ELECTRON SOURCES AND INJECTORS

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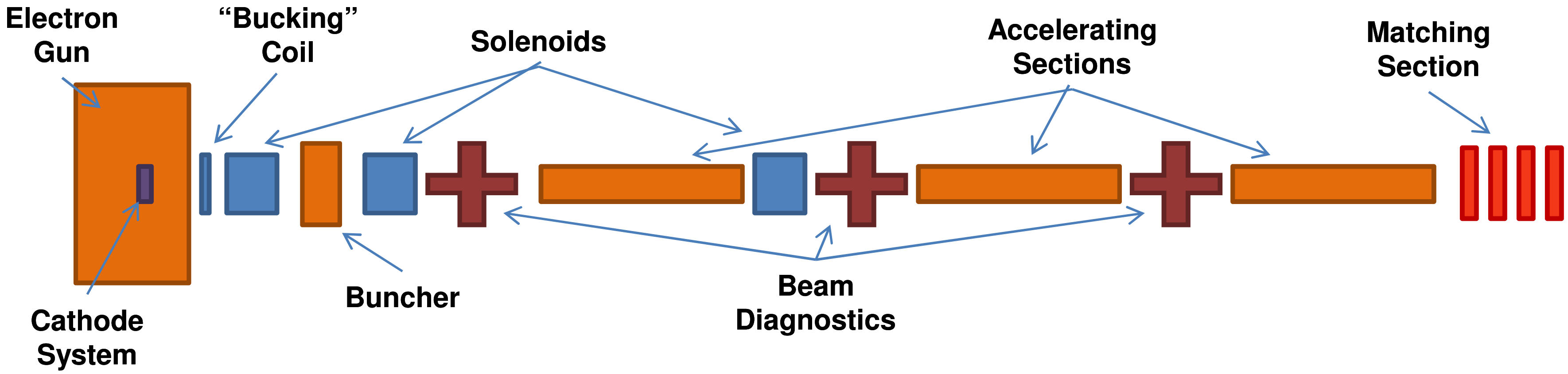
Lecture 1:
- The role of electron sources and injectors in light source
- Requirements for electron sources and injectors
- Injector beam dynamics

Lecture 2:
- Injector components
  - Cathodes systems
  - Electron guns
  - Compression systems
  - Focusing systems
  - Accelerating systems
  - Diagnostics systems
- Challenges and required R&D

Injector Requirement Summary Table

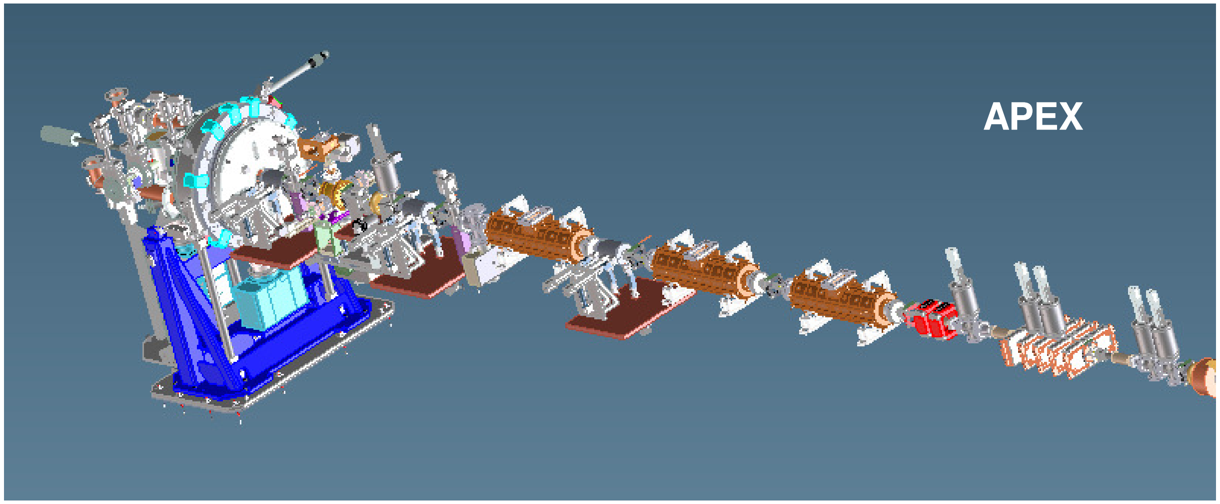
Repetition rate	from ~ 10 Hz to ~ 1 MHz (FELs) up to ~ 1GHz and beyond (ERLs)	up to several 100s mA average current (ERLs)
Charge per bunch (depending on the operation mode)	from $\sim$ 1 pC to $\sim$ 1 nC	
Normalized transverse emittance (slice)	sub 10^{-7} m to 10^{-6} m (from low to high charge/bunch)	
Normalized longitudinal emittance	~ several μm at low charge 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	minimization is 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 in FEL's injectors	
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 an user facility		

The Typical High-Brightness Injector Layout



Injector Sub-Systems:

- Cathode system
- Electron gun
- Focusing system
- Compression system
- Accelerating system
- Diagnostics system



Electron Injectors Sub-Systems

Cathodes

- 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.
(CeB$_6$ at SCSS-Spring 8, XFELO-ANL)

- In high-repetition rates photo-sources high quantum efficiency photo-cathodes (QE>~ 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, …)

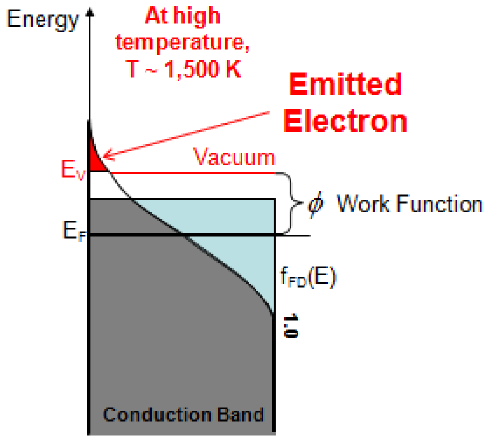
Cathode Parameters: Thermal/Intrinsic Emittance (Metals)

- 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.**

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

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

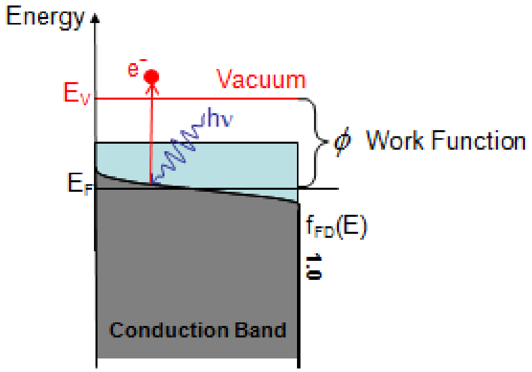
Thermionic cathodes



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

$$\phi_{Schottky\ [eV]} = 3.7947\times10^{-5}\sqrt{E_{z\ [V/m]}^{Gun}}$$

Photo-cathodes



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

- Dowell talk, EuroFEL Workshop Photocathodes for RF guns, Lecce, March 2011 (http://photocathodes2011.eurofel.eu/)
- D.Dowell, et al., NIMA 622, 685 (2010)

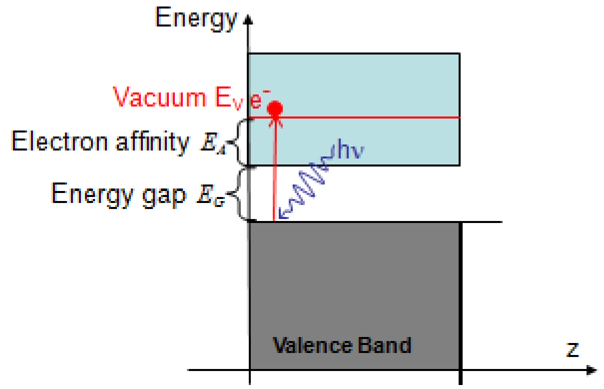
Cathode Parameters
Thermal/Intrinsic Emittance (Semiconductors)

- **Two cases can be distinguished:**

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

$$\phi_{Schottky\ [eV]} = 3.7947\times10^{-5}\sqrt{E_{z\ [V/m]}^{Gun}}$$

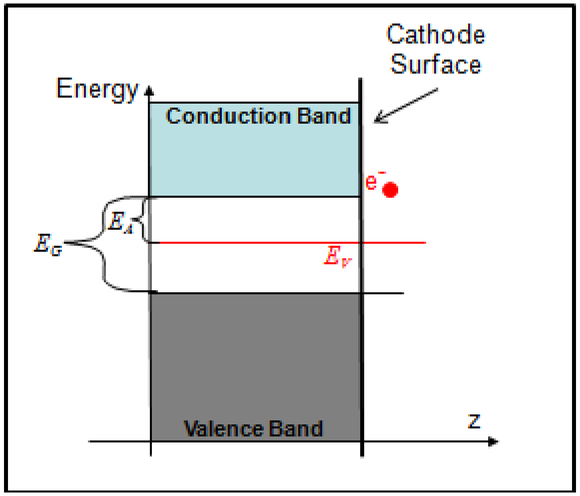
Positive electron affinity cathodes



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

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).

More Cathode Parameters

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

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

Typical photocathodes
(pulsed emission)

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

Thermionic: CeB_6, LaB_6
(continuous emission)

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

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

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

Complex physics, greatly not understood yet!

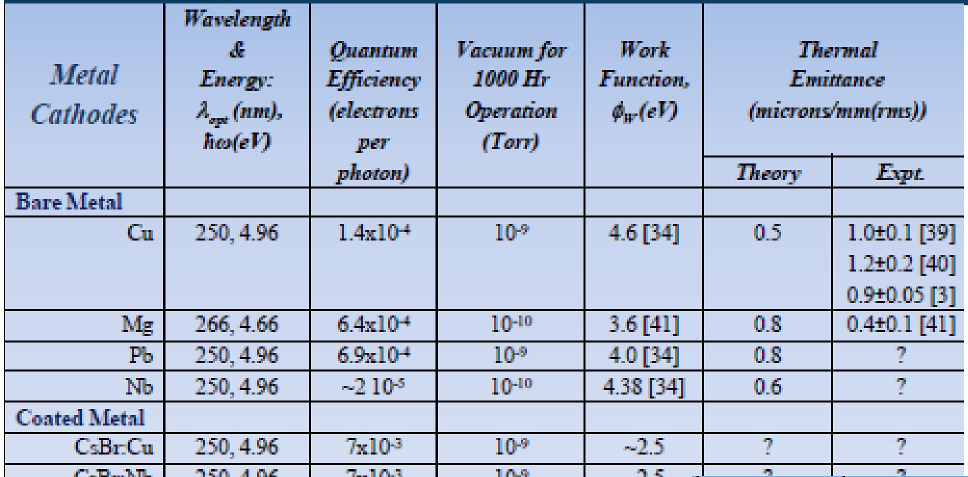
More Photo-Cathode Parameters

- **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 λ 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.**

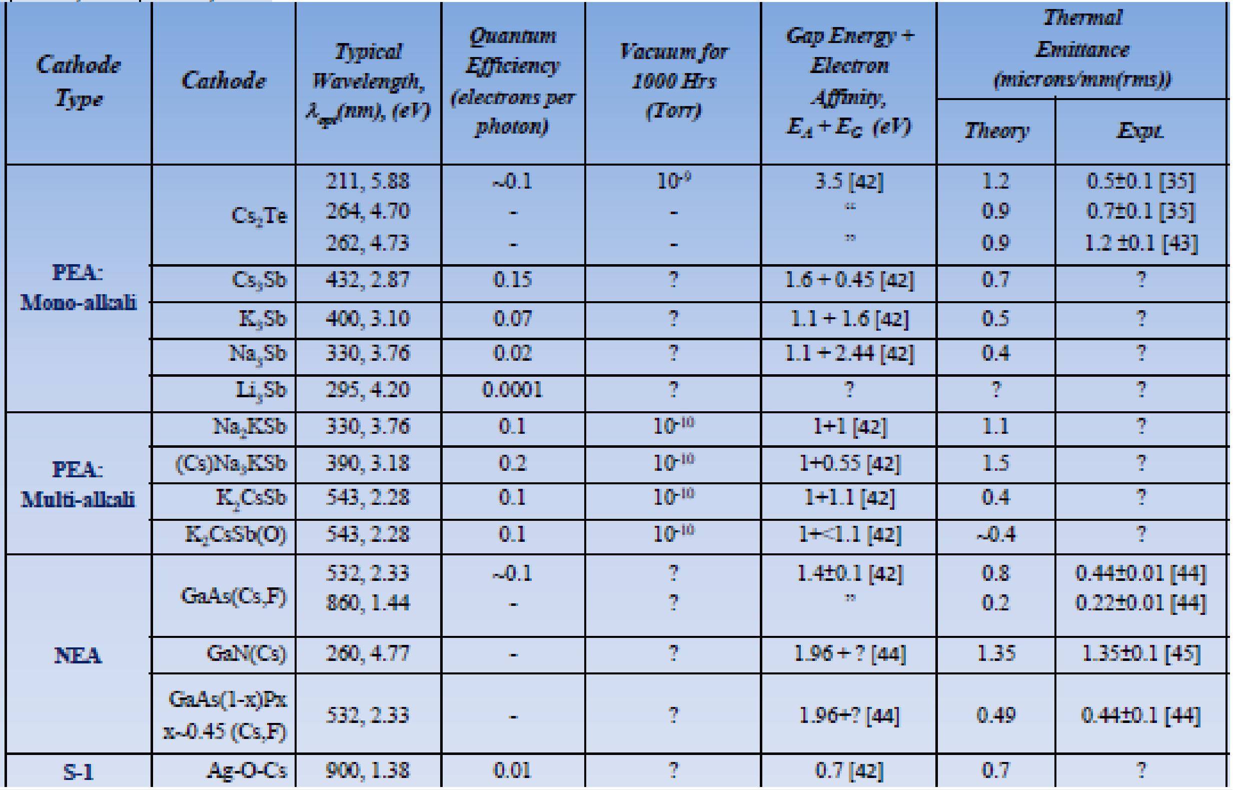
“Popular” Photo-Cathodes



Metal Cathodes	*Wavelength & Energy: λ_{opt} (nm), $\hbar\omega$(eV)*	*Quantum Efficiency (electrons per photon)*	*Vacuum for 1000 Hr Operation (Torr)*	*Work Function, ϕ_W(eV)*	*Thermal Emittance (microns/mm(rms))*	
					Theory	*Expt.*
Bare Metal						
Cu	250, 4.96	$1.4\text{x}10^{-4}$	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	$6.4\text{x}10^{-4}$	10^{-10}	3.6 [41]	0.8	0.4±0.1 [41]
Pb	250, 4.96	$6.9\text{x}10^{-4}$	10^{-9}	4.0 [34]	0.8	?
Nb	250, 4.96	~2 10^{-5}	10^{-10}	4.38 [34]	0.6	?
Coated Metal						
CsBr:Cu	250, 4.96	$7\text{x}10^{-3}$	10^{-9}	~2.5	?	?
CsBr:Nb	250, 4.96	$7\text{x}10^{-3}$	10^{-9}	~2.5	?	?

METALS

SEMICONDUCTORS



Cathode Type	*Cathode*	*Typical Wavelength, λ_{opt}(nm), (eV)*	*Quantum Efficiency (electrons per photon)*	*Vacuum for 1000 Hrs (Torr)*	*Gap Energy + Electron Affinity, $E_A + E_G$ (eV)*	*Thermal Emittance (microns/mm(rms))*	
						Theory	*Expt.*
PEA: Mono-alkali	Cs_2Te	211, 5.88 264, 4.70 262, 4.73	~0.1 - -	10^{-9} - -	3.5 [42] “ ”	1.2 0.9 0.9	0.5±0.1 [35] 0.7±0.1 [35] 1.2 ±0.1 [43]
	Cs_3Sb	432, 2.87	0.15	?	1.6 + 0.45 [42]	0.7	?
	K_3Sb	400, 3.10	0.07	?	1.1 + 1.6 [42]	0.5	?
	Na_3Sb	330, 3.76	0.02	?	1.1 + 2.44 [42]	0.4	?
	Li_3Sb	295, 4.20	0.0001	?	?	?	?
PEA: Multi-alkali	Na_2KSb	330, 3.76	0.1	10^{-10}	1+1 [42]	1.1	?
	$(Cs)Na_2KSb$	390, 3.18	0.2	10^{-10}	1+0.55 [42]	1.5	?
	K_2CsSb	543, 2.28	0.1	10^{-10}	1+1.1 [42]	0.4	?
	$K_2CsSb(O)$	543, 2.28	0.1	10^{-10}	1+<1.1 [42]	~0.4	?
NEA	GaAs(Cs,F)	532, 2.33 860, 1.44	~0.1 -	? ?	1.4±0.1 [42] ”	0.8 0.2	0.44±0.01 [44] 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	?

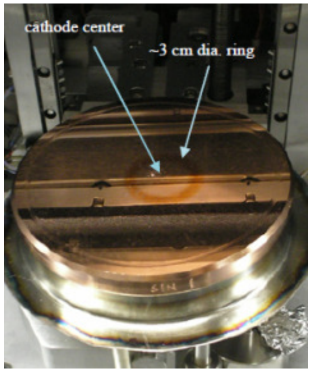
In general, metal cathodes are more robust but present much lower QEs with respect to semiconductor cathodes

- D.Dowell, et al., NIMA 622, 685 (2010)

Examples of Photo-Cathodes & Lasers

Metal: Cu, … (used at LCLS for example)

- <~sub-picosecond pulse capability
- minimally reactive; requires ~ 10^{-8} Torr pressure
- low QE ~ 10^{-5}
- requires UV light (3rd or 4th harm. conversion from IR)
- for nC, 120 Hz reprate, ~ 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 ~ 10^{-9} Torr)
- successfully tested in NC RF and SRF guns
- high QE > 5%
- photo-emits in the UV ~250 nm (3rd or 4th harm. conversion from IR)
- for 1 MHz reprate, 1 nC, ~ 10 W 1060nm required

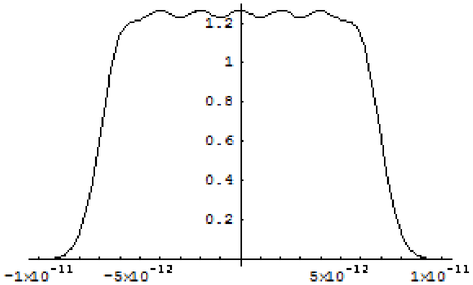
NEA Semiconductor: Gallium Arsenide Cs:GaAs (used at Jlab for example)

- tens of ps pulse capability with phonon damping
- reactive; requires UHV <~ 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, ~50 mW of IR required
- operated only in DC guns at the moment
- Allow for polarized electrons

Laser Pulse Shaping

- 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.

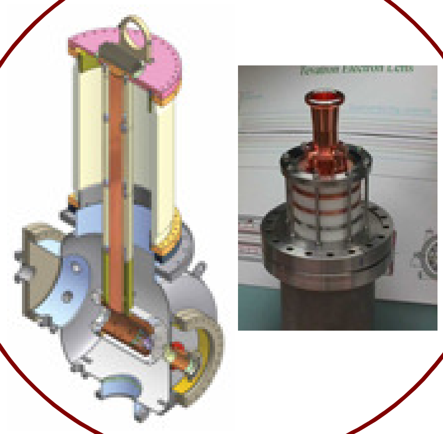
- To generate a longitudinal rectangular-like distribution one can start with a Gaussian short pulse, split it several lower intensity pulses and recombine them with the proper delay.
- The splitting/recombining can be done using conventional beam splitters and delay lines, or using a series of birefringent crystals of proper length.



6 Gaussian pulses with σ_τ = 1 ps added with 2 σ_τ peak to peak distance

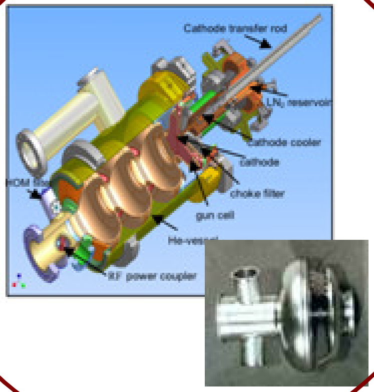
- Top-hat uniform transverse distributions can be obtained by expanding a transversely Gaussian beam and collimating it through a sufficiently small circular aperture (simple but inefficient).
- Nonlinear commercial focusing lens systems can also be used but require excellent alignment and size matched Gaussian beams.

Principal Gun Technologies

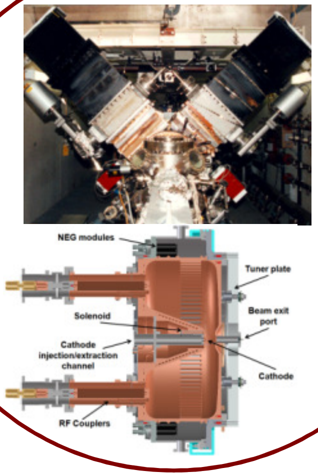


DC guns

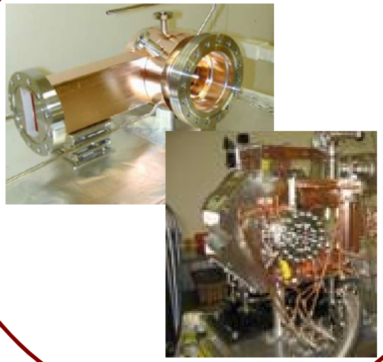
and hybrids



SC RF guns



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

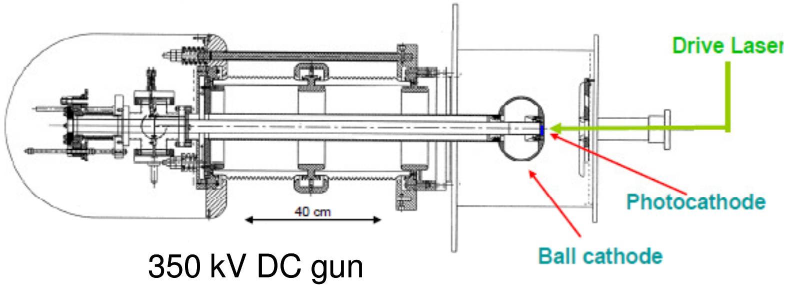


High freq.(> ~1 GHz) NC RF guns

DC Guns

Pros:

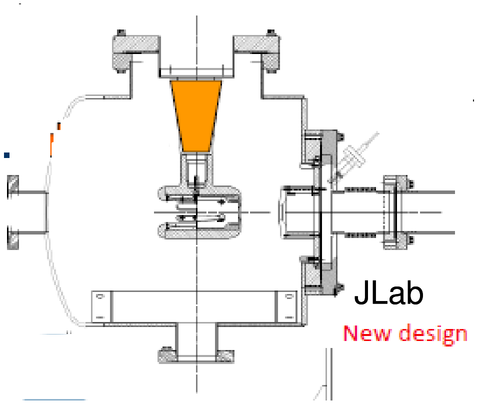
- DC operation
- DC guns reliably operated at 350 kV (JLAB) for many years, ongoing effort to increase the final energy (Cornell, Daresbury, Jlab, …).
- Extensive simulations (Cornell, …) “demonstrated” the capability of sub-micron emittances at ~ 1 nC, if a sufficient beam energy is achieved
- Full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



350 kV DC gun

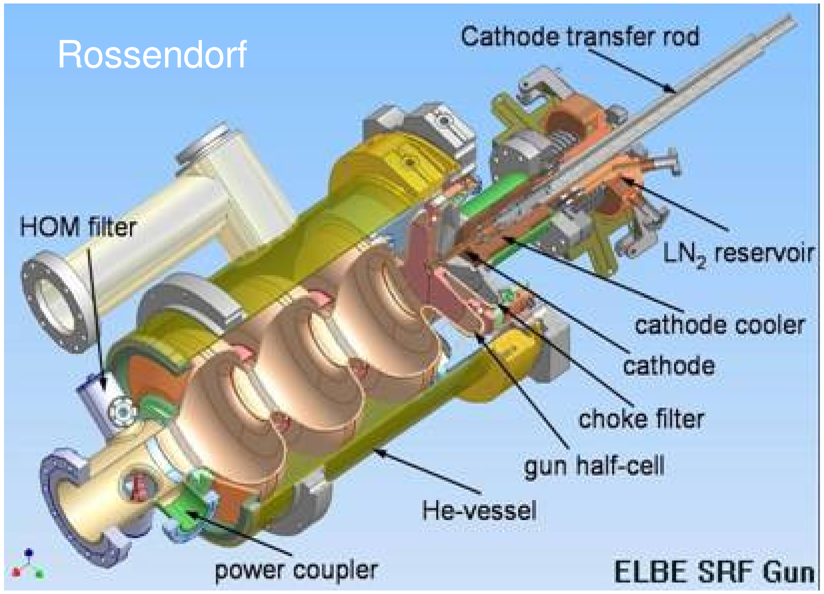
Challenges:

- 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 (>~ 10 MV/m)



- Developing and test new gun geometries (inverted geometry, SLAC, JLab) Very interesting results from a “pulsed” DC gun at Spring-8.

Super-Conducting RF Guns



Pros:

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

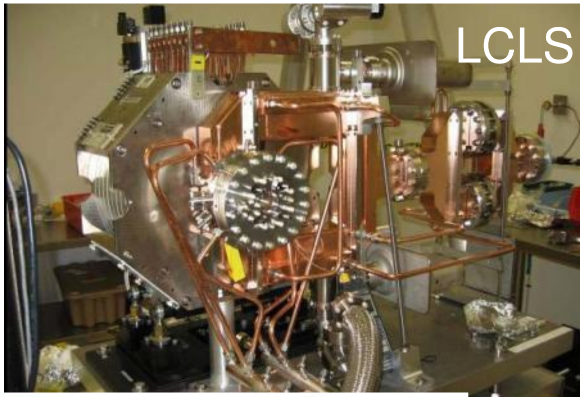
Challenges:

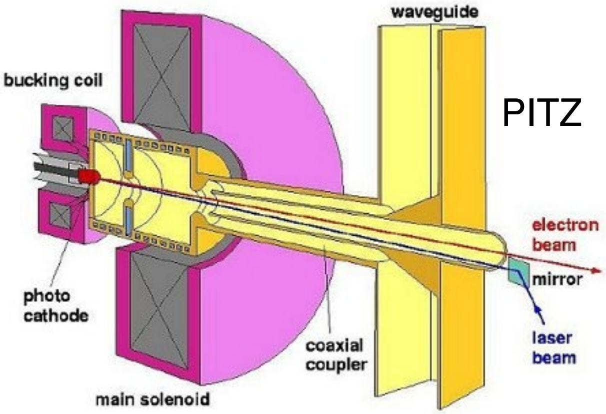
- Move technology from R&D to mature phase. Significant progresses under way.
- Experimentally verify cathode compatibility issues (Promising results with Cs_2Te at Rossendorf, DC-SRF Peking approach)
- Develop and prove schemes compatible with emittance compensation (field exclusion, magnetic field induced quenching, …).

Normal Conducting L and S Band RF Guns (> ~ 1 GHz)

Pros:

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





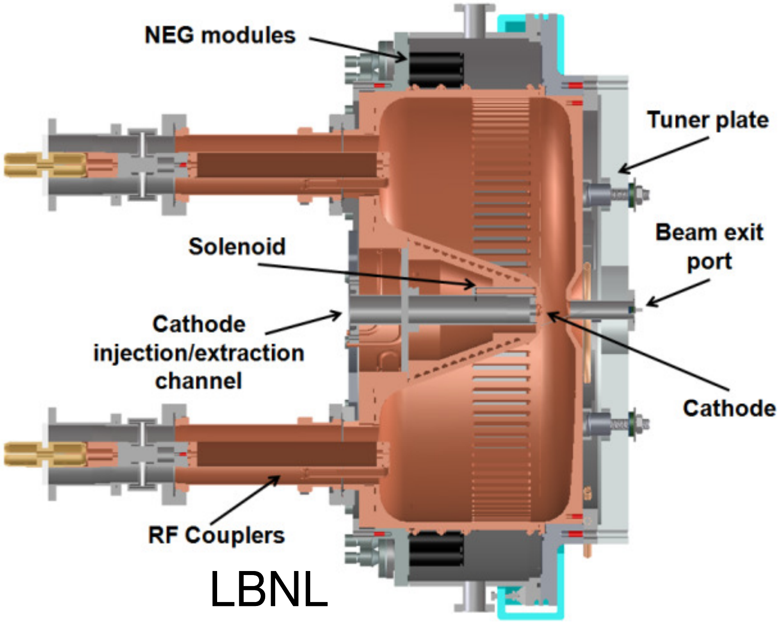
Challenges:

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

Normal Conducting Low Frequency RF Guns

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.



LBNL

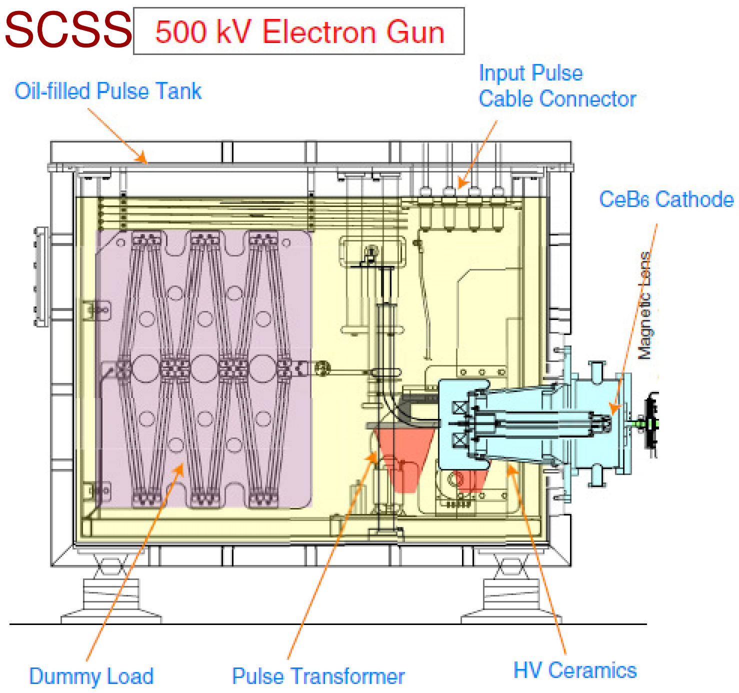
Challenges:

- 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

‘Pulsed DC’ Gun

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 CeB_6 thermionic cathode.



Challenges:

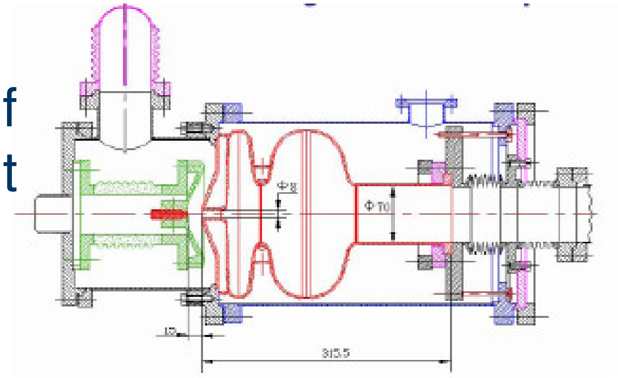
- Modulator technology limits maximum energy and repetition rate (~500 kV at 60 Hz presently, can it go to kHz?).
- Significant injector system complexity when used with thermionic cathodes (“adiabatic” compression requires chopper and multiple RF frequencies). Not integrated yet with photo-cathodes.

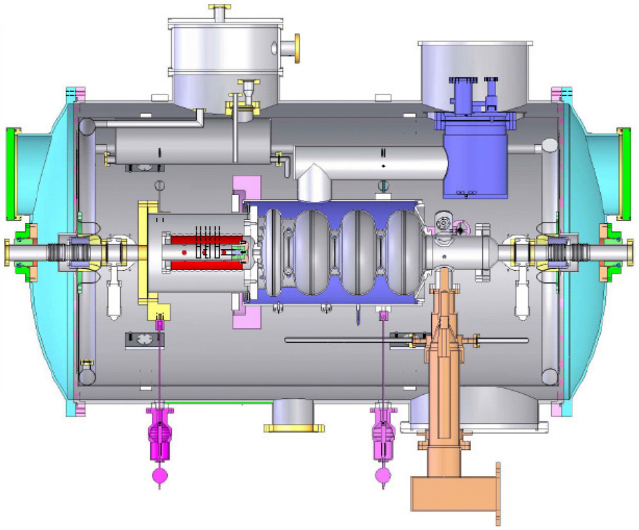
T. Shintake et al., PRST-AB 12, 070701 (2009)

Peking DC-SRF 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.

Challenges:

- Increased system complexity
- Gradient limitation in the DC part

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

Jiankui Hao, *et al.*, SRF2009, p 205, Berlin, Germany

Gun - 4th Generation Light Source Matching

ERL
- Up to hundreds of MHz reprate → DC gun, SC RF Gun, Low freq. NC RF Gun, DC-SRF Gun
- >~ 1 GHz reprate → DC gun, SC RF Gun, DC-SRF Gun

FEL
- Reprate < ~ 10kHz → High freq. NC RF Gun, pulsed DC gun
- Up to hundreds of MHz reprate → DC gun, SC RF Gun, Low freq. NC RF Gun, DC-SRF Gun

XFELO
- Few MHz reprate → Low freq. NC RF Gun with, DC guns, DC-SRF Gun

Remark

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.

Additional References for Existing Gun Project (Incomplete List)

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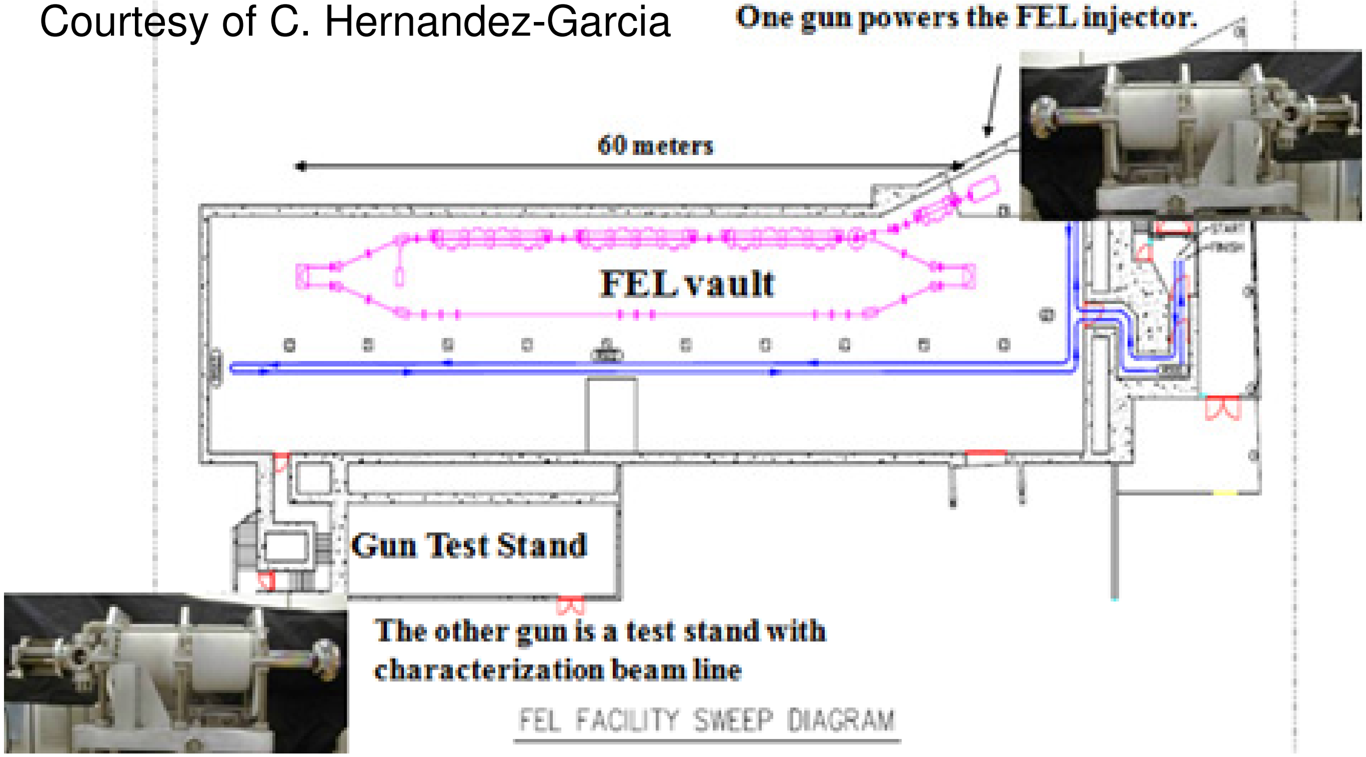
Jefferson Lab FEL DC Guns

Jefferson Lab

Courtesy of C. Hernandez-Garcia



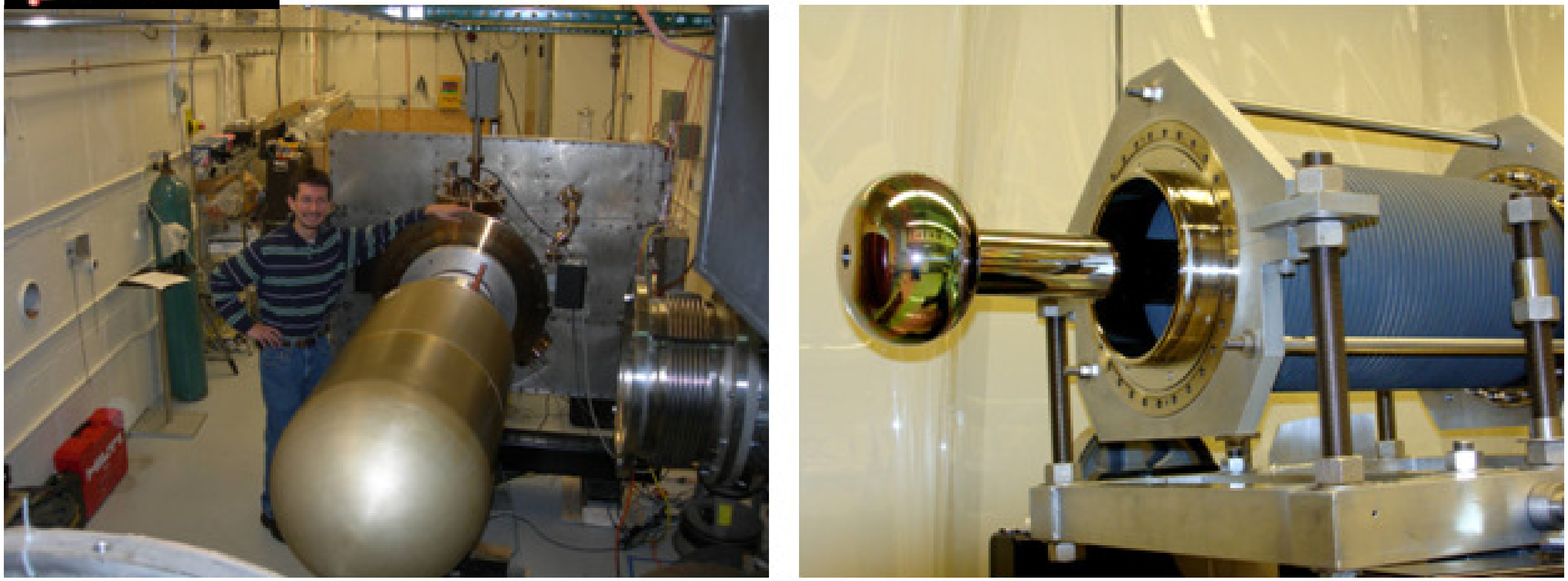
Between 2004 and 2007, operating at 350 kV, the FEL gun delivered over 7000 Coulombs and over 900 hours of beam time at 1-8.5 mA CW with a single GaAs wafer, which was activated into a photocathode a total of 9 times with an average of 6 re-cesiations per activation

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 Results

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

Jefferson Lab

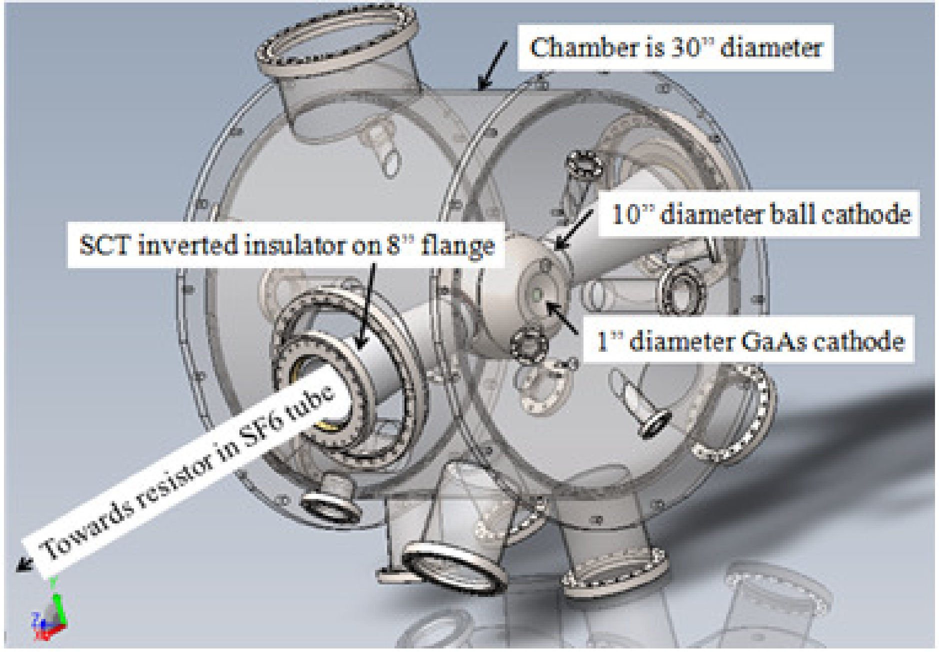


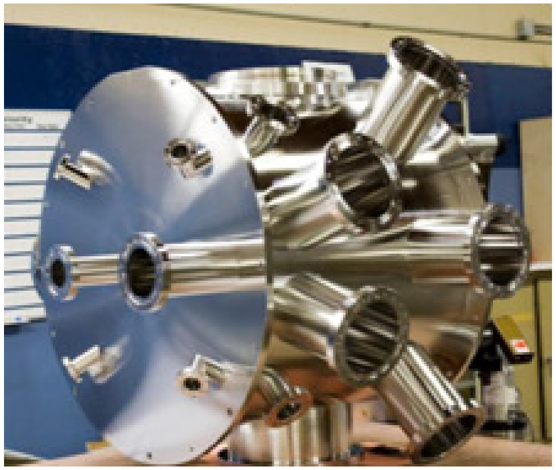
The GTS gun has been rebuilt with bulk resistivity insulator and is ready for installation

Courtesy of C. Hernandez-Garcia

Jlab Inverted DC Gun

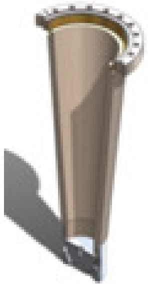
The Jlab FEL is also developing a new gun using the inverted insulator concept





Vacuum chamber ready for delivery

Cut-out of inverted insulator cathode design

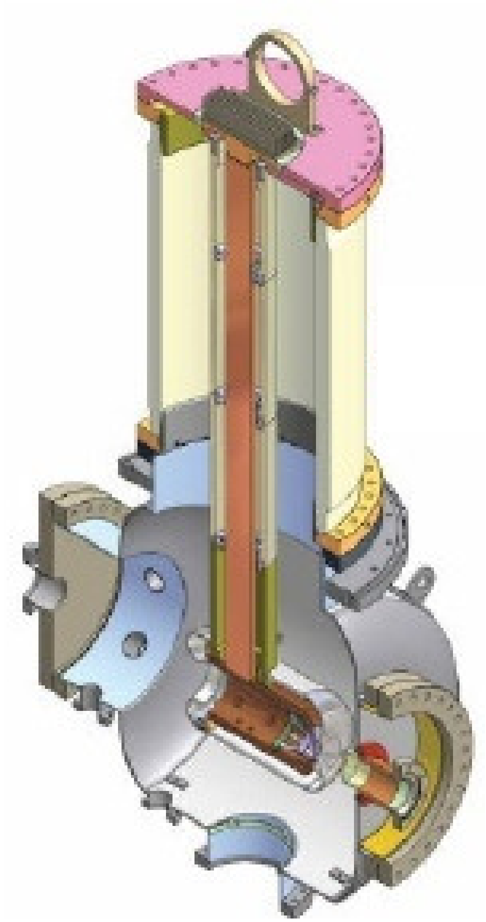


Cut-out of ball cathode design

Courtesy of C. Hernandez-Garcia

Cornell DC Gun

- Present operation limited to ~ 250kV to limit field emission and minimize probability of field punctuation of the ceramic (750kV initial design).



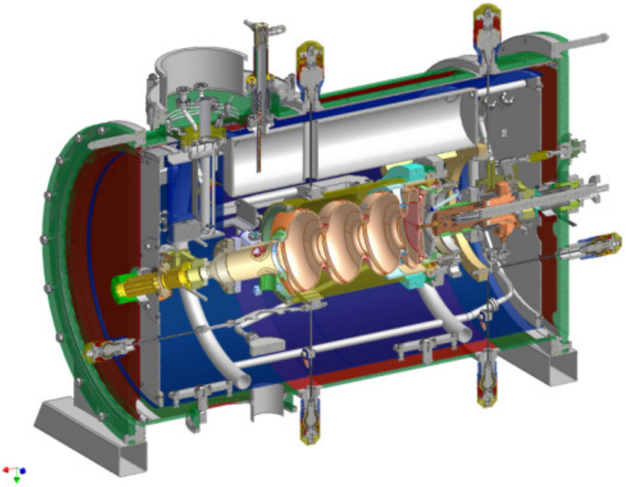
Courtesy of I. Bazarov

A new ceramic with bulk resistivity is being installed. Same ceramic material was used in Daresbury to get to over ~450kV.

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 (~500kV) as an R&D effort separated from the beam running.

BESSY-DESY-FZD-MBI SC RF Gun

Cs_2Te cathodes at 77 K, cavity at 2K,
QE ~ 10^{-3} (poor vacuum transfer chamber)



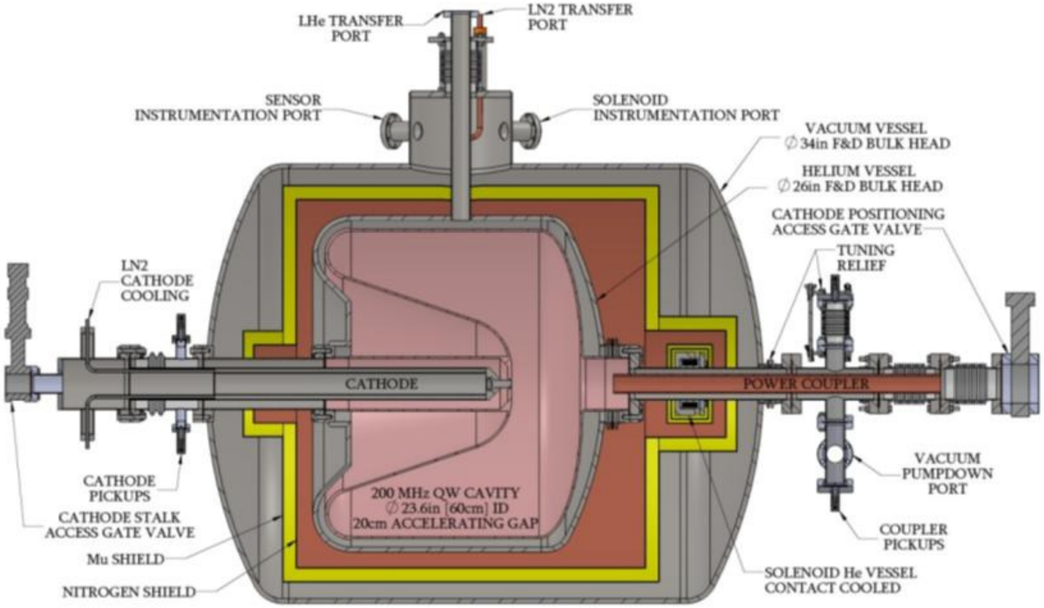
Gradient limited
by damaged cavity

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 Wisconsin SRF 200 MHz Cavity



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

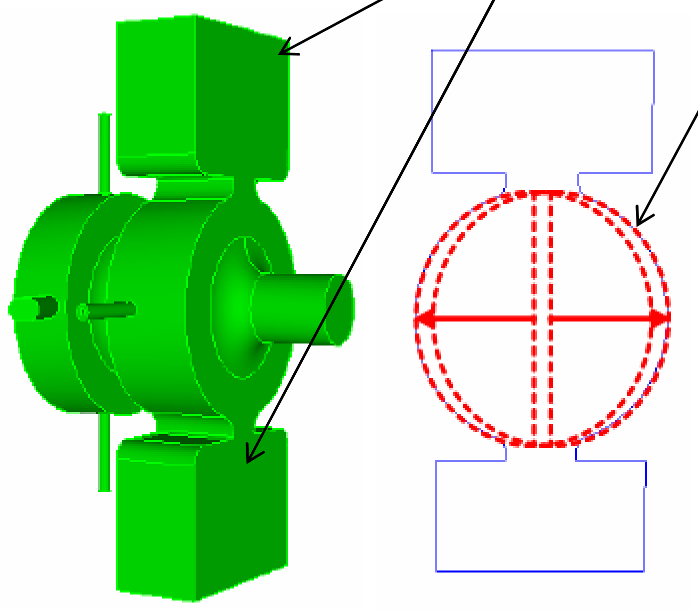
•Cs_2Te cathode, beam blow up regime 30 fs ~0.9 mm hemispherical transverse profile, 37 MV/m at cathode, 200 MHz SRF cavity, 5MeV final energy

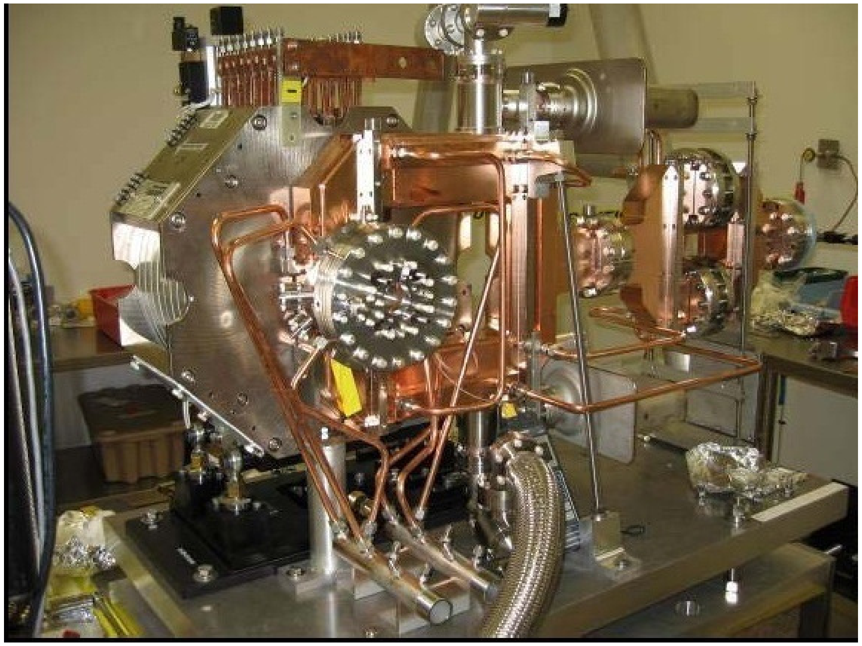
Pulse frequency, MHz	10
Charge per bunch, pC	200
Average current, mA	<2
I_{peak} at first bunch compressor, Amps	50
Peak field in gun, MV/m	41
σ_x at 100 MeV, mm	0.34
σ_z at 100 MeV, mm	0.34
Transverse ε at 100 MeV, mm-mrad	0.9
Longitudinal ε at 100 MeV, keV-mm	2.2

Courtesy of Robert Legg

SLAC NC S-Band RF Gun

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





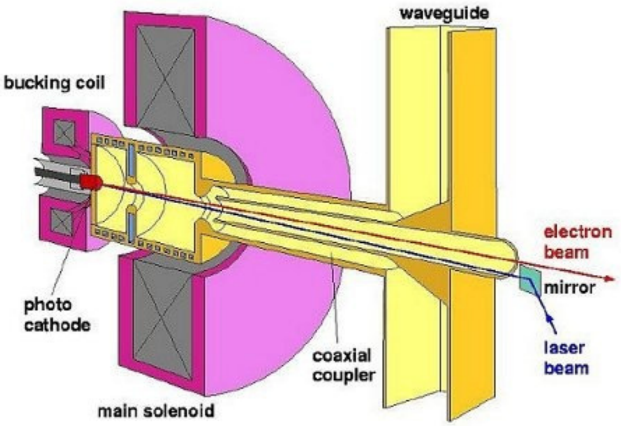
In operation

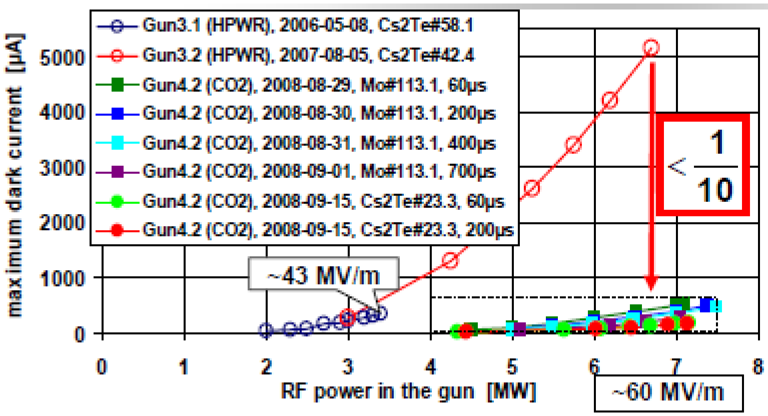
Up to date best performance

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

Courtesy of Dave Dowell

PITZ NC RF L-band Gun

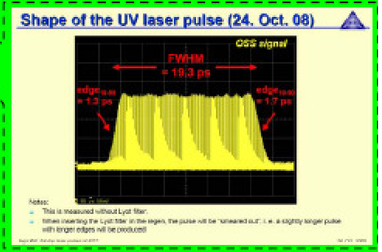


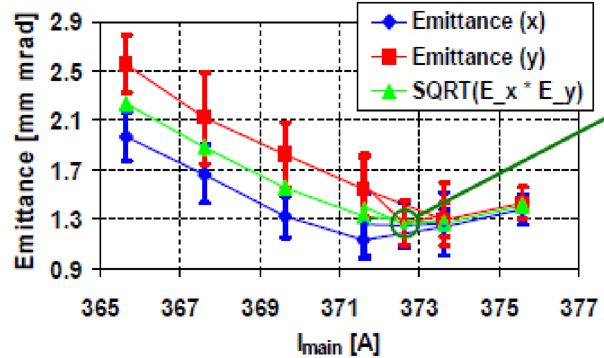


Surface cleaning techniques:

- 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	200us, 1MHz (700us, 1MHz)	FWHM=18..19ps, rt≤2ps , 1nC FWHM=18..19ps, rt≤2ps , 1nC  Shape of the UV laser pulse (24. Oct. 08) 	1 1	0.002 (0.007)
XFEL: to be achieved in 3 Years	10Hz	650us, 5MHz	FWHM=20ps, rt≤2ps		
possible in principle	10Hz	1300us, 5MHz	(?)FWHM=20ps, rt≤2ps(?), 1nC	5	0.065
	50Hz	1300us, 1300MHz	No pulse shaping, 77pC	100	6.5



➔ for **~60 MV/m** we obtained

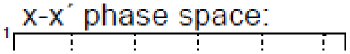
$\varepsilon_{x,n} = 1.25 \pm 0.19$ mm mrad

$\varepsilon_{y,n} = 1.27 \pm 0.18$ mm mrad

@1nC

for 100 % RMS emittance !

➔ in good agreement with prediction from ASTRA

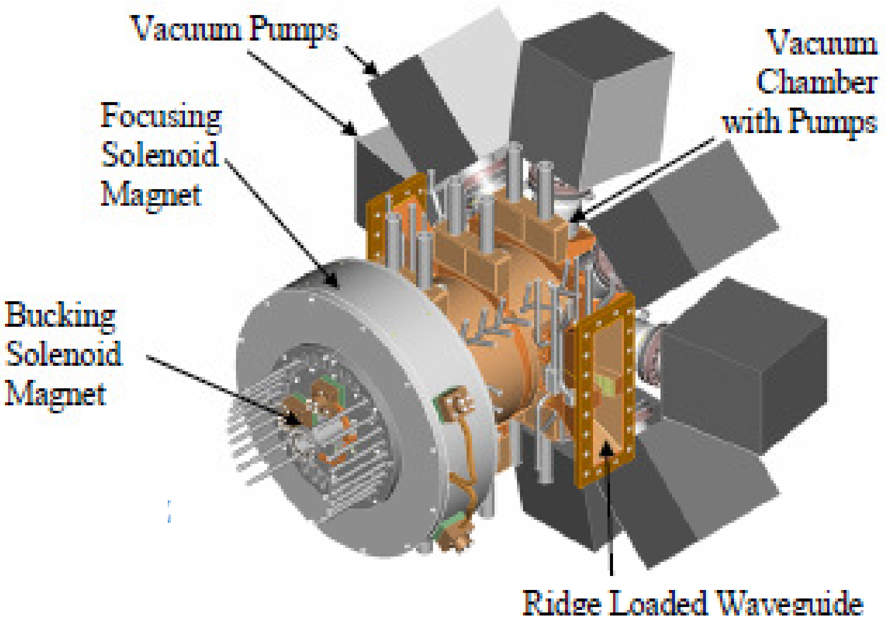


In operation

Courtesy of Frank Stephan

1.3 GHz Copper

LANL/AES NC CW 700 MHz Gun



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

700 MHz CW normal-conducting gun.

Hundreds of kW dissipated in the glidcop structure.

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

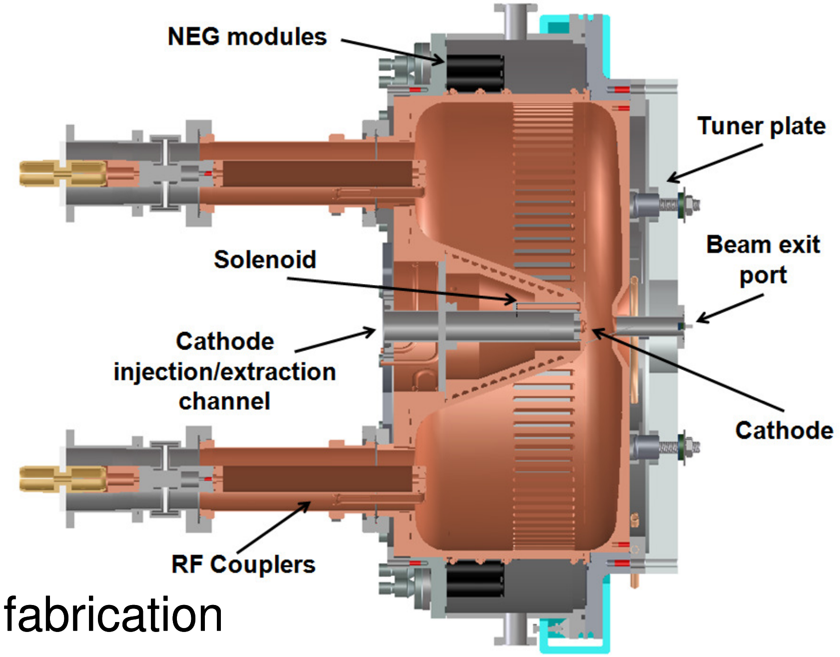
RF conditioning successfully completed.

First beam tests soon

Courtesy of D. Nguyen and B. Carsten

The LBNL CW NC VHF gun

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)

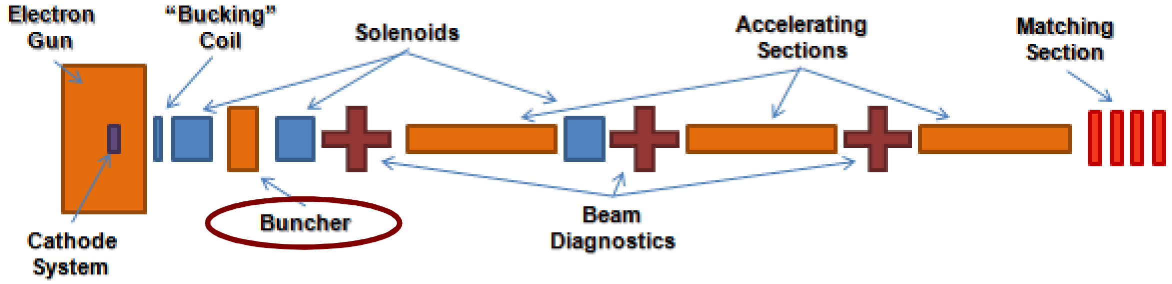
Frequency	187 MHz
Operation mode	CW
Gap voltage	750 kV
Field at the cathode	19.47 MV/m
Q_0	30887
Shunt impedance	6.5 MΩ
RF Power	87.5 kW
Stored energy	2.3 J
Peak surface field	24.1 MV/m
Peak wall power density	25.0 W/cm^2
Accelerating gap	4 cm
Diameter	69.4 cm
Total length	35.0 cm

- 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 λ_{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.

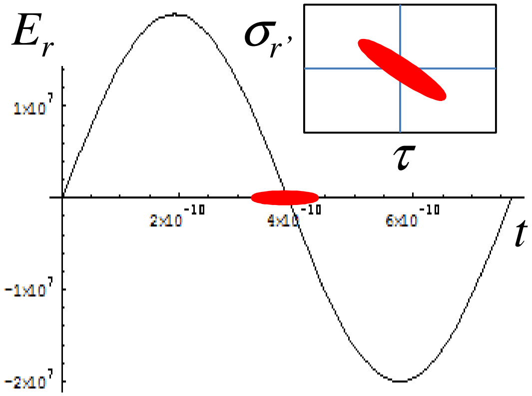
Bunching Systems

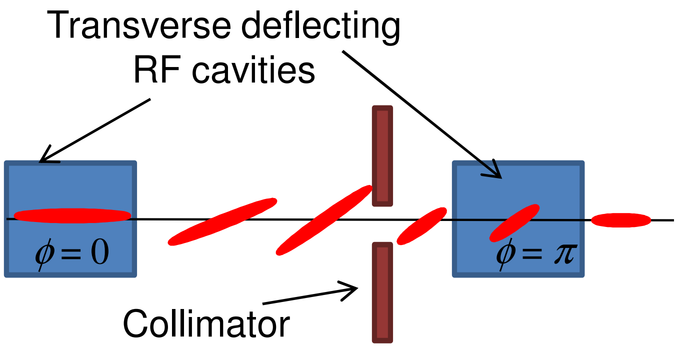
- The systems that allow to compress or define the bunch length in the injector are: **buncher**s, **choppers** and **"dephased" accelerating sections**.

- 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.

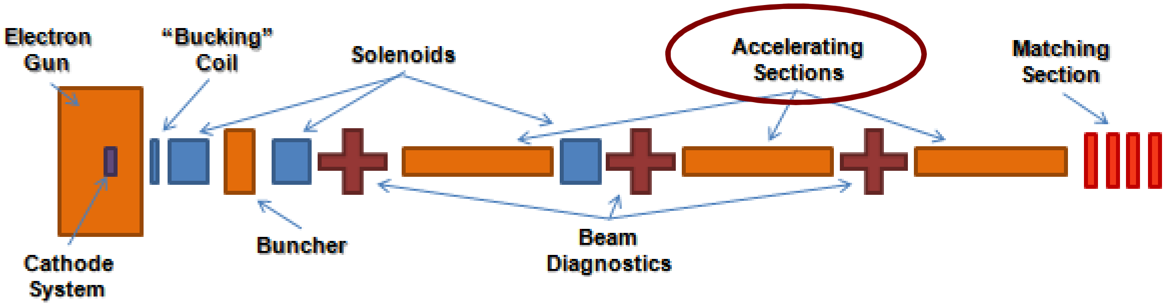




- An **RF chopper** system is used for example for reducing a continuous beam to a pulsed one.

Accelerating System

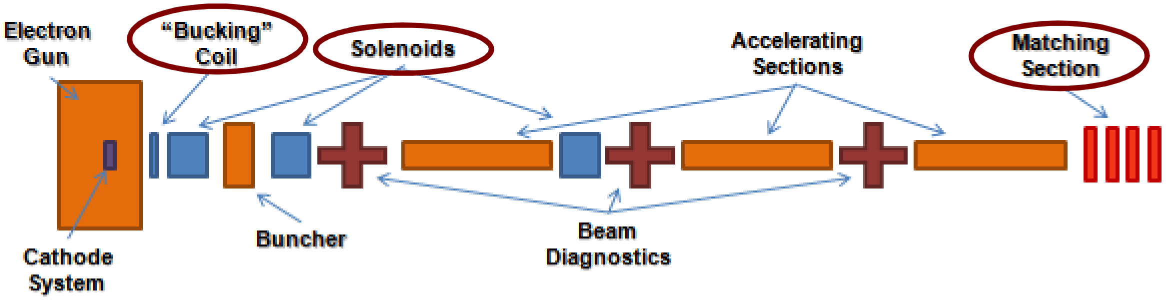
- The main task of the injector **accelerating system** (the first section of which is often referred as the "**RF Booster**") is to take the beam from the gun at the optimum of the emittance compensation process and to "quickly" accelerate it and "freeze" the compensated emittance.



- We already discussed that the RF booster be also used for **velocity bunching** by de-phasing 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 < ~ 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 (~500 MHz to ~5 GHz).
- For SRF the gradients range from ~ 10 to ~20 MV/m from frequencies going from ~ 500 MHz to ~ 1.5 GHz).

Transverse Focusing System

- 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.



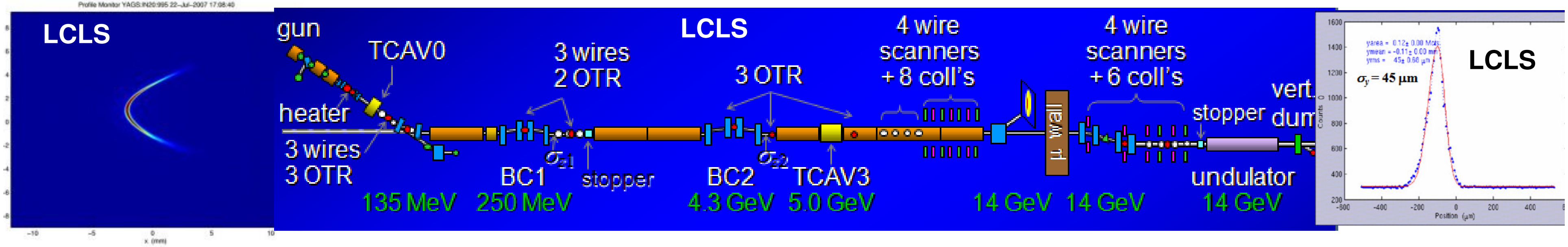
- **Steering coils** distributed along the injector allow to align the beam respect to the component centers.

- The **solenoid**(s) performs the emittance compensation and controls the beam size along the injector. In same 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



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

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