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Plans for Future Megawatt Facilities

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Abstract. Proton accelerators producing beam powers of up to 1 MW are presently either operating or under construction and designs for Multi-Megawatt facilities are being developed. High beam power has applications in the production of high intensity secondary beams of neutrons, muons, kaons and neutrinos as well as in nuclear waste transmutation and accelerator-driven sub-critical reactors. Each of these applications has additional requirements on beam energy and duty cycle. This paper will review how present designs for future Multi-Megawatt facilities meet these requirements and will also review the experience with present high power facilities.

INTRODUCTION

The power of a proton beam is determined by the product of the kinetic energy E of the beam particles and the average current $\langle I \rangle$. Often it is more economical and sometimes even required by the application to pulse the beam with a duty factor DF:

$$P = E \times \langle I \rangle = E \times I_{\text{peak}} \times DF$$

Since space charge forces often limit the possible value of I_{peak} high power beams are more easily produced with a high energy and/or a large duty factor.

High beam power proton accelerators are typically used for the production of intense beams of secondary particles. The usefulness of some secondary particle beams is greatly enhanced by strongly pulsing the high intensity proton beams requiring a low DF. With a well known production time one can either infer the secondary particle's energy from the elapsed time between detection and production, discriminate against out-of-time background events or produce secondary particle beams with a small longitudinal emittance.

Some examples and their requirements for beam energy and duty factor are:

- *Neutrons for material studies:* DF: $CW \dots 10^{-4}$; E: $0.5 \dots 10 \text{ GeV}$. In this energy range the neutron production is approximately proportional to beam power.
- *Neutrons for nuclear waste transmutation or accelerator driven sup-critical reactors:* DF: CW ; E: $0.5 \dots 5 \text{ GeV}$. The lower energy derives from limiting the power disposition in the target window; the higher energy is limited by the need to fully absorb the beam power in the reactor vessel.

- *Kaons:* DF: $0.5 \dots 1$ to minimize detector dead time; E: $> 20 \text{ GeV}$ to be above the kaon production threshold.
- *Neutrinos:* DF: 10^{-5} to minimize background from continuous sources such as cosmic radiation; E: $> 1 \text{ GeV}$ depending on the required neutrino beam.
- *Muons for neutrino factory:* DF: 10^{-5} to limit the up-time of the muon cooling channel; E: $> 3 \text{ GeV}$ to minimize peak current (for a 5 MW facility the peak current is about 150 A).
- *Muons for muon collider:* DF: 10^{-7} to maximize the collider luminosity (for a fixed muon production rate the luminosity scales linearly with the muon bunch intensity); E: $20 - 30 \text{ GeV}$ to minimize peak current (for a 5 MW facility the peak current is about 2 kA).

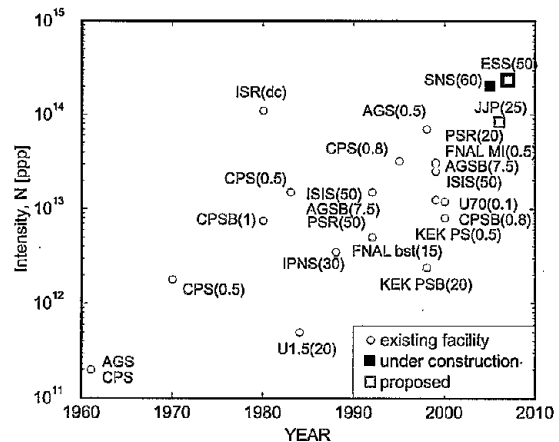


FIGURE 1. Intensity history of multi-GeV proton accelerators. The numbers in parenthesis indicate the typical repetition rate.

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Fig. 1 shows a history of achieved proton intensity per accelerator pulse in multi-GeV machines[1]. As can be seen the progress has been exponential - very much like the famous Livingston plot of the peak beam energy. It is also interesting to note that the original alternating gradient proton synchrotrons - the CERN PS and the Brookhaven AGS - are still at the intensity frontier.

With high intensity beam sources available for many years the main challenges for high intensity accelerators has been the control of beam losses at a level that still allows for maintenance and repair to be performed by hand. This level is about 1 Watt of beam power lost per meter of accelerator structure. For a 10 MW facility with a length of 1 km this translates into a loss of 10^{-4} per meter at full energy. Since losses are not evenly distributed even lower levels are required at some locations.

For very high power facilities the efficiency of converting electric power to beam power is also important. Many of the present facilities have very poor efficiencies of a few percent. The development of new technology is necessary to reach the high efficiency needed for facilities that would produce beam power of tens of Megawatts.

Finally the development and construction of targets for high power beams presents its own very challenging problems. However, this will not be covered in this paper.

DEVELOPMENT OF HIGH INTENSITY PROTON MACHINES

Over the last forty years the acceleration of high intensity proton beams has been a main focus of many accelerator facilities. An incomplete list is shown below together with major contributors in parenthesis:

- Low loss charge exchange injection (PSR, SNS, ...)
- Boosters (CERN, FNAL, BNL, KEK, ...)
- Rapid cycling synchrotron (FNAL, ISIS, ...)
- (CW) Radio Frequency Quadrupoles (RFQ) (LEDA, ...)
- Super-conducting rf (SNS, ...)
- Transition energy jump or avoidance (CERN, AGS, J-PARC, ...)
- RF beam loading compensation (AGS, ...)
- Electron cloud cures (LANL PSR, ...)

Many of these advances in high intensity proton beams have been implemented at the BNL AGS complex. Fig. 2 shows the achieved proton intensity per AGS pulse over the last 40 years up to the present record of 7.4×10^{13} protons per pulse.

The most dramatic increase occurred over the last decade with the addition of the new AGS Booster. The AGS Booster has one quarter the circumference of the

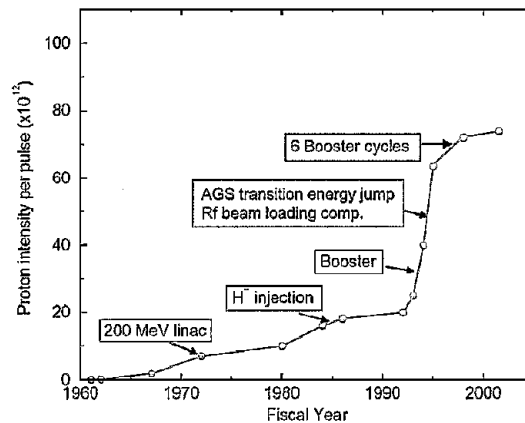


FIGURE 2. The history of the proton intensity at the Brookhaven AGS.

AGS and therefore the incoherent betatron tune spread is reduced by the same factor for the same line density.

A recent upgrade of the 200 MeV LINAC rf system made it possible to operate at an average H^- current of $150 \mu A$ and a maximum of $12 \times 10^{13} H^-$ per 500 μs LINAC pulse. The H^- magnetron source can deliver 90 mA over a 500 μs pulse. The duty factor is quite low (5×10^{-3}) but could probably be significantly improved.

The beam intensity in the Booster reached a peak value of 2.3×10^{13} protons per pulse. This was achieved by very carefully minimizing the peak line density during charge exchange injection and during early acceleration. Best conditions are achieved by ramping the main field during injection with 3 T/s increasing to 9 T/s after about 10 ms. With only one bunch in the Booster a peak intensity of about 1.7×10^{13} was reached with a bunch area of about 3 eVs. Single bunch operation in the Booster allowed for the transfer of six Booster loads into the AGS reducing the need for very high intensity in the Booster.

Fig. 3 shows the total current and peak current in the AGS during operation for the g-2 experiment with 6 injections from the Booster and, after bunch splitting, 12 single bunch extraction to the g-2 production target. During beam injection from the Booster the AGS needs to store the already transferred beam bunches for about 0.8 seconds. During this time the beam is exposed to the strong image forces from the vacuum chamber, which will drive transverse beam instabilities that are damped by a powerful transverse feedback system.

The vertical tune setting is about 8.9 with an incoherent tune shift at the AGS injection energy of 0.1 to 0.2. To reduce the space charge forces the beam bunches in the AGS are lengthened by purposely mismatching the bunch-to-bucket transfer from the Booster and then

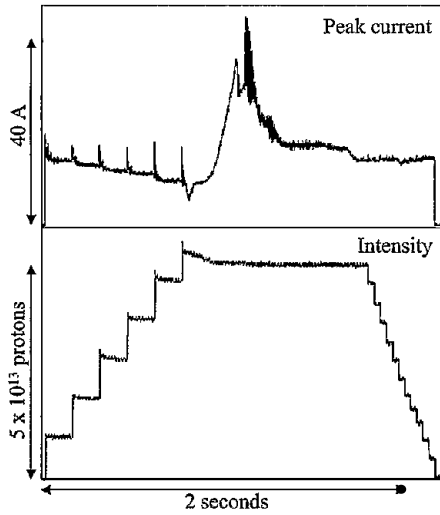


FIGURE 3. Total intensity and peak current in the AGS during operation for the g-2 experiment.

smooth the bunch distribution using a high frequency 100 MHz dilution cavity (Fig. 4). A large part of the injection losses at the AGS are due to a relative slow loss during the first millisecond the transferred bunches circulate in the AGS. No direct cause for this loss could be identified but it is correlated with a sustained transverse coherent beam oscillation also shown in Fig. 4. The coherent oscillations result from miss-matched beam injection to blow-up the transverse emittance and therefore reduce the space charge tune spread. Although the coherence persists over a whole millisecond the middle part of the beam bunch has a coherent space charge tune shift of about 0.1 and therefore very high frequency ver-

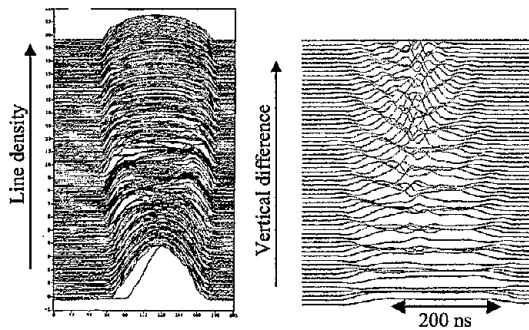


FIGURE 4. Left: Evolution of the line density in the AGS. Right: Evolution of the vertical miss-match at AGS injection. The traces show the vertical displacement of the same bunch every revolution.

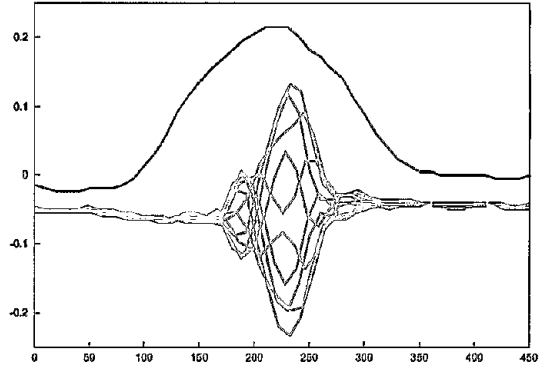


FIGURE 5. Bunch shape (top) and vertical modulation of a high intensity bunch at AGS injection energy of 1.9 GeV during a single bunch head-tail instability. The vertical scale is in arbitrary units and the horizontal scale is in ns.

tical modulations appear. The bunch intensity is about 1.3×10^{13} protons.

At these bunch intensities a vertical single bunch head-tail instability develops. Fig. 5 shows both the bunch shape as well as the vertical modulation. The observed asymmetry suggests that this instability is driven by the broad band impedance or maybe by an electron cloud. The instability can be avoided by adjusting the chromaticity, coupling or betatron tunes.

During acceleration the AGS beam has to pass through the transition energy using a transition energy jump system with only minimal losses even at the highest intensities. After transition, a very rapid, high frequency instability develops, which can only be avoided by purposely further increasing the bunch area using again the high frequency dilution cavity. Similar fast transverse instabilities around transition have also been observed at the CERN PS (Fig. 6) and at the BNL RHIC.

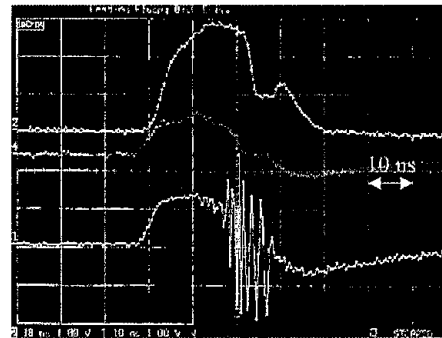


FIGURE 6. Fast transverse instability at transition at the CERN PS

PRESENT AND FUTURE HIGH POWER PROTON ACCELERATORS

Figure 7 shows a compilation of the existing, under construction, and proposed high power proton accelerators. Existing machines and machines under construction are in the range of 100 kW and 1 MW whereas most of the proposed machines aim for several Megawatts. The design of high power accelerators can be divided into two main types: CW or high duty factor machines and low duty factor machines.

CW or high duty factor accelerators

The two main options for CW or high duty factor operation are a cyclotron or a superconducting linac. Both options offer the possibility of providing high beam power with efficient use of electric power. In both cases a high intensity proton source can be used.

The maximum energy of the cyclotron is limited to about 1 GeV at which point the betatron tune approaches an integer. The PSI SINQ facility can presently operate at 590 MeV, 2 mA and a beam power of 1.2 MW and will be upgraded to 2 MW[2]. A design was developed for a 10 MW facility based on a 1 GeV cyclotron operating at 10 mA. High beam power requires high rf voltage for improved turn-to-turn separation.

There have been several proposals for using a superconducting linac to produce CW proton beams at about 1 GeV. Here the potential exists for average currents of 100 mA or higher. The main challenge then is the front-end where space charge dominates and CW operation of the typically normal conducting rf structures is required. Such a front end was successfully demonstrated

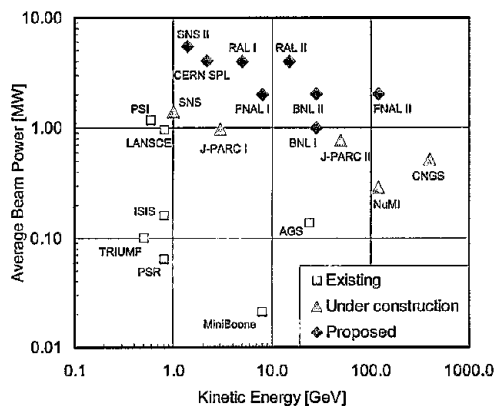


FIGURE 7. High proton beam power machines that are presently operating, under construction, or planned

at Los Alamos with the Low Energy Demonstration Accelerator (LEDA). At 67 MeV a CW current of 100 mA was reached and was used to bench-mark halo simulation codes. A second demonstration effort is ongoing at Scalay[3]. The High Intensity Proton Injector (LPHI) is designed to reach 100 mA at 3 MeV. First beam is expected in 2006 and it might be used as a front end of the Superconducting Proton Linac at CERN.

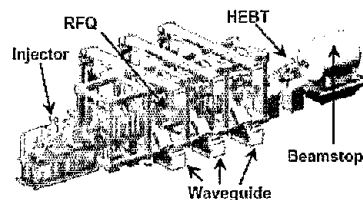


FIGURE 8. The Low Energy Demonstration Accelerator (LEDA)

As part of the world-wide fusion research program a dual deuteron accelerator is being designed reaching 125 mA at 40 MeV each, using two 5 MeV RFQs and two 40 MeV DTLs. The 10 MW deuteron beam would be used to produce fast neutrons to develop container walls for the fusion reactor vessel. Construction could begin in 2009.

After the demise of the "Accelerator Production of Tritium" (APT) project no full CW superconducting linac project is actively being pursued presently. The closest recent design is the "Long Pulse Reference Design" for the European Spallation Source (ESS). At 1337 MeV and 3.7 mA average current it would produce 5 MW of beam power with a duty factor of 3.3%. The AC power usage efficiency would be 24% overall. A fully CW superconducting linac would make it feasible to build a 1 GeV, 100 mA (100 MW) accelerator with high AC power efficiency. The efficiency could be further improved with highly efficient rf sources and couplers and cavities that minimize higher order modes (HOM).

Low duty factor accelerators

The low duty factor and high beam power required by many applications can only be achieved by accumulating protons in a ring at reasonably high energy using charge exchange injection of H^- beams. A compression factor of 100 or more can easily be reached, which is far greater than the intensity difference between proton and H^- sources. In the simplest case the beam is injected into the accumulator ring at full energy. Alternatively, the accumulation can be in a Rapid Cycling Synchrotron (RCS) that allows for further increase of the beam momentum by up to a factor of 10 or into a Fixed Field Al-

ternating Gradient (FFAG) ring for acceleration to up to three times the injection momentum. The maximum repetition rate for the RCS is limited to less than 100 Hz due to eddy current heating in the vacuum chamber and/or magnet coils whereas a FFAG could operate up to 1 kHz limited only by the tuning speed of the rf cavities.

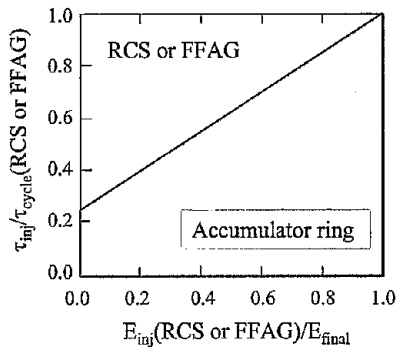


FIGURE 9. Comparison of a full energy linac plus accumulator with RCS or FFAG accelerators.

Assuming equal cost per meter for the linac and the large aperture magnets of the RCS or FFAG, one can then determine the most cost effective option. Fig. 9 shows the parameter region that favors either the RCS and FFAG or a full energy linac plus accumulator ring. For a typical 1 ms source pulse (τ_{inj}) the full energy linac operating at the maximum 1 kHz repetition rate is more cost effective unless the repetition rate of the RCS or FFAG is at least 250 Hz. This excludes the RCS but could be possible with a FFAG.

In fact there has been renewed interest in FFAGs. A scaling FFAG has recently been successfully demonstrated[8]. Non-scaling FFAG with their much smaller aperture requirements result in large betatron tune variations similar to cyclotrons. However, non-scaling FFAG lattices with minimal tune variations are a very active field of development recently and a possible proton driver that would fulfill the guidelines above is presented at this workshop[9].

However, for most existing and proposed accelerators constraints other than maximizing beam power exist. Spallation neutron sources require relatively low repetition rate of 10 - 100 Hz to avoid excessive frame overlap and muon sources require high proton beam energy. The CERN SPL proposal[4] mentioned above consists of a full energy 2.2 GeV superconducting linac running at 50 Hz. With an accumulator and a compression ring it can reach 4 MW and a duty factor of 2×10^{-5} or peak current of 90 A which is suitable for a neutrino factory. The 2 MW proton driver proposals from BNL[6] and FNAL[7] are both based on a new superconducting linac injecting H^- beams into an existing synchrotron. At BNL a 1.5 GeV linac would directly inject into an up-

graded AGS with a 3.33 Hz repetition rate. At FNAL a 8 GeV linac using mostly Tesla-type cavities would inject H^- into the Main Injector allowing for 2 MW beams at either 8 GeV or 120 GeV. A particular challenge of the FNAL proposal is the transport and injection of the 8 GeV H^- beam since all fields encountered by this beam have to be less than 600 Gauss to avoid stripping.

The 4 MW proton driver proposal from RAL[5] is basically a green site proposal. It is based on multiple RCS' to reach 5 GeV with a 50 Hz repetition rate. Because of the double ring arrangement no beam stacking is necessary in the second stage. The final energy of the second stage is close to transition to give extra bunch compression. With a duty factor of about 10^{-6} and a peak current of 1 kA this driver is suitable for both a neutrino factory or a muon collider.

CONCLUSIONS

As the two Megawatt facilities SNS and J-PARC are nearing completion several new Multi-Megawatt accelerators are being planned with duty factors ranging from CW to 10^{-6} and energies from 1 to 120 GeV. Designs for a CW facility with 10 MW beam power are mature and construction of such a facility should be the next step in the development of high intensity proton accelerators. A facility with a superconducting linac could go to even higher beam power.

Several excellent and detailed designs exist for low duty factor facilities. All of these proposals will benefit from the experience obtained with the upcoming commissioning of the new facilities SNS and J-PARC.

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