Preliminary Studies for Basic Design Parameters of an Accumulator Ring for Indian Spallation Neutron Source

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Abstract. There is a proposal to build a pulsed spallation neutron source complex in India, driven by a full energy linac followed by a proton accumulator ring (AR). In this complex, an H^- linac will be used as an injector, which will deliver beam pulses of 1-3 ms to the AR. Using a multi-turn charge exchange injection scheme, the pulses will be compressed to ~1 μs in AR. This extracted proton beam will hit the spallation target to produce the spallation neutrons. This process will repeat with a suitable repetition rate to achieve high average beam power. The repetition rate is limited by the constraint of avoiding the frame overlap in time-of-flight experiments. An initial study to fix the base design parameters has been started. In this paper, we discuss some of the basic issues, which decide the choice of the feasible initial parameter space for the proposed AR. We explore the possibility of reducing the required peak beam current from the linac by increasing the injected pulse width in the AR, which will reduce the intensity related effects. In addition, in this configuration, the required peak RF power in linac will be low and therefore one can even use solid state amplifiers for RF system. Injection of a longer beam pulse into AR will require either a longer circumference AR or higher number of injection turns. We discuss the practical implications of these issues. We also discuss the possible beam power at the target using this configuration (i.e. longer pulse with reduced peak current) at different repetition rates. Considering all these issues, we obtain the possible space of initial parameters for the proposed AR for the spallation neutron source.

Keywords: Accumulator Ring, Spallation Source, Injection Foil.
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INTRODUCTION

In a spallation source, the important parameter is the proton beam power, which has to be maximized under the feasible choices of machine parameters. Average Beam power at the target is given by

$$\overline{P} = qN_p E_{eV} f_{rep} \tag{1}$$

Here, N_p is the number of protons per pulse, E_{eV} is the proton beam energy and f_{rep} is the repletion rate. Spallation reaction generally starts above 180-200 MeV proton energy. The neutron yield varies linearly with proton beam energy up to ~ 1 GeV and above 1 GeV, the linear relation modifies to $E_{GeV}^{0.8}$ [1, 2, 3]. Above 2 GeV, a fraction of proton energy goes into muon production, which results in further reduction in neutron yield. Therefore for spallation sources, suitable energy range lies from ~200

MeV to 3 GeV. For full energy linac, in order to reach up to a reasonable beam power at the target, 1 GeV seems to be a suitable choice of energy. Hence, in this paper, we will concentrate on two energy regimes i.e. 650 MeV (which may be first phase) and 1 GeV. Repetition rate is decided by the frame overlapping problem and resolution of the neutron detectors. Considering theses issues, repetition rate is chosen in the range 50-60 Hz. The first estimation for obtaining the limit of maximum number of protons per pulse comes through the space charge tune shift $\Delta\nu$, which is given by the following relation for uniform beam distribution [4].

$$\Delta \nu = -\frac{3 r_p N_p}{2\pi \beta^2 \gamma^3 \varepsilon B_f} \tag{2}$$

Here r_p is the classical radius of proton, β and γ are the relativistic parameters, ε is the transverse emittance and B_f is the bunching factor. Here it seems that increasing the emittance can lower down the tune shift, but at the same time it will increase the required good field region of the magnets. Inclusion of second/ third harmonic cavity can help in increasing the bunching factor to ~0.4 from ~0.25. In the next section, we discuss the issues related to choice of pulse length from the linac.

PULSE LENGTH FROM LINAC AND FOIL ISSUES

In this section we discuss about the possible longest pulse length which can be injected using stripping foil for the charge exchange mechanism. Using longer pulse lengths, higher average beam power can be achieved for the same peak pulse current of linac. As we increase the pulse length from the linac, the number of turns to be injected in the AR will increase and average number of hits of the beam at the foil during the injection process will also increase. This will raise the temperature of the foil. Therefore, maximum allowed temperature on the foil will provide the maximum number of allowed turns for injection in the AR. The number of average hits of the beam on the foil also depends on the painted emittance and the emittance of the injected beam from the linac. Presently, the parameters taken for studies are shown in Table 1, based on a candidate four-fold lattice under study. Thickness of the foil is chosen on the basis of stripping efficiency in carbon for the H^- beam [5].

Table-1

Linac emittance	0.5π mm-mrad
Linac pulse current	2 mA
Material of foil	Carbon
β at injection	~8-10 m
Foil size	Equal to beam size @ injection
Foil thickness	300 μg/cm^2

For the given number of turns N_{turns}, painted emittance and linac emittance, the average hit by protons on the foil is given by [6]

$$\bar{n}_{hit} = \frac{1}{2}\left(\frac{\varepsilon_{linac}}{\varepsilon_{painted}}\right) N_{turns} \tag{3}$$

This formulation is derived on the basis of exact uniform beam distribution after painting with a horizontal tune ν_x such that $m\nu_x \neq n$, where m and n are integers. If the linac emittance is smaller, number of hits will be reduced. However, in that case, the beam size will also be smaller, resulting in a larger current density at the foil. Hence, this may lead to larger temperature rise. Similarly, larger painted emittance will lower down the number of hits, but will require larger magnet aperture. We first discuss the dependence of the required magnet aperture on the number of protons per pulse for a given average beam power. For this, we first calculate the painted emittance for $\Delta\nu$ = -0.2 and then the machine acceptance is taken to be nearly 2 times painted emittance. We take B_f = 0.25 for the case when only fundamental frequency rf cavity is used in the AR. The bunching factor can be increased to ~ 0.4 by inclusion of higher harmonic RF cavities. Figs 1(a) and 1(b) show the dependence of the required magnet aperture for both the cases (with and without higher harmonic RF cavity). We notice that for a feasible magnet aperture of ~180-200 mm, higher power can be achieved using higher harmonic cavity.

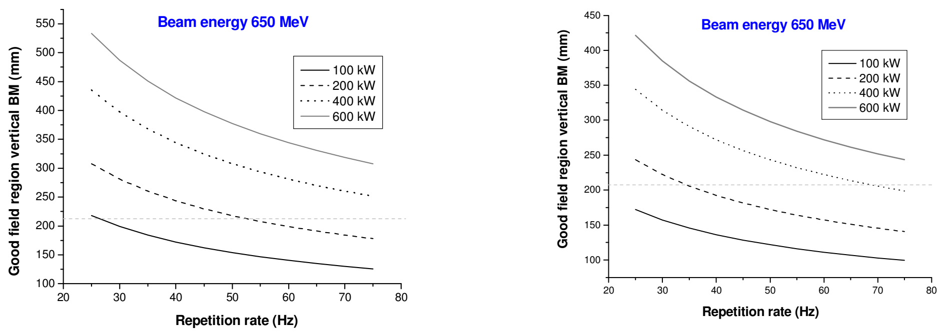


FIGURE 1A & 1B. Power vs good field region at 650 MeV (without and with harmonic cavity)

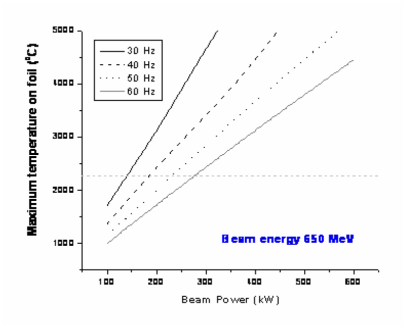
Next, we discuss the issues related to heating of injection foil. The rise in temperature of the foil due to beam hits during the injection process is determined using the following equation [7]

$$\rho V s \frac{dT}{dt} = -2\sigma f e A\left(T^4 - T_0^4\right) + P_c A \tag{4}$$

Here σ, ρ, e and s are Stefen's constant, density of the material, emissivity and specific heat (function of temperature), respectively, and A and V are the area and volume of the foil. P_c is the power deposited per area on the foil by the proton beam and is given by $P_c = k\ b.\ I / A$, where b is the thickness of the foil (in g/cm^2) [6]. Here, the value of k is 6.837×10^5 at 1 GeV and 8.195×10^5 at 650 MeV for above units. During the gap period (i.e. when the injection process is OFF), there will be radiative cooling of the foil. Thus during this time, the temperature of the foil can be obtained by

$$\rho V s \frac{dT}{dt} = -2\sigma f e A\left(T^4 - T_0^4\right) \tag{5}$$

In order to increase the beam power for a fixed pulse current of 2 mA, the pulse length from the linac will increase, which will lead to larger number of injected turns. This will cause a larger temperature rise for the injection foil. The maximum allowed value of the number of injected turns will depend on the allowed temperature rise in the foil. For these calculations, first the number of turns is calculated and the painted emittance is obtained assuming a magnet aperture of 200 mm. The number of hits is evaluated using Eq. 3, which gives the current I falling on the injection foil for P_c. The evolution of foil temperature is studied using Eq. 4 and 5 and Figure-2 shows the saturated temperature of injection foil with and without harmonic RF cavities. The operating regimes that lead to saturated foil temperature below 2500 °C can be obtained from these plots.



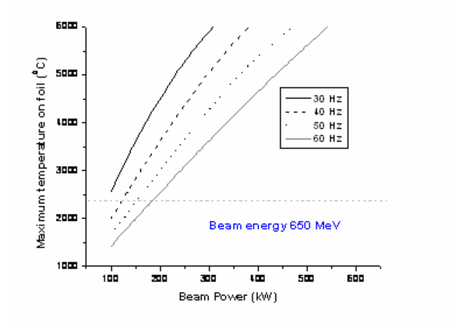


FIGURE 2A & 2B. Temperature rise of the injection foil with beam power at different repetition rate for 650 MeV (without and with harmonic cavity)

We have also carried out these studies with 1 GeV proton beam to explore the feasible operating pulse length and repetition rate to achieve maximum beam power. At 1 GeV, space charge effects are reduced as compared to 650MeV, but temperature rise in foil does not change much.

CONCLUSIONS

Above studies show that using 2 mA pulse current of linac at 60 Hz repletion rate and 650 MeV beam energy, ~150-200 kW beam power can be reached with ~2.2-2.5 ms pulse length. Higher harmonic cavities in this situation can be used to lower down the required aperture of magnets (good field region) from ~180mm to ~160mm. Inclusion of higher harmonic cavities will raise the temperature of the injection foil from ~1800° C to ~2200° C. At 1 GeV, the maximum beam power of ~300 kW can be reached with ~160-170 mm magnetic good field region with a maximum foil temperature of 2300° C using ~2.5 ms pulse length. Increasing the linac pulse current to 10 mA can make 450-500 kW average beam power feasible with ~1ms of linac pulse width at the maximum foil temperature of ~1200° -1300° C.

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