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 …. ???

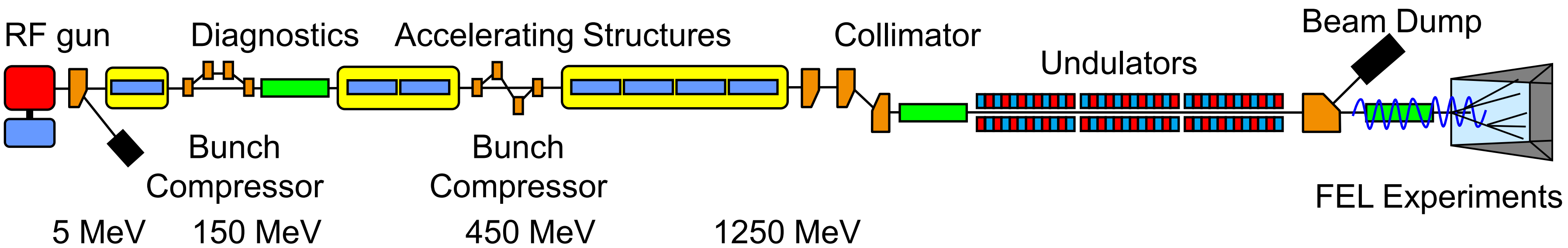
→ property of linacs: beam quality will DEGRADE during acceleration

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

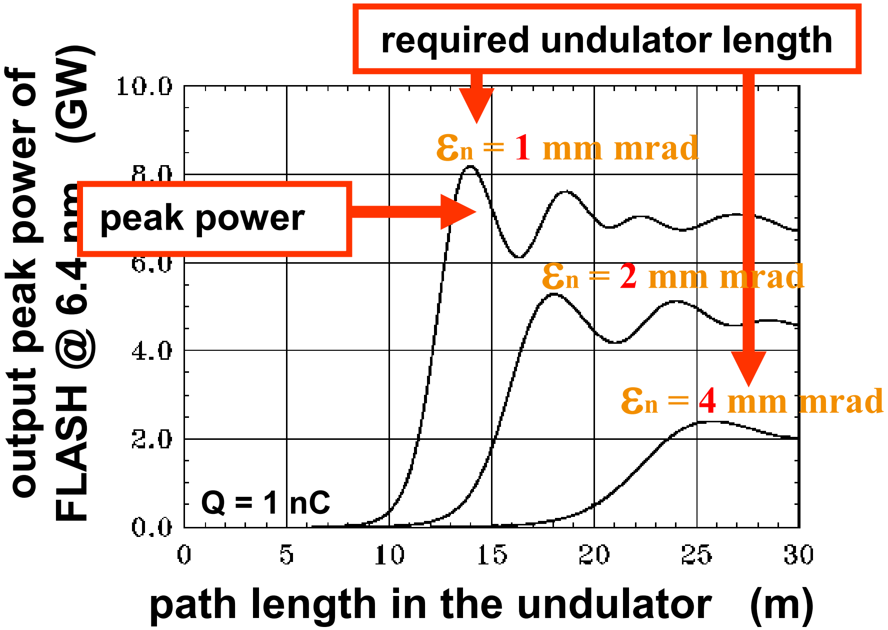


→ electron source has to produce lowest possible emittance !!

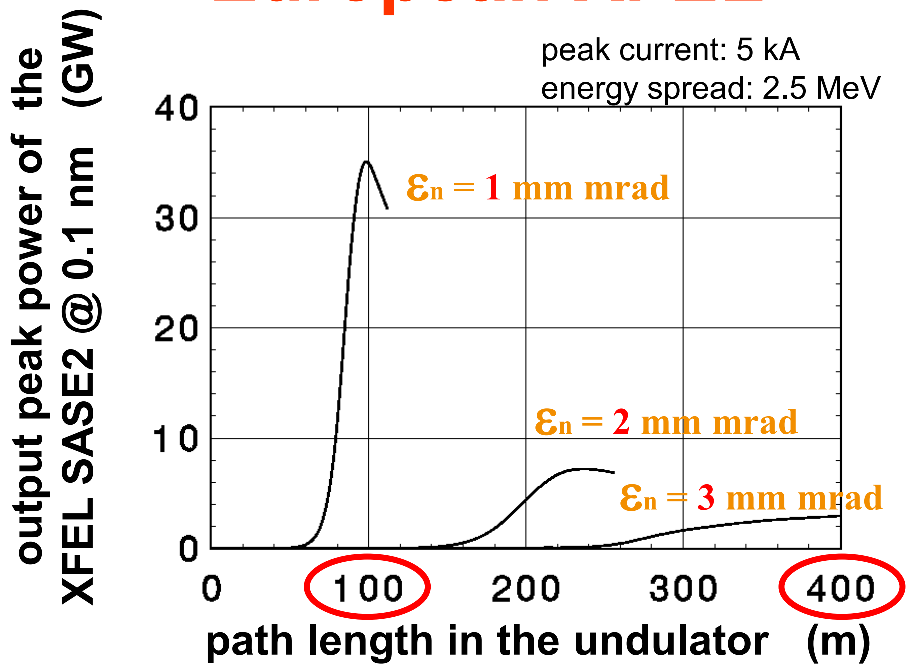
Why electron injector is so important …

- **Why emittance must be small …**

FLASH



European XFEL



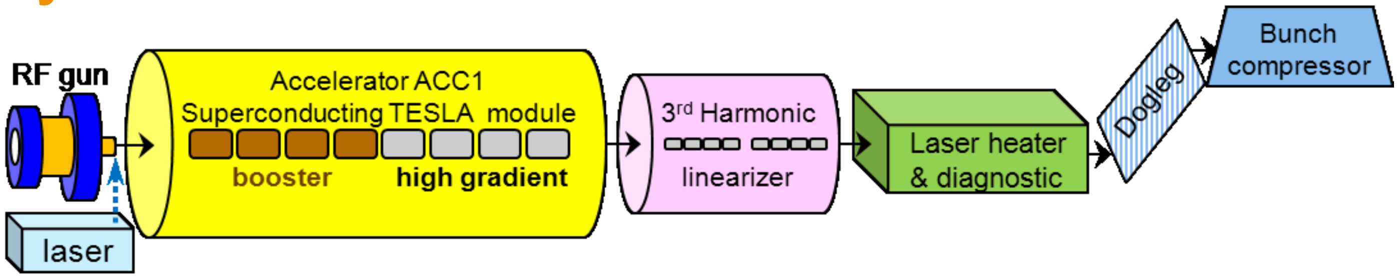
- **e.g. XFEL goal: slice emittance(1nC) = 1.0 mm mrad@undulator**
- **if even smaller emittance ⇒ new horizons:**

  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):

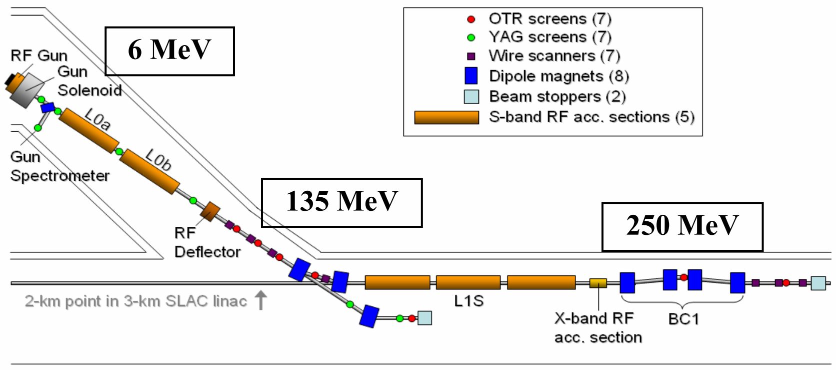
→ relaxes requirements on cathode gradient and gives a lot of additional flexibility !

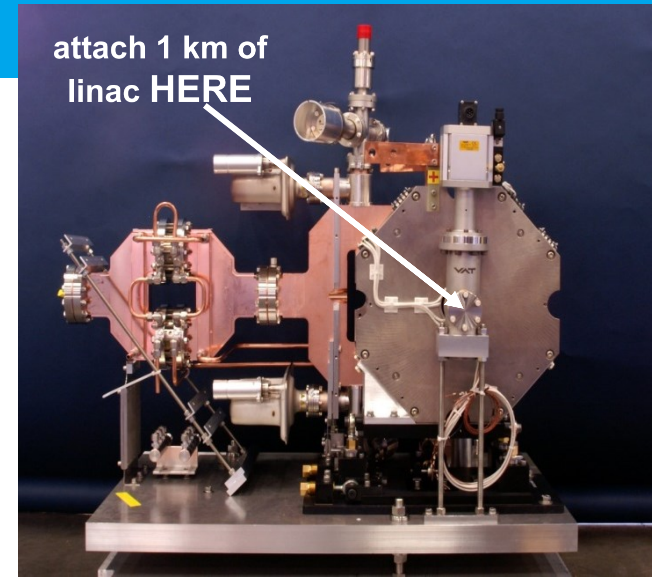
➔ **high cathode gradient helps, but laser shaping is as important !**

Low average current RF guns (<1 µA)

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

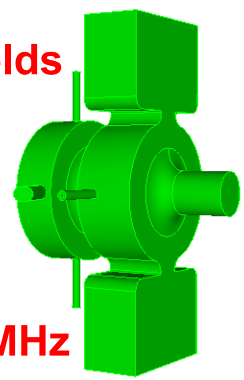
LCLS Injector Setup @SLAC:

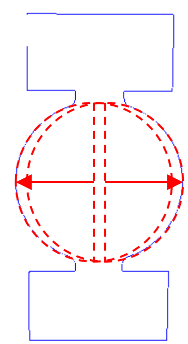


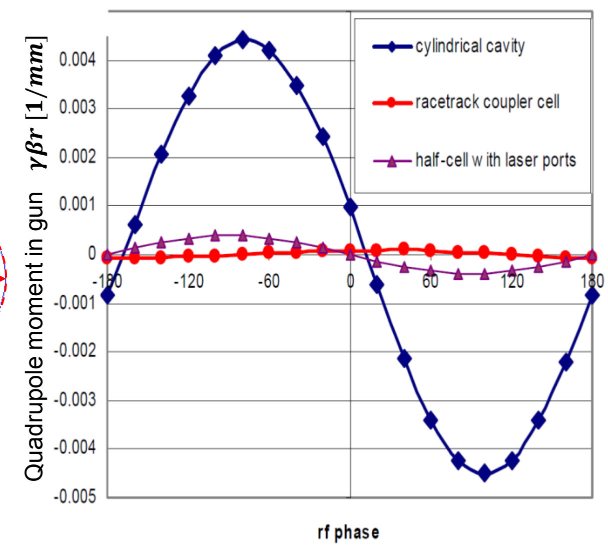


Realised design improvements:

- **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 ∼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

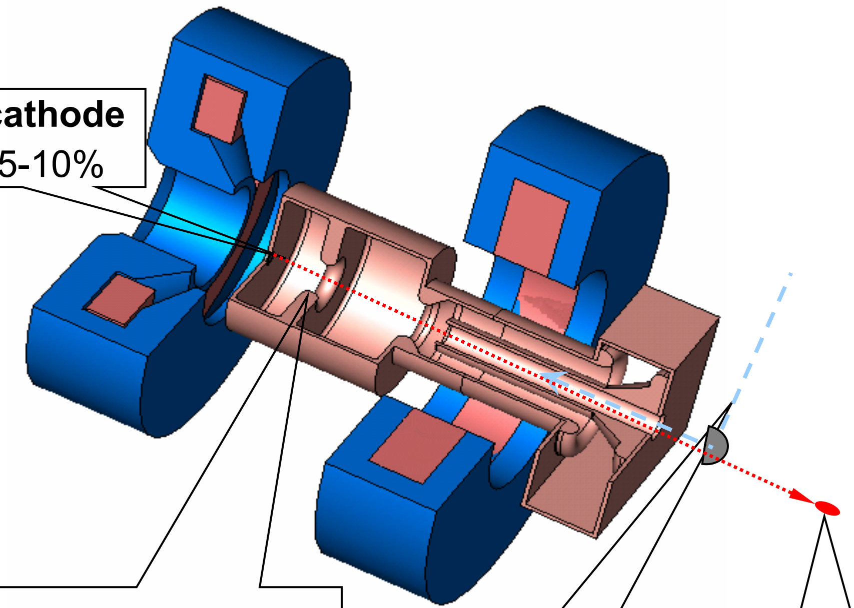
S-band guns

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

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.

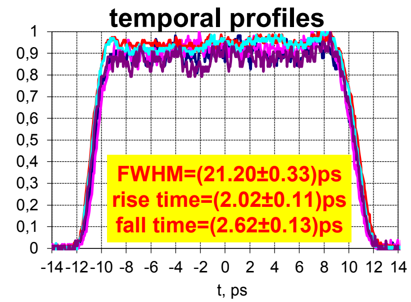
Electron bunches:

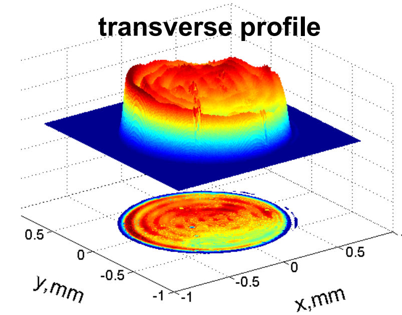
- pC to few nC
- p_{max}: **~7MeV/c**
- Bunch trains

How to achieve small emittance:

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

> Cathode laser pulse **shaping**

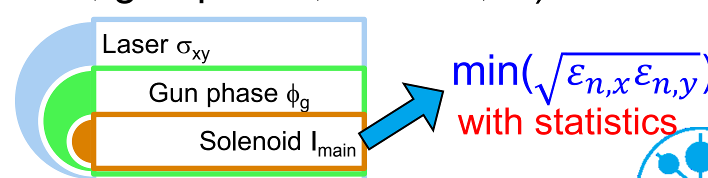




> Gun launch **phase** stability

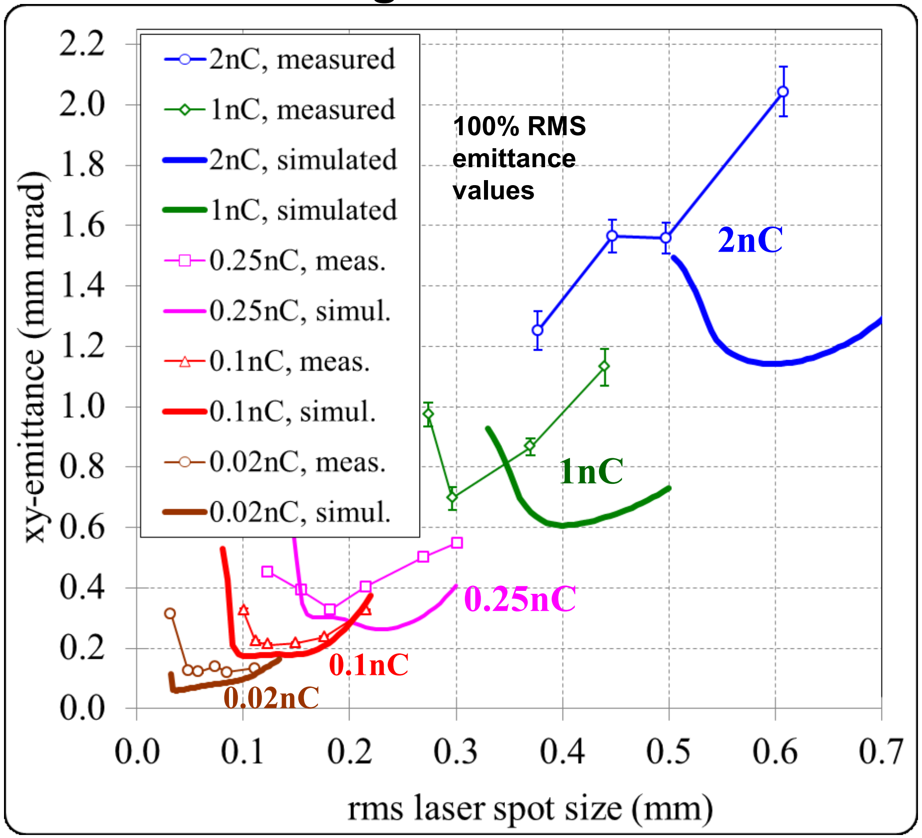
> Beam based **alignment**, trajectory optimization

> Emittance compensation and conservation → multi parametric machine **tuning** (solenoid, laser spot size, gun phase, booster,…)



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

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 ≠ 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

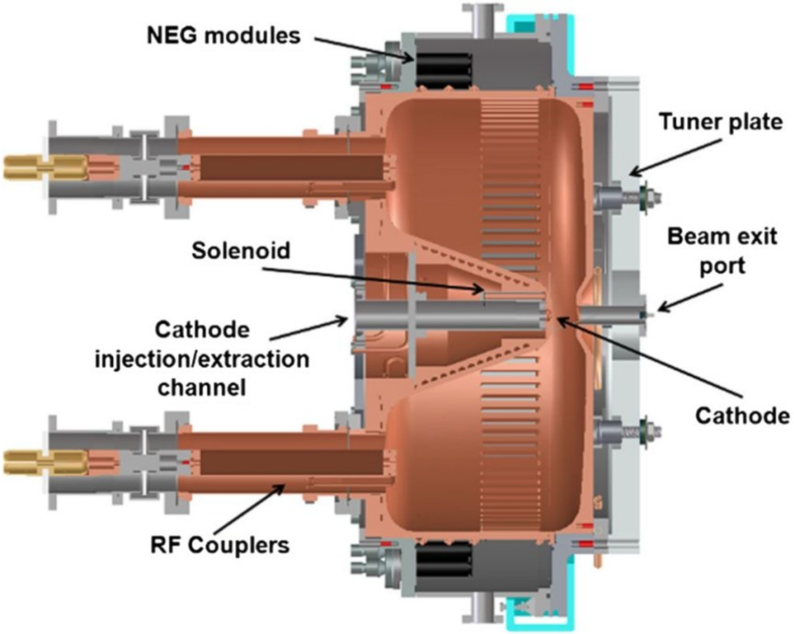
M. Krasilnikov et al., PRST-AB ***15****, 100701 (2012).*

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

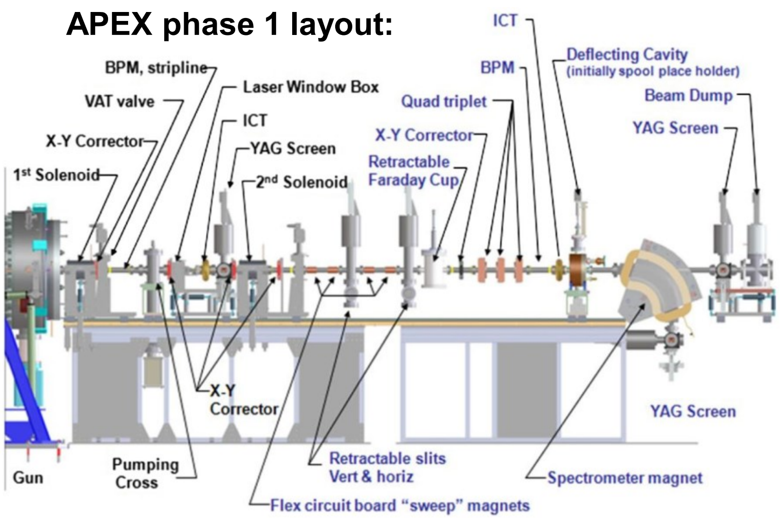
Medium average current RF guns (1 µA < $I_{av.}$ < 1mA)

> 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, $\leq 800 \mu s$ possib.		N/A
Bunch train rep rate	10 Hz			N/A
Total beam charge generated per second	27 $\mu C/s$	6 $\mu C/s$	1.5 $\mu C/s$	up to 300 $\mu C/s$ 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	$\varepsilon_{x,y} = 0.60$ @ 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]

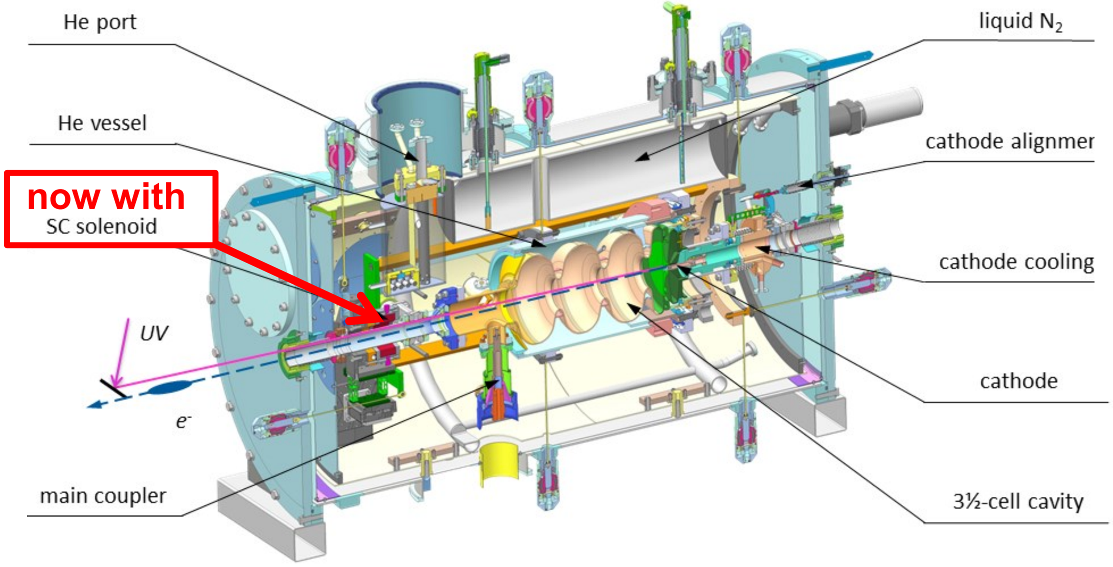
High average current RF guns ($I_{av.}$ ≥ 1mA)

> 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:**

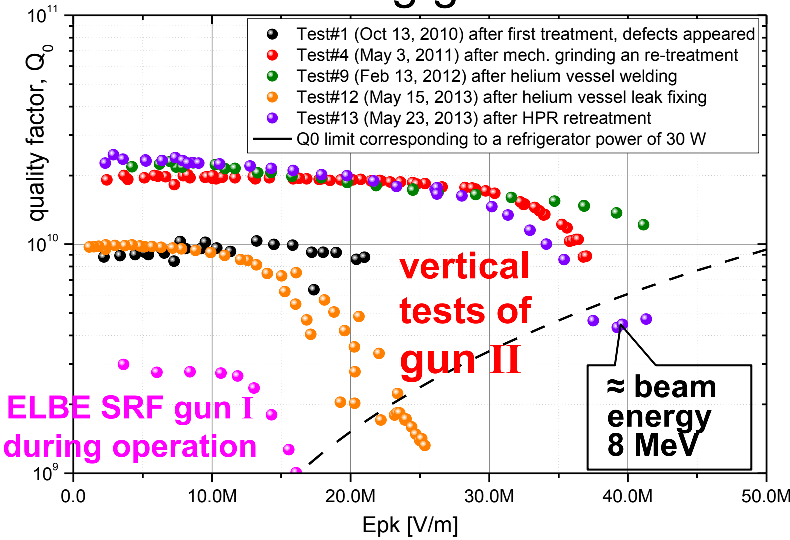
> **gun I** cavity was limited by strong field emission
→ $E_{launch,cathode}$ only 2.2 - 2.6 MV/m, but still …

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

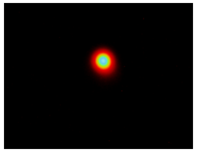


Courtesy J. Teichert

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]

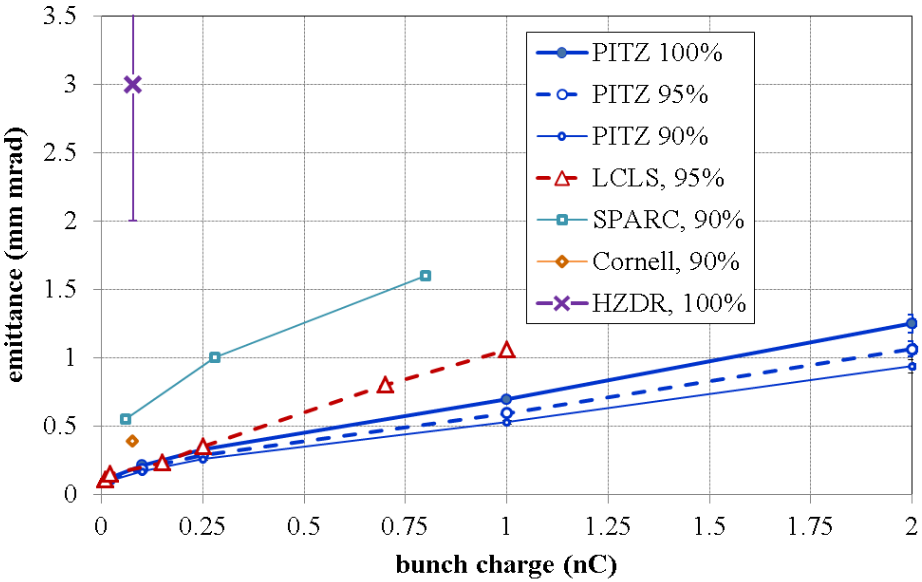
	a)	b)	c)	d)	e)	f)
Location	Cornell, USA		Boeing, USA	HZ Dresden Rossendorf, Germany		
Gun type	DC Gun		4 cell NC RF Gun	SC RF gun, $3\frac{1}{2}$ cell elliptical cavity		
Experimental results or design goals/simulation	design goals	exp. results	exp. results	design goals / simulations		exp. results
Operation 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	~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, ~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.

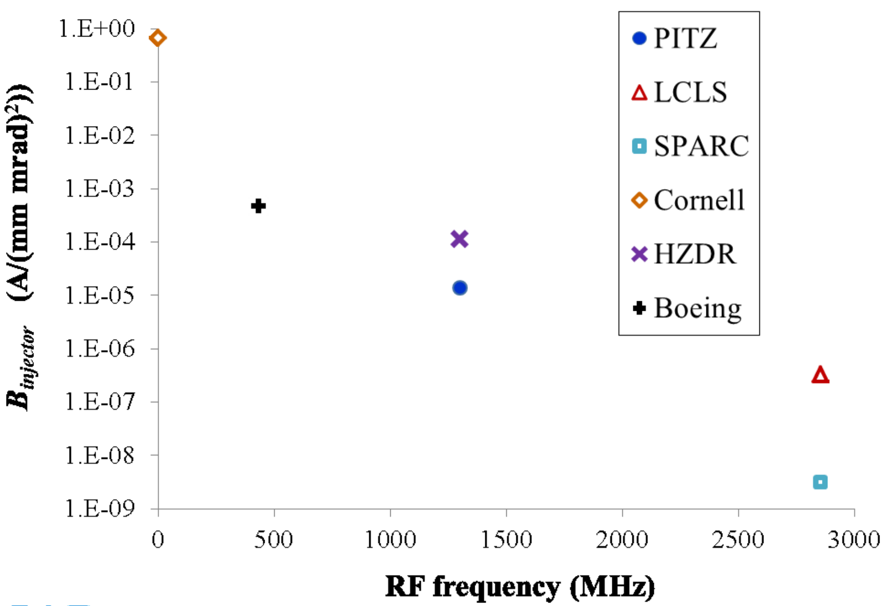
high QE photo cathodes

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 / (mm mrad)²]

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

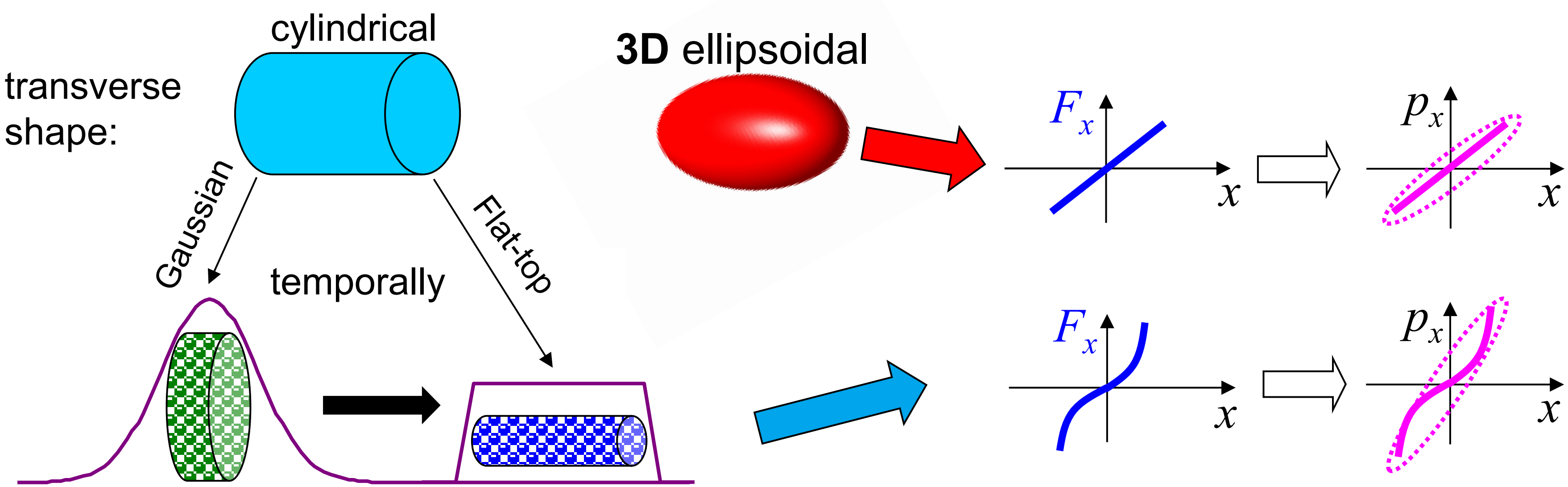
bunch charge | # pulses in train | repetition rate | transverse emittances

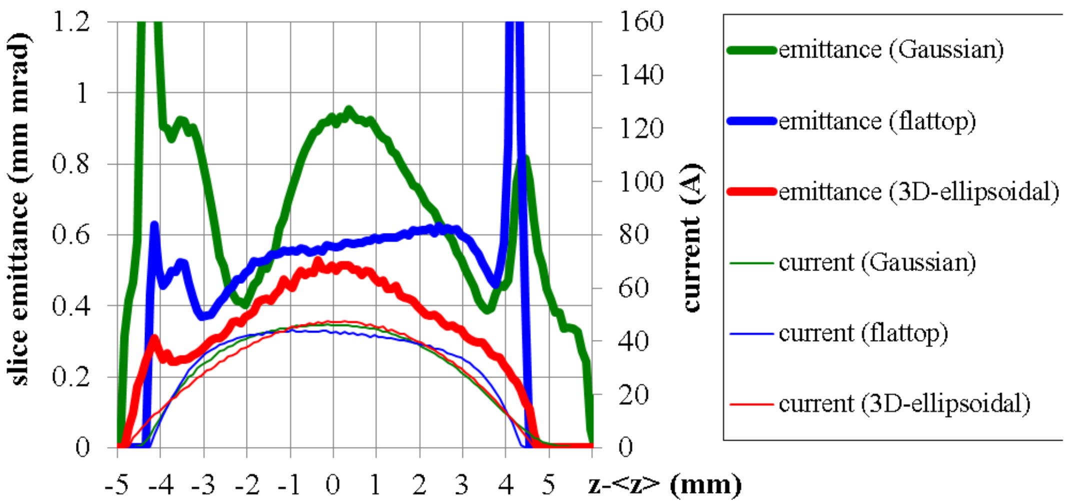
  - **Design** average currents and **measured** single bunch emittances have been used.

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

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**

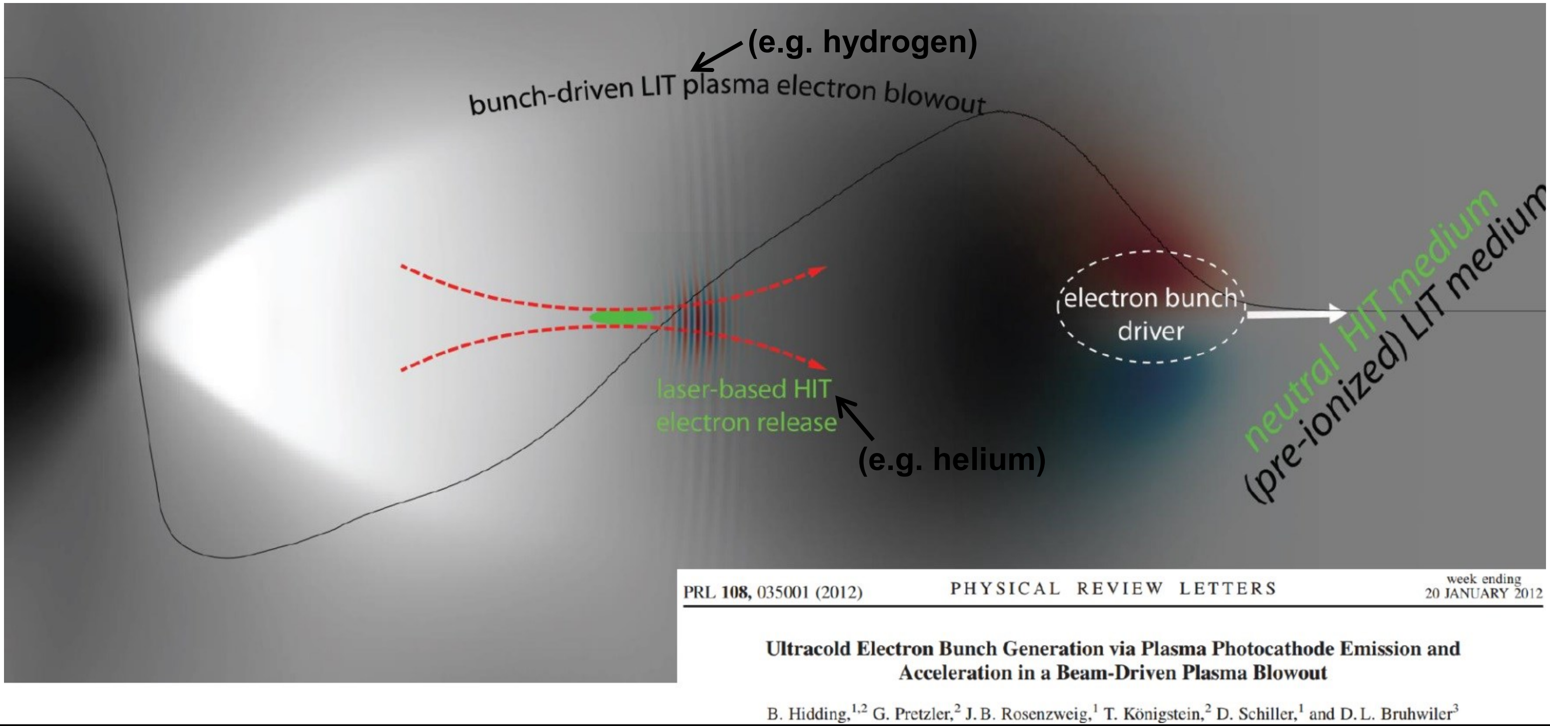
➔ Extensive developments needed to overcome e.g. **thermal lensing + pulse heating** and to allow **stable and reliable operation 24/7** (often specific requests for planned application)

> **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**

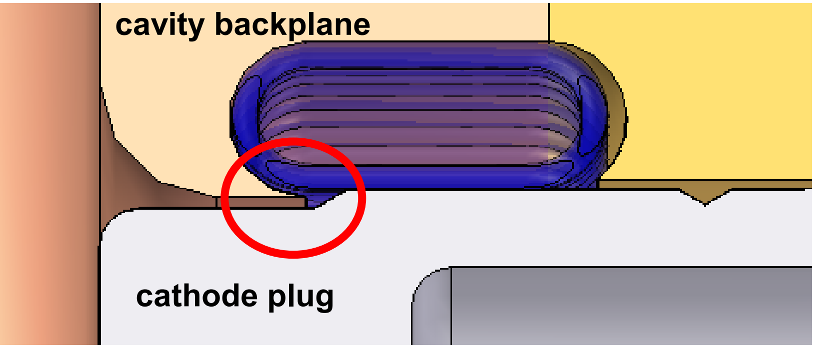
Future trends: A plasma based electron source

- **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, …

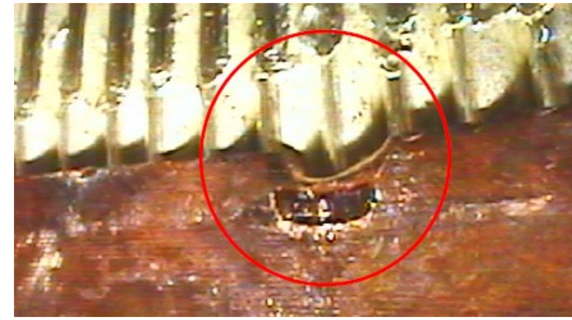


Details are important: here contact cathode ↔ cavity

original watchband design

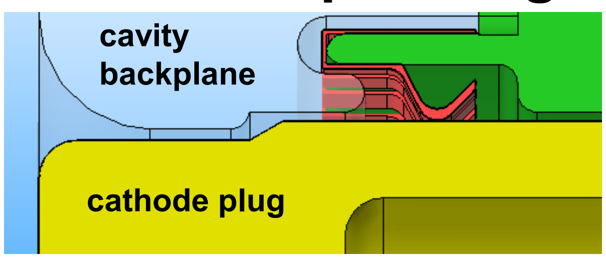


- + robust spring
- - severe damage on peaked nose (part of the gun), mainly when running at high peak power and long pulse length

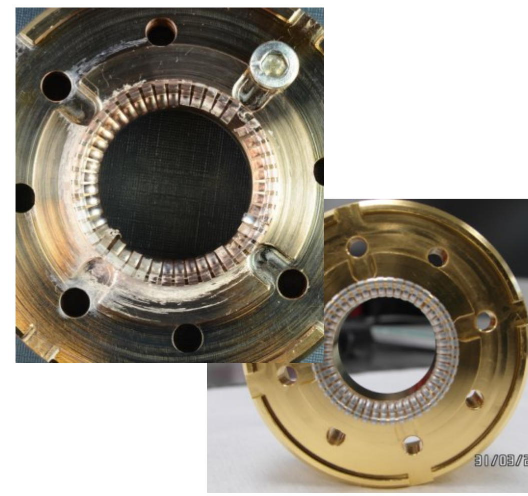


Gun4.1

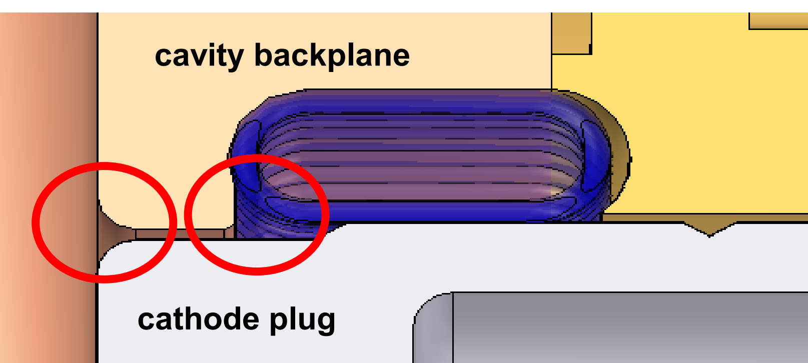
contact stripe design



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



“watchband reloaded”

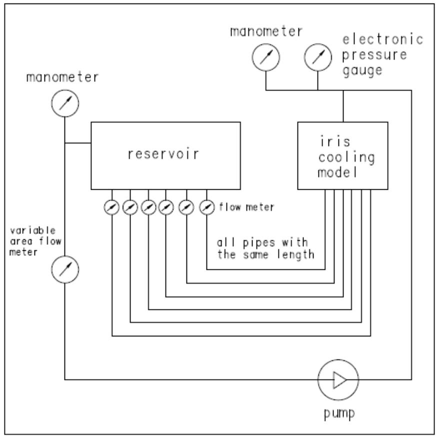


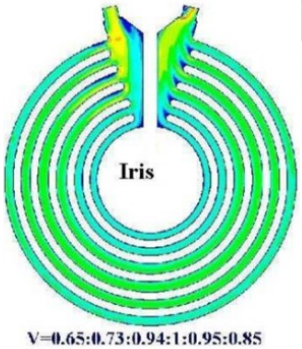
- + robust spring
- + equalized radii
- - still to be tested in experiment !

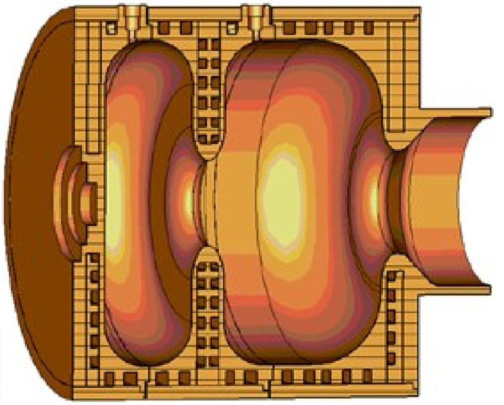
Courtesy S. Lederer

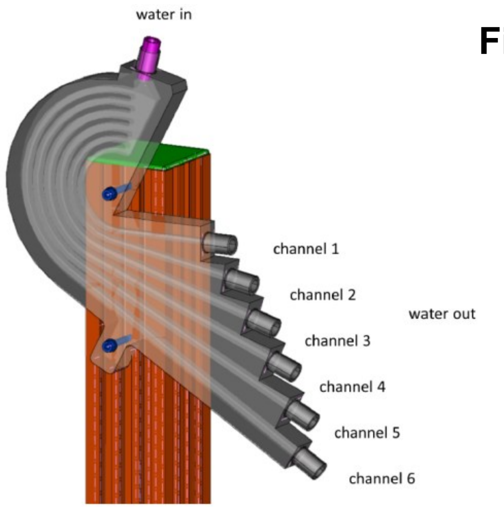
Details are important: here water flow simulations + tests

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

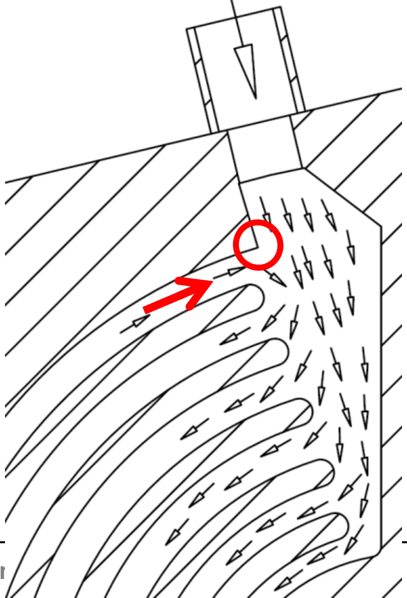




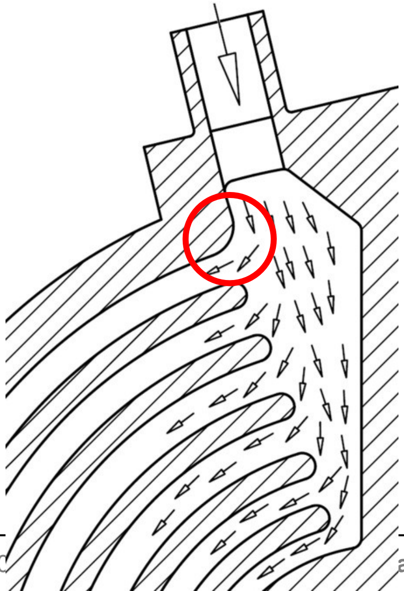




First geometry with reverse flow



Current geometry with correct flow



Courtesy S. Philipp, V. Paramonov

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+ references listed on individual slights

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**” ($\frac{average\ current}{emittance^2}$) **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.