Results from FLASH

Free-electron LASer in Hamburg

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for the FLASH accelerator team

Contents

- FEL basics
- FLASH layout
- Electron beam -- The challenge of fs bunch length
- Photon beam
- The future
- Conclusion

FEL Basics

Radiation power of oscillating point-like charge Q: $P \propto Q^2 \cdot \gamma^2$

$Q = N_e \cdot e$
N_e = # electrons

Point-like bunch radiates coherently $P \propto N_e^2$!

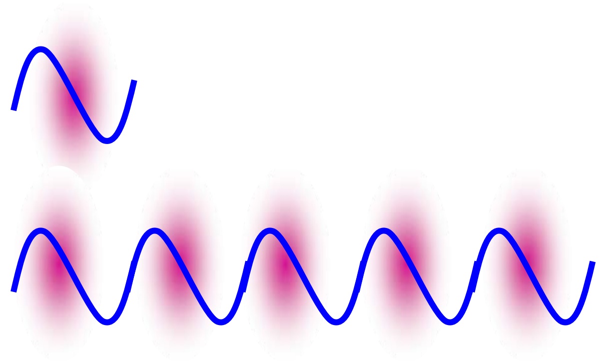
„Point“ means above all: bunch length < $\lambda_{radiation}$

Synchrotron radiation of an incoherent electron distribution: $P \propto N_e$

→ desired: bunch length < wavelength

OR (even better)

Density modulation at desired wavelength



→Potential gain in power: $N_e = 10^9 – 10^{10}$!!

FEL Basics

Idea:

Start with an electron bunch much longer than the desired wavelength
and find a mechanism that cuts the beam into equally spaced pieces automatically

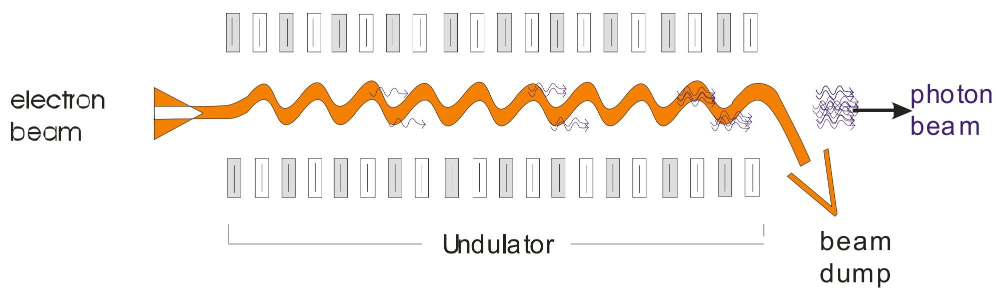
Free-Electron Laser

(Motz 1950, Phillips ~1960, Madey 1970)

Special version: starting from noise (no input needed)
Single pass saturation (no mirrors needed)

Self-Amplified Spontaneous Emission (SASE)

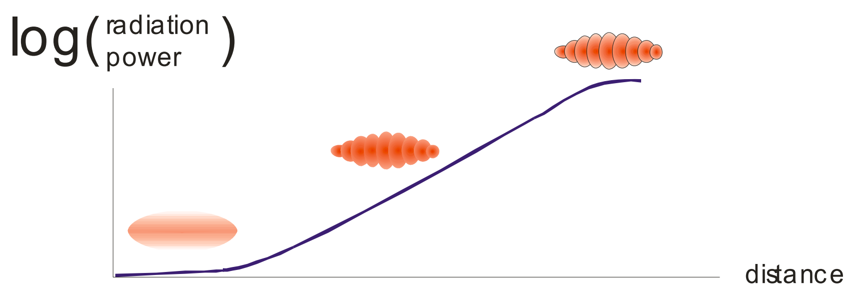
(Kondratenko, Saldin 1980)
(Bonifacio, Pellegrini 1984) ← Don't miss talk on Friday



Resonance wavelength:

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

Undulator parameter ≈ 1 (K)



EPAC 2006

SASE FEL challenges

FLASH

Electron beam parameters needed:

Gain Length (power e-folding): $$L_g = \frac{1}{\sqrt{3}}\left[\frac{2mc}{\mu_0 e}\frac{\gamma^3\sigma_r^2\lambda_u}{K^2\hat{I}}\right]^{1/3}$$

Beam size:

$\sigma_r \approx 50\ \mu m$ ⇔ high electron desity for maximum interaction with radiation field

Emittance $\varepsilon \leq \lambda/4\pi$

need special electron source & accelerate the beam before it explodes due to Coulomb forces

Peak current inside bunch:

$\hat{I} > 1$ kA

feasible only at ultrarelativistic energies, otherwise ruins emittance

⇒ bunch compression

Energy width:

Narrow resonance → $\sigma_E/E \leq\sim 10^{-3}$

⇔ Small distortion by wakefields etc.

Straight trajectory in undulator

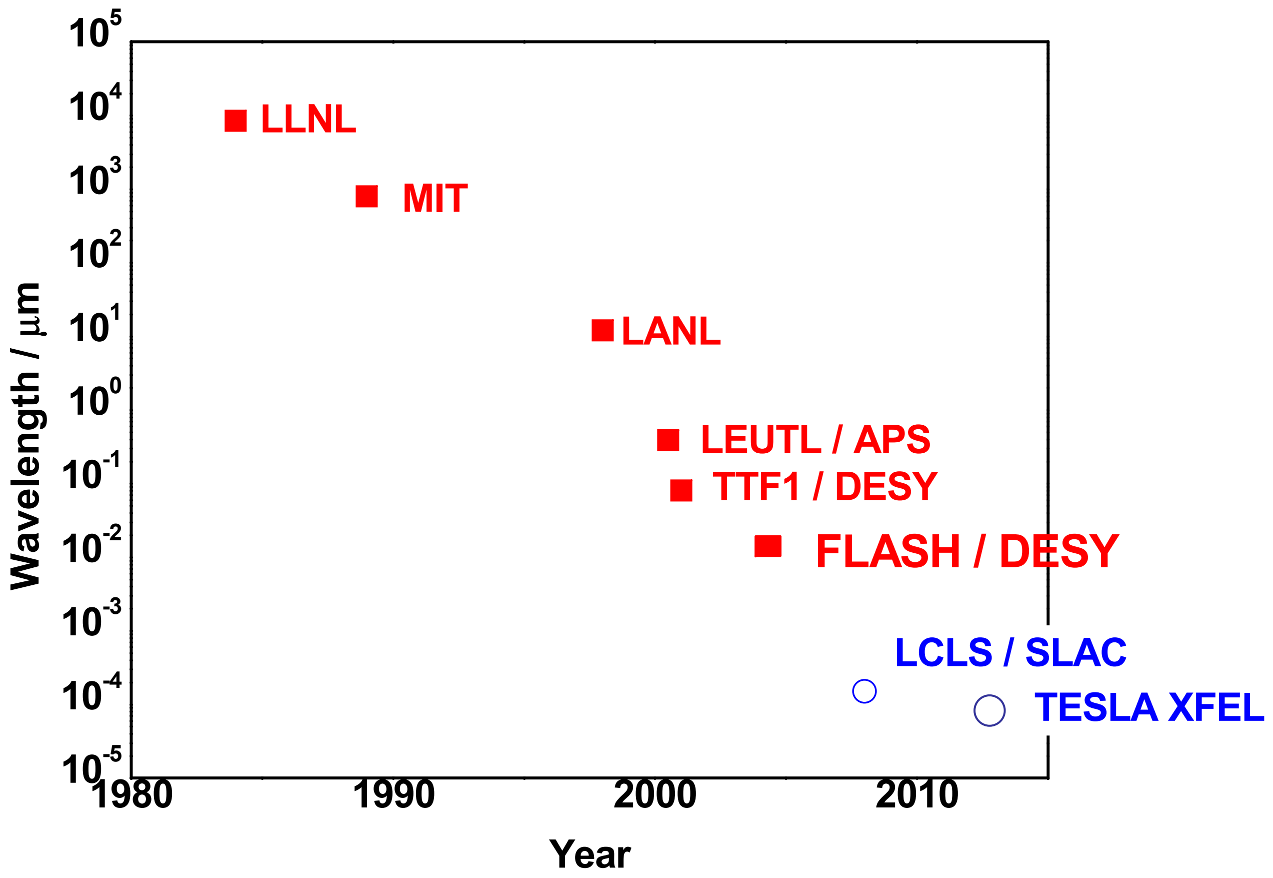
to guarantee overlap electron beam – photon beam:

typically < 10 μm over >10 m

Increasingly difficult for shorter wavelength:

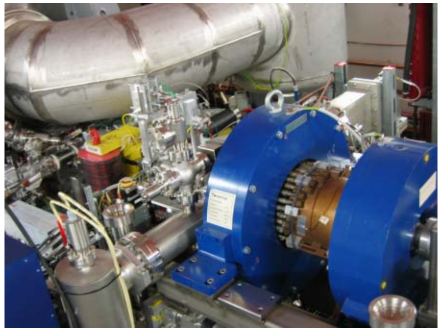
longer undulator, smaller emittance, larger peak current

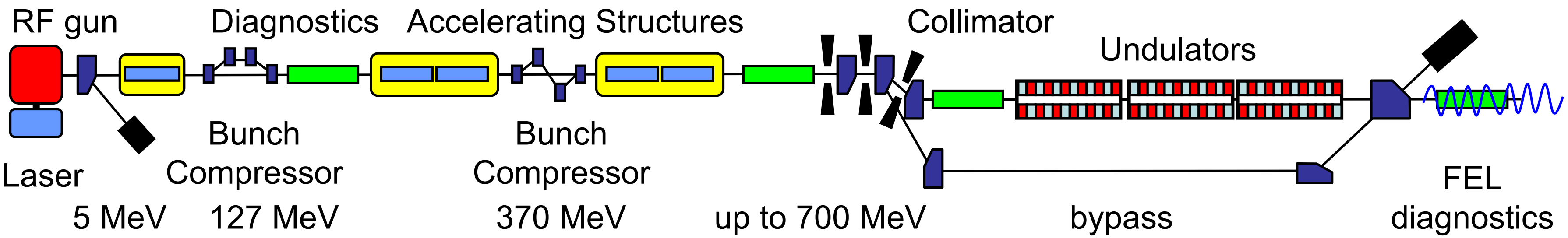
SASE FELs – State of the Art



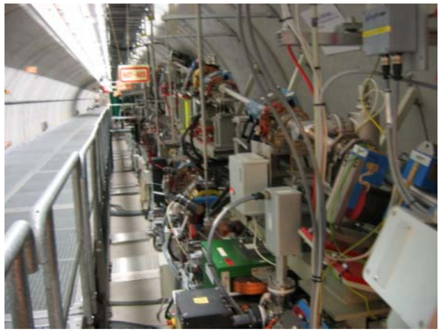
Wavelengths achieved at SASE FELs vs. year of 1st operation

FLASH Layout








250 m

FLASH Aerial View

TESLA Test Facility Injector + bunch compression

s.c. TESLA Modules + undulators

experimental hall

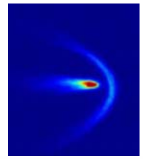
Beam time allocation:

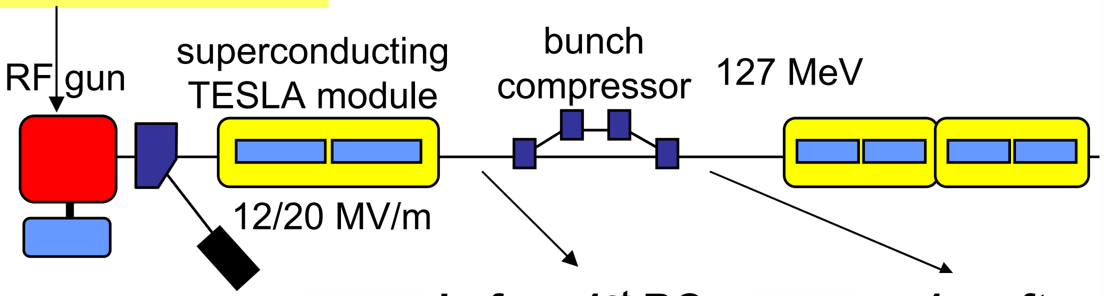
- FEL Users
- FEL studies to further develop the FEL
- accelerator studies, in particular on TESLA technology for XFEL and ILC

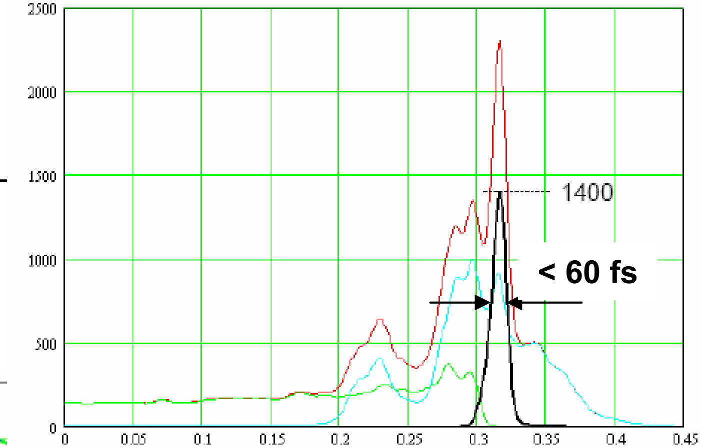
First lasing at 32 nm in January 05

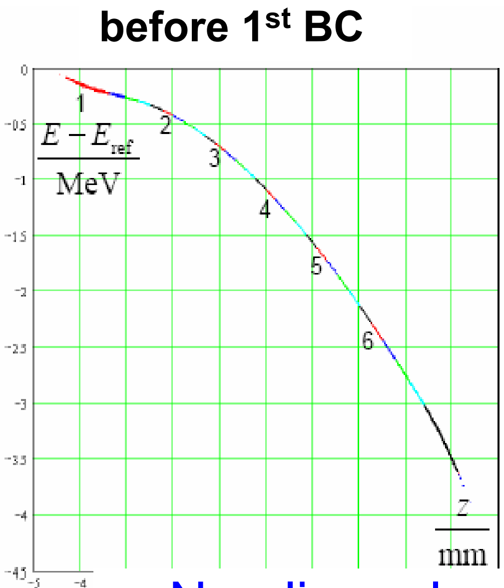
see S. Schreiber WEPLS052

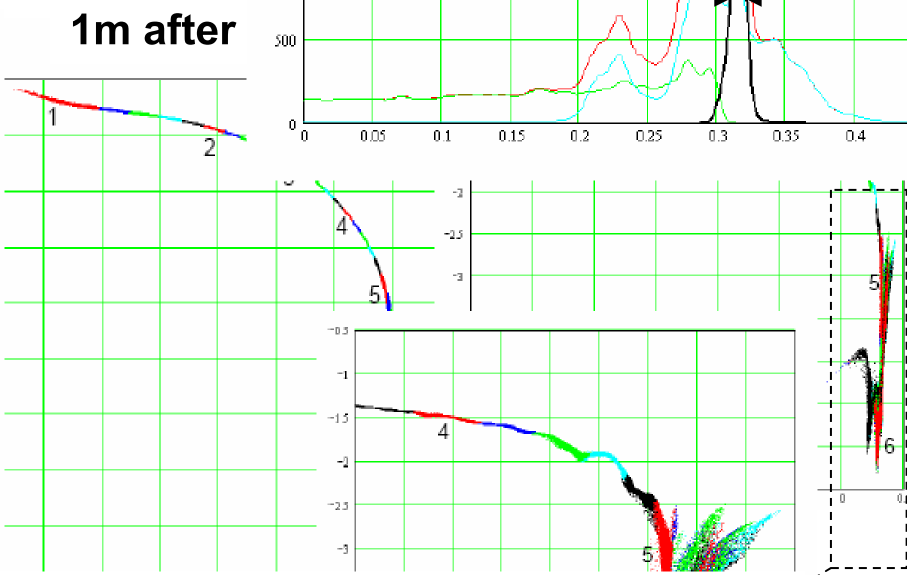
Longitudinal phase space injector



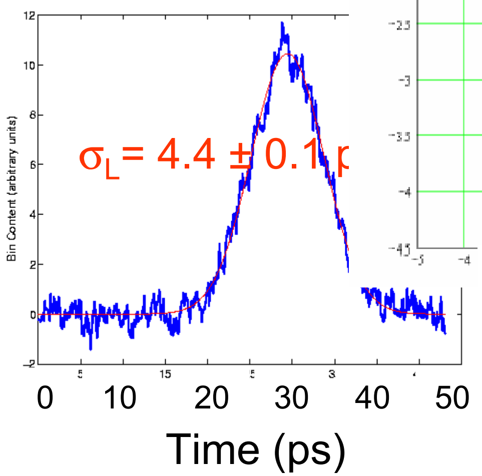








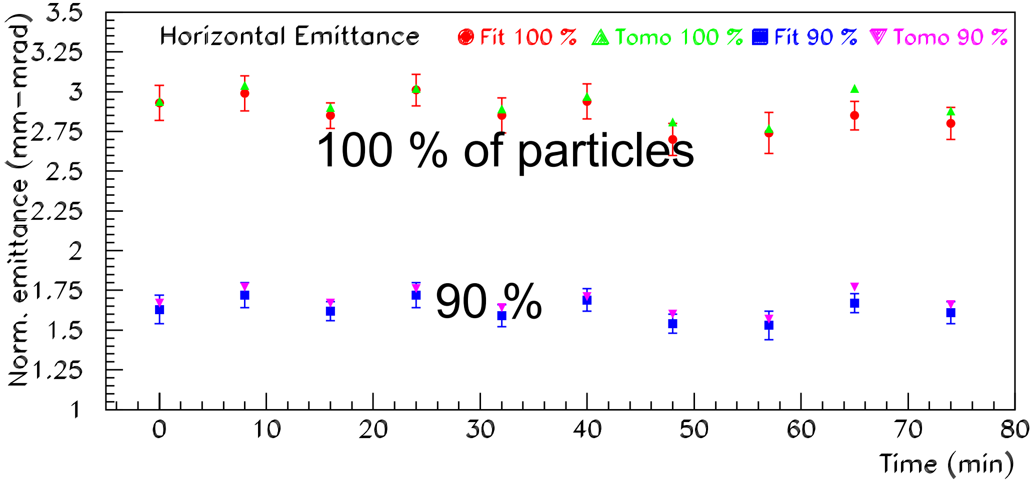
Long initial bunch to reduce space charge on cathode

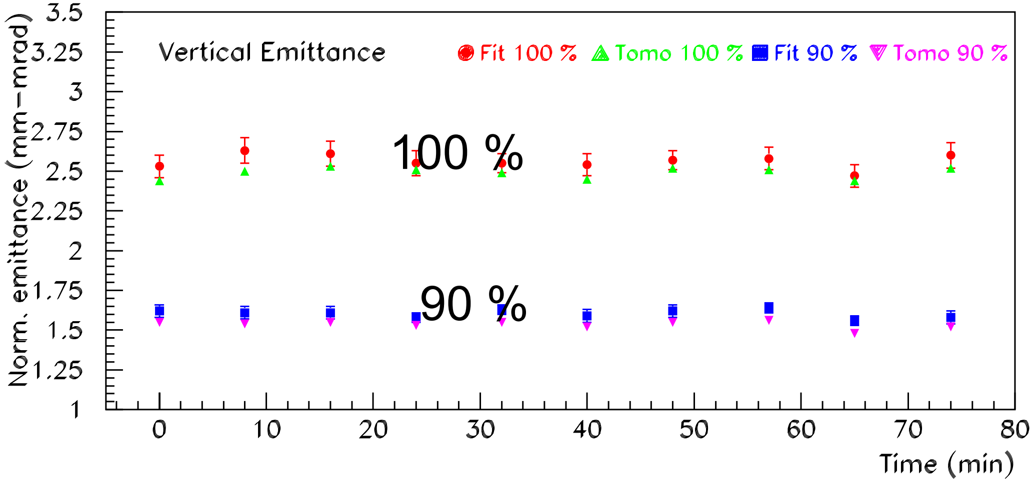


- Non-linear longitudinal compression
- Blowup of projected emittance
- Difficult access to relevant beam parameters
- Ultra-short photon pulses created ~ 30fs FWHM

Transverse Projected Emittance

Observation of beam size at 4 OTR screens simultaneously





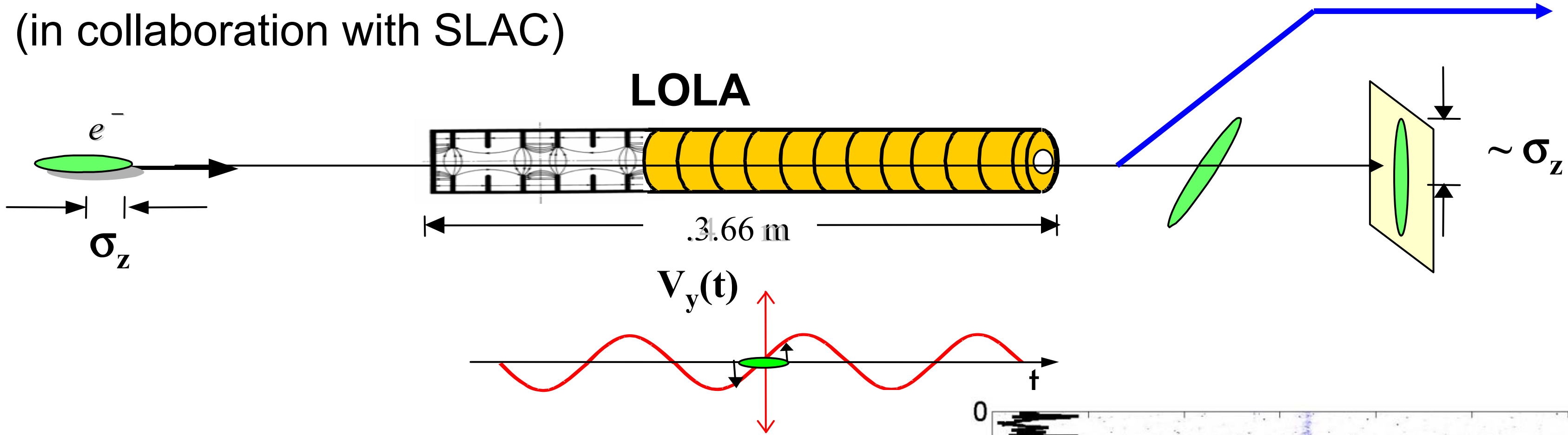
- Continuous measurement of the emittance during a period of ~1.5 hours (1 nC, 127 MeV); **no compression**
- In this example, the projected normalized 90% rms emittance is ε_n = 1.6 mm mrad
- Jitter 2 - 3 % (rms) → agrees with the statistical error

Fitting method, 100% emittance
Tomography, 100% emittance
Fitting method, 90% emittance
Tomography, 90% emittance

Resolving fs properties

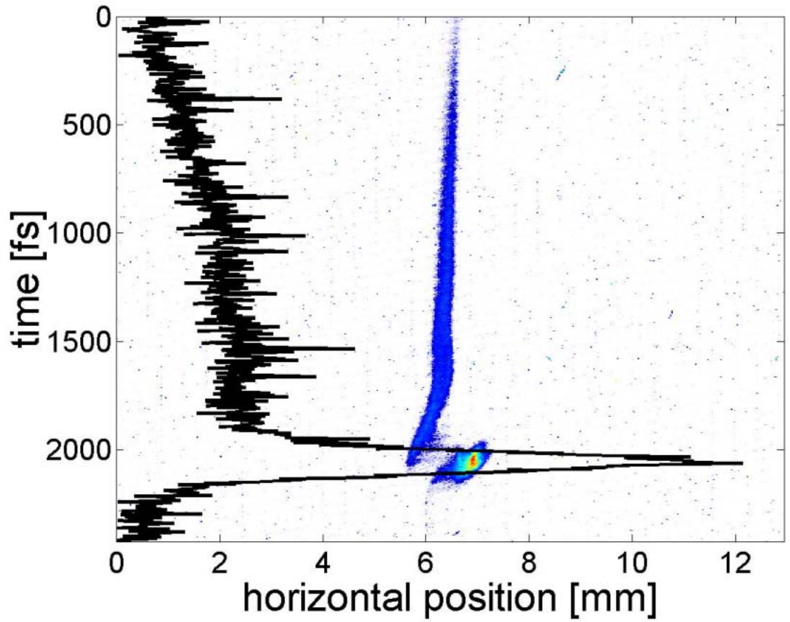
a) by time-dependent deflection in transverse mode cavity „LOLA“

(in collaboration with SLAC)



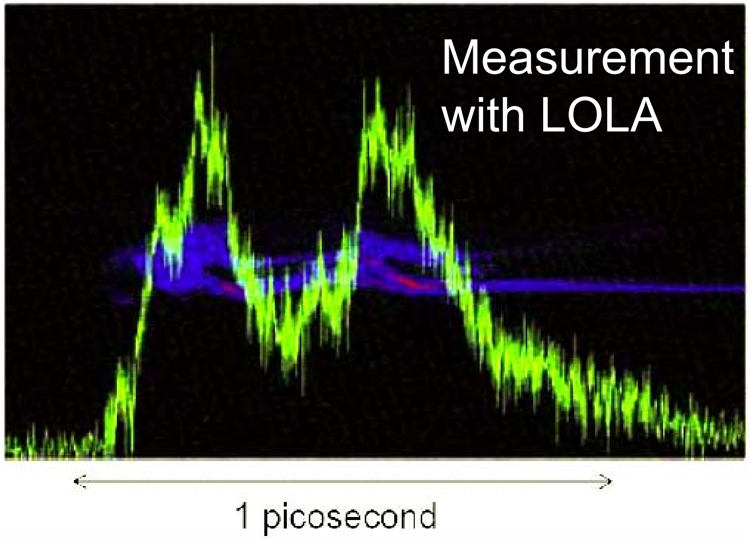
Measurements:

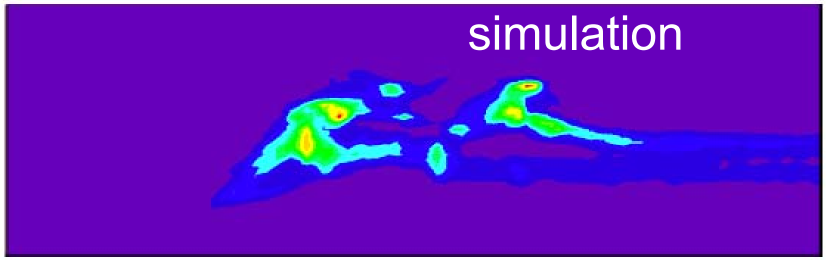
- Longitudinal density profile
- Horizontal slice emittance
- Horizontal slice centroid positions
- Dispersive section: energy-time correlation / slice energy spread



Resolving fs properties

- The observed double peak structure of the FLASH beam is understood by simulations: effect of coherent synchrotron radiation in bunch compressor.
- Qualitative agreement between simulated and measured profiles





LOLA long. resolution ~20 fs

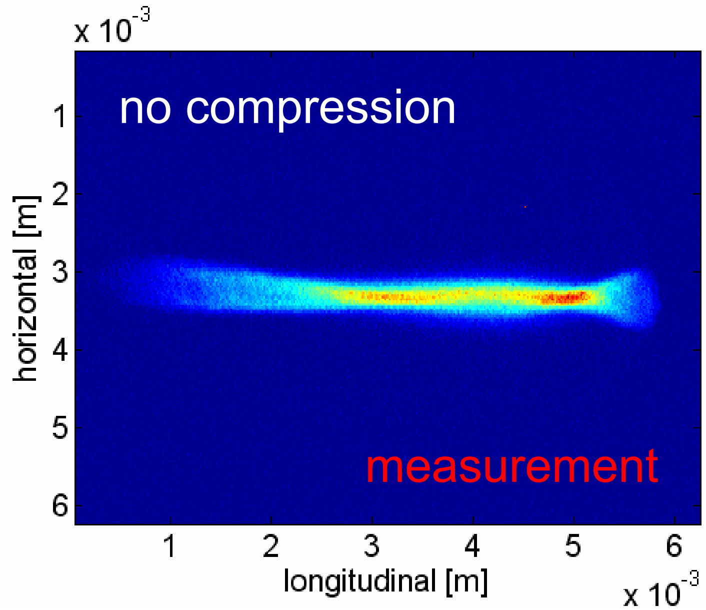
see M. Roehrs MOPCH13 MOPCH14

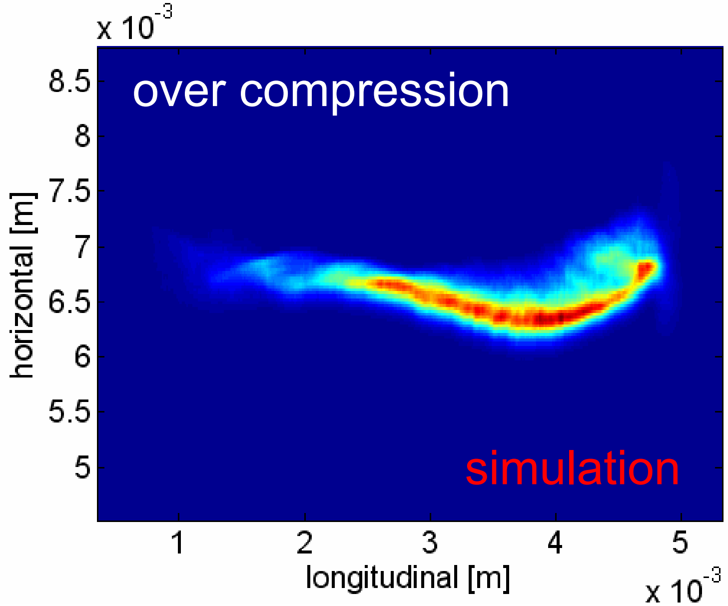
Can we distinguish between csr vs. space charge driven effects on beam dynamics?

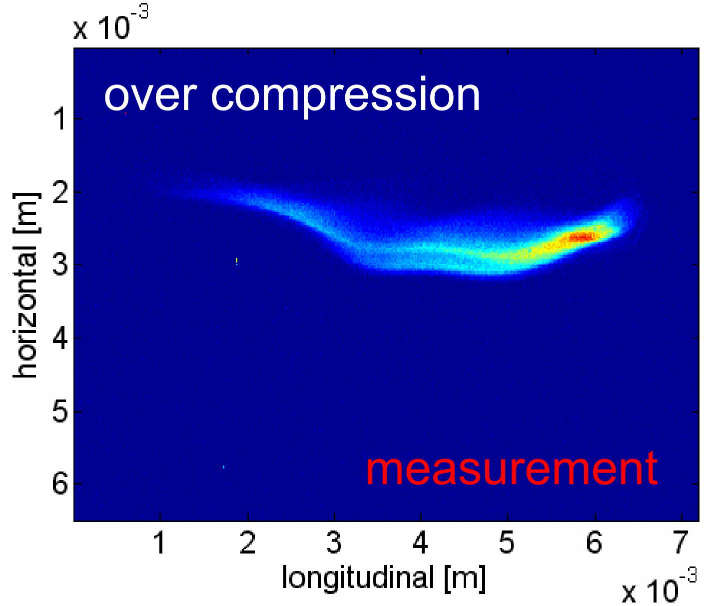
Coherent synchrotron radiation effects

The beam is over-compressed in a way that the bunch length inside the chicane is short but long afterwards.
→ CSR effects inside the chicane dominate while space charge forces are negligible.

CSR emission leads to centroid shifts due to energy loss and non-zero dispersion for off energy particles.







… further fs scale diagnostics

Spectroscopy of coherent THz radiation

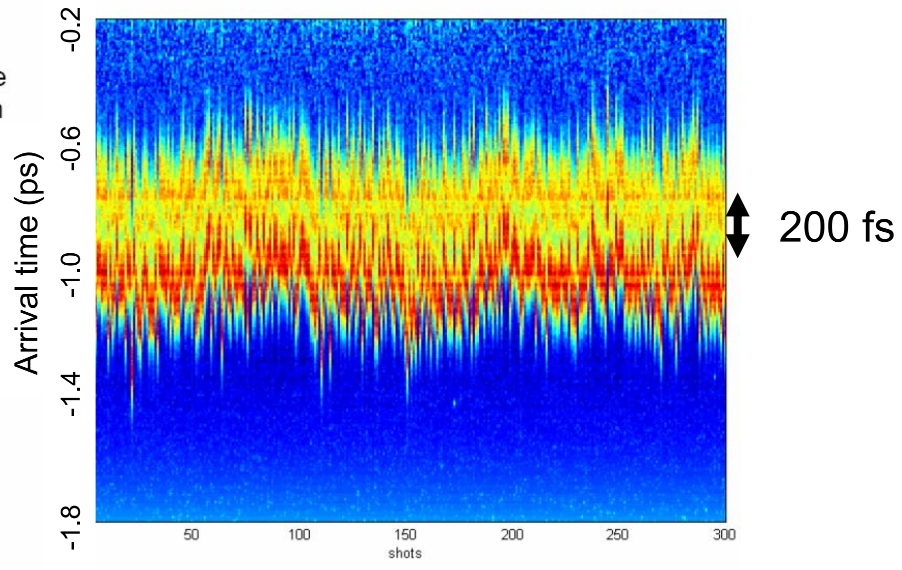
see O. Grimm
TUPCH 021
H. Delsim-Hashemi
TUPCH 016

Beam arrival time stability measured with electro-optic sampling:
rms timing fluctuations 200 fs

300 consecutive bunches on June 5th,

off crest,

1 nC



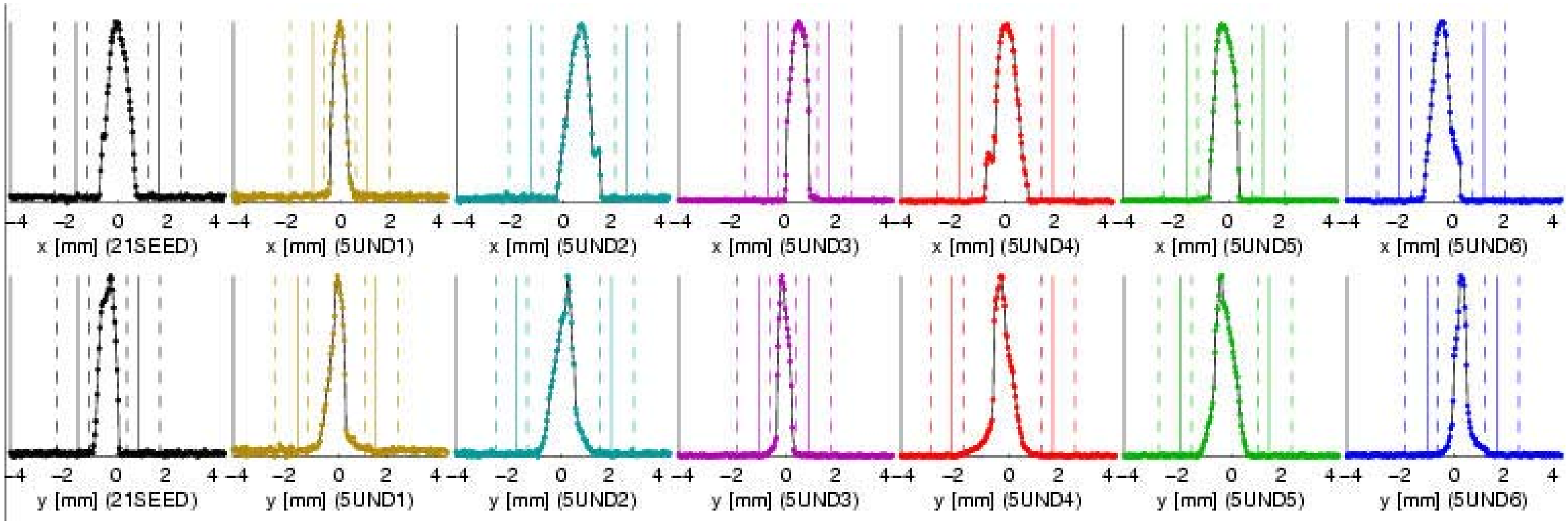
Bernd Steffen, 12.08.2005

see B. Steffen
TUPCH 026
A. Winter
TUPCH 028

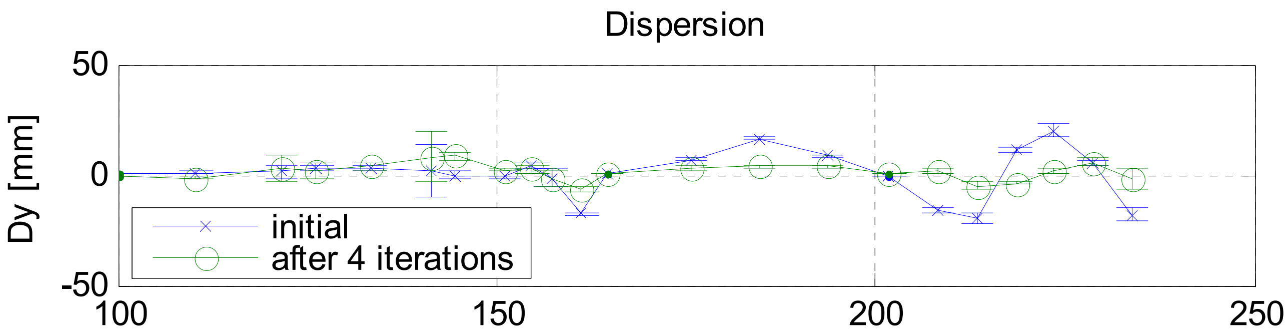
How to achieve
30 fs phase stability:
→Talk by F. Löhl
THOBFI 01

Measurements in the undulator

Wire scanners show rather big beam size:



Cure: Remove spurious dispersion (while keeping constant the orbit)



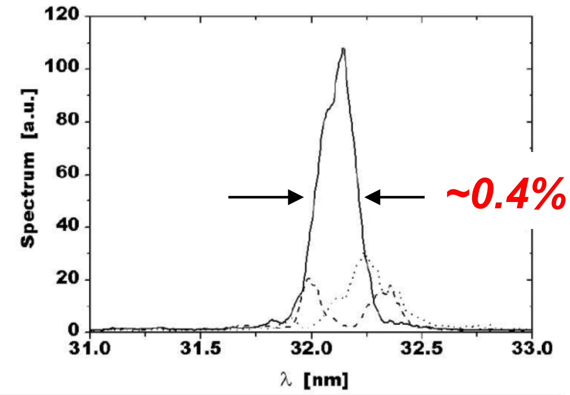
see E. Prat WEPCH 015

FEL radiation at 32 nm

June 2005

3 single pulse spectra:

measured



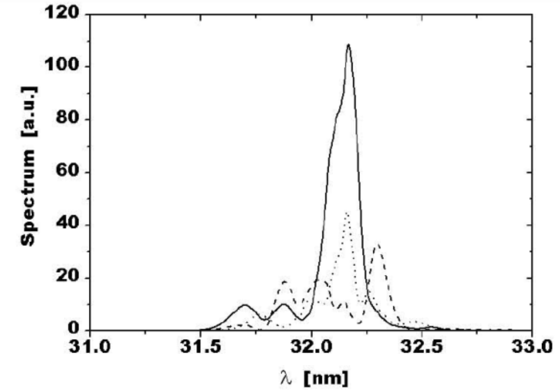
~0.4% → ~25 fs pulse duration

$E_{electron}$ = 440 MeV

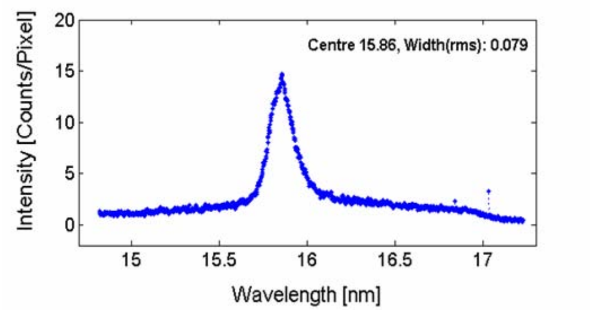
E_{pulse} = up to 130 μJ

→ P_{rad} = up to 4 GW

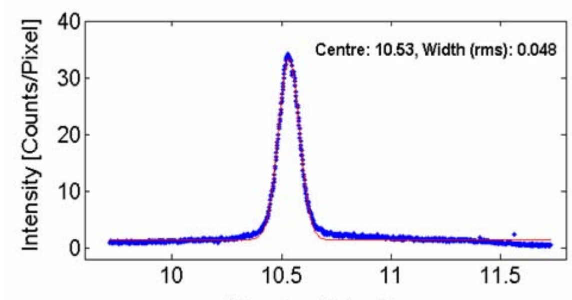
predicted



Harmonics:

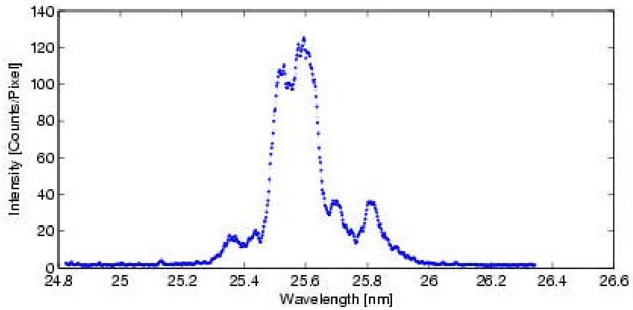


2nd harmonic @ 16 nm
4000 pulses

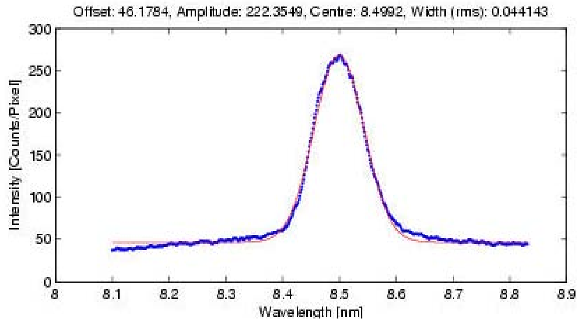


3rd harmonics @ 10.5 nm
4000 pulses

Lasing at 25 nm

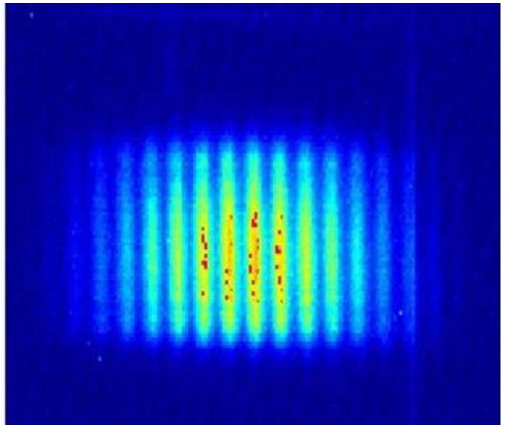


Single shot spectrum



3rd harmonic at 8.5 nm
(2500 shots)

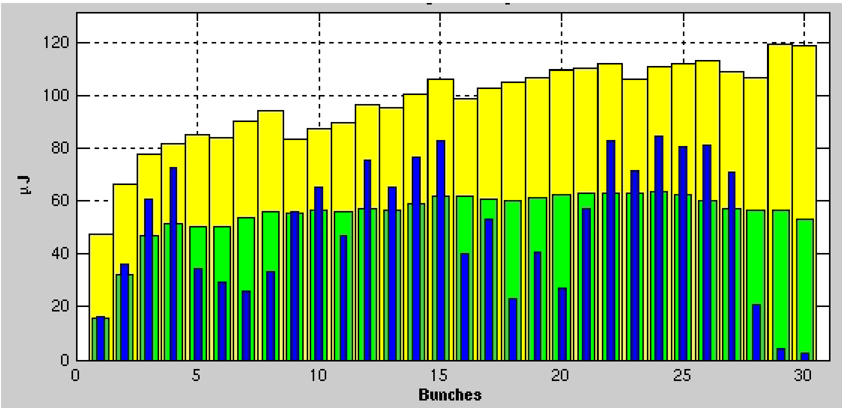
Double slit diffraction



0.15 mm slit distance

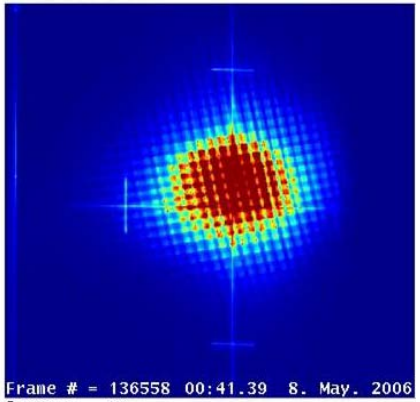
June 6, 2006:

Intensity in pulse train (1 μs separ.)

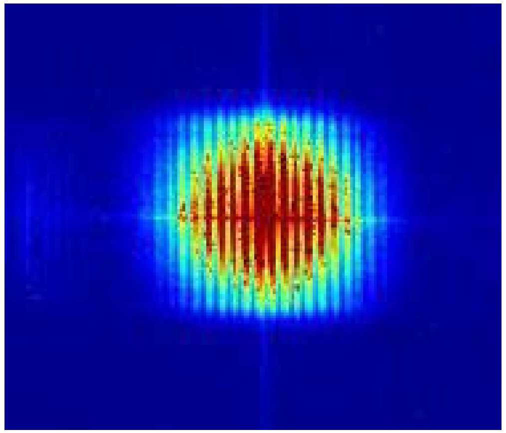


60 μJ avg. pulse energy

Photon beam profile



Single shot on Ce:YAG crystal

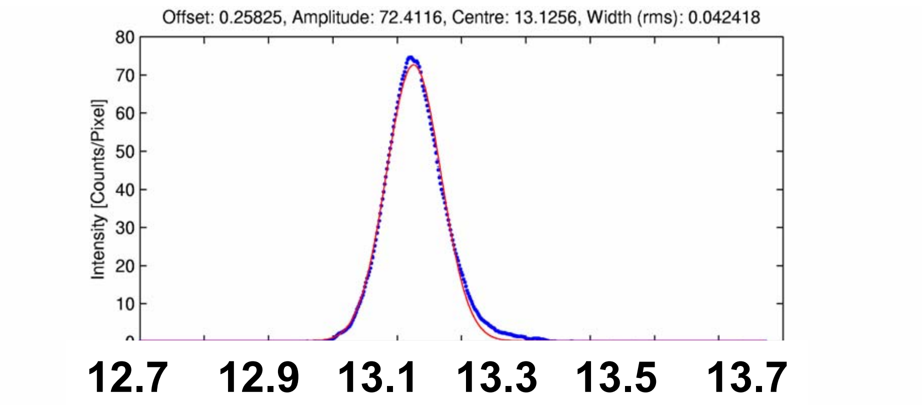


0.6 mm slit distance

EPAC 2006

Jörg Rossbach, Univ HH

Lasing at 13 nm



Wavelength [nm]
(1000 shots)

$E_{electron}$ = 690 MeV

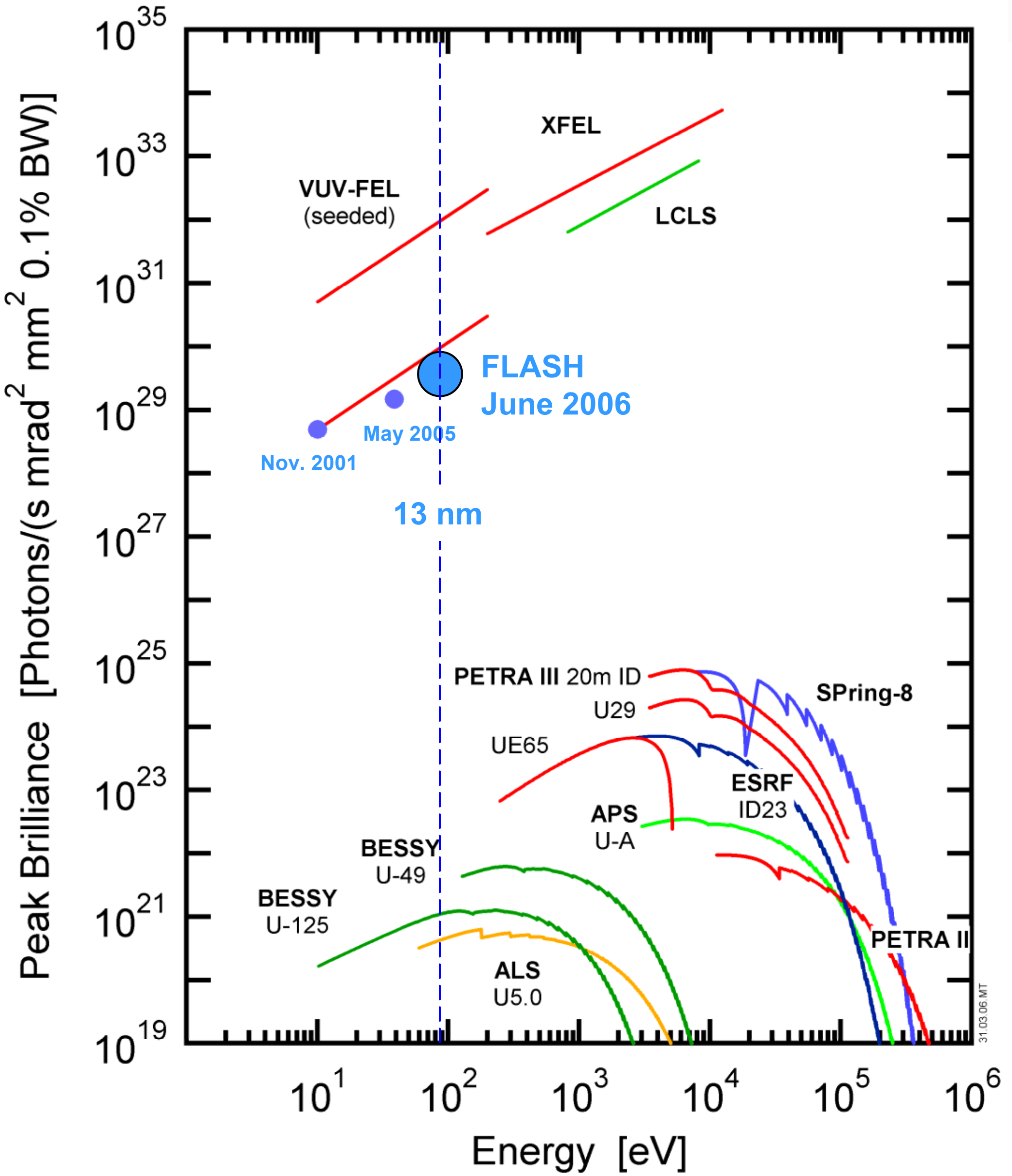
E_{pulse} = up to 30 μJ

→ P_{rad} = up to 1 GW

Summary radiation properties:

Radiation pulse duration (FWHM)	20 -100 fs
Radiation peak power	1 - 4 GW
Spectrum width	~ 1 %
Transverse coherence	almost perfect

Peak brilliance exceeds any source at this wavelength by many orders of magnitude.

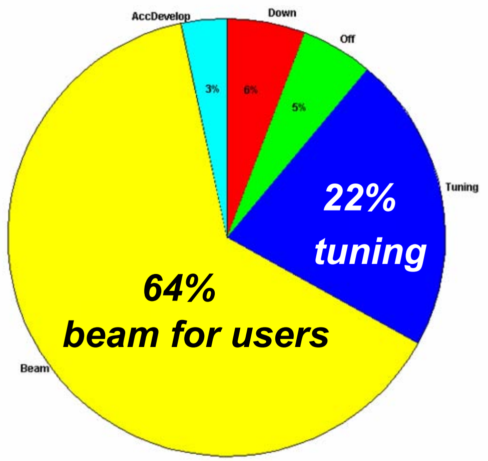


Jörg Rossbach, Univ HH

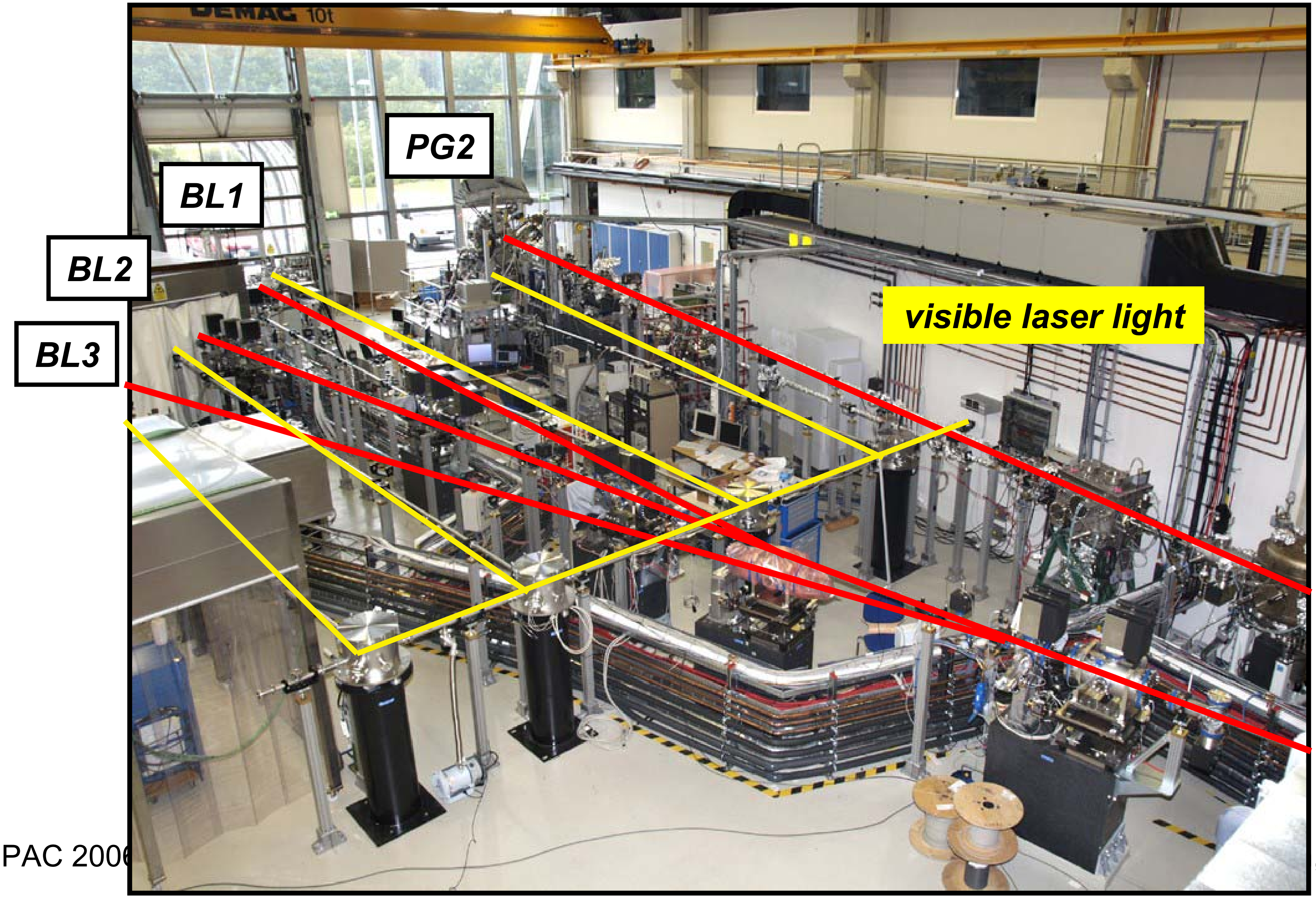
Summary of user experiments

- **16 projects had beam**
- **Most experiments are very complex and include many components ➔ collaborations, large teams**
- **First reports are very promising:**
  - **commissioning of most experiments was quite successful**
  - **most experiments have taken first useful data demonstrating that their concepts work; data are currently evaluated**

Beam statistics 14.Jan.-10.Feb.2006

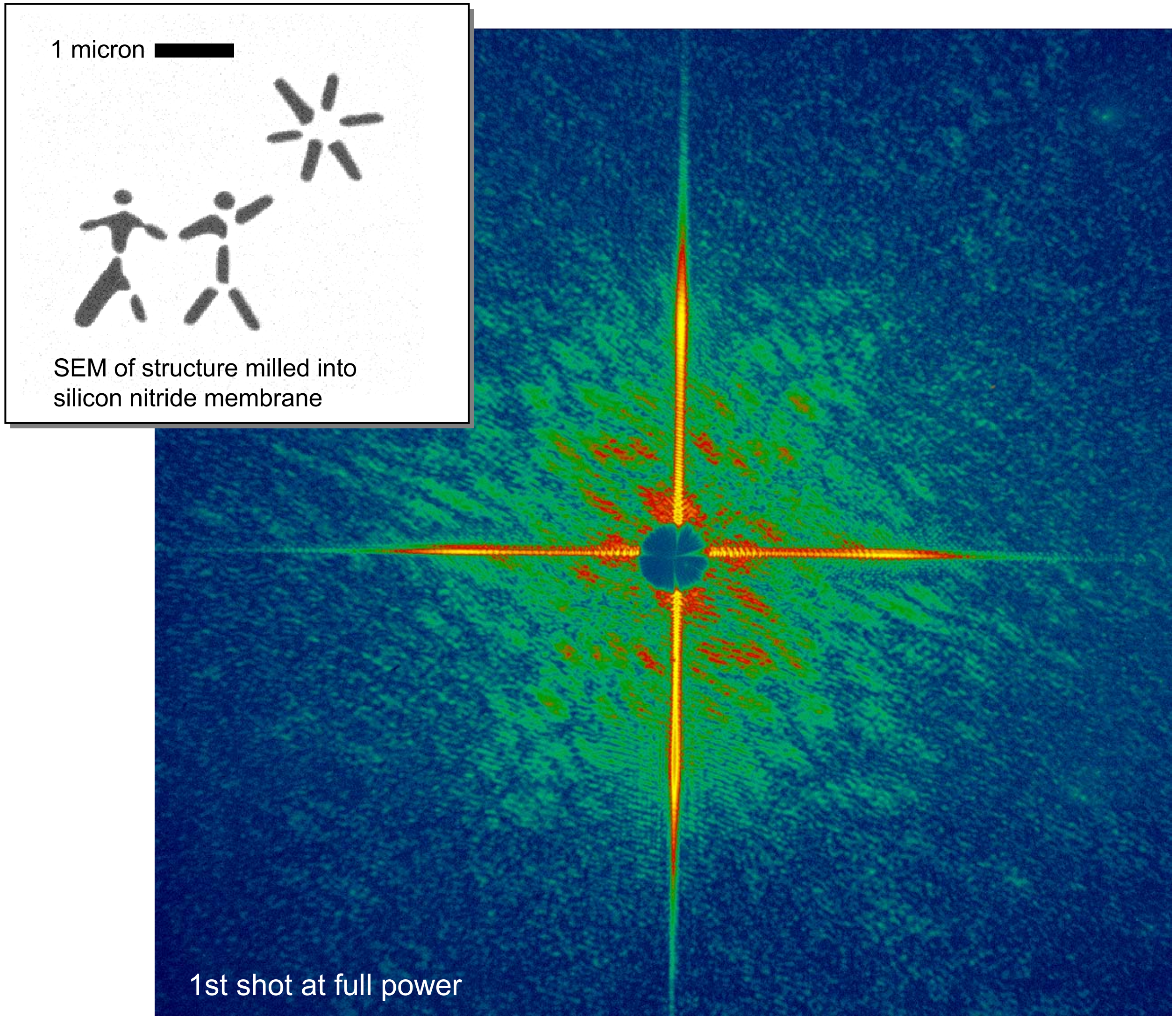


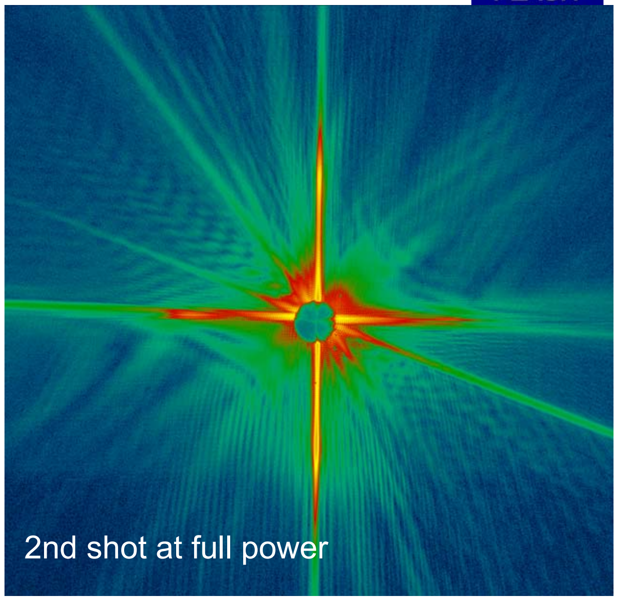
FLASH: the VUV-FEL User Facility at DESY

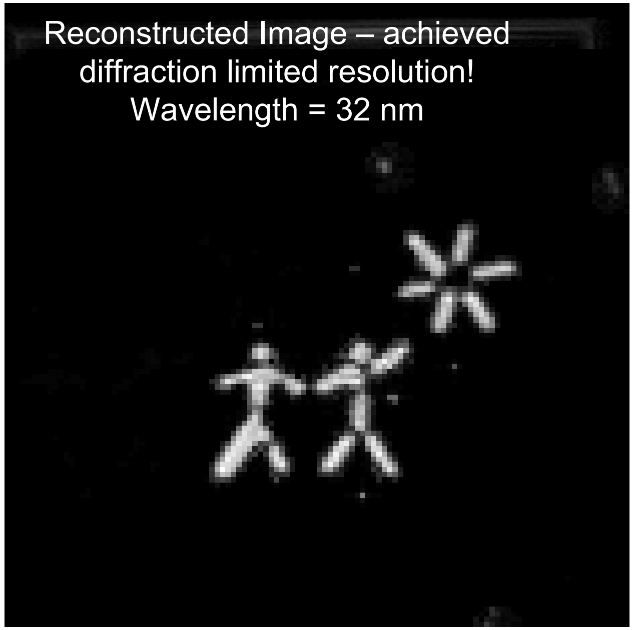


First demonstration of coherent diffraction imaging with a soft-X-ray FEL
(Hajdu, Chapman)

FLASH



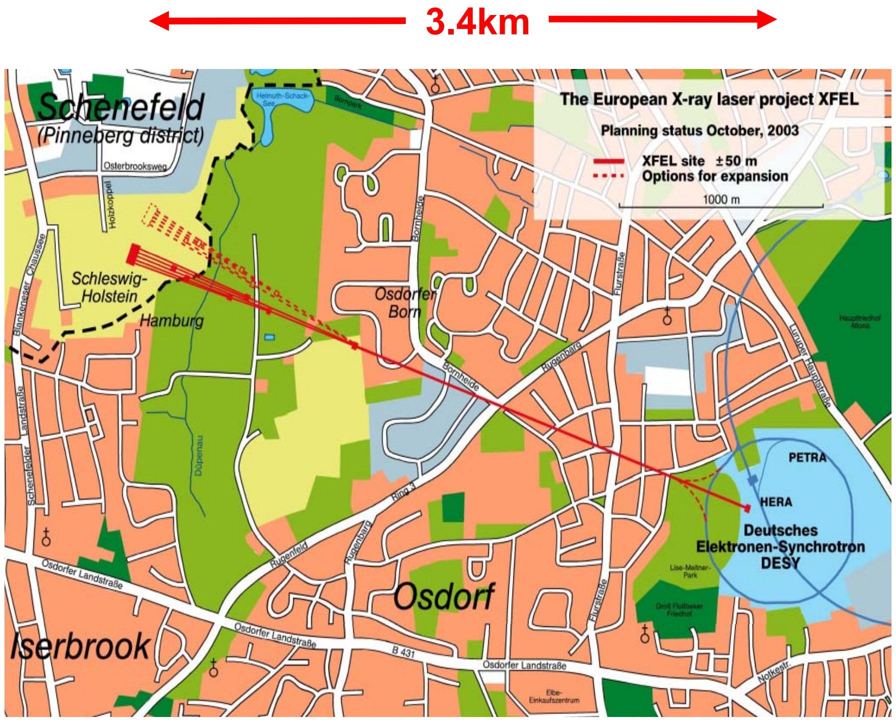


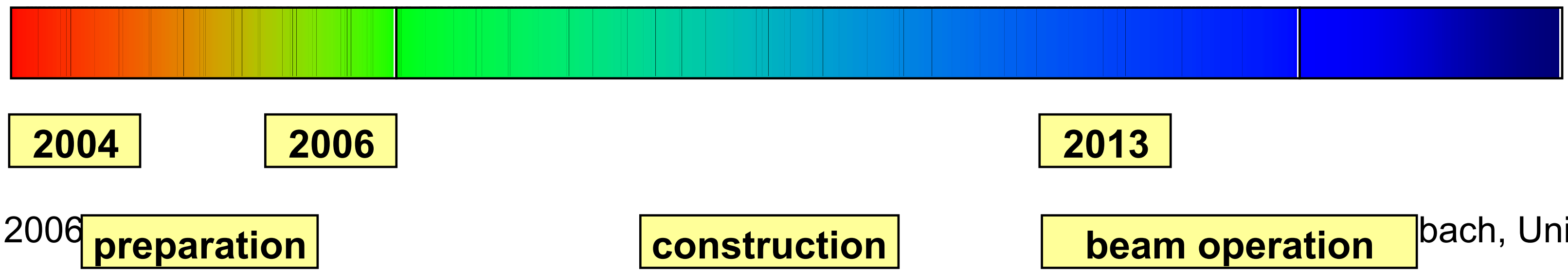


The European XFEL

- Proposal October 2002:

  X-ray FEL user facility with 20 GeV superconducting linear accelerator in TESLA technology
- Approval by German government Feb. 2003 as a European Project
- German commitment for 50% of the funding plus another expected 10% by the states Hamburg and Schleswig-Holstein, 40% from European partners
- Estimated total project cost **970 M€**





The European XFEL

The European XFEL

Future plans for FLASH

- Reach design wavelength 6 nm (need 1 more TESLA module)
- Install 3rd Harmonic Cavity → remove curvature in long. phase space
- Long pulse trains (7200 bunches)
- Fast wavelength tuning (now ~ 1 day)
- Install self-seeding

Conclusion

- fs scale accelerator physics & technology
- SASE FEL principle demonstrated down to 13 nm
- Brilliance 100 Mio above storage ring sources
- Full agreement with theory
- FLASH running for users
- Paves the way towards Ångstrøm FELs

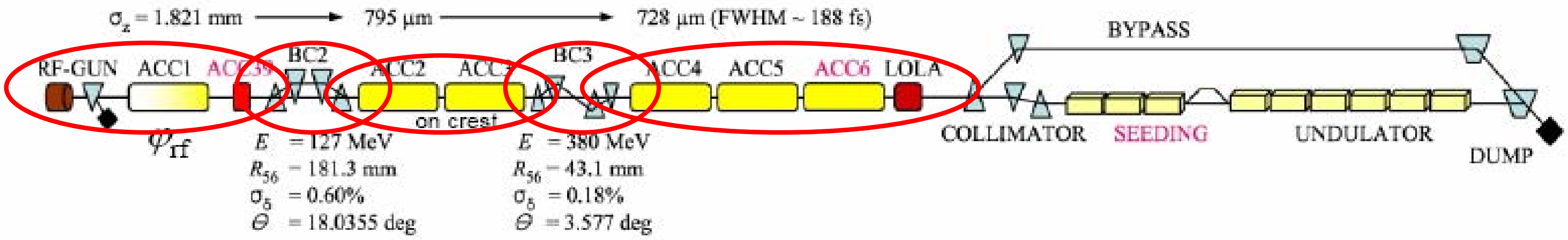
  --- in particular the European XFEL

The FLASH team (part of...)

Simulation Methods

- RF-gun – ***ASTRA***
- Apply wake field kicks of ACC1 & Optics matching
- BC2 - ***CSRTrack*** (projected method)
- BC2 to BC3 - ***ASTRA***
- Apply wake field kicks of ACC2&3
- BC3 – ***CSRTrack*** (projected method)
- BC3 to LOLA - ***ASTRA***

Start-to-end tracking for different phases in ACC1



The VUV-FEL team

- The VUV-FEL is a project of the TESLA Technology Collaboration

† W. Achermann,V. Ayvazyan, N. Baboi, J. Bähr, V. Balandin, B. Beutner, A. Brandt, I. Bohnet, A. Bolzmann, R. Brinkmann, O.I. Brovko, J.P. Carneiro, S. Casalbuoni, M. Castellano, P. Castro, L. Catani, E. Chiadroni, S. Choroba, A. Cianchi, H. Delsim-Hashemi, G. Di Pirro, M. Dohlus, S. Düsterer, H.T. Edwards, B. Faatz, A.A. Fateev, J. Feldhaus, K. Flöttmann, J. Frisch, L. Fröhlich, T. Garvey, U. Gensch, N. Golubeva, H.-J. Grabosch, B. Grigoryan, O. Grimm, U. Hahn, J.H. Han, M. v. Hartrott, K. Honkavaara, M. Hüning, R. Ischebeck, E. Jaeschke, M. Jablonka, R. Kammering, V. Katalev, B. Keitel, S. Khodyachyhh, Y. Kim, V. Kocharyan, M. Körfer, M. Kollewe, D. Kostin, D. Krämer, M. Krassilnikov, G. Kube, L. Lilje, T. Limberg, D. Lipka, S. Liu, F. Löhl, M. Luong, C. Magne, J. Menzel, P. Michelato, V. Miltchev, M. Minty, W.D. Möller, L. Monaco, W. Müller, M. Nagl, O. Napoly, P. Nicolosi, D. Nölle, T. Nuñez, A. Oppelt, C. Pagani, R. Paparella, B. Petersen, B. Petrosyan, J. Pflüger, P. Piot, E. Plönjes, L. Poletto, D. Proch, D. Pugachov, K. Rehlich, D. Richter, S. Riemann, J. Rönsch, M. Ross, J. Rossbach, M. Sachwitz, E.L. Saldin, W. Sandner, H. Schlarb, B. Schmidt, M. Schmitz, P. Schmüser, J.R. Schneider, E.A. Schneidmiller, S. Schnepp, H.-J. Schreiber, S. Schreiber, D. Sertore, S. Setzer, A.V. Shabunov, S. Simrock, E. Sombrowski, L. Staykov, B. Steffen, F. Stephan, F. Stulle, K.P. Sytchev, H. Thom, K. Tiedtke, M. Tischer, R. Treusch, D. Trines, I. Tsakov, A. Vardanyan, R. Wanzenberg, T. Weiland, H. Weise, M. Wendt, I. Will, A. Winter, K. Wittenburg, M.V. Yurkov, I. Zagorodnov, P. Zambolin, K. Zapfe