Superconducting RF Guns: Emerging Technology for Future Accelerators

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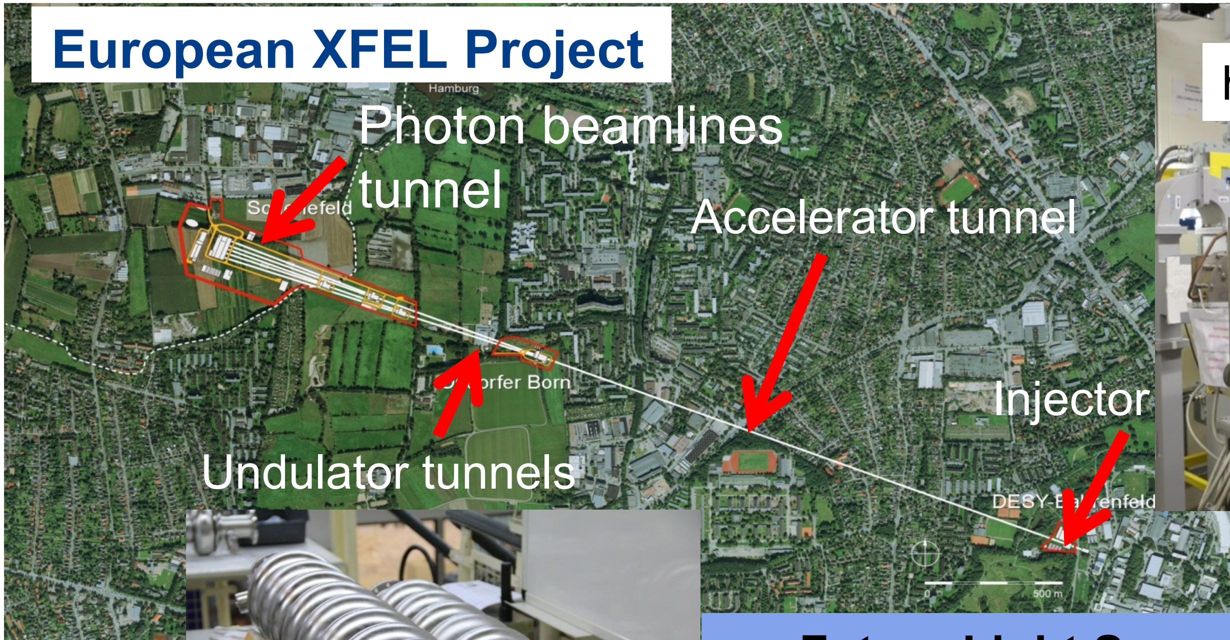
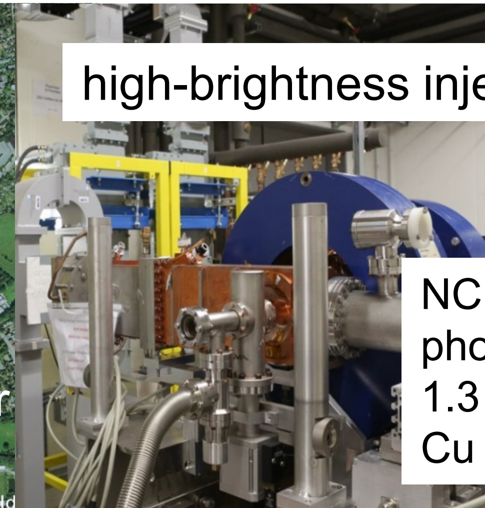
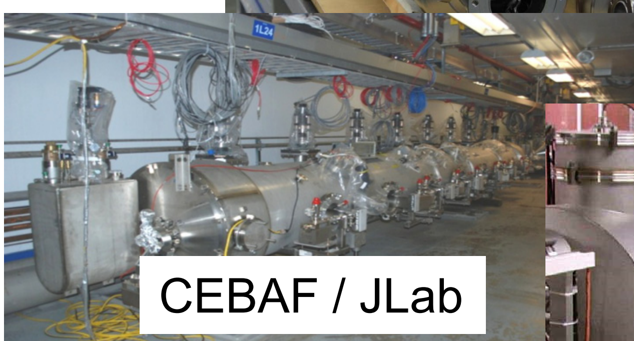
Talk Outline

- Introduction
- SRF Gun Types
  - Guns with SC Photocathodes
  - DC SRF Photoinjector
  - QW Resonators with NC Photocathodes
  - Elliptical Cavities with NC Photocathodes
- Summary





Future Light Sources require the same beam quality at MHz repetition rates

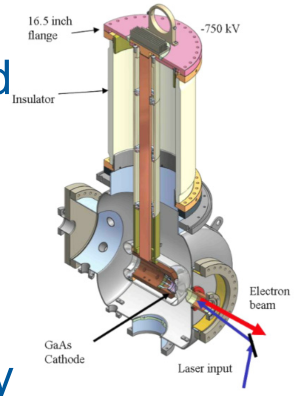


CW SC accelerators

high brightness & high average current injector

NC RF photo gun

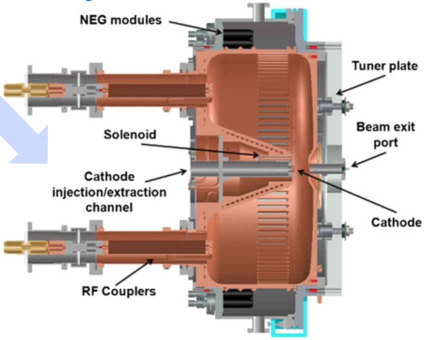
high DC Field



500 kV JAEA DC Gun, 100 mm gap
10.1 MV/m maximum surface field
6.7 MV/m on photo cathode
N. Nishimori et al. Phys. Rev. STAB 17, 053401 (2014)

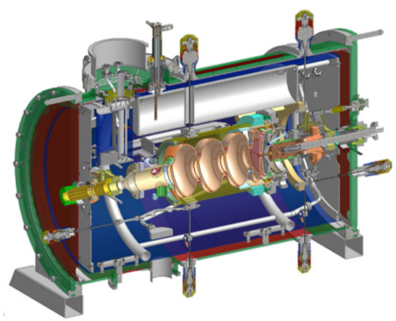
Cornell 250 kV DC Gun, >2000 C extracted
65 mA CW current CsK_2Nb PC
B. Dunham et al., Appl. Phys. Lett. 102, 034105(2013)

low frequency



Berkely 186 MHz CW RF gun
745 keV, 20 MV/m at cathode
300 μA, 300 pC current, Cs2Te PC
39.5 C extracted
F. Sannibale, et al. Proc. PAC2013 p. 709

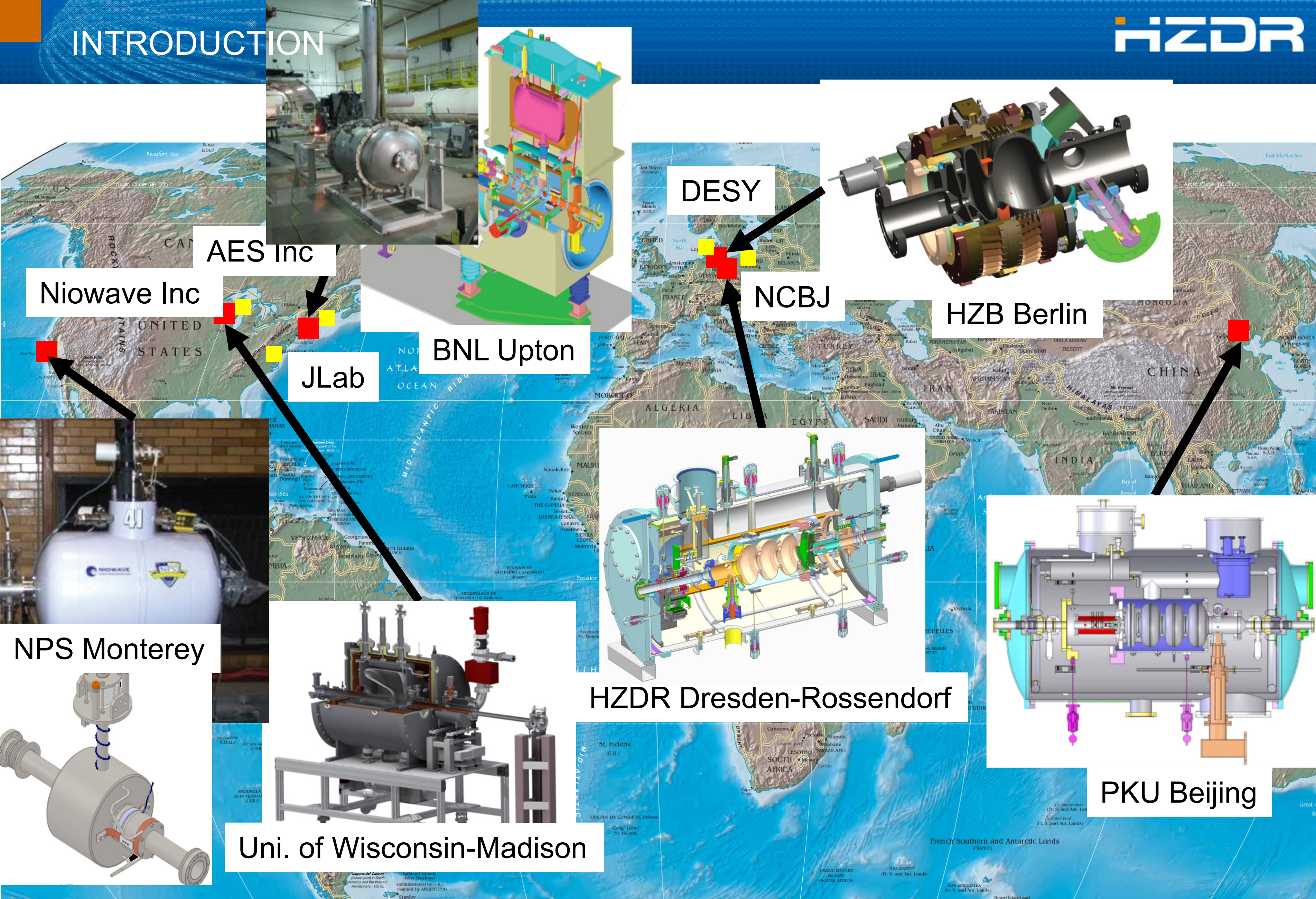
Superconducting cavity



Superconducting photo injector

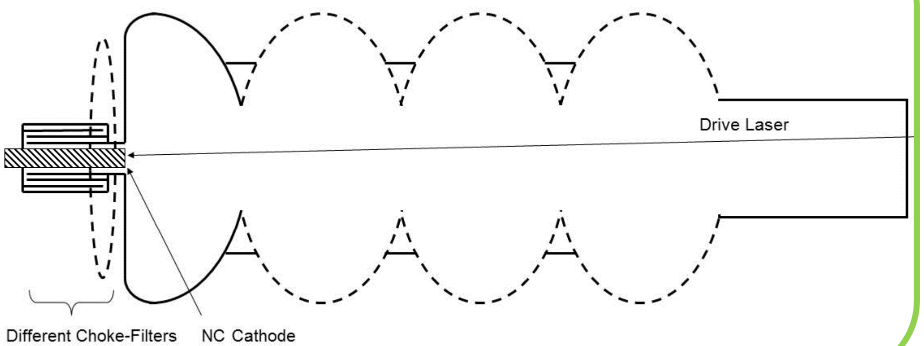
Potential for highest fields
=> low emittance @ high bunch charge

INTRODUCTION

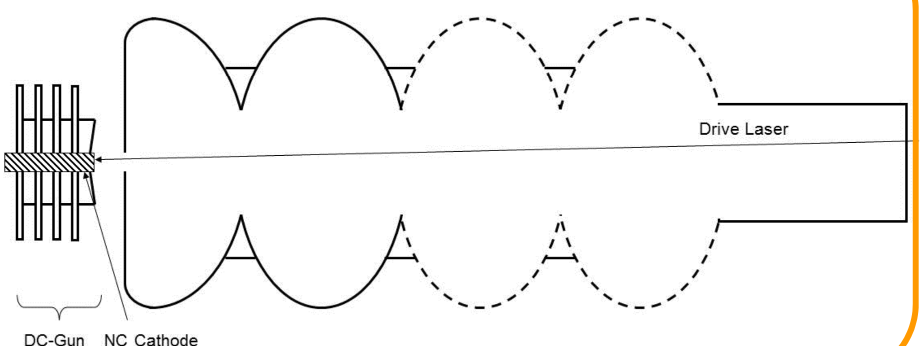


4 different approaches are under investigation

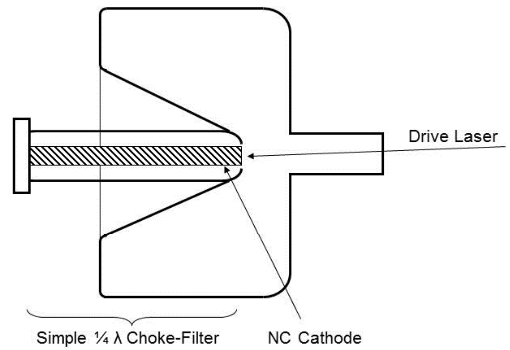
a) NC CATHODE AND ELLIPTICAL SRF CAVITY



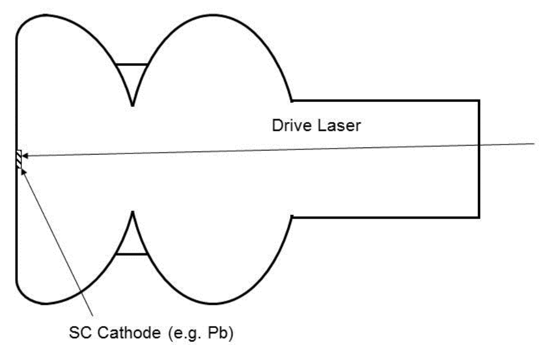
b) NC CATHODE, DC GAP AND ELLIPTICAL SRF CAVITY



c) NC CATHODE AND ¼ WAVE SRF CAVITY



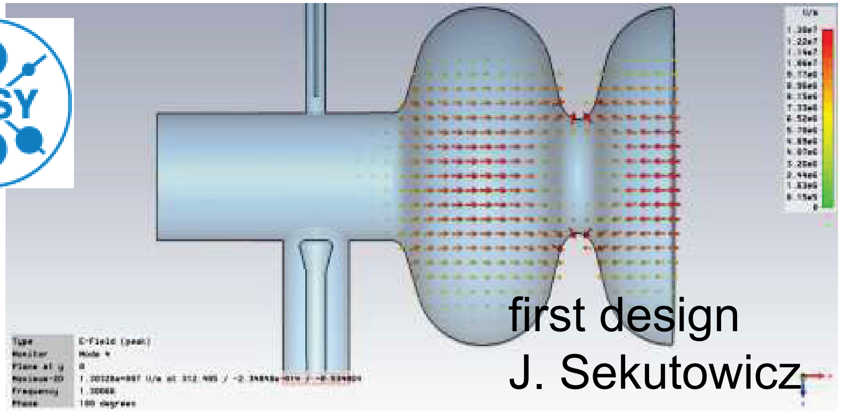
d) SC CATHODE AND ELLIPTICAL SRF CAVITY



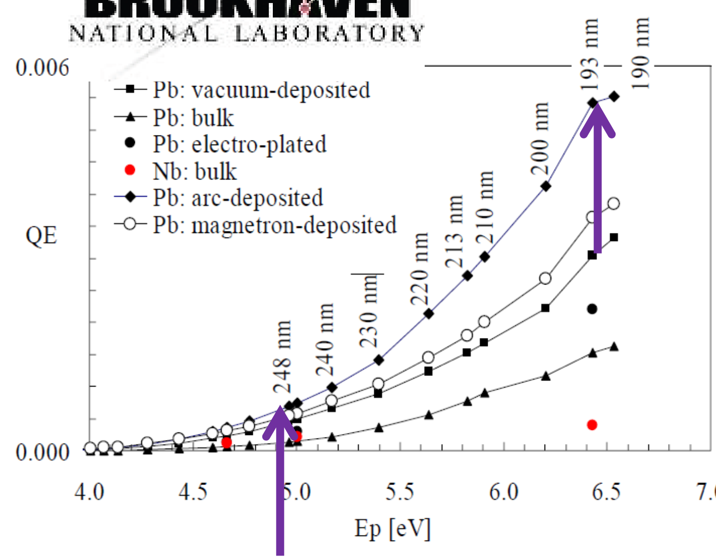
Ref: A. Arnold, J. Teichert, *Phys. Rev. ST AB* 2 14 (2011), S. 024801.

SC Cathode + Elliptical SC Cavity

1.3 GHz 1.5-Cell Cavity with SC Pb Cathode



first design
J. Sekutowicz



J. Smedley *et al, PRST-AB, Volume 11, No. 1, 2008*

Gun 0.1 with lead spot on back wall

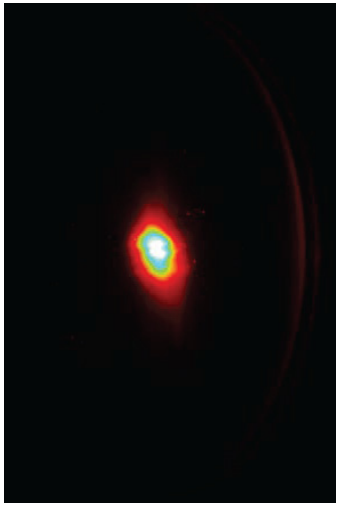
Gun 0.2 had Nb plug with deposited lead

Deposition setup in Świerk

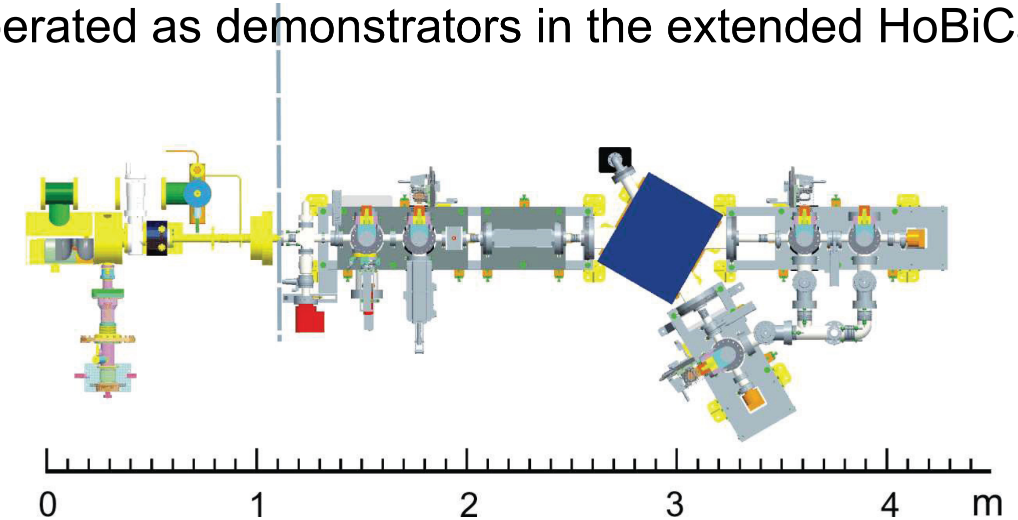
NARODOWE CENTRUM BADAŃ JĄDROWYCH Świerk

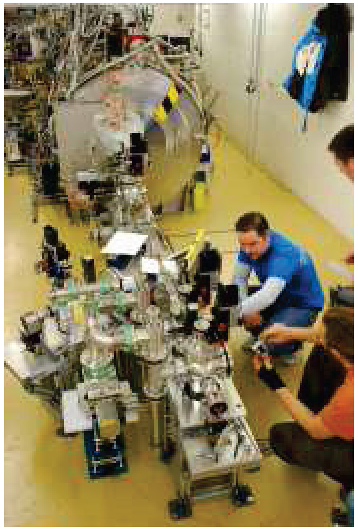
1.3 GHz 1.5-Cell Cavity with SC Pb Cathode

The guns were operated as demonstrators in the extended HoBiCaT facility at HZB



first beam on
21st April 2011





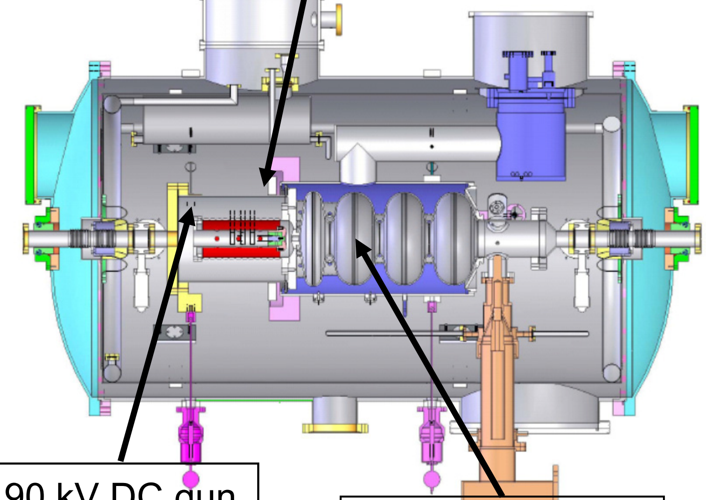
CW peak gradient: 27 MV/m
energy gain: 2.5 MeV
average current: 50 nA
max. bunch charge: 6 pC
norm. emittance: 1.9 mm mrad
Pb, QE: 1 x10^{-4}

Advantages:
- No need for UHV/XHV cathode exchange system
- QE increase by in-situ laser cleaning

Problems to be solved:
Still low QE and high dark current
Pb layer does not resist cavity cleaning procedure

IHIP PKU 1.3 GHz 3.5-Cell DC-SRF Photoinjector

The Peking University hybrid DC-SRF gun combines a 90 kV Pierce DC gun with a 3½ cell superconducting 1.3 GHz cavity



Design Parameters

Drive laser		
Pulse length (FWHM)	**10 ps**	
Laser spot (FWHM)	**3.0 mm**	
Repetition rate	**81.25 MHz**	
Bunch charge distribution	**transverse uniform, longitudinal Gaussian**	
Injector	**ERL mode**	**THz mode**
Gradient	**13 MV/m**	**15 MV/m**
Bunch charge	**60 – 100 pC**	**20 pC**
Energy	**5 MeV**	**< 5 MeV**
Transverse emittance	**1.2 mm-mrad**	**2.1 mm-mrad**
Longitudinal emittance	**15 deg-keV**	**3.0 deg-keV**
Bunch length	**3 ps**	**0.55 ps**
Rms beam spot	**0.3 mm**	**1.7 mm**
Energy spread	**~0.5 %**	**0.55 %**

Advantages:
- No need for a RF filter at cathode side and no multipacting problems

IHIP PKU 1.3 GHz 3.5-Cell DC-SRF Photoinjector

CW peak gradient: 29 MV/m
energy gain: 3.3 MeV
CW average current: 250 µA
max. bunch charge: 3 pC
norm. emittance: 3 mm mrad
Cs_2Te, QE: 0.5% - 8%

A series of experiments have been carried out with the DC-SRF injector at 2 K. 250 µA CW electron beam was obtained with emittance of about 3 mm-mrad. THz radiation will be produced with this DC-SRF injector and a new beam line.

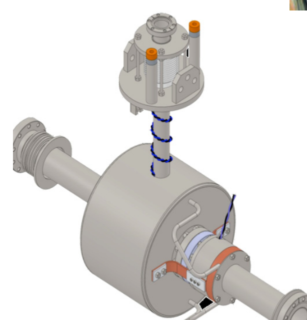
Disadvantage:
Low acc. field at cathode -> higher emittance

NC Cathode + Quarter Wave SC Cavity

Quarter Wave Resonators were built by Niowave Inc.

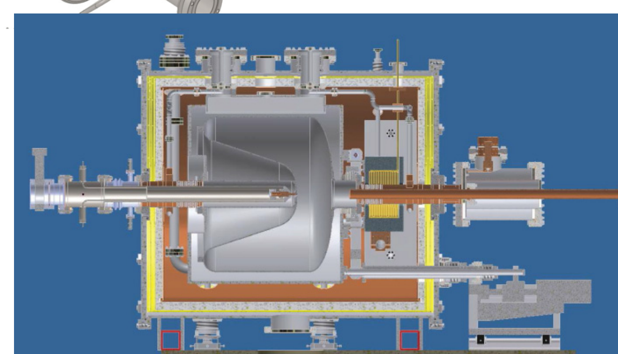
- 500 MHz QWR Gun @ NPS, Monterey
  Infrared FEL project
  J. R. Harris, et al., Phys. Rev. ST Accel. Beams 14, 053501 (2011)

- 112 MHz QWR Gun @ BNL
  Gun forthe Coherent electron Cooling experiment at BNL
  S. Belomestnykh, Proc. SRF2013, p. 50



- 700 MHz QWR Gun @ NPS & Los Alamos
  Tested at Niowave, 260 keV beam, Nb cathode
  T. Grimm, NA-PAC 2013

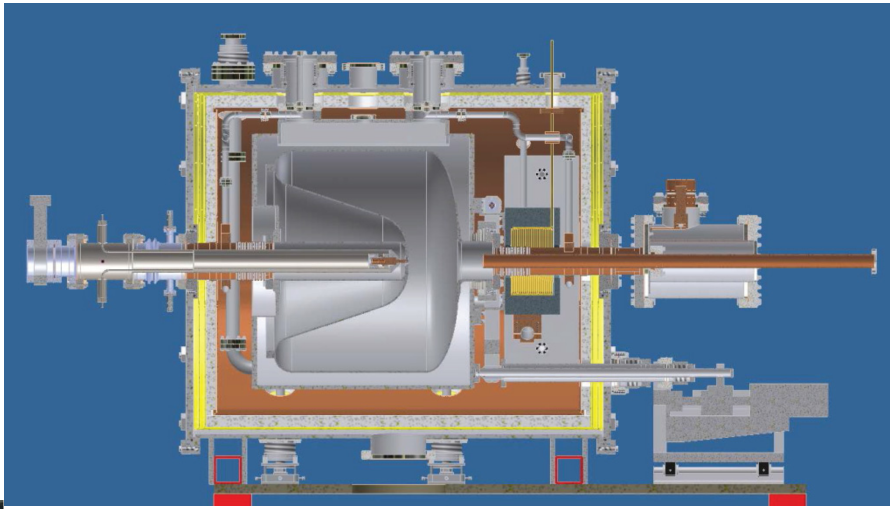
- 200 MHz QWR Gun @ University of Wisconsin
  Gun developed for WiFEL light source project
  First beam 9. July 31, 2013
  J. Bisognano, et al., Proc. PAC2013, p. 622

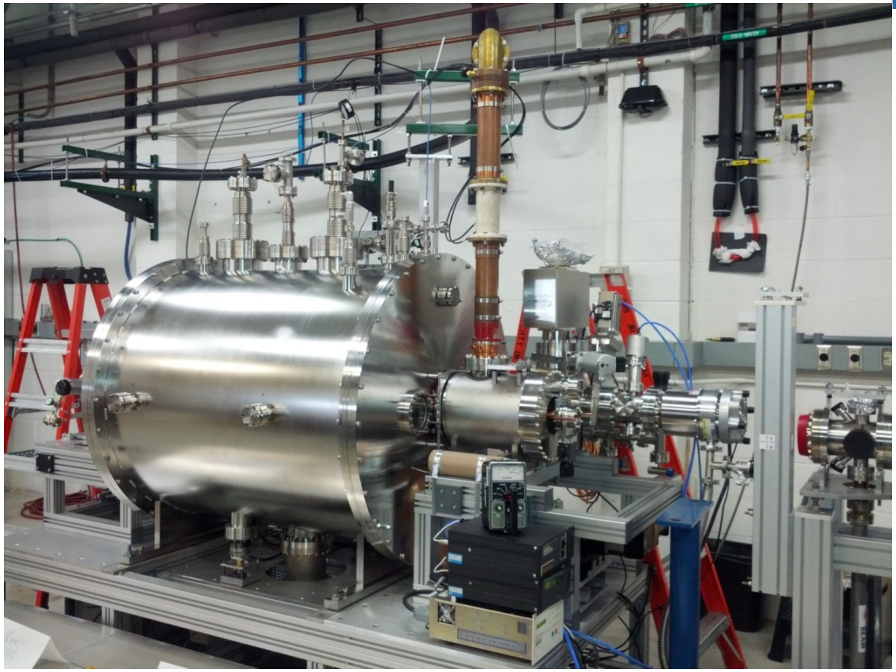


WiFEL SRF Gun at University of Wisconsin

with 200 MHz quarter wave resonator

QWR advantages:
low frequency,
compact design,
near CW field in gap,
4.5 K operation





Design parameters
peak cathode field: 40 MV/m
kinetic energy: 4 MeV
bunch charge: 200 pC
normalized emittance: 1 mm-mrad
average beam current: 1 mA

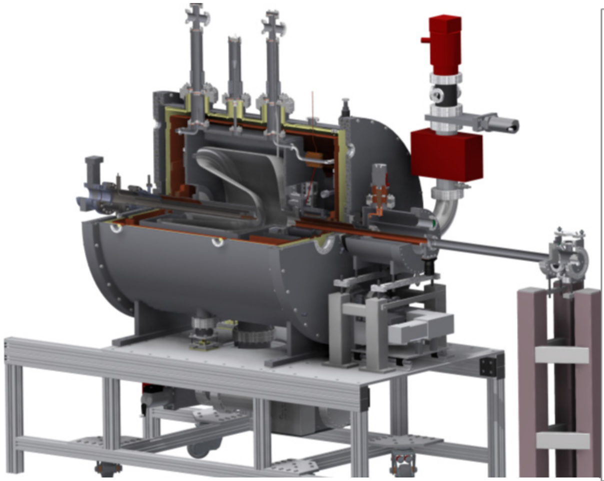
NC Cathode + Quarter Wave SC Cavity

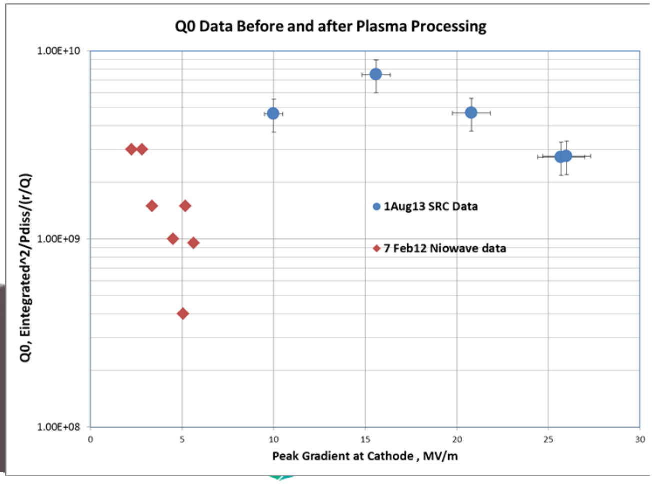
WiFEL SRF Gun at University of Wisconsin

- Cavity achieved a Q_0 of $3x10^9$ at 26 MV/m after Ar:O plasma processing
- System uses a Cu cathode and 1 kHz laser for reliability and cost reduction
- Blow out mode is used; ~200 fs pulse
- First beam on July 31, 2013
- Dark current less than$1x10^{-14}$ A

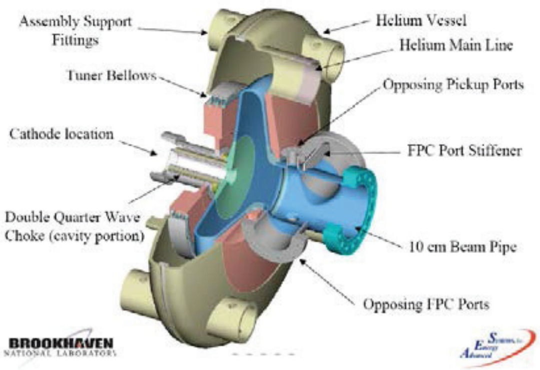
peak gradient: 20 MV/m (29 MV/m)
energy gain: 1.06 MeV
average current: 50 nA
max. bunch charge: 100 pC
norm. emittance (12pC): 0.7 mm mrad

plasma processing of cavity

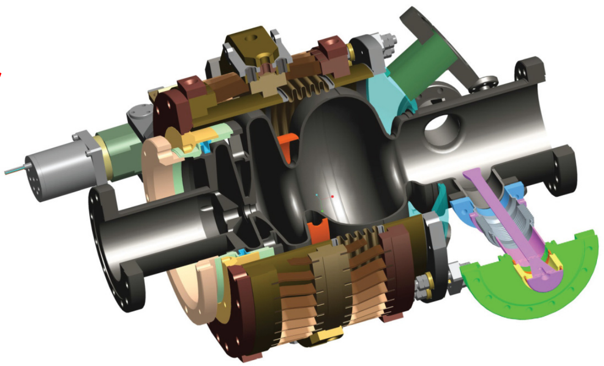




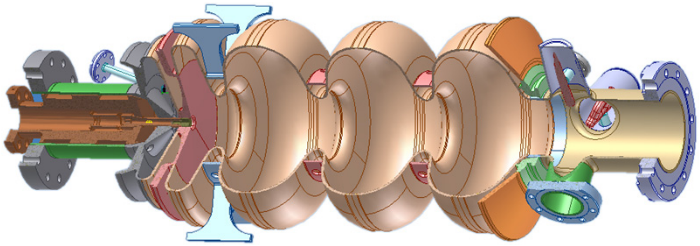
- 704 MHz SRF Gun for Prototype ERL at BNL
  500 mA, with NC CsK_2Nb cathode
  S. Belomestnykh, Proc. SRF2013, p. 50



- High Brighness1.3 GHz 1.4-cell Gun (Gun 1) for B*ERL*inPro at HZB
  4 mA, with NC CsK_2Nb cathode
  A. Neumann, et al., Proc. SRF2013, p. 42

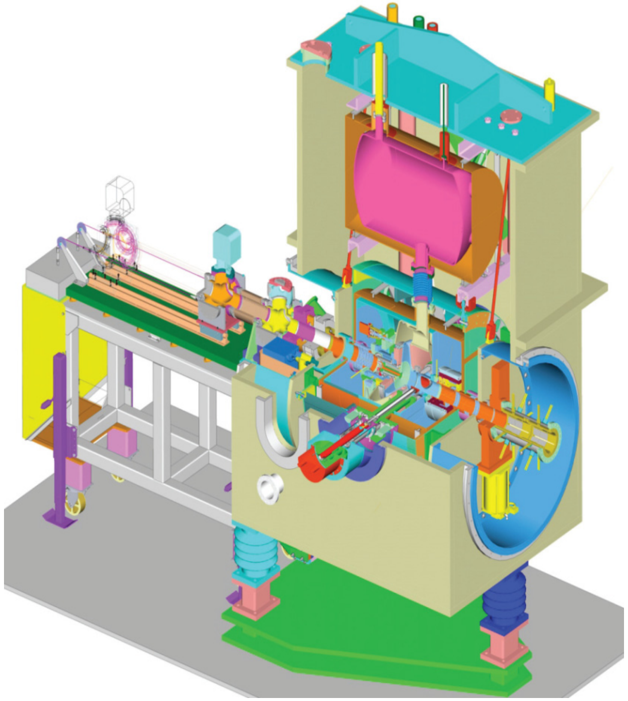


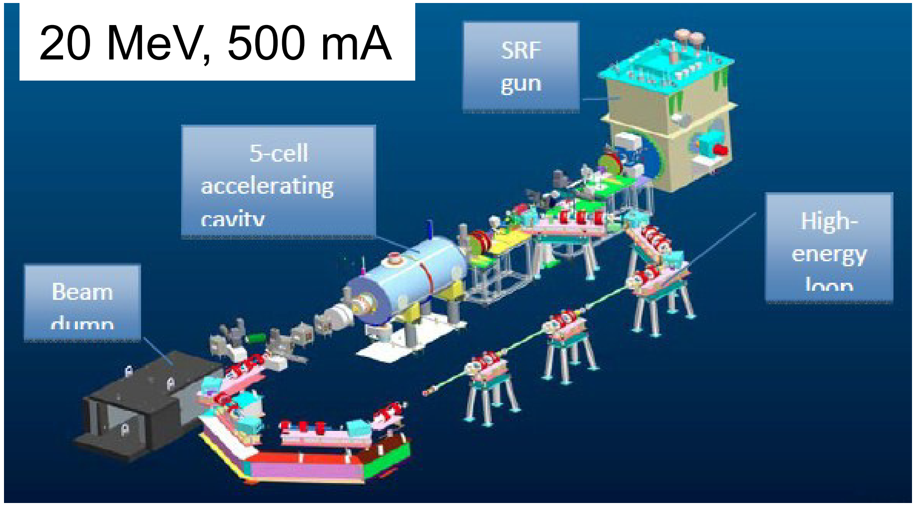
- 1.3 GHz 3.5-cell SRF ELBE injector at HZDR
  ELBE SRF Gun I – in operation 2007 – 2014
  Commissioning ELBE SRF Gun II
  J. Teichert, et al., NIMA 743 (2014) 114
  P. Murcek, et al., Proc. SRF2013, p. 148



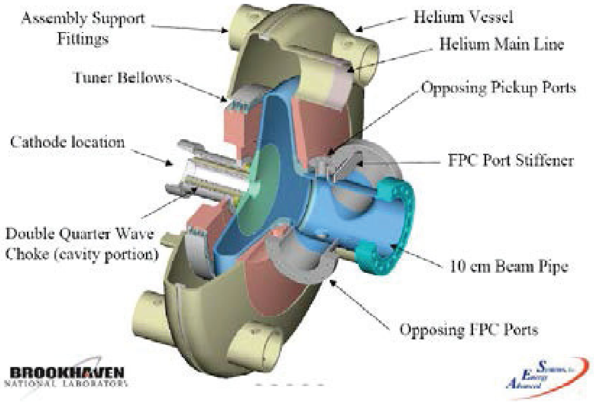
704 MHz SRF Gun for Prototype ERL at BNL

½-cell elliptical cavity 703.5 MHz
500 mA beam current
2 MeV energy gain
1 MW RF power
bunch charge 0.7 - 5 nC
emittance 1.4 - 5 mm mrad
CsK_2Sb photo cathode

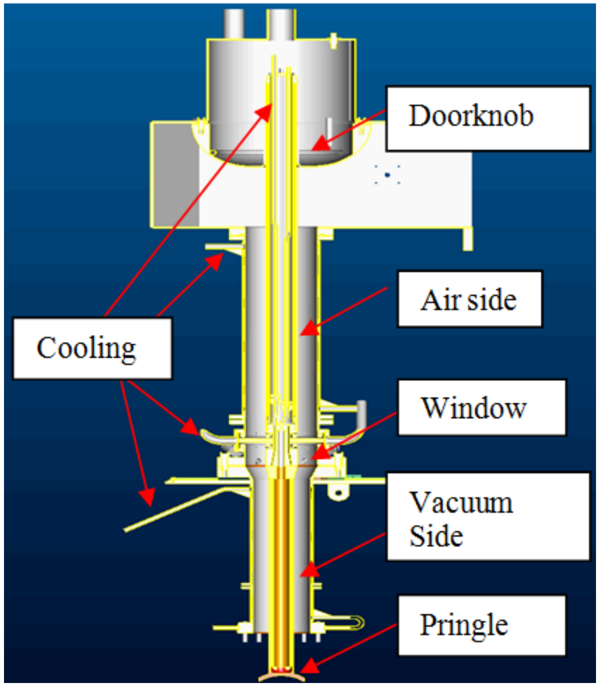




Extremely challenging project in Beam current and RF power

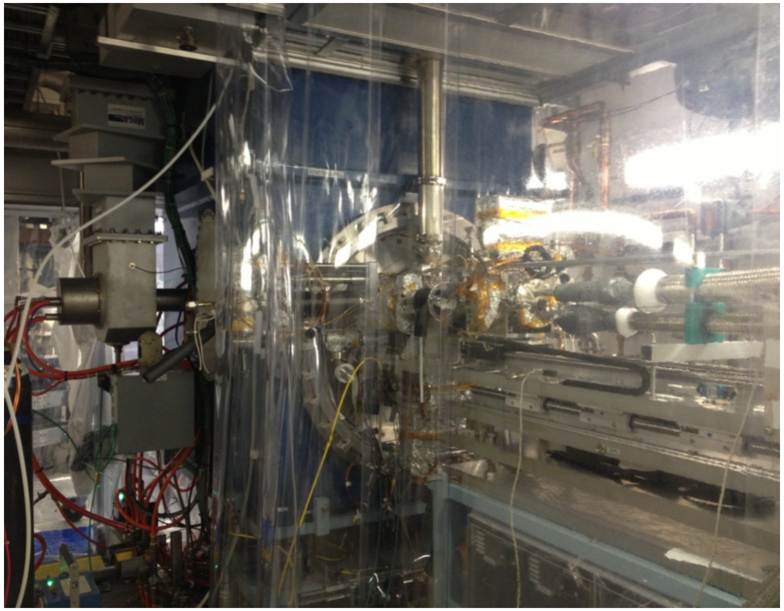


704 MHz SRF Gun for Prototype ERL at BNL



Conditioning of the power couplers up to 500 kW

Initial commissioning of the gun w/o cathode
Is completed (Nov. 2012 – March 2013)
with 2 MV and 220 kW in CW



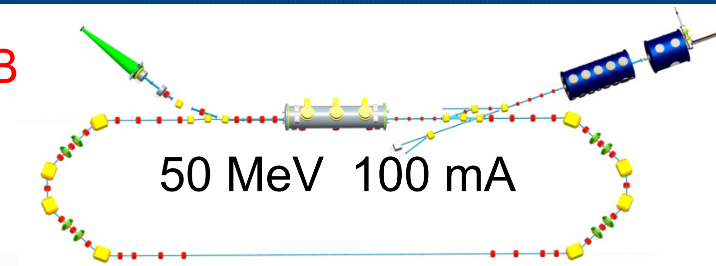
Gun commissioning with a Cu cathode stalk

- 1.8 MV @ 20ms/10Hz
- 2.2 MV @ 0.5 ms/10 Hz

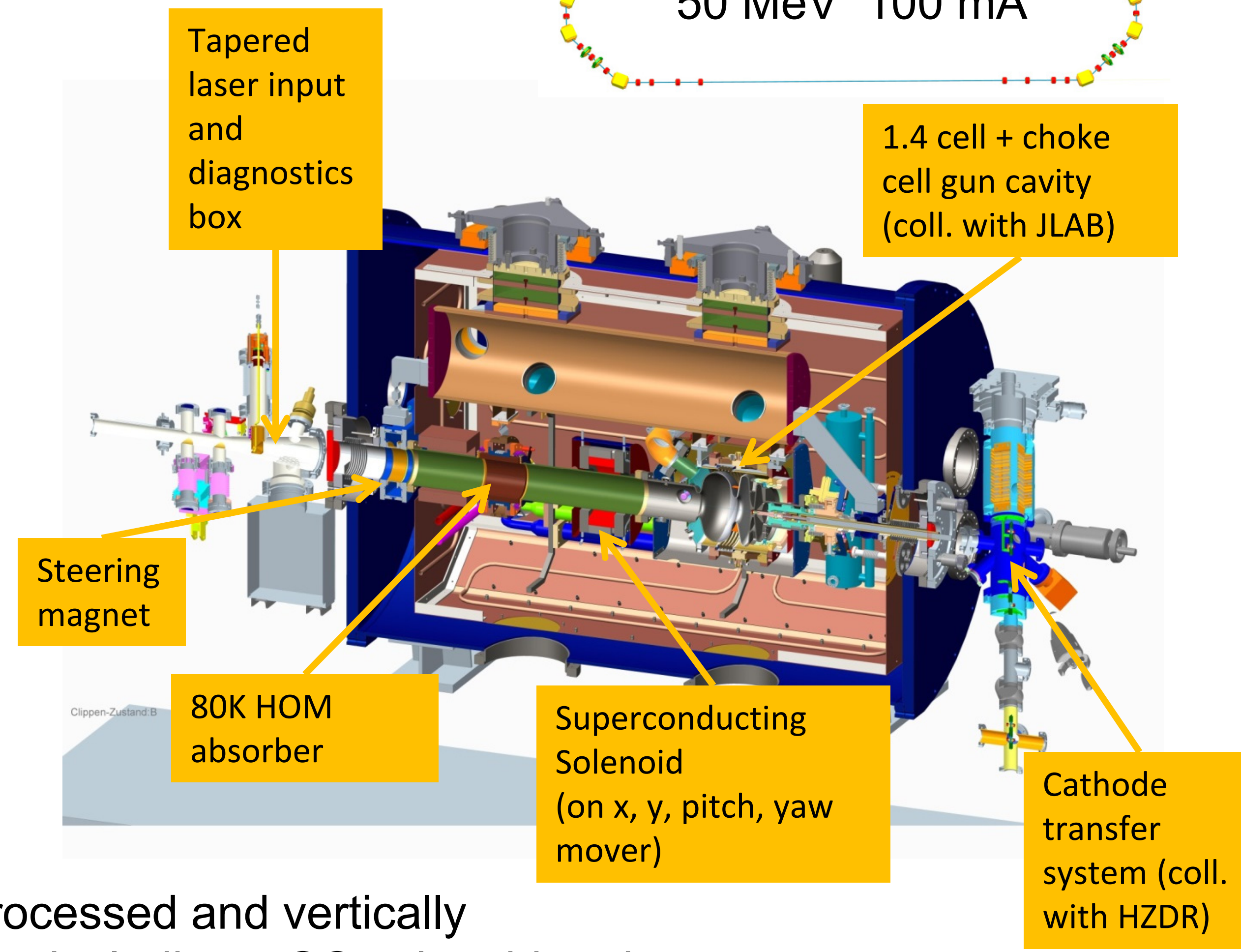
Multipacting in the choke requires redesigned Cathode stalk,
First beam tests with 1.85 MV, 18% have been started now

NC Cathode + Elliptical SC Cavity

High Brightness Gun (Gun1) for *BERL*inPro at HZB



- 1½-cell elliptical cavity 1.3 GHz
- 4 mA beam current
- 2.3 MeV energy gain
- 9.2 kW RF power
- bunch charge 77 pC
- emittance 1 mm mrad
- CsK_2Sb photo cathode



Cavity is being fabricated, processed and vertically tested at JLab. The cold mass including a SC solenoid and a beam tube HOM absorber is assembled at Jlab.

NC Cathode + Elliptical SC Cavity

ELBE SRF GUN I (2007-2014)

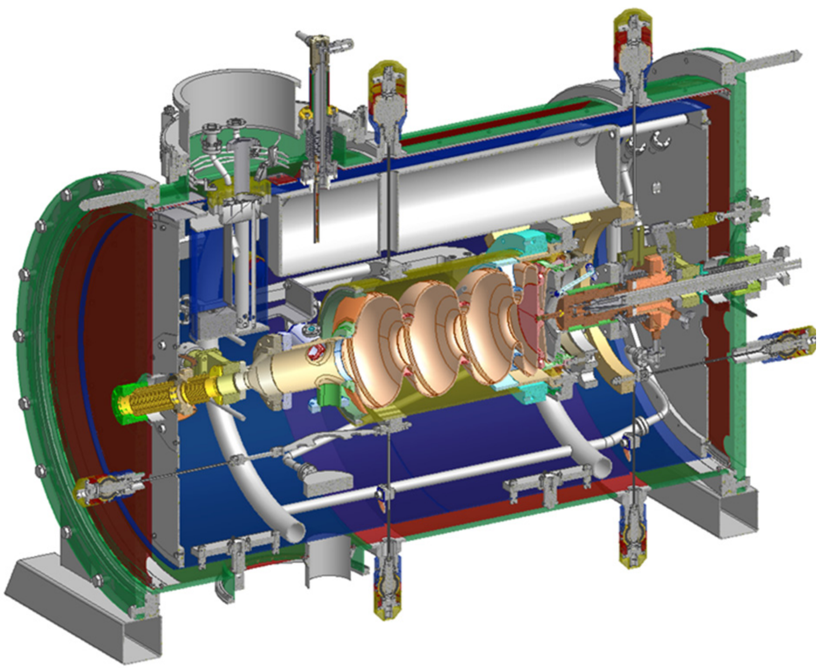


Table 1: Design parameters for ELBE SRF guns I and II

	ELBE mode	High charge mode
RF frequency	1.3 GHz (CW)	
beam energy	9.5 MeV	
drive laser	262 nm	
photocathode (quantum efficiency)	Cs_2Te (≥1%)	
repetition rate	13 MHz	≤ 500 kHz
pulse length (FWHM)	4 ps	15 ps
laser spot size	2 mm	5 mm
bunch charge	77 pC	1 nC
average current	1 mA	0.5 mA
normalized transverse emittance (rms)	1 mm mrad	2.5 mm mrad

Design for

average current: 1 - 2 mA

exchangeable high-QE photo cathode,

LN_2-cooled,

performance of GUN I cavity limited by strong field emission

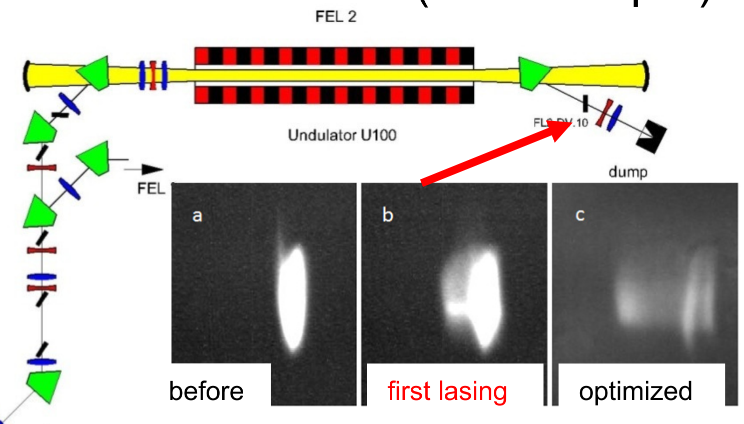
	E_{acc}	E_{peak} on Axis	E_{kin}
CW	6.5 MV/m	17.5 MV/m	3.3 MeV
Pulsed RF	8 MV/m	22 MV/m	4.0 MeV

ELBE SRF GUN I (2007-2014)

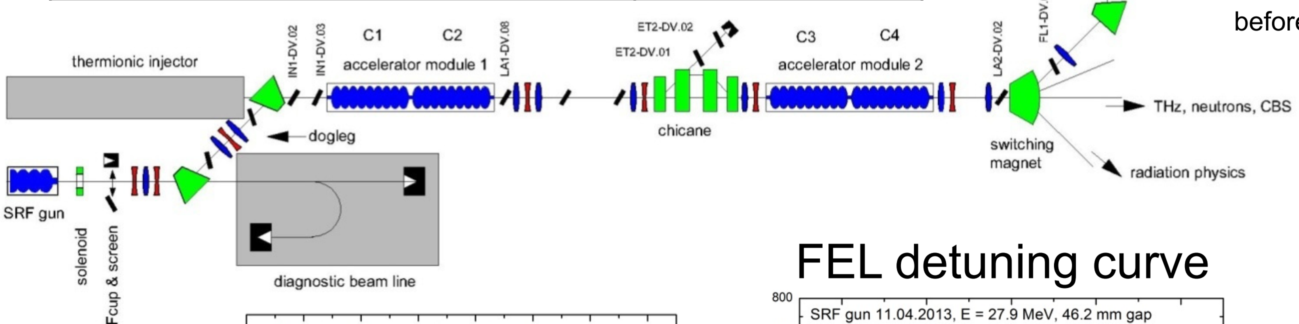
E_{kin} at gun exit	3.3 MeV
Micro pulse repetition rate	13 MHz
Macro pulse repetition rate / length	1.25 Hz / 2 ms
Beam energy at FEL	27.9 MeV
Bunch charge / beam current	20 pC / 260 μA
Photo cathode	Cs_2Te
RMS bunch length	1.6 ps
Normal. RMS emittance	1 mm mrad

First FEL Operation with a SRF Photo Gun

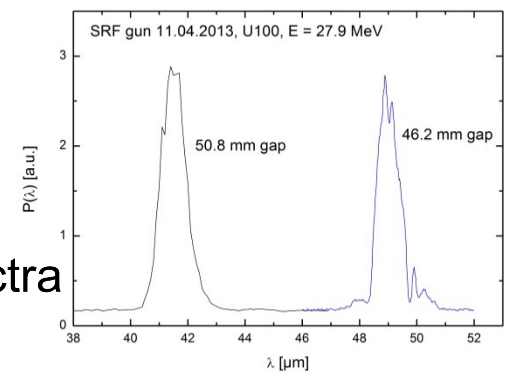
ELBE infrared FEL (20 – 250 μm)



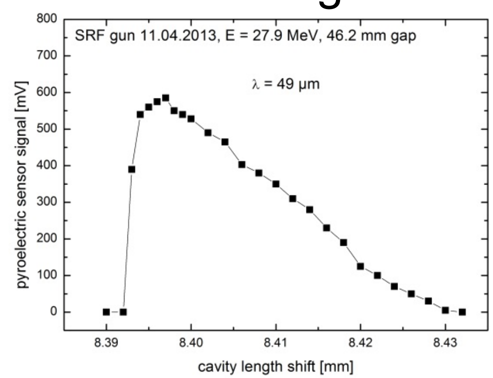
April 11, 2013



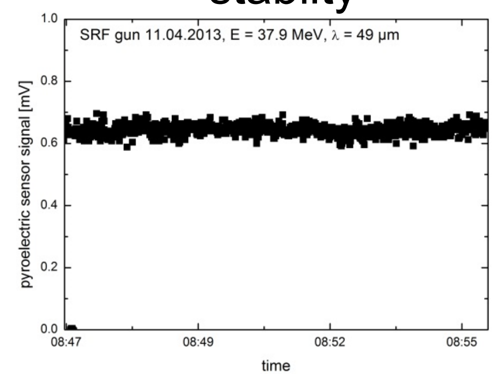
FEL spectra



FEL detuning curve

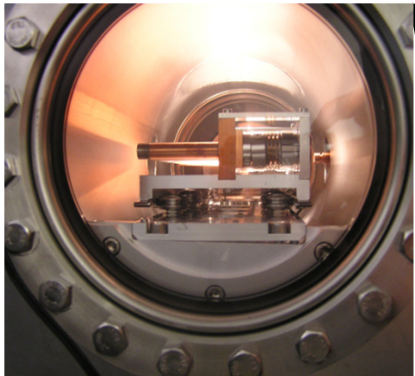


stabilty



NC Cathode + Elliptical SC Cavity

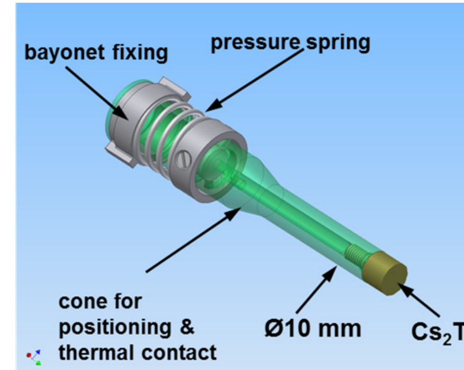
ELBE SRF GUN I (2007-2014)

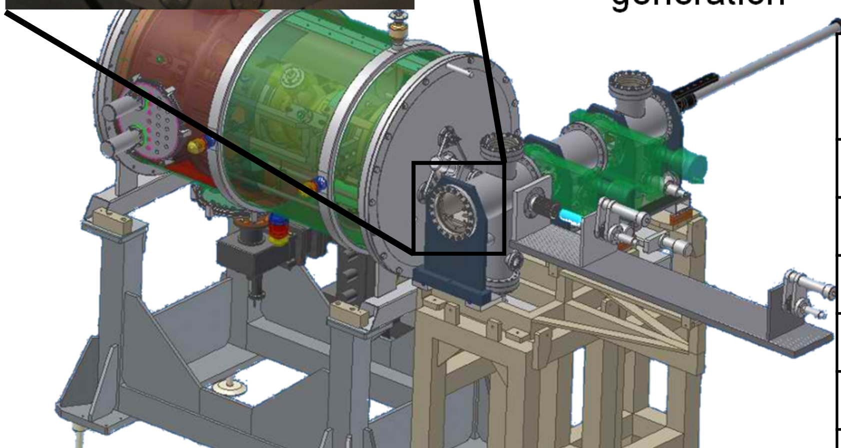


Excellent lifetime of Cs2Te PC in SRF gun

Requirements for Transfer:

- Load lock system with < 10^{-9} mbar to preserve QE ≥ 1 %
- Exchange w/o warm-up & in short time and low particle generation





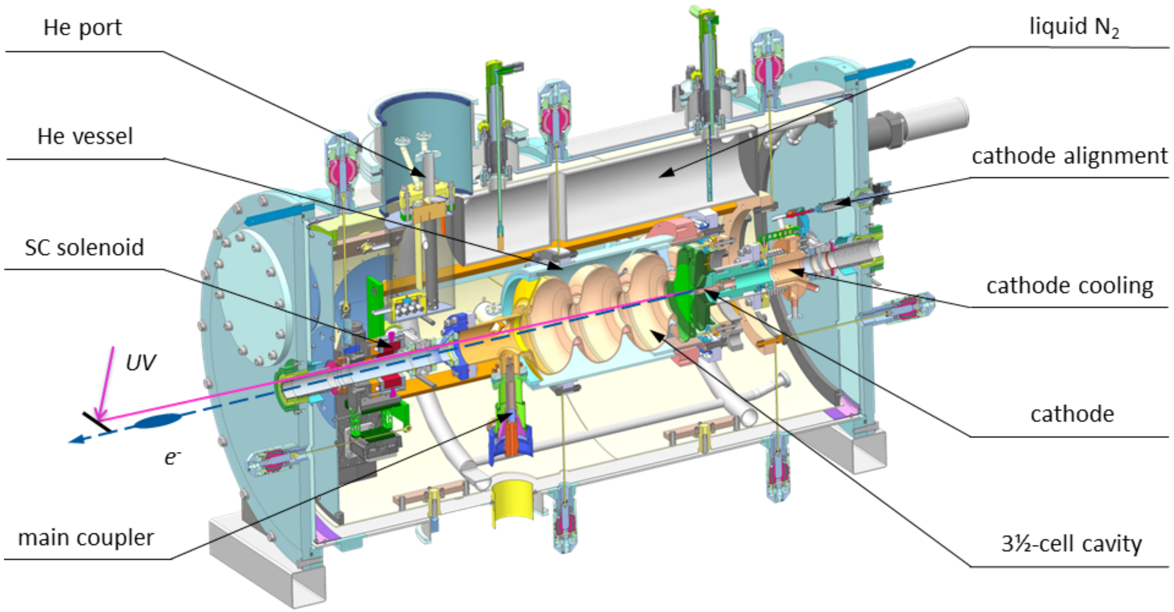
Cathode	Operation days	Extracted charge	Q.E. in gun
#090508Mo	30	< 1 C	0.05%
#070708Mo	60	< 1 C	0.1%
#310309Mo	109	< 1 C	1.1%
#040809Mo	182	< 1 C	0.6%
#230709Mo	56	< 1 C	0.03%
#250310Mo	427	35 C	1.0%
#090611Mo	65	< 1 C	1.2%
#300311Mo	76	2 C	1.0 %
#170412Mo	447	264 C	~ 0.6 %

- fresh QE 8.5%, in gun 0.6%
- total beam time 600 h
- extracted charge 264 C
- Max. CW beam current: 400 µA

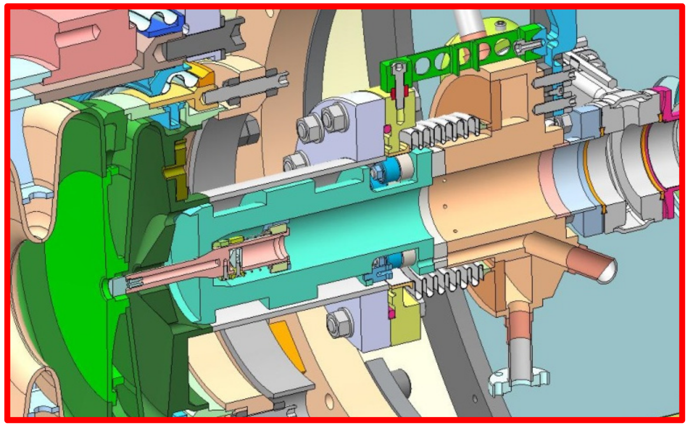
April 2014

problems: multipacting, QE drop-down during storage

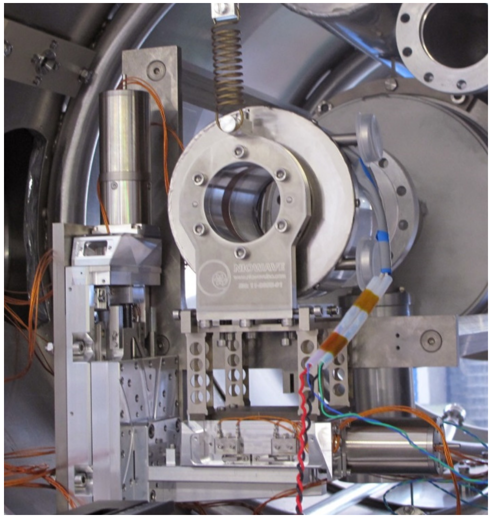
ELBE SRF GUN II at HZDR



old gun NC solenoid

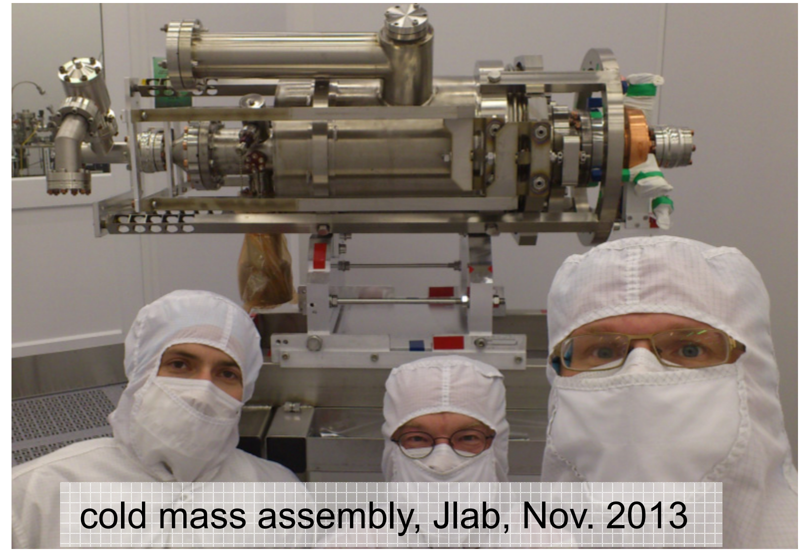


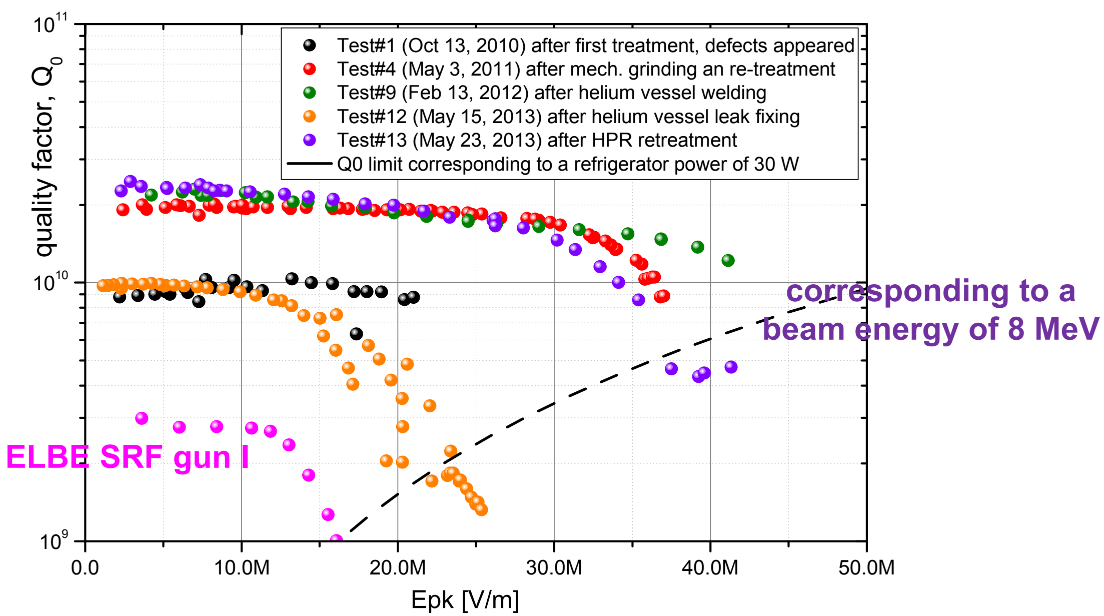
SC Solenoid (NPS, HZB)
by Niowave Inc. (2 K)
on remote controlled
xy-table (77 K)



ELBE SRF GUN II at HZDR

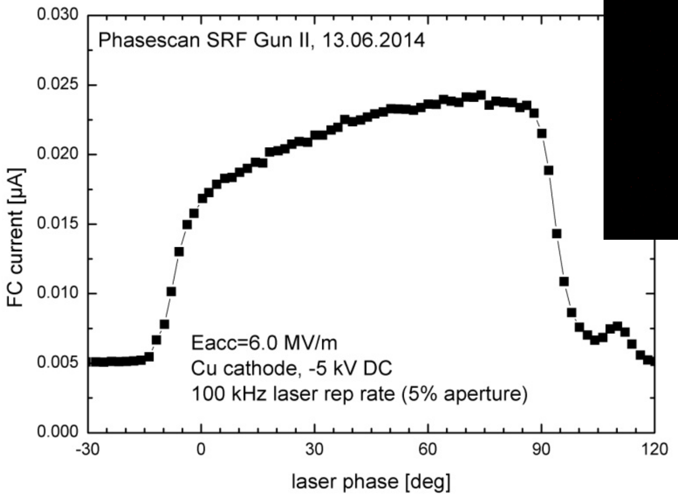

cavity with He vessel at JLab


cold mass assembly, Jlab, Nov. 2013

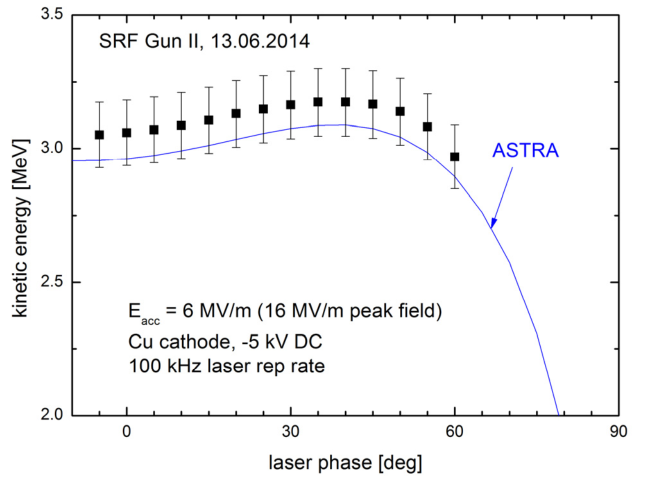



marriage, HZDR, Mar. 2014

ELBE SRF GUN II at HZDR



first beam on screen June 10, 2014



First beam test with moderate RF power (600 W)
- 6 MV/m gradient (16 MV/m peak field)
- 20 nA current with Cu photo cathode
- 3.0 MeV kinetic energy

See also Poster MOPRI022

DRESDEN concept

SUMMARY

- Significant progress of SRF photoinjectors during the last years
- Several guns generated first beam, first FEL lasing was achieved with the ELBE SRF Gun I.
- Guns with quarter wave resonators (Niowave Inc.) are very promising new design
- Normal-conducting, high QE photocathodes can be operated in SRF guns, Cs_2Te photo cathodes with 250 µA at PKU and 400 µA at ELBE
- Two most challenging ERL gun projects (BNL , HZB) based on elliptical cavities and will use CsK_2Nb (green light)
- Demonstration of high current (1 mA) operation and bunch charge of ≥ 100 pC with accelerator quality (> 8 h) needed

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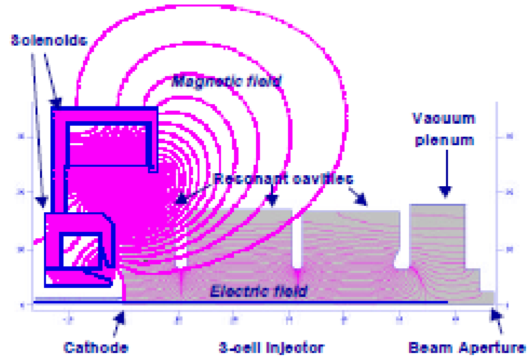
Robert Legg (Jlab),
Andrew Burrill (HZB),
Thorsten Kamps (HZB)

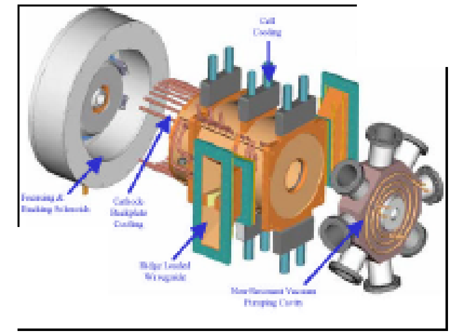
Extra Slices

HZDR

„emittance compensation solenoid“
around the NC RF guns

B.E. Carlsten NIM A285 (1989) 313



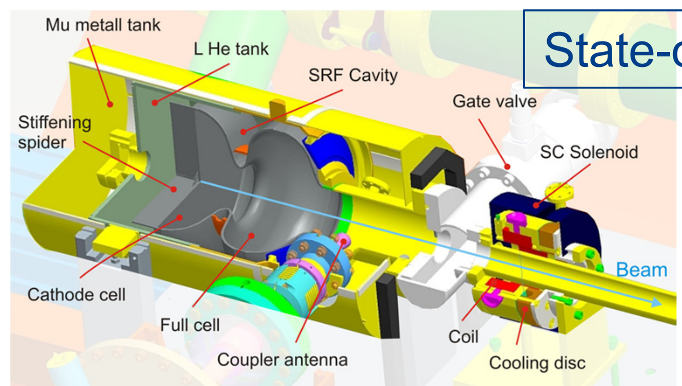


Solenoid Magnetic Field

SRF Gun:

1. A high acceleration gradient at cathode and high energy gain are most important: **Cavity peformance!**
2. Solenoid magnetic field

Cu coil in beamline
ELBE SRF Gun I

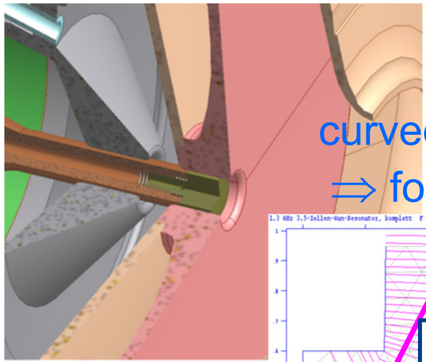


State-of-the- Art

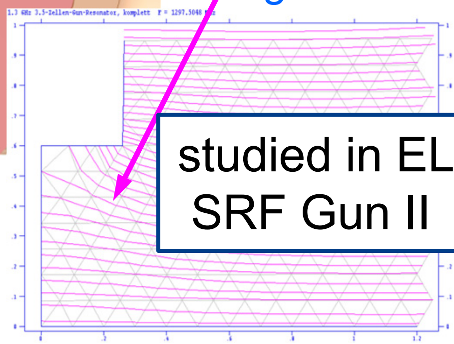
HZB, NPS,
Wisconsin,
HZDR SRF Gun II

SC solenoid in cryomodule

3. RF focusing and additional TE mode magnetic field in SC cavity



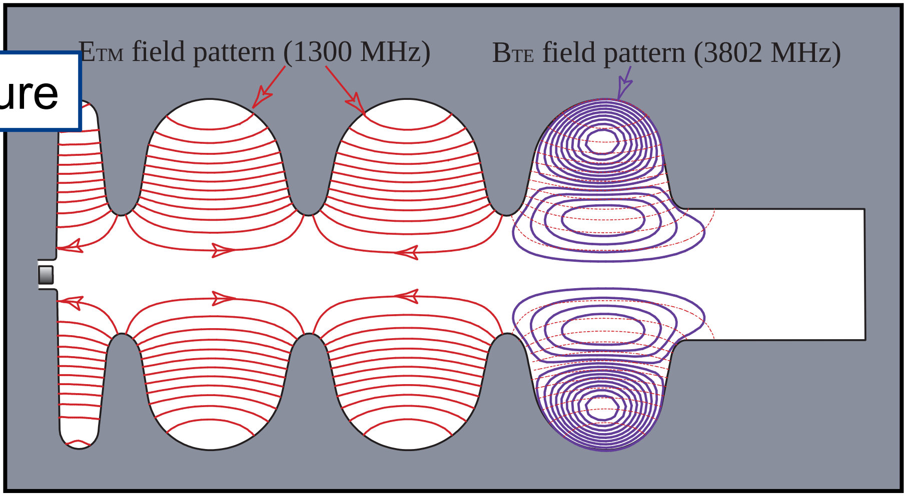
curved field lines
⇒ focusing force



retracted or shaped cathode

studied in ELBE SRF Gun II

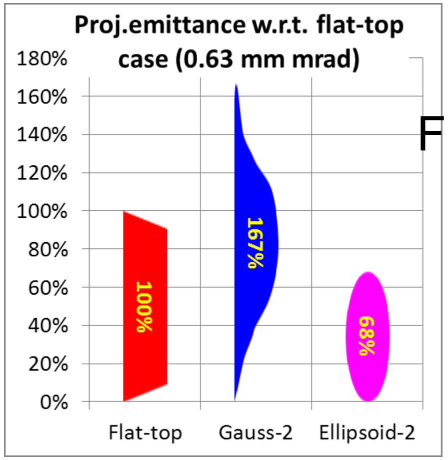
Future



V. Volkov, D. Janssen Phys. Rev. STAB 11, 061302 (2008)

4. Linear Space Charge Forces – Laser Pulse Shaping

demonstrated in NC RF guns



Flat-top pulse

PITZ/XFEL gun
M. Krasilnikov

Blow-out regime
Start with a short (~100 fs) pulse
O. J. Luiten et al., Phys. Rev. Lett. 93, 094802 (2004)

Photoelectron injectors for high-brightness beams and cw operation

Gun type	low f NC RF	¼ wave SC RF	elliptical SC RF	DC voltage
potential	highest brightness in high f guns	best combination of brightness + aver. current		high aver. current
status	succesfull beam tests	first beam	produces beam	routine operation
Examples	LBNL	NPS	HZDR HZB	Jlab FEL Cornell, KEK
present efforts	dark current reduction	higher gradients reducing FE		designs for higher voltage
gradient@cath. final energy *)	19.5 MV/m [1)] 0.75 MeV	25 MV/m [2)] 1.2 MeV	20-30 MV/m [3)] 9.5 MeV	6.75 MV/m [4)] 0.5 MeV
show stoppers	rf heat dissipation	NC cathode in SC cavity ?		high voltage
>100 mA ERL light sources			~1 GHz rep rate	
highest brightness			best combination grad. + energy	

*) design values

1) F. Sannibale, et al., Phys Rev. ST AB 15, 103501 (2012).

2) J.R. Harris, et al., Phys Rev. ST AB 14, 053501 (2011).

3) A. Arnold, et al., NIM A 577, 440 (2007).

4) N. Nishimori, et al., Proc. of LINAC´10, Tsukuba, Japan, 2010, p.995.