

# **ELECTRON SOURCES AND INJECTORS**

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## Lecture 1:

- The role of electron sources and injectors in light source
- Requirements for electron sources and injectors
- Injector beam dynamics

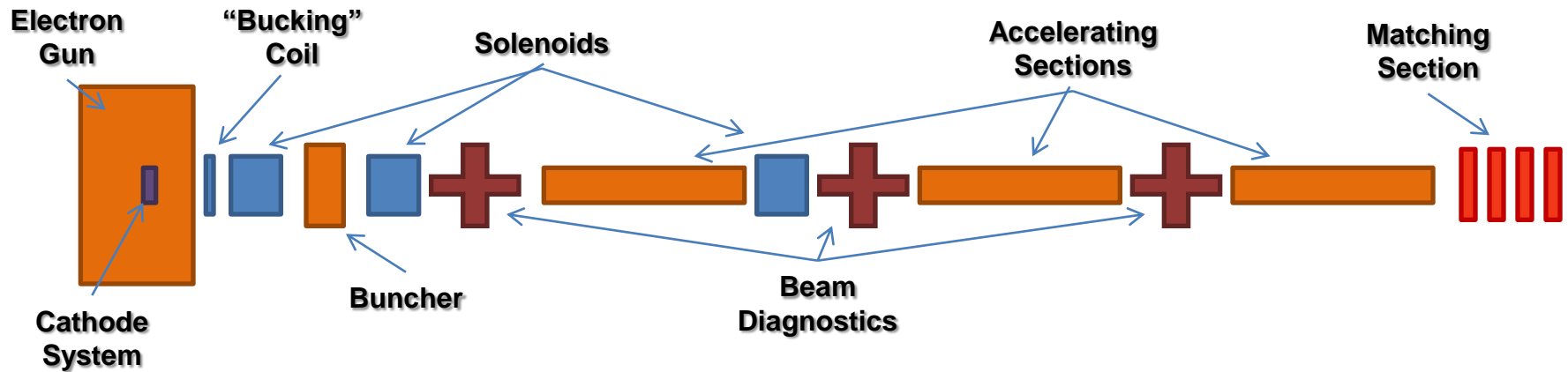
## Lecture 2:

- Injector components
  - Cathodes systems
  - Electron guns
  - Compression systems
  - Focusing systems
  - Accelerating systems
  - Diagnostics systems
- Challenges and required R&D

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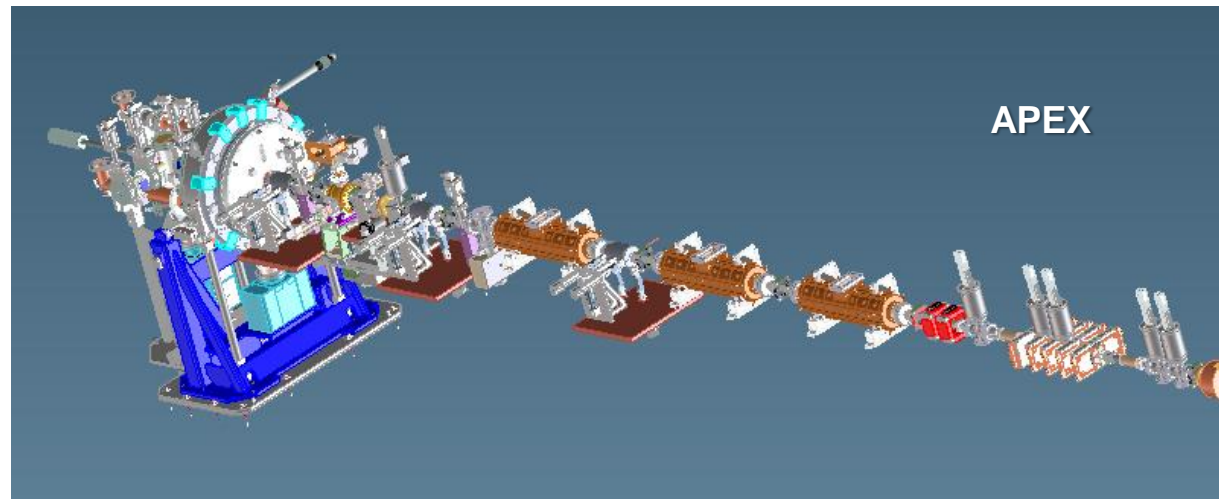
Repetition rate	from $\sim 10$ kHz to $\sim 1$ MHz (seeded mode) up to hundreds of MHz (low charge SASE mode)
Charge per bunch (depending on the operation mode)	from $\sim 1$ pC to $\sim 1$ nC
Normalized transverse emittance (slice)	sub $10^{-7}$ m to $10^{-6}$ m (from low to high charge/bunch)
Normalized longitudinal emittance	$\sim 1$ $\mu$ m outside the MBI regime
Beam energy at the gun exit (to control space charge effects)	$\gtrsim 500$ keV
Beam energy at the injector exit	$\gtrsim 100$ MeV
Accelerating electric field at the cathode (to overcome the space charge limit)	$\gtrsim 10$ - $15$ MV/m
Dark current	Critical for high duty cycle injectors
Bunch length at the cathode (to control space charge effects and for different modes of operation)	from $\sim 100$ fs to tens of ps
Peak current at the injector exit	tens of A
Compatibility with magnetic fields in the cathode and gun regions (for emittance compensation and/or exchange techniques)	
Operational vacuum pressure at the electron gun (compatible with damage-sensitive cathodes)	$10^{-7}$ - $10^{-9}$ Pa ( $\sim 10^{-9}$ - $\sim 10^{-11}$ Torr)
‘Easy and fast’ replacement of cathodes at the electron gun	
High reliability required to operate in a user facility	

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## Injector Sub-Systems:

- Cathode system
- Electron gun
- Focusing system
- Compression system
- Accelerating system
- Diagnostics system
- Low level RF system



# Electron Injectors Sub-Systems

- **Cathodes are obviously a fundamental part of electron sources. The gun performance heavily depends on cathodes**

• **The ideal cathode should allow for high brightness (have a low thermal/intrinsic normalized emittance, low energy spread, high current density) full control of the bunch distribution, and long lifetimes.**

- **In the lower charge regime the ultimate emittance performance of a linac is set by the cathode thermal emittance**
  - **Photo-cathodes** the most used in present injector schemes.
- **Thermionic cathodes** can in some cases, offer low thermal emittances but require complex compression schemes.  
( $\text{CeB}_6$  at SCSS-Spring 8, XFEL-ANL)
  - **In high-repetition rates photo-sources high quantum efficiency photo-cathodes ( $\text{QE} > \sim 1\%$ ) are required to operate with present laser technology.**
- **Other cathodes under study (photo-assisted field emission, needle arrays, photo-thermionic, “photo-dispenser” diamond amplifiers, engineered cathodes, plasmonic, ...)**

- With the progress in electron guns, in many case is now the **cathode thermal or intrinsic emittance**, i.e. the cathode normalized emittance, to define the **ultimate brightness performance of an injector**.

$$\varepsilon_n^i = \sigma_r \frac{\sigma_{pr}}{mc}$$



$$\frac{\varepsilon_n^i}{\sigma_r} = \sqrt{\frac{k_B T}{mc^2}}$$

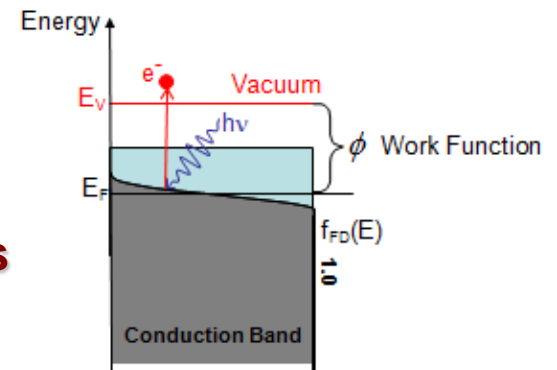
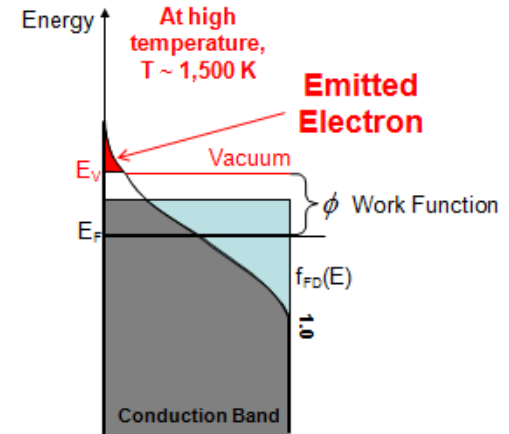
**Thermionic cathodes**



$$\frac{\varepsilon_n^i}{\sigma_r} = \sqrt{\frac{\hbar\omega - (\phi - \phi_{Schottky})}{3mc^2}}$$

$$\phi_{Schottky} [eV] = 3.7947 \times 10^{-5} \sqrt{E_z^{Gun} [V/m]}$$

**Photo-cathodes**



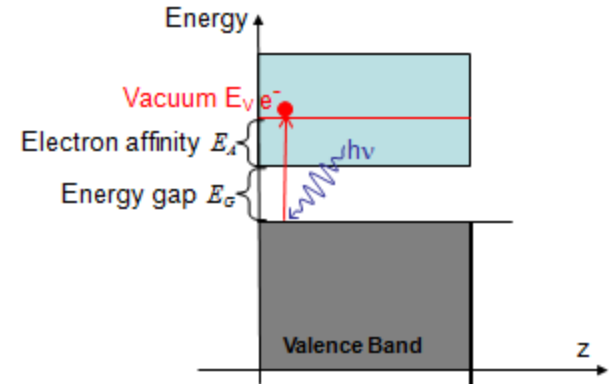
- **For uniform emission:**  $\sigma_r = r/2$

- Two cases can be distinguished:

$$\frac{\varepsilon_n^i}{\sigma_r} = \sqrt{\frac{\hbar\omega - (E_G + E_A - \phi_{Schottky})}{3mc^2}}$$

**Positive electron affinity cathodes**

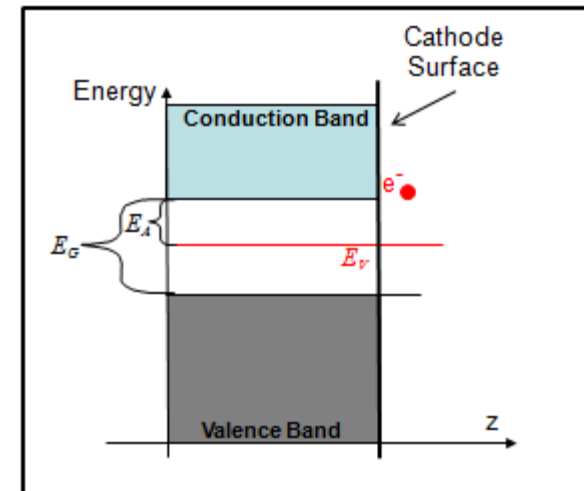
$$\phi_{Schottky} [eV] = 3.7947 \times 10^{-5} \sqrt{E_z^{Gun} [V/m]}$$



$$\frac{\varepsilon_n^i}{\sigma_r} = \sqrt{\frac{k_B T}{mc^2}}$$

**Negative electron affinity cathodes with electron-phonon scattering. (Cesiated GaAs, Hydrogenated diamond)**

**Full thermalization happens only if the energy of the photon is close to the gap energy  $E_G$ . In this regime the response time can be considerably longer.**



- Dowell talk, EuroFEL Workshop Photocathodes for RF guns, Lecce, March 2011 (<http://photocathodes2011.eurofel.eu/>)
- D.Dowell, et al., NIMA 622, 685 (2010)
- Bazarov, et al., Journal of Applied Physics 103, 054901 (2008).



- Maximum **charge density** that can be extracted from a cathode is important when high charge/bunch are required with relatively small emittance:

$$J_{peak} = \frac{Q}{\pi r^2 \sigma_\tau} \sim 5 \times 10^4 \text{ A/cm}^2$$

Typical photocathodes  
(pulsed emission)

$$\langle J \rangle \sim 50 \text{ A/cm}^2$$

Thermionic:  $\text{CeB}_6$ ,  $\text{LaB}_6$   
(continuous emission)

- **Lifetime.**
  - Chemical reactivity,
  - Robustness to ion/electron back-bombardment.

Sets operation vacuum pressure (from  $\sim 10^{-8}$  to  $\sim 10^{-12}$  Torr).

- Surface roughness, crystal domains, homogeneity, reflectivity, field enhancement, ...

**Complex physics, greatly not understood yet!**

- The **Quantum Efficiency QE** is defined as the number of photo-emitted electrons per photon impinging on the cathode.
- The minimum **photon energy or wavelength  $\lambda$**  required for generating photo-emission from the cathode.
- The above parameters jointly with the required electron beam distribution define the characteristics of the laser system to be used for the photo-emission.

Metal Cathodes	Wavelength & Energy: $\lambda_{opt}$ (nm), $h\nu$ (eV)	Quantum Efficiency (electrons per photon)	Vacuum for 1000 Hr Operation (Torr)	Work Function, $\phi_w$ (eV)	Thermal Emittance (microns/mm(rms))	
					Theory	Expt.
Bare Metal						
Cu	250, 4.96	$1.4 \times 10^{-4}$	$10^{-9}$	4.6 [34]	0.5	1.0±0.1 [39] 1.2±0.2 [40] 0.9±0.05 [3]
Mg	266, 4.66	$6.4 \times 10^{-4}$	$10^{-10}$	3.6 [41]	0.8	0.4±0.1 [41]
Pb	250, 4.96	$6.9 \times 10^{-4}$	$10^{-9}$	4.0 [34]	0.8	?
Nb	250, 4.96	$\sim 2 \times 10^{-5}$	$10^{-10}$	4.38 [34]	0.6	?
Coated Metal						
CsBr:Cu	250, 4.96	$7 \times 10^{-3}$	$10^{-9}$	$\sim 2.5$	?	?
CsBr:Nb	250, 4.96	$7 \times 10^{-3}$	$10^{-9}$	$\sim 2.5$	?	?

← METALS

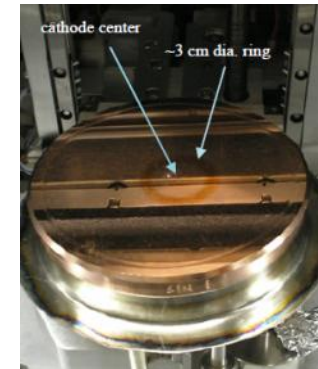
SEMICONDUCTORS

In general, metal cathodes are more robust but present much lower QEs with respect to semiconductor cathodes

Cathode Type	Cathode	Typical Wavelength, $\lambda_{opt}$ (nm), (eV)	Quantum Efficiency (electrons per photon)	Vacuum for 1000 Hrs (Torr)	Gap Energy + Electron Affinity, $E_A + E_C$ (eV)	Thermal Emittance (microns/mm(rms))	
						Theory	Expt.
PEA: Mono-alkali	Cs <sub>2</sub> Te	211, 5.88	$\sim 0.1$	$10^{-9}$	3.5 [42]	1.2	0.5±0.1 [35]
		264, 4.70	-	-	"	0.9	0.7±0.1 [35]
		262, 4.73	-	-	"	0.9	1.2±0.1 [43]
	Cs <sub>3</sub> Sb	432, 2.87	0.15	?	1.6+0.45 [42]	0.7	?
	K <sub>3</sub> Sb	400, 3.10	0.07	?	1.1+1.6 [42]	0.5	?
PEA: Multi-alkali	Na <sub>3</sub> Sb	330, 3.76	0.02	?	1.1+2.44 [42]	0.4	?
	Li <sub>3</sub> Sb	295, 4.20	0.0001	?	?	?	?
	Na <sub>2</sub> K <sub>2</sub> Sb	330, 3.76	0.1	$10^{-10}$	1+1 [42]	1.1	?
	(Cs)Na <sub>3</sub> K <sub>2</sub> Sb	390, 3.18	0.2	$10^{-10}$	1+0.55 [42]	1.5	?
NEA	GaAs(Cs,F)	532, 2.33	$\sim 0.1$	?	1.4±0.1 [42]	0.8	0.44±0.01 [44]
		860, 1.44	-	?	"	0.2	0.22±0.01 [44]
	GaN(Cs)	260, 4.77	-	?	1.96+? [44]	1.35	1.35±0.1 [45]
	GaAs(1-x)Px x~0.45 (Cs,F)	532, 2.33	-	?	1.96+? [44]	0.49	0.44±0.1 [44]
S-1	Ag-O-Cs	900, 1.38	0.01	?	0.7 [42]	0.7	?

## Metal: Cu, ... (used at LCLS for example)

- <~sub-picosecond pulse capability
- minimally reactive; requires  $\sim 10^{-8}$  Torr pressure
- low QE  $\sim 10^{-5}$
- requires UV light (3<sup>rd</sup> or 4<sup>th</sup> harm. conversion from IR)
- for nC, 120 Hz replate,  $\sim 2$  W of IR required



## PEA Semiconductor: Cesium Telluride $Cs_2Te$ (used at FLASH for example)

- <~ps pulse capability
- relatively robust and un-reactive (operates at  $\sim 10^{-9}$  Torr)
- successfully tested in NC RF and SRF guns
- high QE  $> 5\%$
- photo-emits in the UV  $\sim 250$  nm (3<sup>rd</sup> or 4<sup>th</sup> harm. conversion from IR)
- for 1 MHz replate, 1 nC,  $\sim 10$  W 1060nm required

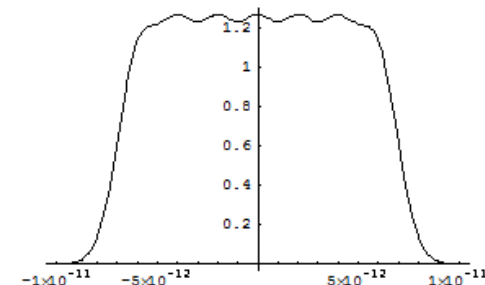


## NEA Semiconductor: Gallium Arsenide $Cs:GaAs$ (used at Jlab for example)

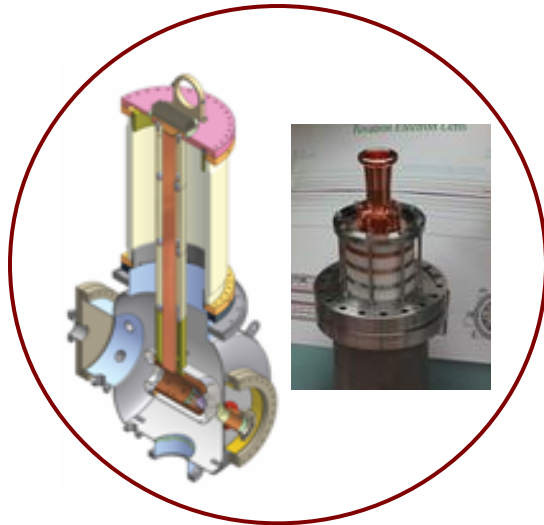
- tens of ps pulse capability with phonon damping
- reactive; requires UHV  $< \sim 10^{-10}$  Torr pressure
- high QE (typ. 10%)
- Photo-emits already in the NIR,
- low temperature source due to phonon scattering
- for nC, 1 MHz,  $\sim 50$  mW of IR required
- operated only in DC guns at the moment
- Allow for polarized electrons



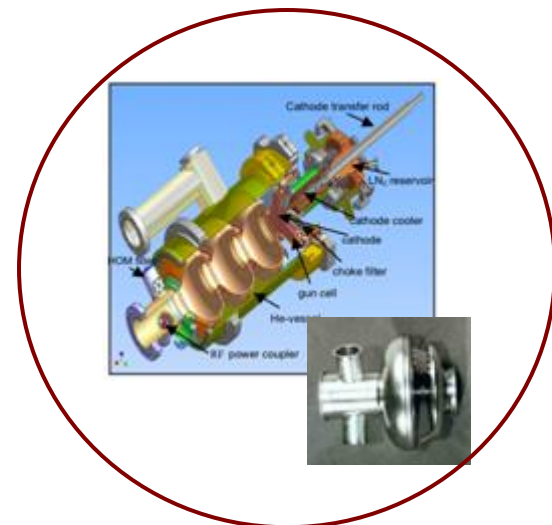
- In the beam dynamics section, we discussed the importance of the **beam distribution in controlling space charge effects**.
- The **3D ellipsoidal distribution with uniform charge density** represents the ideal case where space charge forces are fully linear and do not increase the rms normalized emittance.
- Generate such distribution is quite challenging, and in most cases, the so-called “**beer-can**” with uniform charge density represents a reasonable compromise.
- To generate a **longitudinal rectangular-like distribution** one can start with a **Gaussian short pulse, split it several times and recombine them with the proper delay**.
- The splitting/recombining can be done using conventional beam splitters and delay lines, or using a series of birefringent crystals of proper length.
  - **Top-hat uniform transverse distributions** can be obtained by **expanding a transversely Gaussian beam and collimating it through a sufficiently small circular aperture** (simple but inefficient).
  - **Nonlinear commercial focusing lens systems** can also be used but require **excellent alignment and size matched Gaussian beams**.



**6 Gaussian pulses with  $\sigma_\tau = 1$  ps added with  $2 \sigma_\tau$  peak to peak distance**

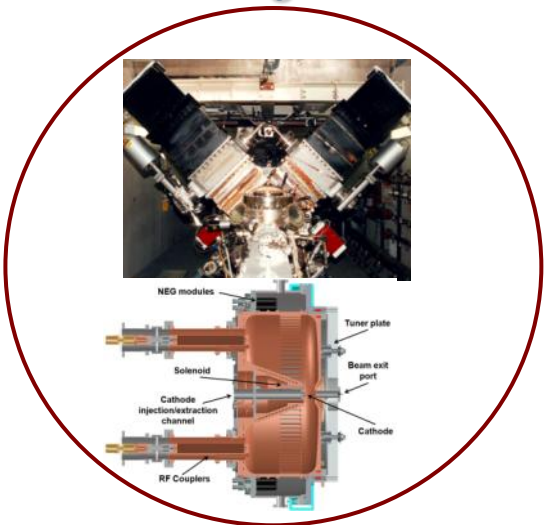


DC guns



SC RF guns

and hybrids



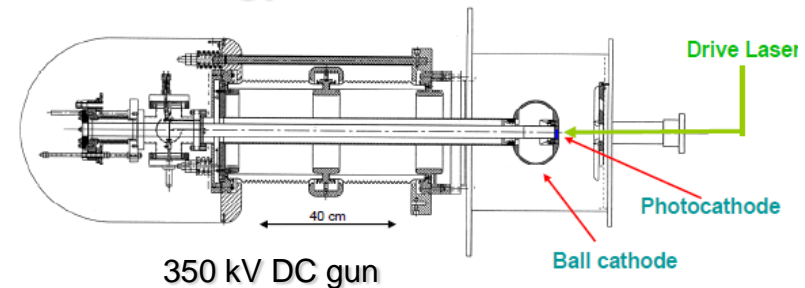
Low freq. (<~ 700 MHz) NC RF guns



High freq.(> ~1 GHz) NC RF guns

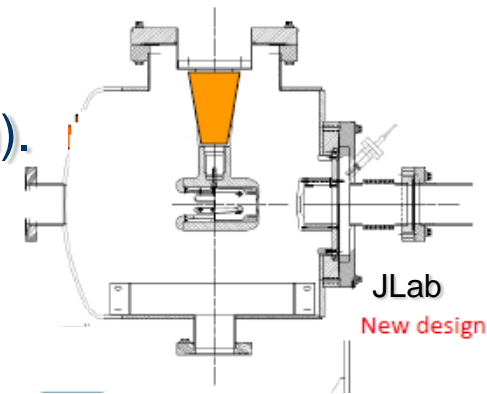
## Pros:

- DC operation
- DC guns reliably operated at 350 kV (JLAB) for many years, ongoing effort to increase the final energy (Cornell, Daresbury, Jlab, ...).
- Extensive simulations (Cornell, ...) “demonstrated” the capability of sub-micron emittances at  $\sim 1$  nC, if a sufficient beam energy is achieved
- Full compatibility with magnetic fields.
- Excellent vacuum performance
- Compatible with most photo-cathodes.  
(The only one operating GaAs cathodes)



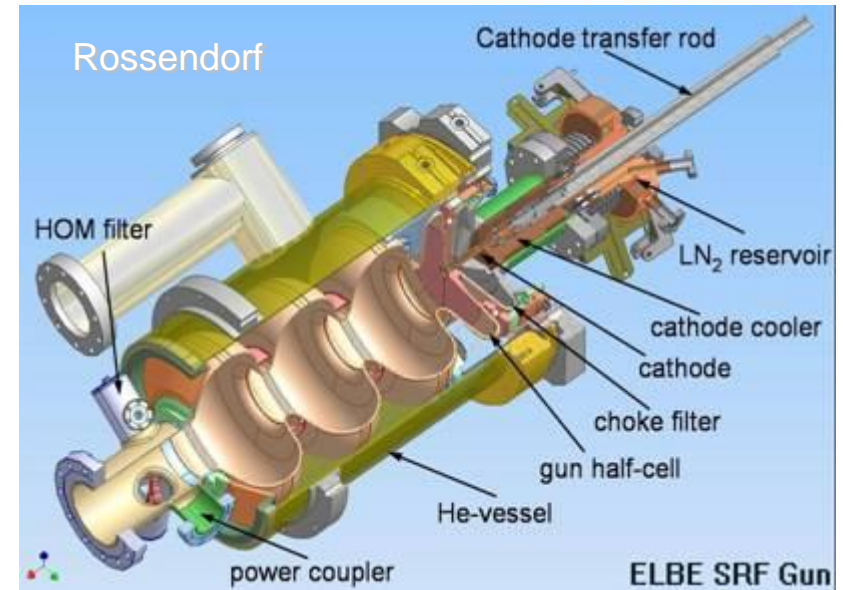
## Challenges:

- Higher energies require further R&D and significant technology improvement (Promising results by JAEA DC Gun).
- In particular, improvement of the high voltage breakdown ceramic design and fabrication.
- Minimizing field emission for higher gradients ( $> \sim 10$  MV/m)
- Developing and test new gun geometries (inverted geometry, SLAC, JLab)  
Very interesting results from a “pulsed” DC gun at Spring-8.



## Pros:

- Potential for relatively high gradients (several tens of MV/m)
- CW operation
- Excellent vacuum performance.



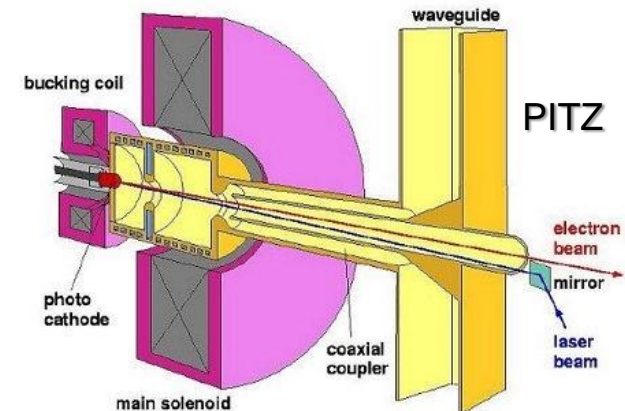
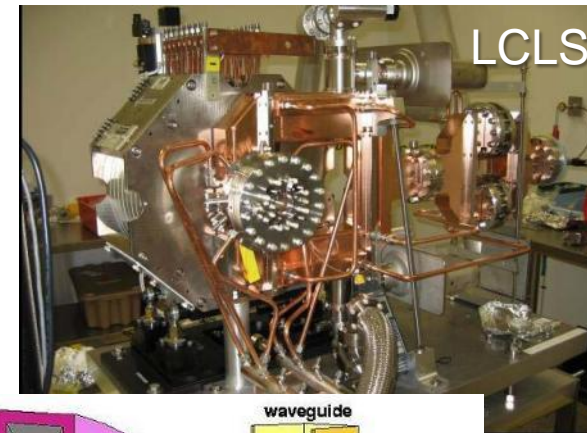
## Challenges:

- Move technology from R&D to mature phase. Significant progresses under way.
- Experimentally verify cathode compatibility issues (Promising results with  $\text{Cs}_2\text{Te}$  at Rossendorf, DC-SRF Peking approach)
- Develop and prove schemes compatible with emittance compensation (“cohabitation” with magnetic fields, HOM schemes, ...).



## Pros:

- High gradients from  $\sim 50$  to  $\sim 140$  MV/m
- “Mature” technology.
- Full compatibility with magnetic fields.
- Compatible with most photocathodes
- Proved high-brightness performance.  
(LCLS and PITZ)

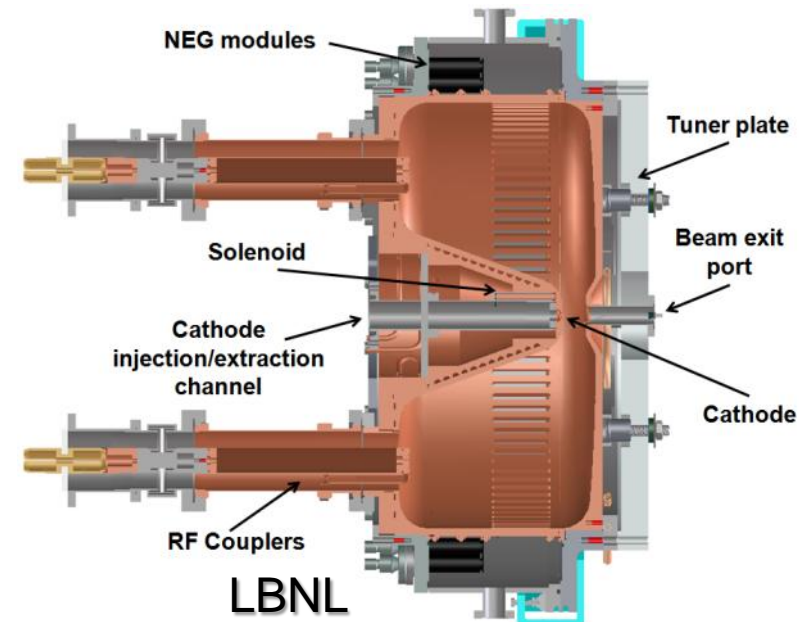


## Challenges:

- High power density on the RF structure ( $\sim 100$  W/cm<sup>2</sup>) limits the achievable repetition rate at high gradient to  $\sim 10$  kHz (LUX).
- Relatively small pumping apertures can limit the vacuum performance.

## Pros:

- Can operate in CW mode
- Beam Dynamics similar to DC but with higher gradients and energies
- Based on mature RF and mechanical technology.
- Full compatibility with magnetic fields.
- Compatible with most photo-cathodes
- Potential for excellent vacuum performance.



## Challenges:

- Gradient and energy increase limited by heat load in the structure
- CW high brightness performance still to be proved
- Vacuum performance still to be proved

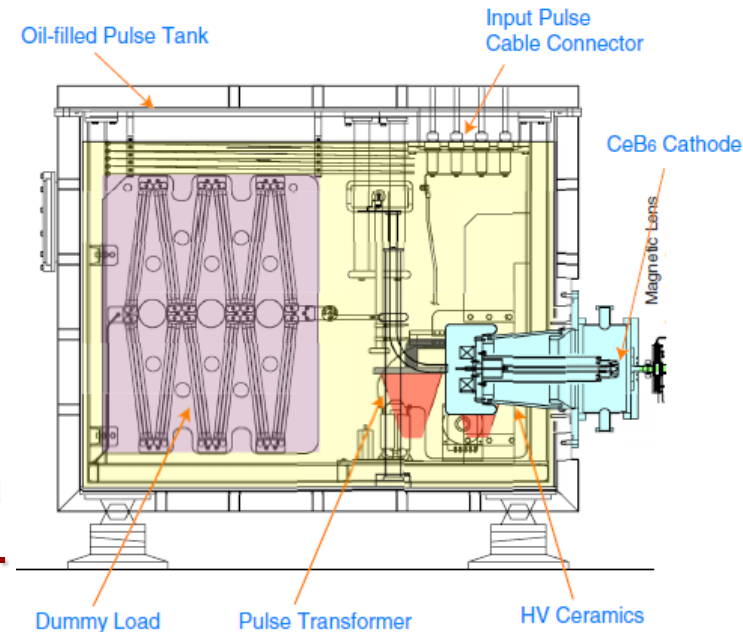
## Pros:

- Based on mature technology.
- The pulsed nature relaxes many of the DC gun issues
- Full compatibility with magnetic fields.
- Compatible with most photocathodes
- Proved high brightness performance with a 3 mm radius  $\text{CeB}_6$  thermionic cathode.

## Challenges:

- Modulator technology limits maximum energy and repetition rate (~500 kV at 60 Hz presently, can it go to kHz?).
- Significant injector system complexity when used with thermionic cathodes ("adiabatic" compression requires chopper and multiple RF frequencies). Not integrated yet with photo-cathodes.

## SCSS 500 kV Electron Gun



## Pros:

- Brings the cathode out of the cryogenic environment
- Allows for a final beam energy higher than in DC guns
- 1.5 cell proof of principle already built. Second generation 3.5 cell under fabrication.

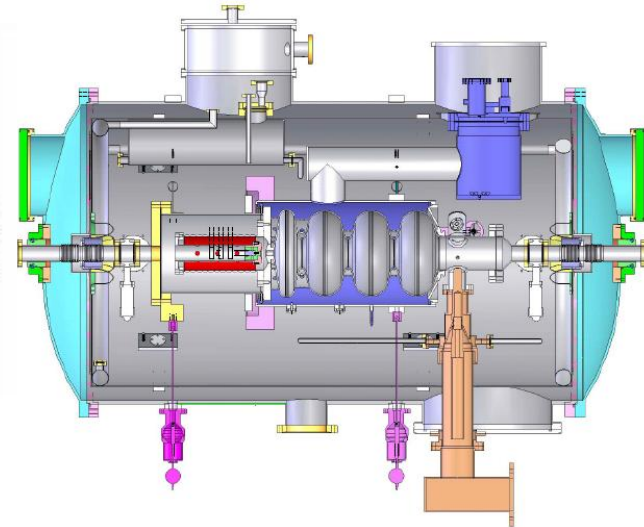
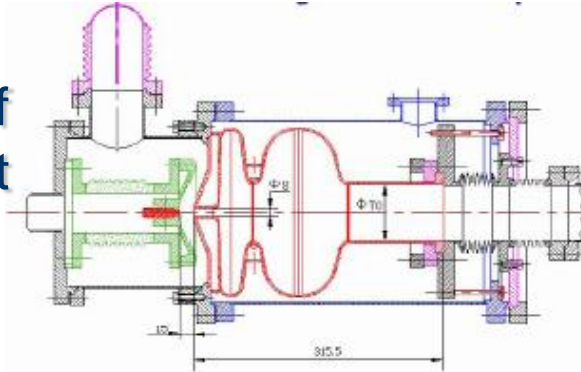
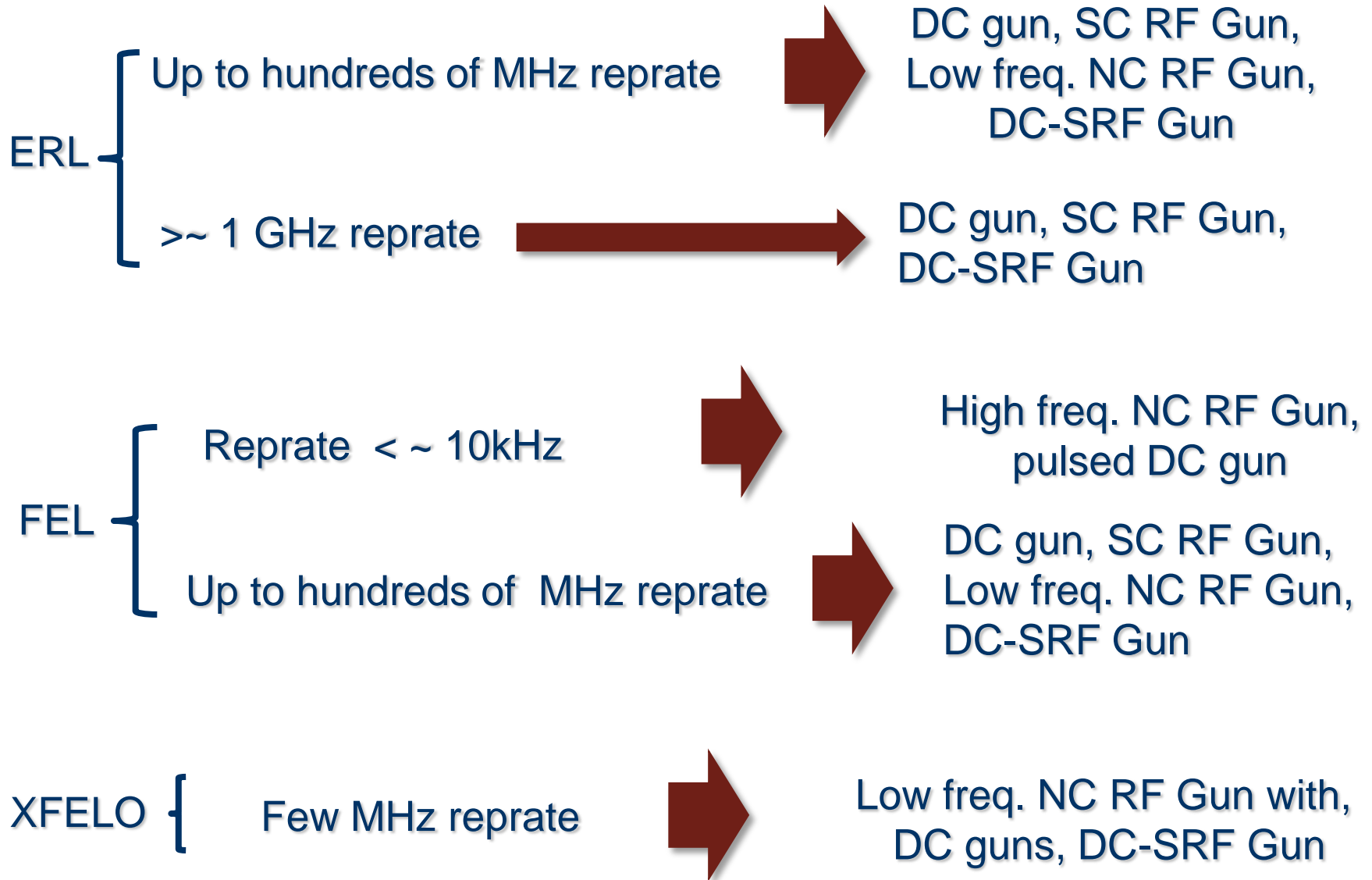


Table 1: Parameters of the new photoinjector

2+1/2-cell cavity	
$E_{acc}$	15 MV/m
Drive laser	
Pulse length	10 ps
Spot radius	2 mm
Repetition rate	81.25 MHz
Electron bunch	
Charge/bunch	<60 pC
Energy	3.72 MeV
Energy spread (rms)	1.68%
Emittance (rms)	2.0 mm-mrad

## Challenges:

- Increased system complexity
- Gradient limitation in the DC part



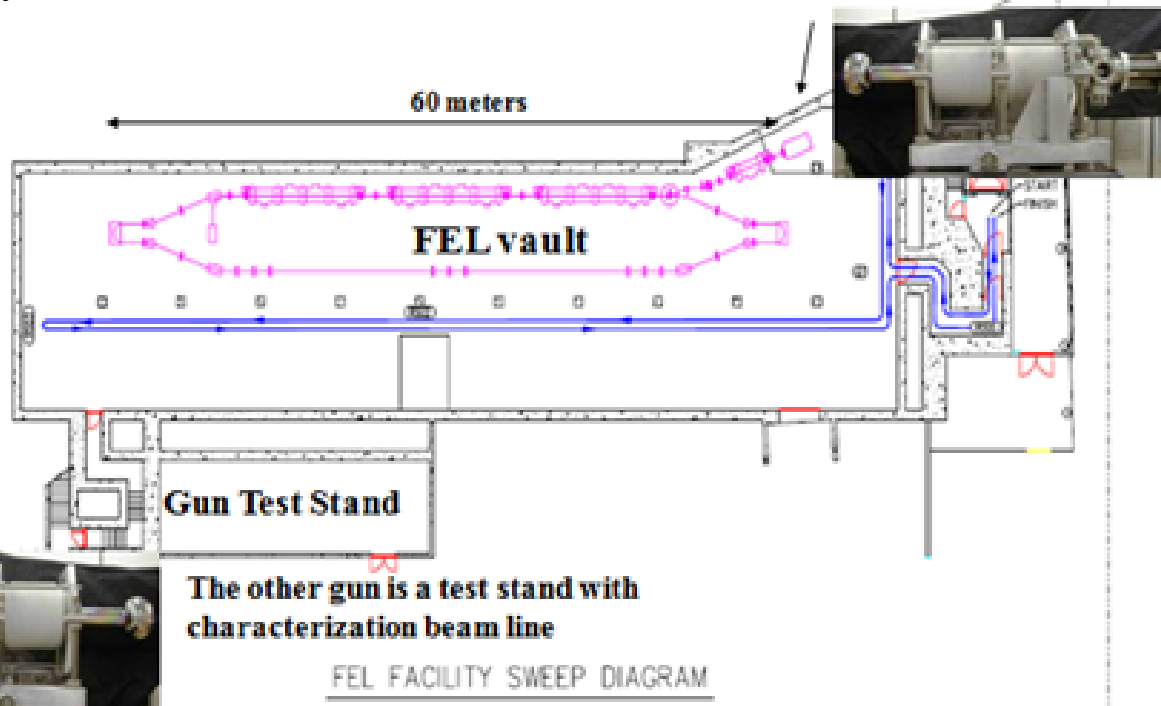
The list of electron gun developments that will be presented hereafter in this lecture is not complete. It only includes examples representative of the different technologies.

- S. Rimjaem, et al., in Proceedings of the 2009 FEL Conference, Liverpool, UK, August 23-28, 2009, p. 251.
- C. Limborg-Deprey, D. Dowell, J. Schmerge, Z. Li, and L. Xiao, RF Design of the LCLS Gun, LCLS TN-05-3, Feb. 2005.
- I. Bazarov, et al., in Proceedings of the 2009 Particle Accelerator Conf. , Vancouver, Canada, May 4-8, 2009, p. 683.
- T. Siggins, et al., Nucl. Instrum. Methods Phys. Res., Sect. A 475, 549 (2001).
- S. V. Benson, et al., in Proceedings of the 2009 FEL Conference, Liverpool, UK, August 23-28, 2009, p. 383.
- Y. M. Saveliev, et al., in Proceedings of the 2008 European Particle Accelerator Conf. Genova, Italy, June 2008, p. 208.
- N. Nishimori, et al., in Proceedings of the 2009 FEL Conference, Liverpool, UK, August 23-28, 2009, p. 277.
- Jiankui Hao, et al., in Proceedings of SRF'09, Berlin, Germany, September 20-25, 2009, p. 205.
- A. Arnold, et al., Nucl. Instrum. Methods Phys. Res., Sect. A 593, 57 (2008).
- I. Ben-Zvi, in Proceedings of Electron Ion Collider Collaboration (EICC), GSI, Darmstadt, Germany, (2009).
- I. Ben-Zvi, et al., in Proceedings of SRF'09, Berlin, Germany, September 20-25, 2009, p. 41.
- A. Fedotov, et al., BNL Collider-Accelerator AP Note: CA/ AP/307, 2008.
- T. Kamps, et al., in Proceedings of SRF'09, Berlin, Germany, September 20-25, 2009, p. 164.
- J.W. Lewellen, et al., in Proceedings of the 2008 FEL Conference, Gyeongju, Korea, August 24-29, 2008, p. 394.
- R. Legg, et al., in Proceedings of the 2008 European Particle Accelerator Conf., Genova, Italy, June 23, 2008, p. 469.
- D.C.Nguyen, et al., Nucl. Instrum. Methods Phys. Res., Sect. A 528, 71 (2004).
- J.Staples, F.Sannibale, S.Virostek, VHF-band photoinjector ,CBP Tech Note 366, 2006.
- K.Baptiste, et al., Nucl. Instrum. Methods Phys. Res., Sect. A 599, 9 (2009).
- F. Sannibale, et al., Status of the LBNL normal-conducting CW VHF electron photo-gun, in Proceedings of the 2010 FEL Conference, Malmo, Sweden, August 23-27, 2010.
- P. N. Ostroumov, et al., in Proceedings of the 2009 Particle Accelerator Conf., Vancouver, Canada, May 4, 2009, p. 461.
- A. Arnold and J. Teichert , "Overview on superconducting photoinjectors", Phys. Rev. ST Accel. Beams – February 2011 Volume 14, Issue 2
- M. Ferrario and T. Shintake , "High Performance Electron Injectors", Reviews of Accelerator Science and Technology (RAST), Volume: 3, Issue: 1 (2010).



Courtesy of C. Hernandez-Garcia

One gun powers the FEL injector.



The other gun is a test stand with characterization beam line

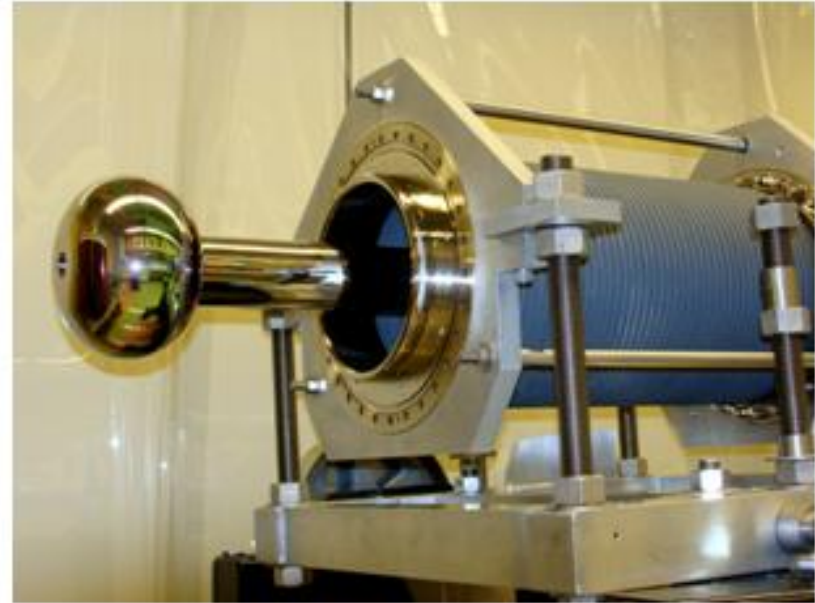
Between 2004 and 2007, operating at **350 kV**, the **FEL** gun delivered over **7000 Coulombs** and over **900 hours** of beam time at **1-8.5 mA CW** with a **single GaAs wafer**, which was activated into a photocathode a total of **9** times with an average of **6** re-cessiations per activation

Since Nov 2008, the FEL is operating a new photocathode at **325 kV** (field emission limited) and close to **625 C** and up to **4 mA CW** has been already delivered



**The Gun Test Stand gun was conditioned up to 485kV DC and demonstrated 1 nC beam at 375 kV in April 2008**

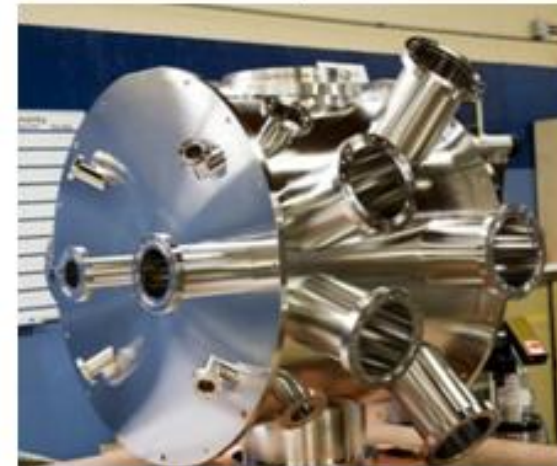
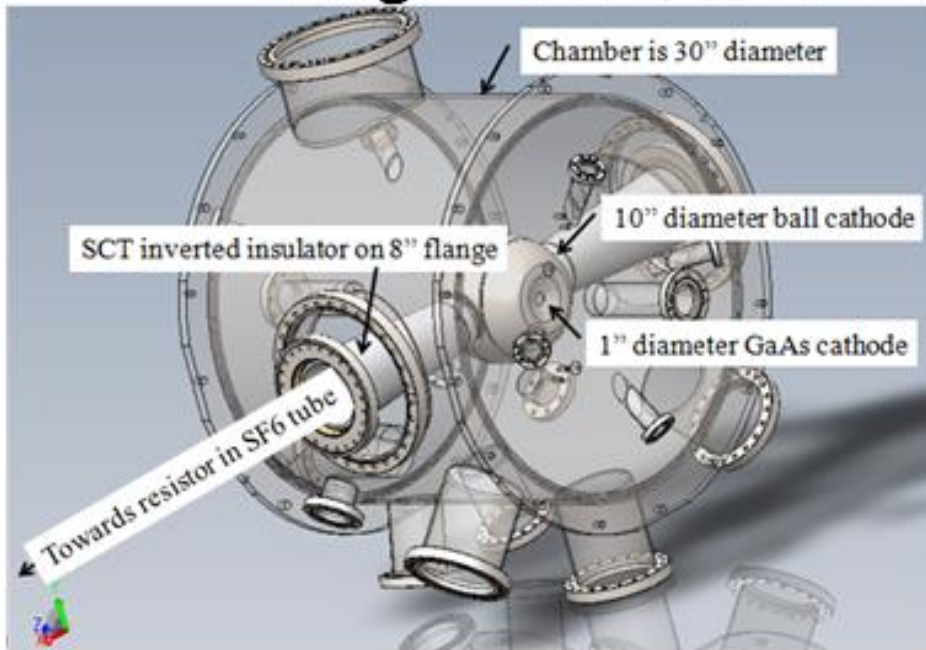
Jefferson Lab



**The GTS gun has been rebuilt with bulk resistivity insulator and is ready for installation**



The Jlab FEL is also developing a new gun using the inverted insulator concept



Vacuum chamber ready for delivery

Cut-out of inverted insulator cathode design



Cut-out of ball cathode design



Courtesy of C. Hernandez-Garcia



- Present operation limited to  $\sim 250\text{kV}$  to limit field emission and minimize probability of field punctuation of the ceramic (750kV initial design).



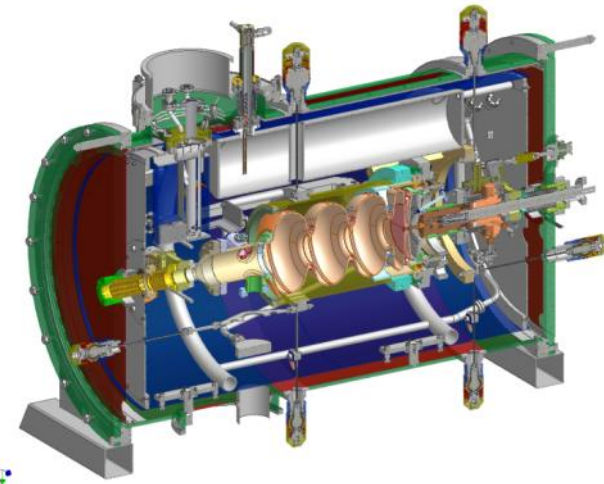
Courtesy of I. Bazarov

A new ceramic with **bulk resistivity** is being installed. Same ceramic material was used in Daresbury to get to over  $\sim 450\text{kV}$ .

The present gun was in beam operation for a number of years allowing for a rich experimental program. For ensuring continuity of such program, the present and funded plan is to build a **second DC gun ( $\sim 500\text{kV}$ ) as an R&D effort** separated from the beam running.


 Cs<sub>2</sub>Te cathodes at 77 K, cavity at 2K,  
 QE ~ 10<sup>-3</sup> (poor vacuum transfer chamber)
 

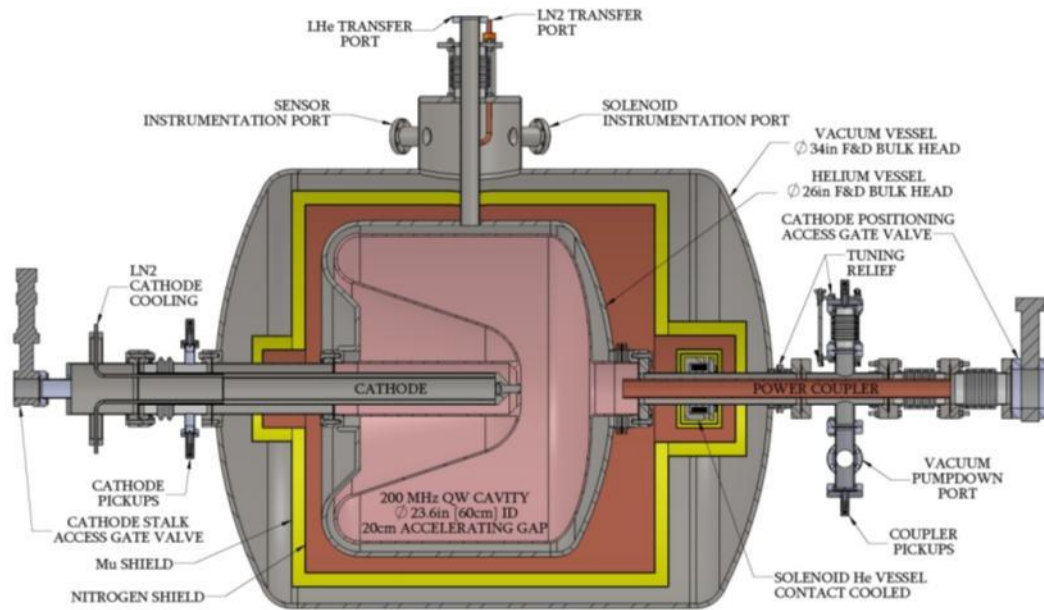
Gradient limited  
by damaged cavity



1.3 GHz TESLA-like  
cells.

J. Teichert et al., FEL08, Gyeongju, Korea p.467

parameter	present cavity			new "high gradient cavity"	
	measured '08	ELBE	high charge	ELBE	high charge
final electron energy	2.1 MeV	3 MeV		≤9.5 MeV	
peak field	13.5 MV/m	18 MV/m		50 MV/m	
laser rep. rate	1 – 125 kHz	13 MHz	2 – 250 kHz	13 MHz	≤500 kHz
laser pulse length (FWHM)	15 ps	4 ps	15 ps	4 ps	15 ps
laser spot size	2.7 mm	5.2 mm	5.2 mm	2 mm	5 mm
bunch charge	≤ 200 pC	77 pC	400 pC	77 pC	1 nC
max. aver. Current	1 μA	1 mA	100 μA	1 mA	0.5 mA
peak current	13 A	20 A	26 A	20 A	67 A
transverse. norm. emittance (rms)	3±1 mm mrad @ 80 pC	2 mm mrad	7.5 mm mrad	1 mm mrad	2.5 mm mrad



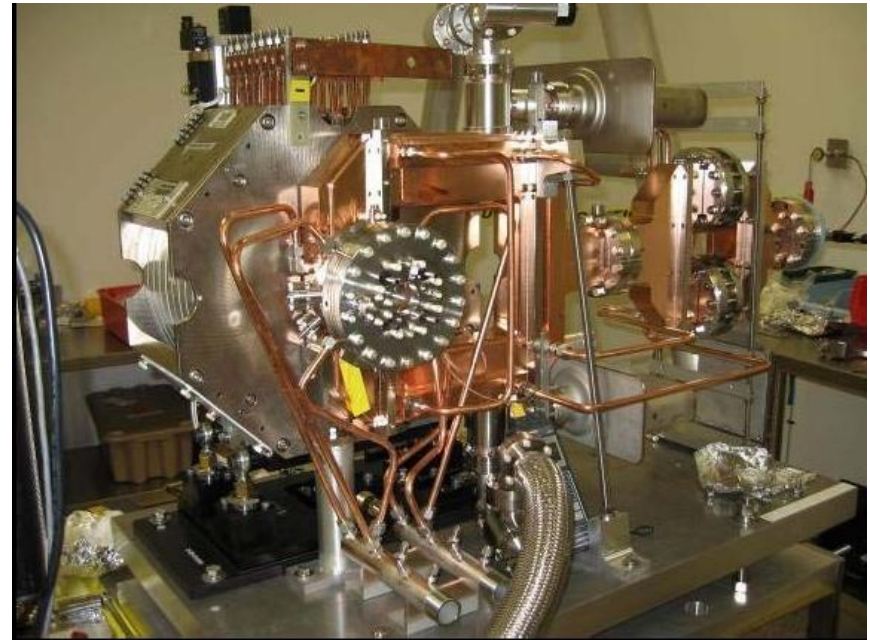
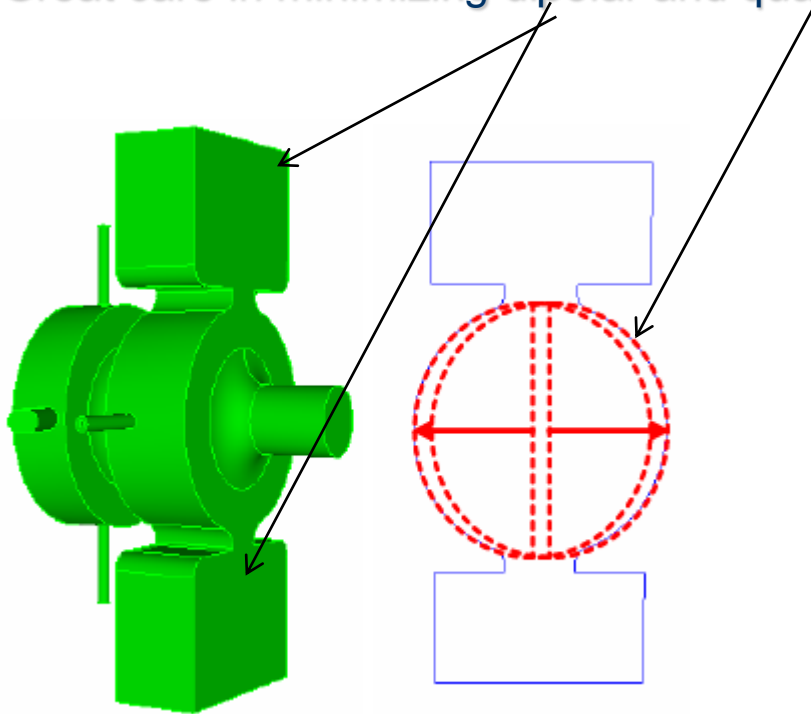
The WIFEL accelerator is required to supply each of the six FEL end stations simultaneously at up to a 1 MHz repetition

- Cs<sub>2</sub>Te cathode, beam blow up regime
- 30 fs ~0.9 mm hemispherical transverse profile, 37 MV/m at cathode, 200 MHz SRF cavity, 5MeV final energy

Pulse frequency, MHz	10
Charge per bunch, pC	200
Average current, mA	<2
I <sub>peak</sub> at first bunch compressor, Amps	50
Peak field in gun, MV/m	41
σ <sub>x</sub> at 100 MeV, mm	0.34
σ <sub>z</sub> at 100 MeV, mm	0.34
Transverse ε at 100 MeV, mm-mrad	0.9
Longitudinal ε at 100 MeV, keV-mm	2.2

Courtesy of Robert Legg

Derived by the BNL-SLAC-UCLA design (S-Band).  
Great care in minimizing dipolar and quadrupolar field components.

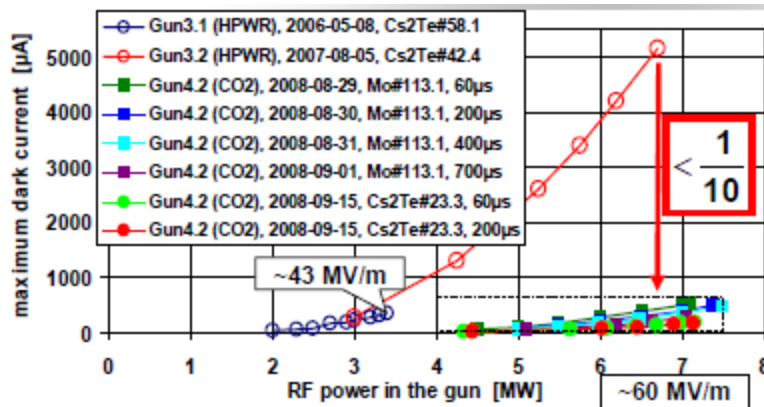
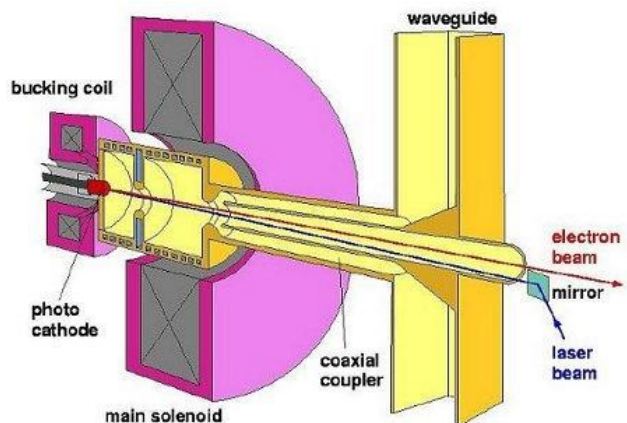


In operation

Up to date best performance



0.5 microns emittance at 250 pC  
0.14 microns emittance at 20 pC

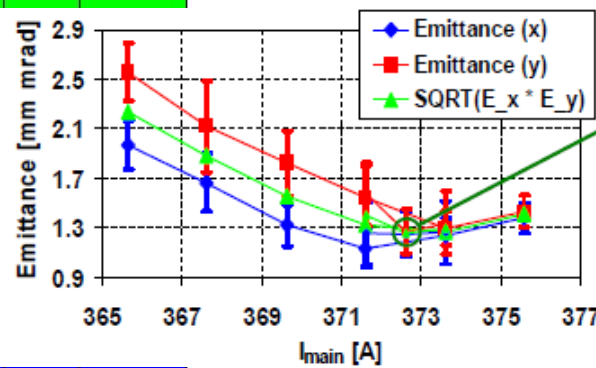
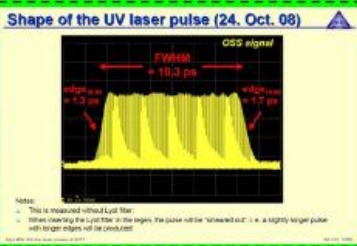


Surface cleaning techniques:

- HPWR: high-pressure water rinsing
- CO2: dry-ice cleaning, for details

**Major reduction of dark current by CO2 snow cleaning**

	Rep. rate	Pulse train length	Individual pulse	Aver. current [mA]	
				in train	long term
achieved at PITZ	10Hz	200µs, 1MHz (700µs, 1MHz)	FWHM=18..19ps, rt<2ps, 1nC FWHM=18..19ps, rt<2ps, 1nC	1	0.002 (0.007)
XFEL: to be achieved in 3 Years	10Hz	650µs, 5MHz	FWHM=20ps, rt<2ps		
possible in principle	10Hz	1300µs, 5MHz	(?)FWHM=20ps, rt<2ps(?), 1nC	5	0.065
	50Hz	1300µs, 1300MHz	No pulse shaping, 77pC	100	6.5



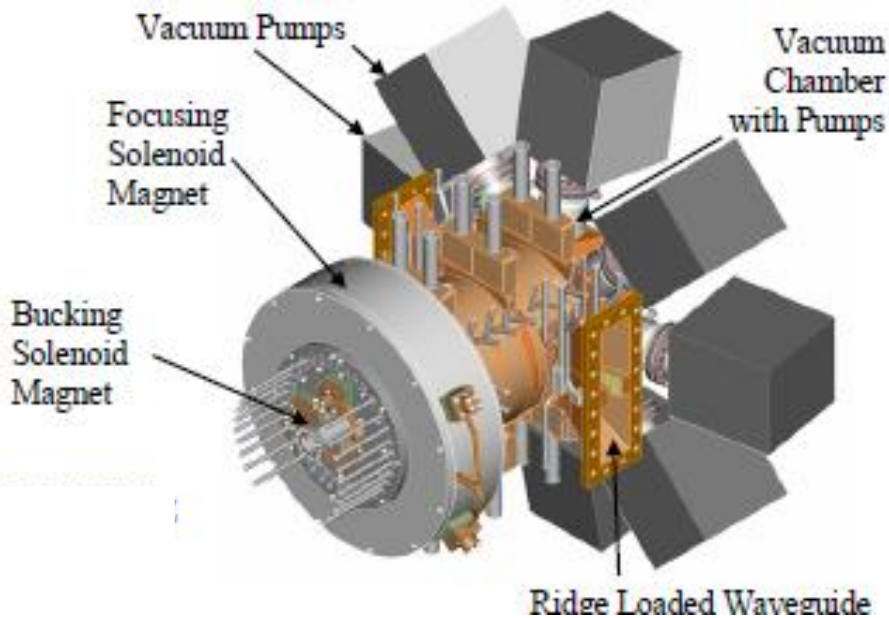
→ for ~60 MV/m we obtained  
 $\epsilon_{x,n} = 1.25 \pm 0.19$  mm mrad  
 $\epsilon_{y,n} = 1.27 \pm 0.18$  mm mrad @1nC  
 for 100 % RMS emittance !  
 → in good agreement with prediction from ASTRA

x-x' phase space:

In operation

Courtesy of Frank Stephan

1.3 GHz Copper



700 MHz CW normal-conducting gun.

Hundreds of kW dissipated in the glidcop structure.

Part of a 100 mA injector for ~ 100kW IR FEL

RF conditioning successfully completed.

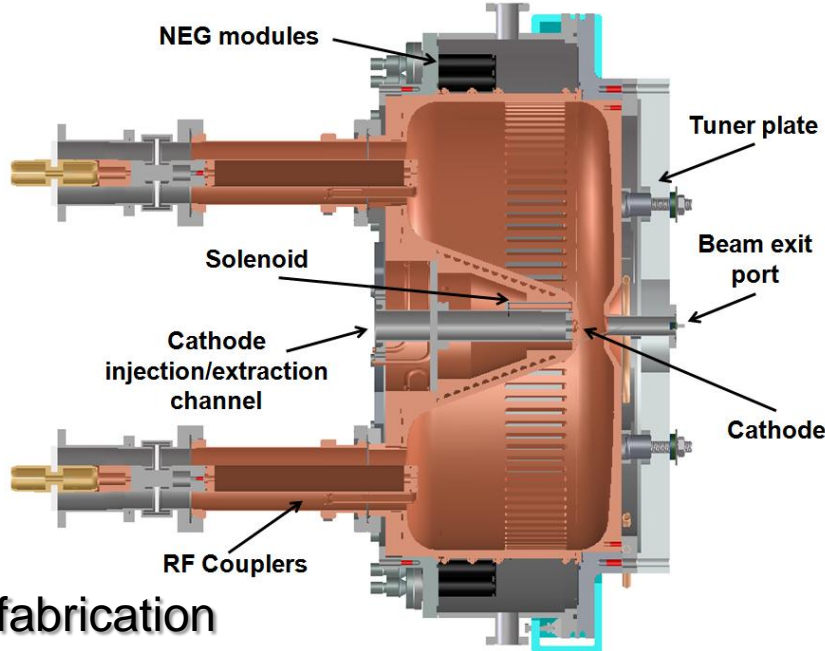
First beam tests soon

Frequency	700	MHz
Energy	2.54	MeV
Current @ 33.3 MHz*	100	mA
Bunch Charge*	3	nC
Transverse Emittance	6	mm-mrad rms normalized
Longitudinal Emittance	145	keV-psec rms
Energy Spread	0.5	%
Bunch Length		psec rms

Courtesy of D. Nguyen and B. Carsten



The Berkeley **normal-conducting** scheme satisfies all the LBNL FEL requirements simultaneously.



In fabrication

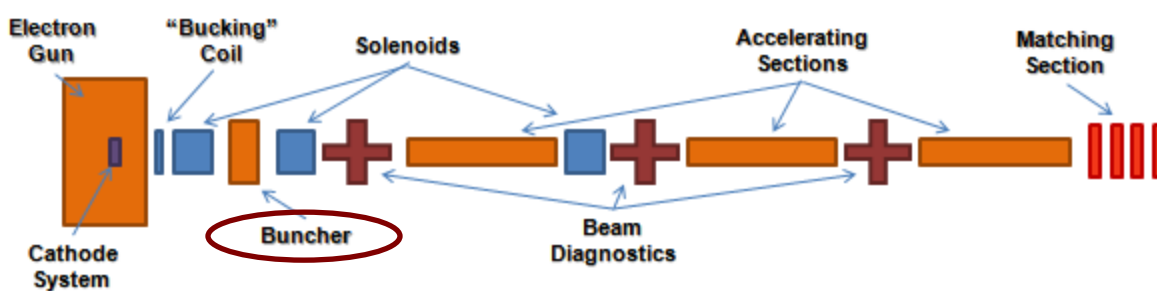
J. Staples, F. Sannibale, S. Virostek, CBP Tech Note 366, Oct. 2006

K. Baptiste, et al, NIM A 599, 9 (2009)

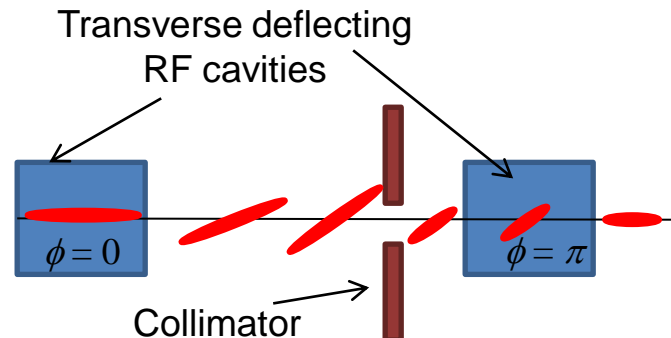
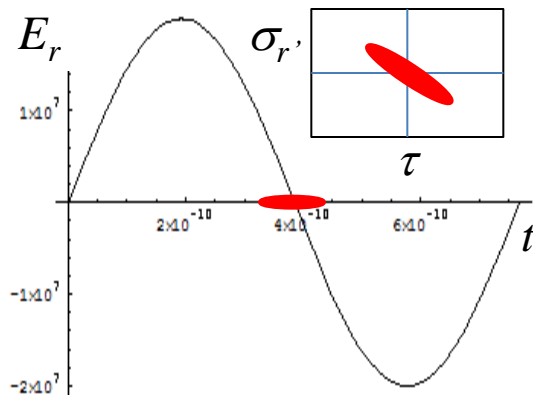
<b>Frequency</b>	<b>187 MHz</b>
<b>Operation mode</b>	<b>CW</b>
<b>Gap voltage</b>	<b>750 kV</b>
<b>Field at the cathode</b>	<b>19.47 MV/m</b>
<b>Q<sub>0</sub></b>	<b>30887</b>
<b>Shunt impedance</b>	<b>6.5 MΩ</b>
<b>RF Power</b>	<b>87.5 kW</b>
<b>Stored energy</b>	<b>2.3 J</b>
<b>Peak surface field</b>	<b>24.1 MV/m</b>
<b>Peak wall power density</b>	<b>25.0 W/cm<sup>2</sup></b>
<b>Accelerating gap</b>	<b>4 cm</b>
<b>Diameter</b>	<b>69.4 cm</b>
<b>Total length</b>	<b>35.0 cm</b>

- At the **VHF frequency**, the cavity structure is large enough to withstand the heat load and **operate in CW mode** at the required gradients.
  - Also, the **long  $\lambda_{RF}$**  allows for large apertures and thus for **high vacuum conductivity**.
  - Based on **mature and reliable normal-conducting RF and mechanical technologies**.
  - 187 MHz compatible with both 1.3 and 1.5 GHz super-conducting linac technologies.

- The systems that allow to compress or define the bunch length in the injector are: **bunchers**, **choppers** and **“dephased” accelerating sections**.
- The operation principle of **bunchers** has been already explained in Lecture 1. Bunchers are used when the **beam** out of the gun is **not extremely relativistic**. Single or multi-cell, typically standing wave, cavities are used. The frequency is often a sub-harmonic of the linac main frequency, for increasing the linearity of the bunching process. Depending on the field intensity NC-RF or SC-RF is used.

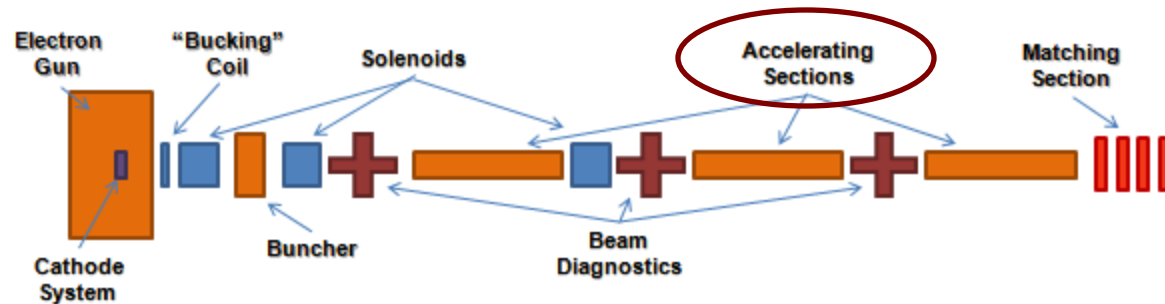


- **Velocity bunching** has been also discussed in Lecture 1, and will be briefly readdressed in the next slide.



- An **RF chopper** system is used for example for reducing a continuous beam to a pulsed one.

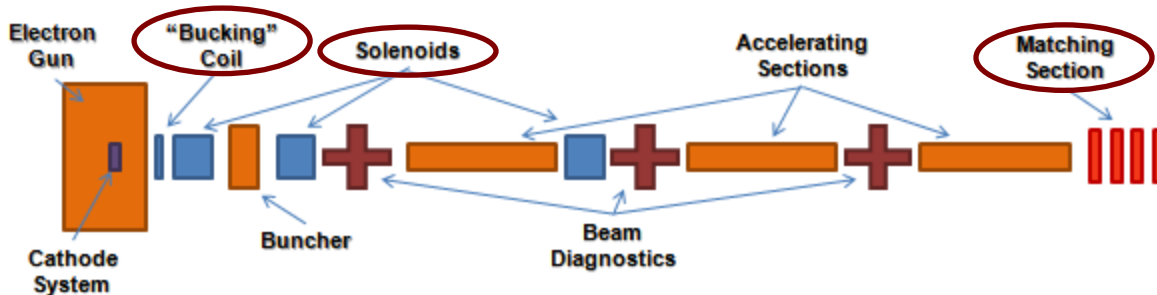
- The main task of the injector **accelerating system** (the first section of which is often referred as the “**RF Booster**”) is to take the beam from the gun at the optimum of the emittance compensation process and to “quickly” accelerate it and “freeze” the compensated emittance.



- We already discussed that the RF booster be also used for **velocity bunching** by dephasing the RF with respect to the beam.

- The booster sections can be of **standing or travelling wave** type.
- The frequency can be a sub-multiple of the main linac RF for improving linearity during injector compression.
  - The repetition rate defines the technology for the booster:
    - Normal-conducting** pulsed systems for **repetition rate**  $< \sim 1$  kHz
    - Super-Conducting** Pulsed (train of bunches) and CW systems otherwise.
- **Accelerating gradients** are in the range of 10 – 40 MV/m for NC RF sections. Higher gradients correspond to higher frequencies ( $\sim 500$  MHz to  $\sim 5$  GHz).
- For SRF the gradients range from  $\sim 10$  to  $\sim 20$  MV/m from frequencies going from  $\sim 500$  MHz to  $\sim 1.5$  GHz).

- The **“Bucking” coil** is used for cancelling undesired solenoidal fields on the cathode that would dilute emittance, or to couple the horizontal and vertical planes in flat-beam or emittance-exchange schemes.

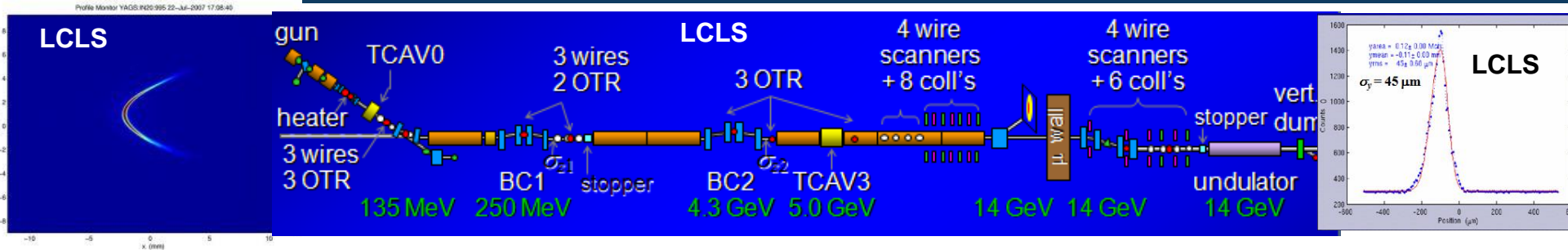


- **Steering coils** distributed along the injector allow to align the beam respect to the component centers.

- The **solenoid(s)** performs the emittance compensation and controls the beam size along the injector. In some cases the solenoids wrap around the accelerating sections.

- **Correcting coils inside solenoids** showed a **dramatic effect** on the LCLS injector **emittance performance**. Steering coils and quadrupole correcting coils compensate for solenoidal field imperfections.

- At energies where space charge is negligible, it becomes cost effective to switch from the solenoid to a **quadrupole** based focusing system.



**Beam Diagnostics is fundamental and necessary for the proper tuning and performance optimization of the injector.**

There are a large number of such a systems, including:

- Current and charge monitors.
- Transverse and longitudinal bunch distribution diagnostics.
- Energy and energy spread monitors
- Transverse and longitudinal phase-space diagnostics.
- Beam position monitoring
- Low Level RF System (lock and control different RFs and laser)
- Cathode and laser diagnostics.

The description of such systems would require much more time and is beyond the scope of this lectures

# Challenges and Required R&D

- Pursue development of various electron source schemes

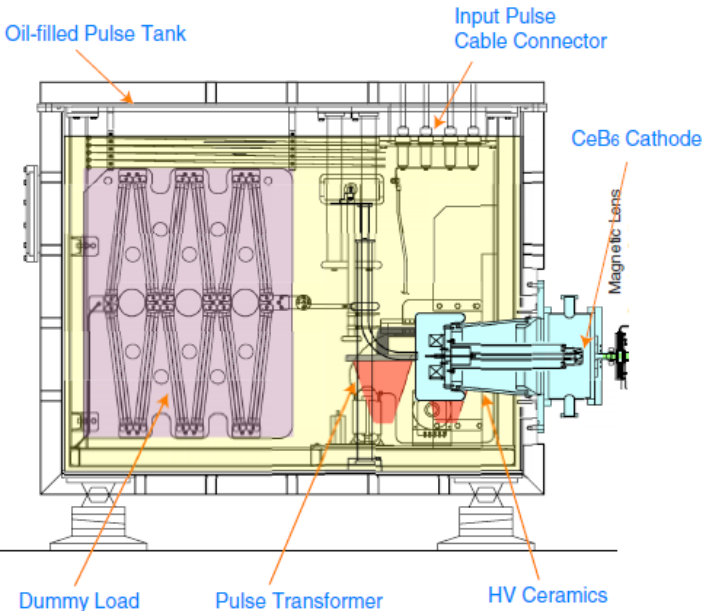
- The performance of an electron source is never fully characterized and demonstrated until the source is integrated in an injector



- Important to built R&D injector facilities that allow testing and optimization of:
  - Emittance compensation and beam manipulation techniques, emittance exchange, velocity bunching, ...
- Cathodes. Physics understanding, cathode test facilities capable of accepting all kind of cathodes, vacuum performance, load-lock, ....
  - Beam diagnostics (especially when considering high repetition rate very low charge and very short bunches)

# Additional Viewgraphs





- 0.6  $\mu\text{m}$  sliced norm. emittance, at  $\sim 0.3$  nC
- $\sim 300$  X compression factor at the injector exit,
- 2  $\mu\text{s}$ , 1 A at the gun,
- 500 kV, 5 cm gap,  $\sim 10$  MV/m
- 60 Hz replate

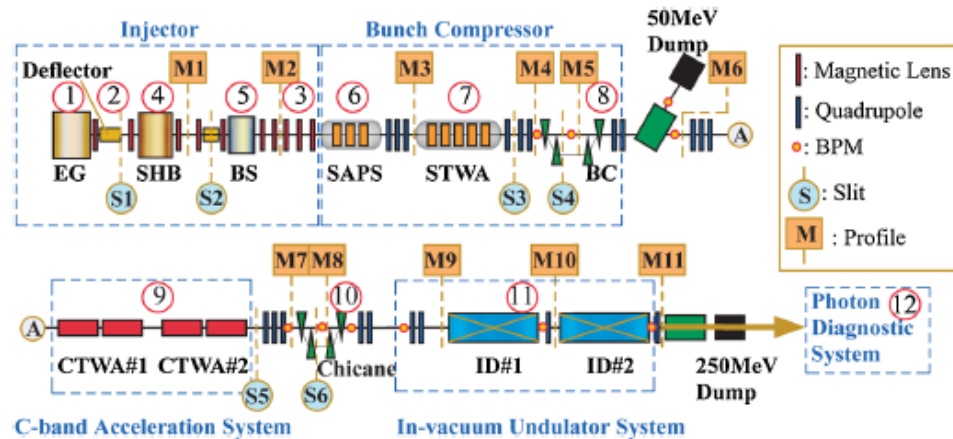
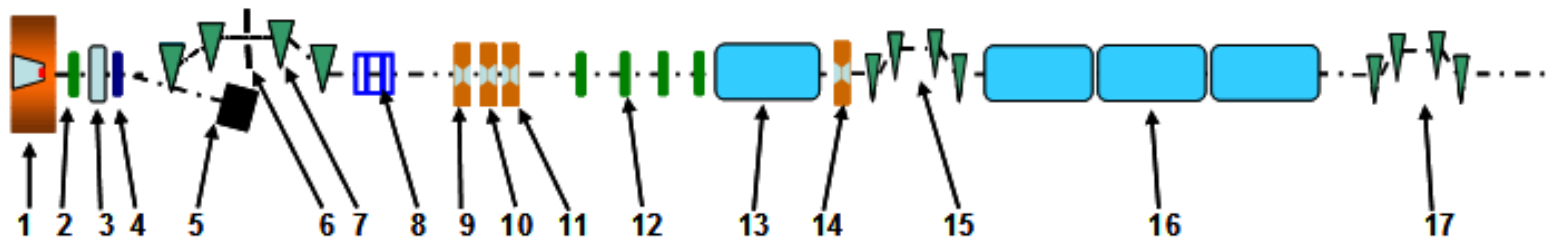


FIG. 1. (Color) Schematic representation of the SCSS test accelerator. 1, 500-kV electron gun (EG); 2, deflector with collimator; 3, a set of ten magnetic lenses; 4, 238-MHz subhamonic buncher (SHB); 5, 476-MHz booster cavity (BS); 6, S-band APS cavity (SAPS); 7, S-band traveling-wave acceleration structure (STWA); 8, bunch compressor (BC); 9, C-band acceleration system (CTWA#1&CTWA#2); 10, chicane; 11, in-vacuum undulator system (ID#1&ID#2); and 12, photon diagnostic system.

## A Novel Injector Concept for XFEL

- Current paradigm of injector design: laser driven rf **photo**cathode
- For low intensity & ultra-low emittance → **thermionic** cathode inside VHF band cavity
- Inspired by the SCSS/Spring-8 success of pulsed DC gun (T. Shintake, K. Togawa,..) but employ low frequency RF cavity for high, constant rep rate
- Performance
  - Normalized rms emittance < 0.2 (**0.3**) mm-mr
  - Bunch length (rms)  $\approx 1$  (**0.1 ps**)
  - Peak current 20 (**100**) A
  - A constant bunch rep rate @  $\sim 1$  MHz

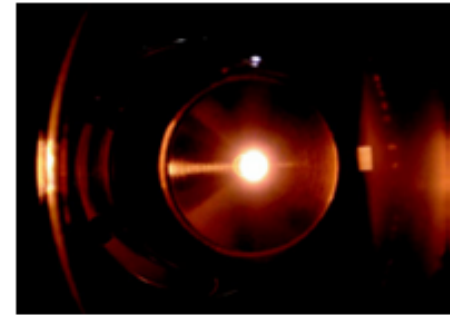
Courtesy of Kwang-Je Kim



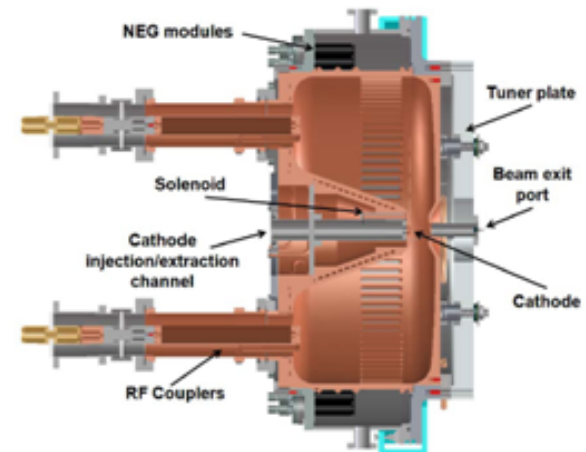
## Critical R&D Items being pursued at Argonne

- Small diameter CeB6 thermionic cathode
  - $\approx 1$  mm (3 mm for RIKEN/SPring-8)
- 100 MHz, 1 MV RF cavity
  - Peak accelerating field=20 MV/m is slightly below 1.8×Kilpatrick limit (1.76)
  - Similar to LBNL 187 MHz cavity but without vacuum holes
- Back bombardment issue
  - Laser-induced cathode-heating
  - Off-centered cathode or magnetic field

Courtesy of Kwan-Je Kim



RIKEN/Spring-8 cathode



LBNL 187 MHz cavity  
Courtesy: F. Sannibale