AREAL – electron accelerator for the precise experimental studies

The opening ceremony of the AREAL (Advanced Research Electron Accelerator Laboratory) laser driven RF gun electron linear accelerator took place in CANDLE Synchrotron Research Institute on the 22nd of July in 2014, permitting to get ultra-short and high precision electron beams for scientific researches in the fields of accelerator technologies, coherent radiation sources and the dynamics of ultra-fast processes. These days these researches are related to the most important directions of leading accelerator centers in the world. The AREAL was constructed during 2011-2013 with the strong support of the State Committee of Science of the Republic of Armenia and in close collaboration with the German accelerator center DESY and the Swiss Paul Scherrer Institute. The review for the new project was provided by the international group of foreign experts, which regularly monitored the design and construction of the new facility in Armenia.

The first beam of the new accelerator was produced on the 20th of December in 2013. The series of precise experimental measurements of the beam parameters were completed in May 2014, and the results were reported on the international accelerator conference in Dresden. The main parameters of the accelerator are: electron energy - 5 MeV, bunch duration - 0.3 picosecond. Several billion of electrons are accelerated in each pulse which enables to reach kilo-ampere pulsed currents with extremely small transverse sizes. The characteristic features of the new accelerator are the precise beam parameters enabling to reach the pick source brightness thousands times exceeding the brightness of electron beams from conventional accelerators.

The impulse for the realization of the AREAL project was the international conference on the advanced accelerator problems held in Yerevan in June 2010. Within this framework an international expert committee was formed to elaborate recommendations for CANDLE synchrotron radiation source promotion in Armenia. After examining the status of the project the commission offered to realize an exit scenario, which had justified itself in many accelerator centers in the world. The essence of the approach assumes the realization of a relatively small project in the first stage, which is not connected with the large accelerator project. At the same time it must correspond to the state-of-the-art developments in accelerating physics and technology, represent a scientific value for the scientific community and give new opportunities for experimental researches. So there came an idea of constructing a precision linear relativistic accelerator AREAL of small energy ultra-short bunches with extremely small transverse dimensions for experimental studies of ultra-fast processes with high space-time resolution, development of new acceleration methods and advanced coherent radiation sources.

As the basic approach for the AREAL project the concept of laser driven RF gun linear accelerator has been taken, which is recently successfully progressing in the leading accelerator centers of the world. The concept is based on electron photoemission from the cathode surface illuminated by the laser beam and the particle acceleration in RF cavity with a high accelerating gradient more than 100 MV/m. To get ultra-short impulses on the stage of electron-generation, a metallic cathode was used in AREAL as a photocathode. Though the metallic cathodes have a very small quantum efficiency and a high-energy threshold for the electron photoemission, the photoelectron excitation time (response time) from the metallic surface is for about 10 femtosecond, which is tens of times less than for the hybrid cathodes with an alkaline spray or semi-conducting photocathodes. In addition to this, the metallic cathodes lifetime is more than a year while the hybrid or semi-conducting cathodes' lifetime is several months or weeks. The vacuum vessel for the metallic cathodes is also lower by tens of times.

The AREAL cooper cathode is illuminated by an ultra-violet laser at a wavelength of 258 nanometer, the pulse duration and the pulse energy are 0.3 picosecond and 200 micro-Joule respectively. At the same time in the RF cavity with a high vacuum, in which the cathode is installed, a standing electromagnetic wave is excited with a 3 GHz frequency and of more than 100 MV per meter peak voltage for the photoelectrons capture into an acceleration regime and bringing of electron energies to relativistic ones. The synchronization of the laser pulse and the high-frequency electromagnetic wave is realized with the help of master-oscillator with a time resolution of about 6 femtosecond. The accelerator is equipped with a state-of-the-art diagnostic and control system and is totally automated based on the feedback system.

In contrast to common accelerators with thermionic cathodes where the parameters of the electron beam are conditioned by the thermal processes and the Coulomb fields, in case of photoelectron emission the parameters of the electron beam (the duration and the transverse dimensions) are set by the parameters of the laser beam, and the Coulomb fields are suppressed by the high-gradient acceleration of particles. The recent years' rapid progress in the field of high energy, focused ultra-short laser impulses gives the opportunity to generate ultra-short (sub-picosecond) focused electron bunches which are in tens of thousands of times brighter than the common accelerators with thermionic cathodes. Taking into consideration the fact that the brightness of the source determines the effectiveness of the beam interaction with the matter in the space-angular and time dimensions, the AREAL accelerator gives new opportunities for the scientific experimental researches with a high-time resolution in some areas, which are inaccessible on conventional accelerators, including large state-of-the-art accelerators. This is an ultra-fast relativistic electron diffraction, an ultra-fast pulse radiolysis and experiments with the sample excitation and its probing by the ultra-short electron bunch (pump-probe experiments). An important direction on the AREAL facility will be the development of new experimental technique enabling the new experimental opportunities for the researchers.

Ultra-fast relativistic electron diffraction

At present, the peculiarities of the atom interaction dynamics are one of the challenging problems in many research fields. Any significant progress in this field will definitely enlarge our knowledge in understanding the dynamical processes in molecular, material and biological systems. Until recently most of the structural changes in the atomic scale were available only indirectly using the spectral analysis technique.

One should use waves of sufficiently small wavelength or particles of sufficiently high energy in order to directly observe the atomic and molecular structures. Only the X-ray radiations or electrons with relatively high energy have the lengths of the atomic dimensions, which can provide sufficient spatial resolution to directly investigate the structural changes.

The time resolution of such investigations can be reached by ultra-short beam generations, which makes the problem of ultra-short pulses generation actual in the sub-picosecond and femtosecond ranges. In present-day linear accelerators with thermionic cathode the durations of bunches are limited to tens of picoseconds because of the Coulomb fields and the thermal spread of particle velocity. In circular high-energy electron accelerators the bunch duration is also limited to tens of picoseconds because of quantum excitation of electrons energy oscillations. In comparison with conventional sources of nonrelativistic electrons, the AREAL beams have tens of thousands of times more intensity, tens of thousands of times shorter pulses and tens of times a greater penetrating ability which is of a fundamental importance while investigating ultra-fast processes.

In this way the AREAL accelerator's precise and ultra-short relativistic electron beams give new opportunities for investigating structural changes with high-time resolution by the help of the ultra-fast relativistic electron diffraction.

The fact is that the efficiency of particle or the photon interaction with the material is determined by the scattering cross section (being defined by the ratio of the scattered particles to the incident ones) and it has a different physical nature for the electrons and photons. At the electron diffraction the scattering cross section is given by the Rutherford scattering, which is hundreds of thousands of times bigger than that for the X-rays given by the Thomson scattering. This means that the diffraction of 10^9 AREAL bunch electrons is equivalent to the diffraction of 10^{14} X-ray photons from state-of-the-art synchrotron radiation sources. The whale of a difference (five orders of magnitude) between two physical processes in the cross section turns the diffraction of electrons into an effective and a competitive instrument of experimental investigations with a high time resolution.

Besides, the 2 MeV energy electrons de Broil wavelength is for about 0,01 Angstroms, which is hundreds of times smaller than the wavelength of a typical X-ray radiation source (1 Angstrom). At the electron diffraction this permits to deeper investigate the structure of matter.

Eventually, the AREAL electron bunch duration is tens of times less than those in the conventional linear or state-of-the-art electron cyclic accelerators, which opens new horizons for investigating the ultra-fast processes of atoms interaction dynamics with the help of relativistic electron diffraction. And this is a deepening of our knowledge in the fields of condensed matter, solid state physics, material science, surface physics, molecular physics, investigation of new materials and so on.

Ultra-fast pulse radiolysis

The success of the development in fundamental investigation of ultra-fast processes in the field of radiation chemistry is connected with the creation of ultra-short pulses of relativistic electrons. The effective instrument of these investigations is the ultra-fast pulse radiolysis, which in its turn is an investigational method of fast chemical reactions and their temporary products when influencing the material by electron bunches of subpicosecond duration. The pulse radiolysis enables the ionization and excitation of the molecule or atom, abortion of any chemical connection and in this way it gets almost any kind of temporal particles and studies the fast reactions.

The AREAL electron beams can be used for the investigation of solvated electrons, free radicals, ion radicals, excited molecules and atoms for the investigation of the rapid reaction kinetics, also for the clarification of radiochemical, radiophysical and radiobiological process mechanisms, for the acquisition of new fundamental knowledge in the sphere of radiation polymerisation, radiation catalysis, radiation corrosion and radio chemical transmutation of materials, elaboration of new nanomaterials and autocatalysts.

The above-mentioned examples already give a clear vision of the ultra-fast experimental investigation highlights on AREAL on the wide spectrum of natural sciences. Last but not least consequence of the new AREAL accelerator is the real perspective of creating AREAL-based radiation sources of the fourth generation in Armenia, since the generation of ultra-short bunches is the key to creating future accelerator technologies and sources of coherent radiation.