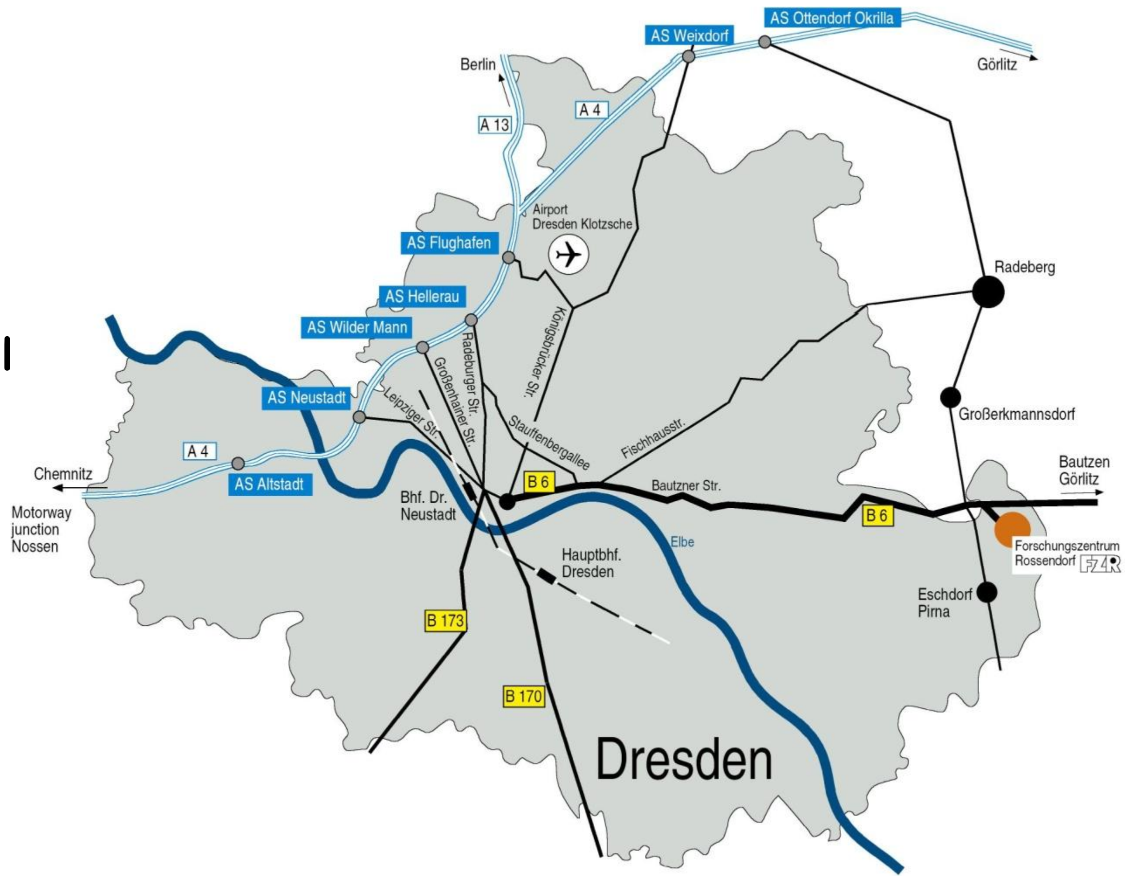
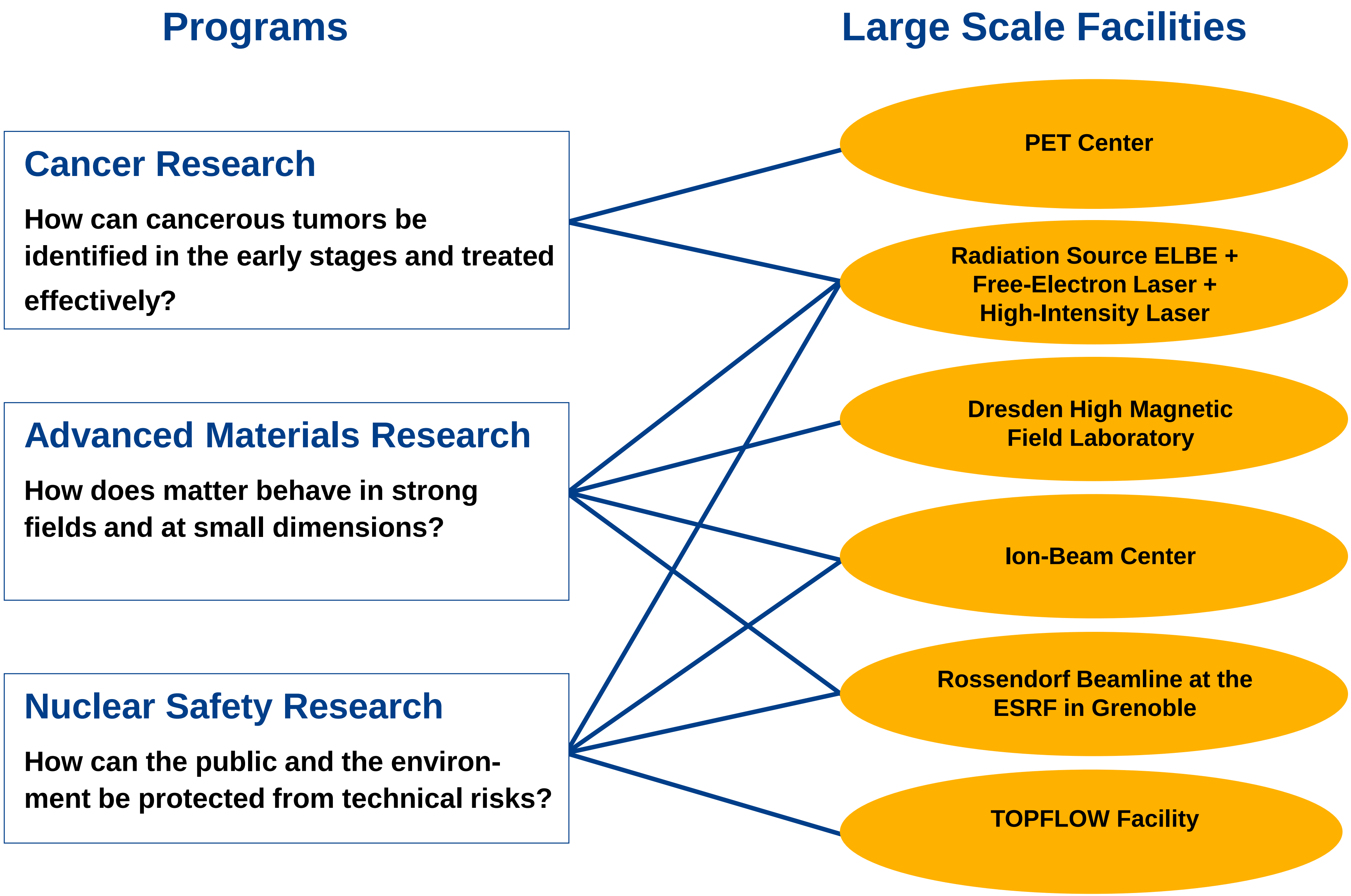
The THz-FEL FELBE at the Radiation Source ELBE

- Introduction
- ELBE concept
- FELs & optical use
- Application
- ELBE extension
- Summary




Programs
Large Scale Facilities
Cancer Research
How can cancerous tumors be identified in the early stages and treated effectively?
Advanced Materials Research
How does matter behave in strong fields and at small dimensions?
Nuclear Safety Research
How can the public and the environment be protected from technical risks?
PET Center
Radiation Source ELBE + Free-Electron Laser + High-Intensity Laser
Dresden High Magnetic Field Laboratory
Ion-Beam Center
Rossendorf Beamline at the ESRF in Grenoble
TOPFLOW Facility

FELBE = FEL @ ELBE

ELBE: Electron Linac with high Brilliance and low Emittance

(Elbe is, besides, the river flowing through Dresden and to Hamburg)

The electron beam is used to generate various kinds of secondary radiation

FELBE = FEL @ ELBE

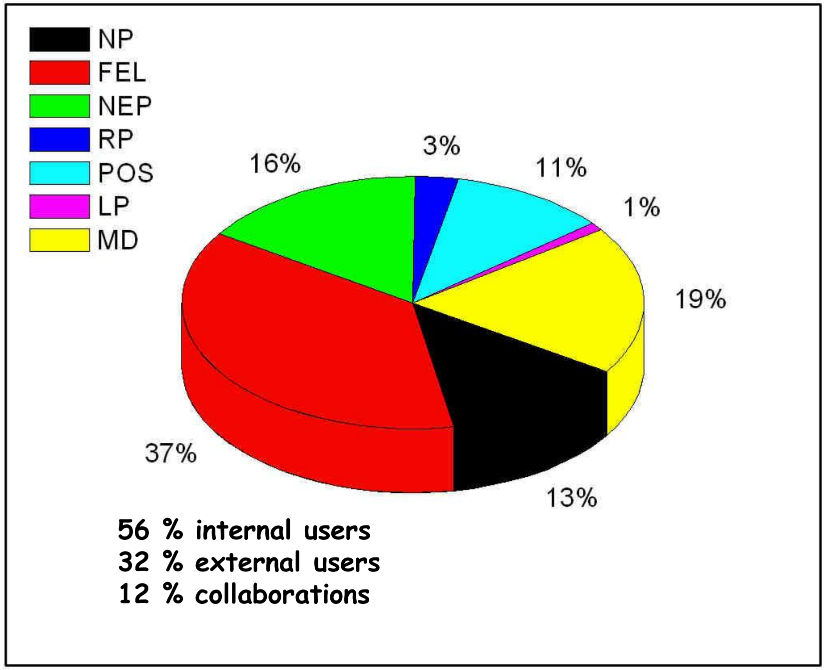
ELBE: Electron Linac with high Brilliance and low Emittance

Starting in summer 2005 user beam time is offered to external users in the frame of the EC funded "Integrating Activity on Synchrotron and Free Electron Laser Science" [www.fzd.de/felbe].

Twice a year users are invited to submit proposals for experiments at ELBE. For the period January - June 2011 the deadline will be November 15, 2010. Proposals are evaluated by the scientific advisory committee of ELBE.

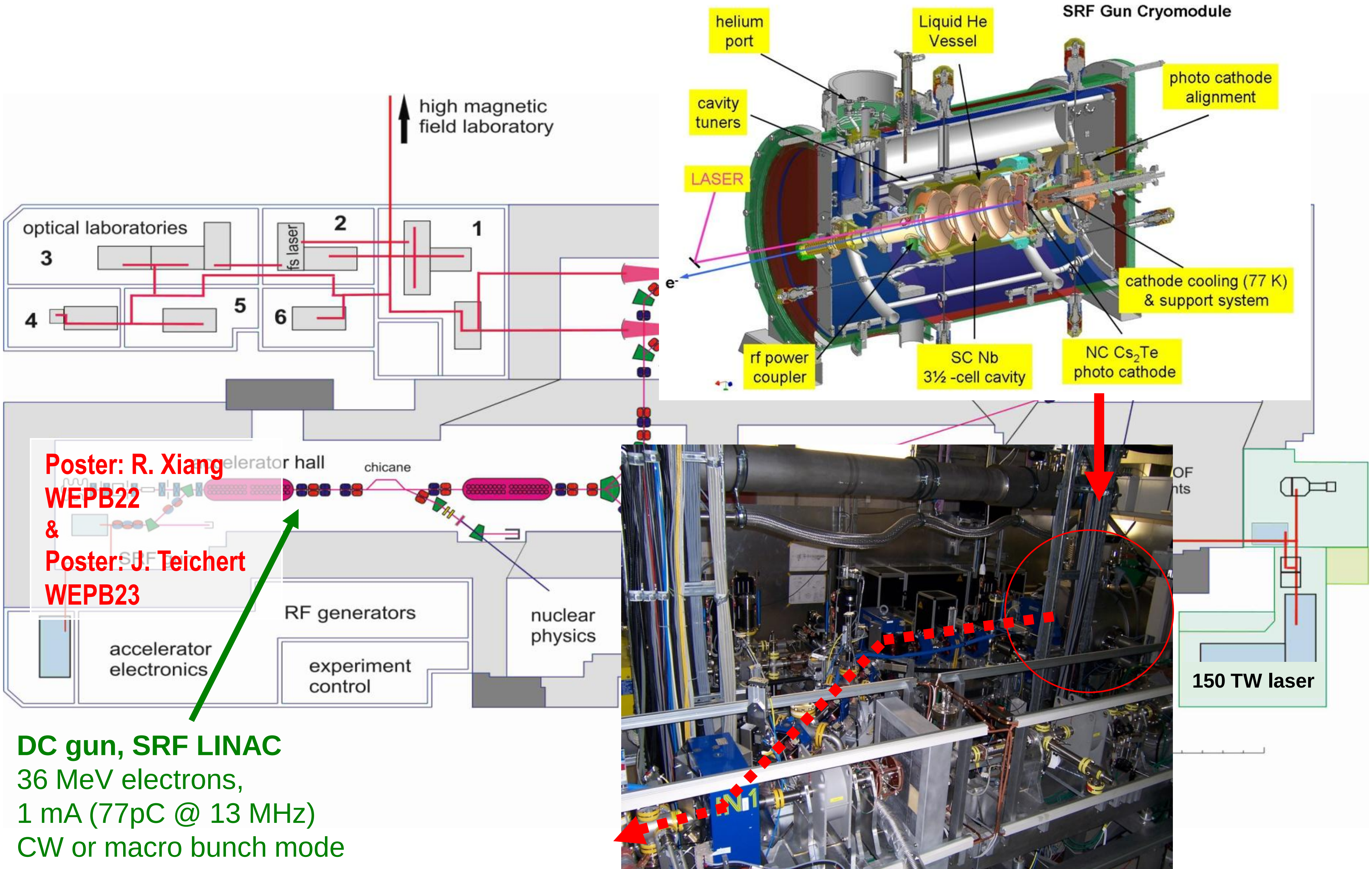
Beam time: 24h/day & 7days/week

Beam time in the period February 2009 to June 2010: All together 8700 h beam time + 150 days shut down



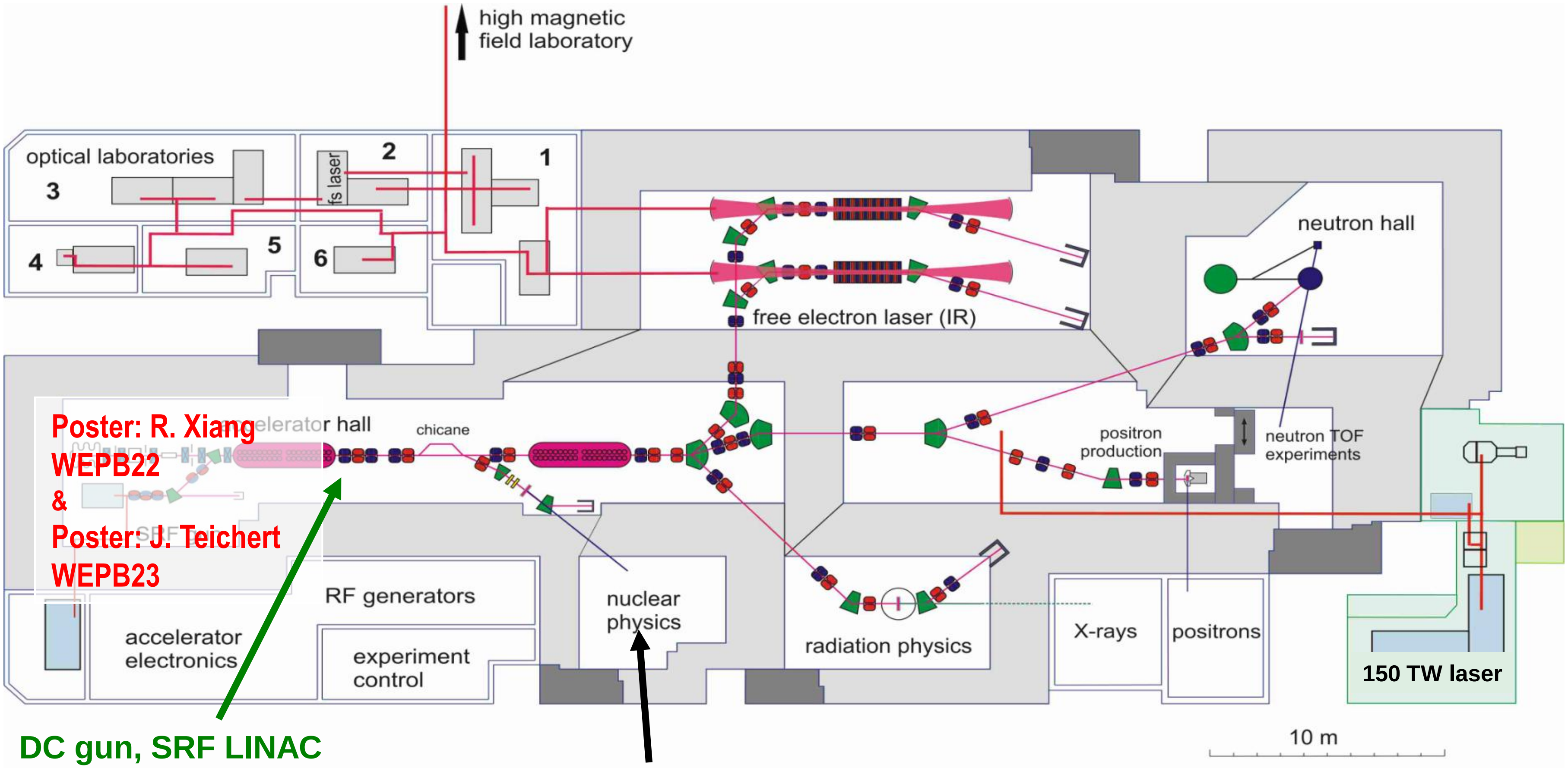
The FEL proposals required the U27 with 49 %, the U100 with 34 % and both together with 17 % of their used beam time. More than 95 % of the FEL beam time was CW-operation!

Radiation source ELBE



Poster: R. Xiang
WEPB22
&
Poster: J. Teichert
WEPB23

DC gun, SRF LINAC
36 MeV electrons,
1 mA (77pC @ 13 MHz)
CW or macro bunch mode
SRF Gun under development



Poster: R. Xiang WEPB22 & Poster: J. Teichert WEPB23

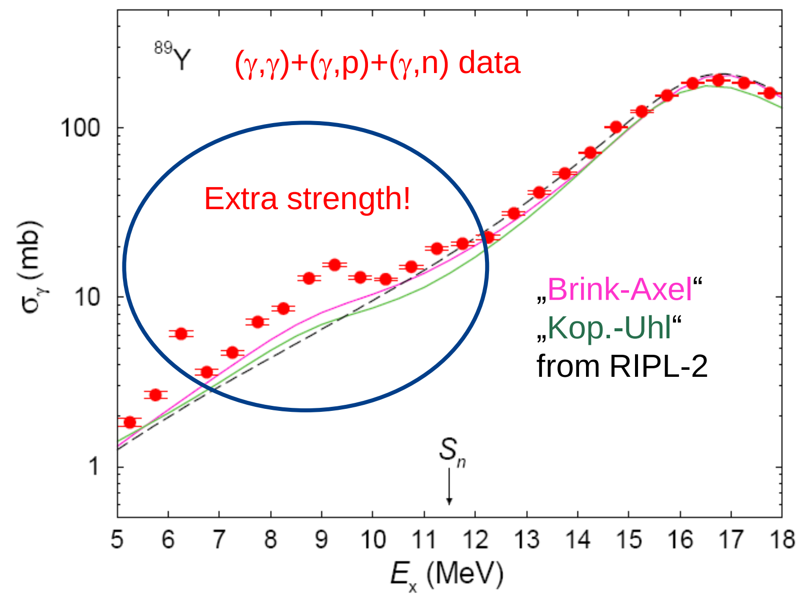
DC gun, SRF LINAC
36 MeV electrons,
1 mA (77pC @ 13 MHz)
CW or macro bunch mode
SRF Gun under development

Bremsstrahlung (polarized) 0 – 17 MeV

Study of gamma-ray strength functions (GSF)

Precise knowledge of GSF needed for modeling of photonuclear reactions in codes based on statistical models

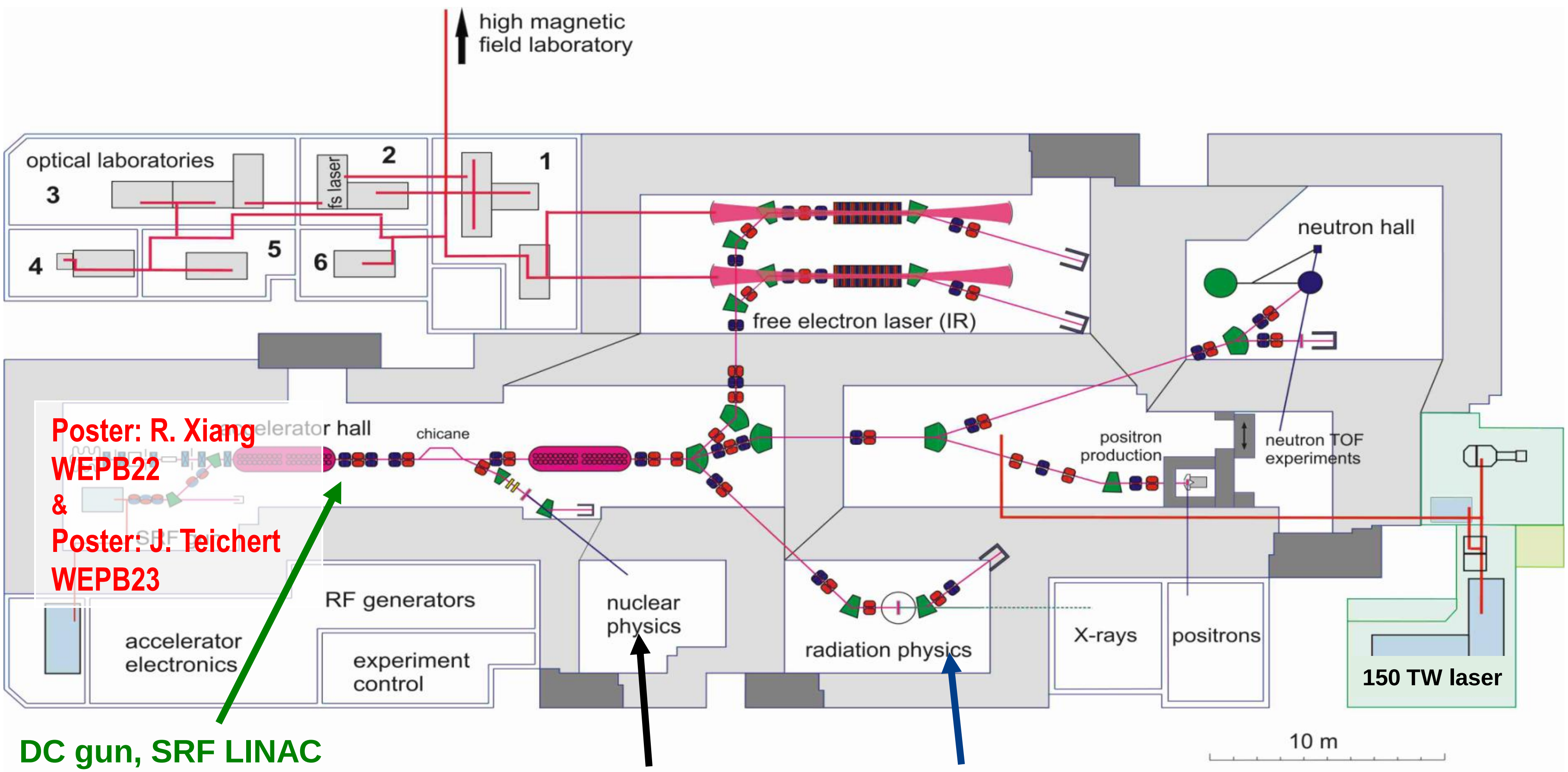
Example of GSF measurements at ELBE
Phys. Rev. C 79, 024301 (2009)
Data also in www-nds.iaea.org/exfor/



Bremsstrahlung facility at ELBE
Sensitive detector setup in combination with intense electron beams of high energy

-Novel ELBE data challenge models for GSF used in nuclear reaction data bases (www-nds.iaea.org/RIPL-2/)
- Improvement of description of (n,γ) and (n,n'γ) cross sections.

Courtesy of R. Schwengner

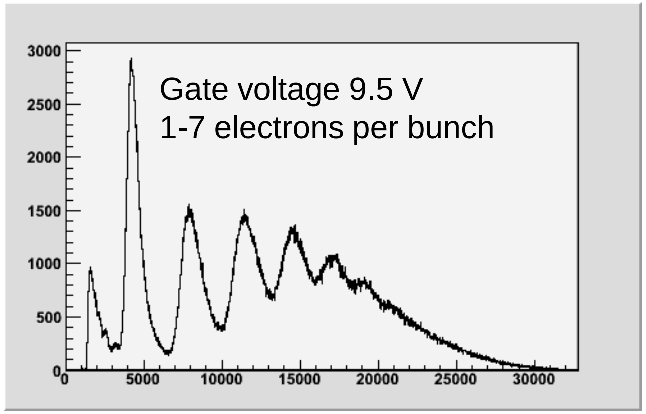


DC gun, SRF LINAC
36 MeV electrons,
1 mA (77pC @ 13 MHz)
CW or macro bunch mode
SRF Gun under development

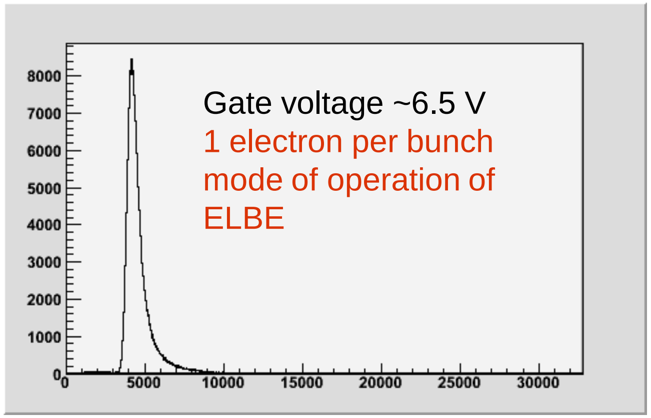
Bremsstrahlung (polarized)
0 – 17 MeV

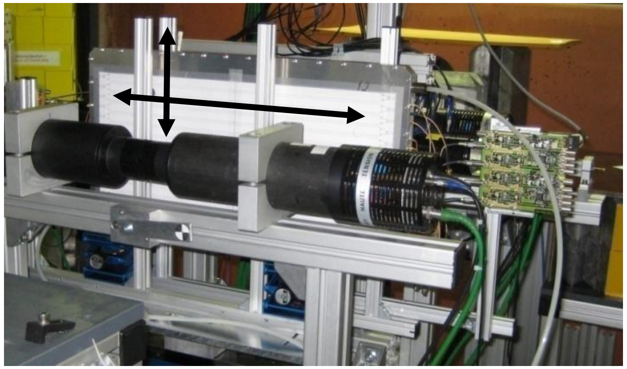
X-rays (quasi monochromatic)
10 – 100 keV &
detector tests

Tests of timing detectors at ELBE

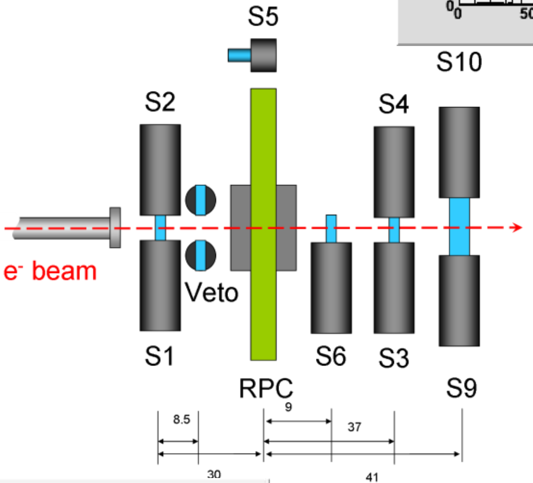


Scintillator pulse height spectra





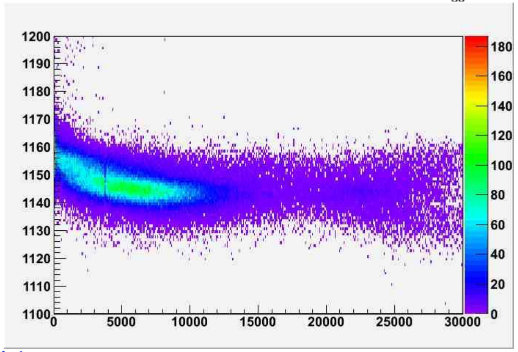
RPC can be moved by remote control.

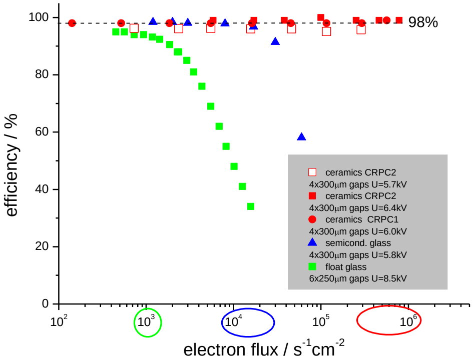


- Use RF signal from ELBE as time reference
- Tunable flux 10^0-10^5 $cm^{-2}s^{-1}$
- 6-8 test beams/year for FAIR detector prototypes
- Open for outside users

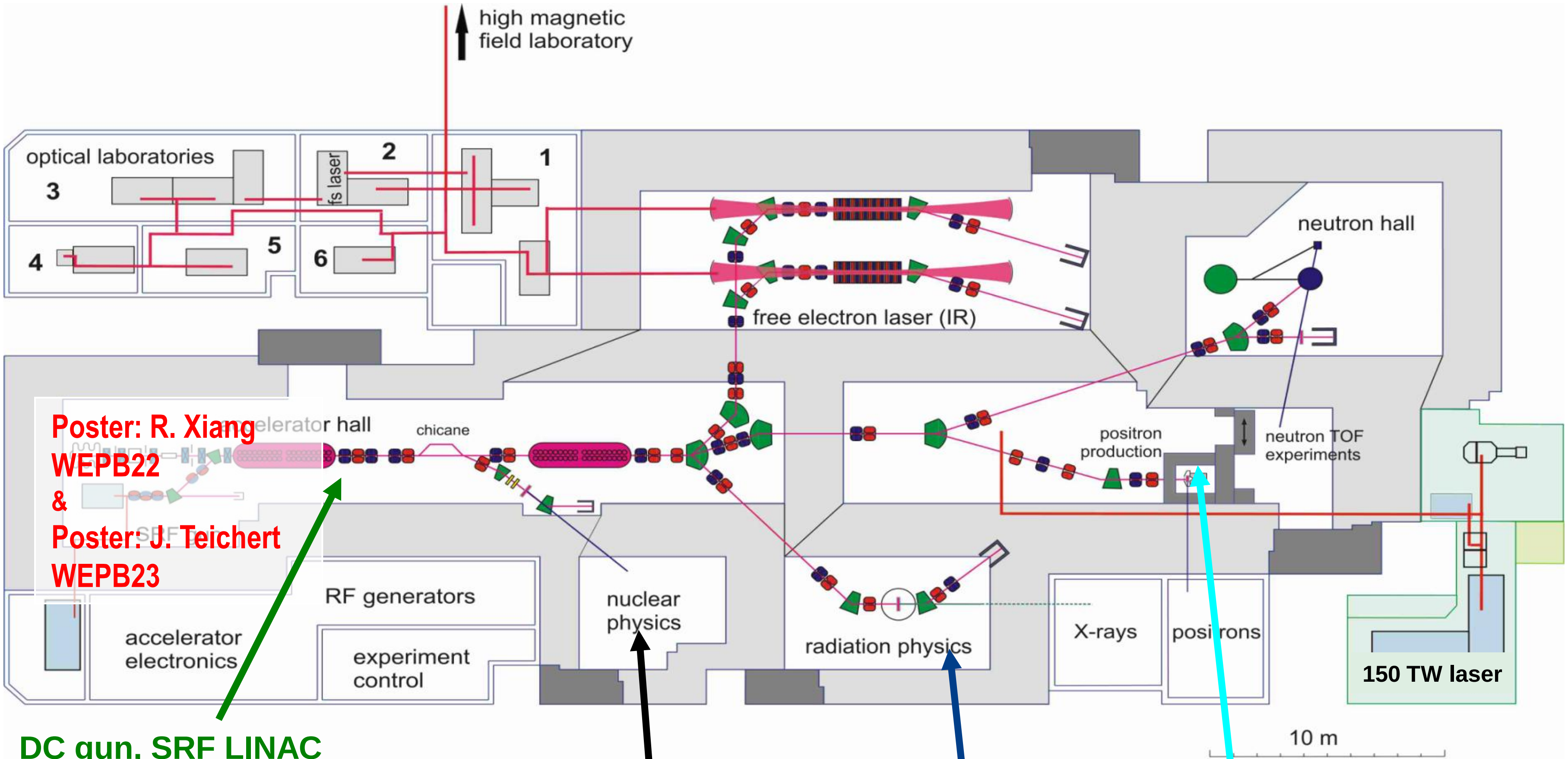
RPC test results:

1. TDC to QDC spectrum
2. Efficiency vs. electron flux for ceramic RPC





Courtesy of D. Bemmerer & L. Naumann



Poster: R. Xiang
WEPB22
&
Poster: J. Teichert
WEPB23

DC gun, SRF LINAC
36 MeV electrons,
1 mA (77pC @ 13 MHz)
CW or macro bunch mode
SRF Gun under development

Bremsstrahlung (polarized)
0 – 17 MeV

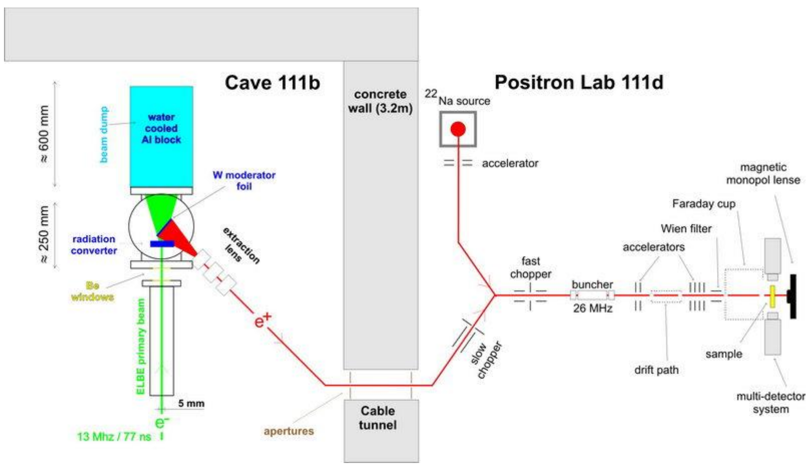
X-rays (quasi monochromatic)
10 – 100 keV

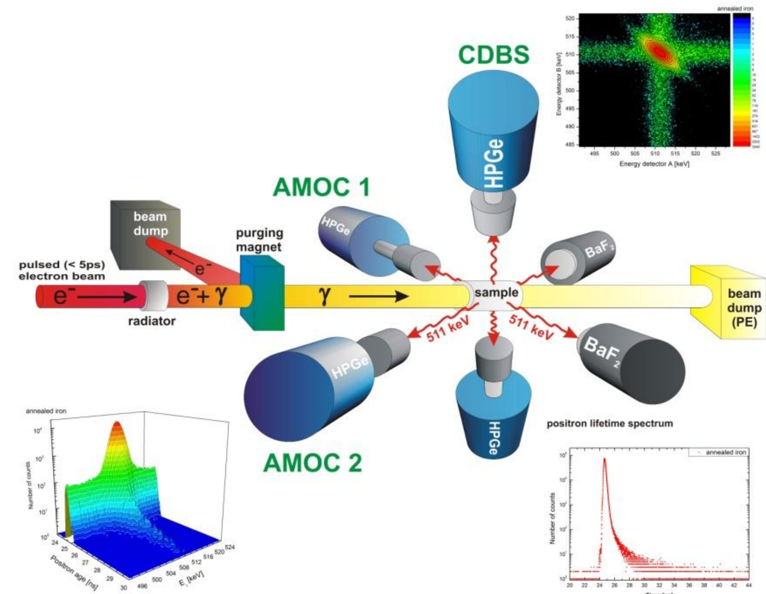
Positrons (pulsed)
0.2 – 30 keV

EPOS (ELBE Positron Source)

MePS
Mono-energetic **P**ositron **S**ource

GiPS
Gamma-**i**nduced **P**ositron **S**pectroscopy



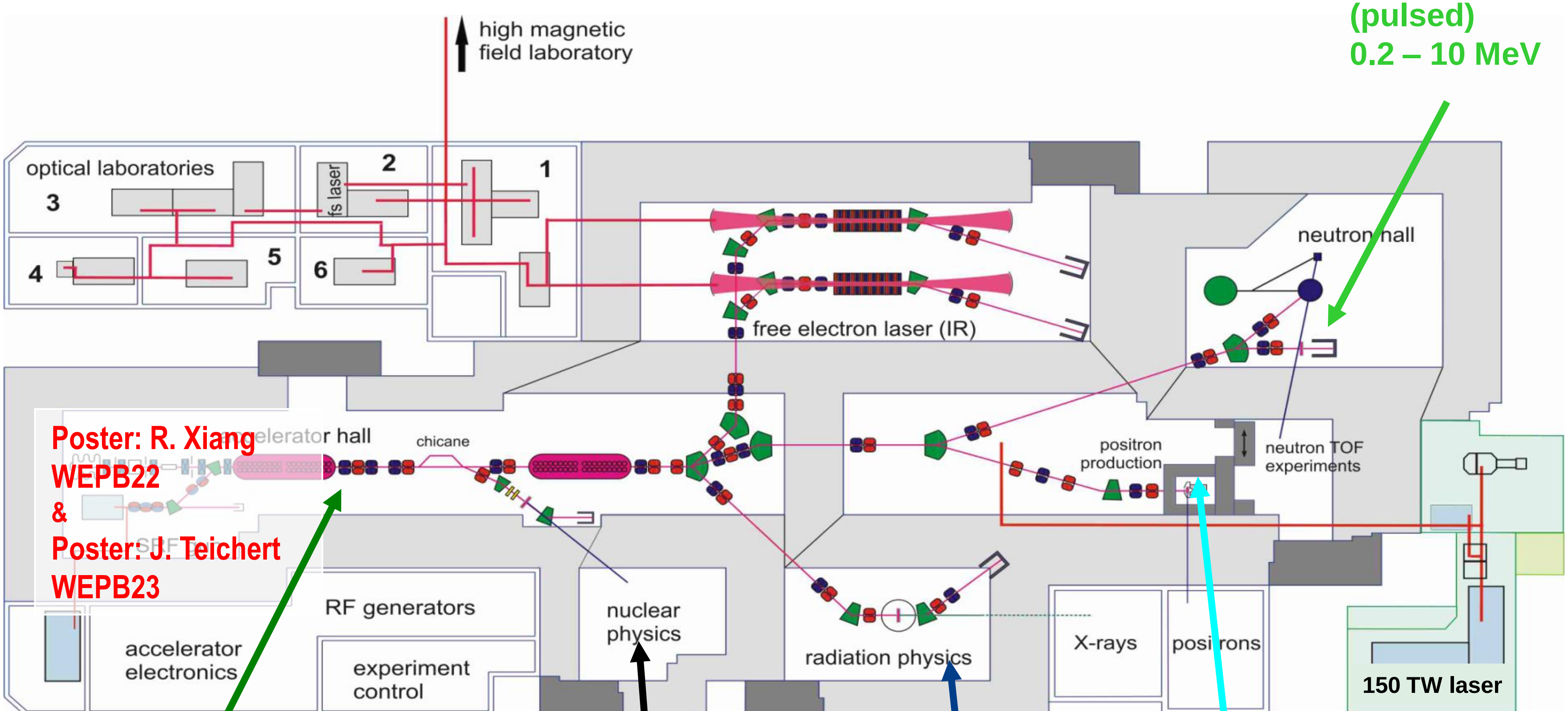


Monoenergetic slow positrons
Information Depth: 0 … 5 µm

Positron generation by Bremsstrahlung
Information Depth: 0.1 mm … 2 cm

Positron techniques: Lifetime, Coincidence Doppler Broadening (CDBS), Age-Momentum Correlation (AMOC)
Investigations of radioactive, liquid and bulky samples are also possible (unique faciltiy)

Courtesy of M. Butterling & W. Anwand



Neutrons (pulsed)
0.2 – 10 MeV

Poster: R. Xiang WEPB22
&
Poster: J. Teichert WEPB23

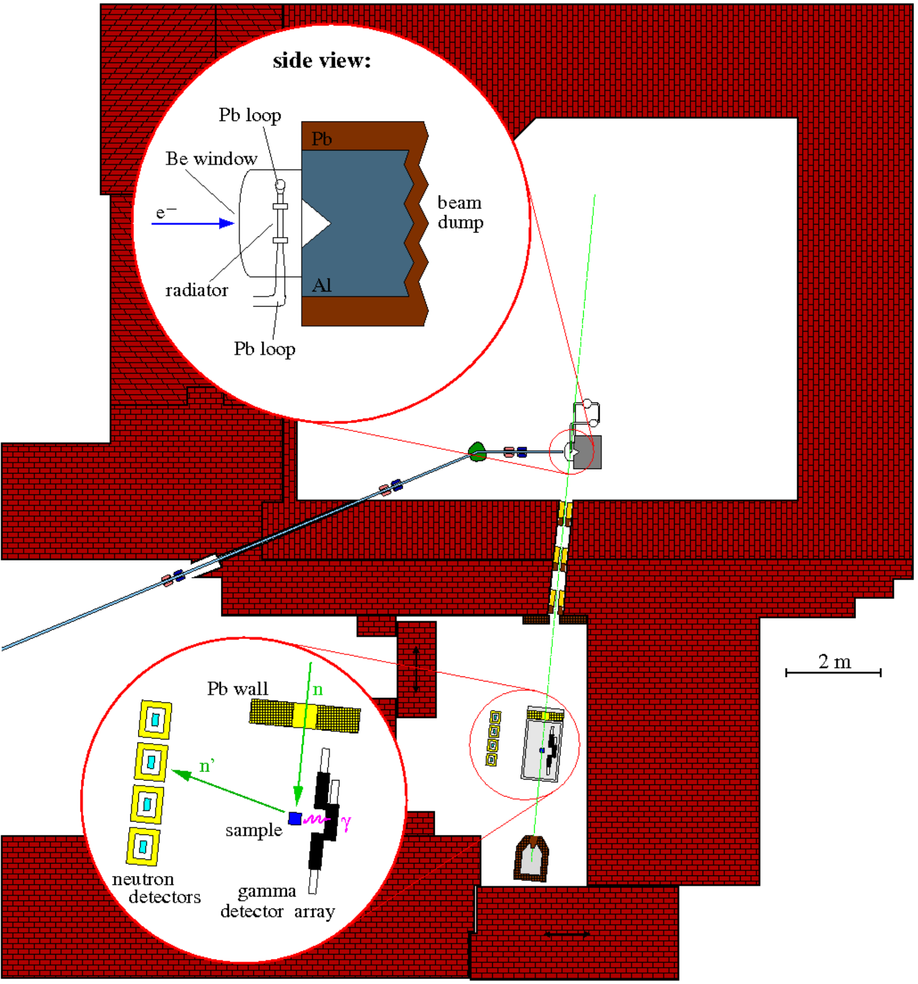
DC gun, SRF LINAC
36 MeV electrons,
1 mA (77pC @ 13 MHz)
CW or macro bunch mode
SRF Gun under development

Bremsstrahlung (polarized)
0 – 17 MeV

X-rays (quasi monochromatic)
10 – 100 keV

Positrons (pulsed)
0.2 – 30 keV

The nELBE photo neutron source:



- Investigation of fast neutron induced reactions of relevance for nuclear transmutation and the development of Gen IV reactor systems

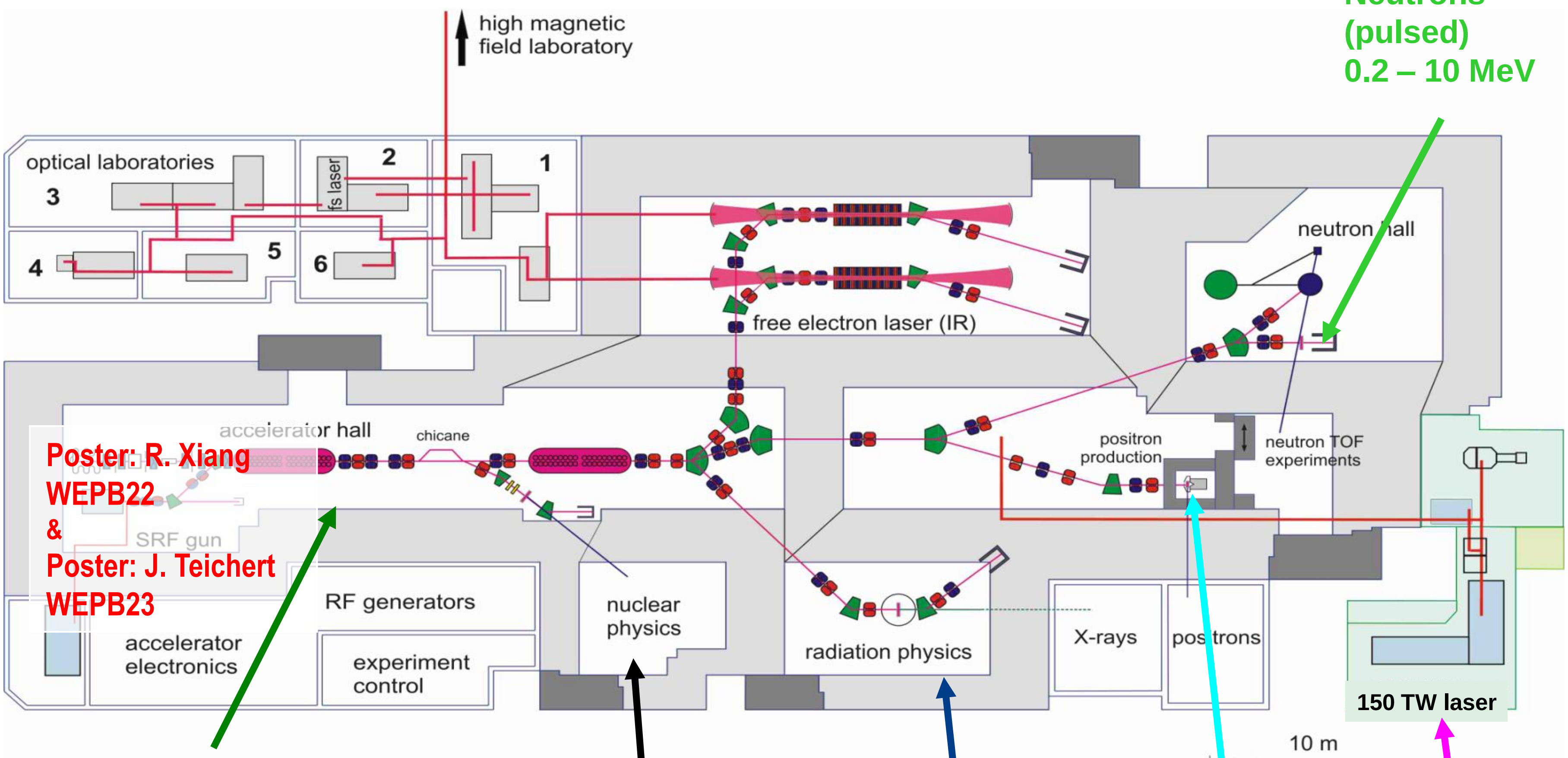
1. **Inelastic neutron scattering (n,n'γ)** ^{56}Fe, Mo, Pb, ^{23}Na and total neutron cross sections σ_{tot} (Ta, Au, Al, C, H)
2. **Investigation of minor actinides (radioactive targets)** Collaboration with n-TOF at CERN Joint research project „Nuclear physics data of relevance for transmutation" (German Federal Ministry for Science and Technology funded , 02NUK13)

GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

Courtesy of A. Junghans

Radiation source ELBE

Neutrons (pulsed)
0.2 – 10 MeV



Poster: R. Xiang WEPB22
&
Poster: J. Teichert WEPB23

DC gun, SRF LINAC
36 MeV electrons,
1 mA (77pC @ 13 MHz)
CW or macro bunch mode
SRF Gun under development

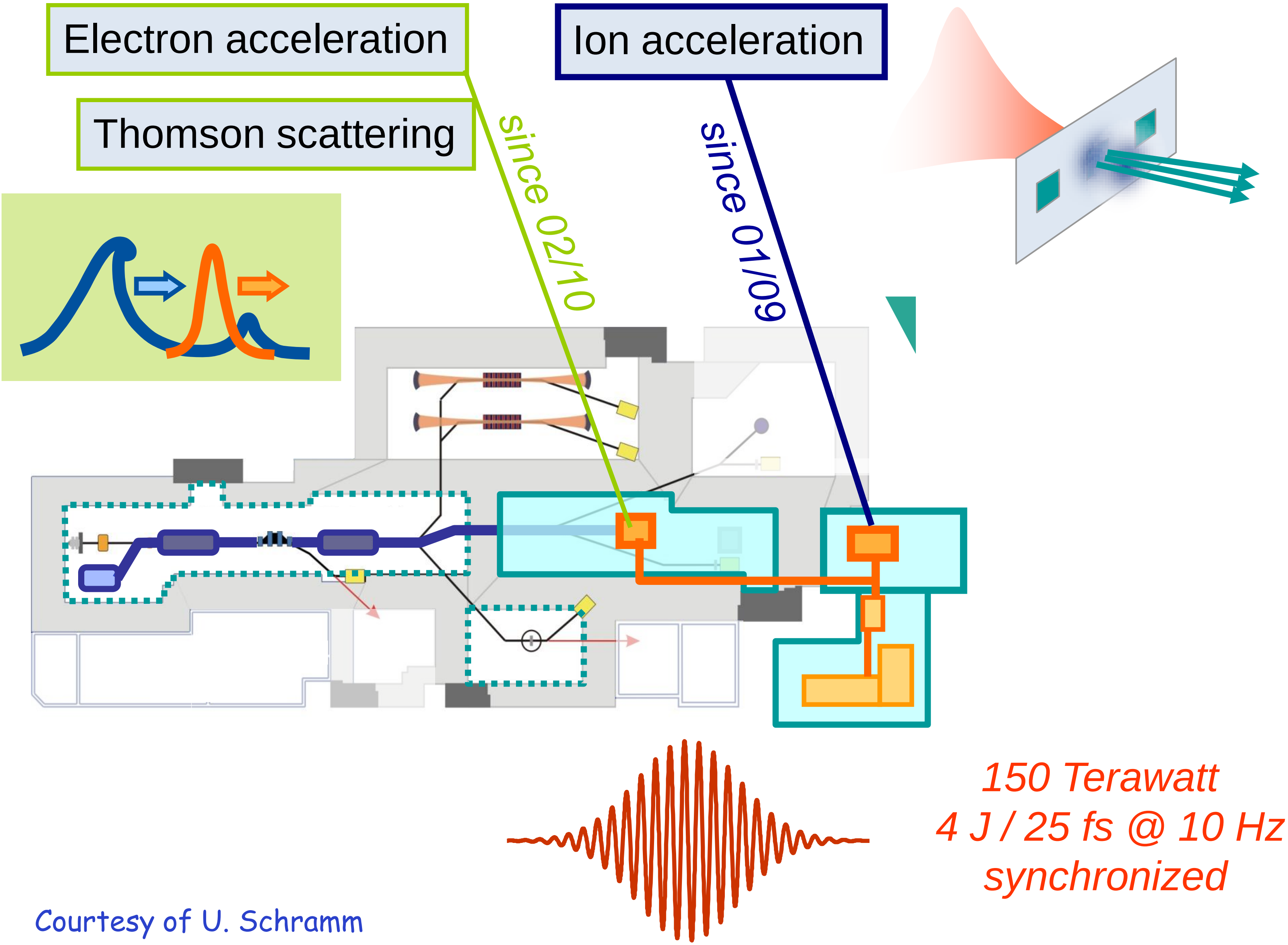
Bremsstrahlung (polarized)
0 – 17 MeV

X-rays (quasi monochromatic)
10 – 100 keV

Positrons (pulsed)
0.2 – 30 keV

High Intensity Laser 150 TW

Running 150 TW laser activities @ ELBE

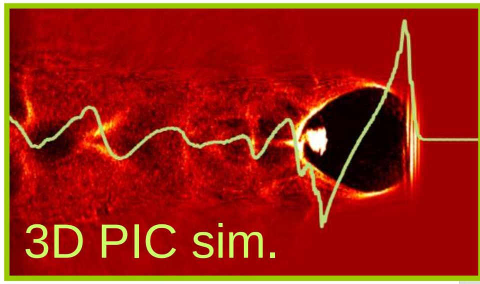


Courtesy of U. Schramm

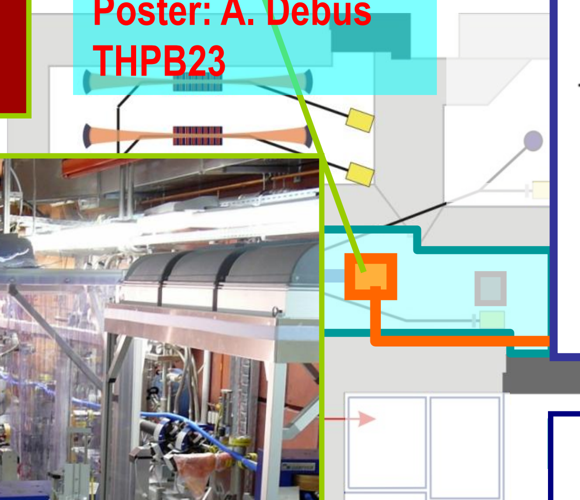
Running 150 TW laser activities @ ELBE

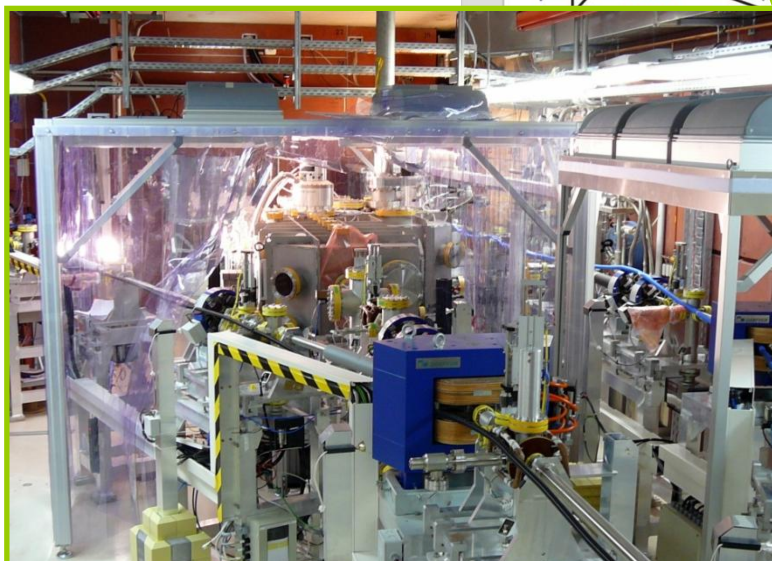
Electron acceleration

Thomson scattering



Poster: A. Debus THPB24 & Poster: A. Debus THPB23



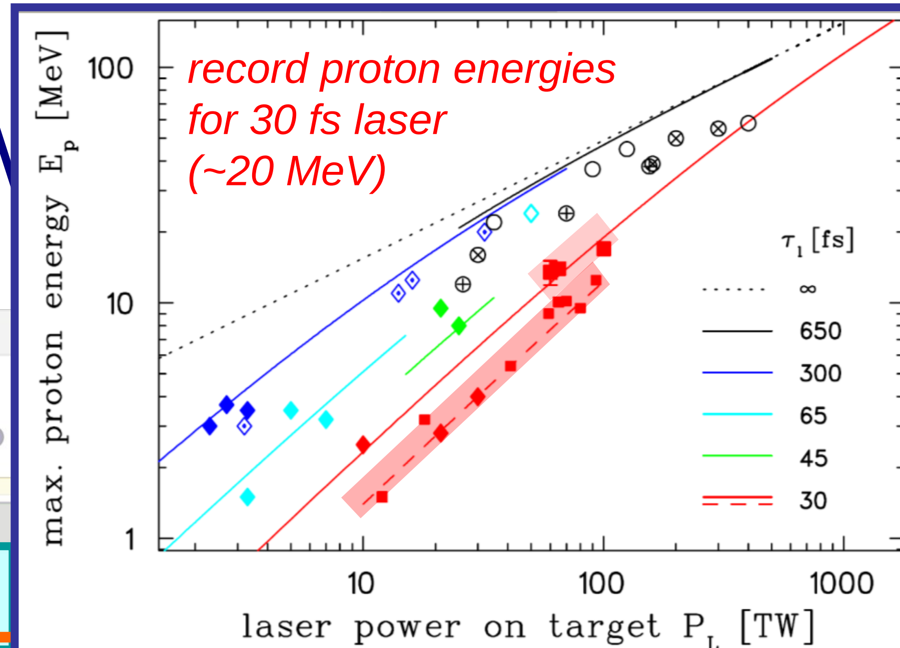


A. Debus, et a., Appl. Phys. B 100, 61 (2010)

Courtesy of U. Schramm

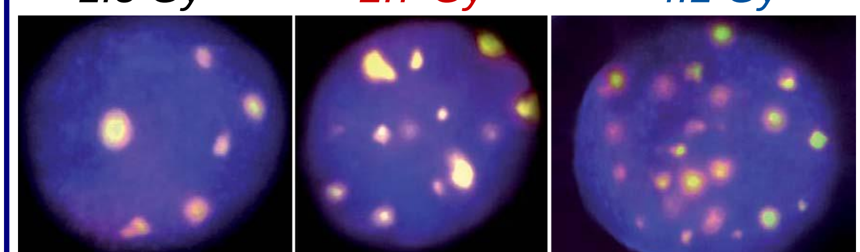
Ion acceleration

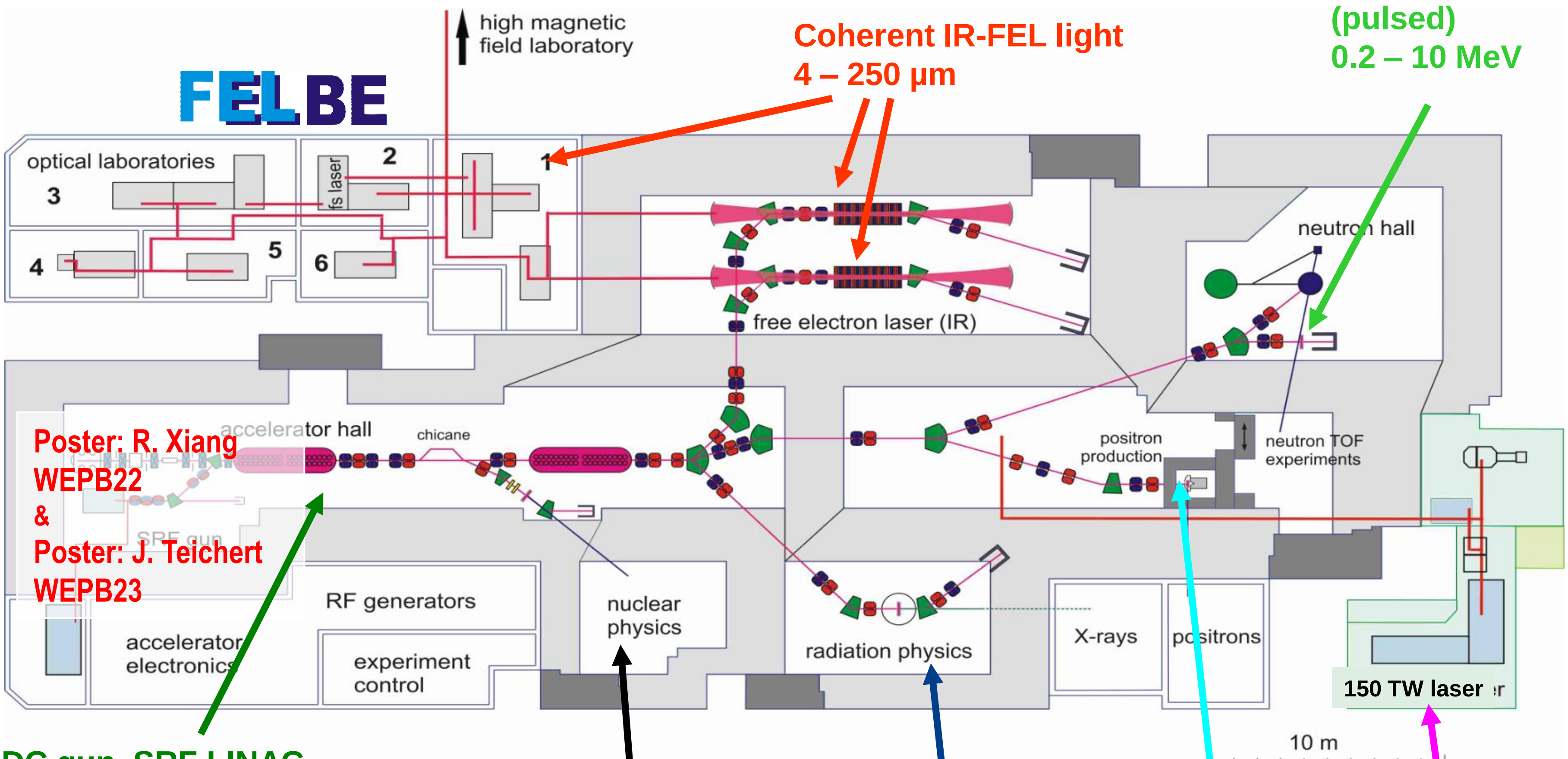
K. Zeil, et al., NJP 12, 045015 (2010)
S. Kraft, et al., NJP 12, 085003 (2010)



first dose controlled cell irradiation

1.5 Gy *2.7 Gy* *4.1 Gy*





Coherent IR-FEL light
4 – 250 µm

Neutrons (pulsed)
0.2 – 10 MeV

Poster: R. Xiang
WEPB22
&
Poster: J. Teichert
WEPB23

DC gun, SRF LINAC
36 MeV electrons,
1 mA (77pC @ 13 MHz)
CW or macro bunch mode
SRF Gun under development

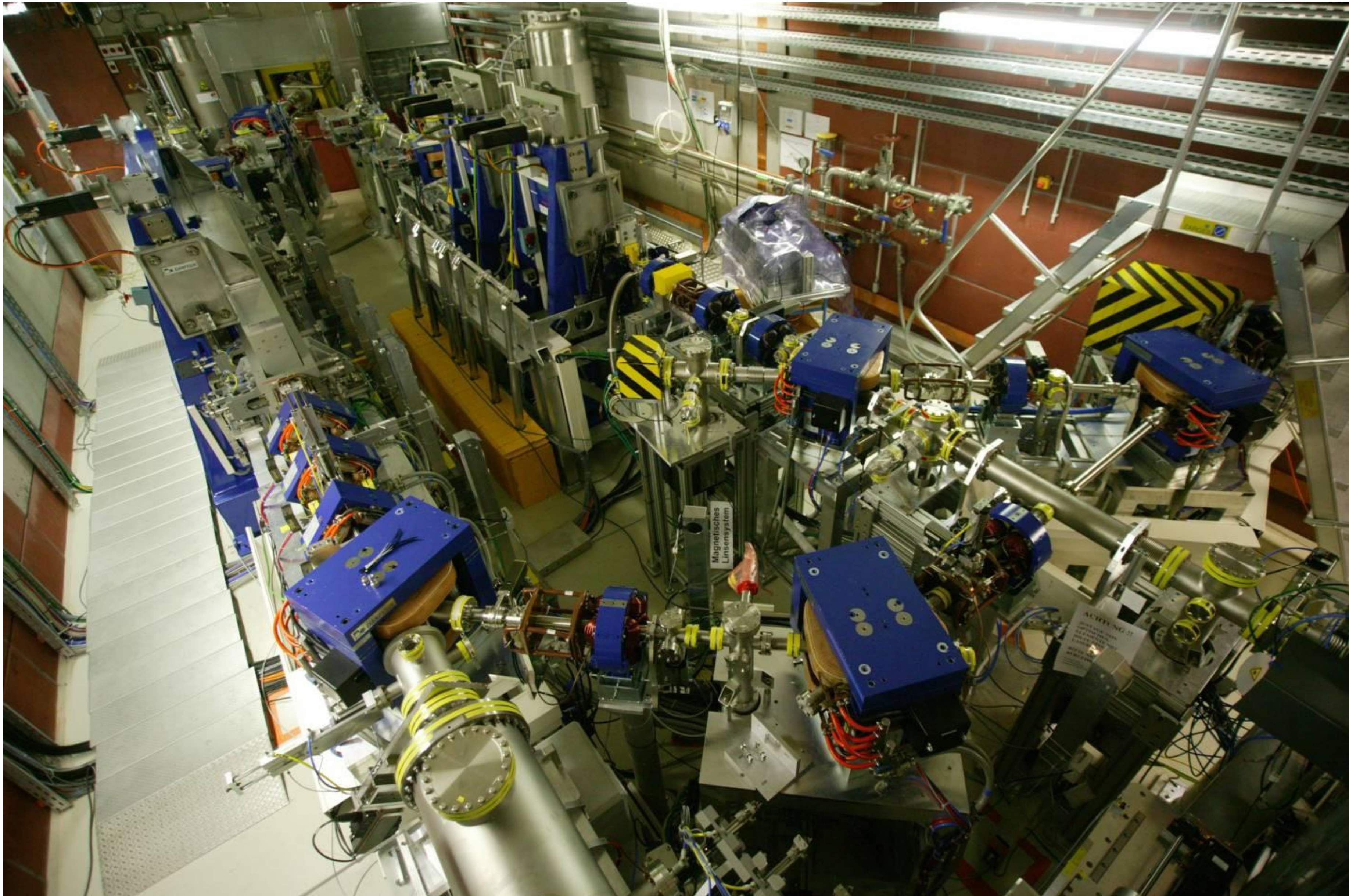
Bremsstrahlung (polarized)
0 – 17 MeV

X-rays (quasi monochromatic)
10 – 100 keV

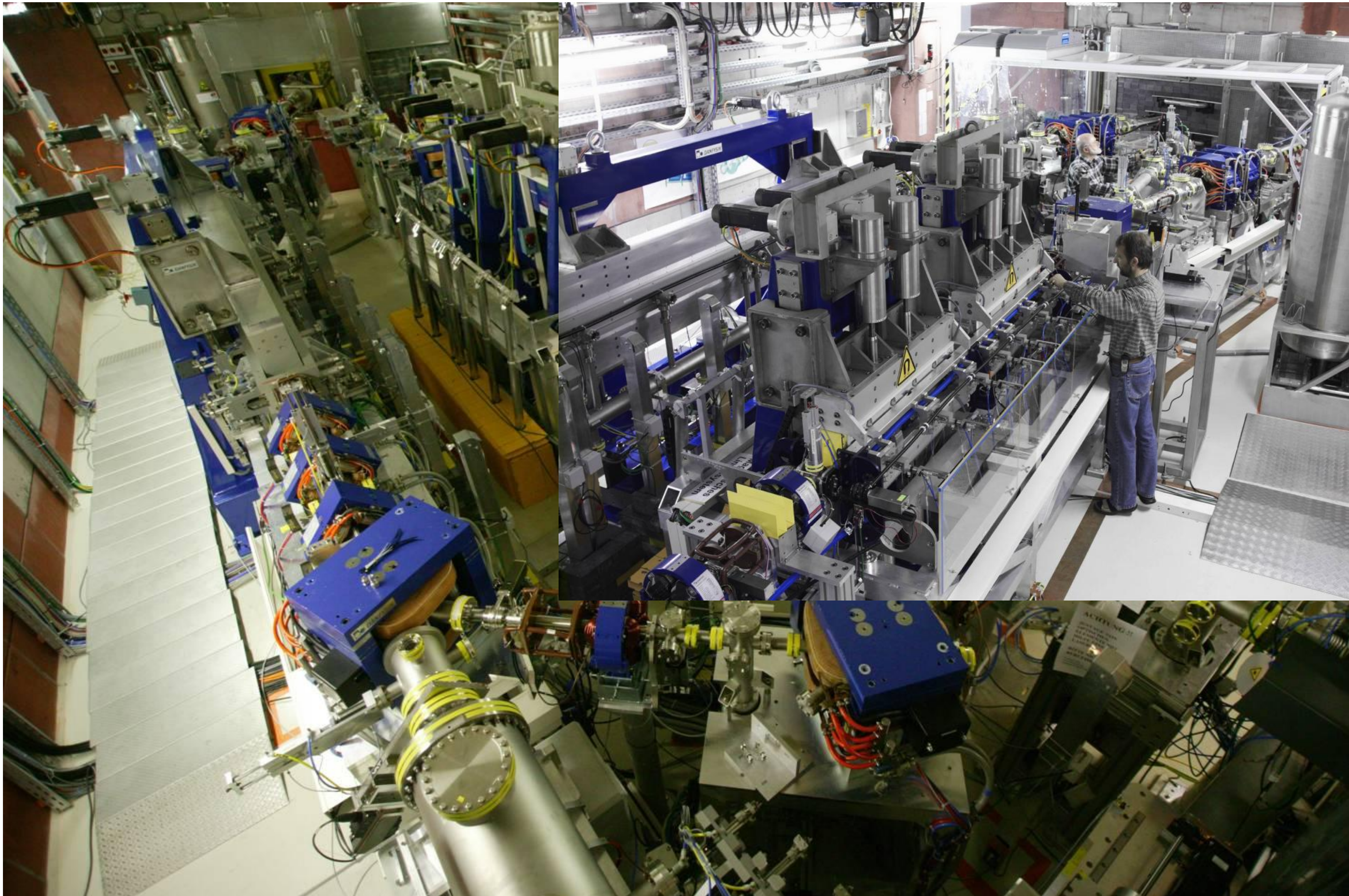
Positrons (pulsed)
0.2 – 30 keV

High Intensity Laser 150 TW

FEL cave



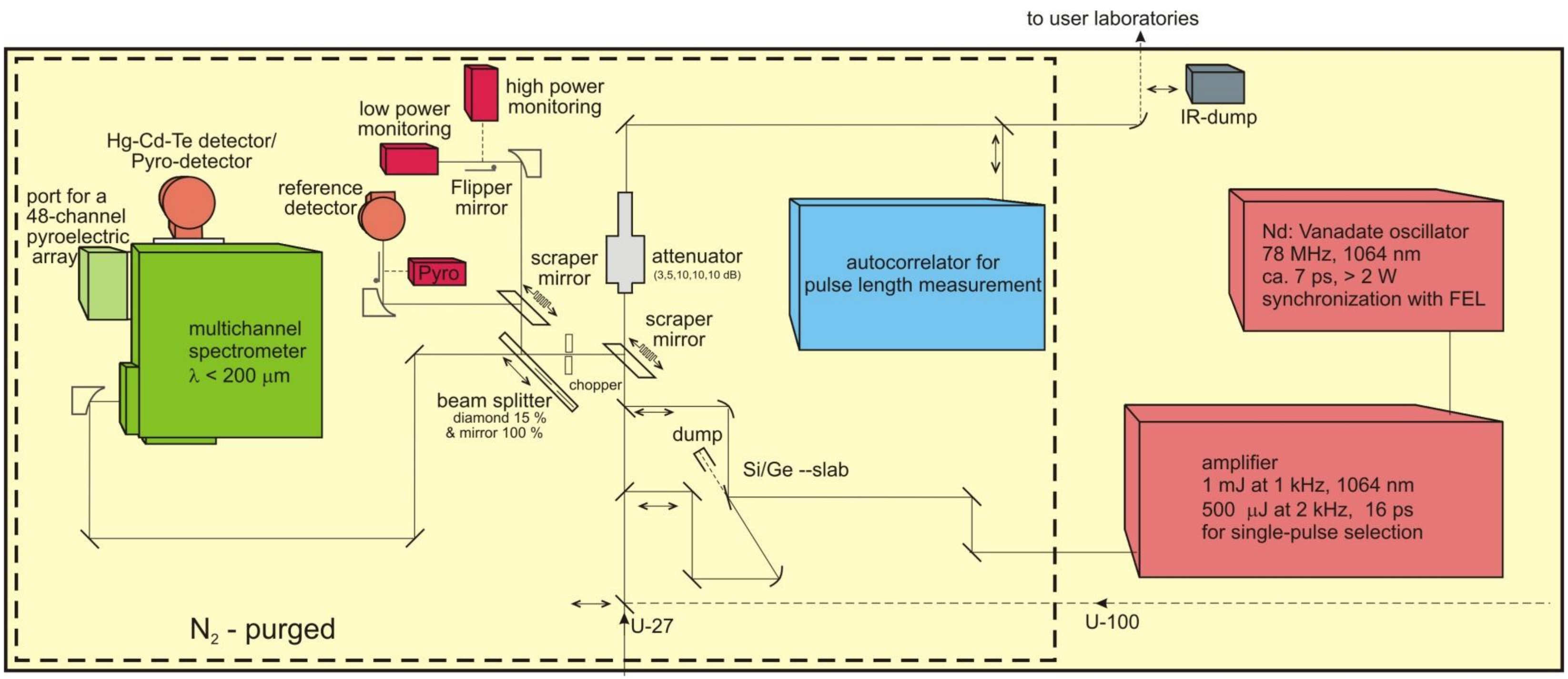
FEL cave



	FEL1(U27)	FEL2(U100)
Undulator period	27.3 mm	100 mm
Number of periods	2 * 34	38
Undulator parameter	0.3 - 0.7	0.5 – 2.8
Undulator type	hybrid NdFeB	hybrid SmCo
Resonator length	11.53 m	11.53 m
Rayleigh length	1 m	1.8 m
Outcoupling holes	1.5 / 2.0 / 3.0 / 4.0 mm	2.0 / 4.5 / 7.0 mm
Mirror R(curvature)	5940 mm (h+v)	6330 mm (h) 3610/ ∞ (v) mm
Mirror diameter	75 mm	160 mm (h) 200 mm (v);
Mirror material	Au / Cu	Au / Cu
Waveguide	no	partial (10 x 70/120/150 x 7922 mm)
Wavelength	4 - 21 μm	18 – 250 μm 75 – 1.2 THz
Max. power (out)	20 W (9-11 μm)	65 W (42, 83 μm)
Pulse duration	0.8 – 4 ps	1 – 25 ps
Peak power (out)	10 kW – 1 MW	
Max. pulse energy	1.5 μJ	5 μJ
Bandwidth $\Delta\lambda/\lambda$	0.4 - 2 %	0.4 – 2 %
Linear polarization	> 98 %	

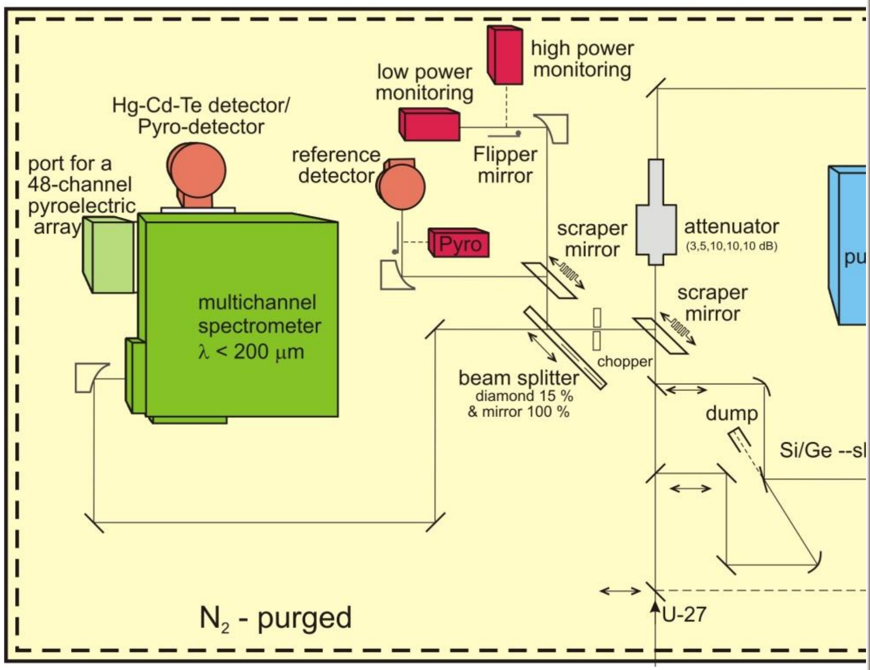
(L.S. Lee et al., Infrared Physics & Technology 51 (2008) 537

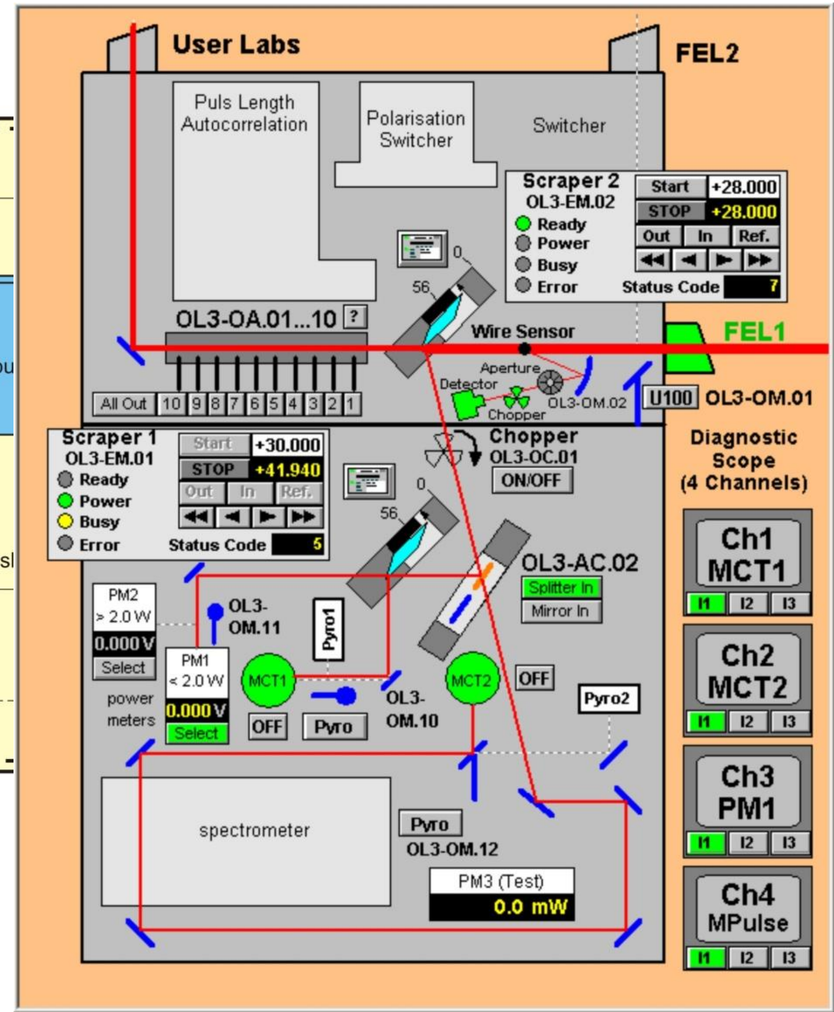
IR-Diagnostic



Interface of the remote controlled
part of the diagnostic station

IR-Diagnostic



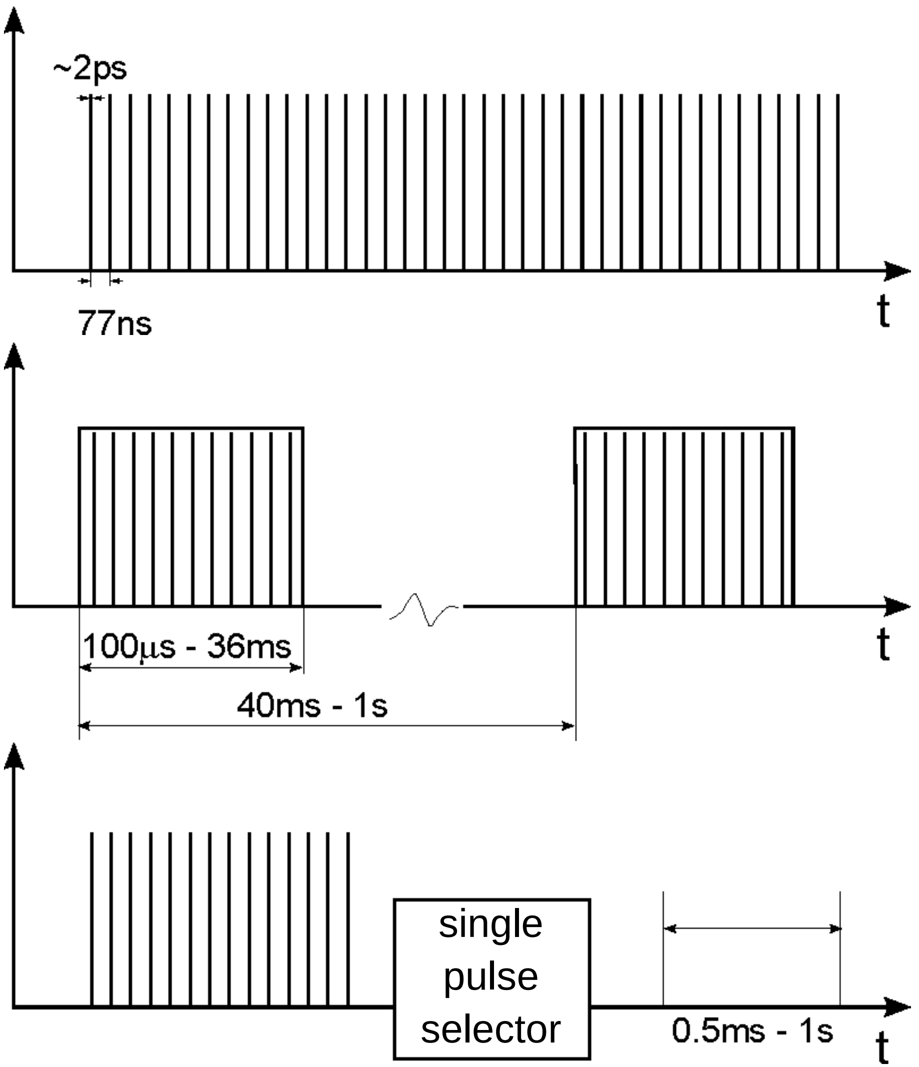


Interface of the remote controlled part of the diagnostic station

high duty cycle (100%)
13 (26) MHz, cw
(only FEL in Europe)

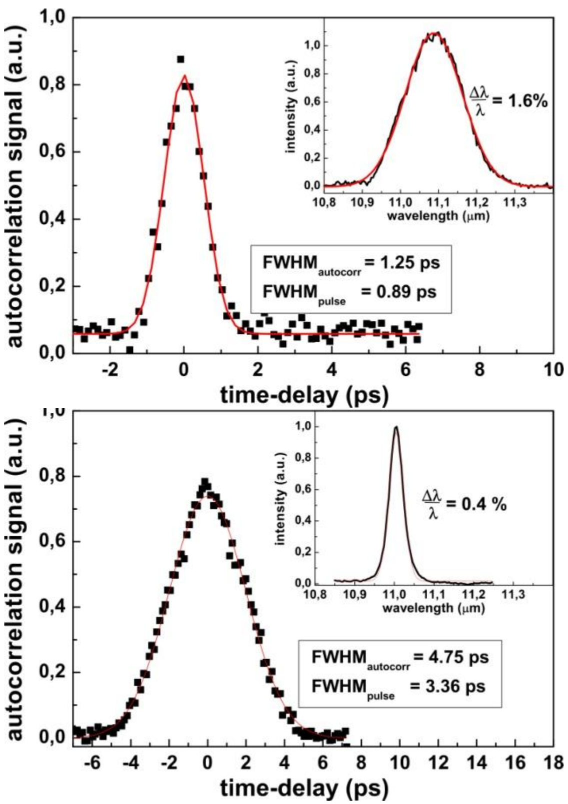
low duty cycle
macropulse structure
1 - 25 Hz,
(up to 100 kHz planned)

single pulse selection
photo-induced reflection
1 Hz – 2 kHz



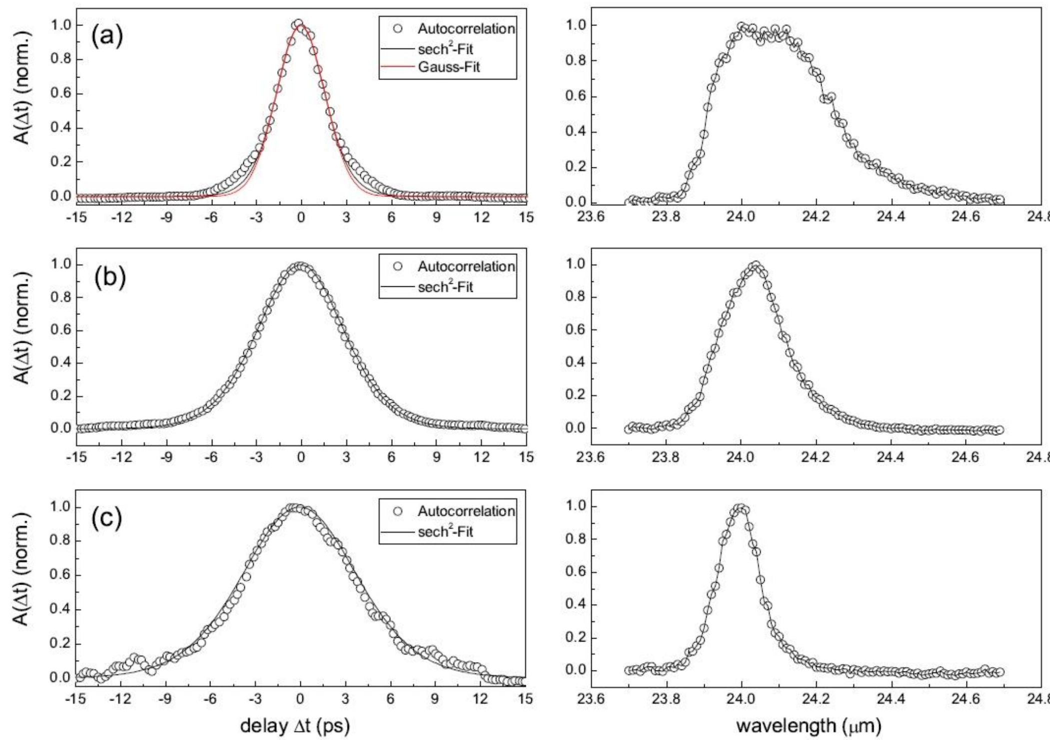
Spectral width and duration of the IR-pulses

U27



Top: ΔL= -1 µm; below: ΔL= -20 µm

U100



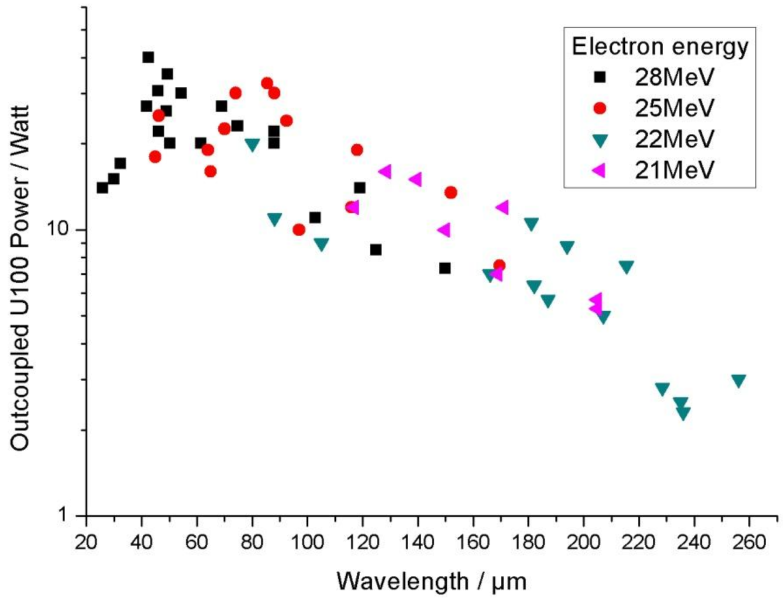
a: ΔL= -2 µm, FWHM= 2.5 ps, Δλ/λ= 1.5 %

b: ΔL= -14 µm, FWHM= 4.4 ps, Δλ/λ= 0.9 %

c: ΔL= -24 µm, FWHM= 5.8 ps, Δλ/λ= 0.6 %

The calculated time-bandwidth product is about 0.4 wich indicates Fourier-transform limited operation

Typical power values of the U100 in user operation (2009)

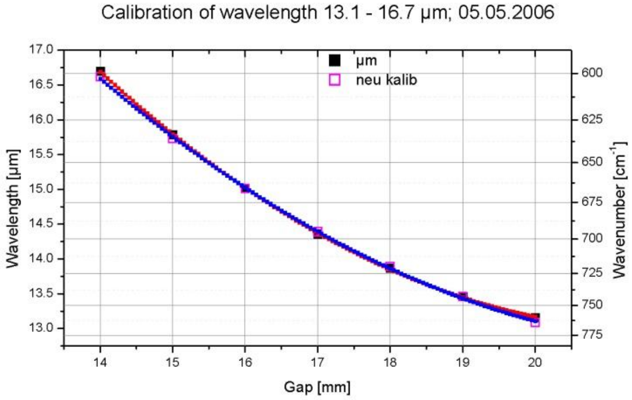


Bottleneck for power:

demage power of the attenuator in the diagnostic > 40 W

U27: free propagation mode

Remote controlled wavelength scan with U27 available



U100: vacuum chamber as an optical partial waveguide

Measurements of FEL power at certain wavelength exhibit a phenomenon of spectral gaps (strong reduced power)

Effect is present independently of electron beam tuning or of cavity configurations

Also at FELIX and CLIO

R. Prazeres et al., Phys. Rev. ST. Accel. Beams,12 010701 (2009)

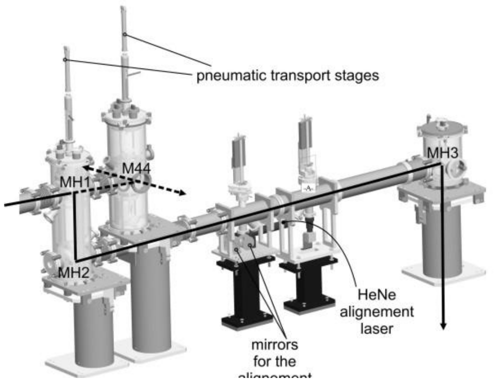
Number of gaps propotional to waveguid length and width

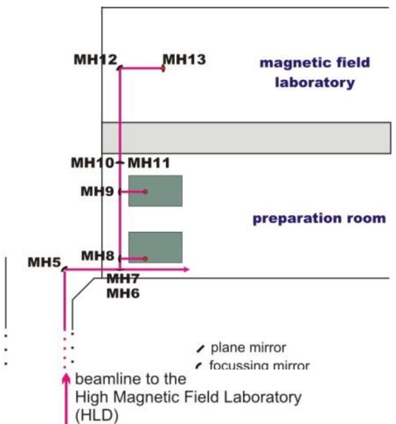
Requirements: Low losses, stable, transparent for 632 nm & 4-250 μm, polarization should be conserved

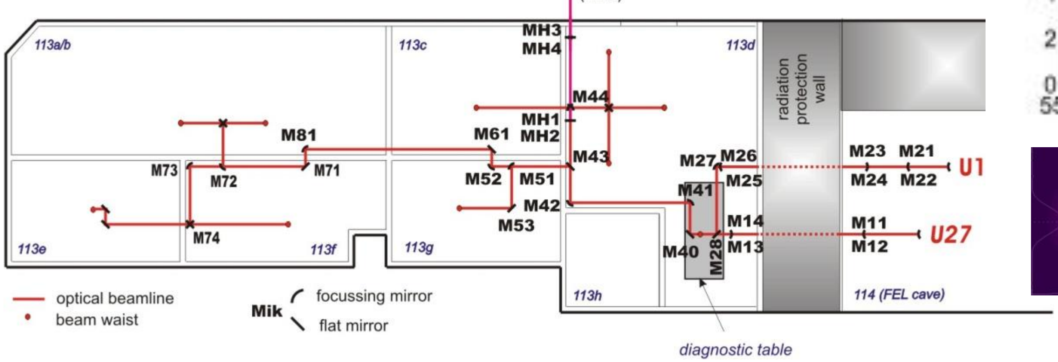
Two operating regimes : Evacuated or purged with dry N_2

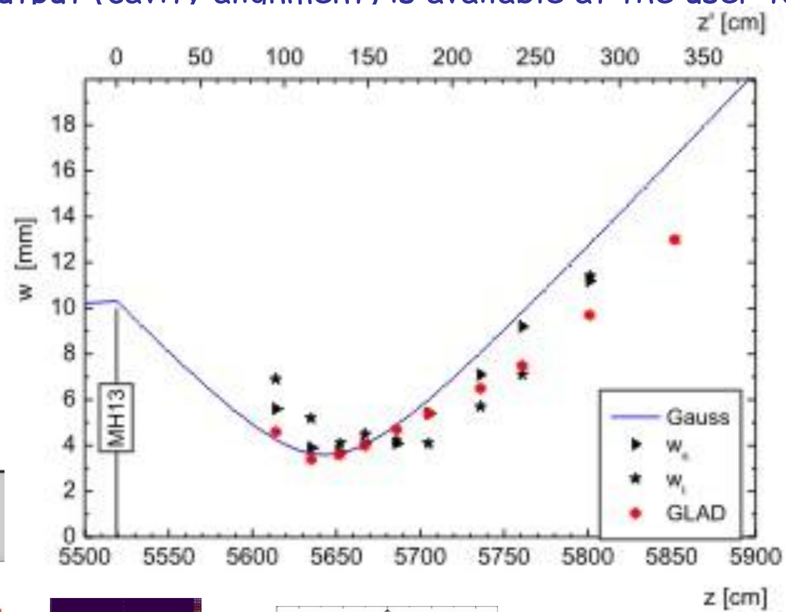
Windows under Brewster's angle: ZnSe, KRS-5, Crystalline Quartz z-cut, CVD Diamond, TPX-foil (only for N_2)

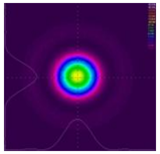
A HeNe laser beam which is well aligned with the FELBE output (cavity alignment) is available at the user tables

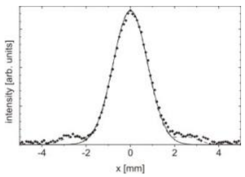












$\omega_0=0.78x\ D_h/2$

Multi-colour pump-probe experiments

- Synchronization of other pulsed lasers to the FEL
- Available lasers:

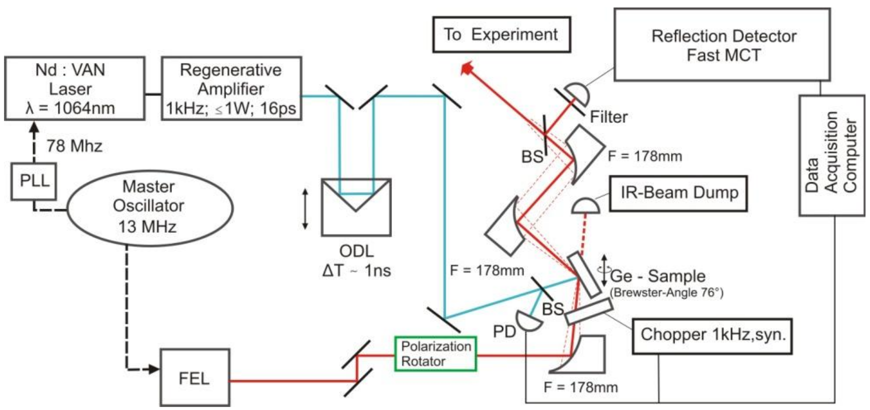
  - ◆ Ti:sapphire laser (70 fs & 3 ps, 10 nJ/pulse, 78 MHz, 730 nm - 870 nm)
  - ◆ Ti:sapphire laser (12 fs, 5 nJ/pulse, 78 MHz, 800 nm) &
    Ti:sapphire amplifier (25 fs, 1 mJ, 1 kHz, 800 nm) & (40 fs, 5 μJ, 250 kHz)
    OPG/OPA (<100 fs, 100 μJ/pulse, 1 kHz, 1150 nm - 2600 nm) &
    Difference frequency mixer (< 100 fs, 0.3 μJ/pulse - 3 μJ/pulse, 1 kHz, crystal 1: 2.4 μm - 11 μm, crystal 2: 5 μm - 18 μm)
  - ◆ Nd:Vanadate oscillator (~ 7 ps, >2 W, 78 MHz, 1064 nm) &
    Nd: YAG amplifier (~16 ps, 1 Watt, 1 mJ@1kHz, 1064 nm)
  - ◆ Erbium fiber laser (100 fs, 3 nJ, 78 MHz, 1550 nm &
    SHG (100 fs, 1 nJ, 78 MHz, 775 nm)

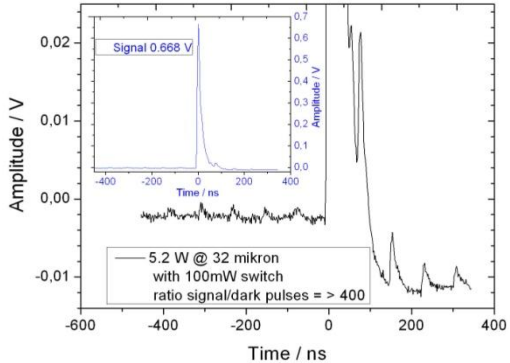
- Generation of broad-band THz-radiation with system 1 & 2

Diff. detectors, spectrometers, digital storage oscilloscopes, diff. cryostats, pump-probe set-up, CO_2 laser, vacuum-tight box for control of experimental environment, Fourier-transform spectrometer, Mirrors & holders etc.

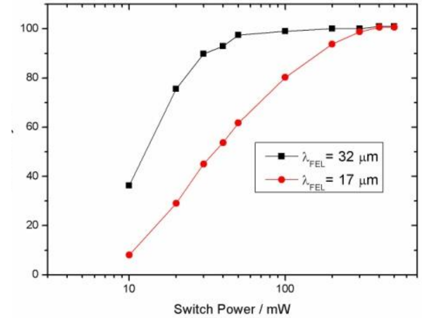
Pulse picking with a laser-based semiconductor plasma switch

- Decreasing the average power as required for certain experiments, high pulse energies but moderate or low average power
- First request of a 1 kHz FEL-user beam for „Vibration control of quantum phases in complex oxides“ by A. Cavalleri et al., MPSD-CFEL Hamburg/University Oxford
- Parameter: λ= 17, 29, 50 μm; rep. Rate 0.5 – 1 kHz; energy/pulse >1 μJ
- Ratio signal/dark pulses > 400
- Future: FEL with macropulses 1–100 kHz, duration 20–50 μs





FEL pulse at 32 μm in two different amplitude scales



Dependence of reflectivity on the pump-laser power(FEL ~0.5 mm^2, YAG ~3 mm^2

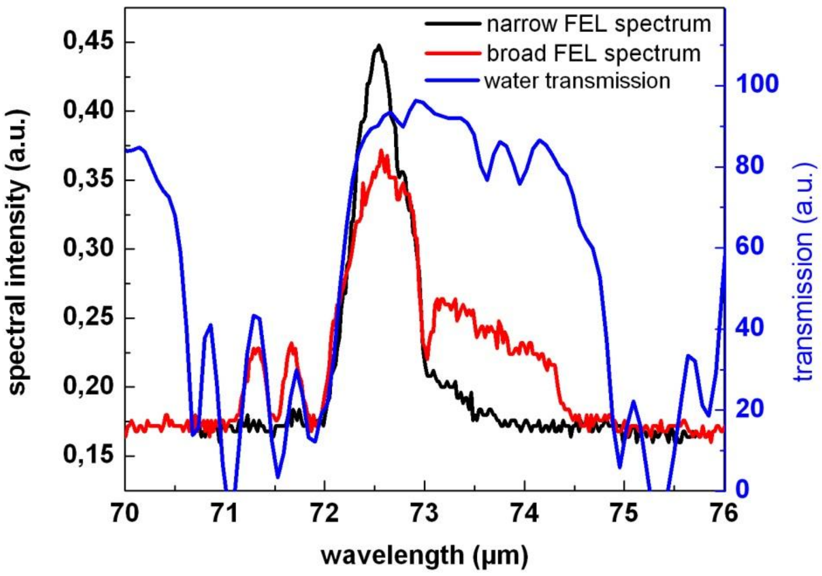
Poster: W. Seidel TUPA02

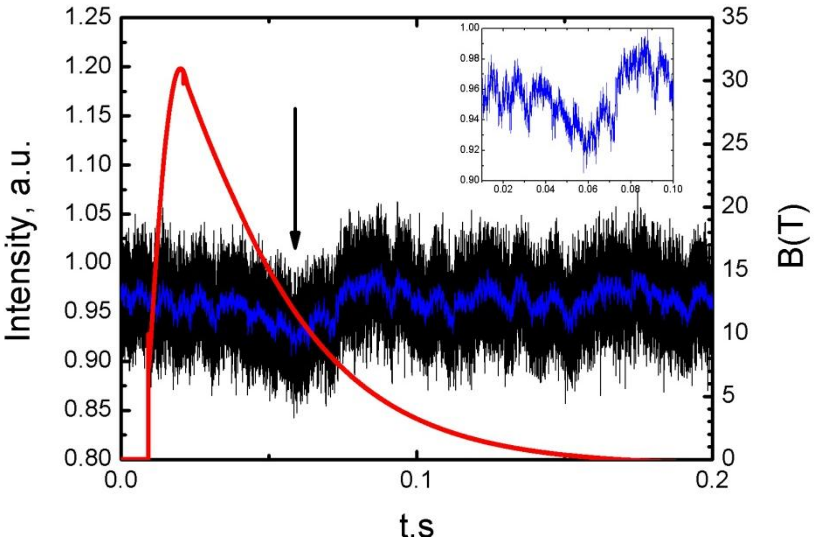
E.H. Haselhoff et al., Nucl. Instr. and Meth. A358 (1995)ABS28
P. Haar, Ph.D. Thesis, Stanford University (1996)
F.A. Hegmann and M.S. Sherwin, SPIE Vol. 2842 (1996) 90-105
G.M.H. Knippels et al., Nucl. Instr. and Meth. B144 (1998) 32-39

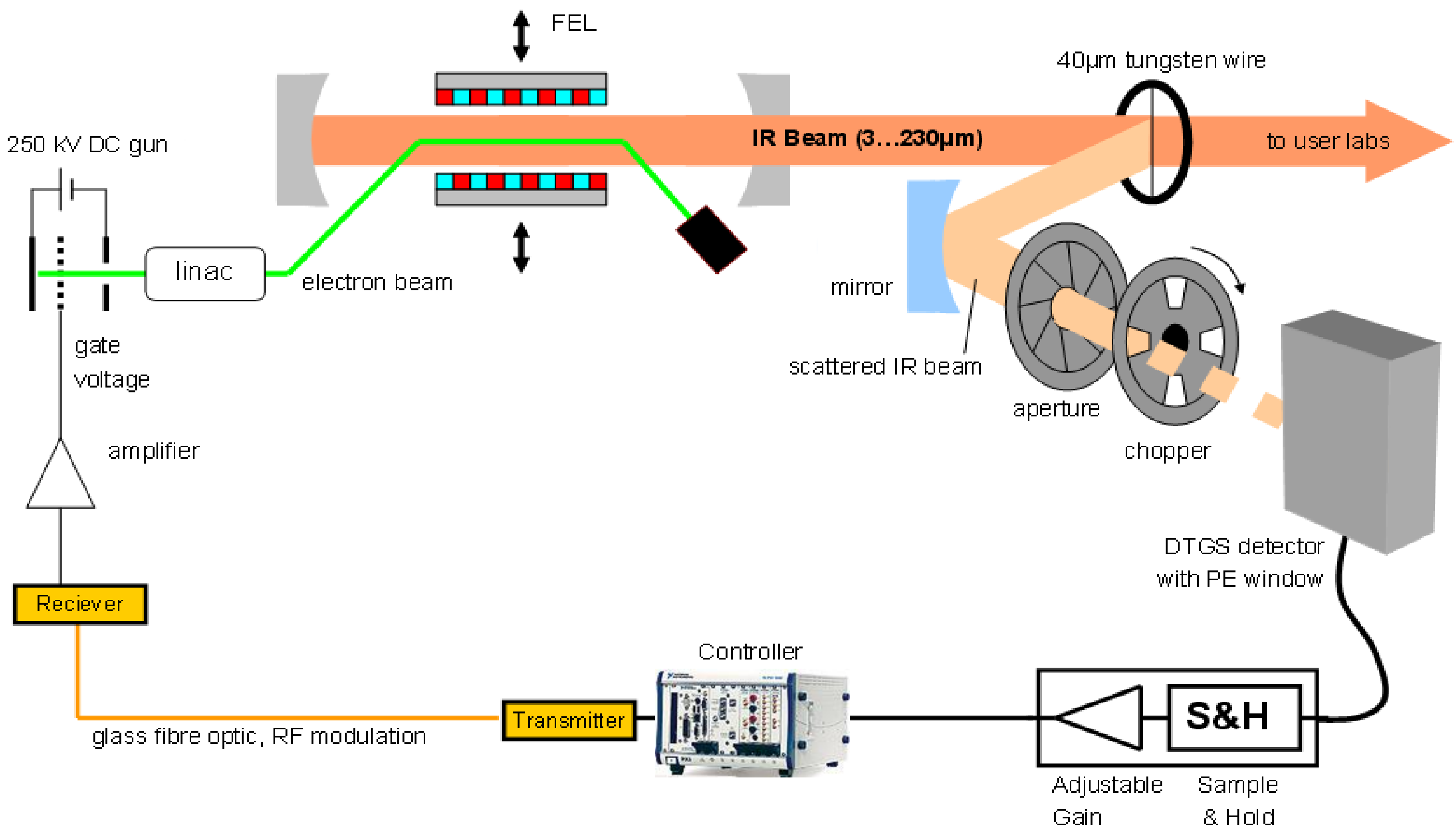
- Measurements between water absorption lines or wavelength gaps of the U100
  require wavelength stability of < 0.5%

- Measurements with small bandwidth require constant wavelength and narrow spectrum

- In-pulse experiments at the High Magnetic Field Laboratory need intensity stability up to the kHz range

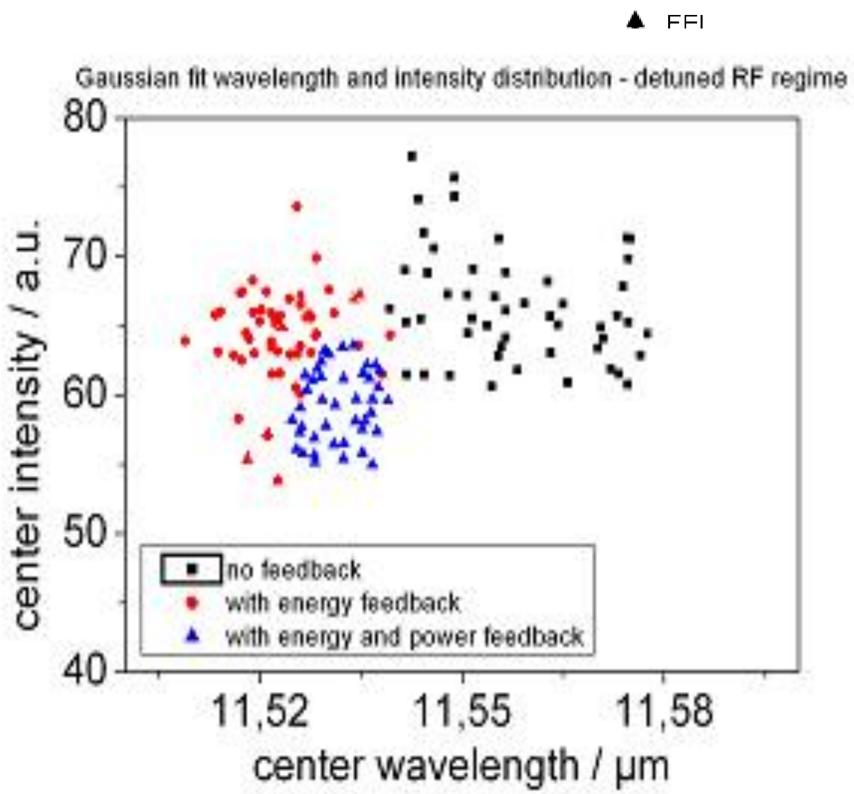


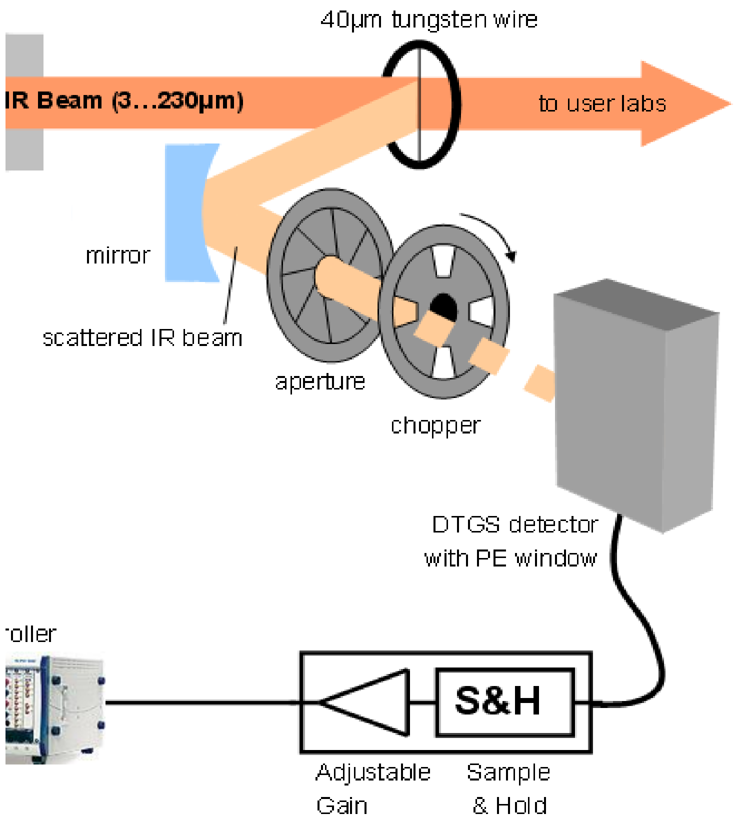




Test with chopper frequency of 2.4 kHz brought an improvement of only ~ 6dB @ 50 Hz due to limitation of the chopper phase stability and the DTGS rise time

Infrared beam stabilization

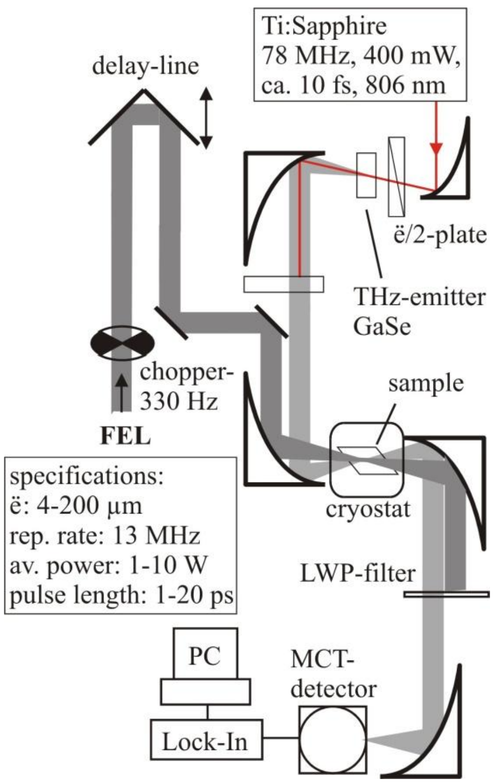


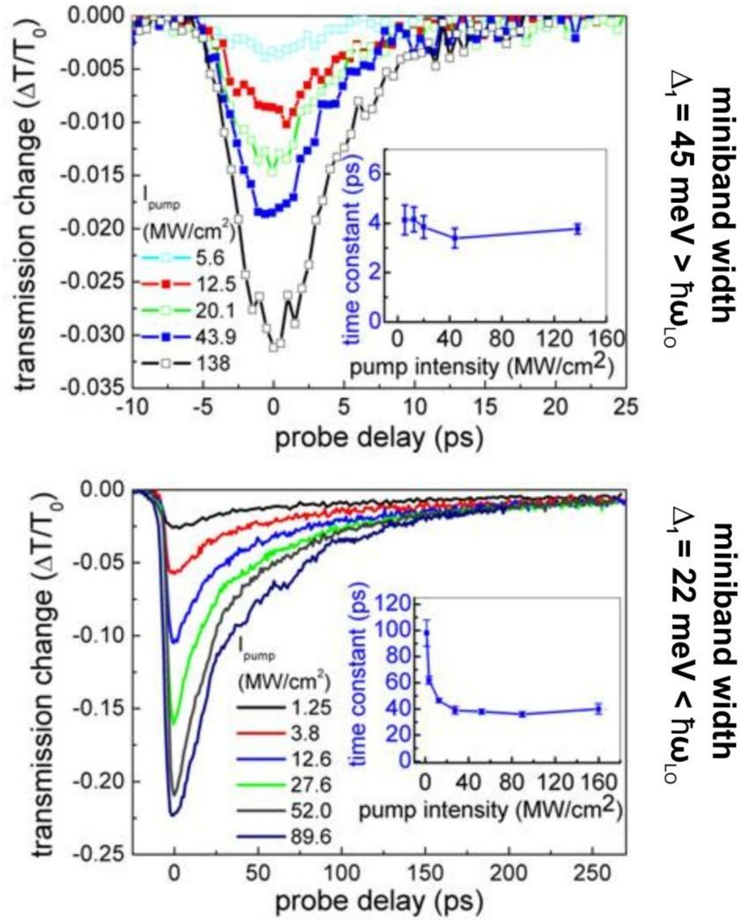


Test with chopper frequency of 2.4 kHz brought an improvement of only ~ 6dB
@ 50 Hz due to limitation of the chopper phase stability and the DTGS rise time

Intraminiband relaxation in doped GaAs & AlGaAs superlattices studied by two-color infrared pump-probe experiment

Intersubband relaxation processes are directly incorporated into the design of quantum cascade lasers and quantum well infrared photondetectors



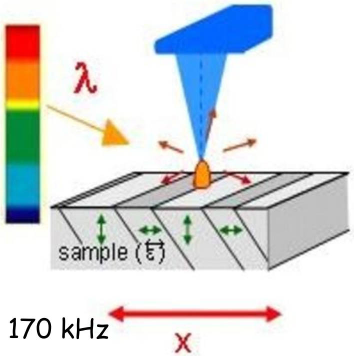


D. Stehr et al., Appl. Phys. Lett. **92**, 051104 (2008)

Scanning near-field microscopy (SNOM)

In all types of near-field microscopy one looks at signals related to evanescent fields, i.e., one throws away 99.99...% of the available power.

⇒ a source with large average power is needed (> 100 mW).



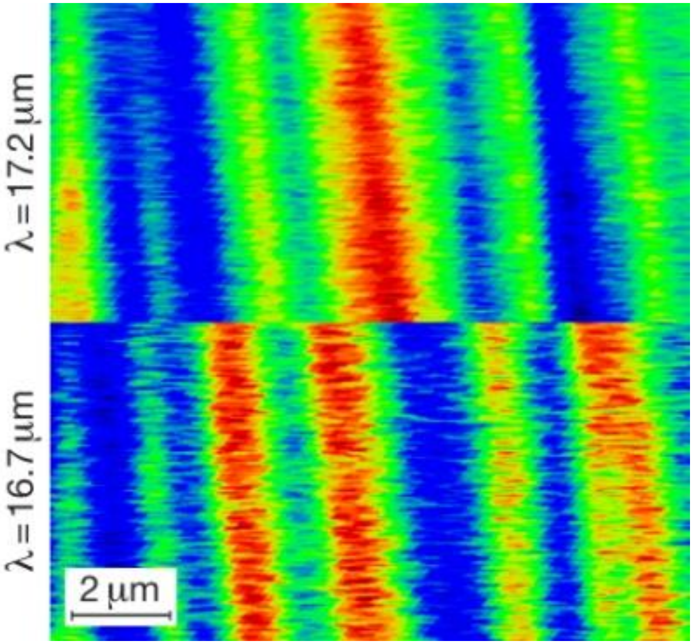
If one wants to study resonant phenomena in materials:

- Non-contact AFM
- Cantilever frequency Ω ~ 170 kHz
- Constant amplitude A = 30 nm
- Resonant excitation: λ = 3.....24 μm

⇒ a tunable source is needed ⇒ FEL !

- in the past: F. Keilmann's group using CO2 lasers
 broad band THz: R. Kersting (Munich), P. Planken (Delft)
 some work also by J.-M. Ortega at CLIO and Stanford

Here: look at ferroelectrics domains in Bariumtitanate using the FEL (Group L.M. Eng, TU Dresden)
(used in electro-optical and elektromechanical devices)



⇒ Characteristic spectroscopic respose

⇒ Anisotropy contrast

⇒ Contrast reversal

⇒ Resolution better than λ/150

S. Schneider et al., Appl. Phys. Lett. **90**, 143101 (2007) & S.C. Kehr et al., Phys. Rev. Lett. **100**, 256403 (2008)

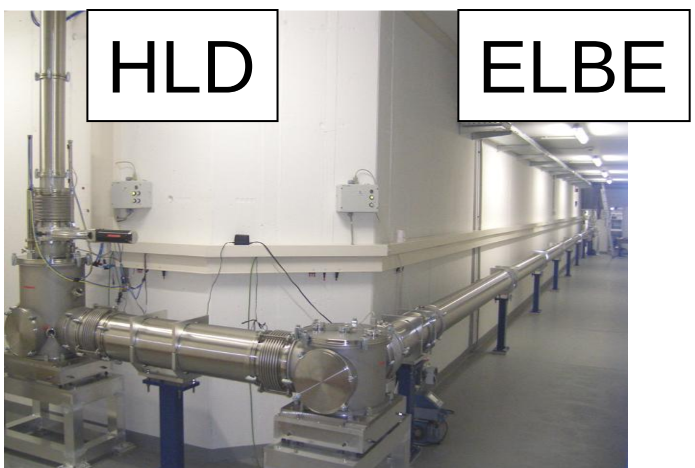
The High Magnetic Field Laboratory Dresden (HLD) focuses on modern material research in high magnetic fields. In particular, electronic properties of metallic, semiconducting, superconducting, and magnetic materials are investigated. Self-designed magnets for fields up to 70 T (100 T in future) for 100ms are available.

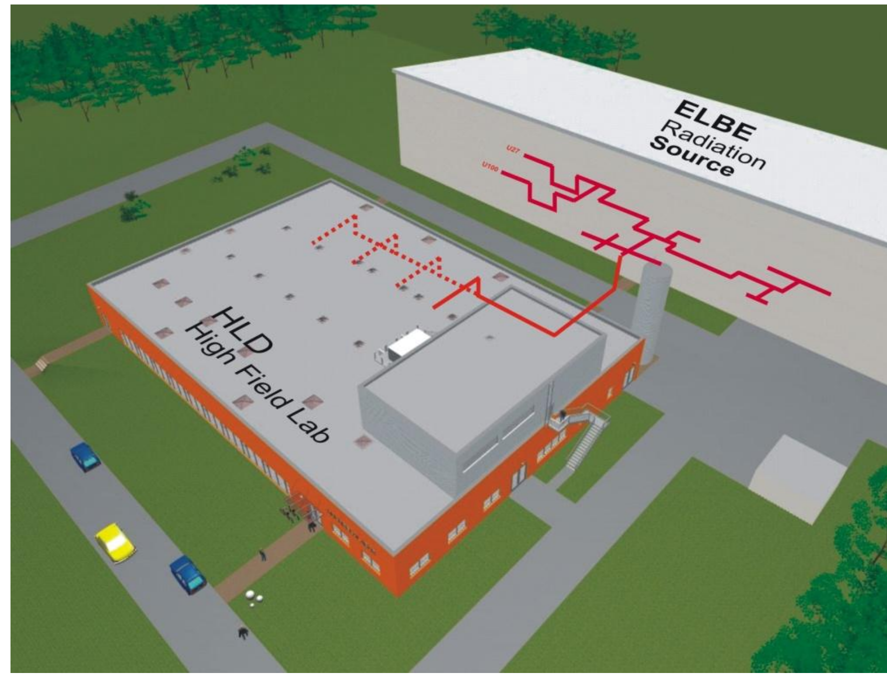
Record 87 T

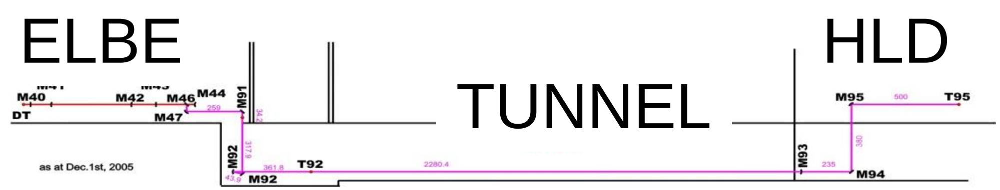
Unique in the world, FELBE can be used in combination with pulsed high-field magnets up to 60 T for magneto-optical experiments at low temperatures.

Wavelength: 4 µm - 250 µm

Transmission over 70 m: 20 % - 50 %
(14 Mirrors)



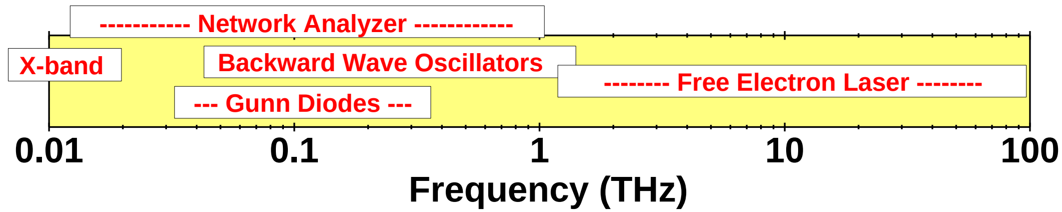


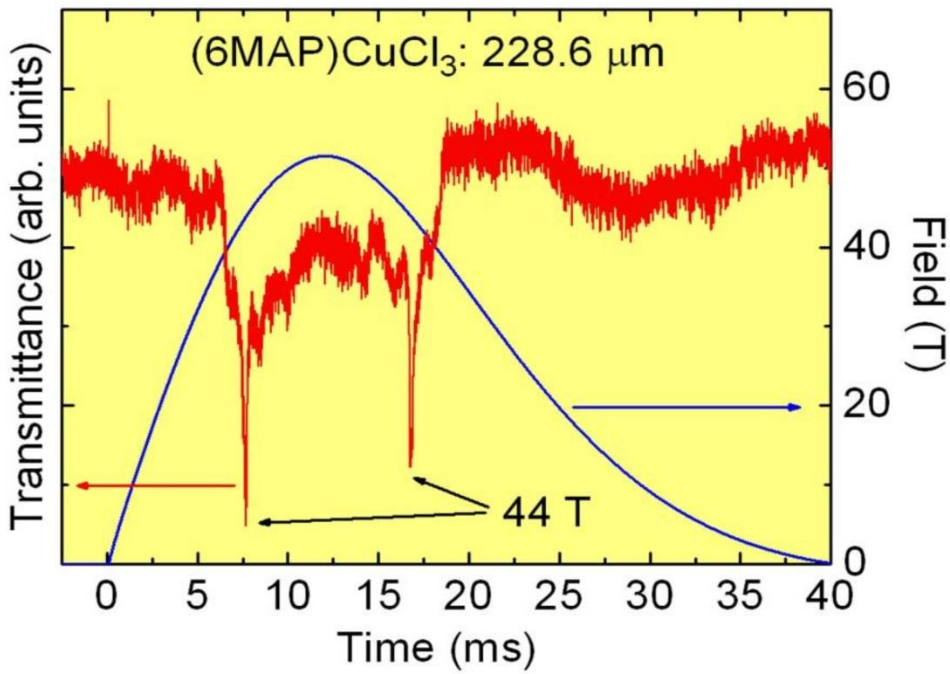


J. Wosnitza et al., J. Physics Conf. Ser. 51 (2006) 619

Pulsed-field ESR with FELBE

Electron Spin Resonance (ESR) is known for ist remarkable resolution and the accessibility of large zero-field spin-level splitting in magnetic materials





No synchronization of the FEL with the magnetic pulses is needed, since the FEL runs continuously at 13 MHz

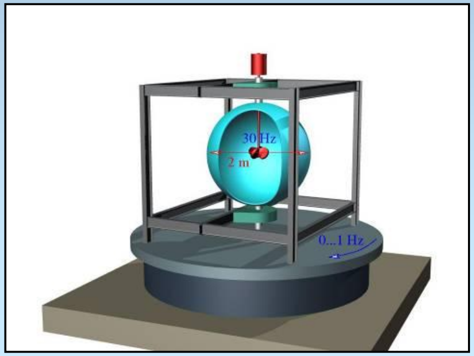
> 10^6 FEL pulses during one magnetic-field pulse of 100 ms length provide excellent measurement conditions

S. Zvyagin et al., Review of Scientific Instruments 80 (2009), 073102

❖ Center for High-Intensity Radiation Sources
to explore extreme conditions of matter
(laser in petawatt regime + broadband THz source + coupling of lasers with Radiation Source ELBE)
2010-2014 | ~ 55 Mio. Euro

❖ Extension of the Dresden High-Magnetic Field Laboratory to an international user center
2011-2013 | ~ 20 Mio. Euro

❖ DRESDYN – European platform for dynamo experiments and thermohydraulic studies with liquid sodium
2013-2015 | ~ 20 Mio. Euro

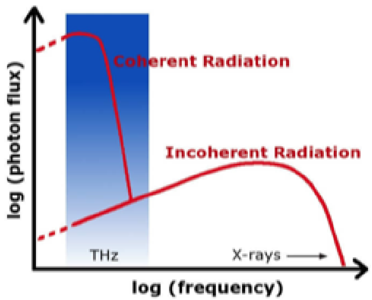


Future: Three complementary THz sources driven by ELBE-beam

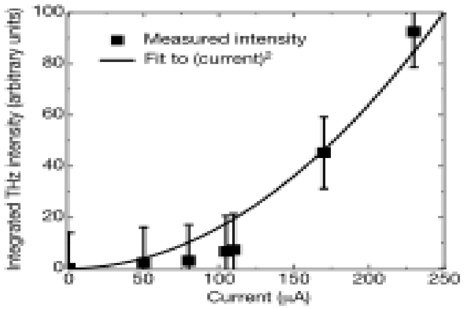
Basis: achieve very short electron bunches (down to 200 fs) through superconducting RF photo-gun & chicane.

Poster: U. Lehnert THPC05

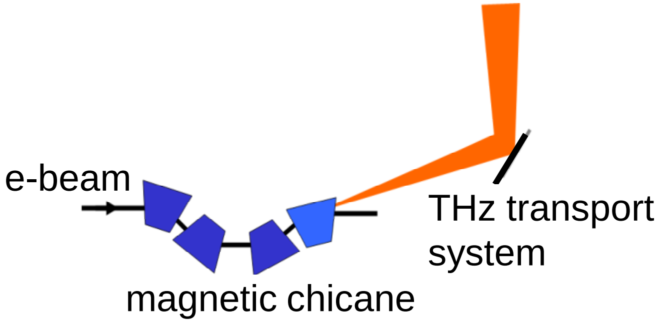
1. Coherent, broad-band THz radiation



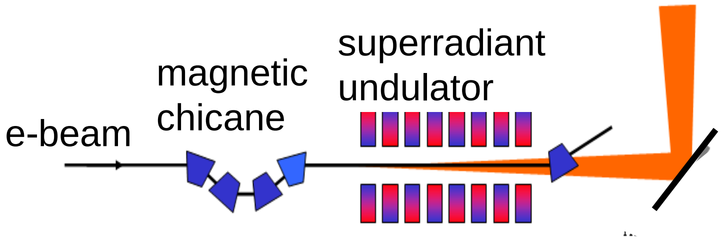
For frequencies $f < 1 / t_{bunch}$ the radiated intensity is proportional to N^2



G. L. Carr et al. Nature 420, 153 (2002).

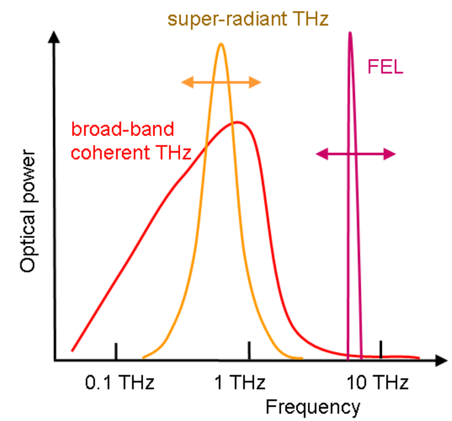


2. Coherent, narrow-band THz radiation (superradiant): undulator with 5-10 periods without resonator



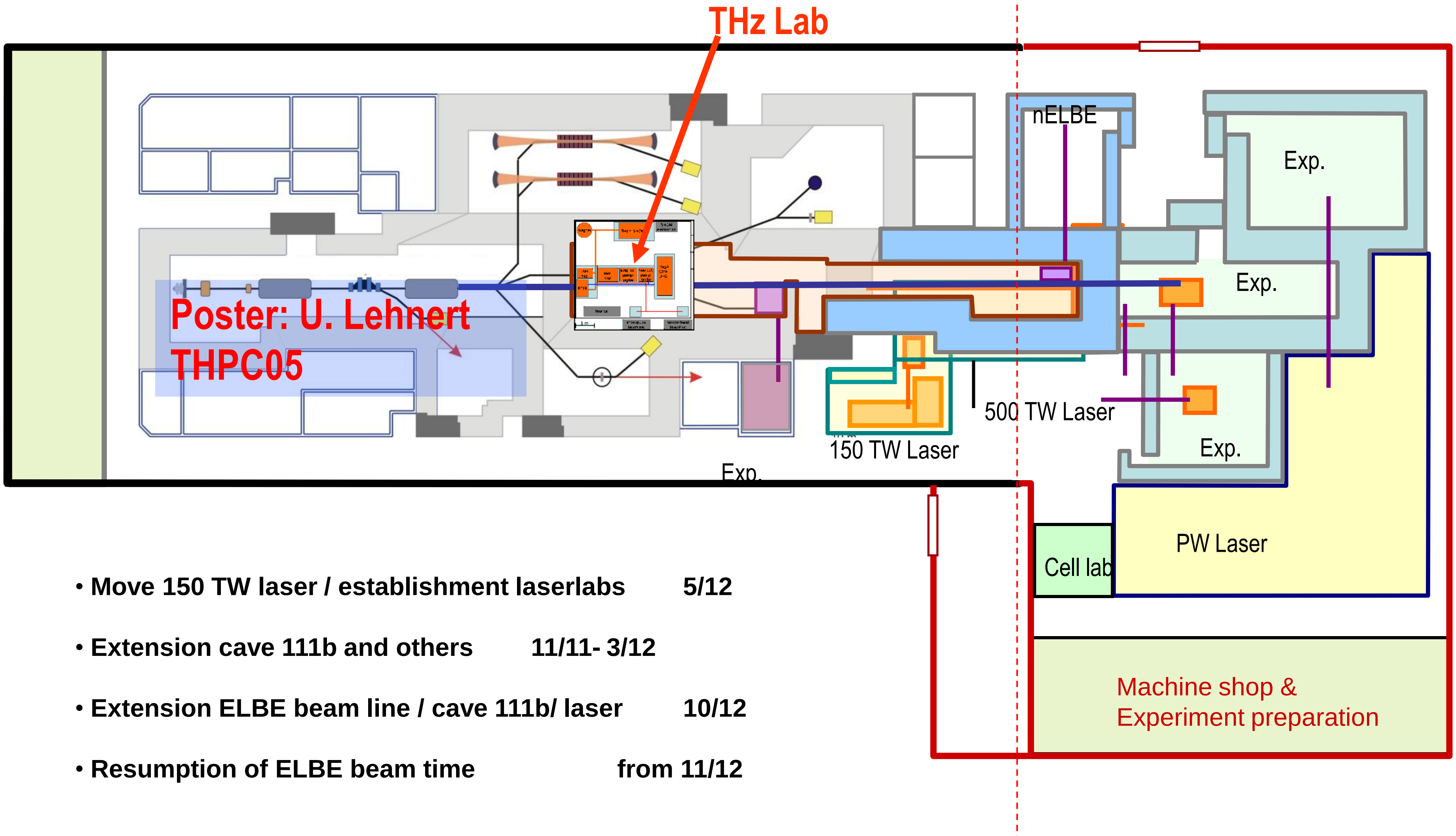
Benefits:

- adjustable rep. rate and bunch charge via pump laser of new electron gun
- shorter pulses and higher peak power than with FEL
- goal: electric-field detection of new THz pulses with electro-optical sampling ⇒ high precision synchronization (<200 fs FWHM) needed.

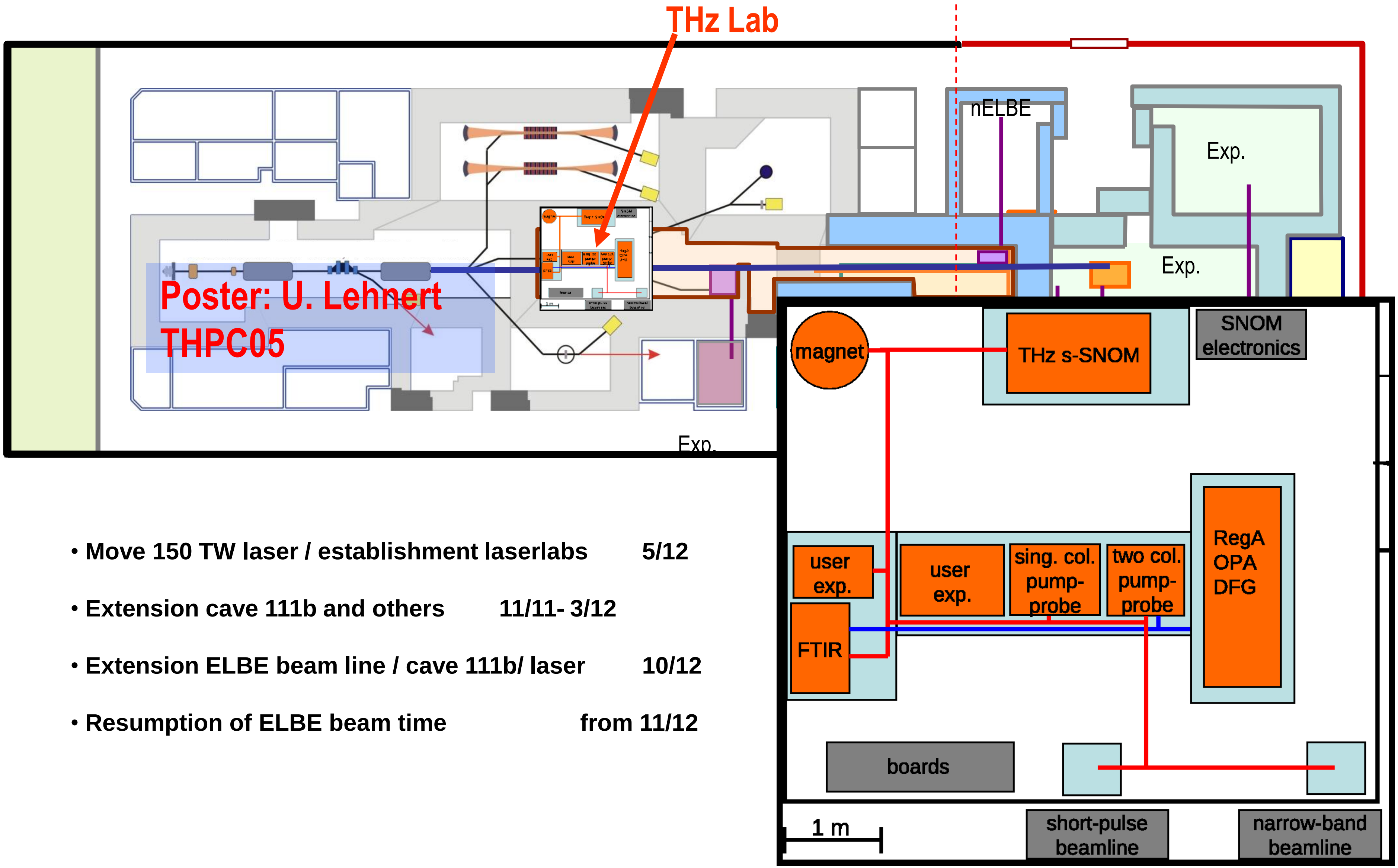


3. FEL-Oscillator (working)

Extension of ELBE & new THz laboratory



- Move 150 TW laser / establishment laserlabs 5/12
- Extension cave 111b and others 11/11- 3/12
- Extension ELBE beam line / cave 111b/ laser 10/12
- Resumption of ELBE beam time from 11/12



- **Move 150 TW laser / establishment laserlabs 5/12**
- **Extension cave 111b and others 11/11- 3/12**
- **Extension ELBE beam line / cave 111b/ laser 10/12**
- **Resumption of ELBE beam time from 11/12**


ELBE


ELBE

- ELBE works very succesfully as user facility with high reliability (>95%)
- Combination of FELBE & HLD unique in the world
- ELBE is overbooked ⇒ 7day/week operation from October 2008!
- Combination of ELBE & high power Laser lab offers new physics
- Low frequency fluctuations (< 50 Hz) could be compensated by a feed back systems
- To control higher frequencies fluctuations (> 50 Hz) new system is under constuction
- Planned new THz sources at FZD: Coherent broad- and narrow-band radiation

Acknowledgment