AREAL test facility for advanced accelerator and radiation source concepts


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1. Introduction

In the last decades the development of advanced accelerator and radiation source concepts has been on the frontier of accelerator physics researches. The AREAL linear accelerator project is aimed for the generation and acceleration of ultrashort electron pulses with small emittance [1]. After the successful operation of the 5 MeV RF photoinjector [2], the facility energy upgrade to 20–50 MeV to be delivered to ALPHA (Ampliﬁed Light Pulse for High-End Applications) and BETA (Booster for Emerging Technology Accelerators) experimental stations is foreseen. ALPHA station is designated for the creation of a free electron laser (FEL) [3] and BETA station is designated as a test stand for advanced particle acceleration schemes and tailored beam formation for coherent radiation.

In this paper, the AREAL project main design consideration and the anticipated experimental program in the fields of particle radiation and accelerator technology are presented. The design speciﬁcations of the RF photoinjector along with the commissioning results are given. The main outlooks for the self-ampliﬁed spontaneous emission (SASE) FEL beam line based on the planar and helical undulators at the ALPHA station are discussed. The experimental program at BETA station is presented, which implies the study of high frequency accelerating structures, the wakeﬁeld induced beam energy modulation schemes and the high transformer ratio wakeﬁeld accelerator (WFA) concepts.

2. Facility design and performance

The AREAL facility design consists of the laser driven RF gun, two S-band accelerating sections, focusing quadrupoles, horizontal/vertical correctors, diagnostic units and beam delivery system. The schematic layout of the facility with ALPHA and BETA experimental stations is presented in Fig. 1.
The main design parameters of the AREAL project are presented in Table 1.

### 2.1. AREAL design considerations

The design specification of the RF photogun implies the usage of the metallic photocathode and ultrafast UV laser. The choice of a metallic (copper) photocathode is stipulated by a high-damage threshold (100 mJ/cm²), short response time (< 0.02 ps) and a long lifetime (~1 year), which provide the facility reliable operation with sub-picosecond electron pulses at the gun exit.

The AREAL RF gun is driven by the Yb doped high energy UV ultrafast laser system (gain material – Yb:KGW). The laser system is capable to provide UV pulse energy of 250 mJ at 258 nm wavelength and 0.4–9 ps tunable pulse duration (FWHM). The laser beam is TEM₀₀ mode with Gaussian intensity profile and the quality factor of M² ≈ 1. The laser system design implies single and multibunch operation modes. In multibunch operation mode each pulse of the amplifier is converted into a train of 16 sub-pulses (0.4 ps duration, 4 × 10⁻¹² J energy) with a repetition rate of 49.9654 MHz.

The RF gun is an S-band 1.5-cell standing wave cavity designed for REGAE facility at DESY [4] with 2.12 MΩ shunt impedance, unloaded quality factor of ~15,000 and filling time of about 0.7 μs. The electric fields of TM₁₀₀ cavity accelerating mode, computed by CST Microwave Studio [5], is given in Fig. 2. The AREAL linac RF gun operates with 7 MW power klystron (pulse duration ~ 4 μs). To obtain flat-top cavity voltage, the cavity is charged with 7 MW input power in the beginning and then is switched to 6 MW (Fig. 3). Thus, in the cavity, a 6 MW RF power of ~2 μs flat-top duration can be obtained. The maximum cavity voltage is about 5 MV, which corresponds to peak accelerating electric field of 117 MV/m. The maximum of electric field at the photocathode provides an effective capture of the emitted photoelectrons into acceleration regime.

Following the emittance and correlated energy spread simulations at the gun exit (Fig. 4), the nominal operating RF phase is 32° for 1 ps bunch length. Following the gun section two 1.6 m long S-Band traveling wave structures accelerate the beam up to 50 MeV energy with maximum acceleration gradient of 15 MV/m. Fig. 5 presents the ASTRA [6] simulations of the beam emittance and rms transverse size evolution for 25 MeV accelerated beam with bunch charge of 250 pC. A normalized beam emittance of about 0.3 mm-mrad and rms energy spread below 0.15% are designed.

### 2.2. RF photoinjector performance

The first stage of the AREAL facility – a 5 MeV RF photoinjector – is completed [2] along with the diagnostic units for beam energy, energy spread, beam charge and profile measurements. The gun section contains the focusing solenoid, magnetic spectrometer, horizontal/vertical corrector magnet, Faraday Cups (FC) and YAG screens. The charge of individual bunches was measured using two FCs. One of them is located at the end of spectrometer and the second one, an insertable FC, is installed downstream after the
3. ALPHA free electron laser station

The topic of terahertz radiation has become of increasing importance in recent years with a wide range of potential applications in the field of life, materials and environmental sciences [8–10]. The ALPHA station for THz FEL, based on self-amplified spontaneous emission (SASE) principle [11,12], is one of the promising outlooks of the AREAL facility.

The SASE FEL process is based on the electron beam interaction with own radiation field while they propagate through an undulator. The interaction results to the electron beam density modulation on the scale of the resonant radiation wavelength \( \lambda \) stimulating the exponential growth of the coherent radiation until saturation is reached. The successful generation of the SASE FEL implies a small electron beam natural emittance \( \varepsilon \) in order to match with diffraction limited photon beam angular and transverse phase-space characteristics \( \varepsilon \leq \lambda / 4\pi \), the beam rms relative energy spread \( \sigma / \varepsilon \) smaller than the Pierce parameter \( \rho (\sigma / \varepsilon < < \rho) \) to avoid radiation spectrum broadening, and high beam peak current [13]. The design typical Pierce parameter \( \rho \) and natural emittance \( \varepsilon \) for the AREAL electron beam at energies 10–50 MeV are at the level of \( \rho > 0.01 \) and \( \varepsilon \leq 0.02 \) mm mrad enabling the effective THz SASE FEL generation of tens MW power in a several meters long undulator. The AREAL SASE FEL performance for the fixed gap planar and helical undulators has been studied for 35 MeV energy of the electron beam with 0.3 mm-mrad normalized emittance, 0.2% energy spread, 250 pC bunch charge and 2 ps bunch rms length [14]. Numerical simulations have been performed by GENESIS 3D time-dependent simulation code [15]. In these simulations 20 initial seeds for the random number generator used for particle phase fluctuation (shot noise) have been considered.

The planar undulator period is taken 3 cm and the magnetic field \( B = 0.72 \) T (undulator parameter \( K = 2.02 \)). Fig. 8 presents the average radiation power evolution along the undulator at radiation wavelength \( \lambda = 10 \) \( \mu \)m (30 THz). The radiation saturation is reached at about 3.5 m with the average radiation peak power of 27 MW (averaged over 20 seeds). Fig. 9 presents the power distribution along the bunch and the radiation spectrum at the saturation point for one particular seed. The radiation pulse energy is about 60 \( \mu \)J. For the given undulator parameters the radiation wavelength is tunable in the range of 5–120 \( \mu \)m for the beam energy variation within 10–50 MeV.
For the helical undulator the SASE FEL with 24 MW peak radiation power at the wavelength of 16.2 μm is predicted with saturation length of 2.73 m. The tunability is within the range 8–200 μm.

4. BETA test stand

The AREAL BETA station is designated for experimental investigations in the fields of advanced accelerator concepts [16–22] and new radiation sources [23–25]. The experimental program anticipates the study of high frequency accelerating structures, wakefield induced beam energy modulation techniques, high transformer ratio collinear and two-beam wakefield accelerator concepts.

4.1. High frequency accelerating structures

The development of new high frequency slow traveling wave structures is one of the promising directions in accomplishment of charged particles high acceleration gradient. The slow accelerating structures for future THz accelerators [26] are of special interest.
The disc- or dielectric loaded structures are the most known structures having an infinite number of slowly propagating modes. A high-frequency laminated accelerating structure with single slowly propagating fundamental mode has been investigated in [27]. The structure represents an internally coated hollow cylindrical metallic waveguide with high conductivity \( \sigma_2 \) outer layer and low conductivity \( \sigma_1 \) thin inner layer. For the conductivities \( \sigma_1 < \sigma_2 \) and inner layer thickness \( d \) less than the skin depth, the structure longitudinal impedance has a narrow-band resonance at frequency \( \omega_0 = c/(2ad) \) (\( c \)-the velocity of light, \( a \)-the tube aperture). The analysis of the structure dispersion relation shows that the resonance corresponds to the slowly propagating TM01 fundamental mode.

Fig. 10 presents the field matching based exact numerical simulations of longitudinal impedance for copper (Cu, \( \sigma_1 = 5.8 \times 10^{7} \, \Omega^{-1} \cdot m^{-1} \)), low conductivity metal (LCM, \( \sigma_1 = 5 \times 10^{3} \, \Omega^{-1} \cdot m^{-1} \)) tubes and copper tube with internally coated thin LCM layer of \( d=1 \mu m \) and \( d=0.25 \mu m \) thickness. The radius of tube is \( a = 1 \) cm. In limiting cases of a very thin or a thick internal layer, the longitudinal impedance coincides with the corresponding well-known single layer resistive tube impedance [28]. In the transition region, the impedance modified to narrow band resonance at the frequency \( f_0 = \omega_0/2\pi \), corresponding to \( f_0 = 0.675 \, THz \) for \( d = 1 \mu m \) and \( f_0 = 1.35 \, THz \) for \( d = 0.25 \mu m \). The impedance has a different nature for single- and two-layer tubes. It has a broadband maximum for the single-layer tube and narrowband resonance at high frequency \( \omega_0 \) for the two-layer tube. An important feature is that the resonance is observed when the inner layer thickness is less than the layer skin depth at resonant frequency. Thus, the resonance is conditioned by the interference of scattered electromagnetic fields from the inner and outer layers.

The relativistic charge in structure under consideration excites the single mode longitudinal wake potential, which can be detected by examining the radiation pattern at the structure exit [29]. Fig. 11 presents the point charge longitudinal wake potentials for two-layer tube with external perfectly conducting (PC, solid) and copper (dotted) layers with internal LCM coating of \( d = 1 \mu m \) thickness. The dashed line represents the point-charge wake potential for a single-layer LCM tube.

The impedance measurement test stand and AREAL experimental set-up for high frequency new type accelerating structures study is under development. The program includes the study of sophisticated laminated structures like the metallic waveguides with germanium (Ge) or cadmium-sulfide (CdS) thin inner films. Fig. 12 presents the narrow band longitudinal impedance of \( a = 1 \) cm radius copper cylindrical waveguide with internal Ge and CdS thin films with \( d = 0.1 \mu m \) and \( d = 5 \mu m \) thickness, respectively. The Ge conductivity is taken \( \sigma = 2 \, \Omega^{-1} \cdot m^{-1} \) [30] and the CdS conductivity is taken \( \sigma = 600 \, \Omega^{-1} \cdot m^{-1} \) [31].

4.2. Wakefield beam energy modulation

It is well known [32], that the charged particles beam interacting with structure induces a longitudinal wake potential, which causes the beam particles energy shaping. The wake potential depends both on the bunch longitudinal distribution and the structure type (e.g. disc-loaded, dielectric or plasma channels). The wake potential of ultrarelativistic bunch is given by the convolution of the charge longitudinal distribution \( \rho(s) \) and the point-charge wake function \( w(s) \) of the structure, where \( s \) is the distance behind the driving charge. For the resonant structures, the wake function is given as a sum of the excited modes wake functions \( w_m(s) = 2K_n \cos((2\pi s/\lambda_n)) \), where \( K_n \) is the mode loss factor, \( \lambda_n \) is the mode wavelength.

For the beam Gaussian longitudinal distribution, the longitudinal potential is usually retarding for the head particles and accelerating for the tail one. However, for non-Gaussian beam profile the wakefields can induce the energy modulation within the beam. The wakefield induced beam energy shaping can be used for the bunch compression [33] or microbunching [25,34]. Fig. 13(a–c) shows the longitudinal wake potentials of Gaussian, rectangular and the parabolic charge distributions with \( \sigma \) rms length induced by the single excited mode of wavelengths \( \lambda = \sigma/4 \). The energy modulations of rectangular and parabolic bunches are at the excited mode wavelength and can be converted to microbunching using ballistic method for non-relativistic electron beam or magnetic chicane for a relativistic one. The resulting microbunched electron beam can be injected into the “radiator” for
producing coherent radiation at the wavelength scale of $\lambda$. In particular, the relativistic charge in ‘cold’ neutral plasma excites the single wake wave at plasma wavelength $\lambda_{pm}(m) \approx 3.34 \cdot 10^9 n_e^{-1/2}$, where $n_e$ is the plasma electrons density in cm$^{-3}$. For the plasma density $n_e \approx 10^{18}$ cm$^{-3}$, the modulation of the above non-Gaussian beams is then at the scale of $\lambda_{pm} \sim 30 \mu m$.

The experimental program at BETA station anticipates the study of wakefield induced beam energy modulation and micro-bunching concepts for various structures and beam configurations enabling the generation of coherent transition, Cherenkov, undulator or table-top FEL radiations in wide wavelength range.

4.3. High transformer ratio WFA concepts

In WFA concepts a low energy, high intensity driving beam induces the wake fields that accelerate the trailing beam. Usually, the structure constitutes the disk, plasma or dielectric loaded channel. The transformer ratio defines the maximum energy gain of the trailing charge with respect to driving charge energy. In collinear WFA the high transformer ratio can be obtained by using a driving bunch [35] or a bunch train [36] with linearly ramped current. The basic approach to obtain high transformer ratio is to provide the same energy loss for the driving beam particles [35,37]. For the Gaussian bunch train, the maximum transformer ratio is obtained, when the maximum retarding potential is seen by the middle of the bunches and the subsequent bunch charge $Q_n$ scales with the bunch number $n$ as $Q_n \approx Q_1 [k_1 \cdot (n - 1) + 1]$, where $k_1$ is the single bunch transformer ratio. The transformer ratio of $N$ bunches is then $k \approx N k_1$. Fig. 14 shows the wake potential of 5 Gaussian bunches with linearly ramped current profile in S-Band disc-loaded structure that provides $TR = 7.5$ [36]. For the multi-bunch WFA, the usage of the AREAL laser multibunch operation mode (16 bunches) with pulse linear shaping, predicts the possibility of obtaining transformer ratio higher than 20.

5. Summary

The AREAL facility performance and its outlooks as a test facility for advanced accelerator concepts and radiation sources are presented. The preliminary experimental program is discussed, which will be modified following the new developments in the field.

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References
