ON THE POLFEL FREE ELECTRON LASER PROJECT

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The fabulous properties of the coherent radiation generated with the free electron lasers (FEL) gained broader perspective on the experimental capabilities in physics, chemistry, biology and medicine. They raise from the nanometer-ranged wavelength, femtosecond-ranged pulse duration and brightness in the range of 10^{29} photons/(s·mrad^2·mm^2·0.1% bandwidth) accompanied by up to megahertz repetition frequency. Such a light source extends experimental capabilities in spectroscopy, photon counting, imagining, photo-induced material processing and warm dense plasma creation.

We propose to settle a high average power VUV FEL facility POLFEL at the Andrzej Soltan Institute for Nuclear Studies in Świerk. POLFEL is planned as a node of the EuroFEL network of complementary facilities, recommended by ESFRI. The great weight of the synchrotron radiation studies in modern science and technology makes us recognize the next, fourth generation light source facility as an instrument which will effectively improve the impact of research being run in Poland. Presented concept benefits from the long and wide experience of Polish scientists and engineers involved in the FEL activities world wide.

Here we present an the overview of the general layout of the planned facility, paying a special attention to its novel solutions. The ground breaking feature of POLFEL is a continuous wave (cw) or near-cw operation. It will be achieved with a linear superconducting (sc) accelerator fed with a low emittance sc-electron injector furnished with the thin film sc lead photocathode. There are three outstanding characteristics of the VUV radiation emitted by FEL, which are often named as its fundamental advantages: femtosecond pulse duration, huge peak brilliance and high average intensity. As the first two of them are adequately accounted in the existing facilities or those being in the advanced phase of construction: FLASH, FERMI and LCLS, we turn our efforts towards the last of mentioned parameters – the average power.

The principal goal, which dictates that approach, is to enable experiments requiring maximization of the time integrated number of interacting photons. They are experiments dealing with diluted samples and/or processes occurring with a low probability [1-3]. For those experiments, the significant improvement of experimental capabilities can be achieved when the recent progress in reduction of detectors readout time [4] goes together with the higher repetition rate of the light source.

POLFEL will operate basing on the SASE (Self-Amplified Spontaneous Emission) principle [5] and will generate the light as displayed in Table 1.

Table 1. Parameters of POLFEL light.

wavelength	7.5 – 230 nm
pulse duration	< 100 fs
pulse energy	> 10 μJ
peak power	> 0.1 GW
repetition rate	10^5 Hz
average power	>0.05 W

The experiments, which benefit from high integrated flux are, *e.g.*, spectroscopy of highly charged ions and cold molecular ions, produced with low concentration in the ion traps [1, 2]; spectroscopy of low *Z* elements [3], and studies of low populated mass selected clusters [6].

High integrated photon flux is greatly appreciated by the photon-induced materials processing applications. They are lithography, pulsed laser deposition, micromachining and photochemistry [7, 8]. The significance of that parameter stems from the time and costs reduction achievable when a larger area is irradiated. To achieve a high duty factor, significant technical improvements are required in the accelerator construction. One of the main limitations precluding the emission of a large number of photons per second is the millisecond duration of the radio frequency (rf) pulse [9, 10]. In the existing and up to now proposed facilities, based on the sc linacs, this disadvantage results from the normal conducting electron injectors, which can operate only in the low duty factor pulse mode when they generate low emittance highly populated beams [11]. Some improvement was made when the sc high purity niobium injector cavities furnished with Cs_2Te photocathode was implemented, however their performance is poor due to the technically challenging integration of the non-superconducting cathode into the sc environment. We propose a fully sc injector, based on the lead photocathode located in the 1.6-cell niobium accelerating structure. The lead film, having one micrometer in thickness, has been chosen due to the superconducting Pb properties below its critical temperature of 7.32 K and high, as compared to other superconducting materials (e.g. Nb) quantum efficiency.

The UHV cathodic arc – based technology of the Pb film deposition onto the back wall of cavity has been proposed and is being currently implemented and optimized [14]. A number of TESLA type injectors were furnished with Pb thin film photocathode (Fig. 1). The quantum efficiency and resonant rf performance tests have been performed at TJNAF, their results have been found promising [15]. However, as a price for the longer lasting stable performance, the quantum efficiency of lead is roughly ten times lower than that for Cs_2Te. This can be partially compensated with stronger pulse of the laser irradiating the photocathode.

Adopting the superconducting injector enables rf pulses lasting hundreds of milliseconds and longer up to continuous wave operation. In such a case, the time structure of FEL source is determined by the beat of the triggering laser. That enables the repetition rate up to 100 kHz, which ramps the average power at the fundamental wavelength up to tens of milliwats i.e. few times higher than the designed topical average power of FLASH.

The accelerator capability to operate with a high repetition rate gives an opportunity to freely shape the time structure of the photon beam. In case of slow data acquisition, the possibility of launching next pulse immediately after the readout is completed, without waiting for the next rf period, yields additional enhancement in number of photons being used in an experiment.

Results of the performed preliminary evaluation of the linac (Fig. 2) performance are given in Table 2. It illustrates two adverse approaches to the operation of linear accelerator. The first is oriented towards maximal acceleration gradient, in cost of rf pulse duration, while the other reaches the maximal time integrated electron current through the undulator, in cost of electron energy. For the emitted photons, that alterative corresponds to the choice of a short wavelength or a high flux. Typical, klystron based accelerators operate in one of those two manners. In our implementation both choices will be possible due to inductive output tubes (IOT) used to generate the rf power. Table 2 shows results for the linac consisted of 3, 5 and 7 cryomodules, each containing eight 9-cell TESLA sc structures. The increase of acceleration gradient bears the rise of power dissipation in the cavity wall. As this leads to increase of the cryogenic load it must be compensated with shortening the RF pulse duration, which at the highest energy gain of 225 MeV/cryomodule will be still ~100 ms long, *i.e.*, two orders of magnitude longer than pulse of FLASH and planned for the European XFEL.

Figure 1. Superconducting electron guns. Upper picture shows lead photocathode spots deposited onto back wall of resonant cavities. The lower picture shows 0.5 and 1.6 – cell acceleration structures.

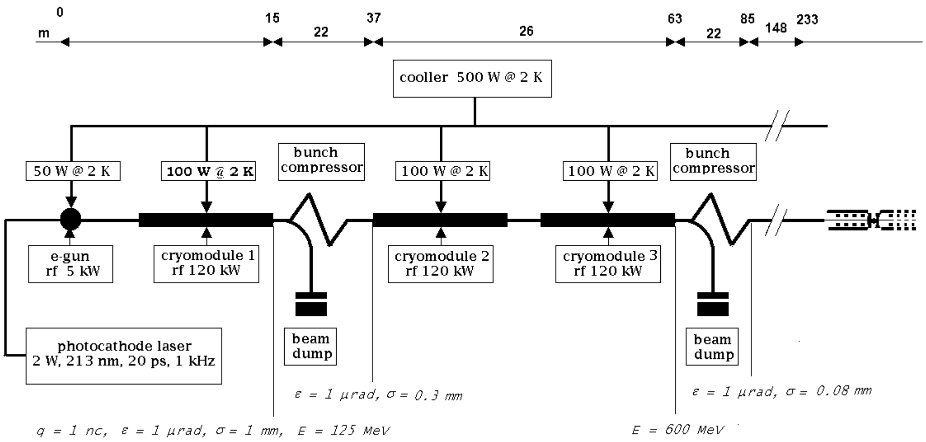

Figure 2. Conceptual drawing of POLFEL linac.

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Table. 2. Polfel characteristics for 3, 5 and 7 cryomodules assuming resonance quality $Q_0=2\cdot10^{10}$, bunch charge 1 nC, max.e. beam current 0.1 mA and undulator period 40 mm. K=0.9.

accelerating gradient [MV/m]		9	12	15	18	21	24	27
electron energy increase per cryomodule [GeV]		0.175	0.100	0.125	0.150	0.175	0.200	0.225
electron energy [GeV]	3 cryomodules”	0.35	0.42	0.50	0.57	0.65	0.72	0.80
	5 cryomodules”	0.50	0.62	0.75	0.87	1.00	1.12	1.25
	7 cryomodules”	0.65	0.82	1.00	1.17	1.35	1.52	1.70
fundamental wavelength	3 cryomodules	79	53	39	30	23	19	15
λ[nm]	5 cryomodules	39	25	17	12	9.6	7.6	6.1
	7 cryomodules	23	14	9.6	7.0	5.3	4.1	3.3
dynamic losses per 9-cell structure at 2K [W]		4.3	7.7	12	17.2	23.5	30.6	38.8
total losses per 9-cell structure at 2K [W]		5.6	8.7	12.7	17.8	23.9	31.0	39.1
duty factor		1.00	0.72	0.49	0.35	0.26	0.19	0.15
repetition rate [MHz]		0.1	0.072	0.049	0.035	0.026	0.019	0.015
max. e-beam peak power [kW]		28	33	38	43	48	53	58
average electron beam power at the dump.[kW]		28	23	18	15	12	11	9

The cryogenic system will enable the accelerator operation in the temperature of 2 K.

In order to achieve the highest available performance of the machine, including long pulses and cw, high repetition rate and high gradients, an effective control system has to be used. To control the field in the cavities, a digital feedback system based on digital signal processing will be used. The analog part of the system must assure low-noise field detection and precise synchronization on the length of hundreds meters. The digital electronics must perform effective real time signal processing based on field programmable gate array (FPGA) devices and digital signal processors (DSP). The whole installation must be integrated with high bandwidth communication infrastructure (like Gigabit Ethernet) to provide on-line real time control and data acquisition. The ability of remote management helps in effective operation and also facilitates the maintenance of the machine. To have a highly automated and distributed installation, made of many small intelligent nodes, the usage of embedded systems will be preferred over the usage of industrial computers, which requires cooling, hard disks, and space in the rack.

As the statistics shows, that many large experimental systems fail due to a failure in power suppliers, an effort is being done in order to provide a robust installation. Particularly ATCA and uTCA standards are considered for electronics panels while the VME is considered as a backup solution.

A 20 m long, single track of APPLE II – type (Advanced, Planar Polarised Light Emitter) [16, 17] permanent magnet undulators will be installed behind the accelerator. It assures the tunability across various orientation of linear and elliptical polarization and wavelength tuning without changing the linac parameters. The whole system will be divided onto 10 sections. Each section will contain about 50 periods of magnetic structure, each period includes four magnets. The system will operate in the K range from 1.0 up to 3.0. Figure 3 and Table 3 show the the peak brightness values in photons/s mrad^2 mm^2 0.1 BW (denoted as p. b. units) and average power achievable for the electron bunch charge 1 nC/bunch, energy 600 MeV and emittance $8\cdot 10^{-10}$ m·rad. Presented data base on the rough assumptions on the injector performance and assume the accelerating modules performance similar to that of FLASH machine. Improved data on POLFEL characteristic will be presented soon after the full start – to end simulation of electron beam propagation.

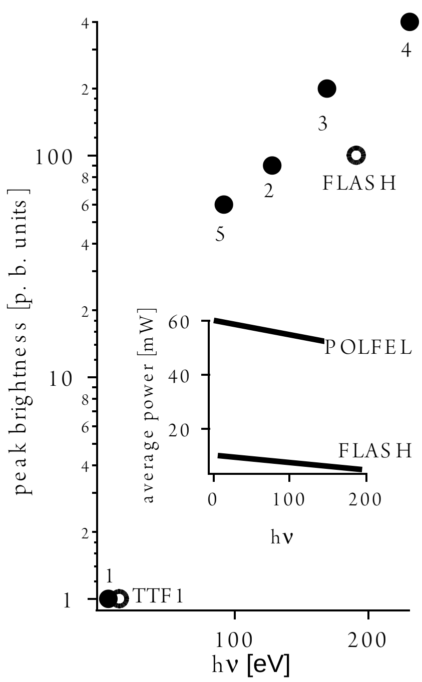

Figure 3 Estimated peak brightness and average

power of POLFEL.

machine parameters				photon energy and wavelength	peak brightness [p. b. units]
1	$q = 10^{-9}$ C ε 1=$\cdot 10^{-9}$ m·rad L=10 × 2 m λ_u=0.04 m	σ=$1\cdot 10^{-4}$ m	E_e=0.35 GeV; K=2.1	5.28 eV, 234 nm	1 10^{28}
2			E_e=1.00 GeV; K=0.9	128 eV, 9.5 nm	$9\cdot 10^{29}$
3		σ=$5\cdot 10^{-5}$m	E_e=1.00 GeV; K=0.9	169 eV, 7.4 nm	$2\cdot 10^{30}$
4			E_e=1.25 GeV; K=0.7	231 eV, 5.36 nm	$4\cdot 10^{30}$
5		σ=$1\cdot 10^{-4}$ m	E_e=0.90 GeV; K=1.1	91.8 eV, 13.5 nm	$6\cdot 10^{29}$
TTF 1	q=2.7 – 3.3$\cdot 10^{-9}$ C $\varepsilon_=$18.8±6.3$\cdot 10^{-9}$ m·rad σ=$4\cdot 10^{-3}$ m L=13.5 m λ_u=0.0273 m		E_e=0.98 GeV; K=1.23	11.8 – 13.5 eV; 105 - 95 nm	10^{28}
FLASH	q=0.5 – 1.0$\cdot 10^{-9}$ C $\varepsilon_=$1.5$\cdot 10^{-9}$ m·rad σ=$8\cdot 10^{-4}$ m L=27.3 m λ_u=0.0273 m		E_e=0.98 GeV; K=1.23	191 eV; 6.5 nm	10^{29} - 10^{30}

Table 3. Estimated POLFEL parameters compared to TTF first lasing and FLASH lasing at 6.5 nm. $K = K_x = K_y$.

Start-to-end simulations will show the electron and photon beams parameters resulting from accelerator, undulators and beamline arrangements. The calculations will start from the photocathode emission and resulted in electron distribution determined from an energy density of UV laser pulse. Next, the electron bunch dynamics calculations will provide in turn: the injector emittance and bunch shapes at consecutive stages of accelerating and compression [18, 19]. The SASE beam parameters will be calculated, based on beams shape at the undulator entrance and its further evolution in the magnetic structure of the undulator [20]. Finally a wave front propagation through the optical path will be simulated and photon beam in the geometric place of experimental station will be revealed. Performed calculations allow the further refinement and optimization of the technical design refinement.

Two optical paths transferring the beam to two experimental end stations will be installed in the first stage of POLFEL operation. They represent the two branches of scientific programme: basic science and technology. The light will be switched between them with the mirror installed behind the common photo diagnostics section. The first branch, will be 25 m long and will be equipped with plane grating monochromator and will provide the micro-focused beam with energy resolution $\Delta E/E$ in the range of 10^{-5}. That branch will be dedicated to the fundamental studies of light interaction with matter. Second beamline will be oriented towards the maximization of photon flux. It is dedicated for materials processing and thus contain extended preparation antechamber. We plan to install eventually 6 beamlines guiding the light to dedicated experimental stations. Auxiliary, plasma sources and synchronized solid state lasers will be installed. They will be hosted in the experimental hall together with appropriate workshop, laboratory and IT infrastructure.

We propose the FEL facility of distinguished average power and thus complementary to existing and planned light sources of this kind. With this project we facilitate new experiments and provide a technological novelty to the FEL physics and technology. The SASE light generation principle has been chosen as already well established approach, which brings us smoothly to the light generation and makes us concentrate on its further development, namely emission by external modulation and terahertz radiation generation.

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