BETA BEAMS FOR PRECISION MEASUREMENTS OF NEUTRINO OSCILLATION PARAMETERS

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Abstract

Neutrino oscillations have implications for the Standard Model of particle physics.The CERN Beta Beam has outstanding capabilities to contribute to precision measurements of the parameters governing neutrino oscillations. The FP7 collaboration EUROnu (2008-2012) is a design study that will review three facilities (Super-Beams, Beta Beams and Neutrino Factories) and perform a cost assessment that, coupled with the physics performance, will give means to the European research authorities to make decisions on future European neutrino oscillation facilities. "Beta Beams" produce collimated pure electron (anti)neutrinos by accelerating beta active ions to high energies and having them decay in a storage ring. Using existing machines and infrastructure is an advantage for the cost evaluation; however, this choice is also constraining the Beta Beams. Recent work to make the Beta Beam facility a solid option will be described: production of Beta Beam isotopes, the 60 GHz pulsed ECR source development, integration into the LHC-upgrades, insure the high intensity ion beam stability, and optimizations to get high neutrino fluxes. The costing approach will also be described.

INTRODUCTION

Beta Beams produce pure ν_e or $\bar{\nu}_e$ beams by storing β emitting ions in a high energy Decay Ring [1]. The neutrino energy depends on the reaction Q-value and of the chosen relativistic boost of the isotopes stored in the Decay Ring. Beta Beam physics reach is limited by the number of charges that can be accelerated and stored in the accelerator complex, the neutrino energy and the neutrino beam divergence. The EUROnu collaboration (EC, FP7) [2] is now in its final phase; the project terminates in August 2012.

The Beta Beam facility studied within EUROnu is based on CERN infrastructure and machines and on existing technologies. The neutrino detector considered in the baseline setup using ^{6}He/^{18}Ne would be built in the Fréjus tunnel (France) 130 km from CERN. The main objective for the Beta Beam in EUROnu is to address the lacking isotope production [3], consolidate an overall acceleration scenario and to give a performance/cost analysis. The proposed solution to the lack of available isotopes, in particular ^{18}Ne, was to use an alternative isotope pair, ^{8}Li and ^{8}B, produced in a small production ring [4]. The two alternative layouts are shown in Fig. 1. The Decay Ring [5] should have a straight section length of $\sim$ 2700 m. The main bending magnet is a 7 T SC magnet. The use of a low energy SPL would be an advantage but a high intensity Linac is envisaged. The paper will emphasize latest developments and present status.

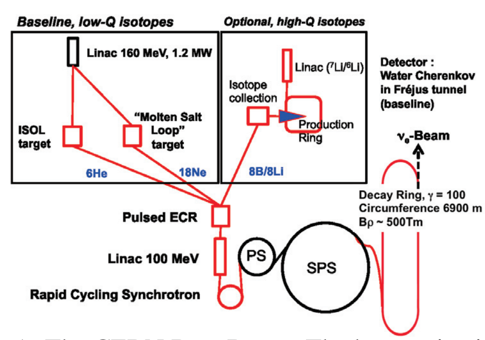

Figure 1: The CERN Beta Beam. The beta active isotopes are accelerated to the Decay Ring: ^{6}He/^{18}Ne (low-Q) with a detector in Fréjus (baseline) and optionally ^{8}Li/^{8}B (high-Q) with a detector at 700 km (Gran Sasso or Canfranc).

RADIOACTIVE ISOTOPE BEAMS

Two isotope pairs have been selected for Beta Beam studies in the CERN Complex : ^{6}He/^{18}Ne (Q-values of 3.5 MeV and 3.3 MeV) and ^{8}Li/^{8}B for $\bar{\nu}_e/\nu_e$ (Q-values of 13.0 MeV and 13.9 MeV), see Fig. 1.

Tests show that ^{6}He can be produced in sufficient rates with a beam power of 200kW (SPL, 2 GeV) [6]. A molten salt target has been proposed to produce rates of ^{18}Ne required for the Beta Beams project [7]. Proton beams close to 1 MW power, from an upgraded Linac4 at CERN, would

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impinge a circulating molten NaF-based eutectic to produce extracted rates of 1.0 10^{13} ^{18}Ne/s (Fig. 2). In this first proposal, the target material consists of an eutectic binary fluoride system NaF:ZrF_4(60:40 % mol.). Thermal stability tests show that ZrF_4sublimates at target operation temperatures, with sublimation rates that limit its use in a molten salt loop. As an alternative, the eutectic binary NaF:LiF system (39:61% mol.) is now tested online at CERN/ISOLDE[1] using a static target unit. The production and release of ^{18}Ne will be monitored accounting for the effects of temperature and proton beam impact, which strongly affects the release efficiency in molten targets. The results will contribute to the validation of a high power molten salt circulating loop.

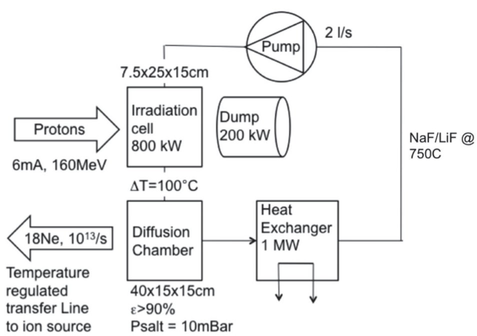

Figure 2: The molten salt loop to produce ^{18}Ne with an upgraded Linac 4 (CERN): 160MeV, 6 mA on average.

Production of ^{8}Li and ^{8}B with an internal target in a production ring [4] is one of the main research tasks in EUROnu. A circulating beam of ^{6}Li/^{7}Li produces the Beta Beam isotopes by repetitive traversals of a supersonic gas jet target, see Fig. 3. The target also serves as a stripper and an absorber for beam cooling. The ^{7}Li beam energy is 25 MeV and the energy loss over the target is 300 keV.

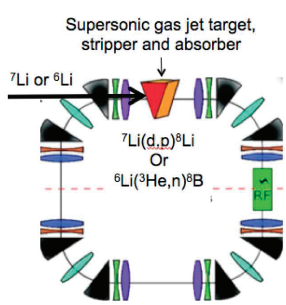

Figure 3: The isotope Production Ring.

A preliminary lattice design for the production ring (see Fig. 3) is available [8]. However, the proposed supersonic gas jet target [4] with a jet velocity of 2200 m/s (volume 4.3 m^3/s) has not yet a realistic design solution. An alternative could be to use the normal kinematics reaction with ^{3}He on liquid ^{6}Li targets [9]. Measurements of the efficiency of the collection device are being evaluated [10].

[1]Isotope Separator On Line-DEtector

The reaction ^{7}Li(^{2}H,p)^{8}Li has been studied at INFN and the University of Naples. The cross section for the ^{8}Li production is 90±18 mb at E_{lab}(^{7}Li) = 25 MeV and the angular distribution is of ^{8}Li is focused between 6 ° and 10 °. Cross section data of the ^{6}Li(^{3}He,n)^{8}B reaction found in literature do not agree. Measurements of the absolute cross section and the angular distribution of the neutrons emitted in the 6.0 MeV ^{6}Li(^{3}He,n)^{8}B reaction have therefore been performed (see Fig. 4). Cross sections are found to be higher than those in literature. However measurements with an impinging energy of 25 MeV (as proposed in [4]) would be necessary to confirm higher cross sections for the production ring setup (INFN-LNL, Legnaro, Italy).


Figure 4: The ^{8}B experiment. 8 Photo Multiplier Tubes cover neutron angles from 15 ° to 140 ° in the lab frame.

The presently estimated production rates of Beta Beam isotopes are summarized in Table 1. With some distribution of the specified runtime of 10 years, the production rates of ^{6}He and ^{18}Ne would be sufficient.

Table 1: The rate (r) extracted from the source (using different production methods (^{6}He estimated from experiments, for ^{18}Ne from experiments and calculations and rates for ^{8}Li and ^{8}B are estimated from calculations).

Isotope	**^{6}He**	**^{18}Ne**	**^{8}Li**	**^{8}B**
Prod.	ISOL(n)	ISOL	P-Ring	P-Ring
Beam	SPL(p)	Linac4(p)	d	^{3}He
I [mA]	0.07	6	0.160	0.160
E [MeV]	2000	160	25	25
P [kW]	140	960	4	4
Target	W/BeO	^{23}Na, ^{19}F	^{7}Li	^{6}Li
r [10^{13}/s]	5	0.9	0.1	0.08

The 60 GHz ECR source prototype has been assembled, its magnetic field has been measured at half intensity allowing a first 28 GHz operation, the experimental data show a good agreement with the simulations. The 60 GHz gyrotron is under assembly in Russia and will be tested in June 2012. The first beam experiments will be performed at 28 GHz in July 2012, and then, 60 GHz operation will be tested and characterized (see Fig. 5).

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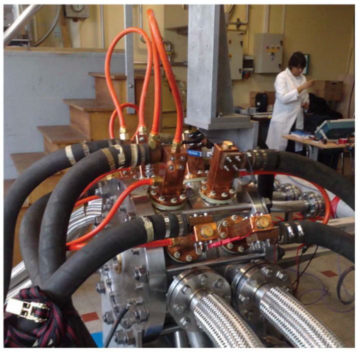

Figure 5: The source prototype under test

BEAM STABILITY AND INTENSITY MITIGATION

Small and intense bunches are required in the Decay Ring to get good physics reach: the number of ions in an SPS bunch for the ^{18}Ne beam is 2.9 $\cdot 10^{11}$ and the required DR bunches are 5 ns long with an intensity of 3.4 $\cdot 10^{12}$ (EURISOL Design Study [3]).This is a serious constraint in particular for the Decay Ring RF (beam loading) and beam stability conditions. However, recent results from neutrino oscillation experiments [11] show that it is possible to relax the requirements on the bunches in the DR and get stable beam behavior (Transverse Mode Coupling Instabilities, TMCI). The design of the Decay Ring, as described in the EURISOL Design Study [3], has also been adapted to be able to store higher intensities (γ-transition has changed from 27 to 18) [12]. Using octupoles showed no significant improvement of the number of ions possible to store (emittance blow up) [13]. A complete analysis including other collective effects in the Decay Ring is necessary.

Since in the SPS machine, contrary to the DR, the ions are accelerated, we have to investigate the beam stability along the acceleration cycle. TMCI have been studied partly for the SPS: with the present configuration the beam is not stable. Lower γ-transition in the SPS is not possible so new acceleration schemes to distribute intensities in the machines to better avoid instability conditions should be studied. The fact that space charge could have a favorable influence is presently investigated [14]. One of the difficult topics is how to pass γ-transition in the PS and in the SPS. The present existing optics without γ-transition for the LHC beams cannot be used for the Beta Beam.

STUDIES AND MEASUREMENTS IN THE PS AND THE SPS

The Beta Beam will be injected into the PS (2.0 GeV proton equivalent). Tune scans in the PS (2 GeV protons) without chromaticity correction have been performed to identify the dangerous lines and measurements with correction are ongoing to avoid vertical tails [15]. Measurements show that the ^{6}He beam (ΔQ_x,ΔQ_y)=(-0.22,-0.31) should survive and the ^{18}Ne beam (ΔQ_x,ΔQ_y)=(-0.28,-0.38) still needs more work (probably resonance compensation). Studies on Head-Tail effects are also needed as well as optimization of the bunch structure in the PS and the SPS (beam stability). Studies for radio-protection of the RCS, the PS and the Decay Ring have been carried out [3]. Within the upgrade studies of the injector complex radiation studies are done for the Beta Beam in the SS42 region of the CERN PS, near Goward Road. The conclusion is that dose rates for Beta Beams are lower by a factor 3 for ^{18}Ne and by a factor 16 for ^{6}He compared to full proton intensities. The energy deposition on the septum blade (SMH42) is 1.0 10^{-4} [GeV/cm^3/primary] for ^{18}Ne. The energy deposition on the blade of the septum SM16 is higher by a factor of 3.7 [16]. No show-stopper has been found, neither for radio-protection nor for the equipment.

COSTING AND COST DRIVERS, SAFETY

EUROnu will provide a performance/cost comparison using a single evaluation procedure of the 3 studied facilities as if implemented at CERN. However the resources available for the cost evaluation of the civil engineering only permits a very shallow estimation, not taking into account infrastructures, which will result in large errors in the estimations. Projections from existing projects will be used for the safety aspects.

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