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Summary Report of H- Injection Session II

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Summary Report of H^- Injection Session II

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1 Introduction

There are 8 presentations in this session:

1. Y.Y. Lee, H^- injection at AGS booster and SNS
2. D. Olsen, Space charge issues in H^- ring injection
3. C. Prior, H^- injection for the European Spallation Source
4. M. Popovic, H^- injection at FNAL and muon collider
5. H. Schönauer and E. Griesmayer, H^- injection and rf trapping for AUSTRON
6. P. Knaus, H^- injection for PS booster
7. H. Schönauer, H^- injection of SPL 2GeV beam into CPS
8. A. Jason, Electron-foil interaction

The transparencies of these presentations are available in the proceedings. We will select several topics to summarize the work reported in these talks.

2 Technical topics

2.1 Longitudinal painting

The ESS injects a mismatched beam with a momentum error. During the 1000 injection turns, the longitudinal phase space painting is done by ramping the momentum linearly so that the momentum error of the injected beam varies from 0-2 $\times 10^{-3}$ to 2-4 $\times 10^{-3}$. In the meantime, the rf frequency is steered to match the momentum change. At the end of the injection, one obtains a well-matched beam with large momentum spread.

The AGS booster also uses momentum ramp ($\dot{B} = 4$ T/s) for the injection painting. One interesting thing is that it is found that partial painting (*i.e.,* the chopped beam injected into the right part of the bucket instead of filling the whole bucket length) gives a beam with better quality. This is because the synchrotron oscillation will give rise to a hollow beam in the bucket, which means a more uniformly distributed beam along the longitudinal axis.

In the study of the SNS injection, it is claimed that the linac beam needs to have large momentum spread ($\sigma_E = 4$ MeV for an injection energy of 1 GeV) in order to get a uniform particle distribution in the longitudinal space. Meanwhile, it is also required that the injection errors must be small. The SNS specs are 0.5° and 0.5% for rf phase and amplitude errors, respectively.

There was not enough time for the discussion of a 2nd harmonic rf system. This is important for: (i) reducing the rf trapping losses and, (ii) improving the bunching factor in the transverse plane. For stationary buckets, the bunching factor can be computed as a function of the voltage ratio $\delta = V_2/V_1$. For moving buckets, however, the best choice of δ is often determined by simulations. A common choice seems to be near 0.5.

2.2 Transverse painting

The ISIS uses the falling side of the $B(t)$ curve and large dispersion in the injection region to paint the beam in the horizontal plane. The advantage is no additional hardware needed for painting. The vertical painting is done simply by a steering magnet, because the ISIS foil has a large vertical dimension.

Another way for transverse painting is by using bump magnets. This method sweeps the closed orbit while keeping the injection point fixed. For example, in the IPNS Upgrade design, the four orbit bump magnets for H^- injection are each individually powered. Therefore, the bumped orbit can vary during the injection period. This is also the method used by the SNS. It has four bump magnets in each plane, which makes the injection scheme flexible. The KEK PS booster, on the other hand, employs two fast bump magnets to sweep the closed orbit. These magnets are in addition to the regular 4 orbit bump magnets for H^- injection, which have fixed field strength during the injection.

The simplest "painting" is realized at the CERN PS. It makes use of the fact that the fractional betatron tune Q_x is close to 1/4. Thus, a 4-turn painting can automatically be done in the horizontal plane with no need of any special hardware.

One issue that needs further discussion is the "brush" size for the painting. Because the transverse emittance of the circulating beam is much bigger than that of the injected linac beam, one would ask if it is necessary to require a small emittance of the linac beam. The answer is probably yes. One reason is that a large size injected beam would mean large number of hits on the foil, which could lead to heating problem.

2.3 Foil physics

The choice of material and thickness is an important issue in foil design. A common material for the foil is carbon, which has high melting temperature. The diamond-coated graphite has excellent vacuum property and does not generate dust. The foil thickness is a more complicated issue. A thicker foil would increase the stripping efficiency, but it would also create heating and emittance dilution problem. Moreover, a thicker foil also implies more intrinsic injection losses due to Coulomb scattering and nuclear reactions. Therefore, one needs a trade-off study.

Both analytical and numerical methods are available for temperature rise ΔT and emittance dilution $\Delta\epsilon$ calculations. For instance, in the case of 2 GeV H^- beam injection into the CERN PS, the results of ΔT and $\Delta\epsilon$ as a function of the foil thickness are presented.

When the H^- beam is injected into an accumulator ring (*e.g.,* the ESS and SNS), a lattice dipole can be used to bend the H^- beam and proton beam toward opposite directions. The foil is placed inside the dipole. The ESS chooses 0.177 T for this dipole so that the $n \geq 5$ Stark states will be stripped magnetically whereas the $n \leq 4$ states won't. The SNS uses a

0.31 T dipole field to strip $n \geq 4$ states. It is found that the position of the foil is important for reducing the fraction of $n = 4$ and 5 states lying outside the acceptance.

One must have H^0 and H^- dump near the injection region. One may also want to consider a device to collect electrons. The ESS placed a water cooled copper and graphite collector right after the foil. The dipole field bends the electrons that will then be dumped on the collector. The PSR has no place for such a collector. But it suffers severely from the so-called *e-p* instability. Therefore, an electron collector at the injection region is desirable. The following method is proposed for the PSR: to place a 6.5 cm radius circular coil above the stripping foil and drive 7 kA current into the coil. This coil will generate multipole magnetic fields near the beam center. The electrons will undergo a downward spiral motion and eventually hit the magnet surface.

The ESS is also interested in another stripping scheme by using a laser beam. (See the summary report of laser stripping session by R. Macek.) Therefore, it has two lattice designs. One is the baseline design that employs a foil, another is a racetrack type lattice that can accommodate both foil stripping and laser stripping schemes.

2.4 Simulations

Injection simulation is an important part of the design study. The ESS uses TRACK1D and TRACK2D, both written by C. Prior, for longitudinal and transverse simulations including space charge effects. The results are widely accepted. The SNS has spent a considerable effort to improve the code ACCSIM. The bench comparison with TRACK1D gives good agreement. It is also compared with the beam profile measurement data at the PSR. At a beam intensity of 3×10^{13}, when the space charge is neglected, the simulation gives a strange double-hump profile in the vertical plane. However, when the space charge is included, the double-hump disappears and the simulation agrees well with the measurement.

The SNS also uses simulation to study halo formation. Its definition of the halo is those particles of which the emittance is larger than 180 π mm-mrad. The halo formation could be due to parametric resonances. One interesting finding in the SNS simulation is that the halo has a strong dependence on the bare vertical tune. At certain tune the halo reaches a peak, at some other tune the halo becomes zero. The reason is unknown.

Several other codes, such as LONG1D (developed at TRIUMF) and ESME (developed at Fermilab), are also used for longitudinal injection simulations. P. Knaus presents his own code, which can simulate the longitudinal dynamics of a linac beam with micro-bunch structures, and applies it to the H^- injection into the CERN PS from a future 2 GeV superconducting proton linac (SPL).

2.5 Other interesting topics

2.5.1 AUSTRON

The AUSTRON uses a 50 Hz resonant power supply. The simulation shows 10.2% particle losses during rf trapping and early acceleration. However, when a dual-frequency (33 Hz + 100 Hz) Praeg circuit replaces the 50 Hz single resonance circuit, it is found the loss is reduced to 0.48%. The reason is not clear. (Note: Although Praeg's circuit was proposed in 1983, it has not yet been applied to any existing machines.)

Another feature about the AUSTRON is that it consists of two rings: a rapid cycling synchrotron ($h = 1$) at 50 Hz and a storage ring ($h = 4$) at 10 Hz. The latter can accumulate

4 bunches from the former and, thus, addresses different needs of the users community (lower intensity at higher repetition rate or higher intensity at lower repetition rate).

2.5.2 Proton driver and muon collider

The proton driver under design at Fermilab is a high intensity rapid cycling synchrotron (1×10^{14} protons per cycle at 15 Hz). Its main purpose is to serve the high energy physics (HEP) community. As a comparison, most other high intensity proton machines serve the nuclear physics (NP) community. What this means is that, unlike in the past when the HEP was mainly interested in high brightness beams for high luminosity, high intensity beams will be in demand by the HEP as well. In the case of the proton driver, it will generate highly intense muon beams, which can be used either for collision (in a muon collider) or for neutrino sources (in a muon storage ring).

3 Conclusions

The H^- injection was invented many years ago and has since been successfully applied in many machines over the last decades. The challenge to the high intensity machines is how to reduce the injection loss, which is usually the major part of total beam losses in a machine. Painting, both longitudinal and transverse, is an effective way to reduce the space charge effects and to minimize losses. RF capture of a chopped beam also gives better efficiency than adiabatic capture. To employ a 2nd harmonic rf system to flatten the rf bucket shape is another commonly used scheme. To compensate the capacitive space charge impedance by an inductive insert could be a new venture, but which is not discussed at the workshop due to time limitation. The foil physics is well understood. Simulations seem to be able to include all the important effects in it, including the space charge.

The general feeling is that we are in a good position concerning H^- injection studies. Although there remains a number of design issues, the knowledge, experiences and tools in our hand should be able to address each of them properly.

4 Acknowledgements

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