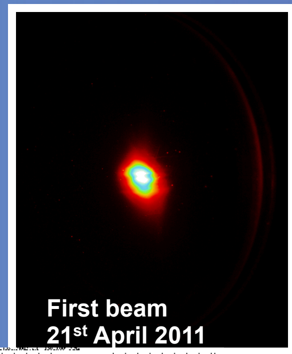
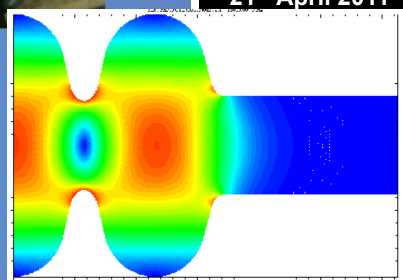
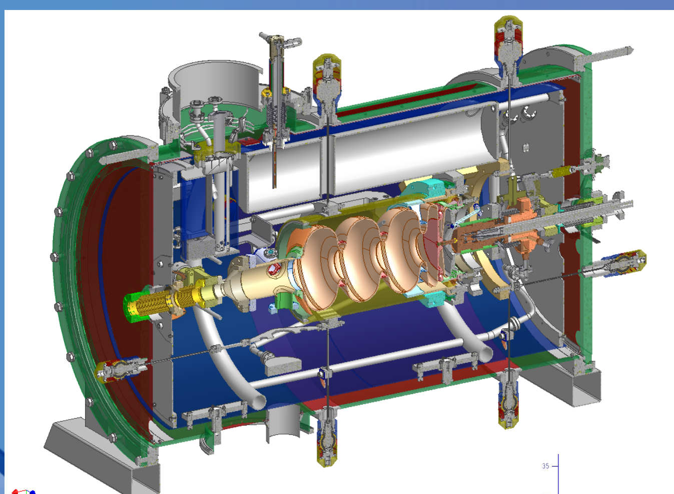


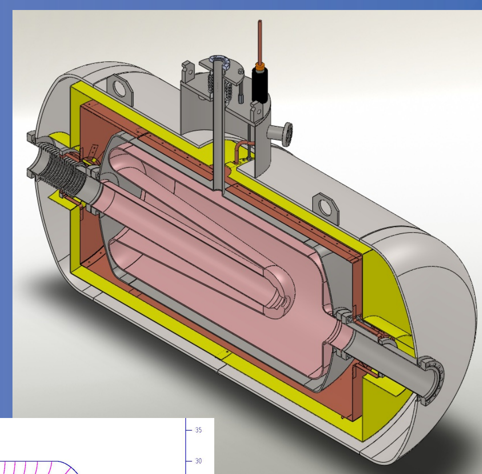


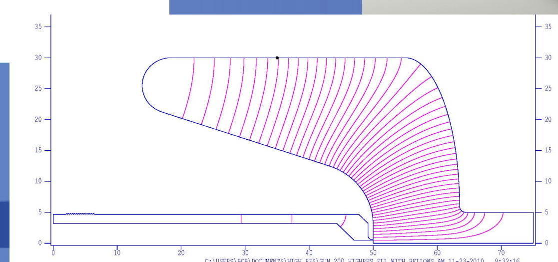
Survey of SRF guns

Sergey Belomestnykh
Collider-Accelerator Department, BNL

July 25, 2011







SRF Conference
Chicago • July 25-29, 2011

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Talk outline

- Overview: Advantages and challenges of the SRF gun technology
- SRF gun types
- Cathode type
- Description of particular projects, recent achievements
- Summary

Overview

- Superconducting RF has become the technology of choice for accelerating systems of many high-intensity accelerators. As the technology has matured, it is now finding other applications.
- One of such applications is photocathode RF guns. SRF has advantage over other electron gun technologies in CW mode of operation, where it potentially can provide higher rate of acceleration, generating high-charge bunches and high average beam currents.
- The first SRF guns were based on elliptic cavity geometries (conventional shapes of high-β SRF cavities).
- Quarter Wave Resonator (QWR) option is gaining popularity. QWRs are especially well suited for producing beams with high charge per bunch.
- After brief review of the gun and photocathode types, we will describe particular projects and their recent achievements: DC-SRF at PKU (FRIOB02); elliptical guns at Rossendorf (MOPO004, TUPO019), BERLinPro (FRIOA07), and BNL ERL; QWR guns at BNL, (MOPO054, TUPO010), NPS, and UW gun (MOPO032).

Challenges and issues

- SRF guns are based on merging several complex technologies: high QE photocathodes, superconducting RF, high repetition rate synchronizable lasers.
- Among the challenges imposed by these technologies are maintaining UHV environment for the cathodes, maintaining cleanliness of the cavity RF surfaces while allowing operation and replacement of the cathodes, designing low RF loss and low heat leak interface between the cold cavities and warmer cathodes, synchronizing high repetition rate lasers with RF.
- **Low emittance**: high acceleration rate; focusing near cathode; first solenoid as close to the cavity as possible; precise synchronization of a laser with RF; transverse and temporal bunch shaping.
- **High bunch charge at high repetition rate**: high QE photocathode with long life time; high average power, high repetition rate lasers.
- **Semiconductor (or other high QE) photocathodes able to operate in SRF cavity environment**: at least one type of photocathodes, Cs_2Te, was demonstrated to have long lifetime, more studies needed for other types.
- **Cavity preparation.** Etching/cleaning a cavity with small opening on one side is challenging. Effect of the NC cathodes on SRF performance is still unclear.
- **Demonstrate stable operation in an accelerator**. High RF power, coupler kick, HOM excitation.

SRF gun types

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **14**, 024801 (2011)

Overview on superconducting photoinjectors

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TABLE I. Comparison of all presently known SRF gun projects and whose expected parameters. Most of the information was provided by the expert named first in the last row. Values taken from other references are additionally marked by an index in the table. Values marked by # are calculated out of V_C and U and those that are marked by * are calculated using P_{diss} and Q_0. Still open parameters are filled in with tbd (to be determined).

		Elliptical cavity + NC cathodes			DC-SC	Quarter wave SRF guns			Elliptical cavity + SC cathodes	
						NPS	WiFEL	BNL		
Parameter	Units	FZD	BNL/AES	HZB BerlinPro	PKU gun	500 MHz	200 MHz	112 MHz	Pb/Nb hybrid gun	HZB HoBiCat
Beam kinetic energy, V_c	MeV	9.4	2	≤ 3.5	5	1.2	4.58	2.7	~5	≤ 3.5
Maximum bunch charge, q_{max}	nC	1/0.077	$5/1.4^{(1)}/0.7$	0.077	0.1	1	0.2	5	1	0.015
Normalized transverse emittance, $\varepsilon_{n,t}$	mm mrad	2.5/1	$5/2.3^{(1)}/1.4$	1	1.2	4	0.9	3	1	1
Average beam current, I_b	mA	0.5/1	$50/500^{(1)}/500$	100	1–5	1	1.0	50	<1 rather 0.1	0.0045
Peak current, I_{pk}	A	67/20	$166/70^{(1)}/35$	5	20	50	50	18.5	50	6
Photocathode		Cs_2Te	CsK_2Sb	CsK_2Sb	Cs_2Te	tbd	Cs_2Te	tbd	Pb	Pb
Quantum efficiency, QE	%	1	18	10	1–5	tbd	1	tbd	0.0017	5×10^{-2}
Driving laser wavelength, λ	nm	263	355	527	266	tbd	266	tbd	213	260
Pulse duration (FWHM)	ps	15/4	$30/20^{(1)}/20$	≤ 20	5	10–40	4	270	<20	2 to 3
Bunch repetition rate, f_{rep}	MHz	0.5/13	$10/352^{(1)}/704$	≤ 1300	81.25	10^{-5}–100	5	9.4	<1 rather 0.1	0.030
Gun frequency, f_0	MHz	1300	703.75	1300	1300	500	200	$112^{(1)}$	1300	1300
Operating temperature	K	2	2	2	2	4.2	4.2	$4.2^{(1)}$	2	2
Dissipated power, P_{diss} at the intrinsic Q_0 of	W	26 @ 1×10^{10}	4.2 @ 1×10^{10}	$12.1^{(3)}$ @ 1×10^{10}	...	8.6 @ 9.5×10^{8}	42 @ 3.2×10^{9}	$16.6^{(1)}$ @ 3.5×10^{9}	143 @ 5×10^{9}	$12.1^{(3)}$ @ 1×10^{10}
Active cavity length, l_{activ}	cm	50	9.5	17.1	41.7	8	19	20	18.4	17.1
R_{shunt}/Q_0, r (R_{shunt} from accelerator definition)	Ω	334	96 / $95.5^{\#}$	$189^{(4)}$, $\beta = 1$ / $101.4^{\#}$	418, $\beta = 1$	185, $\beta = 1$ / $176.3^{\#}$	$155.7^{\#}$	$126.8^{(1)}$ / $126.6^{\#}$	170, $\beta = 1$ / $35.2^{\#}$	189, $\beta = 1$ / $101.4^{\#}$
Transit time factor, V_c/V_0	TTF	0.715	$0.888^{(2)}$	$0.54^{(3)}$	$0.74^{(4)}$	0.94	0.87	$0.99^{(1)}$	...	$0.54^{(3)}$
Stored energy at E_{pk}, U	J	32.4	$8.4/9.5^{*}$	$14.8^{(3)}$	...	2.6	107.2	81.4^{*}	87	$14.8^{(3)}$
Electric cathode field E_{cath}	MV/m	30	20	≥ 10	$\sim 5^{(4)}$	25	45	$19.7^{(1)}$	50–60	≥ 10
Peak electric field, E_{pk}	MV/m	50	35.7	≤ 50	31.8	44	59	51.0	50–60	≤ 50
Peak magnetic flux, B_{pk}	mT	110	74	116	74.5	69.1	90.7	$97.8^{(1)}$	104–125	116
Peak magnetic field, H_{pk}	A/m	87 535	59 000	$\leq 92\,600$	59 285	55 000	72 165	78 000	$(87–99) \times 10^3$	$\leq 92\,600$

Elliptical + NC cathodes

DC-SC

QWRs

Photocathode types

Cathode R&D for future light sources☆

D.H. Dowell[a,*], I. Bazarov[b], B. Dunham[b], K. Harkay[c], C. Hernandez-Garcia[d], R. Legg[e], H. Padmore[f], T. Rao[g], J. Smedley[g], W. Wan[f]

Nuclear Instruments and Methods in Physics Research A 622 (2010) 685–697

Metal photocathodes

Table 2
Properties of metal photocathodes.

Metal cathodes	Wavelength & energy: λ_{opt} (nm), $\hbar\omega$ (eV)	Quantum efficiency (electrons per photon)	Vacuum for 1000 h operation (Torr)	Work function, ϕ_W (eV)	Thermal emittance (microns/mm(rms))	
					Eq. (3)	Expt.
Bare metal						
Cu	250, 4.96	1.4×10^{-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	6.4×10^{-4}	10^{-10}	3.6 [41]	0.8	0.4 ± 0.1 [41]
Pb	250, 4.96	6.9×10^{-4}	10^{-9}	4.0 [34]	0.8	?
Nb	250, 4.96	$\sim2\times10^{-5}$	10^{-10}	4.38 [34]	0.6	?
Coated metal						
CsBr:Cu	250, 4.96	7×10^{-3}	10^{-9}	~2.5	?	?
CsBr:Nb	250, 4.96	7×10^{-3}	10^{-9}	~2.5	?	?

The thermal emittances are computed using the listed photon and work function energies in Eq. (3) and expresses the thermal emittance as the normalized rms emittance in microns per rms laser size in mm. The known experimental emittances are given with references.

Diamond-amplified photocathodes

Semiconductor photocathodes

Table 3
Properties of semiconductor cathodes.

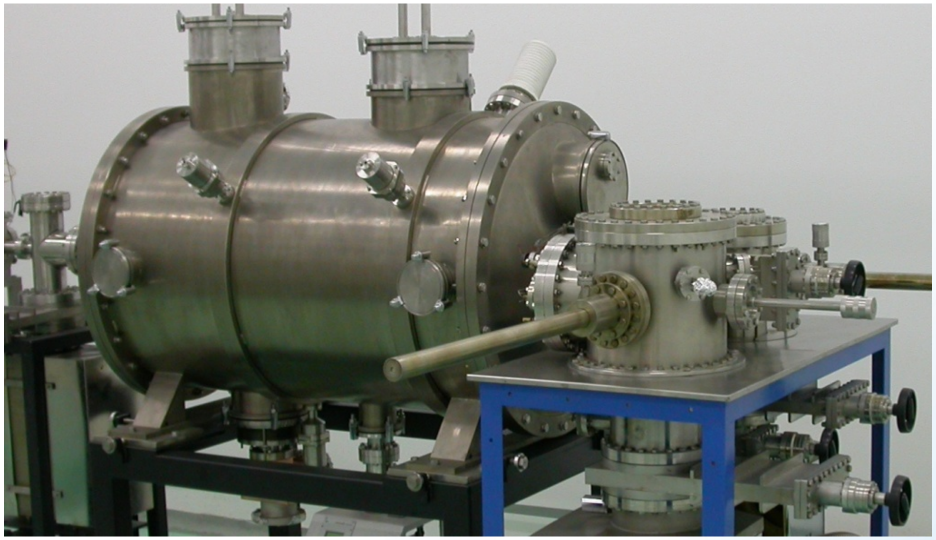
Cathode type	Cathode	Typical wavelength & energy, λ_{opt} (nm), (eV)	Quantum efficiency (electrons per photon)	Vacuum for 1000 h (Torr)	Gap energy+electron affinity, E_G+E_A (eV)	Thermal emittance (microns/mm(rms))	
						Eq. (7)	Expt.
PEA: mono-alkali	Cs_2Te	211, 5.88	0.1	10^{-9}	3.5 [42]	1.2	0.5 ± 0.1 [35]
		264, 4.70	–	–	"	0.9	0.7 ± 0.1 [35]
		262, 4.73	–	–	"	0.9	1.2 ± 0.1 [43]
	Cs_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	?
	$(Cs)Na_3KSb$	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	0.1	?	1.4 ± 0.1[42]	0.8	0.44 ± 0.01[44]
		860, 1.44	0.1	?		0.2	0.22 ± 0.01[44]
	GaN(Cs)	260, 4.77	0.1	?	1.96+?[44]	1.35	1.35 ± 0.1[45]
	GaAs(1−x)Px x~0.45 (Cs,F)	532, 2.33	0.1	?	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	?

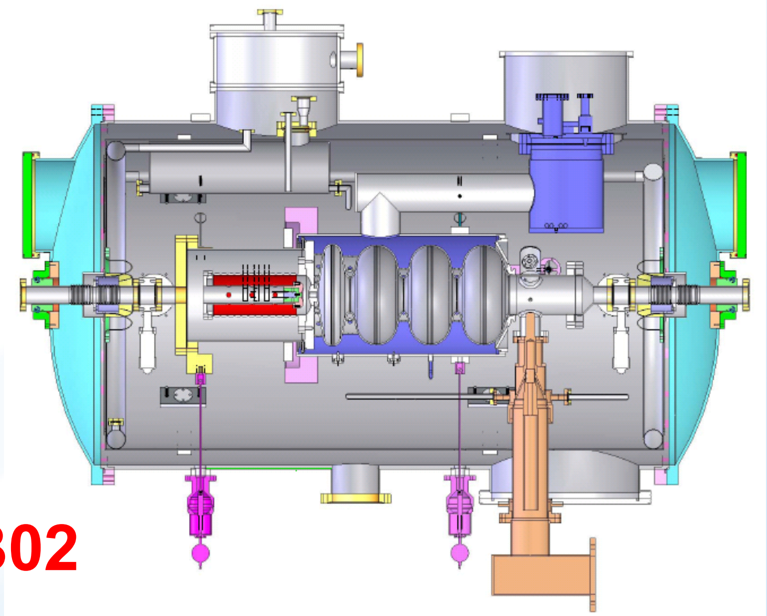
The thermal emittances are computed using the listed photon, gap and electron affinity energies in Eq. (7) and expresses the thermal emittance as the normalized rms emittance in microns per rms laser size in mm.

3.5-cell DC-SRF photoinjector at Peking University

- Core elements: 100 kV Pierce gun and 3.5-cell superconducting cavity operating at 2 K.
- A candidate to provide electron beam with low emittance, high average current and short bunch length.

Drive laser	
Pulse length	8 ps
Spot radius	3 mm
Repetition rate	81.25 MHz
Bunch shape	Transverse: uniform, Longitudinal: Gaussian
3 ½ superconducting cavity	
Accelerating gradient	13 MV/m
Electron bunch	
Charge/bunch	100 pc
Energy	5.0 MeV
Emittance	1.2 μm (rms)
Longitudinal emittance	14 deg-KeV (rms)
Bunch length	2.38 ps (rms)
Beam size	0.4 mm (rms)
Energy spread	~0.5%

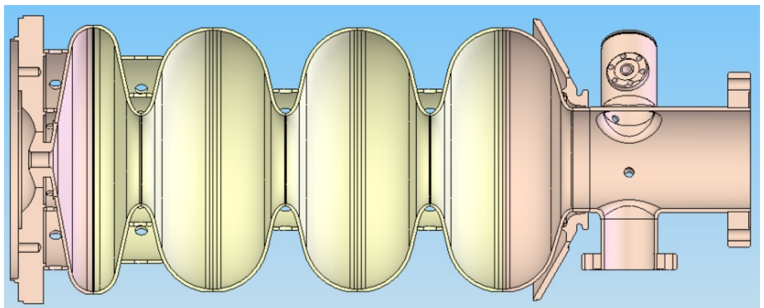


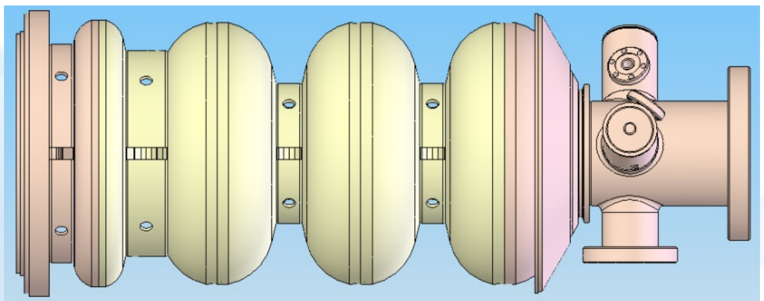


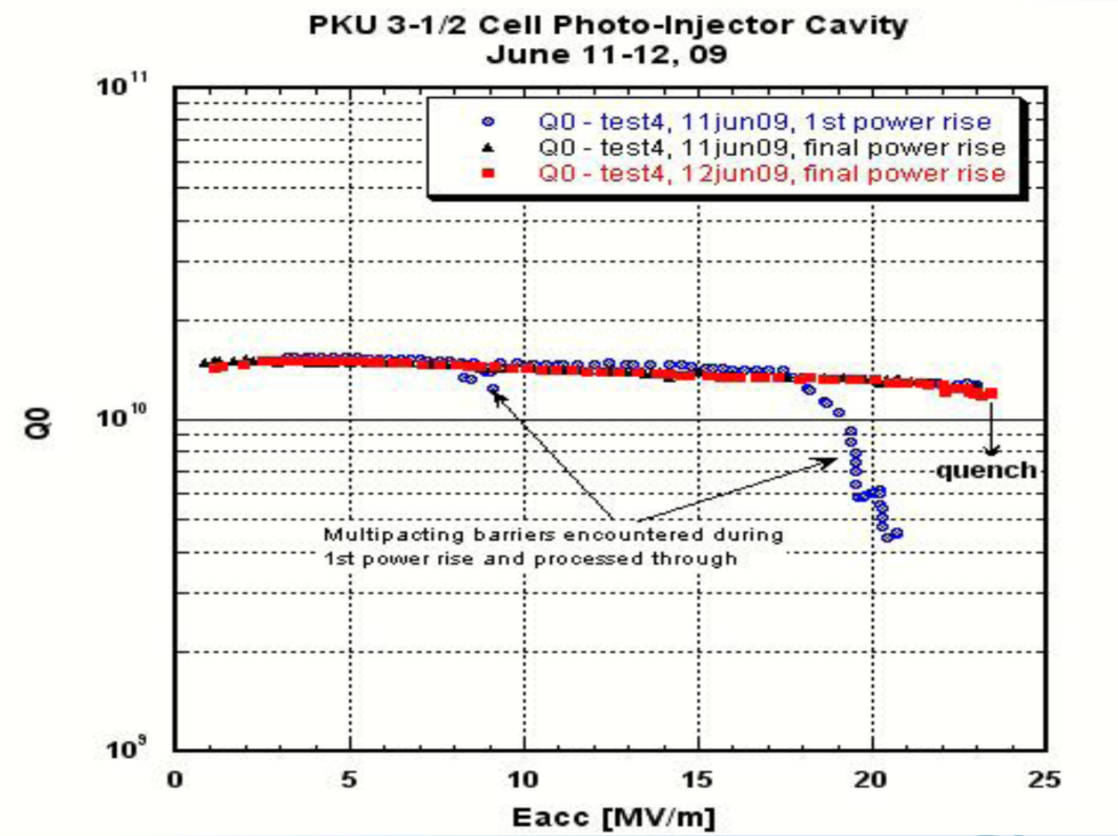
FRIOB02

SRF gun status

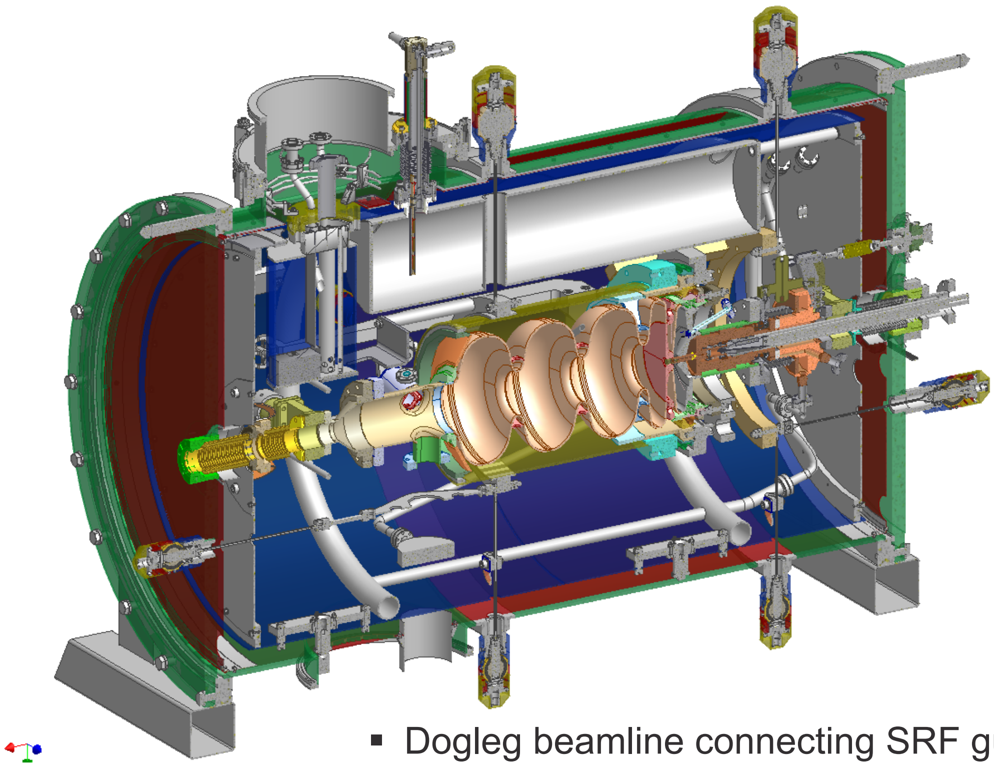
- Good performance during vertical cavity test.
- The cryogenic system is operational, providing 2 K LHe to the 3.5-cell superconducting cavity.
- Accelerating gradient of 11.5 MV/m at Q_{ext} of 6×10^6 was achieved during horizontal cold test, limited by available RF power.
- Beam test of DC-SRF injector is in progress.

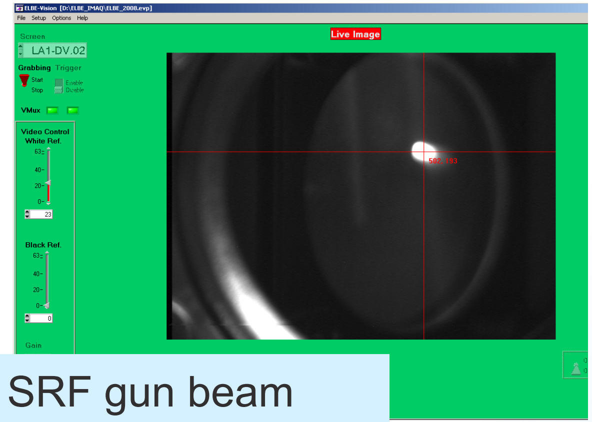






SRF gun for ELBE at HZDR





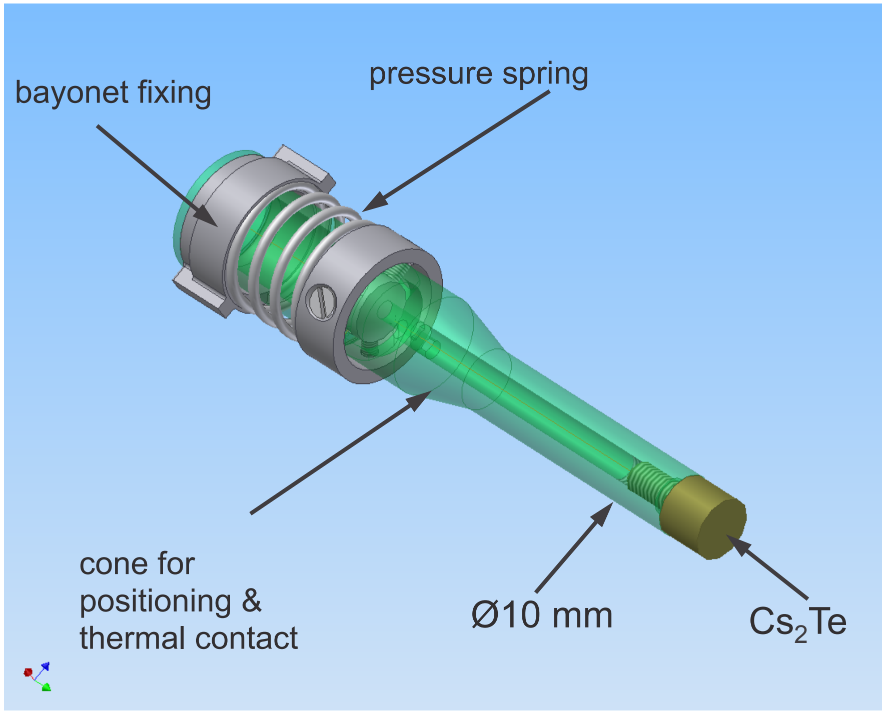
First SRF gun beam
in ELBE on Feb. 5, 2010

- Maximum bunch charge injected and accelerated in ELBE: 120 pC @ 50 kHz (6 μA);
- with 100% transmission: 60 pC @ 125 kHz.

- Dogleg beamline connecting SRF gun to to ELBE installed and commissioned.
- **The first SRF gun in the world to inject beam into an accelerator**.
- Very good performance of Cs_2Te photo cathodes demonstrated (life time of 1 year)
- CW operation of the gun still with the the accelerating gradient of 6 MV/m (3 MeV kinetic energy), 16 MV/m peak.
- In 2011 used pulsed RF with 8 MV/m (4 MeV kin. energy), 21.6 MV/m peak field.
- In summer 2011 the new laser with 13 MHz rep rate will be delivered; up to now the rep rates <= 125 kHz.
- The new fine grain cavity reached 35 MV/m peak field during cold test at JLab.

MOPO004, TUPO019

Photocathode



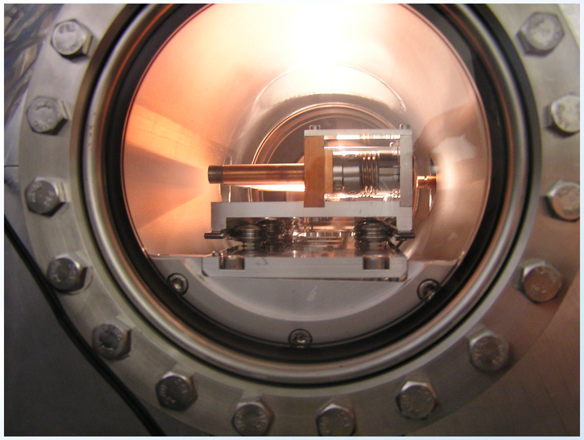
Use of semiconductor photo cathodes like Cs_2Te requires maintaining vacuum of 10^{-9} mbar during preparation, transport, storage and operation.

After several improvements the photo-cathode with QE of ≈ 1% demonstrates very long life time.

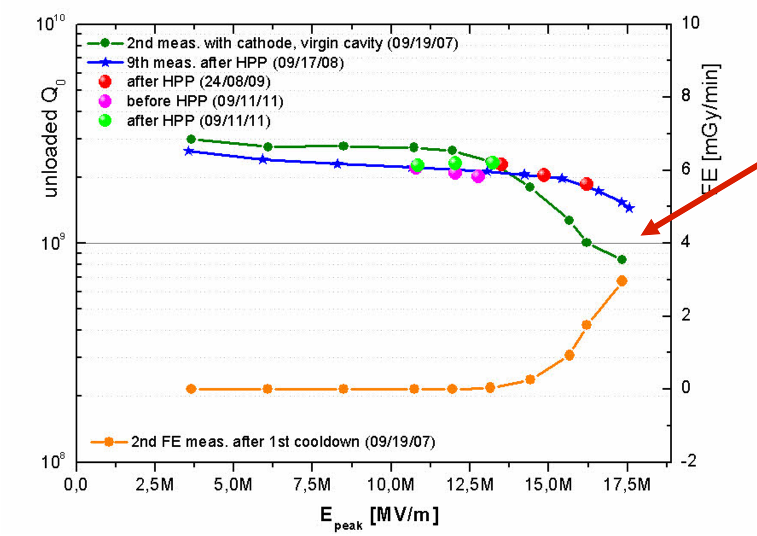
Cathode #250310Mo, in use since May 5, 2010. As of December 2010:

834 h beam time

34.4 C extracted charge

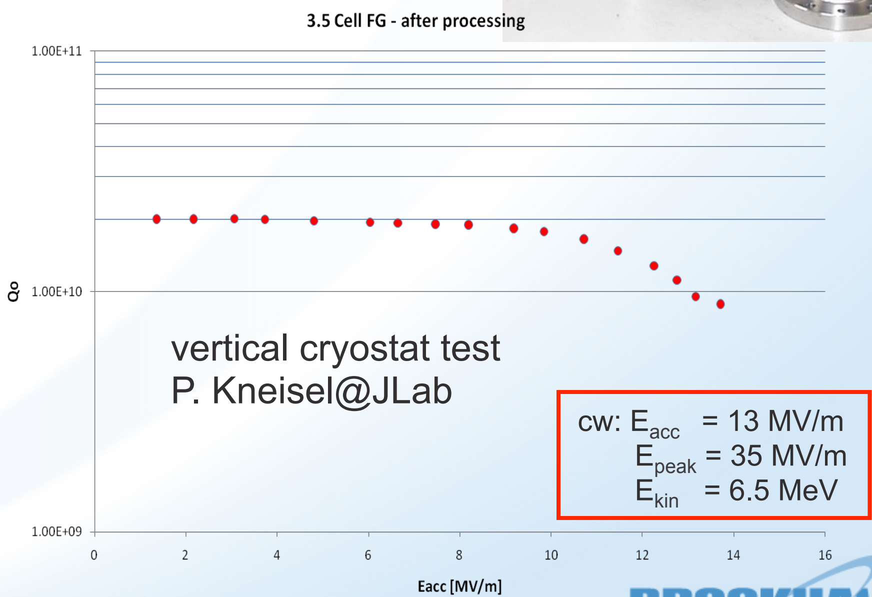


Gun cavity performance



CW max. 16 MV/m peak field
= 6 MV/m acc. gradient
= 3 MeV beam energy
Pulsed: 8 Mv/m -> 4 MeV

Cavity gradient strongly influences
- beam energy
- maximum bunch charge
- beam quality like trans. & long. emittance



- Operational stability

12 h shift stable operation has been demonstrated
- laser synchronization is OK
- laser pulse energy fluctuation -> laser upgrade
- RF instabilities (spikes)? -> cathode shaping for multipacting suppression

SRF guns for BERLinPro at HZB

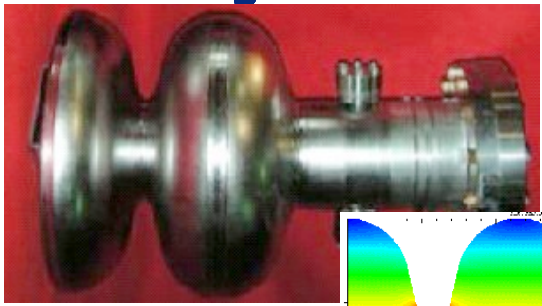
FRIOA07

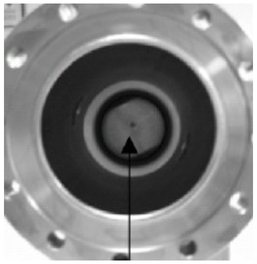
- Performance reqs for BERLinPro:
  - Beam dynamics: need good control on the transverse and longitudinal beam parameters. Mainly determined by field on cathode and setup of focusing elements.
  - Average current of 100 mA: need cathode with high QE, which can operate in SRF environment.
  - Average power: need to couple P_{avg} = 100 mA x E_b power into the cavity.
- Accordingly, three stages:
  1. Gun0 is a beam demonstrator experiment with SC Pb cathode (2011), study beam dynamics, cavity performance.
  2. For Gun1 add NC cathode with high QE at VIS, study cathode lifetime, slice/projected emittance performance (2013).
  3. For Gun2 add RF input power coupler for 200 kW (2014), study high power operation.

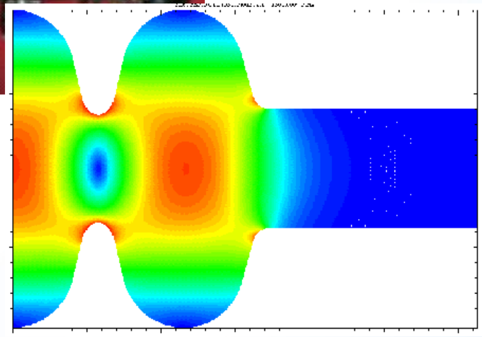
	HoBiCaT Gun0	**Source lab Gun1**	**BERLinPro Gun2**
Goal	Beam Demonstrator	Brightness R&D gun	Current Production gun
Electron energy	≥ 1.5 MeV		
RF frequency	1.3 GHz		
Design peak field	≤ 50 MV/m		
Operation launch field	≥ 10 MV/m		
Bunch charge	≤ 77 pC		
Repetition rate	30 kHz	54 MHz / 25 Hz	1.3 GHz
Cathode material	Pb	CsK_2Sb	CsK_2Sb
Cathode QE	$5*10^{-4}$	10^{-1}	10^{-1}
Laser wavelength	258 nm	532 nm	532 nm
Laser pulse energy	0.15 µJ	1.8 nJ	1.8 nJ
Laser pulse shape	Gaussian	Flat-top	Flat-top
Laser pulse length	2.5 ps FWHM	≤ 20 ps	20 ps
Average current	0.5 µA	≤10 mA / 0.1 mA	100 mA

Gun0: hybrid Nb/Pb gun cavity

- Utilizes a thin Pb film on the back wall of the cavity as photo-electron emitter.
- Pb is a type I superconductor with H_{crit} = 8 mT at 1.3 GHz and 2 K, and has QE at least one order of magnitude higher than bare Nb.
- Collaborative effort:
  - J. Sekutowicz and HZB made engineering design
  - P. Kneisel built, tested and prepared the cavity to be ready for beam tests at HoBiCaT
  - R. Nietubyc coated back wall of the cavity with Pb film.
  - HZB prepared HoBiCaT for beam tests

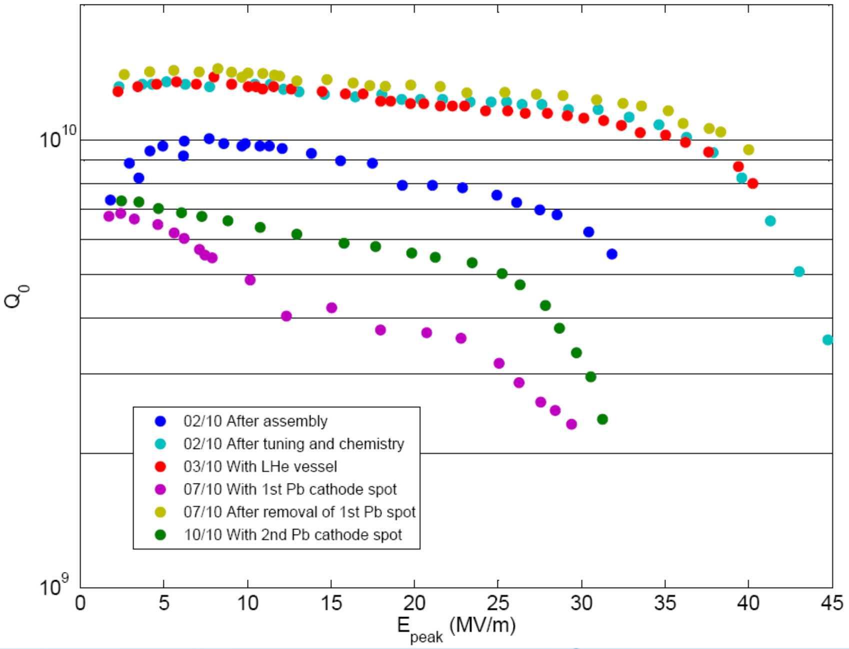




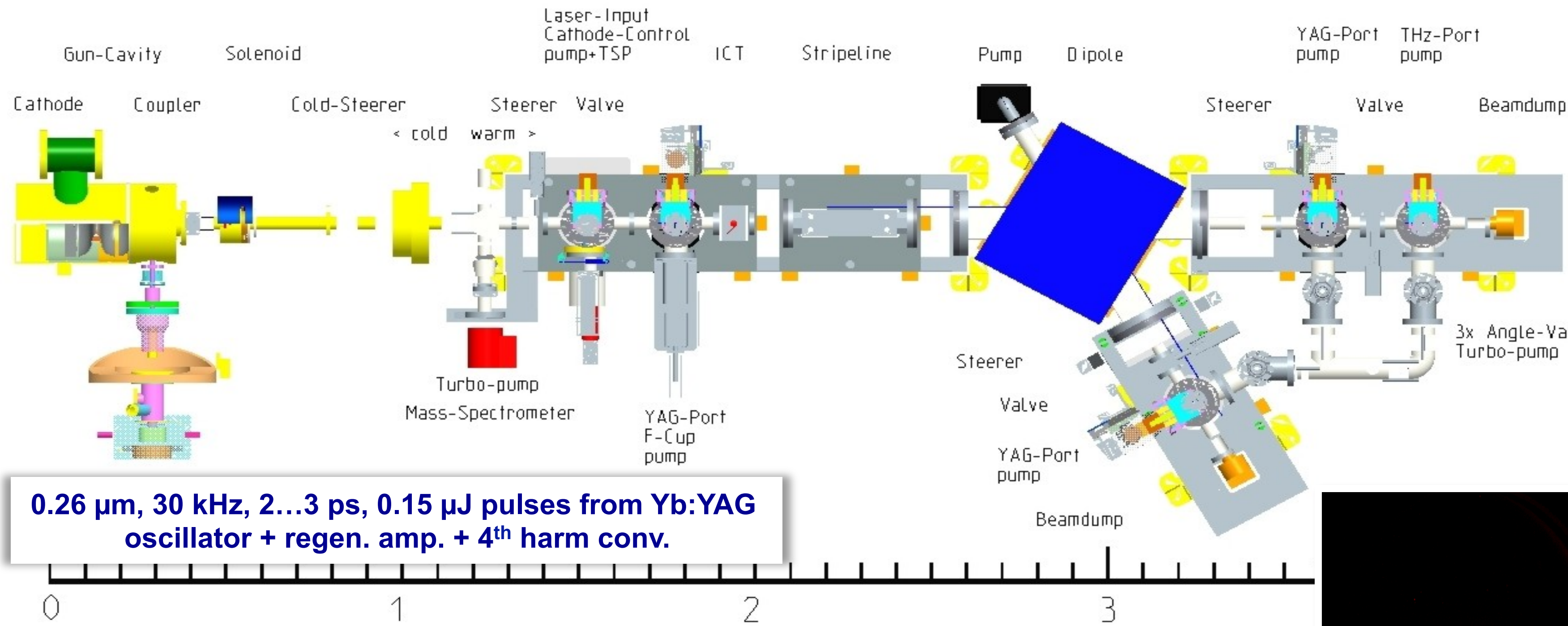


02/10 Initial test after assembly, tuning, BCP etching and rinsing of the cavity. The field flatness was only 66%.
02/10 Further tuning improved field flatness to 94%, the following BCP treatment improved the RF performance.
03/10 After installation of the helium vessel, limitation by moderate field emission.
07/10 With first cathode coating
07/10 Test after accidental loss of lead cathode and removal of remnants by grinding and BCP.
10/10 With second cathode coating

Results from vertical tests at JLAB in 2010

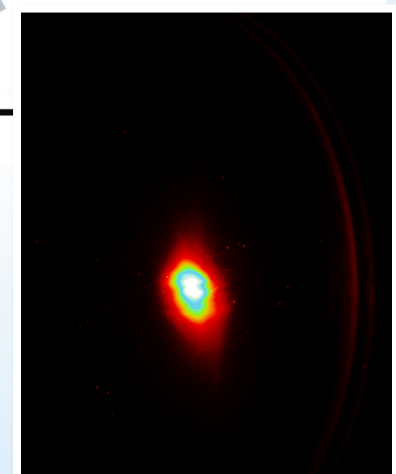


Gun0: diagnostic beamline & first beam



0.26 µm, 30 kHz, 2…3 ps, 0.15 µJ pulses from Yb:YAG oscillator + regen. amp. + 4th harm conv.

- Beam diagnostics to study cavity and cathode performance
- Short pulses of 1 ps rms length → less than 1 deg. → slice equals projected beam dynamics
- Cathode: measure QE, QE map, emission surface, thermal emittance before and after laser cleaning
- Cavity: study microwave properties, Q vs E, LLRF, microphonics, dark current

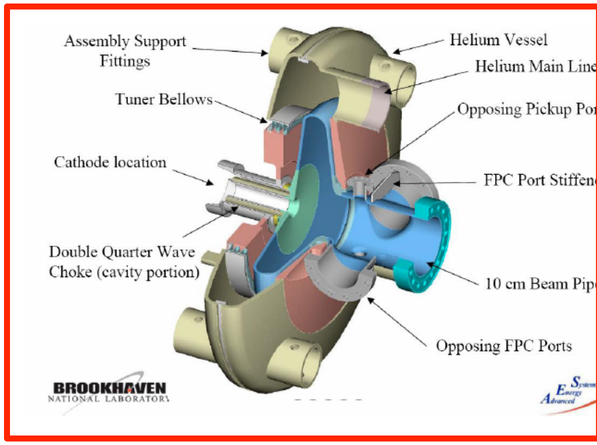


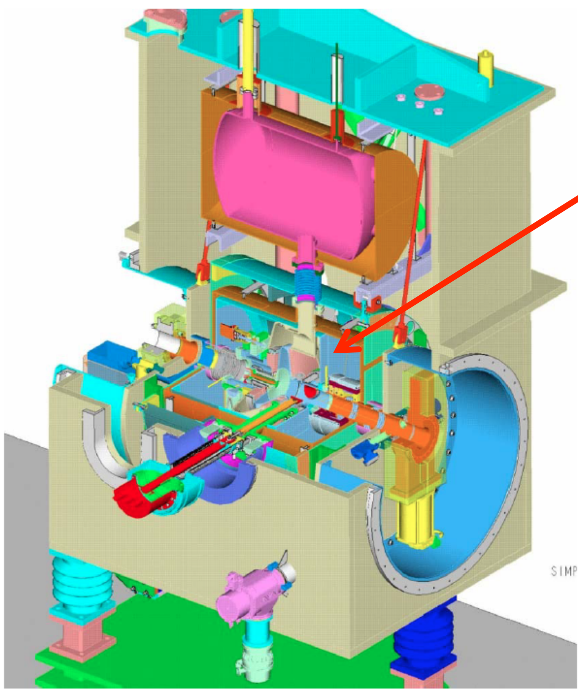
First beam
21st April 2011

Plans for Guns 1 & 2

- Gun1 and Gun2 will be part of BERLinPro project.
- Main activities in the next two years (for first beam with Gun 1 in 2013)
  - Setup of preparation and analysis lab for photocathodes
  - Beam dynamics simulation to fix parameters
  - Development of new gun cavity
  - Design and engineering of cathode insert, cold mass and cryomodule
  - Get new drive laser
  - Change diagnostics beamline setup
- Put all this together in GunLab → gun test area inside HoBiCaT bunker
- For Gun2 start thinking about RF feeds for high average power

704 MHz SRF gun for ERL





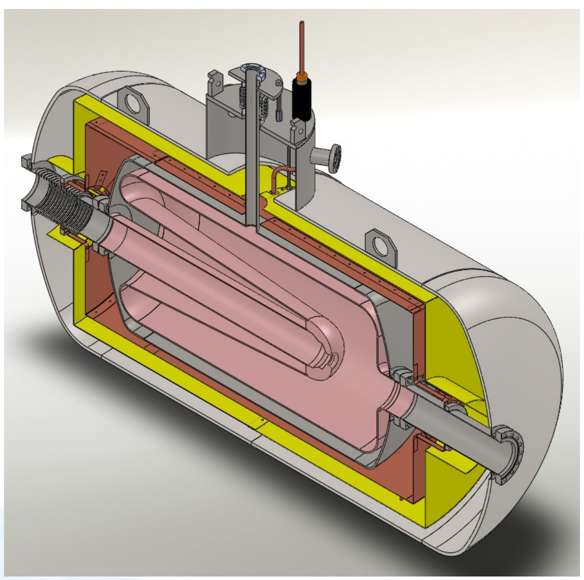
- The 704 half-cell SRF gun has two Fundamental input Power Couplers (FPCs) allowing to deliver 1 MW of RF power to 0.5 A electron beam.
- HOM damping is provided by an external beamline ferrite load with ceramic break.
- The gun and its cryomodule were designed and fabricated by AES.
- FPCs are manufactures by CPI/Beverly.
- The gun cavity was tested in a vertical cryostat last year.
- The FPC test is complete with max power of 125 kWCW in SW.
- The cavity has been cleaned and the cavity string assembled at JLab.
- Assembly of the cryomodule at BNL will begin in August.
- The plan is to finish the cryomodule assembly in September of 2011, following by the gun installation in ERL and cold test.
- First beam will be generated with a metal cathode, following by experiments with CsK_2Sb

Quarter Wave Resonator SRF guns

Parameter	Units	BNL	U. Wi.	NPS
Frequency	MHz	112	200	500
Aperture (beam tube)	cm	10	10	6.35
Cavity Diameter	cm	42	60	24
Cavity Length	cm	110	50.3	20.3
Beam kinetic energy	MeV	2	4.0	1.2
Peak electric field	MV/m	38	53	51
Peak magnetic field	mT	73	80.4	78
Peak / cathode field	-	2.63	1.31	1.8
QR_s (geometry factor)	W	38	85	125
R/Q (linac definition)	W	126	147	195
Q_0 (no cathode, 4.5K)	$x10^9$	3.7	3.3	1.2

More details on QWRs are in I. Ben-Zvi's talk **THIOA04**

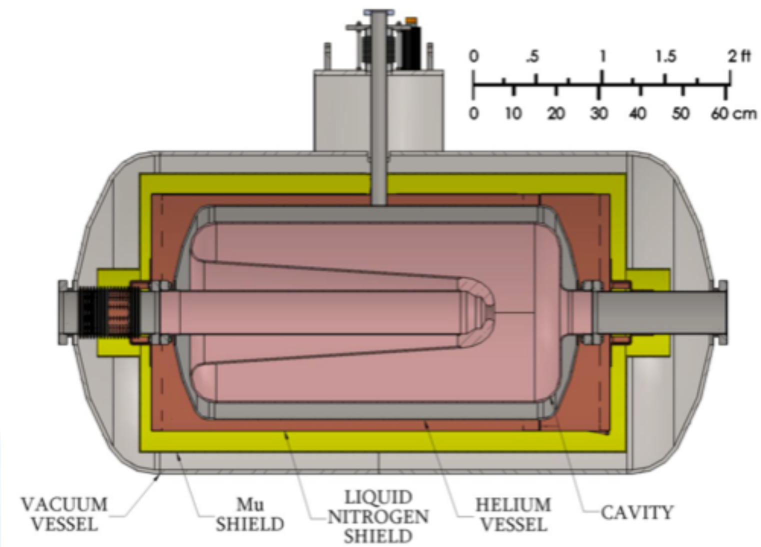
112 MHz QWR SRF gun



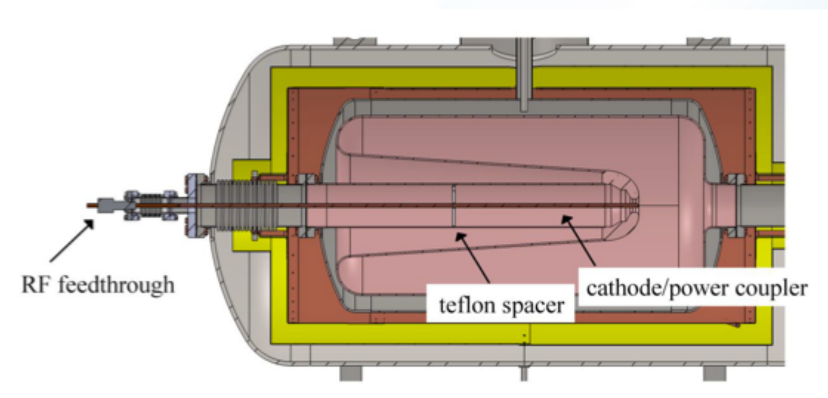
- Superconducting 112 MHz QWR was developed for electron gun experiments by collaborative efforts of BNL and Niowave, Inc.
- Design, fabrication, chemical etching, cleaning, assembly and the first cold test were done at Niowave.
- Why 112 MHz?
  - Low frequency: long bunches ➔ reduced space charge effect.
  - Short accelerating gap: accelerating field is almost constant.
  - Superconducting cavity: suitable for CW, high average current beams.
  - Cathode does not have to be mechanically connected to SRF structure: flexibility in cathode types.
  - Simulated emittance of ~3 mm×mrad at 2.7 MeV

MOPO054, MOPO014

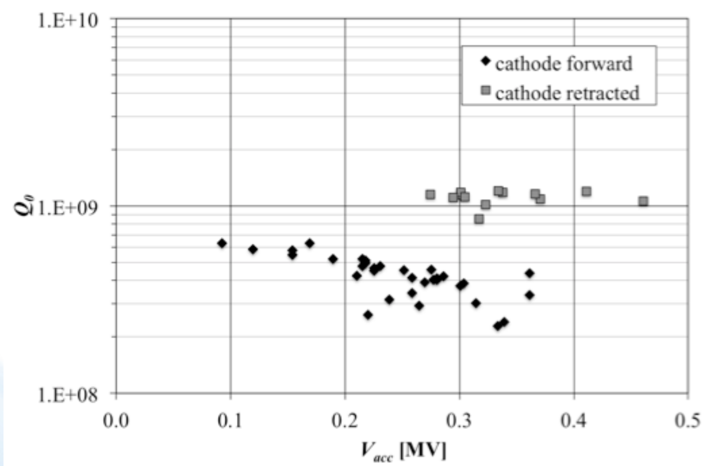
112 MHz cryomodule features



- Cryomodule features:
  - ✧ Nb quarter wave cavity
  - ✧ Stainless steel helium vessel
  - ✧ Superinsulation
  - ✧ LN2 thermal shield
  - ✧ Magnetic shield
  - ✧ Low carbon steel vacuum vessel
- Simple copper rod was used as a combined-function cathode/power coupler.



112 MHz SRF gun cold test & plans

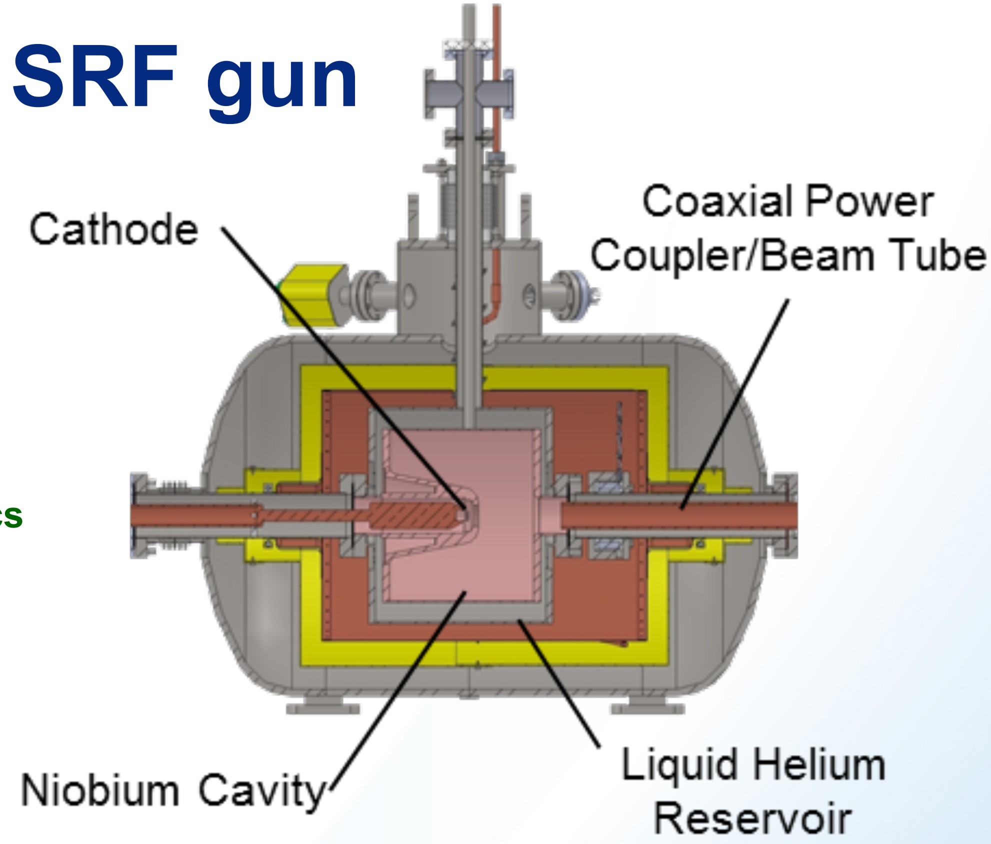


- First cold test was successfully performed at Niowave, Inc. in December of 2010.
- This gun is now a baseline option electron gun for the Coherent electron Cooling Proof-of-Principle (CeC PoP) experiment at BNL. The experiment is scheduled for FY2013/FY2014.
- For CeC PoP, the gun will require some hardware upgrade/modification:
  - Replacing the low carbon steel vacuum vessel with the stainless steel one to satisfy the pressure vessel code requirements.
  - Designing a low RF loss, low heat load stalks for multi-alkali and diamond-amplified photocathodes.
  - Designing a load lock system for multi-alkali photocathodes.
  - Designing a combine function FPC/tuner assembly.
- The design of these upgrades/modifications is in progress. The modifications are expected to be completed by the end of 2011 / early 2012.

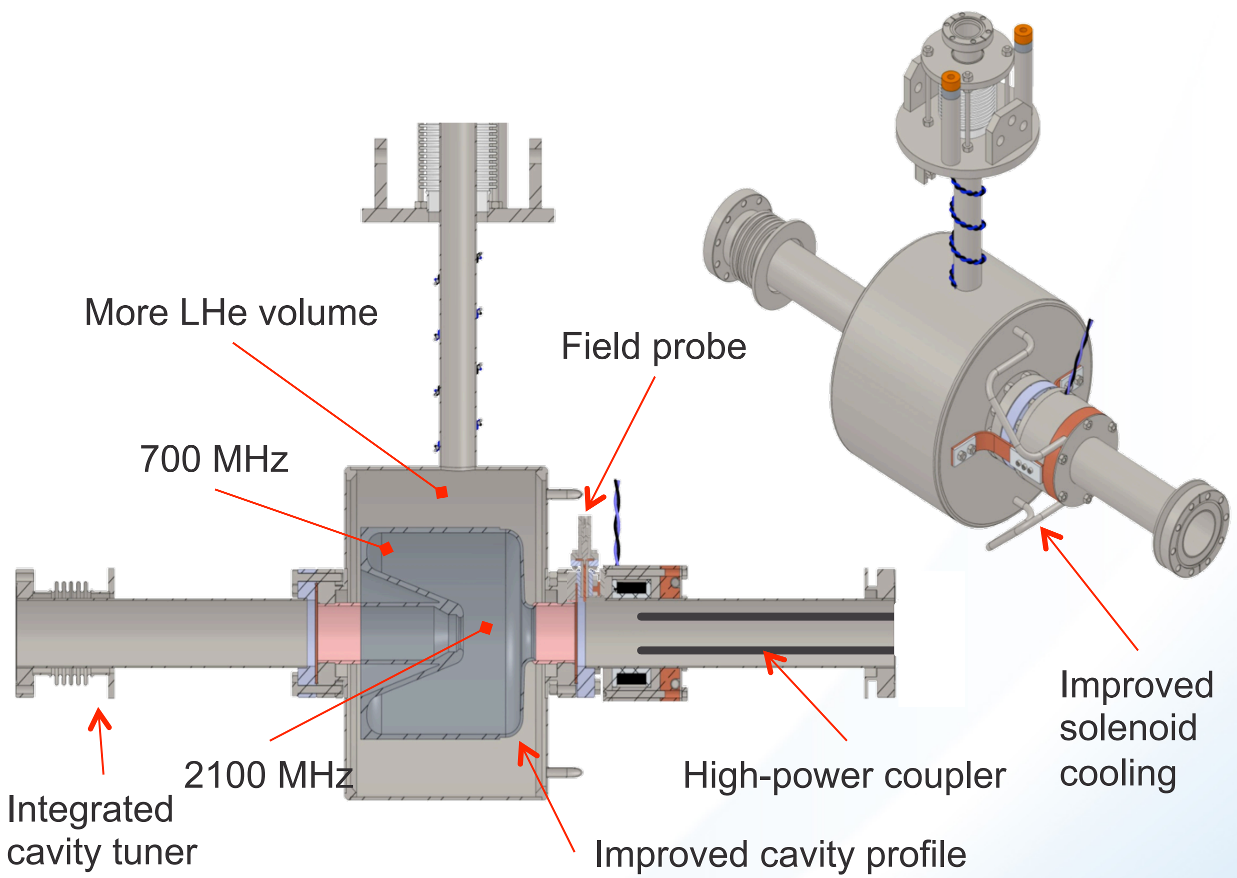
500 MHz (Mk I) NPS SRF gun

J.R. Harris, et al., Physical Review Special Topics – Accelerators & Beams 14, 053501 (2011)

- Built by and tested at Niowave, Inc.
- Nb cathode on Cu stalk.
- Initial results (not optimized):
  - Beam energy > 460 keV
  - Bunch charge > 70 pC
  - Emittance ~5 μm (RMS norm.)
- **First** operation of SRF Quarter Wave gun.
- Successful Navy/Industry/Academia partnership.
- **The only** currently functional SRF gun in USA.

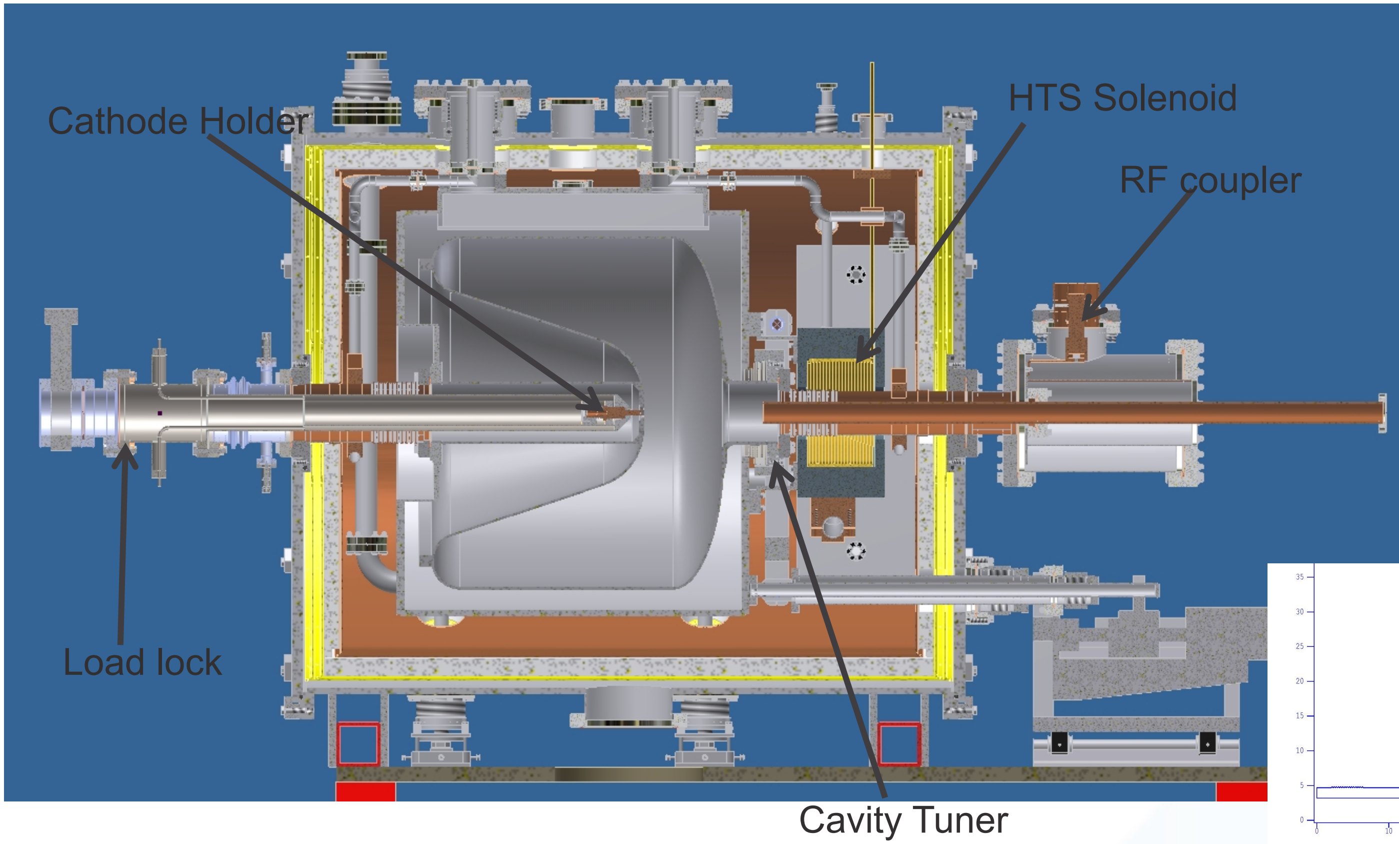


700 MHz (Mk II) NPS SRF gun

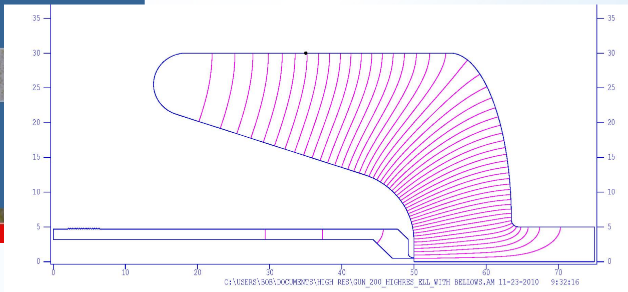


- This is a 700-MHz Mark II follow-on design, and it includes a number of improvements, enhancements, and problem fixes over the Mark I design.

UW 200 MHz SRF gun

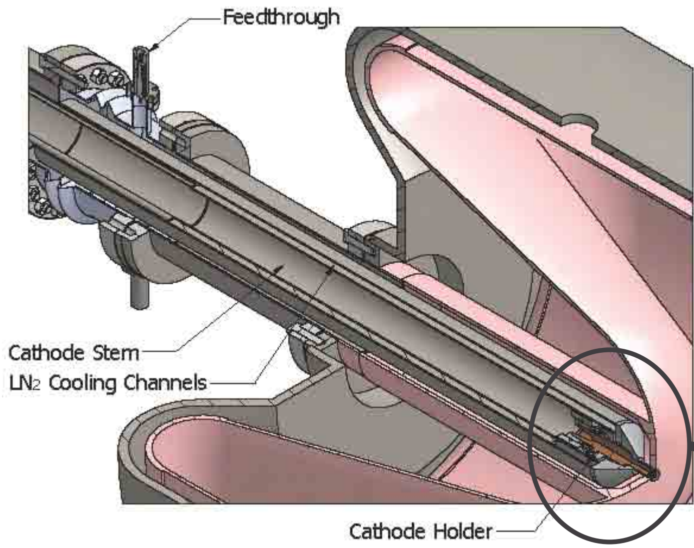


MOPO032

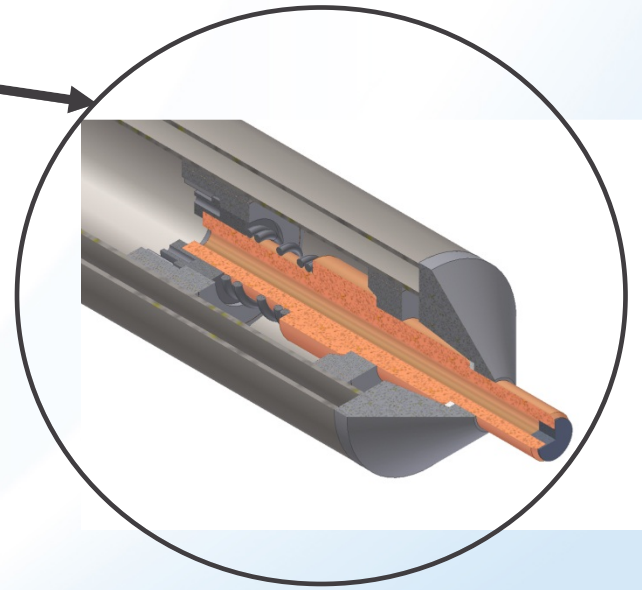


- Demonstrate single bunch beam dynamics and operation of SRF gun.
- Low repetition rate drive laser allows option of using doubled or tripled Ti:Sapphire laser.
- Cu cathode used for initial operation: little chance of cavity contamination from evaporated cathode material; cathode will not degrade over time like semiconductor; no cathode preparation chamber needed.

Cathode holder and mount



- Support structure needs to be accurate from 10 to 20 microns in every axis and linear direction. The cathode adjustment support is fixed to the vacuum vessel.



- The cathode stem is designed to allow liquid nitrogen to flow under the inner conductor for cooling.
- Probe feedthroughs allow monitoring of electric field in cavity for multipactor or quench and feedback in LLRF system.
- Spring loaded cathode stem allows photocathode to be inserted into the cavity after fabrication using a load lock.

Summary

- SRF guns made excellent progress in the last two years.
- Several guns generated beams and one injected beam into an accelerator.
- HZDR/ELBE gun demonstrated feasibility of the SRF gun concept with a normal-conducting cathode. Cs_2Te demonstrated very good performance with life time of 1 year.
- For high average current / high bunch charge operation CsK_2Sb is preferred as it needs green lasers, unlike UV laser for the Cs_2Te ➔ easier to build laser/optics systems.
- Other photocathodes are being developed, most notably diamond-amplified.
- Several QWR guns are under development with one producing beam already. Very promising for high bunch charge operation.
- The field is very active and we should expect more good results soon.

Acknowledgements

- I would like to thank the following colleagues for sending me slides with description of their projects and recent results:

  John Harris and John Lewellen (NPS)

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