Photo Injector Test facility at DESY, Zeuthen site.

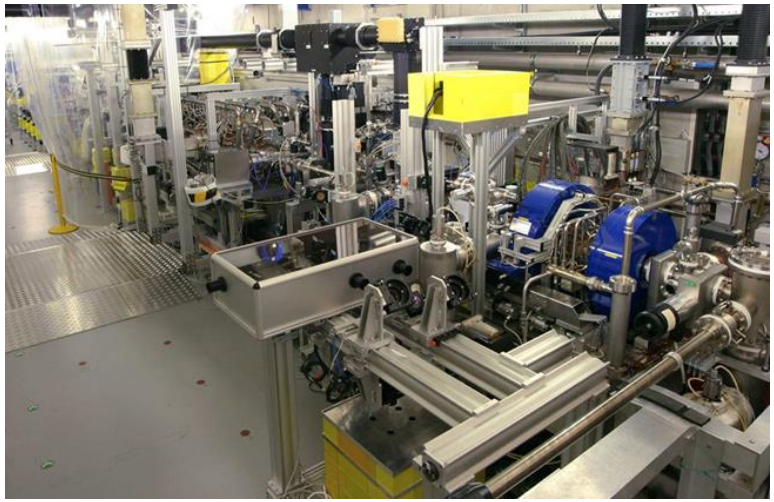
Tunable IR/THz source based on PITZ (-like) accelerator for pump probe experiments at the European XFEL

Mikhail Krasilnikov (DESY) for the PITZ Team

Terahertz Science at European XFEL,
1-2 June 2017, European XFEL, Schenefeld

Outline:

- PITZ Introduction
- PITZ based THz source for p&p experiments
  - CTR/CDR
  - SASE FEL
  - Other options (seeding, single cycle)
- Conclusions and outlook



HELMHOLTZ | ASSOCIATION

DESY

Photo Injector Test facility at DESY, Zeuthen site (PITZ)

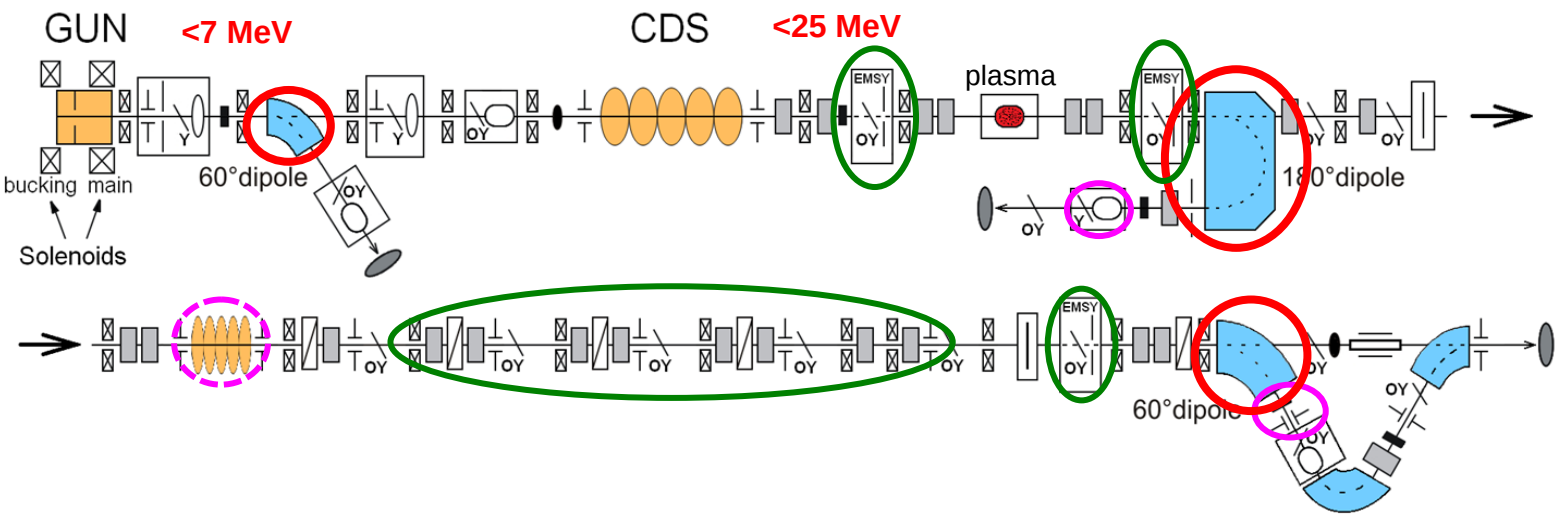
PITZ focuses on the development, test and optimization of high brightness e-sources for SC linac driven FELs:

⇒ test-bed for FEL injectors: FLASH, the **European XFEL** (conditioning and characterization of gun cavities and photo injector subsystems, e.g. photocathode laser)

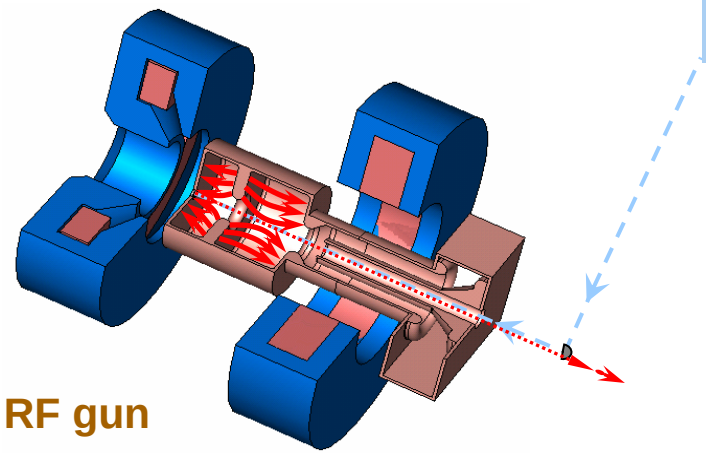
⇒ high brightness → small ε_{tr} (projected and slice)

⇒ further studies → e.g. cathodes: dark current, photoemission, QE, thermal emittance, …

⇒ currently highest priority at PITZ → participate in the solution of the remaining problems of the RF gun for EXFEL (long term reliability and stability, RF windows, cathode RF contact spring)



PITZ “engine”: RF-Gun and Photocathode (PC) Laser

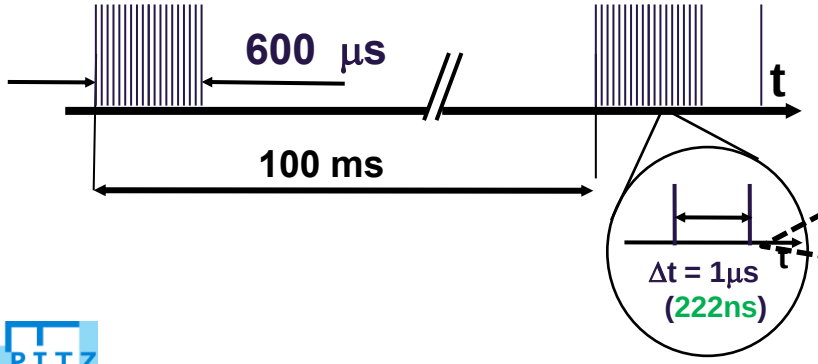


RF gun

- L-band (1.3 GHz) 1.6-cell copper cavity
- Ecath>~60MV/m → **7MeV/c** e-beams
- 650us x 10Hz → up to **45 kW** av. RF power
- Cs_2Te PC (QE~5-10%) → up to 5nC/bunch
- LLRF control for amp&phase stability
- Solenoid for emittance compensation

Pulse Train Time Structure:

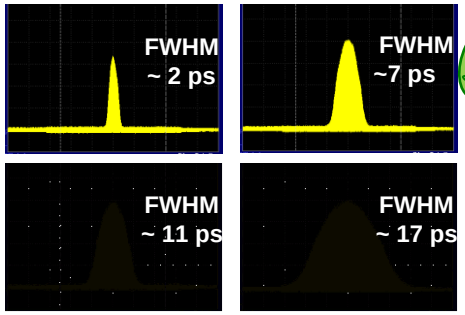
PITZ and **EXFEL** trains with up to 600 (2700) laser pulses

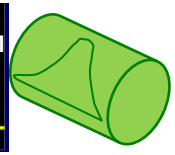


Photocathode laser(s) (UV)

Default PC laser system (Max-Born-Institute, Berlin)

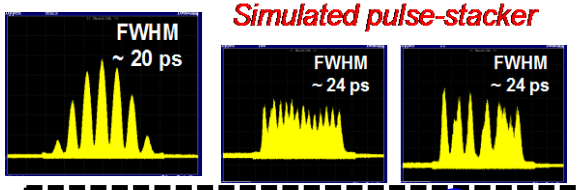
Gaussian:



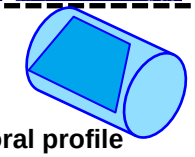


Multicrystal birefringent pulse shaper containing 13 crystals

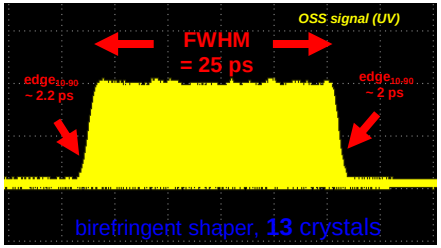
Simulated pulse-stacker



Flattop



Cathode laser pulse: temporal profile



Institute of Applied Physics of the Russian Academy of Sciences

New PC laser ELLA

3D (ellipsoidal) pulse shaper:

- SLM based
- Upgrade with VBG

Oscillator upgrade – Pharos-20W-1MHz frontend

Pulse length 0.25-10ps+

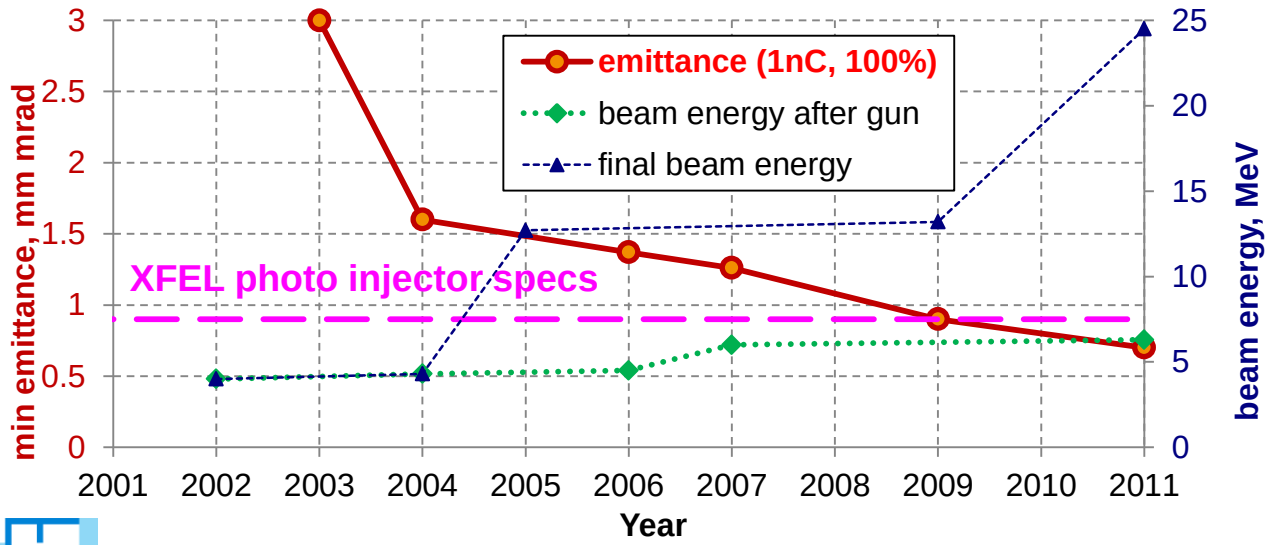
Different lasers

→various **THz options**

→possibility of **simultaneous** usage

PITZ evolution 2000-2017

	Year-->	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
gun	cavity	gun-2	FLASH	gun-1		gun-3.1	FLASH g-3.2	gun-4.2	FLASH	gun-4.1		FLASH g-3.1	4.3 XFEL	g-4.4 XFEL*	gun-4.2	gun-4.6	
gun	Ez,MV/m	35	37	42-->60		43	60										
gun	Ebeam	~4MeV		4.3MeV-->6MeV		4.5MeV	~6.5MeV										
boo	cavity	no			TESLA at 2.5m		TESLA at 3.1m			CDS at 3m				CDS at 2.6m			
boo	Ebeam				~13MeV					~25MeV				22MeV*			
laser	temp ps	10	6/24\6				6/24\6	2/22\2						2/22\2	11*		
emit	EMSY1	z=1.618m			z=4.3m		z=5.74m							z=5.277m			
emit	Ldrift	1.01m			2.334m		2.64m							3.133m			
emit	method	center BL	3xBLs		e-meter	11xBLs			detailed scan							+slice with TDS	
emit	min ε_{xy} mm mrad (charge)		3 (1nC)	1.5-1.7 (1nC)		1.37 (1nC)	1.26 (1nC)		0.9 (1nC)		0.7 (1nC)				0.8 (0.5nC)		
PITZ goals		small emittance (nominal EXFEL)										+reliability at full performance			+emittance (EXFEL startup)		
PITZ goals												+THz		+plasma			



Highlights:

- Increasing the brightness (decreasing the emittance)
- Improving gun stability and reliability
- Extending beam diagnostics
- Use high brightness beam capability

Motivation for accelerator based tunable IR/THz source for pump probe experiments at the European XFEL

Requirements to the pump source

General:

- **Time structure** of IR/THz source → time structure of x-ray pulses
- IR/THz source should have wide **tunability** range
- IR/THz source → wide possibilities for generation of **different temporal and spectral patterns, polarization**. (i.e. strong single-cycle pulses, narrow band radiation)
- Many applications require high peak power (field strength) or **high pulse energy**.
- **Time jitter** of pump and probe pulses should be small enough for resolving time-dependent phenomena

Specific for the European XFEL:

- EXFEL → burst mode: 10Hz x 0.6 ms x 4.5 MHz = =**27000 pulses** per sec
- Current **range** of interest:

	from	to
λ, μm	6 - **20**	**100** - 1000
f, THz	50 - **15**	**3** - 0.3
$h\nu$, meV	207 - **62**	**12.4** - 1.24

- **Pulse energy spans** a lot: μJ → hundreds of μJ → **mJ**
- **Time jitter**: 2 types of experiments:
  - **I. field** driven dynamics where temporal resolution ~few fs → →**CEP stability**
  - **II."intensity"** driven dynamics where temporal resolution ~longest pulse duration (e.g. if THz pulse is 3 ps than the timing only need to be 3 ps).

Generation of IR/THz radiation by relativistic electron beams

Attractive features are:

- clean in-vacuum radiation production
- tunability of radiation with e.g. electron beam manipulation
- potential to provide high power (high field)
- polarization control

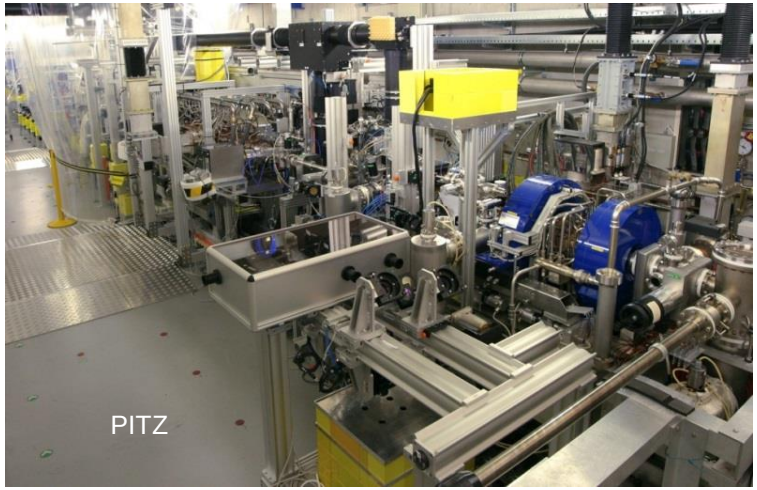
Methods of generation:

- radiation in a bend magnet
- undulator radiation
- transition radiation (i.e., crossing metallic foil)
- diffraction radiation (i.e. passing through an aperture)
- …

Accelerator based tunable IR/THz source: PITZ as a prototype?

E.A. Schneidmiller, M.V. Yurkov, (DESY, Hamburg), M. Krasilnikov, F. Stephan, (DESY, Zeuthen), "Tunabale IR/THz source for pump probe experiments at the European XFEL, Contribution to FEL 2012, Nara, Japan, August 2012

- Accelerator based IR/THz source meets all requirements for pump-probe experiments
- Construction of a radiation shielded annex (like present PITZ facility) is possible close to user experiments at the European XFEL
- Prototype of the accelerator already exists – it is **PITZ** facility at DESY in Zeuthen
- Can be excellent investment of efforts of accelerator consortium after finishing construction and commissioning phases of the European XFEL

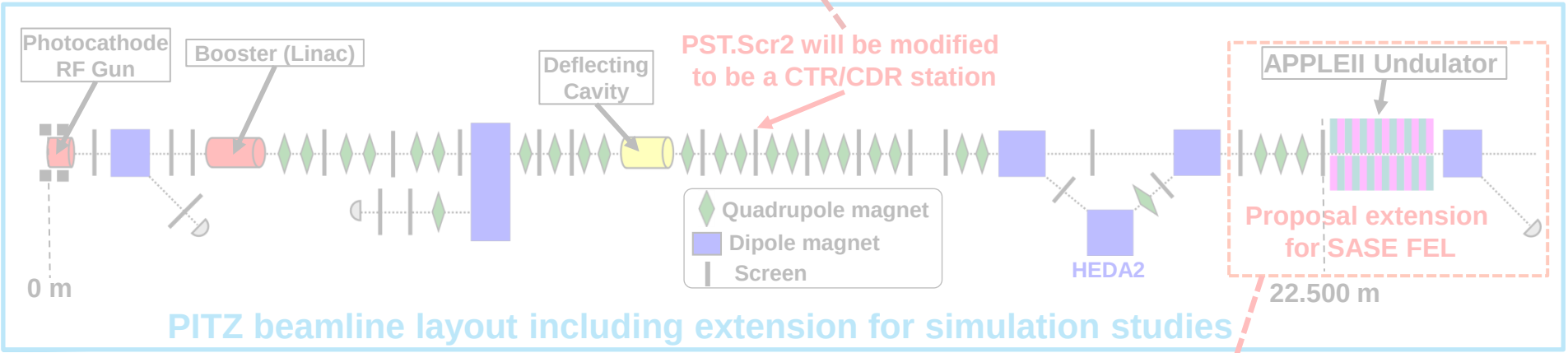


➔ PITZ can serve as prototype for such a development

IR/THz Options at PITZ (High-gain FEL and CTR)

Case studies of THz radiation generation produced by the PITZ electron beam

► **Coherent Transition Radiation (CTR) for $\lambda_{rad} \geq$ 100 µm (f ≤ 3 THz)**



► SASE FEL for $\lambda_{rad} \leq$ 100 µm (f ≥ 3 THz)

PITZ Highlights:
- Pulse train structure
- High charge feasibility (4 nC)
- Advanced PC laser shaping
- E-beam diagnostics
- Available tunnel annex
- …

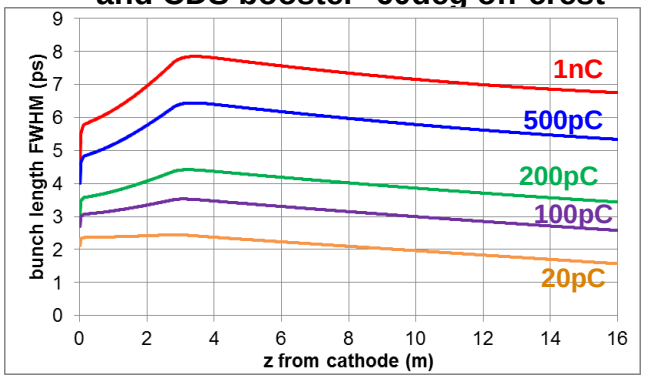
Current PITZ "boundary conditions":
- 22-25 MeV/c max
- No bunch compressor
- …

Experimental tests with electron beams for CTR option at PITZ

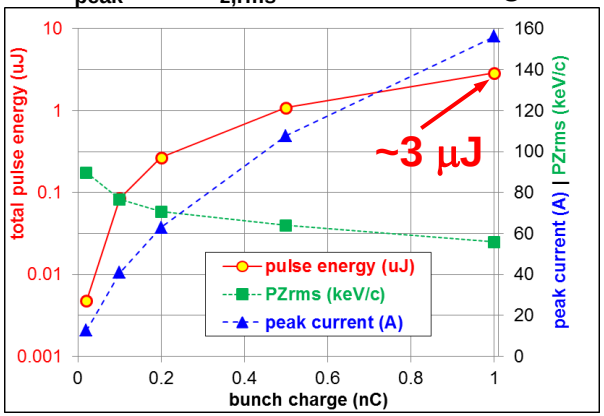
$$\frac{d^2U_{\text{bunch}}}{d\omega d\Omega} \propto N^2\left|F_{long}(\omega)\right|^2; \qquad F_{long}(\omega) = \int_{-\infty}^{+\infty} \rho_{long}(t)e^{-i\omega t}dt \rightarrow T_{bunch} \ll 1/f \rightarrow$$ short bunches for CTR!

CTR Calculations from simulated Velocity Bunching at PITZ

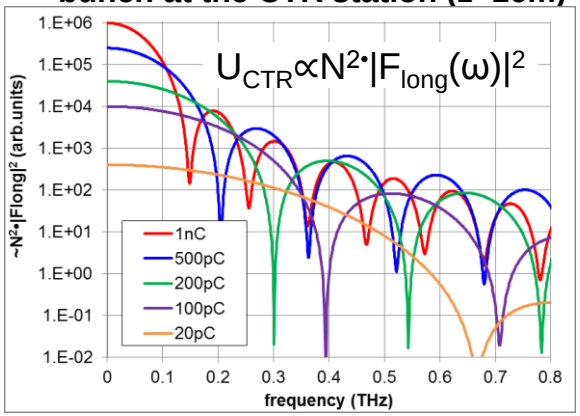
ASTRA simulations with short Gaussian photocathode laser and CDS booster -60deg off-crest



Total CTR radiation energy, I_{peak} and $P_{z,rms}$ vs bunch charge

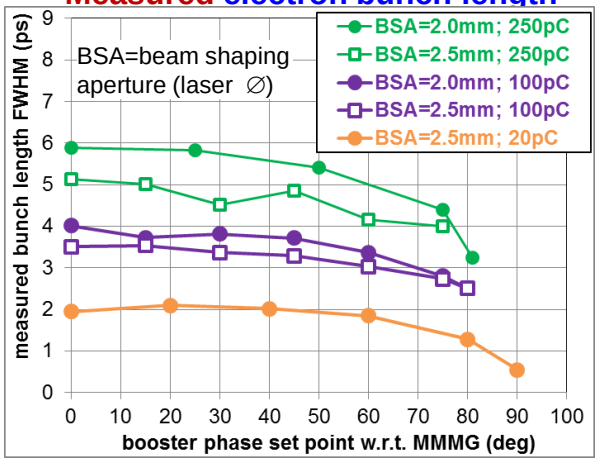


Form factors of the compressed bunch at the CTR station (z=16m)

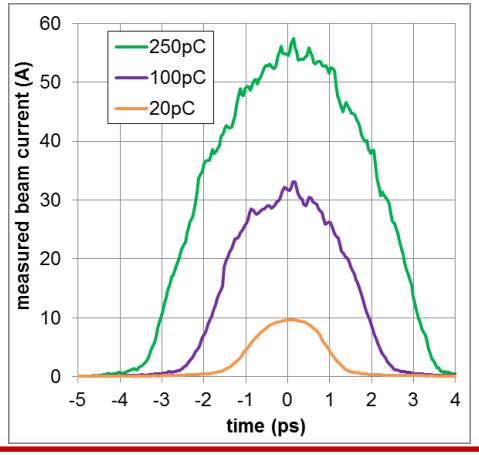


Experiments on velocity bunching with short Gaussian PC laser pulses

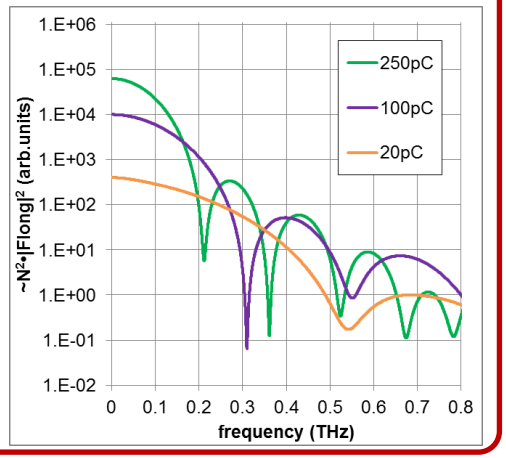
Measured electron bunch length



Measured bunch current profiles



Calculated form-factors



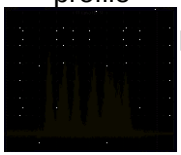
P. Boonpornprasert

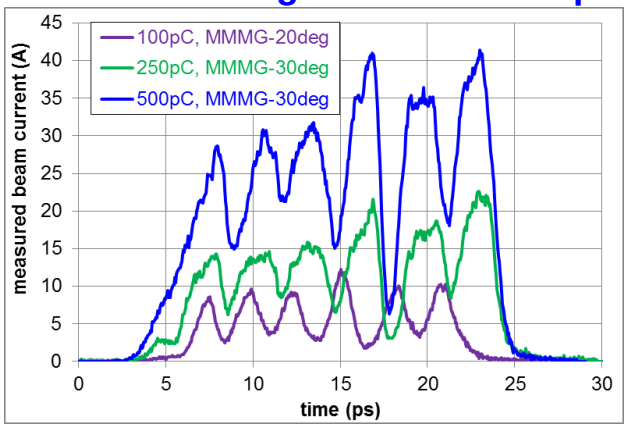
Experimental tests with electron beams for CTR option at PITZ

Experimental Optimization of Comb-beams

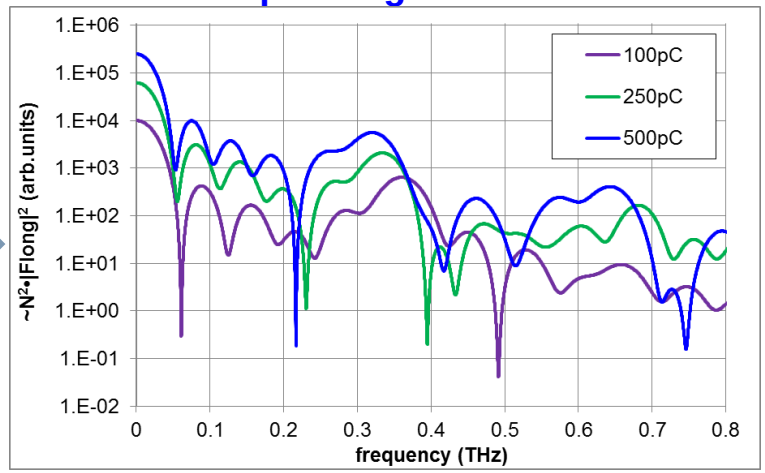
Examples of measured comb-beam profiles with various bunch charges and booster phases

Strongly modulated PC laser temporal profile





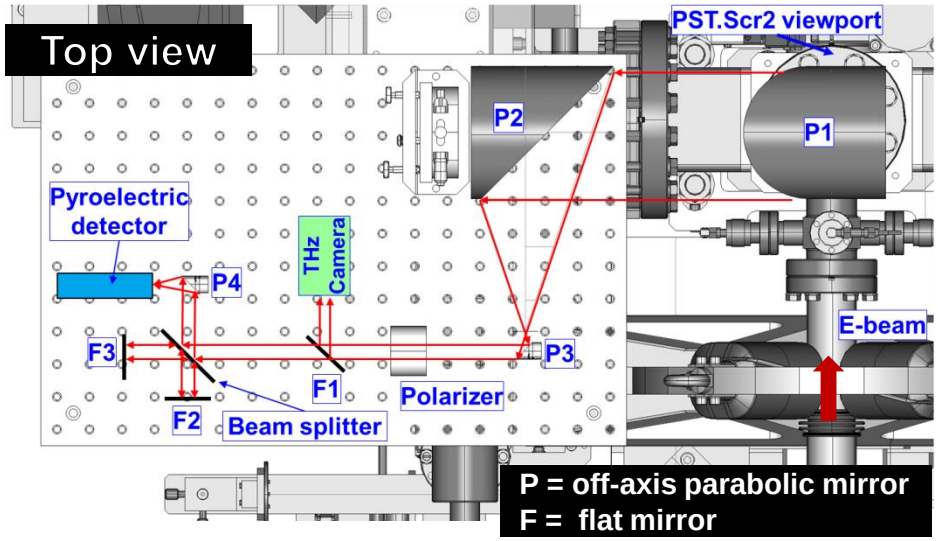
Corresponding form factors



Preliminary Design of CTR/CDR Station

- PST.Scr2 → CTR station
- THz radiation diagnostics system →tunnel
- The system will be used to measure THz radiation:
  - energy/power
  - spatial profile
  - polarization
  - spectrum (Michaelson interferometer)
- The detectors are pyroelectric detector and THz camera with minimum response speed of 10 Hz
- 1st experiments → **Autumn 2017**

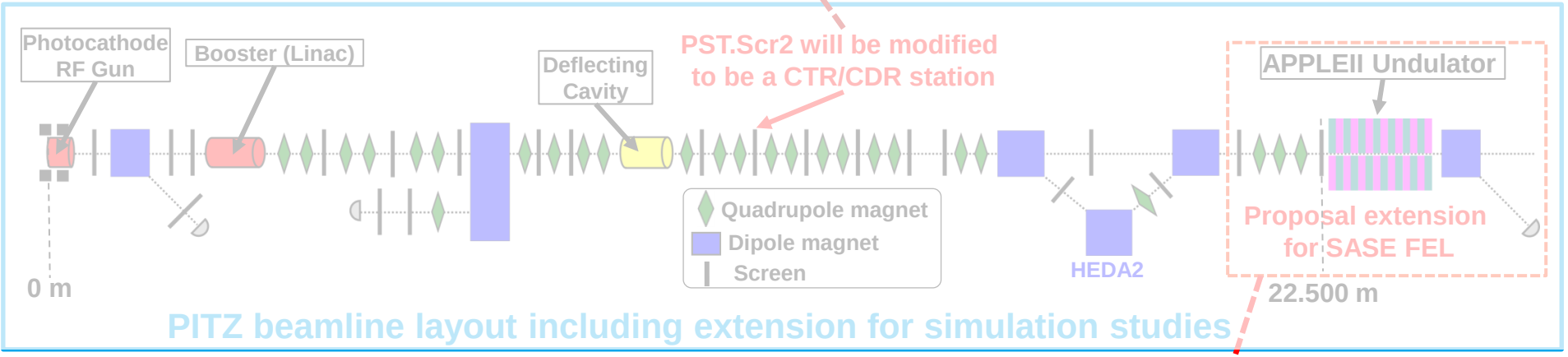
P. Boonpornprasert



IR/THz Options at PITZ (High-gain FEL and CTR)

Case studies of THz radiation generation produced by the PITZ electron beam

► Coherent Transition Radiation (CTR) for $\lambda_{rad} \geq$ 100 µm (f ≤ 3 THz)



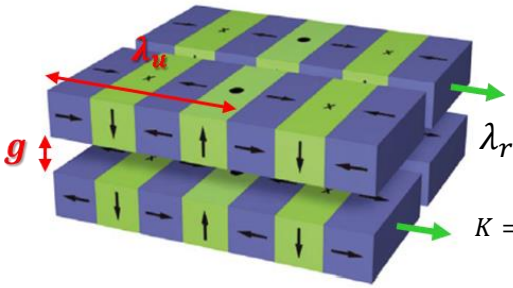
► **SASE FEL for $\lambda_{rad} \leq$ 100 µm (f ≥ 3 THz)**

PITZ Highlights:
- Pulse train structure
- **High charge feasibility (4 nC)**
- **Advanced PC laser shaping**
- E-beam diagnostics
- Available tunnel annex
- …

Current PITZ "boundary conditions":
- 22-25 MeV/c max
- No bunch compressor
- …

THz SASE FEL at PITZ: Undulator and beam parameter space

APPLE- II Undulator*



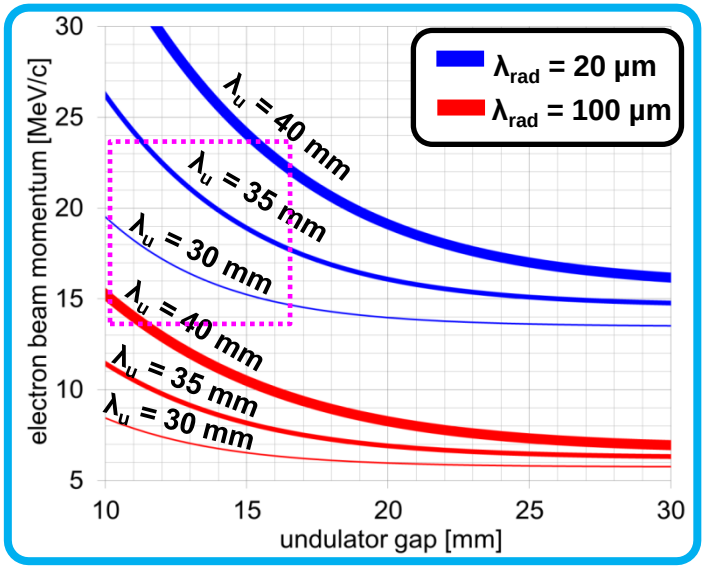
Radiation wavelength

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

$$K = 0.934 \cdot B_0[T] \cdot \lambda_u[cm]$$

$$B_0 = 1.54e^{\left(-4.46\frac{g}{\lambda_u}+0.43\left(\frac{g}{\lambda_u}\right)^2\right)}$$

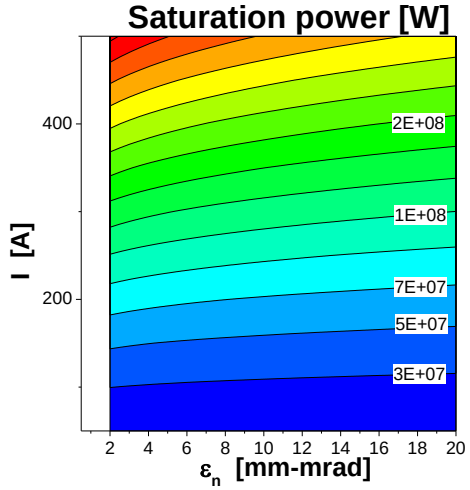
*Conceptual Design Report ST/F-TN-07/12, Fermi@Elettra, 2007

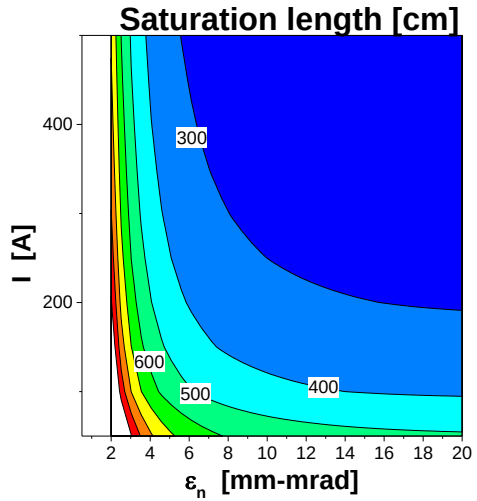


Conditions :
λ_{rad} of 20 – 100 µm
Max P_z ~ 22 MeV/c
gap $g \geq 10$ mm

Selections :
λ_u of 40 mm
22 MeV/c for 20 µm
15 MeV/c for 100 µm

FEL Parameter Space with FAST code (λ = 100 µm)





SASE FEL simulations assuming:

- Helical undulator with period length of **40 mm**
- Electron beam with **15 MeV/c** momentum, **4 nC** bunch charge, **~2 mm** rms bunch length

Preliminary conclusions:

- Transverse normalized emittance ε_n has almost no impact on saturation power
- Higher ε_n → lower saturation length
- Beam **peak current** (charge) → most impact

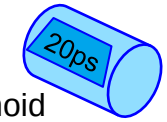
Courtesy M. Yurkov

E.L. Saldin, E.A. Schneidmiller, M.V. Yurkov, "FAST: s three-dimensional time-dependent FEL simulation code", NIM A 429 (1999) 233-237

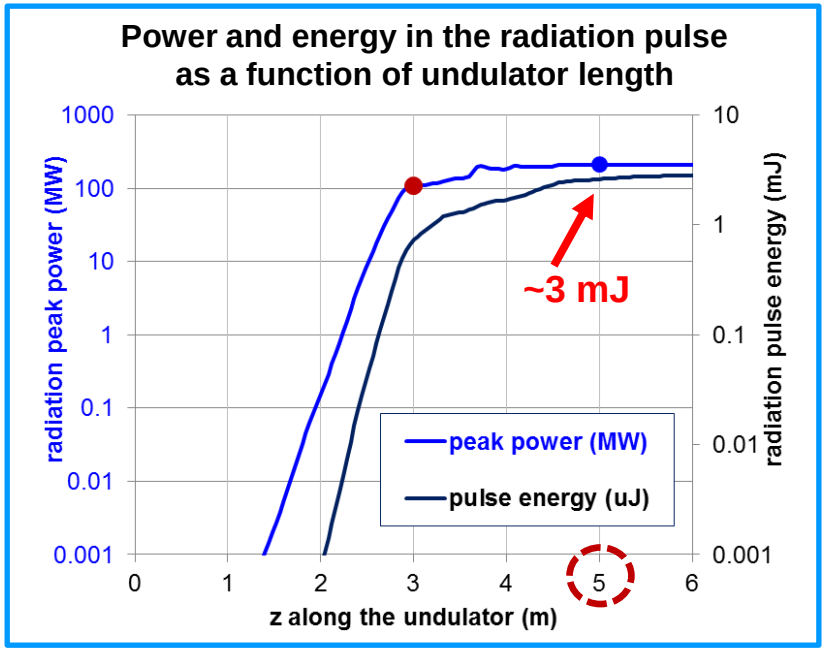
THz SASE FEL: Start-to-End Beam Dynamics Simulations (λ = 100 μm)

Simulation Tools:

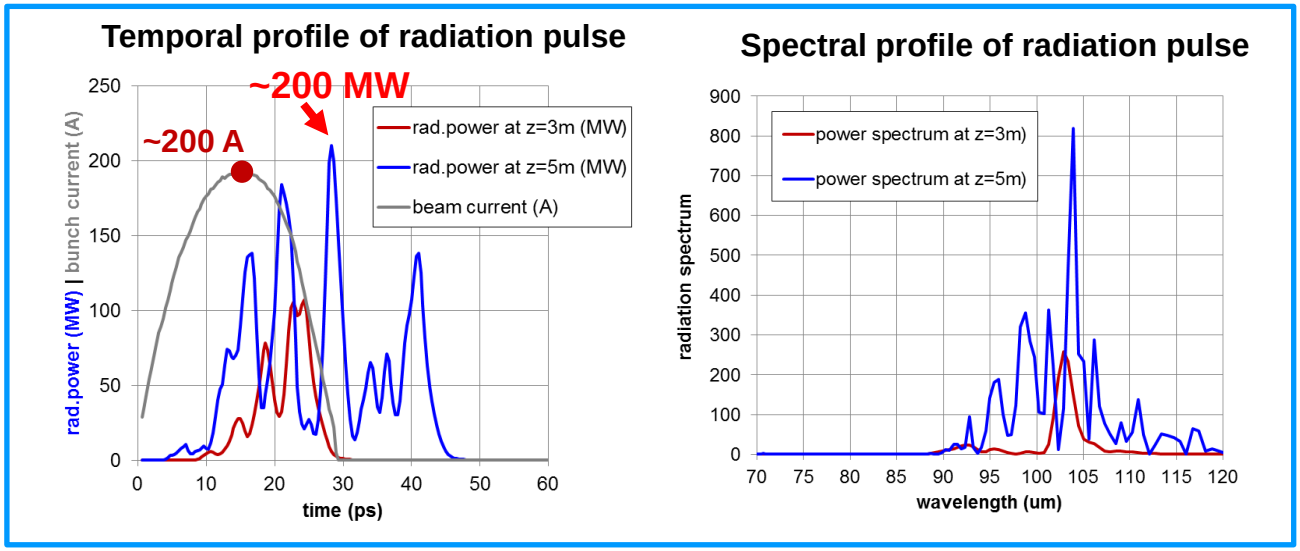
- **ASTRA code** →goals of the beam transport (0→22.5m):
  - **<P_z> ~ 15 MeV/c** at the undulator entrance
  - Symmetric transverse beam sizes and emittances at the undulator entrance
  - Bunch charge **4 nC**
  - PC laser: ∅5mm, flattop 2/20\2ps
  - Gun and booster phases and main solenoid optimized for high I_{peak} and small δE



- **GENESIS 1.3 code (Version 2) for SASE FEL:**
  - Time-dependent mode, space-charge calculation included.
  - Helical undulator with λ_u=**40 mm**
  - SASE FEL, λ_{rad}≈**100 μm (3 THz)**

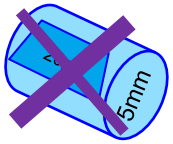


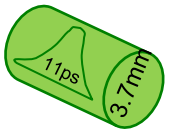
- I_{peak}~200A
- E_{pulse}~3mJ
- L_{und}~5m
- BW~5-10%

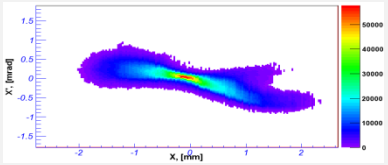
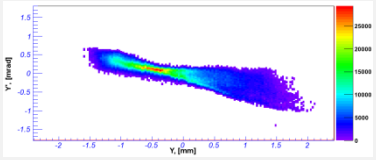
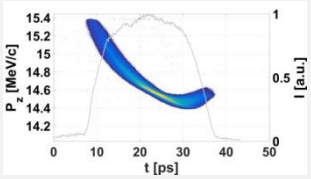


P. Boonpornprasert

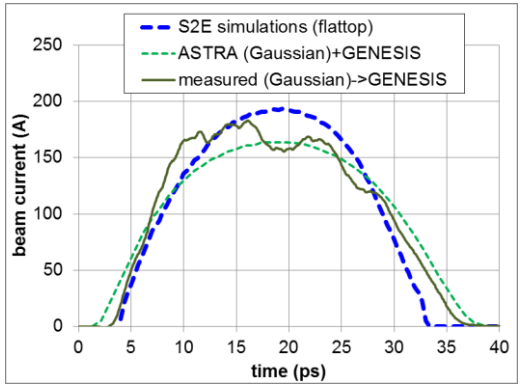
Experimental Characterization of 4 nC Beams for THz SASE FEL Option



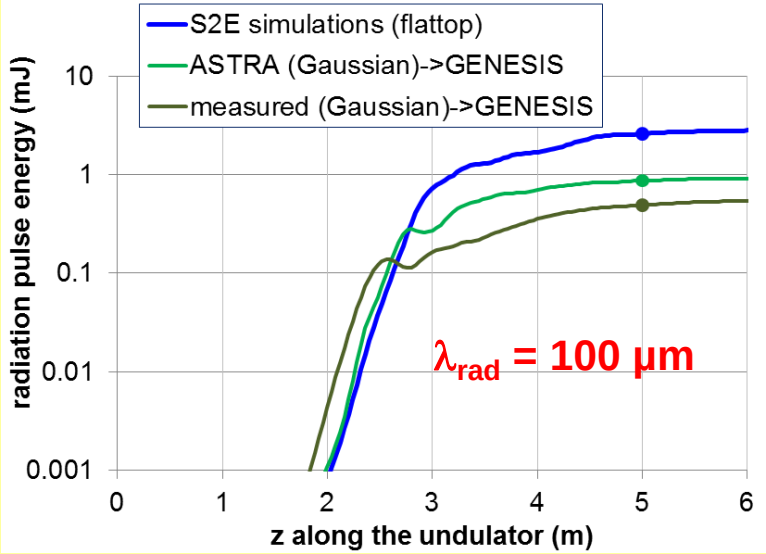


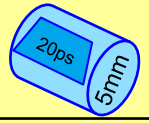
	<Pz>~15MeV/c
X-X'	7.13 mm mrad 
Y-Y'	11.05 mm mrad 
t-P_z	

E-beam Current Profiles



Calculation of SASE FEL for measured profiles

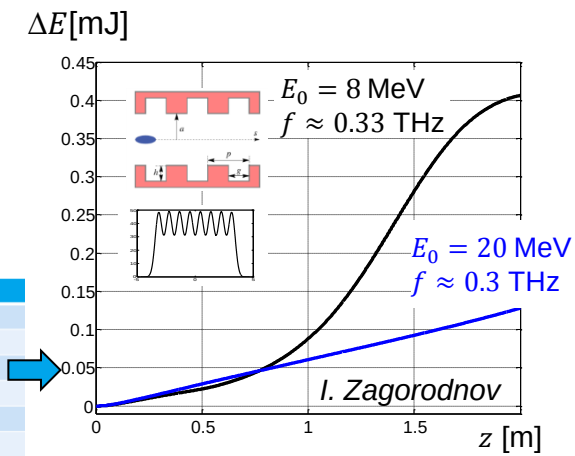


#	Photocathode laser pulse	Procedure	THz pulse energy (z=5m)
1		Start-to-End (S2E) simulations (ASTRA→GENESIS)	**2.6 mJ**
2		ASTRA→GENESIS	**0.9 mJ**
3		Measured (not optimized) electron beam → GENESIS	**0.5 mJ**

Options to improve THz radiation stability

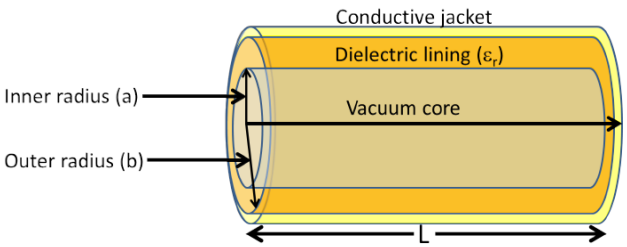
- Pre-bunching → "Seeding"
  - Photocathode laser pulse temporal modulation
  - Using IR laser, modulator and BC for E or δE modulations
  - Exchange transverse to longitudinal modulation
  - Using CDR from short seeding bunch?
  - **Using corrugated structures**
  - **Using Dielectric Lined Waveguides - DLW (first experiments)**
  - …

Pipe radius a, mm	2
Pipe length L, m	0.5-2
Corrugation depth h, mm	0.05
Corrugation period p, mm	0.04
Corrugation gap g, mm	0.02
Gaussian bunch rms σ, mm	0.1-0.3(*8)



First Experiments with DLW at PITZ

> In collaboration with CFEL (F. Lemery) and APC FNAL (P. Piot)

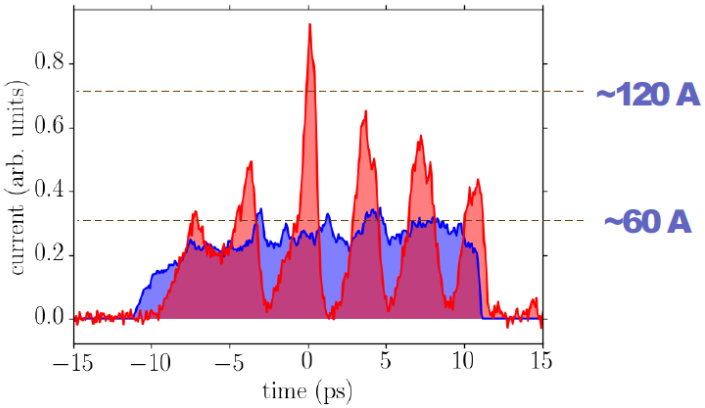


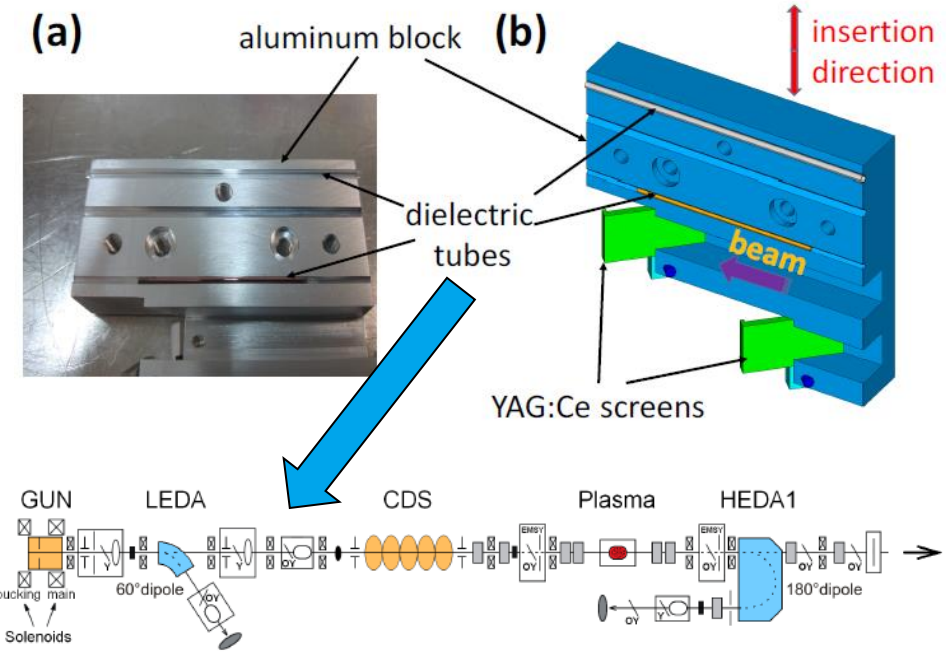
(a, b, ϵ_r, L)=(450 μm, 550 μm, 4.41, 5 cm)

parameter	symbol	nominal	unit
laser launch phase	ϕ_l	0	deg
laser diameter	d	2	mm
RF gun peak field	E_0	60	MV/m
max p_z at DLW	~6.5	MeVc	
linac phase	ϕ	0	deg
linac power	P	2.8	MW
linac peak field	E_1	18	MV/m
bunch charge	Q	1.1	nC
final beam momentum	p_z	20-24	MeV/c

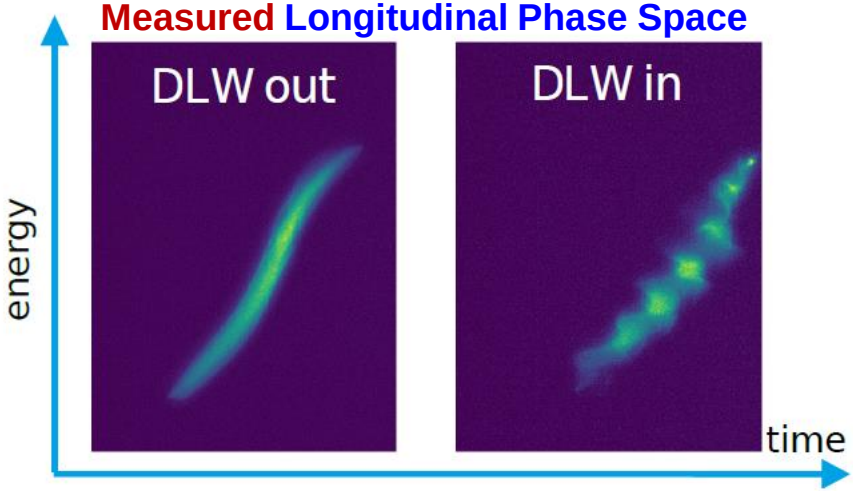
E-beam current profile

without (blue trace) with DLW (red trace), λ=1.03 mm; The peaks are consistent with the wavelength of the structure 3.3 ps.





Measured Longitudinal Phase Space

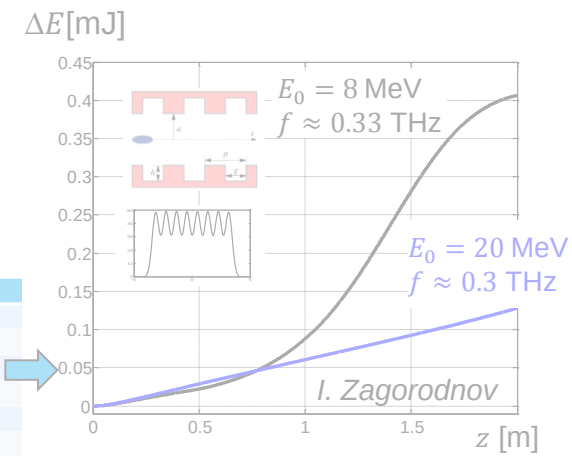


F. Lemery et al., Experimental demonstration of ballistic bunching with dielectric-lined waveguides at PITZ, IPAC 2017, WEPAB122

Options to improve THz radiation stability

- Pre-bunching → "Seeding"
  - Photocathode laser pulse temporal modulation
  - Using IR laser, modulator and BC for E or δE modulations
  - Exchange transverse to longitudinal modulation
  - Using CDR from short seeding bunch?
  - **Using corrugated structures**

Pipe radius a, mm	2
Pipe length L, m	0.5-2
Corrugation depth h, mm	0.05
Corrugation period p, mm	0.04
Corrugation gap g, mm	0.02
Gaussian bunch rms σ, mm	0.1-0.3(*8)

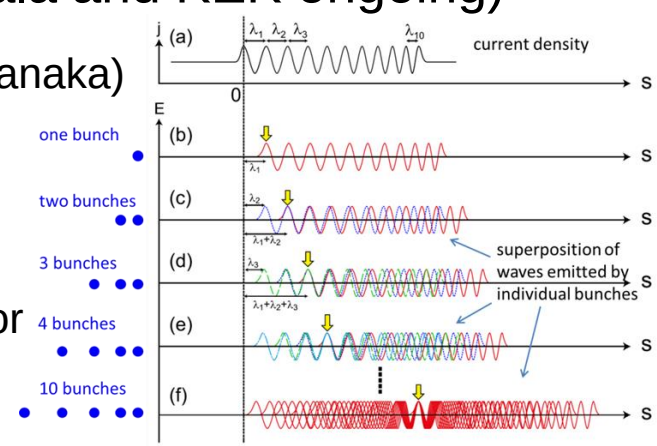


  - **Using Dielectric Lined Waveguides - DLW (first experiments)**
  - …

- Single cycle schemes (discussions with Uppsala and KEK ongoing)
  - **Manipulated undulator radiation** (idea of Takashi Tanaka)

    T. Tanaka. "Proposal to Generate an Isolated Monocycle X-Ray Pulse by Counteracting the Slippage Effect in Free-Electron Lasers." Phys. Rev. Lett.114.4 (2015): 044801

    coherent emission from a chirped microbunched beam passing through a strongly tapered undulator



  - **With short IR laser**
    → Pécs University group (Hungary) simulations

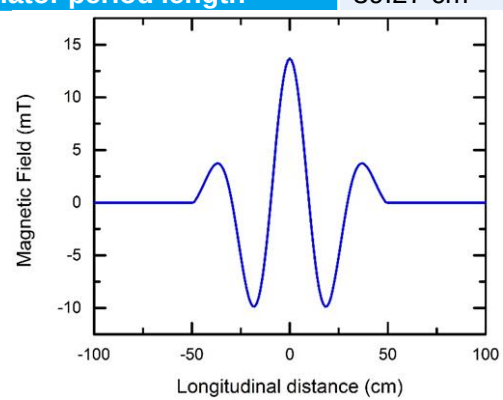
Single cycle schemes by seed (preliminary simulations from University of Pécs)

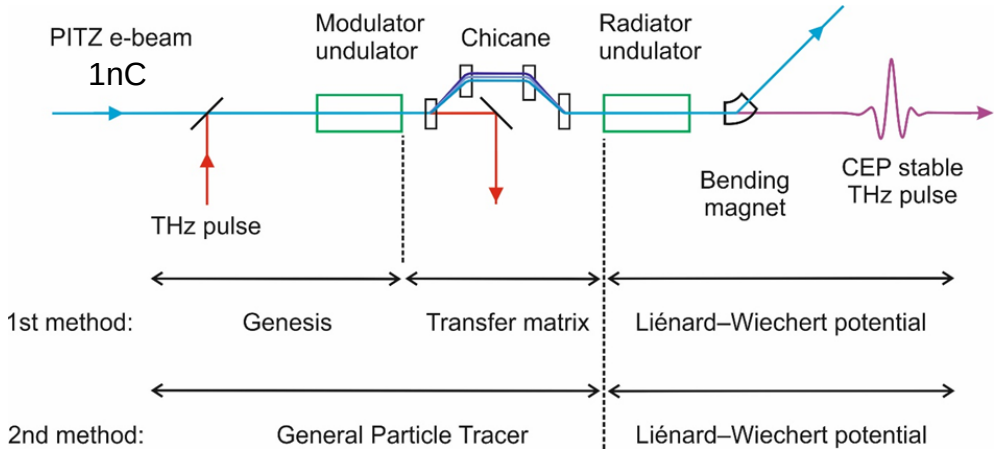
Assumed parameters of the two Seeds and Modulator

	Parameters	Seed 1	Seed 2
Laser	λ_l	1000 um	
	f_l	0.3 THz	
	Waist (w_0)	2000 um	
	Rayleight length	1.26 cm	
	Electric field	1 MV/cm	0.4 MV/cm
	Power $\left(\frac{c_0 \varepsilon_0 E^2}{2} \frac{\pi w_0^2}{2}\right)$	83 MW	13.3 MW
	Pulse duration	~3.3 ps	
	Energy	~0.3 mJ	~0.04 mJ
Undulator	K	10.0	
	λ_u	8.65 cm	
	L/λ_u	1	

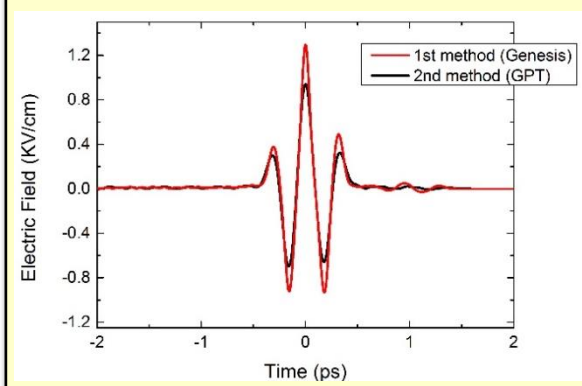
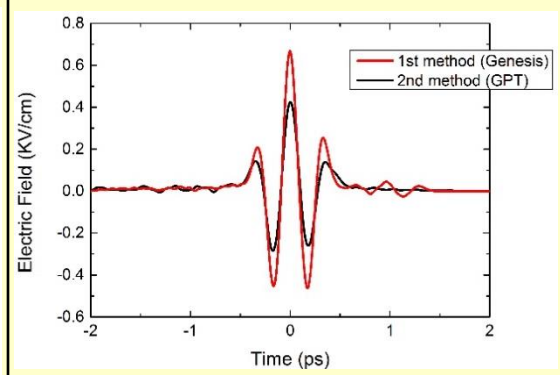
Assumed parameters of the Radiator

Radiation wavelength	100 um (3 THz)
Undulator parameter (K)	0.5
Radiator period length	39.27 cm





Results (calculated 8 m after the radiator undulator)

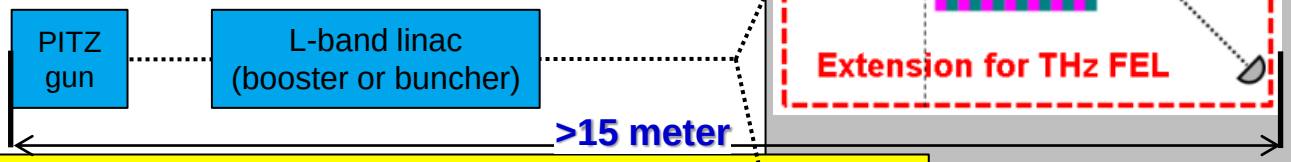
Seed 1		Seed 2	
			
Energy (1st method):	73.4 nJ	Energy (1st method):	22.6 nJ
Energy (2nd method):	113.4 nJ	Energy (2nd method):	47.3 nJ

Courtesy Zoltan Tibai, University of Pécs, Hungary

+ High flux e⁻ diffraction source based on PITZ type accelerator for XFEL

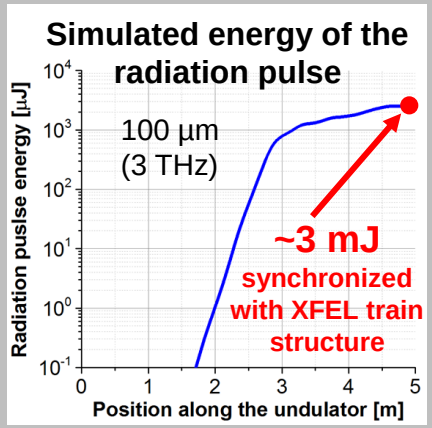
> Idea: Accelerator based **THz (1)** & **electron diffraction source (2)** for XFEL users

Basic PITZ parameters:
- bunch length: sub ps to 22 ps
- bunch charge: sub pC to > 5 nC
- max Pz ~ 24MeV/c
- pulse train structure similar to XFEL



(1) Linac based THz source

Attractive features:
- provides high power (high field)
- tunability of radiation
- polarization control
- clean production of the radiation in vacuum



Possible options:
- Undulator → SASE THz FEL
- Other, e.g. transition, diffraction, synchrotron, edge radiation

Challenges:
- Phase locking (CEP stability) for field driven dynamics
- Short bunches (bunch compression) for single-cycle radiation

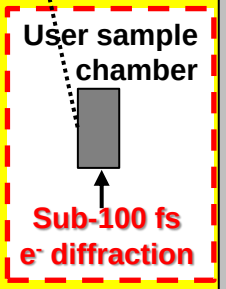
Current status:
- First electron beam measurements for SASE THz FEL option were done
- CTR experiment station is under realization
- Seeding options under study

(2) Femtosecond e⁻ diffraction

v.s. X-ray:
- sub-pm wavelength, good spatial resolution
- ~10^6 higher scattering cross section, good for thin or low density sample

v.s. other MeV electron diffraction source:
- higher rep. rate & higher flux;
- trade flux for higher transverse coherence;

new methodology:
- XFEL pump, electron probe;



Complementary tool for XFEL user to get a full picture of the ultrafast atomic world!

H. Qian

Beam energy	~4 MeV
Rep. rate (bunch/sec)	~10^4 (XFEL like beam structure)
Bunch length	<50 fs (FWHM)
Bunch arrival jitter with XFEL RF spec	~60 fs (FWHM)
Norm. emit. (nm.rad)	~10 → ~0.02
Relative transverse coherence	~10^{-5} → ~10^{-2}
Bunch charge (fC)	~10 → 10^{-3}
Electron flux (e-/sec)	~10^9 → ~10^5

Conclusions

- The Photo Injector Test facility at DESY in Zeuthen (PITZ) develops high brightness electron sources for SASE FELs:
  - specs for the European XFEL (nominal and startup) have been demonstrated and surpassed
  - beam emittance has also been optimized for a wide range of bunch charge (pC→nC)
  - now main focus → stability and reliability (high duty factor performance)

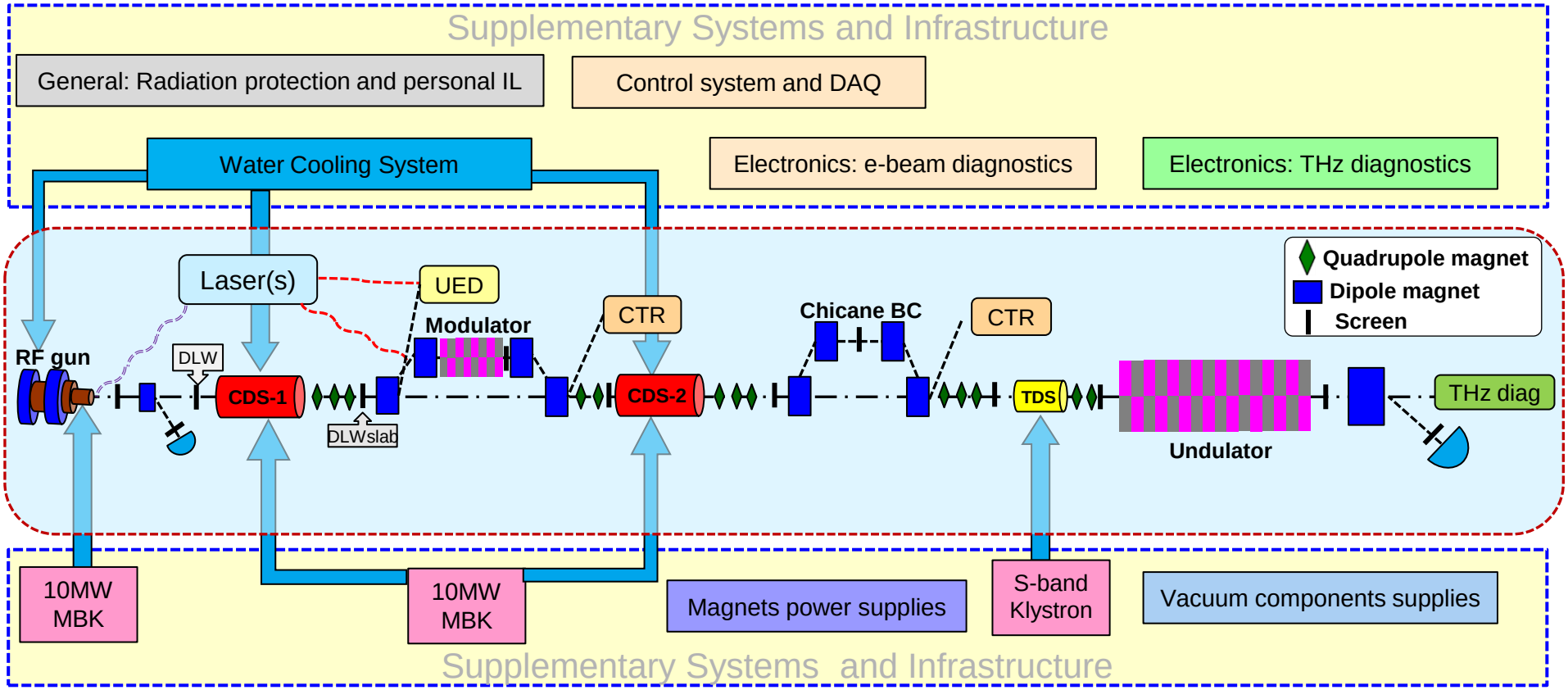
- PITZ highlights:
  - Pulse train structure → EXFEL
  - Advanced PC laser systems
  - High bunch charge (several nC) attainable
  - High stability achieved
  - Extensive beam diagnostics

- THz activities at PITZ (since 2012) ➔ Tunable linac based IR/THz source
  - CTR/CDR with short/pre-bunched using velocity bunching (short Gaussian PC laser pulses + comb-like):
    →Estimations – E-beam measurements – calculations
    → CTR station under construction
  - THz SASE FEL with 4nC bunches:
    →Estimations → s2e simulations (3mJ@100um) → E-beam measurements → simulations
  - Other options:
    Seeding (PC laser modulation, DLW- first tests, corrugated pipe, etc) → under studies
    Single cycle THz production →under discussion in collaboration with Uppsala, KEK, Pécs University group
    Femtosecond e- diffraction

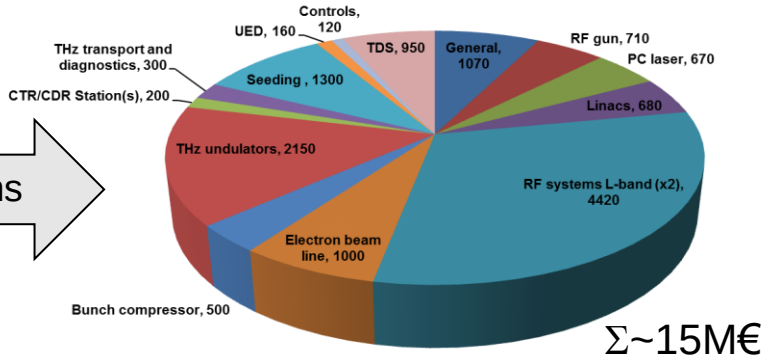
- Outlook

Outlook: Possible "PITHz" Layout

- "all options" included
- reduction in size and costs possible



Hardware costs: VERY rough estimations



Σ~15M€

Section	length	startZ	endZ
PC system	2	0	2
gun	1	2	3
LE	2	3	5
CDS-1	2	5	7
matching	1	7	8
modulator	2	8	10
matching	1	10	11
CDS-2	2	11	13
matching	1	13	14
BC	2	14	16
matching	1	16	17
TDS	1	17	18
matching	1	18	19
undulator	6	19	25
Dump&THzdiag	2	25	27

Backup slides

Outlook: PITZ tunnel(s)

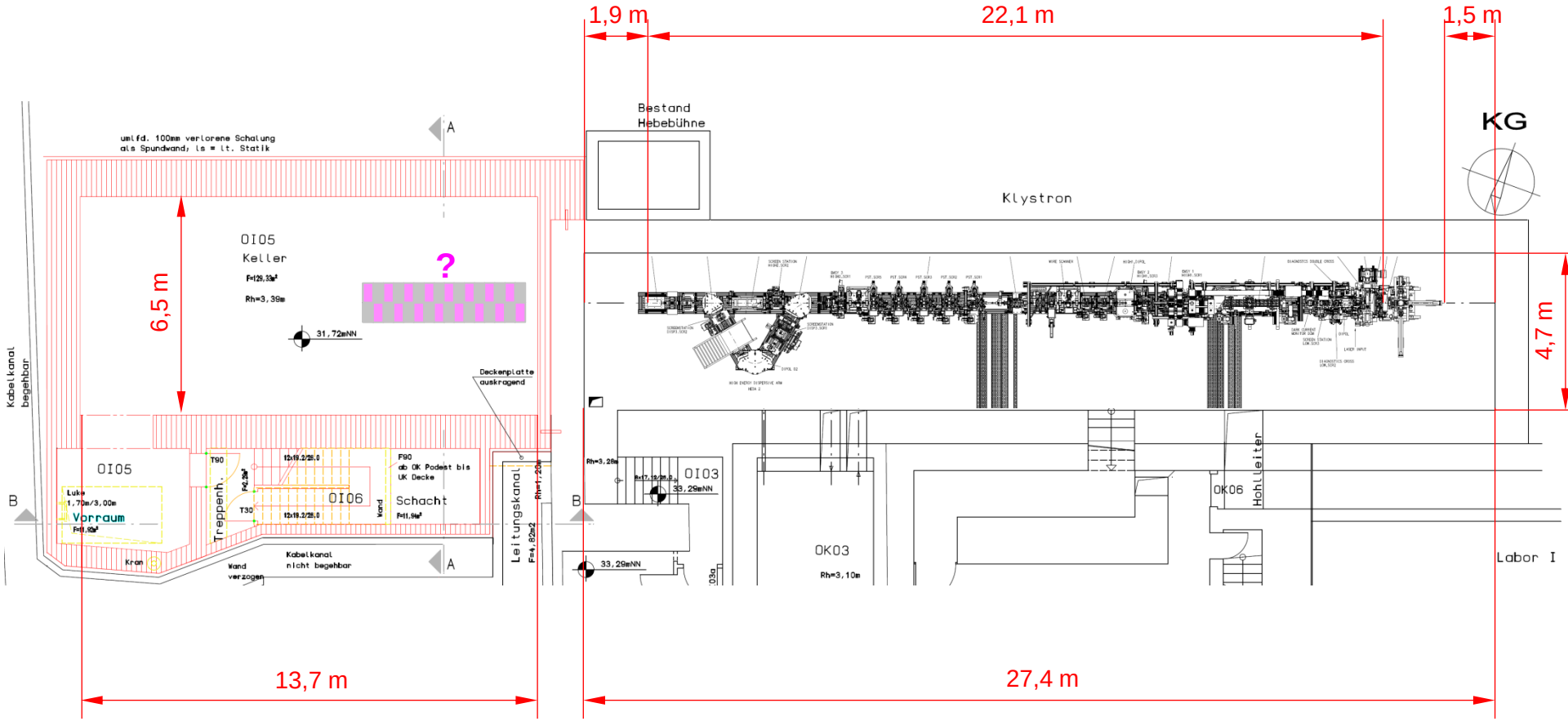


Photo Injector Test facility at DESY, Zeuthen site (PITZ)

PITZ focuses on the development, test and optimization of high brightness e-sources for SC linac driven FELs:

⇒ test-bed for FEL injectors: FLASH, the **European XFEL** (conditioning and characterization of gun cavities and photo injector subsystems, e.g. photocathode laser)

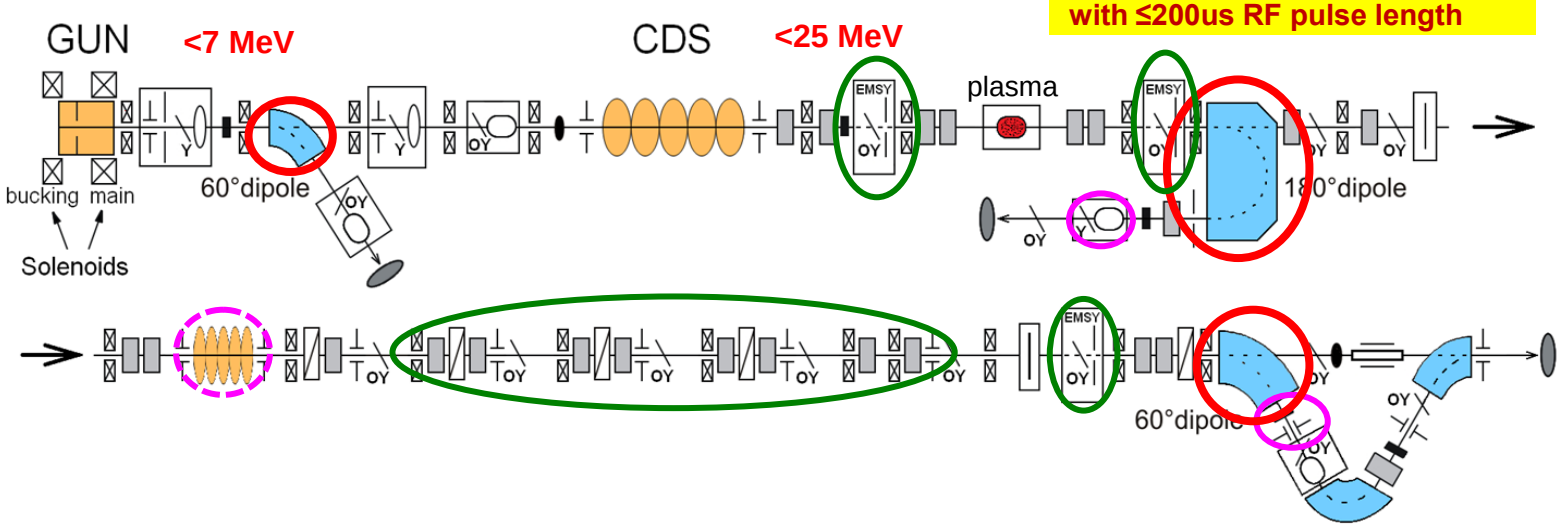
⇒ High brightness → small ε_{tr} (projected and slice)

⇒ further studies → e.g. cathodes: dark current, photoemission, QE, thermal emittance, …

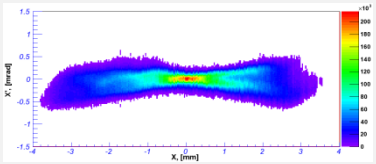
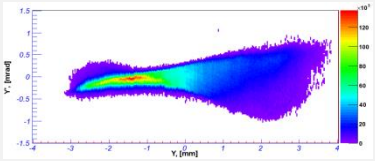
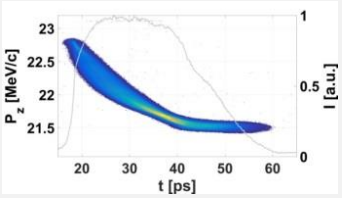
⇒ Currently highest priority at PITZ → Participate in the solution of the remaining problems of the RF gun for EXFEL (RF windows, cathode RF contact spring, stability and long term reliability)

parameter		XFEL injector, nominal	XFEL, commissioning	PITZ, 2015
RF gun gradient (peak power)		E_{cath}=60MV/m (6.5MW)	E_{cath}=50…53MV/m (4.5…5.0MW)	E_{cath}=53MV/m (5MW)
RF pulse length		650us	650us	650us
Repetition rate		10Hz	10Hz	10Hz
RF gun rms stability	ϕ	0.01deg		0.07deg
	A	0.01%		0.02%
Cathode laser (FWHM)		Flattop (2/20\2ps)	Gaussian (~13ps FWHM)	Gaussian (~11.5ps FWHM)
Bunch charge		0.02 – 1 nC	0.1 – 1 nC	0.1 – 1 – 5 nC
Beam emittance		0.4 – 1 mm mrad	e.g. ≤ 1 mm mrad @500pC	0.8 mm mrad @500pC

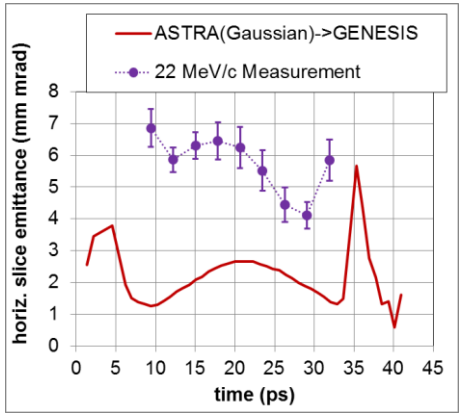
Required electron beam quality demonstrated at PITZ in 2011 with ≤200us RF pulse length



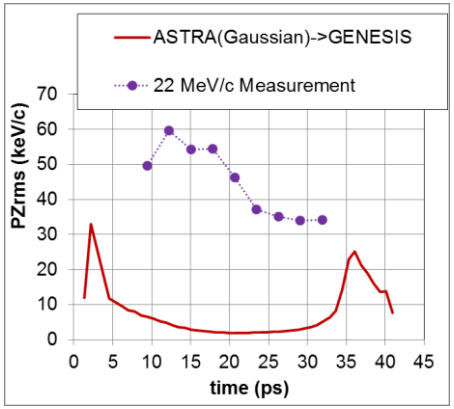
Experimental Characterization of 4 nC Beams for THz SASE FEL Option

	~22 MeV/c
X-X'	6.26 mm mrad 
Y-Y'	6.86 mm mrad 
t-P_z	

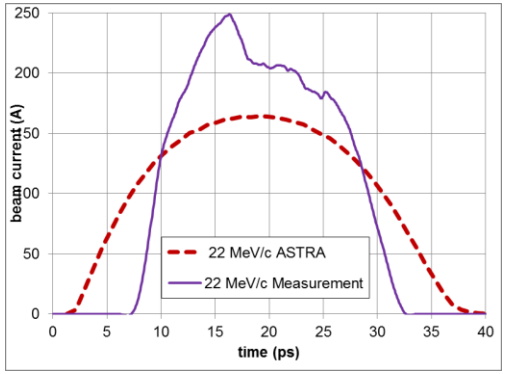
Slice Emittance



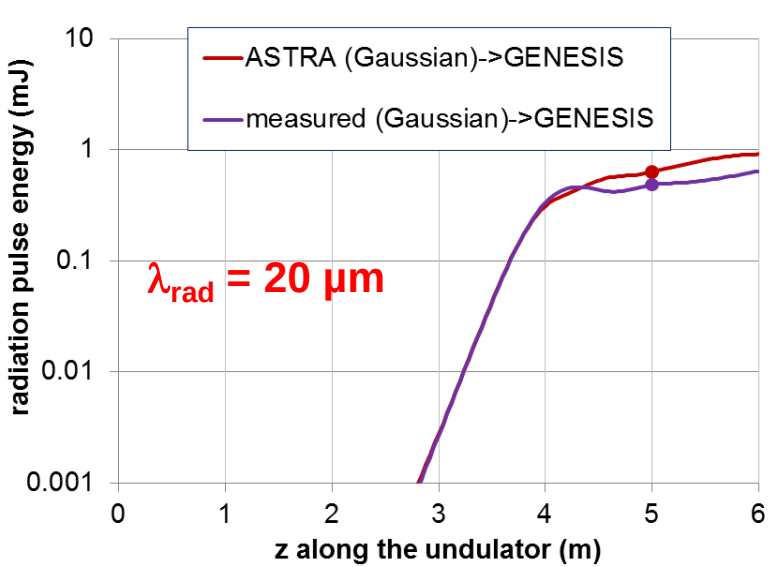
Slice Momentum Spread



E-beam Current Profiles



Calculation of SASE FEL for measured profiles



#	Photocathode laser pulse	Procedure	THz pulse energy
5		ASTRA→GENESIS	**0.6 mJ**
6		Measured electron beam → GENESIS	**0.5 mJ**