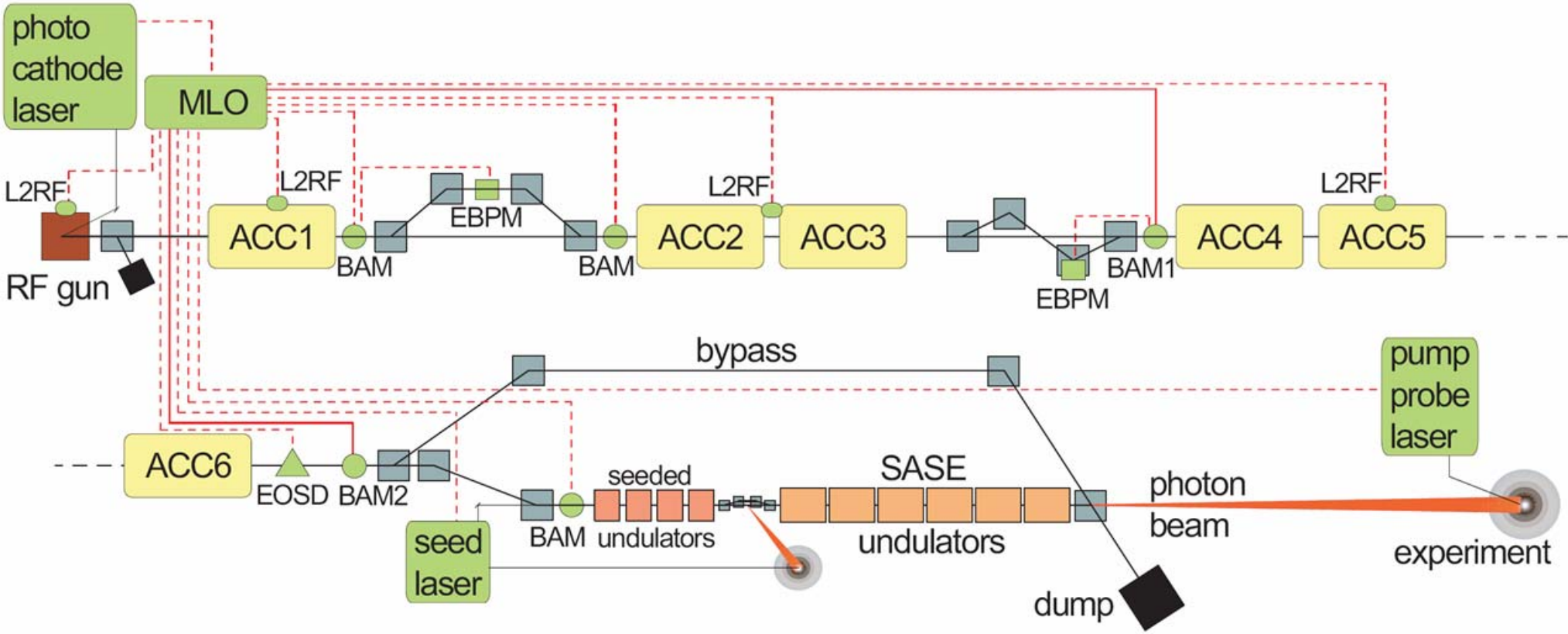
Electro-Optical Modulator EOM





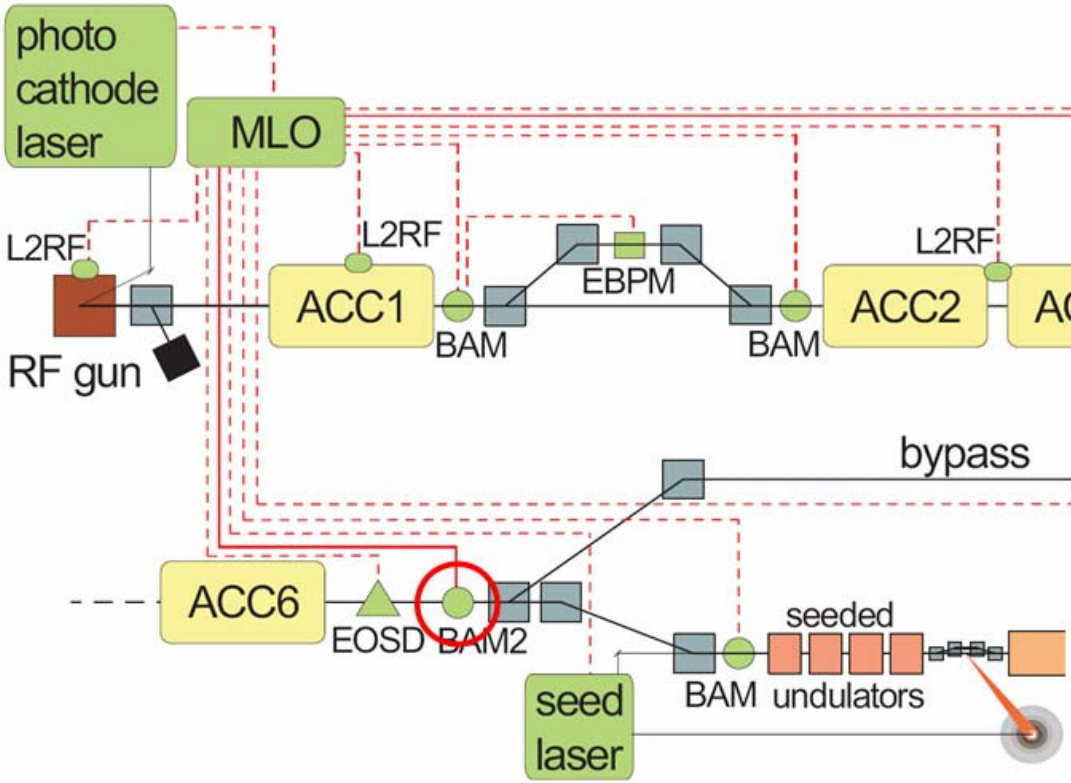
TUPC081

Optical Synchronization System at FLASH



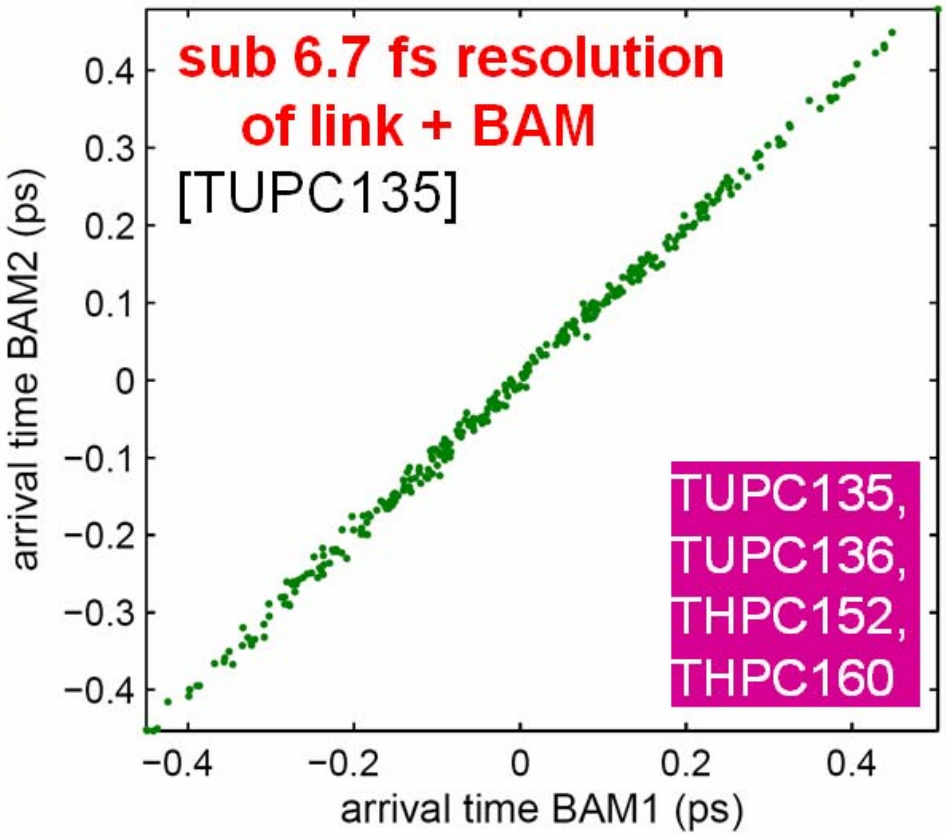
A sub-10 fs stable optical synchronization system is currently being developed at FLASH.

Optical Synchronization System at FLASH

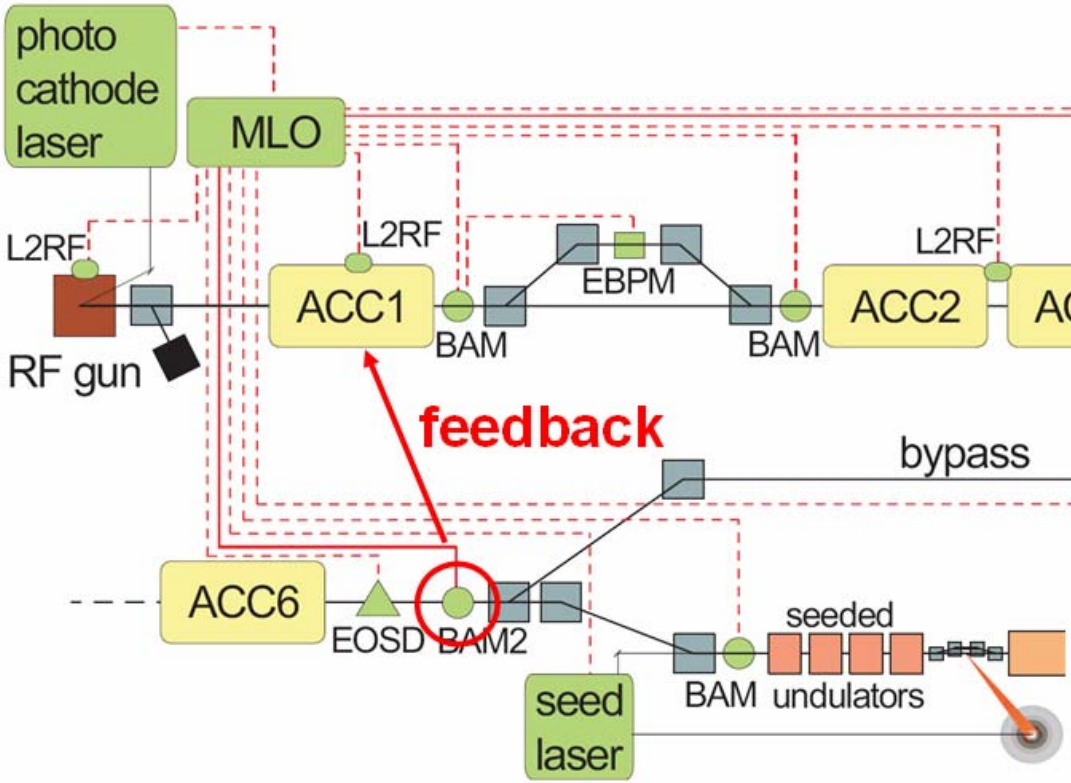


Arrival time measurement with two BAMs in a straight section.

BAMs separated by 60 m.



Optical Synchronization System at FLASH



Arrival time measurement with two BAMs in a straight section.

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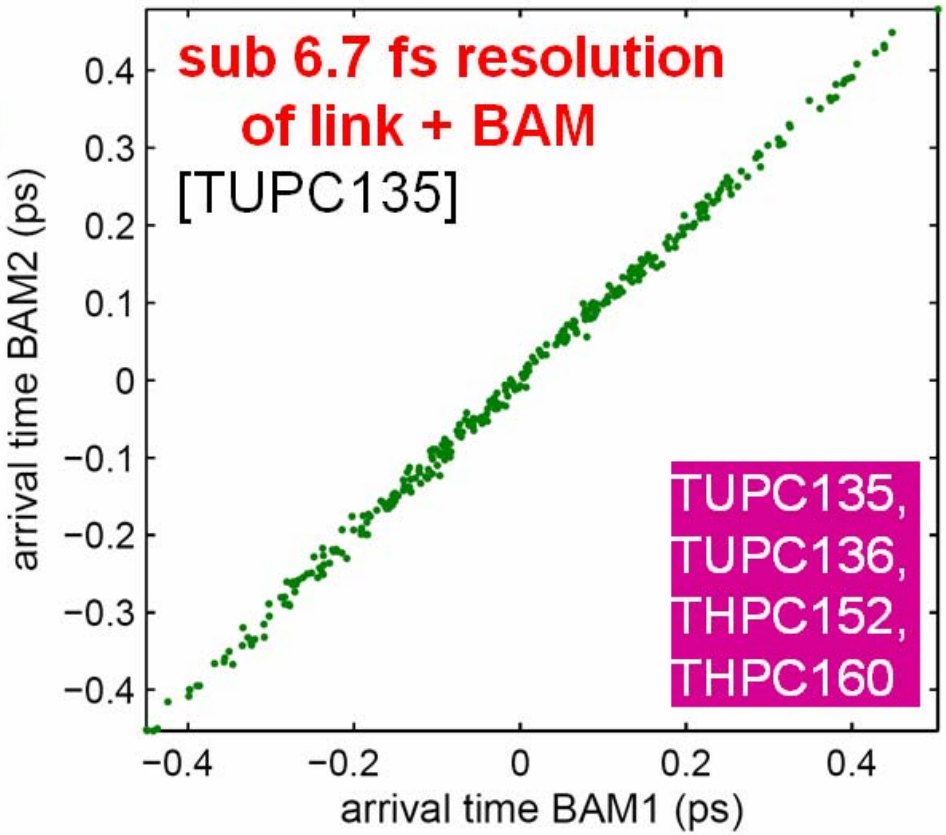
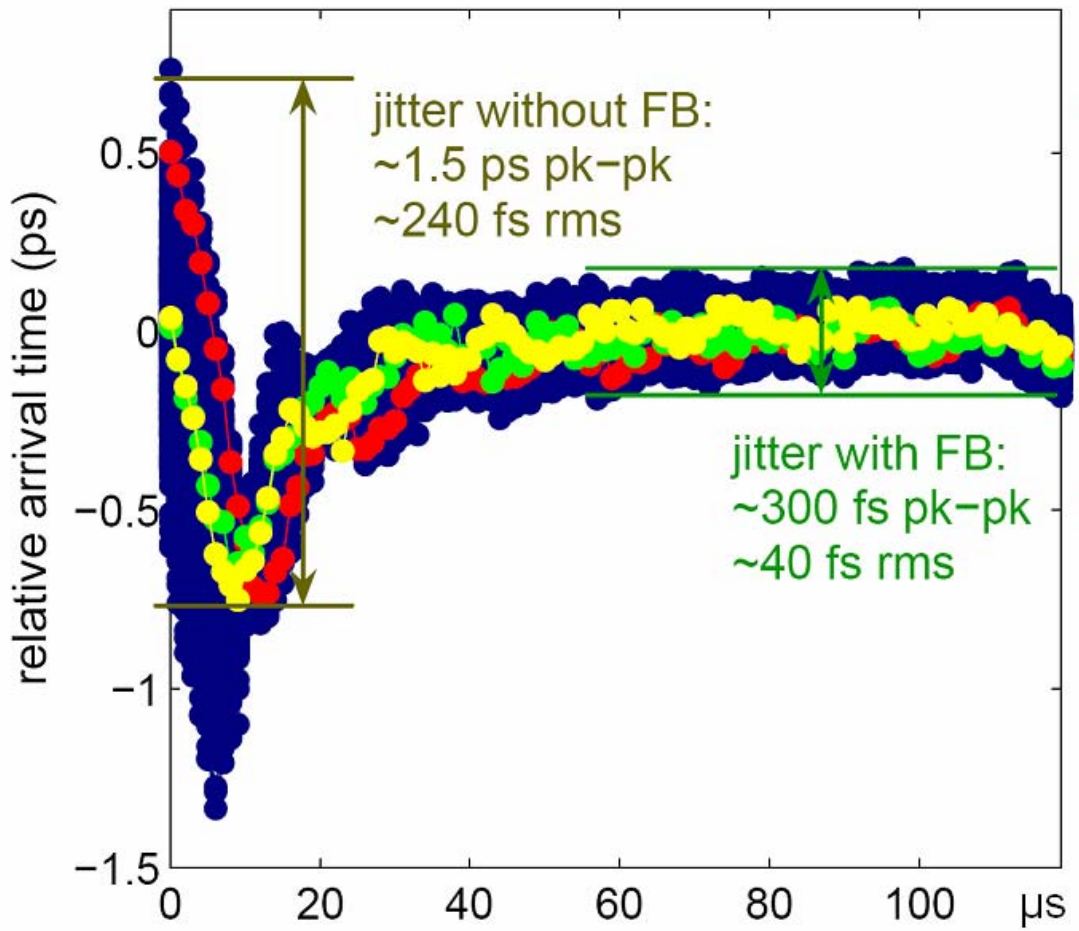


Optical Synchronization System at FLASH

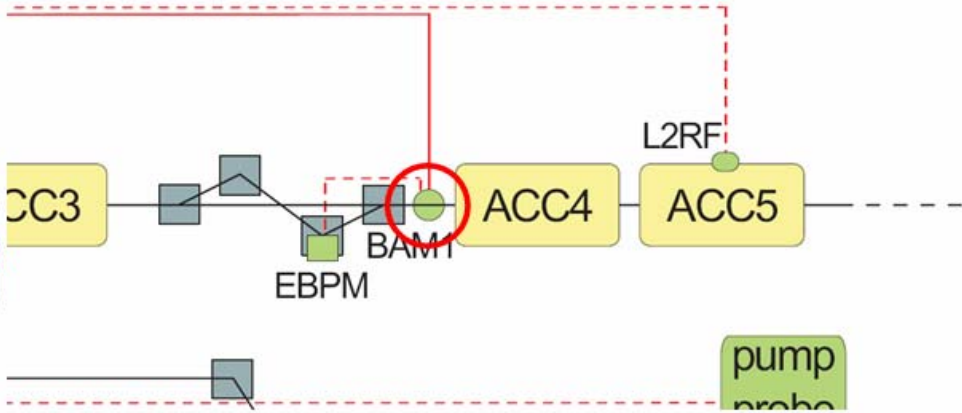


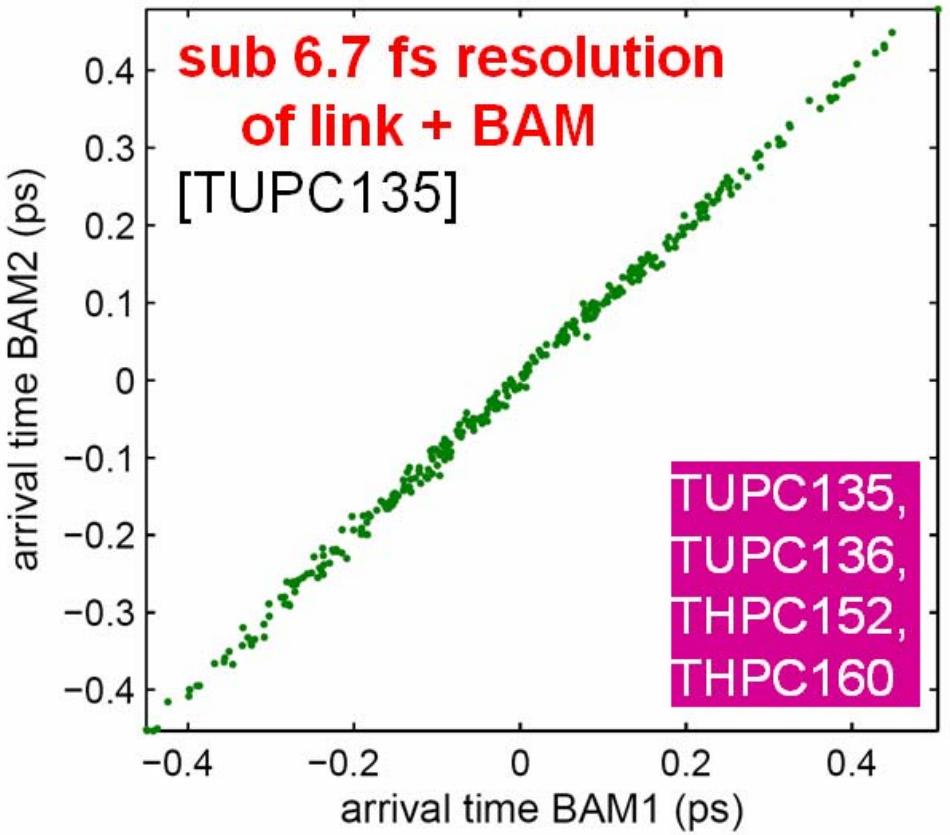
arrival time stability (rms):

240 fs without feedback

40 fs with feedback

THPC158



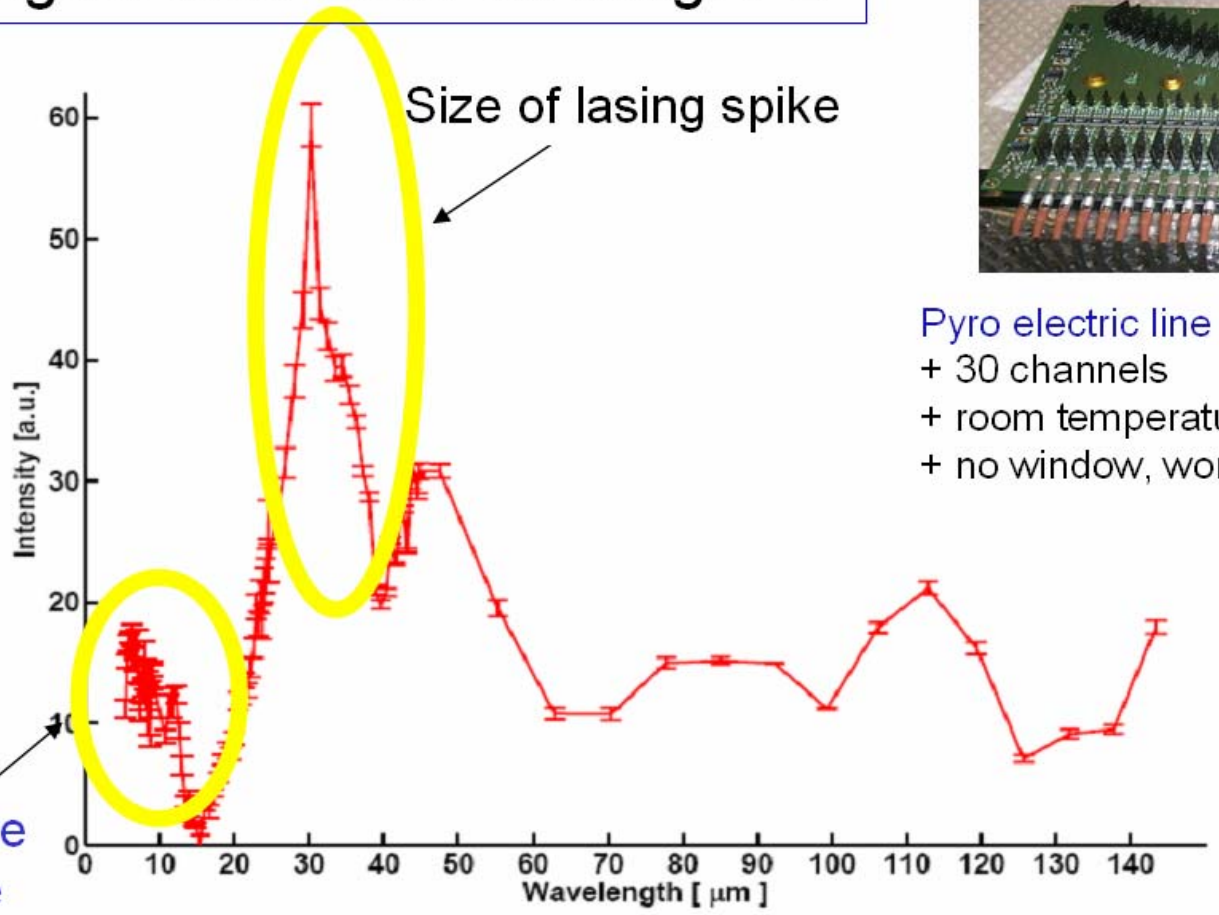


Frequency domain diagnostics with THz rad.

Single shot spectrum of coherent infrared radiation exhibits structure in the longitudinal density modulation < 5 µm !!

Need single shot spectrometer for wide IR bandwidth

THz signal also used for long. FB



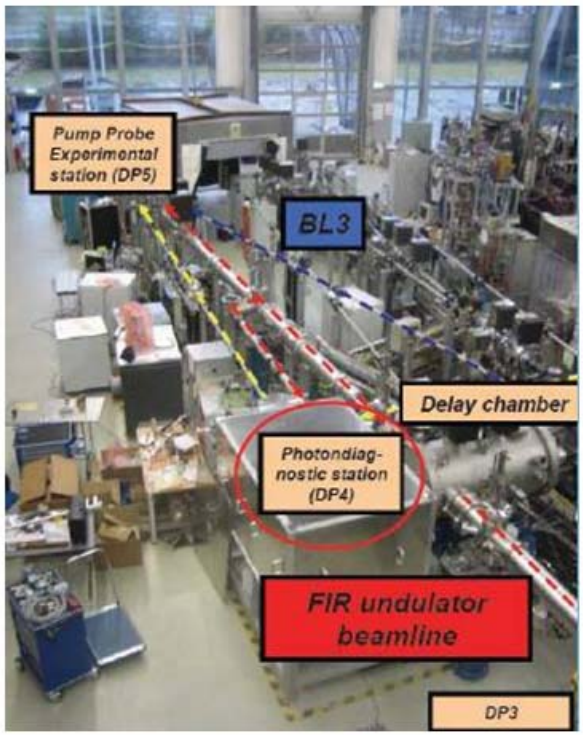
Recent development at DESY/UHH

Pyro electric line detector from individual pyros
+ 30 channels
+ room temperature
+ no window, works in vacuum

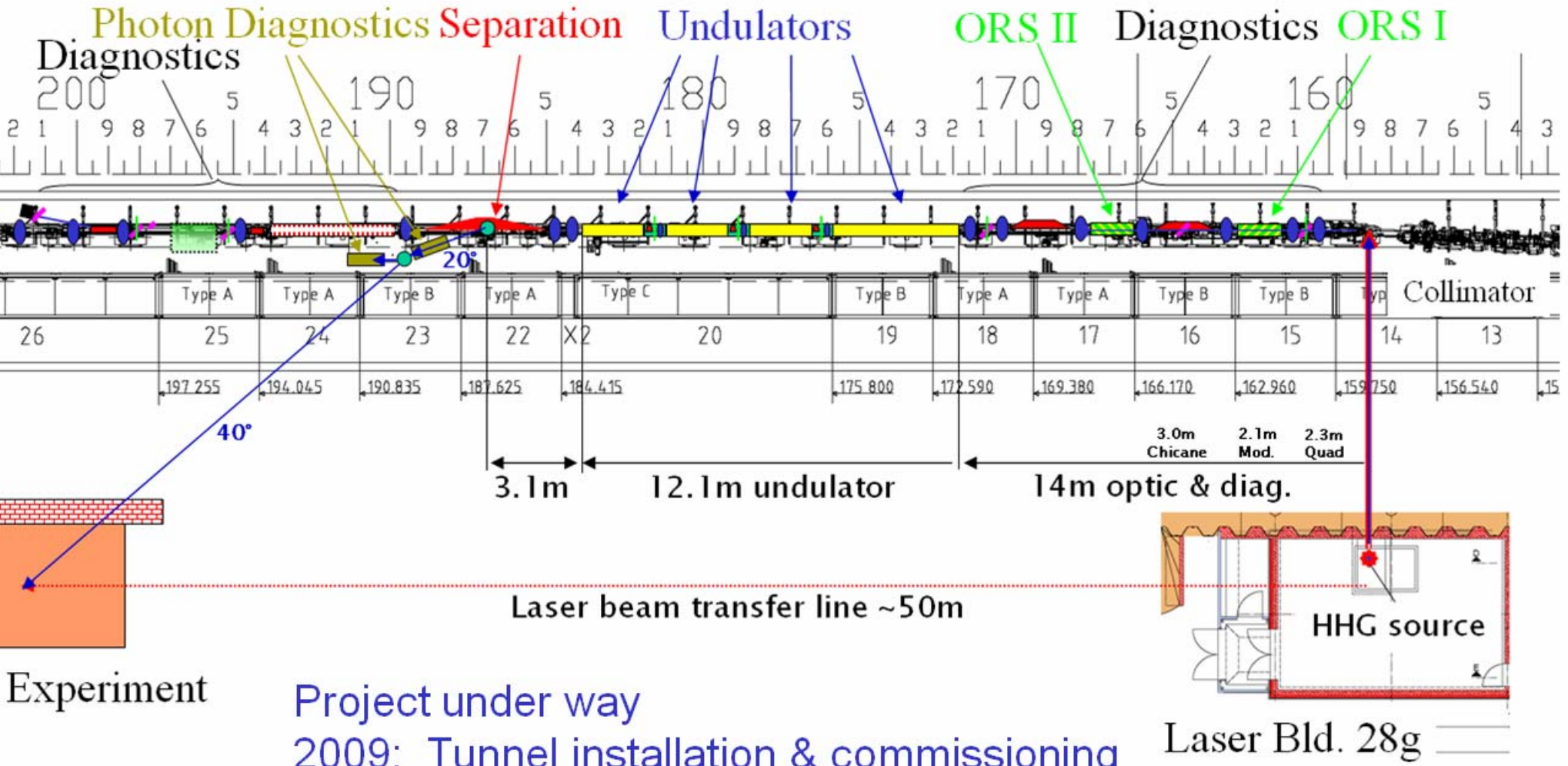
TUPC031

New infrared undulator

- Located downstream of FEL
- Improved coherent THz diagnostics
- FIR pulse naturally sychronized to FEL pulse
- FIR transported into exp. hall for pump-probe
- Status: FIR pulse observed,
  overlap FIR and FEL pulses detected



High Harmonic Laser Seeding at 30nm ("sFLASH")

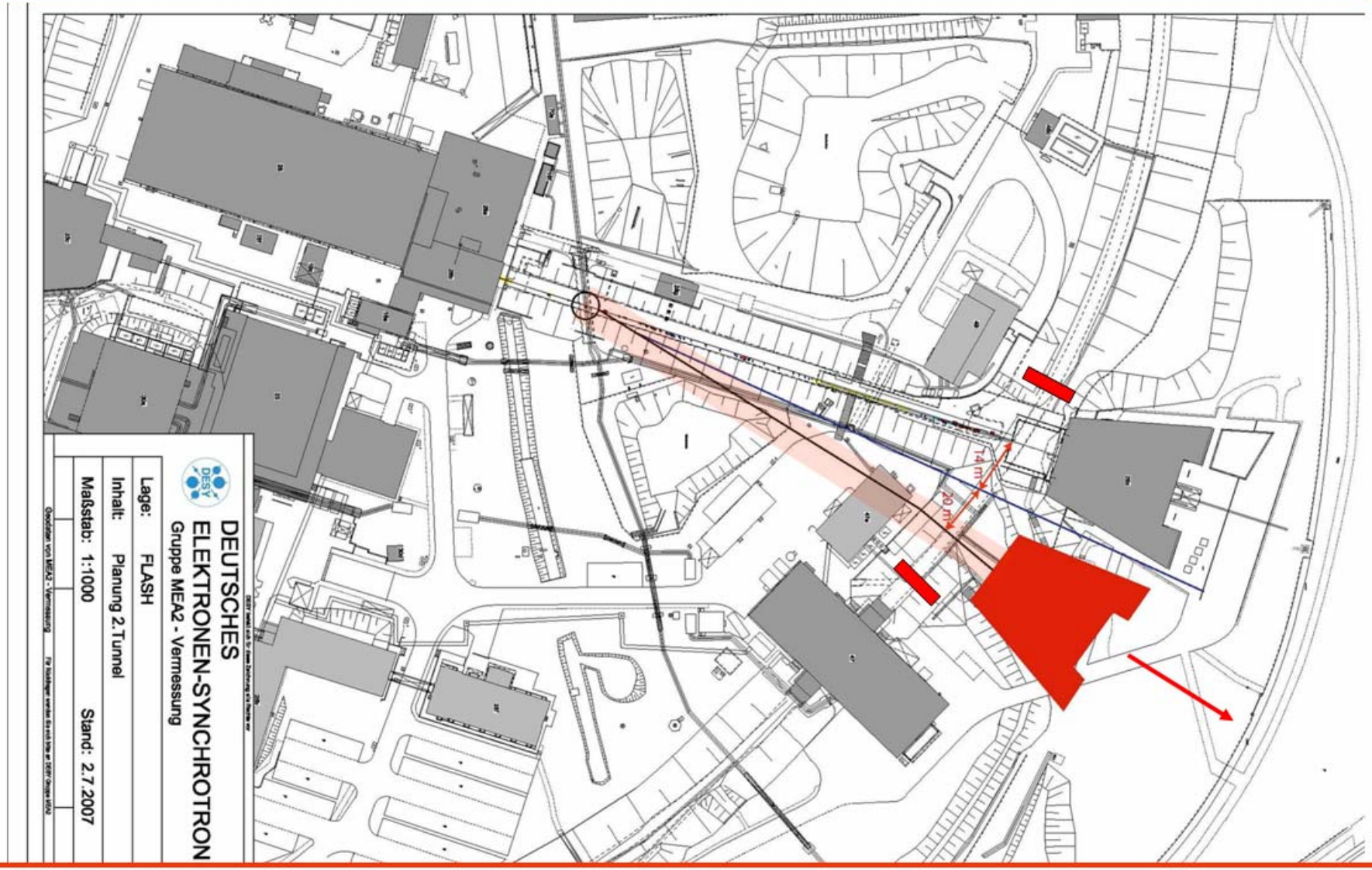


Project under way

2009: Tunnel installation & commissioning

2010: First pump-probe experiments

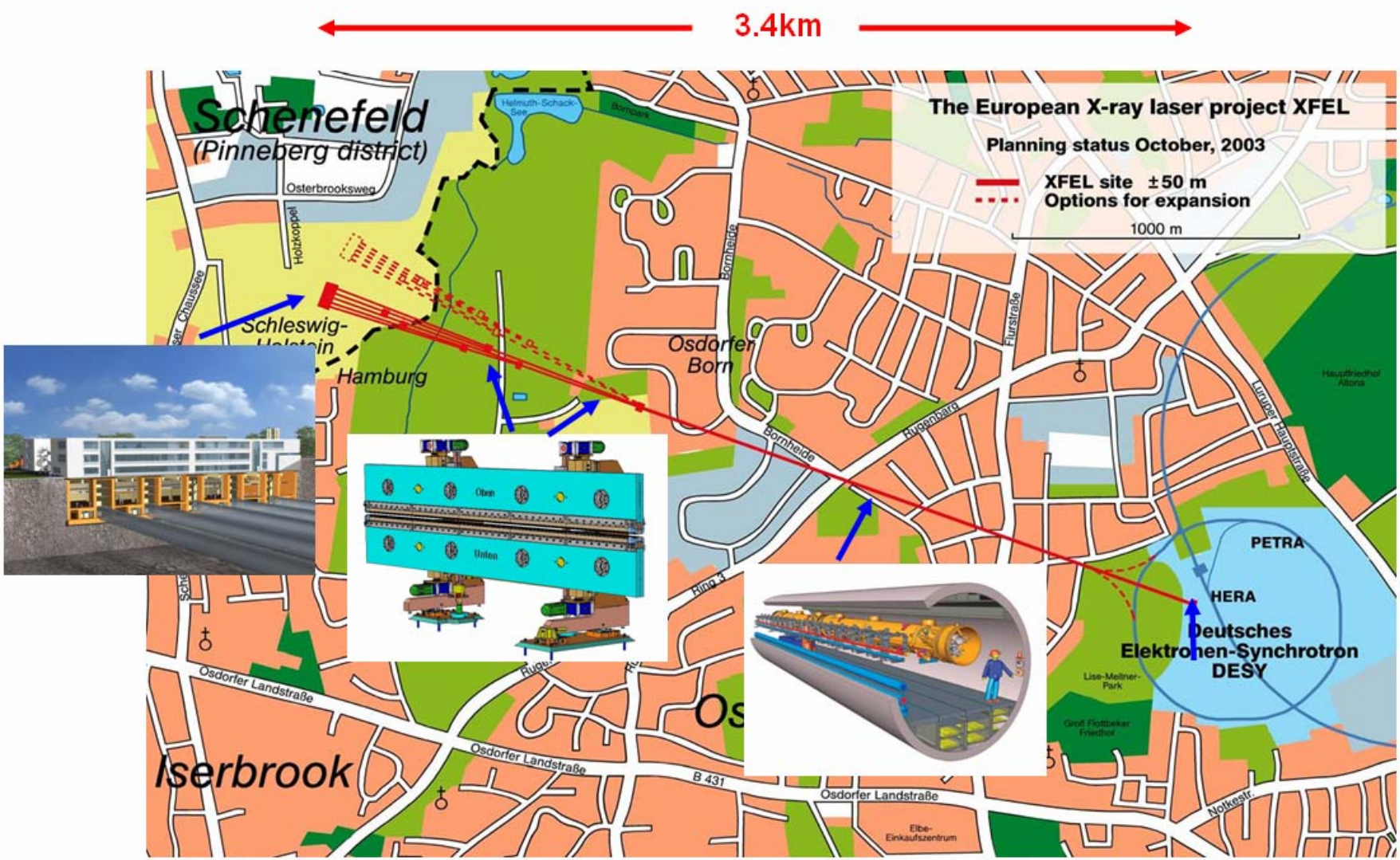
FLASH II: Proposal for a 2nd FEL beamline



More room for users

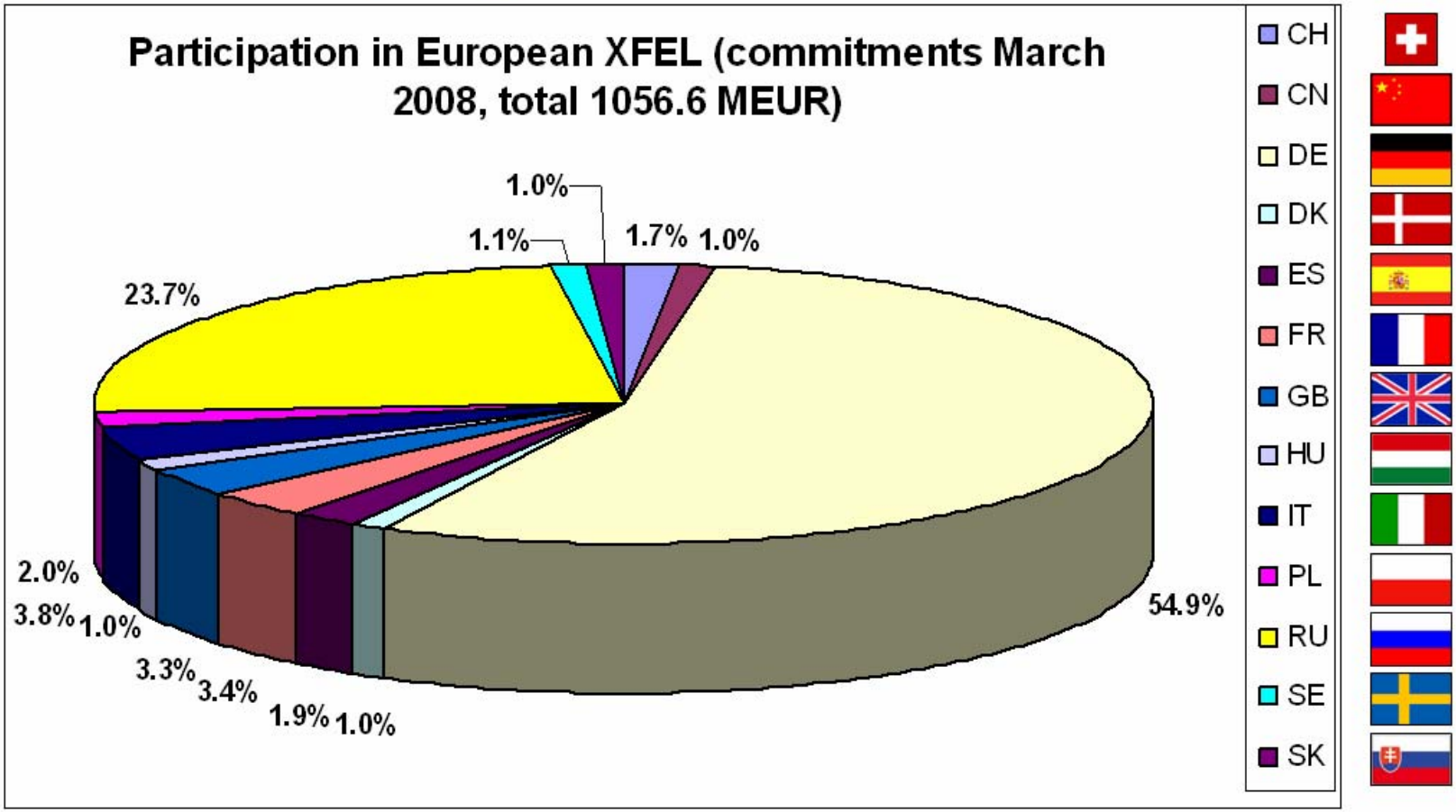
Quasi-simultaneous operation with 2 wavelengths

European XFEL Project Status



Status of financial commitments to European XFEL project

Includes ~90 M€ project preparation phase & commissioning
(contracts not yet signed ↔ minor readjustments may occur)



The European XFEL Company is in the process of being funded

Schenefeld Site

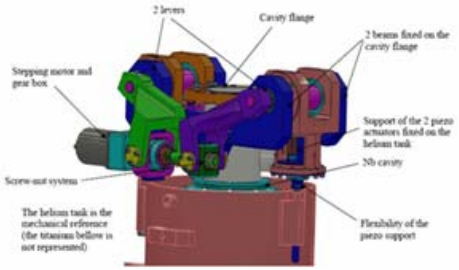
Schenefeld Site Computer Simulation

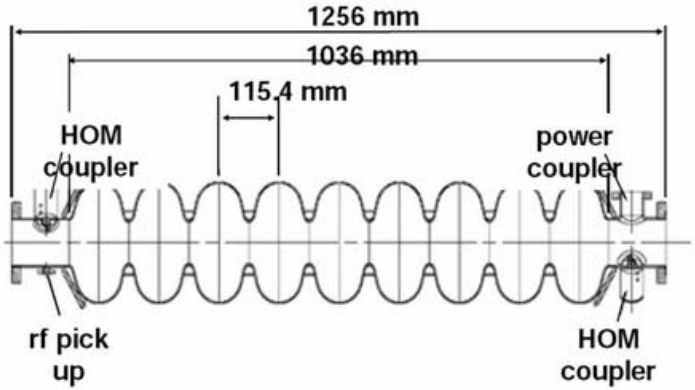
Accelerator technology - collaborative effort

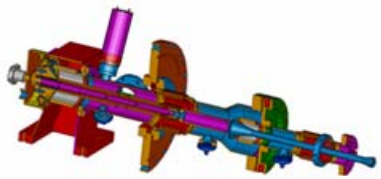
Industrialization in preparation

Integrated HOM absorber

Length quantized n·λ/2 (possibility of ERL)





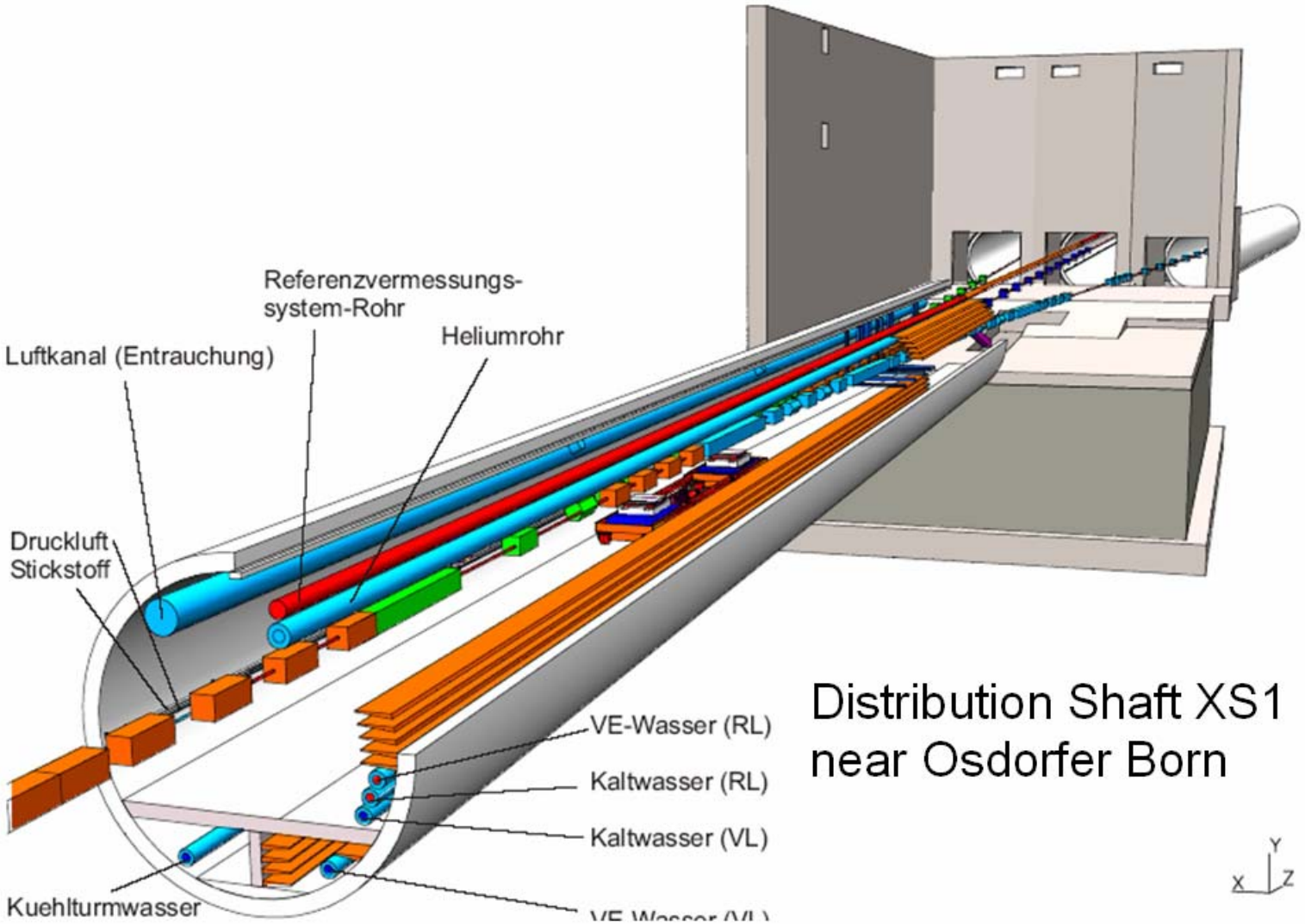


TTF3-type coupler

Tunnel Mock-up

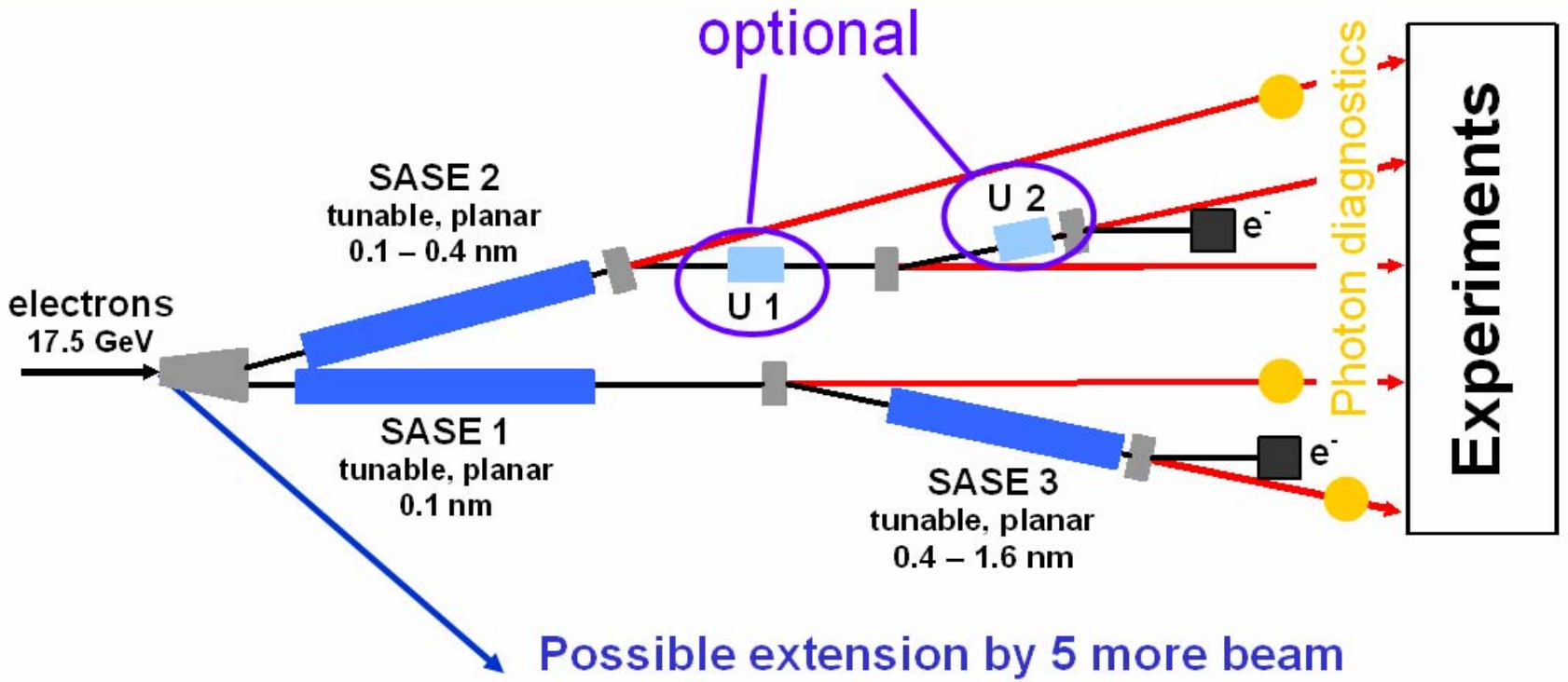
Test of installation procedures for acc. modules incl. RF

Osdorfer Born: Beam Distribution



Distribution Shaft XS1
near Osdorfer Born

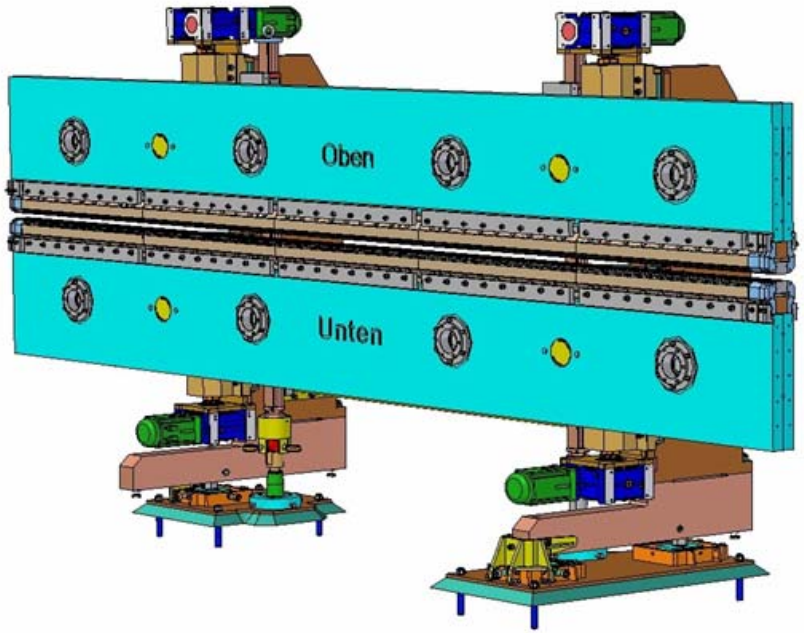
Startup Scenario: 3 FELs beamlines

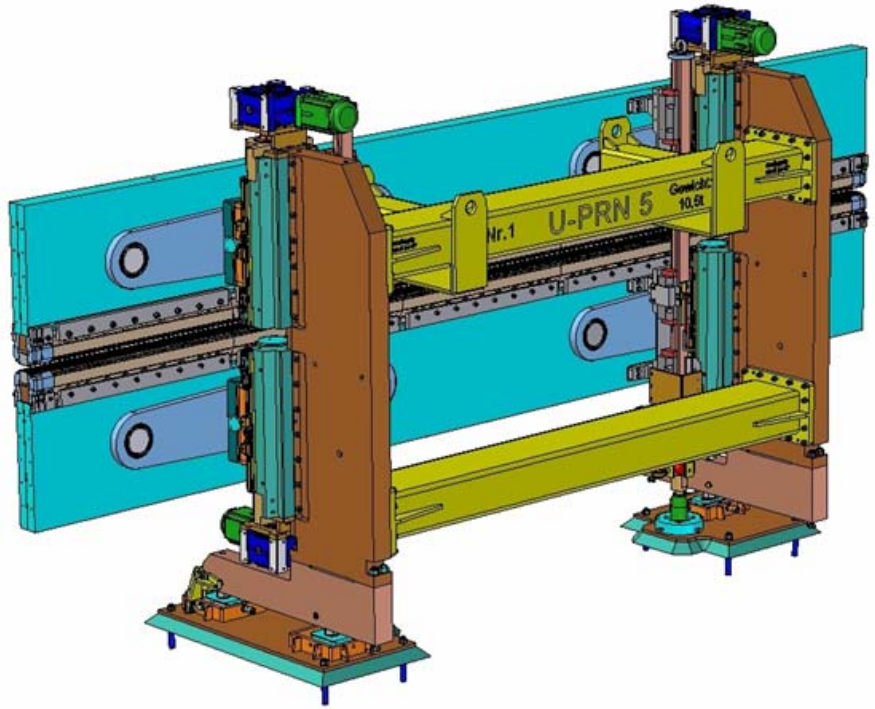


Possible extension by 5 more beam lines/10 experimental stations

	λ_R [Å]	λ_0 [mm]	Gap [mm]	B_0 [T]	K	β_0 [m]	L_{Sat} [m]	N_{Tot}	L_{Tot} [m]
SASE 1 *	1	35.6	10	1.0	3.3	32	133	33	201.3
SASE 2 *	1-4	48	19-10	0.63-1.37	2.8-6.1	46-15	174 - 72	37	225.7
SASE3P *	4-16	65	23-10	0.66-1.76	4.0-10.7	15	≈100	21	128.1
							Total	**91**	**555.1**

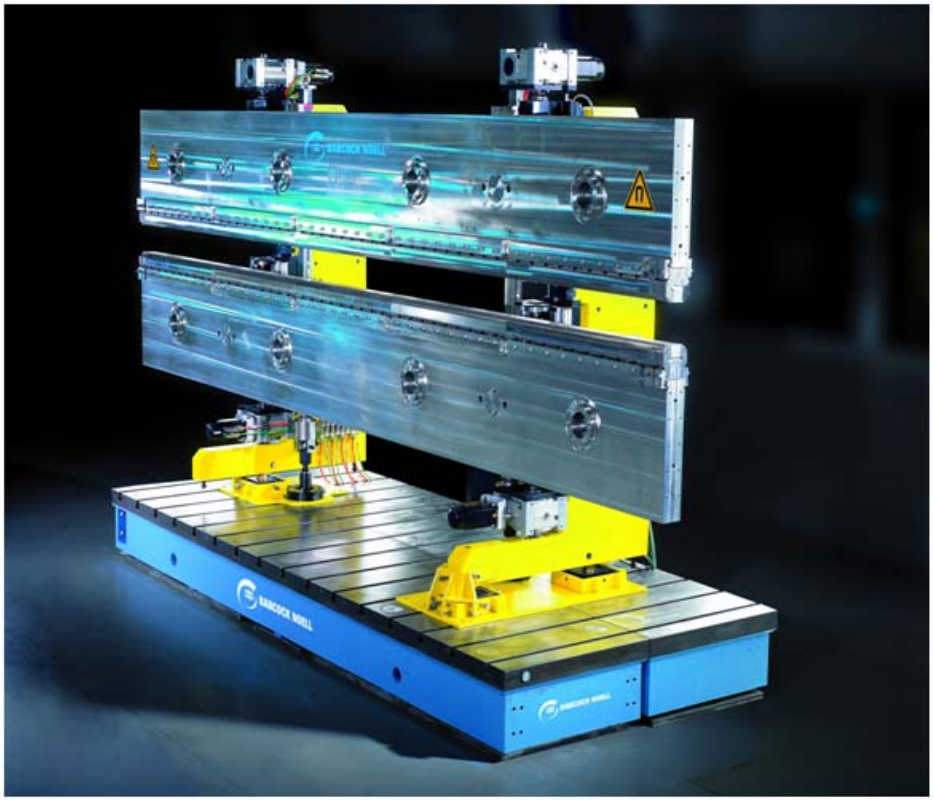
Precision Support Mechanics for XFEL





Special Attention: 1. Shear deformation vs. compressive deformation
5m XFEL Version 2. Material pairing; Bimetallic bending
3. Four point support of girders
4. Four Motors, electronic gears
5. Force free, separate girder guiding
6. Measurement of gap / Motor feedback

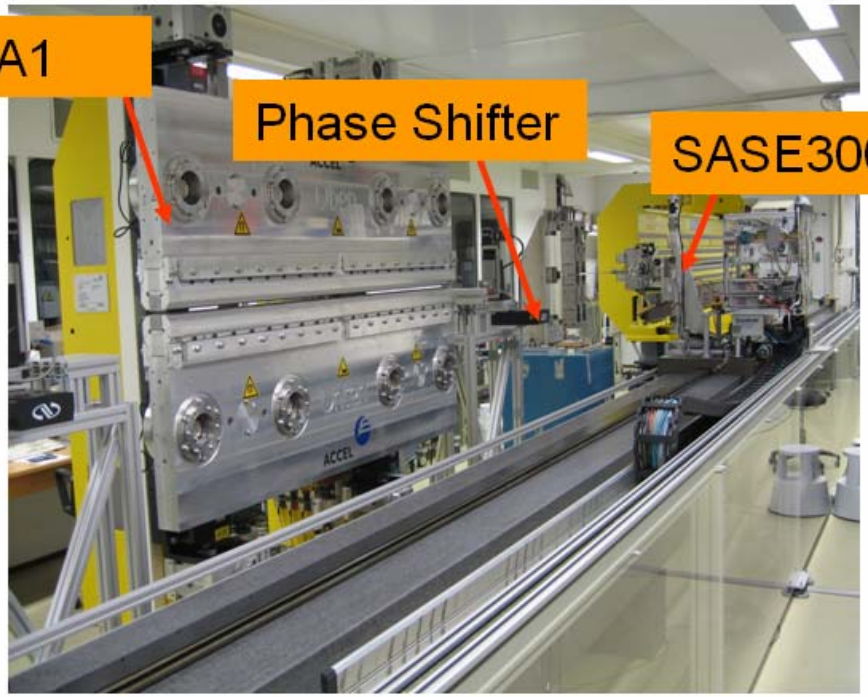
First Prototypes as of March 07



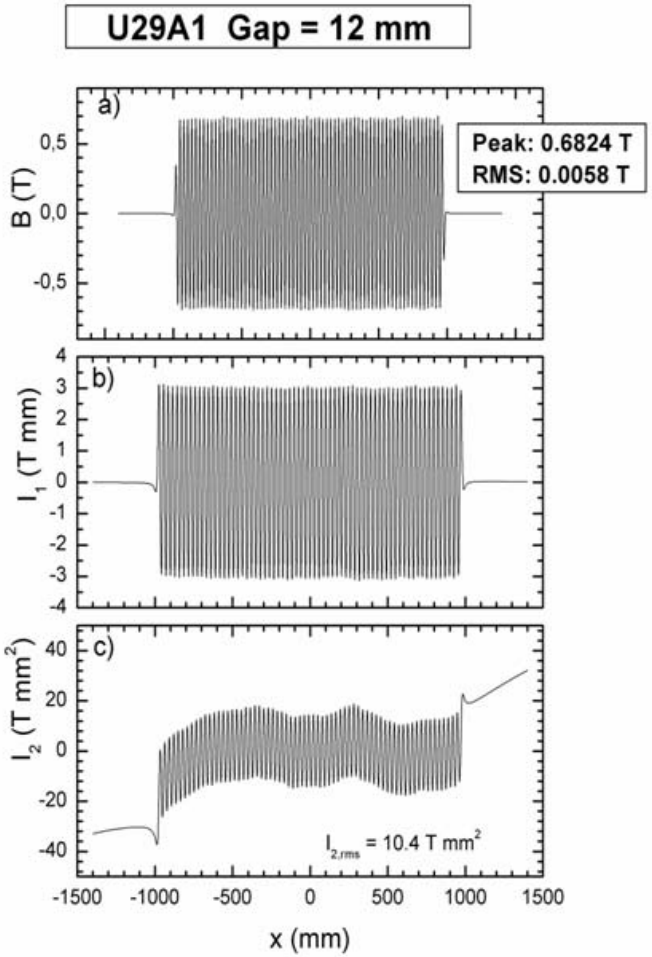
5 m

2 m

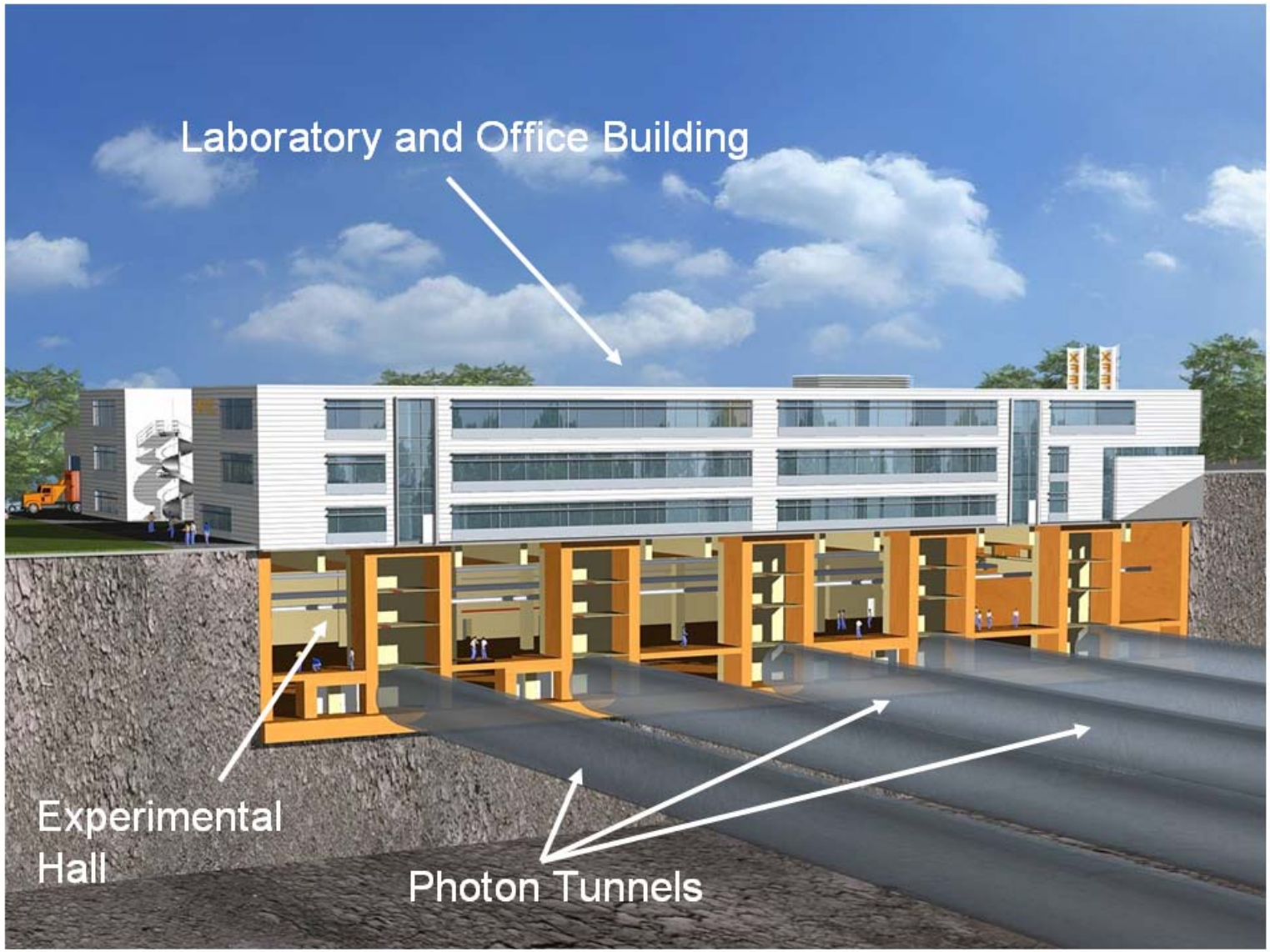
Magnetic Measurements Jan 08



12m Bench 22.1.08



Campus: Experiment Complex



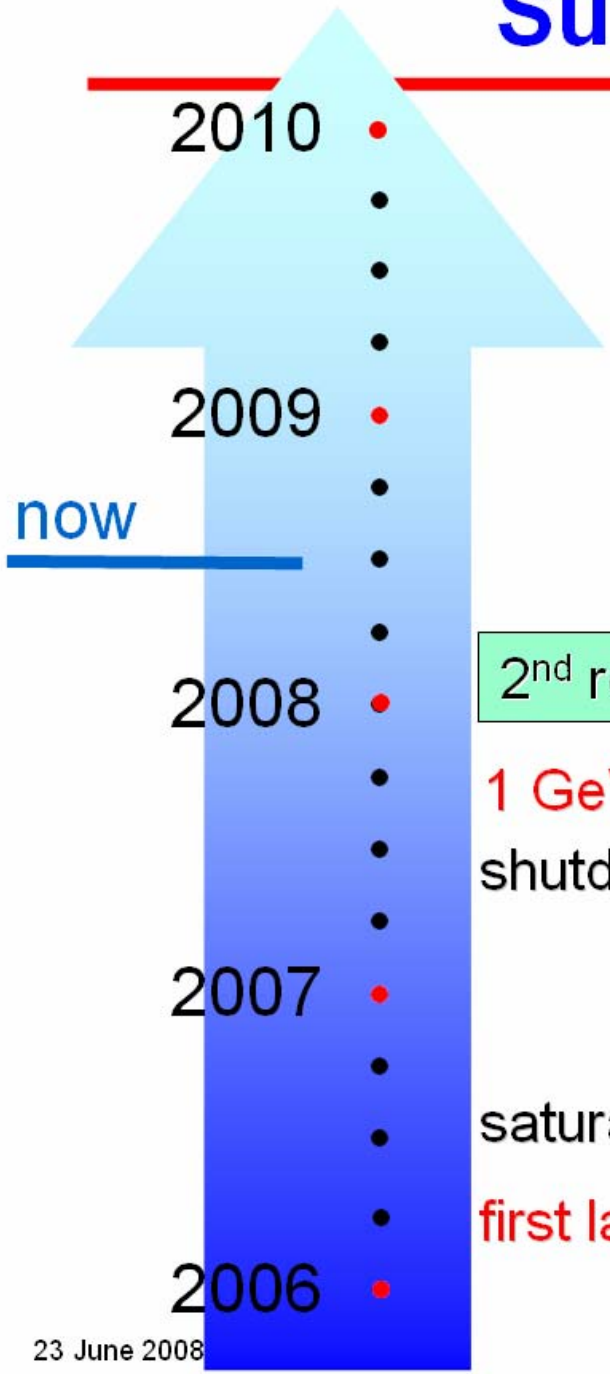
XFEL options

Baseline design relies on physics & technology proven and tested at FLASH (and elsewhere).

Numerous extension & options, e.g.

- further beamlines (circular, planar, SASE, spontaneous)
- attosecond pulses
- pulse energy stabilisation WEOAM02
- tapering
- Harmonic generation
- Timing to pump-probe laser THPC157

Summary and Outlook



- Installation 7th acc. Module → 1.2 GeV/4 nm
- operation with 3rd harmonic cavity
- long bunch train operation
- variable pulse and energy patterns
- beam stability (LLRF and beam based feedbacks)
- Seeding (sFLASH)
- Proposal for a 2nd FEL beamline

2nd round of user experiments starts

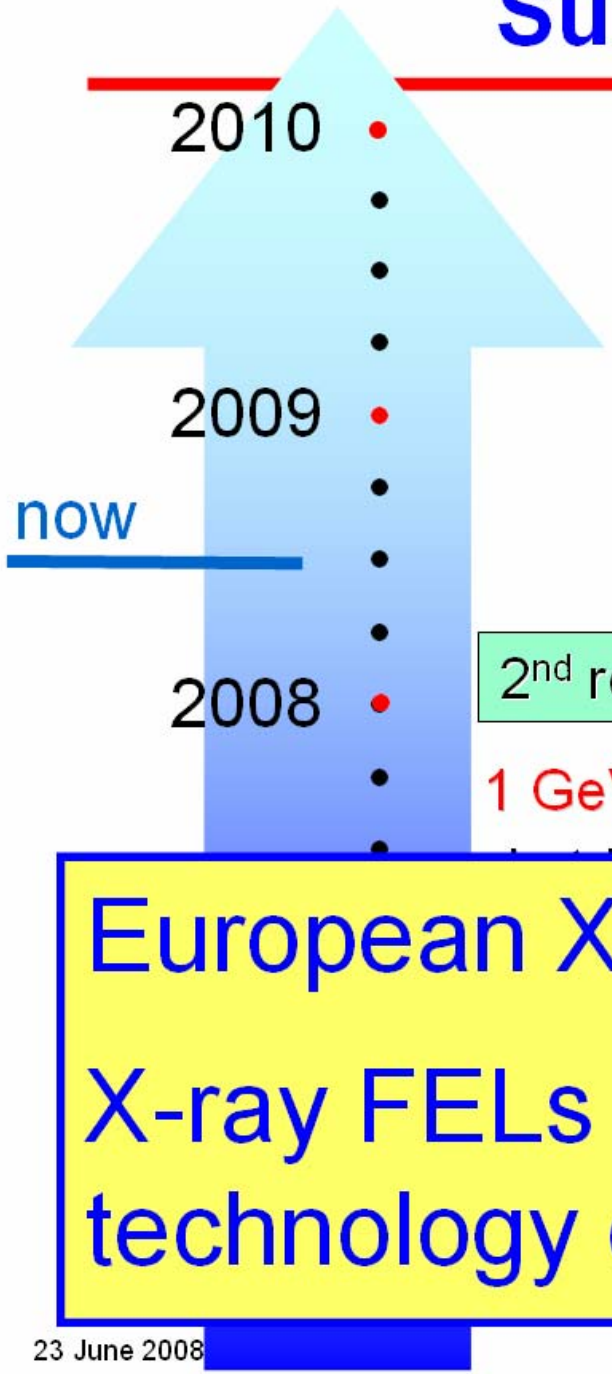
1 GeV beam energy: lasing at 6.5 nm

shutdown: installation 6th module

saturation at 13 nm achieved

first lasing at 13 nm

Summary and Outlook



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European XFEL project well under way.

X-ray FELs evolved into a major technology driver for accelerator R&D.