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The Accumulator Ring for the ESSnuSB Project

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The ESS will have the capacity to offer an additional 5 MW of beam power, which provides an excellent opportunity to produce an unprecedented high performance neutrino beam that intends to measure, with precision, the charge-parity (CP) violating lepton phase at the 2nd oscillation maximum. In order to comply with the neutrino target and horn systems, each long pulse from the ESS linac must be split into 4 sub-pulses and compressed up to three orders of magnitude before impinging on the target. A chopping system will be adopted in the linac to split the pulses while an accumulator ring will be used to compress the pulses from the linac. Multi-turn charge-exchange injection to the accumulator will be adopted since it allows high beam intensity injection with minimal beam loss. Several challenges of the accumulator ring design are encountered, such as low-loss beam injection, a reliable charge stripping system, a set of collimation system with high efficiency, and e-p instabilities. This paper focuses on the accumulator ring design, with numerical simulations of the injection procedure.

The 21th International Workshop on Neutrinos (NuFact2019)
25-31 August 2019
Daegu, Korea

1 Speaker

1. Introduction of the ESSnuSB and its accumulator

The European Spallation Source (ESS) [1], presently under construction in Lund, Sweden, will be the world's highest brightness neutron source. The ESS is powered by a 5 MW superconducting proton linac, by which pulses are accelerated up to 2 GeV, at a repetition of 14 Hz and a duty cycle of 4%, and transported to a neutron target station. RF cavities adopted in the ESS linac can accommodate a duty cycle up to 10%, which means the ESS linac, with moderate modifications, has the capability to provide an additional 5 MW of beam power that could be used for the production of a very intense neutrino beam through a neutrino target system. The ESS neutrino Super Beam (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 kilometers away. The neutrino target station [3] consists of four targets, each equipped with a neutrino horn that provides optimum focusing during about 1.5 μs. The ESS linac, however, provides pulses of around millisecond 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 sent to the neutrino target station. Figure 1 shows a schematic view of the ESSnuSB facility on the ESS site.

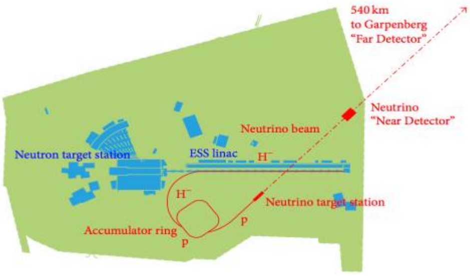

Figure 1: Schematic view of the ESSnuSB facility on the ESS site.

For this high power accumulator design, the primary concern is radioactivation caused by excessive uncontrolled beam loss could limit the machine's availability and maintainability. Based on operational experience at SNS and J-PARC, hands-on maintenance demands an average uncontrolled beam loss not exceeding one watt of beam power per meter. At megawatt power level, for an accumulator ring with several hundred meters in circumference, the tolerable fractional beam loss is about 10^{-4}. Charge-exchange (H^-) injection will be used in order to accommodate the high beam intensity and to minimize uncontrolled beam loss 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 linac. 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 total 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.

2. Lattice design

The current accumulator ring lattice, displayed in Fig. 2, 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. 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.

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 and the optical functions in the injection region are currently setup for foil stripping. Table 1 shows a summary of the lattice parameters.

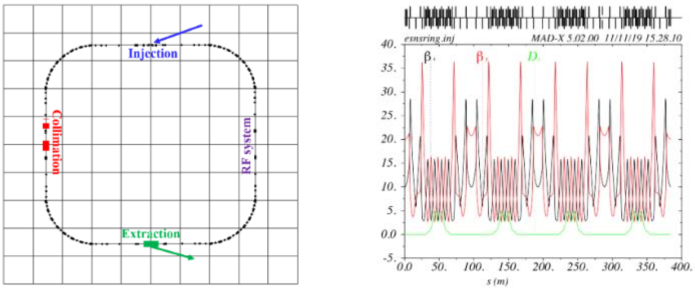

Figure 2: Left: schematic of the lattice; right: betatron and dispersion functions throughout the ring.

Table 1: A summary of the lattice parameters

Parameter	Value
Circumference (m)	384
Inj./Ext. Energy (GeV)	2.5/2.5
Repetition rate (Hz)	14
Ring dipole field (T)	1.3
Magnetic rigidity, Bρ (T m)	11
Max beta hor./ver. (m)	29/35
Hor./Ver. Tune	8.24/8.31
Transition energy, γ_T (GeV)	5.8
Hor./Ver. natural chromaticity	-11.2/-12.4

3. Numerical 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 space charge in the accumulator. Carbon foil is used to strip the convoy electrons of the injected H^- and the scattering model implemented in the code includes multiple Coulomb scattering, large angle Coulomb scattering, and nuclear scattering.

In the simulations, an incoming beam with normalized RMS emittance of 0.35π 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.

In order to reduce space charge effects in the ring and minimize the average hits on the foil, phase space painting will be used. For the painting process, the phase space offset of the injection beam relative to the ring closed orbit varies as per the square-root-type functions. Both correlated and anti-correlated painting schemes have been studied. As shown in Fig. 3, the beam density distribution after accumulation, with anti-correlated painting, both in phase and real space are very uniform. The final 100% geometric emittance before extraction is about 60 π mm mrad, as shown in Fig. 4 (left), where the vertical axis shows the fraction of the beam particles that are outside a specific beam emittance marked on the horizontal axis. The beam halo due to space charge forces is almost invisible. Figure 4 (right) shows the corresponding tune diagram, with a tune spread below 0.03.

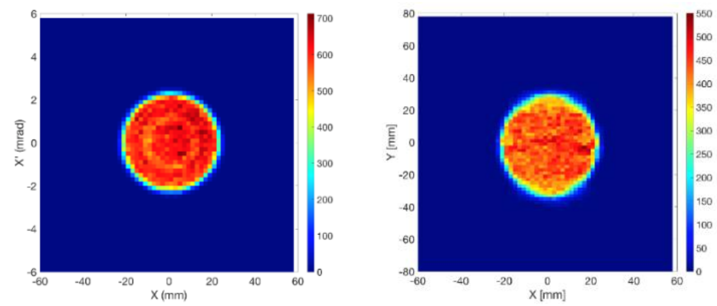

Figure 3: Beam density distribution with space charge in phase space (left) and real space (right).

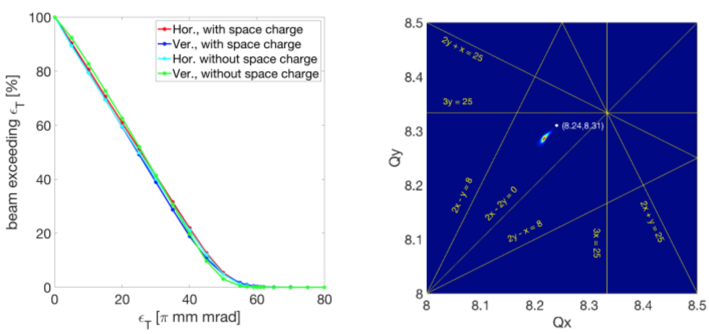

Figure 4: Left: percentage of the beam exceeding a given emittance in the transversal planes with and without space charge; right: tune diagram

4. 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

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of preserving the gap have been taken into account: 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 even larger than the tune spread caused by space charge, unless the natural chromaticity is corrected. 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 5 shows the longitudinal distribution and probability density function of energy dispersion 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, the barrier RF cavity is able to provide the necessary longitudinal focusing to make the gap clean and maintain the energy dispersion very well.

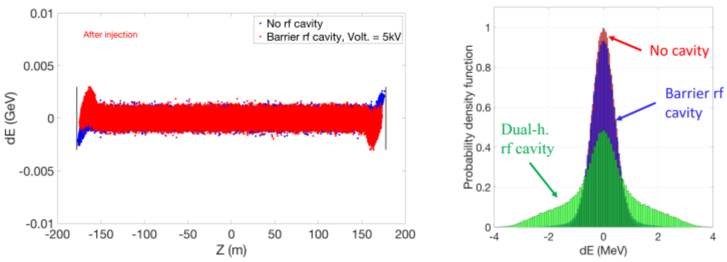

Figure 5: Left: beam distribution in longitudinal phase space without RF cavity (blue) and with a barrier RF cavity (red); right: probability density function of energy dispersion.

The design of the accumulator ring for the ESSnuSB is progressing. The ring will accumulate 2.2×10^{14} particles per fill to a geometric 100% emittance of about 60 π mm mrad and a tune shift of 0.03. The extraction gap can be preserved efficiently using a barrier RF cavity. Detailed studies of the beam loss, foil issue, collimation, and chromaticity correction, are ongoing.

ACKNOWLEDGMENTS

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 777419. This project is supported by the COST Action CA15139 'Combining forces for a novel European facility for neutrino-antineutrino symmetry-violation discovery (EuroNuNet)'.

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