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DESIGN OF AN X-BAND BUNCHING AND ACCELERATING SYSTEM FOR THE AWAKE RUN 2

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Abstract

In Run2 AWAKE aims to demonstrate beam quality and increase the accelerating gradient in the plasma even further and in order to be able to serve high-energy physics experiments. In this framework, a new electron injector, consisting of an S-band RF-gun and a subsequent X-band bunching and accelerating sections, able to produce very short bunches with a small emittance, has been designed. In this paper, two different configurations of the X-band section and their corresponding high power distribution systems are presented. The first one consists of three identical travelling wave cavities to bunch and accelerate the beam while the second one uses a separate short structure for velocity bunching followed by three long pure accelerating structures. A discussion of the strengths and weaknesses of each configuration is carried out; the X-band power distribution systems are described with particular attention to the choice of the high-power klystron, the pulse compression system and the waveguide distribution.

INTRODUCTION

In 2018, RUN 1 of the AWAKE experiment at CERN achieved all its milestones, demonstrating for the first time, the acceleration of electrons to GeV energies using proton-driven plasma wakefields [1]. In 2021 the AWAKE Run 2 started, aiming to demonstrate acceleration of high-quality electron beams appropriate for future high-energy physics experiments. Preservation of beam quality, emittance and low energy spread, is the main goal of the Run 2. Therefore, it is necessary to use two plasma cells, one for seeding the microbunching and one for pure acceleration and a new electron injector to inject high quality electron bunches into the second plasma cell.

The new injector has to produce an energy of about 150 MeV, a small emittance and very short bunches to be able to reach the "blow out regime" during acceleration. The bunch length has to be a fraction of the plasma wavelength to keep the energy spread low. In addition, the injector has to be very compact due to the severe space constraints in the existing tunnel.

In this framework, a novel injection scheme has been proposed, consisting of an S-band Rf-gun followed by X-band structures used for velocity bunching and acceleration to ~200 fs and 150 MeV, respectively.

This paper is focused on the new AWAKE injector's baseline and its RF power distribution system for Run 2c. More details about the experimental program and its phases are described at this conference [2]. The main parameters of the new electron source are listed in table 1. Its installation is scheduled in 2027 in the AWAKE experimental area while a reduced prototype of the injector, called ARTI (AWAKE Run 2 test injector), is being developed in collaboration with CLEAR. In the following sections, the injection baseline is explained in detail, an analysis of the X-Band power compression system is performed and an estimation of the power required for each system is compared.

Table 1: Injector parameters

Parameter	Value
Energy [MeV]	150
Charge [pC]	100
Spread [%]	0.2
Bunch length [fs]	200-300
Nor. Emittance [mm mrad]	2

INJECTOR BASELINE

Initially, two different configurations for the X-band injection system have been considered and are shown in Fig. 1. The first configuration consists of three identical cavities of ~0.9 m; the first one is used for bunching and the other two for pure acceleration. The second configuration includes a small cavity of 30 cm for bunching and three cavities of ~0.9 m for pure acceleration. In both cases, a S-band 1.5 cell photoinjector is used as electron source. To prevent emittance growth, the buncher has been placed in the so-called "Ferrario's working point" and a solenoid is placed right after the GUN and around the first two cavities [3].

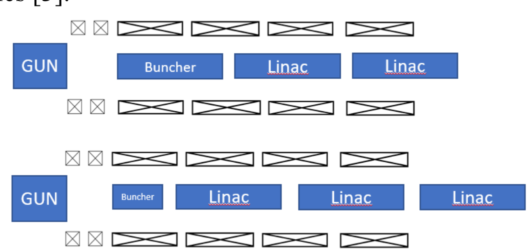

Figure 1: On top the first configuration with 3 identical cavities, on the bottom the second with the small buncher.

When considering the RF power system, which layouts are shown in Fig. 2, each configuration presents strengths and weaknesses. The main advantage of the first layout over the second, is the use of a single klystron. In the second layout an additional "small" klystron is required to feed the buncher. The first choice leads to economic savings and increased simplicity however presents a major disadvantage, i.e., there is a risk of a high breakdown rate due to the energy requirement of 150 MeV which forces the two acceleration cavities to work with a high gradient of 80 MV/m in a magnetic solenoid field. In the second case the gradient of each cavity is only 53 MV/m, significantly reducing the risk of RF breakdowns [4]. For this reason and the lower peak power requirements, the second setup has been

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chosen as a reference system for the new injector since reliability is a major goal of the design.

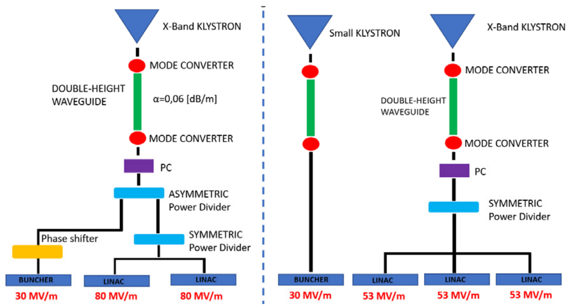

Figure 2: Layout of the first configuration (left), layout of the second configuration (right).

Gun

For the new AWAKE injector an S-band standing wave 1.5 cell RF-gun is foreseen. A prototype has been constructed by INFN-Frascati and is being tested and commissioned at CTF2 (CLIC Test Facility 2). A photo of the device is shown in Fig. 3.

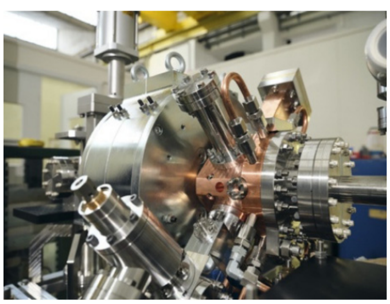

Figure 3: Prototype of the gun.

It is part of a new generation of electron guns fabricated with brazing-free technology [5] and implements a new geometry with 4 pumping ports allowing the cancellation of the dipole and quadrupole components and the increase of vacuum pumping speed. A ~1mm UV laser spot size will be used to produce bunches of ~2ps length with 100 pC charge.

X-Band LINAC

An X-band traveling wave accelerating structure has been selected for the three cavities in our reference system. Its EM design has been performed by INFN-Frascati in the framework of the EUPraxia project, following a procedure described in [6].

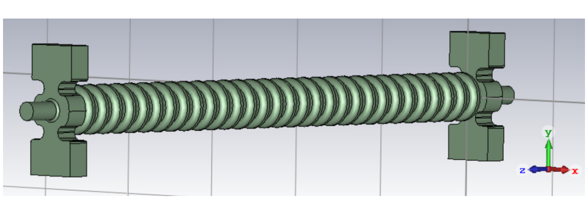

Figure 4: Geometry of the buncher.

It consists of a traveling wave, constant impedance accelerating cavity working on the ⅔ pi mode. An elliptical iris profile has been chosen to minimize the modify poynting vector and a symmetrical feeding for the couplers has been designed to cancel the dipole component. The geometry for the 30 cm buncher cavity is shown in Fig. 4.

The mechanical design has been performed at CERN and its construction is foreseen within the next year.

POWER DISTRIBUTION SYSTEM

Pulse Compressor Optimization

A pulse compressor is foreseen to feed the acceleration cavities; three different candidates have been selected for this purpose. The first one is a SLAC energy doubler (SLED) designed at CERN [7], with a quality factor Q=1.7e05 and beta=5.8, the second one is barrel open cavity (BOC) designed at PSI [8] with a quality factor Q=1.5e05 and beta=7.5 and the last one is still a BOC, under development at CERN [9] with a quality factor Q=2.34e05 and beta=7.4 An optimization for the pulse compression system has been performed in order to understand which compressor suits better for the system.

The three compressors are shown in Fig. 5.

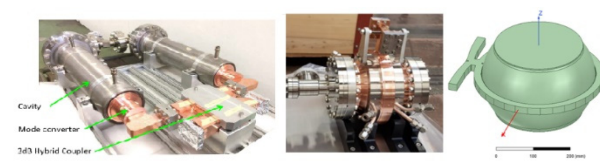

Figure 5: SLED @ CERN (left), BOC @ PSI (centre), BOC @ CERN (right).

For a specific set of values of the LINAC (quality factor, group velocity, shunt impedance) and the compressor (coupling factor and quality factor), one can find a value of the filling time of the cavity, that maximizes the accelerating gradient [10]. The accelerating voltage for a constant impedance cavity with pulse compressor is [6]:

$$V_{acc} = \sqrt{P_k R L_s}\sqrt{\frac{R_s}{R}} \tag{1}$$

Where P_k is the power at the compressor input section, R is the LINAC shunt impedance, L_s is the LINAC length and R_s is the effective shunt impedance, a parameter which defines the efficiency of the system [10]. It is clear from the above formula that Rs is the target parameter to optimize; in [6] has been found that:

$$\frac{R_s}{R} = \left\{\sqrt{\frac{2}{\tau_s}}\left[\gamma\left(\frac{1}{\frac{Q}{Q_l}-1}\right)\left(e^{-\tau_s} - e^{-\frac{Q}{Q_l}\tau_s}\right) + (\alpha-1)\left(e^{-\tau_s}-1\right)\right]\right\}^2 \tag{2}$$

Where:

$$\alpha = \frac{2\beta_c}{1+\beta_c} = 2\frac{Q_l}{Q_e}$$

$$\gamma = \alpha\left(2 - e^{-\tau_1}\right) = 2\frac{Q_l}{Q_e}\left(2 - e^{-\frac{t_1\omega}{2Q_l}}\right)$$

Where τ_s is the section attenuation of the X-band accelerating structure, Q is the quality factor of the single cell, Q_l, Q_e and β_c are the loaded and external quality factor and the

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coupling factor of the compressor. More details about this optimization process can be found in [6] and [10]. For a constant impedance acceleration cavity, the section attenuation is [11]:

$$\tau_s = \alpha_{cell} L_s$$

Where α_{cell} is the attenuation constant of the single cell and L_s is the length of the cavity.
It is then possible to optimize (2) as a function of L_s keeping all other parameters constant.
The plot of the square root of R_s/R as a function of the cavity length is shown in Figure 6.

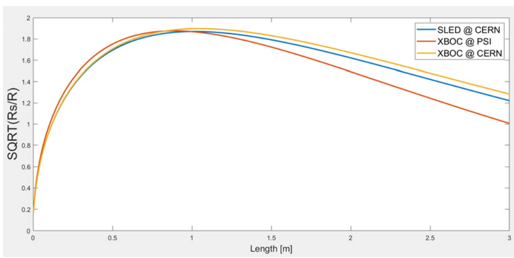

Figure 6: Optimization curves for the SLED@CERN (blue), the XBOC@PSI (RED) and the XBOC@CERN (yellow)

The values of the lengths that maximize the accelerating voltage and the respective R_s are listed in table 2. The accelerating gradient as a function of the compressor input power, for a 0.9 m length cavity and for the case of no pulse compressor are shown in Fig. 7.

Table 2: Injector Parameters

Compressor	Rs [MΩ/m]	Opt. Length [m]
SLED @ CERN	350	1.01
BOC from PSI	352	0.89
BOC @ CERN	360	1.07

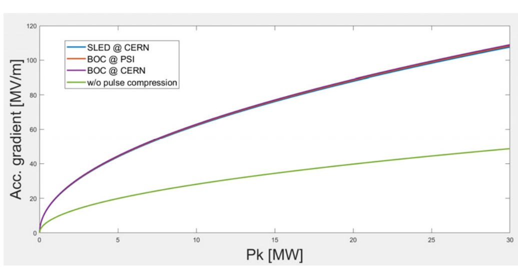

Figure 7: Acceleration gradient as a function of the compressor input power for 0.9 m length.

In [12], a figure of merit is defined to quantify the performance of the compression system, i.e., the compression factor M:

$$M = \frac{V_{acc}(with\ compression)}{V_{acc}(w/o\ compression)}$$

In Table 3 the compression factor is shown for the three cases. With M being almost equal in the three cases, all compressors are a good choice for the system.

Table 3: Injector Parameters

Compressor	Compression factor
SLED @ CERN	2.21
BOC from PSI	2.23
BOC @ CERN	2.23

Input Power Estimation

Using (1), the power required by the klystron can be calculated for the two different schemes. For the second layout in Fig. 2, assuming the three cavities working with an accelerating voltage of 53 MV/m, the power required at the compressor input, for a flat pulse of 1.5 us, is ~21 MW (~7 MW per cavity) while for the small buncher the power required at its input is 6.6 MW. For the power distribution, a double-height (DH) waveguide system has been proposed to reduce losses. For a standard WR90 WG the attenuation constant for the TE10 mode is α=0.01 dB/m while for a DH WG is 0.006 dB/m reducing the losses of 40%. Assuming 30 m of DH WG the losses are in total 1.8 dB or equivalently 34% which implies ~32 MW of output power from the klystron to feed the acceleration cavities and ~10 MW for the buncher for a total power consumption of ~42 MW. The same calculations can be used for the first layout where the power required by the cavities is 34 MW (~16 MW per accelerating cavity and 2 MW for the buncher) for a total power consumption of ~50 MW; another disadvantage for this configuration compared to the second one.

CONCLUSIONS

The new injector for the AWAKE Run 2 and its power distribution system have been proposed and studied. Two different configurations for the X-band bunching and accelerating system have been discussed. The second layout has been chosen because of its reliability against breakdown pulses and power consumption performances. Three different compressors for the system have been studied demonstrating that all of them are good choices.

The prototype of the gun has been installed at CTF2 and conditioned, reaching an accelerating electric field of 120 MV/m at the cathode and beam tests are forthcoming.

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