Review of SRF gun cavities and cryomodules

compiled and edited by Elmar Vogel for the "TTC community"

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

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  - HZB: Axel Neumann, Thorsten Kamps
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  - PKU: Senlin Huang
  - PolFEL: Robert Nietubyć, Paweł Krawczyk, Jacek Sekutowicz
  - DESY: all colleagues contributing to the SRF photoinjector R&D

Structure of this talk

on SRF gun cavities and cryomodules

three slides per laboratory & project

- parameters and project info
  - design beam parameters
  - RF parameters
  - cathode assembly and type
- SRF gun cavity
  - mechanical fabrication
  - surface treatment
  - performance archived
  - special challenges
- Cryomodule
  - principal setup (solenoid position, cryogenics, …)
  - alignment concept
  - magnetic shielding
  - assembly features
  - other special features?

Two types of cavities

Two types of SRF gun cavities

Parameter range, laboratories and projects

VHF-band quarter wave resonator (QWR) SRF guns

RF frequency: 113 MHz to 200 MHz

exit energy: 1 MeV to 1.8 MeV

cathode *E* field: 6 MV/m to 30 MV/m

peak on axis *E* field: 6 MV/m to 30 MV/m

laboratories & projects:

- SLCS-II HE Low-Emittance Injector
  by SLAC/FRIB/ANL/HZDR collaboration
- BNL – SRF gun for hardon cooling
- (Wisconsin/SLAC/ANL SRF gun – no longer used)

L-band (elliptical shaped) SRF guns

RF frequency: 1.3 GHz

exit energy: 1 MeV to 4 MeV

cathode *E* field: 7.5 MV/m to > 40 MV/m (> 60 MV/m?)

peak on axis *E* field: 7.5 MV/m to > 40 MV/m (> 60 MV/m?)

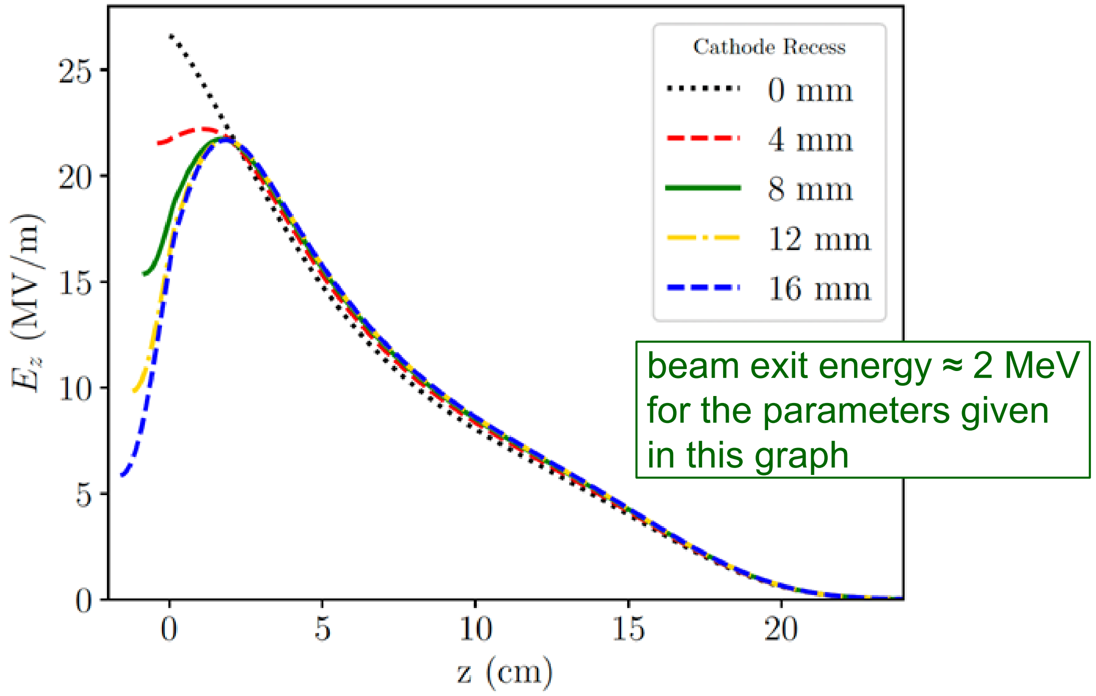
laboratories & projects:

- HZDR – photoinjector for ELBE (THz FEL)
- HZB – for bERLinPro (ERL)
- MSU/KEK – for photocathode R&D (former KEK-ERL)
- Osaka University – for electron microscopy
- PKU – DC-SRF gun
- DESY – for Eu XFEL HDC operation, cavity for PolFEL

Two types of SRF gun cavities

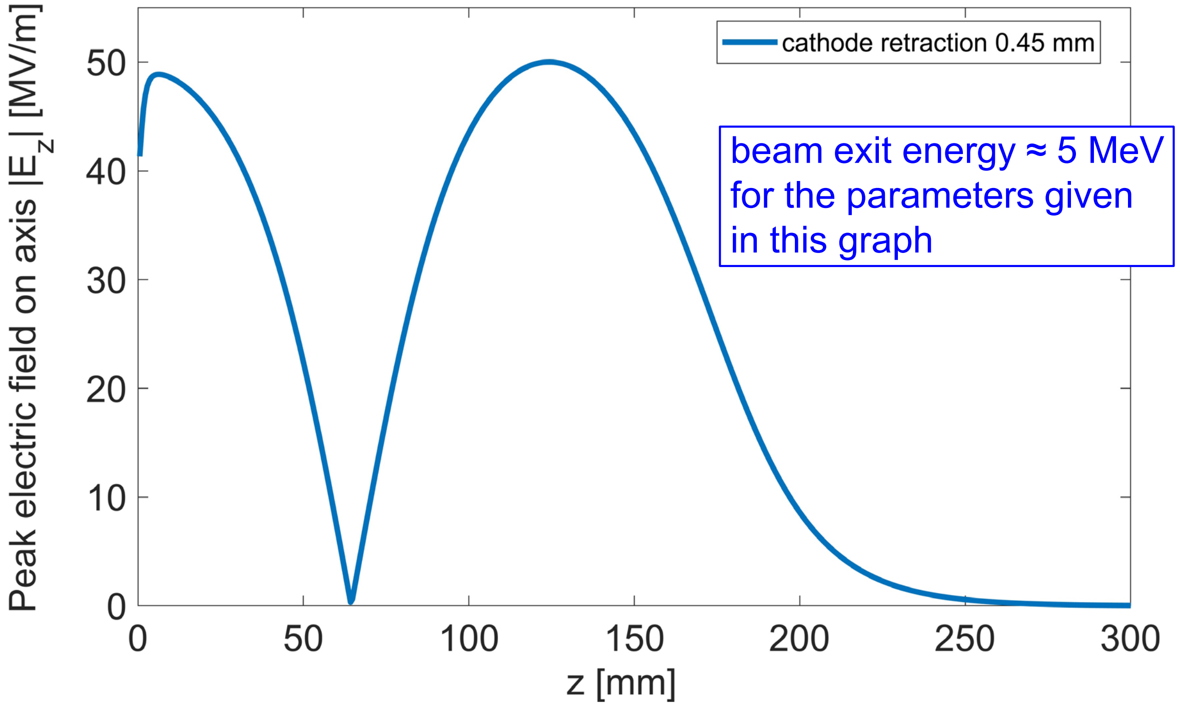
Electric field distribution – difference between quarter wave resonators and elliptical cavities

VHF-band QWR SRF guns – example BNL SRF gun



electric field distribution in 113 MHz BNL QWR SRF gun, graph taken from Irina Petrushina's (BNL) talk for NAPAC19

L-band SRF guns – example DESY SRF gun



electric field distribution in 1.3 GHz DESY L-band SRF gun, graph generated by Dmitry Bazyl (DESY)

VHF-band quarter wave resonator (QWR) SRF guns

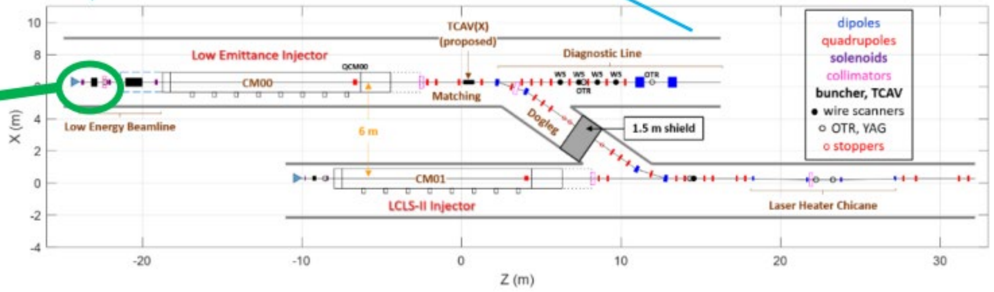
SRF gun for LCLS-II HE Low-Emittance Injector

Under development by SLAC/FRIB/ANL/HZDR collaboration

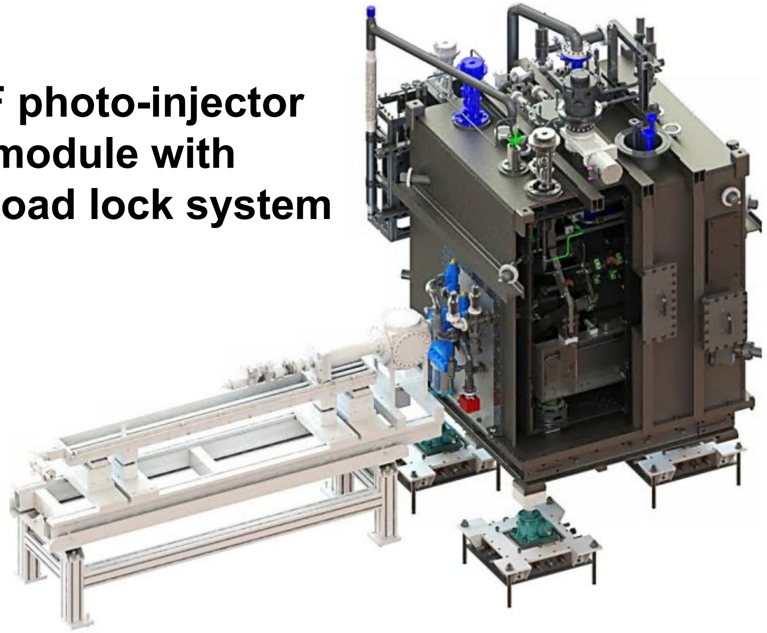
Design beam parameters	QWR SRF gun
Bunch repetition rate	1 MHz
Charge per bunch	100 pC
Transverse emittance	<0.1 µm
Beam energy at gun exit	1.8 MeV

RF parameters	Single gap
Operating frequency	185.7 MHz
Accelerating gradient	n/a
Electric field at cathode	30 MV/m
Peak on-axis *E* field	30 MV/m
Cathode	
Material	Cu/S20(Cs_3Sb+Na_2K Sb)
DC bias	Yes

LCLS-II HE
Low Emittance Injector



LEI SRF photo-injector cryomodule with cathode load lock system



SRF gun for LCLS-II HE LEI

SRF cavity

Fabrication

- At FRIB with industrial partner for electron beam welding
- Achieved required tolerances of 0.1mm
- Resonant frequency tuning: plastic during fabrication, then stepper motor and piezo to actuate the tuner

Surface preparation

- Electropolishing (EP) at ANL, high-pressure rinsing (HPR), clean assembly
- Design includes 4 port extra ports for EP cathodes and HPWR

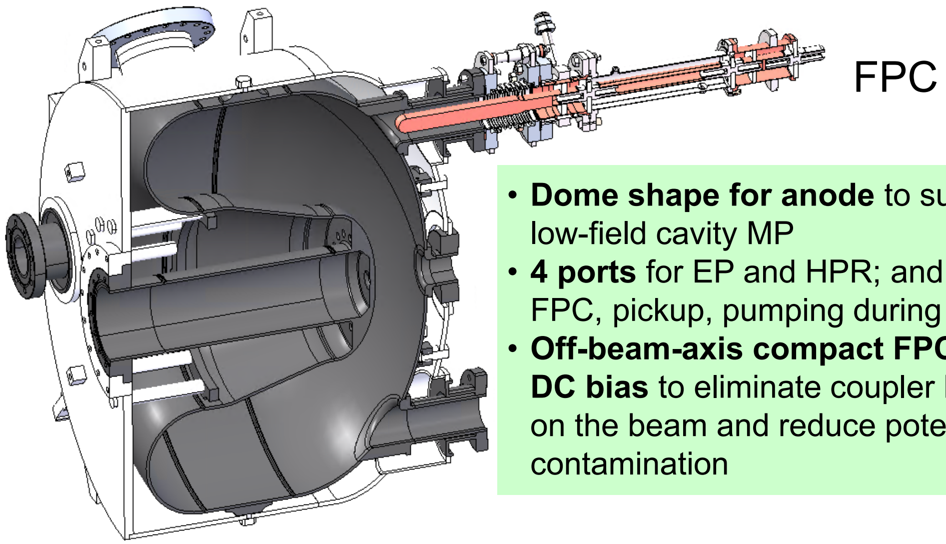
Dewar testing

- Achieved Ec = 32 MV/m, Q0 =1.8E9.
- Initially no X-rays, then field emission turn-on at high field. Plan to retest after light EP and HPWR.
- Multipacting conditioned easily.

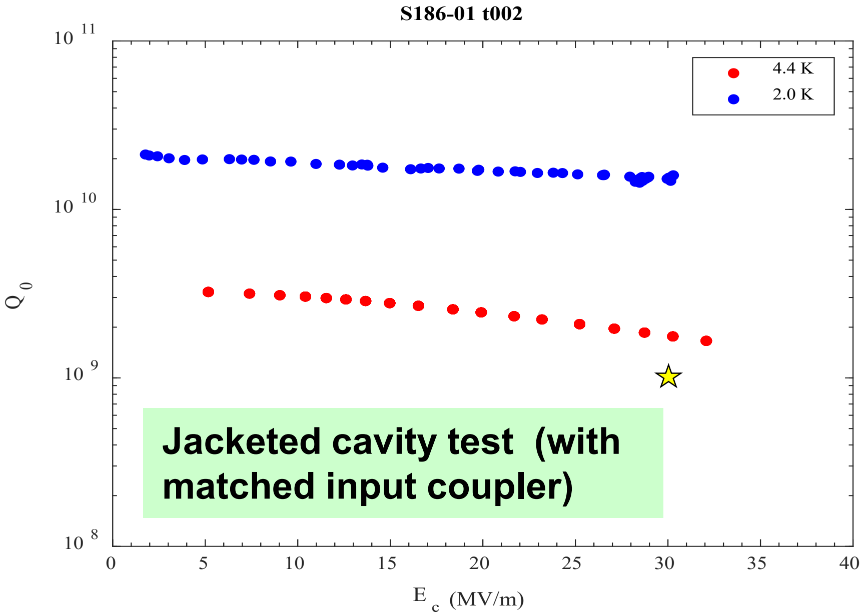
Features

- Cathode temperature: either 300 K or 55 K, cooled by cooled He gas
- DC bias (up to ± 5 kV) on cathode stalk to suppress multipacting

185.7 MHz QWR-based SRF gun cavity for LCLS-II HE LEI



- **Dome shape for anode** to suppress low-field cavity MP
- **4 ports** for EP and HPR; and use for FPC, pickup, pumping during operation
- **Off-beam-axis compact FPC with DC bias** to eliminate coupler MP impacts on the beam and reduce potential contamination



SRF gun for LCLS-II HE LEI

Cryomodule

Overview

- Superconducting (SC) solenoid package inside the module.
- Cavity and solenoid operate at 4.4 K with liquid helium bath
- Gate valves outside the module using triple-junction O-ring seal

Alignment

- Rail system for assembly, installation, and support
- SC solenoid package includes dipole and quadrupole coils for steering and focusing

Magnetic shielding

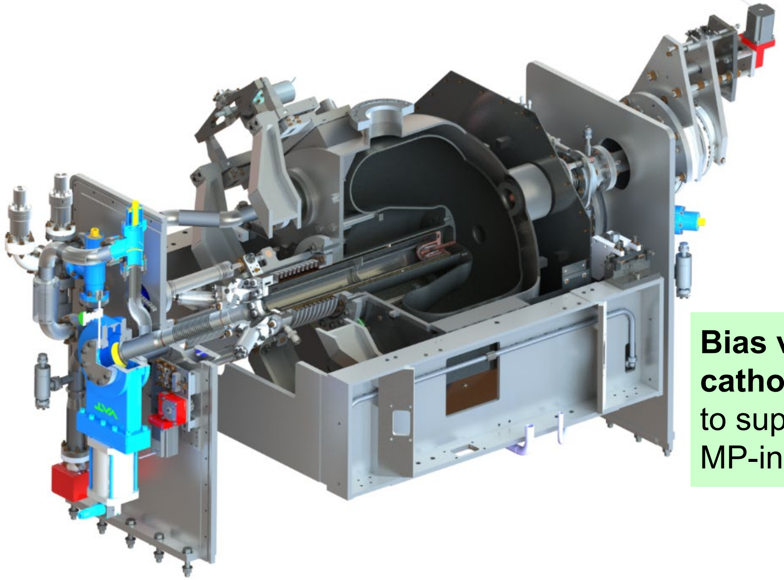
- Single-layer shield to attenuate ambient fields by 80%
- The steel vacuum vessel further attenuates ambient fields

Thermal transitions

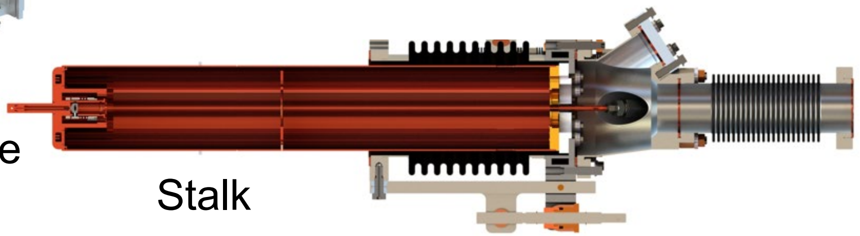
- Thermal shield cooled with helium gas; thermal intercepts for beam line and FPC
- Gas cooling circuit for cathode operation at 300 K or 55 K

Special assembly features

- Load lock system designed to isolate the cathode from the cavity during cathode exchange and operation.



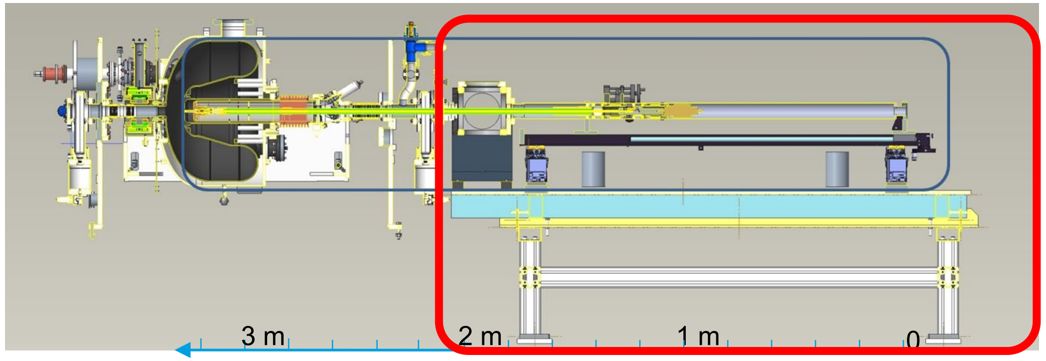
Bias voltage applied to cathode and cathode stalk to suppress MP and hence MP-induced dark current



Cathode

Stalk

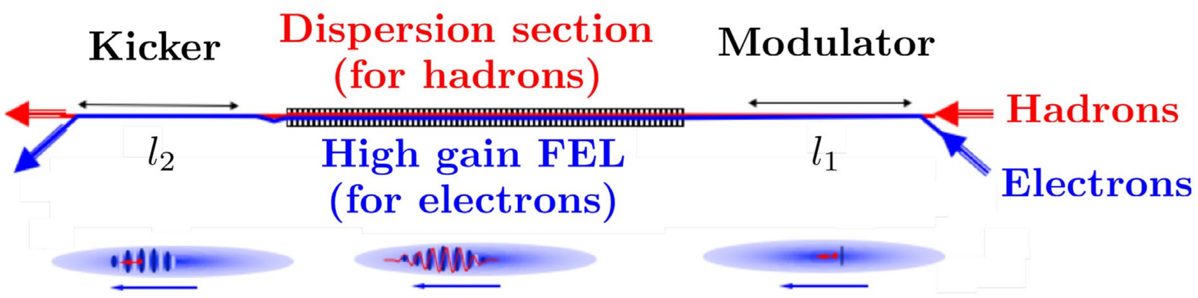
Cathode load-lock

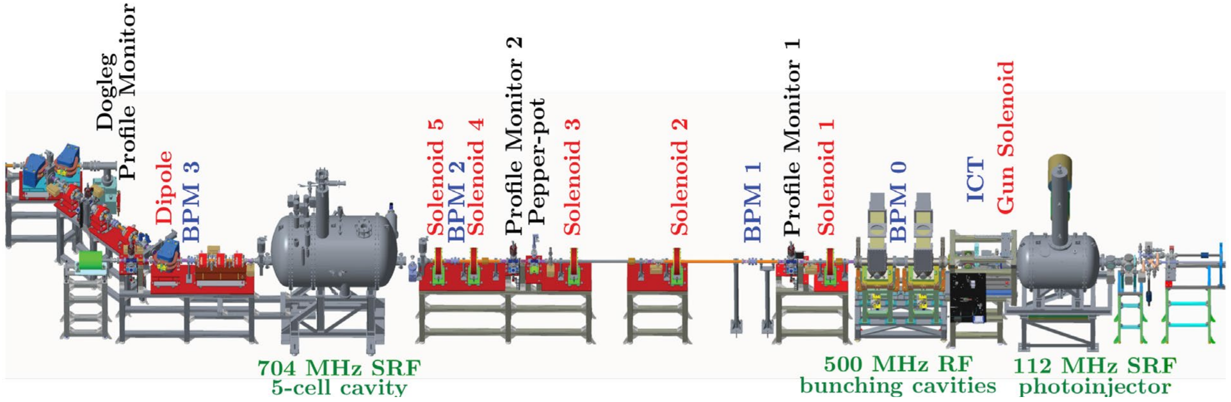


BNL – SRF gun for coherent electron cooling of hadrons

Routine operation since 2016

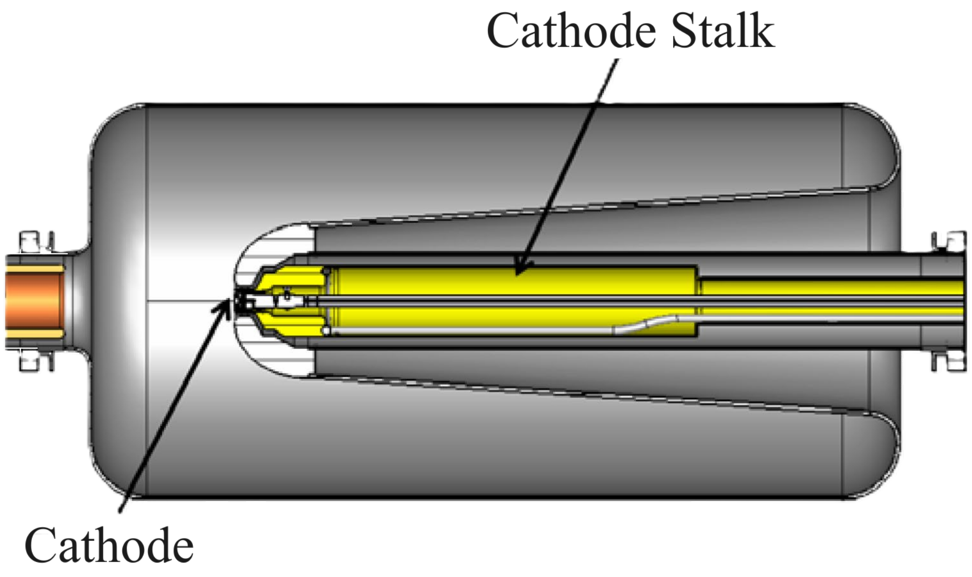
beam parameters	QWR SRF Gun
bunch repetition rate [kHz]	78
bunch charge [nC]	up to 10.7
transverse emittance [µm]	5
beam energy at gun exit [MeV]	1.25 to 1.5
RF parameters	
operation frequency [MHz]	113
accelerating gradient [MV/m]	n/a
electric field at cathode [MV/m]	10 to 20
peak on axis field [MV/m]	14 to 28
Cathode	
Material	CsK_2Sb
Assembly	load lock + RF choke





BNL – SRF gun for coherent electron cooling of hadrons

SRF cavity



mechanical fabrication

- built by the company Niowave

surface treatment applied

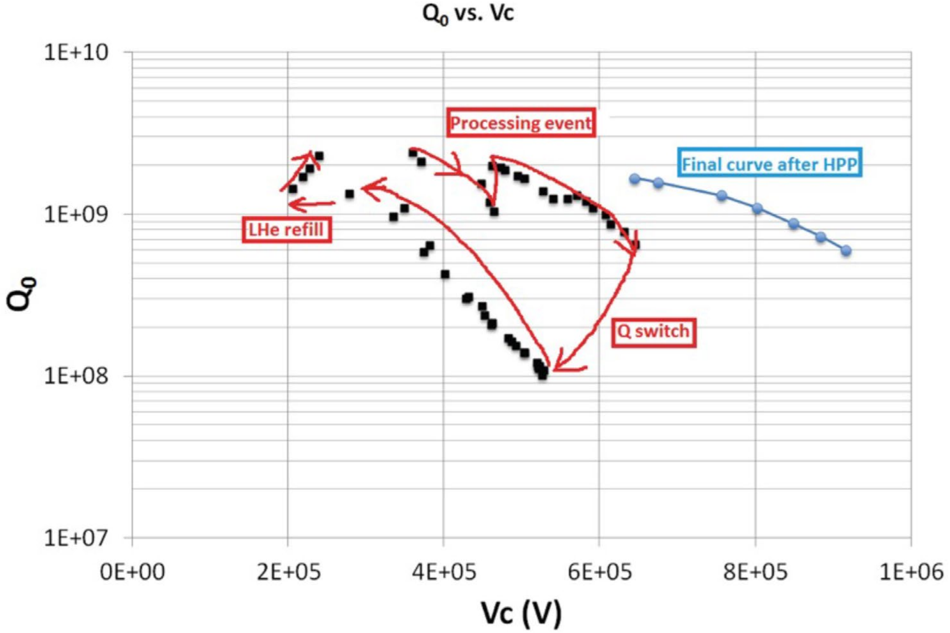
- BCP and HPR were used during fabrication
- processing with helium was used to remove the emitters

performance archived

- $E_{\text{peak on axis}} \approx$ 14 MV/m in CW
- $E_{\text{peak on axis}} \approx$ 18 MV/m with pulsed RF
- limited by strong radiation

special challenges

- multiple multipacting barriers inside the cavity and cathode stalk channel
- multipactors in the gun: if unchecked, kills the cathode instantaneously
- field emission in the cavity: some conditioning and performance increase observed over the years



BNL – SRF gun for coherent electron cooling of hadrons

Cryomodule

principal setup

- solenoid outside the module
- cooling with helium alone, liquid at 4 K and gaseous
- single cryogenic shield

alignment concept

- surveyed at manufacturer
- manufacturer survey information used during installation

concept of the magnetic shielding

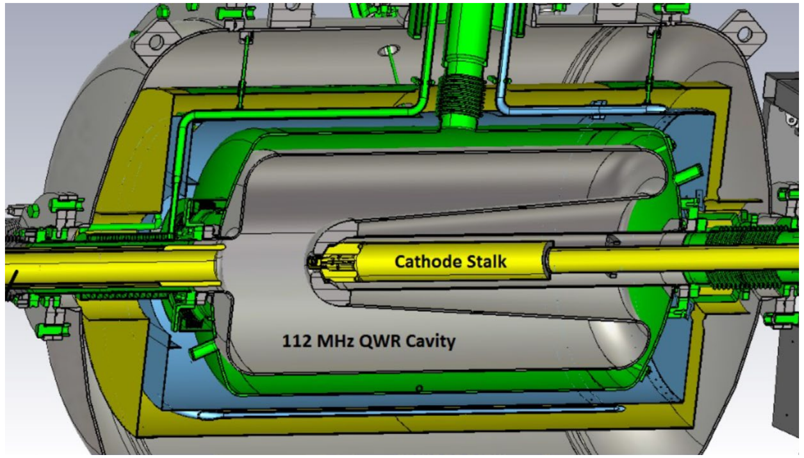
- single magnetic shield of mu-metal

cold warm transitions(s)

- warm parts reaching into the module
- cathode and stalk at room temperature for high QE

special assembly features

- local clean rooms for the connection to beam line and the cathode launch system

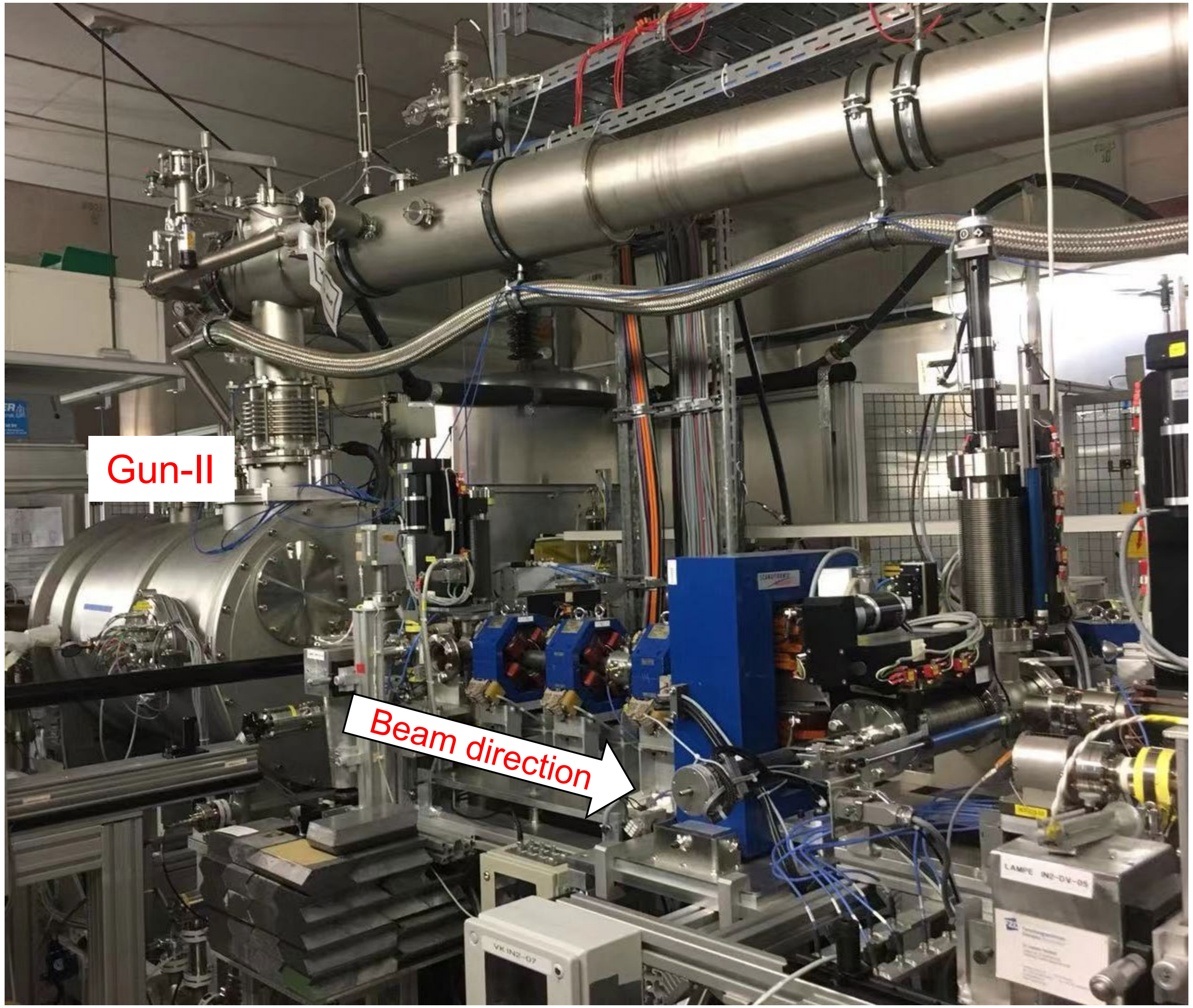


L-band SRF guns

HZDR – SRF photoinjector for ELBE (THz FEL)

~15 years' SRF gun R&D, user operation since 2017

Routine beam parameters	3.5 cell SRF Gun
bunch repetition rate [kHz]	25 – 250, (max. 13000)
bunch charge [pC]	0 – 250 (max. 600)
transverse emittance [µm]	1.3 to 6.3
beam energy at gun exit [MeV]	4.5
RF parameters	
operation frequency [GHz]	1.3
accelerating gradient [MV/m]	8
electric field at cathode [MV/m]	14.4
peak on axis field [MV/m]	20.8
Cathode	
material	Cs_2Te or Mg
assembly	load lock, RF choke



HZDR – SRF photoinjector for ELBE (THz FEL)

SRF cavity

mechanical fabrication

- SRF gun I by RI (former ACCEL GmbH), SRF gun II by JLab
- general tolerances *DIN 7168-m, in most cases* achieved
- cavity tuning: first plastically and in operation by two lever tuners (one for half cell, another one for 3 cells together)

surface treatment applied

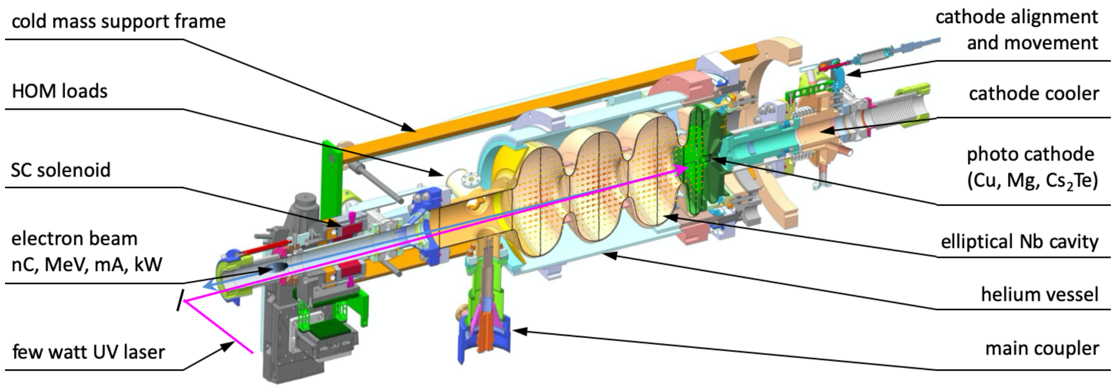
- BCP, HPR, 800°C heat treatment
- special challenge is rinsing of narrow choke cell and half cell

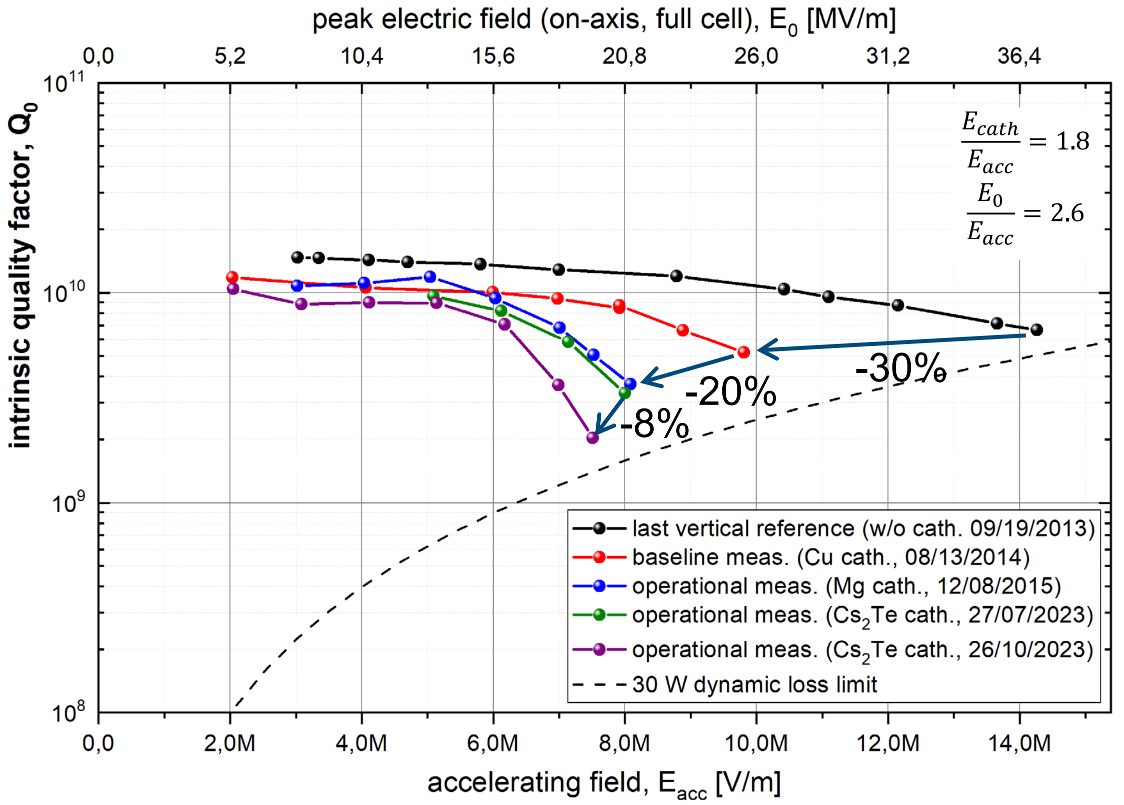
performance achieved

- E0=37 MV/m in vertical test, degradation due to clean room assembly, shipping, bunker installation and issue with Cs_2Te
- but then for 8 yrs and 30 cathodes no additional degradation (until August 2023 when a FE was activated w/o prior notice)
- E_{kin}=4.0 MeV at E0=20 MV/m, routinely for users operation
- cavity limited by FE, MP occurs in cathode stalk channel but easily suppressed by DC Bias of 5kV at the cathode

special challenges

- exchange and operation of cathodes w/o cavity contamination
- RF commissioning with fresh cathodes w/o losing its QE





HZDR – SRF photoinjector for ELBE (THz FEL)

Cryomodule

principal setup

- cathode cooling and alignment is directly attached to cavity
- SC solenoid inside the module, directly screwed onto the helium vessel (no re-alignment after warm-up necessary)
- 2K He, He-gas for pre-cooling, 77K LN for shield cooling

alignment concept

- cold mass with respect to cryomodule during final assembly
- fine alignment later during commissioning later with beam

concept of the magnetic shielding

- warm µ-metal shield around everything (no cryoperm around cavity), but additional cryoperm for solenoid and cold steppers

cold warm transitions(s)

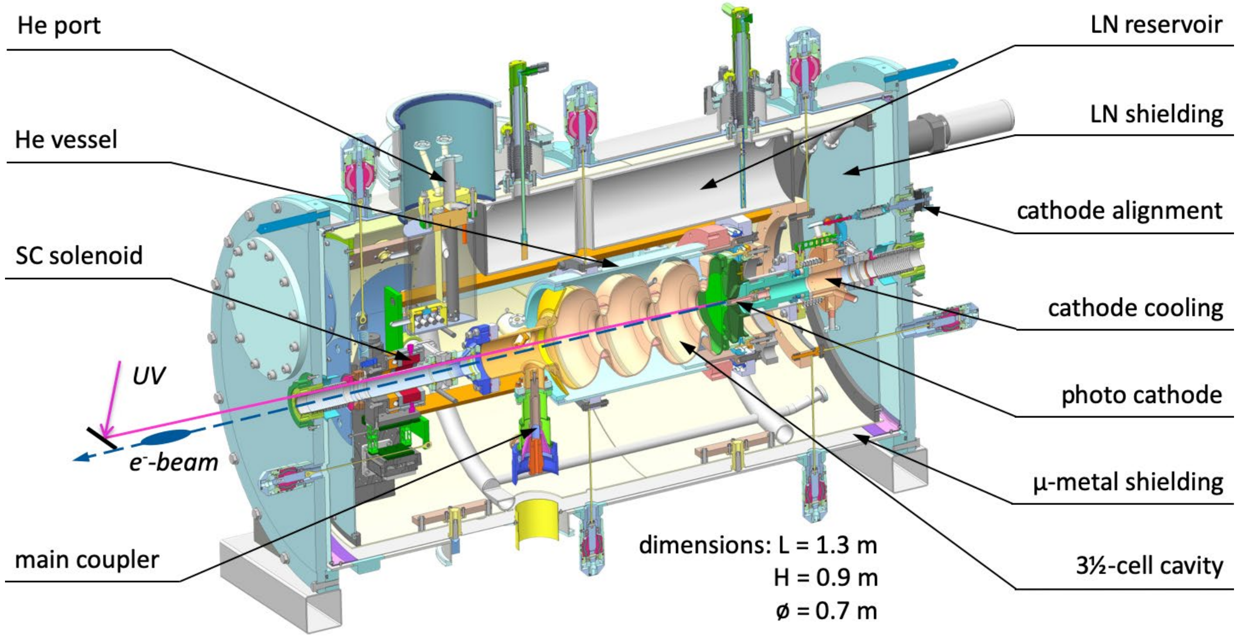
- two long bellows with LN intercepts on both ends of cold mass
- cold mass itself is centered by 10 Ti-spokes with LN intercepts

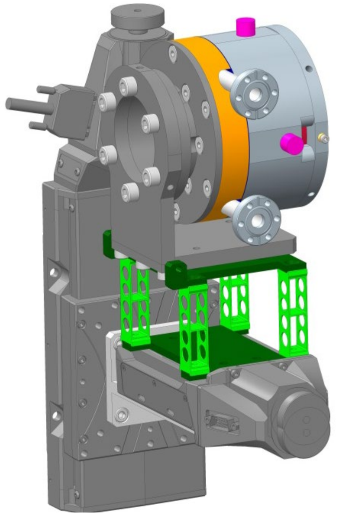
special assembly features

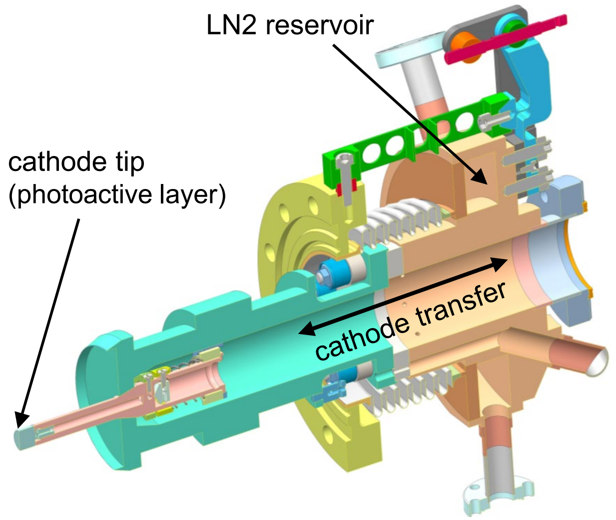
- special tooling for cathode stalk and solenoid assembly
- local clean rooms in bunker for beamline connection and cathode transport chamber exchange (once a year)

any other special features?

- ⇨ very compact and simple design



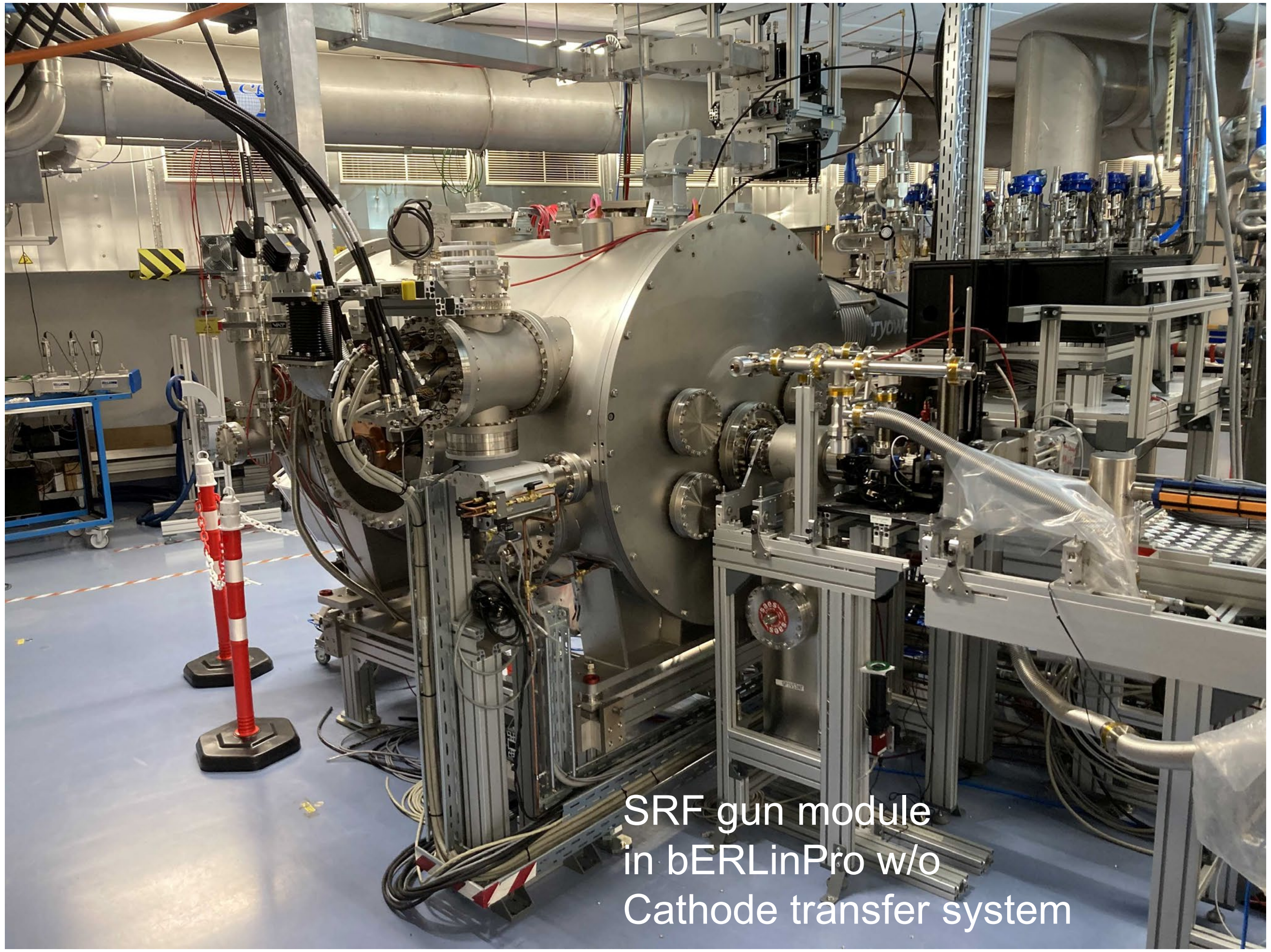




HZB – SRF gun for bERLinPro

~14 years' SRF gun R&D

design beam parameters	1.4 cell SRF Gun
bunch repetition rate [GHz]	0.050 & 1.3*
bunch charge [pC]	77*
transverse emittance [µm]	< 0.5*
beam energy at gun exit [MeV]	2.6*
RF parameters	
operation frequency [GHz]	1.3
accelerating gradient [MV/m]	16
electric field at cathode [MV/m]	26
Peak on axis field [MV/m]	30
Cathode	
material	Cs-K-Sb, Na-K-Sb
assembly	load lock, RF choke

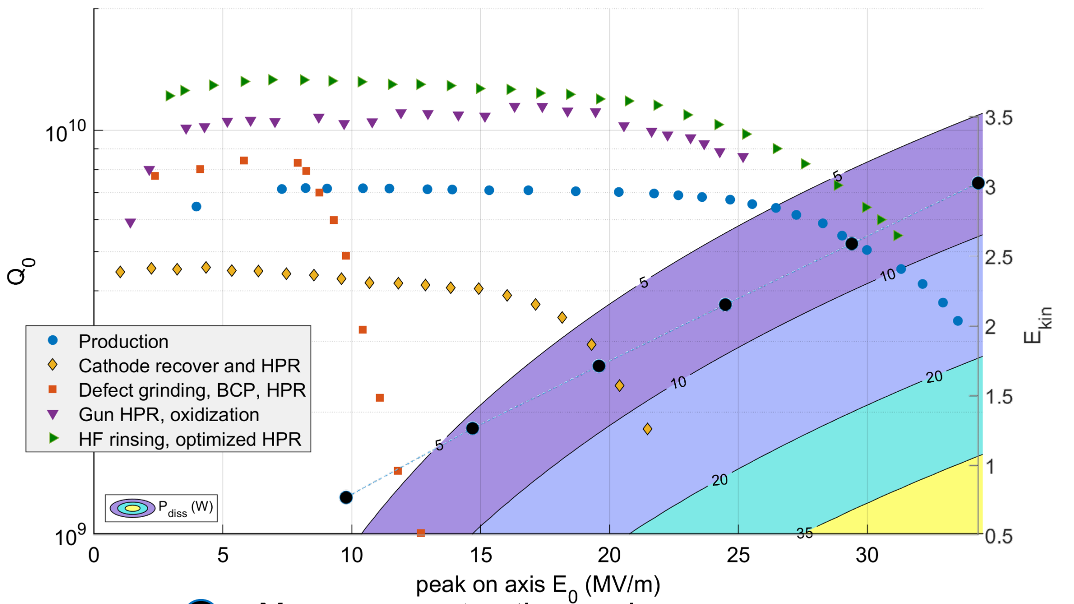

SRF gun module in bERLinPro w/o Cathode transfer system

*100 mA case

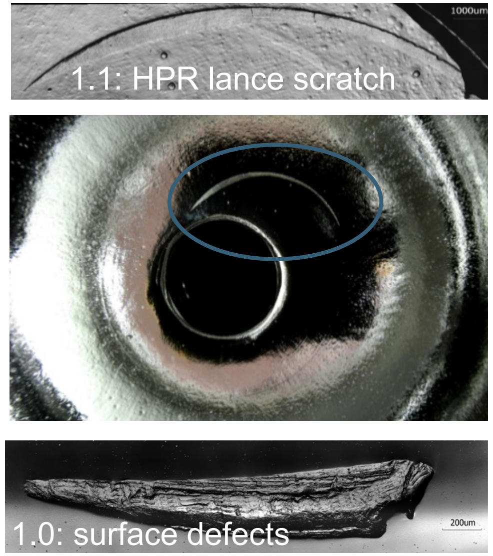
HZB – SRF gun for bERLinPro

SRF cavity

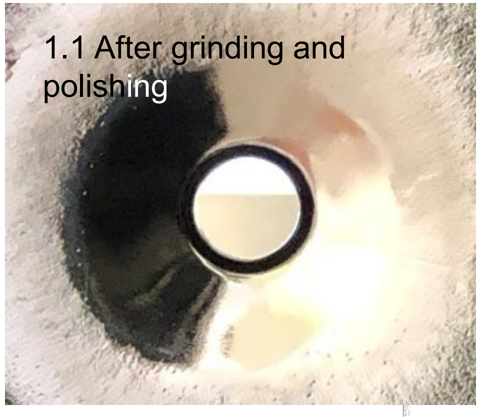
- Two SRF cavities fabricated within collaboration (JLAb) and the second with industry: BCP, HPR, 650°C annealing, 120°C baking
- Both cavities were damaged close to the cathode, 1.0 had initial scratch after fabrication (main dark current source), 1.1 got damaged at manufacturer
- Repair and refurbishment program started by grinding, polishing, BCP, HF rinsing and optimized new nozzle head HPR
  Y. Tamashevich et al., submitted to IOP Eng. Research Ex.
- Both cavities were recovered and did not show any field emission in vertical testing (in contrast to e.g. Gunlab beam tests)

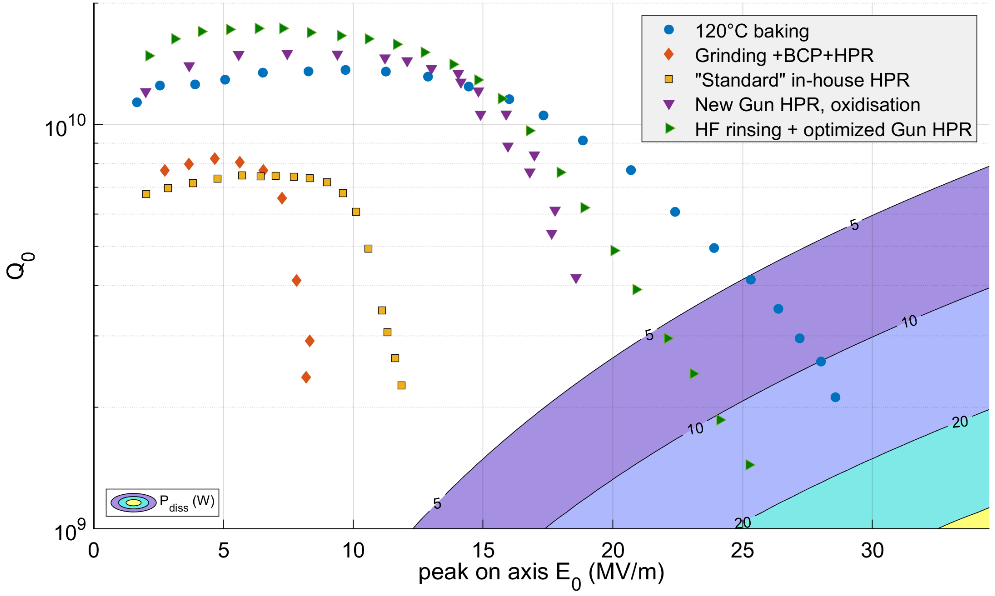


Max. energy at optimum phase



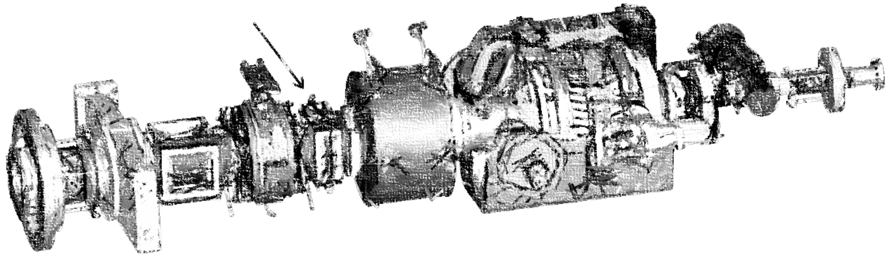
- Currently, cavity is 1.1 installed for first beam in Q2-3 2024



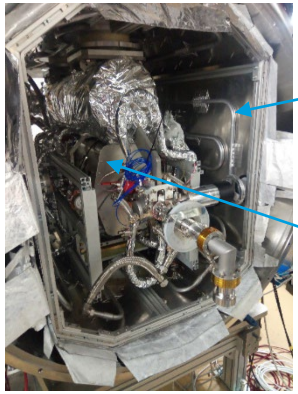


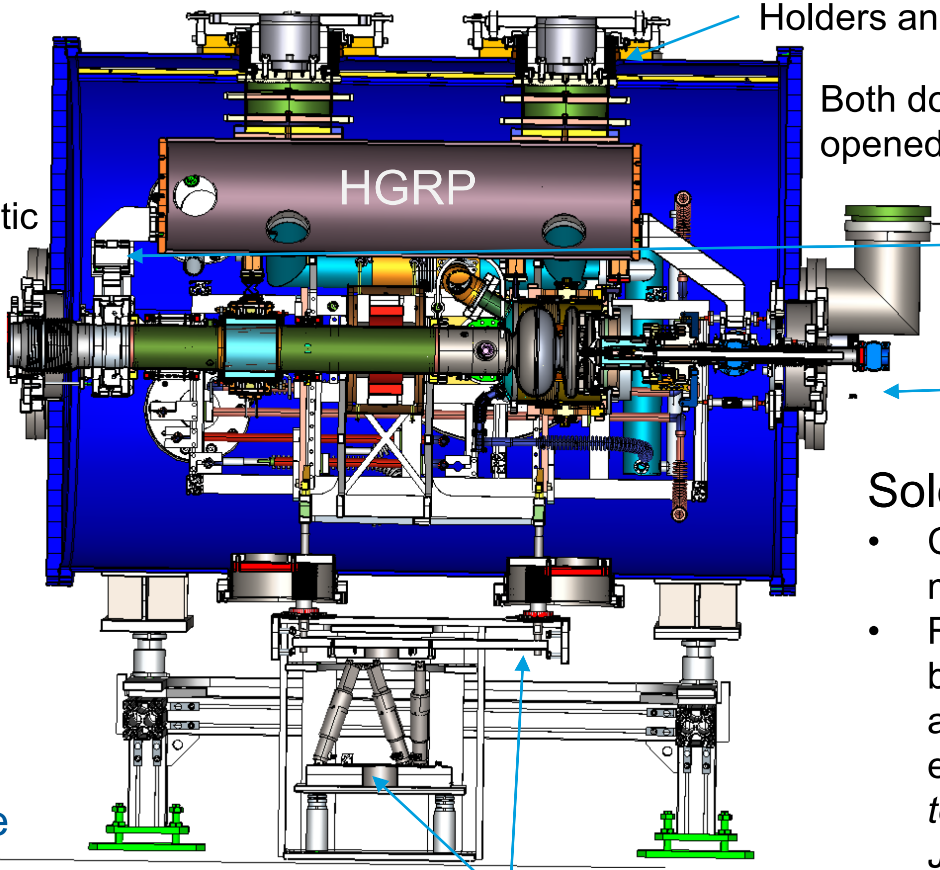
HZB – SRF gun for bERLinPro

Cryomodule



Module layout

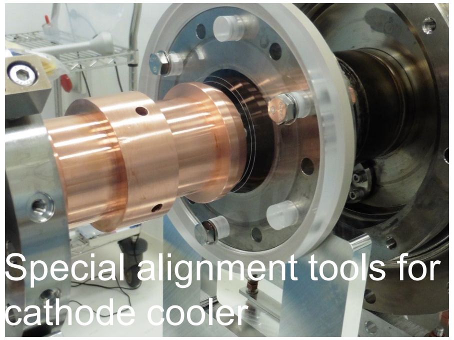


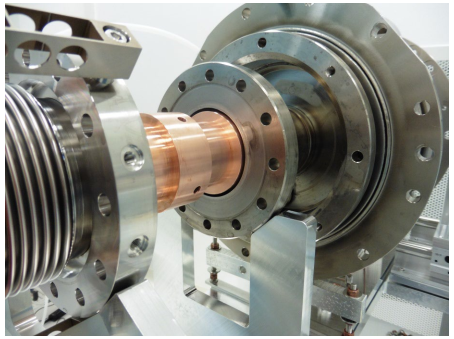


- 4K cooling:
  - Solenoid
  - HOM load
  - FPCs
- 4K filling line cavity
- 1.8 K JT line cavity
- 80K FPC and HOM
- 80 K shield and cathode

Solenoid shielding:

- Cryoperm around solenoid might saturate
- Replaced by Nb disc between Solenoid and cavity outer shield, efficiency factor 5-8 *to be published by J. Völker et al.*





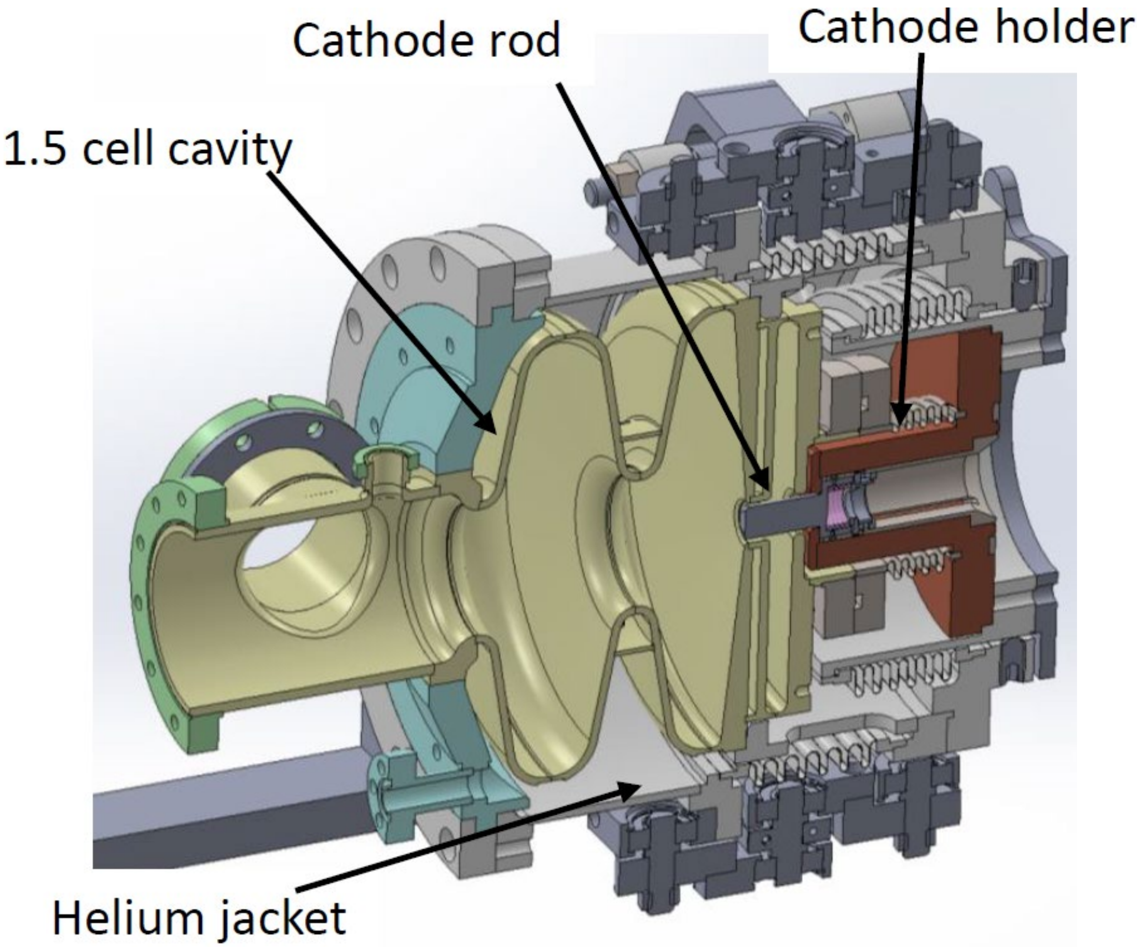
MSU/KEK – SRF gun for photocathode R&D (former KEK-ERL)

Since 2013

design beam parameters	1.5 cell SRF Gun
bunch repetition rate [MHz]	40
bunch charge [pC]	< 0.1
transverse emittance [µm]	< 0.1
beam energy at gun exit [MeV]	2

RF parameters	
operation frequency	1.3 GHz
accelerating gradient [MV/m]	16
electric field at cathode [MV/m]	23
Peak on axis field [MV/m]	31.5

Cathode - excited from the backside!	
material	CsK_2Sb
assembly	Load lock, RF choke



	Purpose
Gun #1	Vertical test, understand cavity treatment
Gun #2	Beam test

MSU/KEK – SRF gun for photocathode R&D (former KEK-ERL)

SRF cavity

mechanical fabrication

- All cavity and jacket was machined and welded at KEK.
- The required tolerance was 0.1 mm.
- Cavity frequency was tuned by plastic deformation at first. Slow and Fast tuner will use in operation.

surface treatment applied

- EP, HPR, 120 ℃ baking.
- HPR was applied both accelerating cell and choke cell.

performance archived

- recent Q/E curve from vertical tests
  - Without cathode plug: $E_{\text{peak on axis}}$ = 55.5 MV/m, Q_o = 3.79 x 10^9
  - With cathode plug: $E_{\text{peak on axis}}$ = 45.6 MV/m, Q_o = 1.12 x 10^9

gradients and exit energy when producing beam

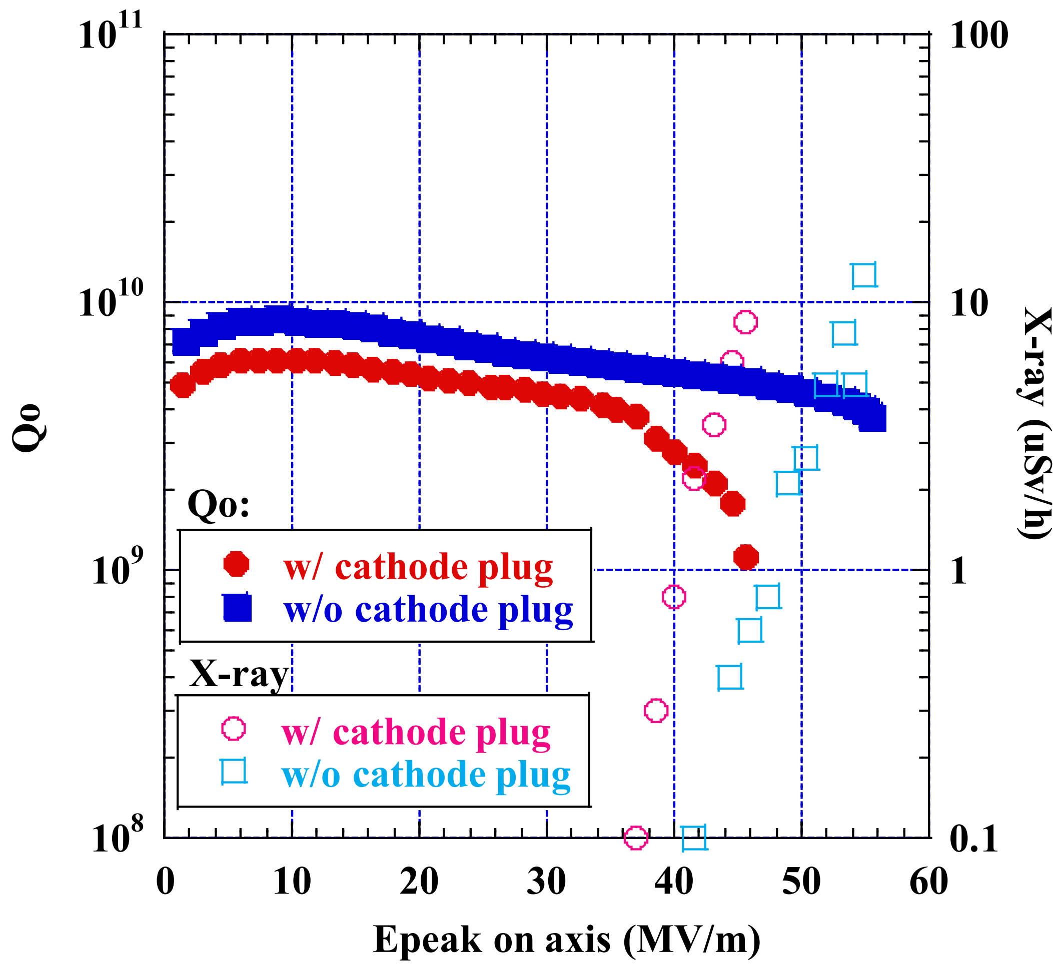
- $E_{\text{peak on axis}}$ = 22 MV/m, V_c = 2 MV

what about field emission, multipacting, etc.

- No MP
- Without cathode plug: FE onset: $E_{\text{peak on axis}}$ = 41.5 MV/m
- With cathode plug: FE onset: $E_{\text{peak on axis}}$ = 37.0 MV/m

special challenges?

- none



MSU/KEK – SRF gun for photocathode R&D (former KEK-ERL)

Cryomodule

principal setup

- Solenoid magnet installed inside of the module and cooled by conducting cooling.
- 40K thermal shield cooled by cryocooler.
- 4K shield cooled by liquid helium.

alignment concept

- Assemble on bed to install
- Adjust solenoid position by XY stage during operation.

concept of the magnetic shielding

- 2 layer of magnetic shield.
- One is inside of He jacket.
- The other one is outside of He Jacket.

cold warm transitions(s)

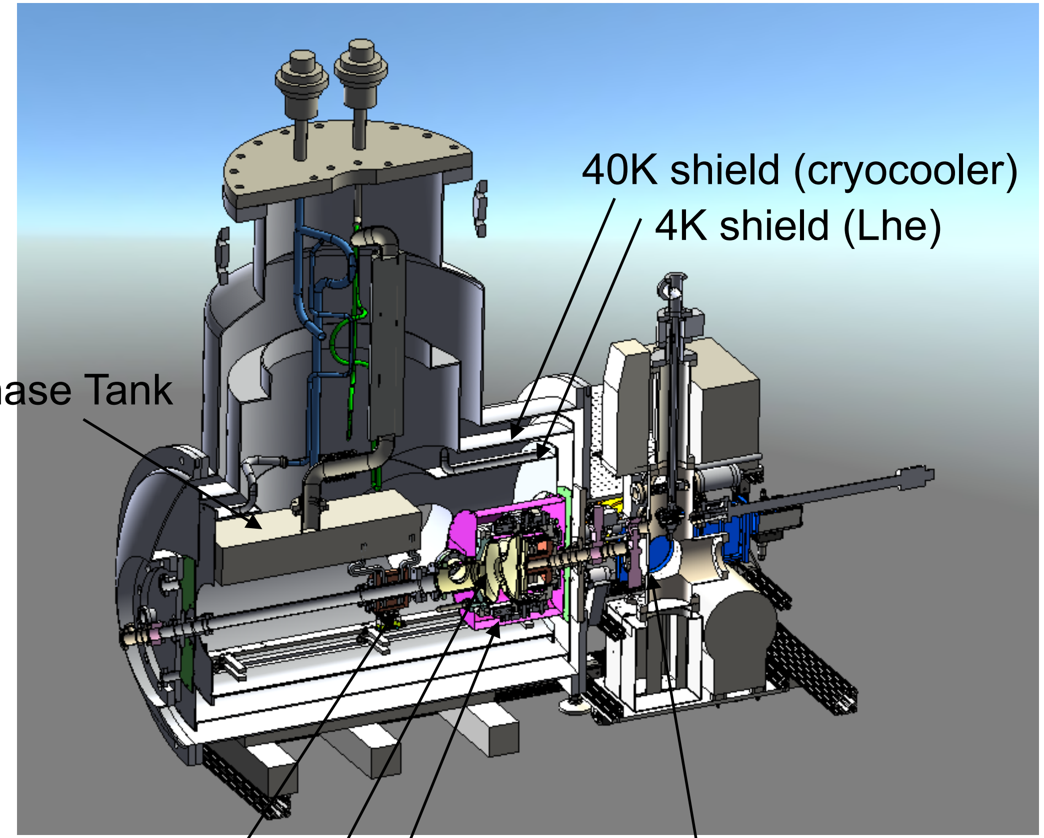
- Gate Valve for beam line moved outside of cryomodule.
- Connected to photocathode chamber with load lock system.

special assembly features

- Cavity and solenoid are assembled in clean room.
- Beam line and photocathode chamber will be connected in local clean booth

any other special features?

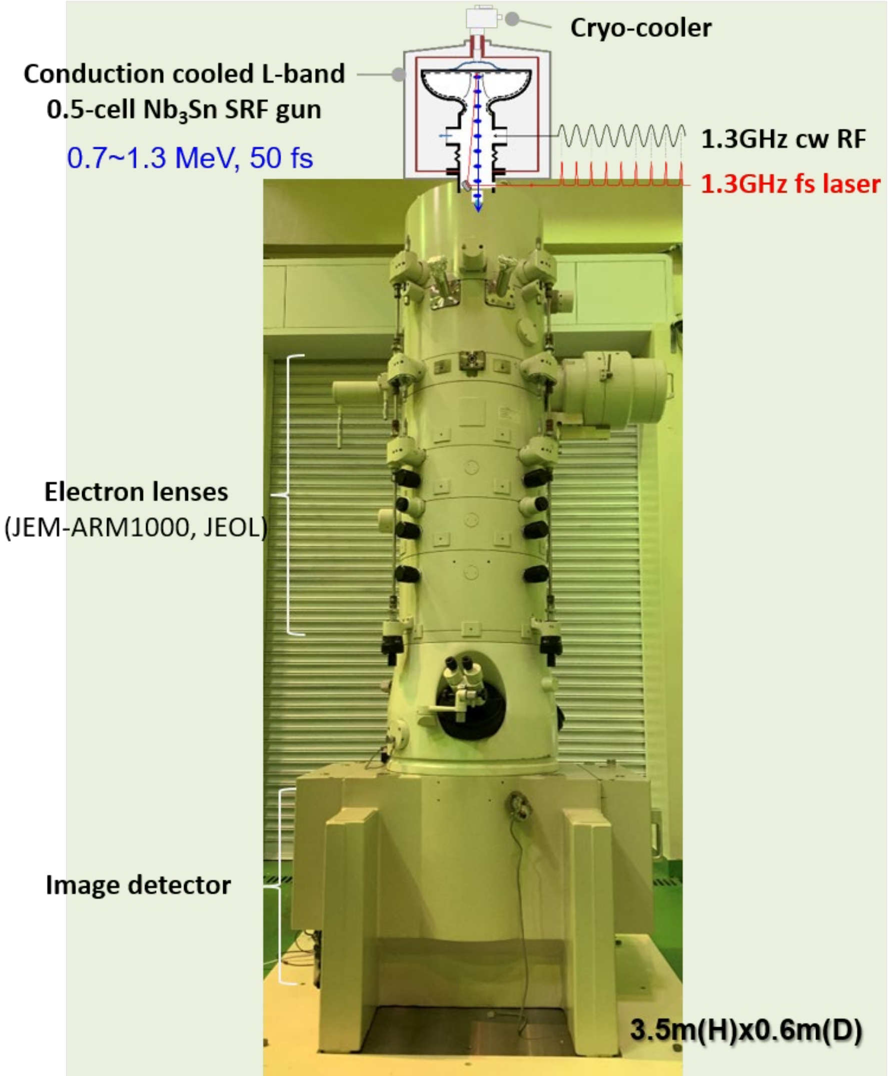
- We reuse the cryomodule which was used for Cryogenic Helium Experiment facility (CHEF) at Florida State University (FSU).



OsakaU/KEK – SRF gun for electron microscopy

design parameters and setup

design beam parameters	0.5 cell SRF Gun
bunch repetition rate [GHz]	1.3
bunch charge [fC]	≤10
transverse emittance [μm]	≤ 0.05
beam energy at gun exit [MeV]	0.7 ~ 1.3
RF parameters	
operation frequency [GHz]	1.3
accelerating gradient [MV/m]	10 ~ 15
electric field at cathode [MV/m]	20 ~ 30
Peak on axis field [MV/m]	20 ~ 30
Cathode	
material	Nb_3Sn
assembly	(none) closed back-wall



OsakaU/KEK – SRF gun for electron microscopy

SRF cavity – special feature: Nb3Sn coating

mechanical fabrication

- (Probably) in house at KEK
- Required and archived tolerances: ≤0.1mm
- Cavity should be well tuned before Nb3Sn coating. Coarse tuner and piezo tuner is used in operation.

surface treatment applied

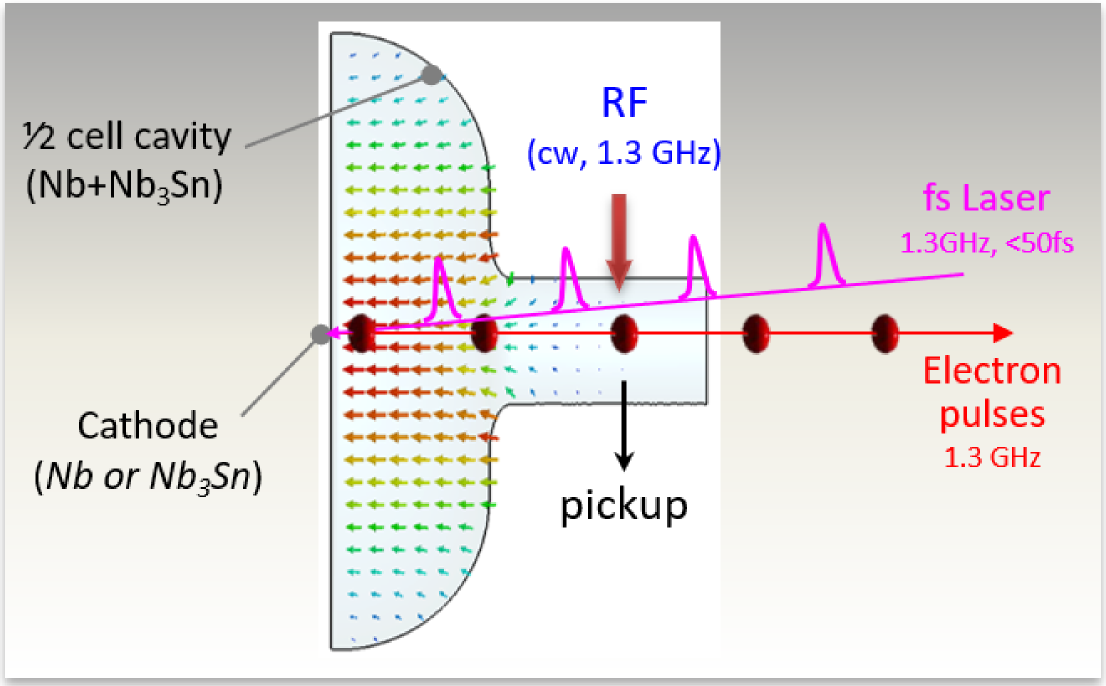
- EP or BCP for Nb surface before coating. Normal (~800C) heat treatment is applied.
- Nb3Sn is coated on the Nb surface (special challenge!!)
- Only HPR is applied after Nb3Sn coating.

performance archived

- Accelerating gradient of 10~15 MV/m with high-Q, Qo > 1e10, is required.
- Now design phase. No test results for Nb3Sn gun cavity.
- Gradient 10~15MV/m. Exit energy 0.7-1.3 MeV.

special challenges?

- Nb3Sn coating to SRF gun cavity



OsakaU/KEK – SRF gun for electron microscopy

Cryomodule – conduction cooling by cryo-cooler, operation at 4.2 K

principal setup

- focusing magnets outside the module
- cryo-cooler keeping cavity at 4.2 K
- First stage of cryo-cooler is used for 40 K thermal shield, which is surrounding the cavity.

alignment concept

- Under discussion

concept of the magnetic shielding

- Normal magnetic shielding is enough.
- Slow cooldown without temperature gradient, to avoid thermal current.

cold warm transitions(s)

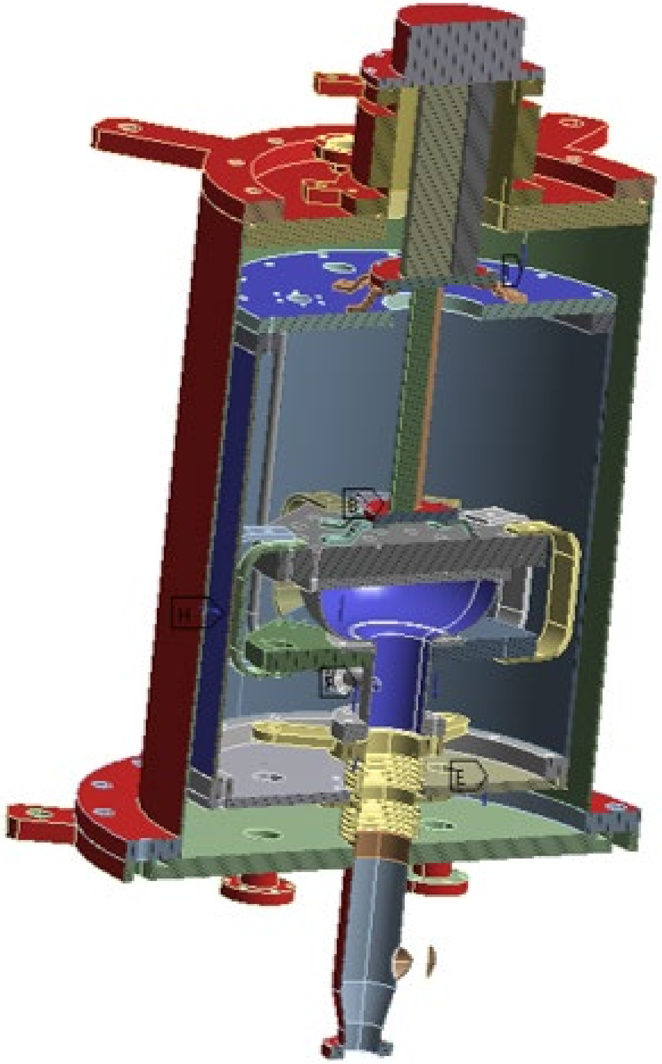
- Beam line. Bellows are adequately used to make thermal gradient.

special assembly features

- Most important parts are assembled in clean room, including gate valve.
- Connection to beam line should be carried out using local clean room.

any other special features?

- Suppress the vibration of cryo-cooler
- Effective conduction cooling and small heat input to 4.2 K region is essential.



PKU – DC-SRF gun

recently changed from 3.5 cell cavity to 1.5 cell cavity

design beam parameters	1.5 cell DC SRF Gun
bunch repetition rate [kHz]	1 and 81.25
bunch charge [pC]	10 to 100
transverse emittance [μm]	<0.6@100pC (achieved)
beam energy at gun exit [MeV]	2.3
RF parameters	
operation frequency [GHz]	1.3
accelerating gradient [MV/m]	14
electric field at cathode [MV/m]	6
Peak on axis field [MV/m]	26.6
Cathode	
material	K_2CsSb
assembly	load lock, screw in

Current progress with DC-SRF-II gun:

- **1.5 cell DC-SRF gun construction & emittance reduction achieved**
  - DC voltage 50 kV ⇨ 100 kV
  - Cathode Cs_2Te ⇨ K_2CsSb
  - laser shaping
  - beamline optimization

PKU – DC-SRF gun

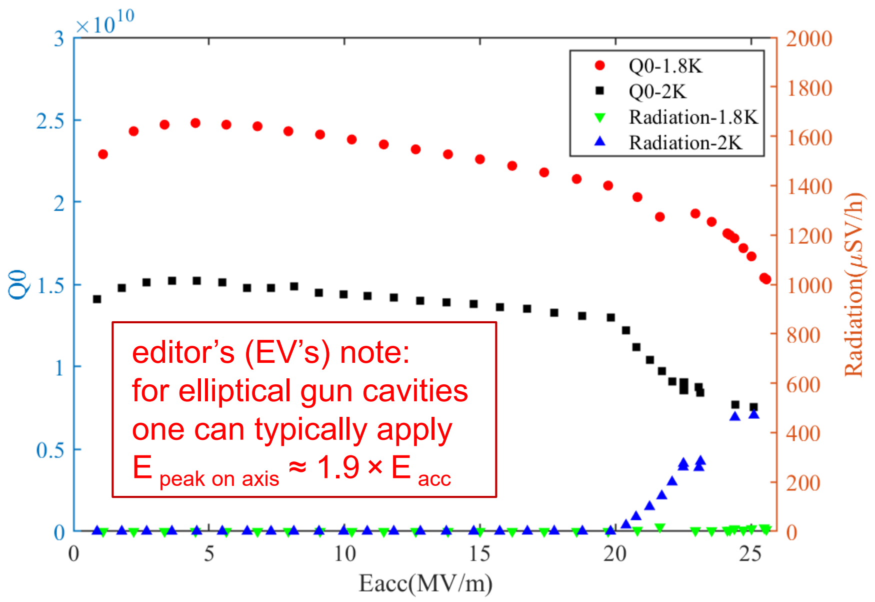
SRF cavity & cryomodule

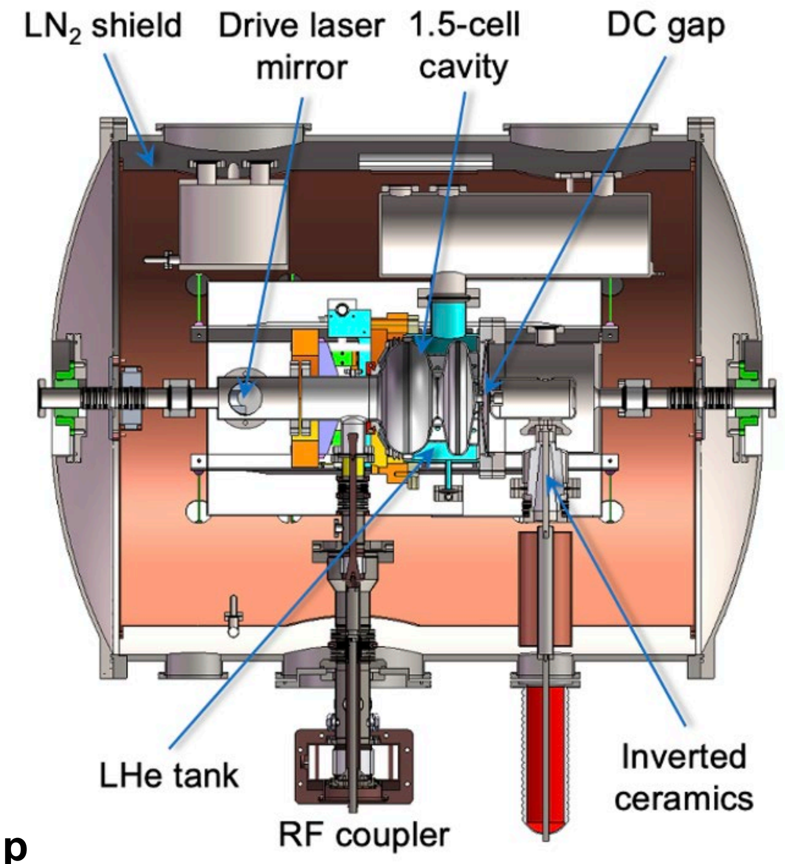
cavity fabrication and treatment

- by industry
- first plastically cavity tuning
- BCP, HPR

cavity performance

- 14 MV/m (E_{acc}) when producing beam: $E_{\text{peak on axis}} \approx 27$ MV/m





cryomodule setup

- solenoid magnet outside the module

special cryomodule features

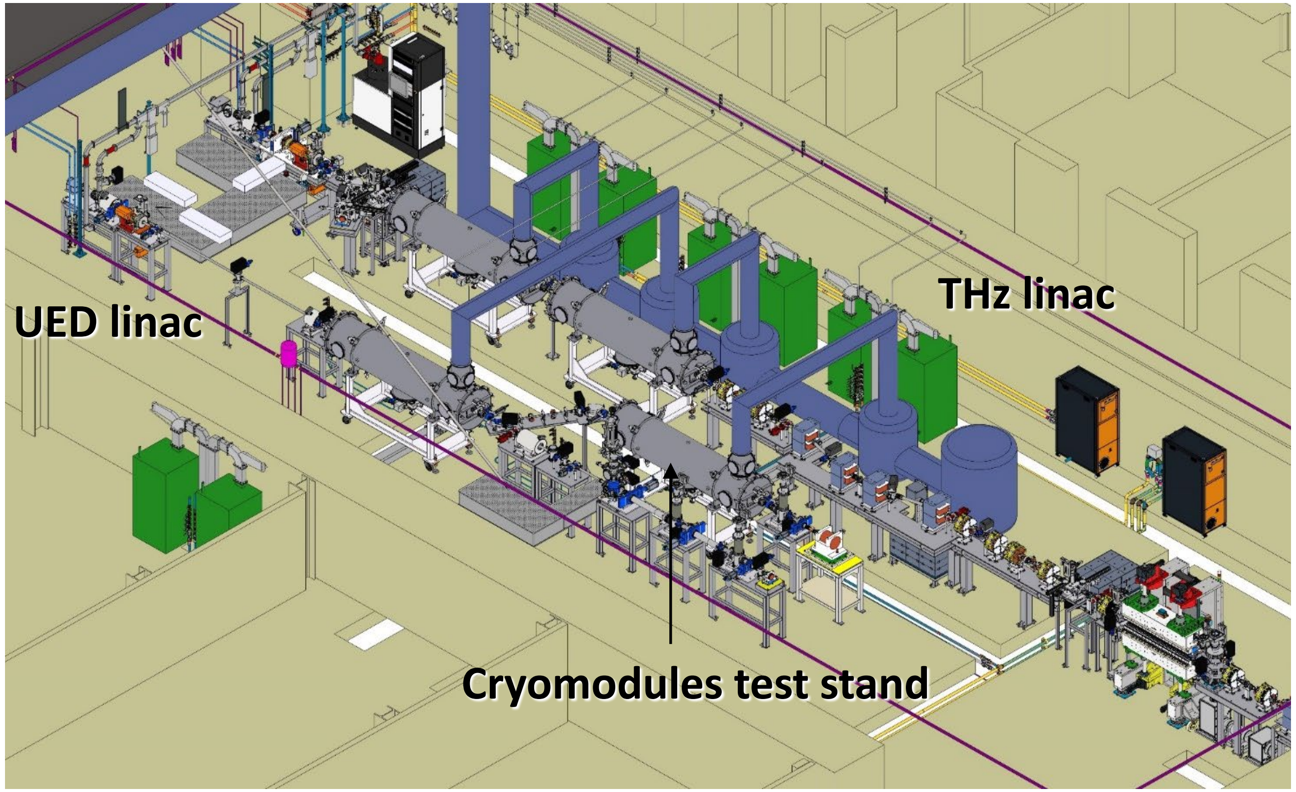
- local clean rooms are used at all assembly steps
- cathode laser mirror chamber inside the module

⇨ publication with more details on PKU work underway

PolFEL – will use a copy of the DESY full metal SRF gun

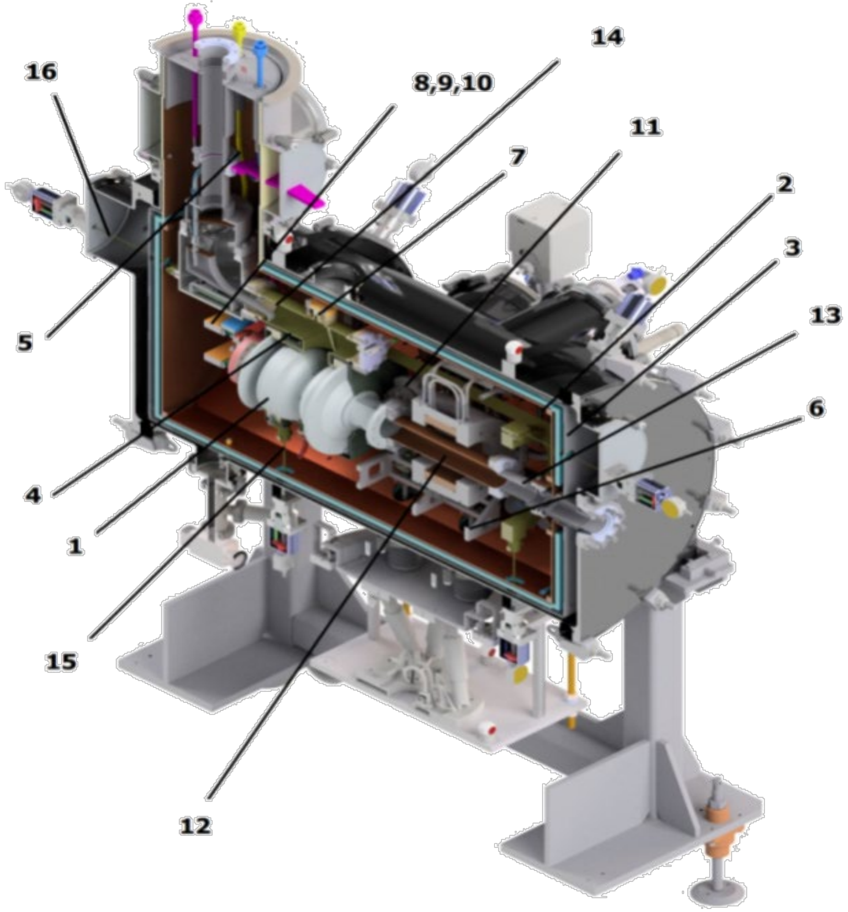
design parameters and setup

design beam parameters	1.5 cell SRF Gun
bunch repetition rate [kHz]	1000 -100
bunch charge [pC]	20 to 250
transverse emittance [µm]	0.4 to 0.8
beam energy at gun exit [MeV]	> 3
RF parameters	
operation frequency [GHz]	1.3
accelerating gradient [MV/m]	21
electric field at cathode [MV/m]	40
Peak on axis field [MV/m]	42
Cathode	
material	copper
assembly	screwed to back-wall

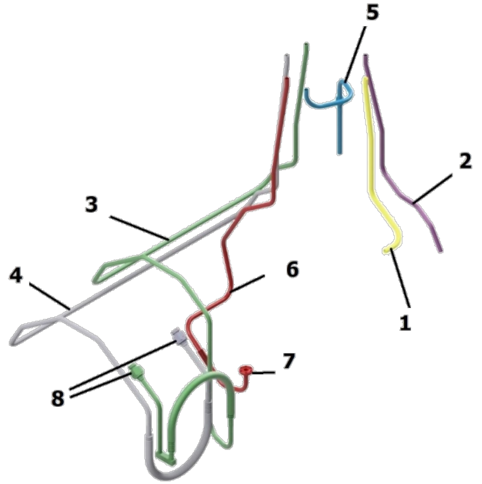


PolFEL – will use a copy of the DESY full metal SRF gun

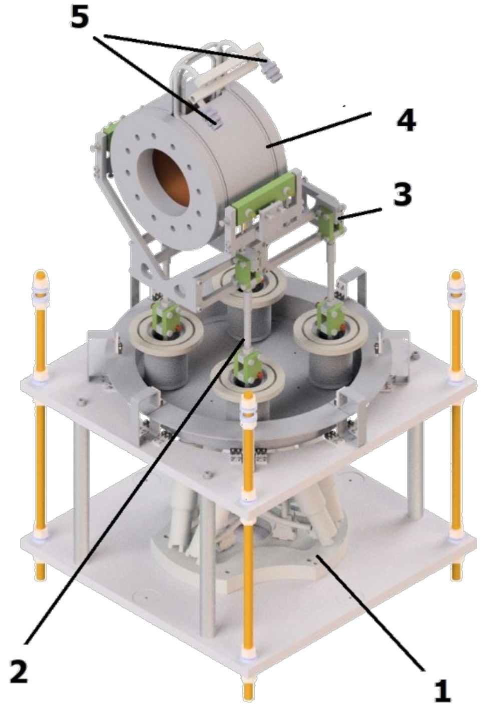
Cryomodule



1. SC structure 1.6-cell (DESY)
2. Thermal shielding
3. Magnetic shielding
4. LHe vessel with chimney to 2-phase tube (Ti, 2-3.7035)
5. LHe tubing (distribution system)
6. Solenoid (HZB) with support (Hexapod)
7. Electrical element: LHe level sensor, …
8. Tuner (DESY)
9. Tuner–to-cavity mechanical connection (HZB/DESY)
10. Adapter for E-XFEL tuner (HZB/DESY)
11. Fundamental Power Coupler (FPC, DESY)
12. Beam tube (solenoid section, (Cu, OFHC)
13. End beam tube with thermal transition and bellows (316 LN)
14. 2-phase tube (Ti, 2-3.7035)
15. Suspensions adjusting radial cavity position (x6)
16. Suspension adjusting axially cavity position (x2)



1. 70K suppling pipe
2. 70K return pipe
3. 5K return pipe
4. 5K suppling pipe
5. Additional 2K suppling pipe
6. 300K-2K suppling pipe
7. He vessel inlet for 300K-2K (DN 16 CF)
8. VCR connection to solenoid



1. Hexapod
2. Rods connecting cold and warm movable parts
1. Solenoid frame
2. Solenoid
3. LHe connections

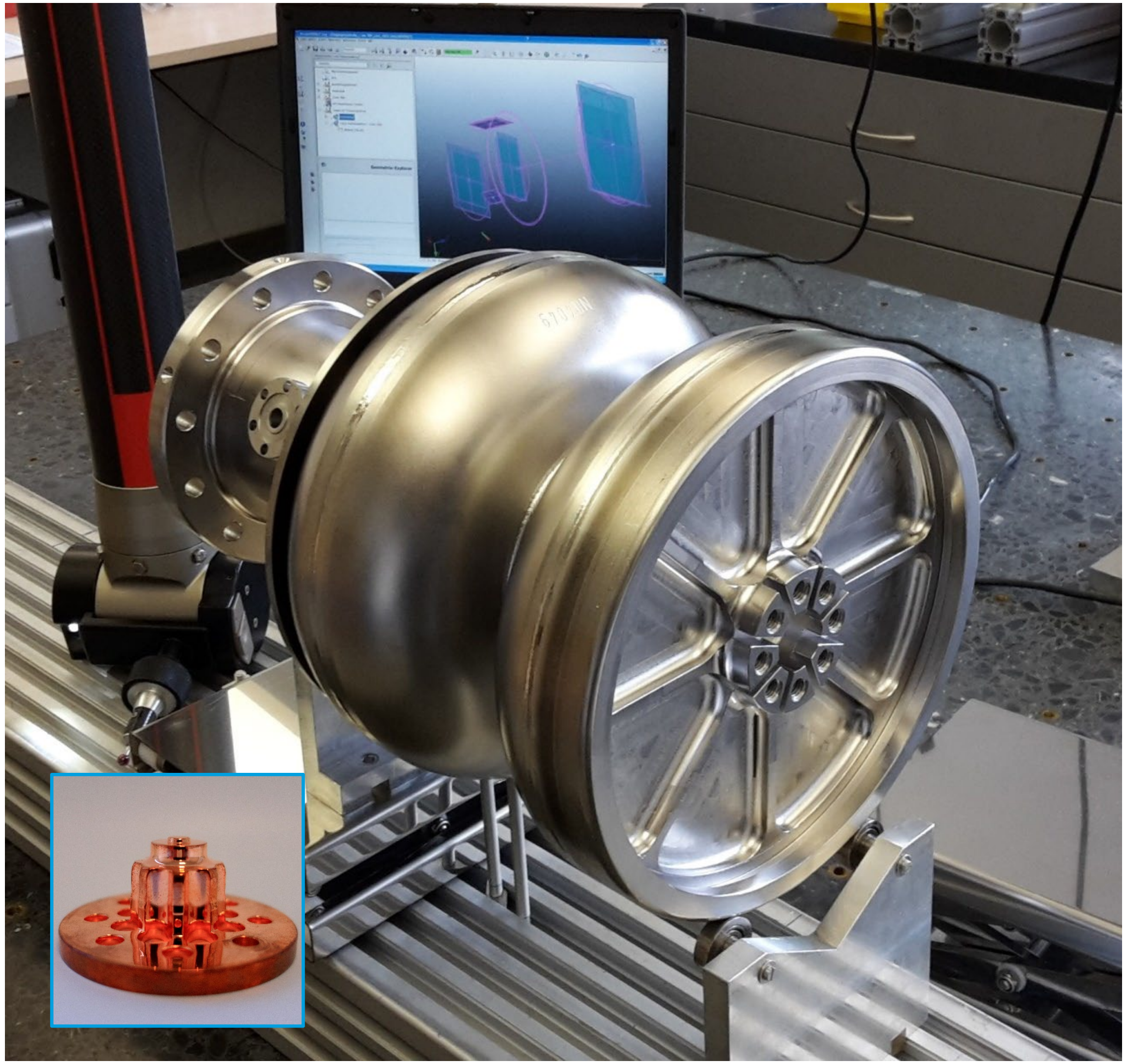
DESY – full metal SRF gun for Eu XFEL HDC operation

design parameters and setup

design beam parameters	1.5 cell SRF Gun
bunch repetition rate [kHz]	1000 -100
bunch charge [pC]	20 to 100
transverse emittance [µm]	0.2 to 0.4
beam energy at gun exit [MeV]	> 4

RF parameters	
operation frequency [GHz]	1.3
accelerating gradient [MV/m]	> 21
electric field at cathode [MV/m]	> 40
peak on axis field [MV/m]	> 42

Cathode	
material	copper
assembly	screwed to back-wall



DESY – full metal SRF gun for Eu XFEL HDC operation

SRF cavity

mechanical fabrication

- by industry, but in close contact with DESY colleagues
- final target for trans. miss-alignment of cells < 0.25 mm
- tuning: first plastically, then by blade tuner with piezzos

surface treatment applied

- BCP, HPR, "usual heat treatments“
- EP at KEK
- challenges: controlling the acid flow

performance archived (with 16G09/10 after BCP)

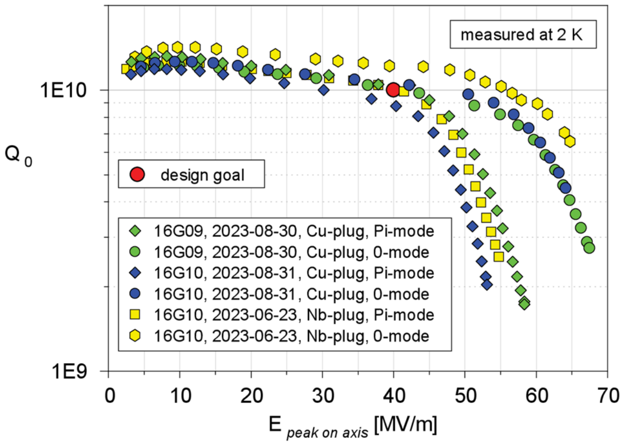
- recent vertical test results with copper cathode plugs
- $E_{\text{peak on axis}} \approx 55$ MV/m at Pi-mode
- $E_{\text{peak on axis}} \approx 65$ MV/m at 0-mode
- finally no field emission (after some conditioning)

special challenges

- adaptation of tooling and treatment methods to comply with the special geometry (close end)
- several years of intense R&D required!

Recent vertical test results

arXiv:2310.02974v1 [physics.acc-ph] 4 Oct 2023



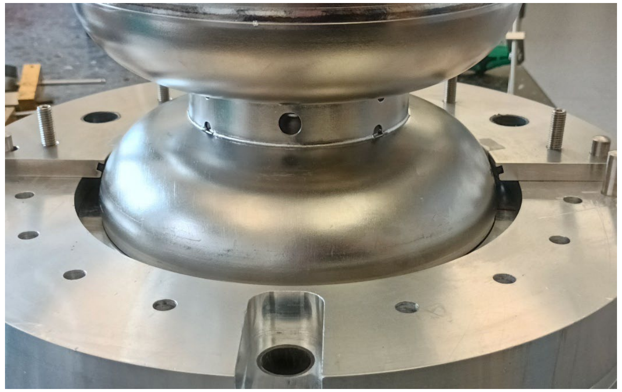
several generations of cavities

Collaboration with KEK

applying horizontal EP and VT at KEK, photograph of 16G4

New tools for SRF gun cavities

for example: some new tuning tools to hit the cathode laser frequency acceptance



DESY – full metal SRF gun for Eu XFEL HDC operation

Cryomodule

principal setup

- solenoid magnet inside the cryomodule
- lines with Johnston-type coupling for frequent exchange
- cooling with helium only (no pre-cooling with nitrogen)

alignment concept

- during assembly and installation max. deviation ± 0.5 mm
- motorized setup inside cryostat with target range ± 2 mm

concept of the magnetic shielding

- CryoPerm housing SRF cavity
- Niobium plate between solenoid and SRF cavity (like HZB)

cold warm transitions

- design still under construction

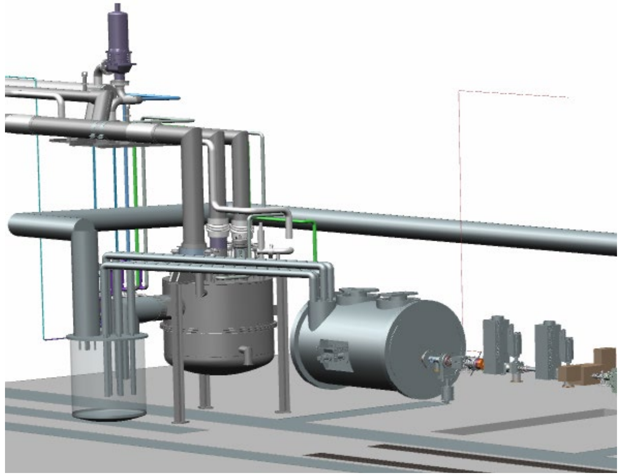
special assembly features

- complete cold vacuum assembly in clean room
- local clean room to connect subsequent warm beam pipe

general remark

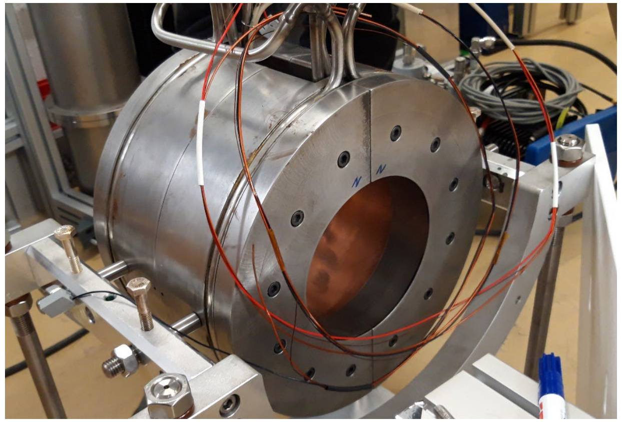
- we are still in the design stage

Module and cryogenic supply



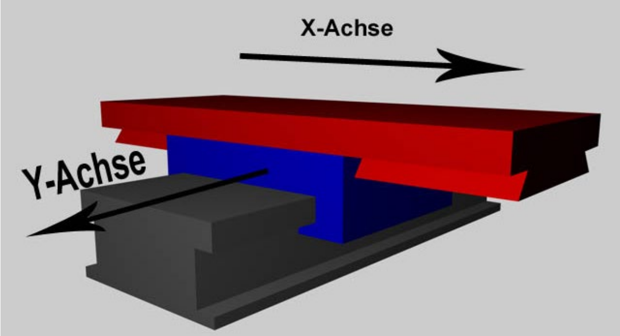
Solenoid magnet

being prepared for first cool down test



Alignment in the cold

question: can we develop some "cold equivalent" to the DESY EASy system?



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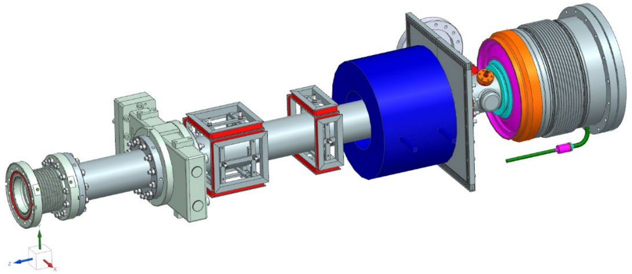
Cold beamline

preliminary sketch showing from right to left the cavity, magnetic shield, solenoid, beam pipe, cold steerers, valve and the cold warm transition …



Putting it all together

Parameter collection

of SRF gun cavities and cryomodules

Cavity	LCLS-II HE LEI	BNL	HZDR	HZB	MSU/KEK	Osaka U	PKU	PolFEL	DESY	Units
Status	R&D	routine op.	routine op.	R&D	R&D	R&D	routine op.	R&D	R&D	N/A
Frequency	185.7	113	1300	1300	1300	1300	1300	1300	1300	MHz
Temperature	4.4	4	2	2	2	4.2	2	2	2	K
Cavity type	QWR	QWR	TESLA (3.5)	TESLA (1.4)	TESLA (1.5)	TESLA (0.5)	TESLA (1.5)	TESLA (1.6)	TESLA (1.6)	Cell
Gun energy	1.8	1.25	3-4	2.6	2	2	2.8	> 3	> 4	MeV
Peak on axis E field	30	14-20	20.5	30	31.5	20-30	26.6	40	> 42	MV/m
Gradient limitation	/	FE	FE	FE	/	/	DC	/	/	N/A
Fabrication	at lab	industry	industry	at lab + ind.	at lab	at lab (tbd)	industry	industry	industry	N/A
Treatment	EP	BCP	BCP	BCP	EP	EP or BCP	BCP	BCP (and EP)	BCP (and EP)	N/A

Module	LCLS-II HE LEI	BNL	HZDR	HZB	MSU/KEK	Osaka U	PKU	PolFEL	DESY	Units
Solenoid	in module with steerers	outside mod.	in module	in module	in module	outside mod.	after mod.	in module	in module	N/A
Cryogenic supply	LHe	LHe	LHe and LN_2	LHe	LHe and cryo-cooler	cryo-cooler	LHe, LN_2	LHe	LHe	N/A
Alignment of cavity and solenoid	only during assembly	only during assembly	motors inside	hexapod outside	motors inside	tbd	?	hexapod outside	motors inside	N/A
Magnetic shielding	single-layer, vessel	mu-metal	mu-metal	mu-metal and Nb plate	two layers	"normal shielding"	?	single-layer	mu-metal and Nb plate	N/A
Cold warm trans.	gate valves outside	gate valves outside	gate valve inside	gate valve inside	gate valve outside	via the bellows	via bellows?	gate valve outside	gate valve inside	N/A

Summary

Purpose & challenges

Purpose of the SRF injectors

- continuous bunch trains (CW operation)
- high current:
  - for electron cooling of hadrons
  - ERL injectors
- low emittance
  - electron microscopy
  - FEL injectors

Challenges

- clean cavities
  - compatibility SC cavity and cathode
- robustness of cathodes
  - during operation at setups with load lock system
  - during preparation at setups w/o load lock system

Summary

Where do we stay concerning injectors for X-ray FELs?

Normal conducting photoinjectors

- VHF-band NC CW gun
  - $E_{\text{peak on axis}}$ ~ 20 MV/m
  - buncher section required
- high gradient pulsed guns (L-band, S-band)
  - $E_{\text{peak on axis}}$ ~ 40 to 60 MV/m
  - used at X-ray FELs
  - direct matching to subsequent linac

Superconducting photoinjectors

- VHF-band QWR CW gun
  - $E_{\text{peak on axis}}$ ~ 30 MV/m
  - buncher section required
  - work in progress
- high gradient SRF guns (L-band)
  - $E_{\text{peak on axis}}$ > 40 MV/m measured at two labs
  - nice choice for X-ray CW FELs
  - direct matching to subsequent linac
  - work in progress

Thank you for your attention!