HIGH-CURRENT, LOW-ENERGY SYNCHROTRONS AND COMPRESSOR RINGS*

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The primary application of high-current, low-energy synchrotrons and linac compressor rings is as proton drivers for pulsed-spallation neutron sources. They operate in the range of 500 to 1500 MeV with extracted beam repetition rates between 12 to 100 Hz. The time-averaged currents on target are a few tens of microamperes today, soon will be a few hundred microamperes, and may be a few thousand in the future. The characteristics for the accelerators and compressor rings, their limitations, and existing and proposed major facilities are described.

Introduction

There is considerable interest in high-current, low-energy synchrotrons and linac compressor rings as drivers for pulsed-spallation neutron sources. Two 500-MeV proton synchrotrons[1-2] and one 800-MeV proton linac[3] are currently operating with spallation neutron targets. A synchrotron[4] and a compressor ring[5] are under construction and more are in the planning and proposal stage. It is the intention of this paper to describe the requirements, performance goals and problems in reaching the goals for machines in this range; namely, 500 to 2000 MeV.

Carpenter and Price[6] suggested the possibility of using proton accelerators for producing intense bursts of neutrons to produce both more intense sources and time-structured beams that could make use of time-of-flight techniques. The use of pulsed sources allows performance of real-time experiments and provides low background noise because the source is off most of the time.

The first spallation source was tested at Argonne in 1974 using the 200-MeV proton accelerator, Booster-I, with a prototype target station, ZING-P.[7] This prototype was operated infrequently and only at very low intensity; yet, it did provide confidence to proceed with the ZING-P' facility at Argonne. ZING-P' was built as the second stage in the development of pulsed-spallation sources with the goals to act as a test bed for source, target, and moderator development; instrument development; and to produce preliminary scientific results. These goals were successfully achieved before ZING-P' was shut down in August 1980 for conversion to the new IPNS facility. The facility has been operating successfully since 1981.

In December 1975, the Japanese government gave approval to construct a Booster Utilization Facility (BSF), which included a neutron scattering target at the National Laboratory for High Energy Physics at Tsukuba. The facility uses the 500-MeV, 20-Hz booster of the 12-GeV KEK accelerator in a time-sharing mode. That facility came on-line on June 18, 1980. Five spectrometers are installed on this facility. It has a room temperature and a cold methane moderator. It is used for neutron scattering physics approximately 30% of the time that the BSF operates.

The Weapons Neutron Research Facility (WNR) at LANL is another pulsed-spallation source that started operation in the 1970's. Beam from the 800-MeV LAMPF accelerator has been directed onto the WNR target since 1977. The system was built for weapons-related research, but is available part time for neutron scattering studies. The main shortcoming of the present WNR facility is the long beam pulse (~10 μs) which deleteriously impacts on the resolution of time-of-flight measurements. This shortcoming will be overcome when a new storage ring currently in construction has been completed. This facility, with the addition of the storage ring, will have the potential to increase the peak flux as much as a factor of 4 or 5 over the IPNS facility at Argonne. The projected operating date of the PSR at the design goal of 100 μa is April 1986.

In June 1977, the British government announced the decision to fund construction of the Spallation Neutron Source (SNS) at the Rutherford Laboratory. Most construction is complete or nearing completion. Commissioning has started and first beam has been accelerated to 140 MeV. This facility will be the largest pulsed-spallation source in the world when the commissioning period ends and full beam is achieved. The design goal is a time-averaged proton current of 200 μA on target at 800 MeV. The pulse repetition rate will be 50 Hz.

A reference design for an advanced pulsed-spallation neutron source has been jointly developed by groups at the Kernforschungszentrum at Karlsruhe and the Kernforschungsanlage at Jülich in Germany. This reference design was started after a recommendation to pursue a spallation source was delivered by a special panel appointed by the German minister for research and technology. The reference design is based on an 1100-MeV proton linac and an isochronous compressor ring with an average current of 5 mA on target. A fixed-field alternating-gradient synchrotron is presently being considered as an alternative to the compressor ring for producing the narrow pulses for time-of-flight measurements.

Argonne National Laboratory has developed a conceptual design for a fixed-field alternating-gradient (FFAG) synchrotron that would deliver 3800 μa of protons at 1500 MeV at a pulse rate of about 45 to 50 Hz.

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Thus, accelerators for pulsed-spallation sources have gone from weak machines in the mid-seventies to modest machines today. More intense sources are under construction and still bolder and more exciting sources are being discussed.

The four important parameters that establish the requirements for these accelerators are the intensity, energy, pulse length, and repetition rate.[8] The intensity is a parameter that is naturally maximized within the economic and technological constraints of the system.

The energy of the accelerator is determined from target and moderator considerations. The yield of neutrons from the target is roughly proportional to E-120 where E is the proton energy in megaelectronvolts. The energy of the neutrons emitted from the target surface is reduced by several orders of magnitude by using polyethylene, liquid hydrogen, or liquid methane moderators in close coupling to the target. Reflectors are added to increase the low-energy neutron flux. The optimal proton energies are in the range of a few hundred megaelectronvolts to two gigaelectronvolts. The moderators are limited in size to avoid excessive time spreading of the neutron pulse. The yield tends to be linear with E-120 for energies up to 2 GeV, but levels off at higher energies because of range and moderator effects.

The energy resolution of neutron diffractometers is affected by the pulse width of the proton beam. Calculations performed by Carpenter indicate that this effect does not alter precision much if the extracted pulse is about 500 ns or less.

The repetition rate between pulses is defined by minimum and maximum energies that are to be measured in a given spectrometer and the distance from the source. Typically, the desired repetition rates are in the range of 10 to 100 Hz, which allow an energy bandwidth of about 10 in typical spectrometers without the high-energy neutrons overlapping with the low-energy neutrons from the previous pulse.

Characteristics of Accelerators and Compressor Rings for Pulsed-Spallation Neutron Sources

Rapid Cycling Synchrotron

The lattice design for a rapid cycling synchrotron (RCS) is not any different than a conventional slow cycling synchrotron. The RCS design can also be either combined-function or separated-function.

The magnetic field excitation is typically generated by driving a resonant circuit with the main-ring magnets, a capacitor bank, and a choke.[9] A pulse modulated or cycloconvertor-type power supply is used to compensate for losses in the resonant circuit and to regulate the injection and extraction fields. A typical wave form for the magnet current and voltage of the 30-Hz IPNS accelerator is shown in Figure 1. The magnetic field is described by

$$B = B_{dc} - B_{ac} \cos \omega t, \qquad (1)$$

where ω is the resonant frequency of the tuned circuit of the magnet excitation system. The injection field is $B_{dc} - B_{ac}$ and the extraction field is $B_{dc} + B_{ac}$.

The injection process into an RCS is an H^- to H^+ technique that was pioneered at Argonne on the now-decomissioned Zero Gradient Synchrotron.[10] A layout for a typical injection scheme is shown in Figure 2.

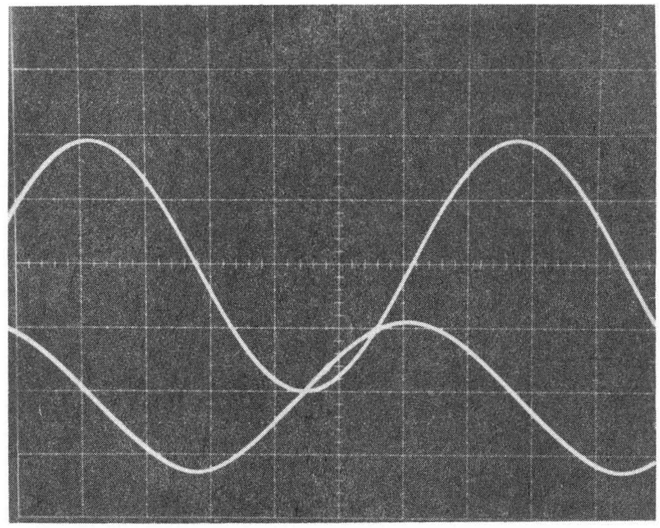

Figure 1. Magnetic field in the IPNS Rapid Cycling Synchrotron - upper trace is current and lower trace is magnet voltage.

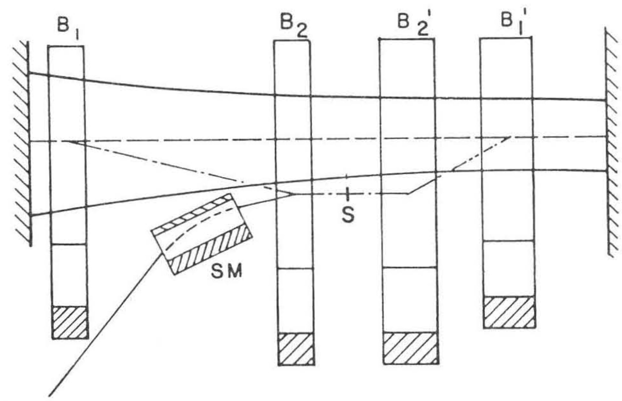

Figure 2. Typical layout for H^- injection showing septum magnets, SM, bumper magnets B_1, B_2, B_1', B_2' and the stripper, S.

An H^- beam at 50 MeV is injected from an RF linear accelerator. The normal orbits for the H^- and H^+ beams deflect in the opposite directions in the bumper magnet B2. The four bump magnets produce a local orbit distortion which places the injection orbit outside its normal position and through the stripper foil indicated by S. The two electrons are stripped from the hydrogen ion, reversing the bending radius of the injected ion. During the injection process the field in bumped magnets is decreased so that beam injected early is drawn off the stripper foil and beam injected later results in increasingly larger betatron oscillations. In this way, the beam can be spread more uniformly in radial space resulting in a higher space-charge threshold. The stripper foils in the Argonne IPNS RCS is a plastic material, poly-paraxylyene. The foil is about 3000 - 5000 Å thick and has a thin flashing of aluminum that is maybe another 100 Å. At higher energies, 200-MeV carbon foils can be used. Typically, the brightness of the source can be enhanced by more than 100 using the charge-exchange technique, the limitation ultimately being beam growth from multiple scattering due to repeated traversals through the foil.

Injection into an RCS occurs during the period in Eq. (1) where B is at a minimum and dB/dt is approximately zero. The period over which B remains near zero is very limited. Consequently, injection and capture time is equally limited. Nonetheless, calculations by Cho et al.[11] indicate that the total process of injection and capture on the IPNS RCS can, with the proper RF capture program, be highly efficient.

The equilibrium orbit in a synchrotron is fixed at a constant radius to within a relatively small value. The energy gain per turn, therefore, is directly proportional to $\dot{B}$; i.e.,

$$\langle v \rangle = \frac{rcp\dot{B}}{fE} \qquad (2)$$

where
- $\langle v \rangle$ = average volts per turn,
- r = bending radius in the magnet, m,
- c = speed of light, 3×10^8,
- $\dot{B}$ = time rate of change of magnetic field, T/sec,
- p = momentum of the ion, eV/c,
- f = frequency of rotation, Hz, and
- E = energy of the ion, eV.

The energy gain per turn required to maintain a constant radius throughout the acceleration cycle sinusoidally varies from zero to maximum to zero, as indicated by the derivative of Eq. (1). In addition to the average energy gain, the RF voltage must also provide an adequate sized synchrotron acceleration bucket. Typically, the phase stable angle is normally chosen to be about 30° requiring an RF voltage of about twice that needed for average energy gain per turn.

The RF frequency varies by factor of 2 to 4 from injection to extraction. The cavity design for a RCS is basically the same as for any synchrotron, i.e., ferrite-loaded cavity with dc bias windings to change the incremental RF permeability so that a tuned circuit can be maintained throughout acceleration.[12] This type of cavity can really only operate with the RF flux in the ferrite around 100 gauss, or slightly higher. The extent that ferrite can radially extend from the beam is limited by the inverse r variation in flux. Consequently, the RF voltage per unit length of straight section is limited to about 10 kV to 20 kV per meter.

The design of the vacuum system has unique problems in the RCS. The value of $\dot{B}$ reaches 60 to 100 T/sec, which eliminates the possibility of using metallic vacuum liners of any practical thickness in the magnetic field regions. The RCS for the ANL-IPNS facility does not use a vacuum liner at all. The magnet laminations are potted in epoxy resin and are inside the vacuum vessel. A thin metal liner is inserted which has periodic slits cut across the liner perpendicular to the direction of the beam. The slits adequately impede generation of eddy currents and still allow the higher frequency image current of the beam to flow in the beam direction. This liner helps shield the image currents from the magnet laminations which would lead to a large RF voltage loss and possibly slow-wave beam instabilities, although in the latter case there is also a danger it could induce others that might otherwise not exist.

The vacuum system for the RCS under construction for the Spallation Neutron Source (SNS) project at the Rutherford Appleton Laboratory in England is much more complex. A bonded ceramic vacuum liner is placed inside the magnets and a metal chamber outside. A complex RF shield is made of an array of longitudinal wires that extend throughout the magnets and are capacitively coupled to a metal chamber outside the magnets. The capacitors are to prevent large induction of eddy currents and yet low RF impedances for the beam image currents.

Extraction from the RCS is in one turn using standard ferrite kicker magnet techniques. The RCS does place a significant demand on component lifetime because of the large number of accumulated pulses developed in a year compared to conventional slow cycling accelerators.

Linac Compressor Ring

The design of the lattice for the compressor ring of a spallation source need not be any different than an ordinary storage or compressor ring. In the case of the conceptual design for the Spallations-Neutronequelle (SNQ) project of the Kernforschungsanlage (KFA) Laboratory, Jülich, Germany, an isochronous ring design (IKOR) was chosen to avoid RF cavities to bunch the beam. The Proton Storage Ring (PSR) of Los Alamos National Laboratory design, however, does have RF cavities for beam bunching.

Injection into the compressor is at full energy, >800 MeV, and, because Lorentz stripping of one electron from the H^- ion occurs at rather weak magnetic fields,[13] is a two-step process from H^- to H° to H^+. The H^- beam is transported to a strong transverse field magnet close to the ring. It is designed to have a sharp edge to minimize angular dispersion in the stripping process. The H° beam then drifts to a carbon stripper foil (200 to 800 μg/cm² thickness) where the final $H^\circ \rightarrow H^+$ stripping takes place. As in the RCS, the normal equilibrium orbit in the compressor ring is displaced through the stripper foil using a bumper magnet arrangement similar to that in Figure 2. The emittance of the linac beam is almost two orders of magnitude smaller than the acceptance of the compressor ring, so that the same technique of spreading the injected beam over the aperture is used in the compressor ring as in the RCS.[14] The injection times are typically 150 to 750 μs long.

Since there is no acceleration in the compressor ring, the magnetic fields are static and the vacuum chamber is fully metallic.

For the IKOR design, the linac beam is chopped at the revolution frequency of the particles in the ring. Since the ring is isochronous, the bunch structure is preserved without the use of RF cavities. For the PSR design, the linac beam is CW and a fixed-frequency bunching cavity is driven at the revolution frequency to form a single bunch for extraction.

Extraction from the compressor ring is the standard one-turn technique using fast ferrite kicker magnets, same as the RCS technique.

Fixed-Field Alternating-Gradient (FFAG) Synchrotron

The fixed-field alternating-gradient (FFAG) synchrotron is a new entrant in the field of proton drivers for pulsed spallation sources. At present, only conceptual designs exist for facilities based on FFAG accelerators.[15] A plan view of a FFAG Ring is shown in Figure 3. The FFAG has a static magnetic field described by:

$$B = B_o\left(\frac{R}{R_o}\right)^k\left[1 + \sum_{n=1}^{\infty} f_n \cos nN\left(\theta - \tan\xi \ln\frac{R}{R_o}\right)\right] \quad (3)$$

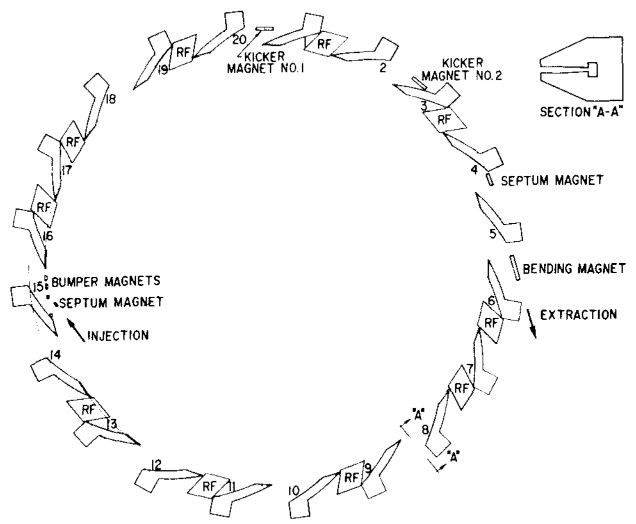

Figure 3. Plan view of Fixed-Field Alternating-Gradient Synchrotron Ring.

where

R = the radial distance from the machine center,

R_o = the injection radius measured from the machine center

$k = \frac{R}{B}\frac{dB}{dR}$, the mean-field index,

θ = azimuthal angle,

f_n = is the harmonic component of the azimuthally varying field,

N = number of sector magnets, and

ξ = spiral angle.

Beam is injected into the ring on the inside radius with the same bumped orbit, H^- to H^+ injection technique as in the RCS. However, since there is no time-varying field, the injection and capture time is arbitrary. The bumper magnets must be open "C" type located on the inner radius of the vacuum chamber.

The combination of the spiral angle and the field index k produces a FDDO or DFFO accelerator lattice. The FFAG is designed with nominally constant betatron tunes from injection to extraction. Acceleration is controlled by the time rate of change of frequency and as the beam gains energy, it grows to larger radii until it reaches the extraction energy and radius. The choice of temporal frequency program is chosen to achieve efficient capture at the start of acceleration, to control the bunching factor during early acceleration to avoid exceeding space-charge limits, and to minimize acceleration time in the later part of the acceleration cycle.

The vacuum chamber is fully metallic in an FFAG since the magnetic fields are static. Extraction technique is identical to the RCS and compressor ring; however, the kicker magnets have to be open "C" type located at the outer radius of the vacuum chamber.

Performance Limitations

Ideally, one wants the most beam possible from a proton driver unto the spallation target. And since intense beams are needed, internal losses in the accelerator have to be kept sufficiently low to allow ordinary maintenance techniques.

Space Charge

The RCS and FFAG accelerators start with a lower injection energy and accelerate the beam to the extraction energy. Consequently, space-charge depression of the betatron tune unto a resonance line is one of the defining limits of peak performance. The space-charge limit is described by[16]

$$N = \frac{\Delta\nu_x \pi B_f \beta^2 \gamma^3 [\varepsilon_x + \sqrt{\varepsilon_x \varepsilon_y}\sqrt{\frac{\nu_x}{\nu_y}}]}{r_p G} \qquad (4)$$

where

N = total number of ions,

$\Delta\nu_x$ = tolerable change in tune between the working point and resonance line

B_f = bunching factor of beam around circumference,

β, γ = relative velocity and energy of ions,

ε_x, ε_y = emittances in transverse x and y planes,

ν_x, ν_y = tunes in transverse x and y planes,

r_p = 1.547 (10^{-18}), and

G = form factor relating to the charge distribution of the beam in the transverse plane.

The slow cycling booster at CERN has achieved values of G between 1.23 and 1.77 and of $\Delta\nu$ between 0.24 and 0.29.[16] The IPNS RCS which has a 50-MeV injection energy has achieved a peak value of N of slightly better than 3×10^{12}. The maximum value of $\Delta\nu$ can be between 0.2 and 0.25. The emittances $\pi\varepsilon_x$ and $\pi\varepsilon_y$ are nominally 200 $\pi(10^{-6})$ and 100 $\pi(10^{-6})$ meter-radians. This would imply that G is about 1.5 to 1.9 if the horizontal and vertical acceptances are filled.

The linac compressor ring has much higher space-charge limits since the injection energy and the extraction energy are the same.

RF Limitations

There is a limited amount of straight-section space available in which RF cavities can be installed. At least 1.5 and preferably 2 times the amount indicated in Eq. (2) is required for a synchrotron. RCS operation at 50 and 60 Hz and 800 to 1100 MeV extraction energy is almost at the limit of where enough RF voltage can be generated.

Beam loading also becomes a limit. Ideally, the amount of power provided to beam should be small compared to the power provided to the cavity and the amount of energy removed from the cavity per turn should be small compared to the stored energy. However, the peak circulating currents in IPNS RCS is 5 A, in the SNS RCS will be approaching 25 A, and in the LANL PSR will be 46.5 A. The beam power requirements are approaching the same level as the power lost in the cavity and significant fractions of the stored energy will be removed per turn. The loading effects on RF cavities have been studied extensively[17-18] and these studies would suggest that the present levels are on the edge of limiting boundaries. The SNS design has included a "feed-forward" system where the bunch shape is detected and a current pulse is driven into the RF cavity using class A amplifiers. The PSR design is working on a power follower design in the hopes of achieving a 10-Ω output impedance.

Instability Limits

The high-peak circulating currents required in these machines put them in the regime of many of the transverse and longitudinal instabilities. However, instabilities with growth times longer than a few milliseconds are no problem because of the short acceleration and storage times. The "head-tail" instability has been seen on both the KEK and IPNS RCS.[19-20] These instabilities cause different betatron oscillations within a single bunch. They were controlled at the presently operating current levels by proper chromaticity control. But clearly, the future machines will be facing increasingly severe problems. The PSR operates beyond the threshold for the transverse resistive instability which has submillisecond growth times.[5] They are planning to use high power active dampers and octupole fields to control the instability.

The machines presently under construction and future, more advanced machines will have to identify the thresholds for various instabilities and design around them. It is clear that operation at the ultimate goals will have to proceed at a rate determined by the speed at which instabilities can be identified and controlled.

Descriptions of Existing and Proposed Facilities
IPNS, Argonne National Laboratory, USA

Figure 4 gives an overview of the IPNS Facility. A beam of H^- ions is accelerated to 50 MeV in a linac and is injected and stripped to H^+ in a RCS and accelerated to 500 MeV. The facility has been in operation since 1979.[1] Its current operating level is 12 μa, with short-term peaks exceeding 14 μa. The overall operating efficiency is about 90%. The percent of beam delivered to the spallation target compared to H^- beam in the injection line is about 90%. Since 1981, the IPNS accelerator has been scheduled for 10076 hours of operation and was available for experiments for 9006 hours.

The repetition rate of the RCS is 30 Hz. It is a strong focusing, combined function machine with a DOFDFO lattice. The average radius is 6.84 m. A list of parameters is given in Table 1.

Table 1
Characteristics of the IPNS Rapid Cycling Synchrotron

Injection Energy (H^-)	50 MeV
Type-Strong, focusing, combined function	DOFDFO
Average Radius	6.84 m
Number of periods	6
Magnetic Field (injection/extraction)	0.281/0.98 T
RF Frequency (injection/extraction)	2.91/5.3 MHz
RF Voltage (peak)	22 kV
Number of Cavities	2
Betatron tunes (ν_x/ν_y)	2.2/2.32
Extraction energy	400-500 MeV
Pulse length - one turn	100 ns
Protons per pulse	$2.4\text{-}3 \times 10^{12}$
Pulses per second	30
Average beam current	12 μA
Peak beam current	14.2 μA

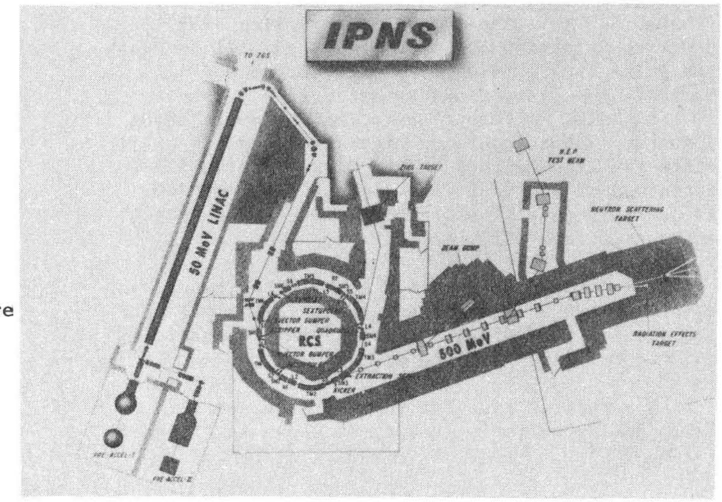

Figure 4. Overview of the IPNS Facility.

KENS', BSF, National Laboratory for High Energy Physics, Japan

KENS uses the 20-Hz booster for the 12-GeV high-energy accelerator during intervals when it is not being used for injecting into the high-energy machine.[2] KENS started operation on June 18, 1980. The effective repetition rate is 16 Hz.

The KEK/KENS RCS is a combined function, strong focusing, FDFO lattice. The injection energy is currently 20 MeV, although this will soon be increased to 40 MeV. The peak charge per pulse is 1×10^{12}, which amounts to a time-average current of about 2.5 μA. At the present time, the limit on protons per pulse appears due to a vertical instability with a growth time of about 100 μs.[21] They are working on damping the instability using sextupoles similar to what was done on the IPNS RCS.

Table 2 provides a list of parameters for the KENS RCS.

Table 2
Characteristics of the KEK/KENS Rapid Cycling Synchrotron

Injection energy (H^-)	20 MeV
Type-strong focusing, combined function	FDFO
Average radius	6 m
Number of periods	8
Magnetic field (injection/extraction)	0.197/1.102 T
RF frequency (injection/extraction)	1.62/6.03 MHz
Peak RF voltage	32 kV
Betatron tune (ν_x, ν_y)	2.2/2.3
Extraction energy	500 MeV
Pulse length - one turn	50 ns
Protons per pulse	1×10^{12}
Repetition rate at BSF	~16 Hz
Average beam current	≃2.5 μA

WNR/PSR, Los Alamos National Laboratory, USA

The Weapons Neutron Research (WNR) facility has been operating since 1977. It uses protons directly

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from the LAMPF linac at 800 MeV, but at pulse widths of about 10 µs. The Proton Storage Ring (PSR) is under construction and when completed will decrease the pulse length to under a microsecond and will increase the present operating current to about 100 µA.[5] Two different operating modes are being planned. The short-bunch high-frequency mode will store six 1-ns bunches in the ring. These will be extracted at a 720-Hz rate. The long-bunch low-frequency mode will store one bunch 270-ns long. The extraction rate will be 12 Hz.

The tunnel construction for PSR has been completed and components are being installed. The present schedule plans for first beam in April 1985 and the full 100 µA in April, 1986.

A parameter list for the PSR is given in Table 3. An artist's drawing is shown in Figure 5.

Table 3
Characteristics of the LANL Proton Storage Ring

Injection energy	800 MeV
Type-Strong focusing, separated function	FODO
Average radius	14.4 m
Number of periods	10
RF frequency (LBLF Mode)	2.795 MHz
Peak voltage (LBLF Mode)	10 kV
Betatron tune (ν_x, ν_y)	3.25, 2.25
Extraction energy - one turn	800 MeV
Pulse length (LBLF Mode)	270 ns
Protons per pulse (estimated)	5.2×10^{13}
Repetition rate	12 Hz
Average beam current (estimated)	100 µA

SNS, Rutherford Appleton Labortory, England

The largest pulsed-spallation source project is currently under construction at the Rutherford Appleton Laboratory in England.[4] The accelerator is a 50-Hz, 800-MeV RCS. The design goal is 200 µA which requires accelerating 2.5×10^{13} protons per pulse. The mean radius of the accelerator is 26.0 meters. H^- beam is injected at 70 MeV from a linac.

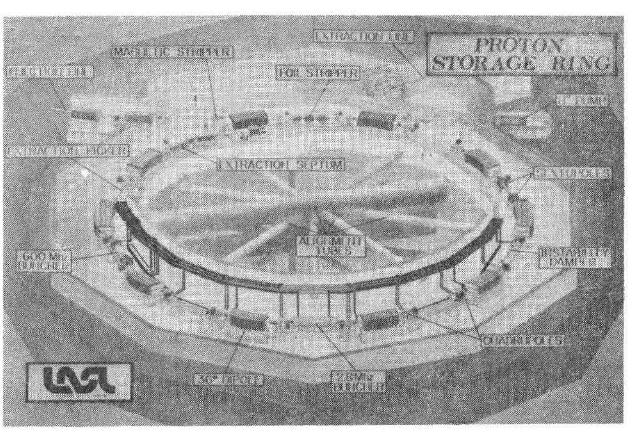

Figure 5. Artist's View of Proton Storage Ring at Los Alamos National Laboratory.

At the present time, all the accelerator components except some of the RF stations have been installed and the target station and beam lines are nearing completion. First beam was injected into the synchrotron in January, 1984. Acceleration to 140 MeV was achieved on April 8, 1984, using only 2 RF cavities. Acceleration to 550 MeV using 4 cavities is planned in this month. Extraction is planned during August/September. Operation with neutrons is planned for December.

A list of the parameters for the SNS accelerator are given in Table 4.

Table 4
Characteristics of the Rutherford Appleton Rapid Cycling Synchrotron

Injection energy	70 MeV
Type-strong Focusing-separated function	DOFODOFO
Average radius	26 m
Number of periods	10
RF frequency (injection/extraction)	1.34/3.09 MHz
Peak RF voltage	162 kV
Betatron tune (ν_x, ν_y)	4.2/3.9
Protons per pulse (estimated)	2.5×10^{13}
Extraction energy	800 MeV
Pulse length (two bunches, one turn)	650 ns
Repetition rate	50 Hz
Average beam current (estimated)	200 µA

SNQ/IKOR, Kernforschungsanlage (KFA) Jülich, Germany

KFA, in collaboration with Karlsruhe, has generated a conceptual design for a linac with an Isochronous Compressor Ring (IKOR).[22] The design goals are 1100 MeV with an average current of 500 µA. The design provides for $H^- \rightarrow H^\circ \rightarrow H^+$ injection at 1100 MeV. The linac macropulses of 500 µs are compressed into short pulses of 0.68-µs long in IKOR. Since the ring is isochronous, no RF cavity is needed for bunching the beam.

Extraction of the beam bunch is accomplished in one turn using ferrite kicker magnets. The repetition rate of the extracted beam is 100 Hz. A list of the IKOR parameters is given in Table 5.

Presently, the KFA laboratory is engaged in building a prototype of the high-current linac. They are also reviewing the possibility of using an FFAG synchrotron ring for part of the acceleration cycle.

Table 5
Characteristics of the Kernforschungsanlage Compressor Ring

Injection Energy	1100 MeV
Type-strong focusing-separated function	FODODO
Average radius	32.18 m
Number of periods	11
Betatron tune (ν_x, ν_y)	3.25/4.40
Extraction energy	1100 MeV
Pulse length (one bunch)	680 ns
Protons per pulse (design goal)	2.7×10^{14}
Repetition rate	100 Hz
Average beam current (design goal)	5000 µA

ASPUN, Argonne National Laboratory, USA

Argonne National Laboratory has developed a conceptual design for a Super-Pulsed-Spallation Source (ASPUN) using a 1500-MeV fixed-field alternating-gradient concept. The injection energy is 200 MeV. The design goal would be 3800 μA at a repetition rate of 45 - 50 Hz.

The injection radius into the machine would be 25.9 m and the extraction radius would be 28.14 m. The injection rate into ASPUN is 250 Hz and the intention is to stack six pulses internally to reduce the extracted rate to 45 to 50 Hz. The beam stacking would be done at the intermediate energy of 1250 MeV.

The peak RF voltage per turn is 400 kV. The spiral angle of the sector magnets is 61°. The field index (R/B) (dB/dR) is 14. The resulting horizontal and vertical tunes are 4.25 and 3.3, respectively. There are 20 identical sector magnets. A list of parameters is given in Table 6.

Table 6
Characteristics of the Argonne Fixed-Field Alternating-Gradient Synchrotron

Injection energy (H^-)	200 MeV
Injection radius (circumference/2 π)	25.888 m
Extraction radius (circumference/2 π)	28.139 m
Number of sector magnets	20
Magnetic field (injection/extraction)	0.413/1.327 T
Field index, k, (R/B)(dB/dR)	14
Spiral angle	61°
Angular width of sector magnet	3.6°
Betatron tune (ν_x, ν_y)	4.25/3.3
RF frequency (2nd harmonic)	2.087/3.09 MHz
(1st harmonic)	1.545/1.566 MHz
Peak RF voltage	400 kV
Number of cavities	10
Pulse length - one turn	325 ns
Protons per pulse (design goal) (injection/extraction)	$1 \times 10^{14}/6 \times 10^{14}$
Repetition rate	45-50 Hz
Beam current (design goal)	3800 μA

References

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