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BETA BEAMS: AN ACCELERATOR BASED FACILITY TO EXPLORE NEUTRINO OSCILLATION PHYSICS

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Abstract

The discovery that the neutrino changes flavor as it travels through space has implications for the Standard Model of particle physics (SM)[1]. To know the contribution of neutrinos to the SM, needs precise measurements of the parameters governing the neutrino oscillations. This will require a high intensity beam-based neutrino oscillation facility. The EUROν Design Study will review three currently accepted methods of realizing this facility (the so-called 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 a decision on the lay-out and construction of the future European neutrino oscillation facility. "Beta Beams" produce collimated pure electron neutrino and antineutrino beams by accelerating beta active ions to high energies and letting them decay in a race-track shaped storage ring. EUROν Beta Beams are based on CERNs infrastructure and the fact that some of the already existing accelerators can be used. To use existing machines is a strong advantage for the cost evaluation, however this choice is also constraining the Beta Beams. In this article we describe recent work that has made the Beta Beam facility a solid option for neutrino production: new ideas and developments to produce and collect different Beta Beam isotopes, the 60 GHz pulsed ECR source development, the integration of Beta Beams in the upgrade program for LHC, work to ensure the very high intensity ion beam stability in the different machines, and optimizations of the decay ring to get high neutrino flux at a gamma boost of 100.

INTRODUCTION

Production of (anti-)neutrinos from beta decay of radioactive isotopes circulating in a race track shaped storage ring was proposed in 2002 [2]. Beta Beams produce pure ν_e or $\bar{\nu}_e$ beams depending on if the accelerated isotope is a β^+ or a β^- emitter. The neutrino energy depends on the reaction Q-value and of the chosen relativistic γ boost of the stored isotopes. Beta Beam physics reach is limited by the maximum number of charges that can be accelerated and stored in the accelerators, the neutrino energy and the neutrino beam divergence. The neutrino energy is given by $E_\nu \leq 2\gamma Q$ and the neutrino beam divergence by $\alpha = 1/\gamma$.

THE CERN BETA BEAM FACILITY

A Beta Beam facility, using the isotope pair ^{6}He/^{18}Ne and detector in the Fréjus tunnel (France) has been studied within the EURISOL Design Study [3]. The studied scenario is based on CERN infrastructure and machines and on existing technologies which is of interest to keep the cost of the neutrino facility low. The research on Beta Beams is continuing with EUROν within the European Framework Programme FP7 [4]. The objective is to address the lacking isotope production, 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 produced in a production ring, namely ^{8}Li and ^{8}B. The two alternative layouts are shown in Fig. 1. The produced isotopes are accelerated in an ion Linac after collection in a charge breeding ECR source [5]. The ionized isotopes then pass through a Rapid Cycling Synchrotron (RCS) [6], the CERN PS synchrotron and the last acceleration stage before the Decay Ring (DR) is the CERN SPS. The Decay Ring [7] would have a circumference of 6900 m and a straight section length of almost 2700 m. The main bending magnet is a 6 T superconducting magnet.

ISOTOPES FOR BETA BEAMS

Two isotope pairs have been selected for Beta Beams 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.

The CERN SPS allows a maximum γ-value of 150 (^{6}He) or 250 (^{18}Ne). The choice of energy, corresponding to a γ-value of 100, was made to optimize the physics reach at a

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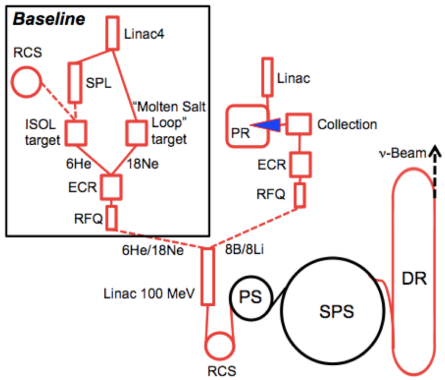


Figure 1: Layout of the CERN Beta Beam. Two beta emitting isotope pairs are considered: ^{6}He/^{18}Ne (low-Q) with neutrinos to Fréjus and ^{8}Li/^{8}B (high-Q) to Gran Sasso or Canfranc.

baseline 130 km from CERN where there could be a possibility to locate a Mton water Cherenkov detector, MEMPHYS, for astrophysics (LAGUNA study [8], in the Fréjus tunnel). Today's measurements and hints on values of some neutrino parameters may require further optimization of γ-boosts and preferred Q-values [9].

Production of Radioactive Beams for Beta Beams

Results from experiments show that ^{6}He can be produced in sufficient rates with an available beam power of 200kW (SPL, 2 GeV) [10]. Production of ^{18}Ne at ISOLDE[1] using a molten NaF salt loop [11] will be experimentally verified from fall 2011, see Fig. 2.

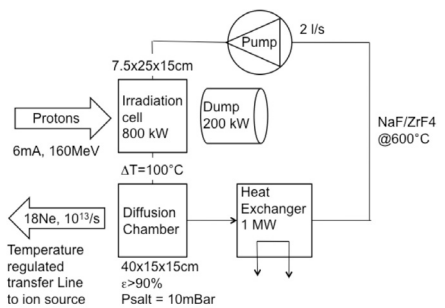


Figure 2: The molten salt loop to produce ^{18}Ne with an upgraded Linac 4 (CERN): 160MeV, 6 mA on average.

Production of ^{8}Li and ^{8}B for Beta Beams with an internal target in a production ring [14] 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. The detector distance for these isotopes would be around 700 km (CERN-Canfranc or CERN-LNGS).

A preliminary lattice design for the production ring (see Fig. 3) is available [15]. However, the supersonic gas jet target [14] 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, now studied at Argonne National Laboratory [12]. Measurements of the efficiency of the collection device (see Fig. 4) are being evaluated [13].

[1]Isotope Separator On Line-DEtector

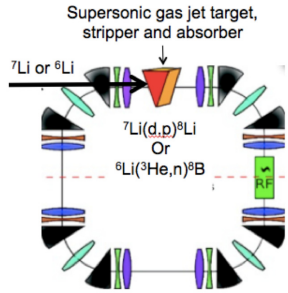


Figure 3: The isotope Production Ring.

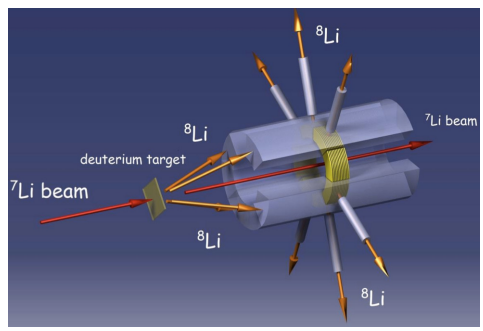


Figure 4: A catcher for Li ions.

Recent cross section data from measurements of ^{8}Li and for ^{8}B production (June 2011) will be available October 2011 (INFN-LNL, Legnaro, Italy).

The presently known rates of isotopes considered for beta beams are summarized in Table 1.

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]	200	960	4	4
Target	W/BeO	^{23}Na, ^{19}F	^{7}Li	^{6}Li
r [10^{13}/s]	5	1	0.1	0.08

The 60 GHz ECR source, pulsing at 10 Hz, injecting 50 μs long pulses, containing $5 \cdot 10^{12}$ atoms, will be assembled (magnet structures and gyrotron) during 2012 [16]. To avoid space charge effects, only charge state +1 will be extracted.

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BEAM STABILITY AND INTENSITY MITIGATION

To permit sufficient signal/noise ratio in the detector, a very small duty factor is required in the Decay Ring. This is a serious constraint in particular for the Decay Ring RF (beam loading) and beam stability conditions; the number of ions in an SPS bunch for the Ne beam is $2.9 \cdot 10^{11}$ and the required DR bunches are 5 ns long with an intensity of $3.4 \cdot 10^{12}$.

Transverse Mode Coupling Instabilities (TMCI) have been studied for the DR and partly for the SPS. The design of the Decay Ring, as described in the EURISOL Design Study [3], has been adapted to be able to store higher intensities (optical γ-transition has changed from 27 to 18) [18]. Damping with octupoles showed no significant improvement of the number of ions possible to store [19].

Iterative calculations with the physics and detector experts within the EUROν collaboration have shown that twice the intensity of ^{6}He, running for 2 years, and half of ^{18}Ne for 8 years can be accepted without important reduction of physics reach. After redesign and introduction of correctors, only half of the bunch intensities could be accepted in the DR using the proposed re-distribution of ions. Recent hints of a large $sin^2 2\theta_{13}$ from neutrino oscillation experiments [9] would permit relaxation of the requirements for the decay ring due to lesser needs for atmospheric background suppression (a duty factor of around 2% compared to 0.6% for smaller $sin^2 2\theta_{13}$). In the case of $sin^2 2\theta_{13} >$0.3, the needed intensities of the bunches to store in the Decay Ring are below the intensity limits. A complete analysis including other collective effects in the Decay Ring is necessary.

We have small margins to add equipment to the SPS as long as LHC is working. The SPS is an existing machine and not designed for Beta Beams. Since in this machine, contrary to the DR, the ions are accelerated, we have to investigate the beam stability along the acceleration cycle. Lower γ-transition in the SPS is not possible so new acceleration schemes to distribute intensities in the machines to better avoid instability conditions will be studied. One of the difficult topics is how to pass γ-transition in the PS and the SPS. The present existing optics without γ-transition for the LHC beams cannot be used for beta beams. Better distribution of ions could help also for the collimation in the DR (not yet studied).

STUDIES AND MEASUREMENTS IN THE PS AND THE SPS

Space charge consideration for the Beta Beam has led to a design energy of 3.5 GeV for the injection into the CERN PS, however the upgrade of the CERN injectors for LHC will bring the injection energy of the PS to only 2.0 GeV. Measurements of tune shifts and of emittance growth, as a function of the intensity, have started [20] as well as optimization of the bunch structure in the SPS (beam stability). Studies for radioprotection of the RCS, the PS and the Decay Ring have been carried out [3]. No show-stopper has been found, neither for radio-protection nor equipment. The PS upgrade studies will permit radiological studies also for the Beta Beam.

COSTING AND COST DRIVERS

EUROν will provide a performance/cost comparison using a single evaluation procedure of the 3 studied facilities. For this exercise CERN is used as the site for the implementation. The result of this exercise should be available before the end of the EUROν project (fall 2012).

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