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THE ACCUMULATOR OF THE ESSnuSB FOR NEUTRINO PRODUCTION

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Abstract

The European Spallation Source (ESS) is a research center based on the world's most powerful neutron source currently under construction in Lund, Sweden. 2.0 GeV, 2.86 ms long proton pulses at 14 Hz are produced for the spallation facility (5MW on target). The possibility to pulse the linac at higher frequency to deliver, in parallel with the spallation neutron production, a very intense, cost effective and high performance neutrino beam. Short pulses on the target require an accumulator ring. The optimization of the accumulator lattice to store these high intensity beams from the linac (1.1 10^{15} protons per pulse) has to take into account the space available on the ESS site, transport of H^- beams (charge exchange injection), radiation and shielding needs. Space must be available in the ring for collimation and an RF system for the extraction gap and loss control. We present the status of the accumulator for the ESS neutrino facility.

NEUTRINO PRODUCTION AT ESS

The European Spallation Source (ESS) [1] presently being built in Lund, Sweden, is a research centre that will have the world's most powerful neutron source. It is based on a 2.0 GeV superconducting linac, giving 2.86 ms long proton pulses at 14 Hz for the spallation facility (5MW on target). By pulsing the linac at 28 Hz, additional interleaved H^- pulses sent to a neutrino production target system, would give an opportunity to produce neutrino beams with unprecedented intensity [2]. The corresponding number of protons on target per year would be 12.7 10^{23}. However, the horn based hadron collector can not, for the time being, handle 2.86 ms long pulses due to ohmic heating of the magnet system current leads. Therefore the linac pulse has to be accumulated in a storage ring to produce pulses, a few μs long, on the neutrino production target.

THE ESS LINAC

The duty cycle of the ESS superconducting linac is relatively low (4%). This fact opens a possibility to add pulses in between those used for the spallation neutron production and use them to produce neutrinos. The linac would then be pulsed at 28 Hz, resulting in a total linac power of 10MW. The additional 5 MW that have to be provided for the neutrino production require an upgrade of the ESS linac, in particular of systems related to the acceleration of the H^-- beams needed for charge exchange injection into the accumulator. An additional H^--source would be added, probably including also additional LEBT, RFQ and MEBT sections for matching the H^--beam and the proton beams separately [1]. It is foreseen that focussing and steering elements necessary to tune the H^- beam may change setting between proton and H^- pulses. The ESS construction has started, therefore an urgent preliminary feasibility evaluation of the needed equipment and infrastructure upgrades has taken place, in particular concerning water, cryogenic distribution and capacity, radio frequency couplers, klystron modulators, and electric transformers and power capacity.

To fill the accumulator ring with 1.1 10^{15} protons is a challenging task and the possibility to split the 2.86 ms linac pulse in shorter linac pulses with the same current, still keeping the 5 MW total power for the neutrinos, would be a possibility to fill the accumulator with less number of particles but more often. The option of accelerating, for example, four shorter linac pulses for the neutrino production would make the Linac pulse at 70 Hz giving one 2.86 ms pulse for neutrons and four 0.72 ms pulses for neutrino production, see Fig. 1. 5MW beam power needs 13.3 MW wall plug power for one 2.86 ms long pulse. 4 pulses of 0.72 ms would need 17 MW power consequently there is an operational overhead for this option. To increase the duty cycle may lead to collective effects, which may limit the maximum usable duty cycle in the cavities. Extensive ongoing testing and future operational experience will show if higher duty cycles can be accepted. The aim is to operate the linac at the lowest possible frequency. The final design considerations and cost optimization of the accumulator will decide the optimal repetition rate.

The accumulator will be designed in order to profit from a possible linac upgrade to higher energy by designing the transfer line from the linac to the accumulator for 2.5 GeV and placing the extraction point in the contingency region of the linac, situated between the end f the linac and the spallation target region, where 2.5 GeV could be reached after adding more accelerating modules.

THE ACCUMULATOR

A preliminary lattice of 376 m circumference is described in [3] and summarized in Table 1. The accumulator has to be installed on the ESS site including the transfer lines and the target station. For the H^- beam transfer line the allowed minimum bending radius is limited by the Lorenz stripping of the H^--ions. The criterion we have used to design the transfer line is to have a beam loss corresponding to less than 0.1 W/m heat deposition. With a 66% dipole filling factor in the transfer line we would get, for 2.5 GeV, a radius of about 110 m (see [4]). The baseline layout for the accumulator, target, transfer lines, and the neutrino beam can be seen in

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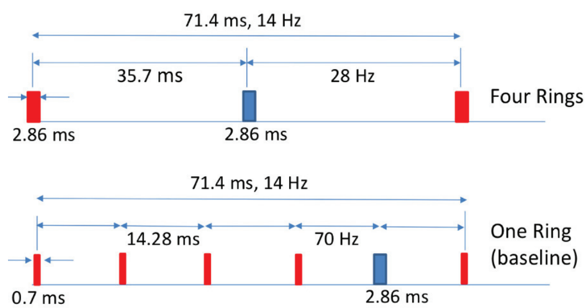

Figure 1: Pulse distribution for the 4-ring and the one-ring options: The upper part of the figure shows the 28 Hz pulsing of the linac with one proton (blue) and one H^- (red) pulse interleaved and the lower part shows the case where four 0.72 ms long pulses of H^- for neutrinos are followed by one 2.86 ms proton pulse for the neutrino spallation target.

Fig. 2. The target station would need to be at a depth of 25 m, requiring special studies regarding the ground water and the neutrino beam would pass below the proton linac;

Table 1: Summary of Lattice Parameters for the Accumulator

Parameter	Value
Circumference	376 m
Number of dipoles	64
Number of quadrupoles	84
Bending radius	14.6 m
Injection region	12.5 m
Revolution time	1.32 μs

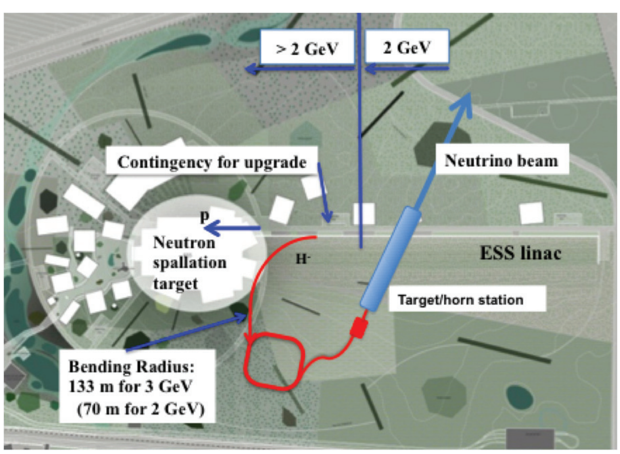

Figure 2: The accumulator on the ESS site.

The Lattice

Following the design concept of the SNS lattice, where the magnet fields in the original 1 GeV lattice are rather moderate, it is possible to copy the 30 m injection straight sections unchanged for 2GeV. However, in view of the large apertures required it makes sense to keep the bending fields in the arcs as conservative as in the SNS; hence the arc lengths are doubled. The circumference is increased from 248 to 376 m, this way reducing the number of turns injected per fill. The collimation layout (in the first long straight section after the injection section) remains the same [5].

Different lattices types will be designed to study space charge; for the first simulations the existing FODO lattice **??** will be used. From [6] we keep in mind that a FODO lattice is very flexible and robust and gives a compact beam size for high energy machines, however a relatively large variation of the beam size. Doublet lattices give more space in the lattice and are optimal for focusing of highly non-spherical beams (mini-β in electron colliders) and can lead to large changes in the transverse beam size and so in the non-linear space-charge kick. Triplets give a very smooth variation of the beam size, and in particular small variations of the ratio between the two transverse sizes, (e.g. mini-β in p-colliders) and an almost uniformly distributed space-charge field.

The Injection

For a pulse length of 1/4 of the original 2.86 ms beam about 1000 turns would need to be injected. We would need an rf-system to keep the gap in the circulating beam to be able to extract the beam out of the accumulator. This gap will be produced in the Linac MEBT section by regularly chopping the beam. The gap corresponds to the extraction kicker rise time which is 100-50 ns, depending on the design of the lattice and the angle of extraction.

As at the SNS, we propose charge exchange injection by foil stripping, as a first approach. Laser stripping is envisaged ultimately, but no design exists so far; an experiment is planned for 2016. By using a foil stripping solution, a future SNS realization could ultimately be ported to the ESS accumulator with limited modifications, provided the SNS-like injection lattice is conserved.

Foil Temperature In Ref [3] stripping foil temperatures were consistently computed in two different ways: firstly by tracking the injection process with the Accsim code [7] to compute the power density at the foil and subsequent evaluation with the 1D model used by [8], assuming radiation cooling only, and secondly by analytical 3D calculations assuming constant power density over the linac beam spot [9]. With method 1 a peak temperature of 2050 K at the hottest spot is produced under the effect of both the linac and the circulating beam (the incident linac beam alone heats only to 1800 K). Although this was considered as tolerable, there remains an interest to reduce the peak temperatures to a region in which operational experience exists, like at the SNS with temperatures not exceeding 1600 K. The average number of foil passes per particle was approximately 4.5. The obvious way to reduce the temperature is reducing the density by an increase of the spot size of the incoming H^- beam. The matching conditions require that the blow-up of the transverse size of the circulating beam, be only local. This was achieved simply by modifying the optics of the injection straight and adding correction quads in the remaining straight sections to conserve the tunes. In this test case, the beta function values at the foil moved from (9.4, 19.5) m to (18.4, 51.6) m, widening the circulating beam by

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Table 2: Comparison of the scenarii discussed in subsection "Foil Temperature"; "$200\pi IPAC'14$" recalls the results published at IPAC 2014 [3], the other column show the results for large beta functions, 200π and 100π emittance respectively, The last colums shows the results for large beta functions, 200π emittance but with only two injection into the accumulator.

Scenario	Unit	**200π IPAC'14**	**200π large β**	**100π large β**	**200π large β 2 rings**
Number of rings or pulses		4	4	4	2
H^- pulse duration/ring	ms	2.86/4	2.86/4	2.86/4	2.86/2
H^- rep. rate	Hz	70	70	70	42
Linac spot size at foil FW	mm	7 x10	10 x 17	10 x 17	10 x 1
Beta functions at foil	m	9.9, 19.9	18.4, 51.6	8.4, 51.6	18.4, 51.6
Linac peak power density	MW cm^2/g	10.01	5.35	5.35	5.35
Linac peak current density	A/m^2	4840	2550	2550	2550
Average number of foil hits		4.5	4.8	8.0	6.5
Max foil temperature Linac/circulating p/both	K	1800/1720/2050	1800/1460/1550	1440/1650/1650	1580/1790/1830

40% and 62%, respectively. This modification brings the peak temperatures down to 1440 K for the incident linac beam alone and 1550 K for the effect of the H^- and p beams together, with about the same average number of 4.8 foil passes. Interesting enough this model brings 100 π normalized emittance beams back into the realm of possible temperatures with the hottest peak at only 1650 K. These facts encourage investigation of more ambitious scenarios. As an example, we looked into the case (for a final beam of normalized emittance 200π) where the ring is filled only twice, each time with a linac pulse of 1.5ms (leaving open the question whether the target can stand the twofold energy per pulse). Indeed, the beam blown up at the foil this leads to peak temperatures of 1560 K for the H^- beam alone and 1850 K for the sum of the effect of p^+ and H^- beams. The maximum space charge tune shifts remain below -0.16, a rather conservative value. See summary in Table 2.

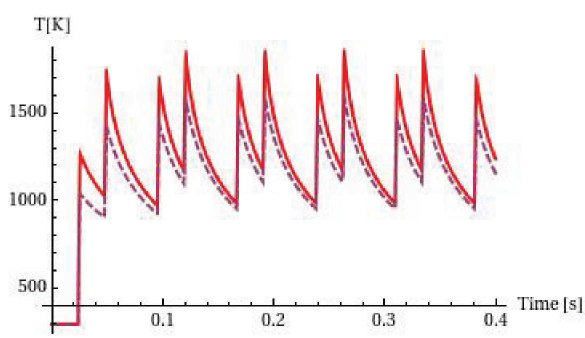

Figure 3: Evolution of maximum foil temperatures [K] at the H^-- spot peak (dashed) and the combined H^- and circulating protons peak (red). Only two injections into the accumulator per linac pulse.

CONCLUSION

To limit the number of charges in the accumulator it needs to be pulsed at higher frequencies and with shorter linac pulses than the 14 Hz and 2.86 ms, respectively, which are the nominal values for the linac pulses going to the neutron spallation target. An evaluation of the feasibility of the suggested upgrades of the linac for the the neutrino beam production has found no show stoppers, however tests of the rf modulators and couplers will need to take place to confirm the possibility of rising the pulse frequency. In order to operate the accumulator before an operational laser stripping system is available, foil stripping can be used as a technologically available solution [5]. First investigations have shown that with 1.5 ms long pulses there is a reasonable margin for the maximum temperature reached as compared to 2500 K, which is a target-value for having the necessary margin to the carbon melting temperature. This gives confidence that the accumulator can initially be operated using foil stripping. Further consolidation and optimization is required of the injection optics and particle distribution on the foil for the development of a stripping system.

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