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STATUS OF THE ESSNUSB ACCUMULATOR DESIGN

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Abstract

The 2.0 GeV, 5 MW proton linac for the European Spallation Source, ESS, will have the capacity to accelerate additional pulses and send them to a neutrino target, providing an excellent opportunity to produce an unprecedented high performance neutrino beam. The ESS neutrino Super Beam intends to measure, with precision, the charge-parity (CP) violating lepton phase at the 2nd oscillation maximum. In order to comply with the acceptance of the target and horn systems that will produce the neutrino super beam, the long pulses from the linac must be compressed by about three orders of magnitude with minimal particle loss, something that will be achieved through multi-turn charge-exchange injection in an accumulator ring, which should be able to accommodate over 2×10^{14} protons. Several design challenges are encountered, such as strong space charge forces, low-loss injection with phase space painting, a reliable charge stripping system, efficient collimation, and e-p instabilities. This paper focuses on the status of the accumulator ring design, with multi-particle simulations of the injections procedure.

THE ESSNUSB

The European Spallation Source (ESS) [1], presently under construction in Lund, Sweden, will be the world's highest brightness neutron source, powered by a 5 MW proton linac. The linac accelerates proton pulses to 2 GeV, at a repetition rate of 14 Hz and a duty cycle of 4%, and transports them to the target station. The RF cavities in the ESS linac can accept up to 10% duty cycle, which means that it has the capability to provide an additional 5 MW of beam power. To this end, the ESS linac can, with moderate modifications, be used for the production of a very intense neutrino beam, the ESS neutrino Super Beam (ESSnuSB). ESSnuSB aims at measuring, with precision, the CP violating angle at the 2nd oscillation maximum [2] using a megaton-scale Water Cherenkov detector located a few hundred kilometres from the neutrino source.

The neutrino target station [3] consists of four targets, each equipped with a neutrino horn which provide optimum focusing during only about 1.5 µs. The ESS linac, however, provides pulses of 2.86 ms duration. In order to make full use of the unique beam intensity of the ESS, these pulses must be compressed through multi-turn injection into an accumulator before they are sent to the target. Figure 1 shows a schematic view of the ESSnuSB facility on the ESS site.

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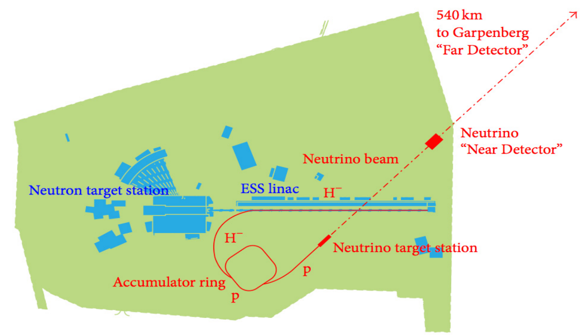

Figure 1: The ESSnuSB baseline layout on the ESS site.

Charge-exchange (H^-) injection will be used in order to accommodate the high beam intensity and to minimize beam losses at injection. Each linac pulse will be split into four sub-pulses, or batches, and each batch will be accumulated separately during roughly 500 turns. Each accumulated batch will then be extracted in one turn and sent to one of the four targets. Through this scheme, the average beam power on each target will be limited to 1.25 MW, and the space charge tune shift in the ring will be kept at an acceptable level.

In order to improve the performance of the neutrino experiment, the ESSnuSB will raise the ESS beam energy from 2.0 to 2.5 GeV, which has the consequence that 5 MW of beam power, for neutrons and neutrinos, respectively, can be reached with a reduced beam intensity in the accelerator. Three gaps of 100 µs duration will be required for reconfiguration of the accumulator in between each batch. In addition, there will be extraction gaps at regular intervals corresponding to the revolution period in the ring. These gaps, which must be generated in the linac, will have a duration of about 10% of the revolution time. Since the beam pulse duration in the linac cannot be extended, the current in the linac need to be increased from 50 mA to about 62 mA, in order to compensate for the intensity loss due to the presence of the gaps. A summary of the ESSnuSB parameters is shown in Table 1.

Table 1: A Summary of the ESSnuSB Parameters

Parameter	Value	Unit
Average beam power	5	MW
Beam energy	2.5	GeV
Pulse average current	62	mA
Pulse duration from linac	2.86	ms
Pulse repetition rate	14	Hz
Beam intensity per filling	2.2×10^{14}	

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THE ACCUMULATOR

Lattice Design

The current accumulator ring lattice, displayed in Fig. 2(a), is an improved iteration of a previous design presented in Ref. [4]. It has a 384 m circumference with four superperiods in order to suppress systematic resonances, see Fig. 2(b). Each of the four arcs contains four FODO cells, and has a horizontal phase advance of 2π for closed dispersion. The long straight sections will accommodate beam injection, extraction, collimation system for beam halo scraping, and RF cavities for longitudinal beam shaping.

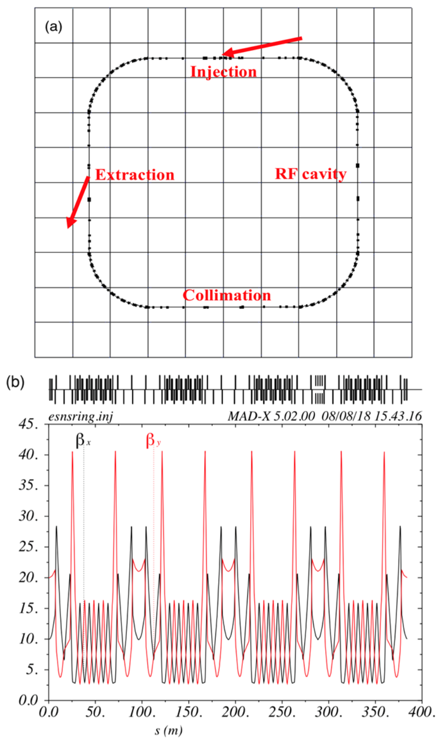

Figure 2: Schematic of the lattice (a) and betatron functions throughout the ring (b).

The injection region houses a fixed orbit bump in combination with a fast, adjustable bump for phase space painting. The high beam intensity and the high batch-to-batch frequency makes the H^- stripping a challenge. The baseline option for the ESSnuSB is to use laser-assisted stripping [5], thus assuming that by the time of project realization, the technique would have advanced significantly. As a start-up option, conventional foil stripping will be used. The optical functions in the injection region are currently setup for foil stripping, and evaluations of the temperature rise in the stripping foil are ongoing.

Simulations

The simulation code pyORBIT [6] with PTC external libraries has been used to characterize the lattice and optics with beam. Direct and indirect space charge forces, based on an FFT model, are included in the code, which are needed to realistically evaluate the effect of the high accumulated charge.

In the simulations, an incoming beam with normalized RMS emittance of 0.25π mm mrad, and an RMS energy spread of 0.02%, has been used. The particles follow a Gaussian distribution in the transverse planes and in energy. In the longitudinal spatial coordinate, the beam is assumed to be uniform but with extraction gaps occurring each 1.3 μs, which corresponds to the revolution period in the ring. Each gap has a duration corresponding to 10% of the revolution period. At extraction, these gaps must be at least 100 ns long for the ramping of the extraction kickers. Several ways of preserving the gaps have been studied.

Injection Painting

In order to reduce space charge effects in the ring, phase space painting will be used. Figure 3 shows the result of a multi-particle simulation of the full injection, with correlated painting, both in phase and real space. Two cases are shown: with (red) and without (blue) space charge activated in the simulation. The population of the beam halo due to space charge forces is clearly visible. The final emittance before extraction is visible in Fig. 4, where the vertical axis shows the fraction of the beam particles that are outside a specific beam emittance marked on the horizontal axis. The emittance tail due to space charge is clearly visible. Figure 5 shows the corresponding tune diagram, with a tune spread below 0.05.

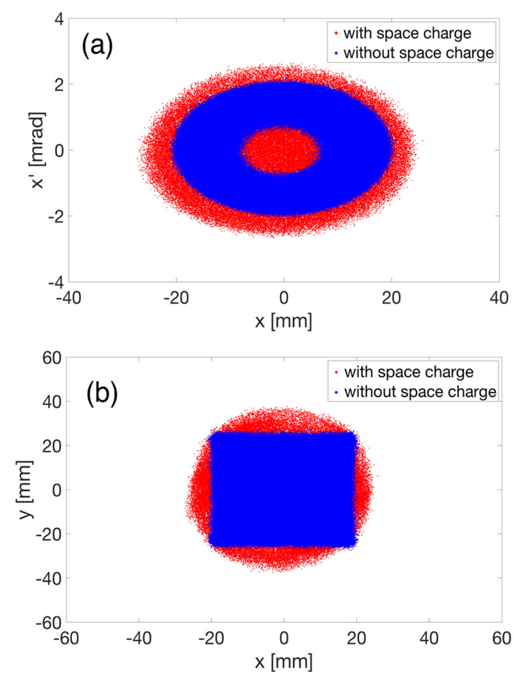

Figure 3: Beam distribution with and without space charge, in phase space (a) and real space (b).

We first conclude that we can reach an unnormalized emittance including 100% of the beam, of around 70π mm mrad, which is well below the 120π mm mrad that was initially targeted in the ring design. More detailed studies of the beam dynamics, foil temperature, and other important factors that may modify this conclusion, are underway.

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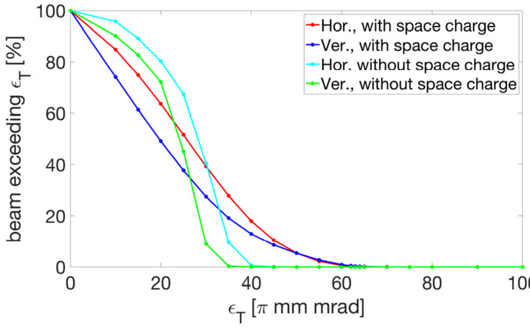

Figure 4: Percentage of the beam exceeding a given emittance in the transverse planes with and without space charge.

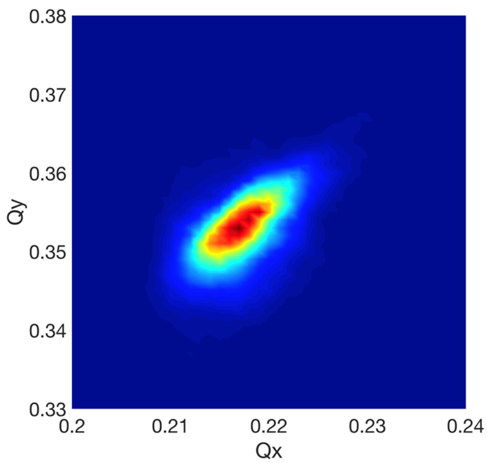

Figure 5: Tune density map.

Longitudinal beam shaping

The 100-130 ns beam gap, which is required to minimize losses during the single-turn extraction, must be created at the beginning of the linac and maintained in the ring. Several ways of preserving the gap have been considered: a) with a single- or dual-harmonic RF systems; b) without RF systems; c) with a barrier RF system [7].

The single- or dual-harmonic RF systems can offer a fairly large longitudinal acceptance and effective gap preservation but unfortunately produce a rather large energy spread, compared to that of the incoming beam. With the increased energy spread follows a chromatic tune spread which is of the same order as the tune spread caused by space charge, unless the natural chromaticity is corrected. Sextupoles have recently been added to the lattice in order to allow for chromaticity correction, but they may also cause a reduction of the dynamic aperture.

To avoid the chromatic tune shift, the option of no cavity was tested through simulations. Despite the fact that the beam has a relatively high stiffness in the longitudinal plane, some leakage into the gap was observed, which excludes this option.

The option of a barrier RF system is the most promising solution since it keeps the gap clean while leaving the majority of the beam unperturbed. Figure 6 shows the longitudinal distribution after the complete accumulation process. The plot contains the case of no cavity compared to the configuration with a barrier cavity. When space charge is activated in the simulation, only the barrier RF cavity provides the necessary longitudinal focusing to make the gap clean.

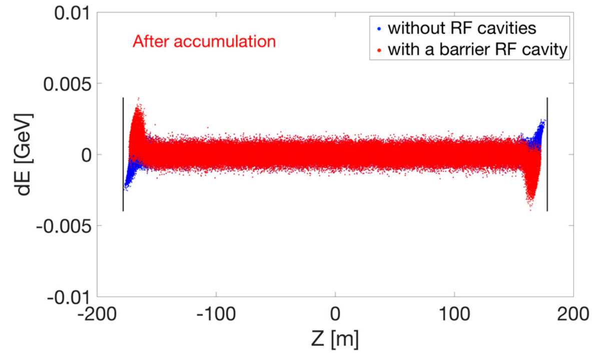

Figure 6: Beam distribution in longitudinal phase space when no cavity is used (blue) and with a barrier RF cavity (red).

CONCLUSIONS

The design of the accumulator ring for the ESSnuSB is progressing. The ring will accumulate 2.2×10^{14} particles per fill to an unnormalized 100% emittance that can be less than 120π mm mrad and a tune shift of 0.05. The extraction gap can be preserved efficiently using a barrier RF cavity. Detailed studies of the beam loss, collimation, and chromaticity correction, are ongoing.

ACKNOWLEDGMENTS

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