13th Int. Particle Acc. Conf. IPAC2022, Bangkok, Thailand JACoW Publishing
ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-THPOPT042

STUDIES FOR A LASER WAKEFIELD DRIVEN INJECTOR AT ELSA

K. Kranz*, K. Desch, D. Elsner, M. Switka
Physics Institute, University of Bonn, Germany

Abstract

At the University of Bonn, electron beams with energies up to 3.2 GeV can be extracted from the storage ring ELSA to hadron physics and novel detector testing experiments. We study the feasibility of replacing the current 26 MeV Linac injector with a laser plasma wakefield accelerator (LPWA). For this, contemporary achieved parameters from current LPWA setups at other laboratories are assumed and matched to the acceptance of the facility's synchrotrons. Moreover, a conceptional draft of a potential LPWA setup is created. This takes into consideration the influence of building conditions such as available floor space and building vibrations to estimate a setup of a plasma generating high power laser system and beamline to the plasma cell.

INTRODUCTION

The Physics Institute of the University of Bonn operates the three staged **EL**ectron **S**tretcher **A**nlage (ELSA) accelerator facility. It can accelerate spin-polarized or unpolarized electron beams up to energies of 3.2 GeV using a synchrotron ring design capable of quasi-continuous electron beam extraction to three experimental stations. The injector system consists of a linear accelerator, pre-accelerating the electrons to energies of 26 MeV, and a booster synchrotron. This combined-function synchrotron accelerates the electrons to a typical energy of 1.2 GeV. With a rate of 50 Hz and an average charge of 2 nC the electrons are injected into the storage ring, where the beam is accumulated up to 25 mA (~ 15 nC), accelerated up to 3.2 GeV and extracted via resonance extraction over several seconds to external experimental stations with a mean current of 1 nA.

It is of great interest, whether the implementation of a novel injector based on LPWA technology is possible, which ideally would form a redundant pre-accelerator to the current Linac. A potential setup with a plasma driving high power laser system, plasma cell assembly and energy compressor is sketched in Fig. 1.

INJECTION REQUIREMENTS

An LPWA could be used to inject directly into the stretcher ring or into the booster synchrotron as an intermediate injector, whose requirements on charge and beam energy are more relaxed. The different requirements for both synchrotrons are given in Table 1.

As typical pulse lengths of LPWAs are in the order of femtoseconds, but contemporary pulse repetition rates are in the order of a few Hertz with pulse charges of a few hundred pico-coulombs [1], it is difficult to satisfy all the conditions required for a direct injection into the storage ring, which requires a homogeneous filling of ~15 nC within a short injection duration of <1 s. Alternatively, an LPWA injector could be used to fill the booster synchrotron with an MeV electron beam, ideally with a total charge of 2 nC at 50 Hz repetition rate. Transverse LPWA beam properties (emittance ~1 μmmrad) tend to suffice the booster requirements. However, the momentum spread, usually in the order of some percent at MeV beam energies, and the very short pulse durations have to be adjusted to fit the requirements.

* kranz@uni-bonn.de

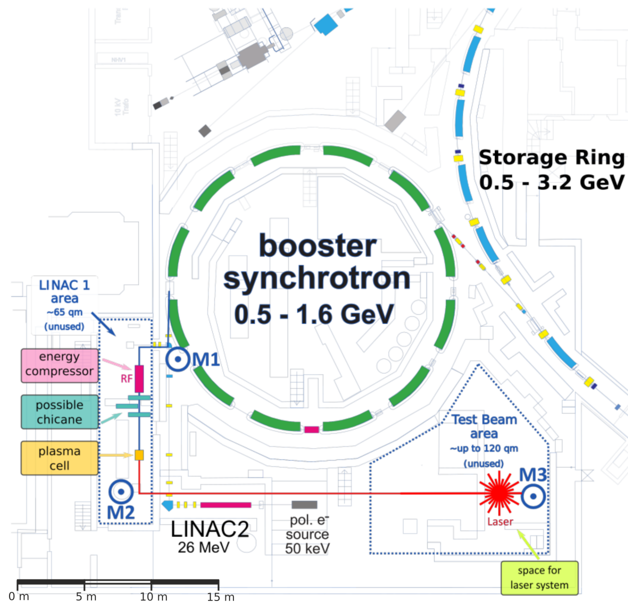

Figure 1: Injector area of the ELSA facility showing currently unused floor space (dashed) which is available for an LPWA injector setup. A high power laser system with multi-square-meter footprint can be installed at the former test beam area whereas the plasma cell and the subsequent beamline including an energy compressor system can be set up at the former LINAC 1-area.

Table 1: Injection Requirements of Both Synchrotron Rings of the ELSA Facility

Injection Requirement	Storage Ring	Booster
Energy	>1 GeV	15-30 MeV
Beam charge	15 nC	2 nC
Buckets	274	116
Rev. period	548 ns	232 ns
Inj. duration	0.5 s	1 µs
Emittance	$2.5{\cdot}10^{-6}$ m rad	$3{\cdot}10^{-6}$ m rad
Energy spread	0.3 %	0.5 %

13th Int. Particle Acc. Conf. IPAC2022, Bangkok, Thailand JACoW Publishing
ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-THPOPT042

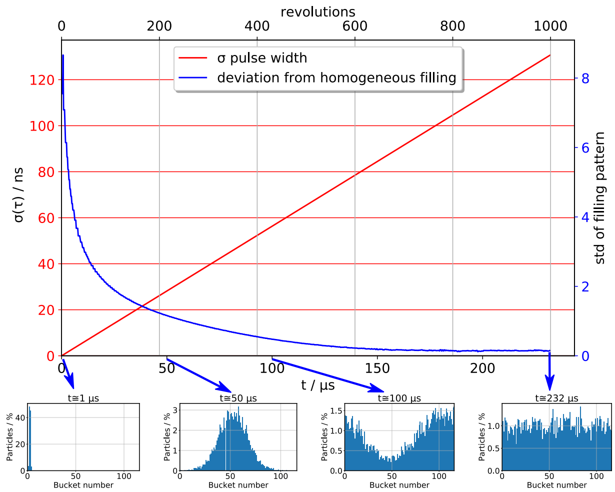

Figure 2: Pulse length (red) and deviation from homogeneous filling (blue) against the number of revolutions and elapsed time. A histogram of the filling pattern is shown below for selected time-frames.

BOOSTER SYNCHROTRON AS DEBUNCHER

The extremely short electron pulse length of an LPWA bunch would only allow for single bunch operation in the booster synchrotron or storage ring. To create a homogeneous filling pattern, we propose to utilize dispersive trajectories within the booster synchrotron's bending magnets. The RF acceptance of the machine is ~ 2π and beam energy loss due to the emission of synchrotron radiation is negligible at the MeV level. Thus, a short single bunch could be injected and circulate for multiple revolutions when the RF is not running, resulting in a pulse broadening according to

$$\frac{\Delta t}{t} = -\alpha_c \delta \ ,$$

where α_c is the momentum compaction factor and δ the momentum deviation. Simulations with the tracking code `Elegant` [2] show that an initial Gaussian distribution of pulse length $\tau = 15\,\text{fs}$ (1-σ, $\delta = 0.5\,\%$) forms a sufficiently homogeneous particle distribution along the ring after ~200 μs, when particles with large momentum deviation have overlapped multiple times and remixed with particles with less deviation. The evolution of the pulse width and the resulting reduction of the standard deviation of the particle population distribution is illustrated in Fig. 2. However, during the debunching phase the sinusoidally oscillating magnetic bending field increases and hence, decreases the orbit radius, potentially leading to beam loss at the inner vacuum chamber, or other apertures. For a 200 μs long delay of RF power deployment, an additional magnetic field of 9.1 mT has risen, resulting in a decreased orbit of only 0.8 mm for a 20 MeV beam. The available aperture diameter of 2.5 cm is sufficiently large and oposes no limit for the use as debuncher.

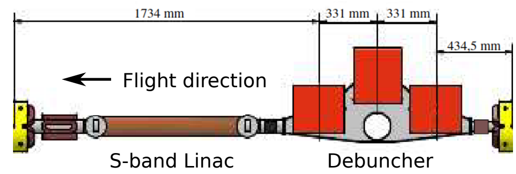

Figure 3: Energy compressor system of the former LINAC 1 of the ELSA facility, consisting of a magnetic chicane and an S-band travelling wave Linac.

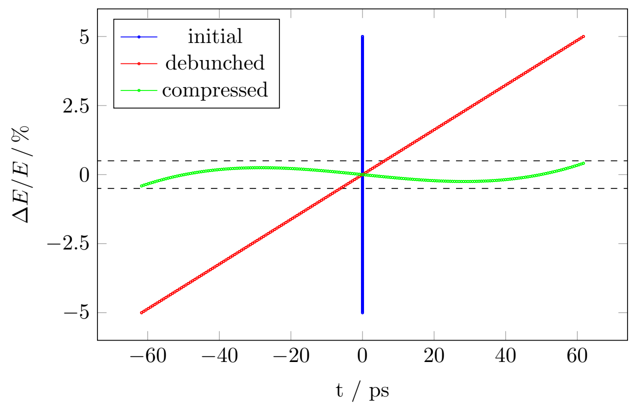

Figure 4: Energy spread distribution of a sub-picosecond long input bunch before and after the energy compressor system. A reduction from 5 % to 0.5 % is possible for a 20 MeV beam and an electric field strength of 1 MV/m.

Energy Spread Modulation

The former convential LINAC 1 was equipped with an energy compression system [3], which had been designed to reduce the Linac's 5 % energy spread to the booster acceptance of 0.5 %. Therin, a debuncher, consisting of a chicane with three dipole magnets, is followed by an S-band travelling wave Linac, as shown in Fig. 3. The debuncher broadens an input bunch length from 15 fs to 60 ps and the electric field strength of ~ 1 MV/m compresses the energy spread at 3 GHz to below 0.5 % for a 20 MeV beam, as shown in Fig. 4. With a pulse length of several picoseconds and compressed energy distribution matching the booster synchrotron's acceptance, the aforementioned debunching scheme utilizing the booster itself can be used to achieve a homogeneous filling.

BUILDING CONDITIONS

Floor Space, LPWA Footprint and Accessibility

Due to the decommissioned LINAC 1 and the currently unused *test beam area* (compare with Fig. 1), the facility offers sufficient space (65 m^2 and 120 m^2) in radiation controlled areas for the setup of a terawatt laser system (typically up to ~4 m×8 m in size) and the plasma cell with subsequent injector beamline.

The facility is usually running for one third of the year, split up in 4-6 week intervals. This imposes access limits to the Linac areas, but the *test beam area* is accessible during

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-THPOPT042

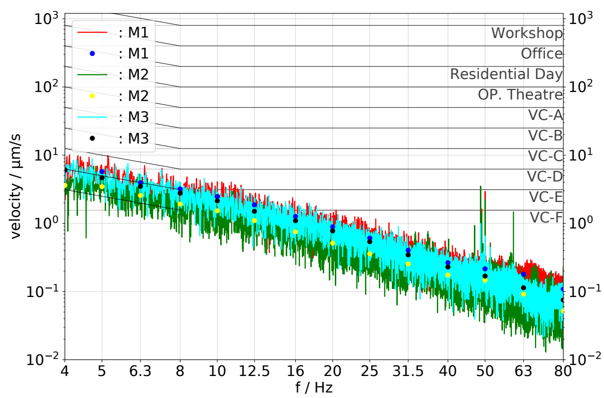

Figure 5: Preliminary results of the vibration measurements via accelerometers. The circular markers represent the 1/3-rms velocity.

beam time, allowing for continuous maintenance and testing of a laser system.

Building Vibrations

To estimate the influence of building vibrations on the operation of the high-power laser system and the pointing stability of the ~30 m long laser transfer beamline, accelerometers were used to measure the spectrum of ground vibrations. Some expected vibration sources are water pumps, which are located directly under the LINAC 1-area, the nearby synchrotron magnets, which operate at a 50 Hz cycle, and the ambient noise created within the institute building and the nearby street. Measurements were conducted at three key areas, emphasized in Fig. 1: the injection point of the booster synchrotron (M1) as reference, the potential location of the plasma cell at the former LINAC 1-area (M2), and the potential laser position at the *test beam area* (M3). For a fully operating facility, we obtain a spectrogram as shown in Fig. 5. Therein, the fast Fourier transformed rms velocities combining all three movement axes are shown. To classify the measurement on the basis of the widely accepted vibration criterion (VC) curves [4], the spectrogram is averaged within 1/3 octave band intervals and compared to the VC classes. These measurements indicate a building vibration classification of laser setup and plasma cell area of VC-E: *Assumed to be adequate for the most demanding of sensitive systems including long path, laser-based, small target systems and other systems requiring extraordinary dynamic stability*. However, in all areas the influence of the booster synchrotron magnets is clearly visible and additional decoupling structures with damping capability around 50 Hz should be considered for future setups of sensitive hardware equipment. In addition, dynamic beam pointing correction systems have been established at many contemporary LPWA setups. Hence, the correction performance of such a system in presence of the facility ground vibrations has to be investigated when a specific laser system and plasma cell design has been chosen.

CONCLUSION AND OUTLOOK

Some requirements for the implementation of an LPWA as injector for the ELSA facility can be fulfilled by using the existing infrastructure, such as parts of the former energy compressor system and the booster synchrotron to create a homogeneous filling pattern from a femtosecond long LPWA pulse with up to 5 % energy spread. The installation of a high power laser system at the *test beam area* seems feasible with the floor space available and the measured ground vibration classification of VC-E. Other requirements, such as the creation of a 2 nC bunch charge with acceptable energy spread at a 50 Hz repetition rate is yet to be demonstrated and feasibility investigations are currently ongoing. In addition, experimental verification of machine properties such as the minimum and maximum injection energy, energy spread and transverse acceptance of booster synchrotron and storage ring will be carried out to further specify the required LPWA parameters. Finally, an LPWA setup with suitable design parameters has to be investigated.

REFERENCES

[1] M. C. Downer, R. Zgadzaj, A. Debus, U. Schramm, and M. C. Kaluza, "Diagnostics for plasma-based electron accelerators," *Rev. Mod. Phys.*, vol. 90, p. 035 002, 3 2018, doi:10.1103/RevModPhys.90.035002

[2] M. Borland, "elegant: A Flexible SDDS-Compliant Code for Accelerator Simulation," in *6th International Computational Accelerator Physics Conference (ICAP 2000)*, 2000, doi:10.2172/761286

[3] F. Klarner, "Konzeption, Aufbau und Inbetriebnahme eines neuen Vorbeschleunigersystems an ELSA," Ph.D. dissertation, Rheinische Friedrich-Wilhelms-Universität Bonn, 2011, https://hdl.handle.net/20.500.11811/5077

[4] C. G. Gordon, "Generic criteria for vibration-sensitive equipment," *SPIE Proceedings*, vol. 1619, 1991.