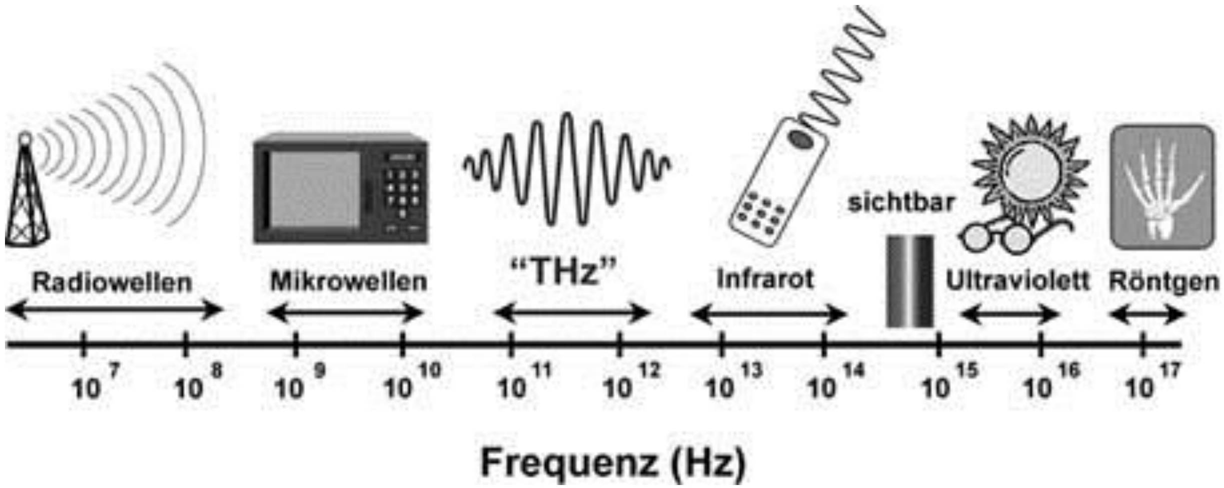
THz Activities in Dresden/Rossendorf

M. Gensch
HZDR & THODIAC coll.

HELMHOLTZ
ZENTRUM DRESDEN
ROSSENDORF

THZ Radiation

Definition



"The term typically applies to electromagnetic radiation with frequencies between high-frequency edge of the microwave band, 300 gigahertz (3×10^{11} Hz), and the long-wavelength edge of far-infrared light, 3000 GHz (3×10^{12} Hz or 3 THz)", ***Wikipedia***

„Der Terahertz-Bereich (THz) liegt im elektromagnetischen Spektrum zwischen Mikrowellen und Infrarotstrahlung. Er ist nicht strikt definiert, aber im Allgemeinen sind damit Frequenzen im Bereich von 0,3 THz bis 10 THz", ***DLR/PTB***

Definition

THz: 10 – 0.3 THz or 30 – 1000 μm or 330 cm^{-1} – 10 cm^{-1}

mid – infrared (MIR)*: 99.9 – 6 THz (3 – 50 μm)
far-infrared (FIR)*: 6 – 0.3 THz (50 – 1000 μm)

*Deutsches Institut für Normung (Hrsg.): *Strahlungsphysik im optischen Bereich und Lichttechnik; Benennung der Wellenlängenbereiche*. In: *DIN*. 5031 Teil 7, 1984-01.

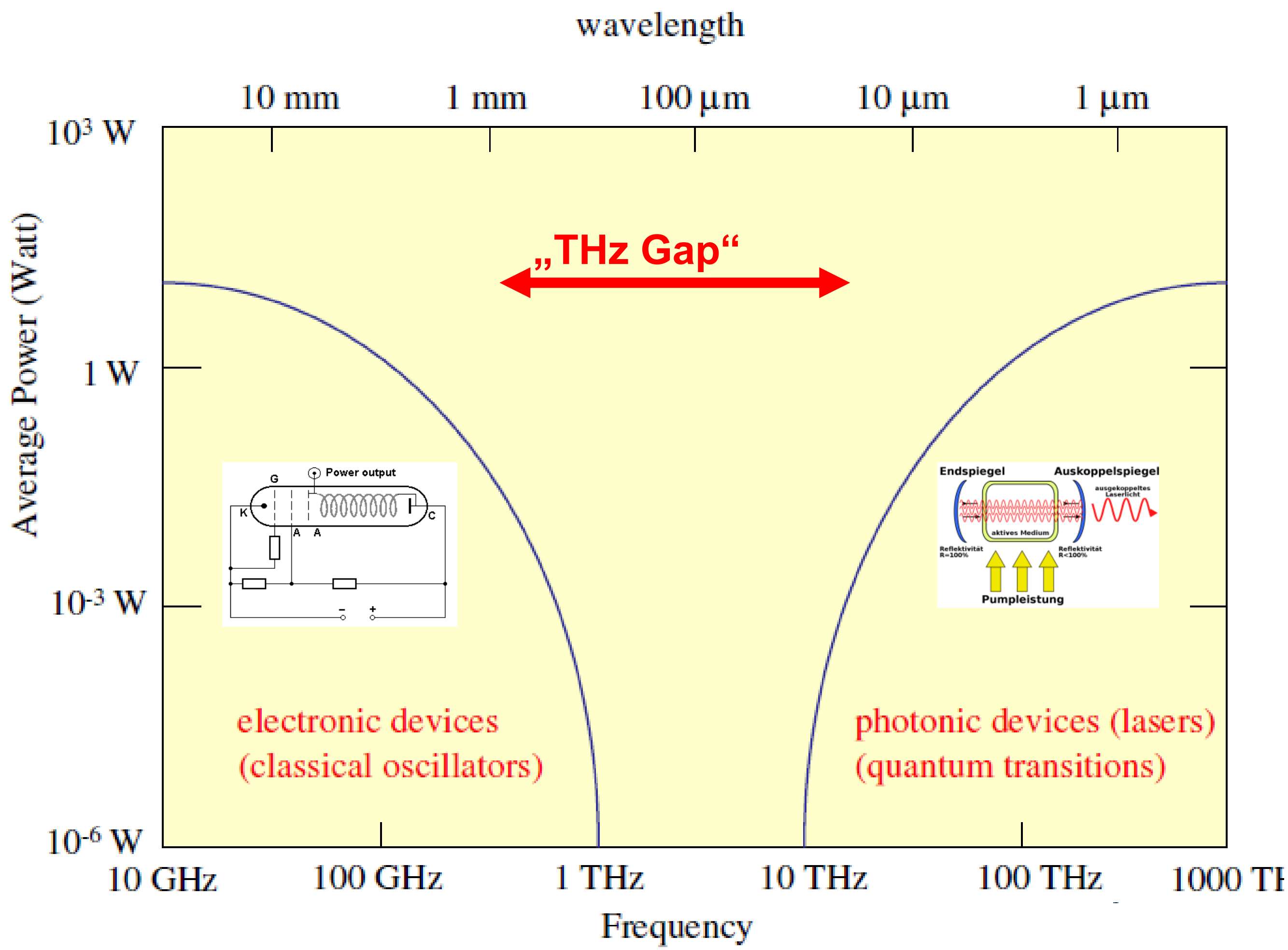
or: 1 THz ~ 300 μm ~ 1 ps

“The term typically applies to electromagnetic radiation with frequencies between high-frequency edge of the microwave band, 300 gigahertz (3×10^{11} Hz), and the long-wavelength edge of far-infrared light, 3000 GHz (3×10^{12} Hz or 3 THz)”, ***Wikipedia***

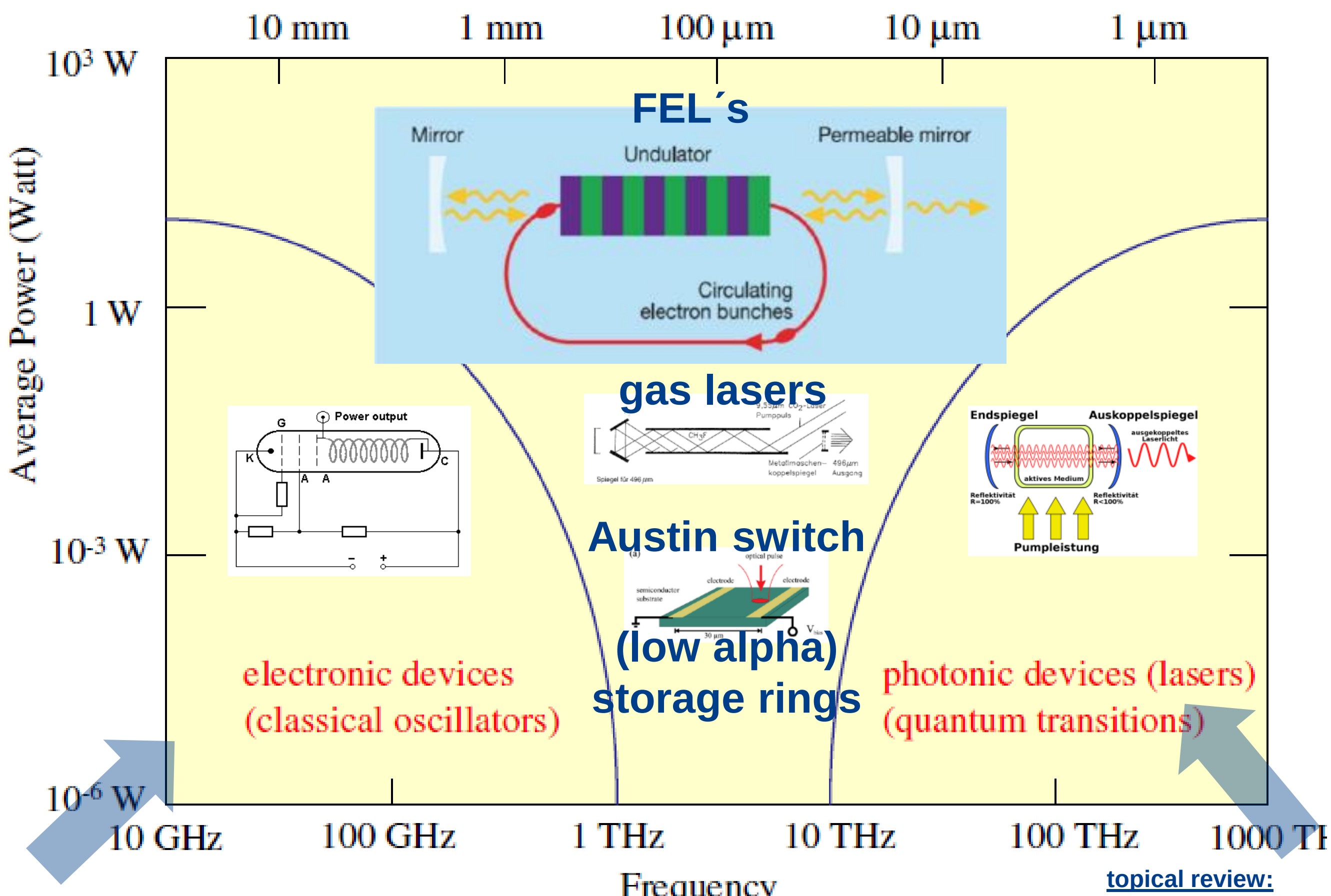
„Der Terahertz-Bereich (THz) liegt im elektromagnetischen Spektrum zwischen Mikrowellen und Infrarotstrahlung. Er ist nicht strikt definiert, aber im Allgemeinen sind damit Frequenzen im Bereich von 0,3 THz bis 10 THz“, ***DLR/PTB***

THZ Radiation

Definition „by the absence of sources“



Definition „by the absence of sources“



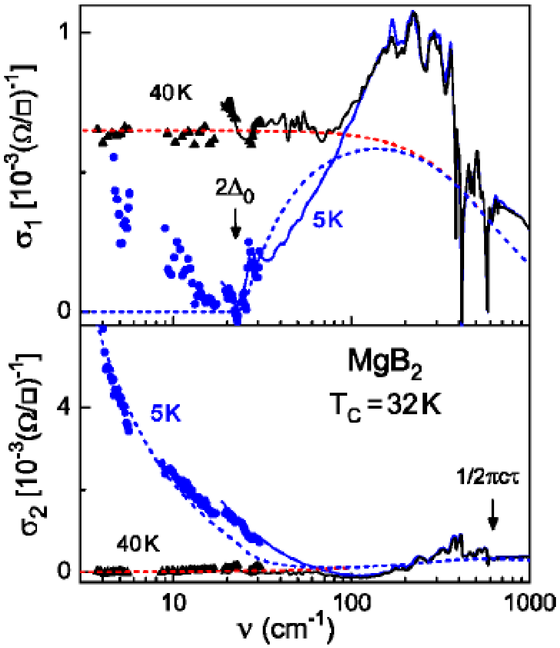
Topical review:
J.H. Booske et. al.,
Vacuum Electronic High Power Terahertz Sources,
IEEE TRANSACTIONS ON TERAHERTZ SCIENCE AND TECHNOLOGY,
VOL. 1, NO. 1,
SEPTEMBER 2011, 54.

topical review:
^M.C. Hofmann & J.A. Fülöp
J. Phys. D: Appl. Phys. 44 (2011) 083001

Applications I

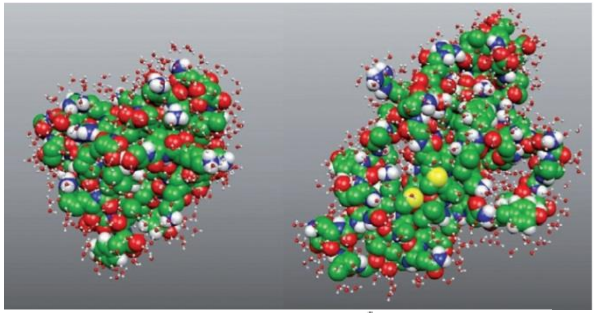
linear spectroscopy – understanding (complex) matter

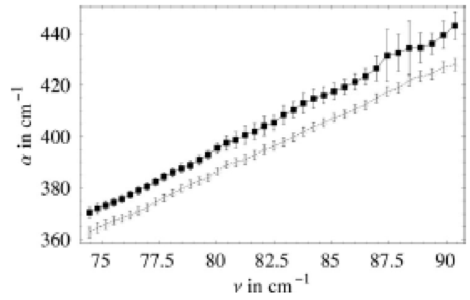
HTC superconductivity

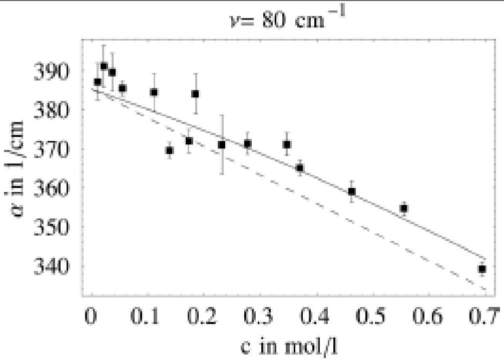


review:
M. Dressel et. al.,
IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS 14 (2008), 399

water, protein-water interactions,…….



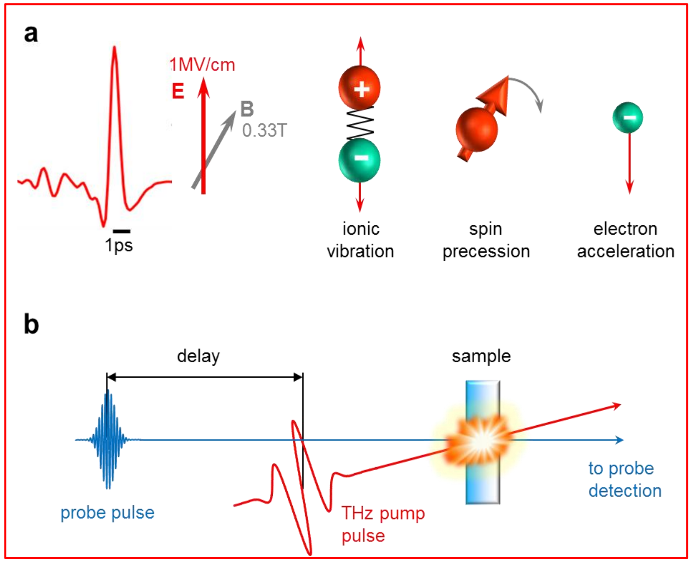




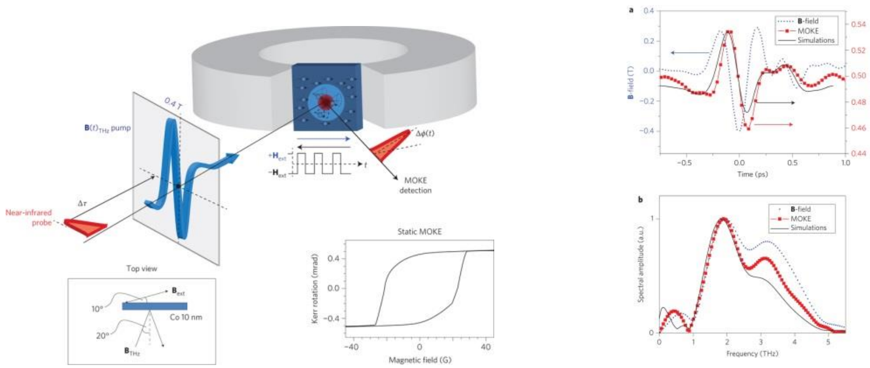
M. Havenith et. al., PNAS (various 2007 – 2013)

Applications II

nonlinear (High-field) THz experiments

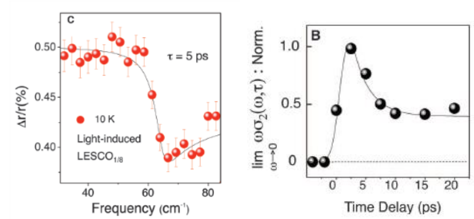


THz control of magnetism

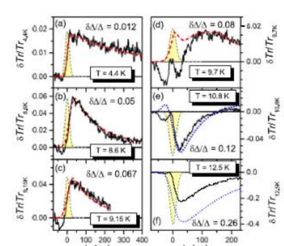


C. Vicario et. al. , Nature Photon. 2013
+ T. Kampfrath et. al., Nature Photon. 2011.

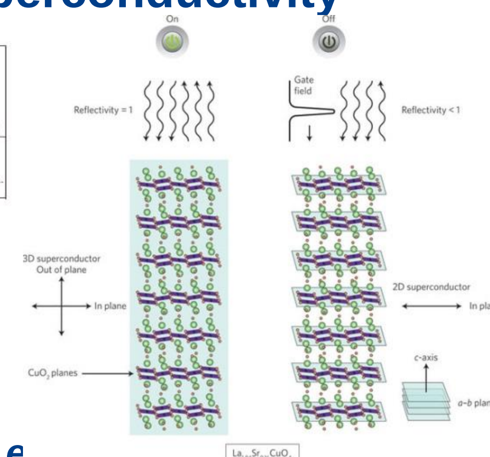
THz control of superconductivity



M. Fausti et. al. , Science 2011

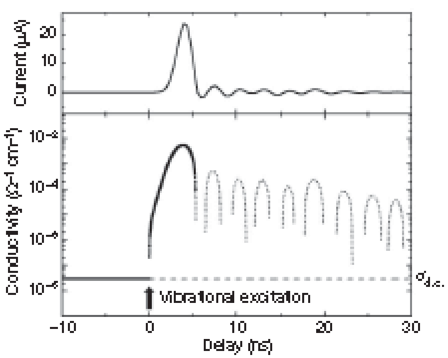


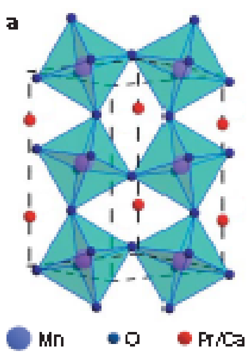
M. Beck e PRL2011



A. Dienst et. al. , Nature Photn. 2011 + Nature Mat. 2013

THz control of conductivity





M. Rini et. al. , Nature 2007
+ M. Liu et. al., Nature 2012.

Applications III

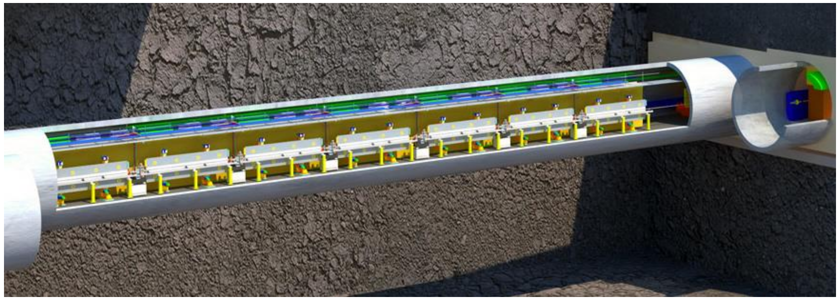
THz-based electron bunch diagn.

super-radiant THz pulses emitted from ultra-short electron bunches in linacs carry information on:

- **shape**
- **arrivaltime**
- **chirp**
- **charge**

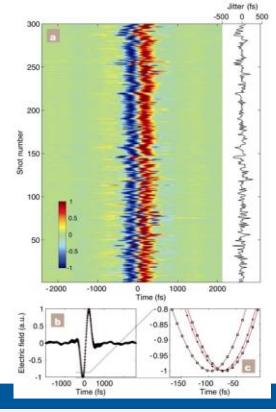
several Nat. Photon./Phys. Rev Lett. + many technical notes

European X-FEL

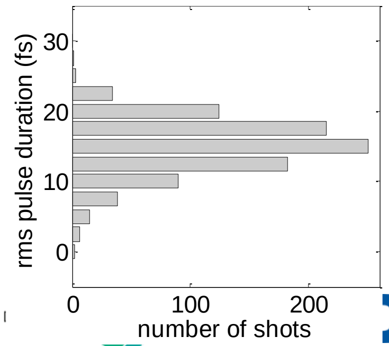


LCLS X-FEL + SACLA X-FEL + PAL X-FEL, …. + ILC

Arrivatime meas.

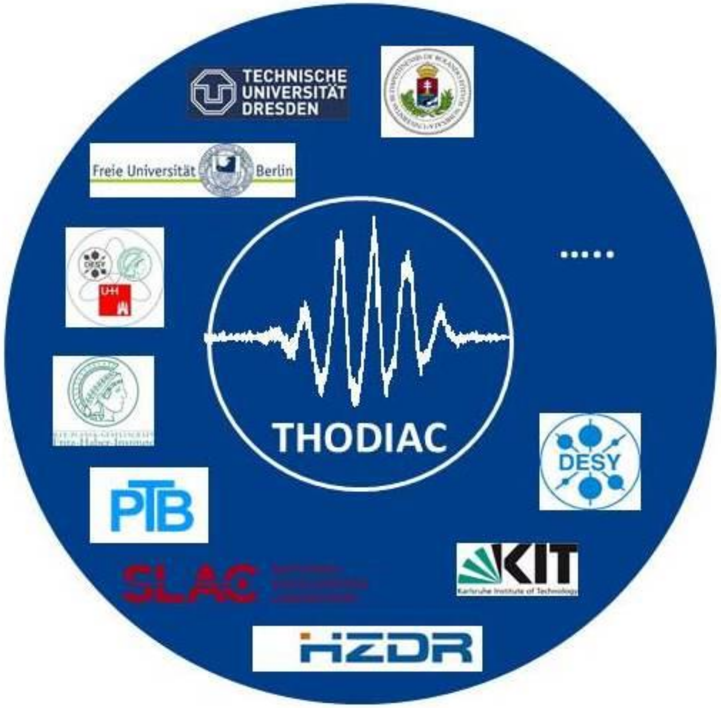


X-ray pulse duration



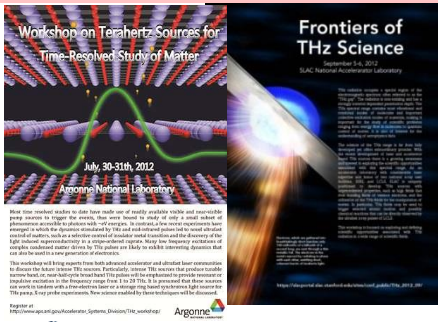
THz photondiagnostic collab. (THODIAC)

N. Stojanovic / DESY
H.W. Hübers / TUB, DLR
A.S. Fisher / SLAC
A.S. Müller / KIT
D. Plettemeier / TUD
A. Steiger / PTB
M. Gensch / HZDR
G. Geloni / X-FEL
…..



pilot „friendly“ users/advisors:

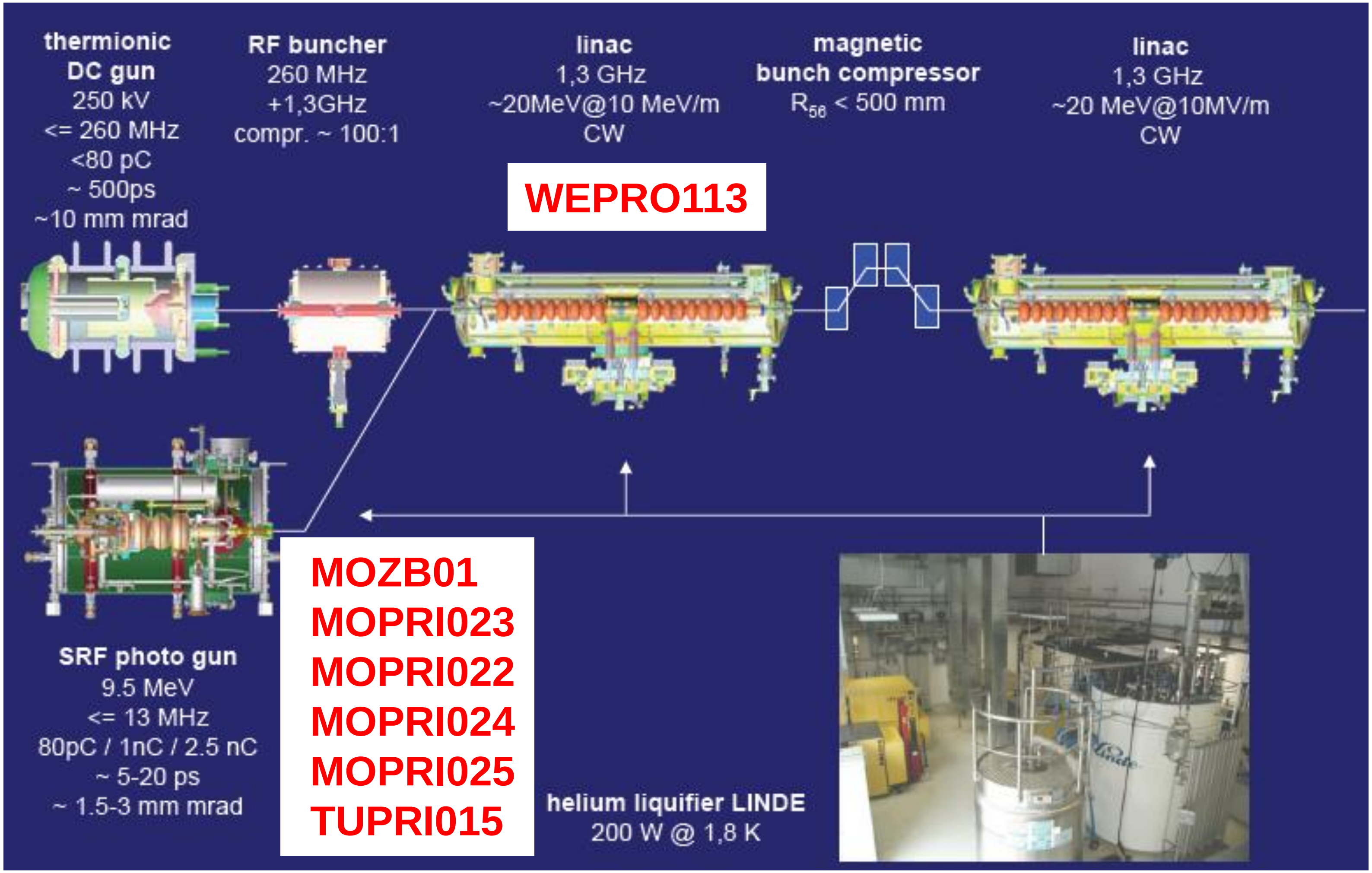
A. Cavalleri – MPSD
T. Cowan - HZDR
A. Deac – HZDR
J. Heberle – FUB
M. Helm - HZDR
R. Huber – U Regensburg
A. Irmann - HZDR
T. Kampfrath – FHI
S. Kehr/L.M.Eng – TUD
J. Lindner – HZDR
A. Lindenberg - SLAC
A. Malnasi – U Budapest
I. Radu – HZB
H. Schneider - HZDR
R. Tobey – U Groningen
S. Wall – ICFO
S. Winnerl - HZDR
S. Zvyagin – HZDR
…..



DRESDEN concept

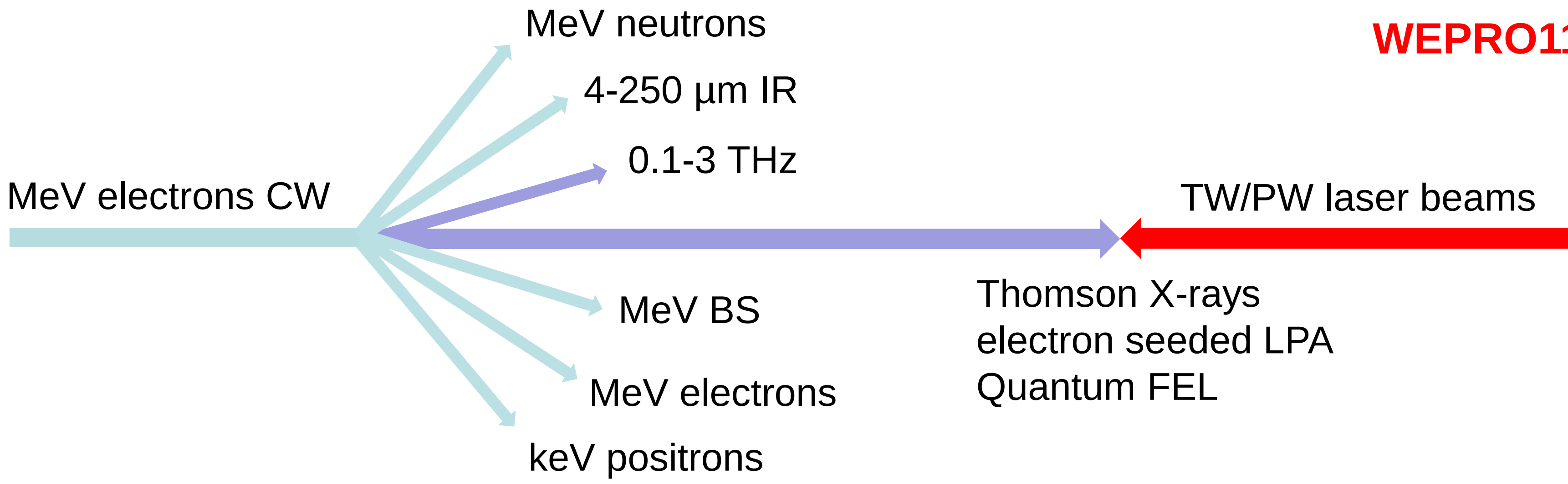
- **ELBE**
- TELBE

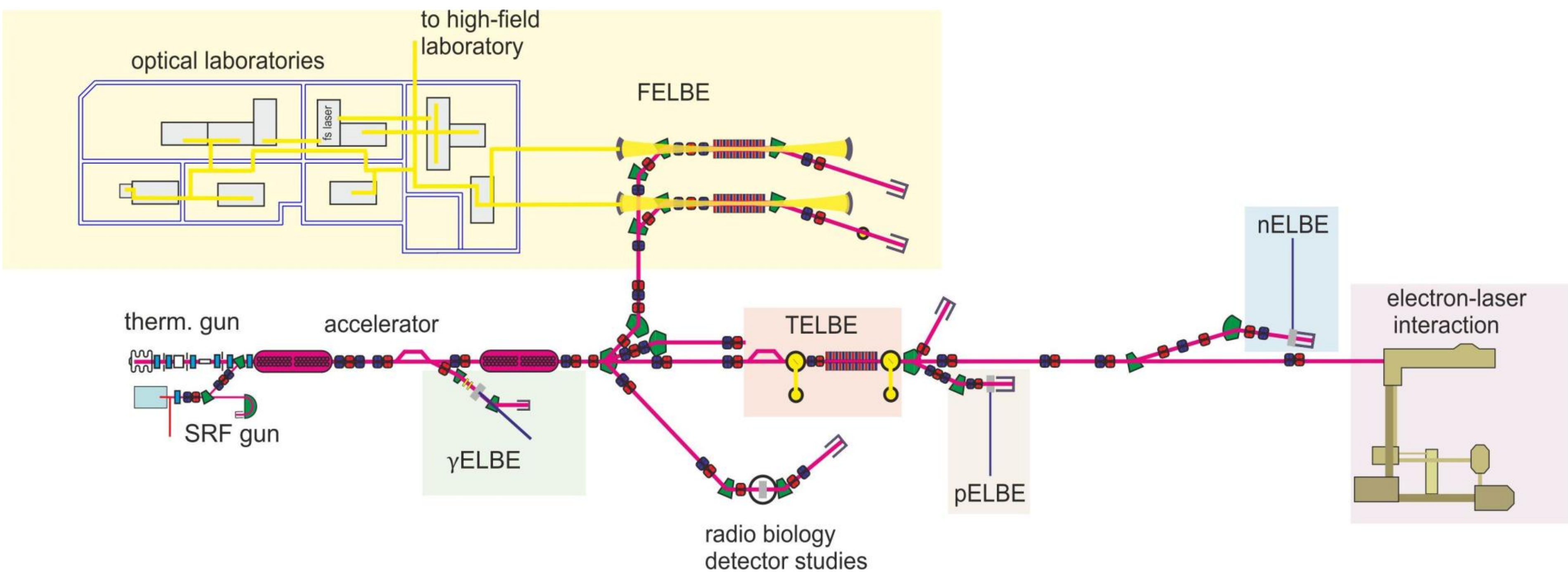
ELBE – Electron Linear Accelerator with high Brilliance and low Emitance



ELBE center for high power radiation sources

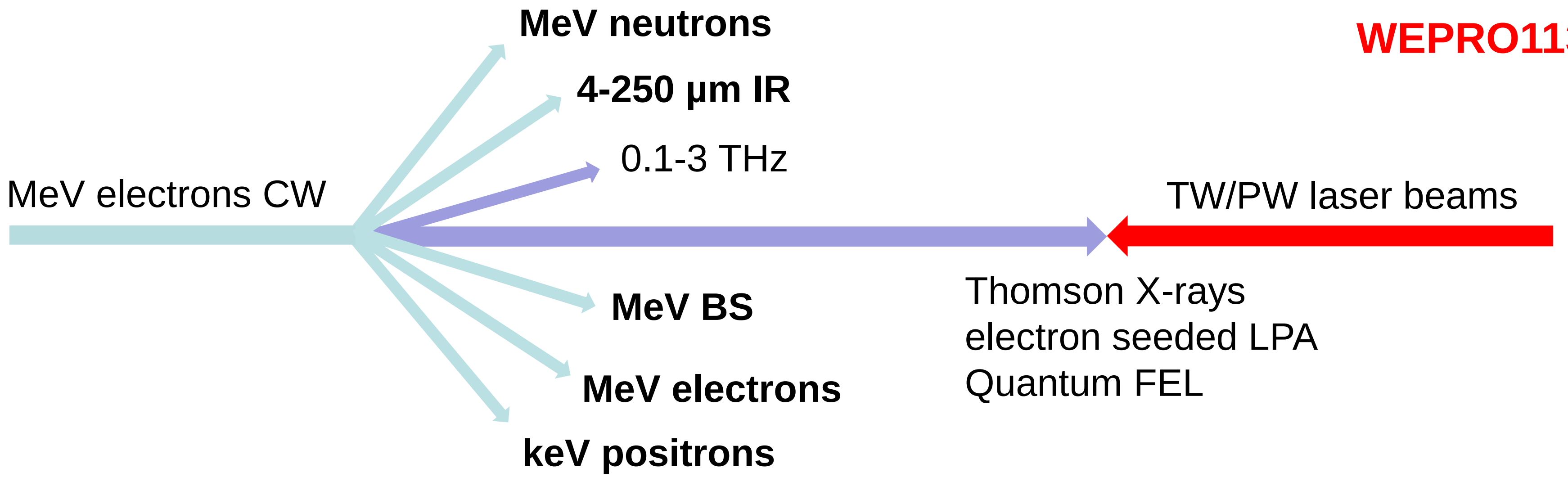
WEPRO113

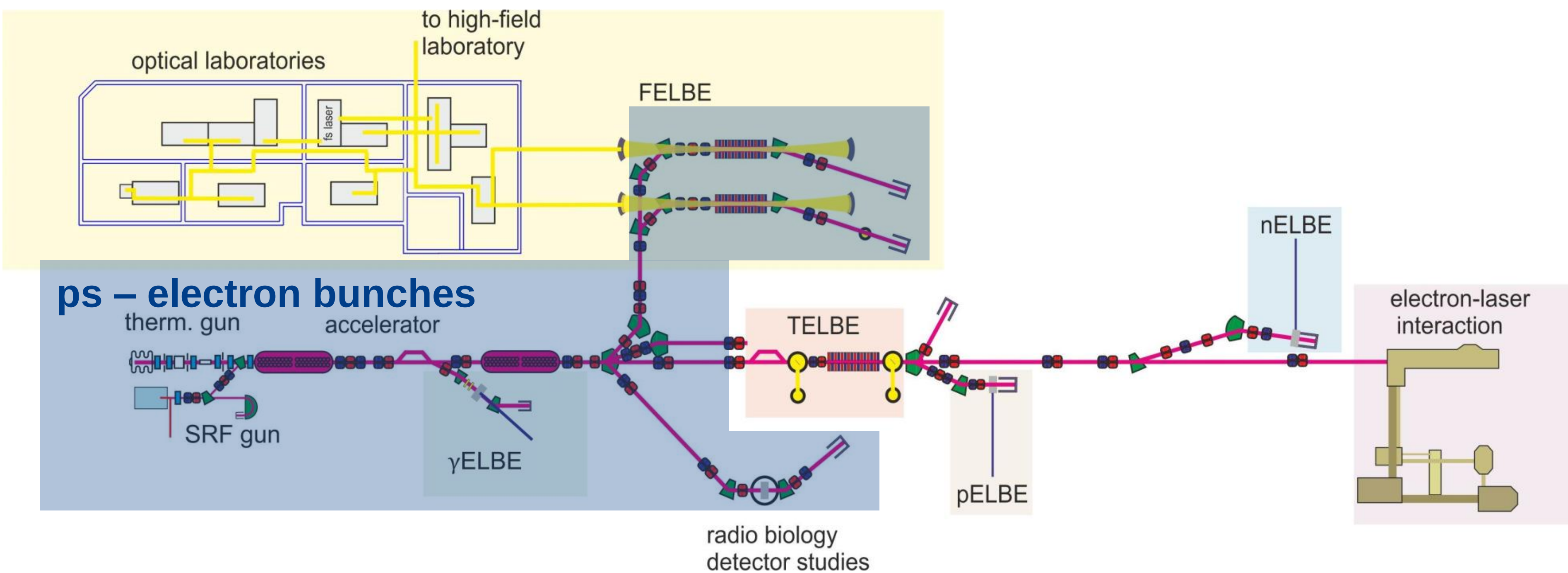




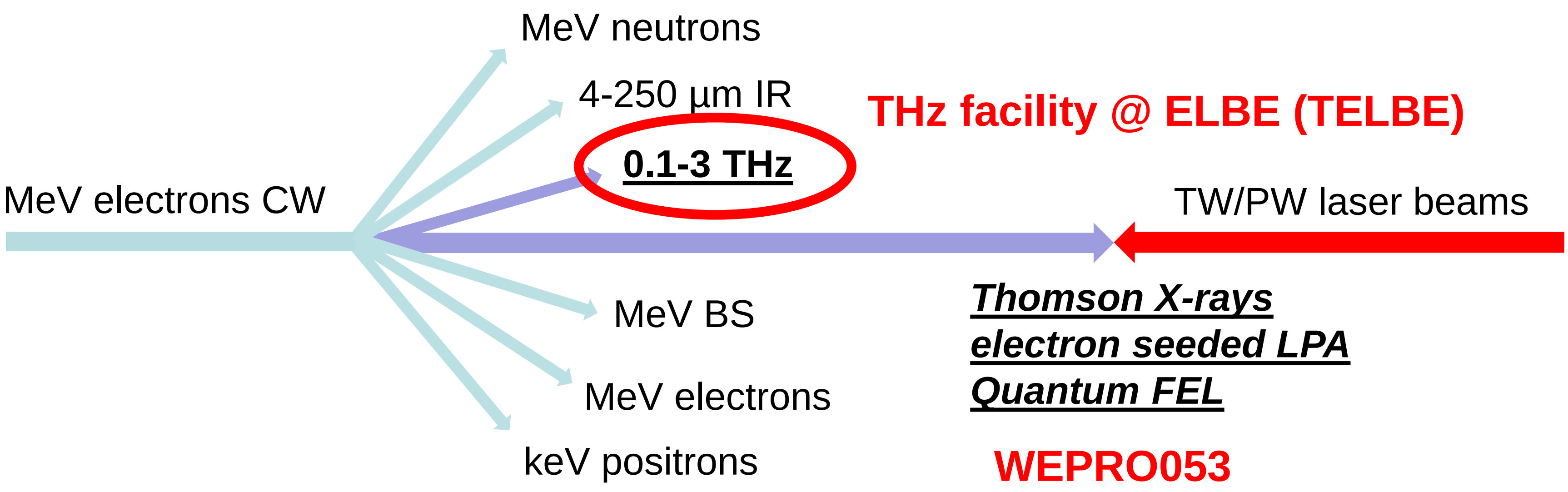
ELBE center for high power radiation sources

WEPRO113





ELBE center for high power radiation sources



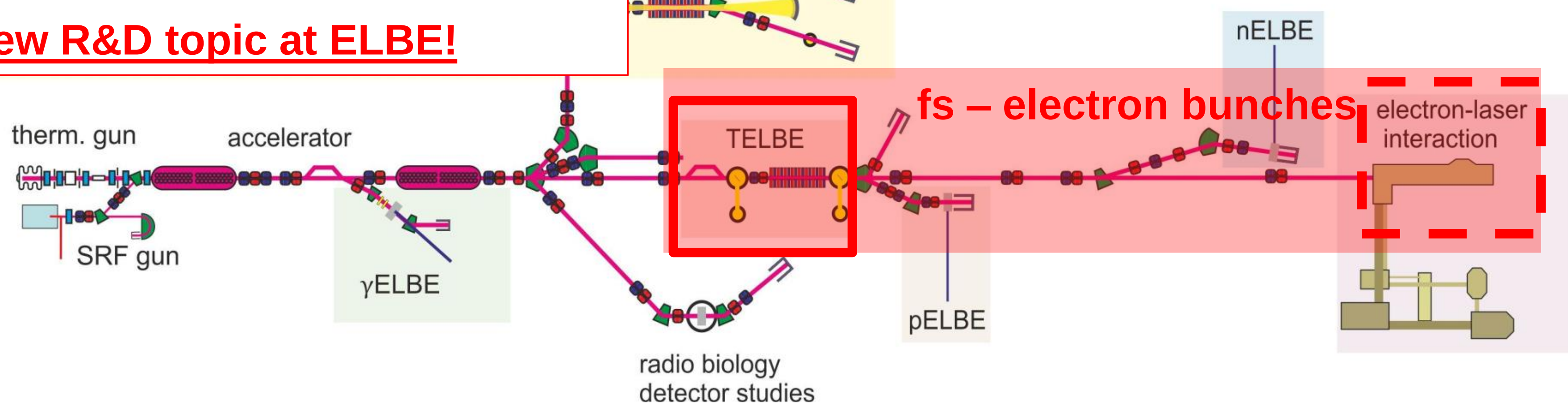
THz facility @ ELBE (TELBE)

Thomson X-rays
electron seeded LPA
Quantum FEL

WEPRO053
WEPRO054
THPRO055

fs –level diagnostic & fs – level control of e-bunches required (form, arrival time, …..)

new R&D topic at ELBE!

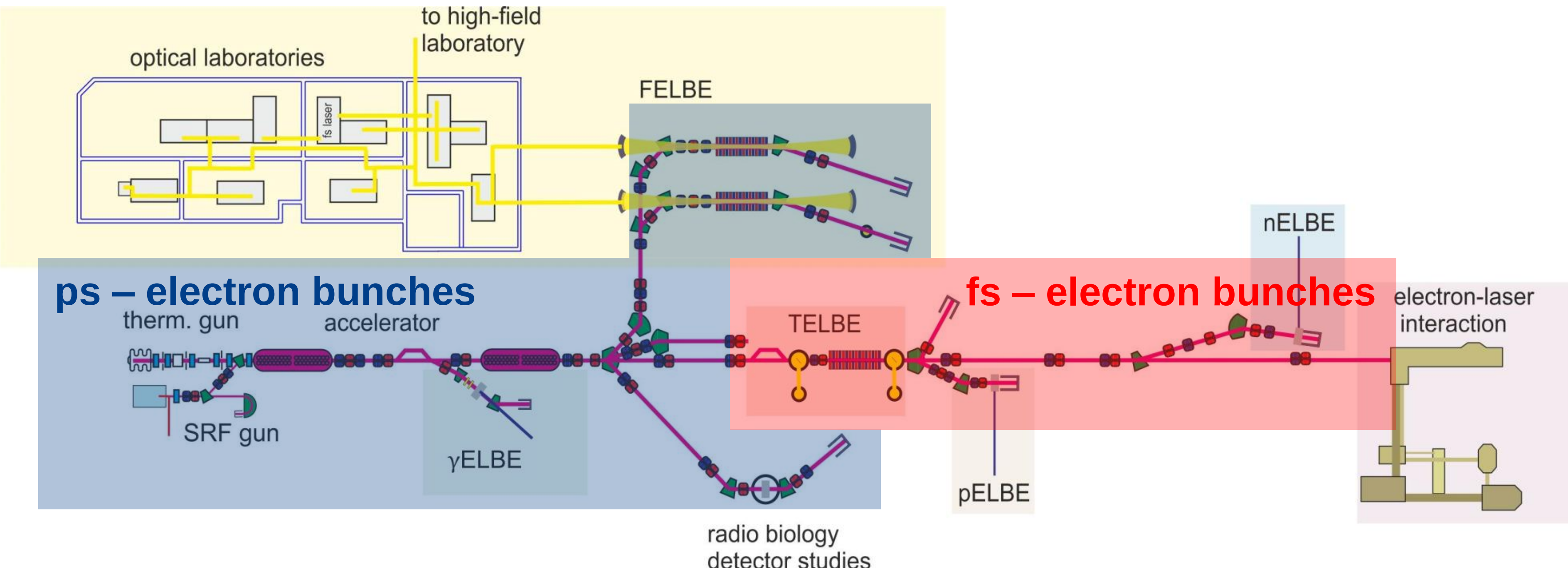


- ELBE
- **TELBE**

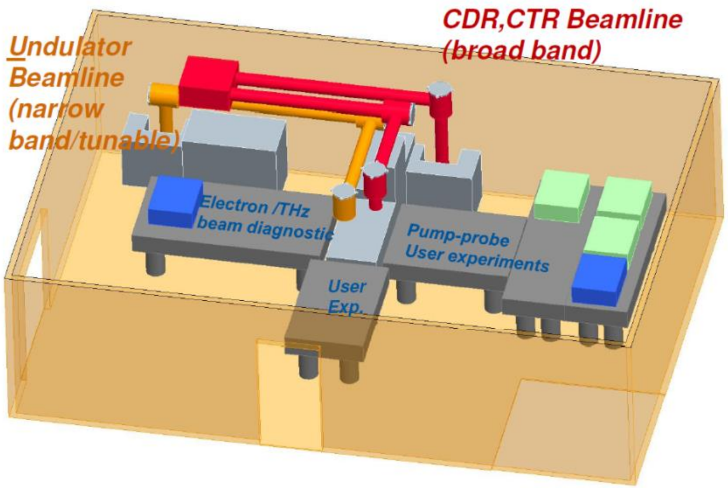
beam energy:
up to 40 MeV

three modes of operation:

1. ***up to 70 pC @ 13 MHz (thermionic gun)***
2. ***up to 1 nC @ few Hz to 500 kHz (SRF Gun)***
3. **diagnostic mode (not more than 100 μA): e.g. 100 pc @ 100 kHz**



TELBE THz source: foreseen applications



<u>High-field THz user facility (by 2016?):</u>

design goals:

- **quasi – cw rep rates: few Hz to 13 MHz (adjustable)**
- **pulsenergies: up to 100 μJ**
- **spectral properties: 0.1 – 3 THz narrow band (10-20%) / broad band**
- **polarization: linear/radially**
- **sub 100 fs synchronisation to fs-laser**
- **intrinsic synchonisation CTR<->undulator**

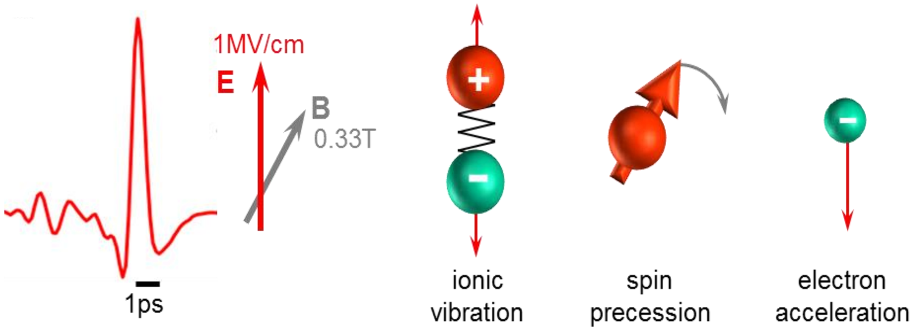
<u>Test facility for e bunch diagnostic on quasi – cw electron beams:</u>

- **quasi – cw reprates: few Hz to 13 MHz (adjustable)**
- **e-bunch charge: few pC – 1 nC**
- **diagnostic table in TELBE lab (access to undulator & CTR source + fs laser + FTIR spectrometer)**
- **monitor test stand in e-beamline directly after THz sources**

Userfacility - Motivation

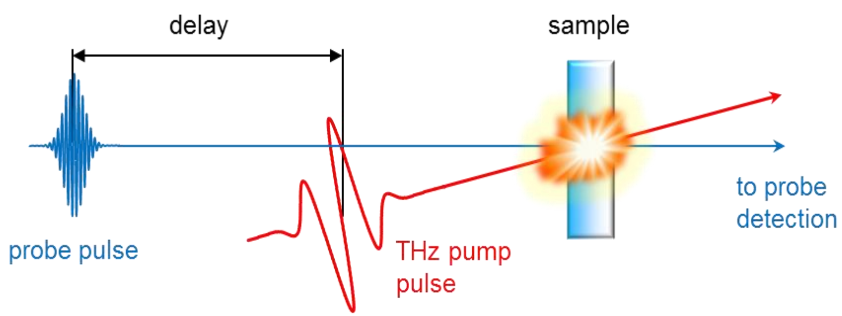
"A striking property of terahertz (THz) radiation is its ability to couple both resonantly and nonresonantly to numerous modes, including the motions of free electrons, the vibration of nuclei in molecules and crystals, and the precession of spins. "

interactions of a THz pulse with matter

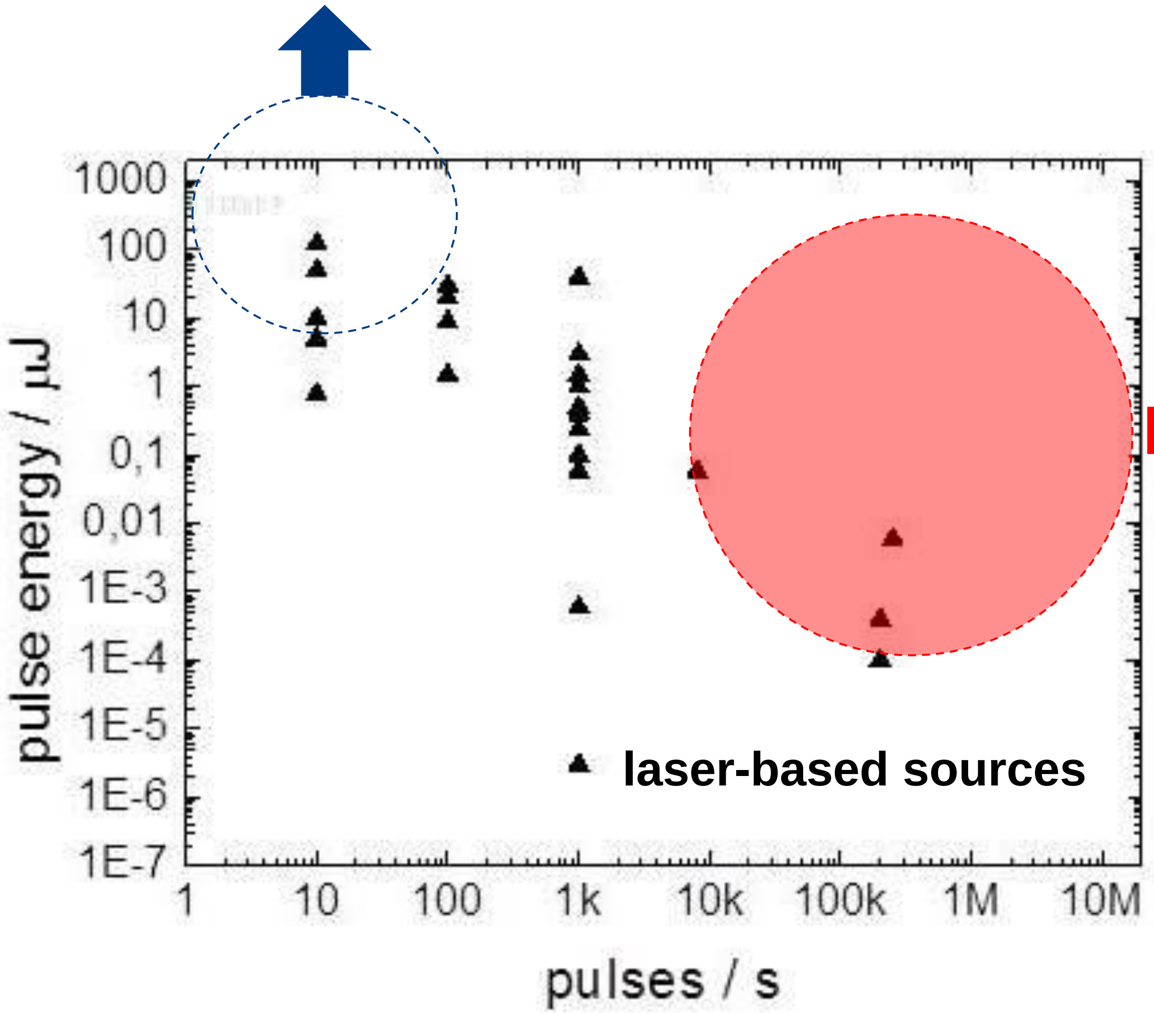


taken from:
Review article by T. Kampfrath, K. Nelson, I. Tanaka,
Resonant and non-resonant control over matter and
light by intense terahertz-transients
Nature Photonics (2013) (Review)

typical pump-probe scheme



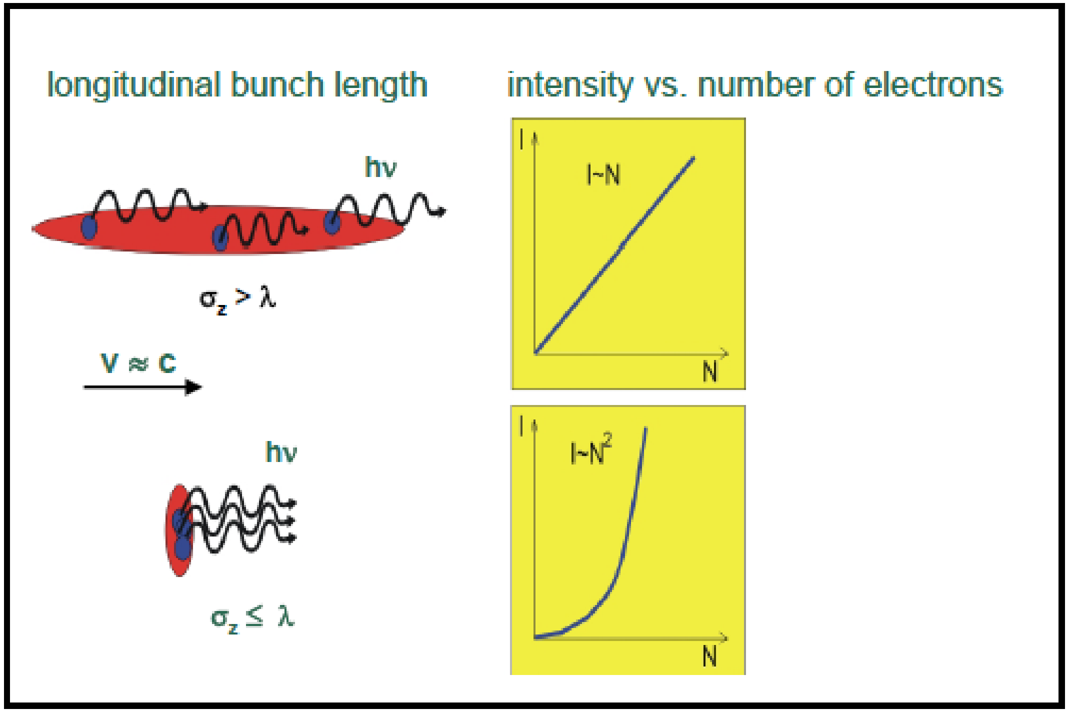
Extreme fields (SLAC, SPARC, FERMI, KIT, PAL,….)



combination of high field & high rep rate (DESY, HZDR)

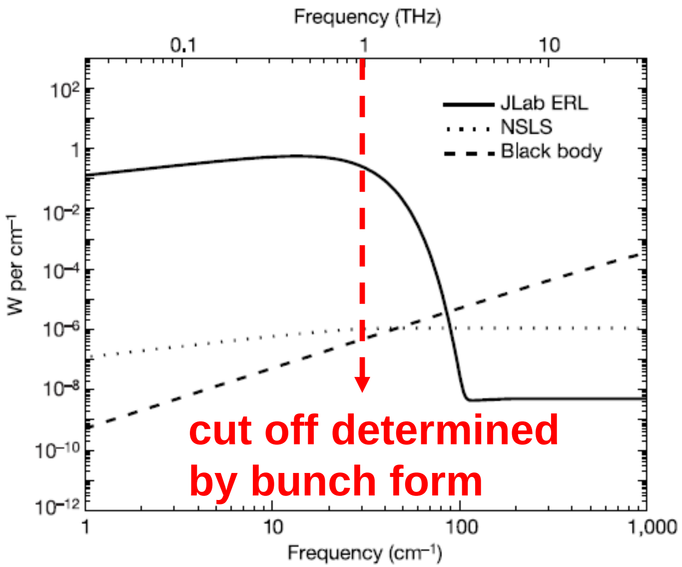
design goal for 2016: 100 µJ/500 kHz

Concept : relativistic electrons + Super-radiance



courtesy G. Wüstefeld (HZB)

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



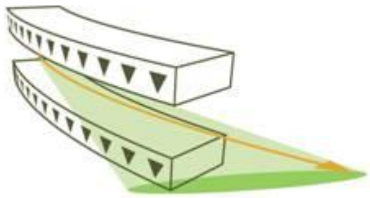
+

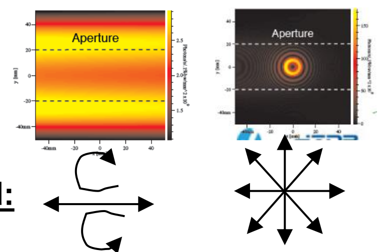
@ storage ring BESSY II, breakthrough 2002.
Abo Bakr et. al. PRL 2003
A. Müller et. al., Proc. of EPAC (2008).

bunch duration (as short as possible): -> larger frequency range+ intensity/peak field
bunch charge (as high as possible): -> intensity/peak field

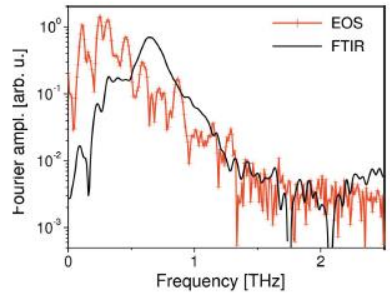
Concept : relativ. electrons + super-radiance + diff. sources

1. bending magnet: dipole + edge radiation

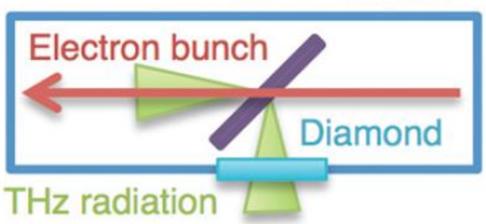




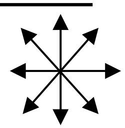
E – field:

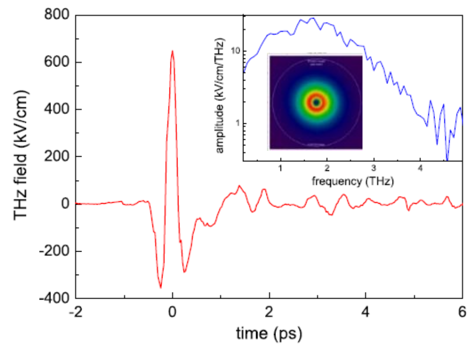


2. Coherent transition/diffraction screens

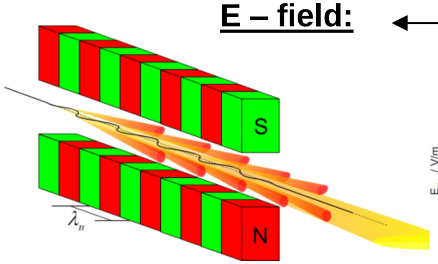


E – field:

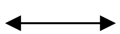


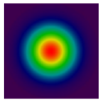


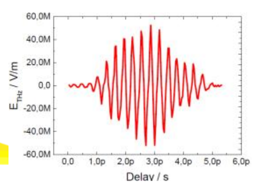
3. Undulator

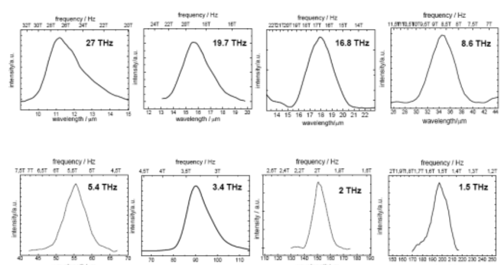


E – field:









+ new concepts (corrugated waveguides, multifoil radiator …)

@ linacs:

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

M. Gensch et. al., Infrared Phys. Technol. (2008),
S. Casabuoni et. al., Phys. Rev. St. Accel. (2009),
M. Gensch AIP conf. Proc, (2010),
F. Tavella et. al., Nature Photonics (2011).
D. Daranciang et. al. , Appl. Phys. Lett (2011).,
M.C. Hoffmann et. al., Optics Lett. (2011),
Y. Shen et. al., Phys. Rev. Lett. (2011),
J. Park et.al., Rev. Sci. Instr. (2011)
……..
……..
……..
E. Chiadroni et. al., Appl. Phys. Lett (2013)
A. Perucci et. al., Rev Sci Instr. (2013)

Concept : relativ. electrons + super-radiance + diff. sources

1. bending magnet: dipole + edge radiation

APPENDIX

Table 1: Super-radiant THz facilities that are/have been operational

+ observed; *intrinsically synchronized

Location (Name)	ν(THz)	source type	E(MeV)	(Micro) Pulse energy	Reprate	secondary source	publication
Tsukuba/ Japan (AIST-THz)	0.1 – 2	bending magnet, CTR	10 – 42	>100 nJ+	1-50 Hz (macro-pulsed)	fs laser	R. Kuroda et. al., Nucl. Instrum. Meth. A 637 (2011), S30.
Daresbury/ UK (ALICE)	0.1 – 0.5	bending magnet	25 (35)	< 70 nJ+	10Hz (macro-pulsed)	–	Y. Saveliev et al, Proceedings of IPAC10, Kyoto, TUPE096.
Stanford/ USA (FACET & LCLS - THz)	0.5 – 5 (FACET) 3 – 30 (LCLS)	CTR	20350 (FACET) 2600 – 20700 (LCLS)	>400 µJ+	10 (30)Hz (FACET) 120 Hz (LCLS)	fs laser OTR* fs-X-rays*?	A.Daranciang et. al., Appl. Phys. Lett. 99 (2011), 141117. Z. Wu et. al., Rev. Sci. Instr. 84 (2013), 022701.
Hamburg/ Germany (FLASH - THz)	0.1 - 30	CTR, undulator, bending magnet	400 – 1200	>100 µJ+	10 Hz (macro-pulsed)	fs laser(s) fs X-rays* OTR*	M. Gensch et. al., Infrared Phys. Technol. 51 (2008), 423. S. Casabuoni et. al., Phys. Rev. Spec. Top. 12 (2009), 030705. F. Tavella et. al., Nat. Photon. 3 (2011), 162.
Idaho/ USA (IAC-THz)	0.27 – 0.33	corrugated waveguide	5 (40)	25 nJ+	30 Hz (macro-pulsed)		A.Smirnov et.al., Proceedings of IPAC13, Shanghai (China), WEOWA080.
Newport News/ USA (Jlab - THz)	0.1 – 2	bending magnet	<150	0.1 µJ+	4.7MHz – 75MHz (quasi-cw)	OTR*	G.L. Carr et. al., Nature 420 (2001), 153.
Nihon/ Japan (LEBRA)	0.1 – 0.3	bending magnet	30 - 125	1 pJ+	<12.5 Hz (macro-pulsed)	IR FEL	these proceedings TUPS066
Pohang/ Korea (PAL-THz)	0.3 – 3	CTR	75	>10 µJ+	10 Hz	fs laser	J. Park et. al., Rev. Sci. Instr. 82 (2011), 013305.
Brookhaven/ USA (SDL-BNL - THz)	0.1 - 1	CTR	200	400 µJ+	1 – 10 Hz	fs laser	Y. Shen et. al., Phys. Rev. Lett. 99 (2007), 043901.
Shanghai/ China (SINAP - THz)	0.3 – 0.8	undulator	14 - 30	2.42 µJ+	50 Hz (macro-pulsed)		J. Zhang et. al., Nucl. Instr. Meth. A 693 (2012), 23.
Frascati/ Italy (SPARC - THz)	0.1 - 5	CTR	120	>1 µJ+	10 Hz		E. Chiadroni et. al., Rev. Sci. Instr. 84 (2013), 022703
Dresden/ Germany (TELBE)	0.1 - 3	CTR, CDR, undulator	< 40	1 µJ 100 µJ	< 13 MHz < 500 kHz	fs laser	M. Gensch et. al., in preparation (2013).

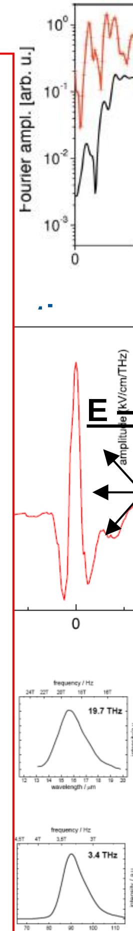


Table 2: super-radiant THz facilities which are currently under construction or proposed

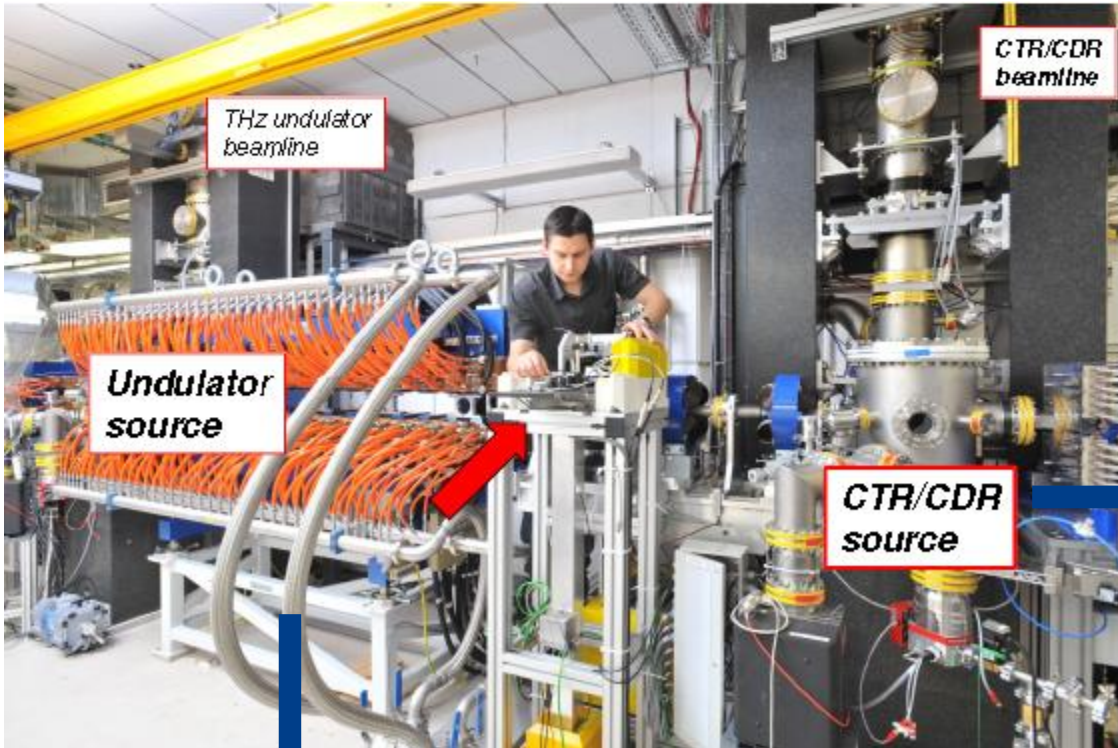
*intrinsically synchronized

Location (Name)	ν(THz)	source type	E(MeV)	Pulse energy	Reprate	secondary source	publication
Hamburg/ Germany (FLASHII - THz)	1 – 30	CTR, undulator, bending magnet	400 – 1200	>100 µJ	10 Hz (macro-pulsed)	fs laser fs X-rays* OTR*	
Karlsruhe/ Germany (FLUTE)	0.1 – 25	bending magnet, CTR	10 – 42	> 100 µJ	1-50 Hz (macro-pulsed)	fs laser fs X-rays*	M. Nasse et. al., Rev. Sci. Instr. 84 (2013), 022705
Newport News/ USA (Jlab-THz)	0.1 – 5	undulator	150	1 µJ	4.7 MHz – 75 MHz	UV*	S. Benson et al., Proceedings of IPAC12, New Orleans, USA (2012) TUPPP086
Daejeon/ South Korea (KAERI-THz)	0.1 - 10	undulator, multi-foil radiator	30	1 µJ	500 Hz	fs X-rays*	these proceedings TUPS032, TUPS038
Lansing/ USA (Niowave-THz)	0.5 – 1.7	undulator	5	few nJ	350 MHz		these proceedings TUPS011
Hsinschu/ Taiwan (NSRRC-THz)	0.1 – 10	bending magnet	30	?	10 Hz (macro-pulsed)		these proceedings TUPS041
Triest/ Italy (TERAFERMI)	0.3 - 15	CTR	1200 - 1500	50 µJ – 1 mJ	10 – 50 Hz	fs laser	A.Perucci et. al., Rev. Sci. Instr. 84 (2013), 022702
Hamburg Germany (X-FEL - THz)	0.1 - 30	undulator, CTR	20000	>100 µJ	10 Hz (macro-pulsed)	fs laser fs X-rays	these proceedings WEOBN004

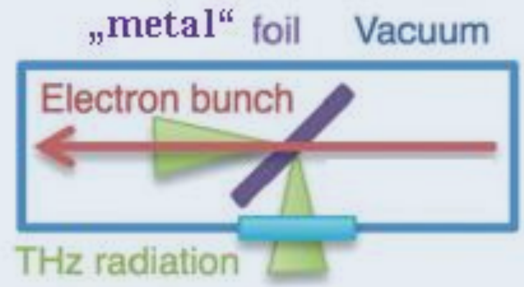
M. Gensch, Proceedings of FEL13, New York, 2013.

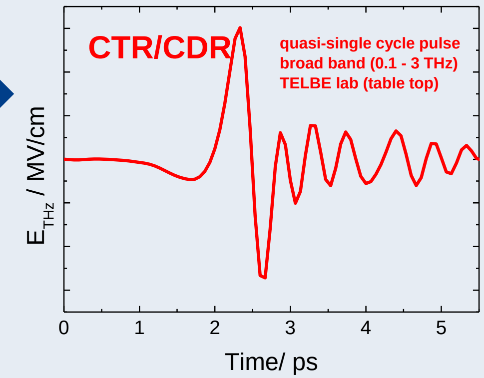
multif

THz facility @ ELBE: sources

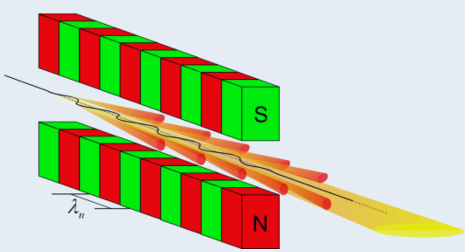


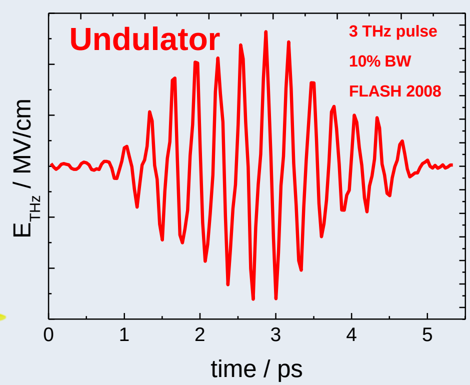
CDR/CTR source





Undulator





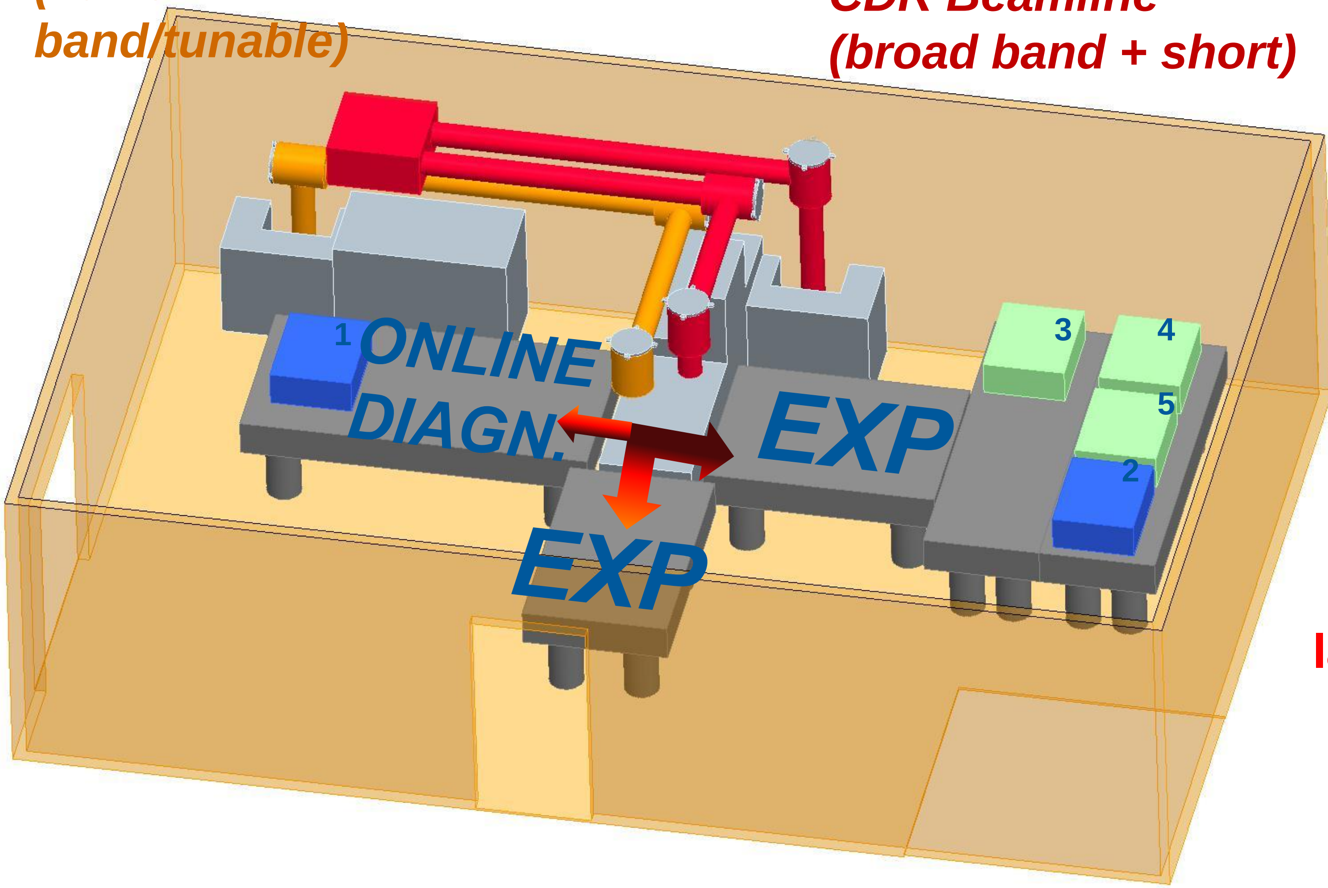
if generated by same electron bunch:
-> intrinsically synchronized to one another!

DRESDEN concept
HZDR

THz facility @ ELBE: laboratory

Undulator Beamline (narrow band/tunable)

CDR Beamline (broad band + short)



Lab infrastructure

2 x FTIR spectrometers (1&2)
- *0.03 - 119 THz*
- *step scan & rapid scan*

1 x laser-amplifier (3) - high peak pow.
- *mJ pulse energy*
- *1 kHz repetition rate*
- *130 fs pulse duraction*

1 x laser-amplifier (4,5) – high rep. rate
- *μJ pulse energy*
- *up to 250 kHz repetition rate*
- *100 fs pulse duration*

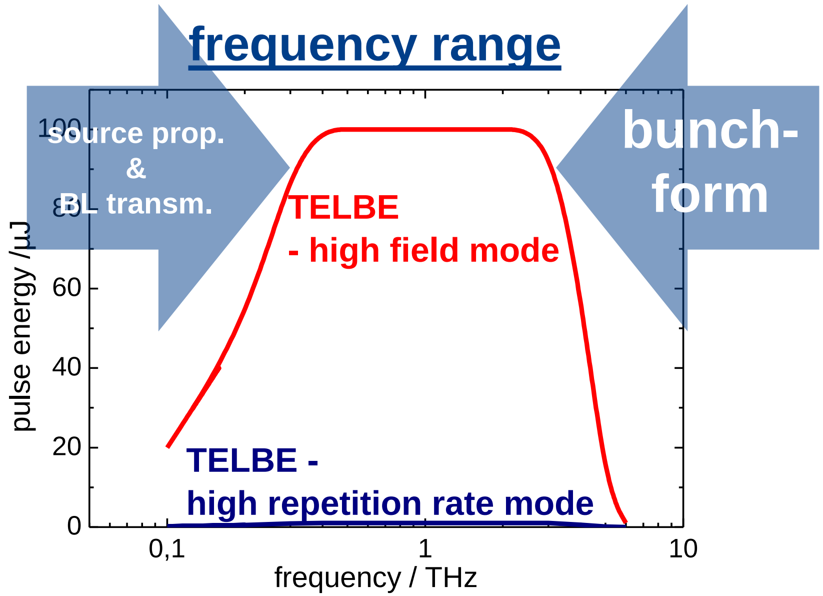
1 x 10 T split coil magnet

+

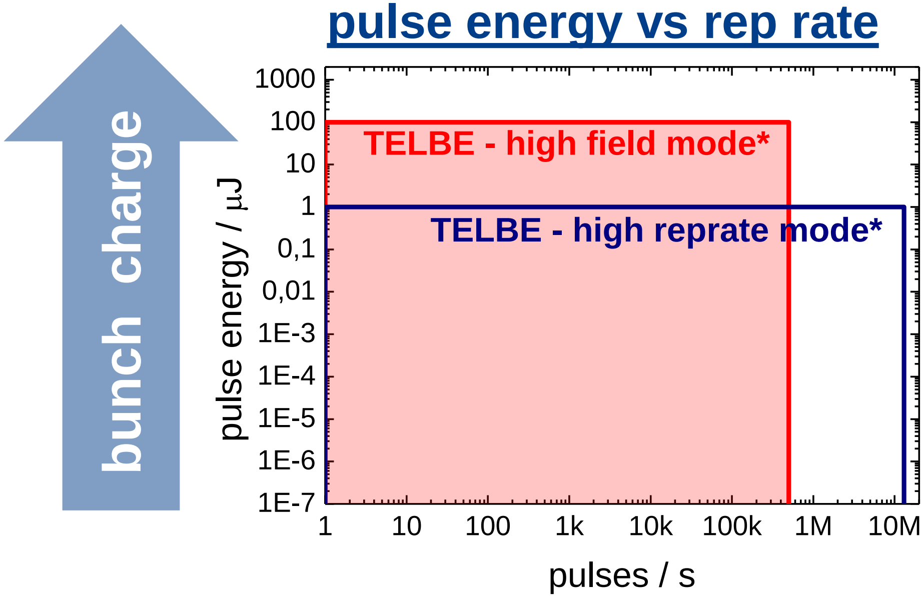
state of the art laser-based THz sources for exp. preparation

THz facility @ ELBE: design parameters

frequency range

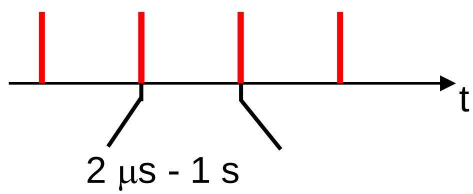


pulse energy vs rep rate

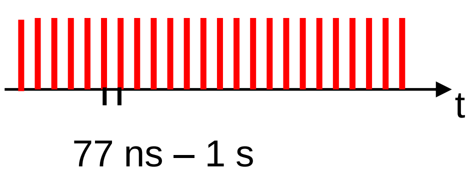


TELBE time structure:

high field mode:

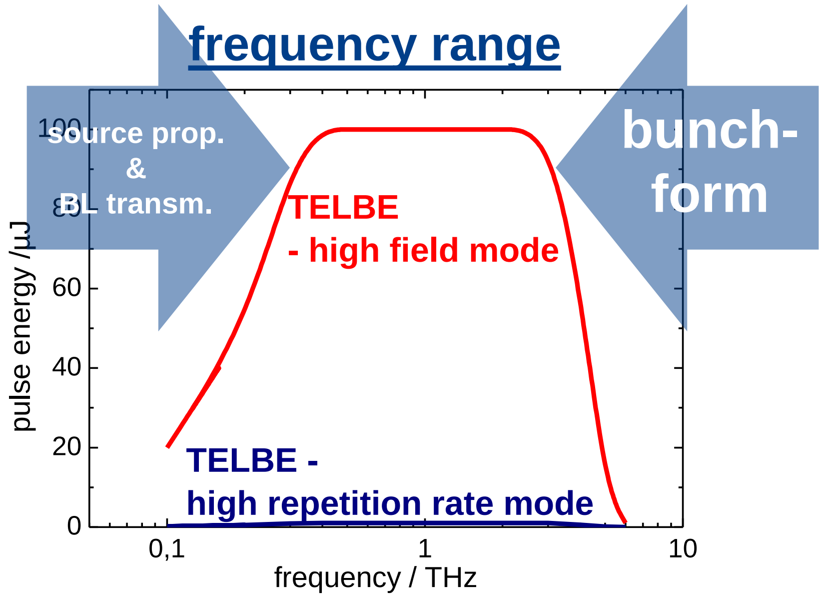


high rep. rate mode:

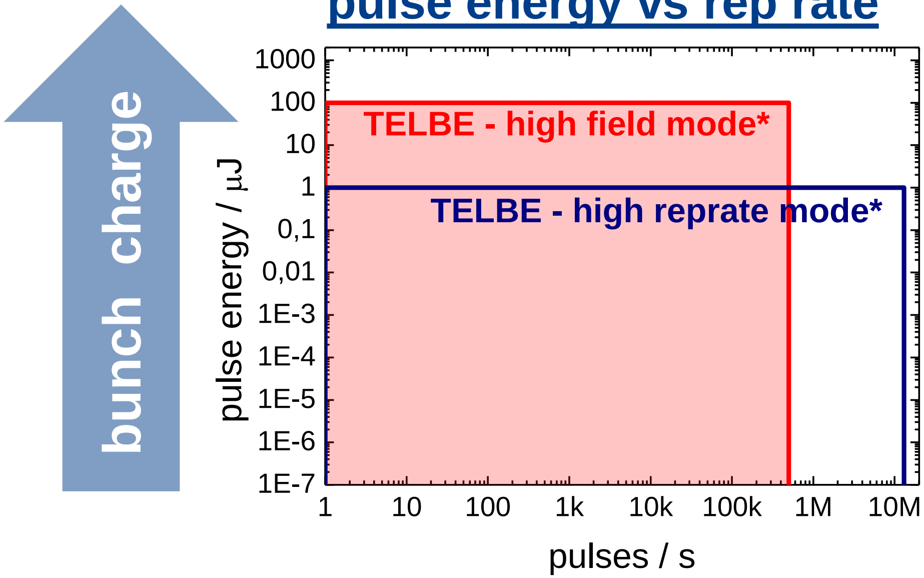


THz facility @ ELBE: design parameters

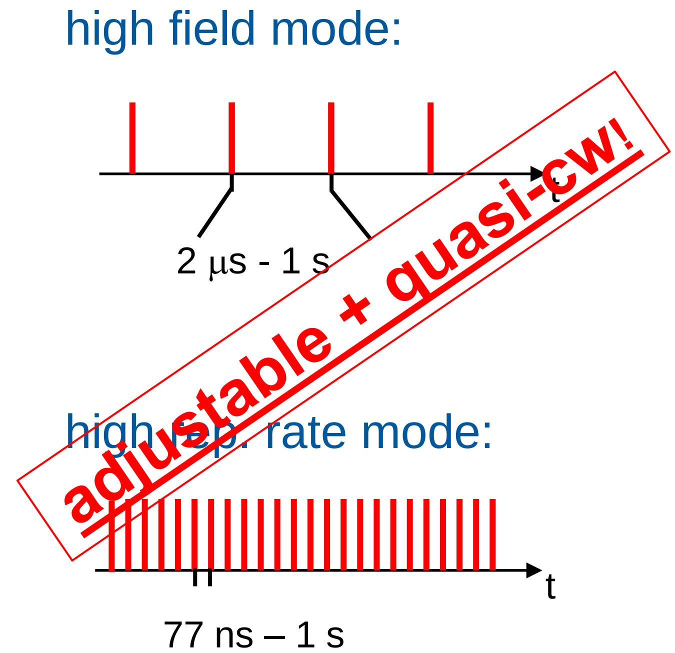
frequency range



pulse energy vs rep rate



TELBE time structure:



Summary 1 – TELBE user facility

- *electron bunches long (>1.2ps)*
  -> spectrum short☹
- *large accelerator-laser jitter (> 2 ps) ☹*

but:

- **understand super-radiant emission (SRW + formfactor)**
- **CDR and undulator can be operated in parallel**
- **intrinsic jitter below 50 fs (peak to peak)**

perspective:

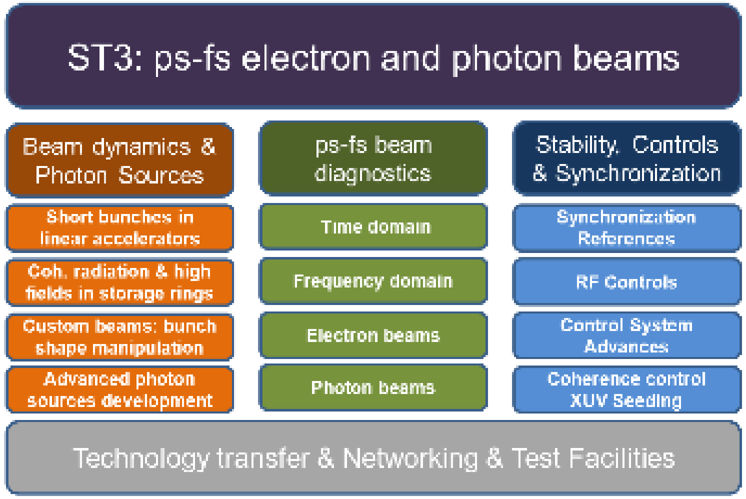
1. **Challenge to reach design parameters in prototype facility until 2016**
2. **Unique test facility to develope electron bunch diagnostic for SRF acc.**

Vision:

new class of compact SRF accel. based THz faciities:

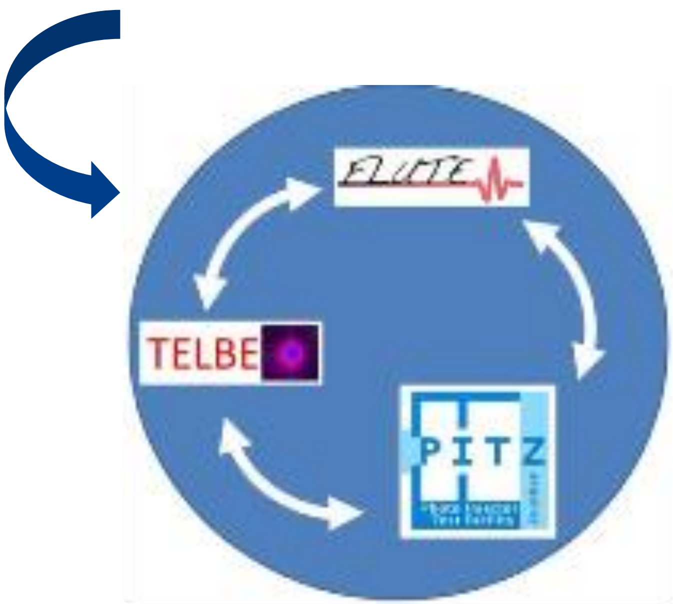
- *multi user/multi source operation*
- *combination with „duty cycle – hungry“ ultra-fast probes (Raman, ARPES, SNIM, IR diff.)*

Accelerator Research and Development (ARD) program in HGF



fs –level diagnostic for quasi-cw beams:

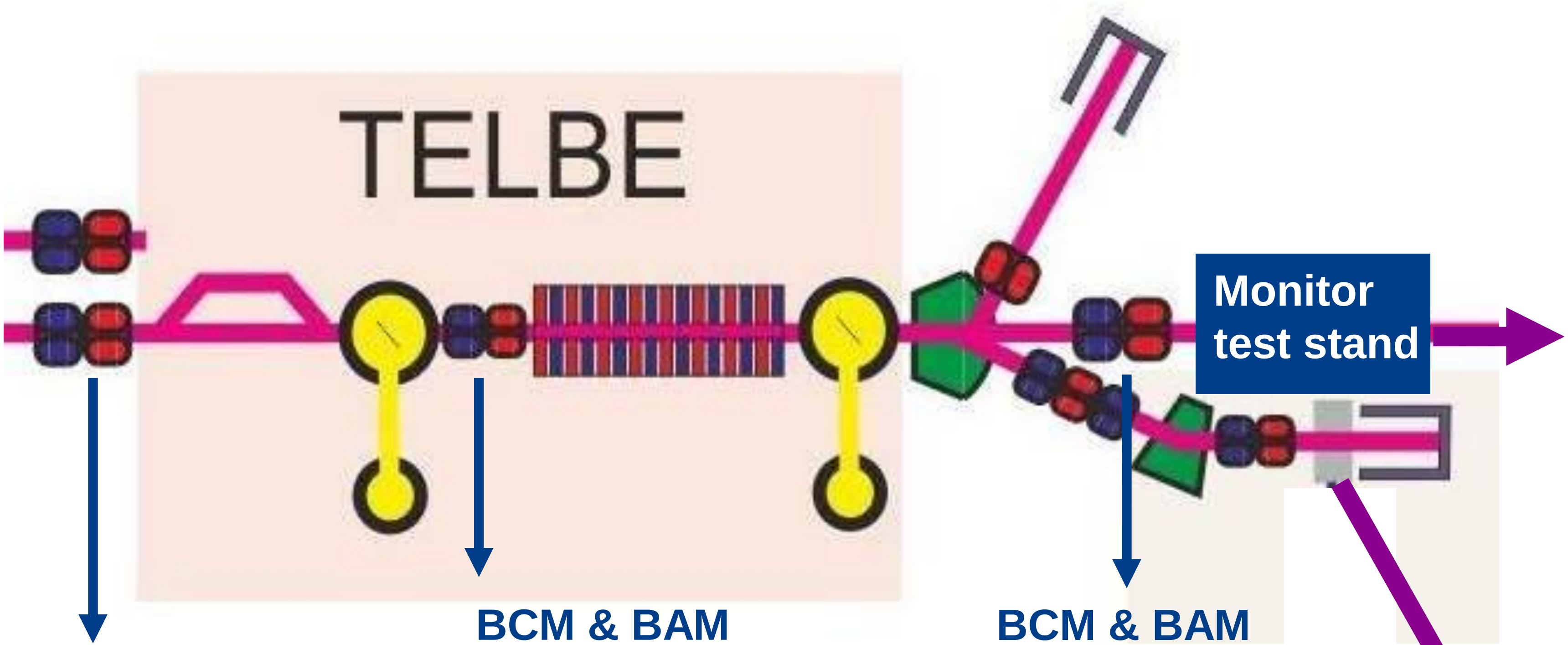
0. **ELBE is a good test bed**
1. **new cw projects/ideas in the HGF (BERLinPRO, X-FEL upgrade)**
2. **new cw projects/ideas worldwide (e.g. LCLSII -> TU0CA01)**
3. **knowhow-transfer to and from ELBE**



ARD – test facility for e bunch diagnostic on quasi – cw electron beams:

- quasi – cw reprates: few Hz to 13 MHz (adjustable)
- e-bunch charge: few pC – 1 nC
- diagnostic table in TELBE lab (access to undulator & CTR source + fs laser + FTIR spectrometer)
- monitor test stand in e-beamline directly after THz sources

(ARD) test facility – current set up



neutron source (n-ELBE) & laser-electron interaction exp.

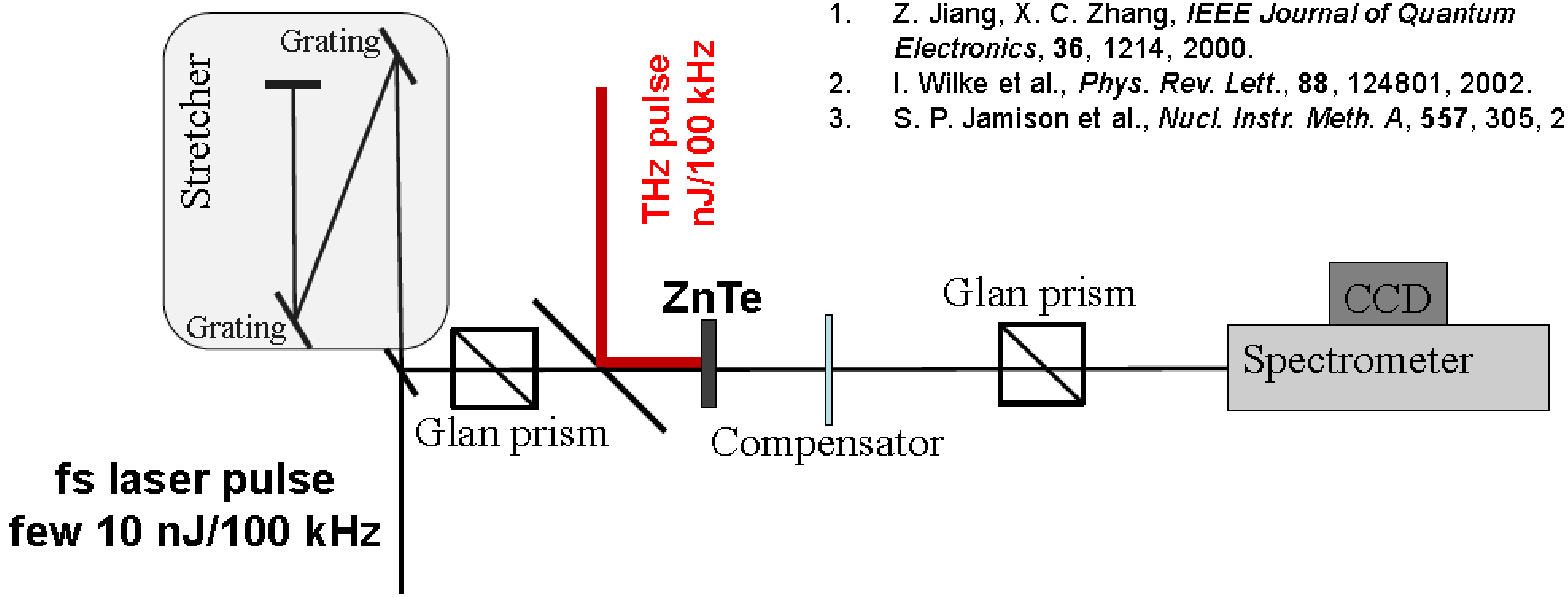
BCM

positron source (p-ELBE).

(ARD) test facility – selected projects

- **THz-based electron bunch monitor for quasi-cw accelerators (arrivaltime, bunch form, bunch energy)**
  TUPRI105, THPME108
- **compact on-chip THz spectrometer for next generation Bunch Compression Monitors**
  THPME106
- ***(near-field-based) bunch arrivaltime monitor for quasi-cw accelerators***
  TUPRI106

working principle:



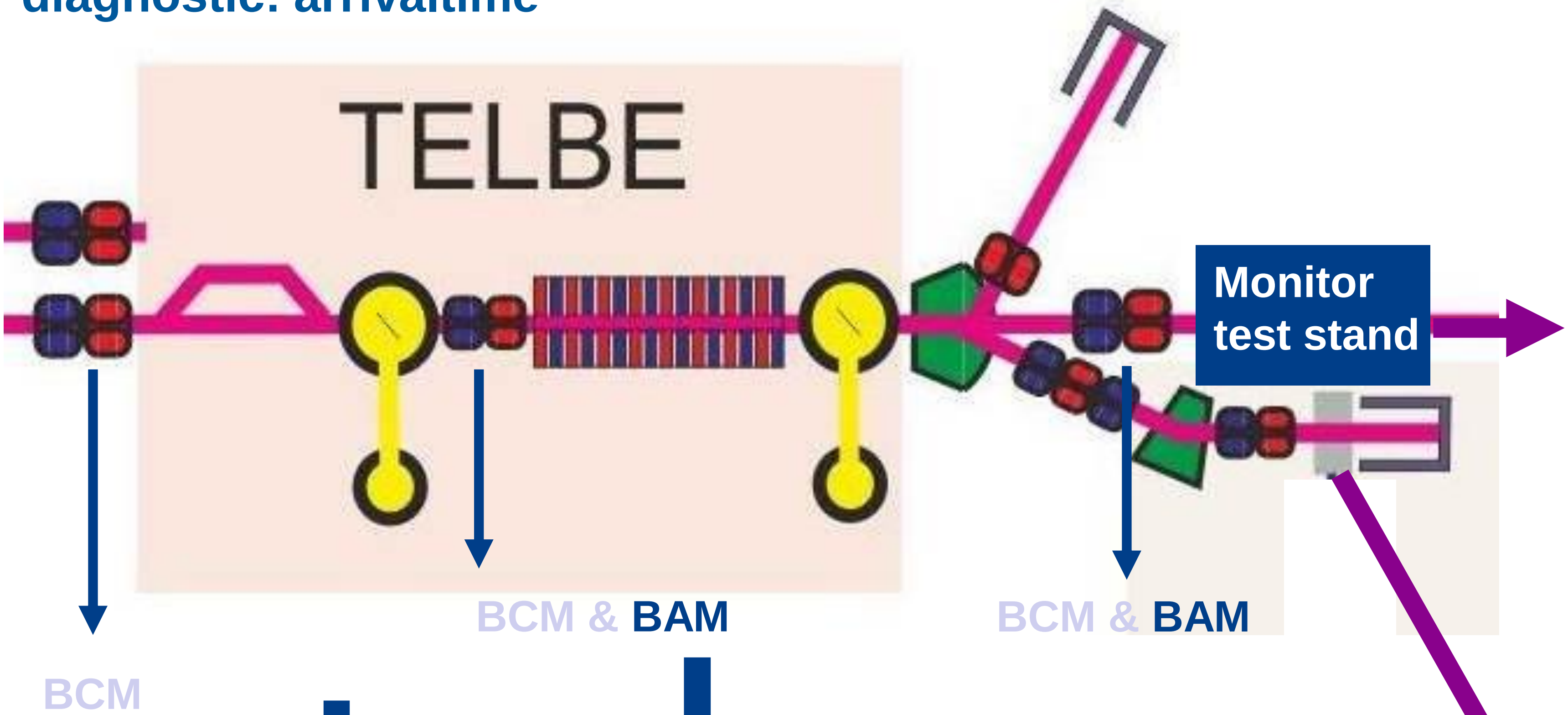
1. Z. Jiang, X. C. Zhang, *IEEE Journal of Quantum Electronics*, **36**, 1214, 2000.
2. I. Wilke et al., *Phys. Rev. Lett.*, **88**, 124801, 2002.
3. S. P. Jamison et al., *Nucl. Instr. Meth. A*, **557**, 305, 2005.

Merits:

- low requirements on fs – laser (works with oscillator)
- operates down to few 100 fC bunch charges
- operable at high reprates
- non-invasive
- few fs resolution

(ARD) test facility – opportunities

diagnostic: arrivaltime



neutron source (n-ELBE) & laser-electron interaction exp.

“3 THz BW”

40 GHz BW

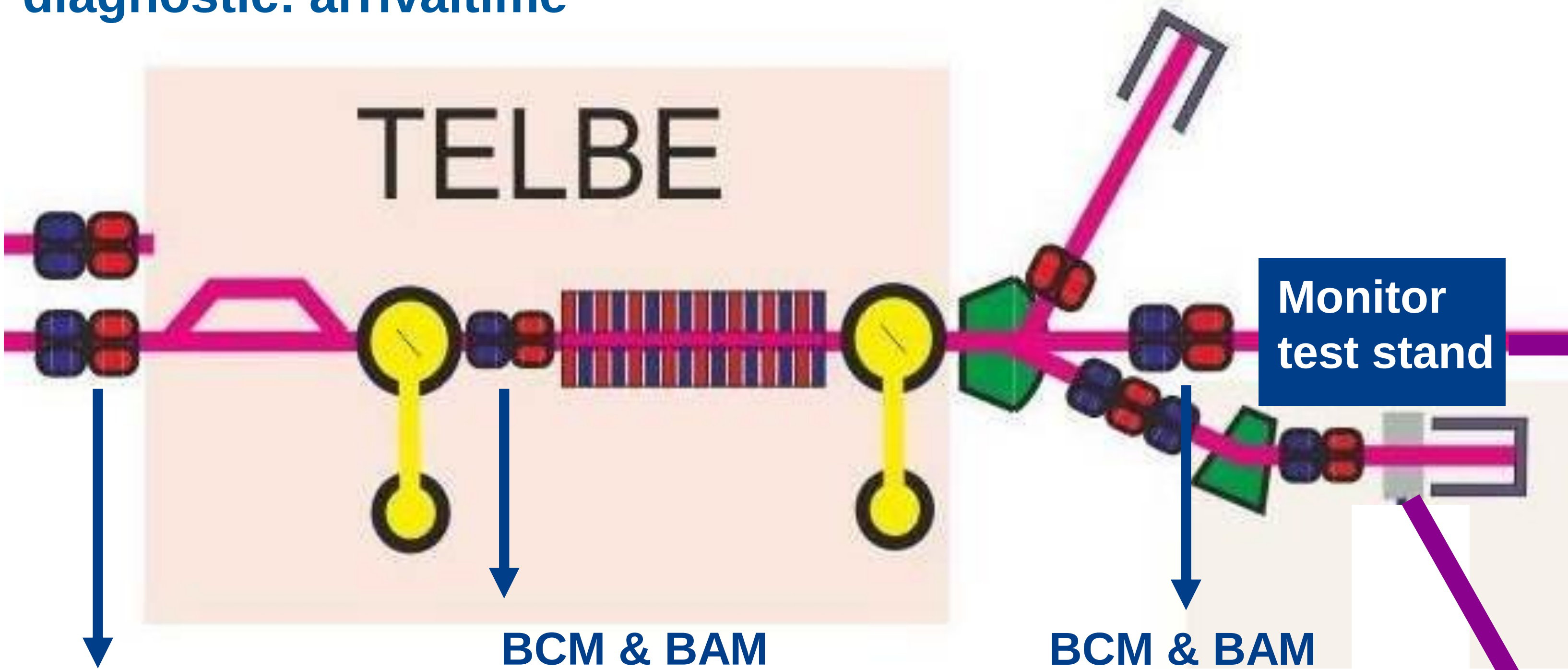
cross calibration

positron source (p-ELBE).

TUPRI105
TUPRI106

DRESDEN concept HZDR

diagnostic: arrivaltime



neutron source (n-ELBE) & laser-electron interaction exp.

BCM & BAM

BCM & BAM

BCM

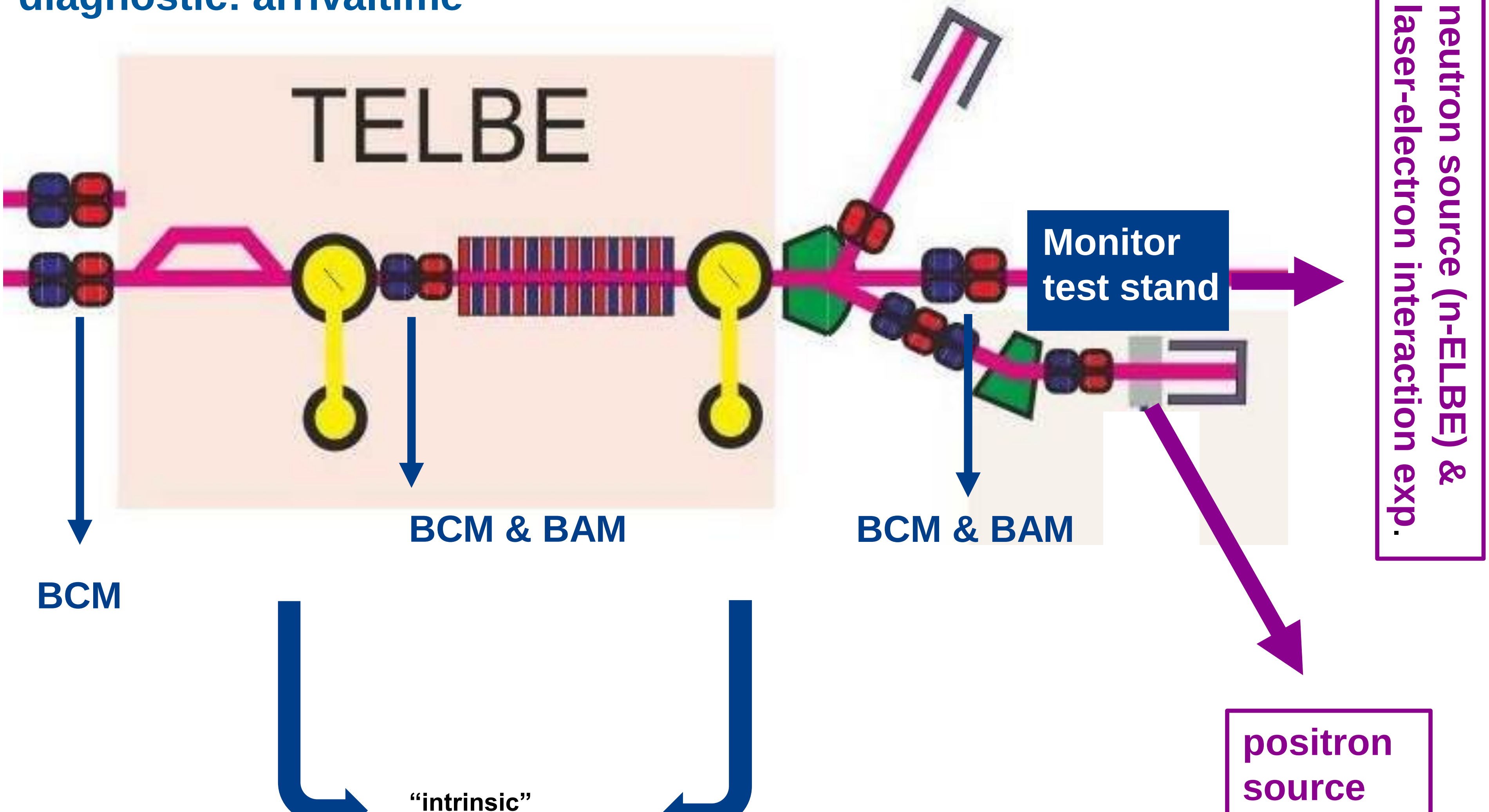
positron source (p-ELBE).

"intrinsic" synchronization*

TUPRI105

- U. Fruehling et. al. Nature Photon. 2008

diagnostic: arrivaltime

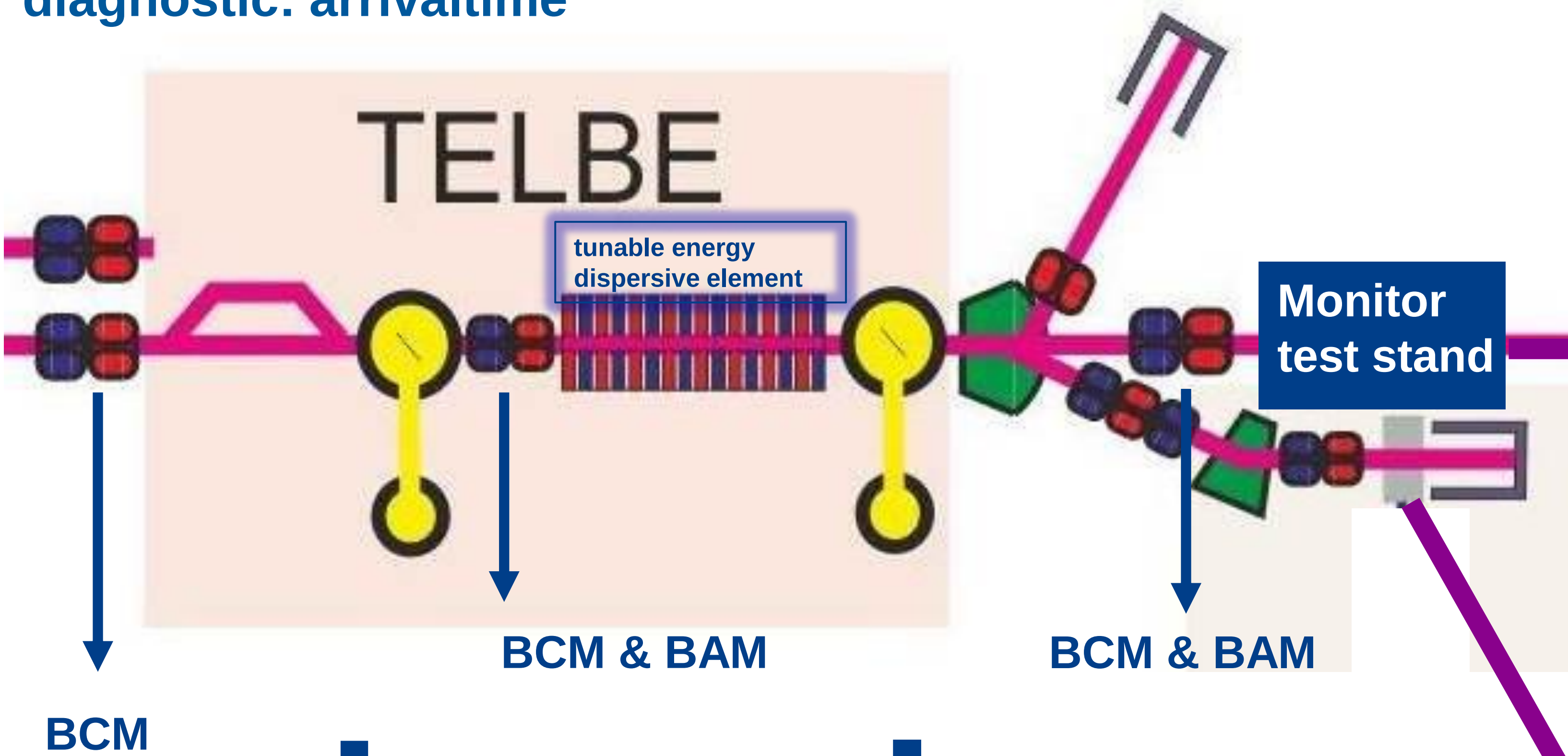


"intrinsic" synchronization*
- beam position instabilities

TUPRI105

- U. Fruehling et. al. Nature Photon. 2008

diagnostic: arrivaltime



neutron source (n-ELBE) & laser-electron interaction exp.

positron source (p-ELBE).

"intrinsic" synchronization*
- beam position instabilities
- energy jitter

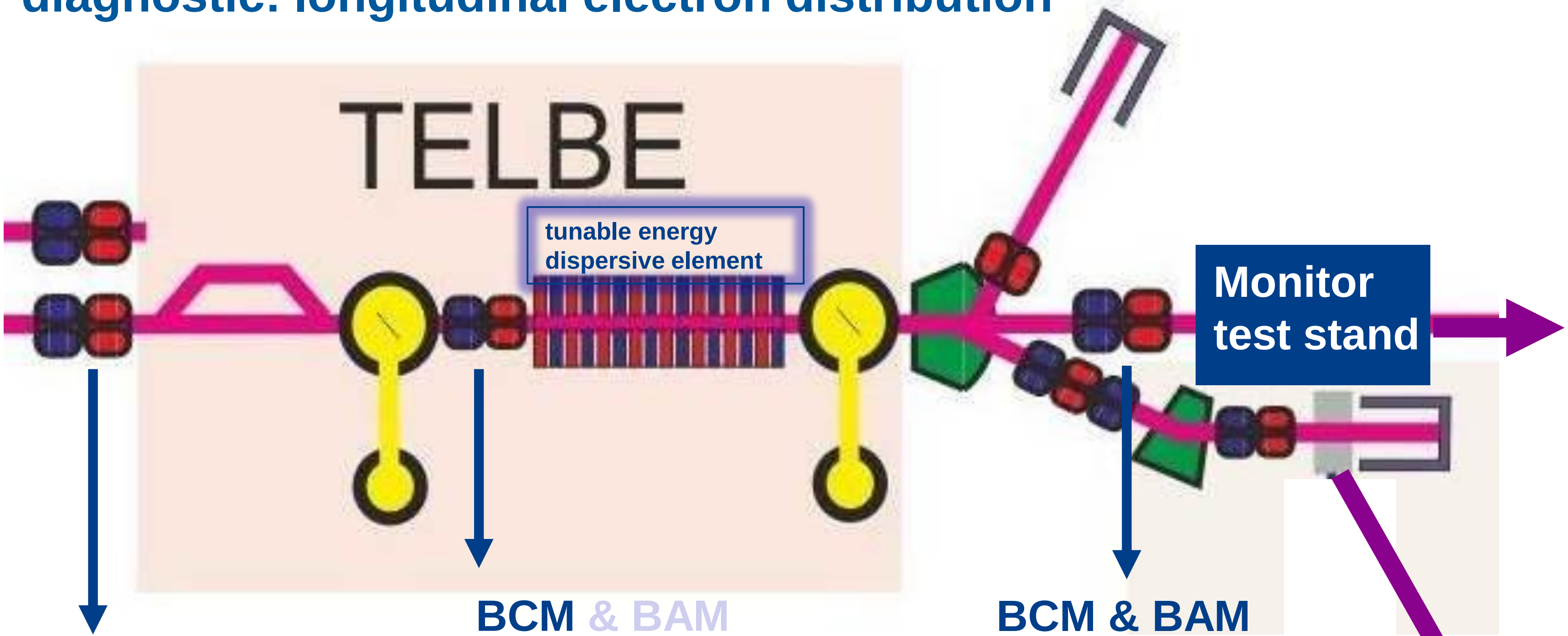
preliminary results/indication:
~ 40 fs (@ tune to 1 THz)
~ 60 fs (@ tune to 0.6 THz)

TUPRI105

- U. Fruehling et. al. Nature Photon. 2008

(ARD) test facility – opportunities

diagnostic: longitudinal electron distribution



neutron source (n-ELBE) & laser-electron interaction exp.

BCM

"quantitative"
EOS + FTIR
+ calibrated detectors
+ cameras

"qualitative"

"quantitative"
EOS + FTIR
+ calibrated detectors
+ cameras

cross- calibration

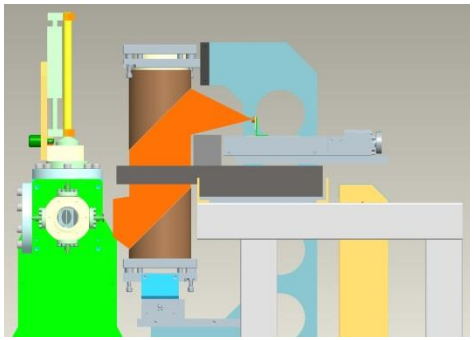
THPME108

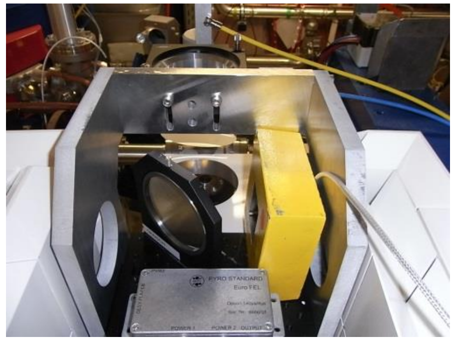
positron source (p-ELBE).

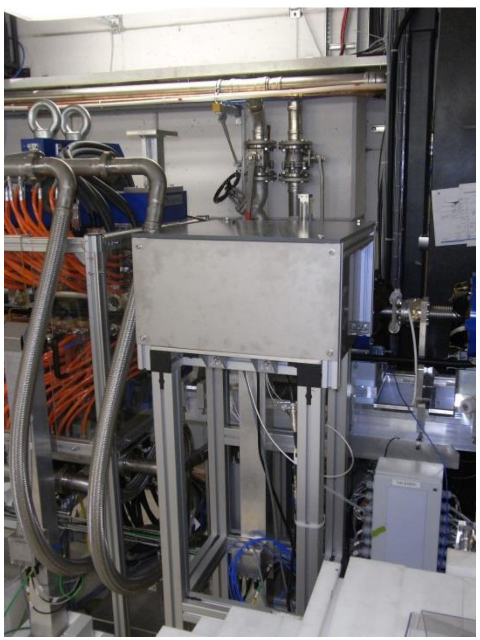
Compact Integrated THz spectrometer for BCM upgrades

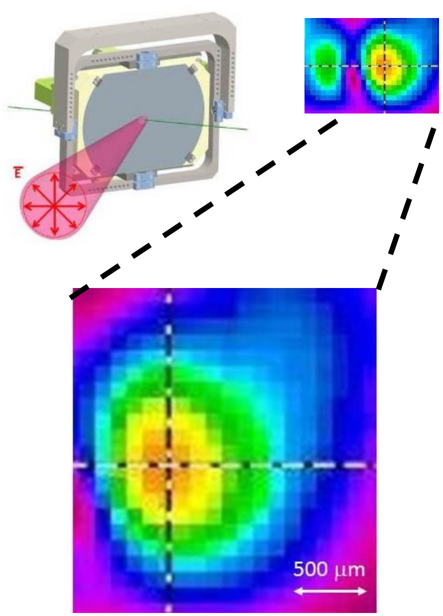
set up at ELBE (combined OTR/BCM station):

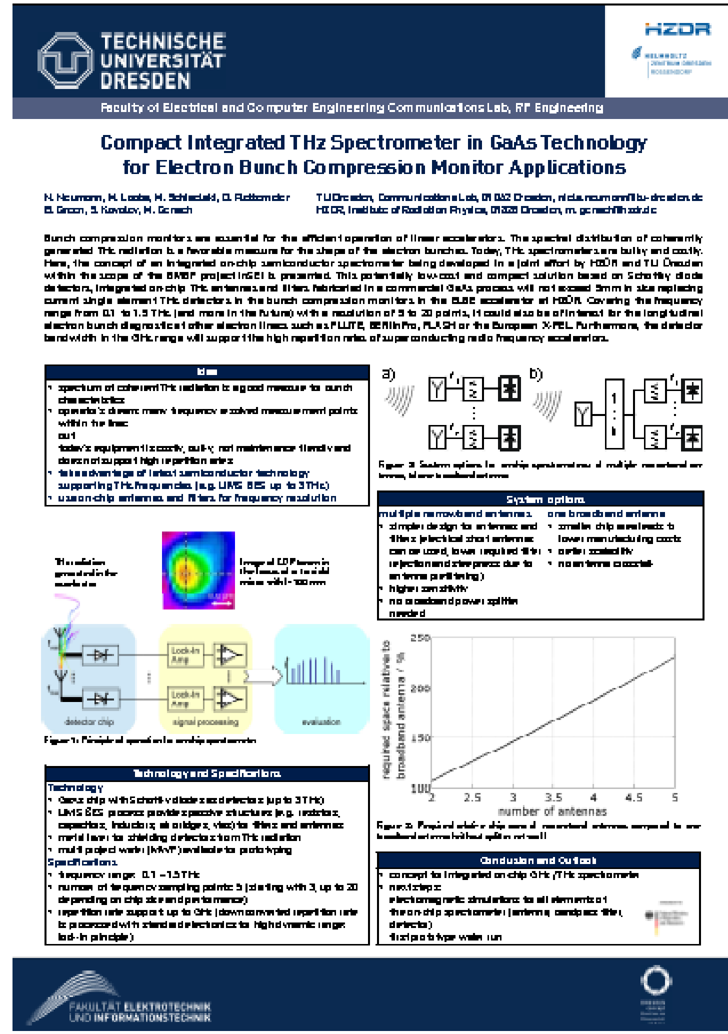
THPME106







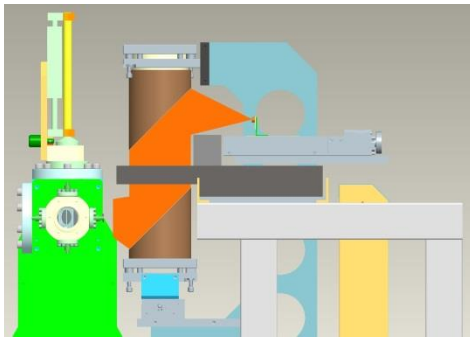


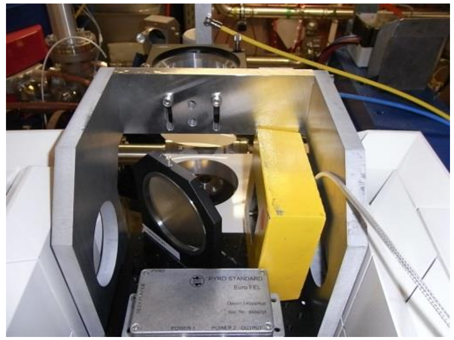


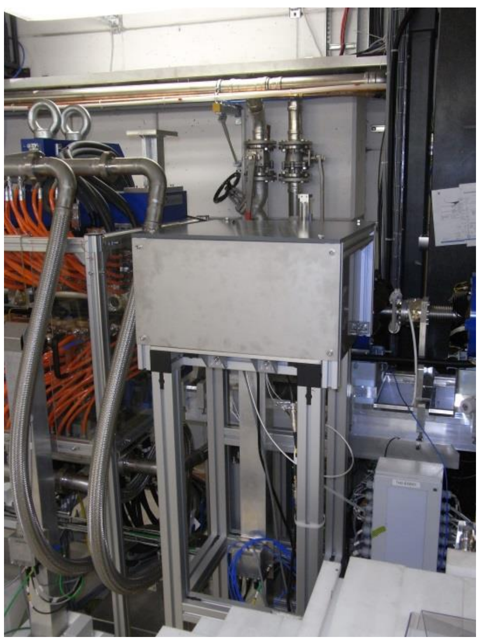
DRESDEN concept HZDR

Compact Integrated THz spectrometer for BCM upgrades

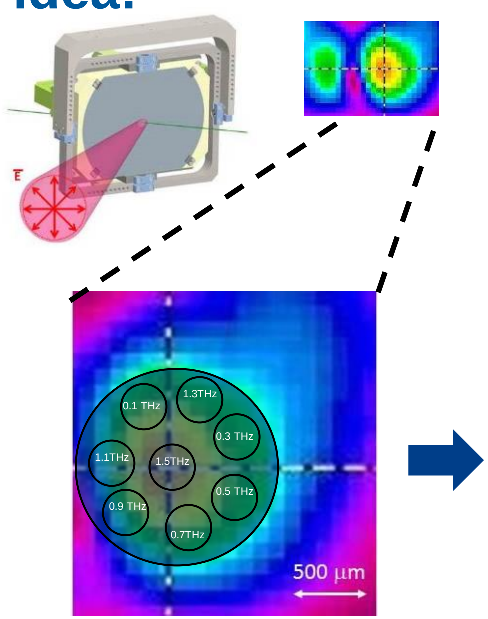
set up at ELBE (combined OTR/BCM station):



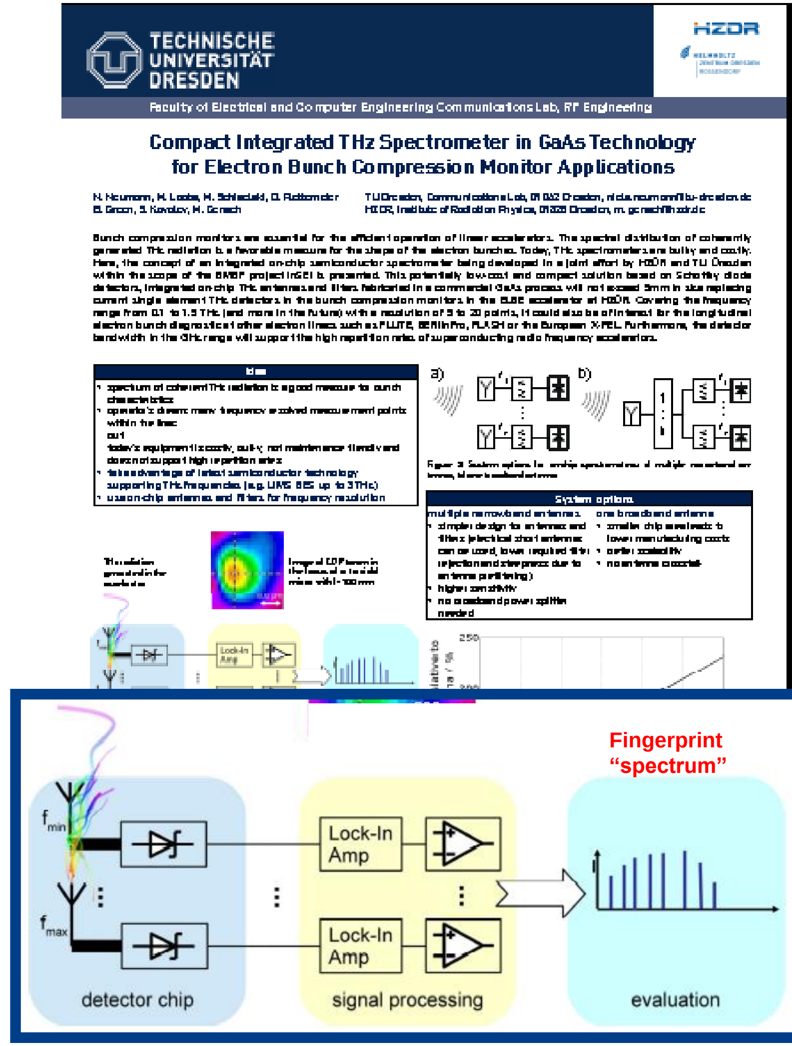




idea:

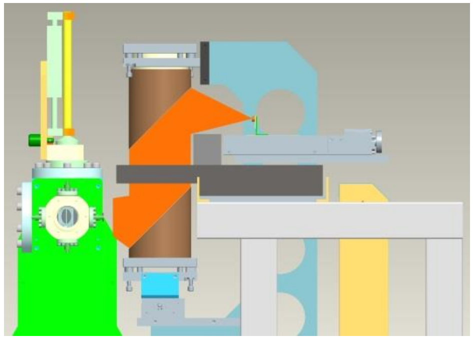


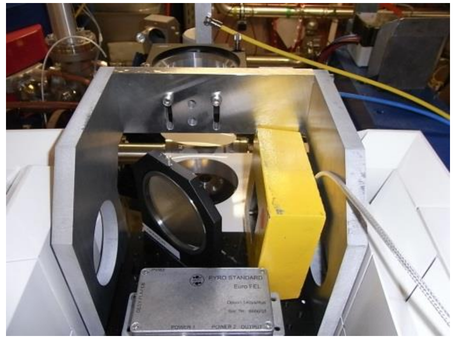
THPME106

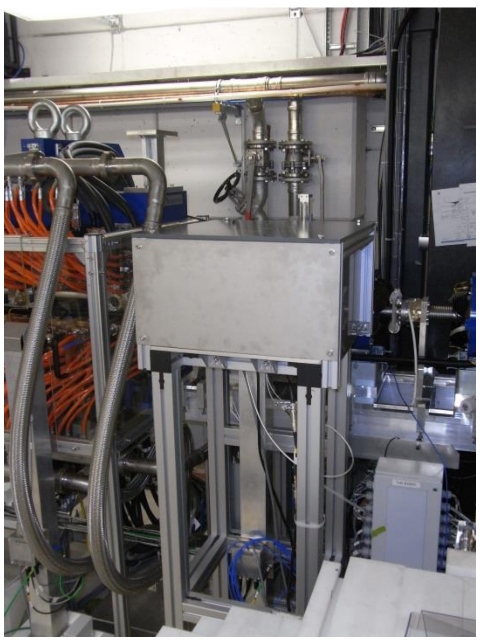


set up at ELBE (combined OTR/BCM station):

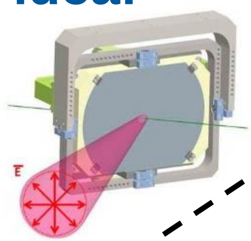
THPME106

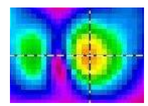


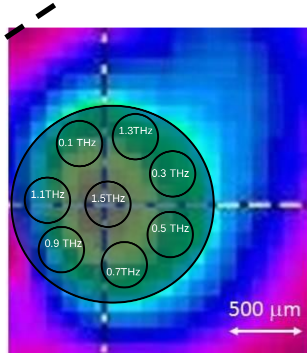




idea:





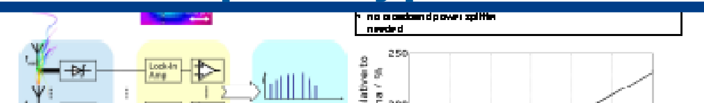


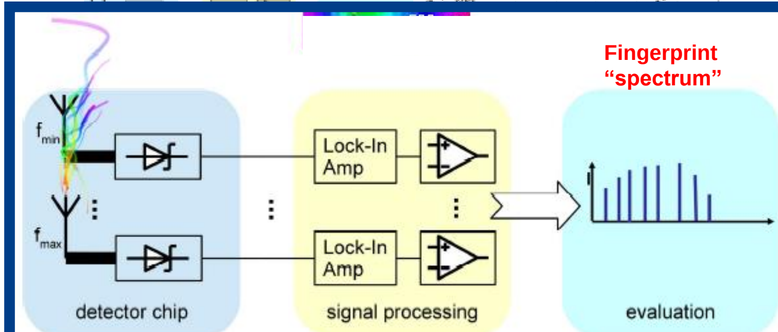
principle:

- integrated THz antennas
- Schottky diode detectors
- (possible) add. narrow bw filters
- phase sensitive det. (optional)

next steps:

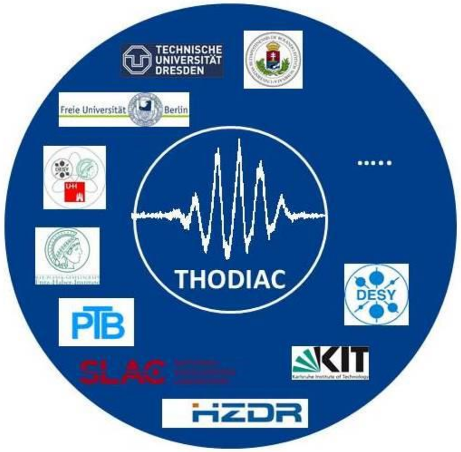
- test in TELBE lab (2014)
- test at prototype BCM (2015)





Summary 2 – ARD test facility for quasi-cw electron beams

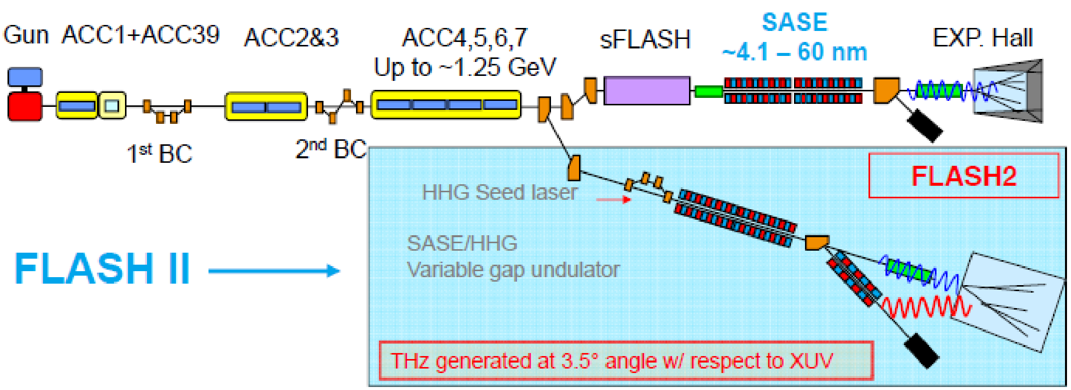
- over the past few years major improvements of ELBE diagn.
- pulse-to-pulse THz – based ONLINE diagnostic for:
  - arrival time
  - (qualitative) bunch shape
- 40 GHz BAM crosscalibrated in quasi-cw mode
- combination of techniques yields bunch duration estimate of 1.2 ps (FWHM)
- several project with (inter)national collaborators underway

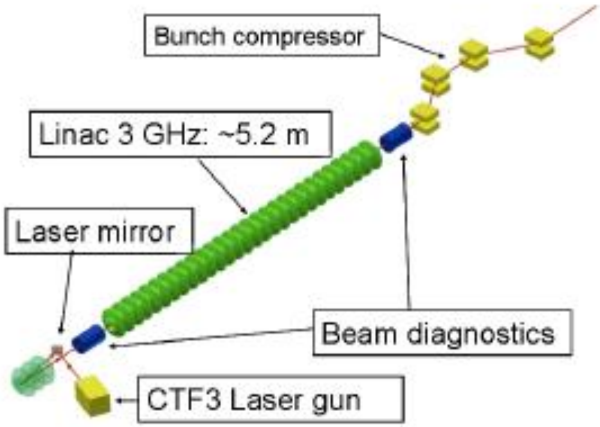


Elsewhere planned…. in Germany

THz @ FLASH II

project @ KIT / Karlsruhe: FLUTE





user facility
nc (Charges)
single cycle THz (CTR): ~ few 100 μJ
narrow bandwth (undulator~ 10%): ~ few 100 μJ
rep rate: up to few KHz (burstmode)
-> **main purpose: THz pump X-ray probe**
planned start of comissioning 2015!

(ARD) Test facility for e-bunch diagn.
nc (Charges)
single cycle THz: ~ mJ -> (expected)
rep rate: few 10 Hz
planned start of commissioning 2014!

THz pump X-ray probe facility at XFEL, LCLSII under discussion!

Acknowledgement

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C. Bauer, S. Winnerl, H. Schneider, B. Green, S. Kovalev, U. Lehnert, Jochen Teichert, Rico Schurig, M. Kuntzsch, M Justus, J. Hauser,

+ FWF & FWK+ FWI

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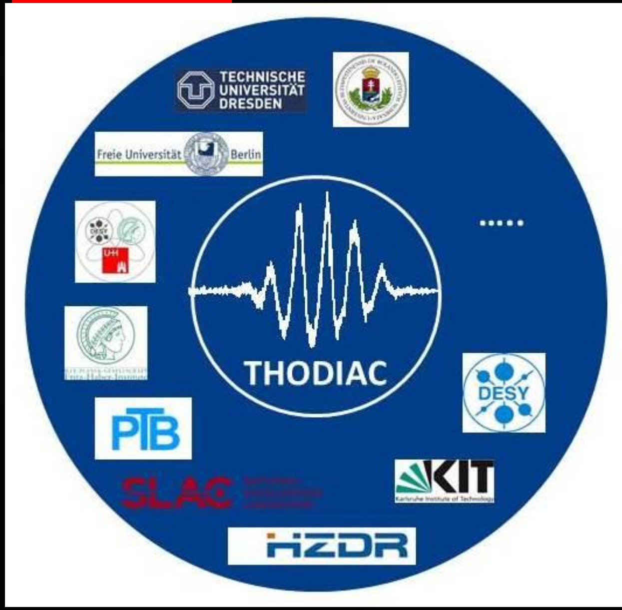
ttner, M. Röhlin . Hesse, B. Schmic
H. Schlarb, B. ldin, M.V. Yurkov,
S. Vilicins. H. Y), U. Frühling, M.
Drescher, O. C berg (UHH),, H.W.
R), W. Seidel, J , B. Wustmann (HZ

C. Bauer, S. Winnerl, H. Schneider, **B. Green, S. Kovalev,**



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. Fisher (SLAC) , A.
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THODIAC – TELBE team
(nightshift 03/2013)