The acceleration and storage of radioactive ions for a neutrino factory

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Abstract

The term beta-beam has been coined for the production of a pure beam of electron neutrinos or their antiparticles through the decay of radioactive ions circulating in a storage ring. This concept requires radioactive ions to be accelerated to a Lorentz gamma of 150 for ^{6}He and 60 for ^{18}Ne. The neutrino source itself consists of a storage ring for this energy range, with long straight sections in line with the experiment(s). Such a decay ring does not exist at CERN today, nor does a high intensity proton source for the production of the radioactive ions. Nevertheless, the existing CERN accelerator infrastructure can be used, as this could still represent an important saving for a beta-beam facility. This paper outlines the first study, while some of the more speculative ideas will need further investigations.

Introduction

The evolution of neutrino physics demands new schemes to produce intense, collimated and pure neutrino beams. In the current paper, we discuss the feasibility of a new concept [zuc02] for the production of a single flavour electron neutrino beam with a perfectly known energy spectrum. If combined with an intense pion source for the production of muon neutrino beam the beta-beam can address similair physics issues as the muon neutrino factory [mez02]. The scheme relies on existing technology.

The acceleration of an intense radioactive ion beam to high energies is a new domain in the field of accelerator physics. Already the production of radioactive ions required for a beta-beam is well beyond the capacity of existing facilities. In the following we have limited ourselves to the possibility of basing a facility on parts of the existing CERN infrastructure, namely the Proton Synchrotron (PS) and the Super Proton Synchrotron (SPS). The study is still in its early stages and much work will be required to fully explore the limitations and potential of this approach. However, our hope is that the baseline scenario we propose can serve as a first-order benchmark for other studies of a beta-beam facility.

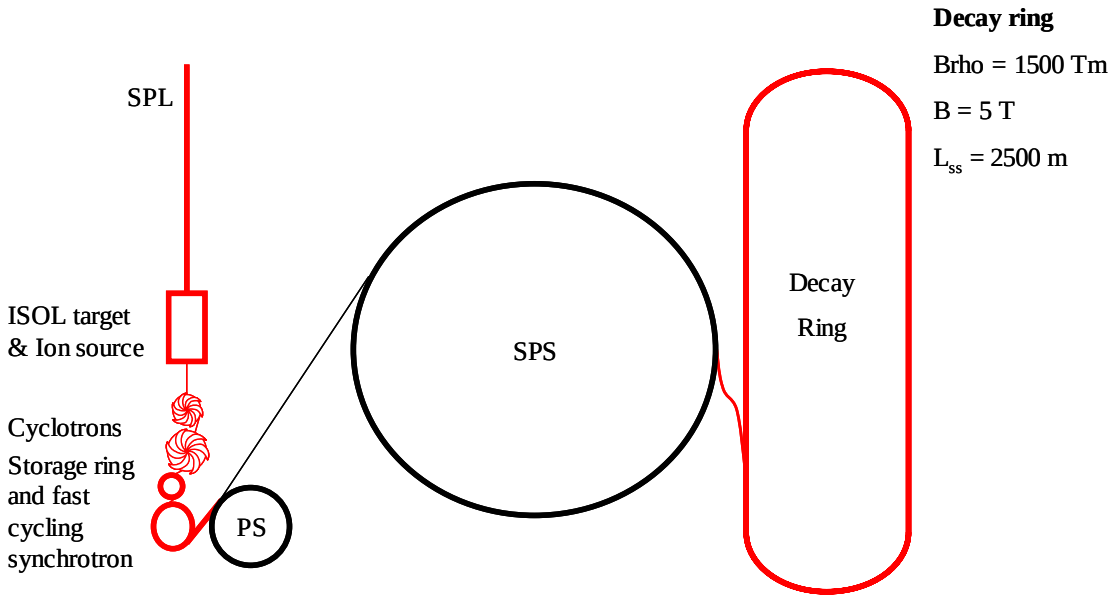

Figure 1: The CERN baseline scenario

Baseline scenario

Radioactive ion production

The beta-emitting radioactive ions will be produced in an isotope separator on-line (ISOL) system using the proposed Superconducting Proton Linac [spl00] (SPL) as a driver. The aim of nuclear physics today is to increase the sensitivity in experiments by at least a factor of 10^5. This has triggered several studies around the world to further develop the production methods of high intensity radioactive ion beams. Plans are being drawn up for a new European facility, EURISOL [eur00], where the ISOL method would

be exploited to its fullest. The estimated intensities from an EURISOL-type target station of the required ions, ^{6}He and ^{18}Ne, would be sufficient for a beta-beam facility.

Ionisation and bunching

The ISOL method produces intense dc beams of ions in low charge states. Such a beam is not well suited for acceleration to higher energies. For acceleration in a synchrotron the ions should preferably be in a higher charge state and bunched. Methods for accumulation and charge breeding at low energies are today being developed in pioneering experiments for accelerated radioactive beams in both Europe and North America [rex,ria,isac]. Unfortunately, the theoretical top intensities that can be reached with any of these methods are not sufficient for a beta-beam experiment. An alternative approach chosen for our baseline scenario is to accelerate the dc beam in a low charge state to a higher energy, 50 MeV/u, with cyclotrons. The beam is thereafter injected into a storage ring utilising charge exchange injection combined with phase space painting, bunched and ejected into a fast cycling synchrotron. The ions are accelerated to a higher energy, 300 MeV/u, and transferred to the PS. The reason for separating the storage ring from the synchrotron is that the accumulation and bunching process must be quasi-continuous to waste as little as possible of the radioactive ions produced.

Acceleration

The PS accumulates16 bunches one at a time. They are then accelerated, merged in pairs to 8 bunches, then transferred to the SPS. The transfer of ions from the PS to the SPS is a well-known space charge bottleneck that already has proven difficult to bypass for the LHC ion beam. In our baseline scenario, bunches fill the maximum available transverse aperture of the SPS and the individual bunch intensity is kept low. The bunches are accelerated in the SPS to the required energy for the chosen ion type. The shortest possible magnetic cycle of the SPS will be used, but it will still induce a dead time for the production and accumulation part of the scenario which, for SPS top energy, will be close to 8 seconds.

Transfer to decay ring

The bunches are injected in batches of 4 bunches at the time on to a dispersion-matched orbit in the decay ring and rotated in longitudinal phase space to the energy of the four stored bunches of radioactive ions. This procedure reduces the requirements on the rise and fall time of the pulsed injection elements needed in the decay ring. A classical ejection procedure would require the fast bumper magnets and the, in that case, required kickers magnets to work with rise and fall times that not can be achieved with existing technology.

Accumulation in the decay ring

Through bunch merging in the decay ring a minimum of longitudinal emittance is added to the circulating bunches. At the equilibrium intensity, which eventually will be reached, this will obviously lead to beam losses. However, we will show that this still will lead to a net increase of decay intensity at the moment of merging.

In the following sections we account for the choice of ^{18}Ne and ^{6}He and the critical parts of the baseline scenario are subjected to a detailed discussion.

Production methods for ν_e emitters

To produce the required high intensities of radioactive ions it is crucial to use "thick targets". An incident driver beam of stable particles (protons, deuterons, heavy ions or neutrons) will traverse the target with multiple chances to interact and produce the required radio-isotope in a nuclear reaction (spallation, fragmentation, direct reaction). The recoiling radio-isotopes are then stopped in the target matrix. The extraction is done on-line by heating the target matrix (roughly beyond the boiling point of the element to be released) to favour diffusion and effusion. The target matrix has to be enclosed into a tight container which only exit is connected to an ion source. After ionisation the radioisotopes are extracted, accelerated by a dc voltage to some ten keV and separated by A/q when passing a magnetic field.

Reusing a maximum part of the existing CERN accelerator structure requires the use of not too short-lived isotopes. For half-lives far below 1 s the decay losses during the acceleration process would become excessive (thus requiring an even bigger primary production rate and causing more radiation damage to the accelerator due to lost beta-decay daughters). On the other hand the half-life should not be too long to assure a sufficient decay rate in the storage ring. For an efficient acceleration the ions have to be highly or completely stripped.

β^- emitters

Table 1 shows candidate β^- emitters. Assuming a space charge capacity of the storage ring of $1x10^{13}$ charges and completely stripped ions it is evident that more low-Z isotopes can be stored at a time than high-Z isotopes. Thus the figure of merit (number of decays per s divided by the average neutrino energy which determines the opening angle of the neutrino beam [zuc02]) is highest for low-Z isotopes. ^{8}He and ^{9}Li are considered to be too short-lived for an efficient acceleration with the existing CERN accelerators. Thus ^{6}He is the best candidate.

Isotope	A/Z	T ½ (s)	Q_β g.s to g.s (MeV)	Q_β eff (MeV)	E_β av (MeV)	E_ν av (MeV)	Ions/bunch	Decay rate (s^{-1})	rate / $E_{\nu\ av}$ (s^{-1})
^{6}He	3.0	0.80	3.5	3.5	1.57	1.94	$5\cdot10^{12}$	$4\cdot10^{10}$	$2\cdot10^{10}$
^{8}He	4.0	0.11	10.7	9.1	4.35	4.80	$5\cdot10^{12}$	$3\cdot10^{11}$	$6\cdot10^{10}$
^{8}Li	2.7	0.83	16.0	13.0	6.24	6.72	$3\cdot10^{12}$	$3\cdot10^{11}$	$4\cdot10^{9}$
^{9}Li	3.0	0.17	13.6	11.9	5.73	6.20	$3\cdot10^{12}$	$1\cdot10^{11}$	$2\cdot10^{10}$
^{11}Be	2.8	13.8	11.5	9.8	4.65	5.11	$3\cdot10^{12}$	$1\cdot10^{9}$	$2\cdot10^{8}$
^{15}C	2.5	2.44	9.8	6.4	2.87	3.55	$2\cdot10^{12}$	$5\cdot10^{9}$	$1\cdot10^{9}$
^{16}C	2.7	0.74	8.0	4.5	2.05	2.46	$2\cdot10^{12}$	$2\cdot10^{10}$	$6\cdot10^{9}$
^{16}N	2.3	7.13	10.4	5.9	4.59	1.33	$1\cdot10^{12}$	$1\cdot10^{9}$	$1\cdot10^{9}$
^{17}N	2.4	4.17	8.7	3.8	1.71	2.10	$1\cdot10^{12}$	$2\cdot10^{9}$	$1\cdot10^{9}$
^{18}N	2.6	0.64	13.9	8.0	5.33	2.67	$1\cdot10^{12}$	$2\cdot10^{10}$	$6\cdot10^{9}$
^{23}Ne	2.3	37.2	4.4	4.2	1.90	2.31	$1\cdot10^{12}$	$2\cdot10^{8}$	$8\cdot10^{7}$
^{25}Ne	2.5	0.60	7.3	6.9	3.18	3.73	$1\cdot10^{12}$	$1\cdot10^{10}$	$3\cdot10^{9}$

^{25}Ne	2.3	59.1	3.8	3.4	1.51	1.90	$9\cdot10^{11}$	$1\cdot10^{8}$	$6\cdot10^{7}$
^{26}Na	2.4	1.07	9.3	7.2	3.34	3.81	$9\cdot10^{11}$	$6\cdot10^{9}$	$2\cdot10^{9}$

Table 1: Candidate isotopes for β^- emitters (charge/bunch = 1×10^{13}, γ=100).

Production of ^{6}He

^{6}He is produced in high-energy (1-3 GeV) proton induced reactions with cross-sections increasing with the target mass: ~0.5 mb for a ^{12}C target [Row58], ~20 mb for a Pb target [Row58] and ~40 mb for a ^{238}U target . Presently ^{6}He is best produced at ISOLDE by 1.4 GeV proton induced fragmentation of heavy targets. With a standard ISOLDE UC_x graphite target (50 g/cm^2 ^{238}U and 10 g/cm^2 C) the yield is about $5x10^7$ ions per μA of primary proton beam [Ber02]. This yield was measured with an ISOLDE type [Sun92] FEBIAD [Kir76] ion source, which had a particularly low efficiency of 0.16% for the ionisation of He. The yield could be increased by orders of magnitude by using a more efficient ion source, see below. Still one would need to send several 100 μA of protons onto the target to produce ~$1x10^{13}$ ^{6}He ions per s. This is far more beam current than this target could stand in its present design.

For the production of ^{6}He it is preferable to use a direct reaction with high cross-section and little power dissipation of the primary beam. One could consider the ^{6}Li(n,p)^{6}He or the ^{9}Be(n,α)^{6}He reactions. The former has an energy threshold of $E_n > 2.7$ MeV, the latter of only $E_n > 0.6$ MeV. The cross-section of ^{9}Be(n, α) peaks around 100 mb and remains above 25 mb for neutrons between 1.6 and 15 MeV, while the cross-section of ^{6}Li(n,p) reaches only 35 mb at maximum. Moreover, Be is more suitable as an ISOL target since it is far more refractory than Li, in particular when bound as BeO.

The required flux of fast neutrons can be produced externally, e.g. by high-energy proton induced spallation in a heavy metal “converter” mounted close to the ISOL target [Rav02]. Already with a 100 μA 2.2 GeV proton beam of the order of $1x10^{13}$ ^{6}He atoms per s could be produced in the target. After all existing experience with oxide targets [Koe02], the He release from BeO should be faster than from metallic Be. The former is moreover more refractory (melting point 2520 °C versus 1278 °C) allowing stable operation at high temperatures. For all oxide fibre targets (even those operated of rather low temperatures of about 1300 °C) discussed in [Koe02] over 80% of the produced ^{6}He is released before its decay. Thus, with a beryllium fibre target, which could be heated to still higher temperatures, also the efficient release from a large-volume target should be feasible.

Note that for each ^{6}He created by the (n,α) reaction, also one ^{4}He is produced. Additionally an important amount of ^{4}He is produced by the ^{9}Be(n,2n)^{8}Be→2α reaction. The threshold is higher, but the cross-section rises rapidly to reach a plateau around 550 mb for neutrons with energies of 4 to 15 MeV. ^{4}He and ^{13}C (released through the water-cooled transfer line as ^{13}C^{16}O molecule) are additionally produced by the ^{16}O(n,α)^{13}C reaction. Further (n,α) reactions in the container material do not contribute significantly. Also the production of hydrogen isotopes via (n,p), (n,d) and (n,t) reactions on ^{9}Be or ^{16}O

is at least one order of magnitude lower. Depending on the neutron energy spectrum, the total radiogenic gas load reaching the ion source will thus be about one order of magnitude higher than the ^{6}He amount.

β^+ emitters

Table 2 shows candidate β^+ emitters. Boron can react with many elements typically used in ISOL targets and ion sources (C, N, O, metals) and is therefore barely released. No ISOL beams of boron were produced up to now. ^{33}Ar is too short-lived for an efficient acceleration in the present scenario and also ^{34}Ar is rather short-lived. This leaves ^{18}Ne as best candidate. As a noble gas it is inert against reactions with the target and ion source materials and can thus be released efficiently even from a bigger target.

Isotope	A/Z	T ½ (s)	Q_β g.s. to g.s. (MeV)	Q_β eff (MeV)	E_β av (MeV)	E_ν av (MeV)	Ions/bunch	Decay rate (s^{-1})	rate / $E_{\nu\ av}$ (s^{-1})
^{8}B	1.6	0.77	17.0	13.9	6.55	7.37	$2\cdot10^{12}$	$2\cdot10^{10}$	$2\cdot10^{9}$
^{10}C	1.7	19.3	2.6	1.9	0.81	1.08	$2\cdot10^{12}$	$6\cdot10^{8}$	$6\cdot10^{8}$
^{14}O	1.8	70.6	4.1	1.8	0.78	1.05	$1\cdot10^{12}$	$1\cdot10^{8}$	$1\cdot10^{8}$
^{15}O	1.9	122.	1.7	1.7	0.74	1.00	$1\cdot10^{12}$	$7\cdot10^{7}$	$7\cdot10^{7}$
^{18}Ne	1.8	1.67	3.3	3.0	1.50	1.52	$1\cdot10^{12}$	$4\cdot10^{9}$	$3\cdot10^{9}$
^{19}Ne	1.9	17.3	2.2	2.2	0.96	1.25	$1\cdot10^{12}$	$4\cdot10^{8}$	$3\cdot10^{8}$
^{21}Na	1.9	22.4	2.5	2.5	1.10	1.41	$9\cdot10^{11}$	$3\cdot10^{8}$	$2\cdot10^{8}$
^{33}Ar	1.8	0.17	10.6	8.2	3.97	4.19	$6\cdot10^{11}$	$2\cdot10^{10}$	$5\cdot10^{9}$
^{24}Ar	1.9	0.84	5.0	5.0	2.29	2.67	$6\cdot10^{11}$	$5\cdot10^{9}$	$2\cdot10^{9}$
^{35}Ar	1.9	1.77	4.9	4.9	2.27	2.65	$6\cdot10^{11}$	$2\cdot10^{9}$	$8\cdot10^{8}$
^{37}K	1.9	1.22	5.1	5.1	2.35	2.72	$5\cdot10^{11}$	$3\cdot10^{9}$	$1\cdot10^{9}$
^{80}Rb	2.2	34	4.7	4.5	2.04	2.48	$3\cdot10^{11}$	$6\cdot10^{7}$	$2\cdot10^{7}$

Table 2. Candidate isotopes for β^+ emitters (charges/bunch = 1×10^{13}, γ=100).

Production of ^{18}Ne

^{18}Ne can be produced by spallation of a close-by target (Na, Mg, Al, Si) with cross-sections of the order of 1 mb at 2.2 GeV. Candidate compounds for an ISOL target are e.g. MgO, MgS, Al_2O_3, Al_4C_3 or SiC. Using e.g. a 1 m long MgO target of 20% theoretical density would produce about $1x10^{10}$ ^{18}Ne per μC of primary proton beam, i.e. $1x10^{12}$ ^{18}Ne per s with a 100 μA proton beam. Note that the 2.2 GeV protons lose only about 130 MeV of their energy when traversing the 1 m long target. Thus in principle the exiting proton beam could be sent onto a secondary production target behind. To avoid a local overheating of the sensible target material, the proton beam has to be spread or scanned over a sufficiently large target cross-section (several 10 cm^2) to disperse the 13 kW beam power over a larger area. Thus the target volume will reach several dm^3. It still needs to be studied how efficient the release of ^{18}Ne from such a target will be. A further increase of the proton beam intensity would require a still bigger target or a system of multiple independent targets, but a priori not impossible.

Neither BeO nor MgO felts are presently available commercially and need to be produced as described in [Koe02].

Ionisation scenarios for ν_e emitters

The produced radioactive elements effuse out of the target container as neutral atoms, and must efficiently and rapidly be ionised in an ion source to reduce the decay losses. The radioactive gas flux from the target is semi-continuous, as the driver beam repetition rate is 50 or 75 Hz. Thus, ideally, the radioactive elements should be collected and ionised during the ramping time of the SPS (approx. 8 s), and then be extracted with a pulse length of <100 μs for fast injection into the circular machines. With present technology, this is several of orders away in terms of required space-charge capacity. Furthermore, standard ISOL ion-sources presents very poor ionisation efficiencies for noble gases as already mentioned. Nevertheless, alternative solutions may be viable. Firstly, the space-charge can be reduced by shortening the collection time to ~2 ½ half-lives, that is to 2 s for ^{6}He and 4 s for ^{18}Ne, as the particle gain for longer collection times is negligible due to the decay. Secondly, highly efficient ion source concepts have recently been developed, and two different methods for ionisation and bunching of the beta emitters could be considered: the ECRIS combination and the gas injection into a duoplasmatron source.

ECR ion source alternative

A compact ECR ion source, with high ionisation efficiency for noble gases (45% for He [Jar02a] and >90% for Ne [Jar02a,Oya98]), connected directly to the target outlet minimises the effusion delay time. The extracted dc beam consists mainly of He^{+} (Ne^{+}), with a He^{2+} (Ne^{n+}) fraction of a few percent. The ionisation time of 50 and 150 ms for 90% of the total number of ions for He and Ne [Jar02b] is relatively short compared with the half-life. The source has no ion-storing capability and the ions leave the plasma volume continuously within some milliseconds after the ionisation[1]. Assuming the above stated radioactive gas fluxes a radioactive current of 10 μA is reached, far below the several mA the source type is capable of. A cold transfer line between target and ion source suppresses the influx of condensable elements. A separator magnet is inserted after the source to separate the radioactive ions from the carrier gas ions.

If a pulsed beam is requested, the feeding of the 1^{+} beam into a highly performing ECRIS would allow for storing and bunching of the ions for some tens of milliseconds. The layout of the complete scheme is illustrated in Fig. 1.

[1] An electrostatic pulsed extraction has been shown to have a limited blocking effect on the beam and works efficiently mainly for repetition frequencies above 500 Hz [Jeo96].

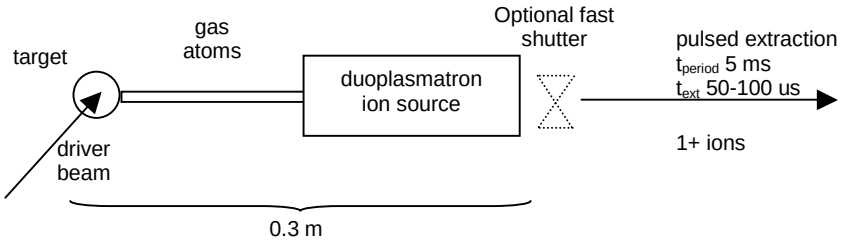

Fig. 1. Ionisation scheme using an effective 1+ ECRIS followed by bunching and charge breeding in a highly performing ECRIS.

The production of a pulsed beam using an ECRIT, that is an ECRIS operated in trapping mode, has been demonstrated [Cha98]. The injected He will after trapping in the plasma be charge-bred to mainly 2^+ (at least 50% can be expected in this charge state), and for Ne the charge state distribution will peak around 3^+ to 5^+ with approximately 25% in the main charge state. The space-charge capacity of the plasma is in principal determined by the plasma volume and RF frequency, and for a 28 GHz source 1.6×10^{13} charges/pulse have been extracted [Thu02]. Highly charged ions (15^+) can have a confinement of several hundred ms [Cha98]. The He^{2+} case is unknown, but if the confinement time is proportional to the ion charge, around 50 ms is expected. The experimental efficiency value for 200 ms bunching and breeding of Rb^+ to Rb^{15+} equals 2.2%. As the charge state distribution is narrower in the beta-beam case, possibly 10% efficiency can be attained for 50 ms bunching and charge breeding to 2^+. A fast pulsed extraction is necessary to attain an effective injection into the circular storage ring. Pulse lengths in the order of 0.15 ms [Müh94] can be achieved by pulsing a low-inductance coil that disrupts the plasma confinement, and with a new source an afterglow extraction time of 280 μs has been reached [Thu02]. To give any confident numbers experimental investigations of these issues are obligatory.

Duoplasmatron ion source

An alternative ionisation method is to use gas flow injection into a pulse-operated duoplasmatron source. The advantages are the simplicity of the system and the short extraction time. The source placed in the vicinity of the target minimises the effusion time. A short extraction time of 20 to 150 μs [Vos66,Hil02] is generated by the ignition of an arc discharge. Peak currents of 250-300 mA [Vos66,Hil02] and a space-charge capacity of at least 2×10^{14} charges covers the requirements from the beta beam scenario.

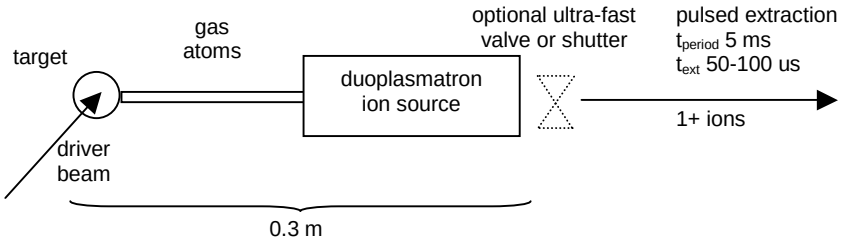

Fig. 4. Schematic layout of the gas injection into the duoplasmatron source.

The duoplasmatron source can reach an ionisation efficiency of 90% [Lej74] for dc operation at low currents, but the efficiency unavoidably decreases for pulsed operation. A pulsed duoplasmatron source for production of 25 mA $^{3}He^{+}$ operated at 360 Hz with 80 μs long pulses has demonstrated an efficiency of 0.5% [Sch98]. For lower extracted currents, as for the beta-beam case, a higher efficiency can be achieved as the extraction hole sizecan be reduced. The set-up could in principle be combined with a fast closing shutter arrangement at the exit of the source to prevent the gas atoms from leaving the source end thereby boosting the efficiency.

Thus, possibly an efficiency of a few percent is achievable for He, and as Ne is heavier than He, its ionisation efficiency will automatically become higher. The exact values remain to be investigated experimentally. The extraction time could be 50 μs and the operation frequency 200 Hz.

Injection into the storage ring

In contrast to a collider, such as the LHC, the requirements for the transverse emittance in the decay ring for the beta-beam are relaxed. This helps, as explained in the previous section, to overcome the space charge bottleneck between the PS and SPS. It also sets a generous upper limit for the physical emittance in the storage ring (see Table 3), which is important considering the long injection times required to transform the dc beam from the cyclotrons to a bunches beam suitable for synchrotrons. The beam will be injected with a combination of charge exchange injection through a thin foil and phase space painting. The latter will reduce the number of passages through the foil for each ion, which will reduce losses and angular straggling of the ions. This process has not been studied in detail. Charge exchange injection for stable He and Ne ions are routinely used at the The Svedberg laboratory in Uppsala [rei00].

Machine		Kinetic energy	Physical emittance	Normalised emittance
			π mm mrad	π mm mrad
ECR		20 keV/u	50	0.5
Cyclotron		50 MeV/u	1.5	0.5
Storage Ring		50 MeV/u	78	26
Fast Cycling Syncrotron		300 MeV/u	30	26
PS	He	3.5 GeV/u	20	93
	Ne	7.8 GeV/u	20	186
SPS	He	139 GeV/u	0.6	93
	Ne	55 GeV/u	3.1	186
Decay Ring	He	139 GeV/u	0.6	93
	Ne	55 GeV/u	3.1	186

Table 3: Transverse vertical emittance of the beam ejected from each machine. The limitation in the horizontal plane is less severe in the existing CERN machines. The normalized emittance is increased by phase space painting during charge exchange injection in the storage ring. A blow-up foil is used in the PS and SPS to reduce space charge effects in the following machines.

Space Charge Bottleneck at SPS Injection

The transfer of ions from the PS to the SPS is a well-known space charge bottleneck that already has proven difficult to bypass for the LHC ion beam.

Considering for simplicity a round Gaussian beam of completely stripped ions, the self-field incoherent ("Laslett") tune shift is

$$\Delta Q_V = -\frac{Z^2}{A_p}\frac{3r_p}{4(\beta\gamma)^2 c}\frac{R}{\tau_b}\frac{N_b}{\varepsilon_V^*}$$

where ε_V^* is normalized at one sigma, τ_b is the total duration of a parabolic bunch, and

$$A_p = m_{ion} / m_p$$

Hence, for the same ΔQ_V, τ_b and physical ε_V at fixed $B\rho$ ($\Rightarrow \beta\gamma \propto Z / A_p$),

$$\frac{N_{b,ion}}{N_{b,p}} = \frac{Z}{A_p^2} << 1$$

Taking the so-called "ultimate" LHC beam (ΔQ_V = -0.07) to benchmark the space charge limit at SPS injection leads to the figures given in Table 4.

	N_b^{Max}	$N_b^{Baseline}$	Missing Factor
p	1.7×10^{11}		
$^{6}He^{2+}$	9.4×10^{9}	$1.2\text{x}10^{12}$	130
$^{18}Ne^{10+}$	5.2×10^{9}	$6.5\text{x}10^{10}$	13

Table 4: Space charge limits, N_b^{Max}, at SPS injection as given by the ultimate LHC beam.

The SPS was designed for fixed-target physics. The machine is well adapted to handle beams with small momentum spread, moderate bunch intensity and large transverse emittance. The LHC beam has large momentum spread, high bunch intensity and small transverse emittance. In fact, the physical emittance is only of the order of 1 μm at SPS injection, whereas the vertical acceptance approaches 20 μm. This alone should allow the missing factor in Table 4 to be reduced by more than an order of magnitude. The SPS cycle for the LHC involves a long wait for up to 4 PS batches, whereas the single beta-beam bunch could even be injected into a moving bucket. This means that the beta-beam could probably tolerate a larger initial tune shift. A further factor of 5 could be gained by installing a moderate (~1 MV) 40 MHz rf system in the SPS. This would be sufficient to accelerate the ions to near transition, where the bunch would naturally be short enough for the standard 200 MHz system to take over.

Induced radiation in the machines

Since the radioactive nuclei have a relatively short life-time, and a large portion of the initial beam will decay during acceleration, and deposit its energy in the machines. Activation of the machines will therefore be an issue. As nuclei change their charge in beta-decay, one could imagine a design for the new purpose-built low energy machines where most of these decays occur in the straight sections, and the magnets act as

separators directing the decay products to dedicated beam dumps. In the existing machines, this might not be so easy, however. In the PS, for example, there are no long straight sections, so the decay losses would be more or less evenly distributed in the machine.

The total deposited power can be written

$$P = N \frac{E_0 \ln 2}{t_{1/2}} \frac{\gamma - 1}{\gamma} ,$$

where N is the number of particles, E_0 is the rest energy of the nuclei, and $t_{1/2}$ is the half-life at rest of the ion species. The factor γ-1 comes from the kinetic energy, and γ^{-1} from the time dilatation. For sufficiently high values of γ, the loss power is thus energy independent; it only depends on the number of particles in the machine.

Averaging over the acceleration cycle, and assuming that losses are evenly distributed around the machine, one obtains the power per unit length, which is what ultimately determines the activation of the machine. Usually, 1 W/m is quoted as the upper limit, since for 1 GeV protons it produces activation just below the US limit for "hands-on" maintenance (100 rem). However, the activation is energy dependent. Simulations made for the SNS show that the activation for a fixed loss power increases with energy up to 1 GeV [har99]. Analytic calculations show that, since high-energy particles are not absorbed in the machine components, at higher energies the machine activation actually decreases with energy [sul92]. Instead, the particles traverse the machine and activate the shielding.

The average deposited power due to beta decay, calculated for the PS and SPS, is given in Table 5. It can be seen that the PS is just above the 1 W/m limit. Of course, in reality one must also add normal losses to these numbers.

Machine	Ions extracted	Batches	Loss power	Losses/length
Source + Cyclotron	$2\ 10^{13}$ ions/s	52.5 ms	N/A	N/A
Storage Ring	$1.02\ 10^{12}$	1	2.95 W	19 mW/m
Fast Cycling Syncrotron	$1.00\ 10^{12}$	16	7.42 W	47 mW/m
PS	$1.01\ 10^{13}$	1	765 W	1.2 W/m
SPS	$0.95\ 10^{13}$	∞	3.63 kW	0.41 W/m
Decay Ring	$2.02\ 10^{14}$	N/A	157 kW	8.9 W/m

Machine	Ions extracted	Batches	Loss power	Losses/length
Source + Cyclotron	$8\ 10^{11}$ ions/s	52.5 ms	N/A	N/A
Storage Ring	$4.14\ 10^{10}$	1	0.18 W	1.1 mW/m
Fast Cycling Syncrotron	$4.09\ 10^{10}$	16	0.46 W	2.9 mW/m
PS	$5.19\ 10^{11}$	1	56.4 W	90 mW/m
SPS	$4.90\ 10^{11}$	∞	277 W	32 mW/m
Decay Ring	$9.11\ 10^{12}$	N/A	10.6 kW	0.6 W/m

Table 5: Intensities and average loss power for the ^{18}Ne (top) and ^{6}He (bottom) beam, assuming a 16 Hz fast cycling synchrotron and 8 s SPS cycle time. Only beta decay losses are taken into account.

Losses in the decay ring

The losses in the high-energy storage ring for continuous operation can be estimated from the fact that no beam is ejected. All injected beam is essentially lost somewhere in the machine. Hence

$$P_{tot} = \frac{N_{inj} E}{t_{rep}}$$

where N_{inj} in the number ions in each injected batch, E is the kinetic energy of the ions, and t_{rep} is the injection repetition rate.

The first thing to notice is the magnitude of the losses is in the kilowatt range. With the present layout of the decay ring, about 14 % of the beta decay products end up in each arc, and 36 % decay in each of the straight sections. For ^{6}He, this correspond to an energy deposition of 8.9 W/m in the arcs, and 56 kW in a hot spot downstream of the first bending after the straight sections. These are large numbers. Thus, some kind of separation scheme must be employed to separate decay products from the beam and dump them in a controlled way. This should be rather straightforward for the isolated hot spots after the straight sections, but might be more difficult for the losses distributed in the arcs.

As mentioned before, at high energy not all kinetic energy of the decay products are deposited in the machine. As an estimate, he relative energy loss per meter iron traversed is about 1% for $^{6}Li^{3+}$ at 150 GeV, and 5% for $^{18}F^{9+}$at 60 GeV. Since the particles would traverse the machine components (vacuum chamber and magnet yoke) at a grazing angle, the traversal length may be several meter or more. However, most of the energy will not be deposited in the magnets but rather in the shielding concrete (or soil). There might also be some issue with activation of the intermediate air (in the tunnel), as is the case in high-power spallation sources.

One possibility to minimize the material in the path of decay products would be to use C-type magnet. For the case of helium, the decay product, lithium, has a higher charge and is therefore lost on the inside of the machine arcs. The neon decay products, on the other hand, would be lost on the outside. A C-magnet would therefore only be beneficial for one ion species. (However, the energy deposition from neon decay is much smaller, due to the lower intensity.)

The magnitude of the losses probably excludes the use of super-conductive magnets, which would increase the length of the decay ring.

The losses that are not due to beta decay will be dominated by longitudinal acceptance limitations, as a consequence of the longitudinal stacking mode. Therefore, a controlled momentum collimation might be required to control these losses.

Electron cooling

To reach the desired intensity, stacking will be required in the high energy decay ring. Without cooling, Liouville's theorem restricts the stacking process. If electron cooling could be used in the decay ring, that could increase the stacking efficiency. All operational electron coolers today work below about 1 GeV/u. High and medium energy electron cooling is currently investigated at Brookhaven [bur00], Fermilab [nag00]and DESY [bal00]. Although so far no experimental cooling results have been achieved, there seem to be no fundamental reason why electron cooling should not work at higher energies. Calculations carried out for 150 GeV protons in the Tevatron at this energy yields cooling times of about 5 minutes [der00]. Re-scaling this result for $^{6}He^{2+}$ and $^{18}Ne^{10+}$ gives 7.5 and 1.4 minutes, respectively. However, these numbers are an optimistic estimate for the decay ring where initial emittances must be large to reduce space charge problems in the injector chain. Considering that the injection repetition rate in the decay ring is 8s, electron cooling would therefore not have any significant effect on the stacking efficiency.

Bunch rotation stacking in the beta-beam decay ring

The decay ring is an accumulator of the bunches delivered by the injector chain. Accumulation is required because the half-life of the stored ions is more than an order of magnitude longer than the cycling time of the injectors. It is complicated by the need to stack the beam in only a few bunches and by the fact that stochastic cooling is excluded. One approach is to use asymmetric bunch pair merging, which combines adjacent bunches in longitudinal phase space such that a small bunch can be embedded in the densest region of a much larger one with minimal emittance dilution.

A fresh bunch must be injected in the neighboring bucket to an existing bunch in the stack, but this is excluded using conventional kickers and septa because of the short rise time that would be required. An alternative injection 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 are injected in a high dispersion region on a matched dispersion trajectory. Subsequently, each injected bunch rotates a quarter turn in longitudinal phase space until the initial conditions for bunch pair merging are met.

The starting point is a series of 4 consecutive stack bunches in a dual-harmonic system. In order to satisfy the bunch length requirements imposed by the experiments, 40 and 80 MHz rf systems are needed.

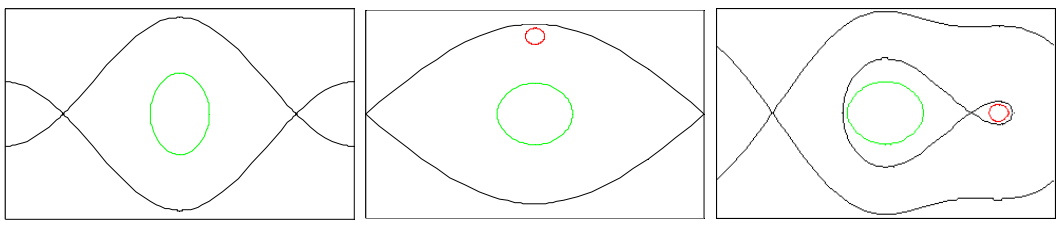

Figure 2: Bunch rotation stacking, longitudinal phase space plots (Energy versa Time): Left, Steady-state stacked bunch in decay mode. Middle, Injected and stacked bunches. Right, Start of bunch pair merging. The horizontal time axis on each plot is 25 ns.

Prior to injection, the second harmonic component is reduced to zero and local closed-orbit bump pushes the circulating bunches towards the blade of the magnetic injection septum. Each new bunch arrives in phase with a circulating one, but separated from it in momentum by an amount which provides the space for the septum blade in the dispersion region.

The local orbit bump must collapse sufficiently during the first turn (~20 μs) to bring the injected bunches across the septum blade. One quarter of a synchrotron period after injection, each new bunch has rotated to the same momentum as the stacked ones and a suitably phased second-harmonic component is snapped on. This is the starting point for asymmetric bunch pair merging.

Given that the half-lives of ^{6}He and ^{18}Ne are both of the order of two minutes at their respective top energies while the cycling time of the injector chain is of the order of 8 s, it is clear that each bunch of the stack will have a longitudinal emittance that is more than an order of magnitude larger than that of an incoming bunch. Asymmetric bunch pair merging allows the fresh, dense bunch to be deposited at the centre of the large accumulated one. Thus the oldest ions are moved to the edge of the stack and, due to their decay, a steady state is reached. Bunch characteristics throughout the baseline scenario are presented in Table 6.

Machine	Number of bunches		Final bunch length (ns)
	Injection	Ejection	
Storage ring	CW beam	1	Not evaluated
Fast cycling synchrotron	1	1	Not evaluated
PS	16	8	20
SPS	8	2 x 4	1
Decay ring	4	-	<10

Table 6: Bunch characteristics.

Merging simulation

As a proof of principal, the accumulation of a complete stack has been crudely simulated (using the SPS as a model for the decay ring). The full-blown scheme sees two batches each of four bunches transferred and stacked in the decay ring. This takes of the order of one second.

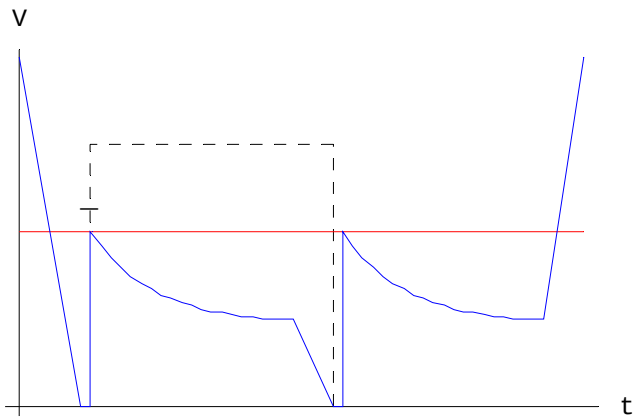

Figure 4: 40 (red) and 80 MHz (blue) voltage components during a single filling cycle. The dashed line indicates the portion repeated in the simulation.

Asymmetric merging is achieved by controlling the relative phase of the two rf components as a function of their decreasing voltage ratio such that the acceptance of the inner bucket containing the stack bunch is gradually reduced while that containing the fresh bunch is maintained. The simulation simply took a single injected bunch of ^{6}He after its quarter turn rotation and stacked this particle distribution again and again. At each repetition, some of the resultant stack was removed at random corresponding to the expected number of ^{6}He decays. A steady state was reached at an intensity, which was within 20% of that which would have been achieved with a stacking efficiency of 100%. This revealed that, provided the emittance of the injected bunch can be kept below 1 eVs, the order of magnitude of the rf voltages required for merging is restricted to a comparatively modest 10 MV. The final intensity of a bunch in the decay ring can exceed ten times that of an injected bunch.

Conclusions

A possible scenario for accelerating radioactive ions for a beta-beam facility has been developed. It makes use of large parts of the existing CERN accelerator infrastructure and ties up with other CERN activities, such as ISOLDE and the muon neutrino beam. Several possible showstoppers have been circumvented, but much work is still required if the facility is ever to be built. It is likely that the charge exchange process into the low energy accumulator ring will prove very difficult to realise. Furthermore, activation is a major problem. Only a detailed study can show if this is possible to handle. Still, it is important that the beta-beam concept be studied thoroughly to permit a full and fair comparison with the muon-based neutrino factory.

A “green field” scenario free from the limitations imposed by the existing CERN accelerator infrastructure should also be considered for a complete picture of the possibilities offered by this exciting concept.

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