EUROPEAN SPALLATION SOURCE AFTERBURNER CONCEPT

D. McGinnis, M. Lindroos, R. Miyamoto, ESS, Lund, Sweden

Abstract

The European Spallation Source (ESS) is a long pulsed source based on a high power superconducting linac. The long pulse concept is an excellent strategy of maximizing high beam power while minimizing peak power on the target. Chopping in the long pulse concept provides the necessary resolution for many neutron physics applications. However, there are some neutron physics applications in which both peak neutron flux and high resolution are desired. The peak flux of the ESS can be enhanced by placing an accumulator ring at the end of the linac. A bunch by bunch extraction scheme can be used to optimize the proton pulse time profile that maximizes peak neutron flux while minimizing instantaneous beam power on the target.

INTRODUCTION

ESS is an accelerator-based neutron source facility that will provide the most intense pulsed neutron beams in the world for scientific research and industrial development. ESS requires 5 MW of proton beam power which is a factor of five larger in power compared to existing spallation facilities. For the spallation target to accommodate the extraordinary amount of beam power provided by the ESS linac, a standard compression storage ring cannot be used. Instead ESS will pioneer the concept of the long-pulse spallation source in which the linac beam is aimed directly on the metal target. The long pulse of neutrons emerging from the target and the moderator is then shaped or "chopped" by neutron choppers. Figure 1 shows the pulse shaping concept.

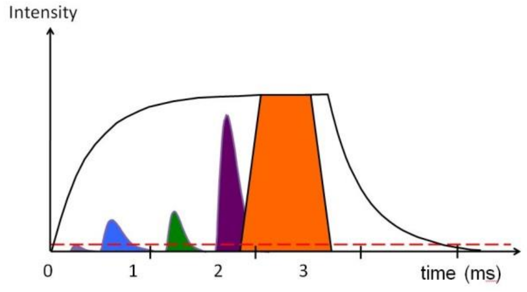

Figure 1: ESS Neutron pulse shaping concept.

The duty factor of the ESS accelerator is dictated by the needs of the long pulse concept. The repetition rate of 14 Hz is set by the maximum speed at which the neutron choppers can rotate. The maximum pulse length of 3 ms is set by the desired peak neutron flux. Thus, to provide 5 MW of average protons beam power to the target, the ESS accelerator must provide a peak beam current of 62.5 mA.

Neutron Moderator Response

The thermalization process in neutron moderators acts as a time integrator which spreads the pulse response of the neutron flux from the target.

$$n(t) = 2\frac{N_n}{\tau_{rms}}\frac{t}{\tau_{rms}}e^{-\sqrt{2}\frac{t}{\tau_{rms}}} \qquad (1)$$

where N_n is the total amount of neutrons created from the pulse and τ_{rms} is the moderator time constant. The time constant of the spreading can be on the order of 100 microseconds for cold neutrons. Figure 1 shows the response to single beam pulse for a τ_{rms} of 100uS.

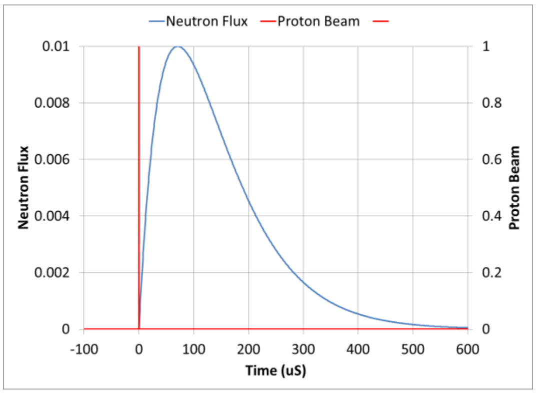

Figure 2: Target and neutron moderator response to a single proton beam pulse.

Figure 3 shows the comparison in the instantaneous neutron flux for a short proton pulse and a long proton pulse of 3 ms with the same number of protons in the pulse. For a typical target-neutron moderator response, the instantaneous flux from a single beam pulse can be 15 times greater than the flux resulting from a proton pulse of 3 ms in length. Although this large instantaneous peak neutron flux is very attractive, a single short pulse required to produce 5 MW of average beam power would destroy the neutron production target and is not feasible to contemplate.

Because the target-neutron moderator response is on the order of 100us, shortening the proton pulse length less than 100uS would not increase the peak flux and would only serve to stress the target with higher incident peak power. To construct a 100us linac pulse length and preserve an average proton beam power of 5 MW, either the linac beam current or the repetition rate would have to be increased by a factor of 30 from the present design.

Increasing the beam current would require a corresponding increase in peak RF power. More importantly, the beam current in the linac is limited by space charge effects, especially at the low energy end of the linac. The energy spread in the neutron beam and distance between the target and the neutron experiments places an upper limit on the repetition rate of the linac.

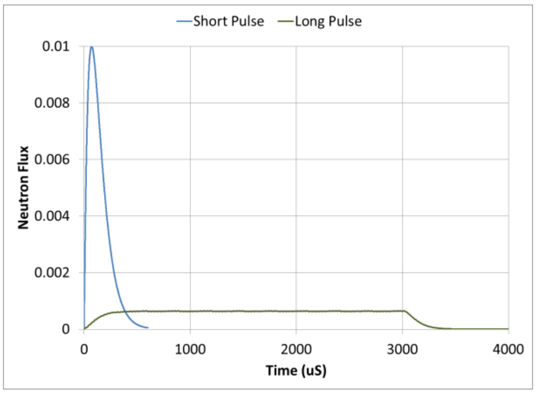

Figure 3: Target and neutron moderator response to a short and long (3 ms) proton pulse with the same number of protons per pulse.

100 MICROSECOND COMPRESSOR RING COMPLEX

A possible alternative is to build a compressor ring that would feed the target with a 100uS long pulse of protons. To inject into each ring, the ESS linac would have to fitted with a H- ion source. Multi-turn injection and H-stripping systems would also be required for the rings. At the energy of 2 GeV, laser stripping might be an alternative to stripping with carbon foils. The wavelength of the laser required would in the visible light range of 560 nm [1].

For a simple single turn extraction, the ring circumference would have to exceed 30km! To extract from a smaller ring, one could consider resonant extraction. Resonant extraction is a well-known technique in high energy physics for extracting the beam from a storage ring when the required extraction time is much greater than the revolution period of the ring. However, the process is inherently lossy and resonant extraction for a 5 MW beam would be problematic.

Another possibility is to consider smaller multiple rings occupying the same tunnel and stagger the single turn extraction from the rings over a 100uS period. As noted previously, the pulse structure of the multiple extractions would be obscured by the moderator response. Multiple rings would also reduce the burden of space charge tune-shift. Figure 4 shows the response to four proton beam pulses spaced 25 us apart for a τ_{rms} of 100uS.

With four proton beam pulses, the peak proton pulse charge is reduced by 75% while the peak neutron flux is reduced by only 12%. However, even with multiple rings, single turn extraction would leave a relatively large gap between sequential extractions giving rise to concerns about peak power on the target. The figure of merit for target cooling is based on transit time of "sound waves" out of the target. For solid targets, this transit time is on the order of 25uS.

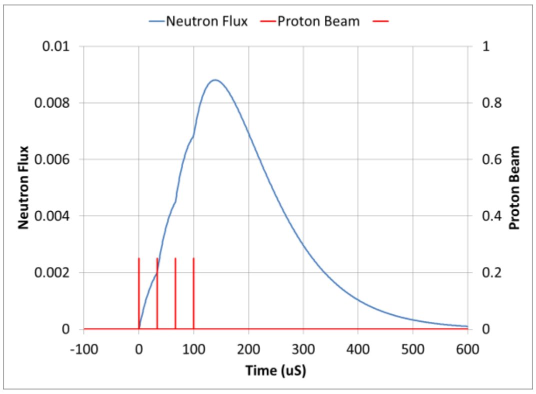

Figure 4: Target and neutron moderator response to four proton beam pulses.

Thus, it would be better to shorten the spacing between proton pulses below 25 us. This could be done by implementing fast bunch-by-bunch extraction kickers into a ring. Such kickers have been planned for the ILC damping rings[2]. Figure 5 shows the target-moderator response for 100 proton beam pulses spaced 1 uS apart for a τ_{rms} of 100uS.

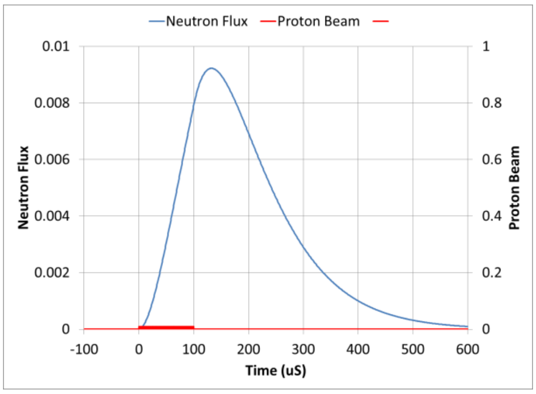

Figure 5: Target and neutron moderator response to 100 proton beam pulses.

The peak proton pulse charge is now only 1 % of the peak charge required for a single bunch but the neutron flux is 92% of the neutron flux obtained from a single beam pulse. To produce 5 MW with a pulse repetition rate of 14 Hz, the peak proton beam power on the target would be 3750 MW for the 100uS burst of protons.

Extraction Kicker

For a stripline kicker to be used as a bunch by bunch extraction kicker, the angle of kick is given as:

$$\Delta\theta = 2g\frac{eV_k}{pc}\frac{L}{d}N_k \qquad (2)$$

where g is a transverse form factor (~0.9), L is the length of the kicker, d is the aperture of the kicker, V_k is the kicker voltage, and N_k is the number of kickers in a ring. The rise time of a stripline kicker is:

$$\tau_f = \frac{2L}{c} \quad (3)$$

The rise time of the kicker should be less than the gap between bunches in the ring:

$$\tau_f < \frac{B_f - 1}{B_f} \frac{N_r}{N_p} \frac{2\pi\rho_r}{\beta_r c} \quad (4)$$

where N_r is the number of rings, N_p is the total number of pulses to be sent to the target, B_f is the bunching factor, ρ_r is the radius of the rings, and β_r is v/c.

The kicker aperture needs to be larger than the beam size and the amplitude of the kick should be larger than ½ the physical beam size in the extraction region. These two criteria place the constraint on the maximum emittance:

$$\epsilon_{n95\%} < N_r \pi \rho_r \frac{B_f - 1}{B_f} g \frac{N_k}{N_p} \frac{eV_k}{E_{rest}} \quad (5)$$

Space Charge Tune Shift Limitations

Space charge would be a major issue for a high intensity compressor ring. Using the zero amplitude space charge tune shift formula[3] places a constraint on the minimum emittance:

$$\epsilon_{n95\%} > \frac{1}{N_r \Delta Q} \frac{6}{4\pi} r_p \frac{B_f}{\beta_r \gamma^2} \frac{I_L \tau_L}{e} \quad (6)$$

where ΔQ is the maximum allowable space charge tune shift, r_p is the classical proton radius ($1.5\text{x}10^{18}$ m), I_L is the linac beam current, and τ_L is the linac pulse length.

Comparing Equations 5 and 6 places a strong emphasis as having as many rings as possible. Many rings permit longer bunches which gives stronger bunch-by-bunch kickers and longer rise times. Also many rings dilute the peak charge in each ring which eases constraints on the space charge tune shift for each ring.

To reduce the cost of the multiple rings, the rings could be constructed from permanent combined function magnets as was done in the Fermilab Recycler [4]. The Fermilab Recycler magnets were constructed of strontium ferrite bricks that could produce a magnetic field of 1400 Gauss in a gap of 50 mm. Increasing the aperture to accommodate larger beam sizes would decrease the magnetic field generated by the permanent magnets and require a larger circumference. As shown in Equation 4, a larger circumference has the additional benefit of easing kicker rise time constraints. The average radius of the ring required is:

$$\rho_r = \frac{B\rho}{P_f B} \quad (7)$$

where $B\rho$ is the magnetic rigidity (0.93 Tesla-meter for 2 GeV protons), P_f is the packing factor and B is the average bending magnetic field. If combined function magnets are use, the packing factor can be as high as 0.75.

Table 1 shows a possible configuration for the ESS Afterburner concept that meets the emittance requirements listed in Equations 5 and 6. The space charge tune shift for each ring is 0.22. This value might be permissible because the beam needs only to be stored in the rings for a duration of less than 3 ms. Also the space charge tune shift formula used in Equation 6 did not assume any phase space painting at injection to optimize the transverse profile that could alleviate space charge forces. Also, advanced tune-shift compensation techniques such as electron beam compensation could also be investigated.[5]

Table 1: Possible Afterburner Parameters

Parameter	**Value**	**Unit**
Linac Energy	2	GeV
Linac Beam Current	62.5	mA
Linac Pulse Length	2.86	ms
Linac Repetition rate	14	Hz
Beam Duration on Target	100	us
Number of Rings	4	
Ring harmonic number	25	
Magnet Packing Factor	0.75	
Aperture	100	mm
Lattice Beta function	50	m
Normalized 95 % emittance	150	π-mm-mrad
Bunching factor	1.5	
Space Charge Tune Shift	0.22	
Average Magnetic field	700	Gauss
Ring circumference	1100	m
Ring RF Frequency	6.4	MHz
Bunch Length	105	ns
Bunch Gap	52	nS
Kicker Length	3	m
Kicker Rise time	21	nS
Number of Kickers/ring	5	
Kicker Voltage	10.4	kV
Average Kicker Power	770	W

REFERENCES

[1] V. Danilov, "Laser Stripping of H- Beams: Theory and Experiments," PAC'07, Albuquerque, July 2007, THYKI02.

[2] T. Naito, "Development of Strip-Line Kicker System for ILC Damping Ring," PAC'07, Albuquerque, July 2007, THPMN028.

[3] D. Edwards and M. Syphers, "*An Introduction to the Physics of High Energy Accelerators*" (New York: Wiley, 1993), 176.

[4] J. Volk, "Experiences with Permanent Magnets at the Fermilab Recycler Ring," FERMILAB-TM-2497-AD

[5] A.V. Burov, G.W. Foster, V.D. Shiltsev, "Space-Charge Compensation in Proton Boosters," PAC'01, Chicago, July 2007, 2896-2898.