Free Electron Laser in Poland

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The idea of building a new IVth generation of light sources of high luminosity, which use accelerators, arose in the 80ties of XXth century. Now, in a numerable synchrotron and laser laboratories in Europe, there is carried out, since a couple of years, intense applied research on free electron lasers (FEL) [17,18]. Similarly, in this country, free electron laser in Poland – POLFEL [9] is, in a design, a coherent light source of the IVth generation, characterized by very short pulses in the range of 10-100fs, of big power 0,2GW and UV wavelength of 27nm, of average power 1W, with effective high power third harmonic of 9nm. The laser consists of a linear superconducting accelerator 100m in length, undulator and experimental lines. It generates a monochromatic and coherent radiation and can be tuned from THz range via IR, visible to UV, and potentially to X-rays. The linac works in quasi-CW or real-CW mode. It is planned by IPJ [9,10] and XFEL-Poland Consortium [16] as a part of the ESFRI [1] priority EuroFEL infrastructure collaboration network [6], part of the European Research Area - ERA [2]. The paper discusses: FEL background in Poland as a part of EuroFEL infrastructure, FEL parameters and performance, FEL research and technical program and

FEL networking in Europe and worldwide. Emphasis is put on the usage of superconducting RF TESLA technology and ties linking Polfel and the European X-Ray Free Electron Laser. The Polfel team of researchers is now dissipated worldwide among such projects as Flash and E-xfel in Desy, Cebaf in JLab, Alba in Barcelona, Elettra in Trieste, ILC in Fermilb, LCLS in SLAC. Polfel creates an unique, but quite transient, chance to gather, and solidly accumulate for a long time this expertise in this country again.

Keywords: photonics, THz, UV, IR, X-ray, photon beam, electron beam, FEL, free electron laser, XFEL, synchrotron, undulator, RF gun, Nb, high field magnets, superconductivity, accelerator, linac, luminosity, brilliance (brightness), SASE, HGHG, SEED, e-bunch,

1. FEL BACKGROUND IN POLAND AS A PART OF EUROFEL INFRASTRUCTURE

Recent developments of technology enabled a number of new fields of basic and applied research. One can mention such areas like: work on fundamental laws of physics, new materials engineering, more efficient semiconductors, quantum optics and chemistry, structural biology, biomedicine with targeted imaging, photo and radiotherapy, new medicines. Research methods in distant fields have common features. Research needs enormous sets of data and immense processing power for simulations and analysis. The researched objects vary from nano, via pico to femtometers. The objects are cells, molecules, micella, atoms, nuclei, elementary particles. Time spans of concern, for the observed dynamic processes like chemical reactions, are also femto and attoseconds. These advanced research methods require large infrastructures including accelerators of high energy particles, synchrotrons, free electron lasers, as well as, classical ones, but of high power and/or high intensity.

Poland never had and till now has not got even a single of such infrastructures. This is a serious obstacle in carrying out own advanced research in a number of the above mentioned fields. The national budget for research was far to small even to dream of such undertakings.

Now, the chance for this country to build its first big research infrastructures, including a synchrotron and FEL centres, has been recently multiplied. There are relevant funds available for building of the common European Research Area (ERA) basing on strong research infrastructures available equally to all participants. There are in this country appropriate research and technical institutions to undertake the effort to design, build, commission, maintain and exploit these infrastructures. There are ready designs of useful infrastructural projects. There is a considerable public demand for this country to enter into an exclusive club of owners of large research infrastructures, commonly exploited with other European Community countries inside ERA. There is a very positive political atmosphere around such undertakings in Poland and Europe. There is also a very positive obligation in this country to consume effectively the European funds designed just for these purposes of research infrastructures. The obtained European structural funds for 2007-13 include 1.3bln € for research infrastructures. These resources are enough to build a few big experiments in Poland fit to the physical and energy scale dimensions, geographical extent, scientific program, research and technical ambitions the European Research Area scale and expectations.

The Polish research community of photonics, synchrotron radiation, FELs, attosecond and HP-HI lasers, organized in a number of associations like Photonics Society of Poland, Polish Committee of Optoelectronics – Association of Polish Electrical Engineers, Section of Optoelectronics – Polish Academy of Sciences, Polish Association of Synchrotron Radiation; as well as consortia – among them XFEL-Poland, Polish Platform of Nuclear Technologies and Femtophysics, participate actively in many European research networks, collaborations and projects like: ELI, HIPER, LaserLab, TESLA FLASH, ILC, E-XFEL, EuroFEL. Access to the knowledge and experience of the whole European synchrotron and laser communities is available. This is a solid gate and background to building our own complementary laser infrastructures, using the newest, yet checked, technologies and avoiding too expensive, and out of reach, development phase of the project like building prototypes for early system commissioning.

The design documents of POLFEL were prepared in this way as to take advantage of these chances – political, financial, scientific, technical and ambitional – and settle, for the first time in history, a research project of the European size in Poland.

2. FEL COMPONENTS AND TECHNICAL DATA

A free electron laser is different in the principle of work and, thus, construction and exploitation from classical ones. It does not have an optical resonator confined at both sides by spectral mirrors, which provide the feedback and amplification to the generated photon beam. FEL is a laser with a single generation, buildup and passage of the beam along the machine, working without mirrors. It is tunable in a very wide spectrum of EM waves. It generates a photon beam, at such wavelengths, where conventional lasers do not, because of the lack of efficient technical solutions of appropriate mirrors. The basic equation of FEL is the following:

$$\lambda_{ph} = \lambda_u(1+K^2)/2\gamma^2, \qquad (1)$$

where λ_{ph} – wavelength of the first harmonic, spontaneous, on-axis FEL undulator photon emission beam, λ_u – undulator period, K – undulator parameter proportional to the periodic magnetic field, $\gamma=(1-\beta^2)^{-1/2}$ – classical electron relativistic factor. The FEL relation shows explicitly an extreme elasticity of the laser to all methods of tuning against the generated wavelength λ.

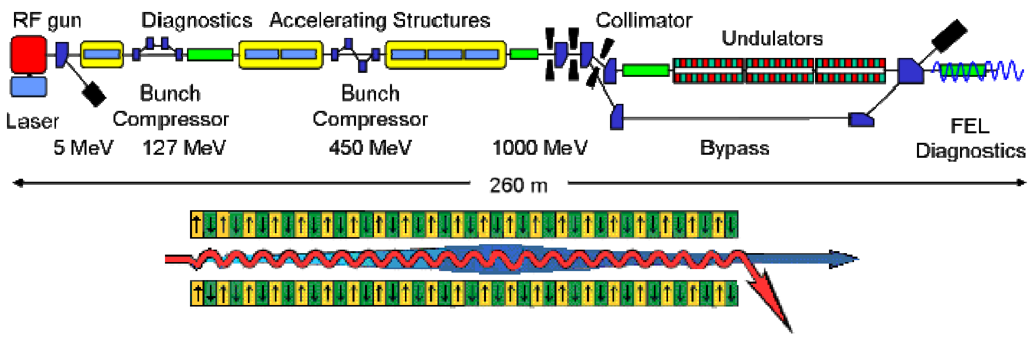

Fig.1. Schematic diagram of FEL on the example of FLASH in DESY [7].

FEL consists of an electron injector, linear accelerator – a linac, undulator, electron beam dump (or energy recovery from the used e^- beam) and photon lines. Future FELs will use superconducting (SC) injectors with Nb cavity. Conventional RF gun consists of a warm Cu cavity with a photocathode of Cs_2Te. The photocathode is excited with a UV pulse of λ=266nm, which is the 4th harmonic from a Nd:YAG laser. A superconducting RF gun has a photocathode covered with Pb, because Pb has lower exit energy for electrons at cryo-temperatures.

A single laser pulse, together with a presence of HV at a cathode, causes emission of an electron cloud of average charge $Q_e \approx 1nC$. The pulse repetition rate is confined to $f_{gun}=1kHz$ by thermal stability of the RF gun, caused by heat release in Cu. The Cu cavity and the following chain of Nb cavities is powered by a HP klystron or a klistrode (inductive output tube - IOT) of $P_{RF}=10MW$. The FEL processes require that the electron bunches have low normalized (transverse) emittance smaller than $\varepsilon_n<2\mu rad$ and the charge in the range $Q_e \approx 0,2 \div 1nC$. These are parameters for the RF electron gun, because the emittance during the acceleration process may only be increased. The predicted RF gun for Polfel would work in CW mode, possess alkali cathode or superconductive and would work in photoemission mode.

The electron cloud from the RF gun has to be magnetically compressed, spatially and energetically, after some pre-acceleration, to a coherent e^- bunch. The injector of e^- energy $E_{ini} \approx 120MeV$, which consists of RF gun and pre-accelerator, gives electron bunches of $L_b \approx 1mm$ in length. The demands for the compact electron bunch of quality stem from the requirements on the resulting photon pulse from the laser, and are as follows: high pulse current $I_e \approx 1 \div 10kA$; average beam current $I_b=1mA$; high beam power $P_b \approx 350kW$; beam power density $dP_b/ds \approx 3,5 \cdot 10^{11} W/cm^2$, bunch separation $t_{sb} \approx 1\mu s$; short spatial, including longitudinal $L_b<100\mu m$ and transverse $D_b=10\mu m$, as well as temporal $T_b<1ps$ dimensions; correlation of position-energy of electrons in the bunch (clear monotonic dispersion character of the bunch). The compressor of the beam consists of a magnetic chicane (4 H type dipole electromagnets of strong $B_H \approx 0,5T$ and homogeneous $s_H=300mm$ field causing U bend of the e^- path), correction coils for each magnet, and three beam refocusing quadrupoles. The resulting e^- bunches from the first compressor, positioned after the injector, are very dense, short, coherent energetically $\Delta E<E_{coh}$, and of small transverse emittance $\varepsilon<1\mu rad$. The second compressor (and beam corrector) is placed just before the undulator and the H field parameters of chicane dipoles are optimized for the incoming bunch energy $E_b \approx 0,5 \div 1GeV$. The input energy of the undulator depends on the active length of the linac, i.e. the number of cryo-modules.

The linac uses a well established, and used widely around the globe, superconducting niobium TESLA cavities, organized in 9 cell structures (resonators) of L_c≈1m (active length) and L_{cc}≈1,2m (total length with collars and flanges for couplers, HOM suppressors and field probes), with 8 ones in a single cryo-module (cold mass). The purity of Nb is RRR>300. Resonant frequency of the cavity is f_c≈1,3GHz (L-band). Each of 9 cell resonators is supplied by RF power P_{RF}≈100÷300kW via rectangular waveguides filled with SF_6. Field intensity in the cell is E_{RF}≈20÷35MV/m. The fundamental mode is TM010. The unloaded/loaded Q of the structure is respectively $Q_{ul}=10^{10}$, $Q_{ld}>10^7$. The work temperature of the structure is T_c=1,8K obtained in three levels, via 40÷80K, and 5÷8K shields to the state of super-fluid helium. The radiative shield is at 4,5K. The cryogenic load of the structure is P_{crl}≈3W.

Each cryo-module contains: 8 TESLA structures; 8 HP RF waveguide/coaxial line cryogenic fundamental mode couplers –FMC; 8 two-function, slow-fast, mechanical tuners of the cavity; 16 high order mode couplers –HOMC; HOM absorber; ion vacuum pump; correcting magnet and quadrupole lens; beam position monitor –BPM; helium vessel; cold mass package for reference positioning of components and thermal insulation; cryogenic cabling for measurements, diagnostics and control.

A natural resonant frequency of the i-th resonator is f_{ci}≈1,3GHz and is statistically distributed around the average cavity frequency f_{ca} by a few hundred kHz. The average f_{ca} frequency should be as close to the required accelerating frequency f_{acc} as possible. Precise tuning of a cavity from the f_{ci} to the f_{acc} value is done by means of a static mechanical method. A set of pulling-squeezing vices is integrated with each structure.

The resonator is subject to Lorentz force detuning (LFD) and microphonics (MP). LFD is a reaction of the Nb SC resonator, of the average wall thickness d_w≈2,5÷3mm, thus, not very stiff, to filling with HP EM RF field. The resonators are stiffened with stiffening rings and collars and sealed titanium chambers for super-fluid He. The LFD, via the change in cavity dimensions L_c and D_c, results in the change in the resonant frequency f_c. Typical value of the frequency dynamic detuning Δf_{LFD} is equal to the cavity 3dB bandwidth Δf_c≈200÷300Hz.

Each resonator is filled with accelerating field, via a power coupler, and then works in a pulse or CW mode. The coupler consists of: waveguide to coax transition; two vacuum – microwave windows, one ambient temperature $T_{w1}=T_a$, the second cold $T_{w2}=70K$; thermal insulation components from T_a to $T_c=1,8K$; Nb coaxial head ended with antenna of controlled coupling to the HP field of the FM in the accelerating structure.

The natural resonance frequency of an i-th cavity is $f_{ci}\approx 1,3GHz$ and is statistically distributed around the average cavity frequency f_{avc} by a few hundred kHz. Precise tuning of the cavity to the work frequency of the accelerator f_a is done on a mechanical way, by means of a squeezing-pulling vice tuner. The tuning is static and off-line.

The resonator is subject to a dynamic, Lorentz force detuning (LFD) and to microphonics. LFD is a reaction of the superconducting Nb resonator to filling with high power, high intensity EM field. The average thickness of cavity wall is $d_w\approx 2,5\div 3mm$, thus, the mechanical structure is not very stiff. The resonators are stiffened by external stiffening rings between cells and collars at the end, as well as by welded titanium chambers for super-fluid He. LFD, by changes in the cavity dimensions L_c and D_c, causes changes in the resonant frequency f_c. A typical dynamic Lorentz force detuning Δf_{LFD} is approximately equal to 3dB bandwidth of the resonator $\Delta f_c\approx 200\div 300Hz$.

Each resonator is filled with the accelerating field via a high power coupler, and then works in a pulse or CW mode. The coupler consists of: waveguide – coaxial transition; two vacuum microwave windows, one warm $T_{w1}=T_a$, and the second cold $T_{w2}=70K$; thermal insulation from T_a to $T_c=1,8K$; coaxial Nb head ended with a coupling antenna to the high intensity field in the accelerating structure.

Beam loading and acceleration at a cost of the accumulated field energy in the structure causes perturbation and excites longitudinal and/or transverse higher order modes (HOM) to propagate. The HOM have higher frequencies than the fundamental mode (FM), thus, can be filtered out by a low pass filter. The HOM distort e^- bunches via a disturbance to the FM field distribution. A HOM filter is an antenna situated on both ends of the structure and strongly coupled to higher frequencies (not coupled to FM).

Each structure is equipped in a two-level, slow and fast, mechanical tuner, with a piezoelectric converter (voltage-shift V-ΔL_c). The resonance f_{ci} of each i-th structure is individually fit to the accelerating frequency f_a by squeezing or stretching the cavity of ΔL_{cs}. Slow tuning, with reaction time t_{st}=1min, for static pre-detuning purpose, is done mechanically in a vice within typical margins $\Delta L_{cs}\approx\pm1$mm for $L_c\approx1$m, what corresponds to $\Delta f_{cs}\approx\pm300$kHz. This value is comparable to the difference $|f_a-f_{ci}|$. Fast tuning, for Lorentz force detuning, and microphonics compensation, as well as dynamic pre-detuning, is done dynamically, during cavity filling, with the reaction time $t_{dLFD}\approx1$ms and frequency tuning range $\Delta f_{cd}\approx\pm0{,}5$kHz. The value of Δf_{cd} is comparable to Δf_c what guarantees a precise tuning tracking of the cavities.

HP RF supply system provides microwave power of $f_{acc}\approx1{,}3$GHz to fill the accelerating cavities with the EM filed and then maintain the field intensity in the range of $E_{acc}\approx25\div35$MV/m. The HP RF system works in a pulse and CW modes and consists of: power amplifiers, modulators, inductive output tubes (IOT), HV HP supply units, control amplifiers, protection and safety circuits, power distribution via transmission waveguides with Y and T couplers, isolators and circulators from IOT to cavities, and auxiliary components.

The accelerator control system (ACS) consists of: low level RF (LLRF), including reference time distribution from the master oscillator, measurement, synchronization and fast control via FF/FB modes; slow control (SCt); e^- beam diagnostics, interlock and experiment diagnostics; and diagnostics of the whole machine and the experiment.

The LLRF system stabilizes the field in accelerating cavities, generates the accelerator clock and synchronizes all equipment with this clock. The SCt controls all FEL infrastructure including: vacuum, cryogenics, gases, HVs, power supplies, ambient parameters. The diagnostics localizes potential causes of system misbehaviour, failures and all unexpected departures from standardized procedures, defined by state machines (SM). Diagnostics has to be nondependent from other systems and highly reliable, similarly to interlocks. The interlock system traces many threshold values in FEL and reacts accordingly when the threshold is crossed, including full stop of the machine when the work parameter values are critical. All these subsystems are managed by SCADA – industrial supervisory control and data acquisition.

The LLRF system of fast control stabilizes the HP RF field using direct, predictive or adaptive feed forward (FF), feedback (FB) or a mixed method FF+FB. The FF compensates deterministic, systematic errors while FB nondeterministic ones (noise). The changes in the accelerating field amplitude and phase, as an error signal, are fed back in the loop to the modulator of the klystron (or IOT) causing relevant changes in the HP generator output. The requirements on the HP RF field stability are: 10^{-4} in amplitude and 10^{-1} in phase in degrees. The RF field in the cavity is probed by an antenna, down-converted from f_{acc} to f_{IF} (intermediate level), sampled by ADC, digitally processed for error, converted to analog in DAC and input to vector modulator, for control of the klystron.

Cryogenics for a single cold mass requires P_{1cold}=50W of cold power at T_c=2K. Accumulated output cold power from the cold plant for injector, six cold masses and helium transport lines in POLFEL is estimated for $P_{cold}\approx$500W. Superfluid helium II is extremely penetrable and has nearly ideal heat conduction. This requires maintaining low pressure in the He installation piping in cryo-modules P_{HeCM}=30mbar. The cold plant produces He in different thermodynamic states and in the following temperatures, required by successive thermal shields in the cold-mass: $T_{1TS}\approx 40\div 80$K, $T_{2TS}\approx 5\div 8$K, T_c=1,9K. The radiation shields work at T_{RS}=4,5K. The cold plant consists of: warm He compressors, heat exchangers, turbine decompressors and Jule-Thomson choking walves. Cold compressors in the He return lines avoid flows of large gas volumes at ambient temperature.

The high quality UHV vacuum line, made of 316LN steel, oil-less, dustless, at $p<10^{-8}$mbar, embraces RF gun, e^- beam path and photon paths. Part of the vacuum lines are cold T_c=2K in the cavities, and part ore warm T_a=20^{o}C in electron optics, undulators and photon diagnostics. The initial out-pumping is done by turbomolecular pumps and then the vacuum is maintained by geter-ion and sorption pumps.

Undulators, which are in series, periodic, linear stack of magnetic dipoles of opposite field direction, are tailored to the e^- energy. There are used in FEL planar hybrid undulator sections with steady NdFeB magnets. The undulator parameters are: slit $s_{und}=5\div 15$mm, period $p_{und}=5\div 30$mm, length $l_{und}=2\div 10$m, magnetic induction B_{und}=0,5T. The e^- beam is monitored and focused inside the undulator, between sections, by quadrupole magnets. The undulator is protected against the stray synchrotron radiation generated inside.

There are two main mechanisms to generate THz-IR-V-UV-X coherent photon beam by the e^- beam in the undulator: SASE – self amplified spontaneous emission or HGHG – high gain harmonic generation and enhanced by SEED – seeding with a laser beam. SASE means that there is a self-modulating interaction between a train of highly relativistic e^- bunches and photons generated by the bunches. The bunches are self-sliced to flat micro-bunches of high density of local charge, and the process is a function of the undulator length. A sliced bunch generates photons coherently and intensely as a point source.

The e^- beam goes to an energy recovery circuit, instead to a dump, in a future FEL.

The distributed diagnostics of the whole length of the e^- beam consists of: toroids, beam position monitor BPM, optical transition radiation OTR, beam lost monitor BLM, beam inhibit system BIS, transversal deflecting structure TDS, laser heater for regeneration of the photocathode, collimators and quadrupoles.

The photon beam diagnostics measures (and reacts with a control feedback): pulse energy; beam intensity; wave spectra; direction, divergence and beam waist, transverse dimensions of photon beam; pulse duration; distribution of the wave front; polarization. Photon beam parameters are essential for the experiments.

The basic parameter to compare different FEL is their brilliance (brightness). For partially coherent light sources (wigglers and undulators) the brilliance BR, expressed in [photons(sec · mrad^2 · mm^2 · 0,1% BW)], may be calculated from the spectral flux SF, expressed in [photons/(sec · 0,1% BW)], divided by the photon rms radius r and divergence d obtained from convolution of the electron beam and photon diffraction parameters:

$$BR=SF/(2\pi rd)^2. \quad (2)$$

In the case of full transverse coherence the following relation is fulfilled $rd=\lambda_{ph}/4\pi$, thus:

$$BR=SF/(\lambda_{ph}/2)^2. \quad (3)$$

The brilliance is a spectral flux divided by the transverse photon phase space. Fig.2.a presents the peak brilliance BR of different FEL families, working now and planned for the nearest decade, as a function of the generated photon energy E_{ph}[eV]. An analogous diagram of average brilliance $BR_{av}(E_{ph})$ for the same laser families has the same shape but the BR level is lower of 6÷8 orders of magnitude, depending on the photon energy, and changes in the range of $BR_{av} \approx 10^{24} \div 10^{27}$. These values BR_{max} and BR_{av} for FEL are higher than for the III[rd] generation synchrotron light sources, respectively of 8÷10 and 4÷5 orders of magnitude. The peak brilliance is scaled to the length of a single pulse, while average brilliance is normalized to seconds at the highest possible repetition rate.

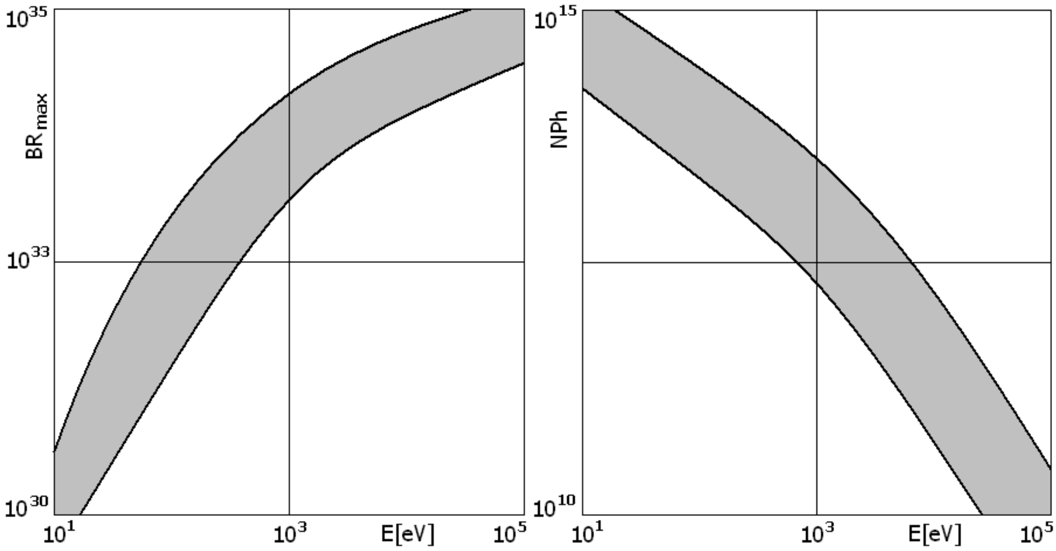

Fig.2. Functions $BR_{max}(E)$, $BR_{av}(E)$, NPh(E) for FEL families. a) A schematic area of peak brilliance (brightness) BR of pulse FEL lasers, working now and planned during the coming decade, including superconductive FEL of TESLA type [5,7,8] and warm ones of LCLS type [12]; function BR_{av} has the same shape but different level; b) Number of photons (per mode) for SASE FEL families. Peak brilliance scaled to a bandwidth $\Delta\lambda/\lambda=1$. Data: BW-bandwidth, NPh-number of photons, BR [$NPh/s \cdot mrad^2 \cdot mm^2 \cdot 0{,}1\%$ BW], E[eV]=E_{ph} -photon energy.

The number of photons generated by FEL per mode can be expressed as:

$$NPh = BR_{max} (\lambda_{ph}^3/4c) \qquad (4)$$

where c-speed of light in vacuum. Fig.2.b presents a function $NPh(E_{ph})$ for the same families of FEL as in fig.2.a.

The FEL is housed in a radiation shielded tunnel with a very stable, one piece floor along the whole length of the electron and photon beams. The quality of the external housing and support for the accelerator and photon lines are interferometer grade. The rest of the housing is technical, for auxiliary equipment, and laboratory for accommodating all experiments. The total power requirements for a FEL of the POLFEL size are $P_{tel} \approx 3MW$. The approximate price range for a machine of POLFEL size is 50÷100M€, depending on the assumed laser parameters and extent of infrastructure.

3. THE SCOPE OF BASIC AND APPLIED RESEARCH PROGRAM FOR FEL

FEL machines have a multiple role. They are strong drivers for technologies for their own development. They require new strong field magnet solutions, new effective undulators for high energy photons, new more compact architectures. On the other hand, a FEL laser enables new research, technologies and applications, among them in the following external -areas:

- research, ultra high field science, attosecond laser science, high energy beam facility, photon physics, two-photon absorption, pump-probe and photo thermal beam deflection PTBD spectroscopy, band edge spectroscopy,
- material processing and engineering, laser ablation and deposition, welding, adiabatic nano-melting, material structure modification, nanostructures formation, new semiconductors and glasses, meta-materials, formation of nano-morphous and nano-amorphous structures in materials, formation of corrosion resistant layers, lithography, organic crystals,
- biomedical and environmental, THz generation for imaging in the range of photon energy 10^{-2}eV, lens-less diffractive imaging, photon bio-probes, molecules imaging and spectroscopy, scalpels, lidars,
- chemical, fs scale time-resolved (TR) observations of chemical reactions, TR spectroscopy and holography, energy levels in strongly charged ions, probing of deep coulomb fields of atom nuclei (10^{9}GV/m), energy probing of molecules.

Together with the increase in available photon energy (now this energy is close to 1keV in FLASH laser, and around 10keV in LCLS laser), FEL turns to a more and more effective tool of experimental research of highly charged ions. The deep level Coulomb field in a strongly charged ion is of the order of 1EV/m. Laboratory observations of deep transitions are performed to verify the quantum electrodynamics theory. Interaction of highly charged ions with strong EM field decides of the state of dense plasma. This phenomena is a subject of investigation in astrophysics (till now indirectly, only by means of telescopes) and thermonuclear fusion (in tokamacs) in order to generate energy. The FLASH research project included investigations of a cloud of trapped Fe^{+23} ions, and absorption spectra of strongly ionized Co [20].

FEL is a tool to investigate material ablation processes in different conditions than those available for classical lasers. These conditions allow to omit partly the nonlinear effects caused by non-equilibrium, abrupt surface phase changes in the material, high temperature and pressure, long wavelength interaction with the material, multiple phonon absorption and absorption on free carriers. The wavelength of FEL, to enable deeper penetration, may be tuned individually to a particular material, in the spectrum between the frequency edge of own plasma resonance and the absorption edge of deep electrons excitation. FLASH laser was used for ablation experiments with Si and GaAs. There were measured penetration depths as function of wavelength and nonlinear effects [20]. The used experimental method was pump-probe with differential time resolved measurement of 100fs resolution. The VUV pump signal was from FEL, while the delayed probe beam was from classical optical lasers, working in IR and visible.

The method of femtosecond spectroscopy with optical pump and probes, from FEL and optical laser, is used for investigations of interactions of optical beam of changing wavelength and high intensity with matter. Photoelectrons excited by a FEL pulse emit or absorb photons of the probing optical laser. The spectrum of photoelectrons consists of two symmetric lines at both sides of the main line. The intensity depends on the time difference between the pump and probe.

Biological macromolecules of noncrystalline structure, like viruses, do not give Bragg diffraction images, while X-rayed. An efficient method of imaging, of an isolated delicate, structurally and mechanically, object, is registration of the distribution of the dissipated light intensity. To register an image, good and useful for object reconstruction, it is necessary to fulfill a number of technical conditions: coherent lighting with a laser beam, the pulse strong enough to give light dissipation of measurable intensity in the full space angle, the pulse short enough not to allow the molecule to denaturize during the interaction and image registration, necessary multiple registrations of the same image in the same conditions and the same object – which is very complex geometrically, to avoid the influence of accidental object orientation on single image and to enable object reconstruction in 3D. The real object image is reconstructed by software basing on the analysis and combination of multiple dissipation and diffraction images. The FLASH laser was successfully used for reconstruction of given nanometer drawings.

The FEL, as a precision tunable IR source, for photon energy range of deV, turns to a research tool of the structure of complex semiconductors. It enables the following measurements of: optical properties, relaxation dynamics, charge carrier dynamics in super-nets, absorption in quantum wells, width of emission lines, dispersion, coherent excitations of resonant effects. These energy levels are characteristic for excitations in such objects and quantum structures as: vibrons, phonons, polarons, polaritons, plasmons, binding energies of dopants, energies of discrete levels in quantum wells, dots and wires.

FEL is an effective, tunable source of THz radiation. The THz spectroscopy, as opposite to optical one, a direct measurement is possible for time dependencies of the field. It means that the amplitude and phase of the field is available for the electrical field E. There is no need to use indirect method with Kramers-Kronig relations as in optics. The THz radiation range is characteristic for vibrations of particles in liquids and many molecules, what is used for identification of chemical compounds. Phototermal spectroscopy PTBD, with usage of a pulsed FEL as a source, allows to selectively excite metal atoms containing compounds created at the surface of minerals. These compounds are characteristic to natural environment pollution, even with very small amounts $10^{-6}\div10^{-8}$ of heavy metals.

FEL radiating in the range of the, so called, water window, i.e. between the K absorption thresholds for C atoms ($\lambda\approx4{,}4$nm; $E\approx284$eV) and O atoms ($\lambda\approx2{,}3$nm; $E\approx543$eV), enables building systems of imaging of biological objects in water with exceptionally good contrast. C atoms absorb, in this energy range, much stronger than O atoms.

4. EuroFEL NETWORK AND OTHER RELATIONS OF POLFEL

A coordinated development of free electron lasers in Europe was defined in the ESFRI – European Strategy Forum on Research Infrastructures document – on 11th June 2004. FELs were defined there as ’technology drivers’.

EuroFEL consortium is a network of complementary European FEL infrastructures. It is a part of ERA, accepted by ESFRI. The members of the EuroFEL, apart from the already mentioned ones E-XFEL and FLASH in DESY and POLFEL (Świerk), are: Fermi at Elettra (Turyn), Bessy FEL (Berlin), SPARX at ENEA/INFN (Milano), 4GLS at Daresbury, Orsay FEL, Grenoble FEL, MAX-IV in MaxLab. A serious hope of the EuroFEL consortium is to build an effective, research and technical, partnership network, in the pan-European scale, according to the assumptions by ERA, in which, after some short time, the laser laboratories will be specializing and slowly transferring to units oriented to the technical and industrial users.

POLFEL is closely related to E-XFEL build in DESY, predicted for commissioning in 2013, and its predecessor FLASH. The essential solutions for these lasers base on superconducting RF TESLA technology. The main European project concerning FEL machine is E-XFEL. It is an international project. The host is DESY Hamburg. The cost of the whole E-XFEL infrastructure is estimated for 2mld €. The demonstrator of TESLA technology, serving the E-XFEL, is under preparation in DESY, since more than a decade. Initially this was TESLA Test Facility – TTF and now it is FLASH laser. The power supply for FLASH and then for E-XFEL is a superconducting electron linac. The pulsed linac in FLASH is 200m long, and generates electrons of E=1GeV energy. The E-XFEL linac will be 2km in length. FLASH generates now EM wave of $\lambda \approx 5$nm. Biomedical and material engineering experiments use, effectively generated, the fifth harmonic of the fundamental wavelength. E-XFEL is expected to generate sub-nanometre wavelengths and of very high intensity, bigger than 10^{35}[Phot/s mrad^2 mm^2 0,1%BW]. Smaller FEL machines are build, tested or designed in Europe, in Italy, France, Sweden, England and Germany.

On the domestic scene, POLFEL is closely related to the Polish Consortium of European X-Ray Free Electron Laser and to the National Center of Synchrotron Radiation, under construction in Kraków.

The biggest FEL now working is FLASH in DESY, generating $\lambda_5 \approx 1{,}5$nm in the fifth harmonic and LCLS commissioned in 2009 working in SLAC. The SLAC-LCLS (Linac Coherent Light Source) laser is a sort of the American counterpart and competitor to E-XFEL. It uses 3km of classical, warm, copper cavity liniac. Out of this length, 1 km is used to inject the e^- beam into the undulator. In April 2009 the laser generated for the first time the wavelength 0,15nm. A further perspective of very high energy FEL development is the ILC experiment in Fermilab with a linac of the accumulated length around 30km. The increase in electron beam energy is now not an obstacle in FEL development, since there are constructed in Europe a few big linacs of relevant energies.

The directions of research work on FEL now are the following, and depend on the working energy range. In the range of big energies of electron beam E_e [multi-GeV], or big photon energy E[MeV], or small sub-angstrom optical wavelengths:

$$\lambda[\text{Å}]=12{,}4/E[\text{keV}], \qquad (5)$$

there are searched new material solutions, new constructions ,designs and methods leading better undulators and higher quality of the beams. In the range of IR and THz waves there are researched compact waveguide FEL machines, especially safe ones, radiating below a so called, neutron threshold (E≈10MeV). Such FEL machines may find very numerable industrial applications.

The European and world research and technical community of FEL i quite big and well organized. It is integrated, among others, by an annual global FEL conference: 2011 open, 2010 Malmo (32 conf. in series), 2009 Liverpool, 2008 Korea, 2007 INFN, etc.

5. CONCLUSIONS AND CLOSING REMARKS

There is a number of important consequences of taking the decision to build a big FEL machine in this country. It is not only a problem of building a single research and industrial infrastructure center. This is rather a problem of general political approach and consequent, long term decisions concerning the development of innovative, high-tech industries in Poland. High-tech industries base, in practice, on a big number of small innovations, which have comparatively easy way from the idea, applied research, through the design and tests to the technical solutions. However, without big technical research centers and big enough technical potential, accumulated in industrial parks around them, it is impossible to overcome a certain critical threshold of really self generated innovativeness. The opposite solution is just to adapt and use the innovativeness of others.

Below there are gathered some relevant remarks concerning the decision of building a FEL in Poland. This decision is combined with building the National Synchrotron Center in Kraków and the National Center of Hadron Therapy, also in Kraków. All these undertakings use similar, accelerator based, technologies.

- Construction of a FEL laser in this country, related on the international level to EuroFEL network, and on the national level with XFEL-Poland and National Center of Synchrotron Radiation is a big chance to create advanced research and technical infrastructure of the European class.
- The conditions favoring the FEL project in this country are: relevant political atmosphere, available funds for building a FEL, there is accessible the required basic infrastructure, there are experts ready to undertake the effort of the project, there are formal institutions taking initiatives in this direction, the project is strongly embedded in international collaboration.
- POLFEL may be realized with a full usage of E-XFEL components, which has several advantages: the most modern, yet checked technology; avoiding of costly and long-lasting research phase of the project; purchase of components in serial production price instead of individual; 'retrieval' of Polish experts working for FEL – mainly in Germany and USE; usage of the know-how of the whole international E-XFEL consortium.
- The conditions which do not favor realization of FEL project in this country: Poland never had a really big research and technical project; there is a big risk of the lack of complementary character of the project and big competition with similar machine infrastructures build in Europe in such countries as: Italy, UK, Germany, France; in this country there is a strong opposition against big investments in science infrastructures.
- Building of a FEL in this country will considerably strengthen high class engineers and physicists, experts in such fields like: cryotechnology; high vacuum technology; superconductivity; high power RF circuits; precise distributed clock networks for time, frequency and phase; distributed measurement systems; advanced electronic and photonic systems; precision mechanics and microsystems, mechatronics, specialized laboratory systems;
- FEL in this country will strengthen national research in material engineering, electronics, chemistry, biology and medicine, environment protection;
- POLFEL seems to be a chance for a large part of the national research, technical and industrial communities. POLFEL may initiate a number of new advanced, hi-tech industries in this country. It is a chance not to be omitted.

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