COMPARATIVE STUDY OF PROTON ACCELERATORS FOR HIGH POWER APPLICATION*

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Abstract

There are many applications requiring high power proton accelerators of various kinds. However, each type of proton accelerator can only provide beam with certain characteristics, hence the match of accelerators and their applications needs careful evaluation. In this talk, the beam parameters and performance limitations of linac, cyclotron, synchrotron, and FFAG accelerators are studied and their relative merits for application in neutron, muon, neutrino, and ADS will be assessed in terms of beam energy, intensity, bunch length, repetition rate, and beam power requirements. A possible match between the applications and the accelerator of choice is presented in a matrix form. The accelerator physics and technology issues and challenges involved will also be discussed.

INTRODUCTION

For many high power application, the most relevant beam parameter is the average beam power delivered on the target due to the fact that the rate of production of the perspective secondary particles is proportional to the average beam power. The expression of average beam power is given in eq.1.

$$P = E * I, ave = E * N * e * f \qquad \text{Eq. 1}$$

Where E is the energy of the proton in eV, N is the number of particles per pulse, and f is the repetition rate in Hz. For a given beam power desired, there are two free parameters to chose. Usually, the beam intensity is limited by either space charge or the coherent instabilities, the high power can be achieved by best combination of the beam energy and the rep rate. For historical reason and discussion in this workshop, we define the high power as any proton accelerator capable of delivering more than one megawatt average beam power.

In this regard, it is instructive to have a quick overview of the status of this field and proposed new projects in the future. To facilitate the discussion, we classify various types of accelerators into three categories, 1) low rep rate (f < 10 Hz), 2) high rep rate(15<f < 100 Hz), and 3) CW and very high rep rate. Due to the low rep rate accelerators in category 1, they have to be of relatively high energy, most of the neutrino facilities, CNGS, NuMI, and AGS-II, Proton Driver of FNAL, fall into this category as shown in fig. 1. In the fast rep rate category are many spallation neutron sources, SNS, J-PARC-1, ESS, and new neutrino proposal SPL of CERN. Finally, in the CW or very high rep rate category are SINQ, APT, IFMIF, and PRISM.

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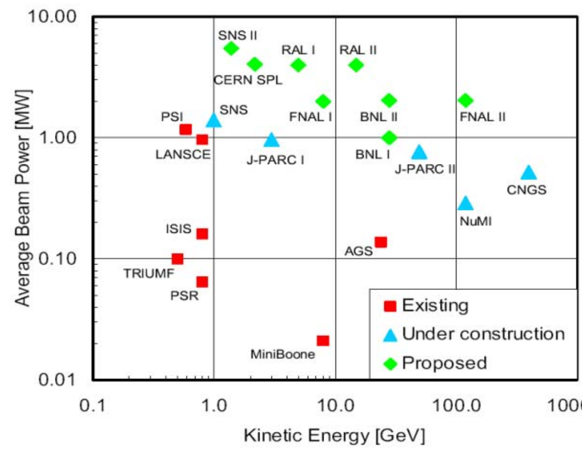

Figure 1: High beam power proton accelerators.

One special type of accelerator under study lately is the proton driver for a neutrino factory which has very stringent requirements imposed by many sub-systems down stream of the proton driver itself. I would like to use the design considerations for this accelerator to highlight the interdependence of many accelerator parameters, involving even the choice of accelerator type and configurations. A comparative evaluation of various types of accelerator for this application is meant to be as a tool of study, not to be as a final judgment of the approaches.

STUDY OF A PROTON DRIVER FOR A NEUTRINO FACTORY

As shown in Fig.2, after the proton driver, there are several major subsystems comprising the complete configuration of a neutrino factory [2]. They are the target and capture system, the bunch rotation, the cooling system, the acceleration system, and finally the decay ring. Each of these systems requires the proton driver to have certain beam qualities for optimal performance.

A neutrino factory may be the best experimental tool to unravel the physics involved in neutrino oscillation and CP violation phenomena [1]. To have sufficient neutrino flux for acceptable physics results within 5 years requires about 10^{22} protons on target per year, which corresponds to 4 MW of proton beam power from the proton driver depending on the beam energy. According to Eq. 1, to achieve 4 MW, possible examples of beam intensities required at given energies and rep rates are shown in Table 1. It is important to realize that typically it requires a beam intensity at the level of 5 10^{13} per pulse, which is at the current limit of what can be reasonably achieved from our past experience, due to the limitation from space charge and other coherent instabilities.

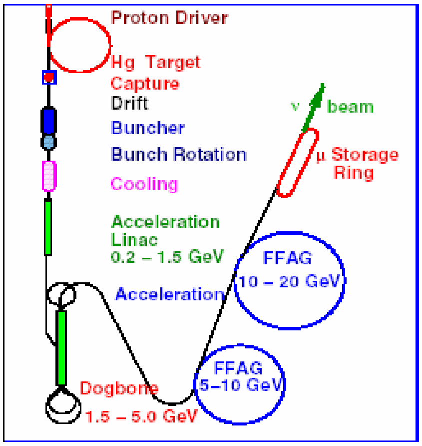

Figure 2: Schematic layout of a neutrino factory.

Therefore, special attention has to be paid to the choice of beam energy and number of bunches.

Table 1: Protons per pulse required for 4 MW. 1 Tp is 10^{12} protons.

	10 Hz	25 Hz	50 Hz
10 GeV	250 Tp	100 Tp	50 Tp
20 GeV	125 Tp	50 Tp	25 Tp

ENERGY CHOICE

We wish to determine the kinetic energy of the proton beam that is most efficient for the production of the soft-pions, which will lead to the maximal collection of muons in a pion decay channel. We process the produced pions through the entire front end of the neutrino factory front end using the Study 2a [3] configuration from the target module to the conclusion of the cooling section. As a figure of merit, we select those surviving muons which are fully contained within the capture transverse acceptance (30 π mm-rad) and the longitudinal acceptance (150 π mm-rad) of the assumed subsequent accelerating section.

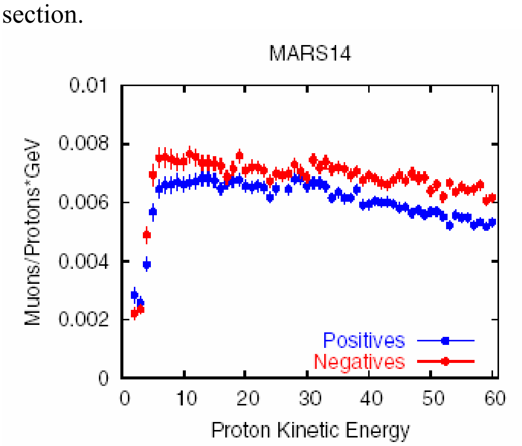

Figure 3: Efficiency of muon collection at the exit of the Study 2a front end versus proton driver energy.

The particle production model used was MARS V14 [4] and the propagation of the particles though the neutrino factory front end was done utilizing the ICOOL code [5]. The efficiency of the muon capture was computed by evaluating the number of collected muons at the end of the neutrino factory front end and normalizing the results to the power of the proton beam such that a beam of e.g. 20 GeV kinetic energy is assumed to contain twice the number of protons as an equivalent beam with 40 GeV kinetic energy. Results of this analysis utilizing a mercury based target is shown in Fig. 3. The target parameters such as radius, tilt angle, and longitudinal placement have been previously optimized in Study 2a.

We also investigated other candidate target types with elements of various Z content with the result that the high-Z materials show the highest proficiency for soft-pion production which will lead to the greatest number of captured muons. In evaluating the most efficient kinetic energy region we found that 6 to 38 GeV protons gave the sum of positive and negative pions within 10% of the maximum efficiency.

TARGET ISSUES

The challenge of delivering 4 MW of beam power on a target (solid or liquid) is governed by two sets of parameters. The first set relates to the production target and specifically the choice of material, as well as its integrated design that allows it to operate as a functional unit. The second set is linked with the proton pulse structure delivered to the target and the parameter choices have a direct impact on the survivability of the target. Whether liquid or solid, the target feasibility issues stem from the inherent material limits that in turn depend on the deposited energy density. This energy density is a function of the proton energy, intensity and spatial structure, as well as the material properties.

Solid vs. Liquid Targets

The issues associated with each of these two target types are distinctively different. On one hand, solid targets are vulnerable to thermo-mechanical shock induced by high energy densities that can lead to failure even with a single pulse on target. Fatigue due to the cyclic nature of the problem can lead to premature failure of the target. Most importantly, solid targets are susceptible to irradiation damage manifesting itself in altering the key properties of the material, both physical and mechanical, that are responsible for shock absorbance and heat diffusion towards the heat sink. The onset of irradiation damage is always expected to compromise the longevity and functionality of a solid target. In addition, solid targets, even under the best of circumstances, must enable the removal of the significant heat load through a feasible and “smart” design. This is particularly challenging because of the constraints brought onto the target by physics requirements that limit the size of the target to avoid re-absorption of secondary particles and thus limiting the available target surface area for heat transfer to the heat sink. Solid targets seem capable of reaching powers of 2 MW at best and only with low Z, high performance materials.

Liquid targets, on the other hand, either in the form of jets or contained volumes, do not suffer from thermal shock, fatigue or irradiation damage. While these serious limitations are avoided altogether, liquid targets face challenges of a different kind. Specifically, interaction of the proton beams with a high Z liquid jet target will lead to an explosive style destruction that, while of no consequence to the secondary particle production, could have serious consequences to the target container. The ability to replenish a liquid jet to meet the repetition requirement of the high power proton driver and the difficulties of adopting a feasible jet scheme to tight geometrical constraints pose additional challenges. In the case of a contained liquid, the generation of high cavitational pressures can induce damage on the target infrastructure. Liquid targets seem capable of supporting a 4 MW proton driver.

Proton Energy

While the energy density distribution in a given solid target will vary within the target depending on the energy of the incoming protons, an important parameter in transferring deposited heat from the target, the maximum energy density increases with increasing energy. Table 2 depicts peak energy densities on a Cu target intercepting proton pulses with the same intensity and pulse shape.

Table 2: Energy Density in Cu Targets at Different Beam Energies (MCNPX Code).

proton energy (GeV)	8	16	24
energy density (J/g)	234	351	377

Repetition Rate

The benefit of increased repetition rate of the proton driver is two-fold. For a given proton driver power an increased rep-rate will lower the demand on the target (especially the solid target) in that the pulse intensity will be decreased. For the same pulse intensity and increased repetition rate the proton driver power increases but the demand on the target increases as well. Specifically, the thermal load of each pulse on the target must, under the higher rep-rate, be removed by the heat sink in a shorter time and the rep-rate limit will be controlled by the ability to remove the dynamic stresses entirely between pulses.

Pulse length, intensity and structure

The survivability of the target depends on the above three parameters. Specifically, the pulse intensity, combined with the beam spot size, controls the quasi-static conditions of pressure and temperature generated in the target upon beam interception. Energy densities of up to 400 J/g, corresponding to ~ 24 10^{12} protons per pulse and σ_r = 1mm, may be tolerated by some high performance solid materials. The pulse length controls the ensuing dynamic stresses and can play a significant role in the way the solid target survives the induced shock. Solid targets favor longer pulses because of the ability to relax during deposition. On the other hand, liquid jet targets will perform best at very short pulses (a few ns) where the onset of jet destruction has not occurred. A pulse structured not as a Gaussian but as a uniform distribution over the same (i.e., 3σ spot) and same intensity will reduce the stress and temperature demand on the target by approximately a factor of three.

BUNCH LENGTH

The proton bunch length has a strong influence on the muon density produced at the end of the front end. The accepted muon density at the end of the cooling channel falls off with increasing proton driver bunch length on the target. This behavior can be partially understood by a simple theory that models the longitudinal dynamics of the muon beam through the RF components of the front end. Longer proton bunches produce initial longitudinal phase space areas that exceed the longitudinal acceptance of the front end. Our calculation shows that the bunch length should be kept below 3 nsec for good capturing efficiency, as shown in Fig. 4.

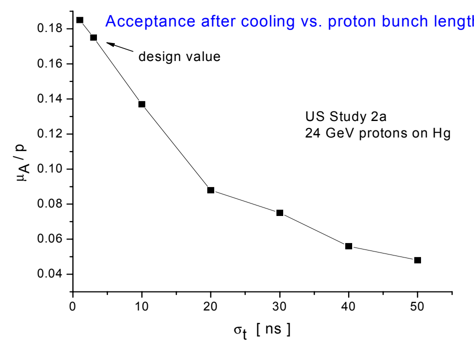

Figure 4: Acceptance after cooling vs. proton bunch length.

REPETITION RATE

The primary downside of a higher repetition rate is the average power consumption for the RF systems. There are two sources of this: the first is the energy to fill the RF cavities for each pulse (the unused portion of which we have no good way of storing for the next pulse), and the second is the cryogenic costs for cooling the dynamic heat load (the heat from the absorption of the cavities' stored energy) in the superconducting cavities.

In Study II [1], the average power required for these systems was 44 MW for a 15 Hz average repetition rate. This portion of the machine's power consumption will be proportional to the repetition rate.

Higher repetition rates will reduce the amount of current per bunch train, which will reduce the beam loading in the RF cavities. The primary effect of beam loading is that the bunches toward the head of the train will gain more energy than those at the tail of the train, since the earlier bunches have extracted energy from the cavities. This would be corrected, at least partially, if particles were undergoing synchrotron oscillations, but they do not do so in scenarios involving FFAGs, and they undergo a relatively small number of synchrotron oscillations in the RLAs and initial linac. Furthermore, some schemes for the storage ring require (superconducting) RF cavities to keep the beam bunched, and higher currents might require more RF power (and possibly more cavities) to compensate for beam loading there.

COMPARISON OF DIFFERENT TYPES OF ACCELERATORS

There are many types of accelerators with different performance parameters and characteristics. There is no single type of accelerators good for all purposes and it takes experiences and careful study to pick the right one for one's application. We will review several most frequently encountered comparisons. The most important distinction is the repetition rate of an accelerator as shown in the introduction. Basically, the application dictates the choice of rep rate at the extreme ends of the spectrum. But in the middle rage, say somewhere between 10 to 30 Hz, there is the competition between Linac plus Accumulator (LAR) and the Rapid Cycling Synchrotron (RCS) configurations, as that of the SNS and J-PARC [6,7].

The comparison between them can be summarized in table 2.

Table 2:

	LAR	RCS
E, inj	High	Low
E, ext	Same	High
Aperture	Moderate	Large
Rep. Rate	CW	High
Eddy Current	No	High
RF Voltage	Moderate	High
Beam Loss	Moderate	High
Reliability	Good	Average

The actual decision is made by a balance among all those considerations. But for the J-PARC case, the injection energy for the main ring dictates the choice of the RCS.

Another possible new competitor in this rep rate range is the FFAG accelerator which promises both the advantage of no ramping and delivery of higher final energy [8]. That is the reason why there is a resurgence of interest in this type of accelerator for muon acceleration for neutrino factory, medical treatment, proton driver and PRISM experiment. The drawback of the FFAG accelerator is the uncertainty of achieving high intensity comparable to that of synchrotron and the difficulty of providing sufficient space for injection and extraction components. FFAG would be unique for very high rep rate application from 100 to 1000 Hz for moderate energy gain. If much higher energy is needed, then a much higher acceleration gradient from the RF cavity would be required.

In table 3, I use a matrix format to illustrate the relative advantage of each accelerator type as a proton driver for a neutrino factory, taking into account the requirements outlined in section 2. This table is meant for a tool for further study and the picture can easily change with more R&D on various key considerations.

Table 3: Assessment for PD for NuFact.

(Picture will change after R&D)

	Linac	RCS	FFAG	LAR
Energy	A	A	A	A
Rep Rate	A	B+	A	A
Intensity	A	B+	B	A
Bunch L	C	B	B_	B
Cost	B	B+	A	B_

Where A denotes the fact that it can be reasonably achieved with today's technology, B denotes that it is within reach with more R&D efforts, and C denotes that it may be very difficulty to achieve the desired requirements.

CW ACCELERATORS

So far, we have been focused on the pulsed accelerators. In fact, as far as achieving high power is concerned, the CW accelerators have the best potential. The two main options for CW accelerators are a cyclotron, or a superconductiong linac.

The possible maximum energy of a cyclotron is limited to about 1 Gev at which point the betatron tune approaches an integer. Currently, the SINQ facility at PSI can operate at 590 MeV, 2mA and a beam power of 1.2 MW. There is a plan to further upgrade to 2 MW by improving the ion source and RF power. A design was developed for a 10 MW facility based on a 1 GeV cyclotron operating at 10 mA. This requires a much higher RF voltage for higher turn-to-turn separation.

A Low Energy Demonstration Accelerator(LEDA) has been developed at LANL to produce a CW current of 100 mA at 67 MeV[9]. Beam measurements has been performed to bench-mark the halo simulation code for halo production mechanism with good agreement. If the energy of the proton is further extended to about 1 GeV by superconducting linac, a facility of about 100 MW can be produced. Such a CW high power beam would be very useful for nuclear transmutation and generation of power by sub-critical nuclear reactor[10].

SPL AS PROTON DRIVER

The last class of accelerator studied for low rep rate application is the superconducting proton linac. The most notable examples are the CERN 3.5 GeV SPL and the FNAL 8.0 GeV proton driver. The FNAL's proton driver study employs mostly Tesla-type cavities to accelerate H- to 8 GeV at 10 Hz[11], as shown in fig.5. The linac beam itself can provide 2 MW power to the target. It can also inject into the Main Injector to be accelerated to either 120 Gev to provide for 2 MW beam for neutrino production.

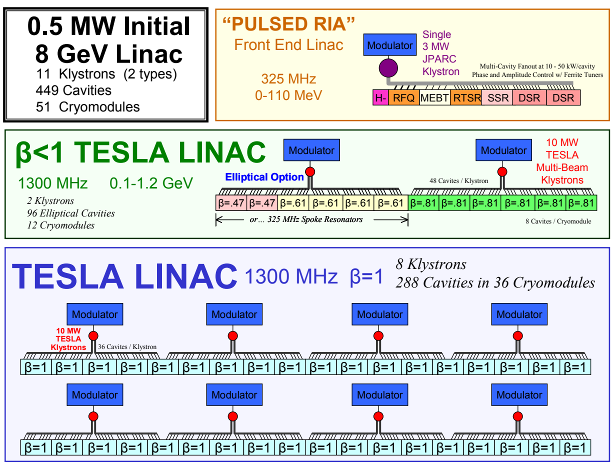

Figure 5: Layout of FNAL Proton Driver.

There are several additional complications of accelerating the H- beam to 8 GeV. They are the stripping of the electron by magnetic field, foil, and the black-body radiation above 5 GeV. To suppress the last effect, the vacuum chamber of the beam transport line has to be kept at a temperature below 100 K to keep the loss at an acceptable level.

R&D REQUIRED FOR IMPROVEMENTS

Although there are many proposals for high power proton accelerators for various applications, there is a need for active R&D on many important issues to assure the performance goals,

1. The space charge effect and coherent instabilities at every stage of the acceleration
2. Generation of short bunches for neutrino factory
3. Study of beam dynamics in an FFAG accelerator
4. Development of reliable high gradient RF cavity
5. Control of beam losses and radiation protection
6. Development of target and beam capture system
7. Reduction of construction cost and assurance of operational reliability

SUMMARY AND CONCLUSIONS

It is evident from the above discussion that there are strong interest of high power proton accelerators for various applications. A careful study of the needs from application and the match of appropriate technology is very important for the assurance of reaching performance goals. Another related system requires equal attention and further R&D efforts is the target and beam capture and focusing after the proton driver. In addition, the consideration of reducing beam losses, providing radiation protection, reducing cost, and enhancing operational reliability should also be included in the design stage.

The achievements of HPPA in the past twenty years is very impressive. However, to realize the dreams of all users, we have to make progress in all areas outlined in R&D requirement section.

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