# Future options for the beta-beam with a focus on production issues

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**Abstract.** Many ideas have been brought forward for how to evolve the beta-beam concept since it first was proposed in 2002 [1]. The focus of most proposals have been on the limitations on the production side and how these problems can be overcome. Other proposals have been made for higher energy beta-beams and how to produce monochromatic neutrino beams from electron capture decaying nuclei.

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## INTRODUCTION

The beta-beam concept for the production of a high intensity neutrino beam for neutrino oscillation physics was first proposed by Piero Zucchelli in 2002 [1]. A first study of the feasibility of such a facility at CERN using the existing proton injectors for the Large Hadron Colliders as injectors was done in 2002 [2]. This study was taken as the baseline for the EURISOL design studies [3] beta-beam task which will deliver a conceptual design report in 2009. In this study the radioactive ions ($^{6}$He for anti-neutrinos and $^{18}$Ne for neutrinos)are produced with the ISOL method using thick targets which are irradiated with 1 GeV protons. For $^{6}$He a cooled neutron converter is used a primary target. This converter can take large beam intensities of the primary ionizing proton beam transforming them into neutrons which induces a nuclear reaction in a surrounding BeO target in which $^{6}$He is produced. For $^{18}$Ne there is no such suitable neutron channel to use so a MgO target has to be directly irradiated with protons to produce $^{18}$Ne directly from spallation. As the cross section for this spallation channel is smaller than the neutron induced reaction channel used for $^{6}$He production and as the MgO target only can handle a limited amount of proton beam there is a shortfall in the production of $^{18}$Ne with a factor of 20.

## NEW IDEAS FOR PRODUCTION AND ACCUMULATION

### Direct production

Merging nuclei to form new nuclei has been the ambition of nuclear physicists from the very early days of nuclear discoveries. It only became possible with the birth of accelerators as no nucleus will merge spontaneously (at room temperature) due to the coulomb forces which keeps the two positively charged bodies well apart. The simplest way to merge nucleus is to accelerate one nuclei and merge it with another nuclei in a target at an energy high enough to overcome the coulomb barrier but low enough to not destroy the newly formed nuclei through spallation or fission. Nucleus formed in this energy interval is referred to as compound nuclei, cross section for this process is usually large and can often be measured in 10-100 mbarns. The main limitation is that it is hard to form any nucleus far away from stability as the starting point usually is two stable nuclei with roughly equal number of protons and neutrons. Consequently, the new nucleus will also have roughly the same number of neutrons as protons which will position it somewhere close to the other stable nuclei. However, for beta-beams the favored isotopes are close to stability so this production method is a possibility.

$^{18}$Ne can be formed in the reaction

$$^{16}O(^{3}He,n)^{18}Ne$$

The process has been studied in detail [4] and is usually referred to us direct production. The cross sections are indeed large for the reaction above but to produce a sufficient number of isotopes for a beta-beam facility 120 mAmps of primary $^{3}$He beam at some 13 MeV of total energy is required. This is far beyond what has been done so far and would require the development of a new concept for the target and the low energy beam dump. In direct production facilities the beam is usually taken directly on a thick target which also serves as beam dump. For the high intensity beam required for a beta-beam production facility the target would be destroyed if it also had to cope with the full beam heating from the stopping $^{3}$He ions. To overcome this problem the target is made sufficiently thick to maximize the production but still thinn enough to let through ion beam so that it can be dumped in e.g. a liquid metal cooled beam dump. If the operating direct production facility in Louvain-La-Neuve in Belgium at the Cyclotron laboratory is taken as the reference, the target of e.g. MgO would have to be 60 cm in diameter to keep the power density at the level of the one used today. The proton beam would have to have to de-focused an wobbled over the target but providing that a sufficiently intense $^{3}$He beam can be produced this scenario seems feasible.

## Production ring

In the previous section the direct production method was discussed. In direct production facilities the part of the beam which doesn't produce a new isotope through nuclear reaction is simply lost in a beam-dump. To avoid this "waste" of useful ions the ions could be re-circulated, re-accelerated and sent through the target again. If the target is made sufficiently thin the ions can be made to pass at the optimum energy for the desired reaction channel each time assuring that the majority of ions that react will produce a "useful" ion. The limiting factor seems, at a first glance, to be the angular straggling which eventually would make the re-circulated beam to "large" to handle. However, it was recently shown [5, 6] that the combination of energy loss in all directions in the target with re-acceleration in one direction in the cavity will result in beam cooling. In [5] a wedge shaped gas target is used in a dispersive region of the ring which adds longitudinal cooling as particles with higher energy can be made to pass through a thicker part of the target compared to those that has lower energy. Furthermore, the use of a gas target makes it possible to handle a large amount of beam power. The produced ions are collected with a second target consisting of e.g. tantalum foils contained in a box with a hole through the center in which the circulating beam can pass the target without interacting with the foils. The produced ions will be thermalised and neutralized in the foil, diffuse to the foil boundary as a neutral gas and through random walk in an effusion process find the exit of the box where they are re-ionized and extracted for bunching and further acceleration. The proposed reaction channels are $^{7}$Li(d,p)$^{8}$Li and $^{6}$Li($^{3}$He,n)$^{8}$B, both assuming a gaseous target and inverse kinematics (projectile lighter than target). The isotopes $^{8}$Li and $^{8}$B emits higher energy neutrinos than $^{6}$He and $^{18}$Ne and could be used for a beta-beam facility with a longer baseline than the the proposed EURISOL beta=beam facility. In [6] a Fixed Field Alternating Gradiant (FFAG) accelerator with large longitudinal acceptance is used to manage the beam without any longitudinal cooling. For both machines the beam is injected partially stripped and the energy of the circulating ions are kept high enough to assure that all of them emerge full stripped after the target.

The production of $^{8}$B and $^{8}$Li in "normal" kinematics with $^{6}$He and Deuterium as projectiles and a liquid Lithium target of enriched $^{6}$Li or $^{7}$Li has been proposed in [7] in which also a full six dimensional analysis of the cooling process is presented. This "direct" kinematics would require a very thin liquid lithium film target. The thin liquid Li film could be produced with a high pressure jet directed at an angle towards a flat deflector as proposed and studied by [8]. The larger separation in magnetic rigidity between projectile and produced ion in this kinematic could permit beam collection off-axes from the circulating beam with the help of e.g. a wien filter after the target. If the circulating beam is deviated, the beam has to be brought back to the nominal closed orbit with a "reversed" Wien filter further downstream. The physical separation of beam and produced ions will also reduce the background of beam particles deviated to large angles - through simple (single) Rutherford scattering in the target - in the collection device and it would increase the total efficiency of the collection as there is no need for a "hole" in the collector.

# OTHER OPTIONS

## Accumulation at low energy

The magnetic field in a synchrotron has to be increased during acceleration which make it impossible to accelerate a continuous beam. New particles can only be injected once the magnets are back to the field corresponding to the injection energy. The time between two injections can be as long as several seconds for a high energy synchrotron s such as the PS and SPS at CERN or as short as 20 milliseconds for a rapid cycling synchrotron s such as the ISIS at Rutherford labs. The combination of synchrotrons proposed for the earlier discussed CERN beta-beam facility will induce a total dead-time of up to almost ten seconds for the production side. The simplest way to make use of this lost production time is to accumulate the produced ions before further acceleration. The accumulation can in principle be done at rest in some form of electromagnetic trap e.g. an ECR source with a long retention time. However, the more common solution is to use a low energy storage ring with a beam cooler to accumulate and cool the ions. Such a scheme is used for the CERN Large Hadron Colliders (LHC) ion physics programme. The acceleration time is used to accumulate and cool intense and small bunches of lead ions to achieve a reasonable luminosity (collision event rate) in the LHC detectors. A study has been done for the beta-beam in a similar set-up [15]. The main difference to the

**TABLE 1.** Some possible decay ring options for a different Lorenz gamma of $^6$He. The decay ring arcs are for all cases considered to be completely filled with dipoles.

| Gamma | Rigidity [Tm] | Ring length* | Dipole Field† |
|---|---|---|---|
| 100 | 935 | 4197 | 3.1 |
| 150 | 1403 | 6296 | 4.7 |
| 200 | 1870 | 8395 | 6.2 |
| 350 | 3273 | 14691 | 10.9 |
| 500 | 4676 | 20987 | 15.6 |

* Assuming a fixed field of 5 T and a single straight section of 36% of the circumference

† Assuming a arc radius of 300 m and a decay ring length of 6885 m

LHC type accumulation ring is that the ions are radioactive and will decay, it is easy to show that only makes sense to accumulate for up to some three half lives in total. However, the gain in intensity can be up to a factor of five which can be significant for isotopes which are difficult to produce.

## Higher Lorenz gamma

Several physics reach studies have been done for a beta-beam with higher energy than the one proposed in [2]. The consequences for the machine are important, not at least the fact that the existing accelerators at CERN which formed an essential part of the accelerator complex in [2] only can accelerate $^{18}$Ne to a gamma of 250 and $^6$He to a gamma of 150. There are also consequences for the focusing of the neutrino beam which to first order is inversely proportional to gamma, $\Theta \approx 1/\gamma$, where $\Theta$ is forward opening angle of the neutrino beam. For the decay ring the most important differences are a) that the life time will be longer due to increased time dillitation which will influence the stacking efficiency and the annual rate at the end of the straight section and b) that the decay ring will have to be larger or the dipole magnets more powerful to cope with the increased magnetic rigidity of the radioactive ions. Assuming a perfect arc completely filled with dipoles the length of the decay ring can be calculated for different gamma, see Table 1.

## Barrier buckets in the decay ring

At neutrino energies corresponding to atmospheric neutrinos it is very important to keep the duty factor low to permit suppression in the experiment of atmospheric background. The result is that only a fraction of the capacity of the decay ring can be efficiently used as only a limited number of injected pulses can be accumulated in a single bunch (see [14]). To make full use of the storage capacity of the decay ring the beam could be kept un-bunched in the decay ring. The problem with an un-bunched beam which fills the full circumference of the decay ring is that it is impossible to inject without disturbing the beam in the ring. A possible solution is to use RF cavities as barriers for the unbunched beam so that an "injection hole" is created for the new beam from the injectors. This kind of longitudinal beam manipulation in a storage ring is referred to as "barrier buckets" and has been tested for high intensity proton beam for the AGS in Brookhaven [9]. The consequence of this is of course that the neutrino beam will have no real duty cycle. The injection hole in the beam will create some empty time slot in the neutrino beam which maybe could serve as a reference for background estimates in the detector.

## Acceleration of partly stripped ions

Proton rich nuclei can also decay via electron capture and the neutrino emitted will in this decay mode be mono-energetic as there is no positron emitted simultaneously. The electron capture process is often the only possible decay mode close to stability where there isn't sufficient energy available in the decay to form the required electron-positron pair for $\beta^+$ decay. The life time of most isotopes decaying with electron capture is generally long which makes it difficult to use this decay mode for the production of a mono energetic electron neutrino beam [10, 11]. The exception are some exotic rare-earth isotopes in which the decay to the ground state in the daughter nuclei is highly hindered so that the electron capture process to a higher laying excited state can compete. The equivalent process on the neutron rich side is bound beta-decay in which the emitted electron is captured in an atomic orbit and the anti electron neutrino is emitted with a definite energy. The branching rate for this process in generally very small but there has been a proposal to use it in combination with electron capture decay for a CP-violation measurement [12].

A definite requirement for electron capture decay is that the nuclei only is partly stripped so that there is an electron available for capture. The acceleration of partly stripped nuclei is fairly straight forward [13]. The main difference compared to accelerating fully stripped radioactive ions is that the loss (or gain) of electrons will change the mass-to-charge ratio of the isotope which will cause additional losses. At high energy the likelihood to pick-up and electron is vanishingly small. However, the likelihood of loosing an electron will, expressed in an equivalent half life, be in the order of minutes in a ring with a modern ultra high vacuum system. The annual rate for electron capture decaying nuclei is modified by the "vacuum half life" which will compete with the radioactive decay in the straight section but without producing any neutrinos.

The isotope $^{152}Tm$ with a half-life of 8 seconds is one the shortest living nucleus with an important part of the decay going via electron-capture. This is still a half-life 5 times longer than $^{6}$He which will have a negative influence on the annual rate for the same amount of isotopes stored in the decay ring. This rather heavy nucleus with 69 protons (Z=69) would typically have a charge state of above 50 at higher energies. The combination of the high charge state, the longer half-life and the electron stripping losses will require a large number of ions to be accelerated and stoored in the decay ring to keep the annual rate high. For this specific case the tune shift in the CERN acceleratrors PS and SPS would peak well above 0.25 to keep the annual rate at $10^{18}$ electron neutrinos at the end of one straight section for a year of $10^{7}$ seconds.

## Conclusion

New proposals for production of isotopes of interest for beta-beam with either direct production at low energy or with the use of production rings have been made and look promising. Detailed studies of target physics, machine physics and engineering aspects of building such production facilities should be done to determine the performance of each proposal. It is too early to state if a solution has been found to the shortfall in $^{18}$Ne production observed for the EURISOL beta beam facility but the new ideas presented here are promising should definitely be further studied. The proposal to use an accumulation ring at low energy to gain in efficiency for any beta-beam facility in which the ions can't be accelerated continuously represent an important improvement. The beta-beam concept is very rich an opens up many possibilities such a high gamma beta-beams, high Q-value beta-beam and monochromatic neutrino beams form electron capture decay and beta bound decay. Al these ideas deserve further studies.

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