ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-TUPOST035

# BOLINA, A SUITE FOR HIGH LEVEL BEAM OPTIMIZATION: FIRST EXPERIMENTAL RESULTS ON THE ADIGE INJECTION BEAMLINE OF SPES

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*Abstract*

A high-level software BOLINA (Beam Orbit for LINear Accelerators) has been designed to fully characterise and automatically correct the ion beams trajectory, to help operators during the beam transport with an easily scalable suite for LINACs. Currently, the high-level software, interfaced with an EPICS control system, acts on accelerator devices to preserve the beam quality, including beam-based alignment and, if needed, dispersion-free steering software. The suite has been developed to satisfy and commutate the software easily on different machines, using interceptive/not interceptive diagnostics. The software was designed for ELI-np and now is under test at Legnaro National Laboratories of INFN using the installed accelerators complex. BOLINA has been successfully tested on the Adige Injector 1+ beamline of the SPES Project, where the system response matrix is measured on interceptive beam diagnostic by varying both electrostatic and magnetic steerers. This paper describes results and strategies to reduce trajectory residuals close to the diagnostic resolutions and their effectiveness to prepare the commissioning of LINACs.

## INTRODUCTION

The study of beam dynamics under ideal conditions is fundamental and the first step to designing particle accelerators. Deviation from the ideal trajectory causes emittance growth and beam degradations or losses. In a real accelerator many fields and misalignment errors of unknown location and magnitude must be expected. Some uncertainties include diagnostic offsets produced both by mechanical displacements and by biases in the electronics readout, others by misalignment of the magnetic centre of the quadrupole or by the electromagnetic centre of accelerating structures. Many other such errors can cause unexpected beam trajectories that degrade the beam quality and force operators to correct it using steering magnets. Especially for user facilities, to speed up the machine set-up, it is fundamental to have a fast online correction suite.

The BOLINA (Beam Orbit for LINear accelerators) software, designed to help accelerator operators, provide simultaneous optimization of the orbit, finding the trajectory that maximises the beam transport and preserve the emittance to reach the accelerator's nominal parameters. For guarantees the flatness of the orbit, consisting of the simultaneous zeroing of the beam position monitor offset readings, the one-to-one correction algorithm is used. The renowned algorithm [1, 2] in BOLINA is used by minimising a $X^2$ in Eq. (1)

$$\chi^2 = | \overrightarrow{b_m} + \boldsymbol{R}\, \vec{\theta} \,|^2 \tag{1}$$

knowing the beam position offset $\overrightarrow{b_m}$ on the diagnostics and the response matrix previously measured by varying the steerer sets $\vec{\theta}$.

The most interesting part of the BOLINA diagnostic and correction suites is the machine independency. This high-level software is meant to be interfaced with the EPICS control system and to manage accelerator devices to allow beam diagnostic measurements.

BOLINA routines are written in Python: it is fully machine-independent and can be automatic re-used for any type of accelerators by changing just the layout file.

Thanks to its characteristics, it has been possible to test and develop rapidly the BOLINA correction suite for ADIGE Injector 1+ beamline [3].

## INTEGRATION WITH THE CONTROL SYSTEM

The EPICS [4] IOC of BOLINA is divided into different databases. The database defines the functionality of the IOC: which process data it provides, how the data is handled and stored. The database can contain any number of records, each of which belongs to a specific record type. For BOLINA we use five different databases, shown in Fig. 1 one for each type of record.

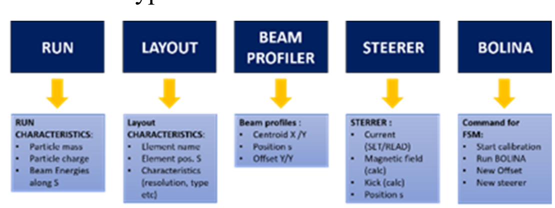


Figure 1: The BOLINA IOC flowchart: dark blue boxes represent the different databases, in light blue the corresponding records and their characteristics.

The RUN database contains all the information of the source and of the beam line characteristics, this is useful to save data in an appropriate way, remembering the beam dynamics characteristics of the specific run like the beam charge, the particle charge, and the beam energy along the beamline. This is used to archive data and remember which accelerator and which beam belongs to it. This allows reuse, saving the calibration file, previous beam response

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matrix and start a new correction from previous conditions. Belongs to the LAYOUT database records that define the machine elements along the beam-line axis (s-axis).

This defines moreover the names of the Beam Profilers and steerer records corresponding to the PVs. In the STEERER and BEAM PROFILER, database records are property of steerer and beam profiler while the records used for the PyEpics Finite State Machine pertain to the BOLINA database.

The Finite State Machine (FSM) uses Pysmlib [5], a useful free software that can be redistributed and/or modified under the terms of the GNU General Public License. This fully useful Python library helps to create event-based finite state machines (fsm) for Epics Control System. Full integration with Epics Channel Access protocol is provided via PyEpics. The user can connect to Process Variables by defining an FSM input /output (I/O) and can therefore access its values and changes via convenient methods. The FSM used methods to process events triggered by the UI (User Interfaces). If the process variable of the BOLINA database's records is true (green lamp) the process continues otherwise it waits. The First process is the calibration, necessary to measure the response Matrix **R**: to start calibration the user needs to enable the steerer used for the automatic trajectory optimization, then the calibration starts by varying steerers and measuring the corresponding beam deflection on the Beam Profiler. When the user finishes the calibration, the beam matrix found can be saved with an appropriate SAVE/LOAD system. After the saving, the user can run the optimization and quickly (in less than a second) the user visualizes the corrected steerer values. The user can then decide to set the new steerer value or not.

Another big improvement necessary to test the BOLINA correction consists of the correction of possible broken wires of the Beam Profile Grid. The wires are corrected by replacing the broken wire with a linear approximation.

## EXPERIMENTAL STRATEGIES AND GOALS

The BOLINA project was born to implement the high-level software for ELI-NP-GBS [3] with online diagnostics and correction suites. ELI-NP-GBS is a very innovative Compton source with the aim of generating photon beams with an energy range between 1- 20MeV, characterized by unprecedented performances in terms of mono-chromaticity, brilliance, spectral density, tunability and polarization. The aim of the BOLINA project for ELI-NP-GBS criticalities is to maximize the overlap area between the laser beam and the electron beam and preserve the beam brightness. These characteristics are critically dependent on unwanted beam trajectories or BPMs offsets that cause a wrong beam paths and consequently an emittance degradation.

Thanks to BOLINA's characteristics, it has been possible to test and develop rapidly the BOLINA correction suite for ion beamlines and ion injectors.

Two main issues have been investigated to adapt the BOLINA suite to ion accelerators. Without thinking of the big differences between the two accelerators type, the bigger feature concerned the use of a different type of diagnostic. In ELI-NP-GBS we use non intercepting diagnostics, Beam Profile Monitors (BPM) while in ADIGE we use intercepting diagnostics Beam Profiler Grids (BPG). This has been resolved weighting the diagnostic differently; the diagnostic closer to the steerer weights more than the farther; if the diagnostic is not inside the beamline the weight is set to zero. The second issue was to change the matrix dimension on-run by the operator, considering or not some steerer magnets or BPG. From beam dynamic simulation studies, for longer accelerator like TANDEM-ALPI, at INFN laboratories of Legnaro, it is more convenient to divide the line in areas and optimise the LINAC stepwise following the beam line from the source to the end.

The goal of BOLINA is to bring the beam onto the golden trajectory defined with the quadrupole shunting technique. This is a technique for determining the quadrupole magnetic centre by varying the quadrupole strength and measuring the resulting deflection of a beam on downstream BPMs. The trajectory so determined is called, in this paper, the golden trajectory.

## EXPERIMENTAL SETUP AND RESULTS

BOLINA has been tested on the ADIGE (Acceleratore Di Ioni a Grande carica Esotici) injector [6] equipped with a surface ionization source [7, 8] able to produce alkali 1+ beam, an electrostatic beam line coupled to a magnetic beam line, where charge multiplication is accomplished by implementing an Electron Cyclotron Resonance (ECR) based charge breeder.

The injector is totally integrated in the SPES (Selective Production of Exotic Species) beam line [9-11], to allow the post-acceleration of neutron-rich radioactive nuclei, with a mass range A = 80÷160, produced by inducing fissions in a multifoil UCx target and is now in an advanced phase of installation. ADIGE up to now is used to start testing the charge breeder prior to the injection of radioactive ions.

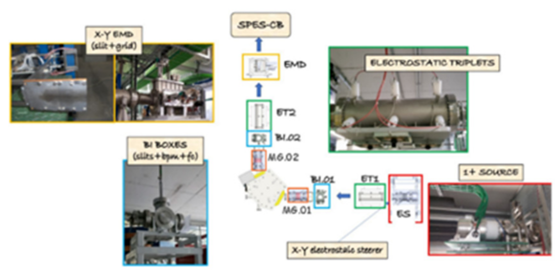


Figure 2: A schematic view of the 1+ beam line of the ADIGE injector.

A schematic view of the 1+ beam line of the ADIGE injector is shown in Fig. 2: allows the use of different ion sources, derived directly from the models will be coupled to the SPES target. The beam is extracted through a 3 mm hole, by applying a maximum voltage of 40 kV on a single gap extraction system, whose distance can be adjusted under vacuum. The beam passes through two couples of X-Y electrostatic steerers (±2 kV max), necessary to correct

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possible beam misalignments and is then be focused by an electrostatic quadrupoles triplet (ET1 in Fig. 2) to the first beam instrumentation box (BI.01 in Fig. 2), equipped with a faraday cup, two beam profile monitors and selection slits. Such box is mounted at the object point of the 1+ selection dipole: it is a 90°, 750 mm radius magnet, with entrance and exit angles of 26.6° and a pole gap of 110 mm. Another beam instrumentation box (BI.02 in Fig. 2) is placed at the image point of the dipole and another electrostatic quadrupoles triplet (ET2 in Fig. 2) further focuses the beam, that arrives at an emittance measurement device (EMD in Fig. 1) two X-Y magnetic steerers (MG.01 MG.02 in Fig. 2) (±5 A max) are placed before and after the dipoles to allow the correct the beam trajectory.

For BOLINA first experimental proof we used the line described previously composed by the two diagnostics BI01 and BI02 and two couple of X/Y steerers, two electrostatic and two magnetic with very different steps, 1 V for ES1 and 1 A for MG1/MG2. The orbit response matrix **R** is very reproducible and can be reused for more days. The orbit response matrix, R, as measured by estimating the orbit difference from correctors kicks and then applying the calibration algorithm to construct the response matrix. Using the quadrupole shunt algorithm, we find the best orbit or golden orbit defined as the orbit that pass through all the centre of the beamline elements. The errors in the beam centroid definition were caused mainly by the beam centroid drift on the diagnostic. Measuring the drift of one day we verified a fluctuation of the centroid readout of 2mm mainly due to the diagnostic resolution and electronic readout. To reduce the fluctuation, the centroid position that we used was the average of the last 10 mensurated values.

The algorithm corrects horizontal and vertical centroid independently and bring the beam in less than 1 second to the golden orbit.

Due to small correlations we need to repeat the procedure once the other orbit is corrected, this happen especially when the uncorrected beam position is very far from the diagnostic center or when the beam is almost lost. In Fig. 3 is reported an example of uncorrected position 10 mm out from the golden orbit. We obtained good results in ADIGE using BOLINA when all the steerer were turned off, at the first iteration BOLINA brought the beam close to the golden orbit.

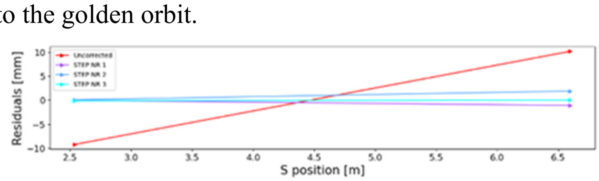


Figure 3: An example of correction for trajectories very far from the golden orbit.

In Fig. 4 we report the measurements of one day shift, residual are close to the variance of the Beam Profiler centroid position.

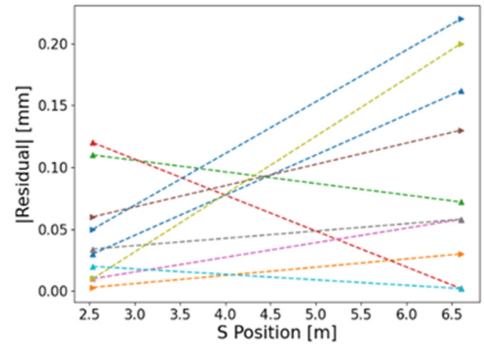


Figure 4: Each line shows the residuals measurements on the two Beam Profiler for every BOLINA correction.

## CONCLUSION

The BOLINA's first experimental results are in line with the expectations. The measured residuals are close to the beam centroid position measured variance (± 0.2 mm).

The software is fast and can be automatic re-used for any type of accelerator starting from a layout file.

Soon, BOLINA will be tested on other ion accelerators of the INFN Legnaro Laboratories. BOLINA is integrated in the control system of ADIGE injector and will help operators during the commissioning phase.

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