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SIMULATION RESULTS OF THE BEAM TRANSPORT OF ULTRA-SHORT ELECTRON BUNCHES IN EXISTING BEAM TRANSFER LINES TO SINBAD

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Abstract

SINBAD, the upcoming accelerator R&D facility at DESY, will host multiple independent experiments on the production and acceleration of ultra-short bunches including plasma wakefield experiments. As a possible later upgrade the option to transport higher energy electrons (up to 800MeV) or positrons (up to 400MeV) from the existing DESY Linac II to the facility is studied. Though existing a possible connection using e.g. a part of the DESY synchrotron as a transfer line and a currently unused transferline, these machines were not designed for the desired longitudinal bunch compression and high peak current required by e.g. beam driven plasma wake-field experiments. Simulation results illustrate the modifications to the current layout that would have to be implemented and the corresponding achievable beam parameters.

INTRODUCTION

The SINBAD project [1] aims to set up a dedicated accelerator R&D facility in the former DORIS facility at DESY, Hamburg. This facility will contain multiple independent experiments in the context of advanced, compact acceleration concepts like plasma wake field (PWFA) or dielectric acceleration for ultrafast science. While there will be a dedicated linac for ultra-short bunches, it's energy will be limited to about 200 MeV. The aim of this study is to investigate if the existing Linac II can be used to accelerate electrons to 800 MeV and to subsequently transport them through existing beam lines to SINBAD. Provided that a sufficiently high beam current could be delivered, this would allow to perform e.g. beam driven plasma wake field experiments and FEL seeding studies. Additionally Linac II is capable of producing 400 MeV positrons which is only possible at very few facilities worldwide. While the maximal achievable positron beam current will not be too high, proof of principle experiments of acceleration in a PWFA could be performed as a first step of studying possible future PWFA-based high energy colliders.

Figure 1 shows the existing beam transport system from the electron gun to the SINBAD facility passing through Linac II, the "Positron Intensity Accumulator" (PIA) ring, the "L-weg", the DESY II synchrotron, the "R-Weg" and finally half of the former DORIS arc. As the lines up to including the DESY II, are used as injector chain to the Petra III synchrotron light source, it must be assumed that no significant modifications interfering with the standard operation can be implemented. On the other hand, the R-Weg and the final former DORIS arc serve no other purpose and are free to be modified. Initially it was studied if an

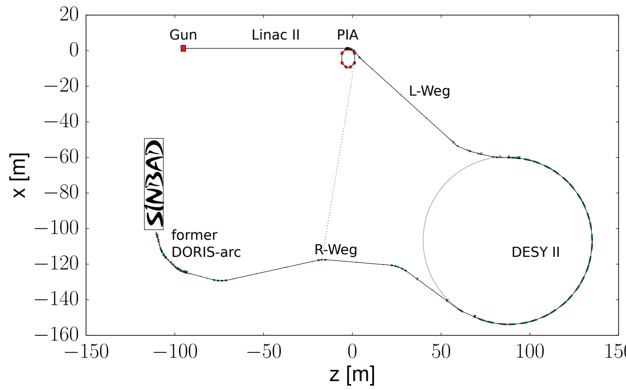

Figure 1: The geometric layout of the beam transport system from the electron gun of Linac II up to the SINBAD facility.

existing, empty direct tunnel from the PIA ring to the R-Weg (see dotted line in Figure 1) could be used instead. This option had to be discarded as the dispersion created by the 90 degree dipole of PIA could no be closed and thus the subsequent long straight section would result in a very large linear momentum compaction factor R56 (the 56 element of the linear transfer matrix R). Furthermore, while the tunnel was originally foreseen for beam transport, by now constructional modifications imply that the radiation protection shielding is no longer sufficient.

Using an unmodified PIA ring-optics and the corresponding section of the DESY ring-optics as transfer-line, the overall optics from the end of the Linac II to SINBAD would result in the very large R56-transfer matrix element (R56 > 150m). It is therefore obvious that significant changes must be implemented to be able to deliver bunches with a reasonable bunch length.

MODIFIED BEAM OPTICS

In a first step the optics of each part was optimized for a small linear momentum compaction (R56) and only then the second order elements (T566) were accounted for. The R56 element of a transfer line is (mainly) determined by the dispersion D in the dipoles and the dipole strength $1/\rho$ ($R56 \propto D \cdot \rho$). While the arrangement and properties of the dipoles is fixed by machine geometry, altering the beam optics allows to modify the dispersion function and thus the overall R56 element.

Gun & Linac

While the electrons at Linac II were until very recently extracted from an old DC-gun with a subsequent bunching cavity, an upgrade to add a second additional DC-gun has

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just been completed [2]. As the initial bunch length from these DC-guns is quite long, for these studies it is therefore assumed that either the old DC-gun is replaced by an RF-gun or a third source branch is installed and equipped with a photo-cathode RF-gun, from which a bunch with a 1σ bunch length of 1ps can be extracted. While the normal conducting, S-band Linac II is in daily operation only used to accelerate up to 400 MeV, sufficient RF power is available to accelerate electrons up to 830 MeV (assuming on-crest operation).

PIA

Given that PIA is rather small and considering the magnet powering schemes, it is clear that no significant change in the beam optics can be achieved which would allow to reduce it's contribution to the overall momentum compaction. While PIA is a vital part of the injector chain to the PETRA III synchrotron light source, it is not relevant for the beam delivery to SINBAD. As there already exists a switch yard just upstream of PIA which allows to deflect the beam towards a beam dump, a bypass around the machine could be installed with relatively little effort. Adding a single dipole and two quadrupoles would allow to create a bypass without interfering with the normal operation.. With this bypass

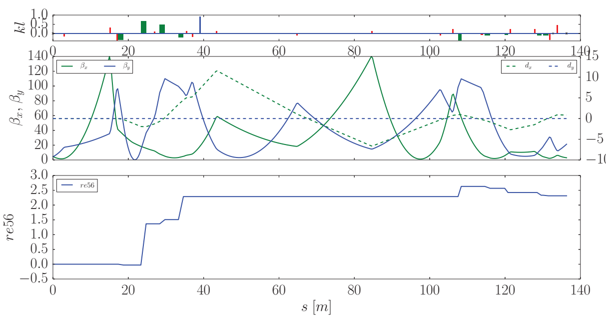

Figure 2: Possible beam-optics solution for a bypass around PIA and the subsequent transfer line to the start of the DESY synchrotron.

and an adapted powering scheme for the rest of the line, a suitable optics could be found (Figure 2) that changes the R56 element of this section from -14m to the desired value of +2.2m while maintaining the matching conditions at the start and end.

DESY II

Next, the beam is injected into the DESY II synchrotron and extracted after only one third of a revolution of the ring. While the extraction could be achieved by a suitable timing of the extraction kickers, for reasons of improved stability, the usage of orbit correctors might be preferably. As the operation for top-up of Petra III must be not be altered and due to the constraint of the resonant powering scheme at 12.5Hz, the optics of this machine must not be changed. Also the low number of independent quadrupole families does not allow for significant changes. Thus the R56 element of -4 m can not be avoided and must be compensated in the other parts of the transport line.

R-Weg & final arc

As the only purpose of the R-Weg was to deliver beam to DORIS, the arrangement of the beam line elements and optics can be altered freely. Equally, the former arc of the DORIS accelerator will be completely dismantled during the currently ongoing preparation for the SINBAD facility and would be reassembled again. While the position of the dipoles (defining the geometry) have to be kept, especially the complicated injection region elements would be replaced by a simpler beam transport. Although the currently installed dipoles are dimensioned for up to 6 GeV beams (and not only for the up to 800 MeV), it is assumed that they are still used and not replaced by smaller, shorter ones [1]. Allowing a complete repositioning of almost all quadrupoles, an optics solution with reasonable small beta functions can be found (Figure 3 and 4) that achieves a tunable R56 between 0 and +4 m.

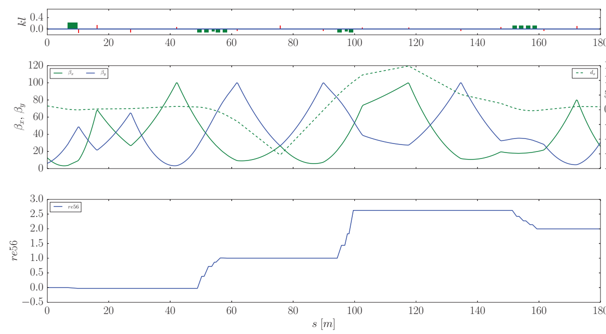

Figure 3: The proposed beam line layout and the corresponding beam optics of the "R-Weg".

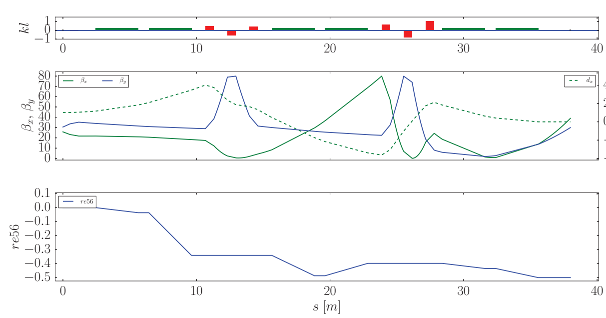

Figure 4: The proposed beam line layout and the corresponding beam optics of the final arc.

T566 & HIGHER ORDER PHASE SPACE DISTORTIONS

Having shown that it is possible to find optics solutions with reasonable small, tunable R56, the next step is to adjust the second order momentum compaction (T566 matrix

[1] This has the additional advantage that beams accelerated by the DESY synchrotron to 5 GeV at longer bunch lengths could also still be delivered to SINBAD

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element). Given the large number of constraints indicated above, the value of T566 cannot be significantly changed by a different optics layout but has to be mitigated by adding a sextupole at a location of large dispersion function. It was found that a sextupole with normalized integrated gradient k2l = 0.7T/m^2 installed in the L-Weg would suffice to correct T566 to zero.

Assuming effects of up to second order only, the optimal R56 and T566 for shortest bunch length as a function of the linac RF-phase ϕ are given by $R56 = 1/(k \cdot tan(\phi))$ and $T566 = k \cdot R56^2/(2tan(\phi))$ where $k = 2\pi/\lambda_{RF}$ [3,4]. To see the effect on the longitudinal phase-space, an initial particle distribution from a photo-cathode was created and accelerated to 800 MeV in the linac at $\phi = 14°$ RF-phase. For these parameters, the corresponding optimal R56 is 6.5cm and T566 is 55cm. The subsequent long transfer line was modeled in three different ways: a) one transfer-matrix with a nonzero R56 element and zero T566, b) one transfer matrix with nonzero R56 and T566 c) element by element tracking using second order transfer matrices.

As expected the values R & T computed from the formulas, result in a significant bunch length compression if the very simple models (a & b) are applied (Figure 5). On the other hand, the element-by-element tracking with second order transfer matrices shows that higher order terms are dominating the resulting bunch shape. Figure 6) compares

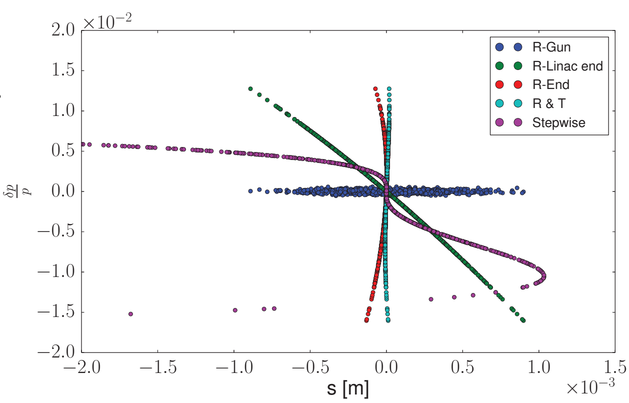

Figure 5: The longitudinal phase space distribution at the photo-cathode, the exit of the Linac II and at the end of the transfer line. For the transfer line three different models (single element with R56, single element with R56 & T566, element wise tracking with second order transfer matrices) were used. It shows that higher order terms are dominating the bunch length.

the histograms of the longitudinal beam profile. It shows that while the higher order terms significantly degrade the achievable performance, sill a noticeable central beam current can be found. Given the long length of the transfer line, space charge effects will have to be considered even at this relatively high energy. Until now, simulations including space charge effect have only been studied for the very few last meters where the beam is already compressed using the ASTRA simulation code. No significant effect on the phase-space

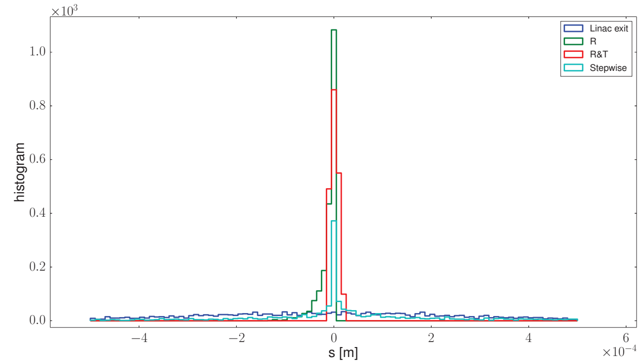

Figure 6: Histograms of the longitudinal bunch distributions of Figure 5. While a compression of the very center of the bunch is possible, long tails are found.

was observed. In subsequent studies, simulations including coherent synchrotron radiation using this optics will be performed. In addition, it might be more beneficial to perform bunch compression already in the linac using RF-velocity bunching and then transport the compressed beam.

CONCLUSION

This first study demonstrates the challenges and limitations of the beam transport of ultra-short bunches in beam transfer lines that were not designed for this purpose. While significant phase-space distortions are observed already in the applied simple models, the center of the beam can be compressed to some extent. Based on this layout detailed space charge and CSR simulations will have to be performed and the alternative of using RF-compression in Linac II be studied. Given the potential of this option to extend the scientific reach of SINBAD, the currently ongoing preparation of the facility will be performed as to allow this option to be added at a later stage.

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