Cryogenic system for Polish Free Electron Laser Facility

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Abstract. Polish Free Electron Laser facility (PolFEL) will be the first free electron laser in Poland. The PolFEL superconducting linear electron accelerator will first consist of an electron gun and four R1-HZDR type cryomodules, each housing two 9-cell superconducting TESLA RF cavities. Such configuration allows the generation of a continuous wave and long pulse beam with 5-50 MeV of energy and a long pulse electron beam with energy up to 187 MeV and photon wavelength ranged from THz region down to 55 nm. In the second stage an extension is planned with two cryomodules, which allows to reach 300 MeV electron beam energy and extreme ultraviolet (EUV) range of electromagnetic radiation. RF cavities will be operated at 2.0 K (optionally 1.8 K). For a four cryomodule linac the static and dynamic loads are estimated to be 61 W and 240 W @ 2 K, respectively. One of the investigated option is that the cooling power will be generated by the TCF50 Linde helium plant. The helium plant has a liquefaction capacity of 6 g/s and 120 W at 4.5K of cooling power. During the beam-on operation mode of the linac, a shortage of cooling power will be compensated by liquid helium supplied from an external dewar, while the warm helium gas stream exceeding the liquefaction capacity will be collected in pressurized storage tanks. During the beam-off mode, the helium gas will be recovered from the storage tanks and re-liquefied to the external dewar. The other option is the installation of a dedicated cryoplant fully corresponding to the linac cryogenic requirements.

1. Introduction to PolFEL project

A FEL is a light source combining the advantages of conventional lasers (high power coherent ultra-short pulses) and synchrotrons (high repetition rate, wide range of wavelengths from THz to X rays). A FEL consists of an electron source, an accelerator providing a high quality e-beam and undulators chain providing an alternating magnetic field which forces the electrons to radiate coherently. The radiated light is directed to the experimental stations while the electron beam can be used to generate neutrons and short x-ray pulses.

FELs have applications in many fields of science and technology. Coherent light of high intensity makes possible diffractive imaging of nanometric scale objects in a single laser shot. Generation of ultra-short laser pulses combined with a high repetition rate gives the possibility of time resolved measurements (making movies) showing the course of physical, chemical and biological processes on the femtosecond scale. Electronic properties of molecules and condensed matter can be studied in pump-probe experiments. High power pulses can create new states of matter like ultra-dense plasma.
Further use of the electron beam creates research opportunities, for instance, in materials physics or nuclear physics.

For the purpose of the PolFEL project the consortium of eight Polish leading scientifically institution has been established. The consortium leader is National Centre for Nuclear Research (NCBJ). Wroclaw University of Science and Technology is responsible for the design, construction and commissioning of PolFEL cryogenic system. The project has been started in 2019 with the aim to complete the construction in 2022 [1, 2]. The device will be located at NCBJ campus at Otwock-Świerk, close to Warsaw.

PolFEL will be designed on the basis of the fundamental assumption that its accelerator will be capable of working in continuous wave mode and thus able to achieve high mean power and flexible time structure of the emitted light beams [1]. Its design will position PolFEL among the most technologically advanced FELs: continuous wave mode operation of an accelerator is currently the subject of intense research at leading FEL laboratories worldwide and many of them are planning to implement it. PolFEL will have the following basic parameters:

- Near-continuous e-beam with energy 130 MeV (in the continuous RF wave mode)
- Minimum photon wavelength (in pulsed mode):
  - fundamental 165 nm
  - third harmonic 65 nm
- Pulse length: < 350 fs
- Max. power of single pulse: 0.2 GW
- Device length: 100 m

The PolFEL accelerator will be constructed using superconducting TESLA (TeV Energy Superconducting Linear Accelerator) technology applied in HZDR type (Helmholtz Zentrum Dresden-Rossendorf) cryomodules [3]. The accelerator will be fed by the RF power generated by a set of solid state microwave amplifiers while an all-superconducting electron gun will allow continuous wave mode operation. The major elements of the accelerator will be four HZDR type superconducting RF cryomodules. Thanks to these, the maximum electron beam energy will reach 130 MeV in the continuous wave mode and 187 MeV in the long pulse mode (with a duty factor of 40%).

An analysis of experimental requirements and the necessity of supplying photon beams of the highest quality to users implies the need to equip the device with two independent undulator lines, one each for its own spectral range (THz/IR and VUV, respectively). Two electron beamlines and two undulators will enable PolFEL to generate experimentally useful radiation with wavelengths in the range from 0.3 mm to 100 nm. Photon beamlines will be equipped with specialized experimental stations for the IR, THz and VUV ranges. The scheme of PolFEL is depicted in figure 1.

2. Requirements of PolFEL cryogenic system

The PolFEL linac will make use of TESLA type SRF cavities cryostated with saturated II He. The cavities will be paired in cryomodules proposed by HZDR.

2.1. Static heat loads at 2 K

Static heat loads at 2 K have been estimated for 61 W and they are comprised of:
- 40 W to HZDR-like cryomodules (conservatively 10 W per cryomodule),
- 11 W to superconducting SRF electron gun (including dynamic losses)
- 10 W to external transfer line (0.2 W/m, 50 m of transfer lines).
Fig. 1: Schematic diagram of the PolFEL design, basic configuration. The main subsystems: SRF electron gun, four HZDR cryomodules housing 2 TESLA superconducting cavities each, bunch compressor, VUV and THZ/IR undulators.

2.2. Dynamic heat loads at 2 K.
Maximal dynamic heat loads to four HZDR-like cryomodules has been estimated for 238 W at CW (continuous wave) operation mode, and for 240 W at LP (long pulses) operation mode (peak value 421 W, filling factor 57%).
Overall heat fluxes are of about 300 W at 2 K. Taking into account the upgrade of the PolFEL to six HZDR type cryomodules, a target cooling power is 450 W.
The recommended cooling rate of PolFEL cold mass is 2-3 K/min. The corresponding liquid helium flow is 8 g/s per cryomodule. The cryomodules would have to be cooled down in a serial way. It may take up to 12 hours for four cryomodules.

3. Layout of PolFEL cryogenic system
One of the investigated option is that the cooling power will be generated by the TCF50 Linde helium plant. The helium plant has a liquefaction capacity of 6 g/s and 120 W at 4.5K of cooling power.
During the beam-on operation mode of the linac, a shortage of cooling power will be compensated by liquid helium supplied from an external dewar, while the warm helium gas stream exceeding the liquefaction capacity will be collected in pressurized storage tanks. During the beam-off mode, the helium gas will be recovered from the storage tanks and re-liquefied to the external dewar.
The layout of the PolFEL cryogenic system is presented in figure 2. The liquid helium leaving the helium plant will be subcooled in valveboxes and throttled to allow IIHe two-phase flow to cryomodules.
The geometry of PolFEL accelerator is shown in figure 3.

The accelerator with the cryogenic distribution system will be located in a dedicated tunnel guaranteeing vibration free construction. The tunnel is being analyzed with respect to ODH and helium evacuation in case of major machine failure followed by helium blow. The estimated helium inventory is of about 800 kg and additionally the PolFEL cryogenic system will comprise LN$_2$ flow from external tank. To guarantee a safe operation of the machine the dedicated precaution measures like ODH monitoring system, proper venting system of the tunnel and personnel training must be applied.
In the work [4] a numerical investigation of cryogenic helium spill in relation to a helium inlet size was performed. It was shown that depending on the helium inlet velocity three distinct forms of spillage were possible. Moreover, it was shown that a stratification in the tunnel was possible if the initial spill had a strong jet momentum. The considered geometry used in the study had similar hydraulic characteristics to the CERN, SLAC and PolFEL accelerator tunnels. Figure 4 shows a quantitatively different helium inflow behavior depending on the area of the hole through which helium vents from the system to the tunnel. Consequently, different pattern of helium propagation could be established in the tunnel. Helium outflows were in each case of the order of 0.5 kg/s.

![Image](image_url)

**Fig. 4.** Different types of helium inflow to the tunnel for various diameters of the helium inlet: from top to the bottom exemplary results for the inlet area 0.01 m$^2$ (a), 0.02 m$^2$ (b), 0.04 m$^2$ (c), [4].

### 4. Conclusions

Polish Free Electron Laser PolFEL will be located at NCBJ campus at Otwock-Świerk. It will be a fully superconducting machine comprising a SC SRF electron gun and four (optionally six) cryomodules with two TESLA-like SFR cavities operated at 2 K. A dedicated cryogenic system is under study. The system will comprise helium plant with the LHe storage possibility, cryogenic distribution system allowing the conversion of LHe to IIHe and auxiliaries. Additionally due to the fact that the HZDR-like cryomodules
require LN\textsubscript{2} for thermal shielding, the cryogenic system will combine both helium and nitrogen flows in the tunnel imposing a dedicated ODH analysis and the design of efficient ventilation system.

5. References

[1] Wrochna G. et.al. “On the PolFEL free electron laser project”, Synchrotron Radiation in Natural Science, Vol. 8, No. 1-2 (2009)

[2] J. Sekutowicz et.al. “Polish Free Electron Laser; short technical description”, Proc. SPIE 11054, Superconductivity and Particle Accelerators 2018, 1105405 (14 May 2019); https://doi.org/10.1117/12.2526756.

[3] M. Pekeler, S. Bauer, P. vom Stein, H. Vogel, Industrialization of TESLA-type technology at ACCEL, Proceedings of LINAC 2006, Knoxville, Tennessee USA.

[4] C. Sinclair and Z. Malecha and A. Jedrusyna, “Numerical investigation of potential stratification caused by a cryogenic helium spill inside a tunnel”, Cryogenics, Vol. 91, pp. 7-20, 2017.

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