

THE ACCUMULATOR OF THE ESSNUSB FOR NEUTRINO PRODUCTION

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Abstract

The European Spallation Source (ESS) is a research centre based on the world's most powerful neutron source currently under construction in Lund, Sweden, using 2.0 GeV, 2.86 ms long proton pulses at 14 Hz for the spallation facility (5MW on target). It would be possible to pulse the linac at higher frequency to deliver, in parallel with the spallation neutron production, a very intense, cost effective, high performance neutrino beam. The minimization of the Joule heating in the target horns requires proton pulses far shorter than the linac pulse. Therefore an accumulator ring is required after the linac to compress the linac pulses. Charge exchange injection of an H^- beam from the linac would be used. The Linac would deliver $1.1 \cdot 10^{15}$ protons per pulse. Due to space charge limits, several rings or one ring re-filled several times during the neutrino cycle are necessary.

NEUTRINOS 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]. However, the horn based hadron collector can, for the time being, not handle 2.86 ms long pulses due to ohmic heating of the magnet system, therefore the linac pulse has to be accumulated in a storage ring to produce μs pulses on the neutrino production target.

THE ESS LINAC

The additional 5 MW that have to be accelerated for the neutrino production require an upgrade of the ESS linac, in particular systems related to the acceleration of the H^- beams for charge exchange injection.

One possibility to cope with the high intensities would be to distribute the linac pulse into 4 accumulators [2]. We propose to use only one accumulator using 4 shorter linac pulses sequentially. The linac would pulse at 70 Hz giving one 2.86 ms pulse for neutrons and four 0.72 ms pulses to the neutrino target, 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. The additional 3.7 MW have to be seen in the light of the construction cost,

the power consumption and the operation of 3 additional accumulators. The injection foil in one accumulator will have to strip 4 times more particles than in the case of the four-ring option.

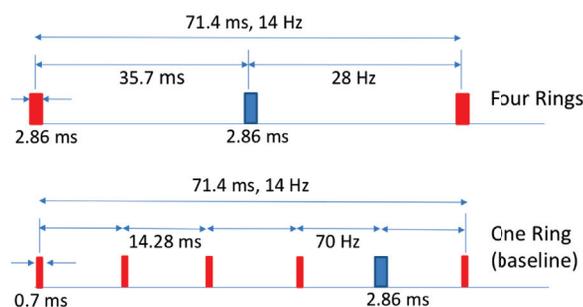


Figure 1: Pulse distribution for the 4-ring and the one-ring options: The upper part of the figure shows the 28 Hz pulsing of the linac with one proton (blue) and one H^- pulse interleaved and the lower part shows the case where four 0.72 ms long pulses of H^- for neutrinos are followed by one 2.86 ms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

THE ACCUMULATOR

At present, we do not attempt to design the ultimate ring lattice but to verify the feasibility of the assumptions quoted so far. For this goal an existing design has been used, the SNS, which is actually the only accumulator operating in the MW and GeV domain worldwide. In particular, the whole charge exchange injection layout has been conserved allowing reliable simulations despite the higher energy of the ESS linac.

The Lattice

The magnet fields in the original 1 GeV SNS lattice being 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 [3].

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The Injection

As at the SNS, we propose charge exchange injection by foil stripping. Laser stripping is envisaged ultimately, but no design exists so far. An experiment is planned for 2016. By using this approach a future SNS realization could ultimately be ported to the ESS accumulator with minor modifications, if the SNS injection lattice is conserved.

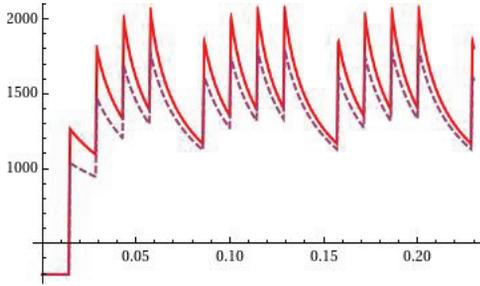


Figure 2: Evolution of maximum foil temperatures [K] at the H⁻ - spot peak (dashed) and the combined H⁻ and H⁺ circulating protons peak (red).

Foil Temperature Calculations

Two approaches have been used to evaluate foil temperatures. The first, considering radiation cooling only is based on work by of Liaw et al. [4]. More recent work has led to modifications in the calculations of the stopping power in thin foils [5]. Modelling the injection process with falling bumps in both planes leads to acceptable peak foil temperatures only if the final emittances of the accumulated beams are of the order of those of the SNS, i.e. about 200 π mm mrad normalized. The simulations made with the ACCSIM code [6] resulted in peak temperatures of 1800 K for the H⁻ beam, 1717 K for the circulating p beam and of 2050 K for the combined peak of H⁻ and p (Fig. 2 and 3).

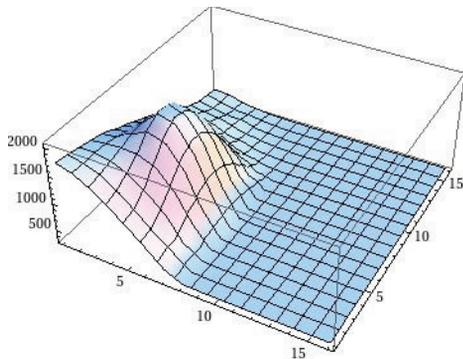


Figure 3: Peak temperature distribution at the Foil for the combined load from injected H⁻ and circulating protons.

The second approach focuses on an analytical treatment of the foil heating discarding the falling injection bump issue and the proton recirculation across the foil. The H⁻ ions are assumed to be fully stripped yielding one proton

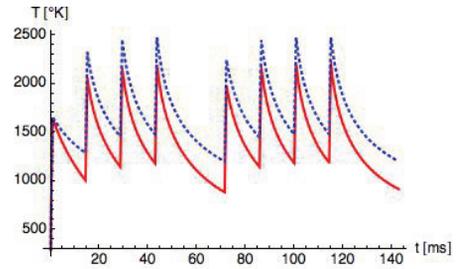


Figure 4: Peak foil temperatures evolution at the H⁻ spot center derived from the 3D model (Eq. [2]) (continuous) and the 1D model (Eq. [5]) without heat conduction (dotted).

and two electrons for the energy deposit into the carbon material. At 2 GeV the proton total stopping power is 1.76 MeV cm²/g [7]. Since protons and electrons have the same velocity at foil entrance the electron energy is 1.09 MeV, yielding a total stopping power of 1.61 MeV cm²/g [7]. The H⁻ total stopping power S_p amounts thus to 4.98 MeV cm²/g. Considering the recent rate of energy loss studies [5] the total stopping power value can be reduced to $S_p = 2.79$ MeV cm²/g. The power density on the carbon foil is given by the expression below (numerically $P_c = 23.2$ MW/m²).

$$P_c = S_p \bar{t}_c I_{av} / (4\sigma_x \sigma_y) \quad (1)$$

Table 1: Parameters and material data for the injection into the Accumulator.

Parameter	Value
Ion kinetic energy	2 GeV
H ⁻ pulse duration	2.86/4 ms
H ⁻ pulse repetition rate	70 Hz, 14.29 ms
H ⁻ mean pulse current	$I_{av}=62.5$ mA
RMS norm. emittance	$\epsilon_{x,y}^n=0.33$ μ m
Beam size	$\sigma_x=1$ mm, $\sigma_y=1.4$ mm
Beta functions at injection	$\beta_x=9$ m, $\beta_y=18$ m
Carbon foil dimensions	17mm/62mm/3.9 μ m
Carbon melting point	3773 K
Foil thickness density	$t_c=750$ μ g/cm ²

A 3D model of the foil heat conduction equation with beam power heat source and radiation cooling was built using *Mathematica*, ignoring the vacuum pipe effect, assumed to be at ambient temperature T_0 , and the heat convection. It can be written in the form

$$c(T(\vec{u}, t)) \rho \partial_t T(\vec{u}, t) - \nabla \cdot [k(T(\vec{u}, t)) \vec{\nabla} T(\vec{u}, t)] = (P(\vec{u}, t) - \sigma \epsilon_c (T^4(\vec{u}, t) - T_0^4)) / t_c \quad (2)$$

given the initial condition $T(\vec{u}, 0) = T_0$ and the 6 boundary conditions (only the first two are shown below)

$$k(T(x, y, 0, t)) \partial_z T(x, y, 0, t) = \quad (3)$$

$$\begin{aligned}
 & -P(x, y, 0, t) + \sigma \epsilon_c (T^4(x, y, 0, t) - T_0^4) \\
 k(T(x, y, t_c, t)) \partial_z T(x, y, t_c, t) = & \quad (4) \\
 & -\sigma \epsilon_c (T^4(x, y, t_c, t) - T_0^4) \\
 & \vdots
 \end{aligned}$$

where T is the foil temperature, t is the time and $\vec{u} = x, y, z$ are the coordinates of the foil width, height and thickness. The carbon thermal conductivity $k(T)$ [W/m-K] and heat capacity $c(T)$ [J/kg-K] are 4th order polynomials that fits measurements [4], ρ is the carbon density [kg/m³], t_c the foil thickness in [m] and σ the Boltzmann constant. $P_c(\vec{u}, t)$ is the beam power density function [W/m²] defined as the product of the power density P_c (Eq. 1) times a super-Gaussian [8] function with a variable exponent $N=3$ to estimate at best the foil temperature rise caused by the injected core spot.

Assuming no heat conduction in the foil, Eq. 2 reduces to the simplified 1D model.

$$c(T(t))\rho \frac{dT(t)}{dt} = \frac{1}{t_c} [P_c - \sigma \epsilon_c (T^4(t) - T_0^4)] \quad (5)$$

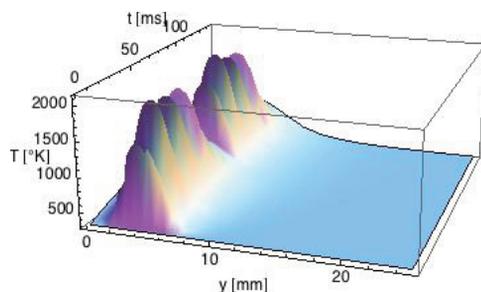


Figure 5: Foil temperatures evolution along the foil height (y-direction). The hot temperatures of the foil remain localized.

In summary Figures 4 to 6 show that the modulation of the foil temperature during the repetitive accumulator filling cycles is quasi stable after the second long cycle, each being made of four 0.715 ms injection pulses (repeated every 14.29 ms) plus a 14.29 ms gap (empty injection cycle) during which the temperature varies between 920 K and 2210 K.

CONCLUSION

The option to pulse one accumulator four times instead of having four stacked accumulators has implications for the accumulator injection system. To have the possibility to start the running of the accumulator before an operational laser stripping system is available, foil stripping is a technologically available solution [3]. The first investigations using two different approaches, the ACCSIM code and an analytical method, for calculation of the temperature of the foil have shown that there is a reasonable margin for the maximum temperature reached compared to 2500 K, which

is a target-value to have a necessary margin to the carbon

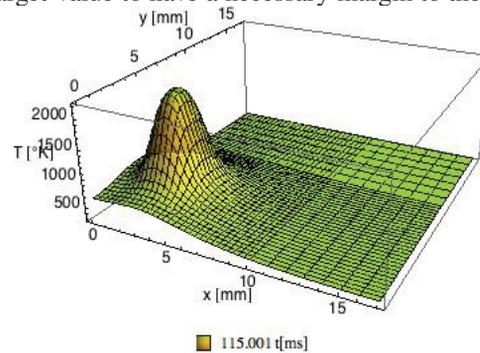


Figure 6: Foil temperatures evolution on the foil surface (x,y-directions). The time is that of the 8th injected spot 115 ms where the peak temperature of 2210 K is reached.

melting temperature, see Table 1. This gives confidence that the accumulator can be initially operated using foil stripping. Further consolidation and optimization of the injection optics and beam is necessary (e.g. the assumptions for the particle distribution on the foil) for the development of a stripping system.

ACKNOWLEDGMENT

We are grateful to many people for fruitful discussions and help, in particular to J. Holmes and M.Plum who generously provided us with the information on the SNS accumulator that we used for the work. W. Bartmann and Y. Papaphilippou have also given information on laser stripping and the SNS lattice files.

REFERENCES

- [1] ISBN 978-91-980173-2-8.
- [2] E. Baussan et al., "A Very Intense Neutrino Super Beam Experiment for Leptonic CP Violation Discovery based on the European Spallation Source Linac: A Snowmass 2013 White Paper", arXiv:1309.7022v3 [hep-ex] 12 Nov 2013 - arXiv.org.
- [3] SNS Design Manual 2003.
- [4] C. J. Liaw et al., "Calculation of the maximum temperature on the carbon stripping foil of the Spallation Neutron Source", PAC, New York, 1999, pp. 3300.
- [5] M. Plum et al., NIM A590 (2008) pp. 43 et private communication 2014.
- [6] IPAC'89, Tsukuba, Japan p.[1409]/199.
- [7] J. M. Berger, "Stopping Power and Range Table for Electrons, Protons and Helium Ions", NISTIR 4999, <http://physics.nist.gov/PhysRefData/Star/Text/contents.html>
- [8] B. Lü, S. Luo, "Beam propagation factor of apertured super-Gaussian beams", International Journal of Light and Electron Optics, Volume 112, Issue 11, 2001, pp. 503-506.