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SINBAD-ARES - A Photo-Injector for external Injection Experiments in novel Accelerators at DESY

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Abstract. The accelerator R&D facility SINBAD (Short Innovative Bunches and Accelerators at DESY) will drive multiple independent experiments in the fields of production of ultra-short electron bunches and tests of advanced high gradient acceleration concepts.
The SINBAD-ARES (Accelerator Research Experiment at SINBAD) linac has been designed to allow the production of high brightness ultra-short electron bunches with excellent arrival-time stability. The accelerator will be used to study experimentally the optimization of the brightness for fs long electron bunches. Such electron bunches, with tunable characteristics, will be then injected into novel accelerators realized in the context of the ATHENA project, the ACHIP international collaboration and the ARIES program. In this paper we describe the principal characteristics of the linac design, we underline the technical challenges connected to the production and characterization of fs bunches and we report on the status of the installation and commissioning.

1. Introduction

SINBAD will host multiple independent experiments in the fields of production of ultra-short electron bunches and test of advanced high gradient acceleration concepts, mostly laser-driven. It has been already underlined in previous publications that the peculiar layout of the SINBAD facility facilitates experiments combining the use of particle accelerators and high power lasers [1]. The motivation for the construction of the ARES linac at SINBAD lies in the strong connection between the production and control of ultra-short electron bunches and research on novel acceleration techniques.

Presently, conventional S-band RF technology can produce stable and reproducible electron bunches. On the one hand, R&D on producing high brightness electron bunches with a bunch length at the fs/sub-fs level and excellent arrival time stability represents an important research in its own right, since it enables understanding ultimate limitations in photo-injectors. The biggest challenges in this branch of research are represented by the capability of characterizing ultra-short ($\approx$ fs), low charge ($\approx$ pC to sub-pC) bunches as well as controlling their reproducibility via fs-level synchronization. On the other hand, short bunches fit naturally into very compact (novel) accelerators, characterized by their short accelerating field wavelength. They constitute excellent probes to measure the energy gain and the quality of the acceleration.

Hence the idea of building a conventional RF-accelerator in the SINBAD facility has been pursued.

The electron bunch energy of the ARES linac (100-230 MeV) is the outcome of a compromise between the need of damping the space charge effect and velocity dispersion in beam transport and the necessity of building a compact accelerator. The chosen energy will allow reaching 5-dimensional brightness of the order of $10^{16}\,\mathrm{A/m^2}$ and more than 1 kA local peak current [2]. The layout of the linac offers the possibility of running multiple user areas fostering synergy among experiments on laser-driven novel acceleration techniques, such as THz-driven accelerators, laser driven dielectric structures or plasma accelerators [3, 4, 5].

It is noted that the ARES linac is sharing several diagnostics components, the controls architecture and beam physics challenges of ultra-short, high density electron beams with the AXSIS ERC Synergy Grant project [6]. AXSIS construction is nearing completion in a next door space in the same SINBAD facility where ARES is located. Part of the work reported here was therefore used for commissioning and training beam instrumentation and procedures that will also be relied on in the upcoming AXSIS beam commissioning (thus minimizing the required time for AXSIS beam commissioning).

Our paper is organized in the following way. In the next section, we will give an overview of the layout of the SINBAD-ARES linac, focusing on the stages of the installation and planned experiments. We will provide the general accelerator parameters and some examples of working points obtained from numerical simulations, while we will refer to other papers for detailed studies related to the different applications.

In the third section, we will describe the present status of the accelerator, giving a few highlights on the progresses of the installation and first electron beam production.

In the fourth section, we will anticipate the design and goals of one of the main upgrades of the accelerator layout, constituted by the high energy diagnostics line including the novel PolariX TDS (Polarizable X-band Transverse Deflection Structure), which is foreseen to be installed in 2020.

Finally we will summarize our results in the conclusion.

2. Overview of the SINBAD-ARES linac

The conceptual layout of the ARES accelerator is shown in Fig. 1.

The baseline layout, shown on top of Fig. 1, is constituted by an S-band photo-injector composed of an RF-gun and two accelerating structures. A detailed description of the ARES linac can be found in [7]. The electron bunch is produced via photo-emission and then accelerated and compressed simultaneously in a linac surrounded by solenoids using the well-known velocity bunching technique [8]. The first temporary experimental area (EA1) and the diagnostic beamline will be located at the end of the linac.

A substantial upgrade of the accelerator has been foreseen within the ATHENAe Project [9] (see middle and bottom pictures on Fig. 1). The upgrade will allow the installation of a third accelerating cavity for energy upgrade of the linac, a bunch compressor including a collimator between the second and third dipole and a high energy diagnostic beamline including the novel PolariX TDS. Finally, the second experimental area EA2 has been foreseen to host Laser Wake-Fields plasma Acceleration (LWFA) experiments combining the electron bunch from ARES and the high power laser KALDERA [10].

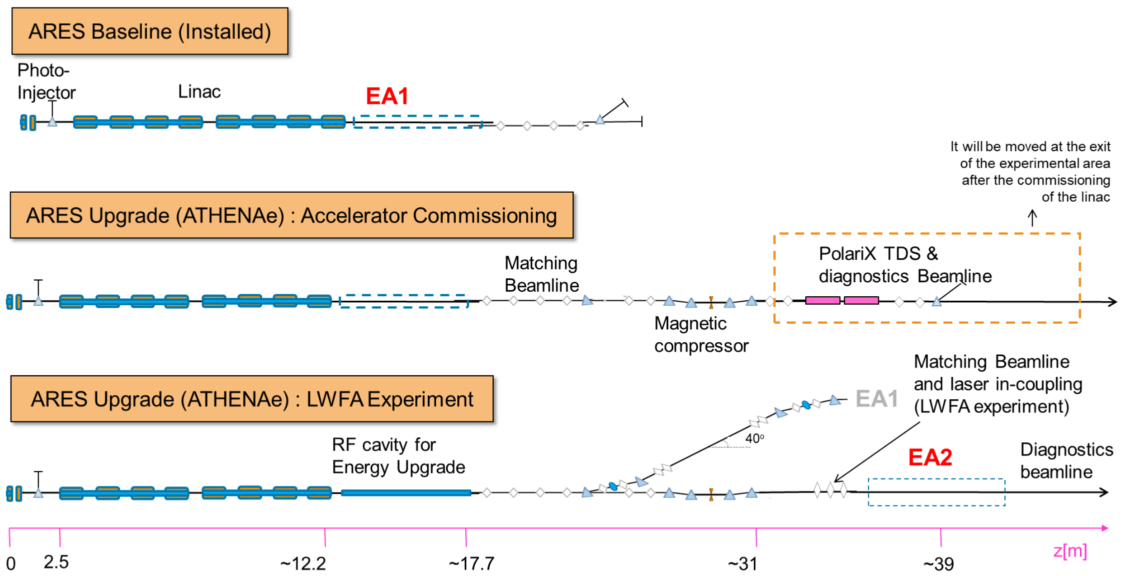

Figure 1. Evolution of the layout of ARES in its different stages. On top is presented the baseline layout, in which the beam will be compressed directly in the linac via velocity bunching. The first experimental area (EA1) is located directly at the linac exit. A temporary diagnostic section will allow to characterize the bunch charge, total transverse emittance and total energy spread. In the middle plot the first linac upgrade is shown. This upgrade will take place in the framework of the ATHENA project. A magnetic chicane will allow performing also magnetic bunch compression; moreover the diagnostics beamline will be upgraded including the novel PolariX TDS. This setup will allow the study of beam dynamics and optimization of the compression of the electron bunch. On the bottom plot the ARES setup for the LWFA experiment foreseen in the ATHENA project is shown. A matching beamline will allow for optimal beam focusing in the second experimental area EA2 and the diagnostics beamline will be shifted downstream of the experiment. The first experimental area EA1 can be potentially shifted at the end of a new dogleg [2].

The beam parameters corresponding to the baseline and upgraded version of ARES are summarized in Table 1. Presently, only the linac and matching section have been installed (top layout in Fig. 1), while the subsequent sections (shown in the middle and bottom pictures) will be installed in the next years.

The first experimental station, EA1, is planned to be installed at the beginning of 2020. This station is located at the exit of the linac, therefore the electron bunch can be compressed via velocity bunching in the RF-cavities and focused down to the experimental area by using the solenoids surrounding the linac. An example of beam parameters achievable with such a setup is presented in Table 2. This experimental area will be open for transnational access through the international ARIES program [11] and will allow testing novel diagnostics devices, dielectrics accelerators or experiments in the field of medical imaging. In particular, we have studied the design of the beam optics and of the experimental station for performing experiments within the ACHIP international collaboration [12]. Detailed descriptions of the focusing optics and technical details about the experimental chamber have been published in [13, 14, 15, 16].

The second experimental area, EA2, is planned to be used for experiments involving external injection into LWFA. The beam accelerated off-crest in the linac will be compressed and scraped in the bunch compressor. The beam will be successively focused to few micro-meter spot-size and

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Table 1. Principal Beam Parameters. The parameters marked with an asterisk (*) are given at the experimental area. The abbreviation RMS stays for Root Mean Square value.

Parameter	ARES Baseline	ATHENA-e Upgrade
RF-Frequency	2.998 GHz	2.998 GHz
Rep. Rate	10-50 Hz	10-50 Hz
Beam Energy*	100 MeV (155 MeV on-crest)	150 MeV (230 MeV on-crest)
Typical bunch charge*	0.5-30 pC	0.5-30 pC
Minimum RMS bunch length*	2 fs	sub-fs
Minimum RMS Arrival Time Jitter*	few tens of fs	10fs

Table 2. Example of working points having fs and sub-fs bunch duration. The numerical simulations have been done using the codes ASTRA [17] and IMPACT-T [18]

Parameter	EA1 (baseline layout)	EA2 (upgraded layout)
Charge	0.5 pC	0.8 pC
tRMS	2 fs	0.3 fs
Beam Energy	91 MeV	200 MeV
Δ E/E RMS	0.06 %	0.16 %
n ϵ_x	0.07 mm mrad	0.11 mm mrad
n ϵ_y	0.07 mm mrad	0.12 mm mrad
xRMS	313 μm	0.97 μm
yRMS	313 μm	1.02 μm
Peak Current	0.06 kA	0.74 kA
5D Brightness	$1.3 \cdot 10^{16} A/m^2$	$5.65 \cdot 10^{16} A/m^2$

injected into a laser driven plasma wake-field acceleration experiment realized in combination with the KALDERA laser. External injection of short electron bunches into LWFA promises excellent beam quality. Moreover, the SINBAD setup would offer unique possibilities for beam manipulation and test of passive synchronization methods [19]. In general external injection experiments with LWFA constitute a stepping stone to a staged multi-GeV high performance plasma accelerator.

An example of working point for a sub-fs long electron bunch is presented in Table 2 and will be refined following the ongoing design of the matching beamline, including the in-coupling optics of the high power laser [20, 21].

3. Status of the installation, conditioning and commissioning

Figure 2 shows the baseline linac installed in the SINBAD tunnel. It corresponds to the layout on top of Fig. 1.

In [22, 23] we have described in detail the design of the photo-injector and we have reported the results of the measurements done for the tuning of the RF-gun cavity. Afterwords, the RF-gun was conditioned and on the 30th of October 2019 first photo-electrons were produced.

Figure 2. Present status of the installation of ARES. The pictures are taken from the middle of the tunnel looking on the left and right side respectively. The layout shown corresponds to the one on top of Fig. 1 but the experimental area EA1 has not been installed yet (a straight vacuum pipe reserves the area).

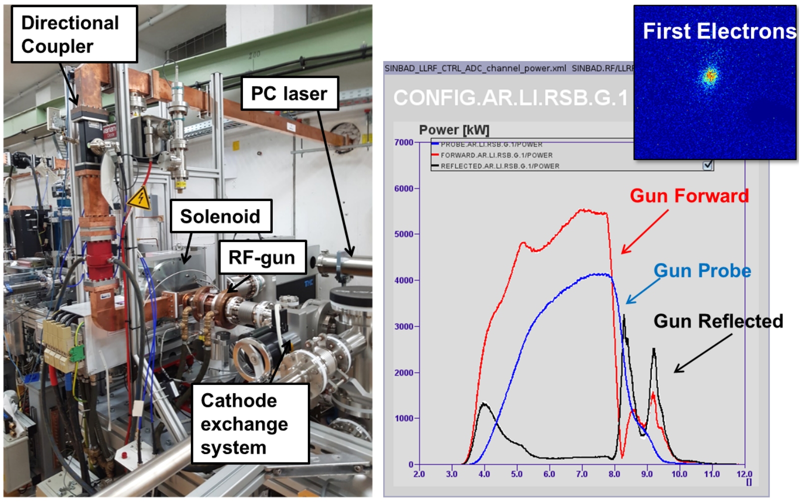

Figure 3. On the left side the RF-gun area is shown in detail. At the position of the RF directional coupler the red and black RF-signals shown on the right side have been picked up. The blue signal is instead picked up directly at the gun cavity. The RF-gun is presently running at its nominal RF-pulse duration and rep. rate at about 4 MW power, which corresponds to a peak gradient of about 95 MV/m. On top of the plot on the right we show the picture of the first electrons visualized on a screen in the RF-gun diagnostics region. Bunches having charge between 100 fC and tens of pC have been produced and their characterization will be reported in future publications.

In Fig. 3 we show the setup of the RF-gun region (left side), typical RF-signals read by the directional coupler located on the RF-network and by the RF-gun-probe (right side) and a snapshot of the photo-electrons captured at the first screen at the gun exit (top picture). The electron beam produced is also being characterized and its characteristics will be presented in future publications. In parallel, the conditioning of the two linac cavities is taking place.

4. High Energy Diagnostics Beamline

One of the key features of the ARES accelerator will be the high energy diagnostics beamline which is depicted in the middle sketch of Fig. 1 and in Fig. 4.

As we have already anticipated in the introduction, one of the biggest challenges in

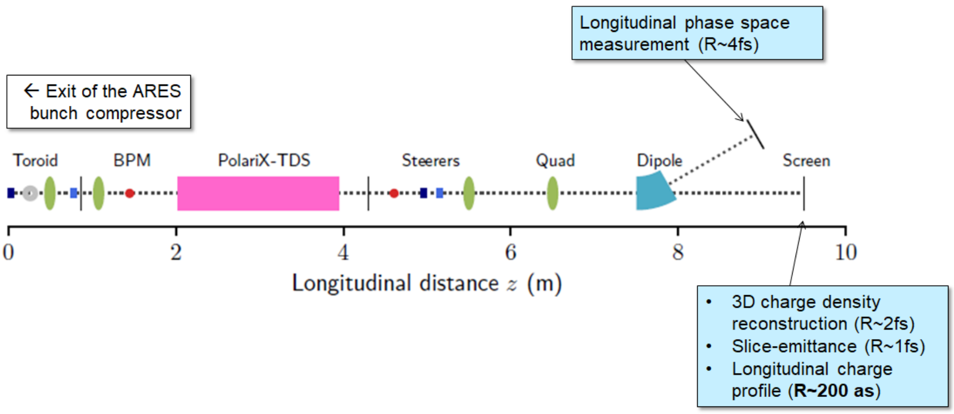

Figure 4. Sketch of the diagnostics beamline including the PolariX TDS. The beamline starts at the exit of the magnetic chicane of the middle sketch in Fig. 1. The quadrupoles before the TDS are used for optimal matching of the beam size in the structure and for quadrupole scan for the slice emittance measurement. The quadrupoles located between the TDS and the measurement screen are used for the optimization of the phase advance, which is crucial for achieving high temporal resolution (R). Beam Position monitors (BPM) allow for monitoring the beam trajectory and a toroid is foreseen for monitoring the bunch charge at the entrance of the beamline.

characterizing fs long electron bunches is the development of ultra-fast, high-resolution diagnostics. This diagnostics must have the capability of resolving the properties of the electron bunch, such as its longitudinal and transverse phase-space, its charge etc.

The key feature of this beamline is the PolariX TDS, which is being developed by a collaboration composed of DESY, CERN and PSI [24, 25, 26].

This TDS will allow sub-fs longitudinal diagnostics at SINBAD-ARES. Moreover, thanks to the additional novel feature of the tunable streaking direction of the field, it will be possible to characterize the projections of the beam distribution on different transverse axes and to reconstruct e.g. the 3D charge density distribution of the electron bunch [27].

The goals of the high energy diagnostics beamline at ARES will be:

- measuring bunch longitudinal charge profile with a resolution of 200 as;
- reconstructing the 3D charge-density of electron bunches with a time resolution of 2 fs;
- measuring the beam slice emittance with about 1 fs resolution;
- characterizing the longitudinal phase space of the bunch with a resolution of about 4 fs. This latter measurement is indeed strongly limited by the energy spread induced in the structure during the bunch transit.

All those measurements have been simulated with numerical codes and recently published in [28, 29]. In parallel, the first prototype of the PolariX TDS has been produced and characterized in the framework of the PolariX collaboration.

5. Conclusion

In this paper we have recalled the goals and plans for the SINBAD-ARES linac, which is currently under commissioning at DESY and we have summarized the status of the experiments.

In October 2019 the first electron beam from ARES was produced and it is currently under characterization. The commissioning of the baseline layout of the linac and the first experiments are planned for 2020.

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