

RF guns for FELs

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Content:

- 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

One FEL key component:

→ the high brightness electron source

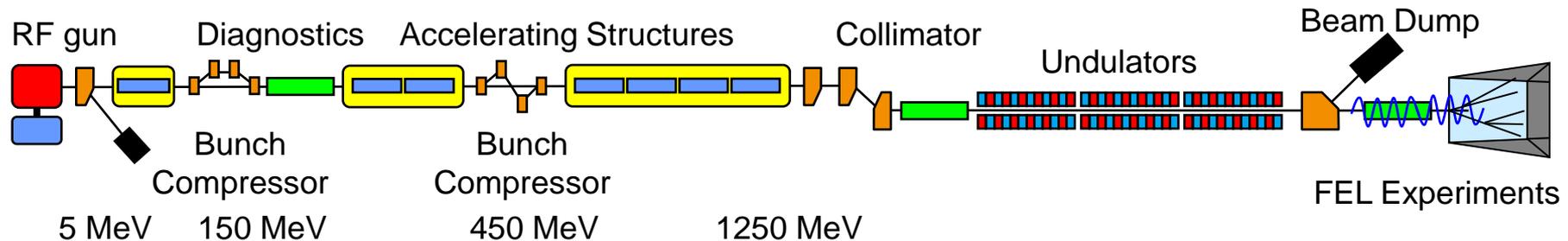
Why electron injector is so important ???

→ property of linacs: beam quality will **DEGRADE** during acceleration

Main components of short wavelength SASE-FELs:

- **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
- } increase normalized emittance

Example: FLASH 1

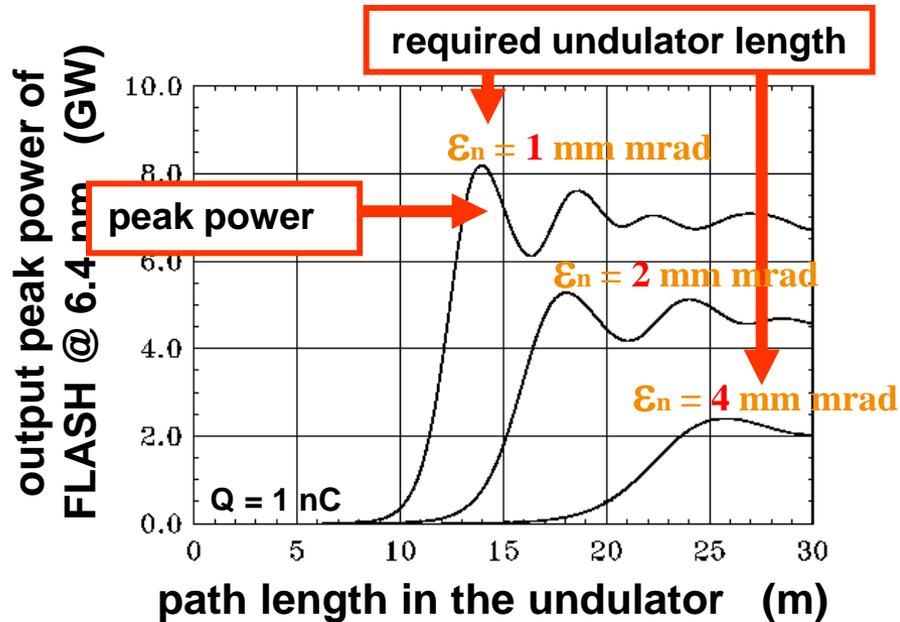


→ electron source has to produce lowest possible emittance !!

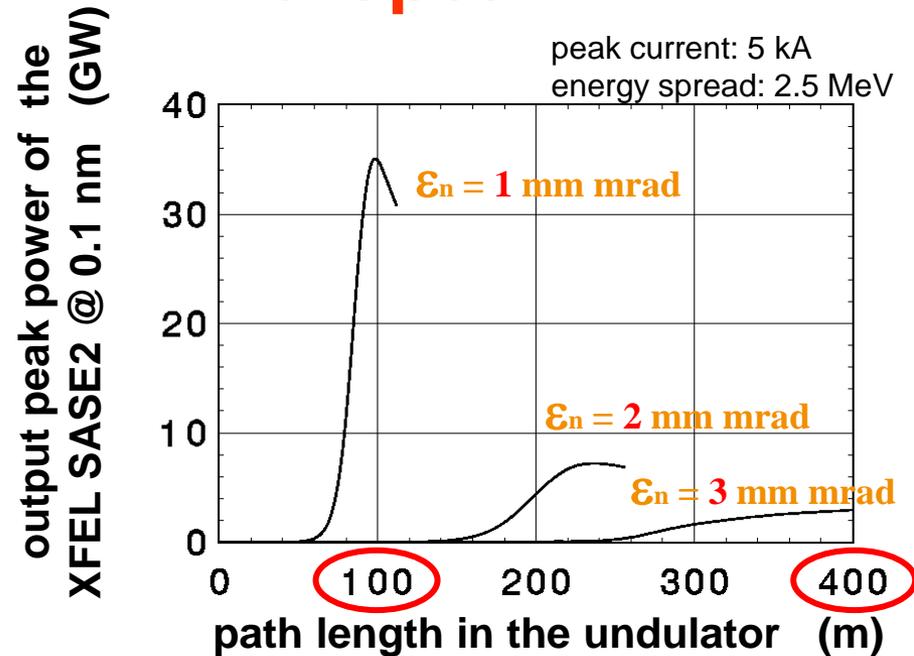
Why electron injector is so important ...

- Why emittance must be small ...

FLASH



European XFEL

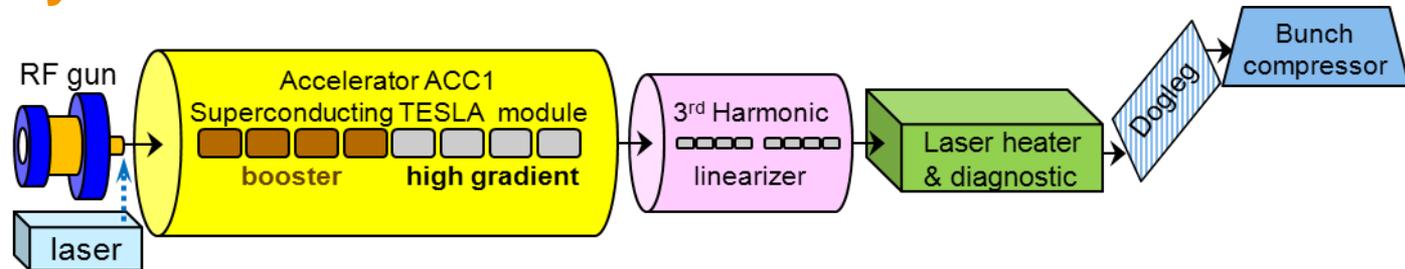


- e.g. XFEL goal: slice emittance(1nC) = 1.0 mm mrad@undulator
- if even smaller emittance \Rightarrow new horizons:
shorter wavelength, higher repetition rate

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):

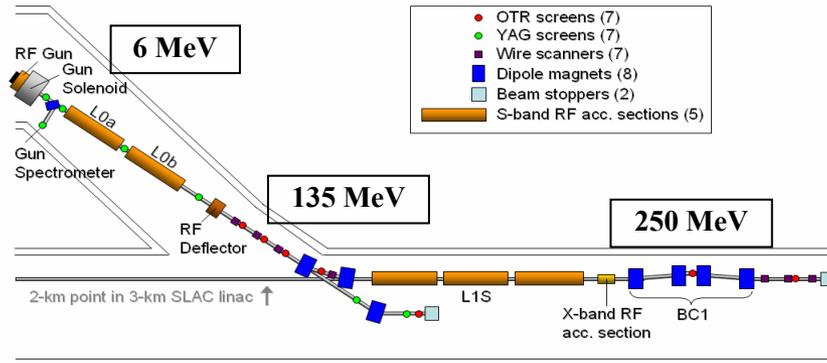
→ relaxes requirements on cathode gradient and gives a lot of additional flexibility !

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

Low average current RF guns (<1 μA)

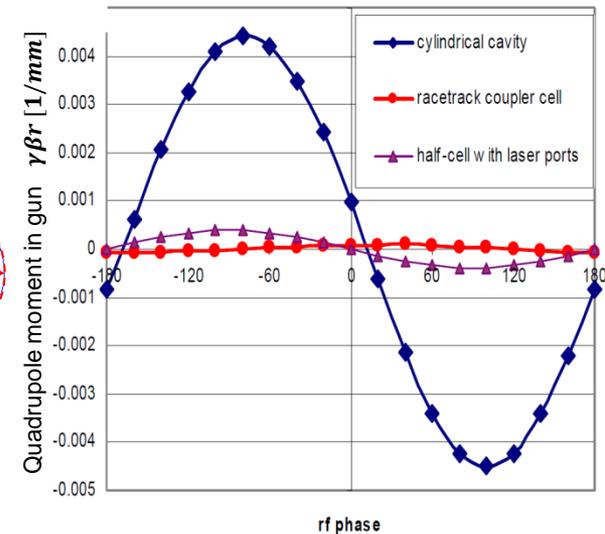
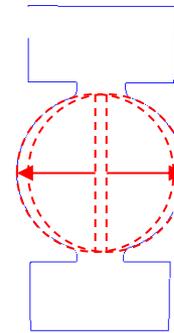
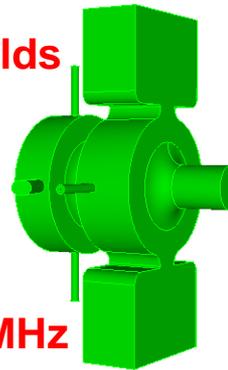
- Most popular S-band gun, the BNL/SLAC/UCLA gun, and its further developments → the **LCLS gun**:

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 $0-\pi$ 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 ~ 200 pC
Single bunch rep rate	120 Hz	10 Hz	~ 1 THz
Length of bunch train	N/A	N/A	currently ≤ 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	~ 5 MeV	4.5 MeV
Norm. transv. emittance (RMS) in [mm mrad]	0.3 - 0.4 for 150 pC @ 135 MeV	~ 1 for 280 pC @ 147.5 MeV	0.54 for 2×90 pC @ ~ 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 ~ 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

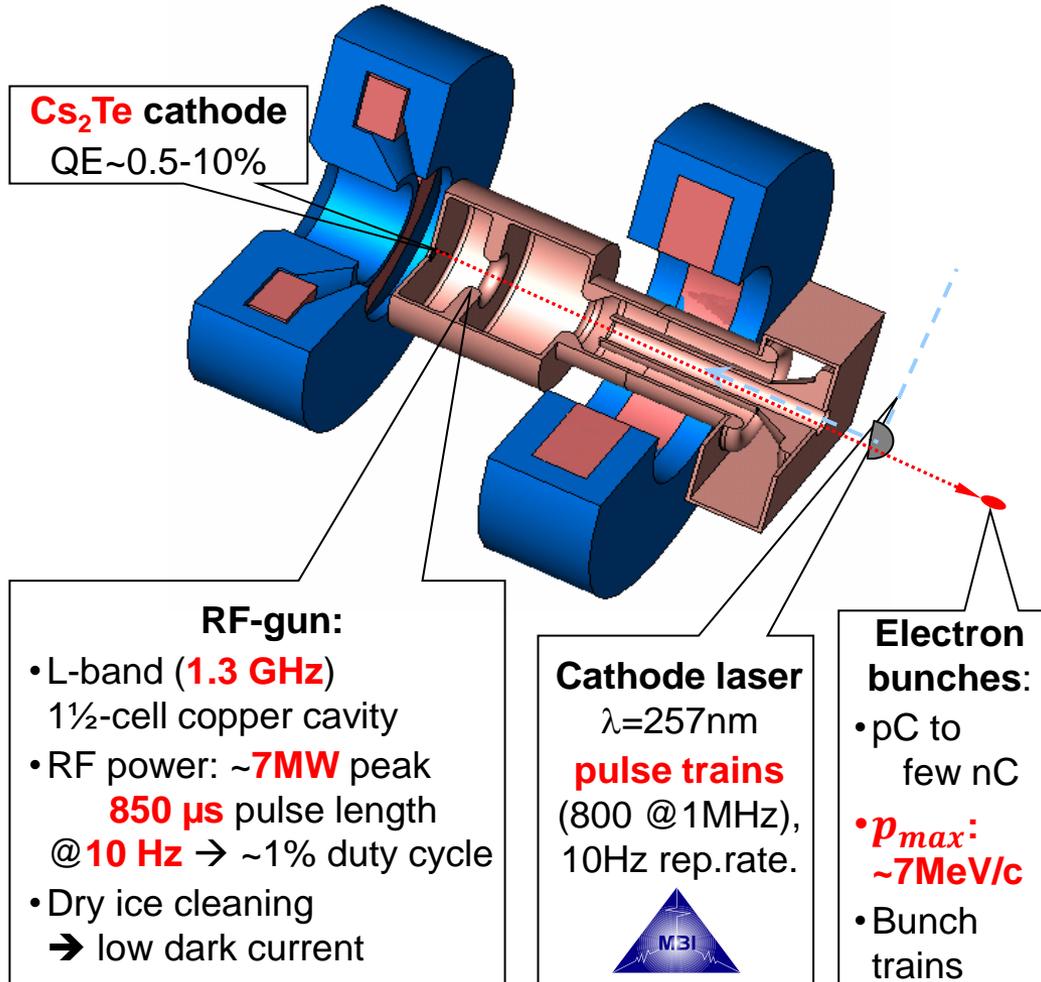
S-band guns

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

1.8. – 5.9. 2014 | Page 7

Medium average current RF guns ($1 \mu\text{A} < I_{av.} < 1\text{mA}$)

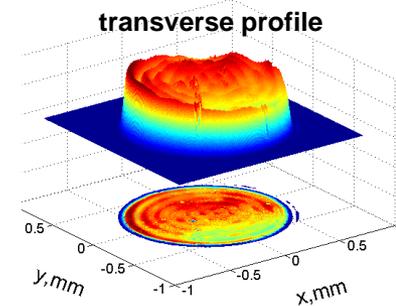
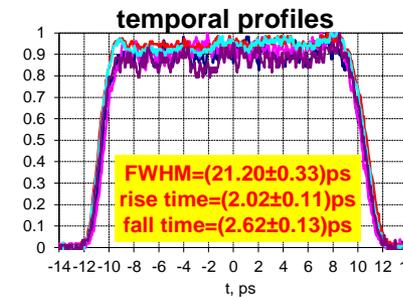
- > The **PITZ gun**, used for FLASH and European XFEL:



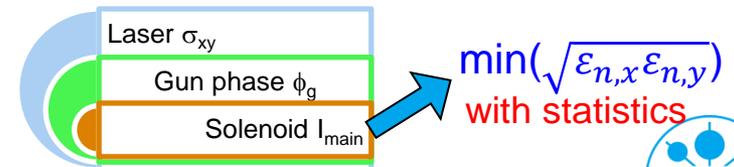
How to achieve small emittance:

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

- > Cathode laser pulse **shaping**

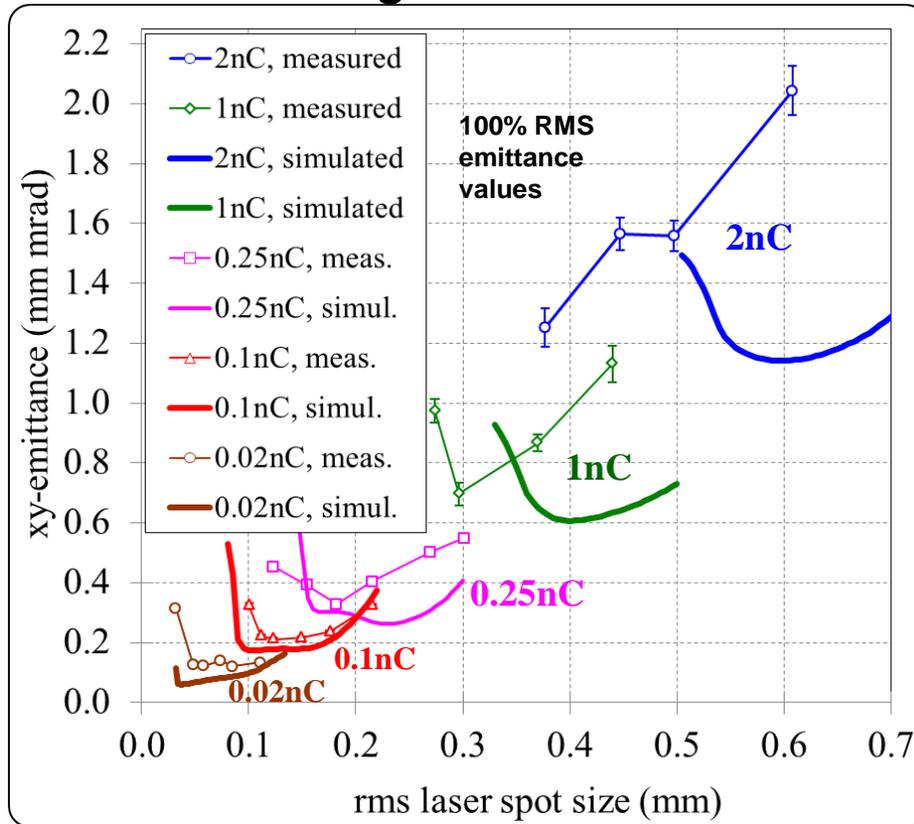


- > Gun launch **phase** stability
- > Beam based **alignment**, trajectory optimization
- > Emittance compensation and conservation → multi parametric machine **tuning** (solenoid, laser spot size, gun phase, booster,...)



Medium average current RF guns ($1 \mu\text{A} < I_{av.} < 1\text{mA}$)

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



- Measured emittance results set a benchmark on **photo injector optimization**
- Optimum machine parameters (laser spot size, gun phase): **experiment \neq 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).

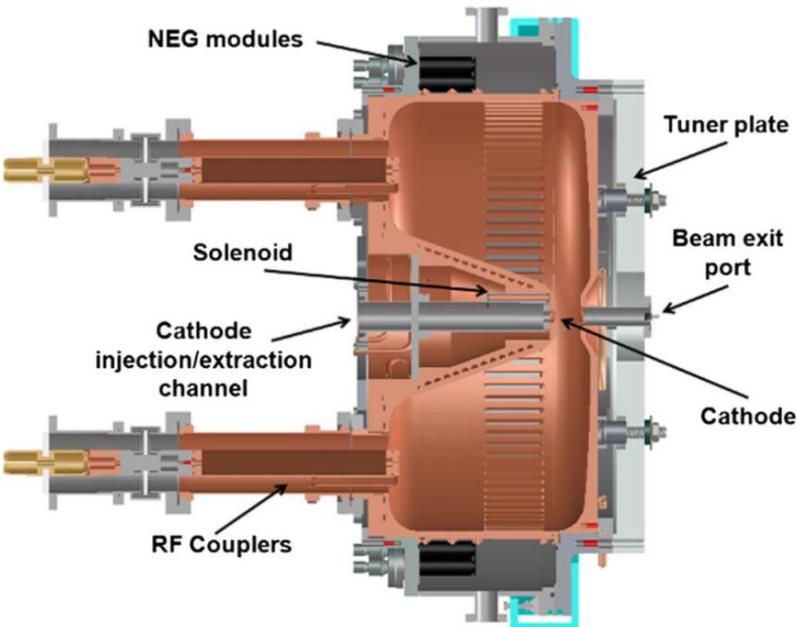
TABLE IV. Core xy-emittance (mm mrad) measured for various charges and gun phases. Only statistical errors are shown

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 ($1 \mu\text{A} < I_{av.} < 1\text{mA}$)

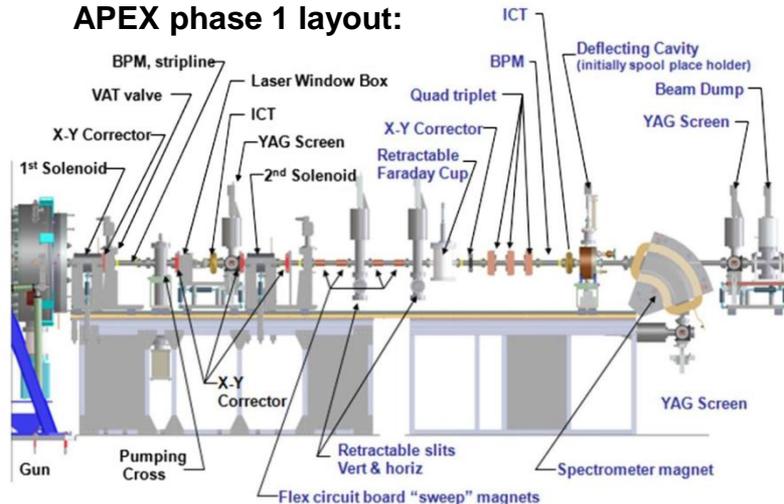
➤ The **APEX gun** at Berkeley: a NC gun for **CW operation**



➤ **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 ($1 \mu\text{A} < I_{av.} < 1\text{mA}$)

	a)	b)	c)	d)
Location	DESY (PITZ), Germany			LBLN, 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 ₂ Te			testing Cs ₂ Te, CsK ₂ Sb 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 , $\leq 800\mu\text{s}$ possib.		N/A
Bunch train rep rate	10 Hz			N/A
Total beam charge generated per second	27 $\mu\text{C/s}$	6 $\mu\text{C/s}$	1.5 $\mu\text{C/s}$	up to 300 $\mu\text{C/s}$ 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	$\epsilon_{x,y} = 0.60$ @ 25 MeV	$\epsilon_{x,y} = 0.29$ @ 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 ≤ 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	\sim flat-top, ~ 0.3 mm RMS	\sim 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 ($I_{av.} \geq 1\text{mA}$)

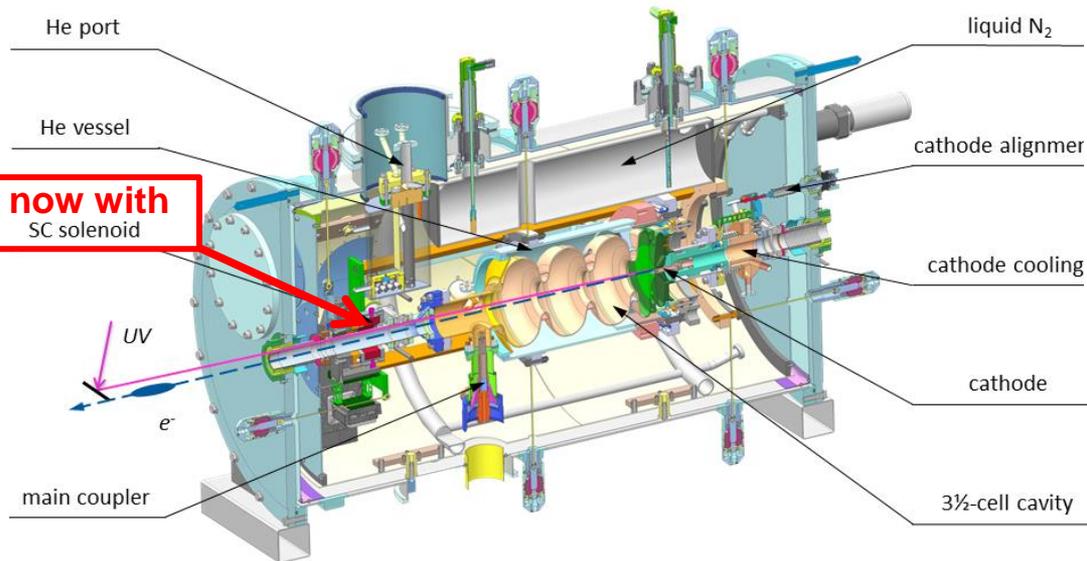
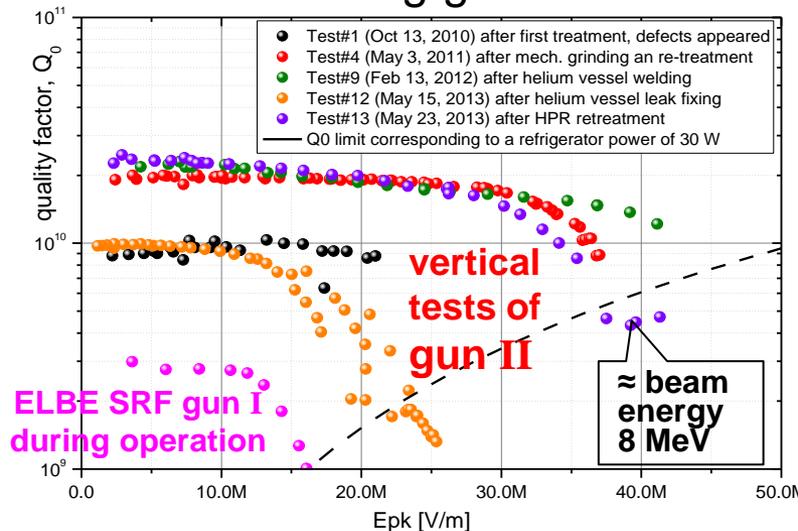
> High current: → high QE photo cathode (NC or SC?), high rep. rate laser, → high duty cycle

→ 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 ...

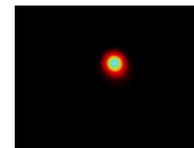
- first FEL operation with an SRF gun at ELBE
- excellent life time of **NC Cs_2Te** cathode was demonstrated (264 C, 400 μA)

Accelerating gradients:



Courtesy J. Teichert

> 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 ($I_{av.} > 1\text{mA}$)

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]

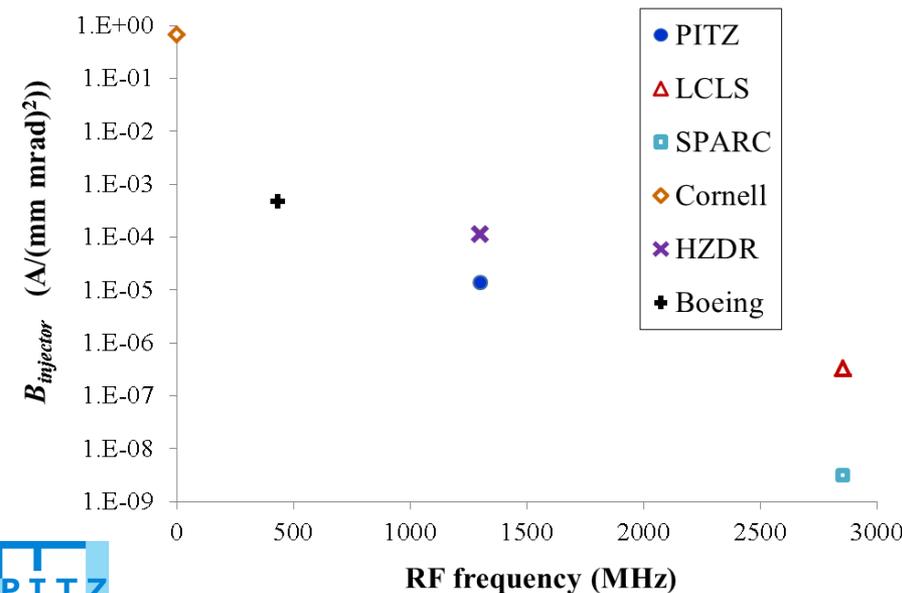
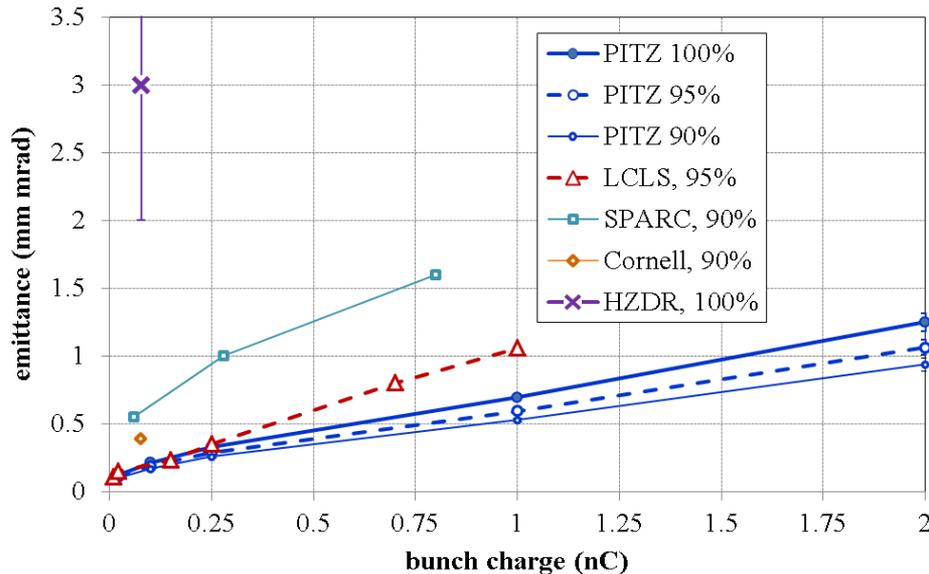
	a)	b)	c)	d)	e)	f)
Location	Cornell, USA		Boeing, USA	HZ Dresden Rossendorf, Germany		
Gun type	DC Gun		4 cell NC RF Gun	SC RF gun, $3\frac{1}{2}$ cell elliptical cavity		
Experimental results or design goals/simulation	design goals	exp. results	exp. results	design goals / simulations		exp. results
Operation 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 ₂ CsSb	Cs ₂ Te		
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 μ s	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	$\sim 1\mu\text{C/s}$	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]	≤ 0.3 @ 10 - 12 MeV	$\epsilon_x = 0.51, \epsilon_y = 0.29$ @ 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]	≤ 0.3 @ 10 - 12 MeV	$\epsilon_{slice,x} = 0.4 - 0.5$ 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, ~ 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, ~ 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

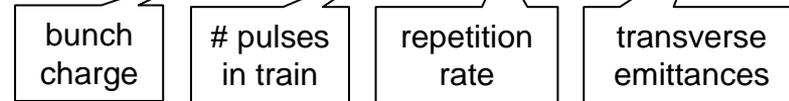


> Comparing the measured single bunch emittance

- 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” $[A / (\text{mm mrad})^2]$

$$B_{injection} = Q_{bunch} \cdot NOP \cdot RR / (\epsilon_{n,x} \cdot \epsilon_{n,y})$$

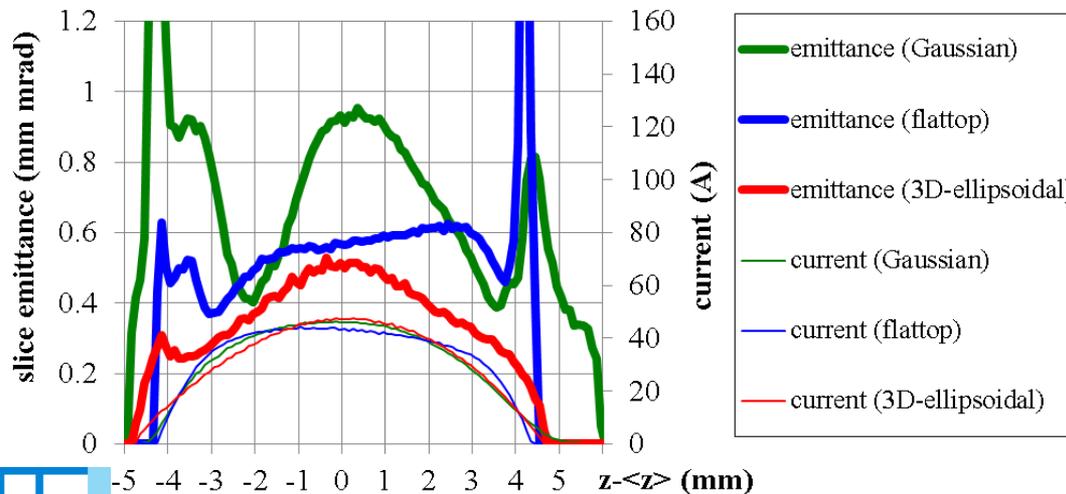
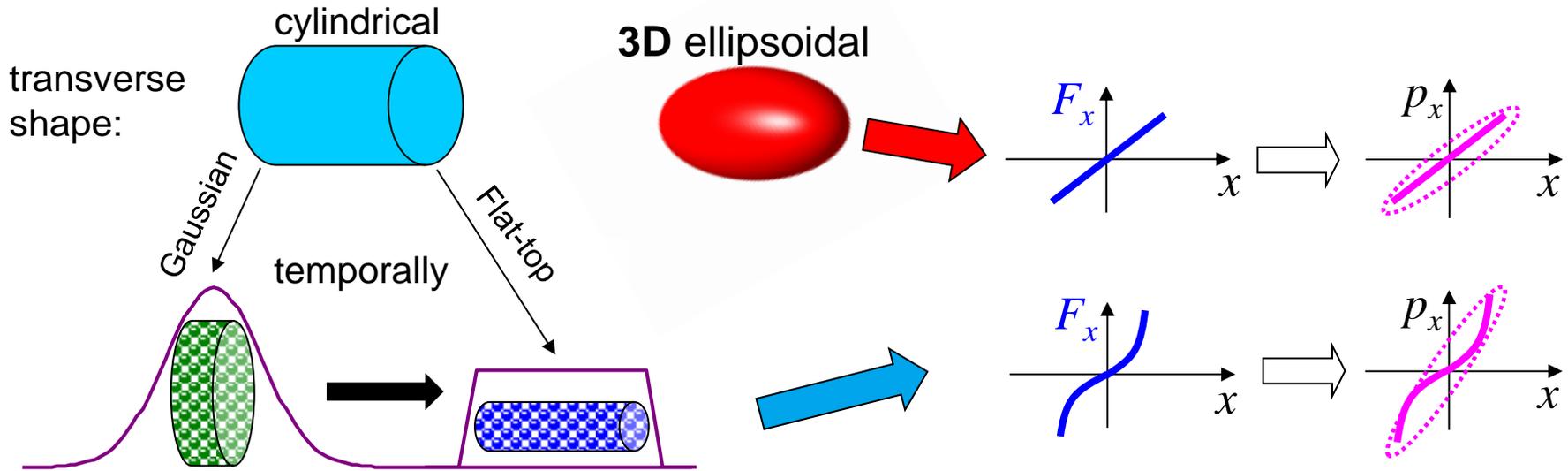


- **Design** average currents and **measured** single bunch emittances have been used.

→ **Lower RF frequency yields higher $B_{injection}$ due to higher $I_{injection}$**

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**

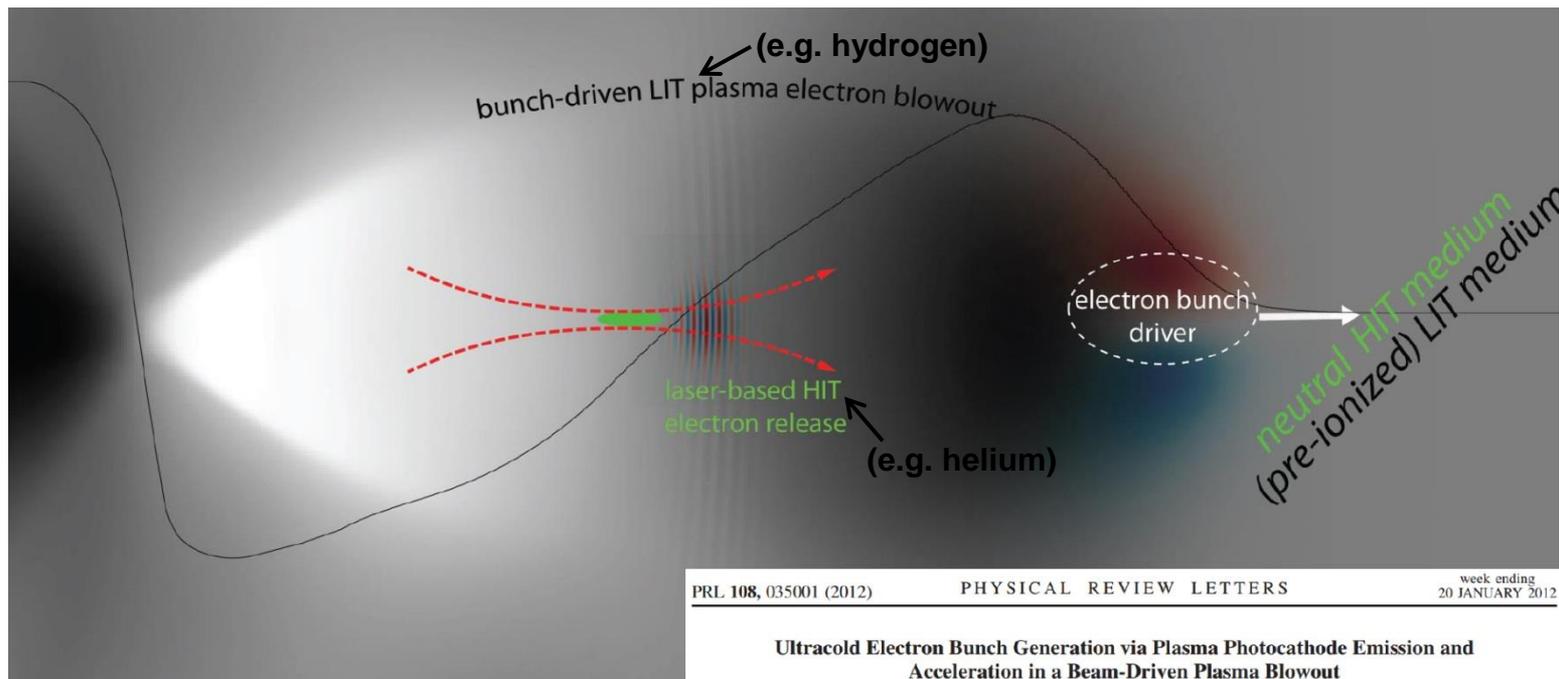
➔ Extensive developments needed to overcome e.g. **thermal lensing + pulse heating** and to allow **stable and reliable operation 24/7** (often specific requests for planned application)

> **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 ionization of He inside plasma wave**
- > emittance estimate inside plasma cavity:
 0.03 mm mrad for 2 pC bunch, but $I_{peak}=300 \text{ A}$
- > Difficulties: **synchronization**, **energy spread**, **extraction** of bunch from plasma, ...

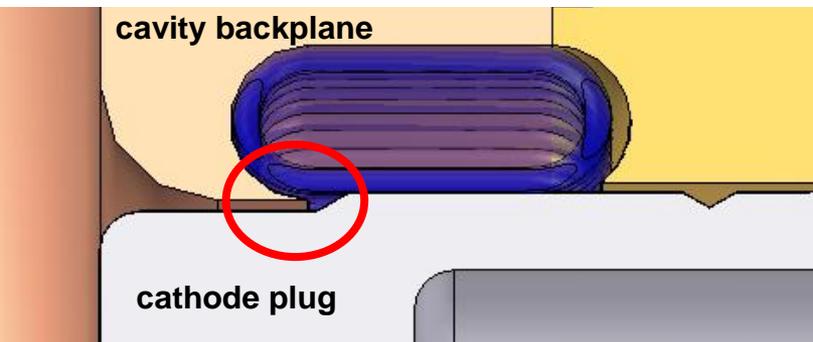


B. Hidding,^{1,2} G. Pretzler,² J.B. Rosenzweig,¹ T. Königstein,² D. Schiller,¹ and D. L. Bruhwiler³

Details are important

Details are important: here contact cathode ↔ cavity

original watchband design

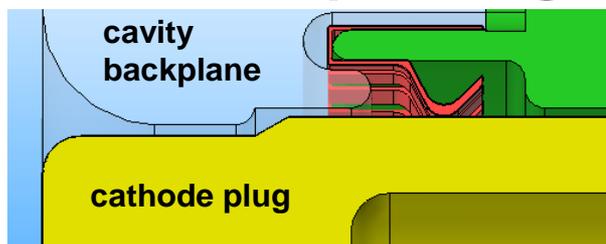


- + robust spring
- severe damage on peaked nose (part of the gun), mainly when running at high peak power and long pulse length

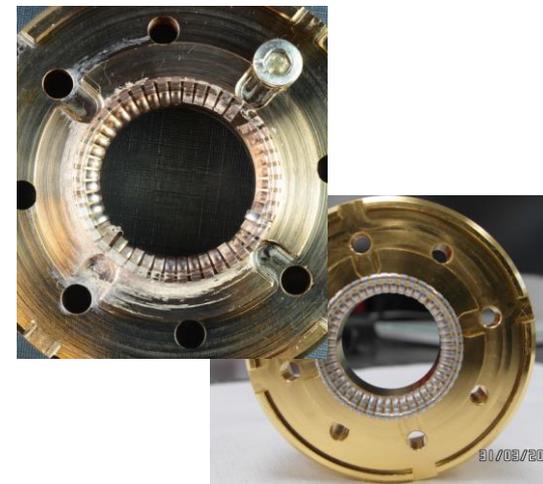


Gun4.1

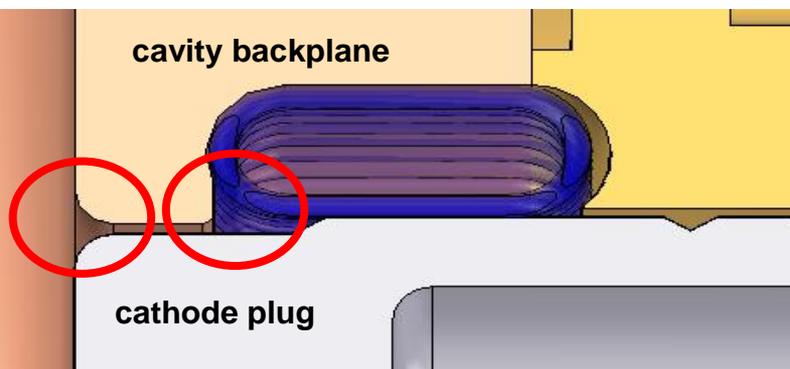
contact stripe design



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



“watchband reloaded”



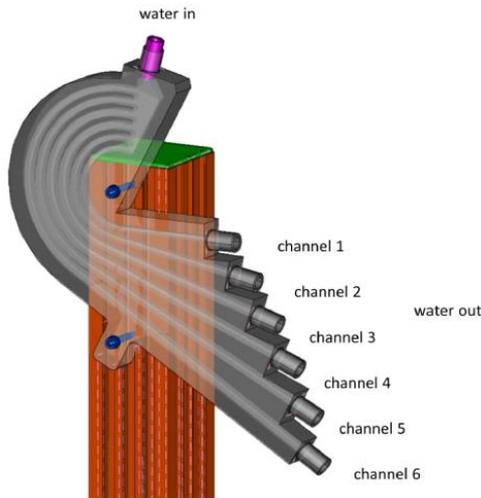
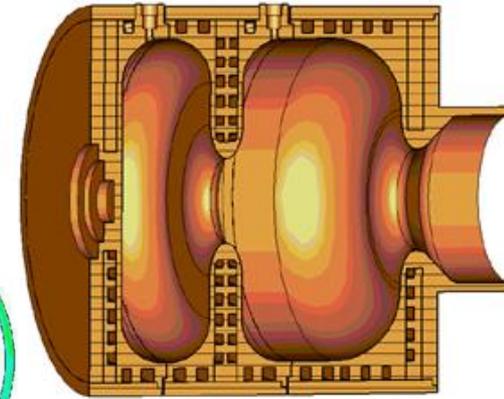
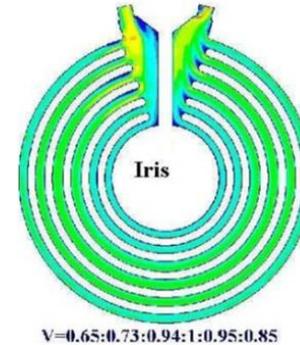
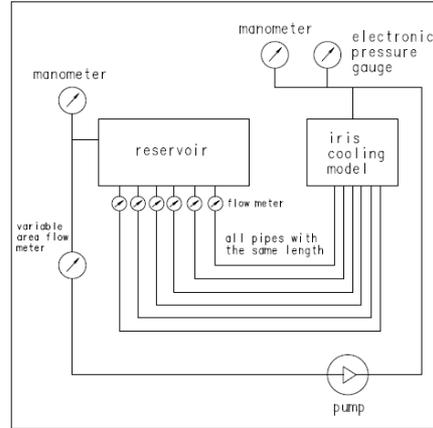
- + robust spring
- + equalized radii
- still to be tested in experiment !

Courtesy S. Lederer

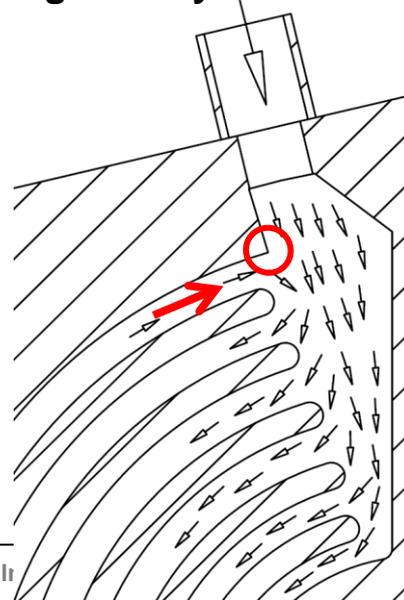


Details are important: here water flow simulations + tests

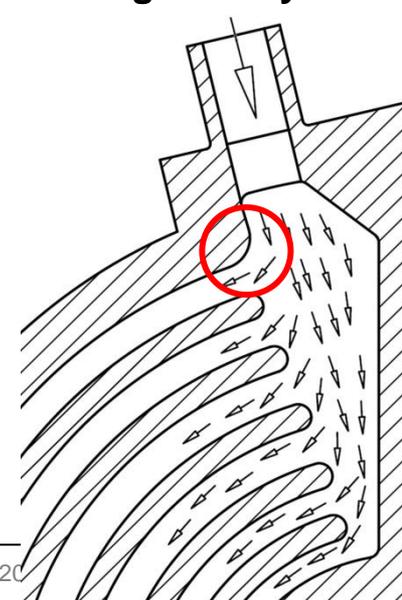
- > Gun5 has: RF pick ups, elliptical irises, circular cell shape, more&smaller cooling channels → internal water distribution → **test**



First geometry with reverse flow



Current geometry with correct flow



Courtesy
S. Philipp,
V. Paramonov

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+ references listed on individual slides

Summary

- > 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**” $\left(\frac{\text{average current}}{\text{emittance}^2}\right)$ **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.