Important Design Issues of High Output Current Proton Rings

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Abstract

High output currents of protons are required for future pulsed spallation neutron sources and Kaon Factories. Typical parameters are 5 mA at 1 GeV or 1.667 mA at 3 GeV for the former, and 0.1 mA at 30 GeV for the latter. The resulting beam powers are 5 and 3 MW, respectively, so that key issues are low beam loss and reliable beam loss protection. The following aspects of the rings' design are considered here: very high efficiency H^- injection, beam optical parameters, vacuum enclosures, radio frequency containment and acceleration, instability considerations, magnet systems, low loss extraction, beam loss collimation and collection, and shielding.

1 INTRODUCTION

Large extrapolations of output proton currents have been proposed for rings of future pulsed spallation neutron sources and Kaon Factories. Both types of facility propose a high repetition frequency ($\lesssim$ 50 Hz): in addition, neutron sources consider enhanced values of circulating currents. Typical output parameters are 5 mA at 1 GeV, 50 Hz, or 1.667 mA at 3 GeV, 50 Hz for the former, and 0.1 mA at 30 GeV, 10 Hz for the latter.

There are a number of accelerator options for the spallation sources: linac and accumulator rings, linac and fast cycling synchrotrons, linac and FFAG accelerator(s), a Kaon Factory type facility or an induction linac. Of these, the first two are currently favoured, and for each it appears advantageous to use more than one ring. Kaon Factories have been studied over many years, both in North America (the TRIUMF KAON and Los Alamos AHF studies) and in Europe (the EHF and the studies at INR, Troisk). Common to these designs is the use of a booster and main ring synchrotron, supplemented by one or more of the following: accumulator, collector, extender. Despite all the studies, no Kaon Factory has received a final approval.

The many rings of the Kaon Factories present a wide range of machine physics issues, far more than do the rings of the proposed spallation sources. However, though the issues are fewer for the latter, they are more challenging because of the higher peak circulating current in the rings.

Kaon Factory studies have been reported extensively, and it is sufficient for this paper to list the relevant design issues, quoting appropriate references. The paper then concentrates on new design issues for the next generation, 5 MW, pulsed spallation sources. A key issue is the design for ultra low loss H^- charge exchange injection.

2 RING DESIGN ISSUES

Kaon Factory designs have had to consider the overall reliability and availability of a facility that has a number of complex, high power rings (3,4 or 5) feeding each other in sequence, so that a failure of any one ring or of the injector leads directly to experimental down time. Individual issues of importance are given in the form of a list:

- H^- painting (H^0 states),[1]
- Beam loss collection,[2]
- Betatron resonances,[3]
- Heavy beam loading,[4]
- Electron-proton instability,[5]
- Fast extraction,[6]
- Ceramic vacuum chambers,[7]
- High transition energy lattices,[8]
- Synchrobetatron resonances,[9]
- Polarisation (Siberian Snakes),[10]
- Low loss slow extraction,[11]
- Coupled bunch instabilities,[12]
- Longitudinal emittance enhancement.[13]

By comparison, the favoured schemes proposed for a 5 MW spallation source consist of a high energy linac and either 2 accumulator rings operating in parallel, or 2 rapid cycling synchrotrons providing output beams in alternate cycles. Then, the loss of a single ring leads only to a halving of intensity, an important consideration due to the short turn around time of neutron scattering experiments.

The first seven items on the Kaon Factory list also apply to the spallation sources, where the larger circulating currents give them more significance. One consequence is that the spallation sources require ultra low loss H^- injection, which, in turn, calls for a new form of halo containment for the H^- linac beam.

Radiofrequency systems for the spallation source rings are different from those for the Kaon Factories. The rapid cycling, large radius main ring of the latter requires a large voltage gain per turn. A frequency of approximately 50 MHz is used to provide this voltage, and also to allow short bunch kaon experiments, in a fast extraction mode.

Lower frequency, dual harmonic systems are selected for the spallation sources, where the ring radii are smaller, with h=1 and 2 in the accumulators, and h=2 and 4 in the rapid cycling synchrotrons. The systems allow improved momentum painting during injection, and lead to lower beam bunching factors and transverse space charge forces. A further gain occurs as the natural bunch gap is sufficient for the risetime of a fast extraction kicker magnet. Total proton pulse durations have to be <1 μs.

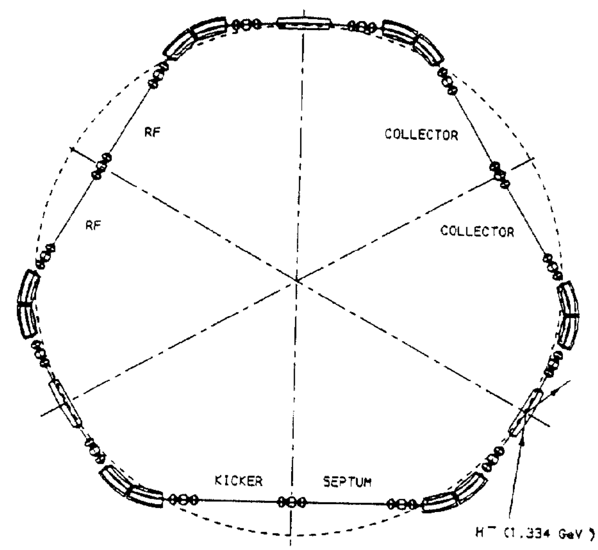

Figure 1. 1.334 GeV Accumulator

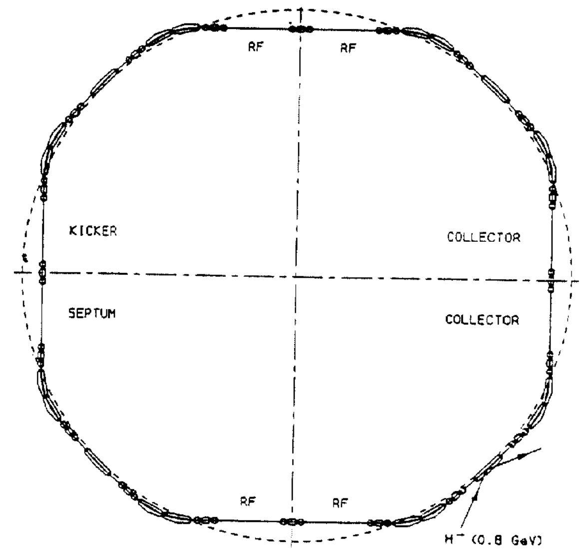

Figure 4. 3 GeV Synchrotron

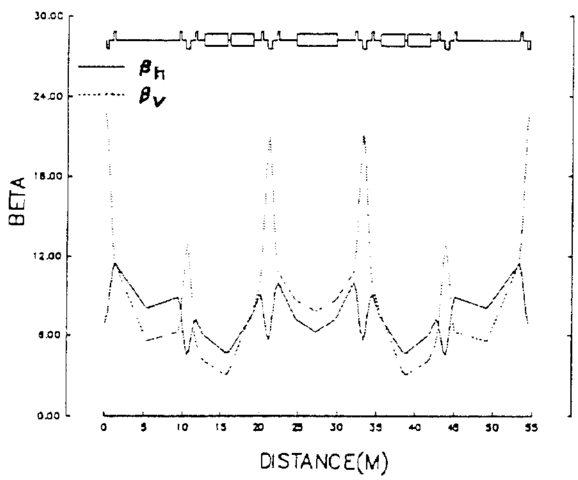

Figure 2. Accumulator β-Functions

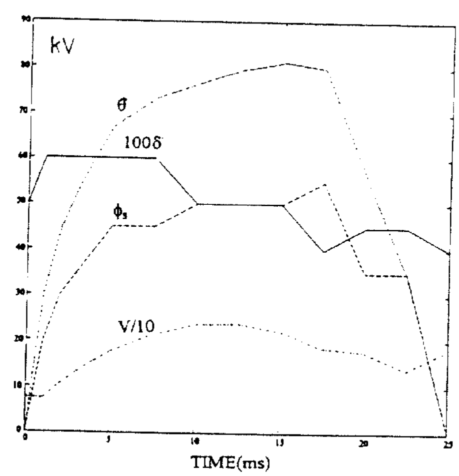

Figure 5. Synchrotron RF Parameters

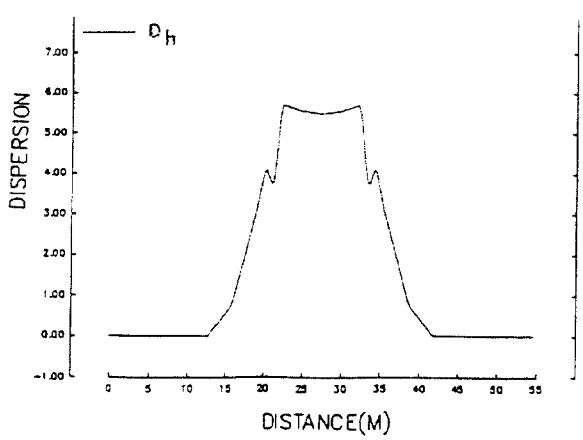

Figure 3. Accumulator Dispersion

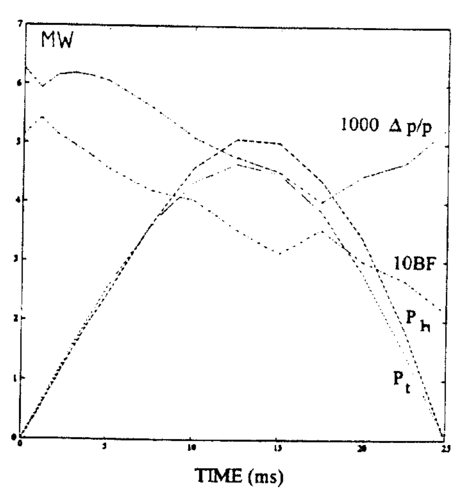

Figure 6. RCS Beam Power and $\Delta p/p$

An overview of future spallation neutron source designs is given in [14], including some linac and target considerations, not considered here. Important issues for the spallation source rings are now addressed separately.

3 H^- INJECTION

Developments in H^- injection systems are described in [1], and the system proposed for a possible 5 MW pulsed source, the European ESS facility, is shown in Figures 7 to 11. Magnet lattices are designed around the injection region; Figure 1 is for a pair of 1.334 GeV accumulators and Figure 4 for a pair of 3 GeV rapid cycling synchrotrons (RCS), both of which are options for the ESS.

At the centre of the injection region is a low field lattice dipole, of a length and bend angle that allows a direct ring exit for unwanted H^0 and H^- particles emerging from the stripping foil. Most of the incoming beam strips to protons within the ring acceptance and continues to circulate, merging with the incoming H^- beam in the centre of the low field dipole. The choice of the field in this dipole is important. It is chosen to give negligible prestripping of H^- ions ahead of the foil, to minimize delayed stripping of H^0 atoms within the ring and to provide a bending radius for the stripped electrons large enough for direct collection, see Figure 10. Different fields are chosen for some ESS options: 0.177 T for the 1.334 GeV accumulators, 0.1252 T for the 0.8 to 3.0 GeV RCS, and 0.1252 T for a 3 ring, 0.8 GeV accumulator option. Identical lattices may then be chosen for the 1.334 and 0.8 GeV accumulators.

A foil thickness is chosen which strips ~98.5% of the H^- beam to protons (eg 345 μgm cm^{-2} Al_2O_3 for 1.334 GeV H^-), leaving most of the rest as partially stripped H^0 atoms, in a range of quantum states. The fate of these depends on their Stark state in the injection magnet. Energy levels for states of principal quantum number n=4,5 and 6 are given as a function of electric field in Figure 8; the vertical dashed lines are the E field equivalents for the B fields of the different options (eg option 2 is for the 1.334 GeV accumulators). Atoms of low n value (<4) remain as H^0 and pass out of the ring for collection; atoms of high n (>6) strip rapidly and are accepted as protons; there remain some intermediate states which strip after some delay, so may be accepted or lost, or become beam halo. The atomic physics is discussed in [15], and a semi-empirical formula derived for the Stark state lifetimes. Those for the states n=4 and 5 are plotted in Figure 9 for the 1.334 GeV H^0 atoms. There is a gap in the graph between the n=4 and n=5 states, and the chosen field of 0.177 T is within this gap. Direct transitions between the two states bordering the gap and the stripped state are forbidden, so the effective gap is enhanced. The options 1 and 3 have injection at 0.8 GeV, and the field of 0.1252 T then corresponds to an equivalent gap between the states n=5 and 6.

It is proposed to use a foil with two free, unsupported edges to reduce the subsequent proton foil traversals. Simultaneous painting is provided in the longitudinal and both transverse planes. Vertical painting is obtained by collapsing the field in the 4 vertical bump magnets, shown in Figure 7. Correlated horizontal and longitudinal painting results from the choice of a finite dispersion at the foil together with a ramping of input beam momentum. The longitudinal painting is improved by chopping the linac beam with a 60% duty cycle at the ring bunch repetition frequency, and also by amplitude and frequency modulation of the dual radiofrequency systems. The transverse painting commences with large horizontal and small vertical oscillations and changes gradually to end with the reverse correlations. Foil traversals are also reduced by mismatching the linac and ring beams, with zero dispersion and low beta parameters for the former at the foil.

Beam losses may result from delayed stripping of H^0, or from inelastic and elastic foil interactions; betatron and momentum tails form, adding to those due to linac beam halo. A negative momentum tail and dispersion at the foil increases the losses. Overall losses are acceptable, however, since there are few foil traversals for the proposed 1000 turn painting. A proviso is that incoming beam halos, longitudinal included, must be at acceptable levels, and this is a new area for linac studies.

Other schemes employ zero dispersion at the foil, merging the H^- beam and protons either in a lattice dipole or in a dipole of a bump magnet set. For these, orbit bumps create less favourable final distributions, with rectangular beam cross sections.

The vertical bump magnets are all within the injection cell, thus separating the ring and injection optics. The price to pay for this layout is a high power current supply, which must be collapsed over the 600 μs injection interval. The peak power is >10 MVA for the ESS design, and varies inversely as the cube of the length, l, see Figure 7.

4 RING PARAMETERS, VACUUM

Large transverse emittances are required to restrict the space charge tune shifts and the proton foil traversals. The chosen 1 σ phase space areas ($/\pi$) are 30 and 35 μrad m for the 1.334 GeV ESS accumulators and 0.8 GeV-injection ESS options, respectively. Machine acceptances (4 σ) are 480 and 560 μrad m, respectively, and collimator limits are set at 260 and 305 μrad m.

Longitudinal bunch areas are chosen to avoid potential instabilities. Each ESS accumulator has a bunch area of 6.5 eV sec, while each ESS RCS has 2 bunches with 5 eV sec per bunch. These values are based on the use of contoured vacuum chambers to reduce the longitudinal space charge forces. For the chosen transverse and longitudinal emittances, the required values of normalised lattice dispersion at the position of the foil are ~2.2 $m^{1/2}$.

It is planned to shape the vacuum vessel dimensions to be a constant ratio of $4/\sqrt{5}$ to the local values of the full beam sizes in the rings. Solid chambers of aluminium are assumed for the accumulators, but ceramic chambers are needed for the RCS main and correction magnets. The ceramic chambers may follow the ISIS designs of [7], and require ISIS-style contoured radio frequency inter-shields.

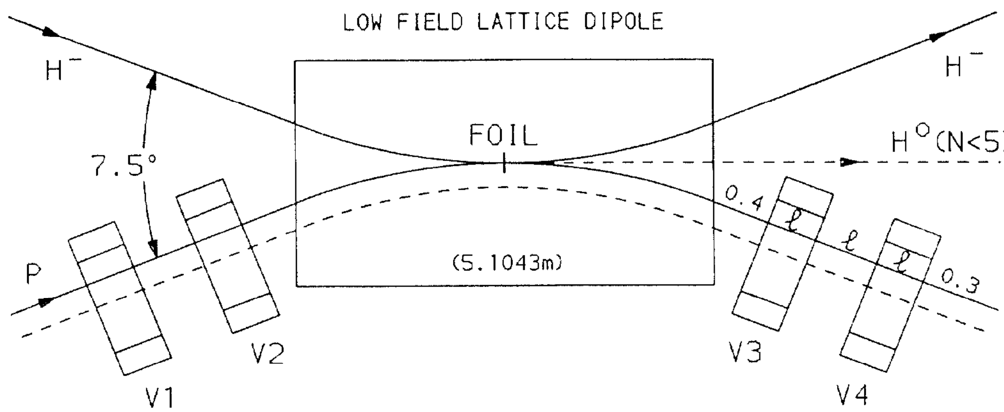

Figure 7. H^- Injection Straight Section

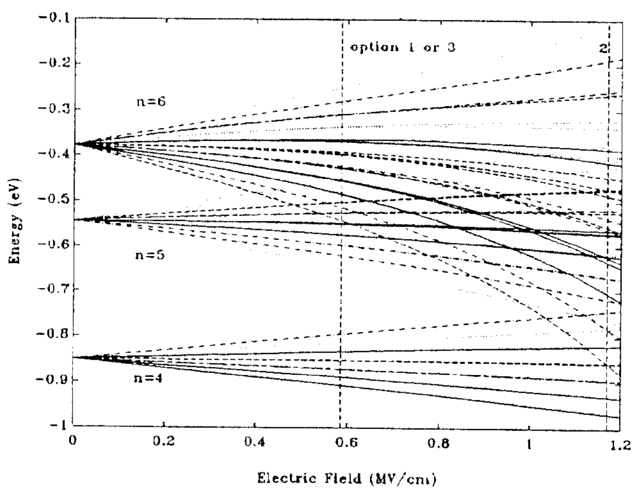

Figure 8. Energy Levels of Stark States

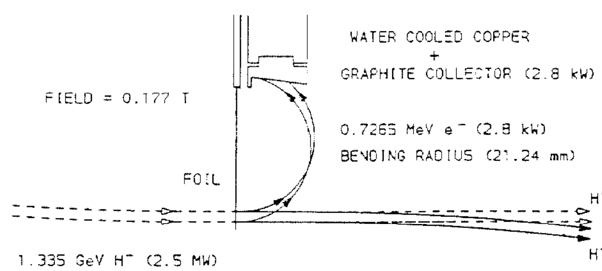

Figure 10. Electron Collection on Stripping

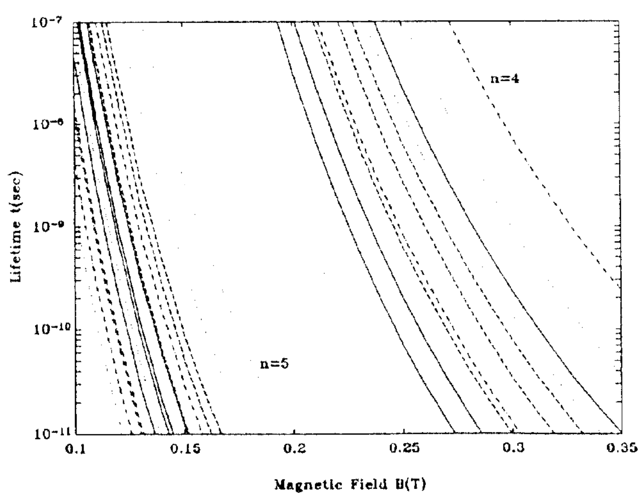

Figure 9. Stark State Lifetimes in Lab Frame

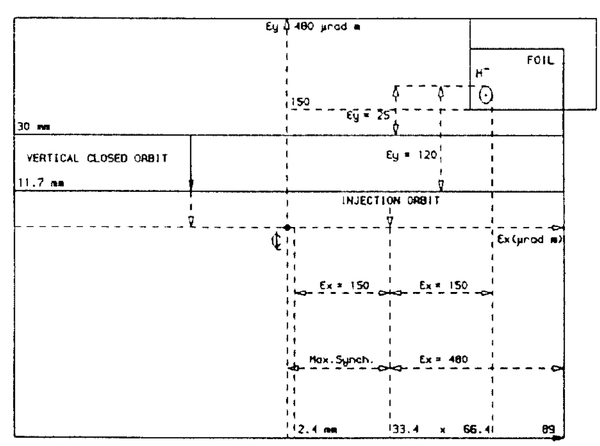

Figure 11. Cross Section at Stripping Foil

5 RADIO FREQUENCY SYSTEMS

Dual harmonic systems are proposed with total voltages:
$V = V_0$ (sin hωt - δ sin(2hωt + θ))
(though Barrier Bucket systems are also to be studied). For the accumulators, h=1, θ=0, δ=0.5, V_0 is raised from ~8 to 30 kV over injection and ω is frequency modulated. For the RCS, h=2, and θ, δ, V_0 and ω change continuously, see Figures 5 and 6. All options have heavy beam loading, reactive in the accumulators, but reaching 5 MW peak resistive in each RCS at mid-cycle. P_t and P_h of Figure 6 are, respectively, the total beam power and that provided by the system of harmonic, h. When $P_t < P_h$, power is absorbed from the beam by the 2h cavity systems. Longitudinal tracking is used to check parameters. Cavities have a single gap for the accumulators, but two gaps for the 25 Hz RCS, where 240 kV peak per turn is required.

6 INSTABILITIES

Bunched beam instabilities alone are relevant as the H^- beam is chopped at the ring bunch repetition frequency and cavities are on through injection to extraction. Though bunched, the beam may still develop an electron-proton instability, as at the PSR, LANL. It is suspected, but not confirmed, that their 30 μs growth time instability is caused by protons migrating into the bunch gap and attracting electrons, formed at pinger and extraction plates, in some avalanche process. The instability does not occur in ISIS at 70 MeV for equivalent levels (4 10^{13} protons), not even in a coasting beam mode. The ESS flux is ~6 larger, but this is offset by larger bunch areas and higher energies. ISIS safeguards are to be adopted: smooth chamber transitions, collection of foil stripped electrons and the use of low impedance, ferrite extraction kickers. Accumulators are potentially safer than RCS as beam is in them for less time, they have fewer cavities and they use solid vacuum chambers, not ceramic with inter-shields. Use of natural chromaticities leads to large head-tail phase shifts, reducing the prospect of transverse instabilities.

7 MAGNETS AND EXTRACTION

ESS dipole field levels, except in the injection dipoles, are 1.13 T in the 1.334 GeV accumulators, and 0.42 to 1.1 T in the RCS. They are dc in the accumulators and have a 20 Hz sinusoidal rise, a 40 Hz fall, and a 2.5 ms flat bottom in the RCS. Quadrupole and bending magnets have apertures comparable to those used in the ISIS ring.

Kicker risetimes must be <190 ns for the accumulators and <300 ns for the RCS. Push-pull, lumped kickers, separated by a ground plane, are to be used, as at ISIS. One design has a pulse forming network ($Z_0/2$), speed-up network and thyratron feeding a resistor Z_0 in parallel with a Z_0 cable linking a half kicker, again as at ISIS. Another has a PFN at Z_0, thyratron, and Z_0 cable feeding a saturating inductor and half kicker, with a speed-up network in parallel. Voltages and kicker currents are 40 kV and 5 kA, respectively, though the thyratron currents for the latter are halved. Coupling impedances for the designs will be checked. Required are 3x2 for the 0.8 GeV rings, 4x2 for the 1.334 GeV rings and 4x2 for the RCS. Lumped kickers are preferred to less rugged delay-line types.

8 COLLIMATORS AND SHIELDING

Beam loss may be localised by collimators and collectors. These are in a dispersion free region for betatron collection and at a point of maximum normalised dispersion for momentum loss. The former are more important for the accumulators, the latter for the RCS. For betatron loss, the primary collimators are set at a normalised transverse position, Z, and the secondary collectors at Z_1 and $-Z_1$, after betatron phase shifts μ_1 and μ_2, respectively. Requirements are $Z_1 > Z$ and $Z_1 \cos \mu_1 = Z = -Z_1 \cos \mu_2$. Typical values are $\mu_1=15°$, $\mu_2=165°$. It helps to angle the upper or lower half of the collimators, and to have μ_2 equal in the two transverse planes over the region. Collectors have to stop primary particles; the first is set just downstream of a collimator, with its surface set back progressively as the distance downstream increases, with Z_1(max) typically 1.02 Z. Large tunnels are envisaged for the rings, ~10 m by 15 m to allow hands on maintenance. Shielding will be 1.5 m steel, covered by 1.5 m of concrete, both for rings and beam lines to the neutron targets.

9 REFERENCES

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