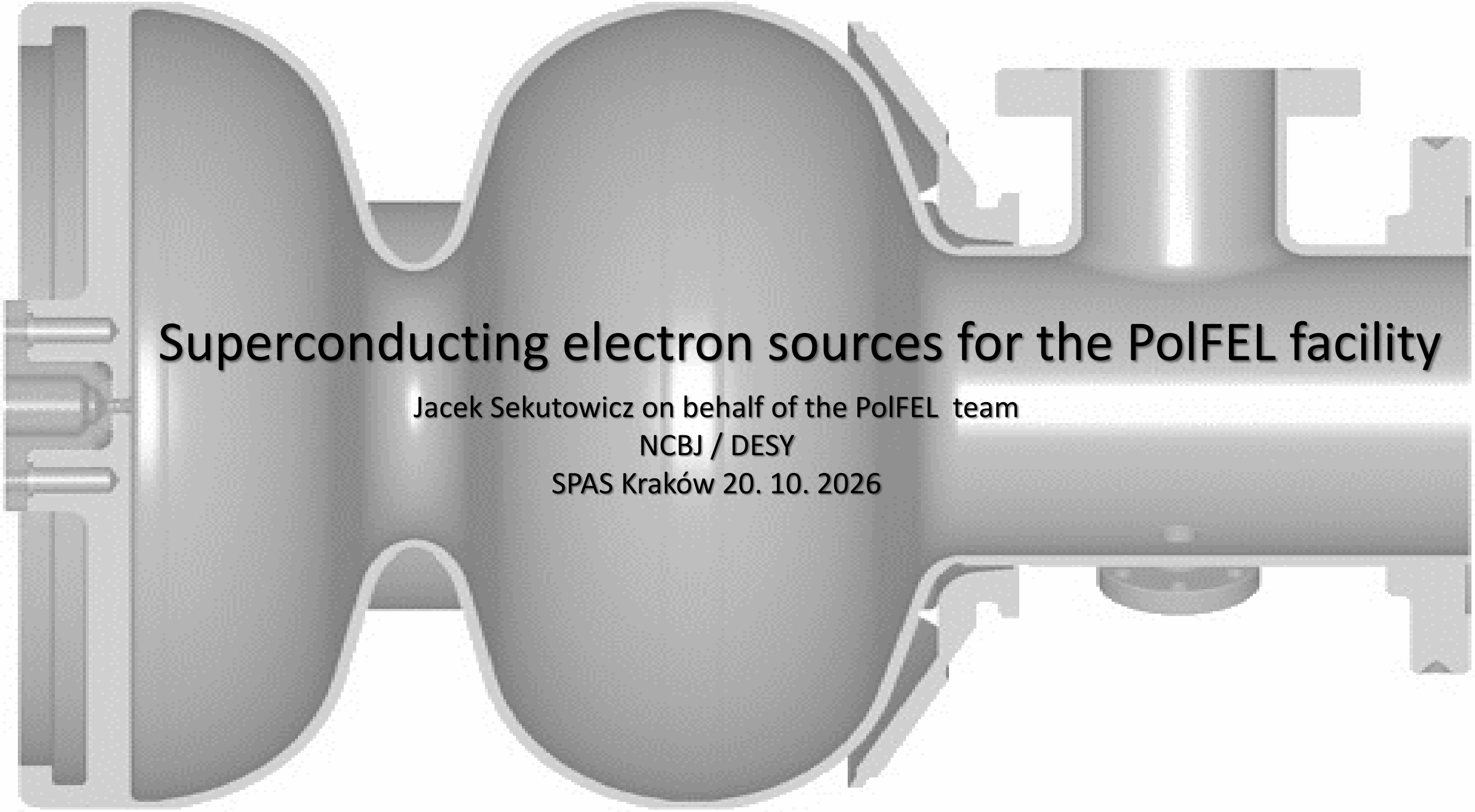


Superconducting electron sources for the PolFEL facility

Jacek Sekutowicz on behalf of the PolFEL team
NCBJ / DESY
SPAS Kraków 20. 10. 2026

Outline

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1. Beam Energy and Bunch Charge Requirements

Beamline	Beam Energy U_e	Bunch Charge q_b	Max. Rep. Rate f_{rep}	Max. Beam Current I_b
-	[MeV]	[pC]	[kHz]	[µA]
THz	4	100-250	5-2[(1)]	0.5
UED	2- 4	0.001-0.100	50-200[(2)]	0.005 (0.02)

[(1)] For the THz beamline, the limitation is imposed by radiation protection requirements.

[(2)] For operation several years after commissioning

2. Requirements Arising from Superconducting Technology and Space Constraints

a. **Final Cavity Cleaning:** The final step in removing residual contamination from the superconducting cavities is high-pressure rinsing (**HPR**), using water jets at pressures of up to 150 bar.
HPR has been successfully applied to 1700 TESLA cavities manufactured for the European XFEL, LCLS-II and SHINE facilities.

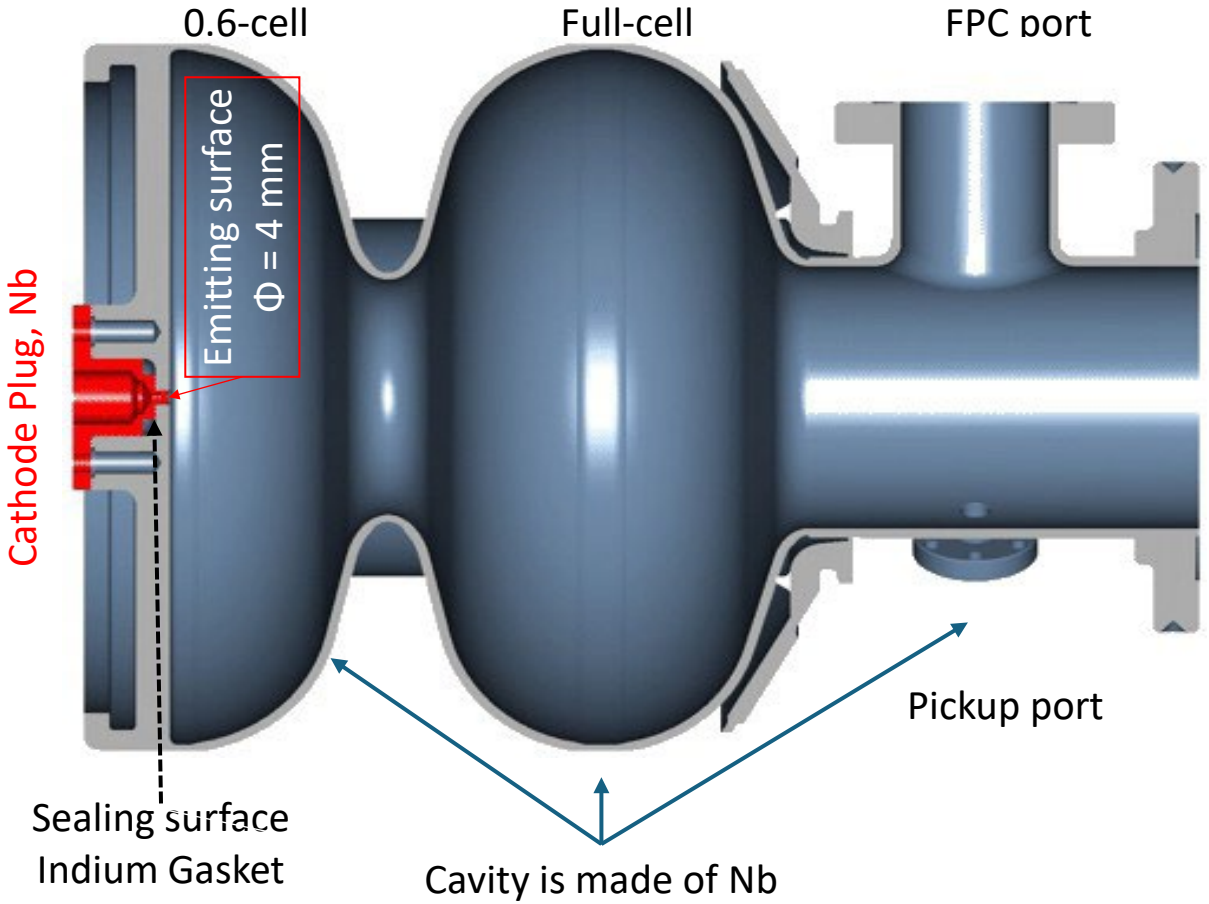
b. **Preferred Cathode Materials: HPR** should be performed with the cathode already attached to the cavity. This requirement restricts the choice of photocathodes to metallic materials, which may be either normal-conducting or superconducting.

c. **Dark current:** I_{DC} is a critical factor in UED experiments requiring very low q_b. For q_b =1 fC and f_{rep}= 50 kHz, I_b=50 pA. The dark current (I_{DC}) must be significantly lower than I_b.
Therefor the cleanliness and smoothness of the cathode surface together with minimising electric field enhancement in the vicinity of the cathode, are of particular importance.

d. **Compactness:** The PolFEL facility is housed in an existing building adapted for this purpose, where space is very limited. Consequently, electron injectors requiring additional components, such as a chopper or booster, cannot be accommodated within the available space.

3. Cavity Design and Recent Vertical Tests

a. Difference from Other Designs



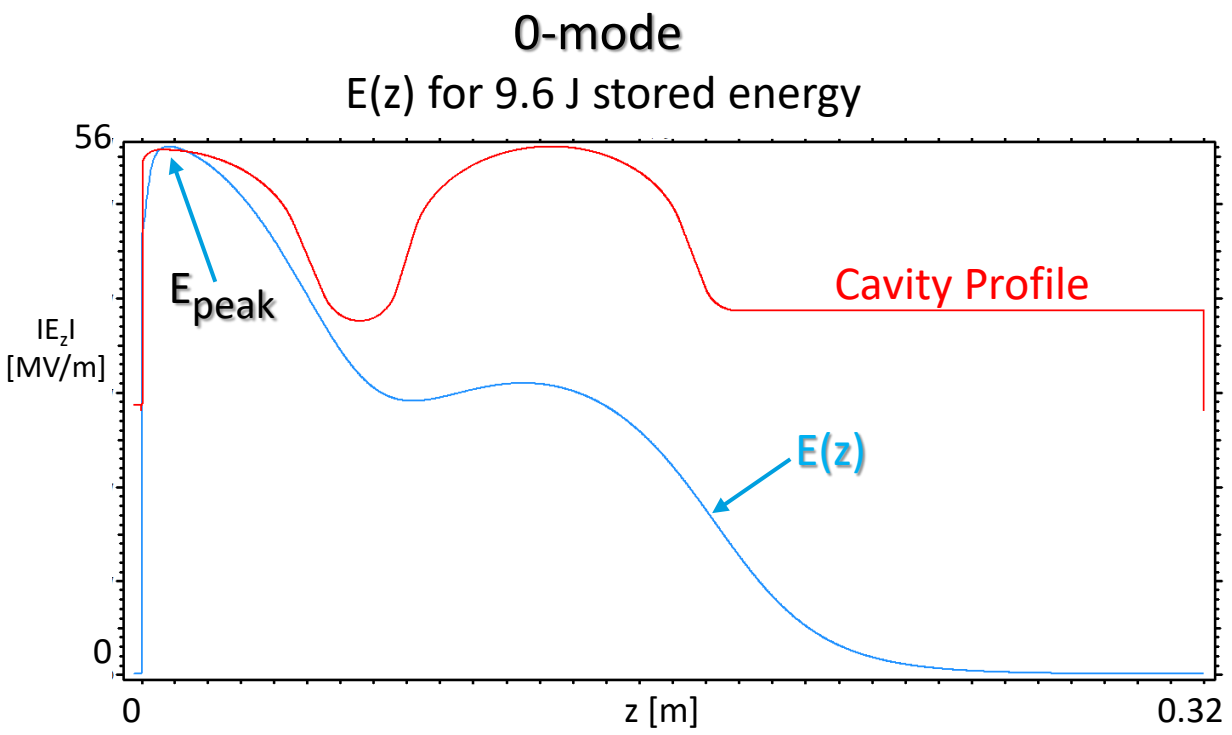
Key Design Features:

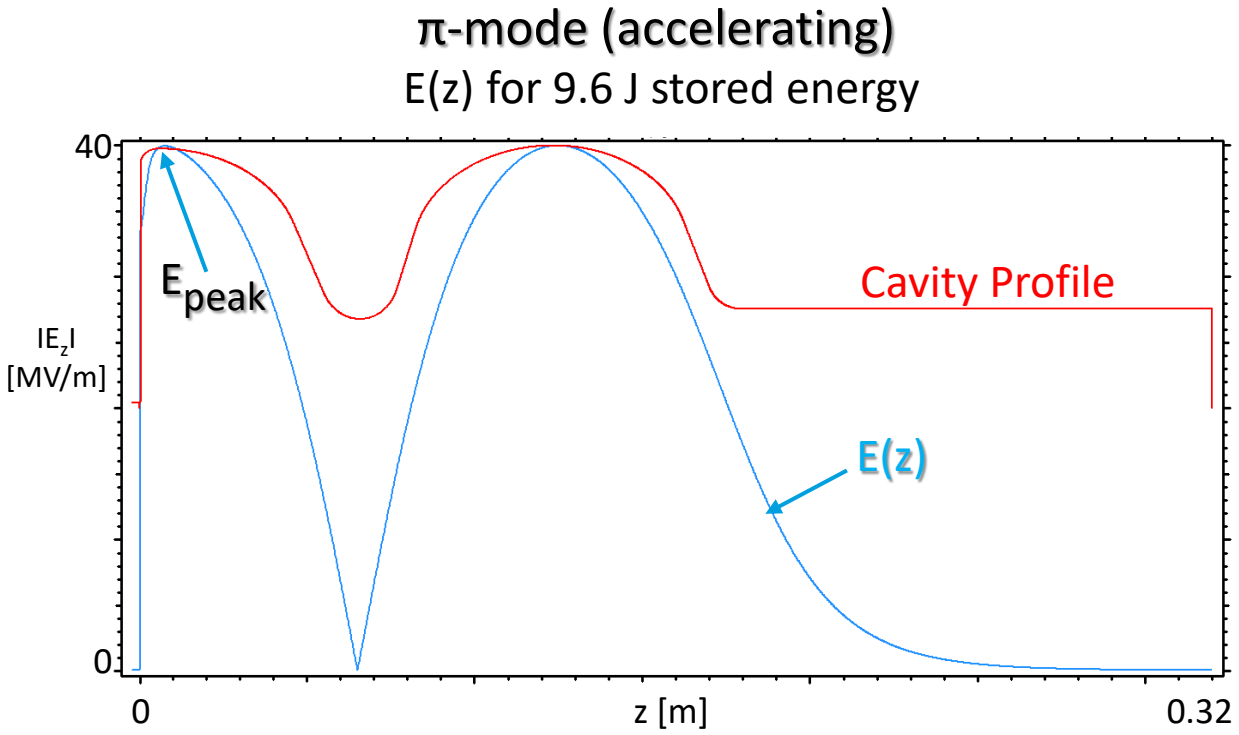
- The cell geometry is based on the TESLA cavity shape, with an operating frequency f_r =1.3 GHz.
- The emitting surface is directly exposed to a high electric field, counteracting space-charge forces.
- The cathode plug is vacuum-sealed to the cavity back wall using an indium gasket, which also prevents RF leakage.
- No RF choke filter or cathode exchange mechanism is required.

3. Cavity Design and Recent Vertical Tests

Vertical Tests:

The cavity is immersed in superfluid He at 2 K, and its intrinsic quality factor (Q_0) and X-rays are measured vs accelerating gradient E_{acc}. For injector cavities data is displayed vs. E_{peak} on axis close to the cathode.

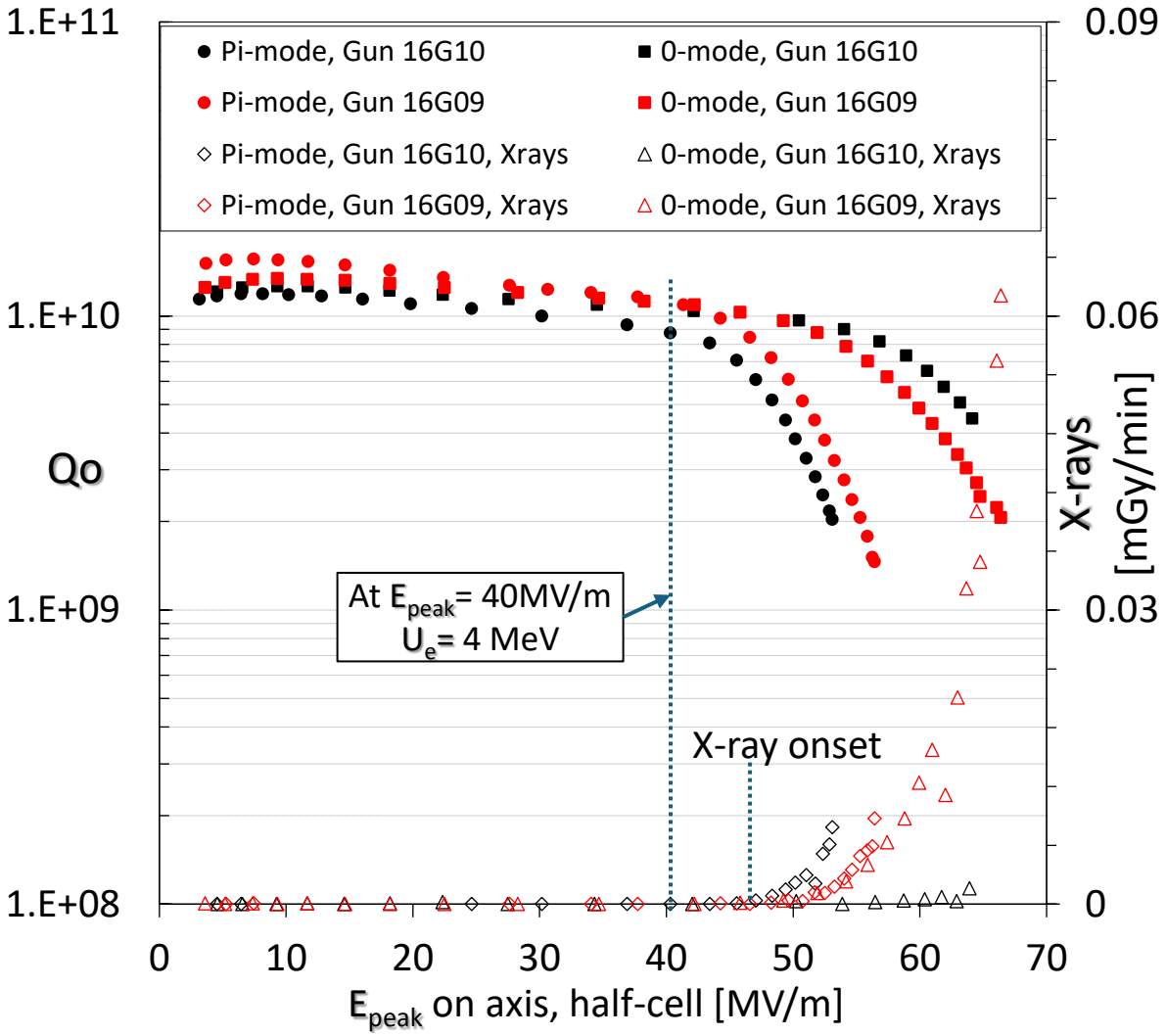




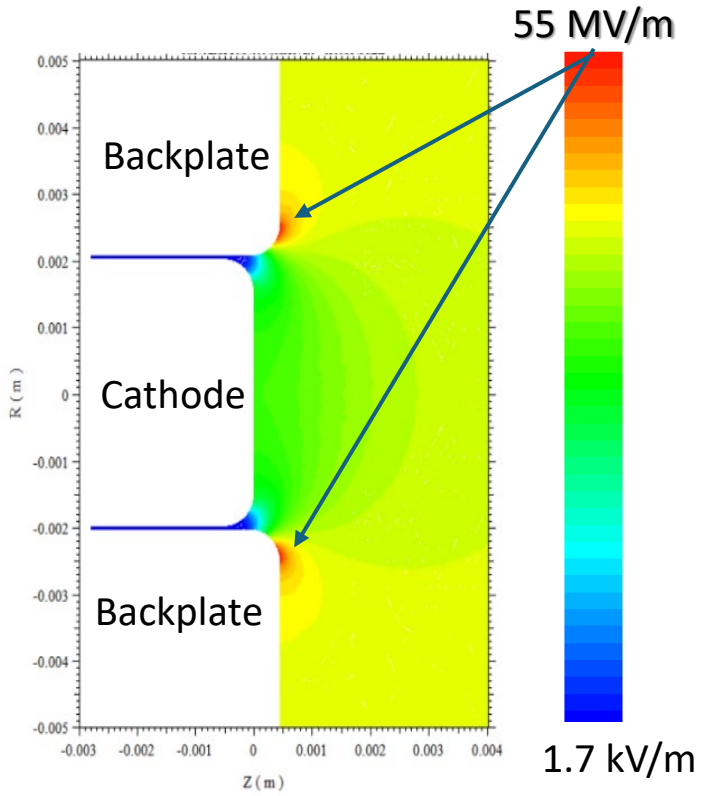
3. Cavity Design and Recent Vertical Tests

a. Recent Tests of DESY Cavities

Vertical test results for DESY gun cavity prototypes, 16G09 and 16G10, with attached polycrystalline copper cathodes



Electric Field Enhancement at the Cavity Wall

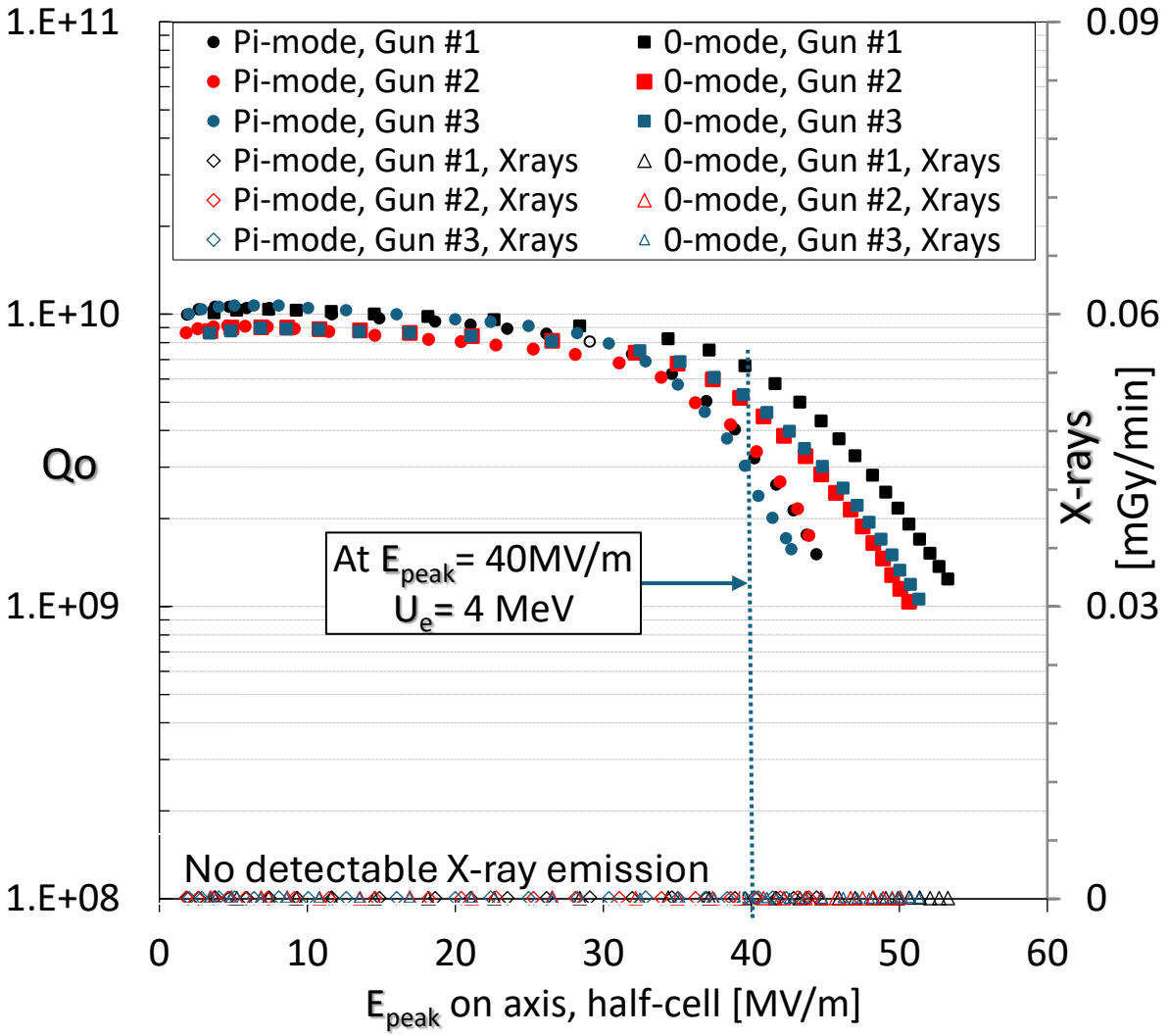


At the circular edge of the DESY cavity backplate, the electric field reaches 55 MV/m when E_{peak}= 40 MV/m. This field enhancement of 38% increases the probability of I_{DC} generation.

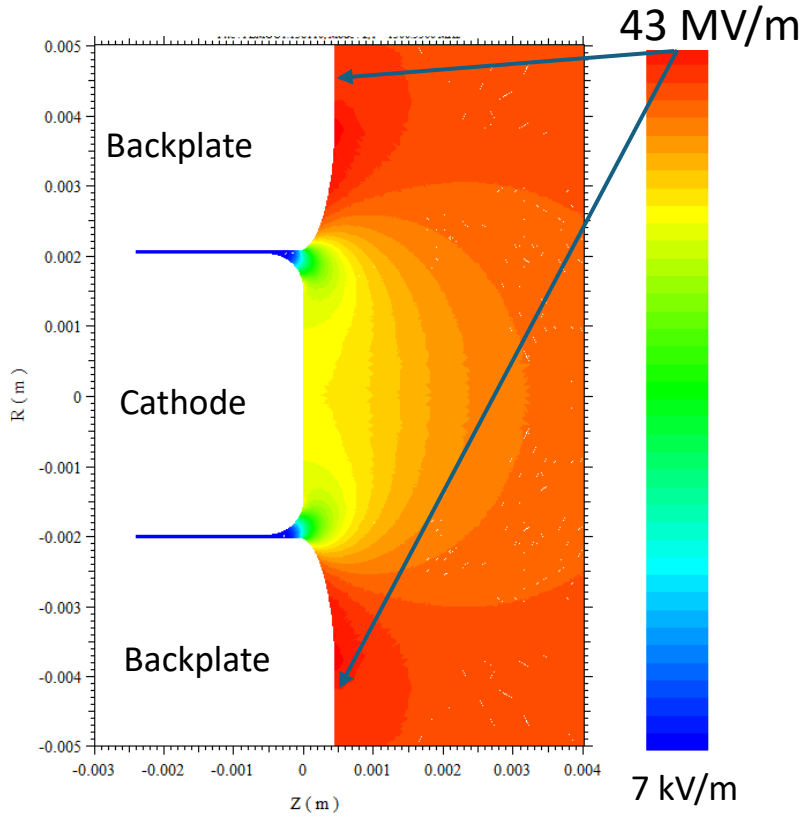
3. Cavity Design and Recent Vertical Tests

b. Tests of PolFEL Cavities

Vertical test results of 3 PolFEL gun cavities with attached **polycrystalline Nb-cathodes**



Electric Field Enhancement at the Cavity Wall

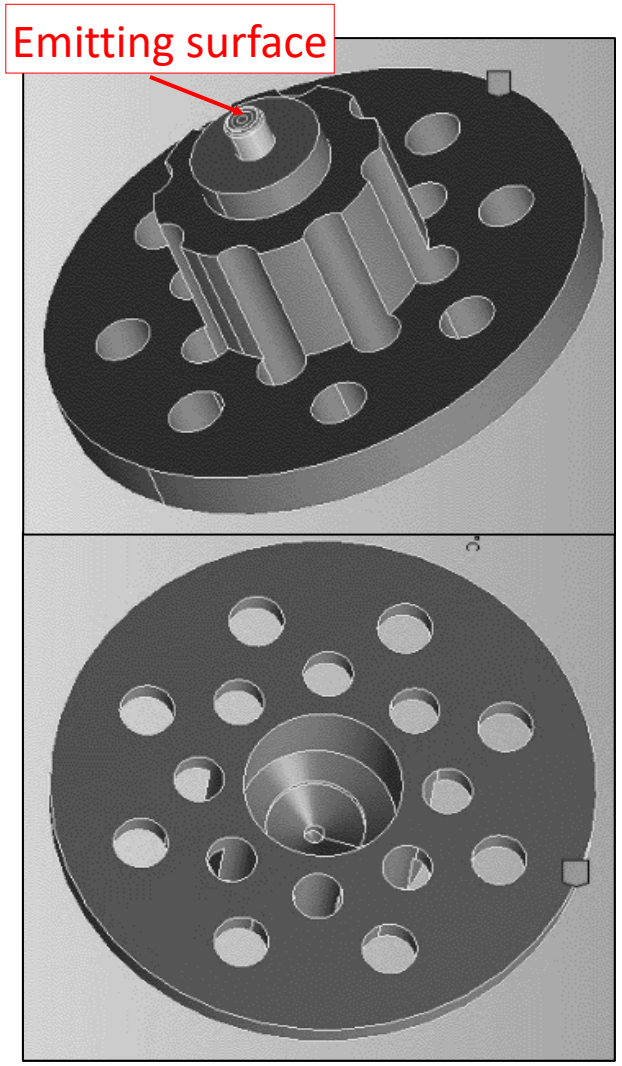


At the elliptical edge of the PolFEL cavity backplate, the electric field reaches 43 MV/m when E_{peak} = 40 MV/m. This modest field enhancement of 7.5% significantly reduces the probability of I_{DC} generation.

- Following the successful and highly encouraging tests at DESY, all 3 evacuated PolFEL gun cavities were stored at the manufacturer's site.
- After several weeks, the vacuum gauges on all 3 cavities indicated a significantly worse vacuum.
- Removal of the cathodes in a cleanroom revealed that all the In-gaskets had turned black and degraded into a brittle material.
- Finally, we were informed by the manufacturer that the cavities had not undergone heat treatment at 95 °C for at least 12 hours. This procedure is always applied to all DESY prototypes, some of which were stored under vacuum for many months without exhibiting any vacuum-related problem.
- The HPR process partially restored the cavity performance. However, chemical removal of a few micrometres from the inner surface appears necessary to fully recover the performance demonstrated in the vertical tests at DESY.

4. Metallic Photocathodes

a. QE and Required Laser Power for Polycrystalline Nb



- The CAD drawing shows a DESY cathode plug.
- The plugs for the PolFEL cavities look similarly and are made of **polycrystalline Nb**.
- The theoretically predicted **QE** for polycrystalline Nb at E_{cath} = 35 MV/m, T=2K and E_{ph}= 4.82 eV (λ=257 nm) is **QE = $6.8 \cdot 10^{-4}$**.

Assumptions for estimating the required laser power:

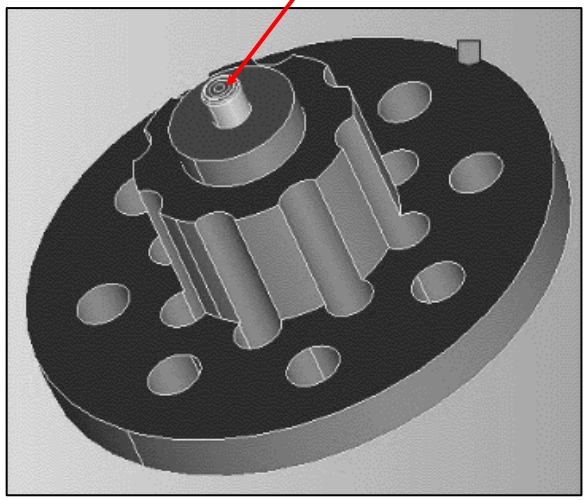
- **QE = $6 \cdot 10^{-5}$** (an order of magnitude below the theoretical value).
- Repetition rate for the **THz beamline = 2 kHz**.
- Repetition rate for the **UED beamline = 50 kHz.**

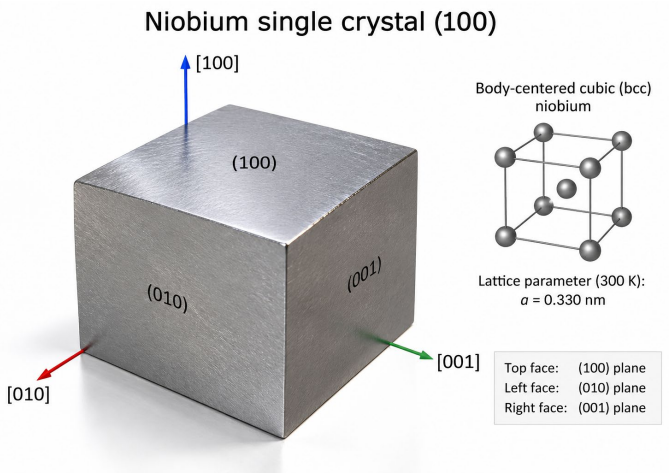
	q_b	Energy/Pulse	Laser Power	I_b
UED	100 fC	8 nJ	0.4 mW	5 nA
THz	250 pC	20 µJ	40 mW	0.5 mA

4. Future R&D on Metallic Photocathodes

b. QE and Required Laser Power for Monocrystalline Nb

Monocrystalline cathode made of (100) Nb Crystal





- The **polycrystalline Nb cathode** will be replaced with a **monocrystalline (100) Nb cathode.**
- The theoretically predicted **QE** for a monocrystalline Nb cathode at E_{cath}=35MV/m, T=2K and photon energy E_{ph}= 4.82 eV (λ=257 nm), **QE = $1.3 \cdot 10^{-3}$**.

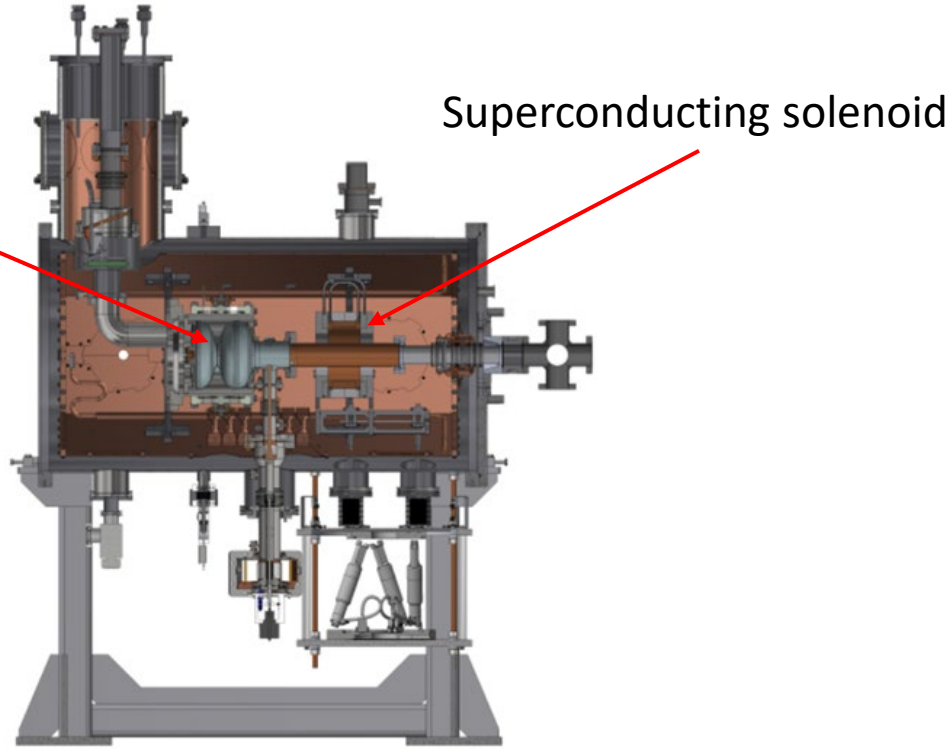
Assumptions for estimating the required laser power :

- **QE = $1.2 \cdot 10^{-4}$** (an one order of magnitude below the theoretical value).
- Repetition rate for the **THz beamline = 2 kHz.**
- Repetition rate for the **UED line = 50 kHz.**

	q_b	Energy/Pulse	Laser Power	I_b
UED	100 fC	4 nJ	0.2 mW	5 nA
THz	250 pC	10 µJ	20 mW	0.5 mA

5. Cryomodule Design

- The injector cryomodule was designed at NCBJ in collaboration with Research Instruments and in consultation with HZB and DESY.
- The cryomodule houses the gun cavity and a superconducting solenoid.
- Its design allows the gun cavity to be removed and reinstalled, for maintenance and/or cathode replacement, without removing the cryomodule from the linac.



6. Final Remarks

The History:

- The R&D programme on this type of superconducting electron gun began in late 2005 as a collaboration between TJNAF, SLAC, BNL, Stony Brook University, NCBJ and DESY.
- For many years, the programme was tolerated rather than actively supported.
- The good performance demonstrated in vertical tests between 2012 and 2023, with both Nb and Cu cathodes, has made this approach the preferred option for the e-injector of the E-XFEL CW upgrade.
  The programme now receives strong support at DESY.

The Present and the Future:

- Two injector cryomodules were delivered to NCBJ in August 2026, with the option of replacing the cavities in the future, depending on progress in surface preparation and cleaning techniques.
- Their installation in the PolFEL beamlines will be carried out in stages. The installation of the THz beamline injector cryomodule is scheduled for spring 2027.
- This will be the first time that an injector of this type has been operated in a facility.
- UED beamline will initially operate with a normal-conducting injector.
- We will continue our efforts to improve the QE of metallic photocathodes.

Thank you for your attention

1) *J. Sekutowicz et al., "Cathodes and shape modification of cavity for DESY superconducting photoinjector", arXiv preprint arXiv:2507.01658*
2) *M. Staszczak et al., "Simulation of electron bunch compression for a megaelectronvolt ultrafast electron diffraction facility at the National Centre for Nuclear Research in Poland", Physical Review Accelerators and Beams 29 (1), 013501*
3) *J. Sekutowicz et al., "Results of R&D Programmes and LP&CW EXFEL Cryomodule Tests in the Period from 2005 to 2023", arXiv preprint arXiv:2606.00723*

Buffered Chemical Polishing (BCP) and EP

For Buffered Chemical Polishing (BCP) of superconducting niobium RF cavities, a mixture of three concentrated acids is commonly used:

Acid	Chemical formula	Typical concentration
Hydrofluoric acid	HF	48–49%
Nitric acid	HNO_3	65–70%
Phosphoric acid	H_3PO_4	85%

The standard mixture is:
HF : HNO_3 : H_3PO_4 = 1 : 1 : 2 by volume

Typical etching conditions
For the 1:1:2 mixture:
- Temperature: approximately 10–15 °C
- Niobium removal rate: approximately 1–3 µm/min, depending on acid concentrations, temperature and flow conditions.

Electropolishing (EP) uses a different mixture: HF and sulphuric acid (H_2SO_4), typically 1:9 by volume

2. Backup Photon absorptivity for Nb

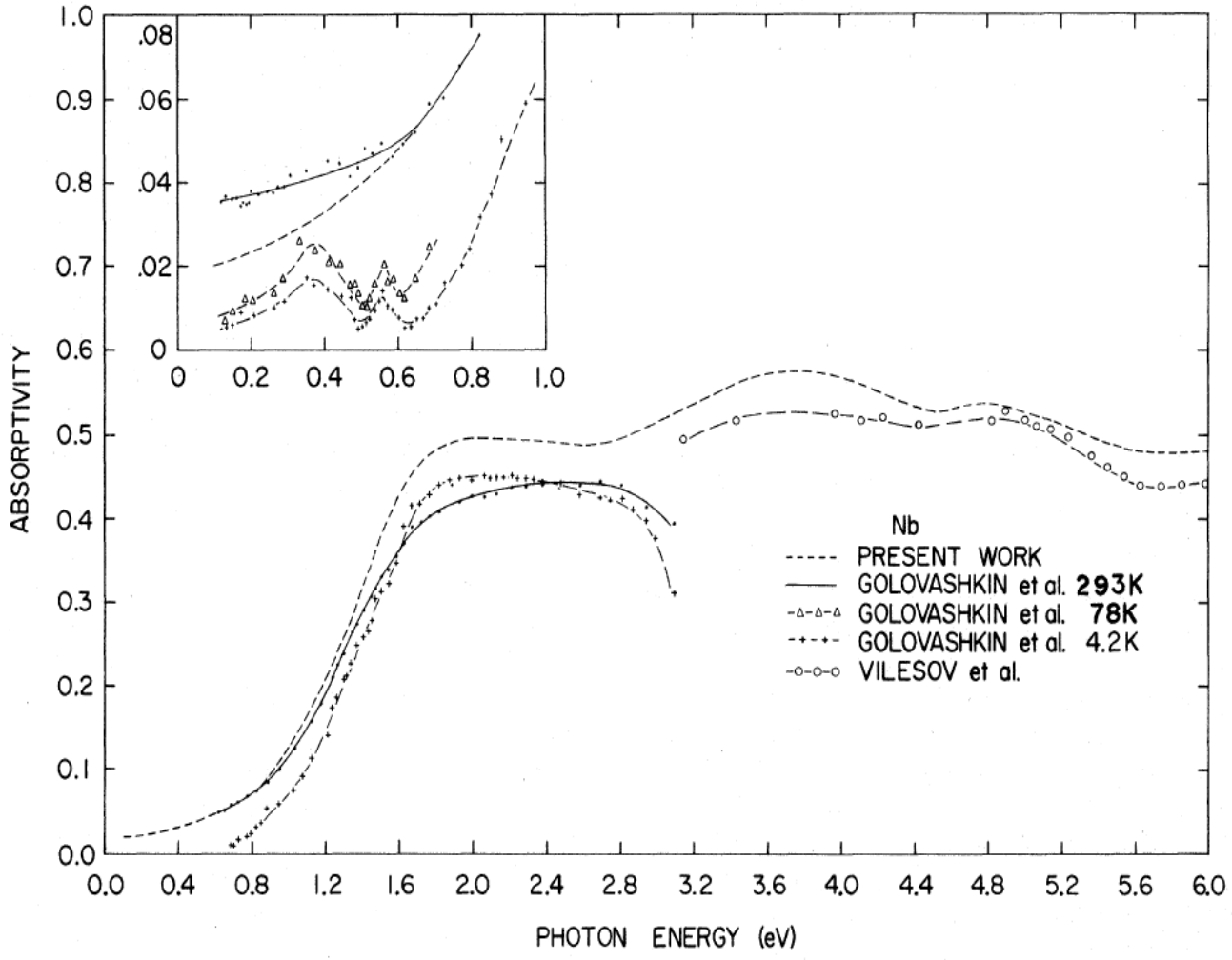
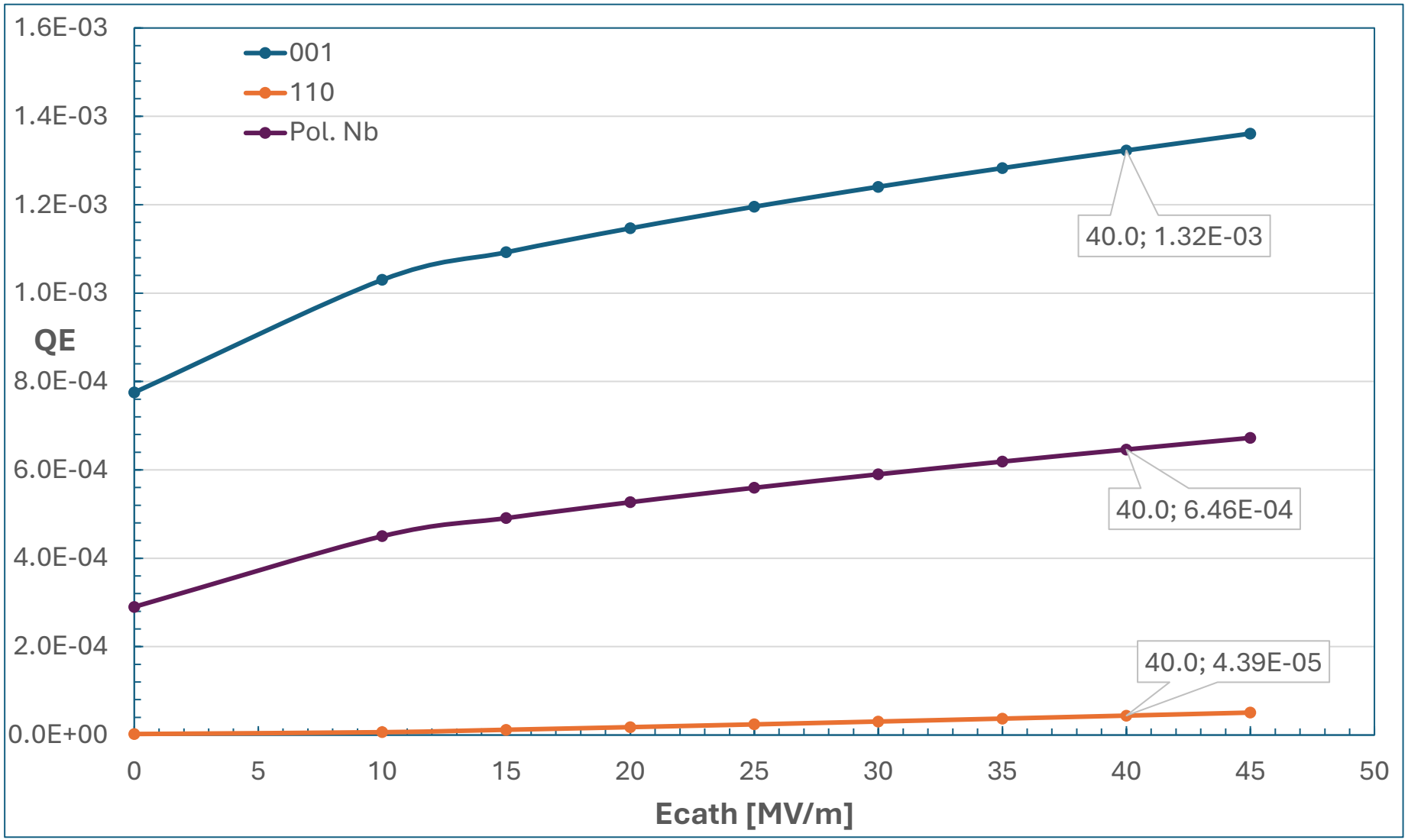


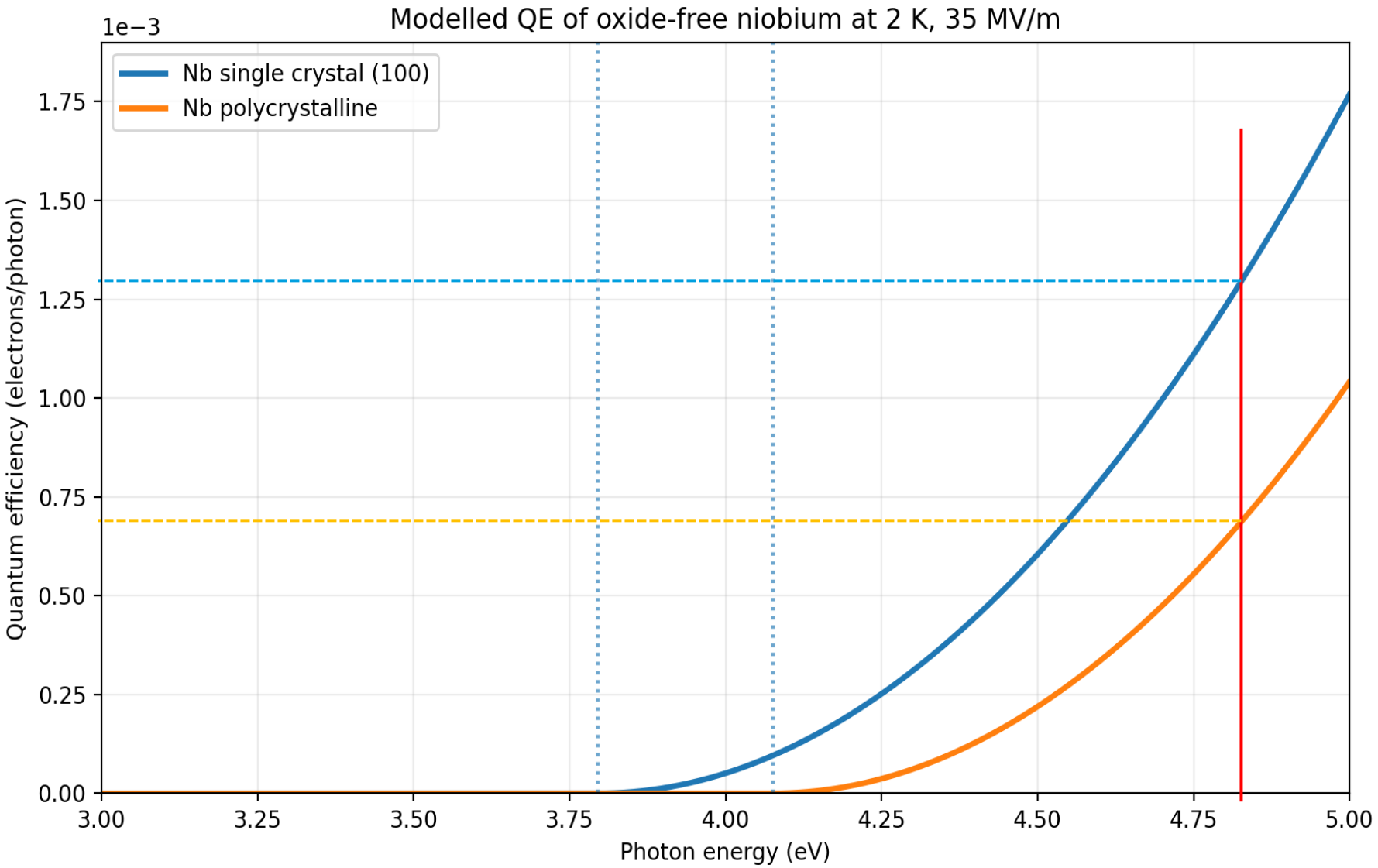
FIG. 1. Absorptivity of niobium at 15° angle of incidence. The data to 4.5 eV were taken at 4.2 °K. The insert shows the low-energy region.

Effect	Expected significance
Temperature dependence of optical absorption	Probably modest
Transition from normal to superconducting Nb	Negligible direct effect at 4.85 eV
Surface oxidation and contamination	Potentially significant
Crystal orientation, e.g. (100) versus (116)	Potentially important for photoemission
Temperature dependence of electron escape and QE	May be important near the photoemission threshold

3. Backup QE vs E_{cath} for single crystal and polycrystalline Nb



4. Backup QE vs E_{cath} for single crystal and polycrystalline Nb



5. Backup Examples of UED Applications

UED uses short electron pulses to observe changes in the atomic structure of materials following excitation by a laser pulse.
The PolFEL UED beamline has the potential to deliver electron bunches with a duration of 10 fs.

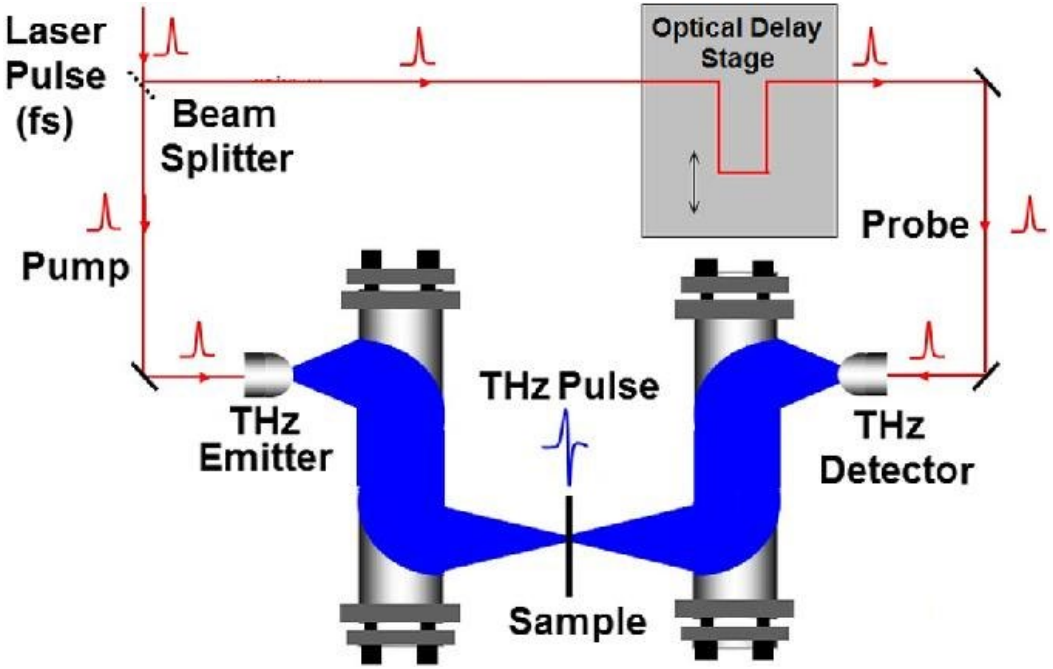
1. Melting of a thin metal film – Observe how the crystalline structure of a metal changes when heated by a short laser pulse.

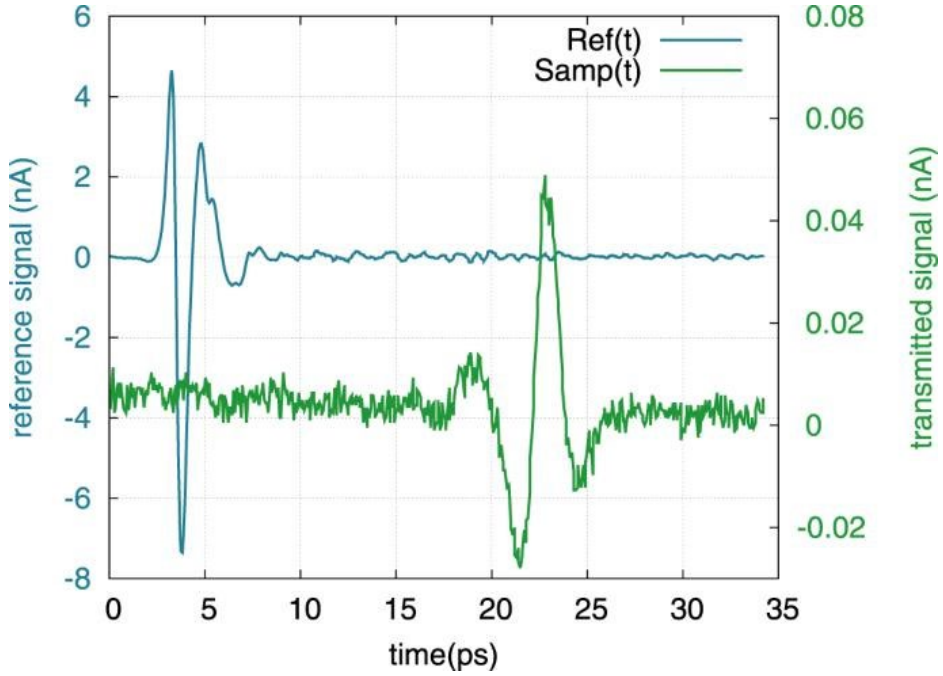
2. Vibrations of atoms in a crystal – Observe how atoms move around their equilibrium positions following laser excitation.

3. Structural changes during a phase transition – Observe how the atomic arrangement changes when a material transforms from one crystalline phase into another.

6. Backup Examples of THz Radiation Applications

1. Material characterisation – Investigating the electrical and optical properties of materials using THz radiation.





2. Non-destructive imaging – Examining the internal structure of materials, such as plastics and composites, without damaging them.

3. Study of molecular vibrations – Investigating low-frequency molecular vibrations and collective motions in solids.