BEAM BASED ALIGNMENT METHODS FOR CAVITIES AND SOLENOIDS IN PHOTO-INJECTORS

M. Rossetti Conti[1], A. Bacci[†], Istituto Nazionale di Fisica Nucleare, Milano, Italy
[1]also at Università degli Studi, Milano, Italy

Abstract

Solenoids are often used as lens-like beam focusing elements in electron linacs, especially in the low energy beam lines aside the Gun solenoid for emittance compensation, a common element of high brightness photo-injectors. There are also many electron linacs worldwide which use the Velocity Bunching beam compression technique, which needs solenoids wrapping the first accelerating cavity. A misalignment between the beam trajectory and the magnetic center of the solenoids produces a decrease in the beam quality and makes it necessary to find a complex steering setting to force the beam on a good orbit. In this proceeding we present a study of two beam based alignment techniques, which are correlated: the first shows a method to find the correct electromagnetic axis of an accelerating cavity, the second shows how to align the solenoids (wrapping the cavity) on this axis. Therefore, the study permits to find the best steering setting and the solenoids positions corrections which have to be done. The work is based on real data acquired on the SPARC linac and on a virtual experiment.

INTRODUCTION

In 2015 started a study of the solenoids misalignments relatives to the magnetic center of the cavities of the SPARC's linac. This machine is a test facility built in Frascati (INFN-LNF, near Rome) and works on diverse experiments at different energies. SPARC is able to produce high brightness electron beams thanks to a special technique, named Velocity Bunching (VB) [1], used to compress longitudinally bunches. In order to carry out the VB, it's needed the use of an external focusing force that, for example, in the SPARC's case is provided by many solenoids, wrapping the accelerating cavities (AC1, the first accelerating cavity and AC2, the second one). These solenoids are disposed in a configuration similar to the Helmholtz one. This external focusing is necessary to contrast the transverse space charge forces acting on the bunch. The presence of these elements greatly complicates the beam dynamics when the beam trajectory is not coaxial with the coils [2], for these reasons the coils positioning is a very sensitive issue.

In test facilities working on different experiments it might be necessary to drive the beam at different operative energies, this means that the introduction of a small misalignment or tilt angle of a linac element produces different beam trajectories for different energies. Having different beam trajectories is a main issue in a solenoids realignment process, issue that must be solved before trying to estimate the correction to apply in the solenoids positions. For this reason, we developed a new beam based method, here referred as the first one, able to determinate the nearest trajectory to the Electro-Magnetic Axis (EMA) of a linac's cavity. This special trajectory that we can name "golden orbit" (GO) is the less variable one versus the beam energy. This method had been tested by simulations and by a virtual experiment.

The second method that we want to introduce here, that is applied in sequence to the first one, is necessary to estimate the exact misalignments between the solenoids axis and the reference beam trajectory. This method is based on real measures made on the machine (beam centroids on a Yag target) and beam simulations in the machine itself.

The method is based on the variation of the beam centroid position, on a target, caused by different magnetic fields imposed on each single solenoid. These data, the beam positions on the target, are taken in laboratory, by real beam measures and then interpolated, by using a home-made tool, with beam dynamics simulations. This method has been verified on the real machine and was able to estimate a displacement manually applied to the solenoid.

The use of the both methods gives us access to the data needed to set an ideal trajectory, stable for different energies of the beam and the values of the corrections to apply, on both the transverse axis, to the position of the solenoids.

ORBIT CORRECTION METHOD

The ability to find a correct beam orbit passing through an active beam-line element is a critical issue, for example, the transversal position of a focusing coil, wrapping an accelerating cavity, has to be centered, as close as possible to that orbit that itself has to be as close as possible to the electromagnetic center of the cavity. Conversely, if is chosen a different axial position, the transversal kick usually is not negligible and further, for different accelerating gradient it changes.

So we started, first of all, to study how to reduce this phenomenon of separation of the trajectories, as function of the accelerating gradient. This one is proportional to the distance between the particle position and the EMA of the cavity.

We can define the EMA of the whole linac as the locus of points (defining a curve) in which unwanted transverse contributions to the particle motion are minimized. These contributions are introduced by the position and the ge-

[†]alberto.bacci@mi.infn.it
[1]marcello.rossetti@mi.infn.it

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ometry of the linac's elements but also by built-in materials imperfections or asymmetries, consequently the EMA is not known exactly a priori and so, the issue to find the orbit closer the EMA, already defined as GO, is not trivial.

The Steering Magnets (SMs) are used to correct the beam's trajectory and to force it as close as possible to the EMA. If we set up an array of currents to the SMs, we can measure the beam centroids positions on a target and see it move by setting a different accelerating gradient. This motion's amplitude is proportional, in average, to the integral distances between the points on any trajectory and the points of the EMA (in a mathematical approach). A trajectory very close to the EMA will show much stable centroids (in position) versus different accelerating gradients of the cavity.

Our idea is to map randomly the possible trajectories at different energies and to observe where centroids gather on a target. To demonstrate the efficiency of the orbit correction method we did a virtual experiment with the aim to find the GO in a short linac.

The Virtual Experiment

Simulations The tracking had been performed with the ASTRA [3] code in order to consider the effects of the space charge forces that dominates the beam dynamics in the initial part of the linac.

We made use of GIOTTO [4], a code able to drive ASTRA to perform statistical analysis or genetic optimizations. Then we have chosen randomly a collection of sets of currents (one for each SM) and 6 different operative energies of the linac. The random sets of the currents were chosen in order to keep the beam in the cavity and the propagation of the beam had been simulated for every current set at any energy. At the end we analyzed 640 different families of trajectories and saved the centroids arrival positions on the target.

To test the method, we simulated the following beamline:

1. A SW S-band photoinjector Gun.
2. The Gun's solenoid.
3. A TW S-band accelerating cavity SLAC type.
4. Two couples of SMs. The first one is just after the exit of the Gun's solenoid, the second one is about 50 cm after the beam entrance in the accelerating cavity.

These elements are placed with the following misalignments and rotations (Z as the propagation axis, X as the horizontal one and Y as the vertical one):

- Gun and Gun's solenoid: same misalignment (X, Y) = (-500.0 µm, 0.0 µm)
- Accelerating cavity: tilted on XZ-plane, 0.17 mrad (referred to the Y axis at the cavity center)
- SMs: centered in 0, 0

GO selection Our goal was to demonstrate that the method is able to find a best trajectory compared to the EMA, i.e. the GO without any information on the elements misalignments and tilts. This goal is achieved by doing a bi-dimensional histogram of the centroids positions on the target and finding were they gather, as shown in Fig. 1, where upper part shows the entire target with the Cartesian axes (X, Y) are in black. The red cross represents the prosecution of the cavity's EMA. In the lower part of the Fig. 1 is shown a zoom of the most populated area and the centroids. The circled centroid families refer to the same SMs settings, but with different accelerating gradients.

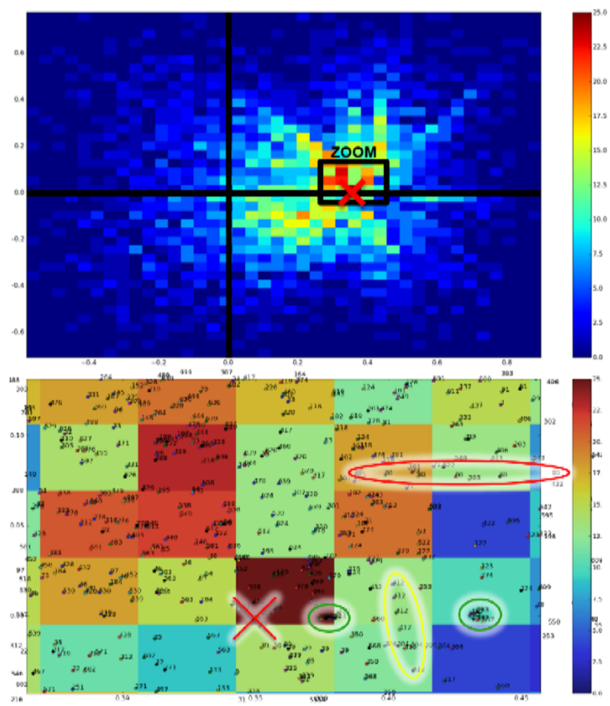

Figure 1: 2D Histogram of the centroids positions on the target plane. In the lower figure a zoom of the most populated area is shown with the most stable trajectories (green circled centroids families) that are close to the EMA (red cross).

We define I as the trajectory instability:

$$I = var(x) + var(y)$$

where var() is the variance of the Cartesian coordinate of the beam centroids position on the target.

In the lowest part of Fig. 1 the two groups of centroids circled in green are the families of more stable trajectories (lower I value), the best of these, that will be called Golden Orbit (GO), is the one on the left and it's very close to the EMA, about 25 µm.

In Fig. 2 are compared two trajectories: a bad orbit, in violet, and the GO, in green. It's easy to see that the found

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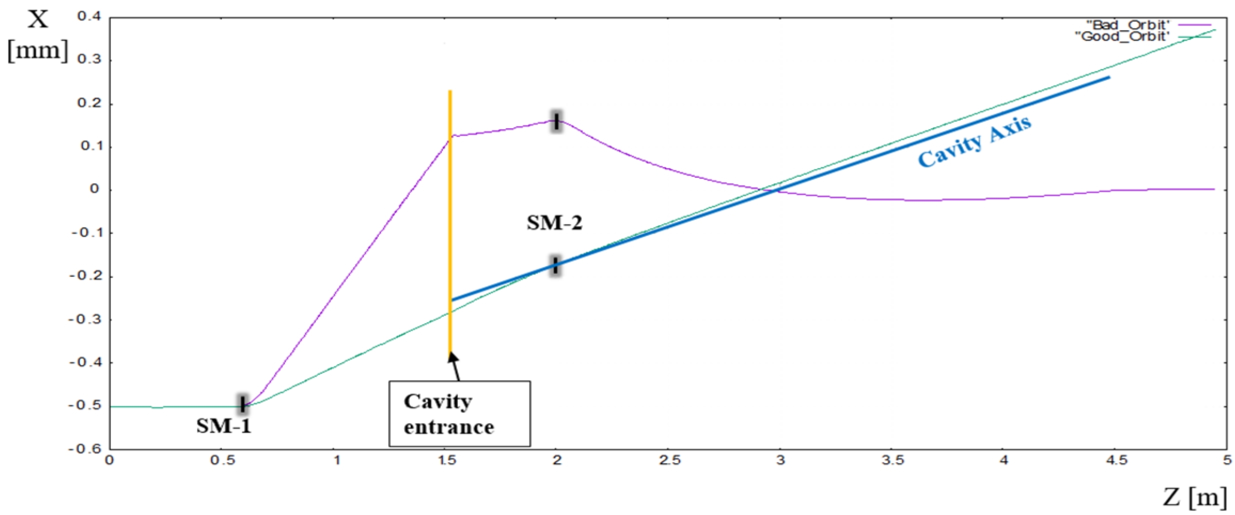

Figure 2: Two trajectories, represented in the horizontal plane. The green one is the best trajectory found, the violet one is a bad trajectory (with high instability). In blue is represented the EMA of the cavity (it's the geometric axis). As one can see, the more stable trajectory found is really near to the EMA of the cavity.

GO is really close to the EMA of the cavity, shown in blue. If needed, the method can be iterated (scanning more trajectories or a smaller area of the target near the supposed EMA position) in order to find a better orbit.

We accepted the best SM currents set found with this method corresponding to the green trajectory in Fig. 2 and pursued with the analysis of the solenoid misalignment.

AC1 SOLENOIDS POSITIONS CORRECTION

We assumed that the incidence angle of the beam on the solenoid face is very small once the GO is set on the machine. This because the solenoids wrapping AC1 are mounted orthogonally to its geometric axis. In this case, solenoid tilt effects on the beam dynamics are minimized and can be ignored in the analysis.

We studied a method to compare the effects of the propagation of the beam in a misaligned solenoid on its dynamics and the real trajectory of the beam.

The following procedure of measurement was applied in laboratory: it is turned on only one coil at a time and ten different values of current are applied to it (0 A, 20 A, 40 A, …, 180 A), for every current a beam of fixed energy (we repeated the experiment at 114 MeV, 165 MeV) propagates in AC1 and hits the target downstream. Data on the centroids positions on the target are taken.

The laboratory data are confronted with ASTRA simulated data obtained in a very similar way. A misaligned coil is simulated with a field map to take into account the field interactions with the metal shell around the coils. We demonstrated that, in absence of effects introduced by the coil tilt, a single field map for every coil can be used to simulate the effects of many other misalignment of the same coil. Indeed, we proved that it is possible to introduce operators (called "stretch" and "rotation") that manipulate the centroids positions on the target obtained with a simulation. This allows to predict exactly the centroids disposition generated with different field maps (corresponding to different misalignments of the coil). This is due to the cylindrical symmetry of the simulated system and is true until the influence of the shell walls on the beam is negligible (it has been verified for misalignments smaller than 4 µm).

We created a Python [5] script to represent for every single coil, at a given operative energy, measured and simulated centroids positions on a Cartesian graph. There are 10 points per dataset, one per current value, disposed on a curve, that can be fitted using the stretch and rotation operator in order to overlap the measured centroids and the simulated ones. Once the fit is done, the misalignment of coil that generates the simulated dataset is taken as the real misalignment of the coil.

CONCLUSION

The two methods previously explained need to be used together in order to correct the positions of the solenoids on a machine that runs at different energies. A more complex virtual experiment, respect to the one here described, has been performed by us to demonstrate that the second method leads to wrong conclusions if used on an orbit with high instability value.

On the other hand, these can also be used properly as stand-alone methods. The first method can be used separately to find an orbit very close to the real EMA of the machine and so to rise the beam quality. This method can also be used to realign cavities, in fact the trajectory found has slope similar to that of the EMA (with this GO the rotation estimation is about 0.19 mrad, the real value is 0.17 mrad). In the case of a machine that operates with a single energy, i.e. with always the same trajectory, the second method predicts the correction to apply to the solenoids respect their position. A study of a "tilt" operator have still to be completed so the latter method, at the moment, is not accurate in case of incident angles $\alpha > 0{,}1°$.

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