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ORBIT CORRECTION STUDIES FOR THE MINERVA 100 MeV PROTON ACCELERATOR

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Abstract

MINERVA entails the first phase of the MYRRHA[1, 2] program, which aims at driving a sub-critical nuclear reactor with a high-power (4 mA, 600 MeV) proton accelerator, commonly referred to as an Accelerator Driven System (ADS). The purpose of MINERVA is to demonstrate the reliability requirements needed for a stable ADS, by the realization of a 100 MeV, 4 mA proton beam.

In order to transport the proton beam with minimal losses, a strategic placement and usage of orbit correctors and Beam Position Monitors (BPMs) along the accelerator are paramount. With this in mind, error studies were carried out with *TraceWin* [3] to determine an optimal steering strategy and put forward requirements on magnet design and alignment. In addition, orbit correction studies were performed with an in-house developed beam dynamics simulation code, *PyAccel*. Comparison of the results obtained with both software packages serves as an important benchmark towards future developments.

INTRODUCTION

The MINERVA accelerator (see Fig. 1) consists of a normal conducting injector followed by a superconducting LINAC. A Radio Frequency Quadrupole (RFQ) installed in the former bunches a 4 mA proton beam originating from an Electron Cyclotron Resonance (ECR) ion source at a frequency of 176.1 MHz and accelerates it to 1.5 MeV. A sequence of normal-conducting CH cavities further accelerates the bunched beam to 16.6 MeV. After passing through a subsequent diagnostics section, the beam is accelerated to the desired 100 MeV by means of a superconducting LINAC with 60 single-spoke cavities pair-wise confined in 30 cryomodules and operating at 352.2 MHz. In parallel to the reliability tests for the accelerators future use as driver of the MYRRHA reactor, two user facilities will be able to receive the beam delivered via a High-Energy Beam Transport section (HEBT): The “Proton Target Facility” (PTF) will perform Isotope Separation On-line experiments using maximum 0.5 mA of proton beam, while the “Full Power Facility” (FPF) is designed to operate at full CW beam power, i.e. 400 kW, and its main goal is fusion material research[4,5].

When considering a real accelerator, machine precisions must be taken into account. Due to misalignments and offsets, the proton beam centre will inevitably deviate from its reference trajectory. This reduces the available aperture for betatron oscillations with regards to beam loss.

In order to counteract these beam orbit excursions, a configuration of corrector magnets in combination with position measurements along the beam line must be implemented.

Naturally, an orbit correction design goes hand in hand with a steering strategy. The two commonly used practices discussed below are employed in this work.

Iterative steering (IS) In this approach, a matching routine is deployed that iteratively minimizes the BPM readouts by tuning the corrector strengths. Such an approach requires a set of initial values for the corrector strengths, from which the parameter space is scanned by updating the strengths with an optimization algorithm. The established simulation tool TraceWin follows this approach.

Depending on the parameter space dimensions, i.e. the number of correctors, and solution space dimensions, i.e. the number of BPMs, matching may become time consuming. Moreover, convergence is not assured and it is up to the user to define a proper matching strategy. A typical use case is a one-to-one sequential minimization of each BPM reading with a single upstream corrector.

Matrix inversion (MI) Matrix inversion assumes linear beam optics, where the transportation through each element can be represented by a transfer matrix in the 6d phase space. Given a set of N correctors and M BPMs, the vector of dipole field kicks $\theta = (\theta_0, \ldots, \theta_N)$, introduced by each n^{th} corrector, that are necessary to minimize the length of the readout vector $u = (u_0, \ldots, u_M)$ can then be found by calculating the following inverse matrix expression:

$$\theta = -M^{-1}u,$$

where the matrix M contains the elements $R_{nm}^{1,2}$, i.e. the value at position (1,2) in the 2x2 transfer matrix between corrector n and BPM m. Depending on the relative number of BPMs and correctors, this equation either provides an exact solution (when N>=M), or minimizes the BPM readouts when N<M [6,7].

The disadvantage of this technique is its reliance on position independent transfer matrices. Thus, with the introduction of real RF cavity fields, this assumption might break down.

The present work covers a first attempt to implement an orbit correction algorithm for the MINERVA injector. Following a detailed overview of the layout, the results of the error studies carried out with TraceWin and PyAccel are discussed and compared.

INJECTOR CORRECTORS

The section of the accelerator for which the orbit correction study in this work is performed, is highlighted by the inset in Fig. 1. In a later stage, the same exercise will be made for the entire accelerator. Five subsections can be distinguished: two accelerating sections CHA (with 7 CH-cavities) and CHB (with 8 CH-cavities) marked in blue, and three medium energy beam transport sections MEBT1(with two re-bunching cavities), MEBT2(with one

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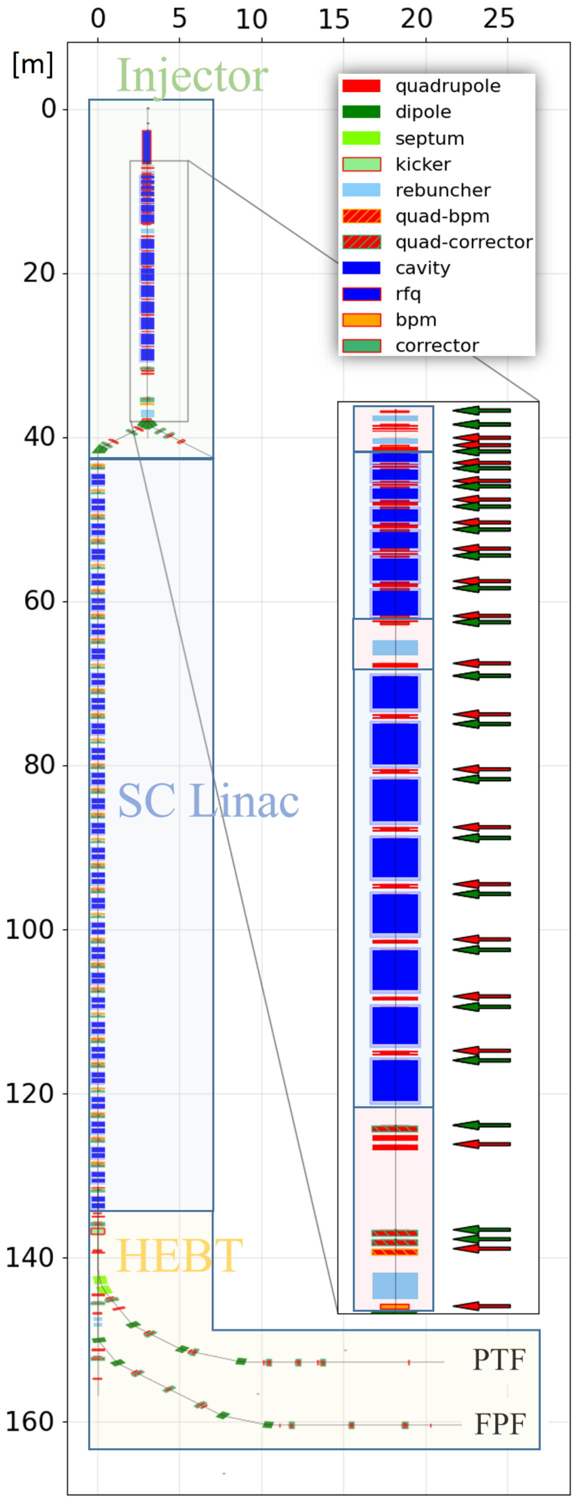

Figure 1: Layout of the MINERVA accelerator. The three main sections are denoted by the coloured areas: the injector (green), the super-conducting LINAC (blue) and the High-Energy Beam Transport section(yellow) deliver a 100 MeV, 4 mA bunched beam to two user facilities (PTF and FPF). The legend on the top right covers the main beam line elements shown in the layout. The inset on the right presents the section for which the orbit correction study in this work is carried out. The green and red arrows correspond to corrector and BPM locations, respectively.

re-bunching cavity), and DS (a diagnostic section), marked in red. The arrows on the right indicate available locations for correctors (green) and BPMs (red). Whether all of these locations should be occupied is to be investigated.

As a first test of the orbit correction algorithm (and for didactic purposes), only subsections MEBT1 and CHA are considered. As indicated by the arrows in Fig. 1, the former contains two correctors and two BPMs. Since this part was already manufactured and operated successfully[8], the need for a design decision is limited to the number and location of the correctors and BPMs in CHA. Furthermore, at the time of CH-cavity procurement an integrated BPM design was already foreseen. This fixes the number (7) and position (behind every CH-cavity) of all BPMs. Hence, the task at hand focuses primarily on the corrector quantity in CHA and field strength requirement. A drawing of the present design of CHA is depicted in Fig. 2, showing the two first cavities with accompanying quadrupole doublets. The integrated BPM design is shown in red and the reserved space for orbit correctors is indicated by the green circle.

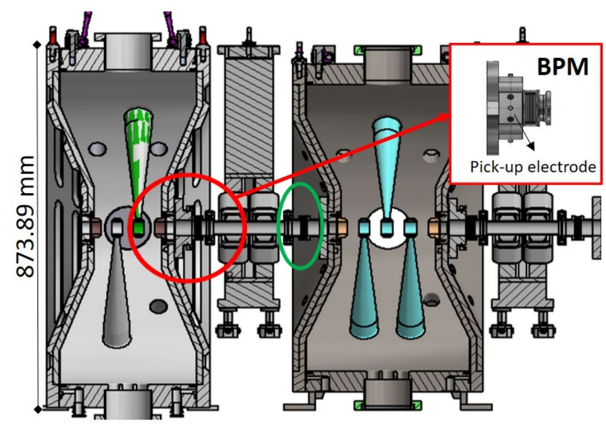

Figure 2: A drawing of the present design of the coupling between the quadrupole doublets and CH-cavities in CHA, where some space is foreseen for the BPMs (red) and correctors (green). In case of the former, a design is already in place, where it is envisioned to provide all cavities with one copy. The design of the correctors is under development.

In total, three orbit correction schemes were evaluated. In the first scheme, called 'CHA empty', CHA is completely void of correctors. Hence, the two correctors in MEBT1 are responsible for minimizing orbit excursions through the entire section, by means of the 9 BPM readings (2 in MEBT1 and 7 in CHA). In the second scheme, called 'CHA intermediate', two additional correctors are placed in CHA, one after the third and one after the sixth quadrupole doublet. In the third scheme, all CH cavities were equipped with an individual corrector, allowing for a one-to-one orbit correction.

To evaluate an orbit correction scheme, one has to perform a statistical study in which relevant errors, i.e. quadrupole and cavity misalignments, are sampled repeatedly from a realistic error distribution. The errors used in the present study are listed in Table 1 and represent realistic misalignment requirements on the quadrupoles and CH-cavities. In addition, offsets are assumed for the beam input

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parameters (estimated from simulations performed on the upstream section): 0.3/0.5 mm for the spatial offset and 0.35°/0.5° for the angular offset. All errors are sampled from a uniform distribution with the specified offset and its negative value used as the upper and lower limits, respectively.

Table 1: Errors Used in the Orbit Correction Study

Error parameter	Quadrupole	CH-Cavity
dx-dy(mm)	0.3	0.5
dϕ_{xyz}(deg)	0.3	0.5

Figure 3 displays the result of the orbit correction algorithms in TraceWin (IS) and Pyaccel (MI).

The top panel shows the layout (and beam envelope) with the cavities in yellow and the quadrupoles in blue. The BPM and corrector positions (in case of full occupation) are indicated by the red and green arrows, respectively.

The panel in the middle demonstrates how orbit correction in PyAccel minimizes the beam excursions for a set of errors sampled as described above.

The bottom panel compares the average radial orbit offset in TraceWin and PyAccel and is a result of sampling 100 machines with the above-mentioned errors. First, the almost one-to-one overlap with TraceWin of the average in the case of 'no correction' demonstrates the validity of PyAccel's tracking algorithm. Second, in the case of the first two correction schemes 'CHA empty' and 'CHA intermediate' PyAccel generally outperforms TraceWin, confirming that the MI strategy better suits global orbit correction in which the number of correctors is lower than the number of BPMs, while the IS algorithm may get stuck in a local minimum. Furthermore, the averages seem to exceed the 2 mm level, entailing extreme excursions up to 5-6 mm, inevitably leading to considerable beam losses. Third, the result for the one-to-one orbit correction scheme, with full occupation of CHA correctors, reveals the breakdown of the MI algorithm due to real RF field maps. It was shown in a separate study that, without field maps, both algorithms bared the same outcome. Evidently, the 'one-to-one' scheme exhibits much lower average orbit excursions, entailing extreme values close to 1 mm and warranting full beam transmission. Applying the safety principle, it was therefore decided to proceed with a full CHA corrector occupation.

Figure 4 shows the maximum required corrector strengths for the 'one-to-one' scheme estimated with TraceWin and PyAccel. Exhibiting comparable values for all correctors, the graph confirms the similarity in convergence for both algorithms. Furthermore, it shows that the corrector strengths do not exceed the value of 0.0018 Tm. Again applying the safety principle, this observation was used to fix the design requirement to 0.003 Tm.

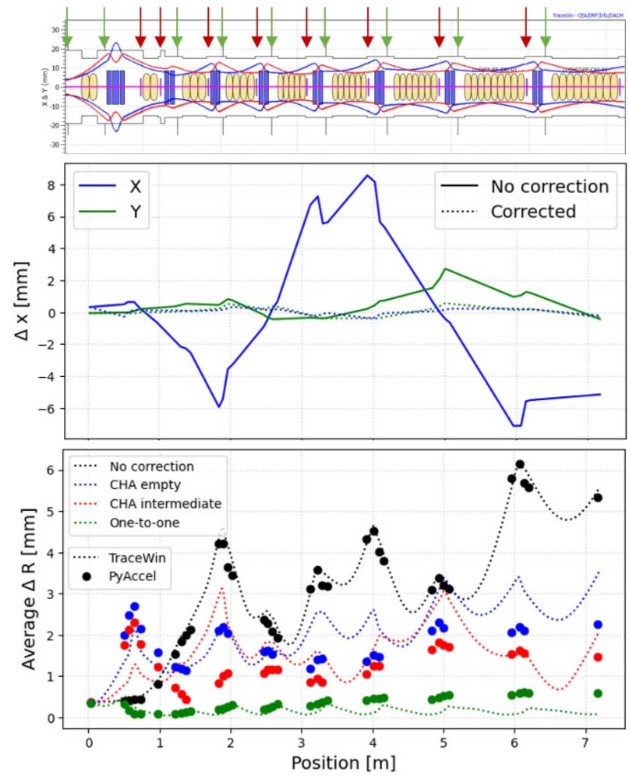

Figure 3: A comparison of the orbit correction performed with TraceWin and PyAccel for the three corrector-BPM schemes discussed in the text. More details are in the text.

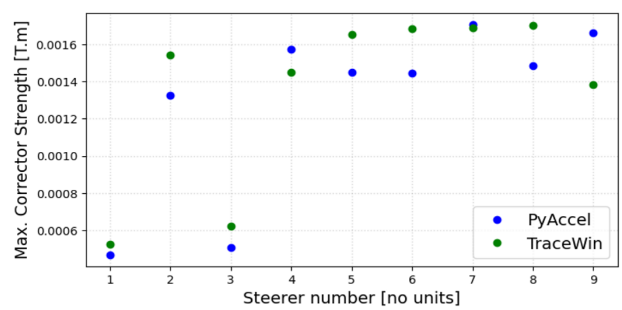

Figure 4: A comparison of the maximum corrector strengths estimated by TraceWin and PyAccel.

CONCLUSION

Error studies for the MINERVA injector performed with TraceWin and PyAccel revealed the performance of respectively the iterative steering (IS) and matrix inversion (MI) orbit correction algorithms. While MI performed better with the global corrector schemes, it exhibited a diverging breakdown introduced by the RF field maps in case of the one-to-one corrector scheme. The necessity for a full corrector occupation in the CHA section was demonstrated with both algorithms. From the observed maximum corrector strengths throughout the CHA section, a design requirement of 0.003 Tm was installed. Further developments, e.g. regarding a combined MI-IS orbit correction algorithm, are in progress.

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