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FEASIBILITY INVESTIGATION OF A LOW ENERGY LASER DRIVEN PLASMA INJECTOR FOR ELSA

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Abstract

The 3.2 GeV electron stretcher facility ELSA at the University of Bonn provides electron beams for fundamental research in hadron, detector and medical physics. The beam is extracted from a storage ring, whose injector consists of a 26 MeV linear accelerator and a 1.2 GeV booster synchrotron. The advent of functional plasma-based electron injectors in the MeV energy range raise the opportunity to replace the conventional Linac, which currently delivers electron pulses of up to 16 nC at a repetition rate of 50 Hz. We conduct a feasibility study of using a plasma based injector for the booster synchrotron as intermediate stage before injection into the storage ring. For this, we improve the diagnostic capabilities of the Linac transfer beamline and the injector synchrotron to obtain and verify its acceptance parameters which are to be matched to beam properties from contemporary operated laser plasma accelerator setups. Possible plasma-based facility operating modes are evaluated.

INTRODUCTION

For the ELSA facility [1] the option of using of a plasma based injector for the storage ring is being considered [2], as recent developments in producing plasma accelerated electron beams show promising potential [3, 4]. The ELSA facility primarily delivers continuous beams to external experimental stations, where beam currents typically range up to 1 nA. However, user-customizable modes of operations are offered, such as single electron extraction [5] for detector testing or high charge ultra-high-energy electron beams (UHEE) for medical irradiation research [6]. The application of a plasma based injector should ideally fulfill the requirements of current and future experimental programs. However, the limited charges being extractable from LPA devices in the range of some 100 pA and the expenditure of creating GeV electrons from such devices nececiate a compromising approach to install and test a redundant injector to the currently used conventional electron gun and Linac. A low-charge application for user operation seems achievable with contemporary LPA technology and steps towards a potential mode of LPA-based operation at ELSA is presented in the following.

THE ELSA FACILITY

0.5 GeV to 3.2 GeV electrons can be stored and extracted from the ELSA storage ring. The facility is designed to deliver polarized and unpolarized electrons with high duty factor, using a resonance extraction scheme. For this, a fast cycling injector chain supplies the storage ring with up to 3 nC at 50 Hz repetition rate (16 nC after the S-band Linac). The injected bunch trains are 232 ns long and distributed across 116 buckets due to circumference and 500 MHz RF system of the booster synchrotron. Hence, a storage ring filling to 25 mA (14 nC) requires typically 21 shots at $\approx 40\,\%$ injection efficiency and takes < 0.5 s. The continuity of the current modes of operation is desired for the usage of a novel plasma injector.

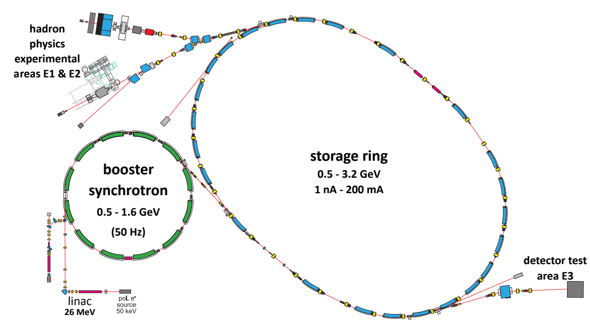

Figure 1: Layout of the ELSA facility. The injector consists of a Linac and booster synchrotron combination operating at 50 Hz repetition rate. Electrons are delivered continuously with high duty factor to experimental stations via resonance extraction.

Facility Modes of Operation

Beam for Hadron Physics 1 nA of continuous beam (polarized, unpolarized) is extracted for up to 10 s requiring 30 nC injected charge within 0.5 s, evenly distributed over 274 RF buckets.

Detector Test Beam Extraction rates of some 10 kHz require only femtoamperes of extraction currents and consequently allow for lower storage ring filling of few nanoamperes (femtocoulombs).

Medical Irradiation Single shot extraction with maximum achievable charge is desired for ultra-high dose rate UHEE irradiation experiments [6]. Currently, up to 2.5 nC can be extracted at 1.2 GeV in a 232 ns long pulse. As 50 Hz repetition is achievable, the shot-to-shot interval is typically in the order of minutes.

POTENTIAL OF LASER PLASMA ACCELERATION

Laser driven accelerators cover a wide range of achievable beam properties, such as pulse charges up to the nanocoulomb level, GeV beam energy, less than a percent

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of energy spread, 10^{-6} m rad emittances and a few femtoseconds pulse duration. However, such best reported values are not achieved simultaneously [7] and cost of equipment generally scales with achievable electron energy. For example, for GeV electron beam generation PW-class laser systems are required (see e.g. [4]), whereas MeV electrons can be generated with less cost-intensive equipment (mJ-class lasers, see e.g. [8]). Such LPA generated MeV particle beams seem utilizable for a selection of experiments at the ELSA facility with only minor changes of the currently operating hardware required. We assume that LPA generated beams of 5 MeV to 20 MeV with ~ 15 % energy spread, 5 pC charge and 5 fs pulse duration at 1 kHz repetition rate are within technological reach and such a system is maintainable with the staff and infrastructure of the ELSA facility.

Similarities to the Previous RF Injector

The space available for an LPA injector is located at the position of the (dismantled) original linear accelerator of the facility which provided 1 ns pulses of 20 MeV electrons with an energy spread of 5 % to 7 %. The Linac to booster transfer beamline is optimized to match a beam of 5×10^{-6} m rad emittance to the injection point [10]. This design provides the foundation to match an LPA beam to the optimum injection parameters given in Table 1.

Table 1: Twiss parameters for booster synchrotron injection and acceptances [10]

horizontal	vertical
$\beta_x = 7.88$ m	$\beta_z = 3.55$ m
$\alpha_x = 3.82$	$\alpha_z = 1.194$
$\gamma_x = 0.070\,\mathrm{m}^{-1}$	$\gamma_z = 0.844\,\mathrm{m}^{-1}$
$A_x = 75.85 \times 10^{-6}$ m rad	$A_z = 34.8 \times 10^{-6}$ m rad

Layout for a Plasma Injector

The beamline layout and available space for a typical sized plasma cell assembly is shown in Fig. 2. For initial focusing of an LPA beam with tens of mrad divergence approximately 5 m of longitudinal space is available for a multi-quadrupole setup for initial beam focusing (compare e.g. with [11]). A magnetic bunch decompressor and S-band Linac may be used for reducing the energy spread via energy compression. Sufficient space for diagnostics is available in the beamline and hutch.

ENERGY COMPRESSION

The energy acceptance of the booster synchrotron amounts 0.5 % and is a magnitude below what LPA output beams typically deliver. However, energy compression via magnetic chicane and traveling wave Linac offer an established technique for reducing the energy spread. A simulation based on the energy compressor used at ELSA, fed with a 20 MeV LPA-like beam of 10 fs pulse length and 10 % energy spread (10^{-6} m rad emittance) yields a transfer

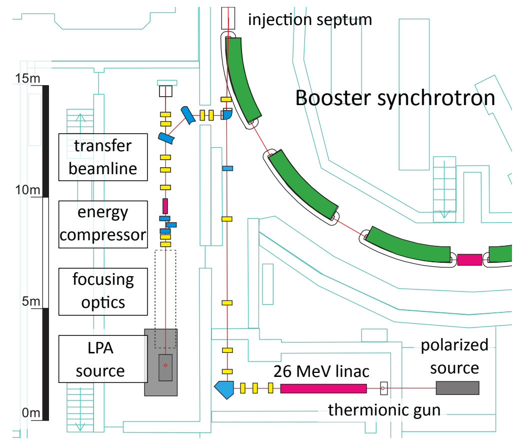

Figure 2: Injector area of the ELSA facility. The former space of the original RF Linac and its transfer beamline offer sufficient space for a plasma based injector and its required focusing optics and diagnostics.

efficiency of ~ 40 % for particles within a ±0.5 % energy acceptance band, as shown in Fig. 3. Hence, an LPA generated pulse stretched to 100 ps length can be injected at reasonable injection efficiency into the booster synchrotron.

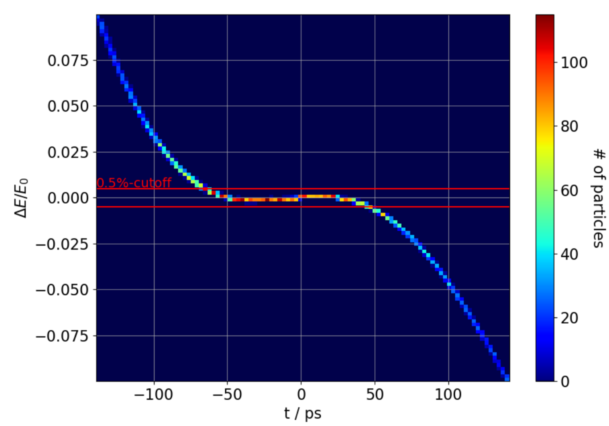

Figure 3: Particle distribution in longitudinal phase space after energy compression. A transfer efficiency of 40 % is estimated.

THE BOOSTER SYNCHROTRON AS PULSE STRETCHER

The booster synchrotron is a combined-function alternating gradient synchrotron which started operation in 1967. Its 50 Hz operation cycle is based on a grid frequency synchronized analogue power supply which creates a sinusoidal magnetic guiding field (see Fig. 4) which dictates the available time window for injection and extraction. The momentum compaction factor of $\alpha_c = 0.11$ causes a natural pulse stretching due to the given momentum spread:

$$\frac{\Delta T}{T} = \left(\frac{1}{\gamma^2} - \alpha_c\right) \cdot \frac{\Delta p}{p}.$$

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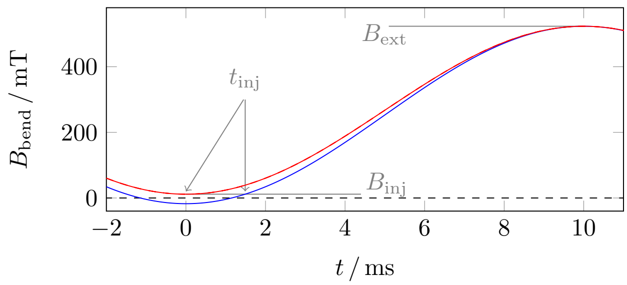

Figure 4: Oscillating bending field of the booster synchrotron. In standard operation peaking-strip trigger signals are obtained for injection timing from the zero-crossing of the magnetic field (blue). A broader time window for injection is available when no zero-crossing occurs (red), requiring modification of the timing system.

Simulations show that a beam *storage* duration of 150 μs results in a complete stretching of an initial femto- or picoseconds long injected pulse to a homogenous filling pattern [2]. The Booster synchrotron is not naturally capable of storing beam, however, for injection energies of < 30 MeV emission of synchrotron radiation is neglectable and the 2π RF acceptance can be used advantageously to *capture* and stretch injected pulses before the RF is switched on and buckets are formed.

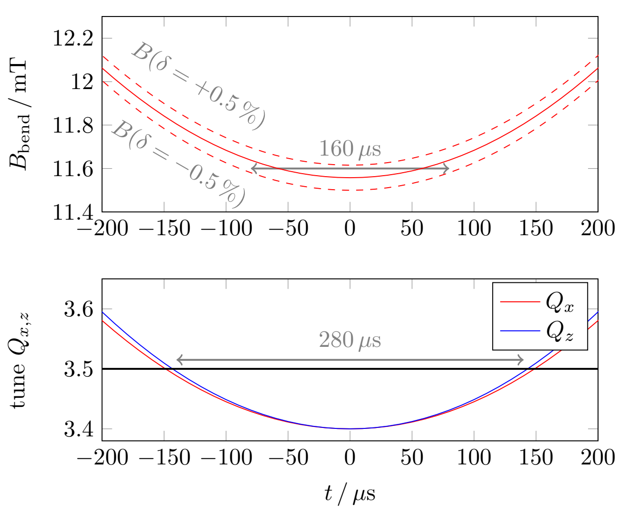

Figure 5: Bending field minimum as injection and pulse stretching window for a 26 MeV electron beam with 0.5 % energy deviation (top). The corresponding tune change of the combined-function magnets allows a longer time window (bottom) before a half-integer stop band is approached.

A suitable time window for pulse stretching is given by the change of the sinusoidal magnetic field, whose time dependence is depicted in Fig. 5 (top) as well as the expected tune change due to the combined-function magnets (bottom, therein). A time window of up to 160 μs is theoretically available for a 26 MeV electron beam. Experimental verification requires a modification of the timing system and power supply stabilization, which is currently under investigation.

CONCLUSION

For low current experimental applications such as the detector test program an LPA-generated MeV beam is potentially usable to generate a homogeneously low-intensity stored beam at the ELSA facility, utilizing an energy compressor and the booster synchrotron as pulse stretcher. For this mode of operation only minor changes of the currently operating hardware would be required. Experimental verification of the concepts described above is currently ongoing, requiring minor improvements of timing hardware and beam diagnostics in the Linac transfer beamline.

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