High-brightness high-duty cycle electron injectors.

Fernando Sannibale

Lawrence Berkeley National Laboratory

Outline

- Why are high-brightness high-repetition rate electron injectors necessary?

- Requirements for high-repetition rate high-brightness electron injectors.

- Technological Issues

- Beam Dynamics Issues

- Recent experimental progress and results by high brightness high-repetition rate guns and injectors (an incomplete list!).

What Is Driving the Need for High-Brightness Linac-Based Electron Injectors?

• The two proposed high-energy linear colliders (ILC and CLIC) require flat beams with tens of nm vertical normalized emittance. Such schemes rely on damping rings to obtain the required beam quality.

• Linear colliders are not one of the driving forces (electron cooling is)!

• 4th generation light sources (FEL or ERL based) require electron beams with very high 6D brightness (high-charge, often very short beams with small energy spread and extremely low emittance in both transverse planes).

• Inverse-Compton Sources of x and γ rays also require beams with similar characteristics.

• Short wavelength light sources are one main driving force!

• Ultrafast electron diffraction (UED) and ultrafast electron microscopy (UTEM) require high 6D brightness.

• UED and UTEM are also a driving force!

• External injection in wakefield accelerators (WA) also requires high 6D brightness.

• WA external injection is also a driving force!

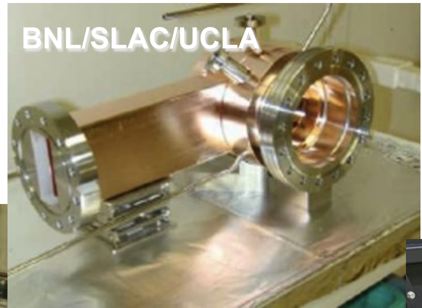
How to Generate High Brightness Electron Injectors?

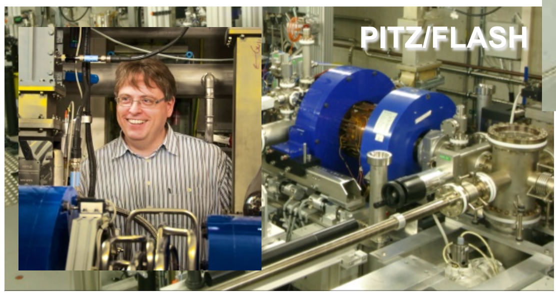
- The beams for such applications cannot be generated in damping rings and linear accelerators are usually required.

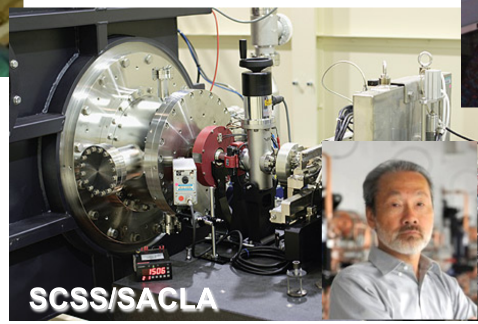
- In linear accelerators the ultimate brightness of the beam is defined at the electron injector and at the electron gun in particular.

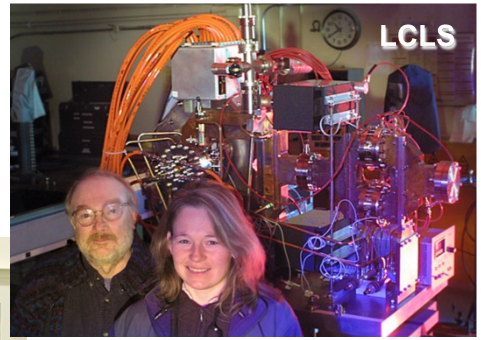
- This has led to the development of a number of high-brightness electrons guns.

For example:





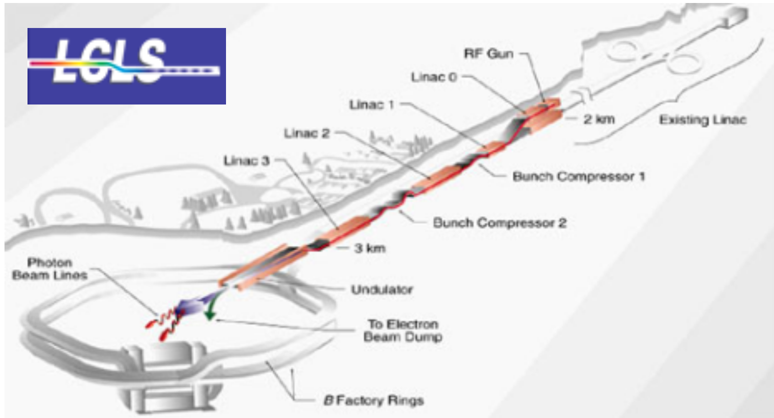




- Most of such sources operate at low duty cycle with repetition rates ranging from few Hz to few hundred Hz.

A Great Example: X-Ray FELS!

High-brightness low-duty cycle electron injector allowed the construction of X-ray FELs.



Their spectacular results represent a revolutionary opportunity for science!

Or: Low- Duty Cycle Inverse Compton Sources!

High-brightness low-duty cycle electron injector allowed the proposal and construction of inverse Compton X and g ray sources.

MIT Center for Accelerator Science and Technology

Inverse Compton X-ray Sources

Laboratory	Geometry	Energy	Rep. Rate	Photons/pulse
LBL	90°	30 keV	2 Hz	10^4-10^5
BNL	180°	6 keV	0.03 Hz	10^7-10^8
LLNL (PLEIADES)	180°	40-140 keV	10 Hz	10^7
NRL	180°	0.4 keV	~0.01 Hz	10^7/macro-pulse
FESTA	90°/180°	2.3/4.6 keV	10 Hz	10^4/10^5
Vanderbilt Univ.	180°	10-50 keV	~0.01 Hz	10^9-10^{10} **
Univ. Tokyo, UTNL*	180°	40 keV	10 Hz	10^8/macro-pulse**
LLNL(T-REX)*	180°	0.1-1 MeV	10 Hz	10^8-10^9 **
Kharkov Institute*	170°/30°	6-900 keV	40-700 MHz	10^5**

* Under Development

** Design value

Massachusetts Institute of Technology D. Moncton 15 May 2006 6

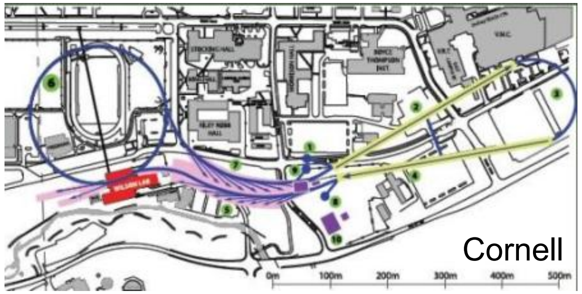
[1] Hartemann, F. V., *et al.*, "Gamma-ray Compton light source development at LLNL" IEEE Particle Accelerator Conference, 1-11, 3444-3446 (2007).
[2] T. Scott Carman, *et al.*, "The TUNL-FELL inverse Compton γ-ray source as a nuclear physics facility", Nucl. Instrum. Methods A 378, 1-20 (1996).
[3] Umstadter D., *et al.*,"Development of a source of quasi-monochromatic MeV energy photons", AIP conference proceedings 1099, 606-609 (2009).
[4] S. Boucher, *et al.*, "Inverse compton scattering gamma ray source", Nucl. Instrum. Methods A 608, S54-S56 (2009).

Opening the way to compact short wavelength light sources !

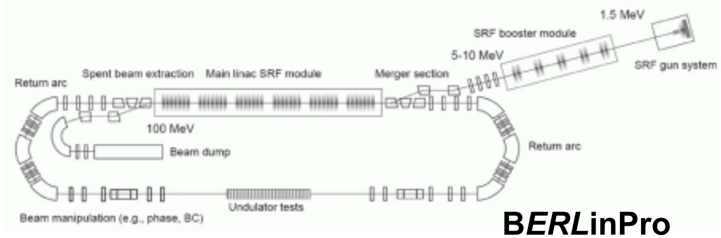
What Is Next?

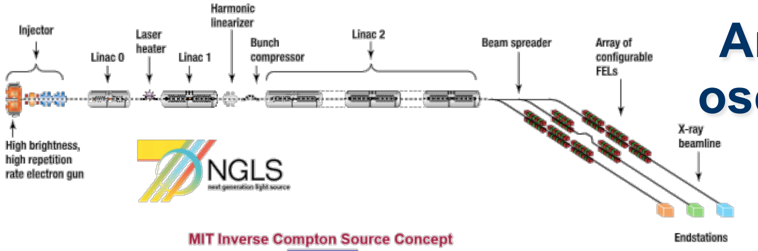
All operating 4th generation light sources are low repetition rate (< 120 Hz)

But science is driving towards much higher repetition rates!

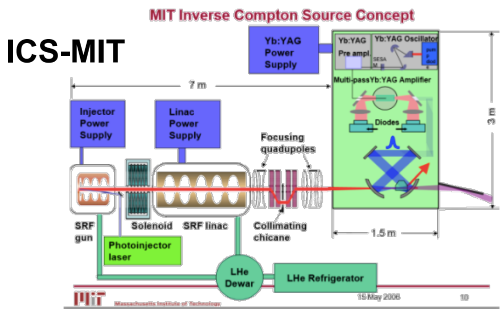


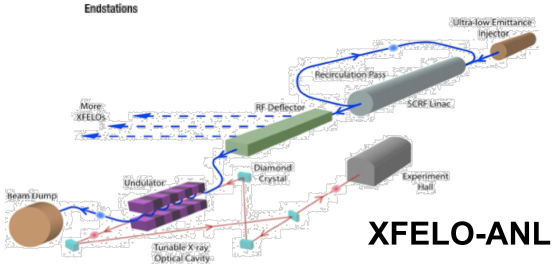
Proposed X-ray ERLs require the same beam quality at GHz repetition rates.

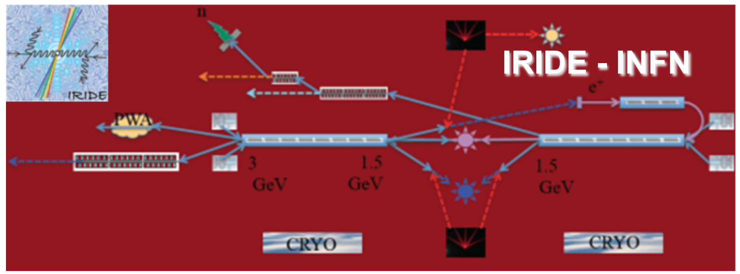




And proposed high repetition rate X-ray FELs, FEL oscillators and inverse Compton sources all require the same beam quality at MHz repetition rates.







High repetition rate wakefield accelerators (drive and witness beams)

High-repetition rates high-brightness electron injectors are now required

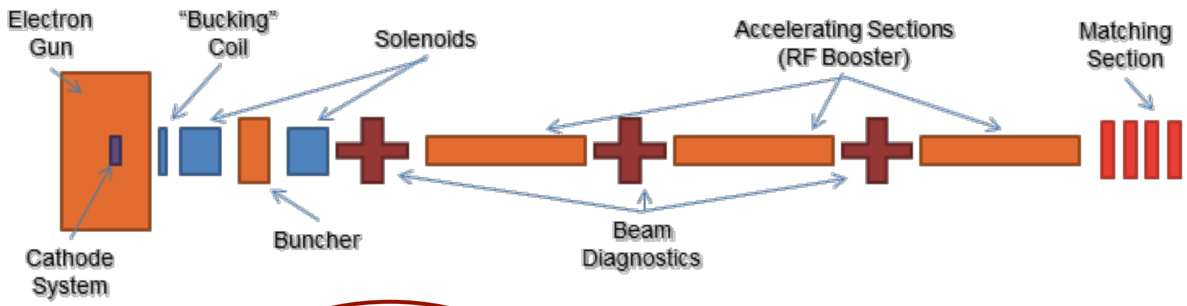
High-Duty Cycle High-Brightness Electron Gun/Injector Requirements

To operate with such facilities, the electron source has to allow for:

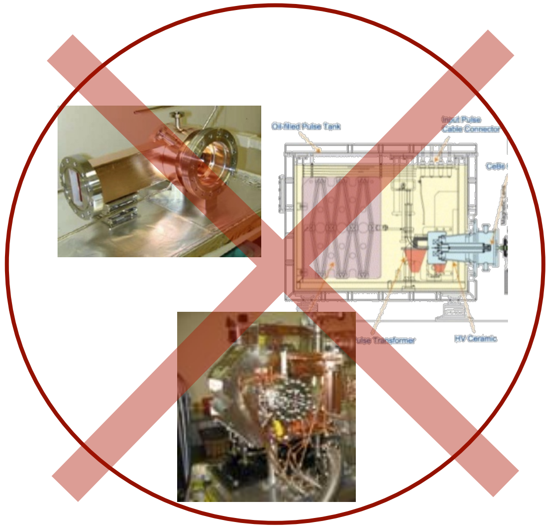
Repetition rate	MHz-class	
Charge per bunch	~ 1 pC - ~ 1 nC	Different modes of operation
Normalized emittance	~ 0.2 – ~ 1 μm	Lower value for lower charge
Beam energy at the gun exit	>~ 500 keV	For controlling space charge
Beam energy at the injector exit	>~ 100 MeV	Negligible space charge forces
Cathode electric field during photoemission	>~ 10 MV/m	Space charge emission limit; maximum brightness limit
Bunch length and shape control	From few to ~ 50 ps	Space charge control; different modes of operation
Cathode/gun area magnetic field compatibility		Emittance compensation; "exotic" modes (flat beams, …)
Dark current at nominal gun energy	< ~ 1 μA	SRF quenching; rad. damage
Gun operational vacuum pressure	$\sim 10^{-10} - 10^{-9}$ Torr	Reactive high-QE cathode lifetime
Loadlock cathode vacuum system		"Quick" cathode exchange
Reliability	>~95%	Required for an user facility

Injector cost is typically a small fraction of such facilities' total cost. Minimizing cost is usually not a top-priority requirement.

Technological Issues…



- The high-repetition rate requires **high QE photo-cathodes** (or thermionic in some cases) due to present laser power availability.



Successful low-duty cycle gun schemes

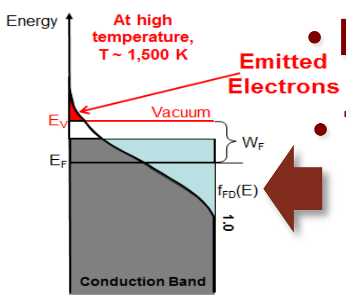
- Successful low repetition rate schemes such as NC high frequency (> 1.3 GHz) RF guns and "pulsed DC" Shintake-like guns **cannot run at repetition rates >~ 10 kHz.**
- **A high-duty cycle high-repetition rate high-brightness gun needs to be developed!**
- The high-duty cycle, high-repetition rate imposes **superconductive accelerating cavities** in the RF booster.
- Beam diagnostics: high heat load, fast acquisition rate requirements, "bunch stealer", low cross section phenomenon exploitation, …

Cathodes

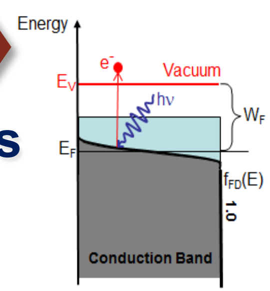
• Cathodes are obviously a fundamental part of electron sources. The gun performance heavily depends on cathodes

• In the low charge regime (tens of pC/bunch) the ultimate emittance performance is set by the cathode thermal/intrinsic emittance

• The ideal cathode should allow for:
  - high brightness (low thermal/intrinsic normalized emittance, low energy spread, high current density, …)
  - full control of the 6D bunch distribution
  - long lifetimes.



• Photo-cathodes (most of present injector schemes)



• Thermionic cathodes can offer low thermal emittances but require sophisticate compression schemes. (CeB_6 at SCSS-Spring 8, XFELO-ANL)

Other cathodes under study (photo-assisted field emission, needle arrays, photo-thermionic, diamond amplifiers, …).

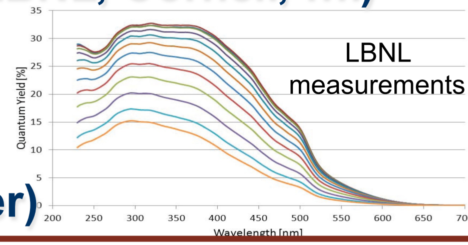
In high-repetition rates photo-guns high quantum efficiency photo-cathodes (QE>~ 1 %) are required to operate with present laser technology.

Examples of Photocathode Systems

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 > 1% over long periods
- photo-emits in the UV ~250 nm (3rd or 4th harm. IR conversion)
- for 1 MHz repetition rate, 1 nC, ~ 10 W IR required (comm. laser))

NEA Semiconductor: Gallium Arsenide GaAs (used at Jlab for example)
- ~ps (green), tens of ps (IR) pulse duration capability
- reactive; requires UHV <~ 10^{-10} Torr pressure
- high QE >1%
- photo-emits in the NIR (tens of ps pulses), allow for polarized e^-
- low emittance due to phonon scattering
- for nC, 1 MHz, hundreds of mW of IR required (comm. laser)

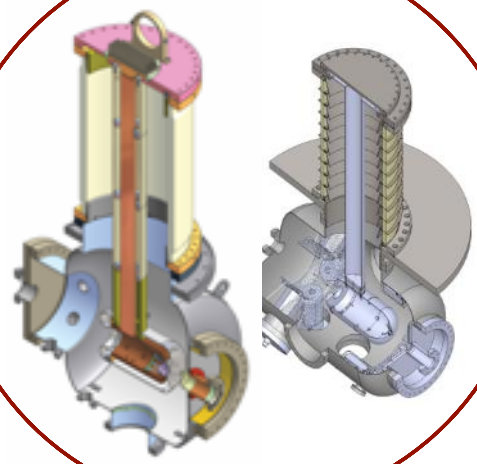
PEA Semiconductor: Alkali Antimonides eg. $SbNa_2KCs$, CsK_2Sb, …
- <~ps pulse capability (studied at BOING, INFN-LASA, BNL, LBNL, Cornell, ….)
- reactive; requires ~ 10^{-10} 10^{-9} Torr pressure
- high QE > 1%
- requires green/blue light (eg. 2nd harm. Nd:YVO4 = 532nm)
- for nC, 1 MHz repetition rate, ~ 1 W of IR required (comm. laser)



Complete cathode review in: D. Dowell, *et al*., NIMA **622**, 685, 2010

Candidate Electron Gun Technologies

High-brightness high-duty cycle electron injectors (F. Sannibale)



DC guns

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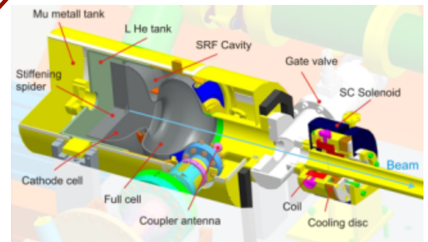
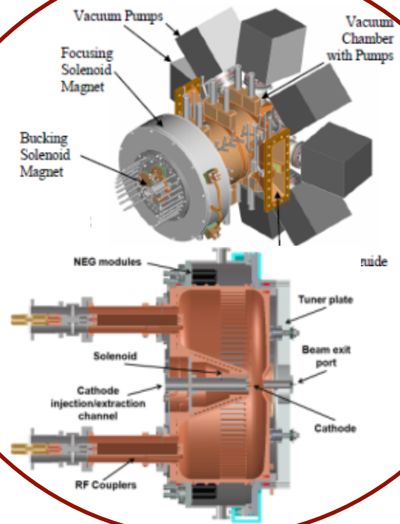
Hybrid Schemes



SC RF guns

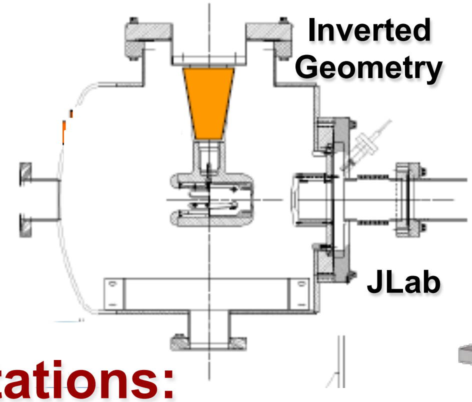


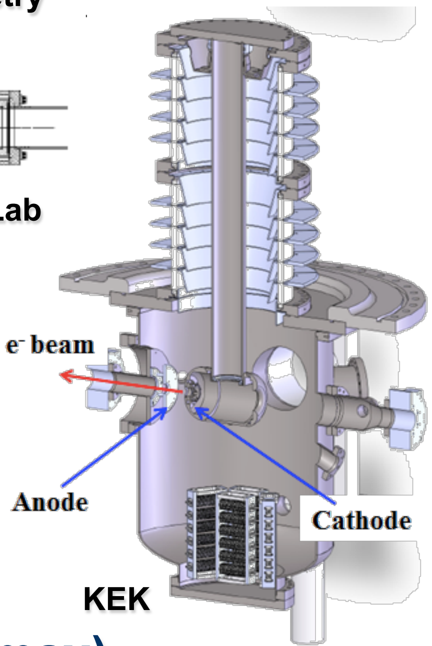
Low freq. (<~ 700 MHz) NC CW RF guns

DC Guns

Pros:

- DC operation
- DC guns reliably operated at 350+ kV in several labs since many years, ongoing effort to increase the final energy (Cornell, JAEA, KEK …).
- Extensive simulation work by several groups "demonstrated" the capability of sub-micron emittances ~ 100 pC, 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)





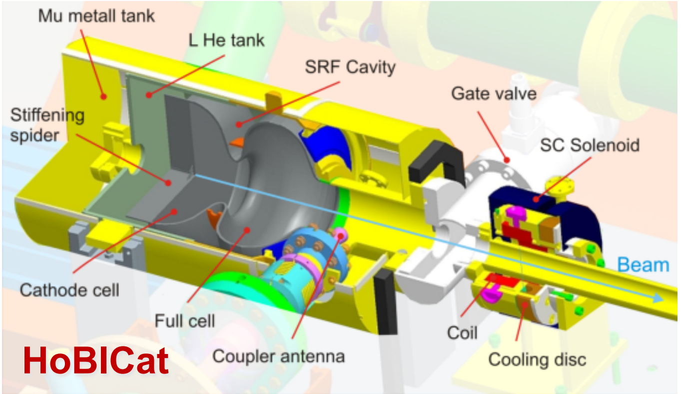
Areas for improvement and potential limitations:

- Higher energy pursue is driving R&D and technology improvements.
- In particular, improvement of the high voltage breakdown ceramic design and fabrication.
- Minimizing field emission for higher gradients (~ 10 MV/m max)
- Developing and test new gun geometries (inverted geometry, SLAC, JLab).

Super-Conducting RF Guns

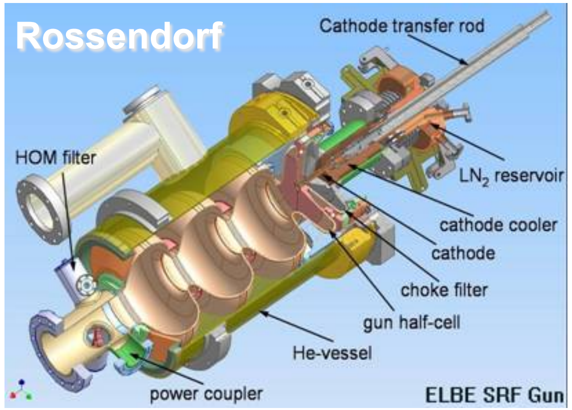
Pros:

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



Areas for improvement and potential limitations:

- Control of multipacting (mainly in RF couplers)
- Control field emission (dark current) at higher gradients
- Performance reproducibility. (vertical/ horizontal performance)

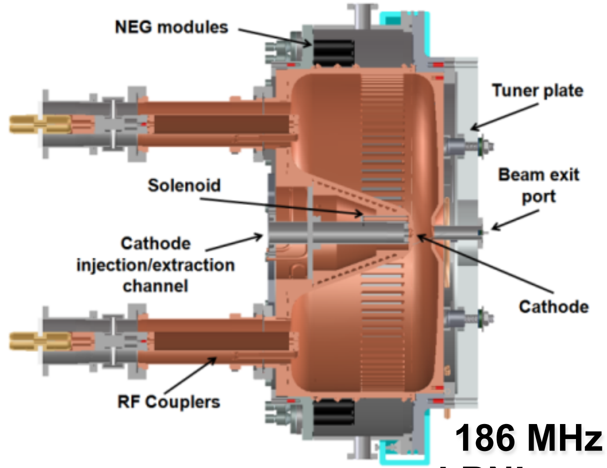


- Evaluate and experimentally verify high QE cathode compatibility (promising results with Cs_2Te at Rossendorf)
- Compatibility with emittance compensation ("cohabitation" with magnetic fields, SC Solenoid…).

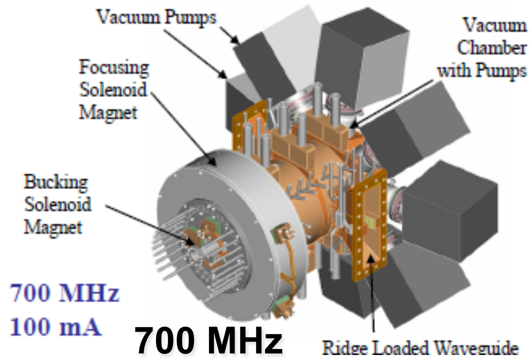
Normal Conducting Low Frequency (<~700 MHz) CW RF Guns

Pros:

- Operate in CW mode
- Beam dynamics similar to DC but with higher gradients and energies
- Based on mature RF and mechanical technology (especially in the VHF range).
- Full compatibility with magnetic fields.
- Compatible with most photo-cathodes
- Potential for excellent vacuum performance (specially in the low frequency range).



186 MHz LBNL gun

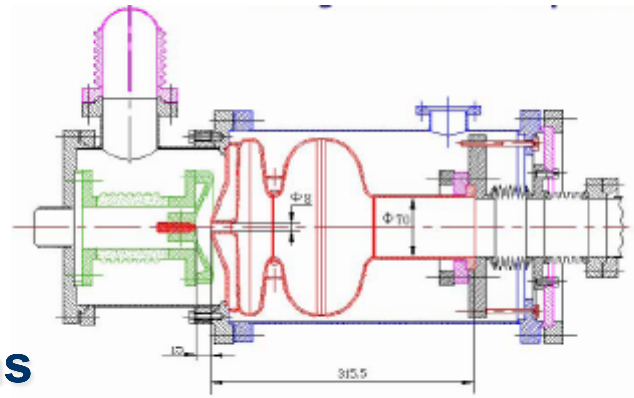


700 MHz LANL gun

Areas for improvement and potential limitations:

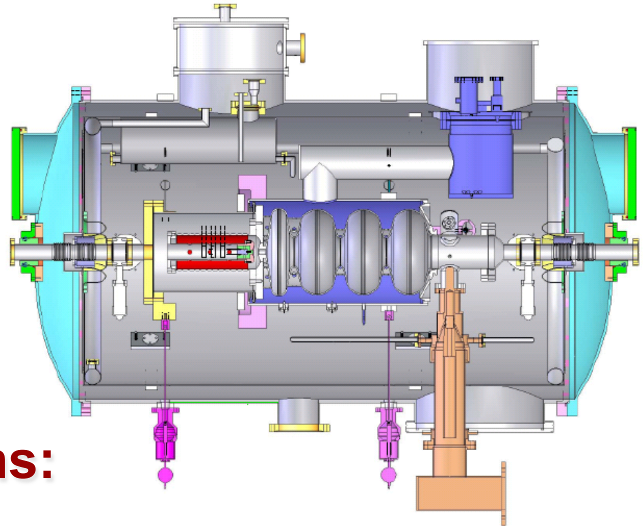
- Gradient and energy increase to be traded with RF power requirements
- Higher frequency range requires state of the art cooling techniques.
- Repetition rates > ~ 700 MHz (required by some ERLs) not achievable

DC-SRF Hybrid Gun



Pros:

- DC gun advantages:
  - potential for magnetic field in the cathode area
  - better cathode compatibility than in SRF guns



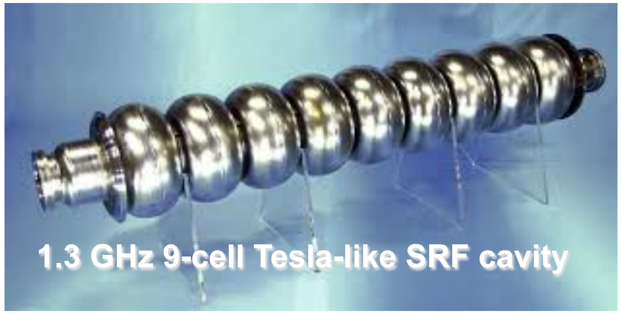
- SRF gun advantages:
  - CW operation
  - Higher accelerating gradient
  - Excellent vacuum

Areas for improvement and potential limitations:

- Low gradient at the cathode
- System complexity

Accelerating System (RF Booster & Buncher)

• The main task of the injector **accelerating system** (or "**RF Booster**") is to take the beam from the gun at the optimum of the emittance compensation point and to "quickly" accelerate it to more relativistic energies "freezing" the compensated emittance.



• The RF booster can be also used for compression by **velocity bunching**, sometimes in combination with a **buncher system**.

• The booster cavities can be of **standing or travelling wave** type.

• The frequency can be a sub-multiple of the main linac RF for improving longitudinal plane linearity.

• The **repetition rate defines the technology for the booster**:
Normal-conducting pulsed systems for **repetition rate < ~ 1 kHz**
Super-Conducting high duty-cycle and CW systems otherwise.

• **Accelerating gradients** are in the range of 10 – 100 MV/m for NC RF sections. Higher gradients correspond to higher frequencies (~500 MHz to ~12 GHz).

• For SRF the gradients range from ~ 10 to ~25 MV/m from frequencies going from ~ 500 MHz to ~ 1.5 GHz).

Beam Dynamics Issues: Selecting the Accelerating Gradient @ the Cathode

The gradient at the cathode during photo-emission plays a fundamental role in beam dynamics.

Indeed, it sets the ultimate brightness that a gun can achieve. Higher gradients are preferable and have been pursued in low repetition rate electron guns (~ 40-60 MV/m in L and S band).

BETTER

BETTER

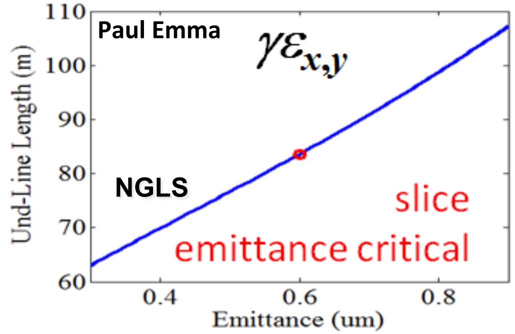
On the other hand, high gradients generate higher dark currents. While this can be acceptable in low-repetition rate applications, it can represent a severe limitation in high-duty cycle and CW applications (SRF quenching, increased radiation doses).

A careful tradeoff must be selected between this two antagonist requirements (~ 10 – 30 MeV).

- **As a consequence, high repetition rate guns typically operate in a beam dynamics regime characterized by relatively low gradients at the cathode.**

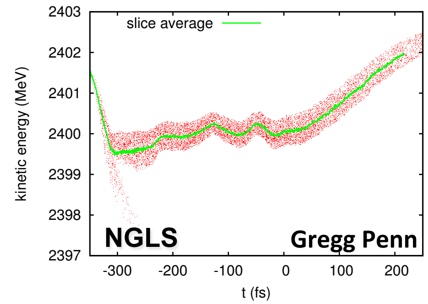
Injector Beam Dynamics in the Low Gradient Regime

- In such a regime, long bunches (tens of ps) must be generated at the cathode to control space charge effects.

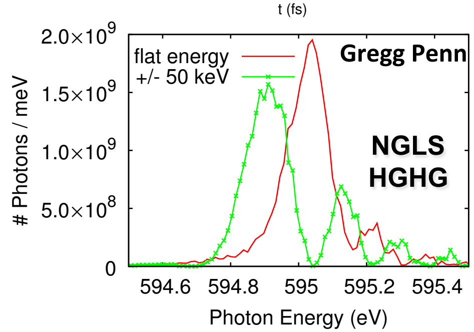


- Transverse emittance affects the FEL gain (and hence beam energy, saturation length, FEL size and cost.)
- A proper emittance compensation of several hundreds of pC bunches has to be performed in the injector.

- Simultaneously, longitudinal compression at the injector must be performed to progressively reduce the beam size while accelerating the beam, finding the balance between injector and linac compression (microbunching instability).



- Extensive studies are showing that minimizing density asymmetries (tails) and high-order correlations in the longitudinal phase space is extremely important in seeded FEL schemes.

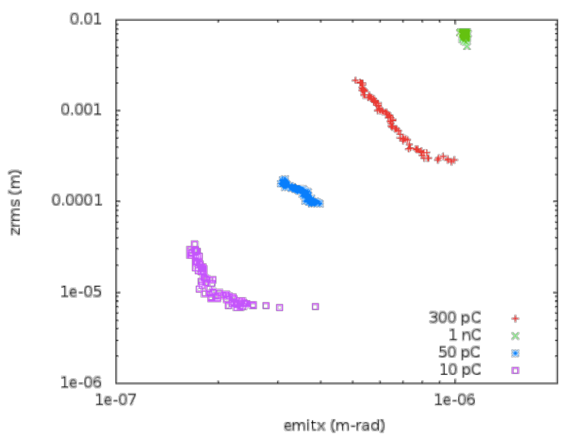


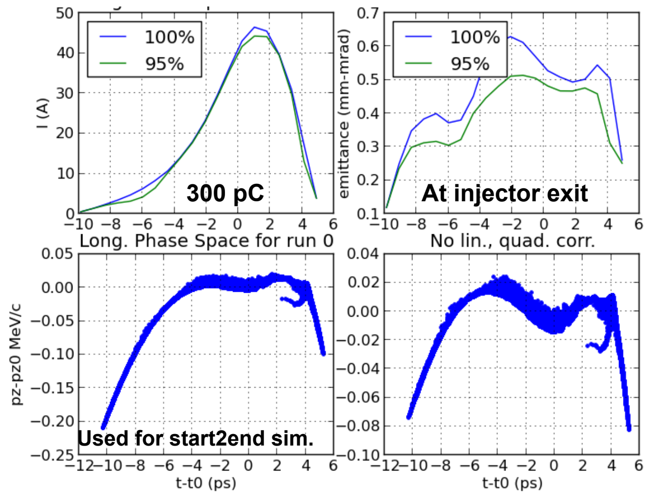
- Indeed, uncontrolled tails affect compression in the linac and longitudinal phase space correlations affect the bandwidth of the x-ray pulse.

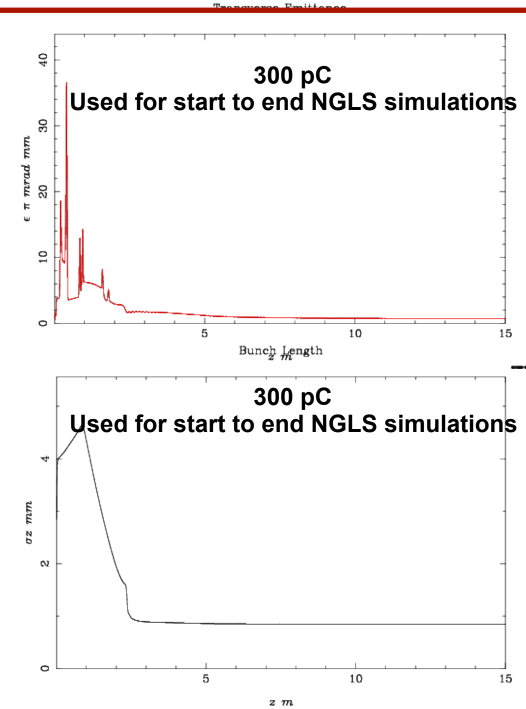
Beam Dynamics Simulations

- It has been shown that a quite **complex beam manipulation at the injector** is required to operate in a high repetition rate FEL.
- Extensive **simulations and studies** (inclusive of start to end simulations including linac and FELs) **are encouraging** showing that the task can be accomplished.

NGLS-Injector example.







- Multi-Objective Genetic Algorithms optimization, trading for example, between final emittance and bunch length, "regularity" of the longitudinal phase space, distribution symmetry, …

C. Papadopoulos

- At the same time, the same simulations clearly show the **interdependence of the "knobs"** and the **relevance of the proper tuning of the injector**, indicating that:

It is critical for such a performance to be demonstrated experimentally.

Present Status and Future Perspective

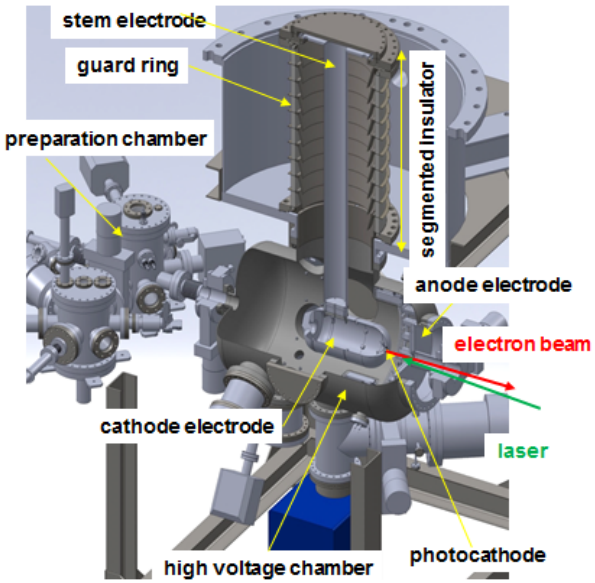
Numerous groups around the world are pursuing the development of high-brightness high-repetition rate electron injectors.

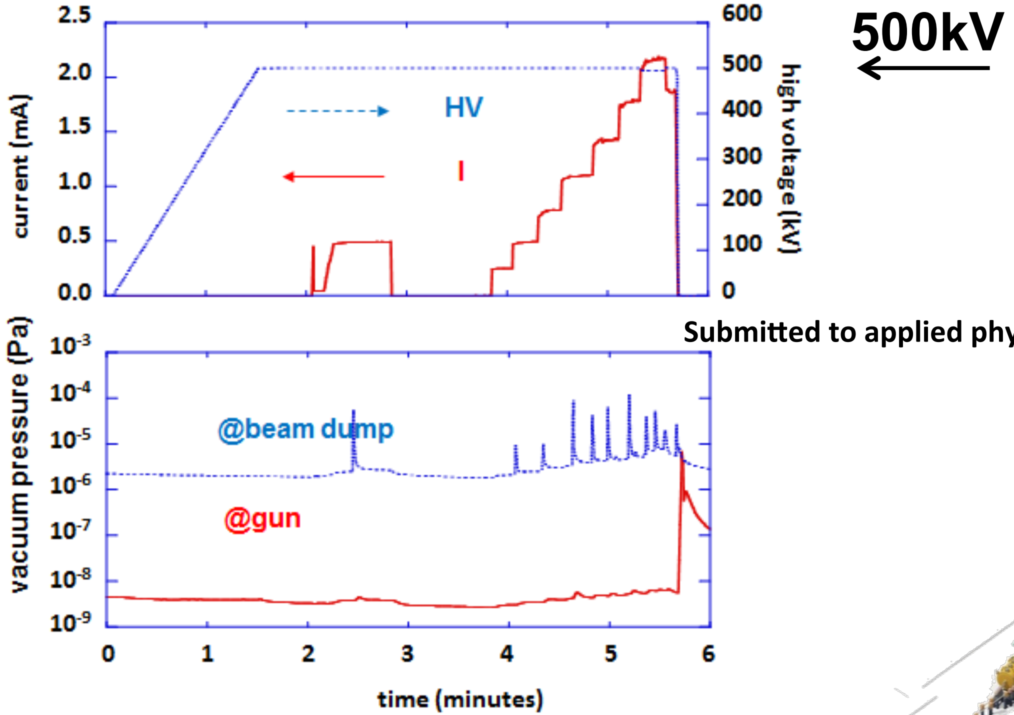
DC Guns are achieving design energy.
DC guns are generating extremely high average currents.
SRF Guns are operating user facilities (not at the final performance).
NC RF guns are generating high charge bunches at MHz repetition rate.
Hybrid DC-SRF guns are entering in their mature commissioning phase.

In what follows an overview of the recent field achievements is presented.

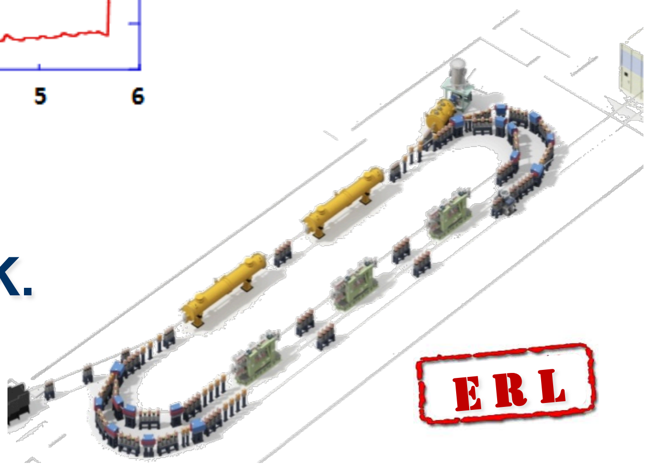
JAEA DC Gun

High voltage conditioning up to 550 kV with cathode electrode in place.
500keV electron beam generation with currents up to 1.8mA.





Submitted to applied physics letters.



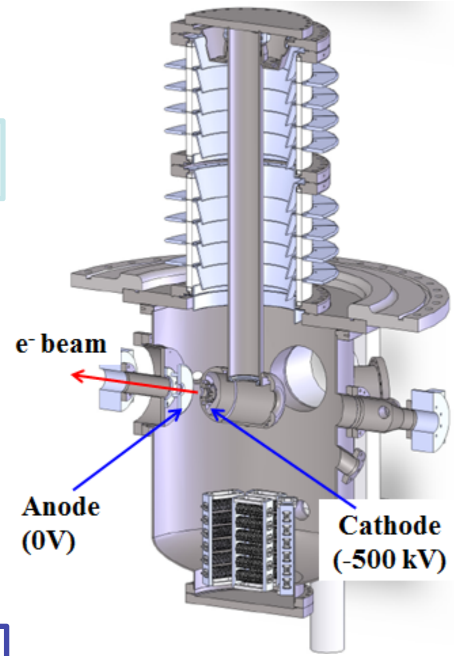
- The gun is now at the JAEA compact ERL at KEK. Running at 390 kV for beam commissioning.

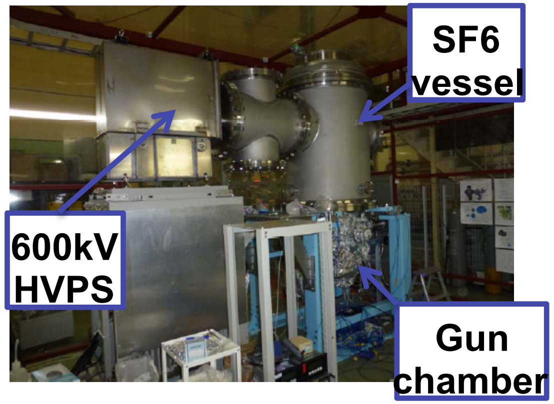
Courtesy of Nobuyuki Nishimori

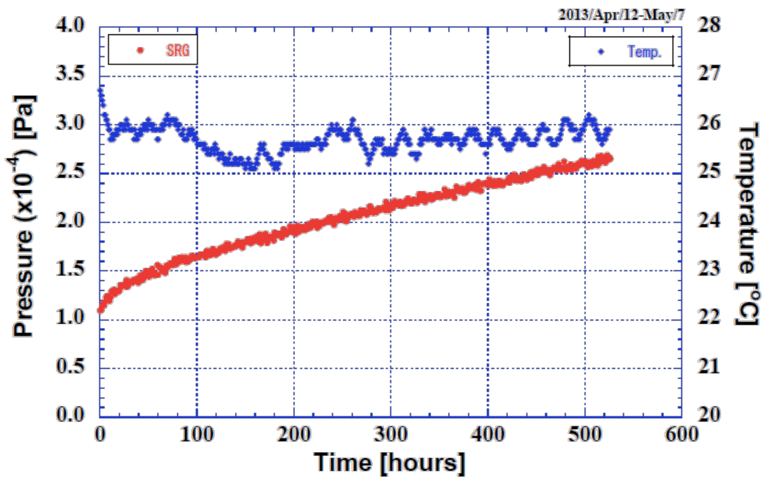
KEK DC Gun

- **KEK 2nd Gun**
  - Operation voltage: 500 kV (Maximum: 600 kV power supply)
  - Beam current: 10 mA (7.7 pC/bunch)
  - Individual HVPS test has been done up to 580 kV.
  - High voltage conditioning with electrodes is in progress.

KEK 2nd Gun



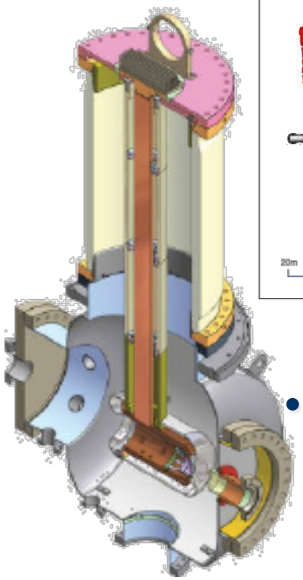


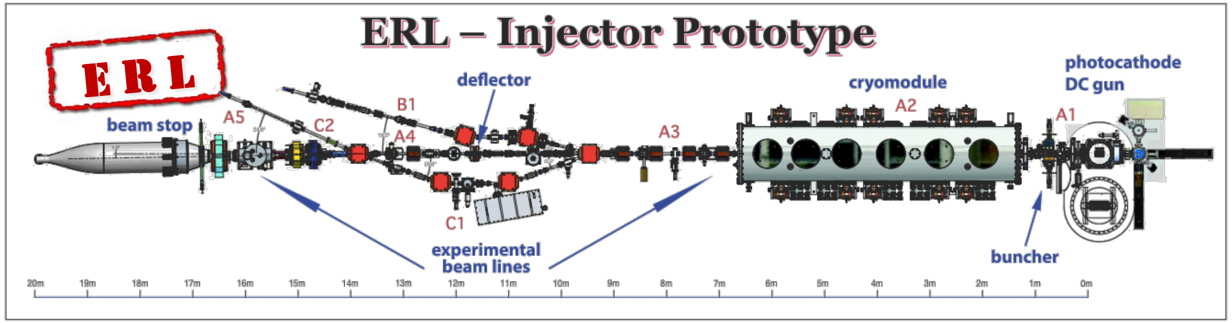


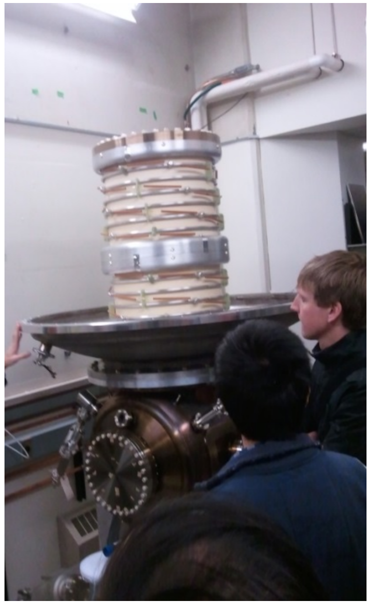
Total outgassing rate has been suppressed to 8.1×10^{-11} Pa m^3/s

Courtesy of Tsukasa Miyajima

Cornell DC Gun



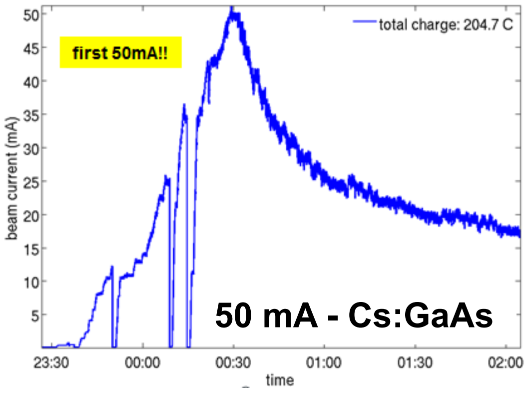


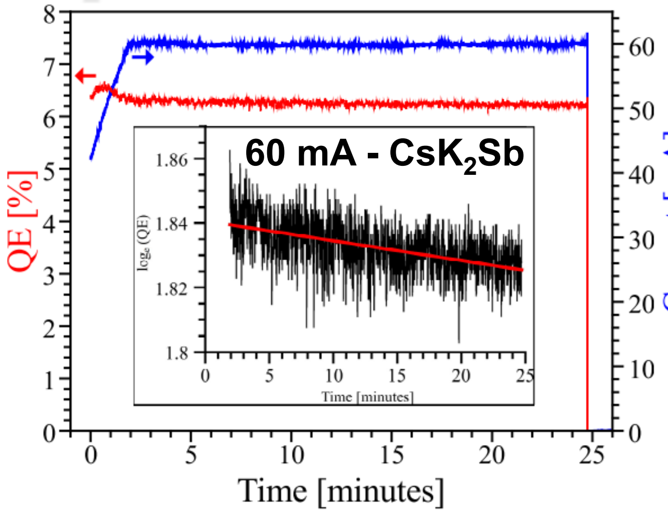


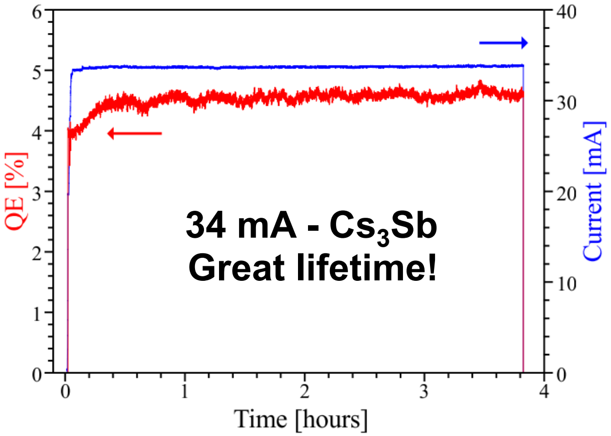
- Present beam energy: 350 kV
- New gun designed for 500kV under conditioning.

(Goal: 100 mA, 77 pC @ 1.3 GHz)

- Recently 75 ma with Na_2KSb. Great cathode achievements!





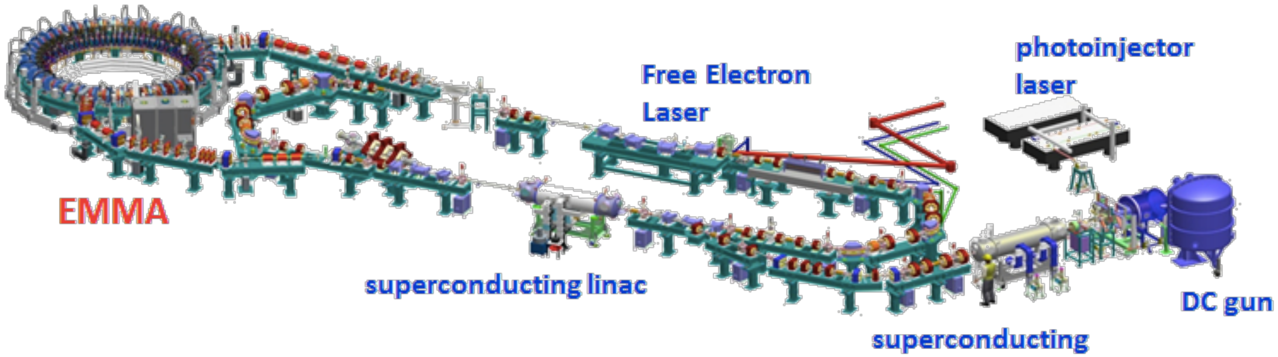


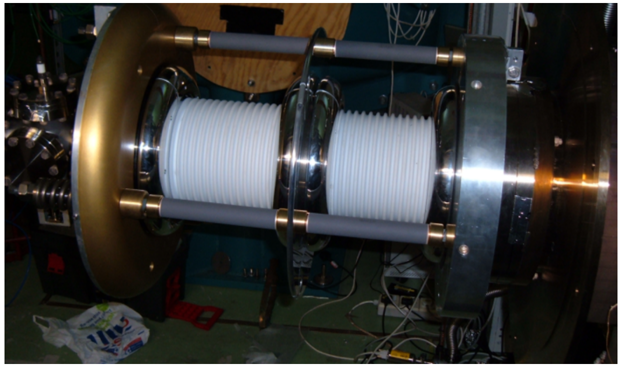
Courtesy of Bruce Dunham

*Dunham, *et al.*, Appl. Phys. Lett. 102, 034105 (2013).

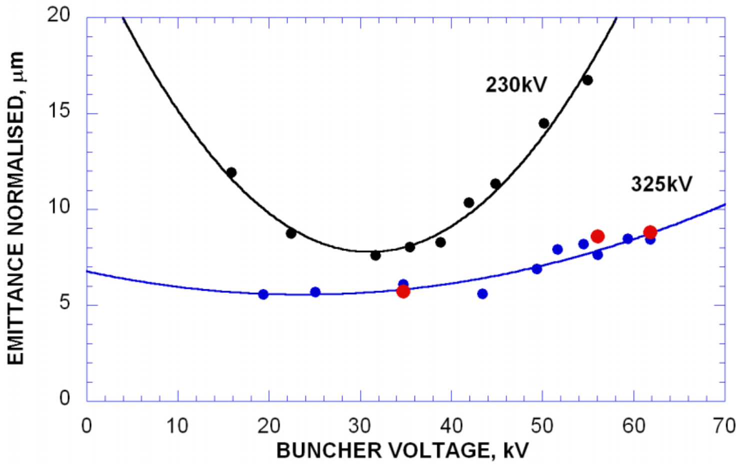
Alice DC Gun

ERL

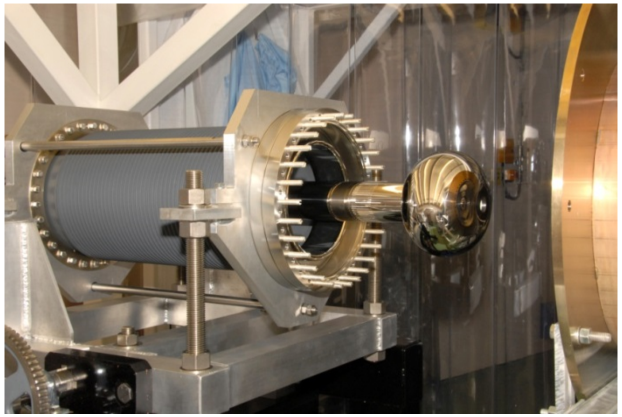




Pulse structure: 16-81MHz; 0-100μs, 1-10Hz
Bunch charge: 60pC



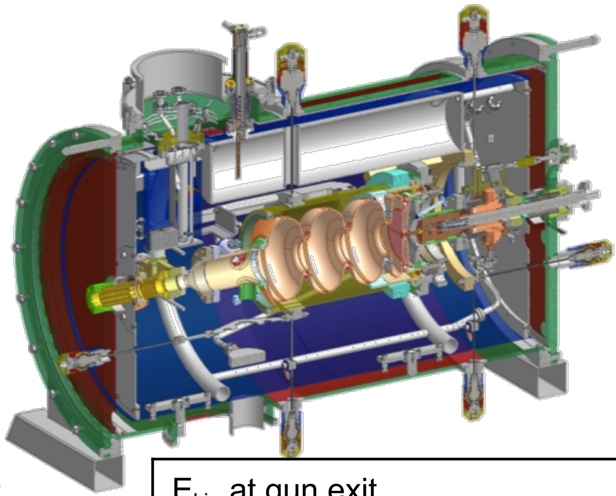
Alice
Accelerators and Lasers
In Combined Experiments



Horizontal normalised emittance v buncher voltage
Exit from booster; gun voltage 230kV and 325kV

Courtesy of Boris Militsyn and Yuri Saveliev

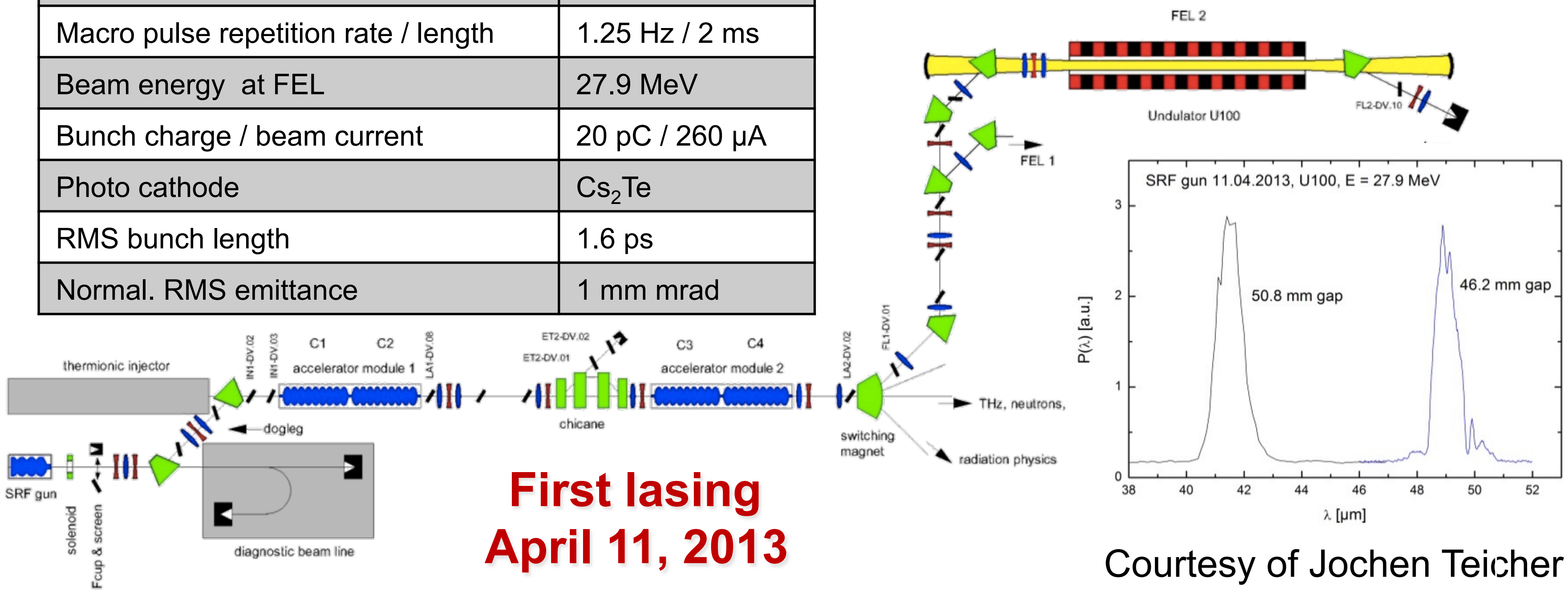
Rossendorf SRF Gun



- Present Cs_2Te cathode:
QE in gun 0.6%
total beam time 512 h
extracted charge 211 C

DRESDEN concept HZDR

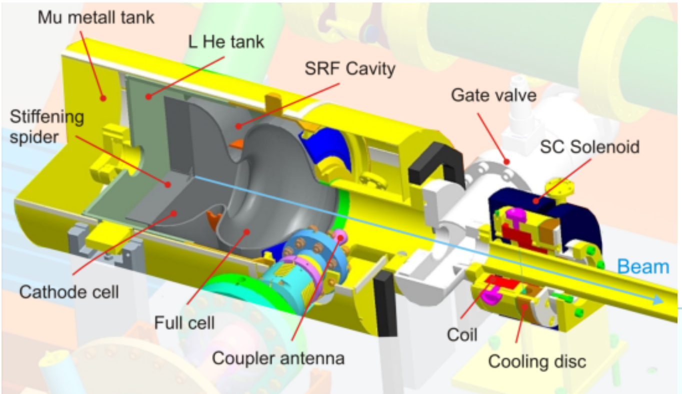
E_{kin} at gun exit	3.3 MeV
Micro pulse repetition rate	13 MHz
Macro pulse repetition rate / length	1.25 Hz / 2 ms
Beam energy at FEL	27.9 MeV
Bunch charge / beam current	20 pC / 260 μA
Photo cathode	Cs_2Te
RMS bunch length	1.6 ps
Normal. RMS emittance	1 mm mrad

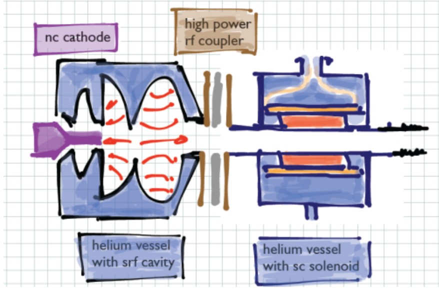


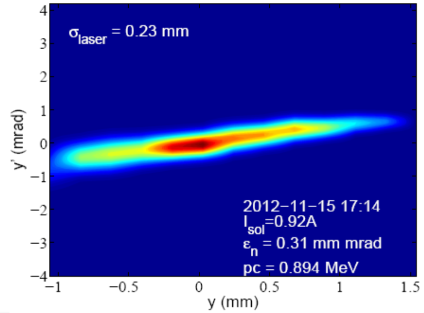
First lasing April 11, 2013

Courtesy of Jochen Teicher

HoBiCaT and BERLinPro SRF Gun







Gun0 tasks close to completion.

First beam demonstrated on April 2011.

SC Pb SC cathode physics and cleaning technique studies

Now focusing on the gun for the BERLinPro ERL

Cs_2Te cathodes.
4 mA first (2014)
100 mA finally (2016)

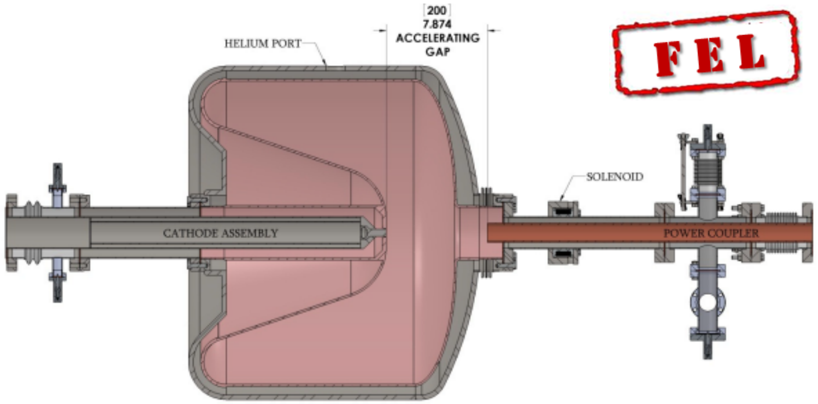
Courtesy of Thorsten Kamps

	Gun0 (HoBiCaT)	BERLinPro Gun
Goal	Beam Demonstration (First beam 04/2011)	Brightness (2014) and average current (2016)
Cathode material	Pb (SC)	CsK_2Sb (NC)
Cathode QE_{max}	1*10^-4@258 nm*	1*10^-2@532 nm
Drive laser wavelength	258 nm	532 nm
Drive laser pulse length and shape	2.5 ps fwhm Gauss	≤ 20 ps fwhm Gauss
Repetition rate	8 kHz	1.3 GHz
Electric peak field in cavity	27 MV/m*	≤ 20…30 MV/m
Operation launch field on cathode	7 MV/m*	≥ 10 MV/m
Electron exit energy	2.5 MeV*	≥ 2.3 MeV
Bunch charge	6 pC*	77 pC
Electron pulse length	2…4 ps rms*o	≤ 6 ps rms
Average current	50 nA*	100 mA
Normalized emittance	2 mm mrad* (proj.)	1 mm mrad (proj.) and 0.5 mm mrad (sliced)

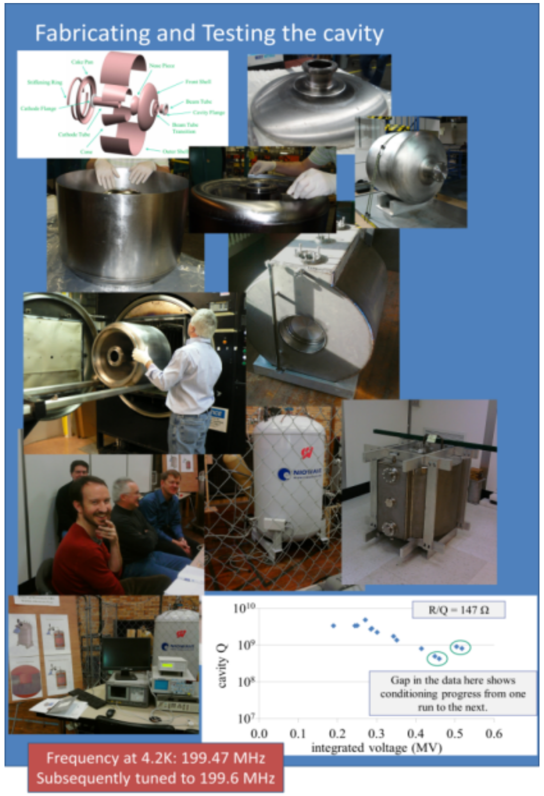
Wisconsin SRF Gun

FEL

PARAMETER	UNITS	
Temperature	K	4.2
Cavity frequency @ 4.2 K	MHz	199.6
Bunch charge, nominal	pC	200
Unloaded Q (Q0), nominal at nominal E Acc		2.5E9
Peak surface electric field, nominal	MV/m	53
Integrated electric field, at nominal Q0	MeV	3.96
Normalized $\varepsilon_{Transverse}$	mm-mr	<1
R/Q	Ω	147.9
Max transverse dimension	m	0.6
Cathode Aperture	cm	1.2
Cavity Mass (Nb)	kg	63.9
Dynamic heat loss at Peak surface electric field	W	39.2
Static Heat loss of cavity and dewar	W	15



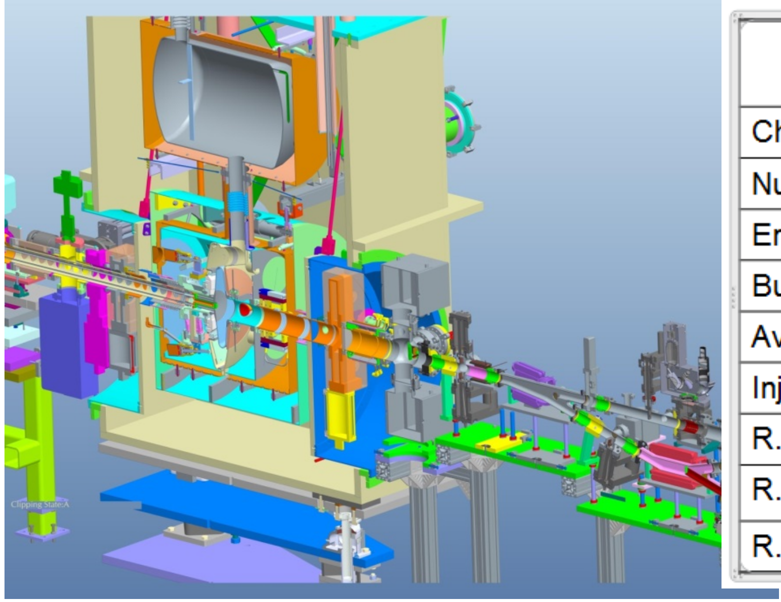
- Cold tests successfully performed at factory.
- RF conditioned at the factory up to 7 MV/m (RF source limited)
- In preparation for full power test



Courtesy of Joe Bisognano

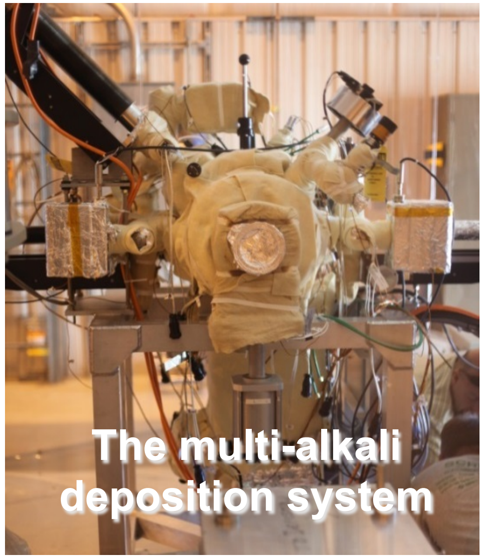
WISCONSIN UNIVERSITY OF WISCONSIN–MADISON   SRC Home of Aladdin   **DOE Award # DE-SC0005264**

BNL 704 MHz SRF Gun



ERL	High Current	High charge
Charge per bunch, nC	0.5	5
Numbers of passes	1	1
Energy maximum/injection, MeV	20/2.5	20/3.0
Bunch rep-rate, MHz	700	9.383
Average current, mA	350	50
Injected/ejected beam power, MW	1.0	0.15
R.m.s. Normalized emittances $\varepsilon x/\varepsilon y$, mm*mrad	1.4/1.4	4.8/5.3
R.m.s. Energy spread, $\delta E/E$	3.5×10^{-3}	1×10^{-2}
R.m.s. Bunch length, ps	18	31

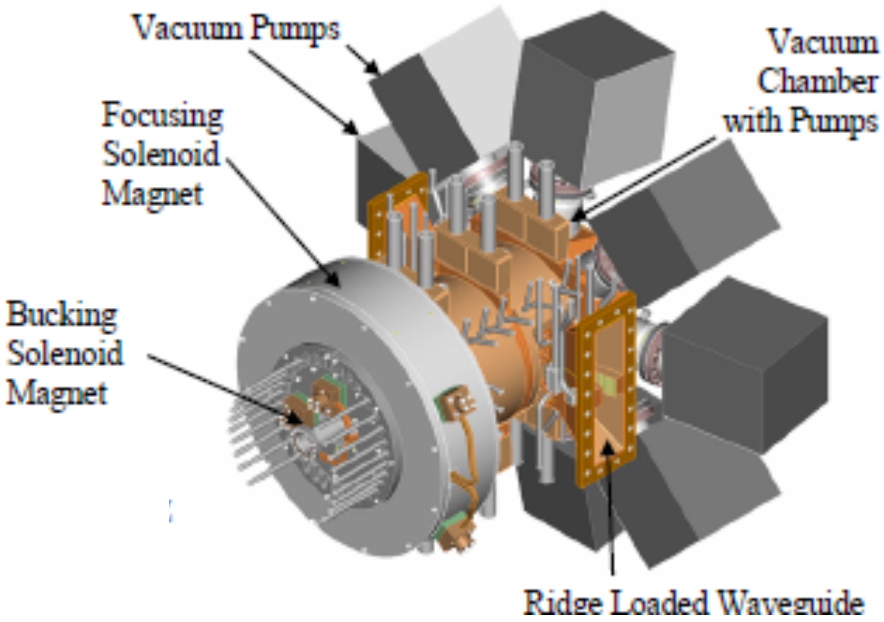
- **The gun has been conditioned to the design field of 2 MV/m.**
- **Measured rms amplitude /phase error 4.8×10^{-4} /0.07° at 1.5 MV.**



Courtesy of Ilan Benz-Vi

LANL/AES
NC CW 700 MHz Gun

FEL



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.

Many hundreds of kW dissipated in the glidcop structure.

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

RF conditioning successfully completed.

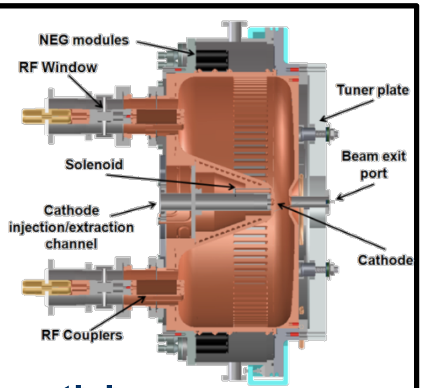
Several photocathode tests under way

Courtesy of D. Nguyen and B. Carsten

The LBNL CW NC VHF gun

High-brightness high-duty cycle electron injectors (F. Sannibale)

VHF Gun achieved milestones:

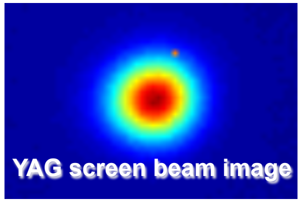


- CW operation capability.
- Excellent RF Performance (no problem in achieving design fields).
- Electron beam design energy (with margin).
- Excellent vacuum performance in terms of absolute pressure and contaminant molecules partial pressures.
- "Dark" current in line with performance of existing gun. (promising active solution to remove dark current under study).
- Excellent reliability and ease of operation.

Gun technology and scheme fully demonstrated.

F. Sannibale, *et al.*, PRST-AB 15, 103501 (2012)

Photocathode achieved milestones:



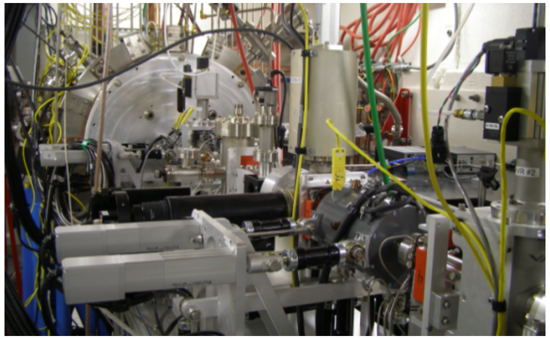
YAG screen beam image

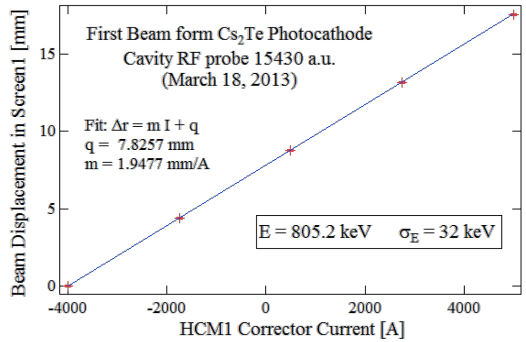
- Cs_2Te generating **hundreds of pC** charge/bunch at **MHz repetition rate**.
- Initial results indicate a performance of Cs_2Te compatible with MHz operation with the charge/bunch required by high repetition rate X-ray FELs.

Near Future Plans:

- Test of CsK2Sb cathodes.
- 6D phase space characterization at the gun energy.

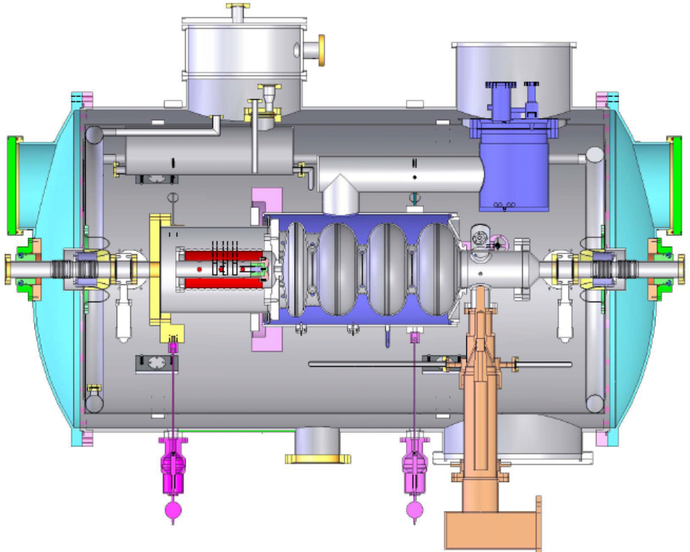
Frequency	186 MHz
Operation mode	CW
Gap voltage	750 kV
Field at the cathode	19.47 MV/m
Q_0 (ideal copper)	30887
Shunt impedance	6.5 MΩ
RF Power @ Q_0	87.5 kW
Stored energy	2.3 J
Peak surface field	24.1 MV/m
Peak wall power density	25.0 W/cm^2
Accelerating gap	4 cm
Diameter/Length	69.4/35.0 cm
Operating pressure	~ 10^{-10}-10^{-9} Torr



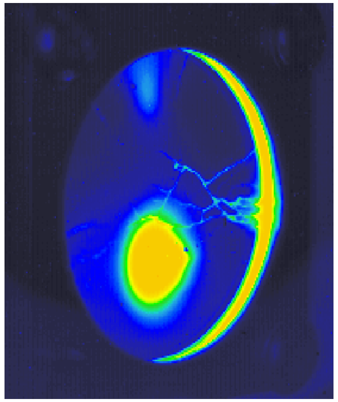


Peking University DC-SRF Gun

❖ 100 KV Pierce DC gun with Cs_2Te cathode matched with SRF cavity



Courtesy of Jiankui Hao



Latest test result (2012-2013)

- Eacc~13 MV/m (CW, w/o beam)
  ~17 MV/m (Pulsed, w/o beam)
- Beam current ~500μA (macro pulse)
- Beam energy ~2.5 MeV
- Beam line is in upgrading
- 2 K beam loading experiment

Drive laser		
Pulse length（FWHM）	8ps	
laser spot（FWHM）	3.0mm	
Repetition rate	81.25MHz	
Bunch shape	uniform transverse distribution Gaussian temporal distribution	
Injector	ERL mode	THz mode
gradient	13 MV/m	15MV/m
Bunch charge	100 pc	20pc
energy	5MeV	<5MeV
Transv. emittance (rms)	1.4mm·mrad	2.1 mm·mrad
Long. emittance (rms)	15 deg—KeV	3.0deg—KeV
Bunch length（rms）	3ps	0.55ps
Rms beam spot	0.3mm	1.7mm
Energy spread	~0.5%	0.55%

Acknowledgements

A sincere "thanks!" to the colleagues that shared their work information and contributed to put together this talk.