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ESS ACCELERATOR LATTICE DESIGN STUDIES AND AUTOMATIC SYNOPTIC DEPLOYMENT

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Abstract

The European Spallation Source is currently under construction in the south of Sweden. A highly brilliant neutron source with a 5 MW proton driver will provide state of the art experimental facilities for neutron science. A peak proton beam power in the accelerator of 125 MW means that excellent control over the beam losses becomes essential. The beam physics design of the ESS accelerator is in a TraceWin format, for which we have developed revision control setup, automated regression analysis and deployment of synoptic viewer and tabulated spreadsheets. This allows for an integrated representation of the data that are always kept synchronized and available to other engineering disciplines. The design of the accelerator lattice has gone through several major and minor iterations which are all carefully analysed. In this contribution we present the status of the latest studies, which includes the first complete end-to-end study beginning from the ion source.

INTRODUCTION

The construction of the European Spallation Source (ESS) is currently ongoing at full force [1], with the first part of the accelerator under commissioning now in the second half of 2018. The ESS is designed to provide the neutron instruments with the world brightest neutron source, coming from the spallation process of a 5 MW proton beam hitting a rotating tungsten target [2]. ESS is built outside of Lund, Sweden, and is a European Infrastructure Research Consortium (ERIC) [3], with 12 founding member countries. A large fraction of the contributions from the member states to the ESS project is done in form of in-kind contracts, and there are currently 38 in-kind partners involved in the ESS project. The ESS user programme is planned to start in 2023.

The ESS accelerator layout is shown in Fig. 1. A microwave discharge ion source is producing approximately 3 ms of stable proton beam pulse of 75 keV at around 70 mA, which is accelerated through an RFQ and DTL, together with two transport sections that make up the normal-conducting front end. After that there are three families of superconducting cavities that bring the beam energy up from around 90 MeV to the final 2 GeV beam energy that is painted onto the rotating tungsten target.

To maintain control over the changes in the beam physics design lattice, and to try to keep the beam physics simulations as close to reality as possible, we have developed a deployment procedure for changing the beam physics lattice files. This procedure involves the use of modern revision control systems, continuous integration, and scripting languages for automated deployment on an interactive web page. Tools which will be familiar to any programmer, but might be a less obvious use case for physicists.

In the second part of this paper, we will go through our recent progress with the large scale integrated error studies of the entire machine, starting from the ion source and up to the target. These studies are essential to confirm that the design can deliver a performance according to specifications, while keeping the losses low enough to not cause problems in the machine.

AUTOMATED LATTICE DEPLOYMENT SETUP

A challenge most accelerator projects face is how to translate beam physics design to accurate locations for all machine elements. Further, during the transition from a pure design phase to an installation and commissioning phase, the physics design might still change, which one wants to make sure to propagate to the appropriate databases when it involves changing physical locations and/or dimensions, or changes such as polarity switches which involves cable routing changes. In the end, most projects end up with some discrepancies between the files used for beam physics studies, and the actual machine installed. This complicates the work for beam physicists, who then need to evaluate which differences may have a relevant impact to beam physics studies, and need to go hunting for errors whenever there is a discrepancy betwen the machine behaviour and what is expected from simulations.

For the ESS, we have predominantly been using TraceWin [4, 5] to simulate the machine, so the beam physics files are stored in TraceWin format. In the beginning these were manually updated and kept in a synchronised folder, with one person being the main responsible for collecting the files for the different sections of the machine and combining to an integrated lattice description. An improvement on this procedure was to store all lattice files in a revision control system (git), so that all changes were authored and could be tracked properly. We extended this with a slightly stricter change control process for what we define as the baseline branch, in order to make sure that all involved parties are aware of and agree to changes to the official machine description.

This quickly ended up being the most accurate and up to date description of element locations, which typically means engineers and other non-physicists started being interested in the data. These users do not know the structure of the TraceWin format, and further, the TraceWin files are not

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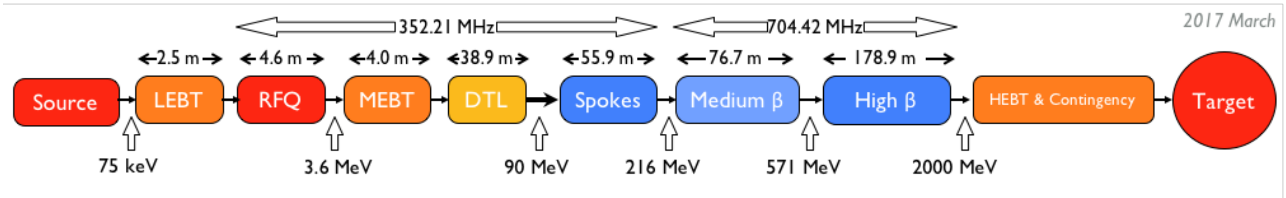

Figure 1: The overall layout of the ESS linac.

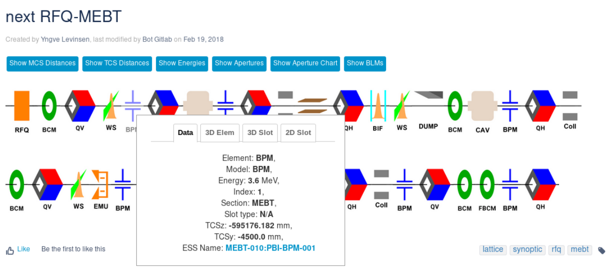

Figure 2: A screenshot demonstrating the synoptic viewer.

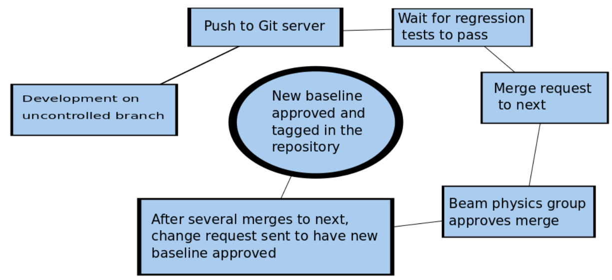

Figure 3: Our work flow for new lattice changes.

really suitable for storing database-like information about the elements. Information such as absolute location of elements are only indirectly available in these files, so a translation is necessary to make them useful to other collaborators.

An initiative was therefore started to tabulate the relevant data from the TraceWin files. This tabulation was automated through a Python script. A few extra descriptors (markers) were needed to fully automate the process, but this was kept to a minimum so that the original files would stay "physicist readable".

This automated process was expanded on, as it now became easy to present the machine in an interactive synoptic viewer. This was realised with a second layer of Python scripts that use the tabulated data as input, and translates them to HTML files that are published on a Confluence Wiki page [6]. A screenshot from this viewer is shown in Fig. 2. All beamline and diagnostic elements are shown in order, and when one clicks on any element one can find useful information about the location with respect to target and source, beam energy at this location, drawings of the element etc. There are several requests to add more information, but we try to only accomodate those in cases when the process can remain automated.

Our current setup allows anyone editing or simulating beam physics files to do so in a way where they can be sure they work on the common and up to date lattice descriptions, and changes they make can be propagated back to the official branches through merge requests that are transparent to everyone involved. The full work flow is shown in Fig. 3. We currently have two controlled versions, one "next" branch which contains a largely stable compilation of the latest changes from the physicists, and one "baseline" branch that contains the latest officially approved lattice. Every time the baseline is updated, a new tag is created so that they can accurately be referred to in publications etc. All other branches in the repository are uncontrolled, which means anyone can add what they want to these branches. When someone has changes that they believe should go in the official branch, they send a merge request from their branch to the next branch. This request is reviewed and approved by the beam physics team. When the next branch contain a significant amount of changes since baseline, the beam physics section prepares a change request which is reviewed and approved by the technical board. The technical board meets 3-4 times per year, which sets a limit on how many times the baseline can be updated.

ERROR STUDIES

The entire ESS lattice has been studied in larger integrated end-to-end studies a few times already, see e.g. [7, 8]. These studies have so far started at the end of the RFQ, adding errors on the input beam that should mimic the real errors from the source, LEBT and RFQ. For the ESS lattice it is important to have excellent knowledge of the expected loss levels in the machine. The machine will deliver 5 MW proton beam power, while the non localised losses are required to stay below 1 W/m at energies beyond neutron production threshold. That means that the relative amount of losses that can be accepted are on the order of 10^{-4} per metre at the front end, and down to 10^{-7} for the 2 GeV beam.

In addition to losses, we also say that the emittance growth should not be more than approximately 10% in each section, which multiplies up to a maximum of around 100% from the MEBT to target. Since a large a large amount of macro particles is required to get good statistics in the beam halo (i.e. good loss patterns), one can make use of the emittance growth as a faster but indirect indication that the real beam going through the same machine may cause losses.

We first apply static errors to the machine according to our requirements. In particular, the RF phase and amplitude

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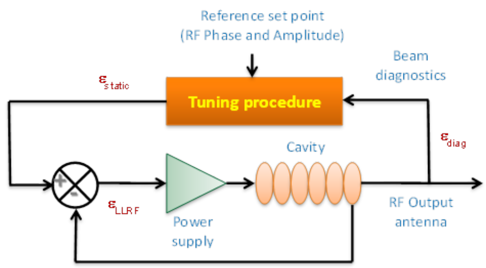

Figure 4: The schematic from the TraceWin manual explaining the concept of the tune cavity procedure [4].

tolerances are expected to be limiting factors for the machine performance. We then run our simulated correction using the beam parameters the diagnostic devices will give us at the location of the diagnostic devices. This matching is an iterative process and requires many simulations of the beam through the machine, which in some cases can take quite some time, even when using envelope calculation. Once the machine is corrected, we then apply the dynamic error tolerances, and finally we do a macro-particle tracking simulation to get accurate prediction of the beam behaviour through a linac that includes realistic errors. It should be noted that in the current configuration, the beam profile is not used for the correction procedure except for in the A2T area.

Such a simulation is performed many times over, and we then get statistical confidence that we will be able to keep at least N% of the machines below the required loss level, and that the emittance stays within reason. We typically aim for up to 99% confidence, which requires around 1000 simulated machines in total to achieve certainty.

For the front-end, there has been studies on how much the output beam from the RFQ varies [9, 10]. We have looked at solenoid scans together with RFQ to see how the transmission through the front-end varies [11]. Lately we have added simulation of the ion source as well using the IBSimu plasma code [12], to get a better agreement between the simulated beam and the actual beam we get from the source that is now under commissioning [13, 14].

Setup

The RFQ errors come from machining of the individual vanes, brazing of vanes to form a segment, and the alignment of each section during assembly of the complete RFQ. These inaccuracies cause errors in the quadrupolar fields of the vanes, as well as introducing dipolar terms. An extensive set of simulation tools have been developed in Python, to evaluate both the defined tolerances, and when available, include the measured vane profiles, brazing errors and alignment errors in the simulation [9, 15]. One can also do a combination, where measured data are used where available, and simulated errors based on defined tolerances are used for the rest.

We have added a new RF tuning procedure in the simulation, which has recently become available in TraceWin (TUNE_CAVITY). The tune cavity procedure is explained in the diagram in Fig. 4. This procedure tries to directly translate the errors we define to how they affect the tuning procedure in the cavity, that involves both the diagnostics that measure the response, as well as errors in the LLRF that provide the tuning feedback to the power supply. This should more closely resemble how a real RF tuning is performed. We should add that we are working on some improvements in the tuning configuration of the DTL that did not make it into the lattice in time for this publication. Hence we might see slightly higher losses than expected in the DTL and downstream of the DTL.

Results

In the error study presented here, we are for the first time including the LEBT and RFQ in the error study directly. For each machine, we take a 1 M sample out of a 10 M IBSimu simulation of the source, which we track through the LEBT and a RFQ vane profile that has been given random errors according to our tolerances. This is used as input for the usual MEBT-A2T error study, where we now no longer add any further input beam errors. At a later stage, we will look into adding errors in the LEBT. We expect that we should be able to reliably correct for the static errors of the LEBT by optimizing the mismatch factor in envelope mode, which is described by [16]

$$M = \left[1 + \frac{\Delta + \sqrt{\Delta(\Delta + 4)}}{2}\right]^{1/2} - 1, \qquad (1)$$

where

$$\Delta = (\Delta\alpha)^2 - \Delta\beta\Delta\gamma, \qquad (2)$$

comparing the difference in Twiss parameters between the matched beam and the measured/simulated beam. Optimizing for the mismatch can be compared to optimizing for transmission through the RFQ, but the latter will be much too time-consuming for an error study of this scale.

If we look at the beams coming out of the RFQ from the different machines, we see about 5-7% spread in the emittances (of the accelerated part of the beam), and around 1.5% of unaccelerated beam, as shown in Fig. 5. We only show the horizontal emittance, but both planes show a similar distribution.

The tracking from a few hundred machines gives the loss pattern shown in Fig. 6. The losses in the RFQ starts around 1 m, which is where the acceleration starts. Around 3-4% of the beam is lost in the RFQ, and another 1.6% is unaccelerated and largely contributes to that first peak we see in the MEBT. The DTL has a tight aperture compared to the downstream linac, so it effectively functions as some sort of collimator for the superconducting section. The spoke section hardly sees any beam losses in our simulations. This is in agreement with earlier simulations, the DTL effectively functions as a sort of collimator for the spoke section, since

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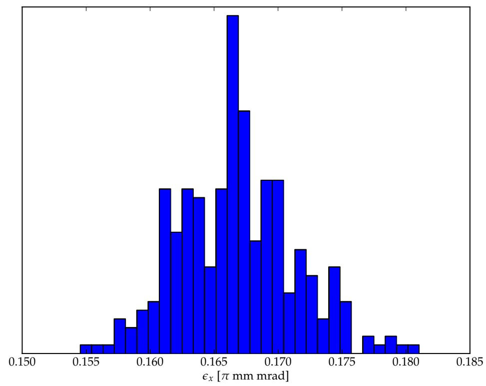
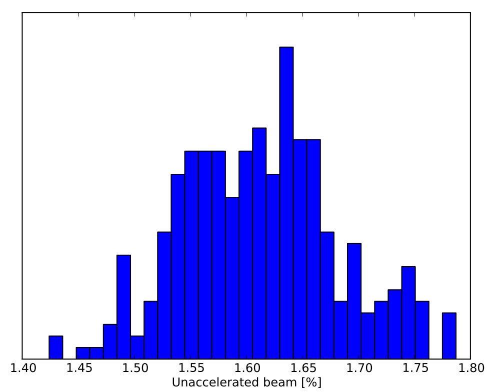


(a) Horizontal Emittance



(b) Unaccelerated fraction

Figure 5: The spread of the beam distributions coming out of the different RFQ's.

the aperture in the spoke section is much larger. The losses in the elliptical cavities (magenta) are essentially all originating from the frequency jump. While we do believe the loss pattern looks largely reasonable, we do believe the absolute numbers can be brought down with a further refinement of the procedure. For this reason we have left the vertical scale as arbitrary units for now.

The spike in the HEBT region is in the area after the neutron shield wall, just before the target. In this area losses on the order of 1 kW are expected. The losses in the simulation is a bit higher than what we would like to see, but not alarming, as we expect further refinement of the tuning configuration should bring the losses down. It is further not unreasonable to expect that correcting for the beam profile at profile measurement locations in the linac might improve the conditions at this location, where we defocus the beam significantly in both planes. Transversal errors generally becomes more relevant when the β-function increases.

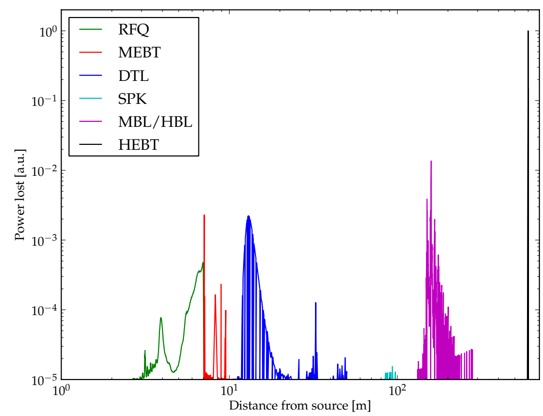


Figure 6: The average losses in W/m from the simulated machines, with a different colour for the different sections of the machine.

SUMMARY

We have developed a set of practices to maintain control over the changes done in the beam physics lattice files for ESS. Using this basis, we have then developed a set of tools to automate retrieval of useful engineering data from these files, and added tests that automatically checks that all representations of the data are consistent. This has made the lattice files useful to several others outside of the beam physics group.

In our latest error study we have done some significant changes, introducing RFQ errors as well as making use of a new RF tuning procedure. The results are already showing reasonable agreement with the old data. Further refinement of the simulated tuning procedure should most likely reduce the losses in the high energy part of the machine compared to the results presented here. We believe this is a good step towards a more realistic simulation of the machine correction, which provides a deeper understanding of the defined error tolerances.

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