A BASELINE BETA-BEAM

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on behalf of the
Beta-beam Study Group

http://cern.ch/beta-beam/
Outline

• **Beta-beam baseline design**
  – A baseline scenario, ion choice, main parameters
  – Ion production
  – Decay ring design issues

• **Ongoing work and recent results**
  – Asymmetric bunch merging for stacking in the decay ring
  – Decay ring optics design & injection

• **Future R&D within EURISOL**
  – The Beta-beam Task

• **Conclusions**
Introduction to beta-beams

• Beta-beam proposal by Piero Zucchelli
  – *A novel concept for a neutrino factory: the beta-beam*,

• AIM: production of a pure beam of electron neutrinos (or antineutrinos) through the beta decay of radioactive ions circulating in a high-energy (γ~100) storage ring.

• Baseline scenario
  – Avoid anything that requires a “technology jump” which would cost time and money (and be risky).
  – Make maximum use of the existing infrastructure.
Beta-beam baseline design

Ion production

Proton Driver
SPL

Ion production
ISOL target & Ion source

Beam preparation
Pulsed ECR

Ion acceleration
Linac

Acceleration to medium energy
RCS

Acceleration to final energy
PS & SPS

Neutrino source

Decay ring
$B \rho = 1500 \text{ Tm}$
$B = 5 \text{ T}$
$C = 7000 \text{ m}$
$L_{ss} = 2500 \text{ m}$

$^6\text{He}: \gamma = 150$
$^{18}\text{Ne}: \gamma = 60$

Experiment
$\nu, \bar{\nu}$
Main parameters (1)

- **Factors influencing ion choice**
  - Need to produce reasonable amounts of ions.
  - Noble gases preferred - simple diffusion out of target, gaseous at room temperature.
  - Not too short half-life to get reasonable intensities.
  - Not too long half-life as otherwise no decay at high energy.
  - Avoid potentially dangerous and long-lived decay products.

- **Best compromise**
  - Helium-6 to produce antineutrinos: $^6_2He \rightarrow ^6_3Li e^- \bar{\nu}$
    - Average $E_{cms} = 1.937$ MeV
  
  - Neon-18 to produce neutrinos: $^{18}_{10}Ne \rightarrow ^{18}_{9}F e^+ \nu$
    - Average $E_{cms} = 1.86$ MeV
• The Design Study is aiming for:
  - A beta-beam facility that will run for a “normalized” year of $10^7$ seconds
  - An integrated flux of $10 \times 10^{18}$ anti-neutrinos ($^6$He) and $5 \times 10^{18}$ neutrinos ($^{18}$Ne) in ten years running at $\gamma = 100$

With an Ion production in the target to the ECR source:
  • $^6$He = $2 \times 10^{13}$ atoms per second
  • $^{18}$Ne = $8 \times 10^{11}$ atoms per second
Ion production - ISOL method

- Isotope Separation OnLine method.
- Few GeV proton beam onto fixed target.

GeV protons

\[
238\text{U} \xrightarrow{\text{spallation}} 201\text{Fr} + \text{fragmentation} \leftarrow 6\text{He via spallation} \quad 18\text{Ne directly}
\]

\[
11\text{Li} + \text{X} + \text{fission} \stackrel{143\text{Cs}}{\leftarrow} \text{p} + \text{n}
\]
$^6$He production from $^9$Be(n,\(\alpha\))

- Converter technology preferred to direct irradiation (heat transfer and efficient cooling allows higher power compared to insulating BeO).
- $^6$He production rate is $\sim 2 \times 10^{13}$ ions/s (dc) for $\sim 200$ kW on target.

Converter technology:
(J. Nolen, NPA 701 (2002) 312c)
\( ^{18}\text{Ne} \) production

- Spallation of close-by target nuclides
  - \(^{24}\text{Mg}\) \((p, p_3n_4) ^{18}\text{Ne}^{10}\).
  - Converter technology cannot be used; the beam hits directly the magnesium oxide target.
  - Production rate for \(^{18}\text{Ne}\) is \(\sim 1 \times 10^{12} \) ions/s (dc) for \(\sim 200 \) kW on target.
  - \(^{19}\text{Ne}\) can be produced with one order of magnitude higher intensity but the half-life is 17 seconds!
From dc to very short bunches

**SPS**: injection of 4 + 4 bunches from PS. Acceleration to decay ring energy and ejection. Repetition time 8 s.

**PS**: 1 s flat bottom with 8 (16) injections. Acceleration in ~1 s to top PS energy.

**RCS**: further bunching to ~100 ns. Acceleration to ~300 MeV/u. 8 (16) repetitions during 1 s.

**Post accelerator linac**: acceleration to ~100 MeV/u. 8 (16) repetitions during 1 s.

**60 GHz ECR**: accumulation for 1/8 (1/16) s ejection of fully stripped ~20 μs pulse. 8 (16) batches during 1 s.

**Target**: dc production during 1 s.
Wasted time or accumulation time?

Ramp time PS

Ramp time SPS

Reset time SPS

Decay ring

SPS

PS

Production

Wasted time?

Time (s)
**Decay ring design aspects**

- The ions have to be concentrated in a few very short bunches
  - Suppression of atmospheric background via time structure.
- There is an essential need for stacking in the decay ring
  - Not enough flux from source and injector chain.
  - Lifetime is an order of magnitude larger than injector cycling (120 s compared with 8 s SPS cycle).
  - Need to stack for at least 10 to 15 injector cycles.
- Cooling is not an option for the stacking process
  - Electron cooling is excluded because of the high electron beam energy and, in any case, the cooling time is far too long.
  - Stochastic cooling is excluded by the high bunch intensities.
- Stacking without cooling “conflicts” with Liouville
Asymmetric bunch pair merging

• Moves a fresh dense bunch into the core of the much larger stack and pushes less dense phase space areas to larger amplitudes until these are cut by the momentum collimation system.

• Central density is increased with minimal emittance dilution.

• Requirements:
  – Dual harmonic rf system. The decay ring will be equipped with 40 and 80 MHz systems (to give required bunch length of ~10 ns for physics).
  – Incoming bunch needs to be positioned in adjacent rf “bucket” to the stack (i.e., ~10 ns separation!).
Simulation (in the SPS)

**BUNCH PAIR MERGING IN THE SPS**

Iter | 0 | 0.000E+00 sec

| H₀ (MeV) | 1.000E+03 | S₀ (eV μ) | 1.315E+01 | E₀ (MeV) | 8.410E+05 | h | 9.24 | V (MV) | 1.000E+01 | η | 1.614E-03 | ψ (deg) | -1.392E+02 |
| 2.122E-03 | 0.000E+00 | 3.151E+00 | 3500 |

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**Diagram**

- E - E₀ (GeV)
- θ (degree)
- RF VOLTAGE (MeV/μl)
Test experiment in the PS

A large bunch is merged with a small amount of empty phase space.

Longitudinal emittances are combined.

Minimal blow-up.
Test experiment in CERN PS

Ingredients
- $h=8$ and $h=16$ systems of PS.
- Phase and voltage variations.

S. Hancock, M. Benedikt and J-L. Vallet,
*A proof of principle of asymmetric bunch pair merging*, AB-Note-2003-080 MD
Decay ring injection design aspects

- Asymmetric merging requires fresh bunch injected very close longitudinally to existing stack. Conventional injection with fast elements (septa and kickers) is excluded.

- Alternative injection scheme
  - Inject an off-momentum beam on matched dispersion trajectory.
  - No fast elements required (bumper rise and fall ~10 $\mu$s).
  - Requires large normalized dispersion at injection point (small beam size and large separation due to momentum difference).
  - Price to be paid is larger magnet apertures in decay ring.
Decay ring arc lattice design

A. Chance, CEA-Saclay (F)

FODO structure

Central cells detuned for injection

Arc length \( \sim 984\) m

Bending 3.9 T, \( \sim 480 \) m \( L_{\text{eff}} \)

5 quadrupole families
Decay ring injection envelopes

A. Chance, CEA-Saclay (F)

Horizontal envelopes:
- \( \Delta p/p = 0 \) bumps off
- \( \Delta p/p = 0 \) bumps on
- \( \Delta p/p = 0.8\% \) bumps off
- \( \Delta p/p = 0.8\% \) bumps on

Vertical envelopes:
- Stored beam
- Injected beam
Decay losses

- **Losses during acceleration**
  - Full FLUKA simulations in progress for all stages (M. Magistris and M. Silari, *Parameters of radiological interest for a beta-beam decay ring, TIS-2003-017-RP-TN*).

- **Preliminary results:**
  - Manageable in low-energy part.
  - PS heavily activated (1 s flat bottom).
    - Collimation? New machine?
  - SPS ok.
  - Decay ring losses:
    - Tritium and sodium production in rock is well below national limits.
    - Reasonable requirements for tunnel wall thickness to enable decommissioning of the tunnel and fixation of tritium and sodium.
    - Heat load should be ok for superconductor.

![FLUKA simulated losses in surrounding rock (no public health implications)](image)
Future R&D

• Future beta-beam R&D together with EURISOL project
• Design Study in the 6th Framework Programme of the EU

• The EURISOL Project
  – Design of an ISOL type (nuclear physics) facility.
  – Performance three orders of magnitude above existing facilities.
  – A first feasibility / conceptual design study was done within FP5.
  – Strong synergies with the low-energy part of the beta-beam:
    • Ion production (proton driver, high power targets).
    • Beam preparation (cleaning, ionization, bunching).
    • First stage acceleration (post accelerator ~100 MeV/u).
    • Radiation protection and safety issues.
Beta-beam task

From exit of the heavy ion Linac (~100 MeV/u) to the decay ring (~100 GeV/u).

- **Proton Driver**
  - SPL

- **Ion production**
  - ISOL target & Ion source

- **Beam preparation**
  - Pulsed ECR

- **Ion acceleration**
  - Linac

- **Acceleration to medium energy**
  - RCS

- **Acceleration to final energy**
  - PS & SPS

- **Neutrino Source**
  - Decay Ring

- **Experiment**
  - $\nu, \bar{\nu}$

NNN05, 8/4/05 22
Beta-beam sub-tasks

- Beta-beam task starts at exit of EURISOL post accelerator and comprises the conceptual design of the complete chain up to the decay ring.
- Participating institutes: CERN, CEA-Saclay, IN2P3, CLRC-RAL, GSI, MSL-Stockholm.
- Organized by a steering committee overseeing 3 sub-tasks.
  - ST 1: Design of the low-energy ring(s).
  - ST 2: Ion acceleration in PS/SPS and required upgrades of the existing machines including new designs to eventually replace PS/SPS.
  - ST 3: Design of the high-energy decay ring.
  - Detailed work and manpower planning is under way.
  - Around 38 (13 from EU) man-years for beta-beam R&D over next 4 years (only within beta-beam task, not including linked tasks).
Can we reach the FLUX?

\[ \begin{align*}
\beta & \\
\beta & \\
\beta & \\
\end{align*} \]

\[ ^{6}\text{He}^{18}\text{Ne} \]

\[ ^{19}\text{Ne} \]

\[ ^{150}\text{Dy} \]
LOW-ENERGY BETA-BEAMS

THE PROPOSAL
To exploit the beta-beam concept to produce intense and pure low-energy neutrino beams.

PHYSICS POTENTIAL
- Neutrino-nucleus interaction studies for particle, nuclear physics, astrophysics (nucleosynthesis).
  Important for neutrinoless double-beta decay.
  C. Volpe, hep-ph/0501233
- Neutrino properties, like $\nu$ magnetic moment.
Conclusions

• Well-established beta-beam baseline scenario.
• Beta-Beam Task well integrated in the EURISOL DS.
  – Strong synergies between Beta-beam and EURISOL.
• Design study started for “base line” isotopes.
• Baseline study should result in a credible conceptual design report.
  – We need a “STUDY 1” for the beta-beam to be considered a credible alternative to super beams and neutrino factories
  – New ideas welcome but the design study cannot (and will not) deviate from the given flux target values and the chosen baseline
  – Parameter list to be frozen by end of 2005
• Recent new ideas promise a fascinating continuation into further developments beyond (but based on) the ongoing EURISOL (beta-beam) DS
  – Low energy beta-beam, EC beta-beam, High gamma beta-beam, etc.
• And this is only the beginning...