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Synchrotron Based Proton Drivers

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Abstract. Proton drivers are the proton sources that produce intense short proton bunches. They have a wide range of applications. This paper discusses the proton drivers based on high-intensity proton synchrotrons. It gives a review of the high-intensity proton sources over the world and a brief report on recent developments in this field in the U.S. high-energy physics (HEP) community. The Fermilab Proton Driver is used as a case study for a number of challenging technical design issues.

INTRODUCTION

Intense proton sources have been around for years. At this time, the highest beam power from a synchrotron is 160 kW at the ISIS (0.8 GeV) at the Rutherford Appleton Laboratory (RAL) in England, from an accumulator is 64 kW at the PSR (0.8 GeV) at the Los Alamos National Laboratory (LANL) in the U.S., and from a cyclotron is 1 MW at the PSI (0.59 GeV) in Switzerland. A proton driver differs from these sources in the following aspects: (1) The beam energy E is higher; (2) The bunch length σ is shorter; (3) The beam power P is larger. These differences come from the requirements of physics experiments, in particular, the neutrino oscillation experiments. Typical parameters of a proton driver are: $E \geq 4$ GeV, $\sigma \leq 3$ ns (rms), $P \geq 1$ MW. When the proton beam energy is below 4 GeV, π^-/μ^- yield from a carbon target would be too low to be useful. When the proton bunch length is longer than 3 ns, the production rate (i.e., number of π/μ particles per unit proton beam power) and π^+/π^- or μ^+/μ^- polarization ratio would be uneconomical. Because the physics case is strong and the capital cost is modest (less than 1/10 of the cost of a linear collider), proton drivers have attracted worldwide attention. A recently issued U.S. HEPAP Sub-Panel Report identified such a facility as a possible candidate for a construction project in the U.S. starting in the middle of this decade.[1]

There are two types of proton drivers: one is synchrotron-based, like the ISIS; another is linac-based (a linac plus an accumulator), like the PSR. Each type has its pros and cons. Compared with a linac-based system, for given beam power, a synchrotron has the advantage of lower cost, higher beam energy and lower beam current. Its injection beam power is lower. Hence, the stripping foil is less demanding and larger injection loss could be tolerated. On the other hand, however, a synchrotron is more difficult to design, build and operate than an accumulator. The hardware is more challenging and the reliability is not as high.

There are many similarities between the two types of proton drivers, in particular in the linac and linac front-end part. However, the design of a synchrotron and an accumulator is quite different. This paper will focus on the synchrotron-based proton drivers. A paper discussing linac-based ones can be found in Ref. 2.

OVERVIEW OF HIGH INTENSITY PROTON SOURCES

Table 1 is a survey carried out during the Snowmass 2001 Workshop. It gives the major parameters of high intensity proton sources over the world, including machines existing, under construction and proposed. In addition to the ISIS and PSR, several other existing machines also provide considerable beam power: AGS, IPNS, Fermilab Booster, Main Injector and SPS. There are two big accelerator projects currently under construction. One is the Spallation Neutron Source (SNS) at the Oak Ridge National Laboratory (ORNL) in the U.S. It consists of a 1 GeV superconducting linac and an accumulator. The beam power is 1.4 MW. Another is the JHF at the JAERI/KEK in Japan. It has a 400 MeV linac, a rapid cycling 3 GeV synchrotron at 1 MW, and a slow ramping 50 GeV synchrotron at 0.75 MW. There are a number of proton driver proposals from several labs, including Fermilab and BNL in the U.S., and CERN and RAL in Europe. There are also various proposals of high intensity proton sources for applications other than a proton driver, e.g., nuclear waste transmutation and plutonium production (AAA), spallation neutron sources (ESS, KOMAC), proton radiography (AHF), and accelerator driven system for multiple purposes (CONCERT, IHEP/China).

TABLE 1. High Intensity Proton Sources

Machine	Flux (10^{13}/pulse)	Rep Rate (Hz)	Flux[†] (10^{20}/year)	Energy (GeV)	Power (MW)
Existing:					
RAL ISIS	2.5	50	125	0.8	0.16
BNL AGS	7	0.5	3.5	24	0.13
LANL PSR	2.5	20	50	0.8	0.064
ANL IPNS	0.3	30	9	0.45	0.0065
Fermilab Booster (*)	0.5	7.5	3.8	8	0.05
Fermilab Main Injector	3	0.54	1.6	120	0.3
CERN SPS	4.8	0.17	0.8	400	0.5
Under construction:					
ORNL SNS	14	60	840	1	1.4
JHF 50 GeV	32	0.3	10	50	0.75
JHF 3 GeV	8	25	200	3	1
Proton Driver proposals:					
Fermilab Study I	3	15	45	16	1.2
Fermilab Study II	2.5	15	37.5	8	0.5
Fermilab Study II Upgrade	10	15	150	8	2
Fermilab MI Upgrade	15	0.65	9.8	120	1.9
BNL Phase I	10	2.5	25	24	1
BNL Phase II	20	5	100	24	4
CERN SPL	23	50	1100	2.2	4
RAL 15 GeV (**)	6.6	25	165	15	4
RAL 5 GeV (**)	10	50	500	5	4
Other proposals:					
Europe ESS (**)	46.8	50	2340	1.334	5
Europe CONCERT	234	50	12000	1.334	25
LANL AAA	-	CW	62500	1	100
LANL AHF	3	0.04	0.03	50	0.003
KOMAC/Korea	-	CW	12500	1	20
IHEP/China	1.6	25	40	1.6	0.1

[†] 1 year = 1 x 10^7 seconds.

(*) Including planned improvements.

(**) Based on 2-ring design.

RECENT DEVELOPMENT IN THE U.S. HEP COMMUNITY

In July 2001, about 1,200 physicists gathered at Snowmass, Colorado, U.S.A. for a 3-week workshop. The topic was the future of the high-energy physics program in the U.S. One of the working groups was focused on high-intensity proton sources. After a 3-week intensive study, this group issued a 33-page report.[3] This report emphasized that the U.S. high-energy physics program needs an intense proton source, a 1-4 MW Proton Driver by the end of this decade. It also identified areas of accelerator R&D needed to achieve the required performance of a Proton Driver, i.e., a comprehensive and prioritized 26-point plan. This plan serves as the basis for future research and development of high-intensity proton machines including both linacs and synchrotrons.

In the meantime, based on the U.S. HEPAP Sub-Panel recommendation, the directors of Fermilab and BNL had, respectively, initiated proton driver design studies at the two labs. The reports of these studies have either been published or will be released soon.[4,5]

TECHNICAL CHALLENGES

The design of a high-intensity proton synchrotron involves a number of technical challenges. It requires a careful balance on the performance of various technical systems. It also calls for trade-offs between performances and costs. In the following we will list the major design issues and highlight the critical ones. The Fermilab 8-GeV Proton Driver, which is shown in Figure 1, will be used as an example in these discussions.

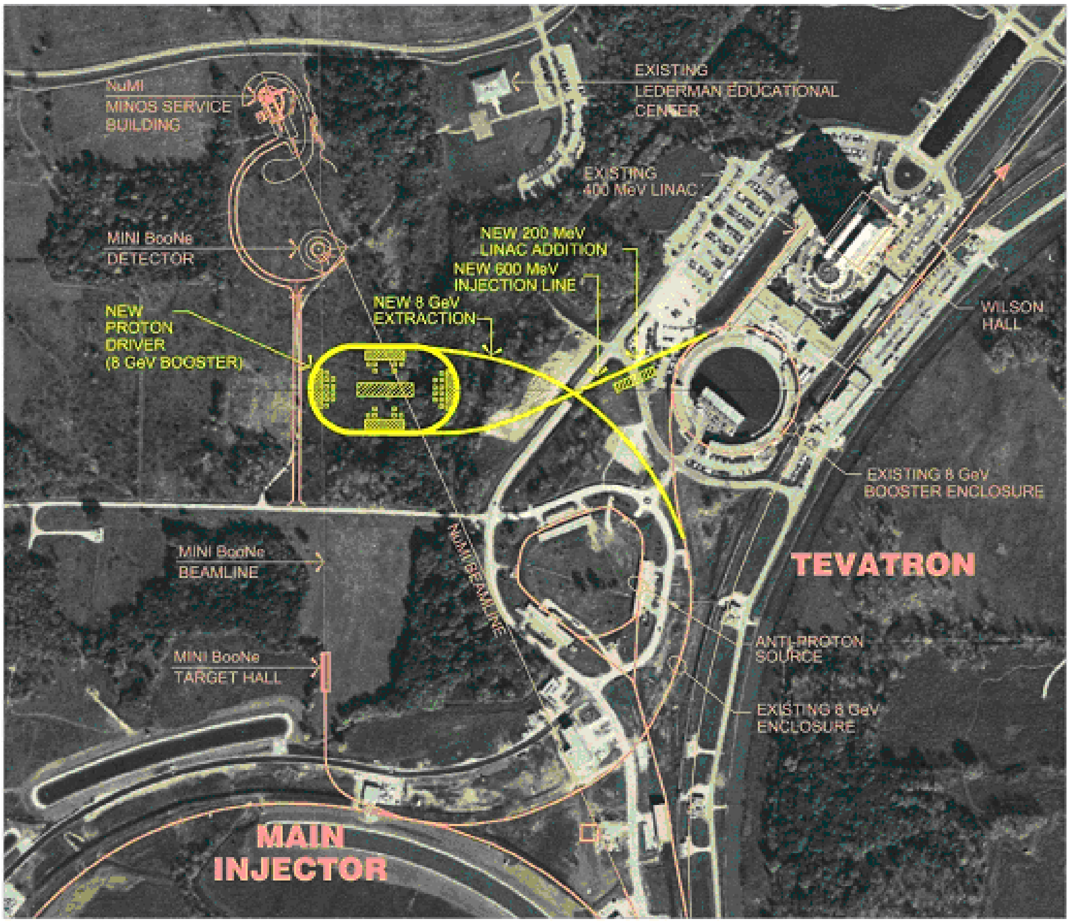

FIGURE 1. The layout of the Fermilab 8-GeV Proton Driver (the ring of the racetrack shape).

1. Lattice Design

Lattice is the foundation of a synchrotron. It is worth every effort to design the best lattice as one can. It would be a mistake to pick a lattice in hurry due to other factors (e.g., pressed by the project schedule, which did happen in the past). A poorly chosen lattice will have adverse effects for the life of the machine. A proton driver has two basic requirements on the lattice: (1) transition free, (2) zero-dispersion in the rf straight sections. The former is to avoid particle loss and emittance dilution during transition crossing; the latter to avoid the synchro-betatron coupling resonance.

For a medium-energy synchrotron (above 6 GeV), the regular FODO lattice (in which $\gamma_t \propto \sqrt{R}$, R the machine radius) is ruled out because it would use too many bending magnets in order to achieve (1). There are several lattices that have been investigated to obtain either a high or an imaginary γ_t. For example, (a) a flexible momentum compaction (FMC) lattice, which is basically a singlet 3-cell modular structure with a missing (or short) dipole in the mid-cell.[6,7,8] (b) a doublet 3-cell modular structure with a missing (or short) dipole in the mid-cell.[9] Figure 2 is an example of (b), which is designed for the Fermilab 8-GeV Proton Driver.

The choice of phase advance per module is of critical importance in this type of lattice. There are two reasons. (i) The chromaticity sextupoles are placed in the mid-cell, where the beta-function peaks and available space exists. In order to cancel the higher order effects of these sextupoles, they need to be paired properly. (ii) The phase advance per arc in the horizontal plane must be multiple of 2π in order to get zero dispersion in the straights without using dispersion suppressors (which are space consuming).

Other requirements in the lattice design include: ample space for correctors (steering magnets, trim quadrupoles, chromaticity and harmonic sextupoles, etc.), ample space for diagnostics, low beta and dispersion functions (to make the beam size small), large dynamic aperture (to accommodate beam halo), and large momentum acceptance (to allow for bunch compression). Table 2 lists the lattice parameters of the Fermilab 8-GeV Proton Driver.

TABLE 2. Lattice Parameters of the Fermilab 8-GeV Proton Driver

Circumference (m)	474.2
Super-periodicity	2
Number of straight sections	2
Length of each arc (m)	161.66
Length of each straight section (m)	75.44
Injection kinetic energy (MeV)	600
Extraction kinetic energy (GeV)	8
Injection dipole field (T)	0.2
Peak dipole field (T)	1.5
Bending radius (m)	19.77
Peak quadrupole gradient (T/m)	10
Good field region	4" × 6"
Max β_x, β_y (m)	15.14, 20.33
Min β_x, β_y (m)	4.105, 4.57
Max D_x in the arcs (m)	2.52
Dispersion in the straight sections	0
Transition γ_t	13.8
Horizontal, vertical tune ν_x, ν_y	11.747, 8.684
Natural chromaticity ξ_x, ξ_y	-13.6, -11.9
Momentum acceptance $\Delta p/p$	±1%
Dynamic aperture	> 120 π

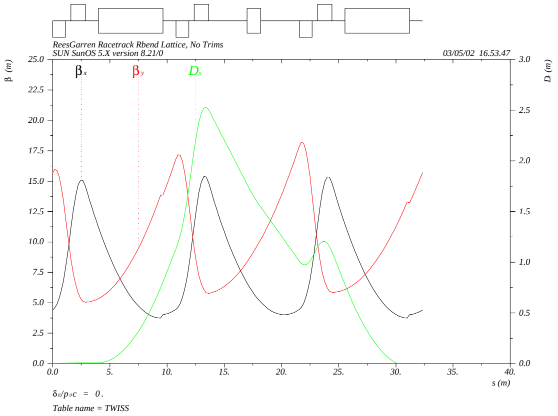

FIGURE 2. Arc module and lattice functions of the Fermilab 8-GeV Proton Driver. Each module has three doublet cells. The dipole in the mid-cell is short. The phase advance per module is 0.8 and 0.6 in the h- and v-plane, respectively. There are five modules in each arc.

2. Space Charge

Amongst numerous beam physics issues, the space charge is a major concern. It is usually the bottleneck limiting the beam intensity in an intense proton source. A useful scaling factor is the Laslett tune shift $\Delta\nu \propto (N/\varepsilon_N) \times (1/\beta\gamma^2)$, in which N is number of particles per bunch, ε_N the normalized transverse emittance, β and γ the relativistic factors. It shows the space charge effect is most severe at injection because the beam energy is low. The situation becomes worse for high-intensity machines not only because the intensity is high but also because the injection time is long. Numerical simulation is the main tool to study this effect. A number of 1D, 2D and 3D codes have been or are being written at many institutions. An example is shown in Figure 3. These codes are particularly useful to the design of the injection kicker current waveform for achieving uniform particle distribution in the beam, reducing emittance dilution and minimizing average number of hits per particle on the stripping foil during the phase space painting process. Several other measures, e.g., tune ramp, inductive inserts, quadrupole mode damper and electron beam compensation are under investigation for possible cures of the space charge effects. This is an active research field.

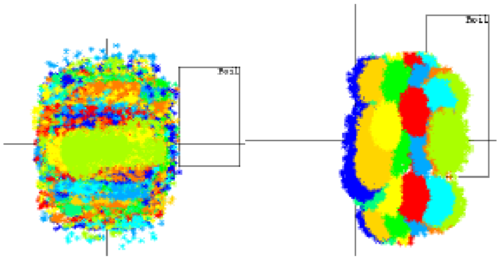

FIGURE 3. Space charge simulation using Track2D (by C. Prior). It shows the particle distribution after 45 turns injection in the Fermilab Proton Driver with (left) and without (right) the space charge effects.

3. Electron Cloud Effect

The electron cloud effect (ECE) has been the No. 1 problem limiting the PSR beam intensity for many years. Recent observations and successful cures of this effect on the CERN SPS, PEP-II and KEK B-factory have stimulated worldwide interest. At this moment, there are six proton machines that have reported observations of ECE. They are: ISR, CERN PS, SPS with LHC beams, SPS with fixed target beams, PSR and RHIC. A key parameter for the ECE seems to be the volume density of particles. It is interesting to notice that, despite enormous differences among these machines in beam energy, number of particles per bunch and bunch size, the volume density takes a remarkably similar value (about $0.2 \pm 0.1 \times 10^8$ /mm^3) when reaching the ECE threshold. [10] This is called the critical mass phenomenon.

It is believed that the ECE is mainly due to secondary electron yield from the wall. Reducing primary electrons (which come from beam loss and stripping foil in proton machines) does not seem to be helpful. It should be pointed out that, by far all reported ECE are either in DC machines (accumulators and storage rings) or AC machines in DC operation (i.e., on flat top or flat bottom). No ECE has been seen in AC machines during ramping. This implies that AC machines could be immune to ECE.

However, all these claims are based on empirical observations or numerical simulations. Lack of a reliable theory for understanding and analyzing the ECE is a loophole that urgently needs to be filled.

4. Other Beam Dynamics Issues

In addition to the space charge and ECE, there are several other beam dynamics issues important to the proton driver design.

- Microwave instability of bunched beam below transition. Because the machine will always operate below transition, the negative mass instability due to space charge would not occur. Would then this machine be immune to the microwave instability?

- Bunch rotation with path length dependence on momentum spread $\Delta p/p$ and space charge tune shift $\Delta \nu$. This is a new problem for proton drivers. Bunch rotation is necessary for obtaining short bunch length (a basic feature of a proton driver). However, due to large momentum spread (a few percent) and large tune shift (a few tenth), the dependence of the path length ΔL on $\Delta p/p$ and $\Delta \nu$ can no longer be ignored. In other words, the momentum compaction factor $\alpha = (\Delta L/L) / (\Delta p/p)$ cannot be treated as a constant during bunch rotation. It is dependent upon the momentum and amplitude of each particle. This results in a longer bunch after rotation.

- A split between the horizontal and vertical tunes is required in order to avoid the strong resonance $2\nu_x - 2\nu_y = 0$ that could be excited by the space charge. However, it is not clear how big the split needs to be. Does it have to be an integer? Or would a half-integer suffice?

5. Beam Loss, Collimation and Remote Handling

The rule of thumb for allowable uncontrolled beam loss in an accelerator enclosure is 1 W/m so that hands-on maintenance can be performed. This number is based on the operation experiences of many machines in many years as well as on numerical simulations at many labs. It is now widely accepted as a design criterion for high-intensity machines. For a 1-MW, 100-m machine, this would mean the loss had to be below 10^{-4}, a mission impossible! To solve this problem, collimators are introduced to localize the beam loss. A 2-stage (i.e., primary + secondary) collimator system can absorb more than 99% lost particles and leave most of the enclosure below 1 W/m. A well-designed collimator system not only has high efficiency, but also is not susceptible to parameter changes (tunes, closed orbit, different stages during the cycle, etc.).

The beam power deposited onto the components near the collimator area can reach as high as ~kW/m. It is a difficult but also critical problem how to handle these components in case they need to be repaired or replaced. Invaluable experiences can be learned from LANSCE (LANL) and PSI. [11] These machines have been handling MW beams for years and have designed several remote-handling systems that work reliably.

6. Negative Ion Sources

Modern high-intensity circular proton machines almost universally adopt the charge exchange injection. The main requirements of the negative ion sources are high intensity (~100 mA), high brightness (rms normalized emittance < 0.2π mm-mrad), high duty factor (several percent) and long lifetime (> 2 months). Low noise surface plasma sources with Cesium catalysis and volume sources are widely used to achieve these goals.

7. Chopper

In order to reduce the injection loss during rf capture, chopping the beam at low energy is crucial. The function of the chopper is to create a macro-structure in the linac beam so that it can fit properly into the rf buckets in the ring. The requirements of a chopper are: fast rise- and fall-time (tens of nsec), short physical length (to minimize the space charge effect, which is dominant at low energies), and flat top and bottom in the current waveform (to minimize the energy jittering in a beam). The ideal place to chop the beam is at the ion source, because the beam energy is the lowest. But the rise- and fall-time would be long (hundreds of nsec) due to the slow response of the plasma. The next best place is in the LEBT (low energy beam transfer) between the ion source and the RFQ. There are two designs. One is the LBL design for the SNS, which places the chopper (made of split electrodes) right after the Einzel lenses. [12] Another is the Fermilab-KEK design, which places the chopper in front of the RFQ. [13] The latter is a pulsed beam transformer made of Finemet cores and does the chopping by using the narrow energy window of the RFQ. It is now installed on the HIMAC linac in Chiba, Japan. A schematic drawing of this chopper is shown in Figure 4. There are also choppers made of traveling wave deflectors placed after the RFQ, which have been in use at the LANL and BNL.

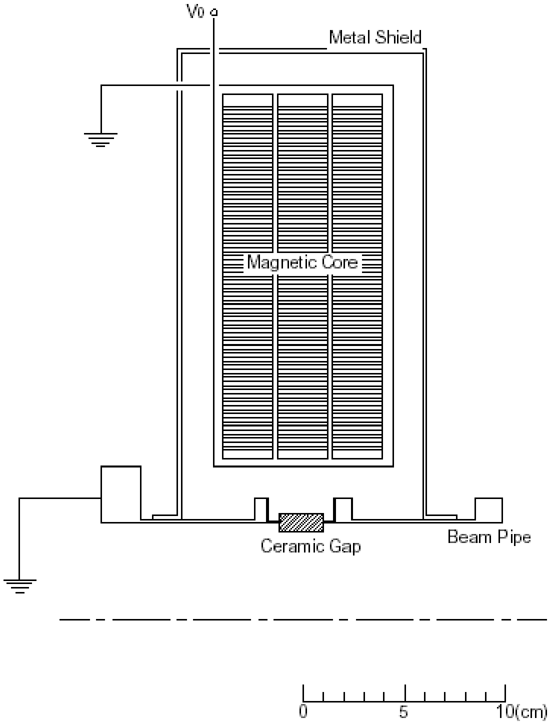

FIGURE 4. A schematic drawing of an rf chopper made of three Finemet cores. It is installed on the HIMAC linac.

8. H^- Injection

This is a complicated part in the proton driver design and has many technical issues involved. Most of particles losses in a synchrotron usually occur at this stage as well as during the rf capture immediately following it.

H^- particles are injected into the ring via a charge exchange process, in which the electrons are stripped by a foil and dumped, and the H^+ (proton) particles stay in the ring. This process takes hundreds or even thousands turns. The stripping foil must be able to stand high temperatures and large shock waves, and must have high efficiency and reasonable lifetime. The unstripped H^-, H^0 and electrons should be collected. Lorenz stripping of H^- ions in a magnetic field must be avoided. Phase space painting in the transverse and longitudinal planes needs to be employed in order to obtain a uniform distribution of particles in a bunch so that the spaces charge and transient beam loading effects can be reduced. Painting also helps minimize the average number of hits per particle on the foil. The emittance dilution due to Coulomb scattering needs to be controlled. Carbon foil is widely used. R&D on diamond foil and laser stripping is being pursued.

9. Slow Extraction

Although the efficiency of one-turn fast extraction can exceed 99%, it is much lower for multi-turn slow extractions. At high-intensity operation, the beam loss in existing machines during slow extraction is usually around 4-5%. This is not acceptable for the next generation of high-intensity machines, in which the beam power will be 1 MW or higher and one percent loss would mean 10 kW or higher. This is a serious problem when physics programs require slow extractions (which is the case for KAMI and CKM at the Fermilab Main Injector, and for kaon and nuclear physics at the JHF). Workshops and beam experiments are planned for tackling this problem.

10. Hardware

Although a number of proton synchrotrons have been built in the past half-century, hardware for MW machines presents particular challenges.

10.1. Magnets

Magnets are one of the most expensive technical systems of a synchrotron. A critical parameter in the magnet design is the vertical aperture of the main bending magnets. The magnet cost is essentially proportional to the aperture. It should be large enough to accommodate a full size beam and its halo. The following criterion was adopted in the Fermilab Proton Driver design:

$$A = \{3\, \varepsilon_N \times \beta_{max} / \beta\gamma\}^{1/2} + D_{max} \times \Delta p/p + \text{c.o.d.}$$

in which A is the half aperture, ε_N the normalized 100% beam emittance, β_{max} the maximum beta-function, D_{max} the maximum dispersion, c.o.d. the closed orbit distortion. The parameter 3 is the estimated size of the beam halo relative to the beam size.

Because this is an AC machine, field tracking between the dipoles and quadrupoles at high field is an important issue. Trim quads or trim coils are needed. The peak dipole field should not exceed 1.5 Tesla. The peak quadrupole gradient is limited by the saturation at the pole root (not pole tip).

The choice of the coil turn number per pole is a tradeoff between the coil AC loss and voltage-to-ground. The former requires the use of many small size coils, whereas the latter requires the opposite, namely, small number of turns. There are two ways to compromise. One is to employ stranded conductor coils, as shown in Figure 5, which was adopted in the JHF 3-GeV ring design. Another is to connect several coils in parallel at the magnet ends, as done in the ISIS. The ratio of the AC *vs*. DC coil loss should be kept around 2-3. The voltage-to-ground should not exceed a few kV. [14]

The aperture and good field region should include a rectangular area (instead of an elliptical area). This is because there will be a significant number of particles residing in the corners of the rectangle. The Fermilab 8-GeV Proton Driver design chose a 4 in × 6 in rectangle.

FIGURE 5. Stranded conductor coils for reducing coil AC losses.

10.2. Power Supplies

This is another expensive technical system. There are several choices for the power supplies in a rapid cycling machine. (1) A single harmonic resonant system, e.g., the Fermilab Booster which resonates at 15 Hz. (2) A dual-harmonic resonant system, e.g., the Fermilab Proton Driver design which uses a 15 Hz component plus a 12.5% 30 Hz component as shown below: [15]

$$I(t) = I_0 - I\,cos(2\pi ft) + 0.125\,I\,sin(4\pi ft)$$

in which f = 15 Hz, I_0 and I are two constants determined by the injection and peak current. The advantage of this system is that the peak value of *dB/dt* is decreased by 25%, as shown in Figure 6, which leads to a saving of the peak rf power by the same amount. (3) A programmable ramp system, e.g., the AGS Booster and AGS. Although this is a most versatile system (e.g., allowing for a front porch and a flat top), it is also most expensive.

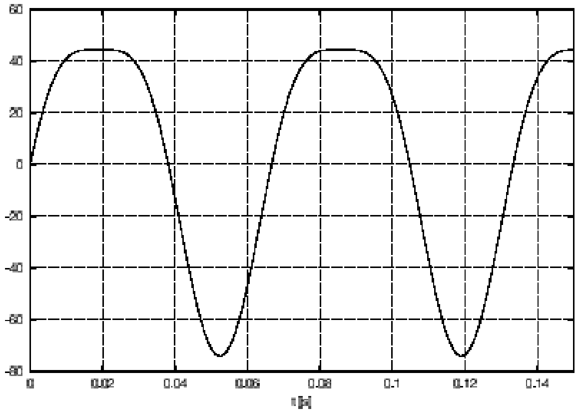

FIGURE 6. Waveform of the time derivative of the B-field (*dB/dt* in T/s) generated by a dual-harmonic power supply system. Compared to a single harmonic system, the peak value during up-ramp is decreased by 25%.

FIGURE 7. A 7.5 MHz Finemet rf cavity installed in the Fermilab Main Injector.

10.3. RF

The rf system is demanding, because it must deliver a large amount of power to the beam in a short period. In addition, it must be tunable, because the particle revolution frequency increases during acceleration. Cavities with ferrite tuners have been in use for decades. Recently the development of the Finemet cavities at the KEK has aroused strong interest at many laboratories. Thanks to a US-Japan collaboration, Fermilab has built a 7.5 MHz, 15 kV Finemet cavity and installed it in the Main Injector for bunch coalescing, as shown in Figure 7. [16] The main advantages of the Finemet cores are high accelerating gradient and wide bandwidth. The former is especially important for high-intensity small size rings, in which space is precious. The main concern, however, is its high power consumption. For example, the Fermilab Finemet cavity needs a 200 kW power amplifier to drive it. New types of magnetic alloys are under investigation for performance improvement.

10.4. Vacuum

Vacuum pipe for a rapid cycling machine is probably one of the most challenging items. Ceramic pipe with a metallic cage inside has been successfully employed at the ISIS. However, this is a costly solution, because it occupies a significant portion of the magnet aperture. Assuming the ceramic wall and the cage need a 1-in vertical space, the magnet aperture would have to be increased from 4-in to 5-in in the Fermilab Proton Driver, a 25% increase. This will directly be translated to a 25% increase in the magnet and power supply costs, equivalent to tens of millions dollars. Therefore, it was rejected by the Fermilab Proton Driver design.

Thin metallic pipe is an alternative. However, it must be very thin (several mils) in order to minimize the eddy current effects (pipe heating and induced magnetic field). Such a thin pipe is mechanically unstable under vacuum. Several methods have been tried to enhance its stability, including ceramic shields, metallic ribs and spiral lining. The first two do not look promising. The third one is under investigation.

In the Fermilab Proton Driver design, a different approach was adopted. The magnets employ external vacuum skins like those in the Fermilab Booster. Perforated metallic liners are used in the magnet gap to provide a low-impedance environment for the beam as shown in Figure 8.[17]

10.5. Diagnostics

A system that can diagnose beam parameters during multi-turn injection is highly desirable. The method for fast, accurate non-invasive tune measurement is being developed. A circulating beam profile monitor covering a large dynamic range with turn-by-turn speed will be crucial for studying beam halo. (A similar instrument has been developed for the linac beam halo experiment at LANL.[2])

11. New Ideas

In the past several years, there are a number of new or revitalized ideas proposed to the proton driver study. For example:

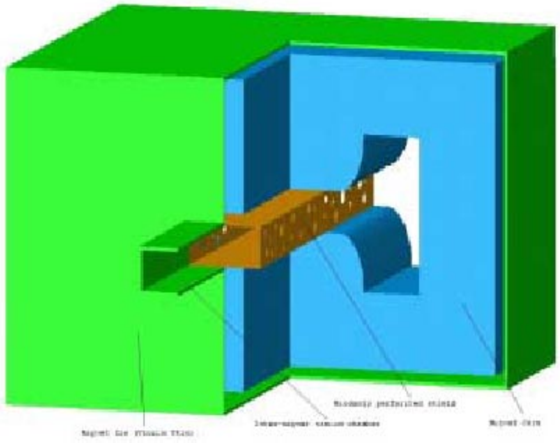

FIGURE 8. Corner section of a canned dipole with a perforated metallic liner.

- Inductive inserts: They are made of ferrite rings and also can have bias current for impedance tuning. Their inductive impedance would fully or partially compensate the space charge impedance, which is capacitive. The first successful experiment was at the LANL.[18] Two ferrite modules made by Fermilab have been installed in the PSR. They help increase the e-p instability threshold, which is a major bottleneck of that machine. Another experiment at the Fermilab Booster is being planned (Figure 9).

FIGURE 9. Inductive inserts in the Fermilab Booster.

- Induction synchrotron: This is a longitudinally separated function machine. In other words, the longitudinal focusing and acceleration are carried out by two separate rf systems. The former uses barrier rf buckets, the latter a constant rf voltage curve. One useful feature of this type of machine is tunable bunch lengths. So the so-called superbunch acceleration could be possible.[19]

- Barrier rf stacking: The application of Finemet and other magnetic alloys makes it possible to build broadband barrier rf cavities with high voltage (~10 kV or higher). They can be used to stack beams in the longitudinal phase space. This is particularly useful when the beam intensity of a synchrotron is limited by its injector (e.g., the intensity of the Fermilab Main Injector is limited by its Booster). Compared to the slip stacking, an advantage of barrier rf stacking is the greatly reduced beam loading effects due to a much lower peak beam current. [20]

- Fixed field alternating gradient (FFAG) accelerator: Although MURA first proposed this idea about 40 years ago, it was almost forgotten. Only the recent activities at the KEK brought it back to the world's attention. KEK has successfully built a 1 MeV proton FFAG and is building a large 150 MeV one. [21] FFAG is an ideal machine for high intensity beams. Its repetition rate can be much higher than a rapid cycling synchrotron (in the range of kHz). One problem of the FFAG, though, is that it is difficult (if not impossible) to fit it into an existing accelerator complex, which usually consists of a linac and a cascade of synchrotrons.

- Repetition rate increase in existing synchrotrons: This is a brute force approach but can be appealing because it is straightforward. For example, in the BNL Proton Driver design, one proposal is to increase the AGS repetition rate from 0.5 Hz to 2.5 Hz. [22] The Fermilab Main Injector upgrade also includes a rep rate increase (from 0.53 Hz to 0.65 Hz). [5]

CONCLUSIONS

Proton drivers are a hot topic in today's accelerator community. Because of their versatile applications, modest costs and great potentials to serve future big projects (a neutrino factory, a muon collider or a VLHC), the designs are being pursued in numerous laboratories over the world. There are many technical challenges. But there are no showstoppers towards the construction of such a facility. The world needs more than one proton driver. International collaborations on a number of R&D items have been formed. Steady progress and fresh ideas can be expected in the coming years in this dynamic field.

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