Review of SRF gun cavities and cryomodules

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

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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)

Beam exit energy ≈ 2 MeV for the parameters given in this graph

Beam exit energy ≈ 5 MeV for the parameters given in this graph
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

<table>
<thead>
<tr>
<th>Design beam parameters</th>
<th>QWR SRF gun</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch repetition rate</td>
<td>1 MHz</td>
</tr>
<tr>
<td>Charge per bunch</td>
<td>100 pC</td>
</tr>
<tr>
<td>Transverse emittance</td>
<td>&lt;0.1 µm</td>
</tr>
<tr>
<td>Beam energy at gun exit</td>
<td>1.8 MeV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>RF parameters</th>
<th>Single gap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating frequency</td>
<td>185.7 MHz</td>
</tr>
<tr>
<td>Accelerating gradient</td>
<td>n/a</td>
</tr>
<tr>
<td>Electric field at cathode</td>
<td>30 MV/m</td>
</tr>
<tr>
<td>Peak on-axis $E$ field</td>
<td>30 MV/m</td>
</tr>
</tbody>
</table>

### Cathode

- **Material**: Cu/S20(Cs$_3$Sb+Na$_2$K Sb)
- **DC bias**: Yes
**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
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.
BNL – SRF gun for coherent electron cooling of hadrons

Routine operation since 2016

<table>
<thead>
<tr>
<th>beam parameters</th>
<th>QWR SRF Gun</th>
</tr>
</thead>
<tbody>
<tr>
<td>bunch repetition rate [kHz]</td>
<td>78</td>
</tr>
<tr>
<td>bunch charge [nC]</td>
<td>up to 10.7</td>
</tr>
<tr>
<td>transverse emittance [µm]</td>
<td>5</td>
</tr>
<tr>
<td>beam energy at gun exit [MeV]</td>
<td>1.25 to 1.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>RF parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>operation frequency [MHz]</td>
<td>113</td>
</tr>
<tr>
<td>accelerating gradient [MV/m]</td>
<td>n/a</td>
</tr>
<tr>
<td>electric field at cathode [MV/m]</td>
<td>10 to 20</td>
</tr>
<tr>
<td>peak on axis field [MV/m]</td>
<td>14 to 28</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cathode</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Material</td>
<td>CsK₂Sb</td>
</tr>
<tr>
<td>Assembly</td>
<td>load lock + RF choke</td>
</tr>
</tbody>
</table>
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
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

<table>
<thead>
<tr>
<th>Routine beam parameters</th>
<th>3.5 cell SRF Gun</th>
</tr>
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<tbody>
<tr>
<td>bunch repetition rate [kHz]</td>
<td>25 – 250, (max. 13000)</td>
</tr>
<tr>
<td>bunch charge [pC]</td>
<td>0 – 250 (max. 600)</td>
</tr>
<tr>
<td>transverse emittance [µm]</td>
<td>1.3 to 6.3</td>
</tr>
<tr>
<td>beam energy at gun exit [MeV]</td>
<td>4.5</td>
</tr>
</tbody>
</table>

**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$_2$Te 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 Cs2Te
- but then for 8 yrs and 30 cathodes no additional degradation (until August 2023 when a FE was activated w/o prior notice)
- Ekin=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

<table>
<thead>
<tr>
<th>design beam parameters</th>
<th>1.4 cell SRF Gun</th>
</tr>
</thead>
<tbody>
<tr>
<td>bunch repetition rate [GHz]</td>
<td>0.050 &amp; 1.3*</td>
</tr>
<tr>
<td>bunch charge [pC]</td>
<td>77*</td>
</tr>
<tr>
<td>transverse emittance [μm]</td>
<td>&lt; 0.5*</td>
</tr>
<tr>
<td>beam energy at gun exit [MeV]</td>
<td>2.6*</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>RF parameters</th>
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</thead>
<tbody>
<tr>
<td>operation frequency [GHz]</td>
<td>1.3</td>
</tr>
<tr>
<td>accelerating gradient [MV/m]</td>
<td>16</td>
</tr>
<tr>
<td>electric field at cathode [MV/m]</td>
<td>26</td>
</tr>
<tr>
<td>Peak on axis field [MV/m]</td>
<td>30</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cathode</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>material</td>
<td>Cs-K-Sb, Na-K-Sb</td>
</tr>
<tr>
<td>assembly</td>
<td>load lock, RF choke</td>
</tr>
</tbody>
</table>

*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)

• 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.

Both doors can be opened

Modified: Issue with thermal short

External Solenoid hexapod mover with feedthroughs

80K helium shield

2nd magnetic shield

HGRP

Holders and bellows for alignment

Cathode transfer system port

Beam

Special alignment tools for cathode cooler

Concentricity check with Dummy cathode in cleanroom
### MSU/KEK – SRF gun for photocathode R&D (former KEK-ERL)

**Since 2013**

<table>
<thead>
<tr>
<th>design beam parameters</th>
<th>1.5 cell SRF Gun</th>
</tr>
</thead>
<tbody>
<tr>
<td>bunch repetition rate [MHz]</td>
<td>40</td>
</tr>
<tr>
<td>bunch charge [pC]</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>transverse emittance [µm]</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>beam energy at gun exit [MeV]</td>
<td>2</td>
</tr>
</tbody>
</table>

**RF parameters**

<p>| | |</p>
<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>operation frequency</td>
<td>1.3 GHz</td>
</tr>
<tr>
<td>accelerating gradient [MV/m]</td>
<td>16</td>
</tr>
<tr>
<td>electric field at cathode [MV/m]</td>
<td>23</td>
</tr>
<tr>
<td>Peak on axis field [MV/m]</td>
<td>31.5</td>
</tr>
</tbody>
</table>

**Cathode - excited from the backside!**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>material</td>
<td>CsK₂Sb</td>
</tr>
<tr>
<td>assembly</td>
<td>Load lock, RF choke</td>
</tr>
</tbody>
</table>

**Purpose**

<table>
<thead>
<tr>
<th>Gun #1</th>
<th>Vertical test, understand cavity treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gun #2</td>
<td>Beam test</td>
</tr>
</tbody>
</table>
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 °C baking.
- HPR was applied both accelerating cell and choke cell.

performance archived
- recent Q/E curve from vertical tests
  - Without cathode plug: \( E_{\text{peak on axis}} = 55.5 \text{ MV/m}, Q_0 = 3.79 \times 10^9 \)
  - With cathode plug: \( E_{\text{peak on axis}} = 45.6 \text{ MV/m}, Q_0 = 1.12 \times 10^9 \)

gradients and exit energy when producing beam
- \( E_{\text{peak on axis}} = 22 \text{ MV/m}, V_c = 2 \text{ MV} \)

what about field emission, multipacting, etc.
- No MP
- Without cathode plug: FE onset: \( E_{\text{peak on axis}} = 41.5 \text{ MV/m} \)
- With cathode plug: FE onset: \( E_{\text{peak on axis}} = 37.0 \text{ MV/m} \)

special challenges?
- none
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

<table>
<thead>
<tr>
<th>design beam parameters</th>
<th>0.5 cell SRF Gun</th>
</tr>
</thead>
<tbody>
<tr>
<td>bunch repetition rate [GHz]</td>
<td>1.3</td>
</tr>
<tr>
<td>bunch charge [fC]</td>
<td>≤10</td>
</tr>
<tr>
<td>transverse emittance [µm]</td>
<td>≤ 0.05</td>
</tr>
<tr>
<td>beam energy at gun exit [MeV]</td>
<td>0.7 ~ 1.3</td>
</tr>
</tbody>
</table>

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                     | Nb₃Sn            |
|                             | (none) closed back-wall |
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 (~800°C) 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

<table>
<thead>
<tr>
<th>design beam parameters</th>
<th>1.5 cell DC SRF Gun</th>
</tr>
</thead>
<tbody>
<tr>
<td>bunch repetition rate [kHz]</td>
<td>1 and 81.25</td>
</tr>
<tr>
<td>bunch charge [pC]</td>
<td>10 to 100</td>
</tr>
<tr>
<td>transverse emittance [µm]</td>
<td>&lt;0.6@100pC (achieved)</td>
</tr>
<tr>
<td>beam energy at gun exit [MeV]</td>
<td>2.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>RF parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>operation frequency [GHz]</td>
</tr>
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</tr>
<tr>
<td>electric field at cathode [MV/m]</td>
</tr>
<tr>
<td>Peak on axis field [MV/m]</td>
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<table>
<thead>
<tr>
<th>Cathode</th>
</tr>
</thead>
<tbody>
<tr>
<td>material</td>
</tr>
<tr>
<td>assembly</td>
</tr>
</tbody>
</table>

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$_2$Te → K$_2$CsSb
  - 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

<table>
<thead>
<tr>
<th>design beam parameters</th>
<th>1.5 cell SRF Gun</th>
</tr>
</thead>
<tbody>
<tr>
<td>bunch repetition rate [kHz]</td>
<td>1000 -100</td>
</tr>
<tr>
<td>bunch charge [pC]</td>
<td>20 to 250</td>
</tr>
<tr>
<td>transverse emittance [µm]</td>
<td>0.4 to 0.8</td>
</tr>
<tr>
<td>beam energy at gun exit [MeV]</td>
<td>&gt; 3</td>
</tr>
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<table>
<thead>
<tr>
<th>RF parameters</th>
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<tbody>
<tr>
<td>operation frequency [GHz]</td>
<td>1.3</td>
</tr>
<tr>
<td>accelerating gradient [MV/m]</td>
<td>21</td>
</tr>
<tr>
<td>electric field at cathode [MV/m]</td>
<td>40</td>
</tr>
<tr>
<td>Peak on axis field [MV/m]</td>
<td>42</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cathode</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>material</td>
<td>copper</td>
</tr>
<tr>
<td>assembly</td>
<td>screwed to back-wall</td>
</tr>
</tbody>
</table>
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)
### DESY – full metal SRF gun for Eu XFEL HDC operation

#### design parameters and setup

<table>
<thead>
<tr>
<th>design beam parameters</th>
<th>1.5 cell SRF Gun</th>
</tr>
</thead>
<tbody>
<tr>
<td>bunch repetition rate [kHz]</td>
<td>1000 - 100</td>
</tr>
<tr>
<td>bunch charge [pC]</td>
<td>20 to 100</td>
</tr>
<tr>
<td>transverse emittance [µm]</td>
<td>0.2 to 0.4</td>
</tr>
<tr>
<td>beam energy at gun exit [MeV]</td>
<td>&gt; 4</td>
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</table>

#### RF parameters

<table>
<thead>
<tr>
<th>RF parameters</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>operation frequency [GHz]</td>
<td>1.3</td>
</tr>
<tr>
<td>accelerating gradient [MV/m]</td>
<td>&gt; 21</td>
</tr>
<tr>
<td>electric field at cathode [MV/m]</td>
<td>&gt; 40</td>
</tr>
<tr>
<td>peak on axis field [MV/m]</td>
<td>&gt; 42</td>
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</tbody>
</table>

#### Cathode

<table>
<thead>
<tr>
<th>Cathode</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>material</td>
<td>copper</td>
</tr>
<tr>
<td>assembly</td>
<td>screwed to back-wall</td>
</tr>
</tbody>
</table>
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

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

effective Q = 1.5E10 measured at 2 K
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

cancept 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?

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

<table>
<thead>
<tr>
<th>Cavity</th>
<th>LCLS-II</th>
<th>HE</th>
<th>LEI</th>
<th>BNL</th>
<th>HZDR</th>
<th>HZB</th>
<th>MSU/KEK</th>
<th>Osaka U</th>
<th>PKU</th>
<th>PolFEL</th>
<th>DESY</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Status</td>
<td>R&amp;D</td>
<td>routine op.</td>
<td>routine op.</td>
<td>R&amp;D</td>
<td>R&amp;D</td>
<td>R&amp;D</td>
<td>routine op.</td>
<td>R&amp;D</td>
<td>R&amp;D</td>
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<td>Frequency</td>
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<td>1300</td>
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<td>1300</td>
<td>1300</td>
<td>1300</td>
<td>1300</td>
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<td>2</td>
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<td>2</td>
<td>4.2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>K</td>
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<tr>
<td>Cavity type</td>
<td>QWR</td>
<td>QWR</td>
<td>TESLA (3.5)</td>
<td>TESLA (1.4)</td>
<td>TESLA (1.5)</td>
<td>TESLA (0.5)</td>
<td>TESLA (1.5)</td>
<td>TESLA (1.6)</td>
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<td>Gun energy</td>
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<td>2.8</td>
<td>&gt; 3</td>
<td>&gt; 3</td>
<td>&gt; 3</td>
<td>&gt; 3</td>
<td>MeV</td>
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<td>Peak on axis E field</td>
<td>30</td>
<td>14-20</td>
<td>20.5</td>
<td>30</td>
<td>31.5</td>
<td>20-30</td>
<td>26.6</td>
<td>40</td>
<td>&gt; 42</td>
<td>MV/m</td>
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<td>Gradient limitation</td>
<td>/</td>
<td>FE</td>
<td>FE</td>
<td>FE</td>
<td>/</td>
<td>/</td>
<td>DC</td>
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<td>Fabrication</td>
<td>at lab</td>
<td>industry</td>
<td>industry</td>
<td>at lab + ind.</td>
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<td>at lab (tbd)</td>
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<td>Treatment</td>
<td>EP</td>
<td>BCP</td>
<td>BCP</td>
<td>BCP</td>
<td>BCP</td>
<td>EP or BCP</td>
<td>BCP</td>
<td>BCP (and EP)</td>
<td>BCP (and EP)</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Module</th>
<th>LCLS-II</th>
<th>HE</th>
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<th>PKU</th>
<th>PolFEL</th>
<th>DESY</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solenoid</td>
<td>in module with steerers</td>
<td>outside mod.</td>
<td>in module</td>
<td>in module</td>
<td>in module</td>
<td>outside mod.</td>
<td>after mod.</td>
<td>in module</td>
<td>in module</td>
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<tr>
<td>Cryogenic supply</td>
<td>LHe</td>
<td>LHe</td>
<td>LHe and LN₂</td>
<td>LHe</td>
<td>LHe and cryo-cooler</td>
<td>cryo-cooler</td>
<td>LHe, LN₂</td>
<td>LHe</td>
<td>LHe</td>
<td>N/A</td>
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</tr>
<tr>
<td>Alignment of cavity and solenoid</td>
<td>only during assembly</td>
<td>only during assembly</td>
<td>motors inside</td>
<td>hexapod outside</td>
<td>motors inside</td>
<td>tbd</td>
<td>?</td>
<td>hexapod outside</td>
<td>motors inside</td>
<td>N/A</td>
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<td></td>
</tr>
<tr>
<td>Magnetic shielding</td>
<td>single-layer, vessel</td>
<td>mu-metal</td>
<td>mu-metal</td>
<td>mu-metal and Nb plate</td>
<td>two layers</td>
<td>&quot;normal shielding&quot;</td>
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<td>single-layer</td>
<td>mu-metal and Nb plate</td>
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<tr>
<td>Cold warm trans.</td>
<td>gate valves outside</td>
<td>gate valves outside</td>
<td>gate valve inside</td>
<td>gate valve inside</td>
<td>gate valve outside</td>
<td>via the bellows</td>
<td>via bellows?</td>
<td>gate valve outside</td>
<td>gate valve inside</td>
<td>N/A</td>
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</tbody>
</table>
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
  - $E_{\text{peak on axis}} \approx 20 \text{ MV/m}$
  - buncher section required

- high gradient pulsed guns (L-band, S-band)
  - $E_{\text{peak on axis}} \approx 40$ to $60 \text{ MV/m}$
  - used at X-ray FELs
  - direct matching to subsequent linac

Superconducting photoinjectors

- VHF-band QWR CW gun
  - $E_{\text{peak on axis}} \approx 30 \text{ MV/m}$
  - buncher section required
  - work in progress

- high gradient SRF guns (L-band)
  - $E_{\text{peak on axis}} > 40 \text{ MV/m}$ measured at two labs
  - nice choice for X-ray CW FELs
  - direct matching to subsequent linac
  - work in progress
Thank you for your attention!