BASELINE DESIGN FOR A BETA-BEAM NEUTRINO FACILITY

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Abstract

The term beta-beam has been coined for the production of pure beams of electron neutrinos or their antiparticles through the decay of radioactive ions circulating in a storage ring. The neutrino source itself consists of a high-energy storage ring (gamma ~150), with long straight sections in line with the experiment(s). The radioactive ions (^{6}He and ^{18}Ne) will be produced in an ISOL type target system. Due to the short life times of around 1 s at rest, the beam needs to be accelerated as quickly as possible. For this a staged system of accelerators is proposed. The chain starts with a linac followed by a rapid cycling synchrotron for acceleration up to ~300 MeV/u. For further acceleration the existing PS and SPS machines are used. Finally, after acceleration to SPS top energy, the ions are transferred to a decay ring where they are merged with the existing bunches through a longitudinal stacking procedure. The baseline design of the beta-beam facility will be presented together with its major problems. Potential solutions to the latter will be discussed.

INTRODUCTION

The proposed beta-beam facility[1] can be divided into two parts: a low-energy part stretching up to 100 MeV/u and a high-energy part for further acceleration and ion stacking and storage in a decay ring, which serves as the neutrino source (see Figure 1). This division is logical as the low-energy part corresponds to the requirements for an ISOL-type radioactive beam factory as proposed and promoted by the European nuclear physics community. The high-energy part, serving the neutrino physics community, would be one of several users of such a radioactive ion beam facility and would consequently share the cost and operation of the low-energy part with other physics applications.

The radioactive ions ^{6}He and ^{18}Ne will be produced in an ISOL system using the proposed Superconducting Proton Linac (SPL) as a driver. The ions will then be fully stripped, bunched and accelerated by a linac to approximately 100 MeV/u. Further bunching will be achieved by multi-turn injection into a Rapid Cycling Synchrotron (RCS), followed by acceleration to 300 MeV/u before injection into the CERN Proton Synchrotron (PS). The beam will then be accelerated in several bunches to PS top energy, transferred to the Super Proton Synchrotron (SPS) and accelerated to the desired top energy. Finally, the ions will be transferred to the decay ring where they will be merged with the already circulating bunches through a longitudinal stacking procedure.

Several bottlenecks exist in this process, not least the bunching at low energy, space charge limitations in PS and SPS, decay losses along the accelerator chain and the longitudinal stacking procedure at high energy in the decay ring. In this paper, the problems encountered are discussed and some potential solutions are outlined.

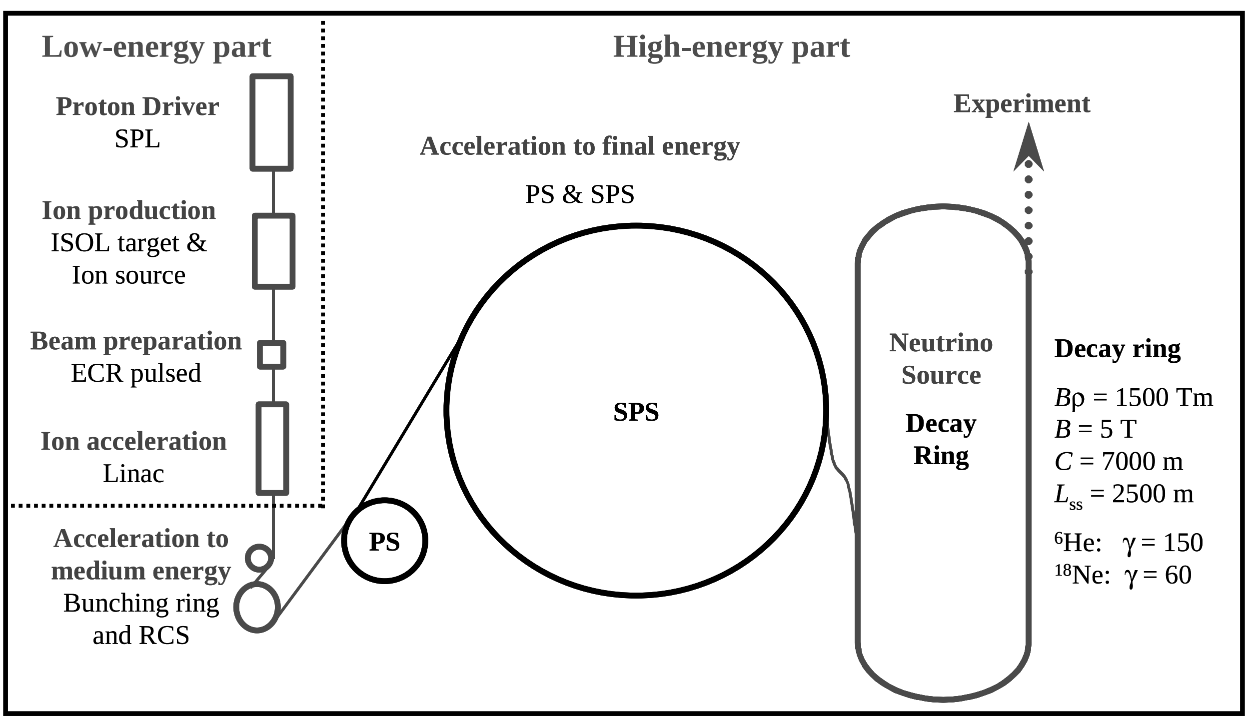

Figure 1: Beta-beam base line design, partially using existing CERN accelerator infrastructure.

ION PRODUCTION

The flux at the detector depends on the average energy of the neutrinos at rest as this determines the focusing of the neutrino beam. A further constraint is set by the decay losses in the accelerator chain; these increase with shorter lifetimes. Another aspect to consider is the decay products that could create long-lived contamination in the low-energy part. Together these considerations suggest two isotopes of particular interest: 6He, giving electron anti-neutrinos, and 18Ne for neutrinos[2].

Both species can be produced in large quantities by the so-called ISOL method. The helium isotope is best produced in a beryllium target using a very intense primary proton beam of a few GeV impinging on a so-called neutron converter. For the neon isotope, spallation in a MgO target with a less intense proton beam hitting the target material directly is the method of choice. Due to the use of converter technology, typically ten times more helium than neon isotopes can be produced.

IONIZATION, BUNCHING AND PRE-ACCELERATION

The ions can be transported away from the ISOL target directly in gas form since the chosen elements are noble gases. Alternatively, a high efficiency (for noble gases) mono-charge ECR source[3, 4], close to the target, can be used to transport the singly charged ions using classical beam transport. In either case the beam has subsequently to be ionized and bunched for further acceleration in the injector chain.

Efficient bunching (<20 μs pulse length) and full stripping of a high-intensity beam can be achieved using a high-frequency 60 GHz ECR source[5]. While such a system does not exist today theoretical calculations are very encouraging. Furthermore, the required components are expected to be available soon and the rf generator is already available off the shelf, so that a first feasibility test could be envisaged in the near future.

Once fully stripped, the ions are first accelerated in a linac to increase their lifetime. The acceleration of high-intensity radioactive ion beams to ~100 MeV/u using a linac has already been studied within the EU-financed study EURISOL[6]. This study is planned to continue as design study within the 6th EU framework programme.

ACCELERATION

Further acceleration of the ion beam can be achieved using the PS and SPS machines of the CERN accelerator infrastructure. However, space charge effects at injection dictate a beam energy of at least 300 MeV/u before the intensities required for the beta-beam can be digested by the PS machine. This constraint, together with the requirement for bunches much shorter than those provided by the linac, means that an additional stage of bunching and acceleration is required. The most promising scenario involves multi-turn injection of the linac beam into a (new) RCS, followed by bunching, rapid acceleration and transfer to the PS. This procedure is repeated until all PS rf buckets are filled (8 or 16 bunches). Then the beam is accelerated to top energy and sent to the next CERN synchrotron, the SPS.

Injection into the SPS is an established space-charge bottleneck[2]. so the bunches must fill the maximum available transverse aperture. This requires a controlled transverse emittance blow-up that could be achieved by introducing foils in the transfer line from PS to SPS. It is also foreseen to keep the bunches as long as possible to decrease the bunching factor at SPS injection, but this requires a new 40 MHz rf system for the early part of acceleration until the standard 200 MHz high-frequency system can take over near transition.

STACKING

The energy of the beta-beam neutrinos will be in the range of atmospheric neutrinos. As the time structure of the neutrino beam mirrors that of the ions circulating in the decay ring, the beam has to be concentrated in as few and as short bunches as possible to permit efficient background suppression in the detector. Four bunches, each 10 ns long, were chosen for the baseline design.

The decay ring acts an accumulator for the bunches delivered by the injector chain because the lifetime of the highly relativistic stored ions (~100 s) is more than an order of magnitude longer than the cycling time of the injectors (~8 s). Together with the requirement for few and short bunches this means that stacking in the decay ring is required. Classical techniques, based on electron or stochastic cooling, are excluded because the cooling times would be far too long.

A new scheme for longitudinal stacking has been proposed for the beta-beam[2]. Asymmetric bunch pair merging employs a dual-harmonic rf system to combine adjacent bunches in longitudinal phase space such that a fresh, dense bunch is embedded in the core of a much larger one with minimal emittance dilution. The fact that only the central part of the resident bunch is affected results in a net increase of the core intensity. The surrounding "older" ions are pushed out towards the bucket separatrix, where the "oldest" ions will eventually be lost. Asymmetric bunch pair merging has recently been demonstrated in the PS[7].

To prepare the merging, each new bunch must be injected in a neighbouring bucket to an existing bunch in the stack, but this is excluded using conventional kickers because of the short rise-time that would be required. An alternative scheme exploits the fact that the stack is located at only one azimuth in the decay ring and that the revolution period is relatively long. The new bunches are off-momentum and injected in a high dispersion region on a matched trajectory. This allows a full turn for a collapsing injection bump to bring the off-momentum orbit inside the machine at the entry point of the beam. Subsequently, each injected bunch rotates a quarter of a turn in longitudinal phase space until the initial conditions for bunch pair merging are met and stacking can proceed.

INTENSITY

The equilibrium number of ions stored in the decay ring (assuming an ideal stacking efficiency) just after a fresh injection will be

$$N_{tot} = N_{bunch} \frac{1}{1 - 2^{-\frac{T}{(\gamma T_{half})}}},$$

where N_{bunch} is the number of ions injected into the ring every T seconds and T_{half} is the half-life at the corresponding relativistic gamma[1]. The neutrino flux at the detector is proportional to the circulating beam current and will therefore only depend on N_{bunch} and the injector cycling period T, assuming that the stored ions are only lost through beta decay.

Starting from the production rates for ^{6}He and ^{18}Ne at the ECR source, and taking into account only beta-decay losses, the beam intensities along the accelerator chain can be calculated. Table 1 lists the estimated production rates at the source, the beam intensities at extraction from the synchrotrons in the injector chain and the average circulating beam intensities in the decay ring for the beta-beam baseline scenario. 16 Hz operation of the RCS and 8 s cycling time of the SPS is assumed. The number of batches required to fill the downstream machine is also indicated.

Table 1: ^{6}He and ^{18}Ne ion intensities along the accelerator chain for the beta-beam baseline scenario. (Only beta-decay losses are taken into account.)

Machine	**^{6}He ions extracted**	**^{18}Ne ions extracted**	**Batches**
Source	~2×10^{13} /s	~8×10^{11} /s	dc
RCS	1.0×10^{12}	4.1×10^{10}	16
PS	1.0×10^{13}	5.2×10^{11}	1
SPS	9.5×10^{12}	4.9×10^{11}	∞
Decay Ring	2.0×10^{14}	9.1×10^{12}	-

Experience from operation of high intensity ion beams at CERN suggests that, in addition to the decay losses quoted in Table 1, around 50% of the beam will be lost along the accelerator chain. Applying this rule of thumb shows that in the decay ring typical average intensities of 1×10^{14} for ^{6}He and 4.5 10^{12} for ^{18}Ne can be expected.

DECAY LOSSES

The most important difference between the acceleration of stable ions and radioactive ions are the beam losses caused by radioactive decay during the acceleration process, especially at low energies. The isotopes proposed for the beta-beam have been chosen such that no long-lived activity is left to contaminate the accelerator chain.

A first study based on the simulation of ion losses in the decay ring reveals that the induced dose rate in the arcs is limited to 2.5 mSv/h after 30 days of operation and 1 day of cooling down time[8]. It was also shown that the induced radioactivity in ground water will have no major impact on public safety. The study demonstrates that, except in the PS, the decay losses in the injector chain will be below the commonly accepted power limit of 1 W/m for "hands-on" maintenance[9]. The analysis of losses in the PS and their consequences clearly deserves more attention. Obviously, the losses in the decay ring are even higher and special care will have to be taken in its design to deal with this problem. Table 2 summarizes the average decay losses along the accelerator chain for helium operation. For neon, the figures are typically one order of magnitude smaller.

Table 2: Average beam losses along the accelerator chain for ^{6}He operation. (Only beta-decay losses are taken into account.)

Machine	**Loss power**	**Losses/length**
Source	N/A	N/A
RCS	~11 W	60 mW/m
PS	760 W	1.2 W/m
SPS	3.6 kW	0.4 W/m
Decay Ring	157 kW	28 W/m

CONCLUSIONS

The baseline design for a beta-beam neutrino facility using the existing CERN accelerator infrastructure is presented. The design is mainly based on available technology with some conservative extrapolations. Beam losses and radiation aspects are clearly identified as major concerns that will require special attention during the detailed design work.

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