Photo injectors:

- RF guns for FELs
- New developments at PITZ

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RF guns for FELs:

- Motivation: Why electron source is so important for linac based FELs ?
- Basic principles and challenges
- Examples: - low average current RF guns
  - medium average current RF guns
  - high average current RF guns
- comparing experimental results and designs
- future trends
- personal remark: details are important for good performance and reliable operation
- summary 1

New developments at PITZ:

- 3D ellipsoidal laser pulse shaping
- plasma acceleration activity
- tunable IR/THz source
- possible PhD positions for future ITN
- summary 2

HELMHOLTZ
ASSOCIATION

PITZ
Photo Injector Test Facility
Zeuthen

DESY

One FEL key component:
→ the high brightness electron source

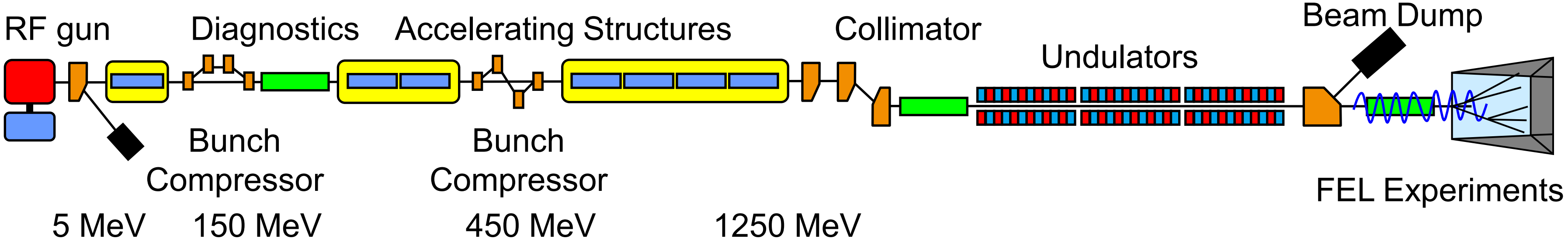
Why electron injector is so important …. ???

Any linac based short wavelength, high brilliance light source (e.g. SASE-FELs) contains the following main components:

- **electron source**
- **accelerating sections** → **e.g. wakefields, coupler kicks**
    - in between: **bunch compressor(s)** → **e.g. coherent synchrotron radiation (CSR)**
- **undulator** to produce FEL radiation
- electron **beam dump**
- **photon beamline(s)** for the users

} **increase normalized emittance**

Example: FLASH 1



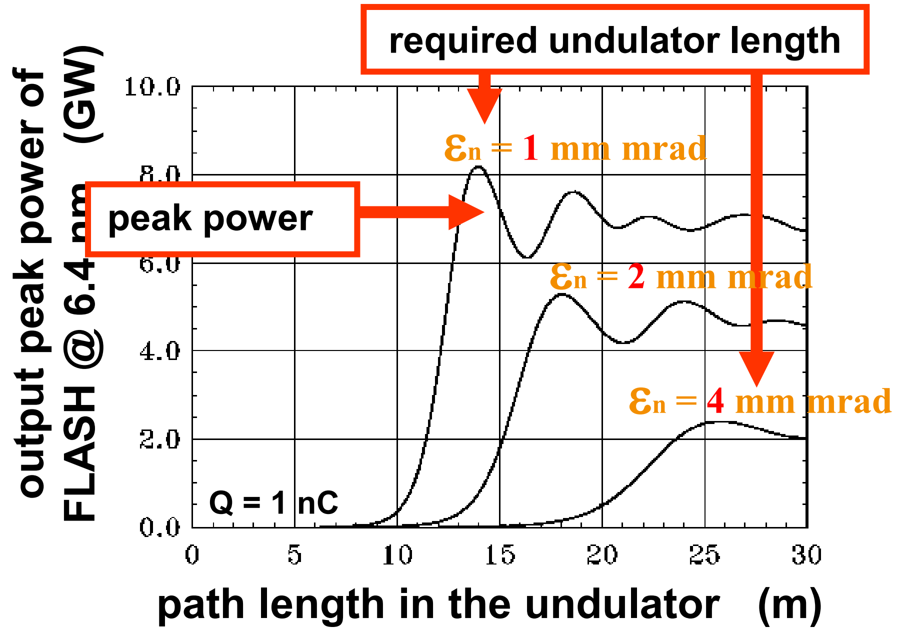
property of linacs: beam quality will DEGRATE during acceleration in linac

➔ electron source has to produce lowest possible emittance !!

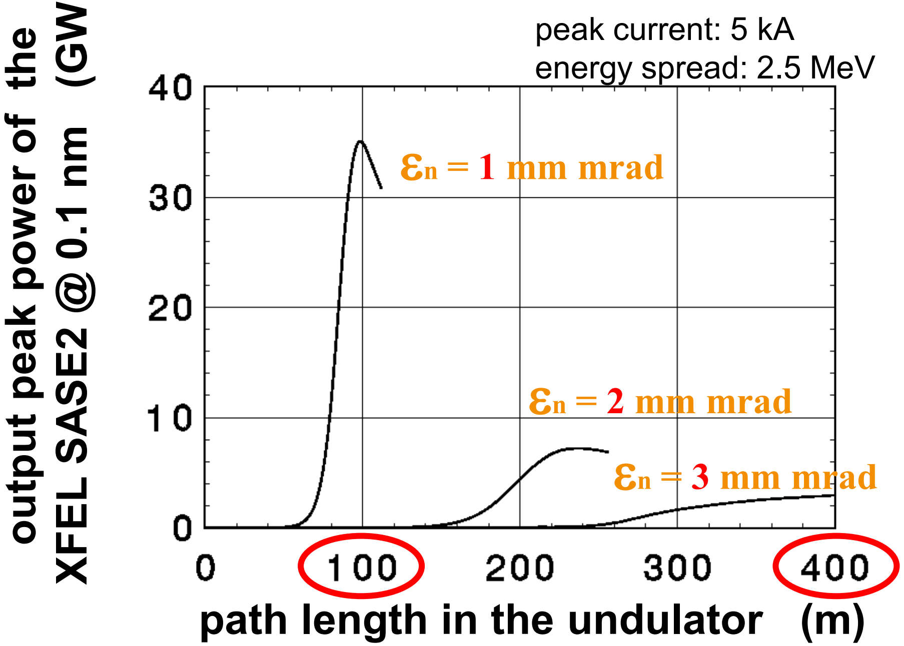
Why electron injector is so important …

- **Why emittance must be small …**

FLASH



European XFEL



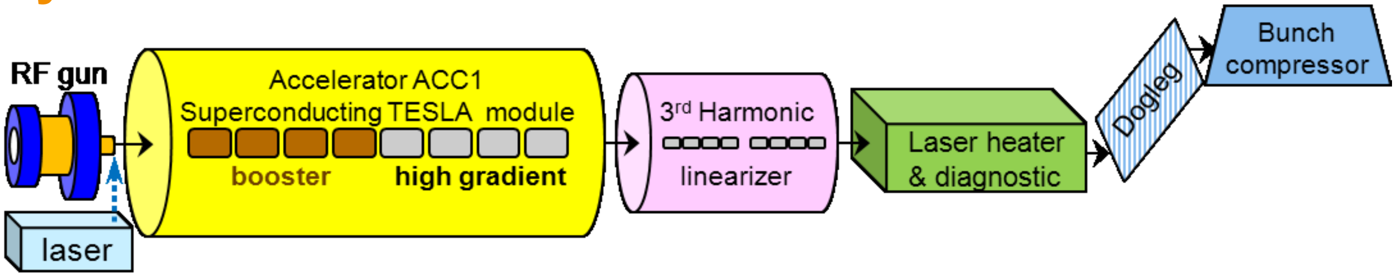
- **e.g. XFEL goal: slice emittance(1nC) = 1.0 mm mrad@undulator**
- **if even smaller emittance ⇒ new horizons:**

shorter wavelength, higher repetition rate

Basic principles and challenges:

Generic Injector Layout

Example:
European XFEL



in general:

- RF **gun** (high gradient, amplitude and phase stability, 1 ↔ many ↔ cw bunches)
- Space charge compensating **solenoids** (positioning, no higher field components)*
- Photo **cathode laser** system (synchronization, laser pulse shaping in time + space)
- **Booster** cavity (synchronization, matched gradient and position**, later: high energy gain)
- **3rd harm. cavity** to linearize longitudinal phase space (synchr., matched gradient + phase)[5]
- **Laser heater** to increase uncorr. energy spread (prevent μ-bunching instability) [6,7,8]
- Detailed **diagnostics** of electron and photo cathode laser beam
- **Bunch compression** and then **further acceleration** of beam (→ **wakefields**)

* “Emittance compensation“ [1, 2, 3] ** “Emittance conservation“ [3, 4]

Basic principles and challenges:

Emittance budget: $\varepsilon_{tot} = \sqrt{\varepsilon_{th}^{2} + \varepsilon_{RF}^{2} + \varepsilon_{SC}^{2}}$

- **thermal emittance** $\varepsilon_{th} \propto \sigma_{x,y} * \sqrt{E_k}$
  [9, 10]
  where $\sigma_{x,y}$ = RMS laser spot size @cathode
  E_k = mean kinetic energy of emitted e^-
- **RF induced** emittance growth $\varepsilon_{RF} \propto \sigma_{x,y}^{2} * \sigma_z^{2}$ [11], σ_z = electron bunch length
- **Space charge** induced emittance growth ε_{SC} = subject to numerical optimization, different dependencies for different photo cathode laser shapes

High accelerating gradient at cathode

\+

- mitigates space charge effects
- allows to extract higher Q for fixed beam dimensions

−

- cathode roughness plays larger role
- reliability issues, heat load
- larger ε_{RF} for long bunches

Photo cathode laser pulse shaping (in time and space):

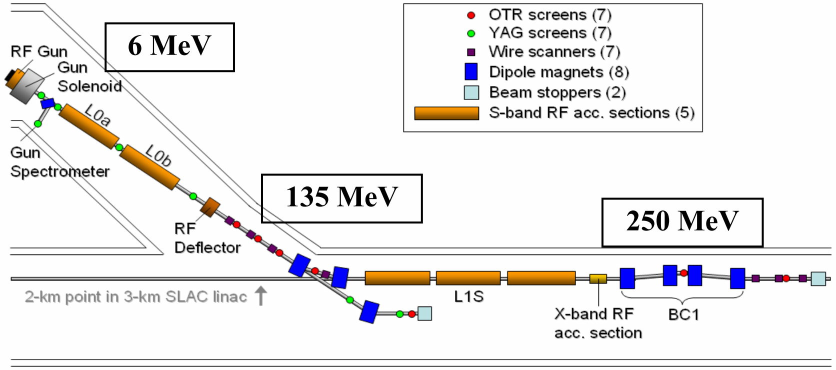
→ relaxes requirements on cathode gradient and gives a lot of additional flexibility !

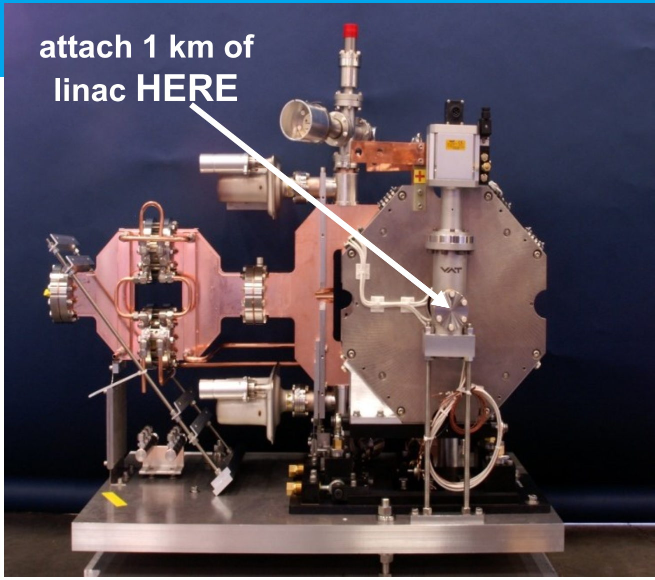
➔ high cathode gradient helps, but laser shaping is as important !

Low average current RF guns (<1 µA)

- Most popular S-band gun, the BNL/SLAC/UCLA gun, and its further developments → the **LCLS gun**:

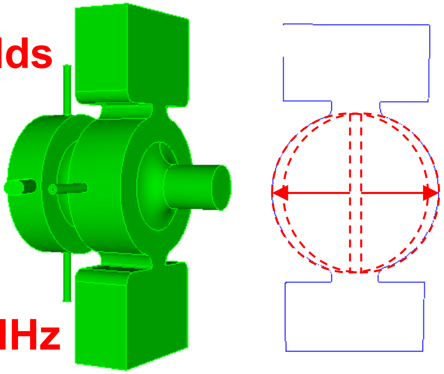
LCLS Injector Setup @SLAC:

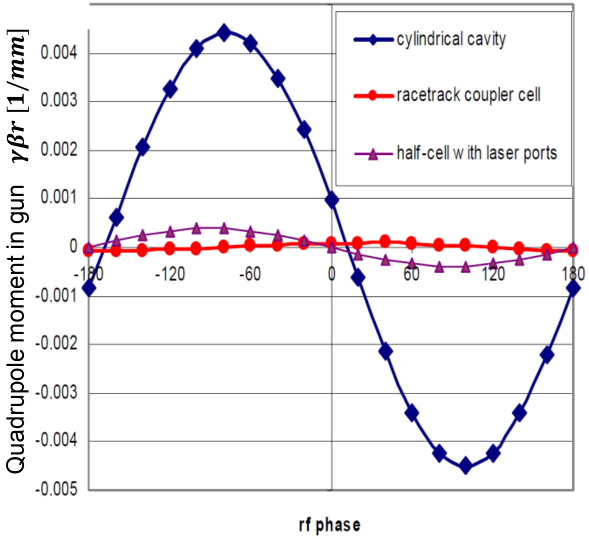




Realised design improvements:

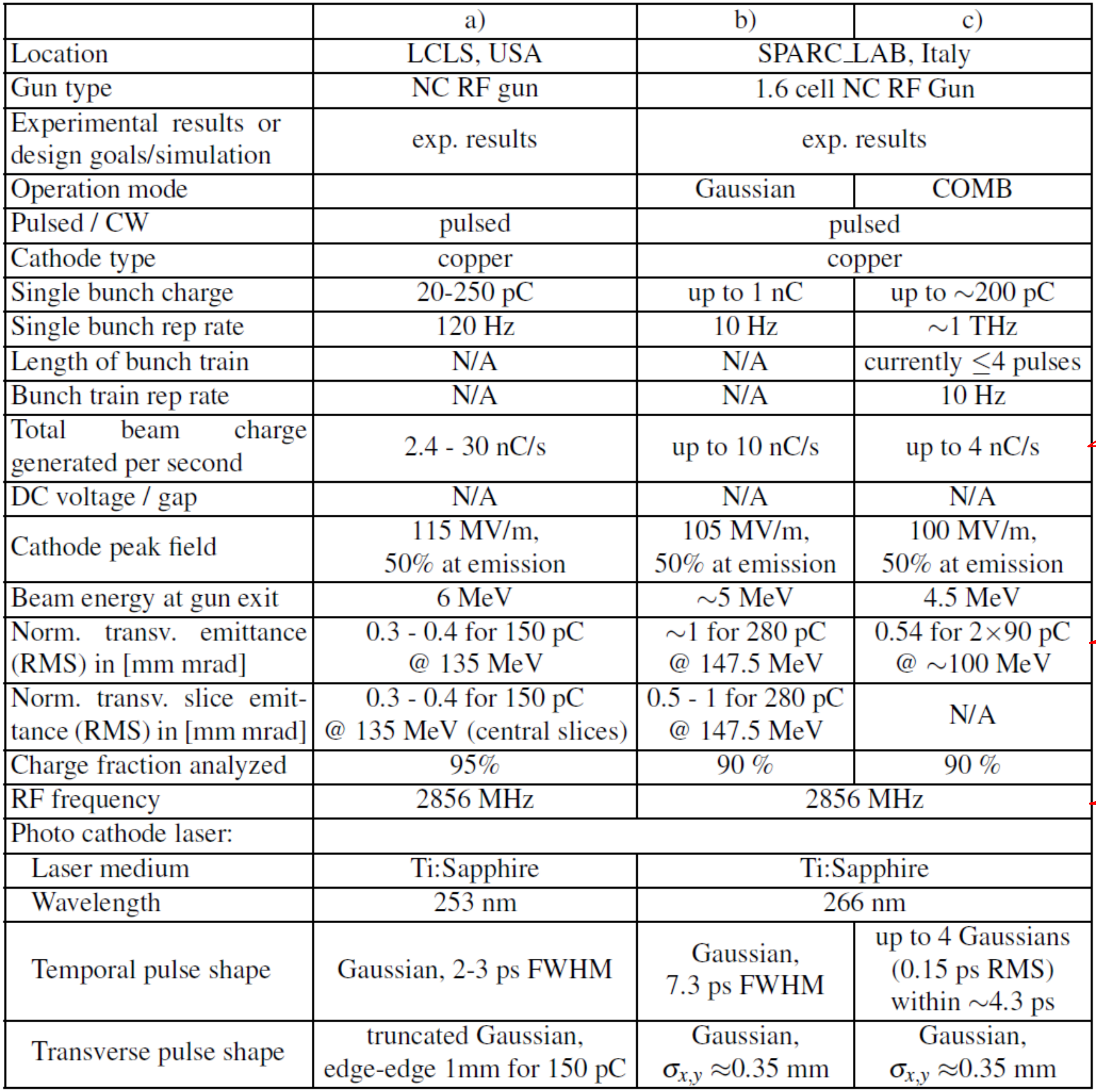
- **Z-coupling** (reduces pulsed heating, increases vacuum pumping)
- **Racetrack to minimize quadrupole fields**
- Deformation tuning to eliminate field emission from tuners
- Iris reshaped, reduces field 10% below cathode
- **Increased 0-π mode separation to 15MHz**
- All 3D features included in modeling (laser port and pickup probes, 3D fields used in Parmela simulation)





For more details see D. Dowell et al., SLAC, FEL 2007, Novosibirsk;   R. Akre et al., PRST-AB 11, 030703 (2008); C. Limborg et al., "RF Design of the LCLS Gun", LCLS-TN-05-3; L. Xiao et al., "Dual feed rf gun design for the LCLS," Proc. 2005 PAC.

Low average current RF guns (<1 µA)



	a)	b)	c)
Location	LCLS, USA	SPARC_LAB, Italy	
Gun type	NC RF gun	1.6 cell NC RF Gun	
Experimental results or design goals/simulation	exp. results	exp. results	
Operation mode		Gaussian	COMB
Pulsed / CW	pulsed	pulsed	
Cathode type	copper	copper	
Single bunch charge	20-250 pC	up to 1 nC	up to $\sim$200 pC
Single bunch rep rate	120 Hz	10 Hz	$\sim$1 THz
Length of bunch train	N/A	N/A	currently $\leq$4 pulses
Bunch train rep rate	N/A	N/A	10 Hz
Total beam charge generated per second	2.4 - 30 nC/s	up to 10 nC/s	up to 4 nC/s
DC voltage / gap	N/A	N/A	N/A
Cathode peak field	115 MV/m, 50% at emission	105 MV/m, 50% at emission	100 MV/m, 50% at emission
Beam energy at gun exit	6 MeV	$\sim$5 MeV	4.5 MeV
Norm. transv. emittance (RMS) in [mm mrad]	0.3 - 0.4 for 150 pC @ 135 MeV	$\sim$1 for 280 pC @ 147.5 MeV	0.54 for 2$\times$90 pC @ $\sim$100 MeV
Norm. transv. slice emittance (RMS) in [mm mrad]	0.3 - 0.4 for 150 pC @ 135 MeV (central slices)	0.5 - 1 for 280 pC @ 147.5 MeV	N/A
Charge fraction analyzed	95%	90 %	90 %
RF frequency	2856 MHz	2856 MHz	
Photo cathode laser:			
Laser medium	Ti:Sapphire	Ti:Sapphire	
Wavelength	253 nm	266 nm	
Temporal pulse shape	Gaussian, 2-3 ps FWHM	Gaussian, 7.3 ps FWHM	up to 4 Gaussians (0.15 ps RMS) within $\sim$4.3 ps
Transverse pulse shape	truncated Gaussian, edge-edge 1mm for 150 pC	Gaussian, $\sigma_{x,y} \approx$0.35 mm	Gaussian, $\sigma_{x,y} \approx$0.35 mm

Collection of current photo injector parameters for

- LCLS
- SPARC-LAB

average beam current in the nA range

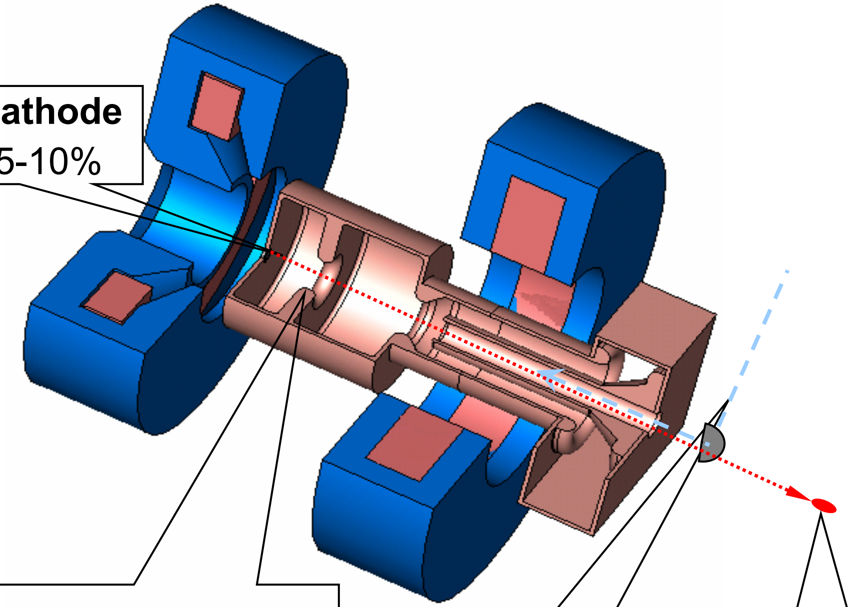
low emittances

S-band guns

Table from F. Stephan, M. Krasilnikov (2014) [12]

Medium average current RF guns (1 µA < $I_{av.}$ < 1mA)

> The **PITZ gun**, used for FLASH and European XFEL:



Cs_2Te cathode
QE~0.5-10%

RF-gun:
- L-band (**1.3 GHz**) 1½-cell copper cavity
- RF power: ~**7MW** peak **850 µs** pulse length @**10 Hz** → ~1% duty cycle
- Dry ice cleaning ➔ low dark current

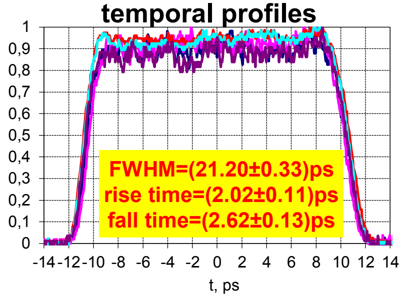
Cathode laser
λ=257nm
pulse trains
(800 @1MHz),
10Hz rep.rate.

Electron bunches:
- pC to few nC
- **p_{max}: ~7MeV/c**
- Bunch trains

How to achieve small emittance:

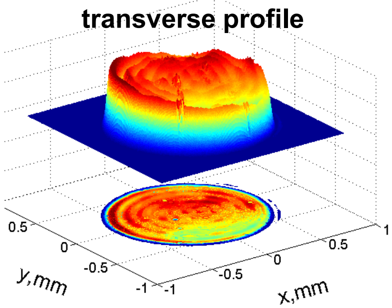
- > High **gradient** at cathode: ~60MV/m (1.3GHz)
- > Cathode laser pulse **shaping**

temporal profiles

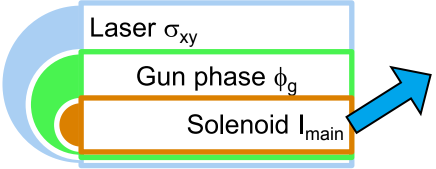


FWHM=(21.20±0.33)ps
rise time=(2.02±0.11)ps
fall time=(2.62±0.13)ps

transverse profile



- > Gun launch **phase** stability
- > Beam based **alignment**, trajectory optimization
- > Emittance compensation and conservation → multi parametric machine **tuning** (solenoid, laser spot size, gun phase, booster,…)

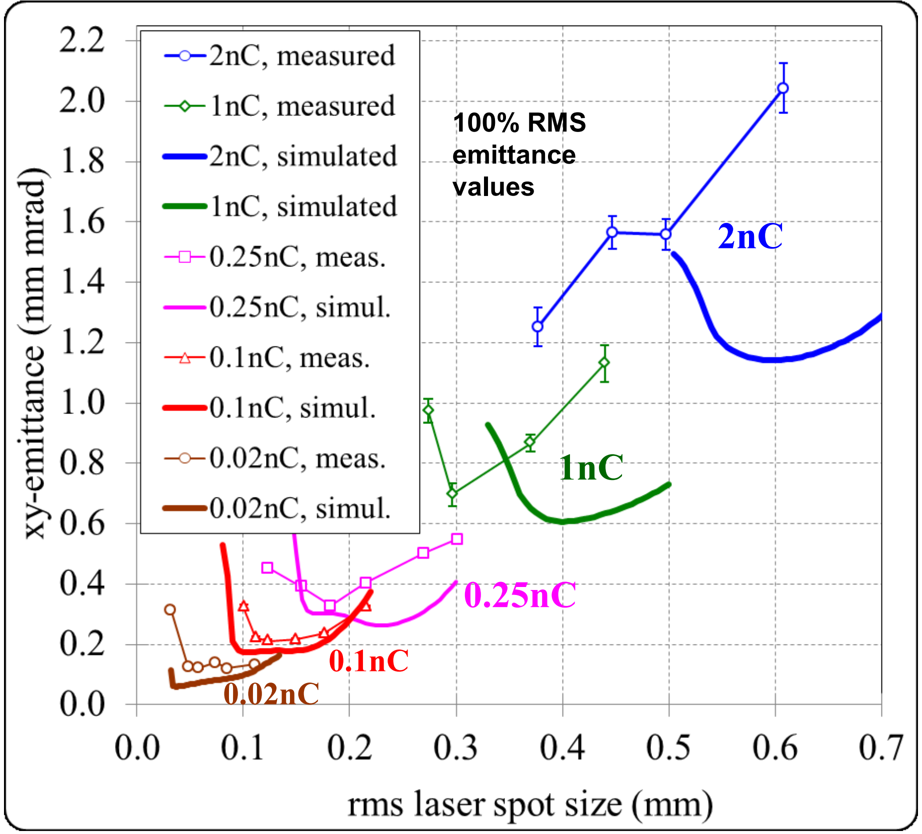


Laser σ_{xy}
Gun phase ϕ_g
Solenoid I_{main}

$\min(\sqrt{\varepsilon_{n,x}\varepsilon_{n,y}})$
with statistics

Medium average current RF guns (1 µA < $I_{av.}$ < 1mA)

PITZ: Measured emittance versus laser spot size for various charges w.r.t. simulations



100% RMS emittance values

- Measured emittance results set a benchmark on photo injector optimization
- Optimum machine parameters (laser spot size, gun phase): experiment ≠ simulations
- Difference in the optimum laser spot size is bigger for higher charges (~good agreement for 100pC)
- Simulations of the emission need to be improved

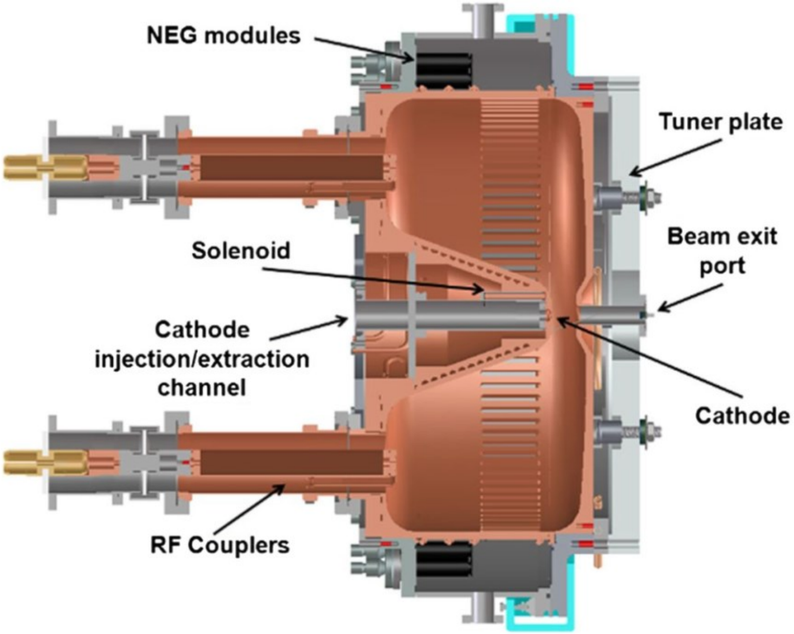
*M. Krasilnikov et al., PRST-AB **15**, 100701 (2012).*

TABLE IV. Core xy-emittance (mm mrad) measured for various charges and gun phases. Only statistical errors are shown

bunch charge	gun phase	charge cut 0%	5%	10%
2.0 nC	0 deg	1.558±0.050	1.324±0.045	1.173±0.039
2.0 nC	6 deg	1.251±0.064	1.064±0.054	0.939±0.048
1.0 nC	0 deg	0.833±0.038	0.711±0.033	0.629±0.029
1.0 nC	6 deg	0.696±0.020	0.596±0.017	0.529±0.015
0.25 nC	0 deg	0.328±0.010	0.289±0.009	0.260±0.008
0.10 nC	0 deg	0.212±0.006	0.188±0.006	0.170±0.006
0.02 nC	0 deg	0.121±0.001	0.108±0.001	0.098±0.001

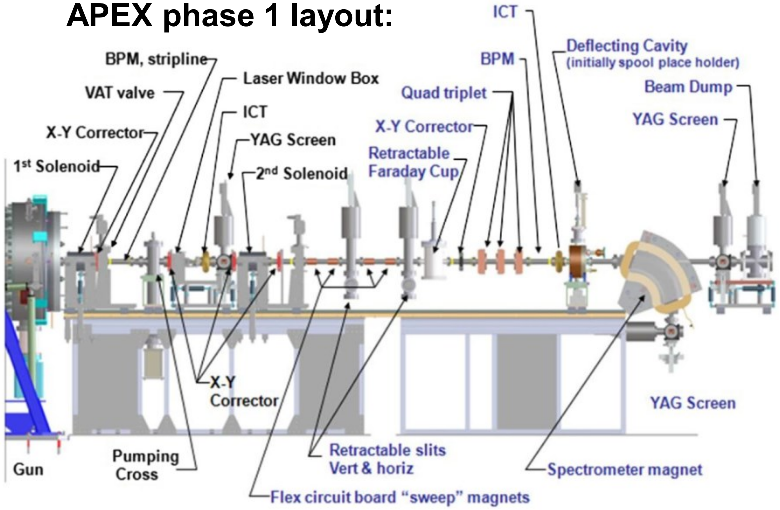
Medium average current RF guns (1 µA < $I_{av.}$ < 1mA)

> The **APEX gun** at Berkeley: a NC gun for **CW operation**



- **186MHz**:
  - \- reduced **cathode gradient** w.r.t. L-/S-band
  - \- low **beam energy** at gun exit
  - \+ reduced RF **power density** on surface
  - \+ allows longer laser pulse on cathode
    - → reduced **space charge density**
  - \+ good vacuum conductivity
    - → **high QE** photo cathodes (Cs_2Te, CsK_2Sb)
    - → reduces power request for cathode laser

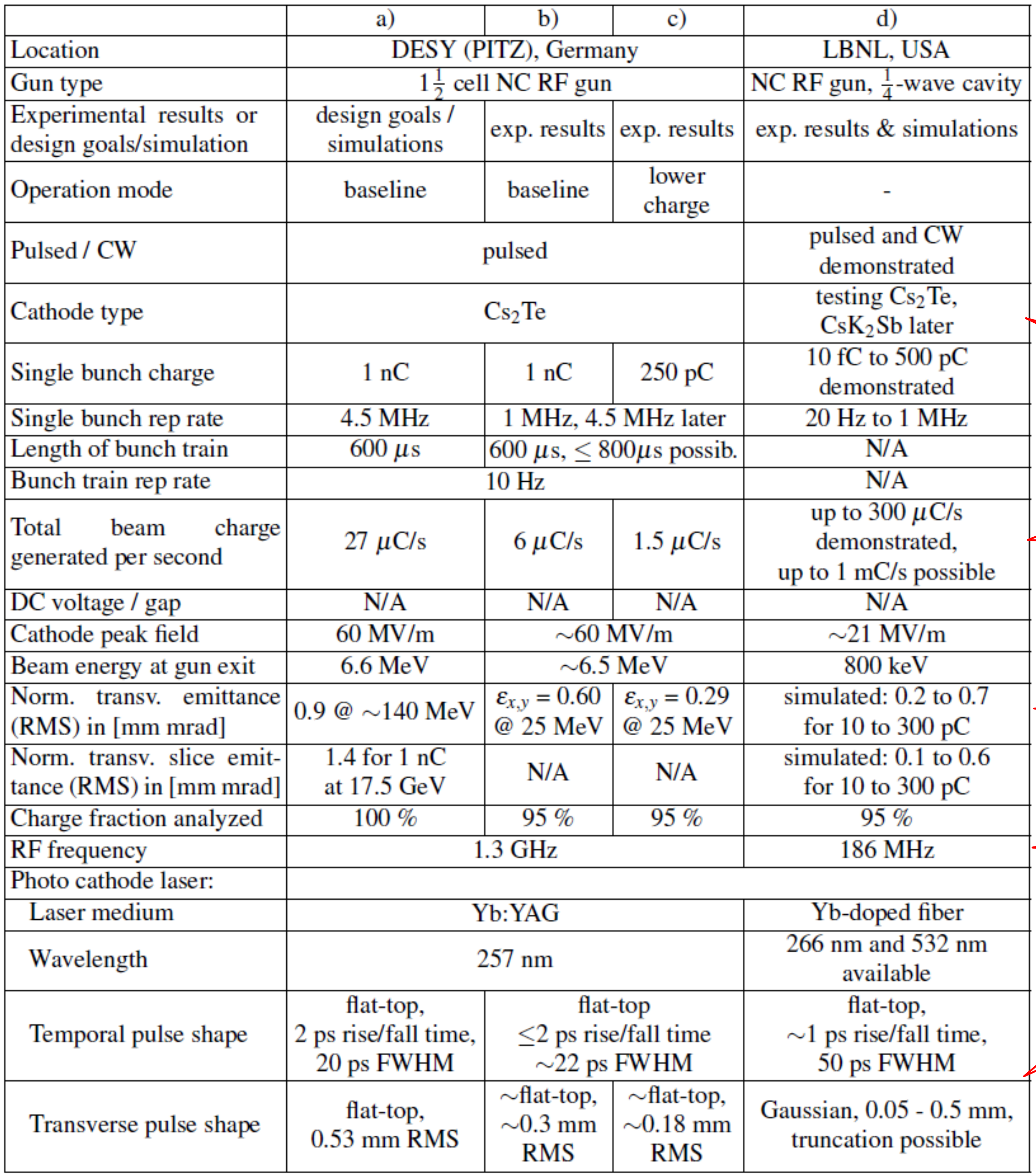
APEX phase 1 layout:



- Commissioning ongoing successfully → table
  - \- dark current @19.5 MV/m → 350 nA
  - \- 300 µA operation (300 pC @1MHz)
  - \- Cs_2Te lifetime (1/e) is 3 days
- Continuous **extension** is **ongoing**

Courtesy F. Sannibale

Medium average current RF guns (1 µA < $I_{av.}$ < 1mA)



	a)	b)	c)	d)
Location	DESY (PITZ), Germany			LBNL, USA
Gun type	$1\frac{1}{2}$ cell NC RF gun			NC RF gun, $\frac{1}{4}$-wave cavity
Experimental results or design goals/simulation	design goals / simulations	exp. results	exp. results	exp. results & simulations
Operation mode	baseline	baseline	lower charge	-
Pulsed / CW	pulsed			pulsed and CW demonstrated
Cathode type	Cs_2Te			testing Cs_2Te, CsK_2Sb later
Single bunch charge	1 nC	1 nC	250 pC	10 fC to 500 pC demonstrated
Single bunch rep rate	4.5 MHz	1 MHz, 4.5 MHz later		20 Hz to 1 MHz
Length of bunch train	600 μs	600 μs, $\leq$ 800μs possib.		N/A
Bunch train rep rate	10 Hz			N/A
Total beam charge generated per second	27 μC/s	6 μC/s	1.5 μC/s	up to 300 μC/s demonstrated, up to 1 mC/s possible
DC voltage / gap	N/A	N/A	N/A	N/A
Cathode peak field	60 MV/m	~60 MV/m		~21 MV/m
Beam energy at gun exit	6.6 MeV	~6.5 MeV		800 keV
Norm. transv. emittance (RMS) in [mm mrad]	0.9 @ ~140 MeV	$\varepsilon_{x,y} = 0.60$ @ 25 MeV	$\varepsilon_{x,y} = 0.29$ @ 25 MeV	simulated: 0.2 to 0.7 for 10 to 300 pC
Norm. transv. slice emittance (RMS) in [mm mrad]	1.4 for 1 nC at 17.5 GeV	N/A	N/A	simulated: 0.1 to 0.6 for 10 to 300 pC
Charge fraction analyzed	100 %	95 %	95 %	95 %
RF frequency	1.3 GHz			186 MHz
Photo cathode laser:				
Laser medium	Yb:YAG			Yb-doped fiber
Wavelength	257 nm			266 nm and 532 nm available
Temporal pulse shape	flat-top, 2 ps rise/fall time, 20 ps FWHM	flat-top $\leq$2 ps rise/fall time ~22 ps FWHM		flat-top, ~1 ps rise/fall time, 50 ps FWHM
Transverse pulse shape	flat-top, 0.53 mm RMS	~flat-top, ~0.3 mm RMS	~flat-top, ~0.18 mm RMS	Gaussian, 0.05 - 0.5 mm, truncation possible

Collection of current photo injector parameters for

- PITZ @ DESY
- APEX @ LBNL

high QE photo cathodes

average beam current in the µA range

low emittances

L-band and VHF guns

extensive photo cathode laser shaping

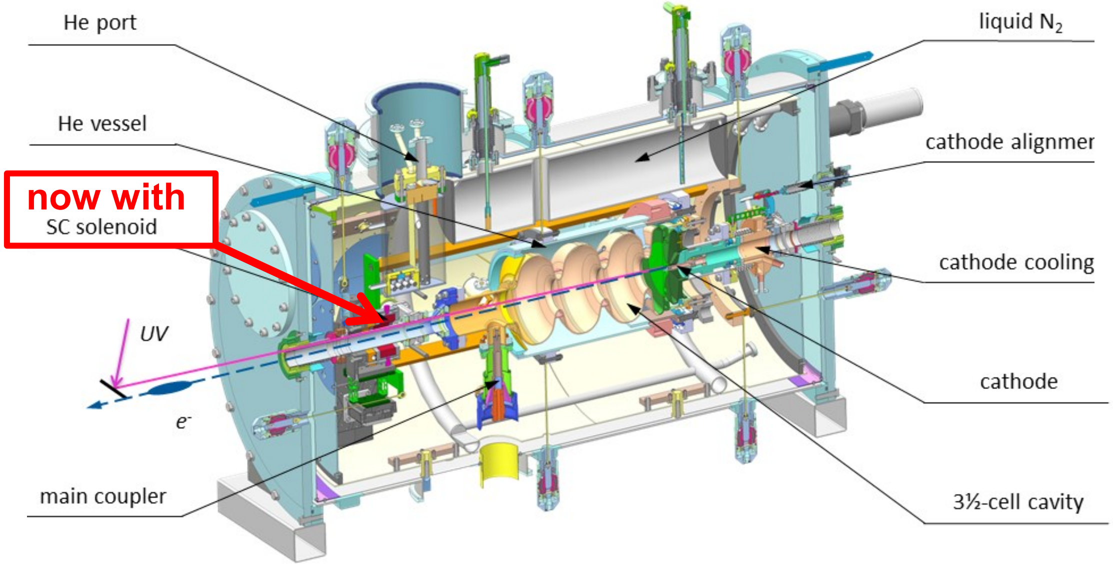
Table from F. Stephan, M. Krasilnikov (2014) [12]

High average current RF guns ($I_{av.}$ ≥ 1mA)

- High current: → high QE photo cathode (NC or SC?), high rep. rate laser, → high duty cycle

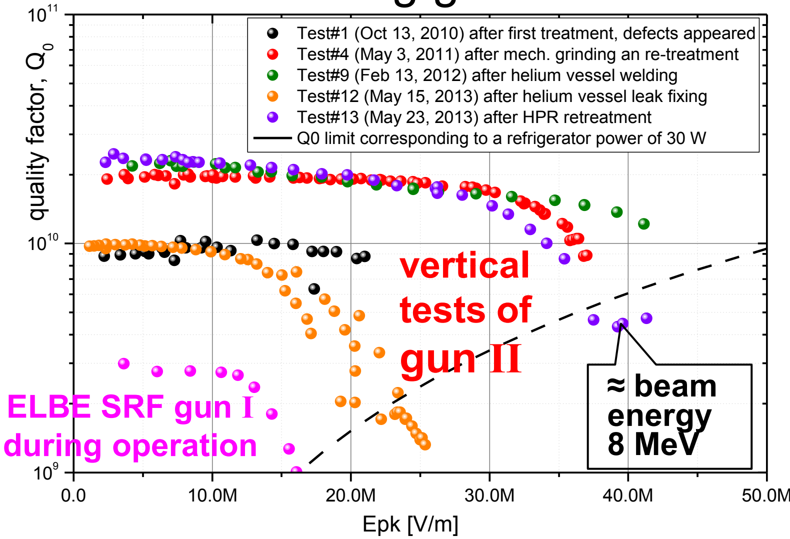
➔ an interesting example for SRF gun: the 3.5 cell (1.3 GHz) **SC RF gun @ HZDR:**

- **gun I** cavity was limited by strong field emission → $E_{launch,cathode}$ only 2.2 - 2.6 MV/m, but still …
  - first FEL operation with an SRF gun at ELBE
  - excellent life time of **NC Cs_2Te** cathode was demonstrated (264 C, 400 µA)

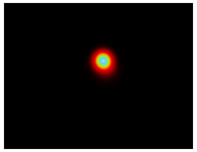


Courtesy J. Teichert

Accelerating gradients:



- First beam operation with **gun II** in June 2014



- Possible future:
  Cavity design allows for additional magnetically focusing RF mode

High average current RF guns ($I_{av.}$ > 1mA)

Collection of photo injector parameters for

- (DC gun @ Cornell)
- NC RF gun @ Boeing
- 3.5 cell SRF gun @ HZDR

Table from F. Stephan, M. Krasilnikov (2014) [12]

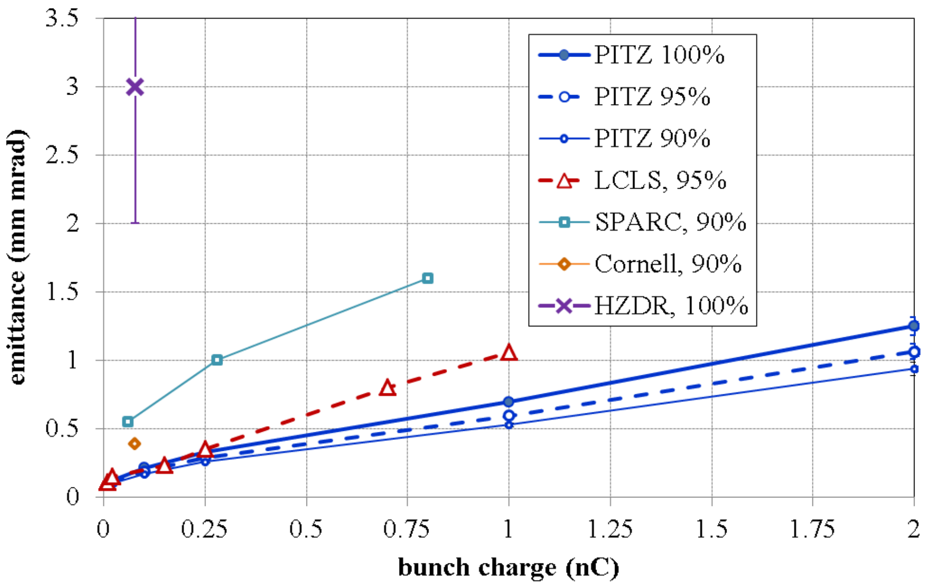
	a)	b)	c)	d)	e)	f)
Location	Cornell, USA		Boeing, USA	HZ Dresden Rossendorf, Germany		
Gun type	DC Gun		4 cell NC RF Gun	SC RF gun, $3\frac{1}{2}$ cell elliptical cavity		
Experimental results or design goals/simulation	design goals	exp. results	exp. results	design goals / simulations		exp. results
Operation mode	high current	measurement mode	-	ELBE	high charge	ELBE
Pulsed / CW	CW	pulsed, CW possible	pulsed	CW, pulsed operation possible		
Cathode type	alkali-Sb / GaAs	GaAs	K_2CsSb	Cs_2Te		
Single bunch charge	77 pC	77 pC	1 - 7 nC	77 pC	1 nC	max. 77 pC
Single bunch rep rate	1.3 GHz	50 MHz, 1.3 GHz possible	27 MHz	13 MHz	0.1 - 0.5 MHz	13 MHz
Length of bunch train	N/A	0.1 to 10 μs	8.3 ms	N/A	N/A	N/A
Bunch train rep rate	N/A	1 - 5 kHz	30 Hz	N/A	N/A	N/A
Total beam charge generated per second	100 mC/s	$\sim$1μC/s	6.7 - 47 mC/s	1 mC/s	0.5 mC/s	max. 0.5 mC/s
DC voltage / gap	500 kV / 5 cm	350 kV / 5 cm	N/A	N/A	N/A	N/A
Cathode peak field	5 - 6 MV/m	4 MV/m	26 MV/m	20 MV/m		7.6 MV/m
Beam energy at gun exit	500 keV	350 keV	5 MeV	9.4 MeV		3.3 MeV
Norm. transv. emittance (RMS) in [mm mrad]	$\leq$0.3 @ 10 - 12 MeV	$\varepsilon_x = 0.51$, $\varepsilon_y = 0.29$ @ 8 MeV	5 - 10 @ 5 MeV	1 @ 9.4 MeV	2.5 @ 9.4 MeV	3$\pm$1 @ 3.3 MeV
Norm. transv. slice emittance (RMS) in [mm mrad]	$\leq$0.3 @ 10 - 12 MeV	$\varepsilon_{slice,x} = 0.4 - 0.5$ for central slices	N/A	N/A	N/A	N/A
Charge fraction analyzed	100 %	90 %	90 %	100 %	100 %	100 %
RF frequency	1.3 GHz for buncher and booster		433 MHz	1.3 GHz		
Photo cathode laser:						
Laser medium	Yb-doped fiber	Yb-doped fiber	Nd:YLF	Nd:glass & Nd:YLF		
Wavelength	520 nm	520 nm	527 nm	258 nm		
Temporal pulse shape	flat-top, 20-30 ps	flat-top, $\sim$27 ps FWHM, <1 ps rise/fall time	Gaussian, 53 ps FWHM	Gaussian, 4 ps FWHM	Gaussian, 15 ps FWHM	Gaussian, 4 ps FWHM
Transverse pulse shape	flat-top, 2.5 mm diameter	Gaussian truncated at 35% intensity, 2mm diam.	Gaussian, 3 - 5 mm FWHM	flat-top, 1-3 mm diam.	flat-top, 5 mm diam.	flat-top, $\sim$2.7 mm diam.

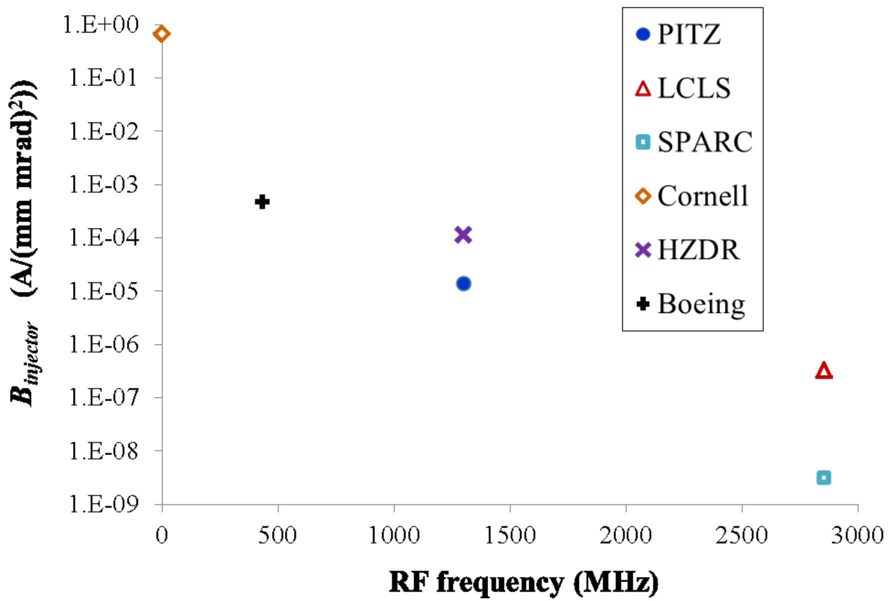
high QE photo cathodes

av. beam current in the mA range

from DC to L-band guns

Comparison of experimental results / designs





- Comparing the measured single bunch emittance
  - Notice the different charge fractions analyzed
  - Notice that the values are measured at different beam energies and with different measurement methods
- Comparing the “Average Injector Brightness” [A / (mm mrad)^2]

$$B_{injector} = Q_{bunch} \cdot NoP \cdot RR \Big/ (\varepsilon_{n,x} \cdot \varepsilon_{n,y})$$

bunch charge

pulses in train

repetition rate

transverse emittances

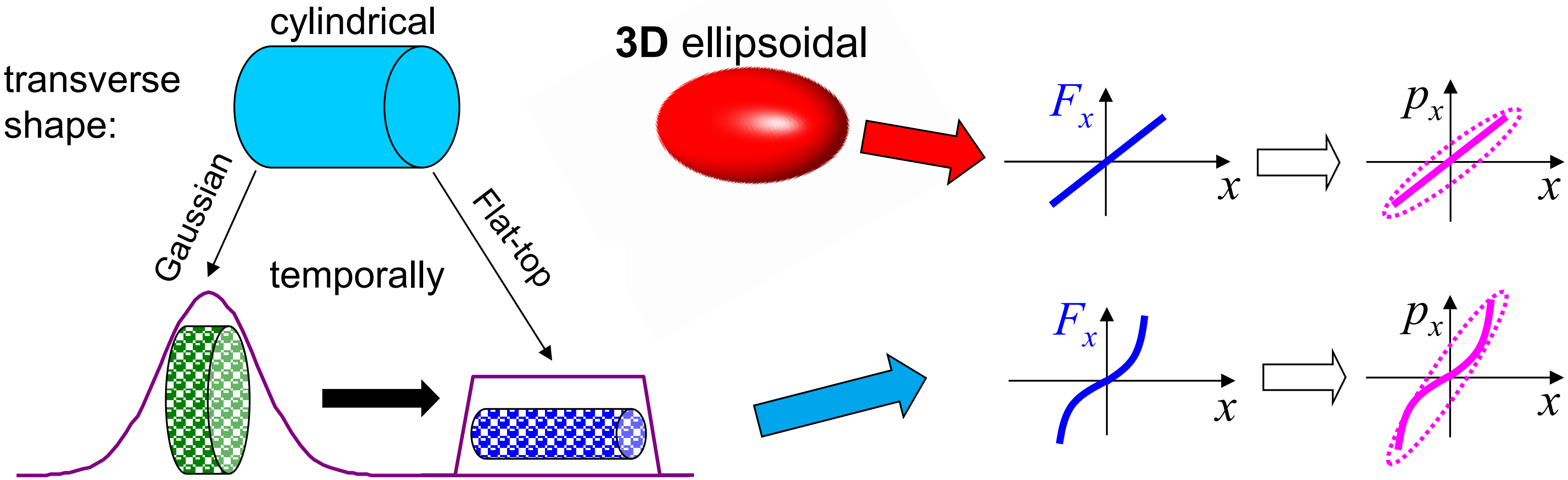
  - **Design** average currents and **measured** single bunch emittances have been used.

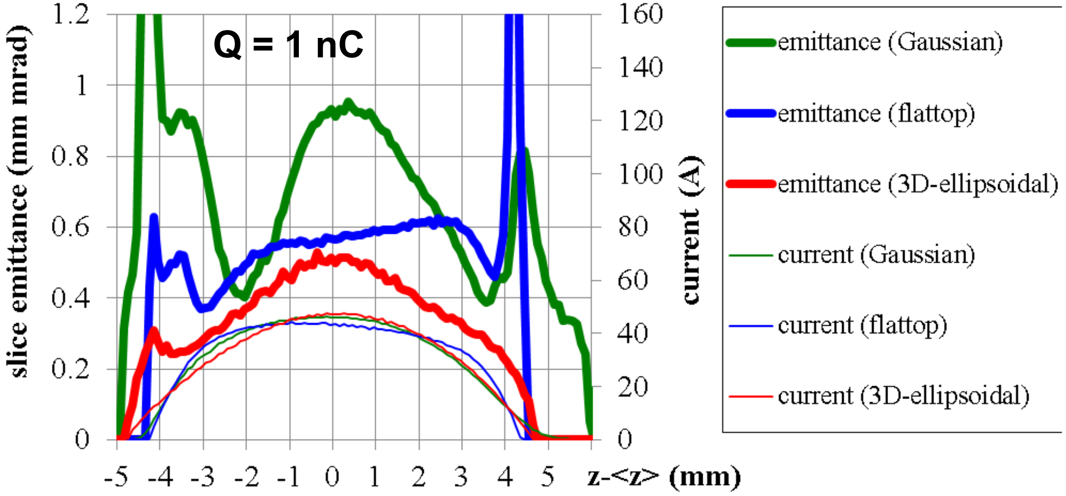
➔ **Lower RF frequency yields higher $B_{injector}$ due to higher $I_{injector}$**

Figures from F. Stephan, M. Krasilnikov (2014) [12]

Future trends: Photo cathode laser pulse shaping → towards 3D ellipsoid

Main idea: minimize the impact of the space charge on the transverse emittance.





Potential of 3D ellips. for all FELs:

- **30-50% lower av. slice emittance**
- Better longitudinal compression
- Reduced beam halo
- Less sensitivity to machine settings

→ **German-Russian collaboration:**

- ***IAP (Nizhny Novgorod) builds laser***
- ***Installation at PITZ starts autumn 2014***

Future trends: Higher average currents

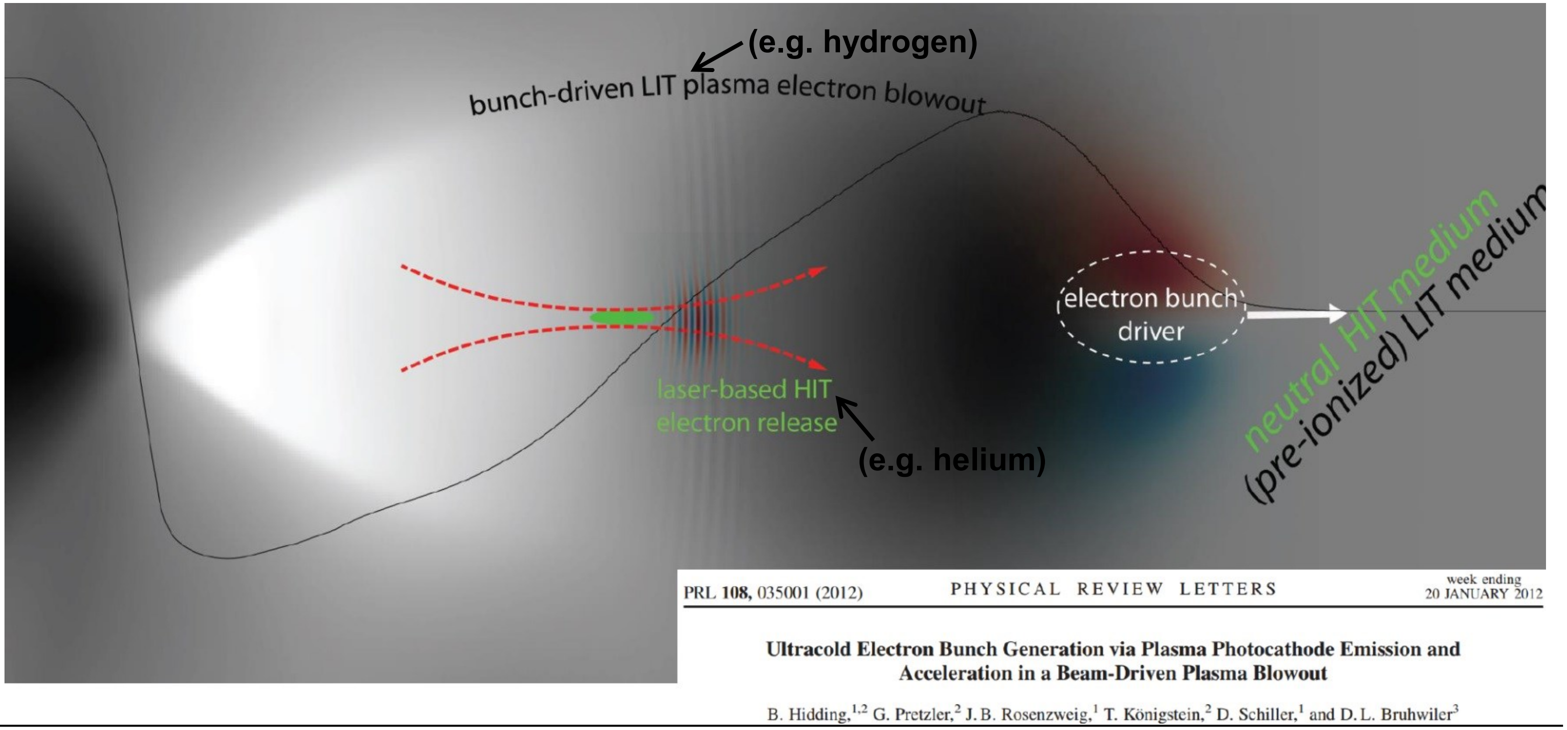
- Photo cathode **laser** developments:
  - Laser **pulse shaping** (time + space) requires significant overhead in laser **peak power**
  - **High average beam currents** in addition require **high average laser power**

➔ Extensive developments needed to overcome e.g. **thermal lensing + pulse heating** and to allow **stable and reliable operation 24/7** (often specific requests for planned application)

- **Photo cathode** developments needed to relax the laser requirements:
  - **High quantum efficiency at visible wavelength** ('cathodes for green light')
    ➔ less power needed at basic laser wavelength, allows to omit second conversion stage (laser pulse deformation, sensitivity on laser power)
  - **Reliable and robust, low thermal emittance**

Future trends: A plasma based electron source

- **two-component gas plasma cell** [e.g. H(13.6 eV) and He(24.6 eV)]
  ➔ beam driven plasma wave in H → accelerating gradients **>10GV/m**
  ➔ witness electron bunch by **very local laser ioniziation of He inside plasma wave**
- emittance estimate inside plasma cavity:
  $0.03\ mm\ mrad$ for 2 pC bunch, but I_{peak}=300 A
- Difficulties: **synchronization**, **energy spread**, **extraction** of bunch from plasma, …



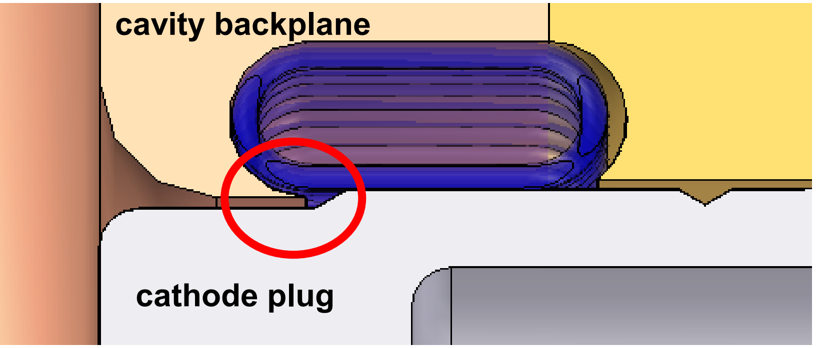
PRL **108,** 035001 (2012) PHYSICAL REVIEW LETTERS week ending 20 JANUARY 2012

Ultracold Electron Bunch Generation via Plasma Photocathode Emission and Acceleration in a Beam-Driven Plasma Blowout

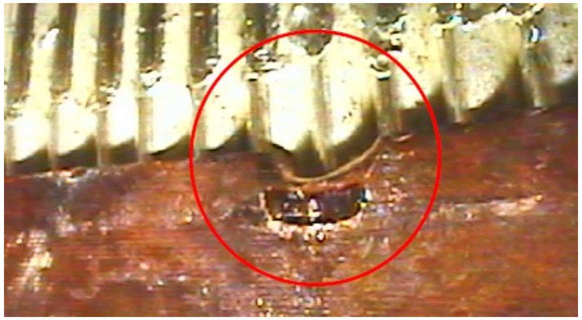
B. Hidding,[1,2] G. Pretzler,[2] J. B. Rosenzweig,[1] T. Königstein,[2] D. Schiller,[1] and D. L. Bruhwiler[3]

Details are important: here contact cathode ↔ cavity

original watchband design

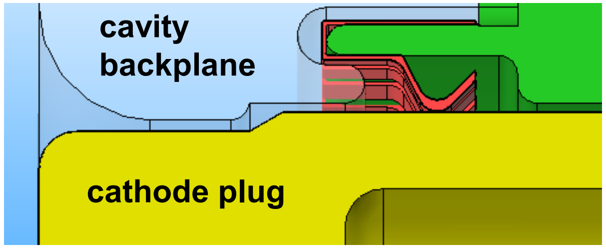


- + robust spring
- - severe damage on peaked nose (part of the gun), mainly when running at high peak power and long pulse length

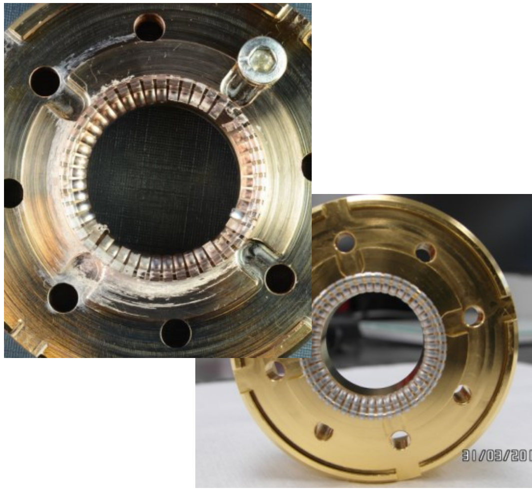


Gun4.1

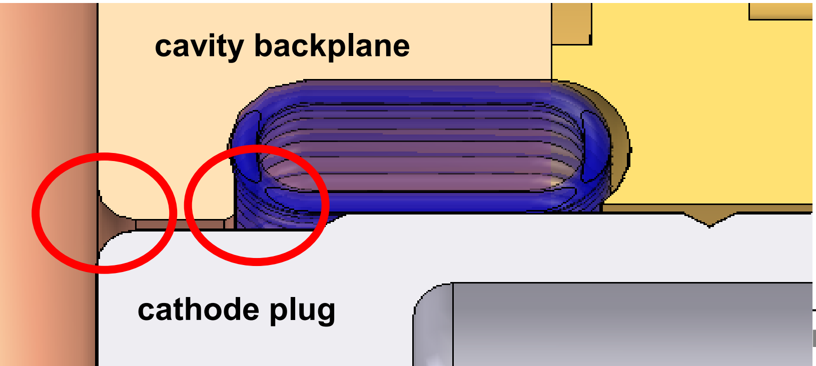
contact stripe design



- + spring insert can be exchanged
- - originally: breaking of leaves, limited electrical contact
- ○ gold coating + electro polishing seems to help



“watchband reloaded”

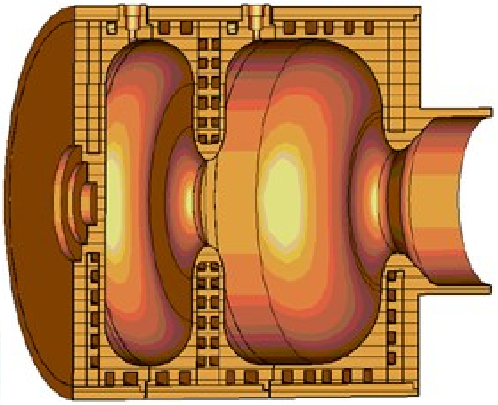


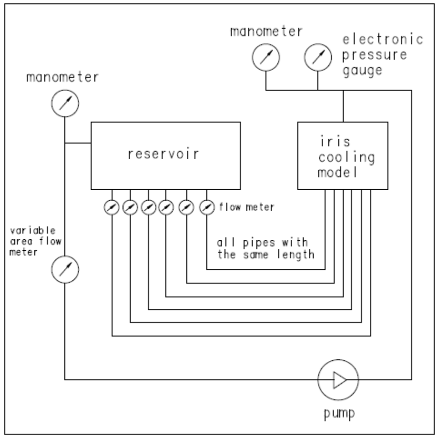
- + robust spring
- + equalized radii
- - still to be tested in experiment !

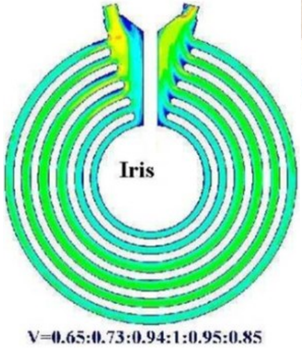
Courtesy S. Lederer

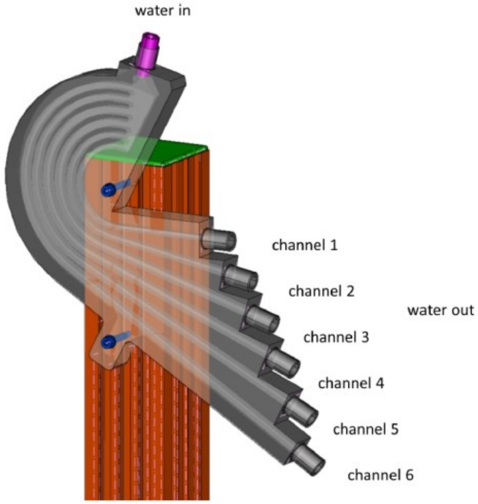
Details are important: here water flow simulations + tests

- Gun5 has: RF pick ups, elliptical irises, circular cell shape, more&smaller cooling channels → internal water distribution → **test**

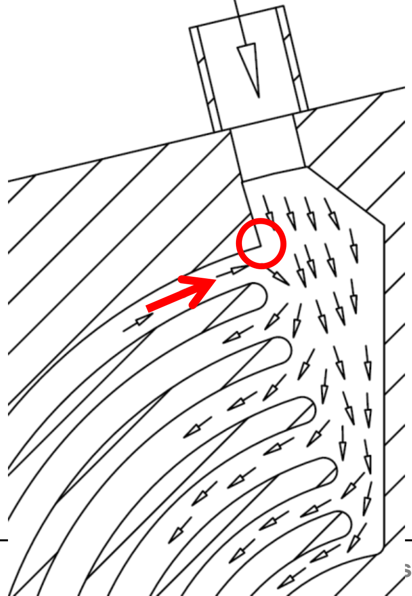




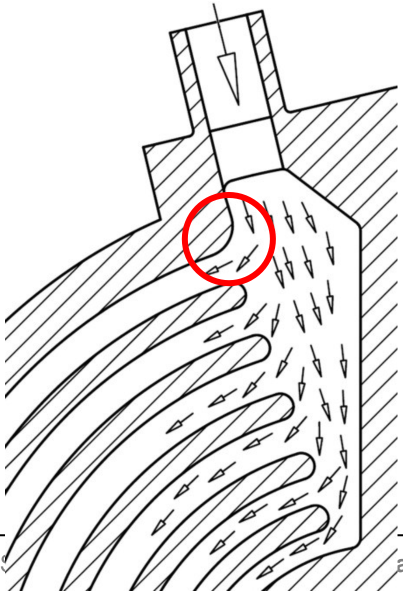




First geometry with reverse flow



Current geometry with correct flow



Courtesy
S. Philipp,
V. Paramonov

References

[1] B.E. Carlsten, Nucl. Instr. Meth. A285, 313-319 (1989).

[2] B.E. Carlsten, Part. Acc. 49, 27-65 (1995).

[3] L. Serafini and J.B. Rosenzweig, Phys. Rev. E 55, 7565-7590 (1997).

[4] M. Ferrario, J.E. Clendenin, D.T. Palmer, J.B. Rosenzweig, L. Serafini, "HONDYN Study for the LCLS RF Photo-Injector", SLAC-PUB-8400, March 2000.

[5] K. Flöttmann, T. Limberg, P. Piot, "Generation of ultrashot electron bunches by cancellation of nonlinear distortions in the longitudinal phase space", TESLA FEL Report 2001-06.

[6] E.L. Saldin, E.A. Schneidmiller and M.V. Yurkov, "An analitical description of longitudinal phase space distortions in magnetic bunch compressors", NIM A 483 (2002) 516-520.

[7] Z. Huang et al., "Supression of microbunching instability in the linac coherent light sources", PRST AB, 7, 074401 (2004).

[8] Z. Huang et al., "Measurements of the LCLS laser heater and its impact on the x-ray FEL performance", SLAC-PUB-13854.

[9] K. Flöttmann, "Note on the Thermal Emittance of Electrons Emitted by Cesium Telluride Photo Cathodes", TESLA-FEL report 1997-01, DESY, 1997.

[10] D. Dowell and J. Smerge, "Quantum efficiency and thermal emittance of metal photocathodes“, PRST-AB, 12, 074201 (2009).

[11] K.-J. Kim "Rf and space charge effects in rf guns", NIM A 275, 201 (1989).

[12] F. Stephan, M. Krasilnikov (2014) “High brightness photo injectors for brilliant light sources”. In: E. Jaeschke, S. Khan, J. Schneider, J. Hastings (ed) “Synchrotron Light Sources and Free-Electron Lasers”. Springer, Dordrecht (in preparation). → draft copy is available by email !

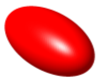
+ references listed on individual slides

Summary 1 (first half of talk)

- The electron source is one of the **key components** of FELs.
- Different FEL facilities (average beam current, beam quality, linac type, …) need different electron sources → **no universal solution !**
- Different types of electron source have been developed successfully for the specific demands of „their“ FEL → **from nA to mA beam currents !**
- Common issues: **stable and reliable**
  - RF design,
  - photo cathode laser system,
  - synchronization,
  - diagnostics, …
- For high "**Average Injector Brightness**" $\left(\frac{average\ current}{emittance^2}\right)$ **lower RF frequencies** seem to be beneficial.
- Ultimate beam quality requires **3D ellipsoidal electron bunches** (→ laser pulse shaping).
- **Higher average beam current** get increasingly important (e.g. for ERLs).
- **Plasma acceleration** might offer interesting options in future.

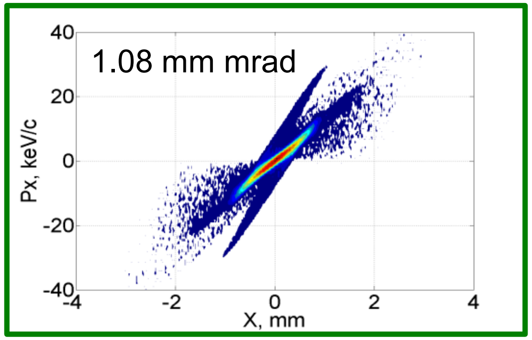
Photo cathode laser shaping → 3D ellipsoid: Simulations

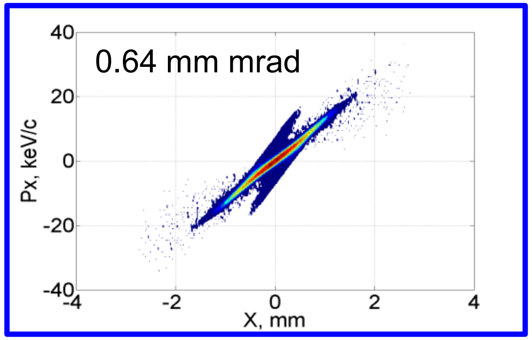
Beam dynamics for 1 nC bunch charge:

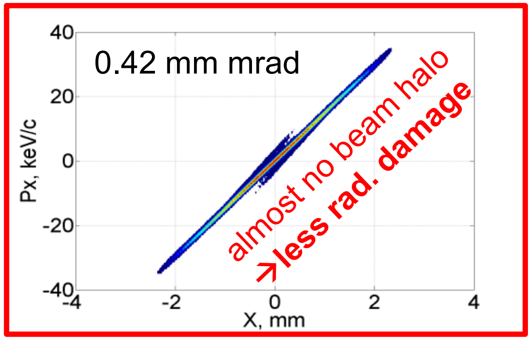


generic research

Transverse phase spaces at z=5.74m

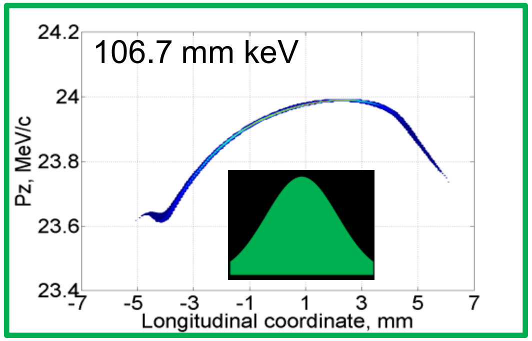


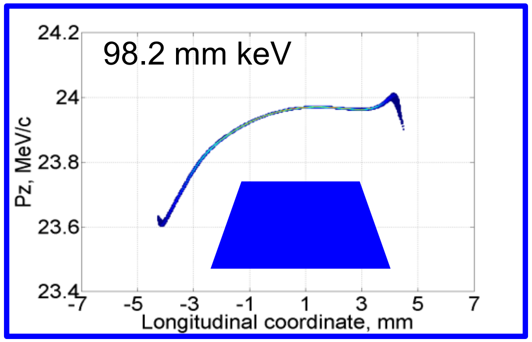


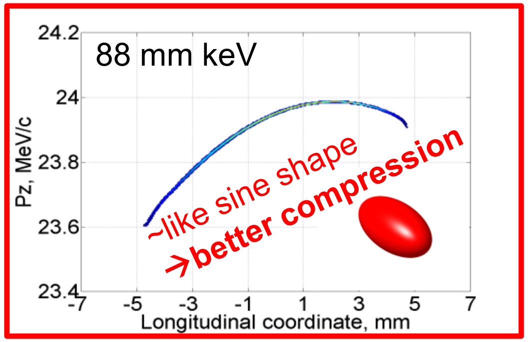


Gaussian **Flat-top** **Ellipsoid**

Longitudinal phase space (Z-Pz) at z=5.74m



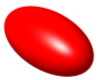




> **Benefits** from 3D ellipsoidal laser pulses for **ALL linac driven light sources**:

- **30-50% lower average slice emittance** → higher **brilliance**
- ~pure sinusoidal longitudinal phase space +3rd harm. →simplify/allow required **compression**
- ~no beam halo → better signal/noise, reduced **radiation damage**
- less sensitive to machine settings → higher **stability**

Photo cathode laser shaping → 3D ellipsoid: Realization



generic research

Practical realization:

> Collaboration: **DESY – JINR**(Dubna, Russia) **– IAP**(Nizhny Novgorod, Russia)

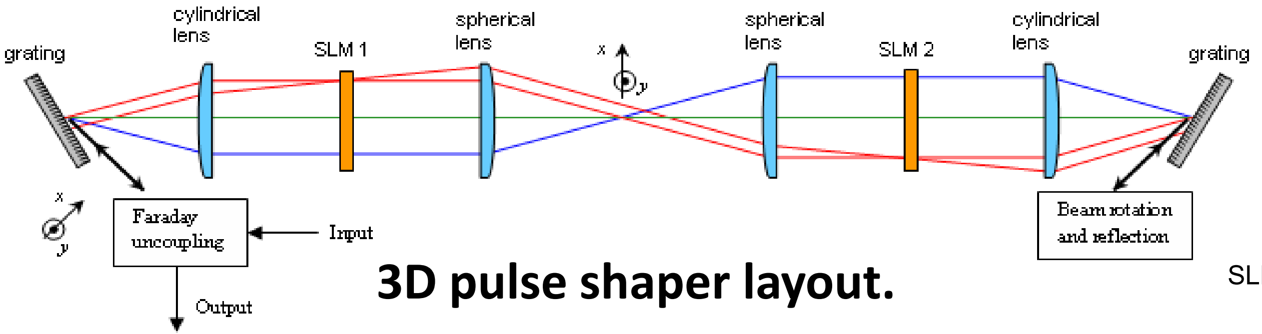
> Goal – develop a photo cathode laser system with following parameters:

parameter	value	unit	remark
wavelength	258	nm	1030 nm fundamental λ
micropulse energy	15	µJ	for 1 nC bunch production from Cs_2Te photo cathodes
pulse train frequency	1	MHz	In the future 4.5 MHz will be a goal
pulse train length	**0.3**	ms	In the future 0.6 ms will be a goal
pulse train rep.rate	10	Hz	1,2,5 Hz as an option
micropulse rms duration	6±2	ps	**3D quasi ellipsoidal distribution**
transverse rms size	0.5±0.25	mm	

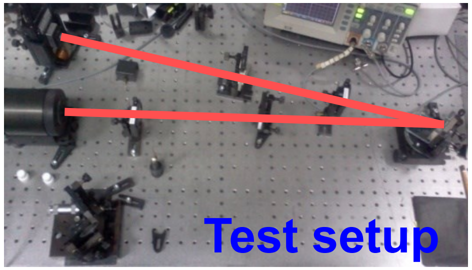
BMBF project **"Development and experimental test of a laser system for producing quasi 3D ellipsoidal laser pulses"**:

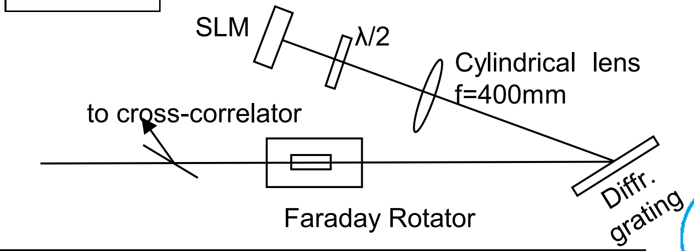
→ **Laser system development at IAP**

→ **Installation at PITZ for tests with e- beam starts Oct. 2014**



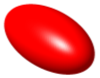
3D pulse shaper layout.


Test setup



SLM = Spatial Light Modulator,
HOLOEYE Photonics AG (Germany)

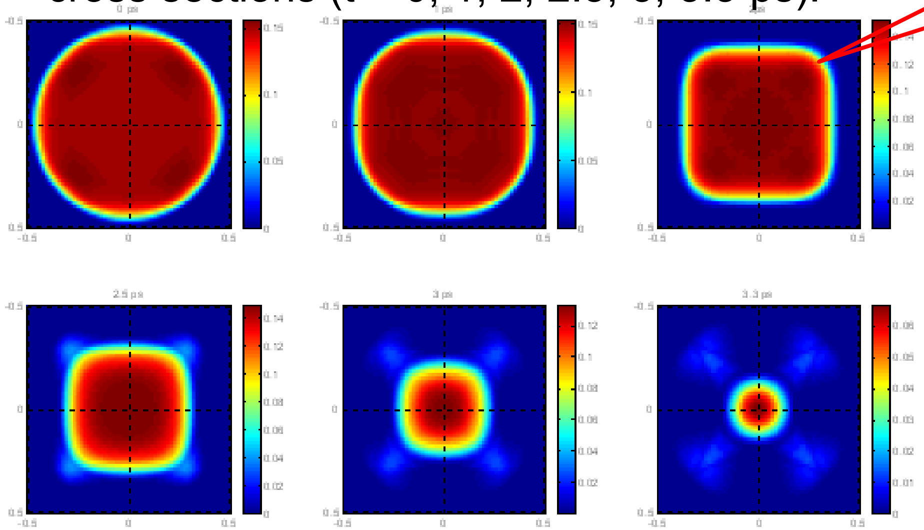
Photo cathode laser shaping → 3D ellipsoid: Difficulties



generic research

3-D ellipsoid laser transverse distribution at different time cross sections (t = 0; 1; 2; 2.5; 3; 3.3 ps).

optics simulation

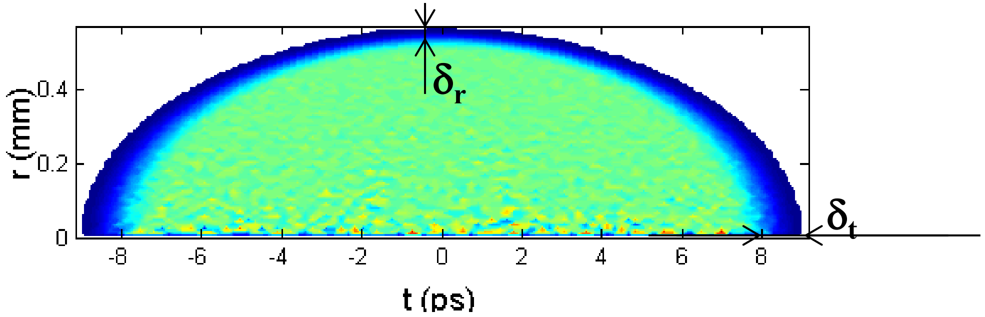


shaping in only 2 transverse planes

3-D ellipsoid laser pulse shape imperfections are studied for tolerances:

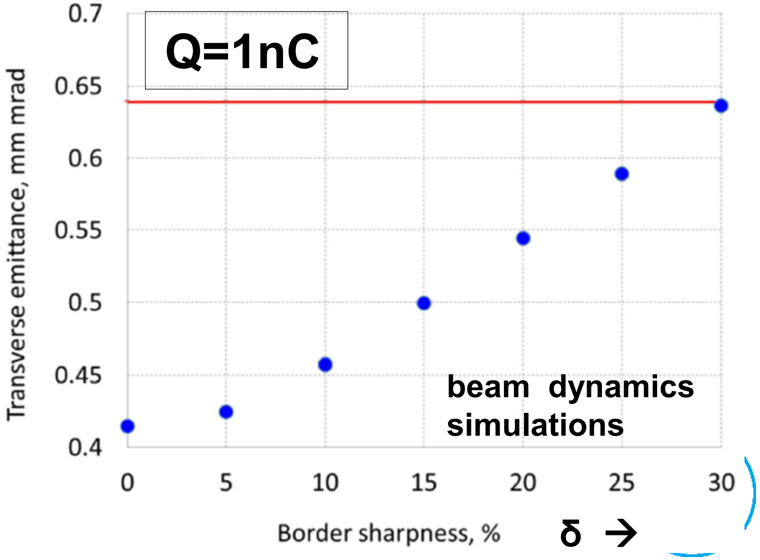
1. Sharpness of edges
2. Rotational symmetry distortions
3. Shape stability

1. Sharpness of 3D ellipsoid edges



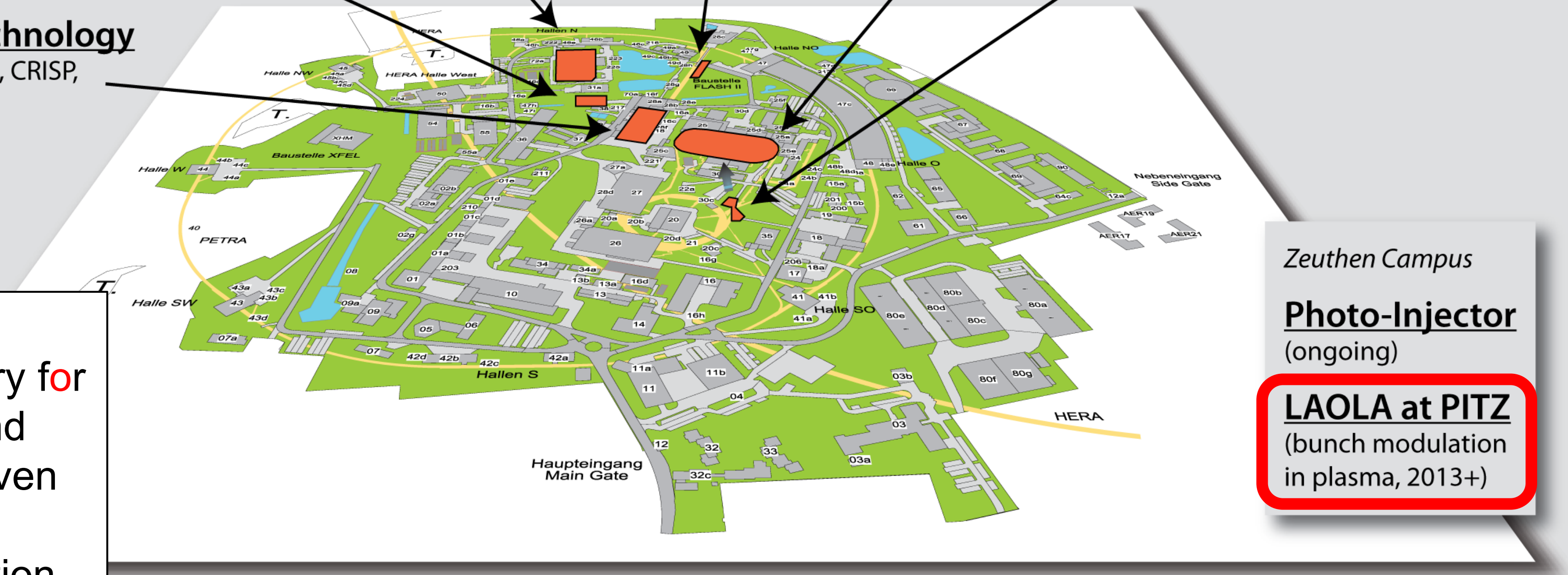
Imperfections in radial direction show stronger effect on transverse emittance than temporal imperfections !

Emittance growth vs. $\delta = \delta_t = \delta_r$



beam dynamics simulations

Accelerator Research & Development Activities at DESY



SC Technology
(R&D on CW, cryo module test bench, ongoing)

SC Processes
(large series production & testing of sc cavities and modules, AMTF, ongoing)

FEL Seeding
(sFLASH, FLASH2 seeding, ongoing)

FLASHForward
(beam-driven plasma acceleration, 2016+)

SINBAD (ultra-short bunches, LAOLA, proto-type table-top FEL, 2017+)

AXSIS (atto-second bunches, ICS, 2014+)

LAOLA at REGAE
(laser-driven plasma acceleration, 2013-2016)

Surface Technology
(cavity surfaces, CRISP, ongoing)

Zeuthen Campus

Photo-Injector
(ongoing)

LAOLA at PITZ
(bunch modulation in plasma, 2013+)

LAOLA:
Laboratory for
Laser- and
beam-driven
plasma
Acceleration

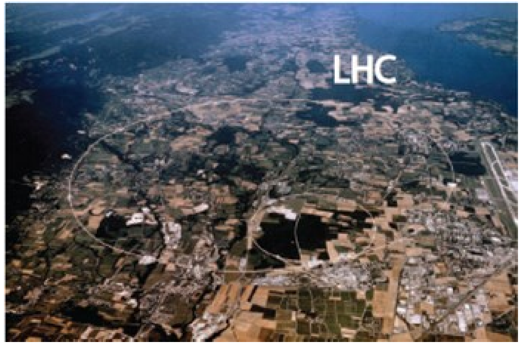
Courtesy: Ralph Aßmann

LAOLA@PITZ: Self Modulation → Background

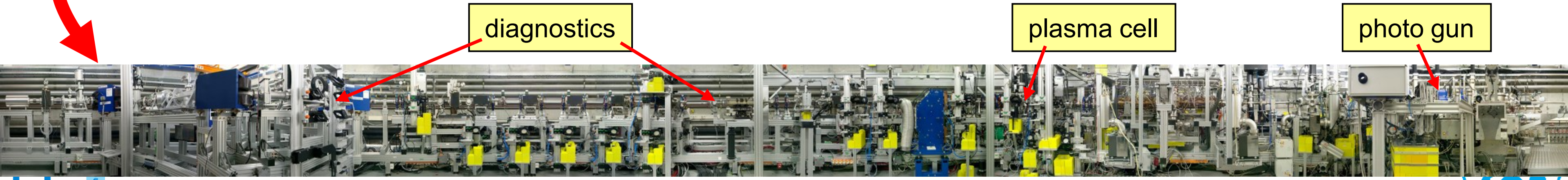
- Background: proton driven PWFA experiment at CERN (AWAKE collaboration) plans to utilize beam-plasma instability for **self modulation**
  - Use high energy proton beam to drive wake and convert the **proton beam** energy into **electron beam** energy in a **single** stage
  - Problem:

$$E_{z,max} = 240(MV\ m^{-1})\left(\frac{N}{4x10^{10}}\right)\left(\frac{0.6}{\sigma_z(mm)}\right)^{2}$$

Caldwell et al., Nature Physics (2009)

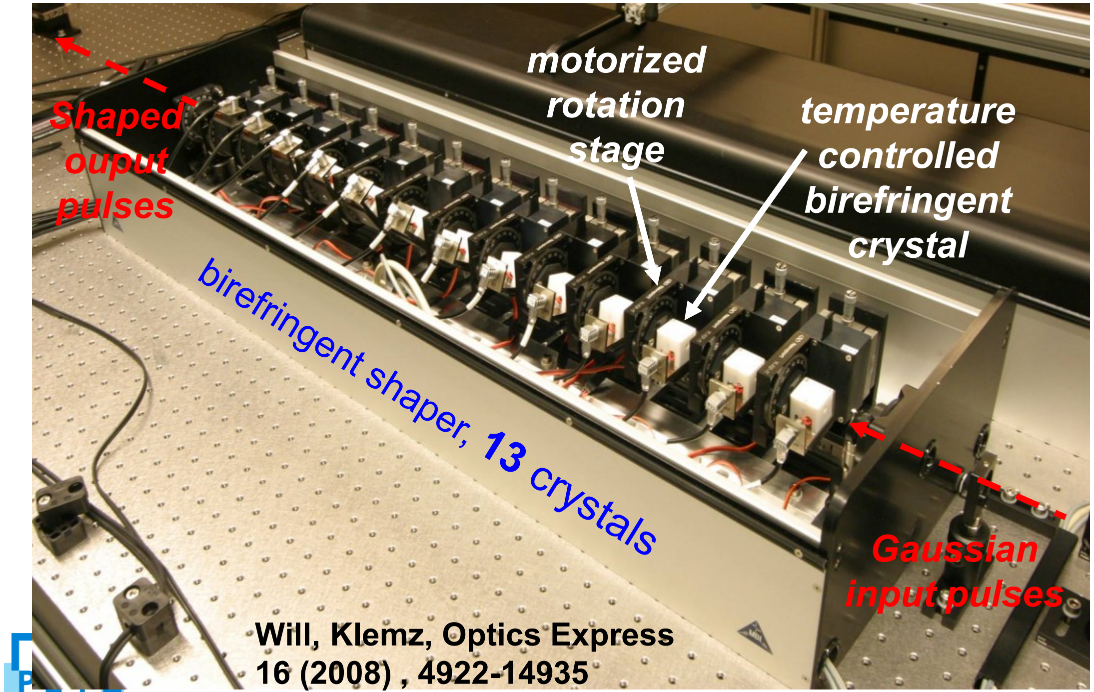


    - High accelerating gradient requires **short** bunches $\sigma_z < 100\ \mu m$
    - Existing proton machines produce **long** bunches $\sigma_z \approx 10$ cm
  - Solution: use beam-plasma instability to **modulate the beam at the plasma wavelength**, driving strong plasma waves for acceleration
  - But: so far simulations only (no direct experimental evidence)
- Goal: detect and characterize **self modulation of electron beams** in PITZ beam line to gain critical insights into **relevant physics** (dephasing, hose instability etc.)



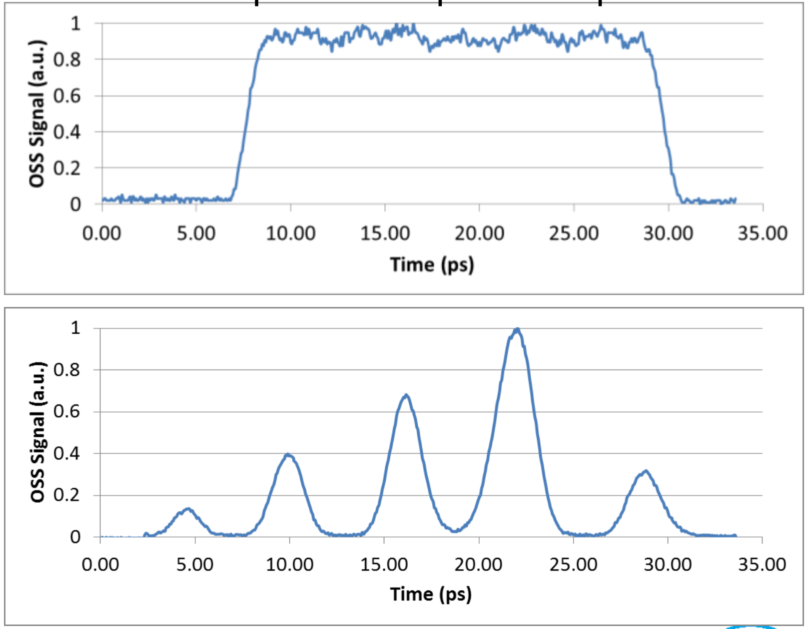
LAOLA@PITZ: Self Modulation → PITZ assets

- Well developed electron beam **diagnostics**
- High flexibility of facility (pure **R&D facility**)
- Very **flexible photo cathode laser pulse shapes**, system developed and built by Max-Born Institute, Berlin
  - **Key element**: the **pulse shaper** (13 birefringent crystals. Pulses are split according to polarization. Delay is given by crystal thickness; relative amplitude can be varied freely by adjusting relative angle between crystals)



Will, Klemz, Optics Express 16 (2008) , 4922-14935

Temporal laser pulse shapes

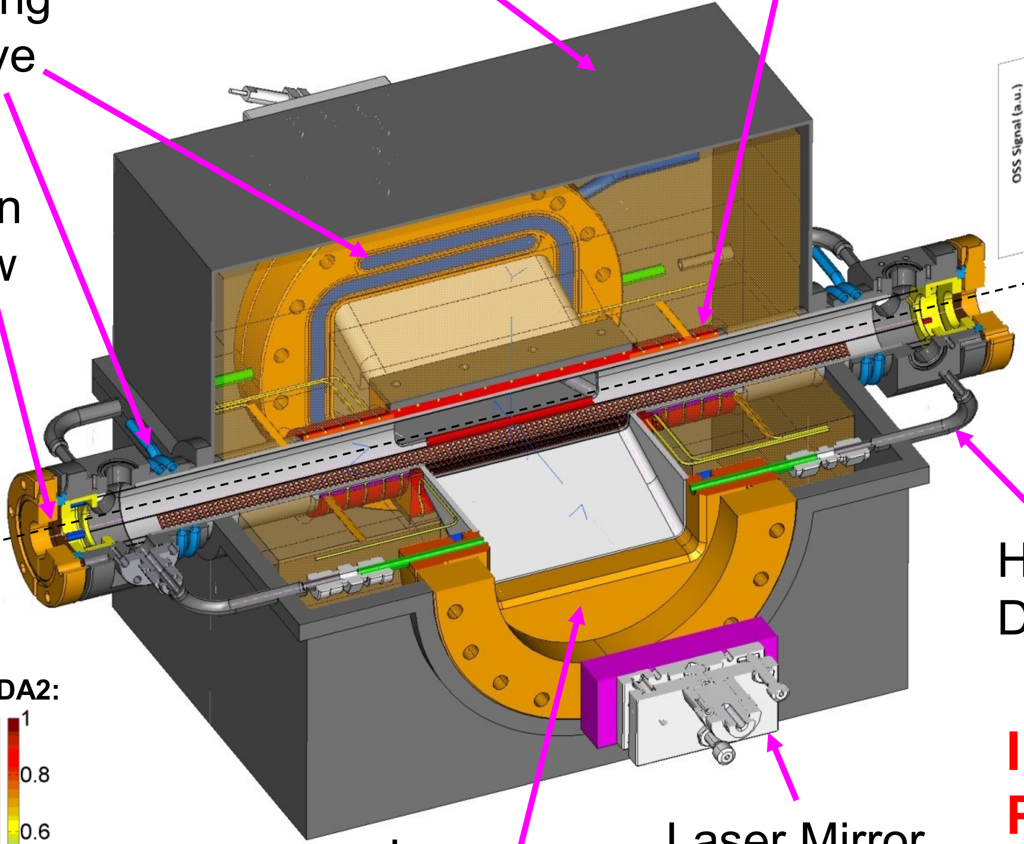


Electron bunch ≙ Laser pulse

LAOLA@PITZ: Self Modulation → new plasma cell design

→ **Heat pipe oven (Li) with transverse access**

Design:
Gerald Koss



Thermal Insulation

Heating Coils

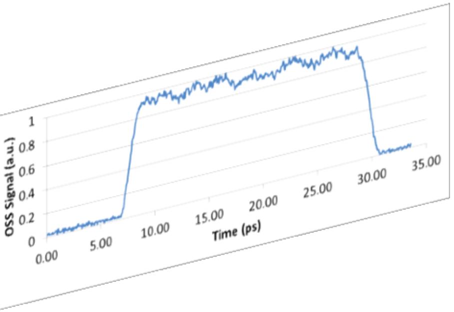
Cooling Sleeve

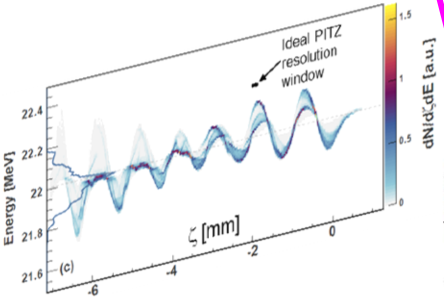
Electron Window

Helium Distribution

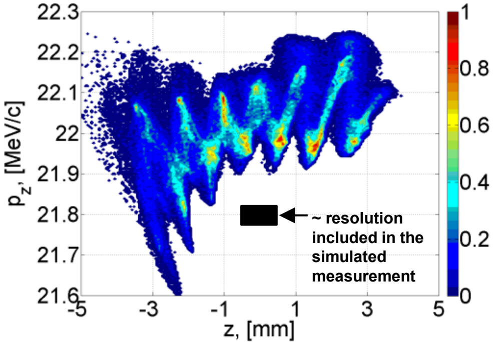
Laser Window

Laser Mirror





Simulated measurement at HEDA2:



~ resolution included in the simulated measurement

Installation in PITZ beamline in autumn 2014

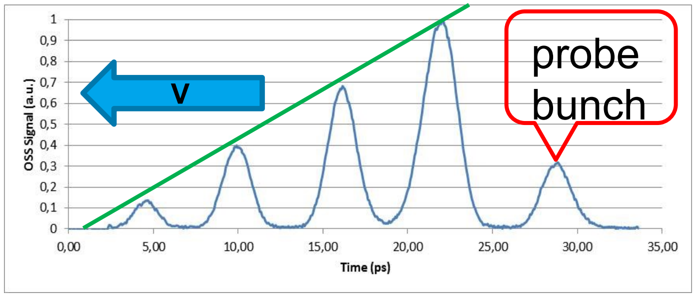
LAOLA@PITZ: High Transformer Ratio (TR) studies

- TR is defined as $R = \dfrac{\hat{W}(\zeta)}{\check{W}(\zeta)}$ ← accelerating field behind bunch ← decelerating field within bunch

- Fundamental beam loading “theorem”: $R \leq 2$ for bunches with symmetric current profile

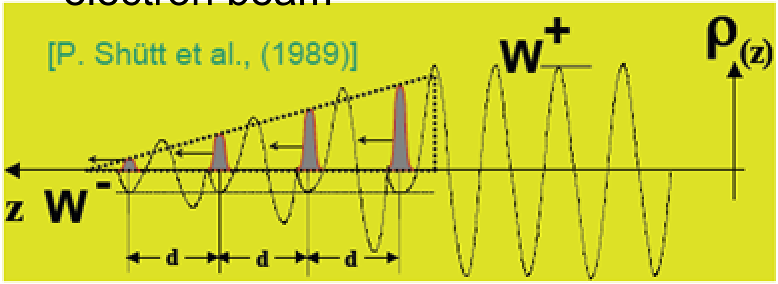
- Idea: Tailored bunch current profile (asymmetric bunch)

PITZ Laser capability:



$\Rightarrow$

electron beam



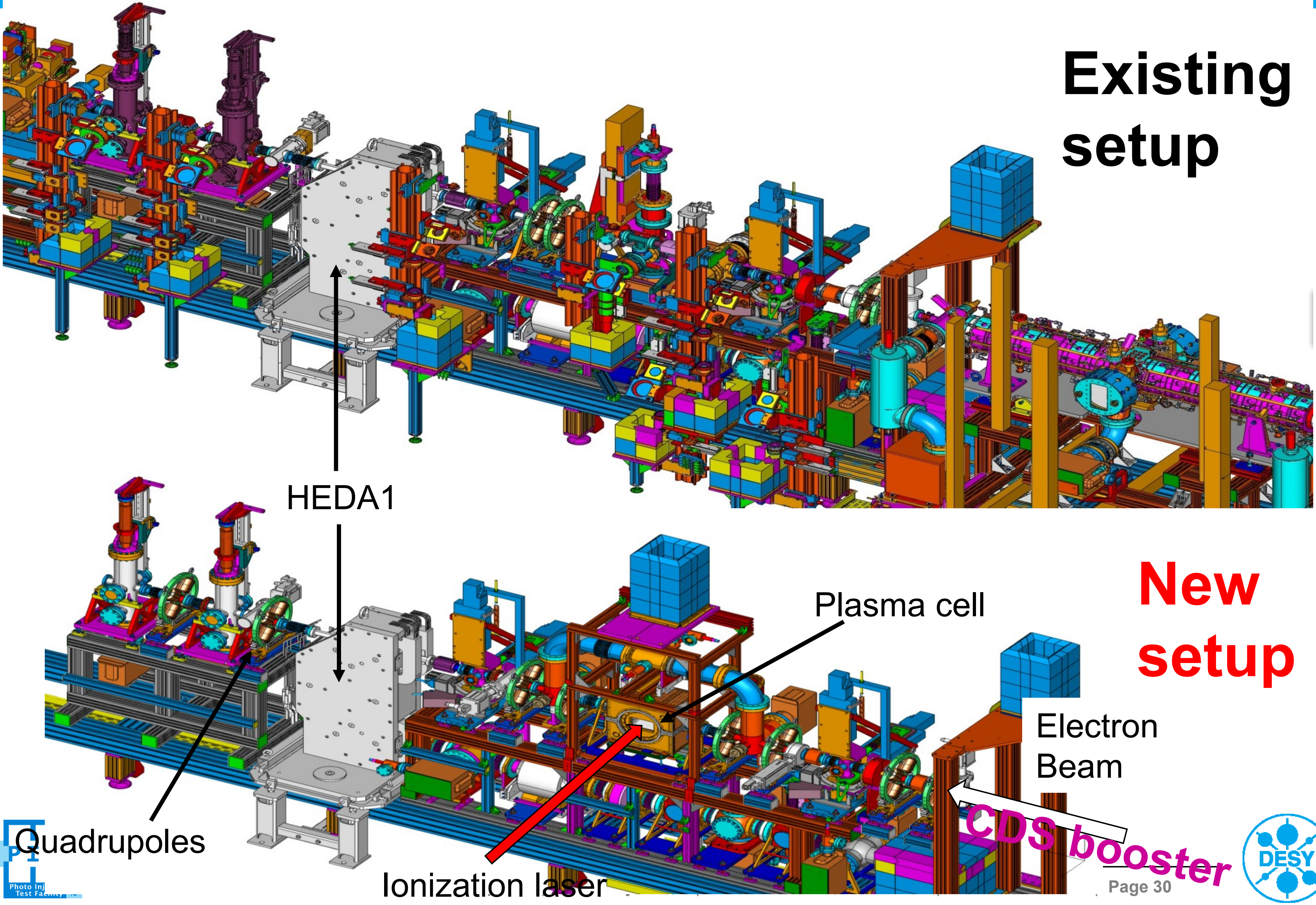
- Significant plasma acceleration of a probe bunch could be possible:

  → **Transformer Ratio up to 8** with matched plasma wavelength

- Needs bunch compressor for high absolute energy gain

  ↳ Design is ongoing in collaboration with LAL Orsay (T. Vinatier, C. Bruni)

LAOLA@PITZ: Beam line remodeling with plasma cell



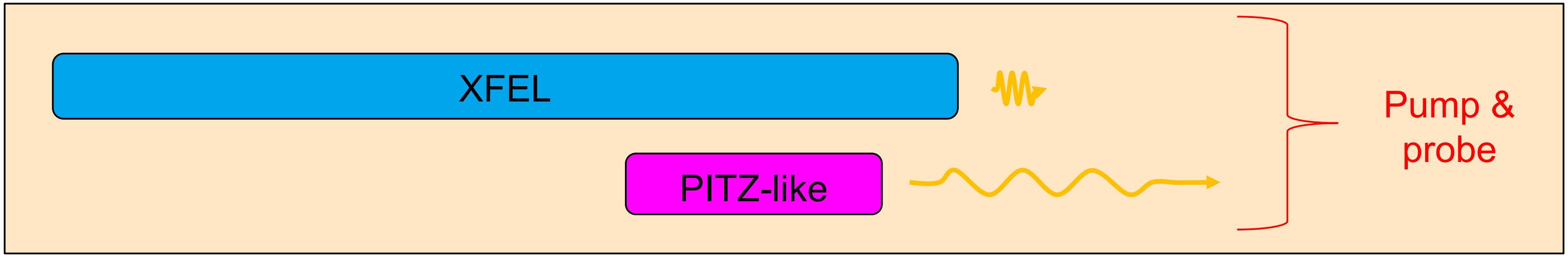
Why a THz source at PITZ?

- Combination of **tunable IR/THz** and X-ray pulses in **pump and probe experiments** at the European XFEL facility finds **wide applications**
- Requirements: spectral and temporal characteristics, peak power, polarization, precise synchronization
  → no universal solution from traditional techniques up to now !

⇨ **TUNABLE IR/THZ SOURCE FOR PUMP PROBE EXPERIMENTS AT THE EUROPEAN XFEL**

E.A. Schneidmiller, M.V. Yurkov, DESY, Hamburg, Germany
M. Krasilnikov, F. Stephan, DESY, Zeuthen, Germany

Contribution to FEL 2012,
Nara, Japan, August 2012

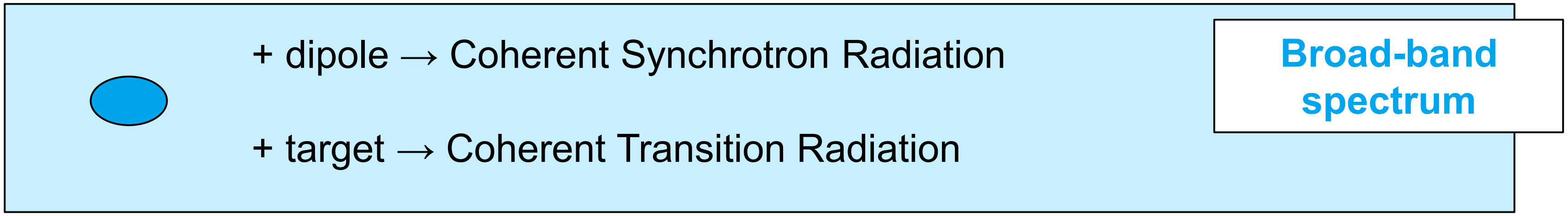


- PITZ-like setup: - can produce required IR/THz radiation
  - **identical pulse train pattern** as XFEL
  - could be installed **close to XFEL experimental end stations**
    [→ additionally: allows pump-probe experiments with **low-energy ultra-short** electron bunches (Q ≤ pC)]

➔ PITZ can serve as prototype for such a development.

What kinds of THz sources are feasible at PITZ?

- Single cycle radiation source delivering a peak Electric field of few MV/m

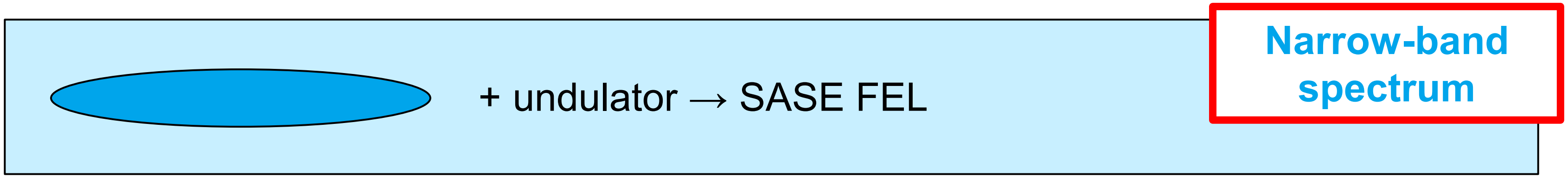


+ dipole → Coherent Synchrotron Radiation

+ target → Coherent Transition Radiation

Broad-band spectrum

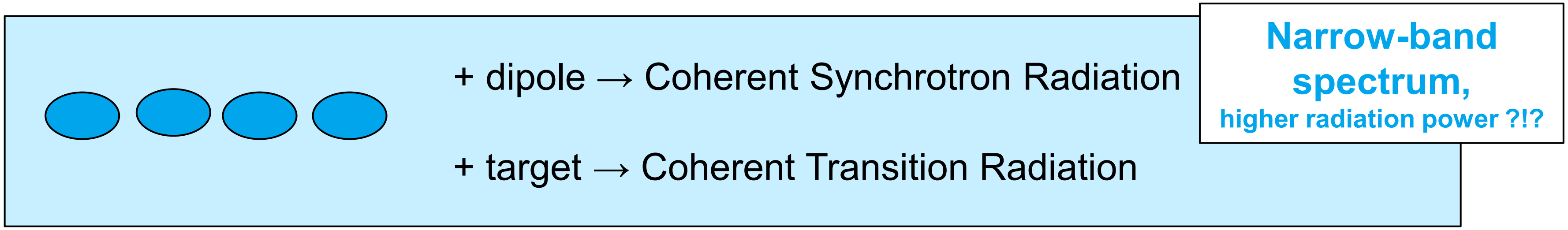
- Narrow band source



+ undulator → SASE FEL

Narrow-band spectrum

- Modulated e-beam source



+ dipole → Coherent Synchrotron Radiation

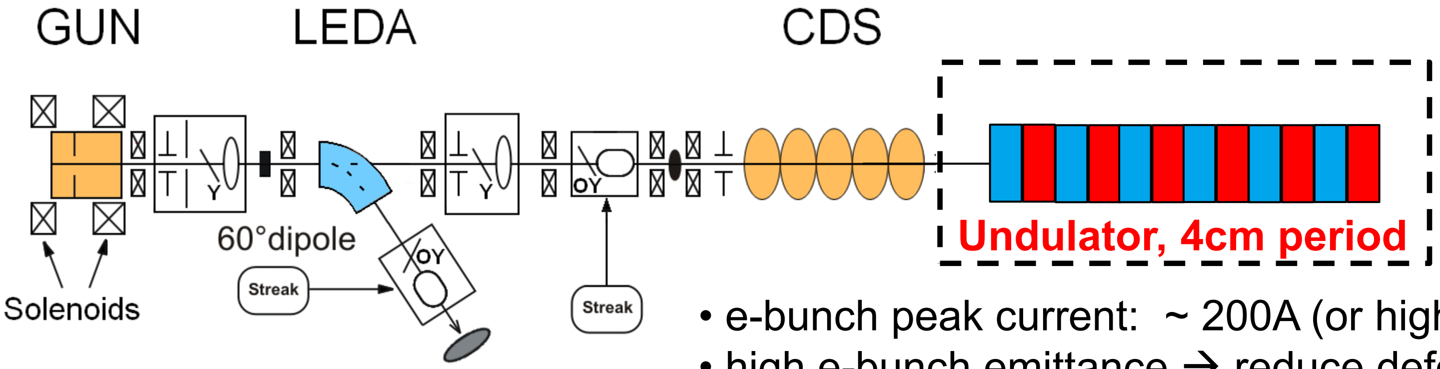
+ target → Coherent Transition Radiation

Narrow-band spectrum,
higher radiation power ?!?

● = electron bunch

Prototype of tunable IR/THz source for XFEL

> Example: narrow-band source:

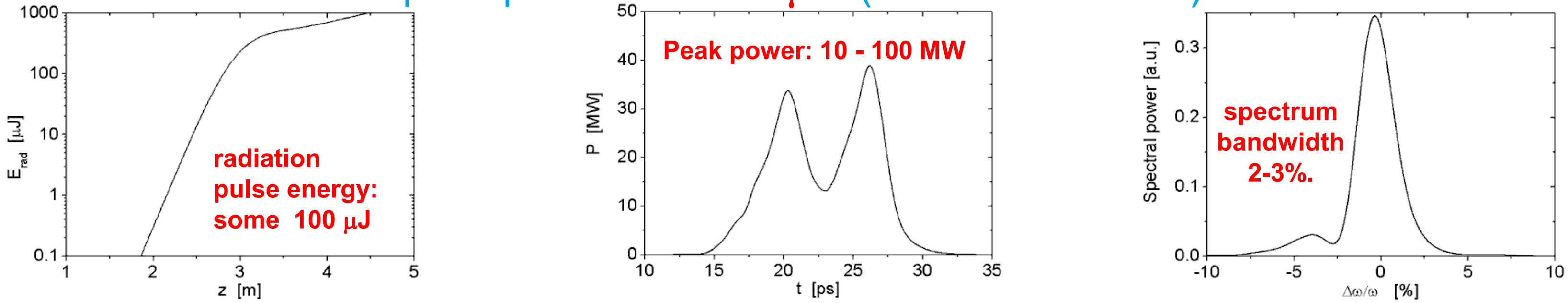


- e-bunch peak current: ~ 200A (or higher)
- high e-bunch emittance → reduce defocusing due to SC
- charge: as high as possible ⇨ **Q = 4 nC**

> Parameters used:

- NC RF gun (E ~ 7 MeV) + NC booster (E ~ 25 MeV), bunch charge: up to ~4 nC
- use existing undulator designs (e.g. APPLE-II, period: 4 cm, length: 5 meters)
- simulated radiation: λ: ~10 µm → 1 mm (30 → 0.3 THz):
  - λ > 200 µm → powerful coherent undulator radiation by tailored (compressed) e-beam
  - λ < 200 µm → by **SASE FEL**

Example: operation at **100 µm** (FAST simulations)



E.A. Schneidmiller, M.V. Yurkov, M. Krasilnikov, F. Stephan "**TUNABLE IR/THZ SOURCE FOR PUMP PROBE EXPERIMENTS AT THE EUROPEAN XFEL**", FEL 2012 Conference, Nara, Japan, August 2012

PhD student positions proposed for future ITN @PITZ

> Electron beam applications: R&D on IR/THz source @PITZ

Work program: There are several methods to produce IR/THz radiation at PITZ. This includes broad-band THz radiation by using coherent synchrotron (CSR in a bending dipole) and coherent transition radiation (CTR from a target) as well as narrow-band THz radiation which can be produced by a SASE FEL using an undulator. Another possibility for the narrow-band THz radiation is to use the flexibility of the PITZ cathode laser and produce modulated electron bunches utilizing CSR and CTR.

The applicant should combine theoretical work, including simulations of radiation properties from various THz sources, and experimental implementations. THz sources based on CSR and CTR can relatively easy be realized experimentally. Certain efforts have to be devoted to the design of the output ports and THz diagnostics. Extensive start-to-end simulations of the SASE FEL based source at PITZ have to be performed before its experimental realization.

> Advanced Beam Diagnostics R&D for plasma acceleration @PITZ

Background: Initially the self-modulation of a long electron beam when travelling through a plasma will be characterized at PITZ. Later on asymmetric multi-pulses will be utilized to study high transformer ratios (TR up to 8).

Work program: The main task is the development of more robust diagnostics to characterize the effects of plasma wakefield acceleration. Criteria are amongst others the robustness of operation (beam transport, alignment accuracy of involved devices, etc.), achievable accuracy, measurement time, etc. The applicant will first learn the operation of the existing hardware and then start the development of alternatives.

Challenges: To detect early signs of self-modulation during alignment a highly sensitive observation screen with sufficient spatial resolution is needed.
The specific challenge for the high transformer ratio experiments will be to provide good energy resolution over the range of particle momentum resulting from the deceleration and acceleration of the driver and witness bunches.

Summary 2 (second half of talk)

New developments at PITZ:

- The laser system capable of producing **3D ellipsoidal bunches** will open the door for significant improvements in **beam quality.**
  - Continuous work will be needed to make it a device usable at user facilities.

- The **plasma activities** at PITZ (self-modulation, high transformer ratio) can deliver important input to the plasma acceleration community
  - It will require a detailed usage of the **transverse deflecting system** (TDS) and high energy spectrometer (HEDA2) to analyze the **longitudinal phase space**.

- A **IR/THz source** based on the PITZ setup promises **unique capabilities** for pump-probe experiments at the **European XFEL**.
  - The design of the system is ongoing.