The Technical challenges of Beta-beams *

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The beta-beam concept for the production of intense electron (anti-)neutrino beams is now well established. A first feasibility study, made at CERN in 2002, aimed to identify possible showstoppers. The results were very encouraging and the work is now continuing as an integral part of the EU-supported EURISOL Design Study. The first study at CERN is a good starting point for a conceptual design study, but that the annual rate of neutrinos even with a revised parameter list is insufficient. A number of technical challenges must be faced to improve on the annual rate, e.g. target technology for higher beam powers, space charge related limitations in the existing CERN accelerators and activation issues in the CERN PS.

1. Introduction

The beta-beam concept for the generation of an electron (anti-)neutrino beam was proposed [1] in 2002. A first study [2,3] of the possibility of using the existing CERN machines for the acceleration for radioactive ions to a relativistic gamma of roughly 100, for later storage in a new decay ring of approximately the size of SPS, was made in 2002. The results from this very first short study were very encouraging, but as no resources could be allocated at CERN for this work, it was not continued. In 2004 it was decided to incorporate a design study for the beta-beam within the EURISOL DS proposal. EURISOL [10] is a project name for a next-generation radioactive beam facility based on the ISOL method [4] for the production of intense radioactive beams for nuclear physics, astrophysics and other applications. The proposal was accepted with the beta-beam task as an integral part. The design study officially started 1 February 2005 and will run for 4 years resulting in a conceptual design report for a beta-beam facility as one potential user of EURISOL.

2. First study

The first study of the feasibility of using the existing CERN accelerator complex for a beta-beam facility was made over a few months with very limited manpower (see figure 1). The main objectives were twofold: i) to identify a possible scenario for bunching, acceleration and storage in a few very short bunches of a sufficient amount of radioactive ions for a beta-beam and ii) to identify possible bottlenecks in the proposed scheme. A main objection raised early on concerned the possible activation of the accelerators. Consequently, some time was spent to simulate the activation problem in the decay ring and to calculate the average losses in the accelerator chain. The overall result was encouraging but unfortunately no further work was approved due to other commitments for the accelerator departments at CERN. The study proposed to use a thick ISOL target for production of ^{6}He and ^{18}Ne as both isotopes can be produced in large quantities and are easy to handle. Neither of the isotopes have any long-lived daughter products that could create a problem in the low-energy part of the facility. Several iterations were required for the “bunching” but eventually a high frequency (60 GHz) ECR source was identified as a possible highly efficient tool to create sufficiently short bunches after the target for multi-turn injection into a synchrotron. For the first stage of acceleration, it was proposed to use the 100 Mev/u linac of the EURISOL facility. Further acceleration was to be done with a new rapid cycling synchrotron (RCS), the PS and finally the SPS. A new injec-

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tion and stacking method was proposed to keep the duty factor of the decay ring low. The method makes use of a dispersion orbit in the decay ring to avoid that the injection elements interfere with the circulating beam, bunch rotation to bring the fresh bunches to the central orbit and asymmetric bunch merging to take the newly injected ions into the centre of the circulating bunch [5,6]. The maximum gamma of 150 that can be reached for fully stripped ^{6}He ions in the SPS, was initially chosen for the coasting beam in the decay ring but later revised to lower values taking physics reach considerations into account. The main bottlenecks in the scenario chosen for the first study were shown to be the tune shift at PS and SPS injection and the activation of the PS ring.

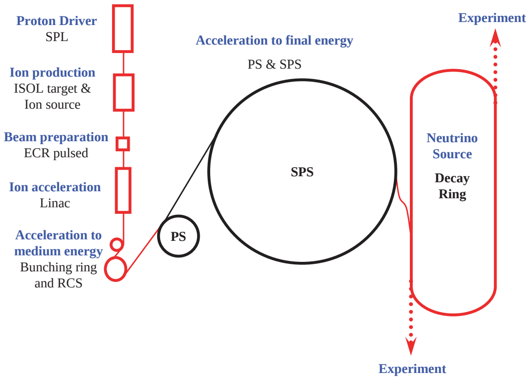

Figure 1. CERN conceptual design

3. The beta-beam task in EURISOL

The beta-beam task within EURISOL has six participating institutes and receives close to 1 MEuros over four years from the EU. Together with the contribution from the participating institutes, a total of almost 35 manyears is available for the study. The study officially started 1 February 2005 and the short term objective is to freeze a parameter list for the end of 2005. The deliverable of the study is a conceptual design report (CDR) for a beta-beam facility at CERN by the end of 2008.

3.1. Version 1

In the first study no consideration was made of the charge state distribution after the ECR. While it seems feasible to extract most He ions in the fully stripped charge state 2^+, it is unlikely that more than a maximum of 30% of Ne ions can be extracted in one single charge state. Furthermore, the multi-turn injection into the RCS is typically done with an efficency of 50%. Revising the first study with these points taken into consideration, the annual rate of neutrinos from ^{18}Ne was found to be drastically reduced [7], while the annual rate of anti-neutrino from ^{6}He was acceptable.

3.2. Version 2

The second version [8] was primarily motivated by the need to deal with space charge issues in the PS and SPS. The first study had a duty factor of the neutrino beam of 2×10^{-3}, with a moderate increase the known space charge induced limitations of PS and SPS were shown to be respected for an annual rate of 10^{18} (anti-)neutrinos per year. However, the second version still fails to deliver this rate for neutrinos. In table 1 the main differences between the different versions are listed together with the resulting annual rate. The increase of the number of bunches also resolves a problem with a RF incompatibility at transfer between the 40 Mhz Rf system and the 200 MHz RF system during acceleration.

4. Technical challenges

The main challenge for the beta-beam study is to reach the required annual rate for a physics reach that would make the beta-beam an attractive option for neutrino physics in 10-15 years time. Detailed physics studies available in these proceedings show that a beta-beam facility must deliver at least 10^{18} (anti-)neutrinos at the end of the straight section per year in the direction of a MegaTon detector to be of any interest in this time perspective. At a higher rate of some 10^{19}

Table 1
A comparison of three different scenarios for a CERN beta-beam facility

Publication		NuFact02	Version 1	Version 2
Date		2002	April 05	Aug 05
Target	rate to ECR [s^{-1}]	2×10^{13}	2×10^{13}	2×10^{13}
		(0.8×10^{12})	(0.8×10^{12})	(0.8×10^{12})
ECR	Type	Compact	60 GHz pulsed	60 GHz pulsed
	T ejection [keV/u]	20 keV/amu	U=50kV	U=50kV
	Efficiency			
Post accel.		Cyclotron	LINAC	LINAC
	T ejection [MeV/u]	50	100	100
RCS	Rep. rate [Hz]	16	16	10
	T ejection [MeV/u]	300	500 (1124)	500 (1124)
PS	Number of RCS bunches/cycle	16	16	20
	T ejection [GeV/u]	3.5 (7.8)	7.8 (14)	7.8 (14)
	Number of ejected bunches	8 (top merge)	8 (top merge)	20
SPS	T ejection [GeV/u]	139 (55)	92.5	92.5
	γ	150 (60)	100 (100)	100 (100)
Decay ring	Cycle time [s]	8	6 (3.6)	6 (3.6)
	Imax, stored [ions]	2.02×10^{14}	5.88×10^{13}	9.7×10^{13}
		(9.11×10^{12})	(1.19×10^{12})	(3.11×10^{12})
	Neutrino flux (ν/year)	Not given	1.76×10^{18}	2.9×10^{18}
			(0.02×10^{18})	(0.046×10^{18})
	Duty factor	2×10^{-3}	2×10^{-3}	$4.5(3.9) \times 10^{-3}$

Values given for the two baseline isotopes as ^{6}He(^{18}Ne)

(anti-)neutrinos per year the detector size could be greatly reduced and still leaving the facility as a highly competitive alternative to even the neutrino factory.

The achievable production rate of the isotopes of interest for a beta-beam facility was a major issue in the first study at CERN. The numbers presented in ref. [2] were compiled from general parameters for beam current and targets taken from the EU-supported EURISOL RTD project [9]. The possibility of increasing these numbers has been discussed ever since then. Different options have been proposed, such as multiple target of MgO in series for the production of ^{18}Ne. However, the production of the baseline isotopes will again be carefully investigated within the EURISOL DS [10] target tasks. Any improvements will translate linearly into annual rate making it the most straightforward way to increase the flux of (anti-)neutrinos. In Table 4 the required production rate for version 2 of the beta-beam facility with an annual rate of 1.1×10^{18} anti-neutrinos and 2.9×10^{18} [11] neutrinos are given.

Tests with a 28 GHz ECR source at LPSC in Grenoble [13] have demonstrated that short pulses of noble gas in a high charge state can be extracted through the so-called pre-glow effect. Theoretical estimates show that he increased plasma density at 60 GHz could produce an intense pulsed beam of noble gases suitable for a multi-turn injection into a synchrotron. Such a source, at a 10 Hz repetition rate, could feasible generate 10-20 microsecond long pulses of up to a few 10^{12} charges per pulse. A similar set-up in Louvain-La-Neuve operates with high efficiency for the production of a radioactive ion beam where the ions are produced on-line in a thick target [12]. The He ions would, in the proposed 60 GHz ECR source, be extracted almost exclusively in the highest charge state (2^{+}) but

Table 2
The assumed possible production [2] (for atoms at the entrance to the ECR) compared to a theoretically required production [8].

	Nominal production rate [ions/s]	Required production rate [ions/s]	Missing factor
6He	2×10^{13}	2×10^{13}	1
18Ne	8×10^{11}	1.9×10^{13}	24

the Ne ions would be extracted as a spectrum of several charge states with a maximum of 30% in one single state.

A high energy ion beam requires acceleration in large synchrotrons. Such synchrotrons are costly and, consequently, the re-use of existing accelerators at e.g. CERN is essential to keep the cost down. The PS and SPS at CERN were built for fixed target physics with protons and have later been adapted to accelerate ions for the CERN heavy-ion physics programme. The aperture and space charge limitations of these two accelerators have been carefully studied over many years of operation. This is a great help for the study as it sets strict limits for the number of charges per bunch that can be injected and accelerated, but it also shows that neither of the two machines are well adapted for very high intensity ion beams. Already in the first study a modifications of the RF system was proposed to reduce the tune shift at injection in the SPS.

The activation of magnets and tunnels is a major concern for all accelerators and in particular for the beta-beam where the ions decay (and are lost) during acceleration. The lost ions will be distributed all along the circumference making it very difficult to construct efficient beam collimation and magnet protection systems. Following the first study a first attempt was made [14] to estimate the decay losses. The losses in the PS for He are serious enough to make further hands on maintenance of the machine difficult while the losses in the SPS are comparable to losses already experienced with operational beams. The losses in the decay ring were simulated and shown to be important but not a cause of major concern as the subsequent secondary production of radioactivity in the surrounding rock were shown to be well below national limits.

Synchrotrons are highly efficient considering space and number of RF cavities compared to linacs, but with the inherent limitation of requiring a long repetition time between macropulses as the synchrotron, once “filled”, has to ramp the magnetic field to accelerate. This produces long gaps between injections of ions from the source. For the beta-beam baseline scenario, the repetition time between injections can be several seconds and, as the injection is only sustained for a second a large fraction of the ions produced are already lost at the exit of the ion source.

A further challenge is caused by the rather low energies reachable with the SPS at CERN as this implies a low duty factor ($< 2 \times 10^{-3}$) of the neutrino beam to permit a clean discrimination between atmospheric background and signal in the detector. This requires that the ions are kept in a few short bunches in the decay ring. The proposed injection scheme in the baseline scenario results in an acceptable duty factor, but due to longitudinal aperture limitations, it quickly saturates and prevents a further increase of the total number of stored ions. The long-term stability of the short high-intensity ion bunches in the decay ring due to intra-beam scattering is another point of concern which has to be addressed in the next stage of the study.

5. Conclusions

The conceptual design of the first study of the beta-beam facility has been taken a step further with the start of the EURISOL design study’s beta-beam task. The first objective is to establish the maximum annual rate of (anti-)neutrinos from a given the production rate [2] and with the re-use of the PS and SPS for acceleration. The next step, which has already started [3], will be to identify possible measures to increase the annual rate within the framework of the existing and possible future infrastructure at CERN. A green field study to establish the ultimate limit of the beta-beam concept is beyond the scope of the on-going design study. However, before a final decision on the construction of the next generation neutrino source, such a study must be done.

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