Overview of high current electron sources for ERL ecooler

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Electron Ion Collider – eRHIC

EIC Hadron Cooling Workshop 2019

BROOKHAVEN NATIONAL LABORATORY

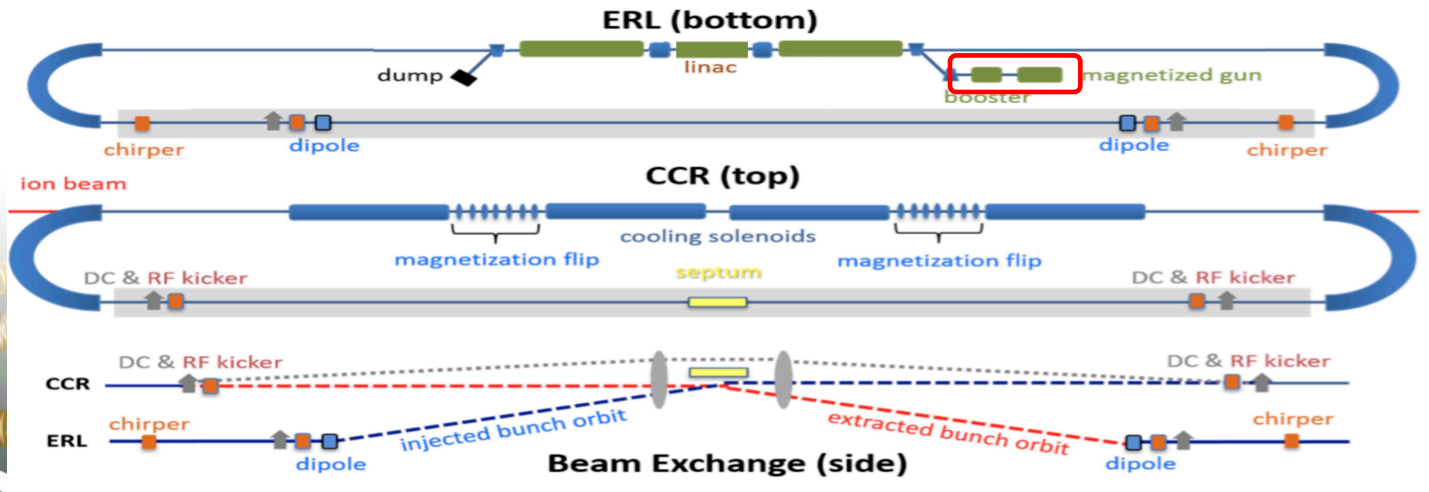
U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

- JLEIC and BNLEIC cooler injector plan
- CW high current gun options
  - HVDC gun
  - NCRF gun
  - SCRF gun
- Cathode options

JLEIC cooler esource specification

	CCR: High luminosity	ERL: Lower luminosity
Bunch charge	3.2 nC	420 pC
Bunch rep. rate	43.3 MHz	476 Mhz
Current	139 mA	200 mA
Magnetized/drift emittance	36 mm mrad	36 mm mrad
Bunch length at cooler	2 cm FWHM	2 cm FWHM
Uncorrelated emittance budget	19 mm mrad	10 mm mrad
Bunch shape	'Beer can'	'Beer can'



JLEIC Injector plan

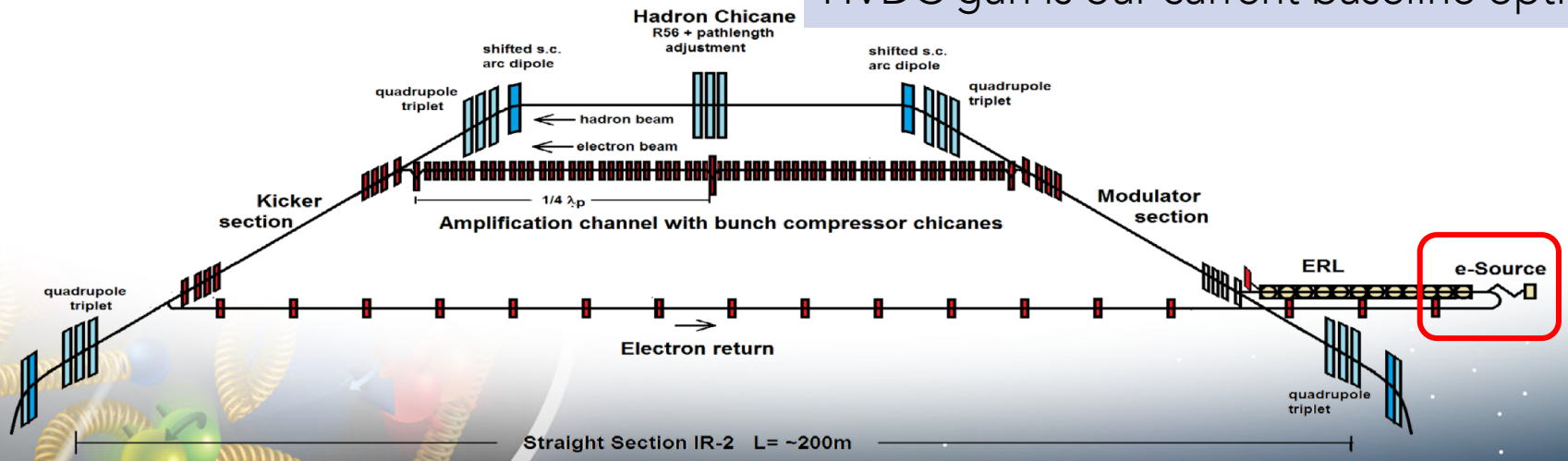
- 3.2 nC, 139 mA is both demanding and beyond state of the art.
- To date have investigated a 400 kV DC photo-gun (~4.5 MV/m on cathode) and normal conducting RF photo-gun (~26 MV/m).
- RF Gun is baseline design.

Parameter	RF Gun	DC Gun
Injector energy	5.84MeV	6.8 MeV
Bunch charge	3.2nC	3.2 nC
Uncorrelated transverse emittance	6.8mm mrad	7mm mrad
Bunch length rms	4.4mm	4.03mm
Longitudinal emittance	27keV mm	26keV mm
Injector length	2m	5m

BNLEIC strong cooler esource specification

	Parameter
Bunch charge	1 nC
Bunch length	1-2 cm
Normalized emittance	2 mm-mrad
Energy spread	1e-4
Rep. Freq	98.7 MHz
Average current	98.7 mA

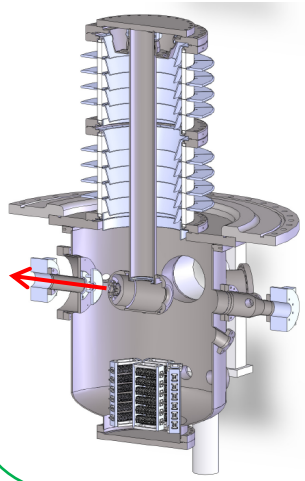
HVDC gun is our current baseline option



Common challenges

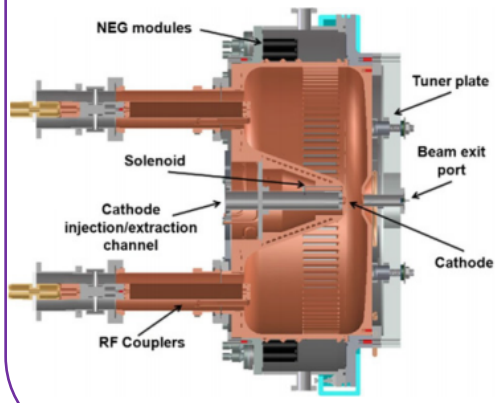
- Bunch charge ~ 1 to 5 nC
- Average current ~ 50 to 150 mA CW
- Flat beam generation
- Photocathode lifetime > 50 kC / cathode
- Energy spread < 10^{-4}
- Low noise (smooth in both **longitudinal** and transverse)
- Beer can distribution

DC, SRF, NCRF guns comparison



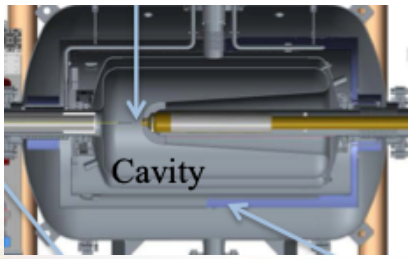
DC gun:
- Matured
- Demonstrated high current, good lifetime
- Cathode gradient<7MV/m
- Gun voltage:550kV

Cornell, Jlab, BNL ,KEK, JAEA,IHEP



NCRF gun:
- Operation
- Cathode Gradient: 20MV/m
- Gun voltage:0.75-3 MV
- Poor Lifetime

LBNL, SLAC,SHLS,DESY



SCRF gun:
- Cathode gradient:20~35MV/m
- Gun voltage:1~4 MV
- High current not demonstrated yet
- Not mature

BNL, HZD, HZB, NPS, WiFEL, SLAC, ANL

Goal:

High gradient,
Low frequency,
High gap voltage
High power
UHV
Low dark current
Capable add solenoid field on cathode

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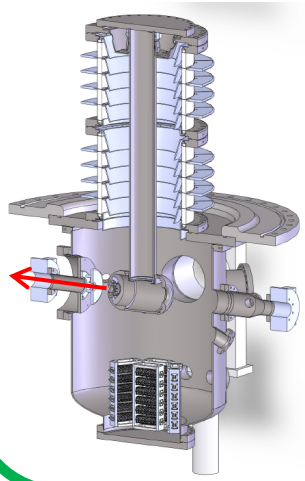

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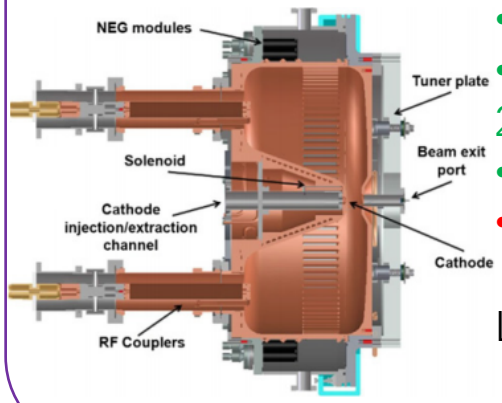

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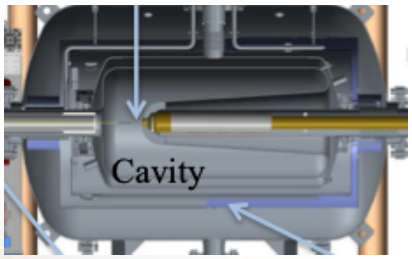

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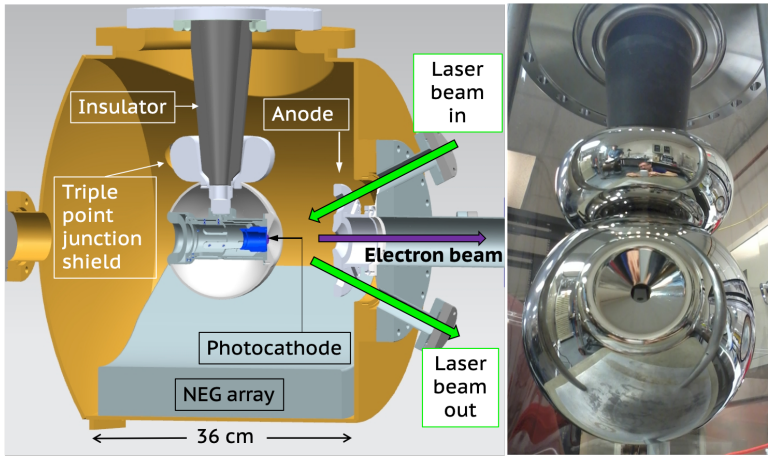
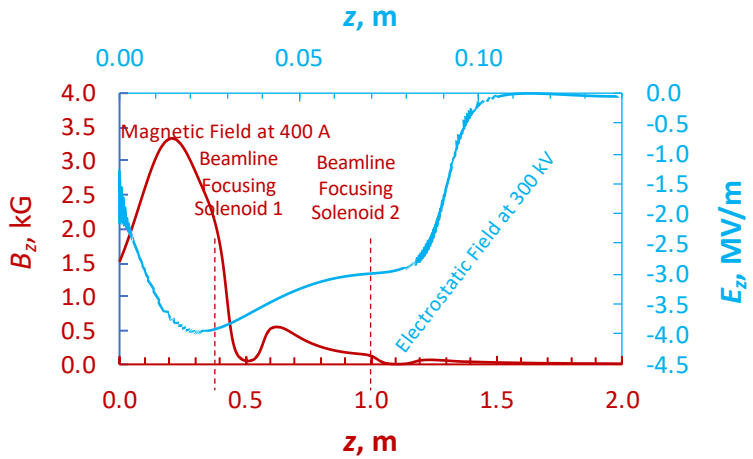
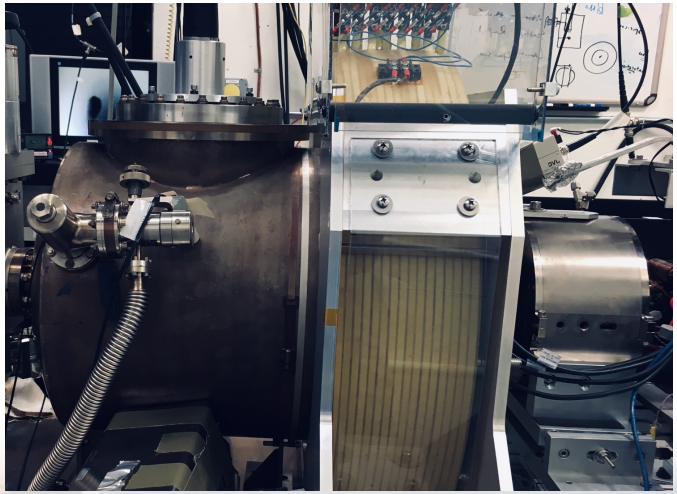
300 kV Inverted Gun and Cathode Solenoid



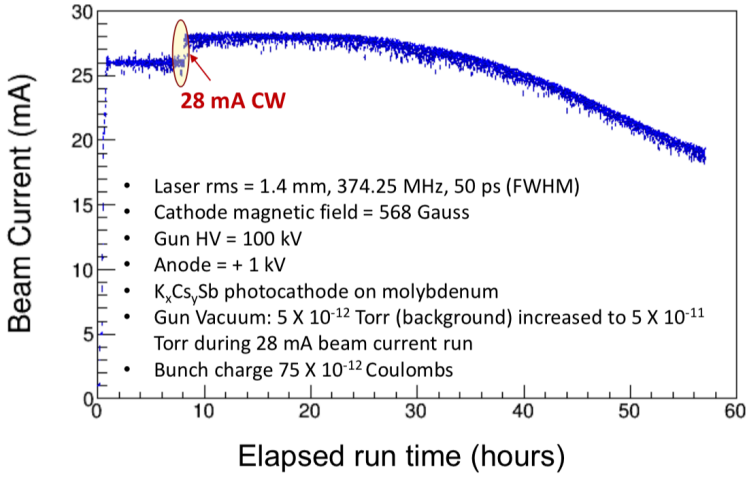


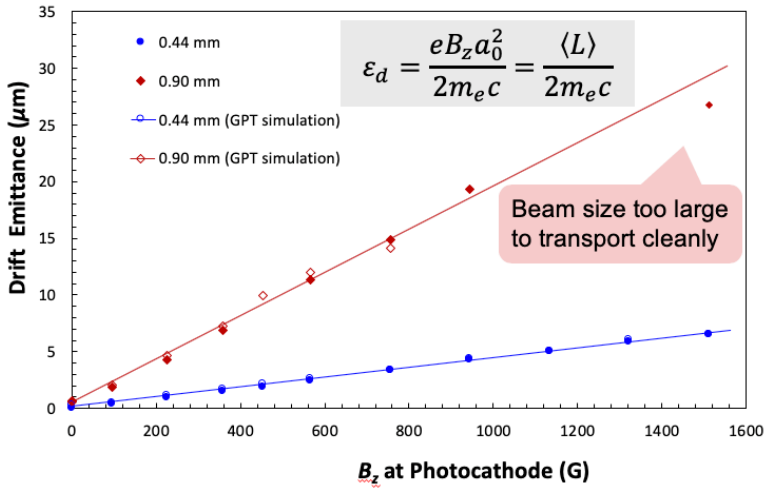
- Has been high voltage conditioned to 360 kV in 70 hours
- Nominal vacuum levels ~5x10^{-12} Torr



- Cathode solenoid provides magnetic field up to 1.51 kG
- Learned how to energize solenoid without exciting new field emitters
- Photogun operated at 300 kV with gun solenoid at 1.5 kG

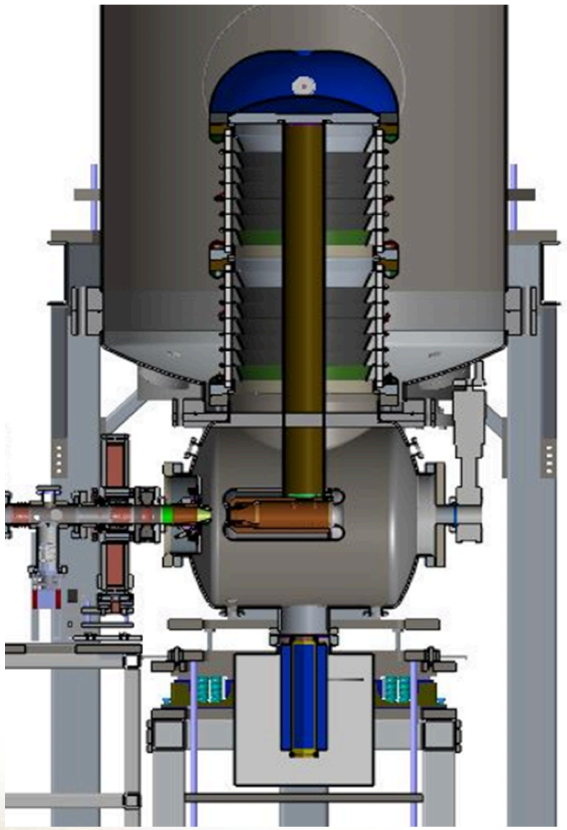
Cathode lifetime and Correlated Emittance



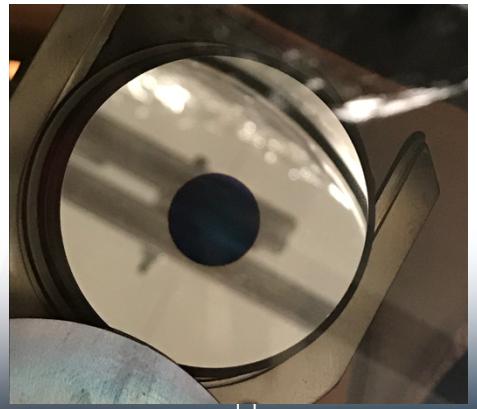


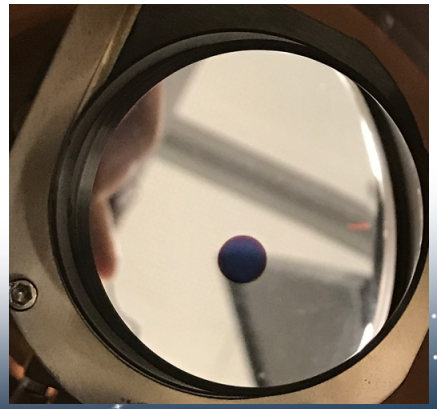
- Measured correlated or drift emittance of magnetized beam **for different laser sizes at 200 kV**
- Thermal (uncorrelated) emittance of bi-alkali antimonide photocathode was measured to be 0.5 μm/mm (laser RMS)
- **GPT simulation and experimental results show good agreement**

Cornell/LEReC(BNL)/KEK HVDC gun



	BNL achieved	Cornell achieved	
I_{ave}	30 mA	65 mA	2 μA
Bunch charge	100-200 pC	60 pC	2 nC
Lifetime	2 weeks	66 hrs	
QE	6-9 %	5 %	
dp/p	2.0×10^{-4}	/	
ε_n	Hor = 1.1 μm; Ver = 1.7 μm	1.6 μm	

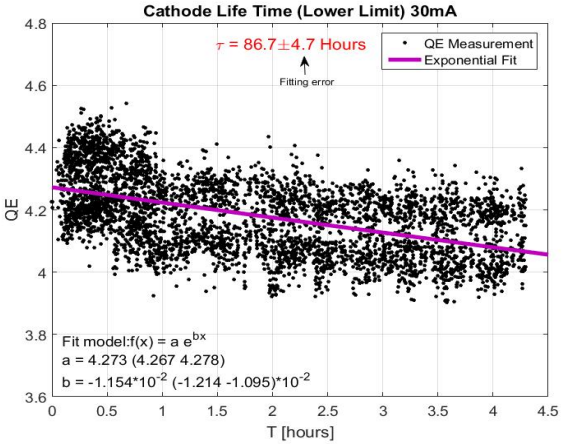




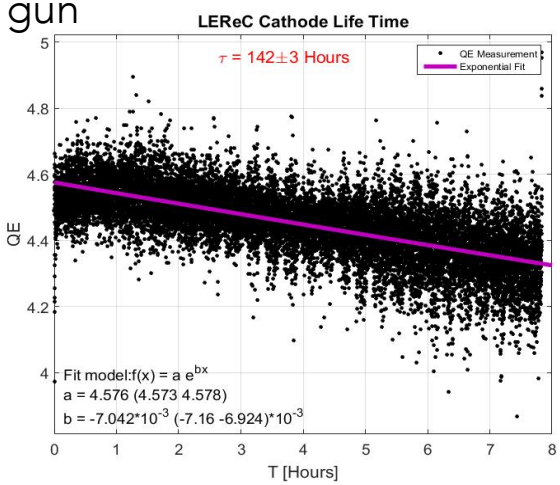
Cathodes lifetime in the HVDC gun

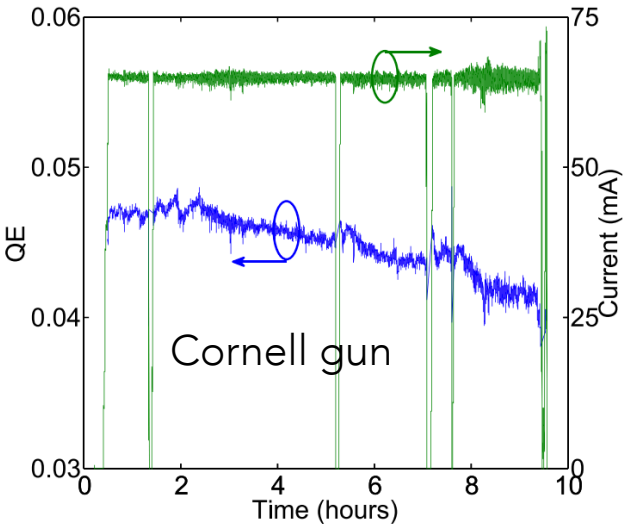
30 mA, t = 87 h, QE > 4%

BNL gun

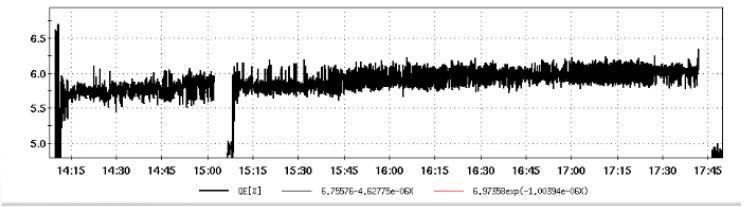


25 mA, t = 142 h, QE > 4%



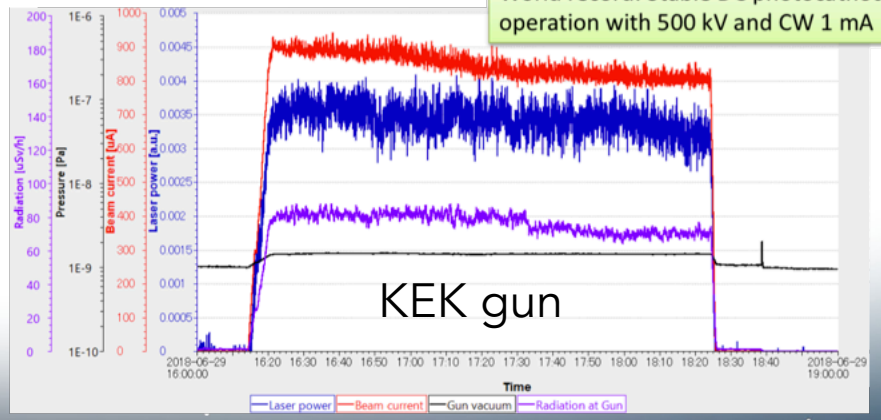


17 mA, t = inf, QE > 6%

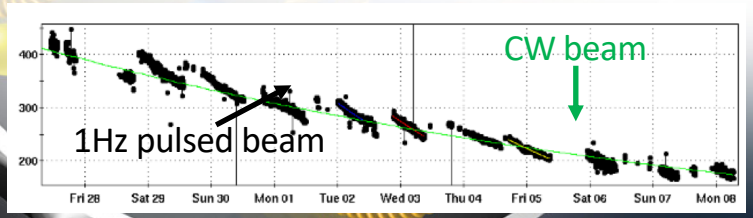


by *courtesy* of M. Yamamoto

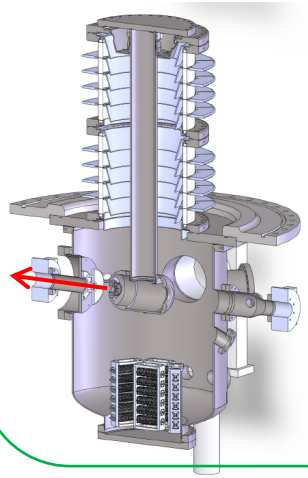
World record: Stable DC photocathode gun operation with 500 kV and CW 1 mA



QE decay at pulsed beam, QE 3-8 %

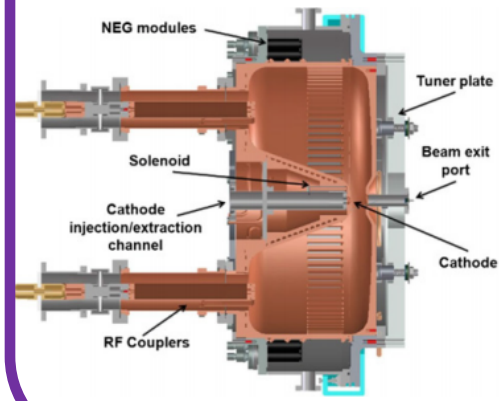


DC, SRF, NCRF guns comparison



DC gun:
- Matured
- Demonstrated high current, good lifetime
- Cathode gradient<7MV/m
- Gun voltage:550kV

Cornell, Jlab, BNL ,KEK, JAEA,IHEP



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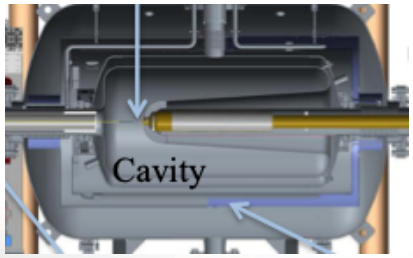
- Operation
- Cathode Gradient: 20MV/m
- Gun voltage:0.75 -3 MV
- Poor Lifetime

LBNL, SLAC,SHLS,DESY



SCRF gun:
- Cathode gradient:20~35 MV/m
- Gun voltage:1~4 MV
- High current not demonstrated yet
- Not matured

BNL, HZD, HZB, NPS, WiFEL, SLAC, ANL

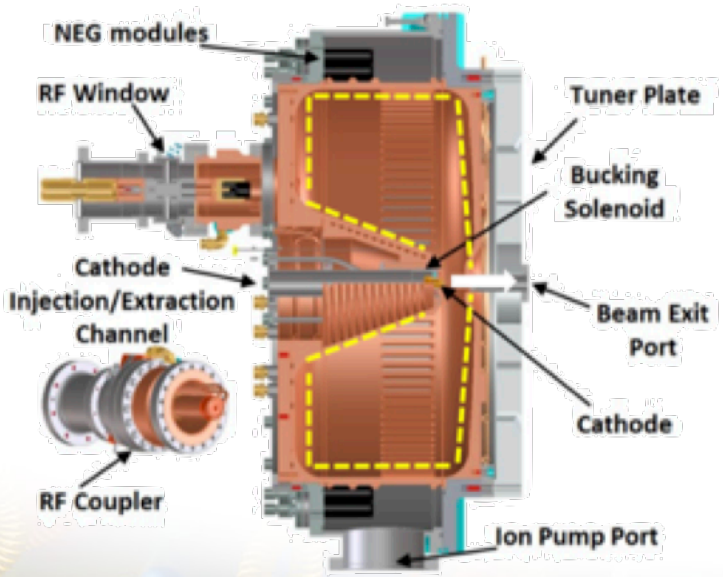
Goal:

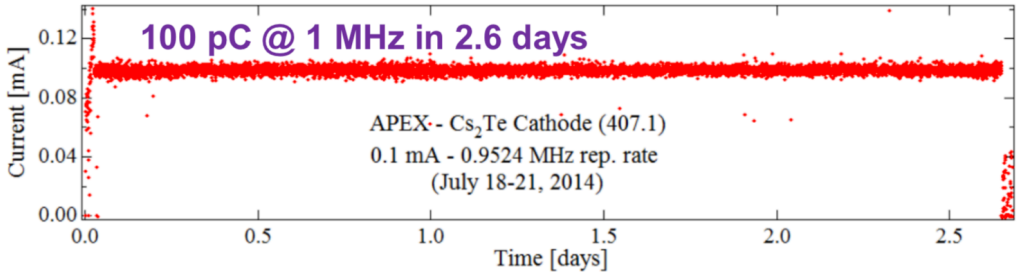
High gradient,
Low frequency,
High gap voltage
High power
UHV
Low dark current
Capable add solenoid field on cathode

APEX gun at LBNL

Based on mature NC VHF technology
Low frequency
Large longitudinal acceptance (15ps/deg)
Better for heat dissipation

Frequency	185.7 MHz
Cathode gradient	19.5 MV/m
Gun voltage	750 kV
Average RF power	90 kW
Operating pressure	10^{-10}-10^{-9} torr
Dark current	0.1 nA

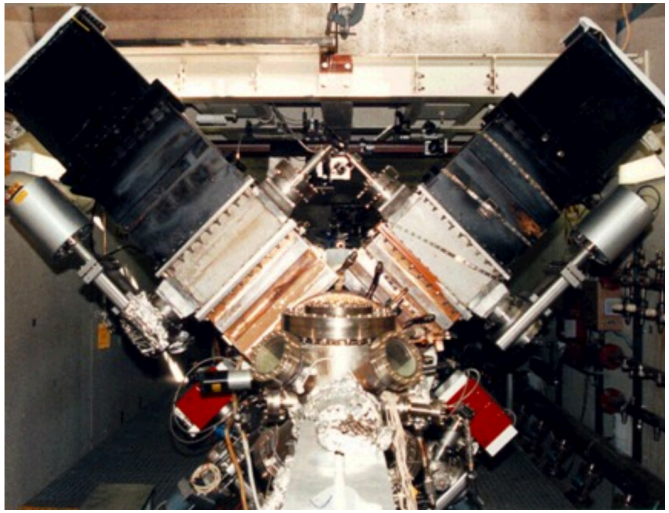




QE: 16%-11% in 7 days

Average RF power limited by the cavity temperature, cavity stress and vacuum
RF breakdown is another limitation

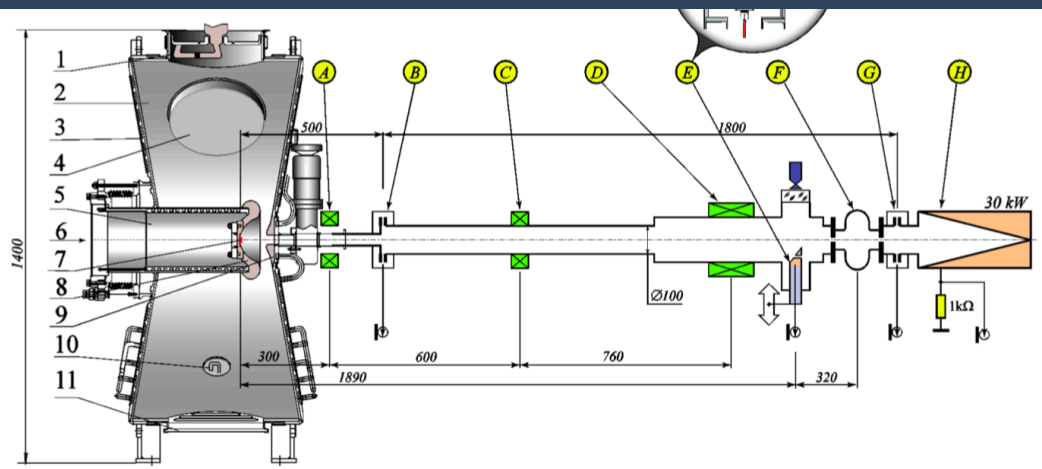
Boeing 433 MHz RF gun

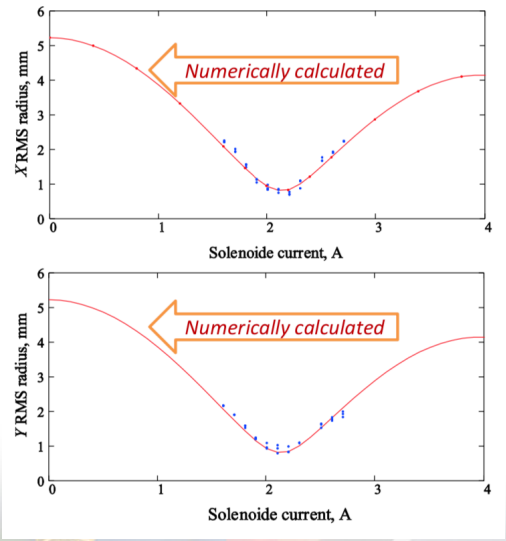


A 1992 demostratration of a two cell, 433 MHz photocathode gun at 32 mA of average current and 25% duty factor

	Parameters
Charge	1-7 nC
Average current	32 mA
Bunch length	50 ps
Duty factor	25 %
Energy spread	3%
Lifetime	2.3 hrs

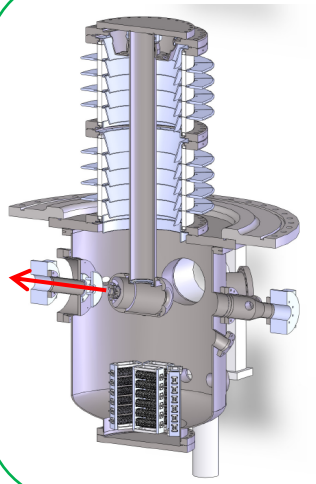
Thermionic cathode RF gun Novosibirsk





Measured RF gun parameters	
Average current	100 mA
Gun freq.	90 MHz
Bunch energy	100-400 keV
Bunch length	0.06-0.6 ns
Bunch charge	0.3-1.1 nC
Rep. rate	0.01-90 MHz
Pressure	10^{-7}-10^{-9} Torr

DC, SRF, NCRF guns comparison



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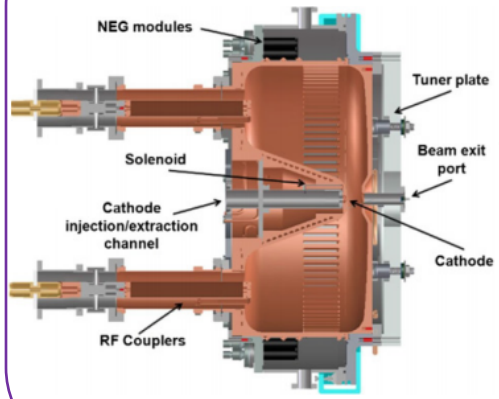

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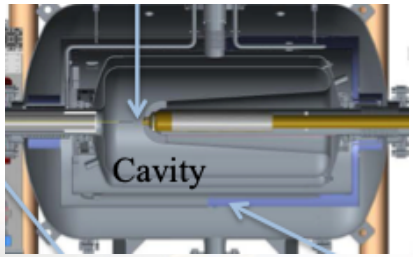

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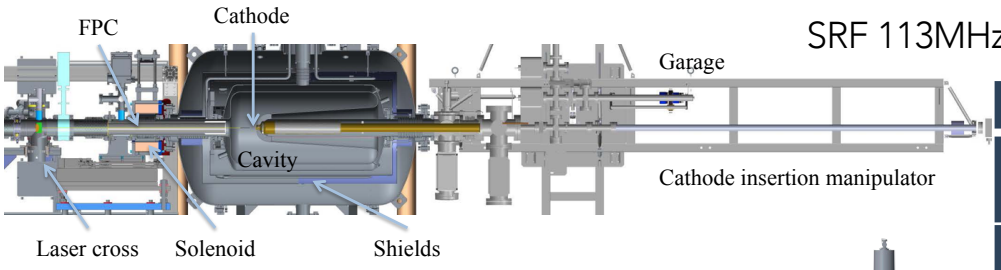
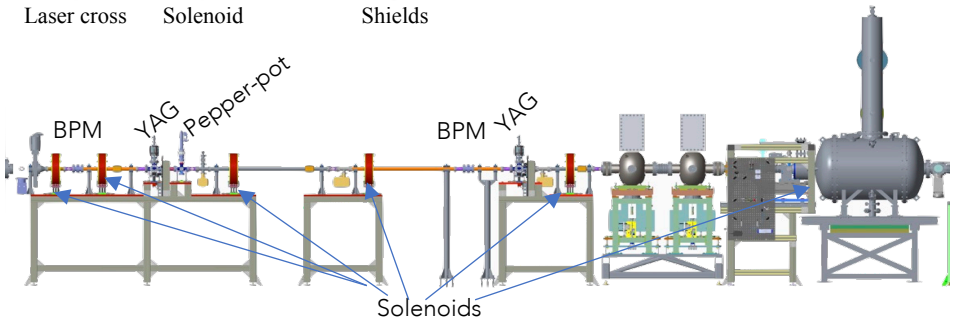
SRF 113MHz electron gun for CeC



SRF 113MHz electron gun



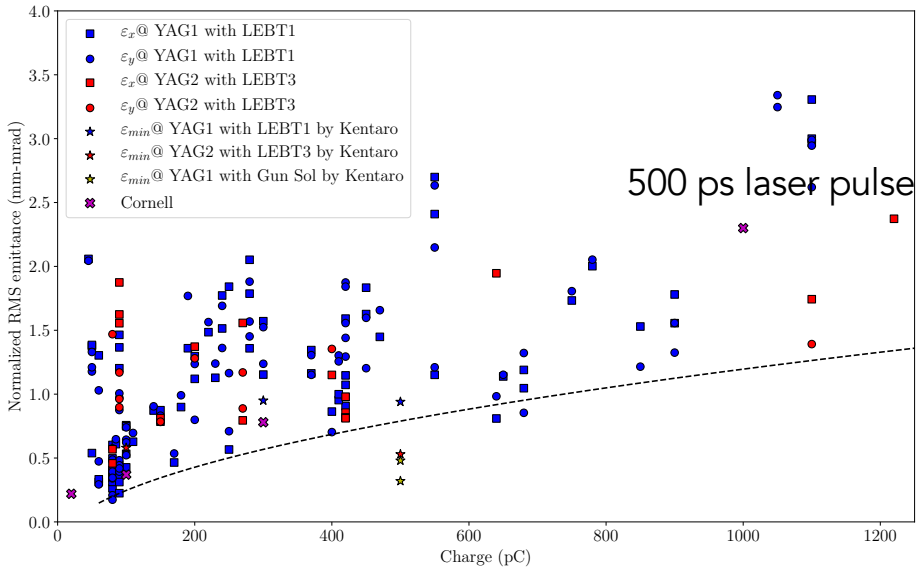
	Design Goal	Achieved
Charge per electron bunch	0.5-5 nC	0.1- 10.7 nC
Peak current	100 A	50 -100A
Bunch duration, psec	10-50	12
Normalized beam emittance	< 5 mm mrad	3 - 5 mm mrad
Repetition rate	78.17 kHz	78.17 kHz
CW beam	<400 μA	150 μA

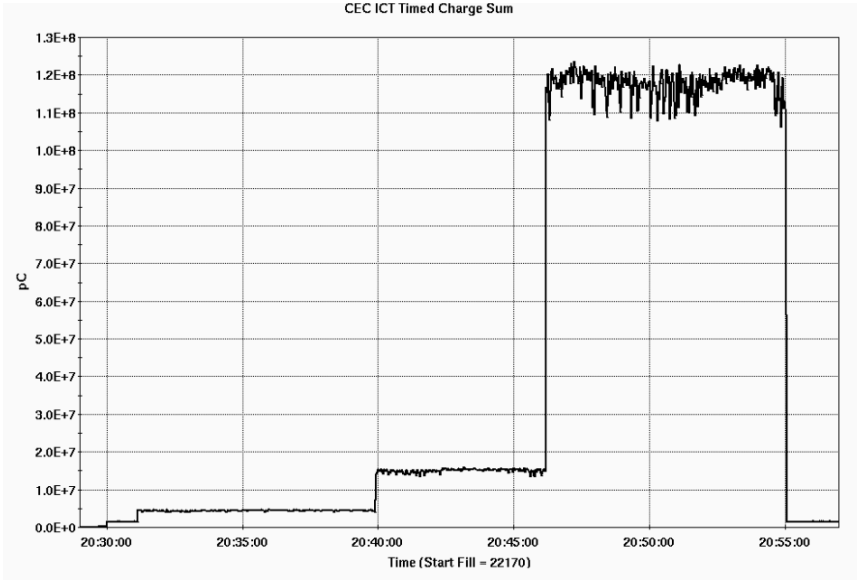
SRF Quarter wave resonator advantages: (DC like+RF)

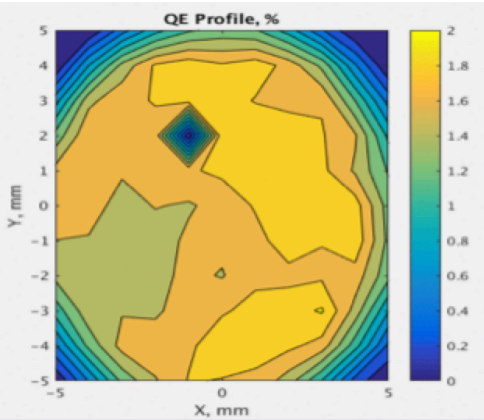
- 4K operation: Simple cryogenic system; Low cost
- High gradient: Small emittance; High bunch charge
- Long bunch: Reduce the space charge; Generate high bunch charge
- Constant field: Small energy spread
- Good vacuum: Long lifetime

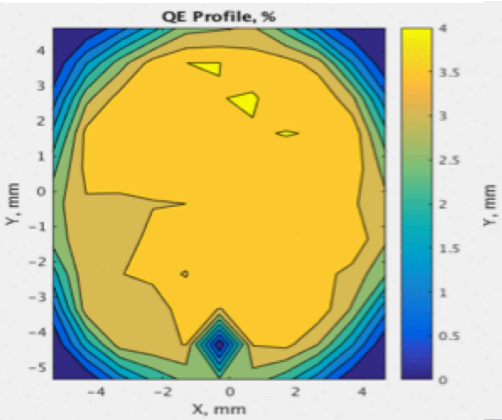
Gradient limited by the field emission
Average current limited by coupler and RF source

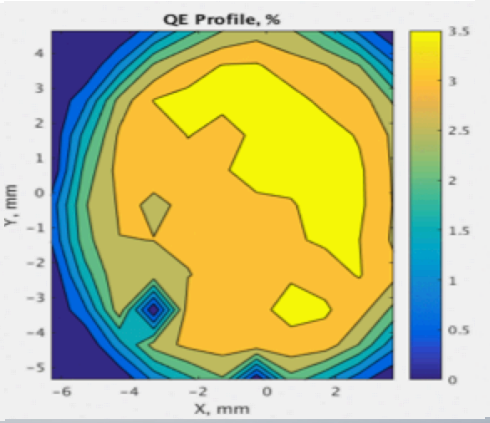
Emittance, Current and Lifetime

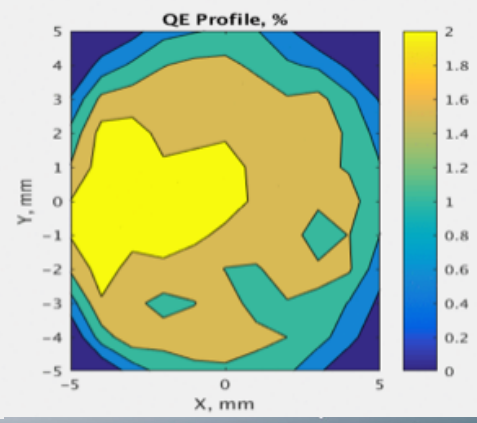








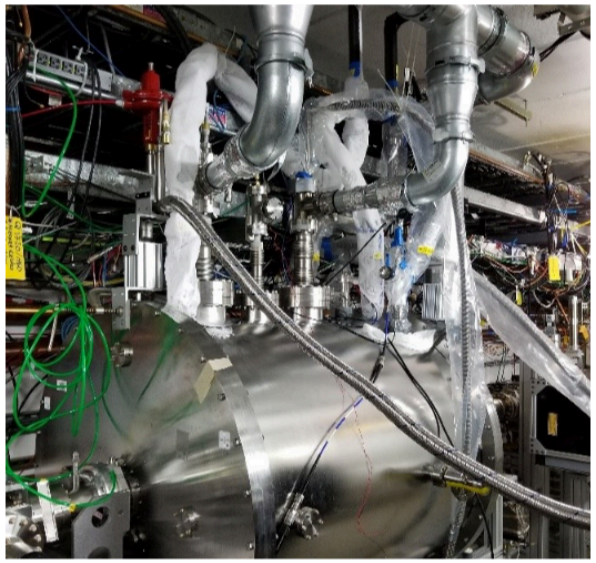


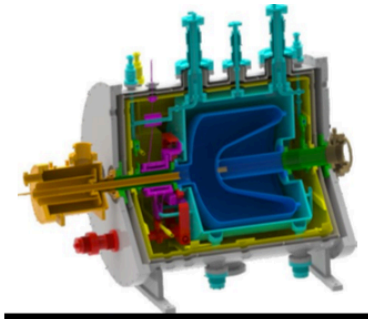


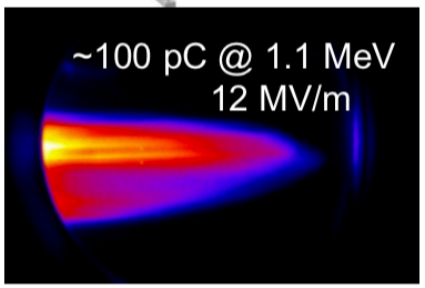
DAY1 DAY3 DAY7 DAY 23

Wisconsin/SLAC/ANL-SRF gun

Design parameters	
Frequency	200 MHz
Bunch charge	100 pC
Beam energy	4 MeV
Cathode gradient	45 MV/m
Cathode	Cu
Bunch Rep. rate	1 MHz

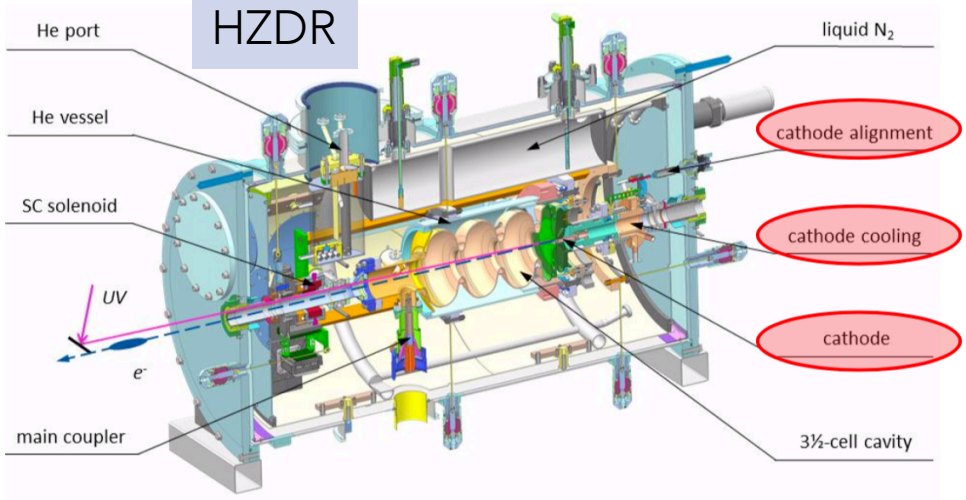




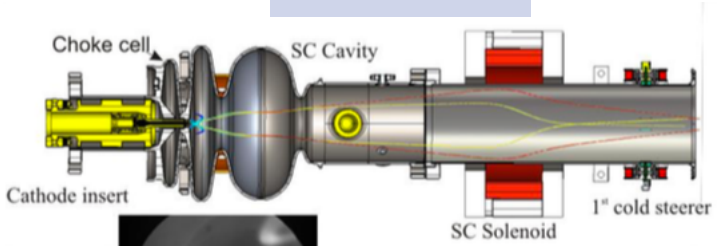


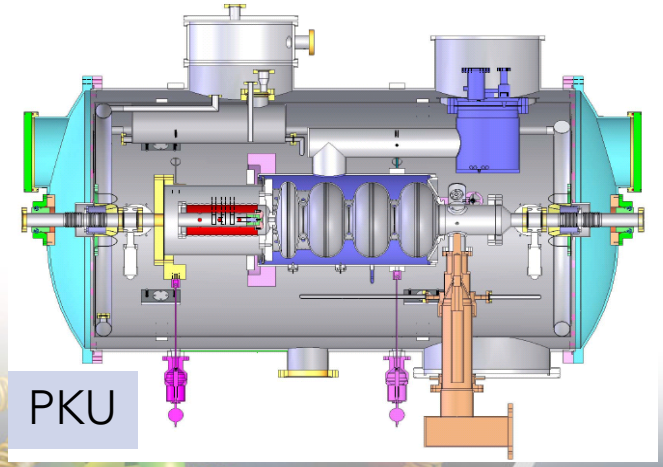
HZDR/ PKU/bERLinPro/DESY SRF guns

HZDR

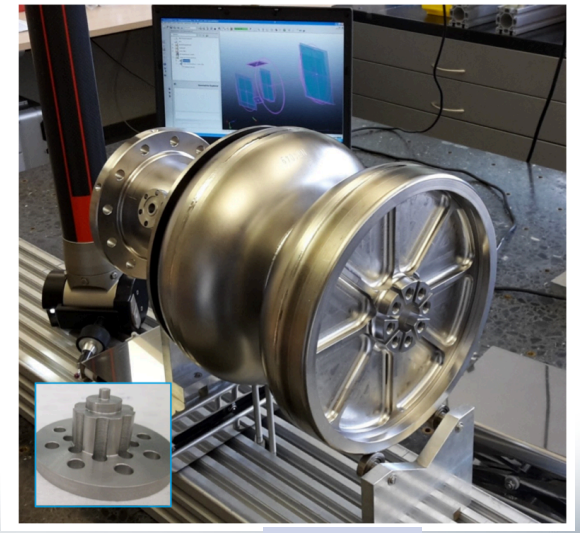


bERLinPro





PKU



DESY

1.3 GHz SRF gun comparison

	HZDR	PKU	DESY	HZB
Status	In operation	In operation	R&D	R&D
Gun energy [MeV]	4	4	3	1.5-2.3
Peak field on cathode	12	2.6	40	7.5
Cathode material	Mg (Cs_2Te)	Cs_2Te	Pb	KCsSb
Bunch charge [pC]	300	50	250	100
Ave. current [mA]	0.03(1)	1	0.25	50
Peak current [A]	100	9	6	/
Lifetime	1 year(days)	3 weeks	months	/
Nor. Emittance[um]	13	1.5	0.8@20pC	<0.5

Cathodes

Photocathode	Wavelength(nm)	QE	Thermal emittance (mm-mrad/mm)	Lifetime@mA
$K_2Cs(Na)Sb$	532	10%	0.4	Week
GaAs	532/780	>10%	0.44	hr
Cs_2Te	266	16%~1%	0.7	Month~Year
Diamond amplifier	Electron beam	Gain >200 times	?/ Energy spread σ=0.12eV	no decay @nA
Diamond /Si field emitter	Field emitter	NA	?	Month~Year@ uA
Plasmonic	800	nonlinear	1.4	Year@ uA
Metal	266	< 0.1%	0.6	Year

Thermionic cathode will have very long lifetime, but longitudinal phase space is not good and difficult to control the pulse structure.

Electron source choices for ecooler

- Cathode
  - Multialkali or Thermionic (if not require small emittance)
- Photoguns: All three types of gun possible generates high current, high charge electron beam

Peak gradient:

NCRF(20-35 MV/m)>SCRF(10~20 MV/m)>HVDC(3-8 MV/m)

Beam energy:

SCRF(1-4 MeV)>NCRF(0.75-1.64 MeV)>HVDC(<0.55 MeV)

Maturity:

HVDC>NCRF>SCRF

Vacuum:

HVDC(10^{-12} torr)>SCRF(10^{-11} torr)>NCRF(10^{-10} torr)

Thanks for your attention!

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- HZDR: Rong Xiang
- PKU: Huamu Xie
- HZB: A. Neumann
- KEK: M. Yamamoto
- Cornell: L. Cultrera
- BINP: V. Volkov

Thermionic gun (recently arrived)