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SYNCHROTRONS AND ACCUMULATORS FOR HIGH INTENSITY PROTONS: ISSUES AND EXPERIENCES*

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Abstract

This paper summarizes physical and engineering issues of high-intensity synchrotrons and accumulators, and discusses future applications and outlook.

1 INTRODUCTION

For the five decades since the discovery of the synchrotron [1] and the principle of alternating-gradient focusing [2], the development of accelerator science and technology has sustained exponential growth in both the energy and intensity of the proton beam as shown in the "Livingston chart" ([3, 4] and Fig. 1). Combined with an increasing repetition rate, the high proton beam power has extended its use from nuclear and high-energy physics to modern applications including spallation neutron production, kaon factories, nuclear transmutation, energy amplification, neutrino factories and muon collider drivers.

Several factors have made the use of synchrotrons and accumulators possible for high intensity beams. One is the development of intense, high-duty factor, low emittance H^- and H^+ ion sources. A second is the invention of the Radio-Frequency Quadrupole (RFQ) [5], replacing Cockcroft-Walton as pre-accelerator, combining focusing and acceleration while preserving emittance. A third is the development of linear accelerator technology including permanent magnet quadrupoles for drift-tube linacs and super-conducting technology for operational economy and reliability.

This paper discusses mainly the development of synchrotrons and accumulators, emphasizing experiences gained in recent years, current issues, and the future outlook. Section 2 outlines design philosophy. Section 3 discusses physical and technical issues ranging from lattice design, injection, ramping, transition crossing, extraction, magnet fringe field and compensation, space charge and halo development, electron cloud, and instabilities. Section 4 lists future applications, and Section 5 is a summary.

2 LOW-LOSS DESIGN PHILOSOPHY

The primary concern in the design of high-intensity proton facilities is that radio-activation caused by uncontrolled beam loss can limit a machine's availability and maintainability. Based on past operational experience, hands-on maintenance (1 – 2 mSv/hour at 30 cm from the surface, 4 hours after shut-down) demands an average uncontrolled beam loss not exceeding about two Watts of beam power per tunnel-meter [6]. For example, for a ring of 200 m

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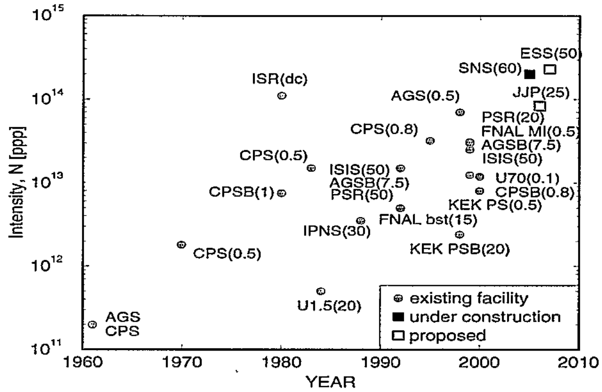

Figure 1: Evolution of ring intensity (particles per pulse). The parentheses indicate repetition rate in Hz.

circumference handling a 2 MW beam power, this corresponds to a fractional uncontrolled beam loss of 10^{-4}.

Existing proton synchrotrons and accumulators have beam losses as high as several tens of percent, mostly occurring at injection, capture, initial ramping, transition crossing, and through instabilities. The lowest beam loss is about 3×10^{-3}, achieved at the Proton Storage Ring (PSR) at the Los Alamos National Laboratory [7]. Uncontrolled beam losses are usually attributed to (1) a high space-charge tune shift (0.25 or larger) at injection resulting in resonance crossing; (2) limited physical and momentum acceptance; (3) premature H^- and H^0 stripping and injection foil scattering; (4) large magnet field errors, misalignments and dipole-quadrupole matching errors during ramping; (5) instabilities (*e.g.* head-tail instability, coupled bunch instability, negative mass and microwave instability, PSR instability); and (6) accidental beam loss (ion source and linac malfunction, extraction kicker mis-fire, etc.).

A low-loss design or upgrade must address the above issues. Furthermore, with a large transverse and momentum aperture, multi-stage collimation and momentum cleaning can be incorporated to localize beam loss to shielded locations. Flexibility and robustness (tune adjustment, injection option, ramp-dependent correction, adjustable collimation, foil interchange, spare interchange) need to be reserved for commissioning and operation, and engineering reliability (heat and radiation resistance) and availability (a foil interchange mechanism, quick-disconnect flanges, crane, etc.) need to be addressed at an early design stage.

Fig. 2 illustrates the layout of a typical ring for high-intensity applications [8]. The machine circumference is 248 m. Four straight sections are designed for injection, collimation, radio-frequency (RF) system, and extraction, respectively.

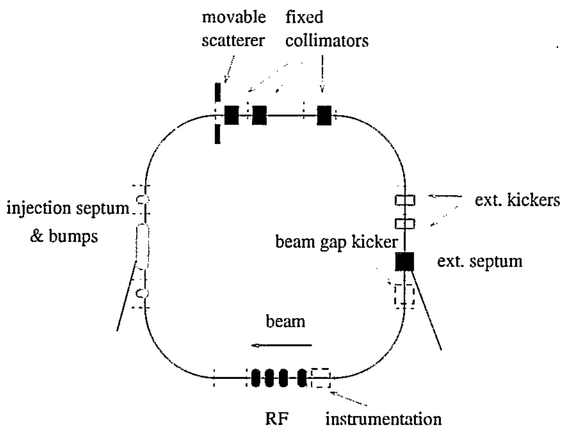

Figure 2: Schematic layout of the Spallation Neutron Source (SNS) accumulator ring.

3 PHYSICAL & TECHNICAL ISSUES

3.1 Lattice

The lattice is the back-bone of a ring. Recently designed ring lattices often prefer separate-function magnets instead of combined-function magnets for robustness. Tunes are often split by at least half to reduce space-charge coupling and suppress systematic skew quadrupole components.

A traditional choice is the FODO and its variations. FODO structures require modest quadrupole gradients, and the alternating transverse beam amplitudes easily accommodate correction systems. With various arrangements of dipoles, one can create dispersion-free regions for injection, extraction, and RF systems [9, 10], and low momentum compaction to avoid transition crossing [9].

A lattice consisting of doublets/triplets has the advantage of long uninterrupted drifts for flexible injection and optimal collimation. Synchrotrons of this structure also have fewer vacuum chambers and joints [11].

The SNS accumulator ring adopts a hybrid structure with FODO arcs and doublet straights. It combines the FODO structure's simplicity and ease of correction with the doublet structure's long drift (12.5 m) for flexibility [8]. The

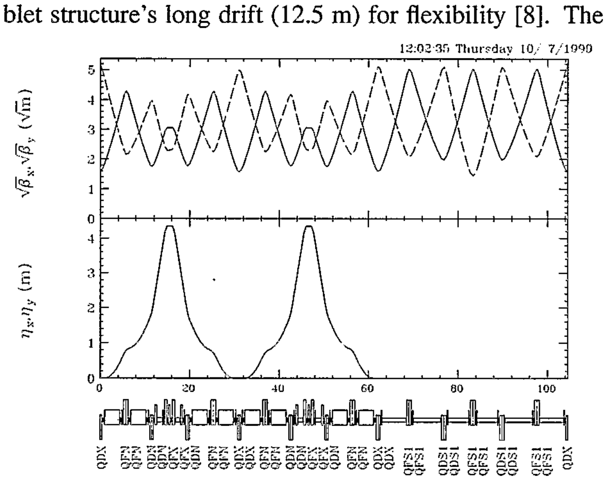

Figure 3: Japan Joint Project (JJP) 3-GeV ring lattice super-period (courtesy S. Machida) of FODO structure. The machine super-periodicity is 3.

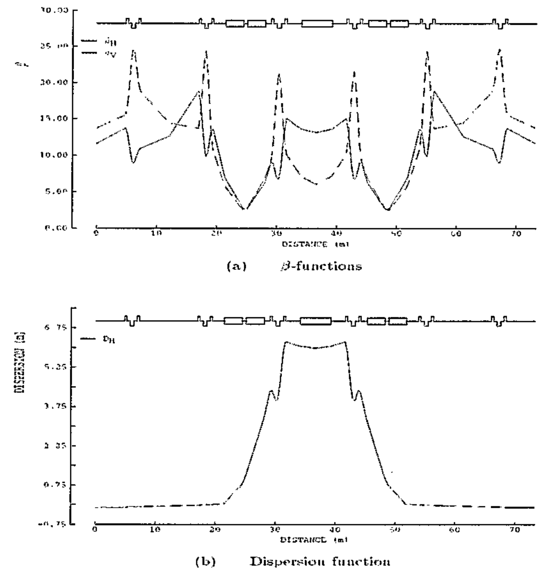

Figure 4: European Spallation Source (ESS) ring lattice super-period (courtesy G.H. Rees and C.R. Prior) of triplet structure. The machine super-periodicity is 3.

arcs and straights are optically matched to ensure maximum betatron acceptance. A horizontal phase advance of 360° across each arc makes the straights dispersion free. Each dipole is centered between two quadrupoles so as to maximize the vertical acceptance of the dipoles.

3.2 Aperture, Collimation, Collection

For new rings, the linac-ring transport is usually designed to clean linac beam halo, prevent source and linac malfunction, and reduce injection activation. Transversely, foils can be used for H^- scraping. Longitudinally, an achromat bend is often used to create dispersion for energy tail cleaning.

Any beam halo and tail generated in the ring can be cleaned with high efficiency using two-stage collimation systems [12]. Momentum cleaning can be achieved in several ways: (1) injecting at a high-dispersion region and collecting at 180° phase advance downstream (ISIS, ESS [11]); (2) scraping at a high-dispersion lattice location (JJP

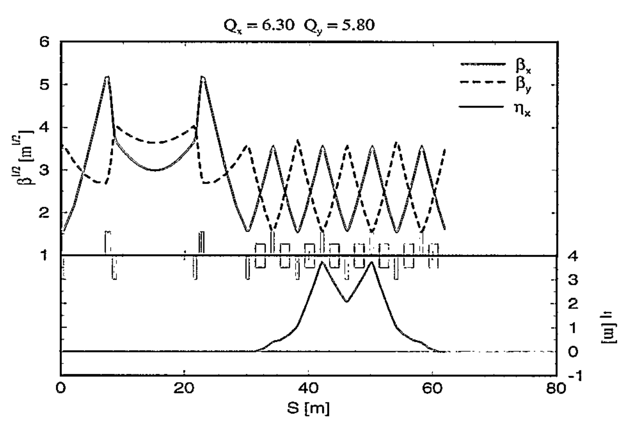

Figure 5: SNS ring lattice super-period of FODO/doublet structure. The machine super-periodicity is 4.

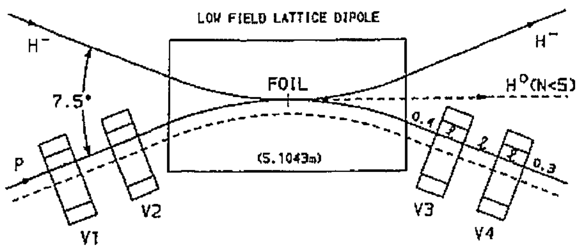

Figure 6: ESS dispersive injection layout.

[9]); and (3) using a beam-in-gap (BIG) kicker (SNS [13]). To reduce activation at extraction, the beam in the gap needs to be cleaned either during the initial ramping for synchrotrons, or with BIG kickers for accumulators.

Efficient beam collimation and low beam loss requires an adequate clearance between the beam core and the vacuum chamber limit. Typically, an acceptance-to-emittance ratio of at least 2 is needed. Momentum collimation using the BIG kicker requires an adequate momentum clearance so that particles can reach the gap without loss.

3.3 Injection

Single-turn injection with septum and kicker requires optical matching between the transfer line and the ring. Multi-turn injection can be assisted by skew quadrupole induced coupling (CERN PSB, AGS Booster).

Multi-turn charge-exchange injection painting using a stripping foil is preferred for most new rings. The magnetic field must be chosen carefully to prevent premature stripping of both H^- and H^0 [14]. ISIS/ESS prefers injecting at a high-dispersion region (Fig. 6). The lattice dipole simplifies the injection magnet arrangement and facilitates momentum halo collection. SNS prefers injection in a zero-dispersion straight (Fig. 7). The decoupled longitudinal motion allows independent momentum correction and broadening before injection, and is more tolerant to linac energy deviation. A long, uninterrupted straight is preferred to contain the injection chicane, allowing independent lattice tuning. Intentionally mismatched injection [16] can noticeably reduce the foil hits. Laser stripping [18] has been explored as an alternative but the required power and efficiency are very demanding.

Stringent beam profile and uniformity are often required for application targets. Various beam profiles can be achieved using fast orbit bump or injection steering. Scenario (b) and (c) of Fig. 8 ideally produce uniform den-

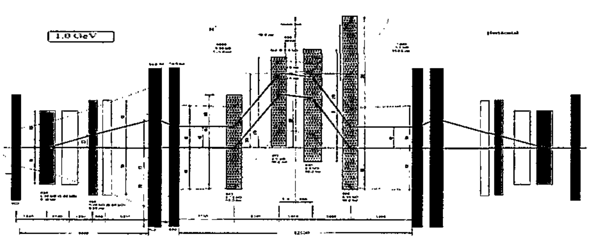

Figure 7: SNS dispersion-free injection. Elements shown are the chicane (red), the ring lattice quadrupoles (blue), and dynamic kickers (yellow H and green V).

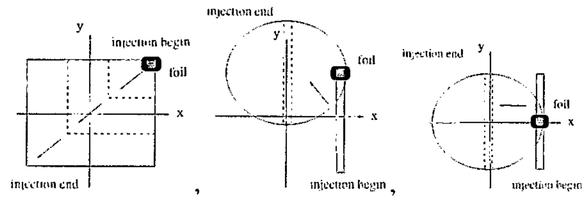

Figure 8: Beam transverse profile of (a) correlated-bump painting (b) anti-correlated bump painting and (c) horizontal painting / vertical steering.

sity beams but practically are susceptible to halo development. Resonance correction and decoupling are crucial in preserving the painted beam shape.

3.4 Space Charge and Halo

Space charge is a fundamental limitation for ring injection. Particle-core parametric resonance, which is the primary source of halo generation in a proton linac, is often unimportant especially for a multi-turn injected ring [19] when the halo is covered by subsequently injected beam. On the other hand, space charge produces tune spread which can easily be excited by magnetic nonlinearities [16].

Space charge can be alleviated by longitudinal manipulation (double RF, barrier cavity, etc) to enhance bunching factor, painting and controlled injection (e.g. smoke-ring), or by simply raising the injection energy. Compensation using inductive inserts is also demonstrated [17].

3.5 Capture and Ramping

Beam pre-chopping is commonly used to reduce capture beam loss. Techniques employing wide-band cavities (barrier cavity) have been successfully demonstrated to increase beam intensity [20].

Acceleration is typically achieved with ferrite-loaded RF cavities. Cavities using Magnetic Alloy material [21] have been successfully tested at AGS to achieve a gradient of 50 kV/m. The use of IGBT power supplies allows magnet ramping to be programmed, reducing peak ramp rate and current-induced imperfections.

Conventionally, the ring vacuum chamber is either made of metal pipe or is directly attached to magnets (FNAL Booster). For rapid cycling synchrotrons, the vacuum chambers need to be RF shielded to give high impedance to the eddy current but low impedance to the image current. Possible candidates are ceramic chambers with (1) sustained metal wires following the beam envelope (ISIS), (2) printed, internal silver wires (KAON factory [22], SNS RCS [23]), (3) external shielding and internal coating (JJP), and (4) extra thin Inconel chamber (FNAL PD).

3.6 Extraction

Extraction is usually an area of heavy radio-activation. In newly designed rings, multiple lumped kickers are used so that beam loss is tolerable when one kicker fails. The pulse forming network is often installed outside of the ring tunnel for easy maintenance. In the case of spallation applications, the phase advance is also chosen so that the beam position on target does not change with kicker failure. In accumulators, cleaning the beam gap with the BIG kicker further reduces uncontrolled extraction loss.

3.7 *Magnet Field Error & Compensation*

Magnetic errors produce beam orbit deviation, coupling, tune spread, and resonance excitation. For rapid cycling synchrotrons, the leading sources are ramping eddy current and saturation. Ramp rate and peak field need to be moderated, and ramp-dependent corrections need to be implemented to control orbit and coupling.

Accumulators are only susceptible to geometric errors. The leading error components are those allowed by magnet symmetry, and can usually be corrected locally by magnet pole shaping and shimming [24].

Contributions from magnet fringe fields is important for rings of large acceptance and moderate circumference. The relative impulse is approximately equal to the ratio between beam emittance and magnet length [25], which can be corrected by multipole correctors [26].

Chromaticity control is essential for rings operating above transition energy. For rings operating solely below transition, chromatic sextupoles, especially powered in multi-family preserving lattice symmetry, offer tune spread control, instability damping, and off-momentum optics matching. The SNS ring uses four-family chromatic sextupole magnets located in high-dispersion regions, complemented by resonance correction sextupole windings located in zero-dispersion regions [27].

Resonance correction has been used successfully on several machines including CERN PS, AGS and AGS Booster. At the AGS Booster, resonance correction up to normal and skew sextupole has been essential during high-intensity operations (Fig. 9) [28].

3.8 *Transition Energy*

Among existing rings where the beam has to cross transition energy (AGS, CERN PS, SPS, KEK PS, FNAL Booster, etc.), beam loss and emittance growth are often observed due to chromatic nonlinearity, self-field mismatch, and instabilities [29]. At CERN SPS, the injection energy is raised to avoid transition during intense single-bunch operation. Longitudinal head-tail instability caused by nonlinear momentum compaction further complicates injection near transition. At AGS, transition jump [30] using pulsed quadrupoles has been used to minimize beam loss at high intensity. The large lattice distortion introduced by the jump system prior to the crossing severely limits machine aperture. Efforts to correct the distortion with existing sextupoles have been partially successful (Fig. 10) [31].

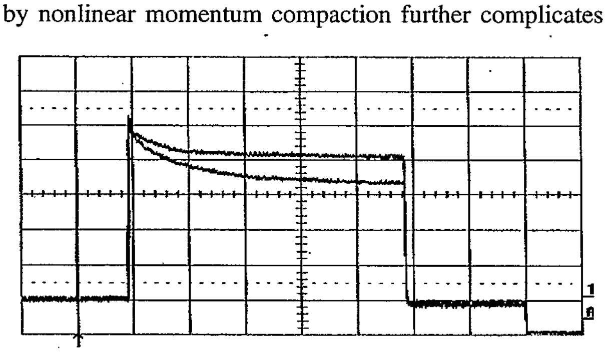

Figure 9: Increase of beam survival with sextupole resonance correction in the AGS Booster (x: 10 ms per box; y: 2×10^{13} ppp at flat top, courtesy C. Gardner).

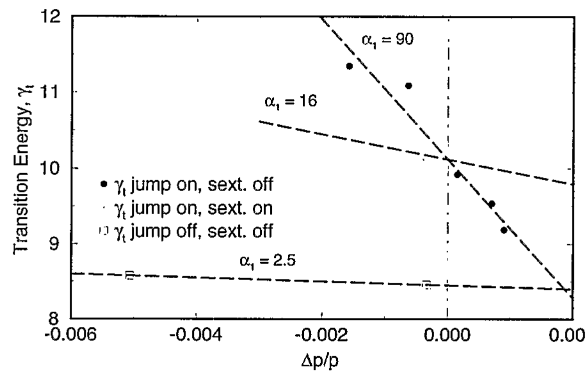

Figure 10: Measured transition energy as a function of the momentum deviation of the gold beam at AGS [31].

Newly designed rings usually avoid transition either by the choice of injection and extraction energy, or by lattice manipulation creating negative dispersion in the bends. For rings that must cross transition, an optically matched transition jump using multiple quadrupole families located at different values of dispersion is preferred [32].

3.9 *Impedance and Instabilities*

Instabilities are commonly observed in proton rings. Head-tail instability was observed near injection in KEK PS, CERN PS and AGS, and suspected to be due to chromaticity change caused by eddy current-induced sextupole fields (proportional to $\dot{B}/B$) in the vacuum chamber under dipole magnets. This type of instability can be cured by chamber correction windings (AGS Booster), chromaticity control, octupole field damping, and tune manipulation. Negative mass and microwave instabilities are observed at CERN PS, SPS, AGS, and KEK PS, and can be cured by impedance reduction measures including shielding of vacuum ports and septa, increasing the bunch length and reduction in bunch peak density using dilution cavities. Coupled bunch instability has been observed at CERN PS Booster, PS, SPS, and AGS, and damped by fast feedback systems and Landau damping systems. ISIS programs tunes in each cycle to accommodate natural chromaticity variation, space-charge tune depression, and to avoid resistive-wall head-tail instability [14].

A fast, high-frequency, transverse instability was observed at PSR with both coasting and bunched proton beams, associated with peak intensity-dependent electron accumulation. The electron accumulation is associated with secondary emission from the vacuum chamber, and TiN coating of one straight section suppresses the measured electrons by a factor of about 100. All effective control involves Landau damping [7] (RF voltage and momentum spread increase, inductive insert, sextupole adjust-

Table 1: Example of future high-intensity applications [36].

Project	E [GeV]	$\langle I\rangle$ [mA]	Rep. [Hz]	$\langle P\rangle$ [MW]	Type
SNS	1	2	60	2	LAR
ESS	1.33	1.9	50	2.5	LAR×2
JJP	3	0.33	25	1	RCS
CERN NFPD	2.2	1.8	75	4	LAR
RAL NFPD	5	0.4	25	2	RCS×2
FNAL NFPD	16	0.125	15	2	RCS×2
CERN EA	1	10/20	CW	10/20	Cyclotron
APT	1.03	100	CW	103	linac
TRISPAL	0.6	40	CW	24	linac
ADTW	0.6/1.2	20/50	CW	> 20	linac
μ PD (US)	30	0.25	15	7.5	RCS

ment, etc.). A similar instability was observed at ISR and cured by installing more clearing electrodes [33], and at AGS Booster during coasting beam operation [34].

Impedance minimization is an important measure to prevent instabilities. Improved vacuum chamber by-pass is planned at CERN PS Booster, and shielding of magnet septa and vacuum ports are underway at CERN SPS. ISIS incorporates RF shielding that follows the beam contours and smooth chamber transition, collects stripped electrons, and uses low impedance ferrite extraction kickers.

With the SNS ring, a momentum aperture of $\pm 2\%$ is designed for the beam with $\sim 290\pi$mm·mr normalized emittance to allow adequate Landau damping. Vacuum chamber steps are tapered, and bellows and ports are shielded. Chromatic sextupole families are designed for instability control. A relatively high RF voltage and a gap-cleaning (BIG) kicker help preserve a clean beam gap. Magnets near the injection foil are specially tapered to collect stripping electrons. The vacuum chamber's inner surface is coated with TiN to reduce the secondary electron emission yield. Other measures include winding solenoids on straight-section chambers, and reserving space for future wide-band damping systems [8].

4 FUTURE APPLICATIONS

Table 1 lists some high-intensity applications including spallation neutron sources, neutrino-factory proton drivers (NFPD), muon collider drivers, nuclear transmutation, and energy amplifier (EA) [35, 36]. For pulsed applications, the linac-accumulator (LAR) scenario is advantageous in loss minimization (no main magnet ramping, better magnet field quality, and shorter storage time for instability development). On the other hand, rapid cycling synchrotrons (RCS) are economical for energy and power upgrade (multi-ring cluster, multi-purpose), and are easier to realize a short bunch length.

5 SUMMARY

The design and optimization of high-intensity rings mainly involve physical and momentum acceptance consideration, space-charge control, injection design, magnet field and alignment error correction, instability control, beam halo collimation and protection. With five decades of understanding and progress, synchrotrons and accumulators in the high-intensity frontier are meeting the challenge of next-generation applications.

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