CW SRF H^- LINAC AS A PROTON DRIVER FOR MUON COLLIDERS AND NEUTRINO FACTORIES[*]

MILORAD POPOVIC[1†], CHARLES M. ANKENBRANDT[2], ROLLAND P. JOHNSON[2]

[1]*Fermilab, P.O. Box 500, Batavia, IL, 60510, USA*

[2]*Muons, Inc., 552 N. Batavia Ave., Batavia, IL, 60510, USA*

We describe a Project-X proton driver based on a CW Superconducting RF Linac with final energy as high as 8 GeV. This machine would have the potential to produce multi-MW H^- beams to drive the Fermilab neutrino programs, rare kaon and muon decay experiments, muon cooling R&D programs, neutrino factories, and muon colliders. Keys to a CW machine to suit these uses include ways to generate the desired bunch trains and ways to accumulate many protons in an intermediate storage ring before they are bunched and directed to a target. Enhanced carbon foil techniques can allow accumulation of intense proton beams from a CW linac, which we propose to be extended from 3 GeV to as much as 8 GeV for the most efficient muon production for colliders and neutrino factories and to replace the Booster for improved Main Injector operation.

1. Introduction

One of the possible realizations of Project X [1] at Fermilab is a CW Superconducting RF Linac accelerating H^- beam to 3 GeV. The initial mission of the linac would be to provide intense kaon and muon beams for rare-process experiments. Such experiments typically require high macroscopic duty factors; a variety of bunch lengths, intensities, and patterns are required. Elaborate chopping and beam switching techniques are envisioned to satisfy these requirements simultaneously for multiple experiments. The chopping would occur at high enough frequencies that the high-Q RF cavities would effectively average over the beam microstructure. The beam needed for these experiments, with average beam current as high as 1 mA and kinetic energy as high as 3 GeV, would, with additional acceleration, also provide the basis for the higher-energy, multi-MW beams that are needed for neutrino factories and muon colliders. Additional acceleration beyond the energy of the CW linac of Project X would also allow beam to be delivered to the Main Injector.

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[†] popovic@fnal.gov

2. Low Energy Linac Front End

The proposed front end for Project X based on a CW SRF Linac assumes a 10 mA H^- source with a warm CW RFQ. The RFQ would operate at 325 MHz or 162.5 MHz to allow the chopper to reject individual bunches. To reduce residual radio-activation, it has been suggested that the output energy of the RFQ be less than 2.5 MeV. Since the required beam peak current is low, the input energy of the RFQ can be 30 keV. Except for the continuous beam requirement, these parameters are not very demanding for the RFQ. The input energy and relatively low peak current also make chopping of input beam less difficult. SNS operation has demonstrated that an ion source extraction system combined with electrostatic focusing and a very short LEBT can preserve the beam emittance even with a peak current of 40 mA. The present SNS LEBT is 12 cm long and allows chopping 200 ns of 40 mA beam at 1 MHz rep rate.

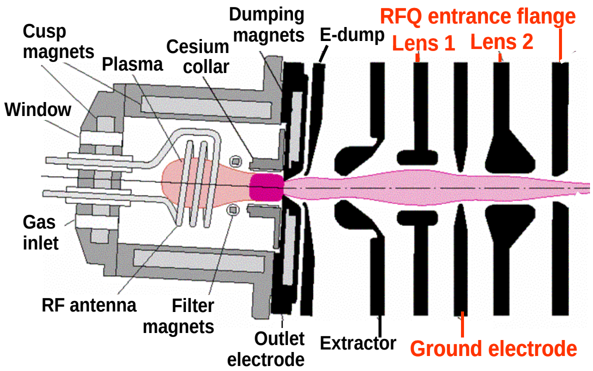

Figure 1: SNS Ion Source with LEBT.

Lowering the peak current to 10 mA reduces space charge effects, removes the need for beam neutralization, and allows a longer electrostatic focusing system with less demanding peak voltages for chopping. It is assumed that the very different beam structure requirements for different experiments can be satisfied by chopping at low energy and splitting with transversely-kicking RF to multiple experiments downstream of the linac.

3. CW Linac from 3 GeV to as high as 8 GeV

It is likely that the 3 GeV Linac, after the Front End and the MEBT, will be based on 325 MHz spoke cavities up to ~200 MeV, continued with 650 MHz beta=0.6 five-cell bell-shaped cavities up to ~500 MeV, followed with 650 MHz beta=0.9 cavities up to about 2 GeV and 1.3 GHz ILC-like cavities up to 3 GeV. It is natural to assume that the linac extension beyond 3 GeV also will be based on the same 1.3 GHz technology extended to a final energy as high as 8 GeV.

4. Beam Delivery and Beam Accumulation

A currently open issue is whether the linac extension should be pulsed or CW. There are various pros and cons. A CW extension would seem reasonable because no modifications to the original 3 GeV CW linac would be needed, no additional R&D would be needed for the beta=1 cavities, and there is not yet a convincing method to make the transition from CW to pulsed mode that conserves the potential beam power enabled by the CW portion.

Muon colliders and neutrino factories need a relatively small number (as few as 10 for a collider, as many as 300 for a factory) per second of intense, short (<~3 ns rms) proton bunches arriving at a pion production target. One or more "post-processing" rings will undoubtedly be necessary to provide the required bunch structures. The crux of this paper is to consider whether and how a CW linac can be used to fill an accumulator ring for these purposes. There are two issues, the long accumulation time and, if a classical stripping foil is used, foil heating.

Another likely use of a higher energy linac would be to fill the Main Injector for its neutrino program to allow the aging Booster synchrotron to be retired. This case is considered first as an example of how to cope with long accumulation time and foil heating. We assume protons are accumulated in the Recycler from a 1 mA CW linac at 8 GeV using existing foil stripping technology. For 4 mm linac beam radius, 600 $\mu g/cm^2$ carbon foil, and assuming that on average every proton comes back onto the foil every 5th turn, we calculate that the temperature of the foil can be kept below 1800 degrees, and 1.5×10^{14} protons can be accumulated in the Recycler in less than 100 ms. Techniques discussed below can reduce the time to inject the whole beam in 2200 turns into the Recycler in 24 ms. Figure 2 shows the foil heating and cooling for the case of injecting in the Recycler. Similar considerations would apply for the case of injecting directly into the Main Injector from a CW linac of less than 8 GeV.

Injection into an accumulation ring for the neutrino factory and/or muon collider case is considerably more challenging, requiring more turns to be injected, because each of these applications requires about 4 MW of beam power and because the accumulation ring must be considerably smaller in circumference than the Recycler (or Main Injector) to alleviate space-charge effects in the subsequent bunch-shortening ring. However, there are also a few factors that will make it easier. The aperture of the ring will be considerably larger than the Recycler in order to accommodate the very large beam sizes that are required in any case to make space charge effects tolerable. The added phase space for the circulating beam, combined with the small emittance of the injected beam, makes it less likely that circulating protons will strike the foil. And the smaller CW injected beam current (~ 1 mA or less) means that the foil does not overheat where the incoming beam strikes it. Basically, stretching out the injection process in the CW case allows the foil to radiate considerable power during the injection process, whereas in the pulsed case the injection time is too short to allow much radiative cooling during the incoming beam pulse.

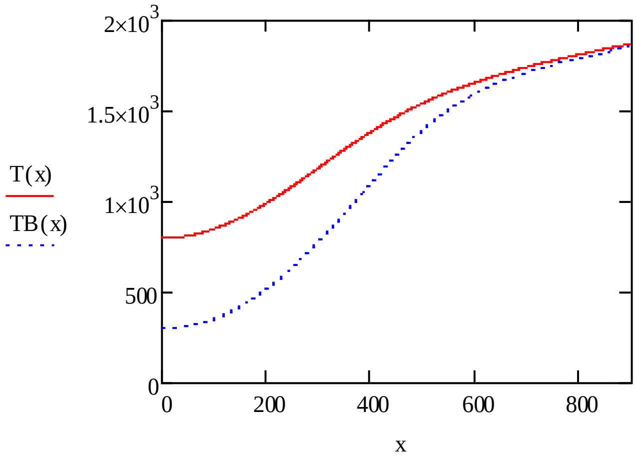

Figure 2: Foil Temperature vs. number of injected turns for initial foil temperatures of 300K (TB-blue dotted) and 800K (T-red solid).

The above factors are probably not sufficient to make a convincing case that foil-stripping injection is feasible from a high-power CW linac. Fortunately, four new concepts have been developed that make it plausible that injecting as many as 10^5 turns into a ring using a stripping foil will be feasible. Of course detailed simulations of the whole process will be necessary to help decide the issue.

Resonant Foil Bypass: The first new idea was presented at the Workshop on Applications of High Intensity Proton Accelerators at Fermilab [2], and dubbed "resonant foil bypass" by the organizers of the parallel session. Basically, the idea is to modulate the incoming beam at a relatively high frequency (so high that the high-Q SRF cavities average over the gaps) using the chopper, and to move the closed orbit synchronously at the foil so that it is closest to the foil only when the incoming beam is "on". In other words, the idea is to run the CW linac with pulsed beam, albeit beam that is pulsed at a high frequency. If the average current during the pulses is 10 mA and the macroscopic average current is 1 mA, then the probability of a circulating proton hitting the foil might be reduced by about an order of magnitude by this means.

Longitudinally Segmented Stripping Foils: The second idea is to take advantage of the facts that the optimum stripping foil thickness for a multi-GeV beam is about 600 μg/cm^2 and that 200 μg/cm^2 thick stripping foils have proven to be quite durable. Thus the stripping foil can be segmented longitudinally into (say) 3 foils, so that there are six surfaces to dissipate the heat by radiation instead of two. The use of at least two foils has been advocated in the past to mitigate the effects of any “pinholes” in the foils.

Rotating Stripping Foils: The third idea is to rotate a circular foil rapidly, with an annulus having a radial extent of about 1 cm exposed in one corner of the aperture. That will spread out the energy deposition over an effective area of several square cm. Mechanical concepts for mounting and supporting such a rotating foil are being developed.

In-ring Debuncher Cavities that also Decelerate: The fourth idea is a so-called in-ring debuncher. Conventionally, debunching cavities are located after a long drift downstream of the linac to reduce the momentum spread of the linac beam before it enters the ring. It is possible that such cavities could instead be located in the ring itself, almost a full turn downstream of the injection region. If they are operated in such a way as to decelerate the incoming beam as well as to rotate it in longitudinal phase space, and if the foil is located in a dispersive region, then this can also reduce the probability that circulating beam strikes the foil on subsequent turns. If the RF frequency of the debunching cavities is not an integer multiple of the revolution frequency, then they will not form buckets that would capture the beam. Simulation will show whether the quasi-random kicks on subsequent turns are tolerable. With luck, they may serve to stabilize the beam rather than to disturb it.

Conclusions

We have presented a concept of a multi-MW CW linac with energy up to 8 GeV that could serve as a natural upgrade to the 3 GeV CW SRF Project X linac that is now under active consideration. We have shown that injection of 1.5×10^{14} particles in 100 ms in the Recycler can be done using conventional foil stripping, keeping the foil temperature below 1800K. Four new concepts were presented that may allow injection of very large numbers of turns from a CW linac into a proton accumulation ring. The accumulated proton beam can then be transferred to another ring where the intense bunches are shortened by a rotation in longitudinal phase space and targeted to create intense pion and muon beams for a neutrino factory and/or a muon collider.

References

[1] Fermilab Project X http://projectx.fnal.gov/

[2] C. Ankenbrandt, “Accumulation and Bunch Rotation Schemes”, Workshop on Applications of High Intensity Proton Accelerators, October 19-21, 2009, Fermi National Accelerator Laboratory, Batavia, IL, USA. http://conferences.fnal.gov/App-Proton-Accelerator/index.html