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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 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). The possibility 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 high current in the horns of the target system for the neutrino production requires proton pulses far shorter than the linac pulse. Therefore an accumulator ring is required after the linac to produce the shorter pulses. Charge exchange injection of an H− beam from the linac would be used. The Linac would deliver 1.1 1015 protons per pulse. Due to space charge limits, several rings or one ring re-filled several times during the neutrino cycle are necessary.

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Abstract

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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 the secondary particle focussing system 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. This has 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.

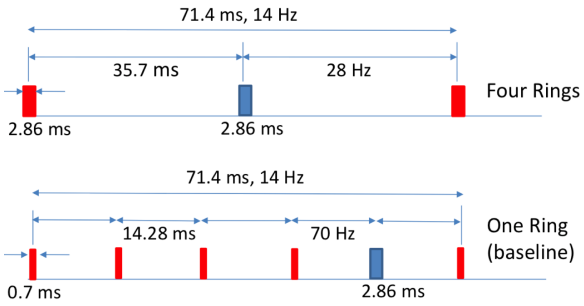

Figure 1: Pulse distribution for the 4-ring and the one-ring options: The upper part of the figure shows the 28 Hz pulsing of the linac with one proton (blue) and one H^- (red) pulse interleaved and the lower part shows the case where four 0.72 ms long pulses of H^- for neutrinos are followed by one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

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 the best starting from an existing design, 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 SNS lattice being rather moderate, it is possible to take over 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].

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 experimental is planned, beginning in 2016. This way a future SNS realization could ultimately be ported to the ESS accumulator with minor modifications, if the SNS injection lattice is conserved.

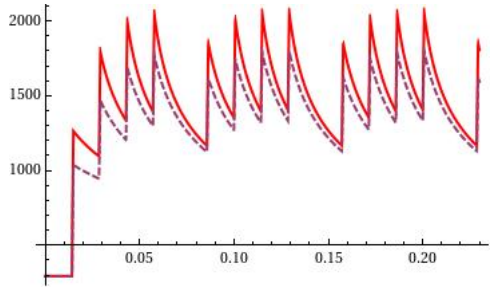

Figure 2: Evolution of maximum foil temperatures [K] at the H^-- spot peak (dashed) and the combined H^- and H^+ circulating protons peak (red)

Foil Temperature Calculations Two approaches have bee used to evaluate foil temperatures, firstly, by considering only radiation cooling and neglecting conduction. Foil temperatures were studied by the approach 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).

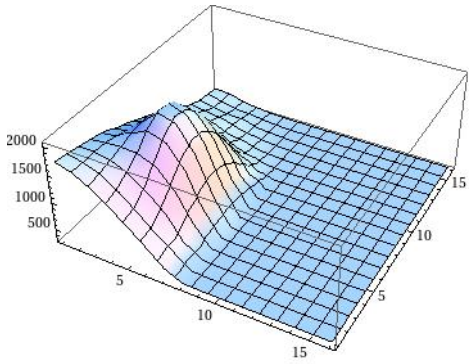

Figure 3: Peak temperature distribution at the Foil for the combined load from injected H^- and circulating protons

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 and two electrons for the energy deposit into the carbon material. At 2 GeV the proton total stopping power is 1.76

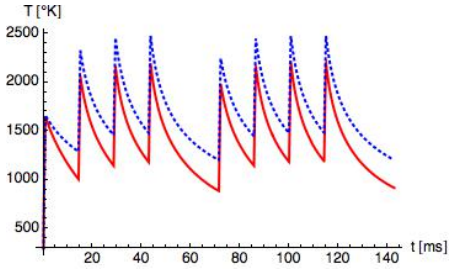

Figure 4: Peak foil temperatures evolution at the H^- spot center derived from the 3D model (continuous) and the 1D model without heat conduction (dotted).

MeV cm^2/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 cm^2/g [7]. The H^- total stopping power S_p amounts thus to 4.98 MeV cm^2/g. Considering the recent rate of energy loss studies [5] the total stopping power value can be reduced to $S_p = 2.79$ MeV cm^2/g. The power density on the carbon foil is given by the expression below, numerically $P_c = 23.2$ MW/m^2.

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

Parameter	**Value**
Ion kinetic energy	2 GeV
H^- pulse duration	2.86/4 ms
H^- pulse repetition rate	70 Hz, 14.27 ms
H^- mean pulse current	I_{av}=62.5 mA
RMS norm. emittance	$\epsilon^n_{x,y}$=0.33 μm
RMS norm. beam size	σ_x=1 mm,σ_y=1 mm
beta functions at injection	β_x=9 m,β_y=18 m
Carbon foil dimensions	17mm/62mm/3.9μm
Carbon melting point	2500 K
Foil thickness density	$\bar{t}_c$=750 μg/cm^2

Table 1: ESS beam characteristics at injection into the Accumulator.

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

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

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

$$\begin{aligned} &k(T(x,y,0,t))\partial_z T(x,y,0,t) = \\ &\quad -P(x,y,0,t) + \sigma\epsilon_c(T^4(x,y,0,t) - T_0^4) \end{aligned} \tag{3}$$

$$k(T(x,y,t_c,t))\partial_z T(x,y,t_c,t) = \quad (4)$$
$$-\sigma\epsilon_c(T^4(x,y,t_c,t) - T_0^4)$$
$$\vdots$$

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 4^{th} order polynomials that fits measurements [4], ρ is the carbon density [kg/m^3], t_c the foil thickness in [m] and σ the Boltzmann constant. $P_c(\vec{u}, t)$ is the beam power density function [W/m^2] defined as the product of the power density P_c (Eq. 1) times a super-Gaussian function with a variable exponent N=3 to estimate at best the foil temperature rise caused by the injected core spot.

A reduced form 1D model of Eq. 2 is derived assuming no heat conduction in the foil

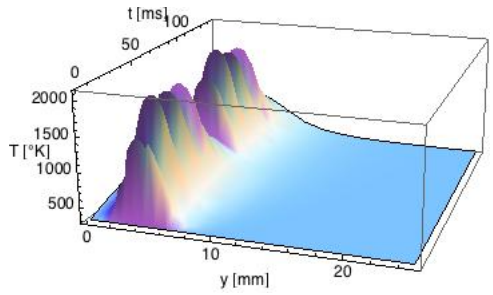

Figure 5: Foil temperatures evolution along the foil height (y-direction).

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

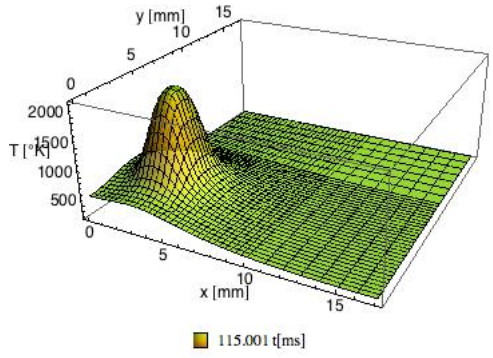

Figure 6: Foil temperatures evolution on the foil surface (x,y-directions). The time is that of the 8^{th} injected spot 115 ms where the pic temperature of 2210 K is reached.

In summary Fig. 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 ACCIM 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 carbon melting temperature. This gives confidence that the accumulator can be initially operated using foil stripping. Further consolidation of the calculations is necessary (e.g. the assumptions for the particle distribution on the foil) for the development of a stripping system.

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