Development of CW SRF L-band photoinjector for future High-Duty-Cycle EuXFEL

Electron beams for CW FELs

Dmitry Bazyl and Elmar Vogel on behalf of the SRF photoinjector team at DESY and collaborator partners
UK AI Seminar at Daresbury Laboratory, UK
July 25, 2024

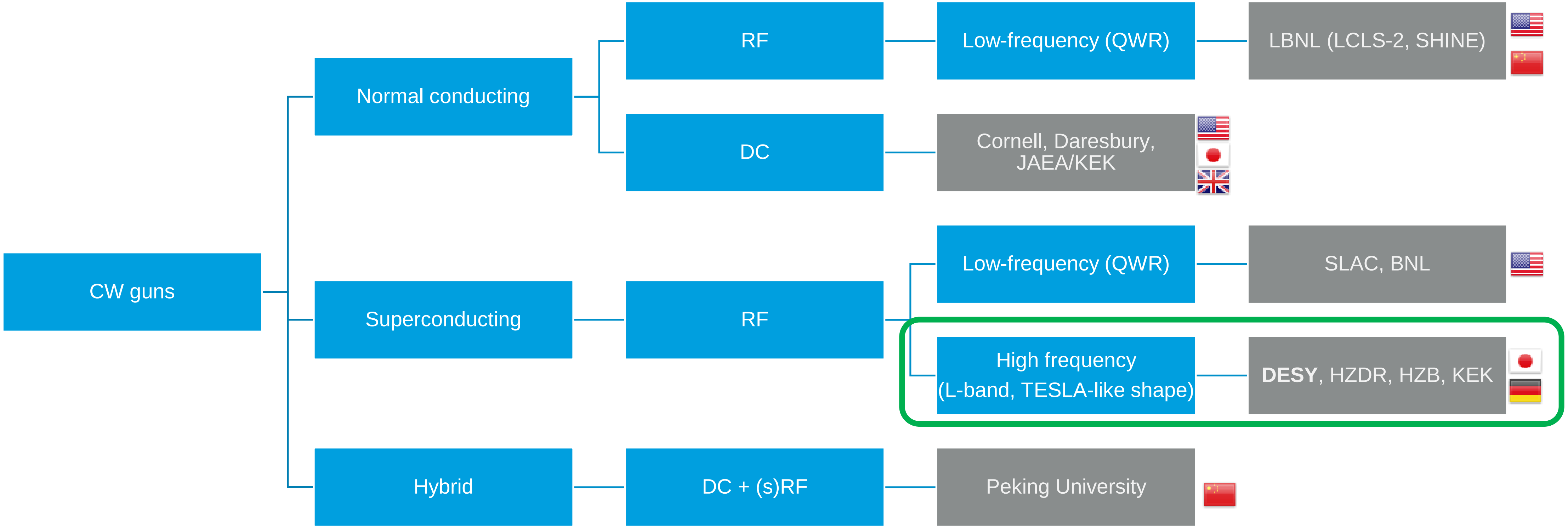
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

European XFEL

DESY.

CW electron photoinjectors

Classification



Overview of CW photoinjectors - DOI: 10.3389/fphy.2023.1150809

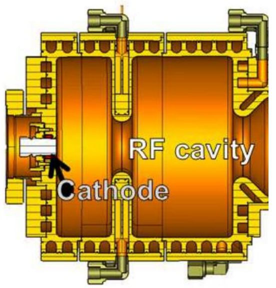
CW photoinjector for the future CW and HDC EuXFEL

CW photoinjector for the future CW and HDC EuXFEL

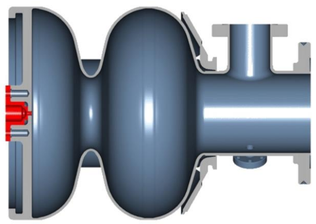
DESY CW L-band SRF gun cavity as the electron source

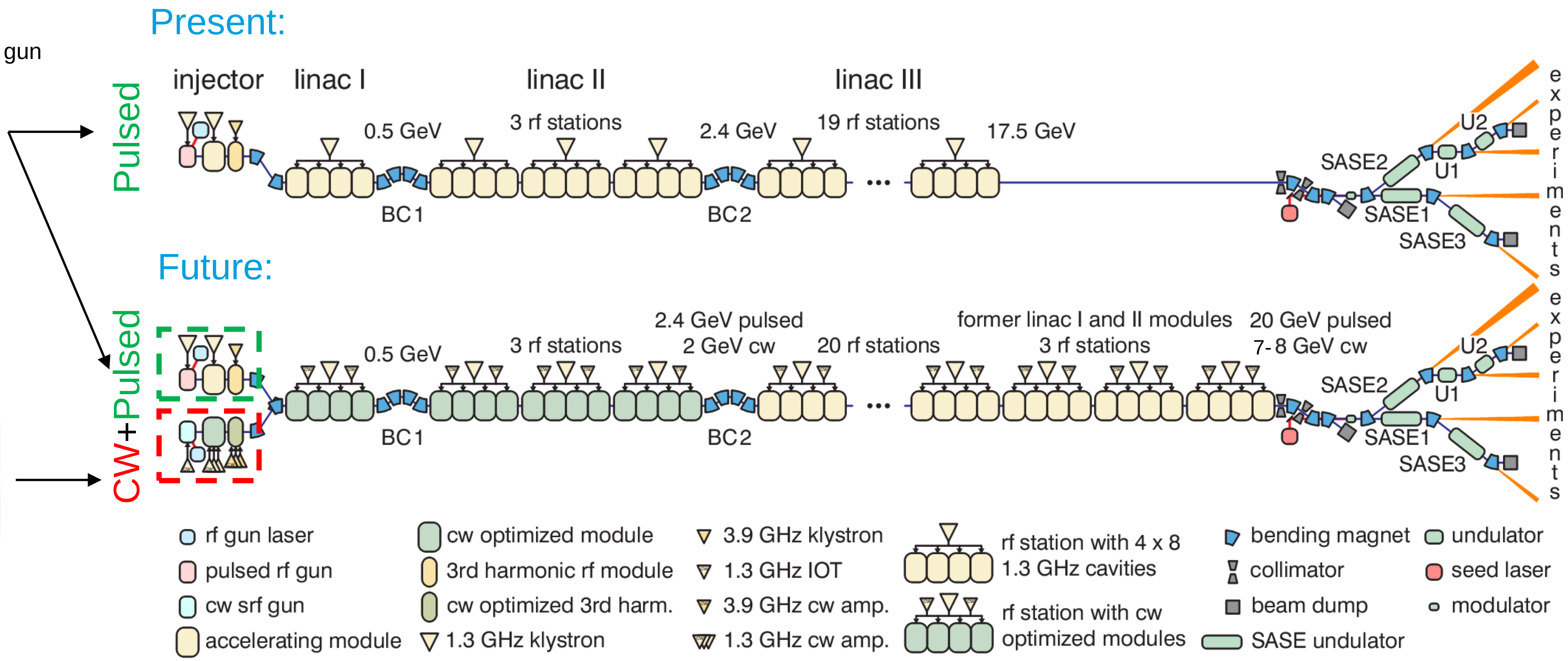
- EuXFEL is presently operated in pulsed mode with duty cycle of around 1%
- Future upgrade assumes operated with duty cycle ranging from 5% up to full CW mode
- CW photoinjector for high duty cycle mode is needed

Normal conducting 1.3 GHz RF gun



SRF 1.3 GHz gun



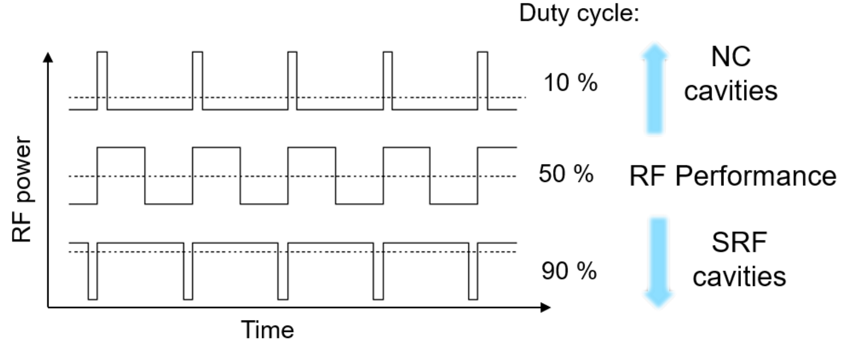


Prospects for CW and LP operation of the European XFEL in hard X-ray regime, R. Brinkmann, E. A. Schneidmiller, J. Sekutowicz, M. V. Yurkov

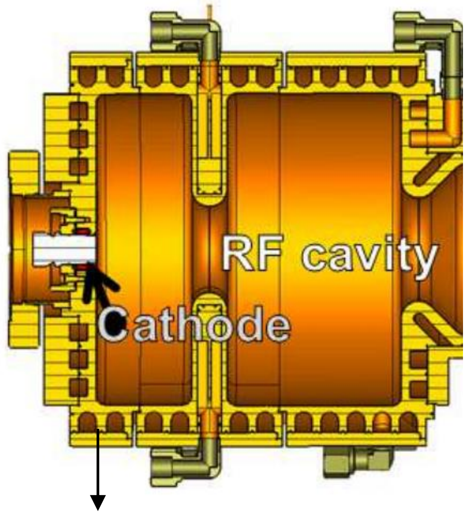
CW photoinjector for the future CW and HDC EuXFEL

DESY CW SRF gun cavity

- Idea suggested in 2005*: keep everything as simple as possible
- Gun design which would produce bunches similar to what we have in pulsed mode
- General challenge for L-band SRF guns: cathode insertion
    - Load lock system (HZDR, HZB, KEK) allowing semiconductor cathodes
    - All metal gun – approach followed by DESY
        - Copper cathode is inserted via the cathode plug screwed directly to the back wall

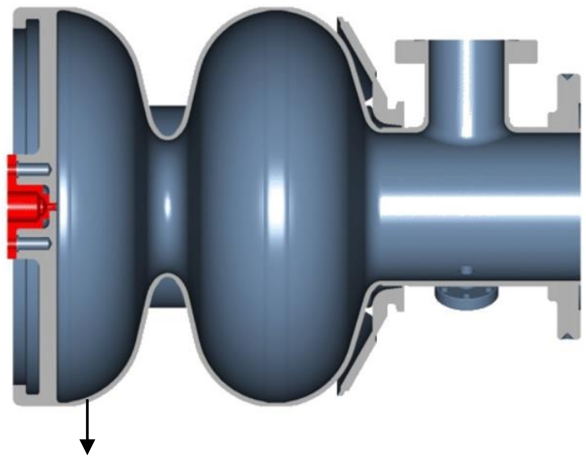


DESY 1.3 GHz **pulsed** DESY **nc** RF gun:



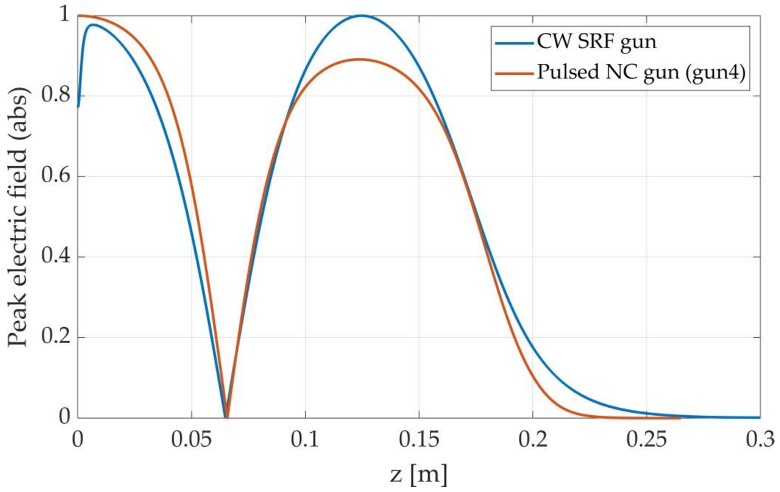
Copper (room temperature)

DESY 1.3 GHz **CW** DESY **SRF** RF gun:



Niobium (cryogenic temperature, 2 K)

Electric field on axis:



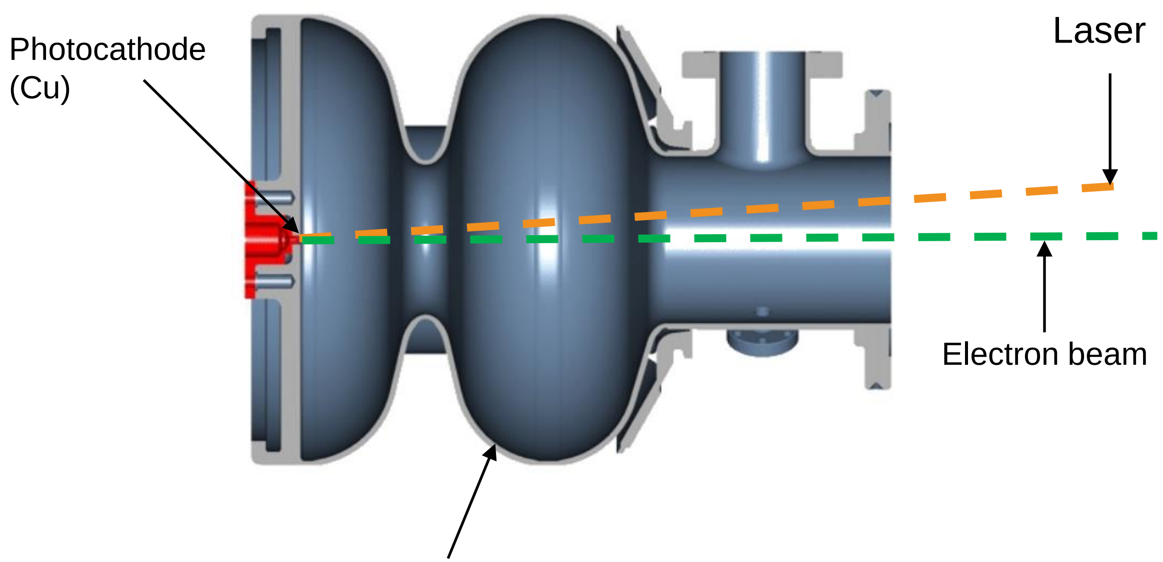
*J. S. Sekutowicz et al., “Nb-Pb Superconducting RF-Gun”, in Proc. EPAC'06, Edinburgh, UK, Jun. 2006, paper THPLS092, pp. 3493-3495.

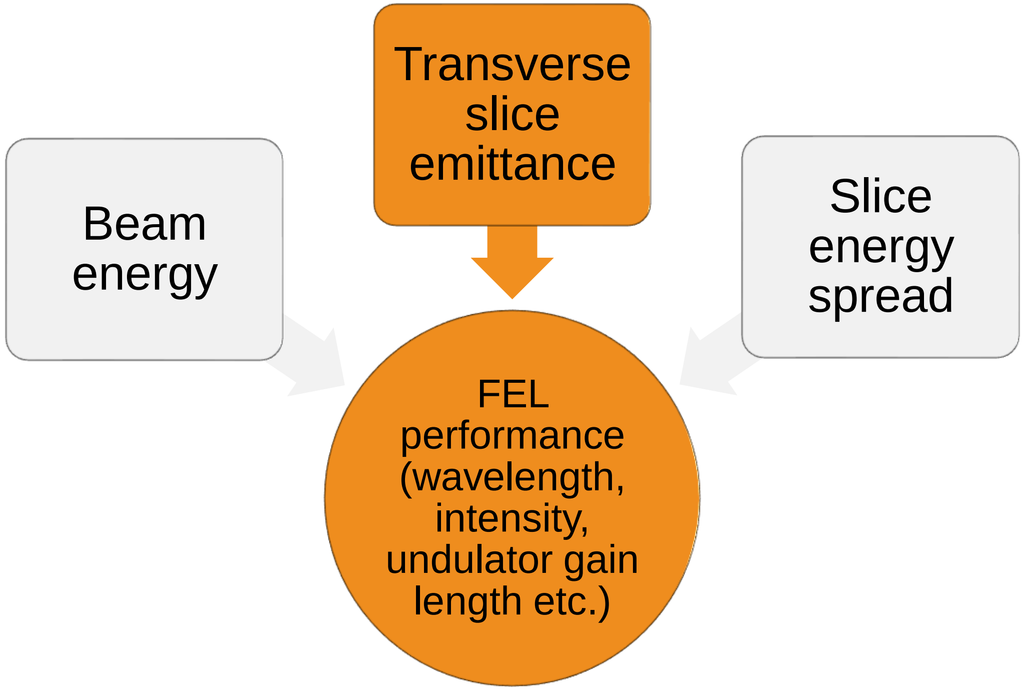
CW L-band RF electron photoinjector

Key requirement for the photoinjector

E. Saldin et., al., "Design formulas for short-wavelength FELs"
https://doi.org/10.1016/j.optcom.2004.02.071

DESY CW L-band SRF gun cavity:





Example: FEL at 20 keV in CW regime (reduced linac energy)

⇩

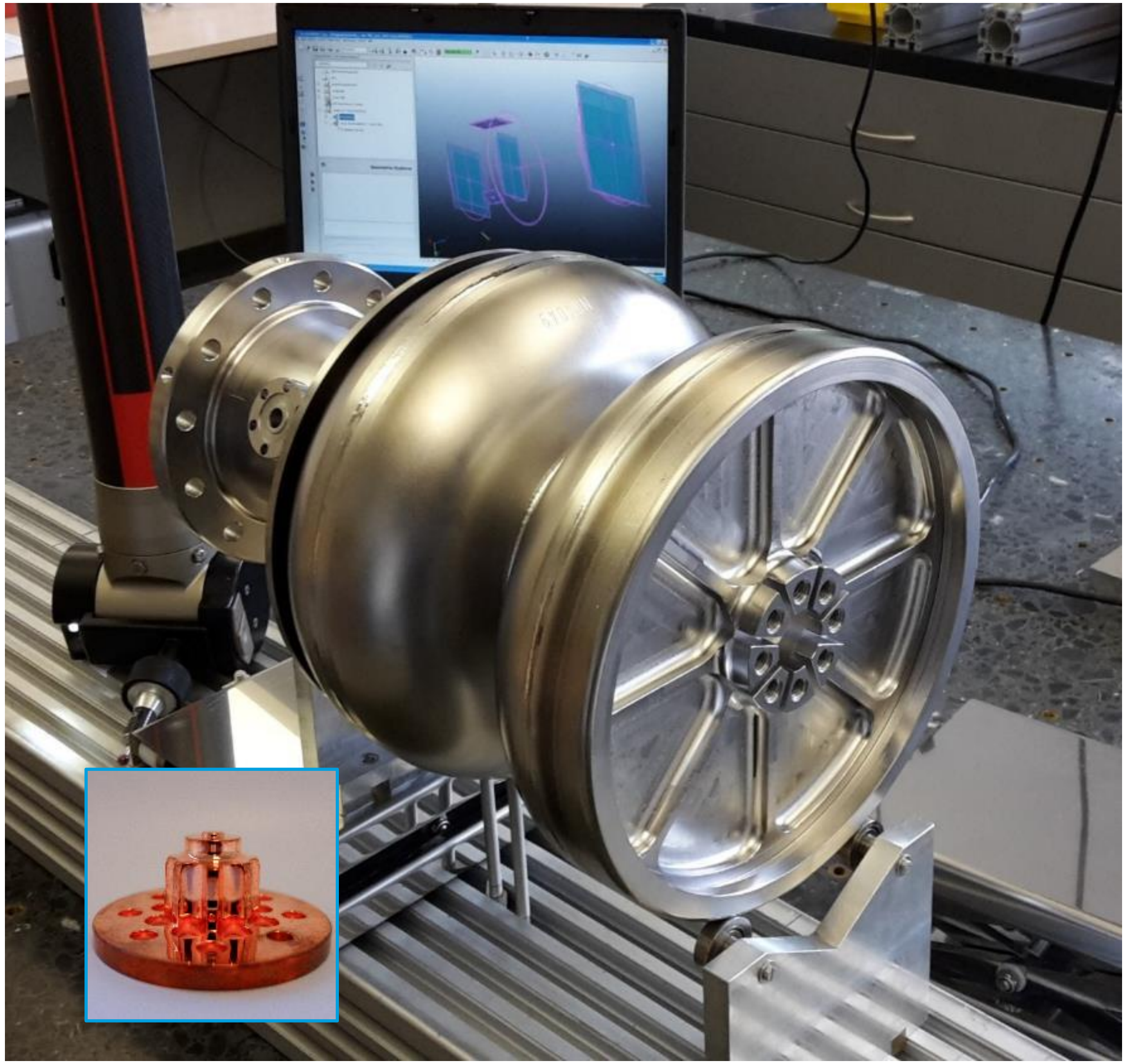
transverse slice emittance
at the level of 0.2 µm and below; 100 pC bunches

High peak electric field amplitude (> 40 MV/m) at the cathode is the key!

CW photoinjector for the future CW and HDC EuXFEL

DESY CW SRF gun cavity: design parameters

design beam parameters	SRF Gun
bunch repetition rate [kHz]	100 - 1000
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 backwall



DESY CW L-band SRF gun cavity

RnD history

16G1:

- Nb as the cathode material
- Nb has low QE
- lead proposed as the cathode material
- lead coating at the back wall - unsuccessful
- Lesson: cavity surface preparation must be decoupled from the cathode preparation using a cathode plug

16G2:

- cathode plug screwed to back wall, sealed with indium
- the cavity achieved the required gradients in vertical tests at DESY
- after many cathode insertions the backwall in the region of cathode plug became mechanically unstable and no longer leak tight

16G3/4:

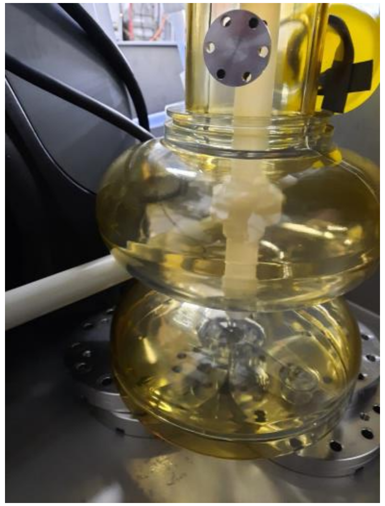
- backside mechanically reinforced, improved cathode plug design
- backside without deformation, leak tight
- poor RF performance up to October 2020
- after EP at KEK 55 MV/m demonstrated in vertical test

DESY CW L-band SRF gun cavity

RnD history

16G5/6:

- plane backwall, no cathode opening
- evaluate backwall cooling
- improved the BCP removal at the back wall became much more homogeneous
- mechanical tolerances added up resulting in not tunable cavities
- measurements of the 16G6 with detuned field flatness – up to 48 MV/m for 0-mode in the half cell



16G7/8:

- foreseen to overcome field flatness issue of G5/6
- acceptable field flatness demonstrated
- more homogenous removal by main BCP due to improved "edging head“

16G9/10:

- incorporating all lessons learned
- backwall of G3/4, RF shape of G7/8
- repetitively demonstrated > 50 MV/m peak field on axis
- **breakthrough results with Cu cathode plug**

DESY CW L-band SRF gun cavity

https://arxiv.org/abs/2310.02974

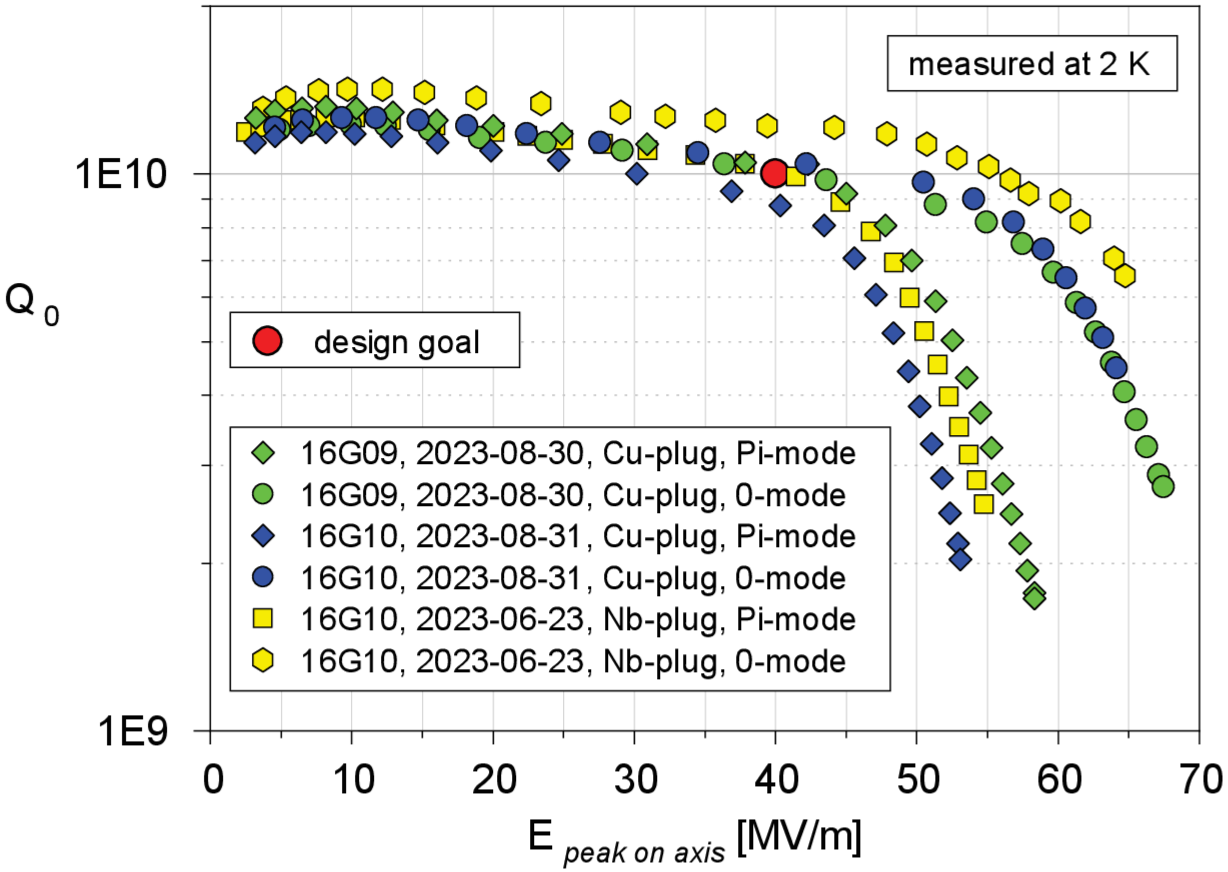
SRF Gun Cavities 16G09 and 16G10

brief history

- June 2023 initial tests with Nb-plugs at DESY
  - 16G09 showed cold leak
  - 16G10 $E_{\text{peak on axis}} \approx 55$ MV/m
- July 2023 (with Nb-plug)
  - 16G09 retightened
  - 16G09 re-measured with poor result
- **August 2023** both cavities equipped **with Cu-plugs**
- End-August 2023
  - both cavities $E_{\text{peak on axis}} \approx 55$ MV/m at Pi-mode
  - both cavities $E_{\text{peak on axis}} \approx 65$ MV/m at 0-mode

⇨ **copper cathodes are the new baseline!**

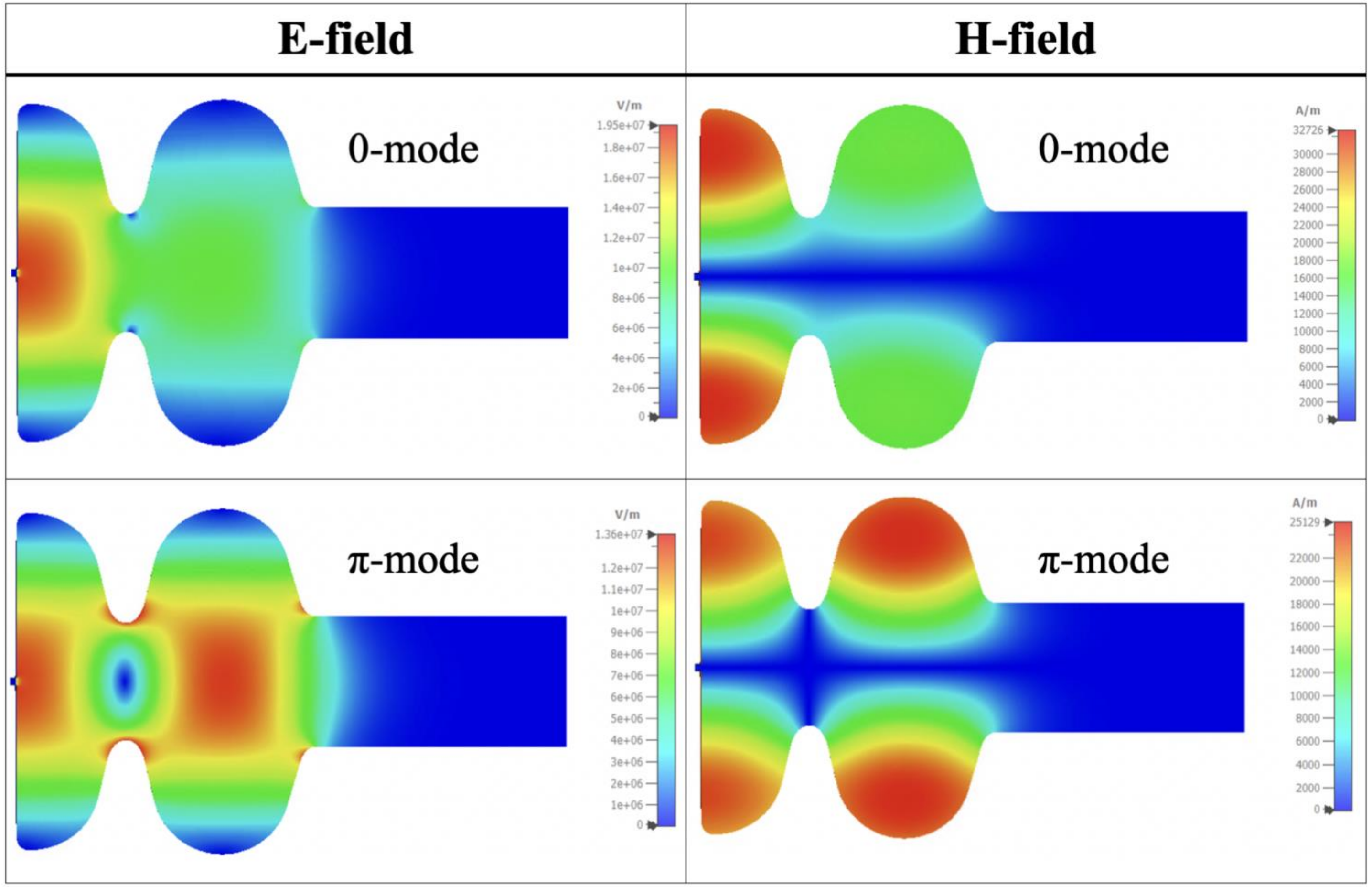
…up to 3 orders of magnitude improvement for QE as compared to Nb



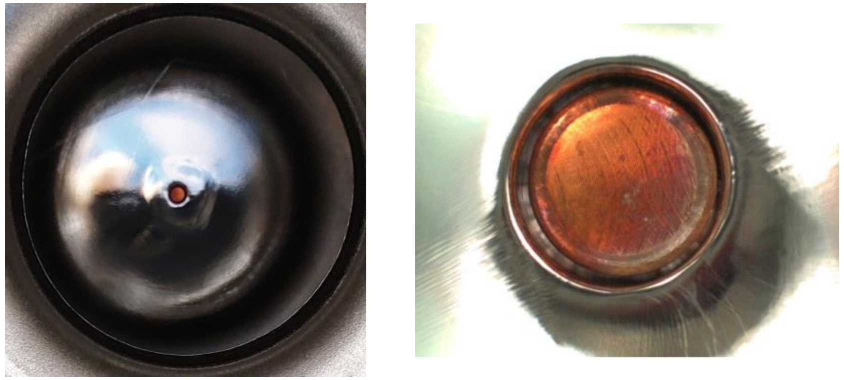
DESY CW L-band SRF gun cavity

SRF Gun Cavities 16G09 and 16G10: Cu cathode

- Field distribution for TM010 mode in the SRF gun cavity



view on the backwall of the cavity:



magnetic field distribution at the cathode (1 J norm.)

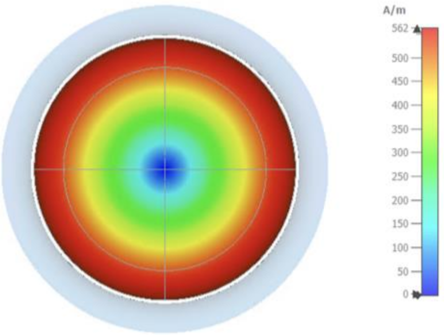


FIG. 5. Magnetic field distribution at the surface of the cathode for the TM010 π-mode. The field amplitude is normalized for 1 J stored energy in the photoinjector cavity.

DESY CW L-band SRF gun cavity

https://www.desy.de/~evogel/files/wepa144.pdf

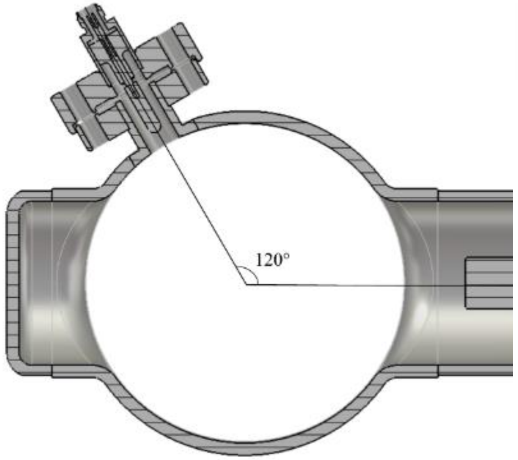
Future generations 16G11 and 16G12 with modified end group

design goal

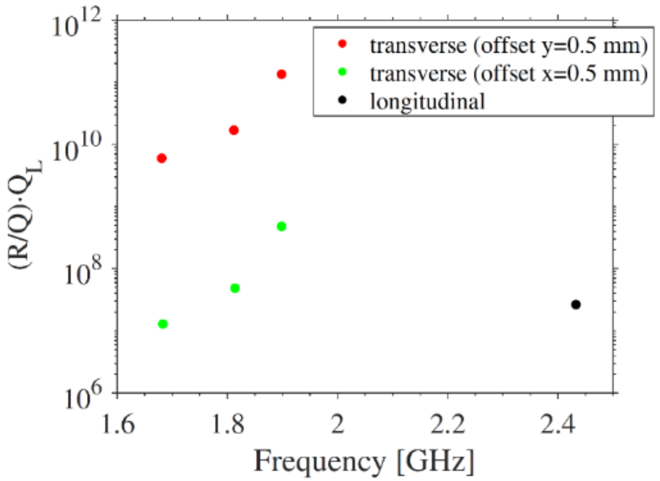
- keep it as simple as possible
- no HOM couplers

topics investigated

- power coupler and coupler kick compensation
- higher order modes
  - calculations
  - studies with beam at FLASH for detection via PU
- position of PU antenna



potentially dangerous HOMs



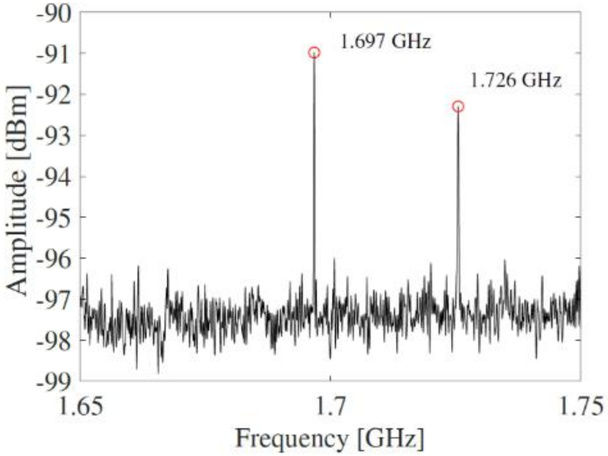


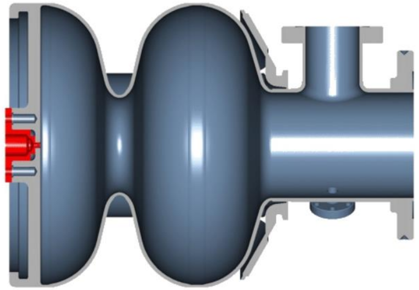
Figure 6: Spectrum analyzer output displaying two distinct peaks at the noise level, corresponding to two modes in the passband of TE111.

Beam dynamics performance

Beam dynamics performance

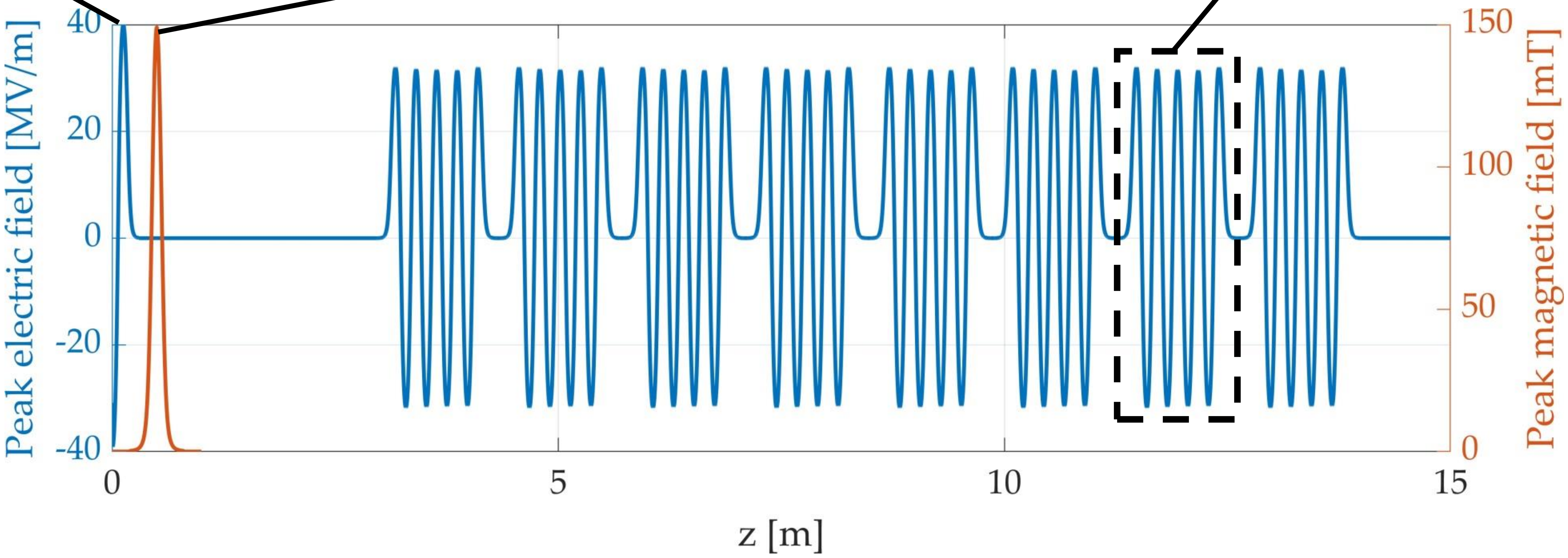
Multi-objective optimization of the photoinjector

DESY SRF gun #10



Improved copy of HZB sc solenoid

SRF 9-cell TESLA cavities (x8)

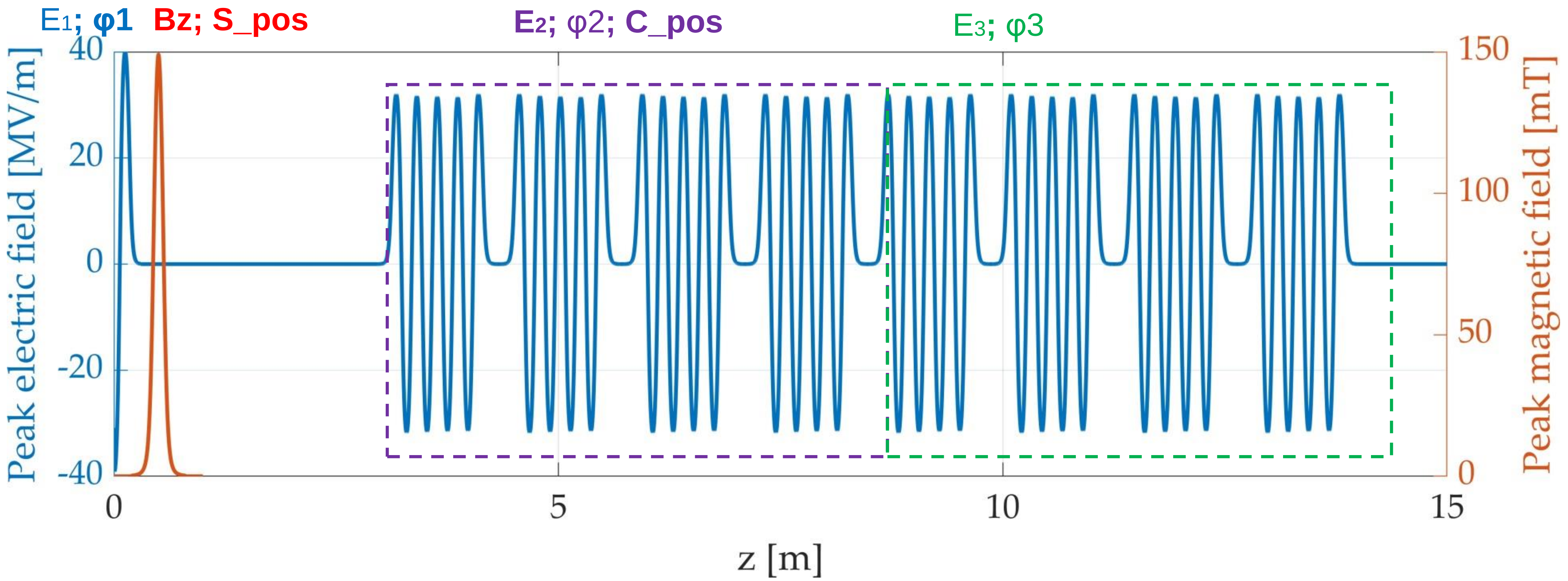


Beam dynamics performance

Optimization of the photoinjector

Cathode:
- Copper
- Intrinsic emittance ranging from 0.5 um/mm to 1 um/mm
- Charge 100 pC

Laser profile:
- Longitudinal laser shape – Gaussian
- Transverse laser shape – radial uniform
- Laser spot size (rms) – **sig_x/sig_y**
- Laser pulse duration – **sig_z**

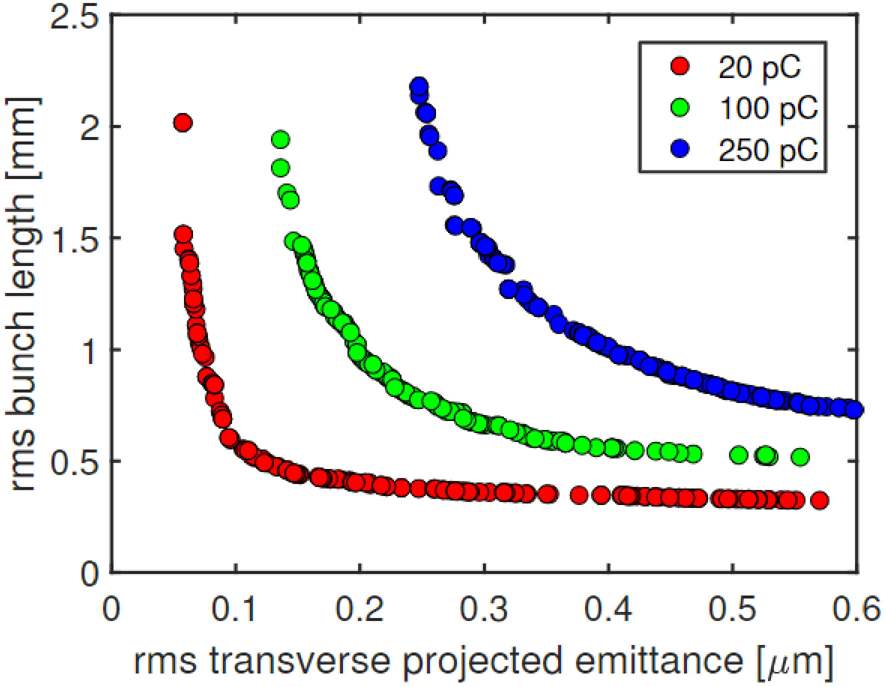


Beam dynamics performance

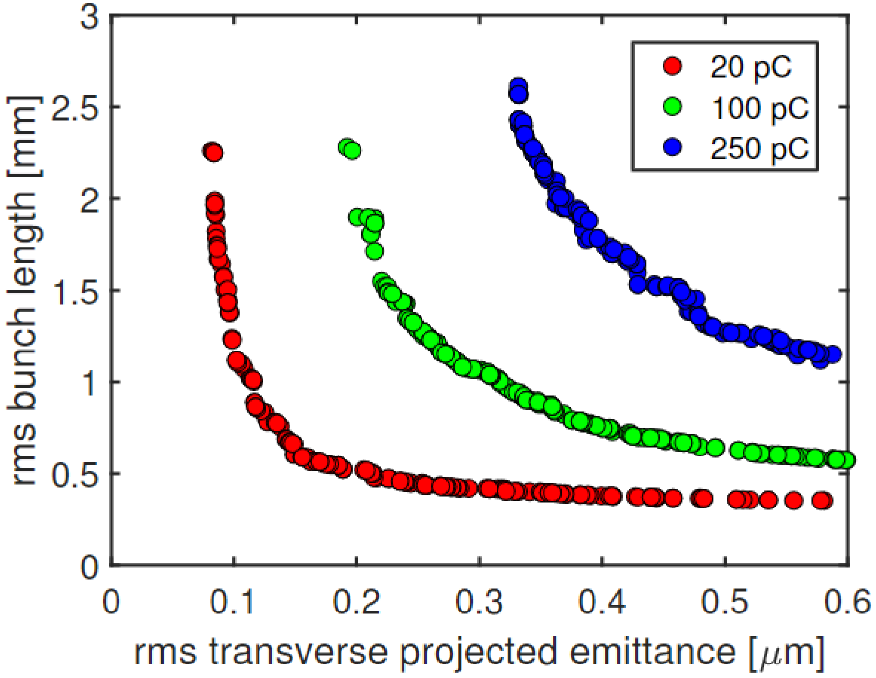
Results of MOGA optimization: pareto frontiers

- Based on RF test results with Cu cathode 55 MV/m assumed for the peak electric field in the gun cavity
- Bunch charge 100 pC
- Thermal emittance corresponds to lower and higher values reported in literature

Intrinsic emittance 0.5 um/mm



Intrinsic emittance 1.0 um/mm

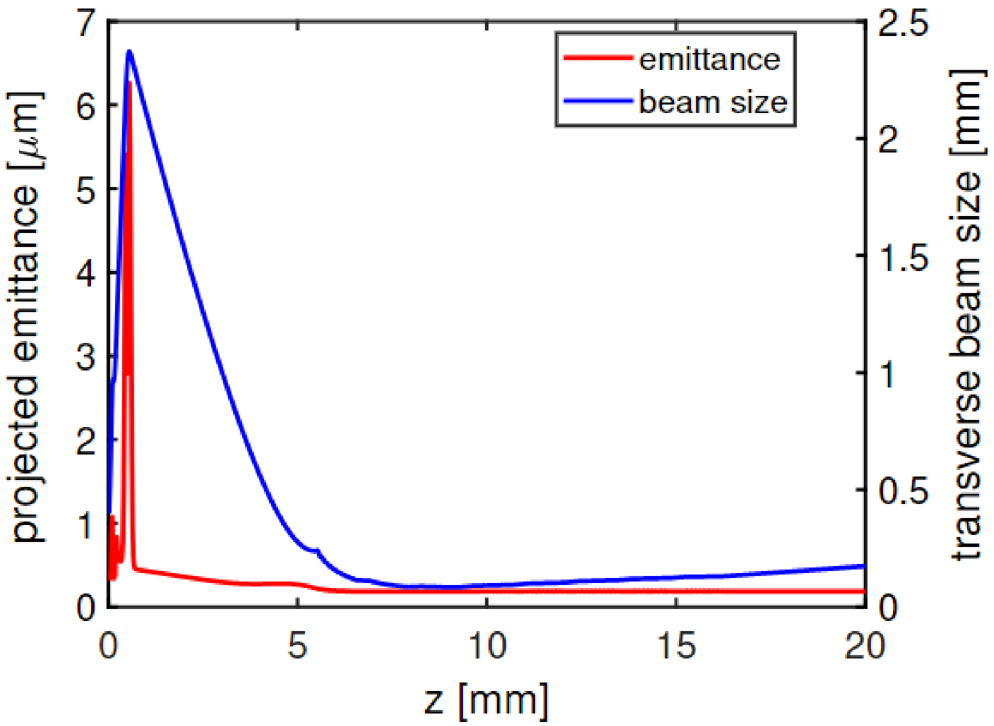


Beam dynamics performance

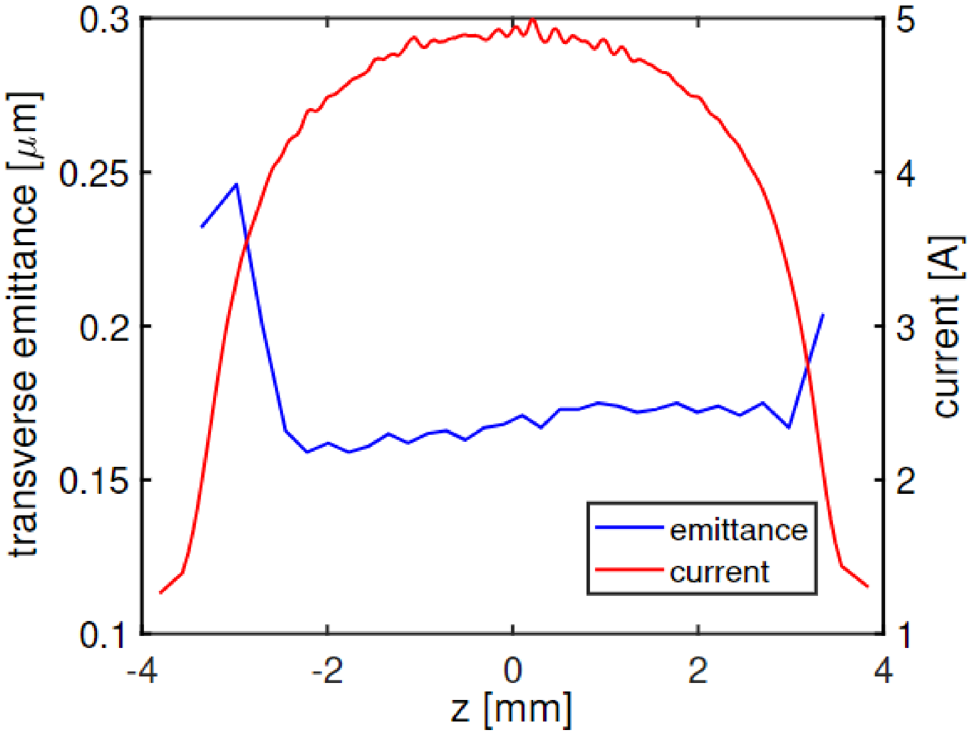
Beam size and transverse projected emittance evolution. Slice emittance and current.

- Conservative estimate for thermal emittance: 1 um/mm, bunch length allows compression to design peak current 5 kA

Transverse emittance and beam size evolution along the injector



Slice emittance and current at 20 m from the cathode



SRF Photoinjector Test Stand Ts4i

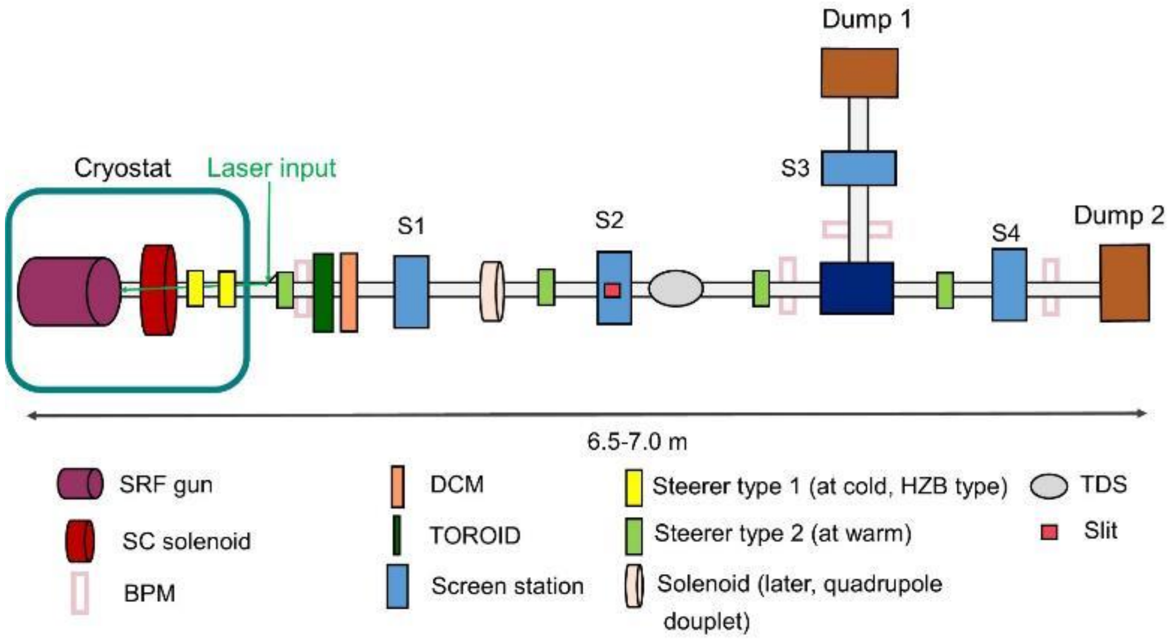
ts4i.desy.de

SRF Photoinjector Test Stand Ts4i

Concept fully worked out

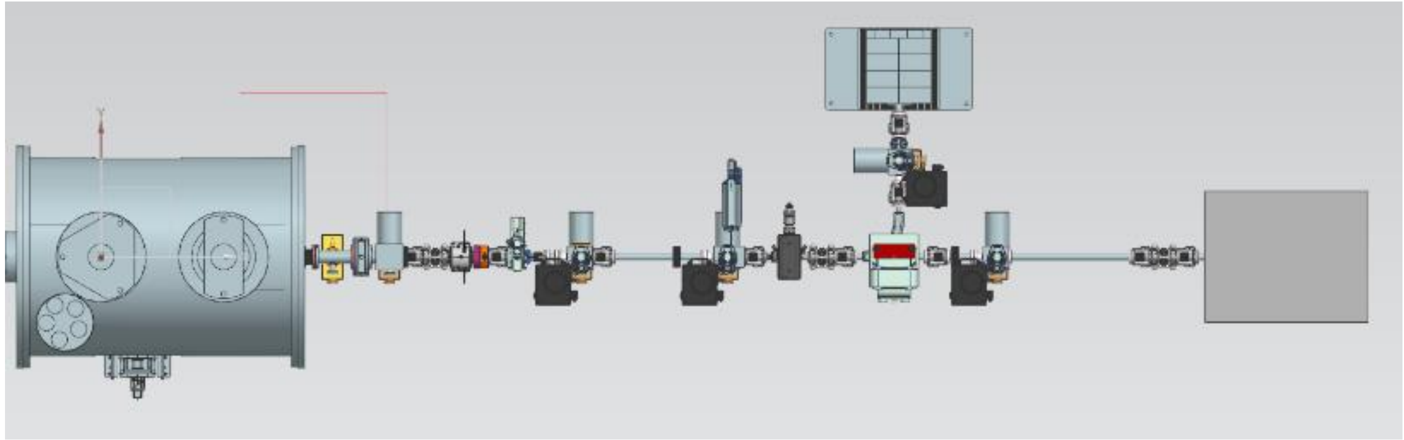
Diagnostics

- layout of warm beam line is finalized and collectively reviewed from physics point of view (Summer 2023)
- measurements: charge, dark current, slice emittance, energy + energy spread, bunch length
- slice emittance
  - slit based method, requiring TDS



Present work topics

- final adjustments for the slit method
- cable planning
- earth magnetic field shielding
- infrastructure within the bunker



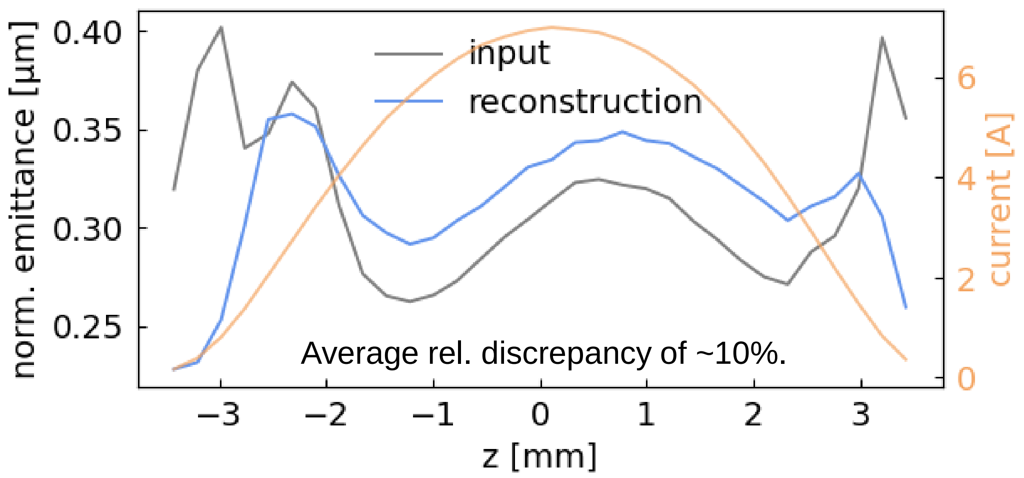
SRF Photoinjector Test Stand Ts4i

Ts4i slice emittance characterization

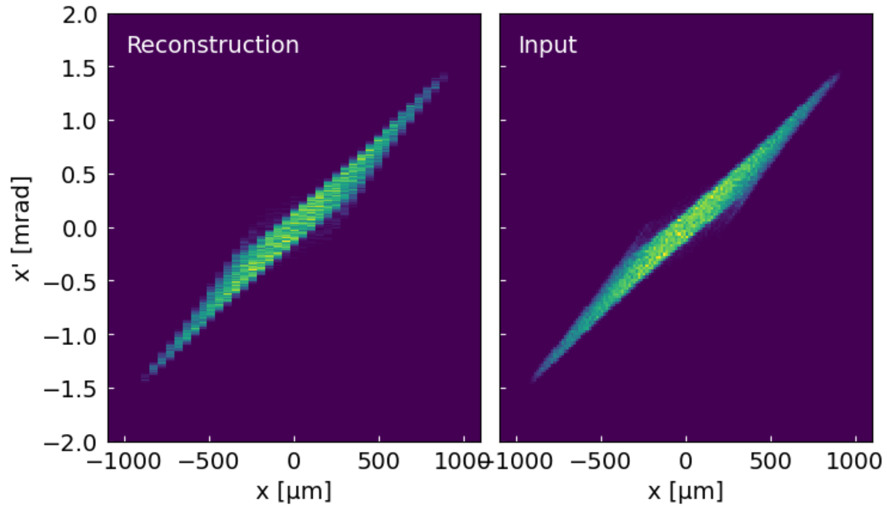
- Combination of a **slit mask scan** in horizontal direction with a vertical streaking of the beam using a **TDS**[1].
- Two quadrupoles for optimizing the longitudinal resolution → Goal: 300 fs.
- Drift of ~2.1m from slit to observation screen.

First **preliminary simulations** studies with optimized solenoid and quadrupole strengths for a minimal projected emittance at the slit location and a longitudinal resolution of ~700 fs:

Slice emittance



Hor. phase space of central slice



[1] G. Kourkafas et al., LINAC2018-THPO083

SRF Photoinjector Test Stand Ts4i

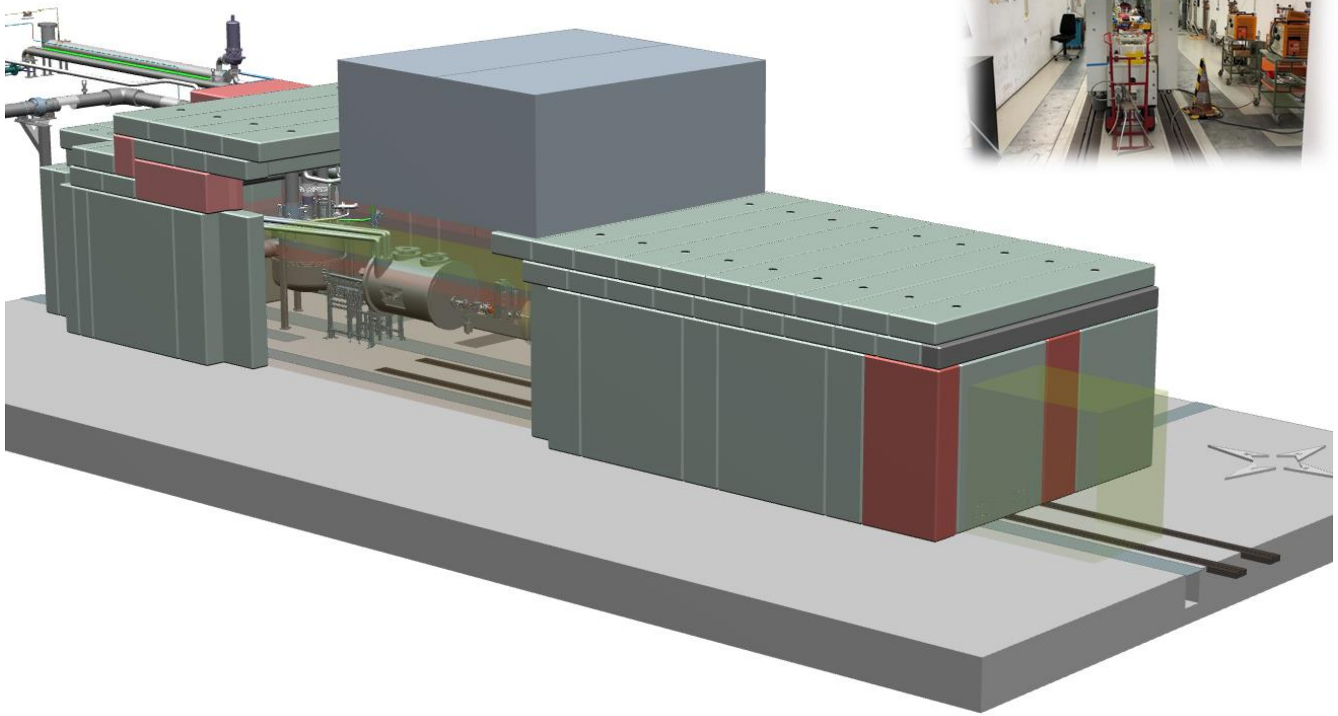
Concept fully worked out

Goals

- demonstrating SRF photo injector meets requirements
- quality check of components foreseen for operation
- for further R&D

Status

- test beam line concept ready
- solenoid (HZB design) purchase from industry done
- CW RF power source available
- Funding approved by EuXFEL directors board
- First beams to be produced in 2027



Photocathode RnD for the DESY CW L-band SRF gun cavity

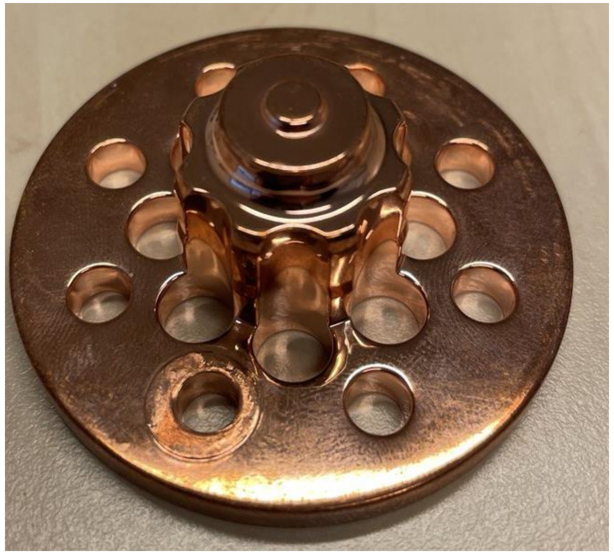
Copper photocathode

…integrated for the DESY CW SRF gun cavity

- Photocathode is screwed to the backwall of the gun (no load lock system)
- Limitations of Existing Expertise at DESY:
  - Traditional semiconductor cathodes for normal conducting guns (PITZ, EuXFEL, FLASH) are not applicable for DESY SRF gun cavity
  - Unique requirement: air-stable cathode that sustains high-pressure rinsing, operated at cryogenic temperatures
  - In-house RnD activities

➢ **Collaboration of DESY EuXFEL with STFC UK FEL on photocathode topic**

- Developing and improving air-stable cathodes:
  - Infrastructure for CW SRF gun photocathode testing
  - Material science expertise and technical support
  - R&D for laser cleaning of the cathode surface (!)
    - Exposure to air and water – 7 to 10 nm layer has to be removed
    - R&D for novel methods and solutions



Parameter	Value
Charge [pC]	100
Rep. rate [MHz]	0.1-1
QE	>1e-04
Therm. Emittance [um/mm]	0.5-1.0

Ongoing collaboration with STFC on photocathode RnD

Content curiosity B. Militsyn (STFC) on behalf of collaborator partners

- Activation procedures and characterization at low field Cu photocathode
  - Cleaning procedures (air plasma and BPS172 cleaning both followed by bakeout)
  - Photocathode characterization: surface quality, QE and MTE measurements
- Integration of photocathode activation procedure into the preparation protocol of SRF cavity
  - Sample cleaning and activation with BPS172

➢ ASTeC procedure

- ❑ Exposition to air for ~2 hours
- ❑ Heating up to 150 ºC, different time with RGA
- ❑ Low field QE test

➢ DESY procedure

- ❑ Exposition to air for ~2 hours
- ❑ HPR
- ❑ Heating up to 90 ºC, different time with RGA
- ❑ Low field QE test

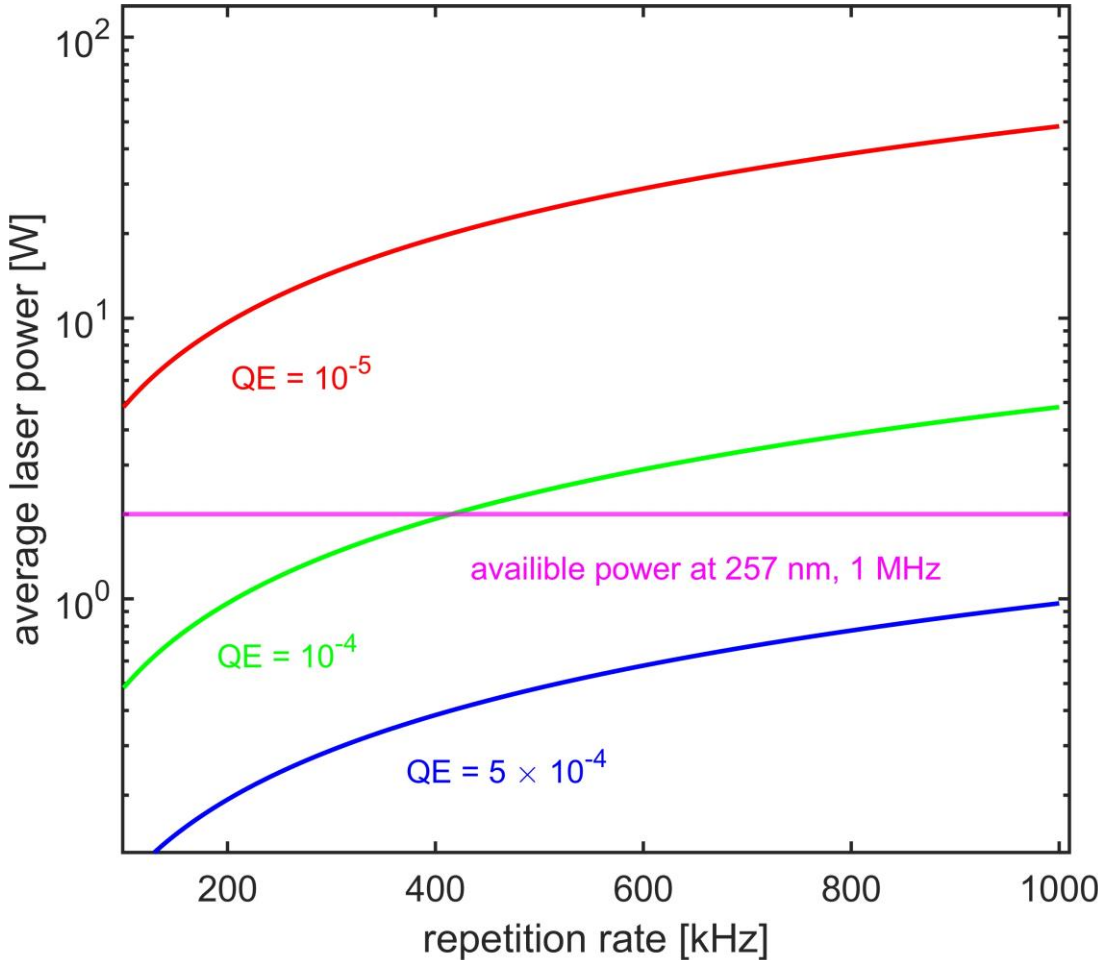
- Test of the low field QE during and after cooling down photocathode up to liquid N2 temperature in a room temperature vacuum chamber

Laser power requirements

Practical limits of Cu photocathode in terms of repetition rate

- QE of copper is reported within 10^{-5} - 10^{-4}
  - UV laser cleaning is reported to improve QE
- Presently, PHAROS laser at DESY can deliver up to 2 W average power at 1 MHz repetition rate
- For presently available hardware, optimistic assumption for QE of 10^{-4} suggest 400 kHz repetition rate for CW generation of 100 pC bunches
- Towards higher repetition rates:
  - What about cathode laser RnD to increase power ?
    - Complex and resource demanding
    - Thermal management of the photocathode in cryogenic environment
  - ➢ Explore methods to increase QE of copper

Required laser power in order to generate 100 pC bunches in CW mode:



Improving QE of copper

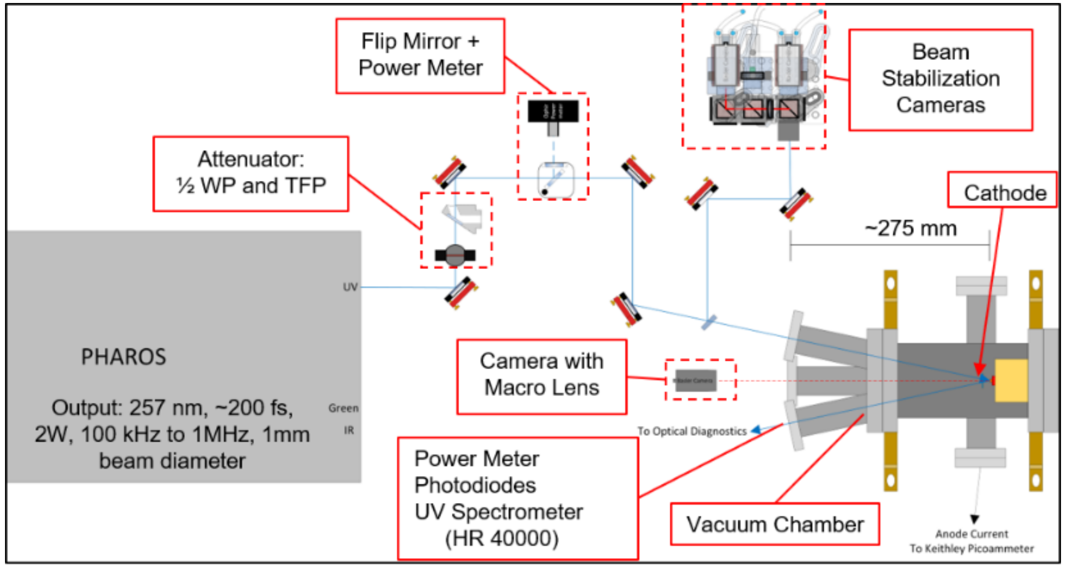
Improving QE of copper

Laser cleaning studies

R&D plans for Cu cathode (flat surface)

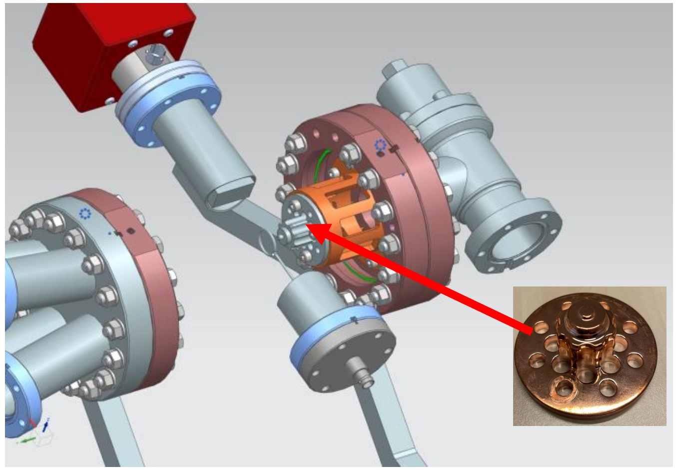
- QE measurements at low field, study UV laser cleaning
  - Learn from LCLS experience with Cu cathode*
- target QE >= 10^{-4}

Setup for QE measurements / laser cleaning studies:

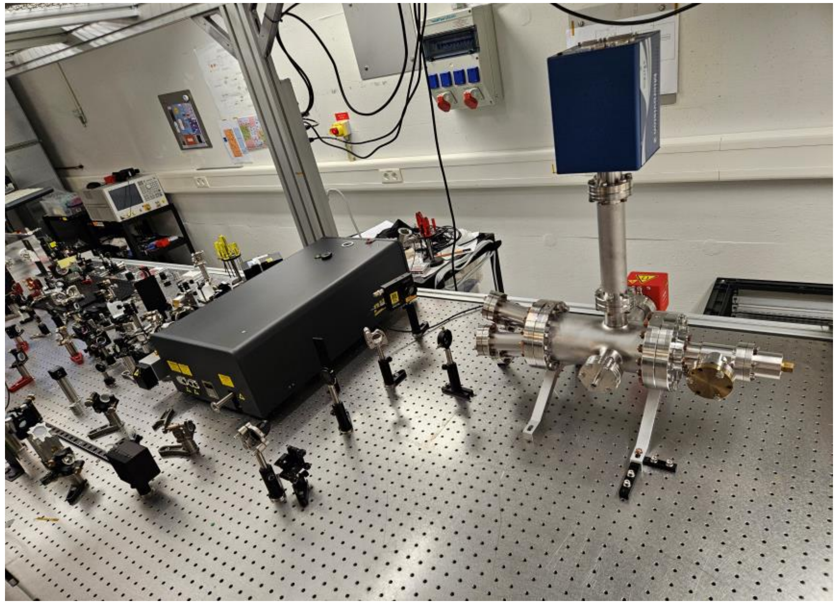


*DOI: 10.1016/j.nima.2015.02.029

inner interior of the vacuum chamber



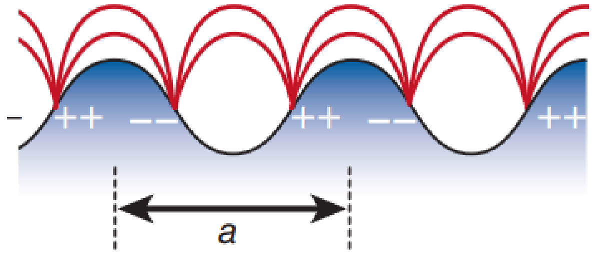
pharos laser, optical table and the vacuum chamber for RnD purposes



Improving QE of copper

Nanostructured copper photocathodes

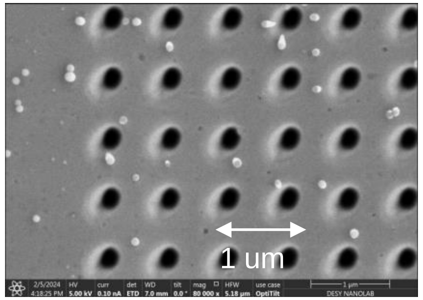
- Advanced photocathode R&D at DESY aims to increase QE of metal photocathodes
- R. Li et al. investigated surface-plasmon assisted photoemission to enhance QE of copper photocathode*
  - Interest increased due to promising test reports of nanostructured photocathode in JLab's SRF gun cavity**
  - Both studies explored 4-photon emission process
  - Significant QE enhancement compared to flat surfaces was reported
- Confirmed infrastructure at DESY for producing structured photocathodes using focused ion beam (FIB)
- Risk factors: dark current, increased emittance
- Low investment research with high potential



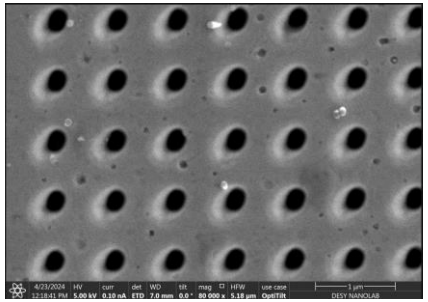
[Image from Barnes et al., Nature 424, 824]

First structured Cu cathode suitable for 780 nm laser produced at DESY in collaboration with DESY NanoLab* (credit A. Pandey, S. Kulkarni, T. Keller)

before CO2 cleaning



after CO2 cleaning



*DOI: 10.1103/PhysRevLett.110.074801

**DOI: :10.18429/JACoW-IPAC2019-TUPTS069

Improving QE of copper

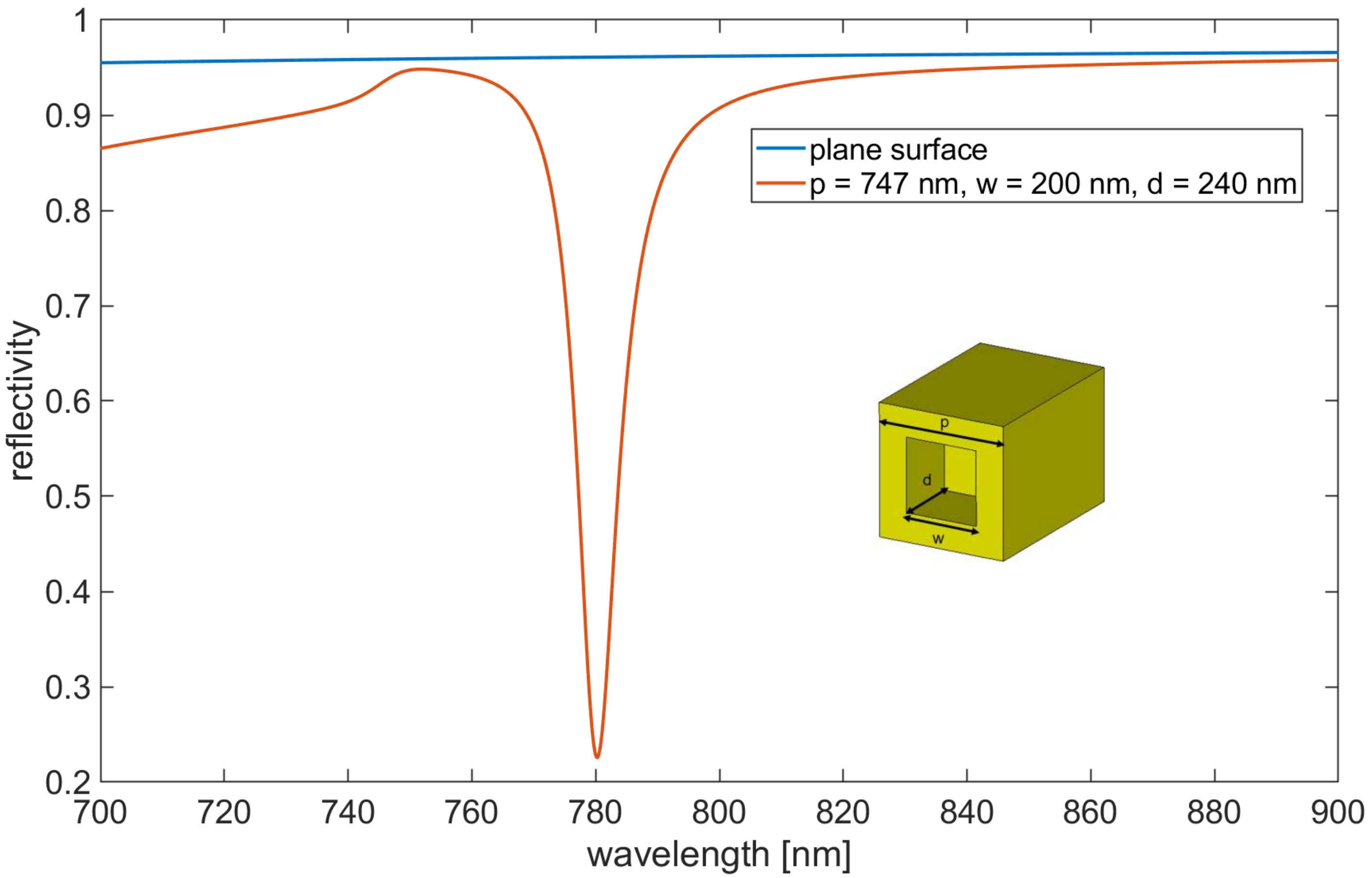
Nanostructured copper photocathodes

- Photoemission
  - Photon absorption -> electron transport to the surface -> overcoming the metal-vacuum barrier
- Coupling the incident light (excitation laser) to an electron density wave on the metal surface allows the excitation of the Surface Plasmon Polaritons (SPPs)
  - Momentum matching scheme is needed for excitation of SPPs
    - For example, periodically structured metal surface
- SPPs enable the coupling of incident light to electron density waves on the metal surface
  - This coupling increases the absorption of light, making the metal more efficient at absorbing photons compared to a flat surface
  - Generation of SPP leads to strong field localization at the metal surface, reducing the electron travel distance
- Nanophotonics / nano-optics applied to photoemission has interesting applications beyond QE improvement

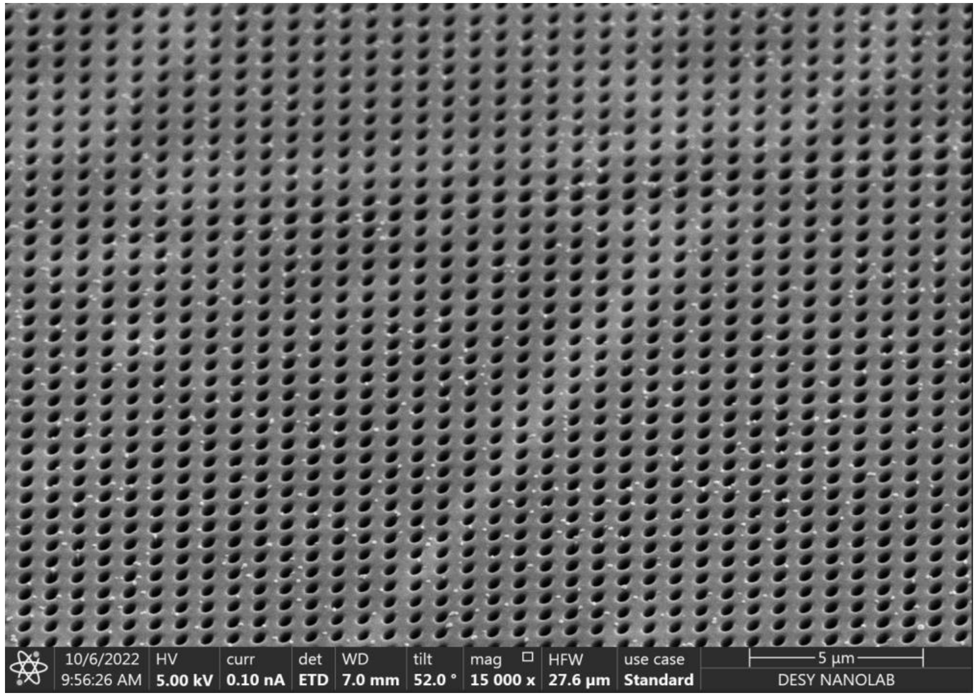
Improving QE of copper

Nanostructured copper photocathodes: pattern for test purposes in 2022

Numerical results of frequency domain solution (FEM) of reflectivity of copper



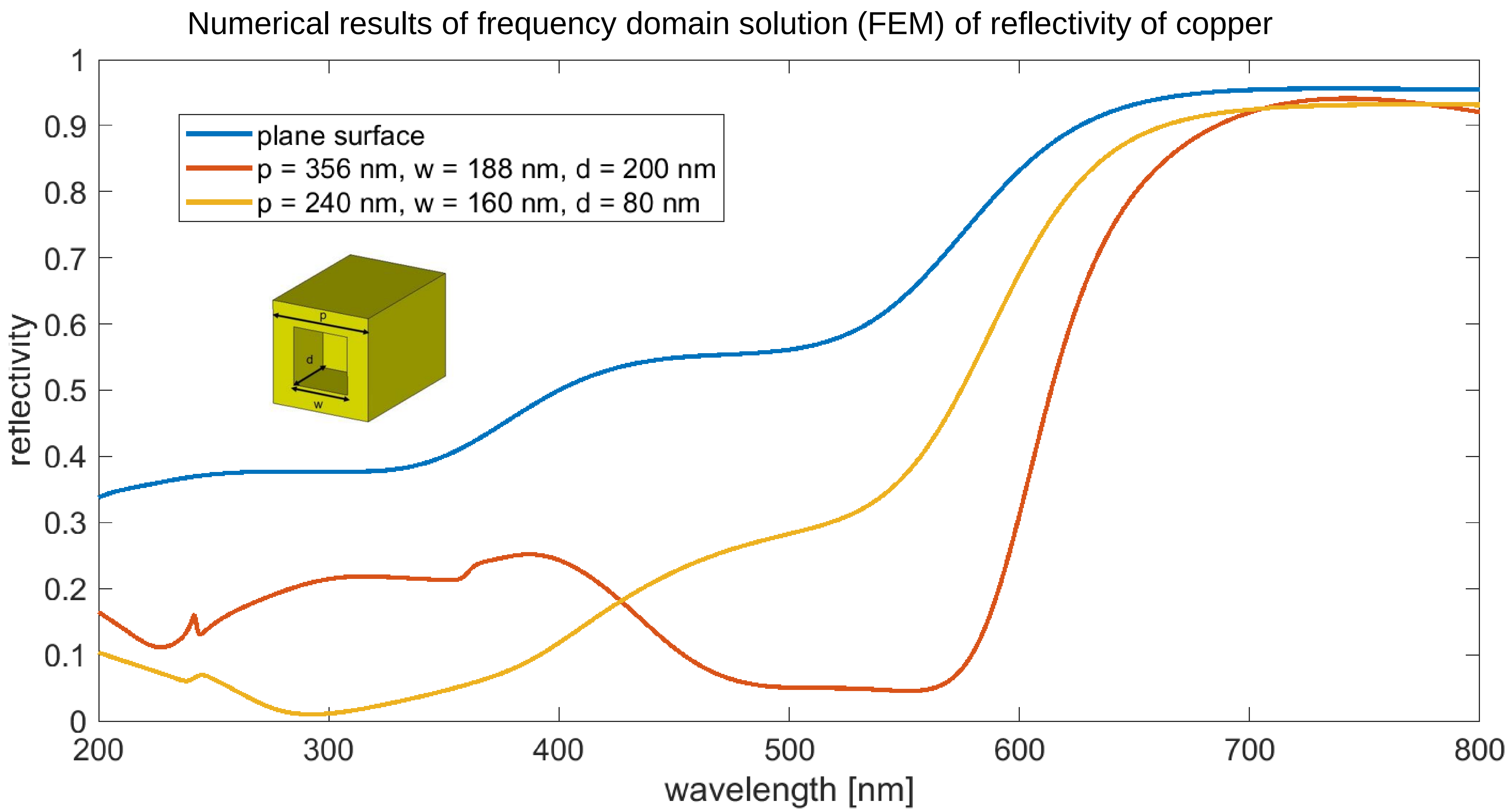
First structured Cu cathode suitable for 780 nm laser produced at DESY in collaboration with DESY NanoLab (credit A. Pandey, S. Kulkarni, T. Keller)



Outcome: successful FIB attempt to produce structured surface

Improving QE of copper

Fundamental studies on 1,2,3 photon photoemission with improved optical absorption

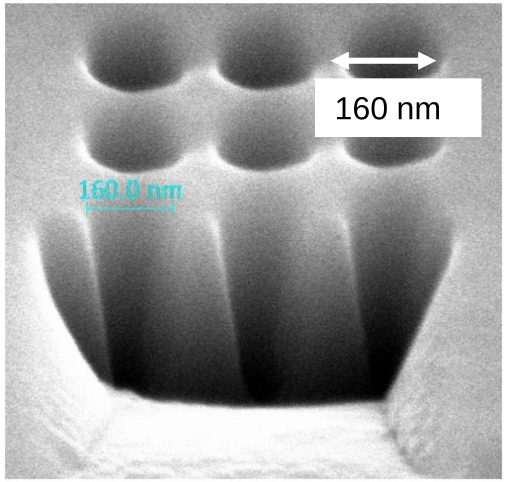


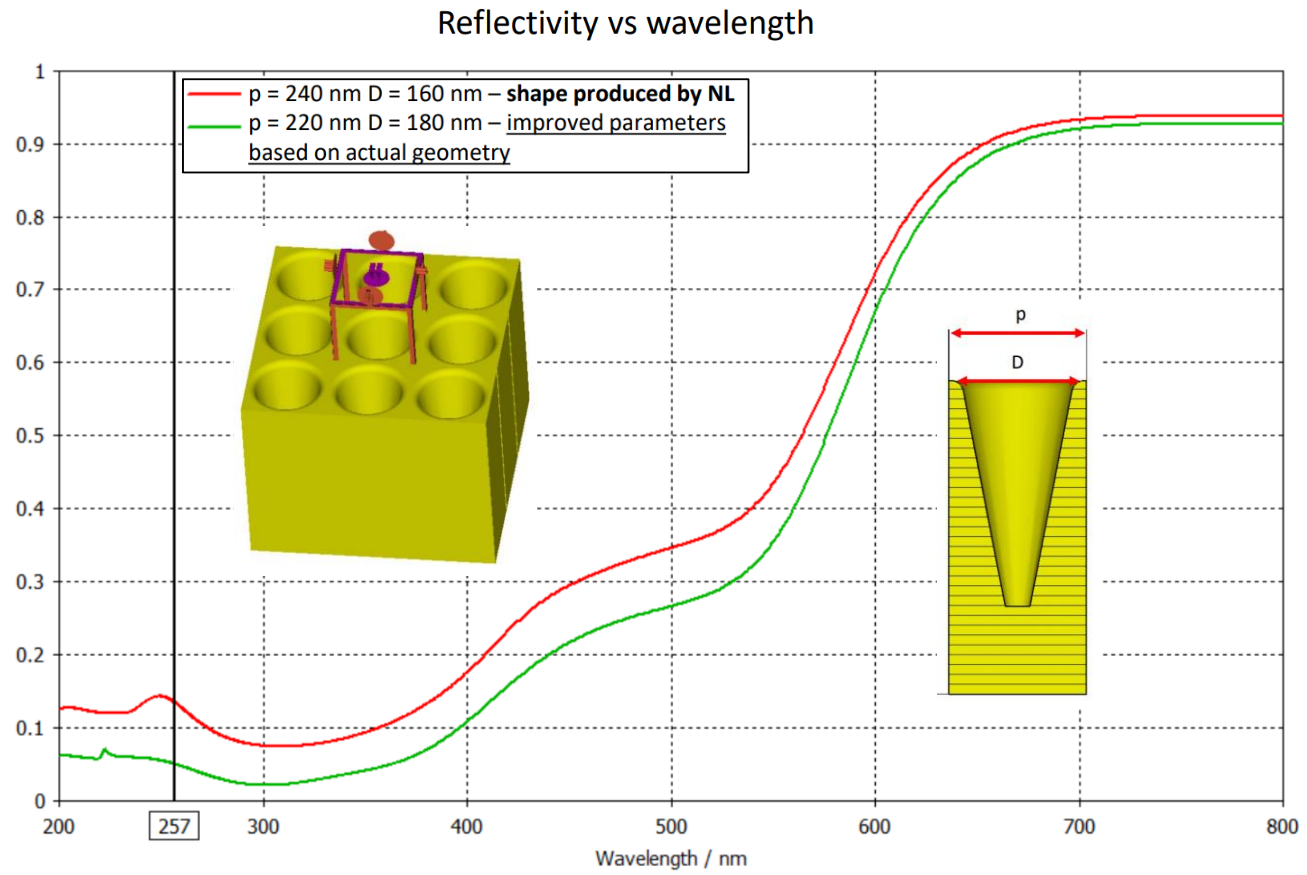
Improving QE of copper

Fundamental studies on 1,2,3 photon photoemission with improved optical absorption

- Attempt to produce structured surface with improved absorption in UV range (257 nm)
  - Attempt of DESY NanoLab resulted into conical shape
  - Further optimized w.r.t FIB aspects

FIB attempt by DESY NanoLab (credit A. Pandey, S. Kulkarni, T. Keller)





Improving QE of copper

Fundamental studies on 1,2,3 photon photoemission with improved optical absorption

- FIB production of circularly patterned area for the required spot size of the excitation laser in the RF gun cavity at REGAE*
- Confirmed (07.2024), crystallinity is required for FIB patterning
- Production of single crystal Cu suitable for REGAE gun cavity initiated
  - Sensitive dark current analysis and beam quality characterization t.b.d

Circular patch produced using FIB: credit Miriam Barthelmess (FS-CFEL-1)

Polycrystalline sample

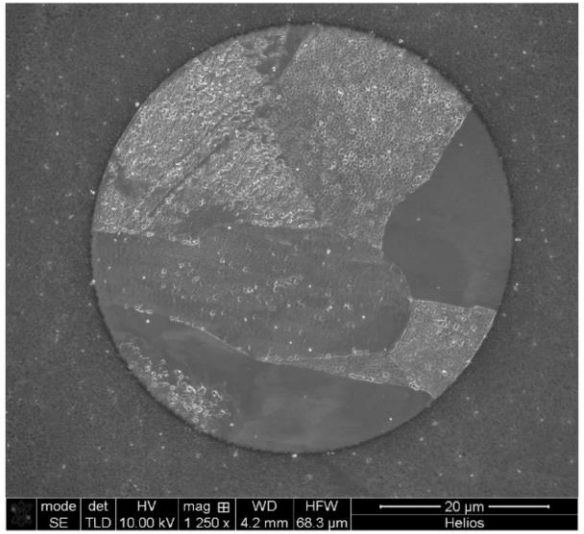


Figure 1: 50µm pattern in uncleaned polycrystalline Cu

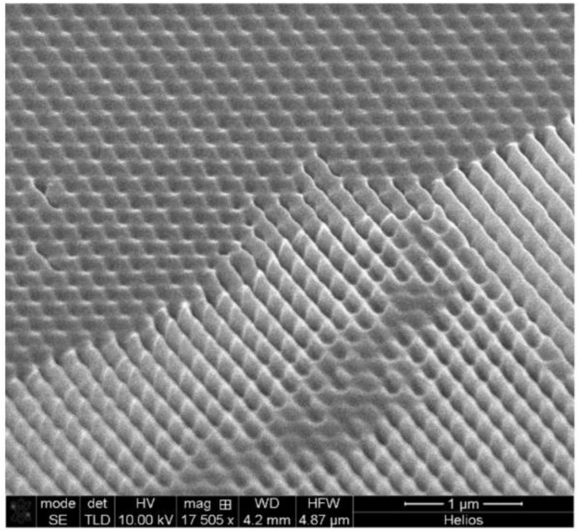


Figure 2: section of 50µm pattern under an angle of 52° on a grain boundary

Single crystal sample

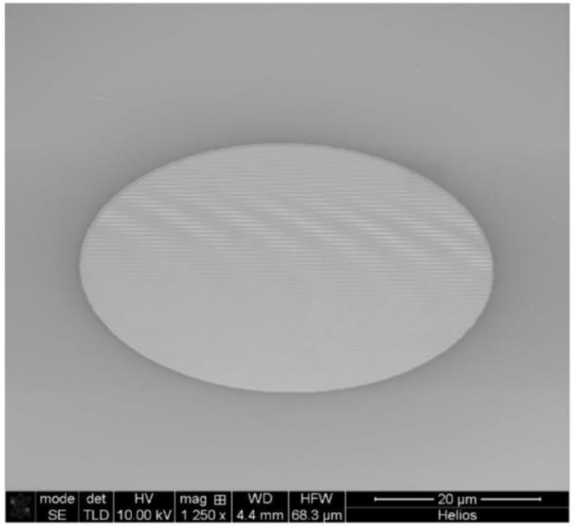


Figure 3: 50µm pattern in Cu single crystal at 52° angle

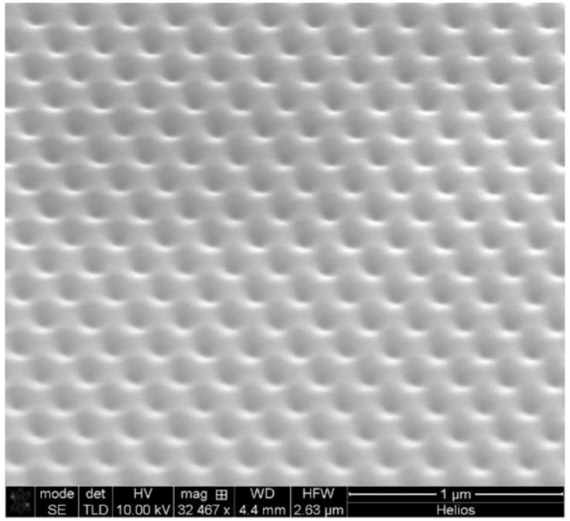


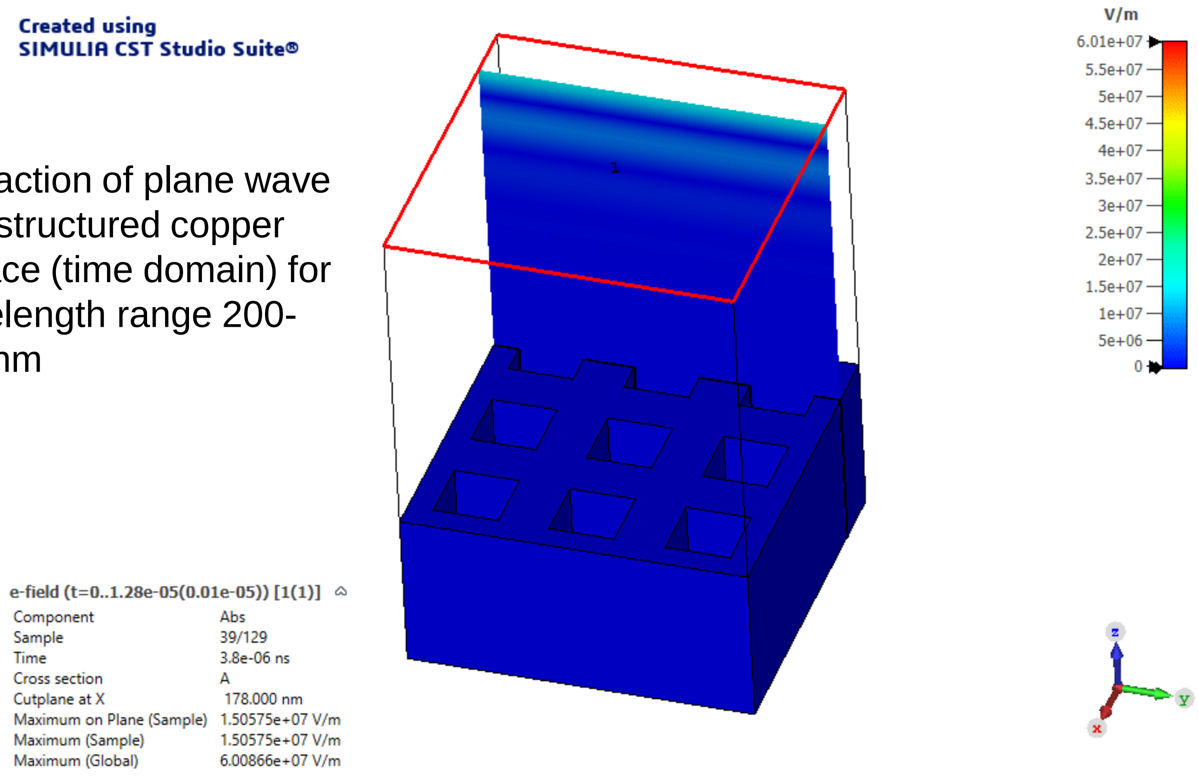
Figure 4: section of Fig 3

Improving QE of copper

Fundamental studies on 1,2,3 photon photoemission with improved optical absorption

- Improved optical response in wide wavelength range, can not be solely explained by the theory of SPPs
- Work ongoing to verify numerical results by means of experimental reflectivity measurements

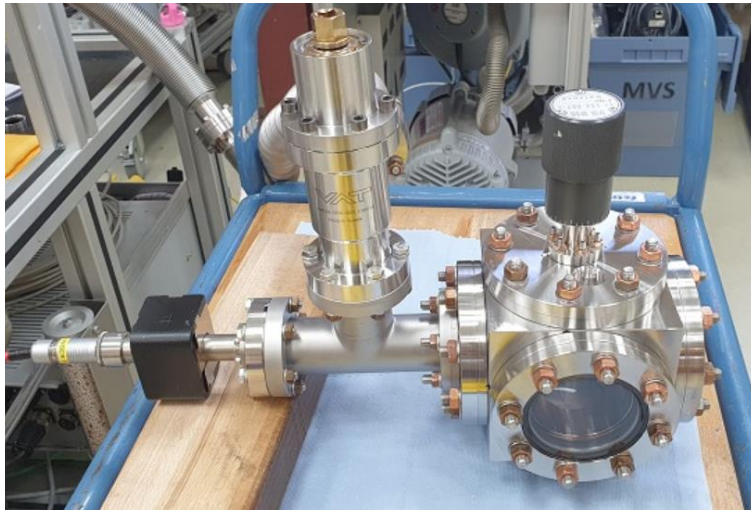
Interaction of plane wave with structured copper surface (time domain) for wavelength range 200-800 nm

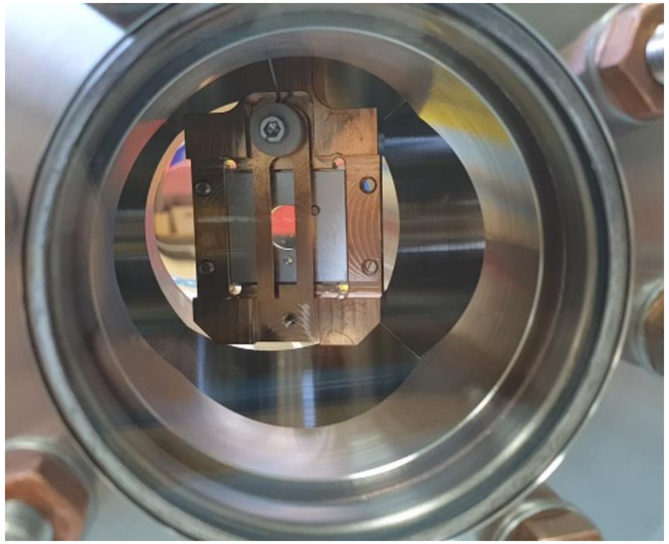


Improving QE of copper

Experimental infrastructure

- Aim to investigate photoemissive and optical properties of nanostructured photocathodes
- Vacuum chamber for low field QE measurements
    - High precision motorized feedthrough for sample rotation





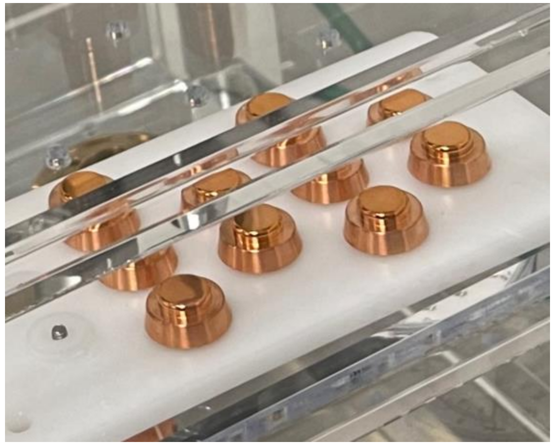
TLS-EQ-77-UV

Improving QE of copper

Further steps: photoemission from structured Cu cathode in the RF photoinjector at REGAE

- Exploring possibilities of improved optical response from UV to green wavelength range
  - Factor of 5 to 10 improvement of reflectivity in UV range can already make a difference for high repetition rate operation
  - QE enhancement is expected to exceed improvement of reflectivity due to local field enhancement
  - Studies of photoemission ranging from single to multiphoton for structured surface
- Next milestone: test of the nanostructured photocathode at REAGE facility in the real RF gun cavity conditions (normal conducting cavity)
  - Sensitive dark current measurements
  - Beam quality characterization

cathodes suitable for REGAE gun cavity



Credit: Miriam Barthelmess (FS-CFEL-1)

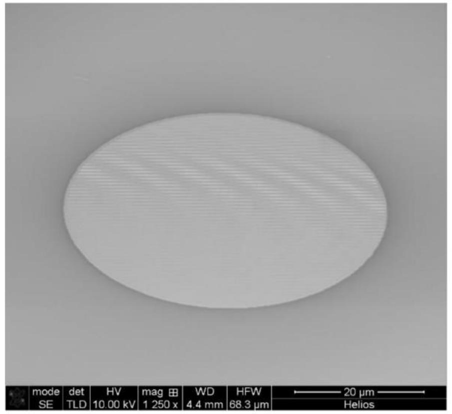


Figure 3: 50µm pattern in Cu single crystal at 52° angle

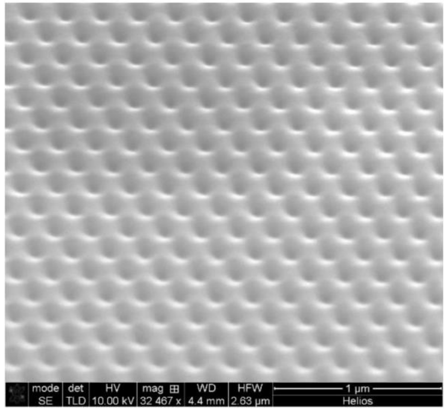


Figure 4: section of Fig 3

Improving QE of copper

Electromagnetic simulation & preliminary beam dynamics

Content courtesy of **TU Darmstadt, TEMF**
PhD student **Margarita Bulgacheva** under
Supervision of **Erion Gjonaj**

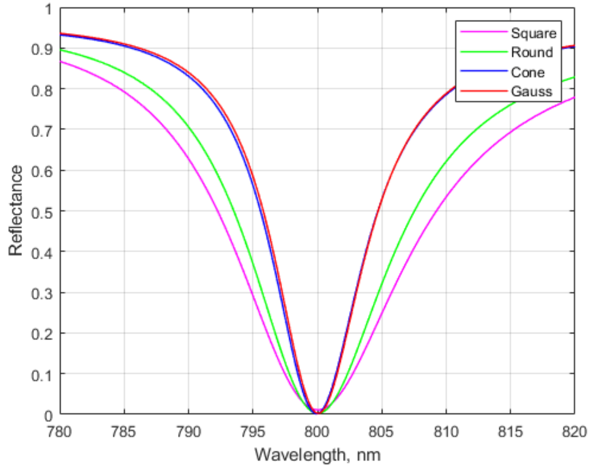
Electromagnetic simulation:

- Defined dispersive material properties – own fitting of Johnson and Christy data
- Optimized geometrical parameters to achieve lowest reflectance
- E-field enhancement distribution

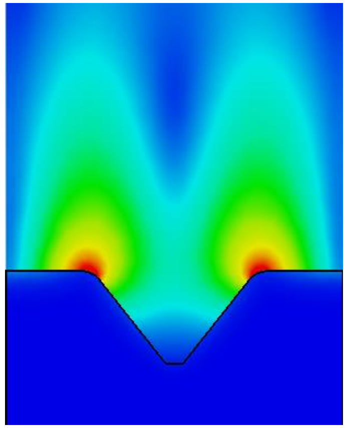
Preliminary beam dynamics:

- Simulated optically induced emission model without time dependence with fixed QE
- Added time distribution and calculated beam dynamics at the near-cathode vicinity

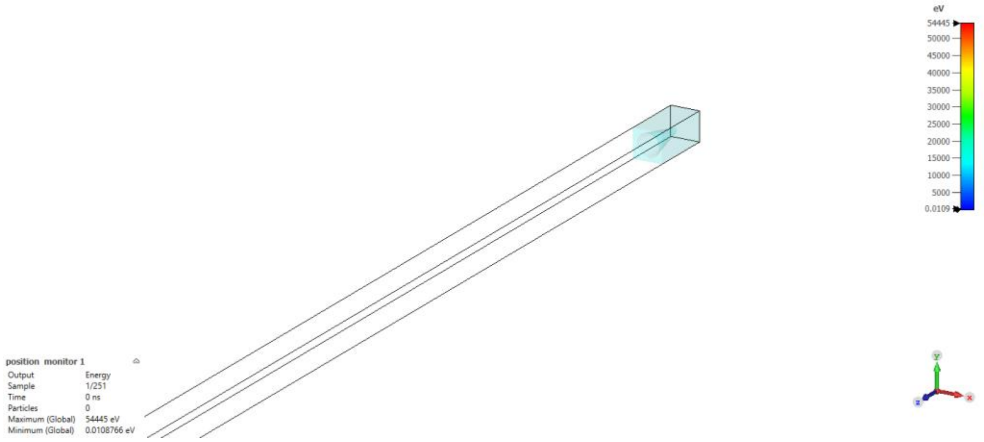
Next step: integrate local absorption enhancement into beam dynamics



Reflectance for various geometries



E-field distribution



Beam dynamics (cone-shaped nanohole)

Summary

Summary

- DESY CW L-band SRF gun repeatedly demonstrate peak electric field of up to 55 MV/m on axis in vertical tests
  - Recent major breakthrough: up to 55 MV/m with integrated Cu cathode plug
- In simulations, we demonstrate feasibility of generating 100 pC beams with the slice emittance below 0.2 um
- Using present PHAROS laser system and assuming QE of Cu cathode of 10^{-4} DESY CW photoinjector can generate 100 pC bunches with the 400 kHz repetition rate
  - Going towards higher repetition rates assumes increasing available laser power in CW mode or improving QE of the photocathode
- We are working on establishing infrastructure on metal photocathodes for CW SRF gun cavity at DESY
  - Valuable collaboration with STFC Daresbury on photocathodes on behalf of the collaboration of EuXFEL and UKFEL
- Implementation of nanostructured photocathodes allows to increase QE in comparison to flat surface
  - At the cost of increased intrinsic emittance
  - Experimental evaluation of the structured photocathode is foreseen in the RF gun cavity at RAGAE

End of the talk.