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EXTRACTION FOR ISABELLE*

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Summary

The design specifications for ISABELLE, a superconducting proton storage ring facility under construction at Brookhaven National Laboratory call for circulating beam intensities of up to 6×10^{14} protons at 400 GeV energy in each ring.[1] The energy stored in the beam is 41 Megajoules, an order of magnitude more than what has been dealt with in the past. This beam energy cannot be safely disposed of within the confines of the ISABELLE lattice if damage to the dump or quenching of the superconducting magnets is to be avoided. Therefore the full intensity beam must be extracted from the storage rings under all circumstances of emergency or routine beam disposal. Beam losses in excess of 10^{-3} of the full beam can jeopardize the extraction components and lead to magnet quenching as well.

In this note we summarize a conceptual design of the extraction system and discuss the major constraints which lead to the parameters chosen.

Introduction

Beam extraction under emergency conditions imposes the most exacting design constraints on the system. It is estimated that the system must respond within 1 msec to cover all emergencies as presently conceived. When the emergency beam extraction system is perfected, the problem is simultaneously solved, with much safety margin to spare, for the case of normal scheduled beam disposal. Thus we shall discuss here only the emergency beam extraction. An internal dump (not discussed here) is contemplated to limit the damage in case of an extraction system malfunction.

Several problems arise which have not always had to be addressed with rigor in the past. The principal constraints stem from the fact that the beam may be stored in the unbunched condition, a condition which cannot be altered in the short time available for emergency response. As will be seen below, the aperture requirements for coasting beam extraction are larger than for bunched beams. Moreover, while bunched beams can be extracted without loss, such loss is unavoidable when extracting coasting beams, and may jeopardize the integrity of the extraction components. The transition from the normal state to the extraction state must be sufficiently fast (a small fraction of one beam revolution) if damage to the extraction magnets is to be prevented. One also finds that there is a very constricted choice of materials and physical configurations. The deposition of secondary stray particles in nearby superconducting magnets must be limited, because very small energy deposition densities will render the superconductor normal and quench the magnets. After summarizing the layout of the system we shall discuss these design constraints.

Layout

The principal components of the extraction system are a bank of magnets of the "current septum" variety, strong enough to deflect the beam outside the lattice, and a fast kicker system which switches the beam from its nominal orbit into the extraction channel. The stray field of the extraction magnets is low enough in the region of the normal orbit that they can be brought to full strength without perturbing the circulating beam significantly. The fast kicker must switch the beam very quickly, in 0.3 μsec, in order to prevent excessive losses on the septa. Defocussing devices in the extraction channel outside the ring structure disperse the beam in a sufficiently large beam dump volume.

The layout of the extraction system in the 6 o'clock straight section of ISABELLE is displayed in Fig. 1. The kicker and septum magnets are located upstream of the intersection point, the extraction lines cross over about 1.2m below the normal crossing point, and the beam dumps are located underground far downstream.

The fast kicker has a strength of about 1 T.m for a deflection of about 0.7 mrad at 400 GeV. The septum magnet string achieves a downward deflection of about 1 degree, and is located in such a way as to maximize the distance between the beam loss point and the downstream superconducting dipoles.

Aperture Considerations

In the ISA, beam extraction will take place in vertical phase space. Since all of the horizontal aperture is reserved for the momentum stacking process, the aperture reserve which will be needed for the extraction of unbunched beams is available only in the vertical plane.

In the normal state the beam with emittance ε (a function of energy) will be found somewhere within an admittance area A. For our purposes the admittance "A" defines the limit of permissible beam excursions prior to extraction. When the beam is found to approach the boundary of A, the emergency extraction system will be triggered. If the beam is bunched, and if the kicker is brought on in the time between the passage of two successive bunches, only the admittance A needs to be extracted and there will be no losses. For unbunched beams one must do more. Beam that

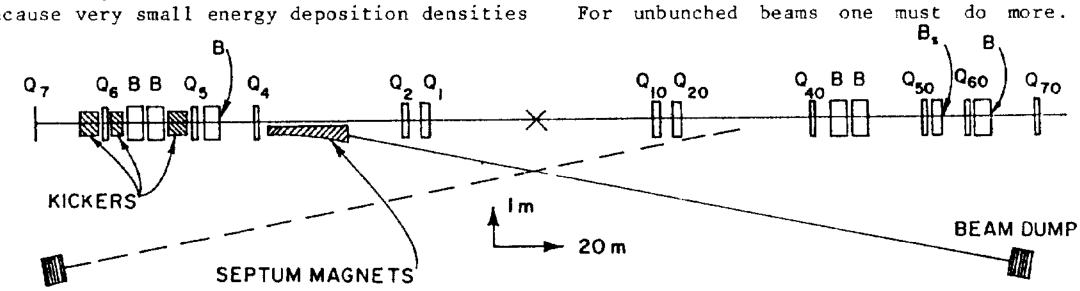

Fig. 1. Layout ISA Extraction, vertical plane. B - Bending Magnets. Q - Insertion Quadrupoles.

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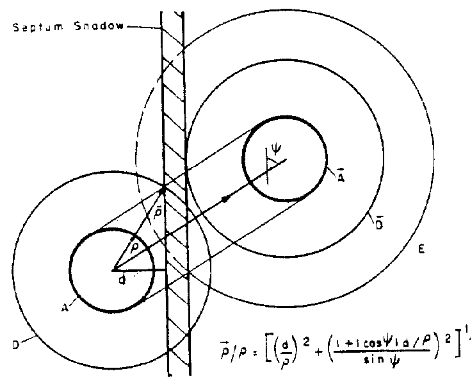
passes through the kicker while its field is rising may be driven outside the admittance A but not yet into the admittance of the extraction line. This perturbed portion (the "whipping tail") must perform another trip around the ring without being intercepted, before it encounters the kicker, now at full field, once again. This requires that an admittance D > A be available all around the ring and that the kicker transfer all of D into the extraction channel.

The situation in phase space at the location of the septum magnet is illustrated in Fig. 2, where we use the well known coordinates that represent the machine admittance as circles, and betatron motion as pure rotations. From the geometrical relationships displayed in this illustration it can be readily seen that ratio of the radius $\bar{\rho}$ of the admittance D and the radius ρ of the admittance A are a function of the betatron phase advance between the kicker and the septum. (The formula is displayed with the figure).



$$\bar{\rho}/\rho = \left[\left(\frac{d}{\rho}\right)^2 + \left(\frac{1+|\cos\psi|\, d/\rho}{\sin\psi}\right)^2\right]^{1/2}$$

$$\left.\begin{aligned} &= 1/\sin(\psi/2), \quad \psi \leqslant \frac{\pi}{2} \\ &= 1/\cos(\psi/2), \quad \psi \geqslant \frac{\pi}{2} \end{aligned}\right\} d = \rho$$

Fig. 2. Betatron phase space relationships at septum entrance.

In one of the possible kicker layouts for our system $\psi = 117°$ and $\bar{\rho}/\rho = 1.9$, i.e. the phase space area D to be kicked into the extraction channel is about 3.6 times larger than the original admittance A. Similarly one can see that the minimum kick $(\rho + \bar{\rho})/\sin\psi$ required to transfer all of D across the septum is about 45% larger than the minimum $(2\rho/\sin\psi)$ that applies for bunched beams. Finally, the extraction channel admittance E must be larger still than D. None of these enlargements would be required if the beam were always bunched.

The aperture requirements and the kicker strength scale in a simple way with the admittance A. The ISABELLE design parameters call for normalized beam emittance $\varepsilon\beta\gamma = 15\pi \times 10^{-6}$ rad-m or $\varepsilon = 0.5\pi \times 10\text{-}6$ rad-m at the injection energy of 30 GeV. For possible beam excursions we specify $A = 2\pi \times 10^{-6}$ rad-m which implies rather tight tolerances for the injection process. In the interest of conceptual simplicity one is tempted to treat this admittance A as a constant of the accelerator, although the actual emittance of the beam decreases inversely proportional with its energy. This "brute-force" solution requires a very large kicker with a field integral of about 1 T.m at 400 GeV, with an operating range of 13:1. If on the other hand one reduces the aperture allowance in proportion to the beam size during acceleration, the kicker can be proportionately smaller and have a smaller operating range, a significant saving in scale at the expense of increased system complexity. The issue is not fully resolved at present, but space is reserved for implementing the simpler "brute-force" solution, and in the following discussion we regard A as a constant.

Beam Loss During Extraction

While the kicker rises to full strength the first septum of the string of septum magnets is hit directly by the unbunched beam. It shadows and protects the downstream ones from direct exposure. The beam loss, expressed as a fraction L of the total circulating beam can be seen to be

$$L = \frac{1}{T} \cdot \frac{s}{\dot{k}}$$

(independent of the beam size to first order), where T ($12.8\,\mu$sec) is the beam revolution period, $\dot{k}$ is the transverse velocity of the beam displacement, as measured at the instant of the septum exposure, and s is the effective thickness of the septum.

It should be remembered that very weak long septa present considerable obstacles (large s) to a beam of finite angular divergence even though they may be very thin. At the other extreme a strong magnet needs a thick septum (large s again) to carry the current. Between these extremes an optimum thickness can be found. Of course this optimum depends strongly on the admittance area that the septum must steer into the extraction channel.* For $A = 2\pi \times 10^{-6}$ rad-m we find this optimum to be an effective thickness of about 0.25 - 0.35 mm for an assumed range of current densities of 50-100 kA/cm^2. The first septum to be installed at ISABELLE will be at the high side of this optimum, with a physical thickness of 0.5 mm, an effective thickness s = 0.55 mm and a current density $j < 70$ kA/cm^2, yielding a deflection of 1 mrad at 400 GeV. The septa of the subsequent magnets, located in the widening shadow cast by the first, will be increasingly thicker, permitting stronger deflections (3.33 mrad in each of five magnets).

The other critical parameter for beam losses is the rise rate $\dot{k}$ of the kicker deflection at the instant of the septum exposure. Details of the kicker pulse design are addressed in another paper at this conference[2] (Nawrocky et al). Since the full aperture for the whipping tail is not required until the tail end of the spill it is possible, and indeed profitable, to build in some initial pulse overshoot, thus obtaining a high speed of transition $\dot{k}$ during the rise. The kicker is required to give a 40 mm deflection at the septum location, the transition velocity will be $\dot{k} > 120$ mm/μsec, and the extraction losses will be $L < 4 \times 10^{-4}$. Note that solutions with smaller kicker deflections require faster rise times if the losses are to remain the same.

Septum Survival

The beam that sweeps across the first septum is very narrow, only 1.3 mm full width in the plane of the septum at 400 GeV. It induces a nuclear cascade, which heats a narrow strip of septum material almost instantaneously (20-30nsec), subjecting it to stresses that can easily exceed its yield strength and making its survival questionable. Of particular concern is the electromagnetic cascade that develops from the production of neutral pions and their descendant gamma rays. The problem is most severe in high Z materials, such as copper, which have short radiation lengths. Obvious remedies are proper choice of septum material and reduction of beam loss. One crucial parameter is the septum thickness. Making it thin prevents the cascade from building up to bulk

* We find that electrostatic septa are not sufficiently strong to be useful for the admittance A adopted here.

material level, since a considerable fraction of the secondaries generated escape sideways. Stevens has performed Monte Carlo calculations[3] to evaluate the maximum energy deposition per unit volume as a function of the septum thickness, using a modified version of the cascade simulation code CASIM.[4] The calculation yields the instantaneous local temperature rise ΔT. This result is uncertain by a factor of three for several reasons. The computation assumes a rectangular beam distribution, and may thus underestimate the heating in the core of the beam. The computer code has been found to over-estimate the energy deposition far from the beam core, but has not been experimentally verified inside the core of very small beams, and under the unusual material boundary conditions applicable here.

Bowen has shown[5] that for thin sheets the dynamic stress does not exceed $\sigma = Y\alpha\Delta T$ (Y = Young's modulus, α = linear thermal expansion coefficient). As he points out, however, the thin sheet approximation begins to break down when the exposure time (30nsec in our case) becomes shorter than the "accommodation time" in the thin dimension (septum thickness/speed of sound; 200nsec for s = 1 mm). Thus between 0.1 to 1 mm septum thickness we may begin to encounter dynamic bulk stresses as much as six times higher than σ (for a Poisson ratio of 1/3). The situation is summarized in Fig. 3, where the stress ratio ($Y\alpha\Delta T$/yield strength) is plotted for several materials, with septum thickness s as a free variable. This ratio must be well below 1.0, perhaps as low as 1/6 (dashed horizontal lines) for the range of parameters under consideration. Copper appears marginal even if very thin conductor sheets are used. Aluminum may be unsuitable because it anneals and loses strength under typical bakeout temperatures (300°C) needed to achieve ultrahigh vacuum (10^{-11} Torr). Beryllium, not shown, would look similar to, perhaps somewhat more favorable than, aluminum on this figure. One notes that for lower Z materials the problem of the cascade buildup is safely avoided for septum thickness < 1 mm. Titanium presents a favorable combination of properties and its application is being evaluated for ISABELLE, although its electrical resistivity makes it a far from ideal conductor material.

In the light of the foregoing discussion it is prudent to keep the first septum thickness much below 1 mm. Our adopted value of 0.5 mm involves some risk, and the situation must be carefully monitored as the machine intensity increases in time.

Quenching of Superconducting Magnets

ISABELLE's superconducting magnets will be quenched, that is, their conductors will be driven into the normal, nonsuperconducting state, if energy is deposited in them at densities above a few milliJoule per cm^3. Minor beam losses and particularly the secondaries that result from the extraction of coasting beams yield energy deposition densities of that order. A detailed Monte Carlo simulation of extraction losses and associated secondary particle production has been carried out by Stevens[6] (these proceedings). It shows that a fractional loss that exceeds 10^{-3} of beam intensity is likely to quench the accelerator at 400 GeV. The calculation assumes that the magnets are protected from most of the secondary particle flux by careful collimation and that the enthalpy reserve of the superconductor is about 1.5 mJ/cm^3 in the dipoles and 3 mJ/cm^3 in the quadrupoles at maximum field.

Aside from the difficulty of the computation itself, it is still an open question how close to the short sample limit of the superconductor the accelerator can operate. Thus the whole problem is difficult to assess. A beam loss of 5×10^{-4} or less seems acceptable if proper precautions are taken. Eventually the problem of magnet quenching from extraction losses must be addressed empirically early in the life of the accelerator. It is conceivable that an occasional quench during the emergency extraction of a coasting beam, considered to be very undesirable at the moment, may still be tolerable. Scheduled extraction can be preceeded by rebunching, if necessary, to yield negligible loss.

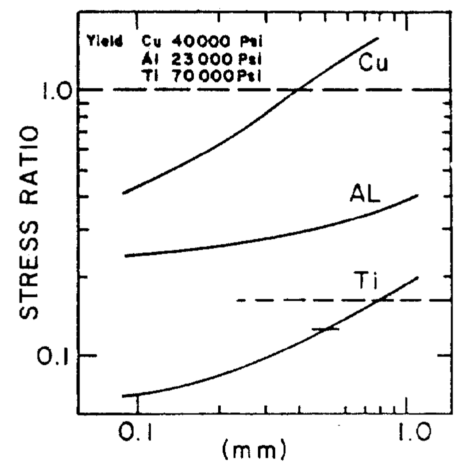


Fig. 3. Septum stresses as a function of septum thickness. Thin sheet approximation.

Discussion

The aperture requirements and the equipment dimensions for protective beam extraction at ISABELLE are well understood, and some trade-offs of system scale against system complexity can still be made. The crucial questions of system reliability are now beginning to be addressed. Computer simulations help in choosing parameters which assure the integrity of the system under the inevitable extraction losses, but exact numbers are elusive. They will be verified, for better or for worse, only as the machine approaches operation near full intensity. It appears at this time that at high energy the superconducting magnet lattice is more sensitive to the secondary particle spray, than the septum components are to the direct primary proton exposure during extraction. We aim for a fractional beam loss of $L < 5 \times 10^{-4}$.

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