Beta-beam design status and technical challenges ahead

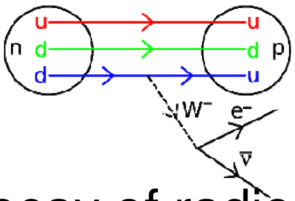
Elena Wildner, CERN

European Strategy for Future Neutrino Physics, CERN 1-3 Oct 2009

Outline

- Beta Beam Concepts
- A Beta Beam Scenario
- Ion Production
- Other Challenges
- Other Beta Beam Scenarios
- Summary

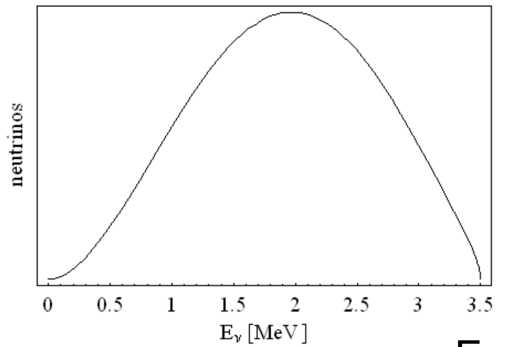
Beta-beams, recall



Aim: production of (anti-)neutrino beams from the beta decay of radio-active ions circulating in a storage ring

- Similar concept to the neutrino factory, but parent particle is a beta-active isotope instead of a muon.

Beta-decay at rest



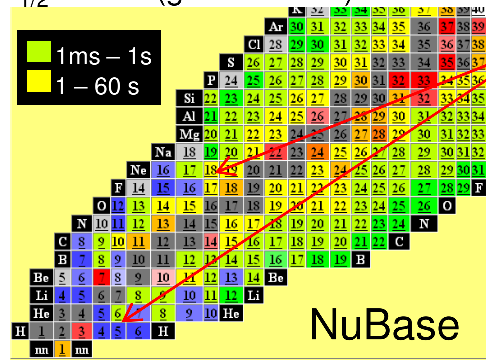
E_0

- ν–spectrum well known from the electron spectrum
- Reaction energy Q typically of a few MeV
- Accelerate parent ion to relativistic γ_{max}
  - Boosted neutrino energy spectrum: $E_\nu \leq 2\gamma Q$
  - Forward focusing of neutrinos: $\theta \leq 1/\gamma$
- Pure electron (anti-)neutrino beam!
  - Depending on β^+- or β^-- decay we get a neutrino or anti-neutrino
  - Two different parent ions for neutrino and anti-neutrino beams
- Physics applications of a beta-beam
  - Primarily neutrino oscillation physics and CP-violation (high energy)
  - Cross-sections of neutrino-nucleus interaction (low energy)

Choice of radioactive ion species

- Beta-active isotopes
  - Production rates
  - Life time
  - Dangerous rest products
  - Reactivity (Noble gases are good)

$t_{1/2}$ at rest (ground state)



6He and 18Ne

8Li and 8B

- Reasonable lifetime at rest
  - If too short: decay during acceleration
  - If too long: low neutrino production
  - Optimum life time given by acceleration scenario
  - In the order of a second

- Low Z preferred
  - Minimize ratio of accelerated mass/charges per neutrino produced
  - One ion produces one neutrino.
  - Reduce space charge problems

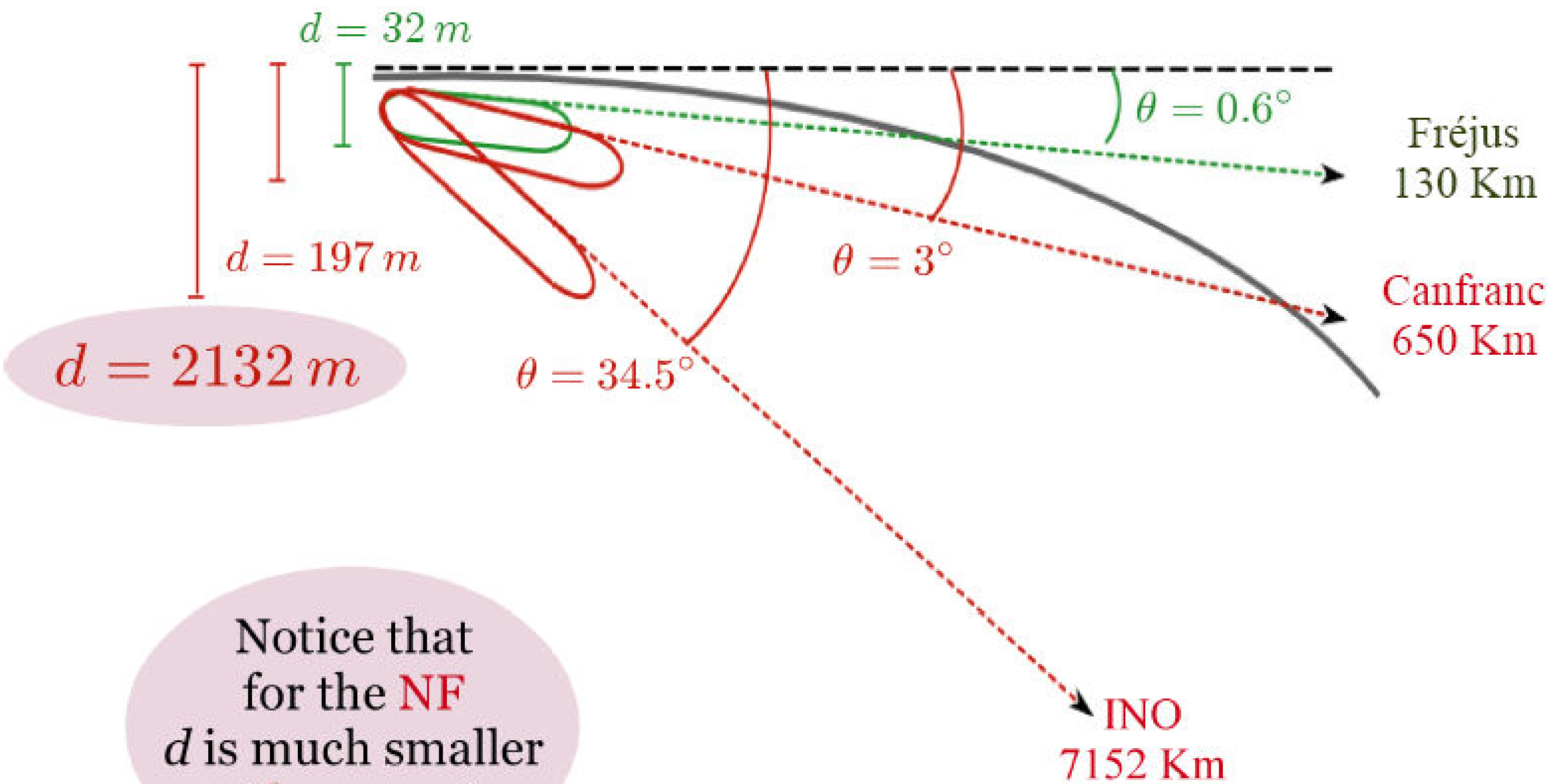
Isotope	A/Z	T ½ (s)	Q_β g.s to g.s (MeV)	Q_β eff (MeV)	E_β av (MeV)	E_ν av (MeV)	Ions/bunch	Decay rate	rate / $E_{\nu\ av}$ (s^{-1})
^{6}He	3.0	0.80	3.5	3.5	1.57	1.94	$5\cdot10^{12}$		
^{8}He	4.0	0.11	10.7	9.1	4.35	4.80	$5\cdot10^{12}$		
^{8}Li	2.7	0.83	16.0	13.0	6.24	6.72	$3\cdot10^{12}$		
^{9}Li	3.0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

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	$9\cdot10^{11}$	$3\cdot10^{8}$	$2\cdot10^{8}$

Some scaling

- Accelerators can accelerate ions up to Z/A × *the proton energy.*
- $L \sim \langle E_\nu \rangle / \Delta m^2 \sim \gamma Q$, $Flux \sim L^{-2}$ => $Flux \sim Q^{-2}$
- Cross section $\sim \langle E_\nu \rangle \sim \gamma Q$
- Merit factor for an experiment at the atmospheric oscillation maximum: $M = \gamma / Q$
- Decay ring length scales $\sim \gamma$ (ion lifetime)

Beta beam to different baselines



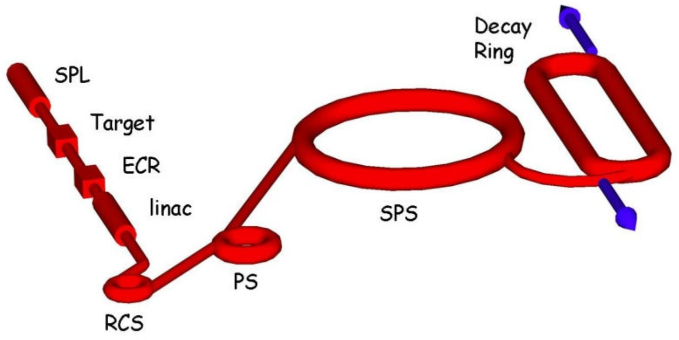
Notice that
for the NF
d is much smaller
(d= 423 m)

Pilar Coloma
Optimization of the Two-Baseline β-Beam

The EURISOL scenario(*) boundaries

- Based on CERN boundaries
- Ion choice: ^{6}He and ^{18}Ne
- Based on existing technology and machines
  - Ion production through ISOL technique
  - Bunching and first acceleration: ECR, linac
  - Rapid cycling synchrotron
  - Use of existing machines: PS and SPS
- Relativistic gamma=100 for both ions
  - SPS allows maximum of 150 (^{6}He) or 250 (^{18}Ne)
  - Gamma choice optimized for physics reach
- Opportunity to share a Mton Water Cherenkov detector with a CERN super-beam, proton decay studies and a neutrino observatory

EURISOL scenario



- Achieve an annual neutrino rate of
  - $2.9 \cdot 10^{18}$ anti-neutrinos from ^{6}He
  - $1.1\ 10^{18}$ neutrinos from ^{18}Ne

top-down approach

- The EURISOL scenario will serve as reference for further studies and developments: Within Euroν we study ^{8}Li and ^{8}B

(*) FP6 "Structuring the European Research Area" programme (CARE, contract number RII3-CT-2003-506395)

The EURISOL scenario

Design Study

Aimed:

He 2.9 10^{18} (2.0 10^{13}/s after target)

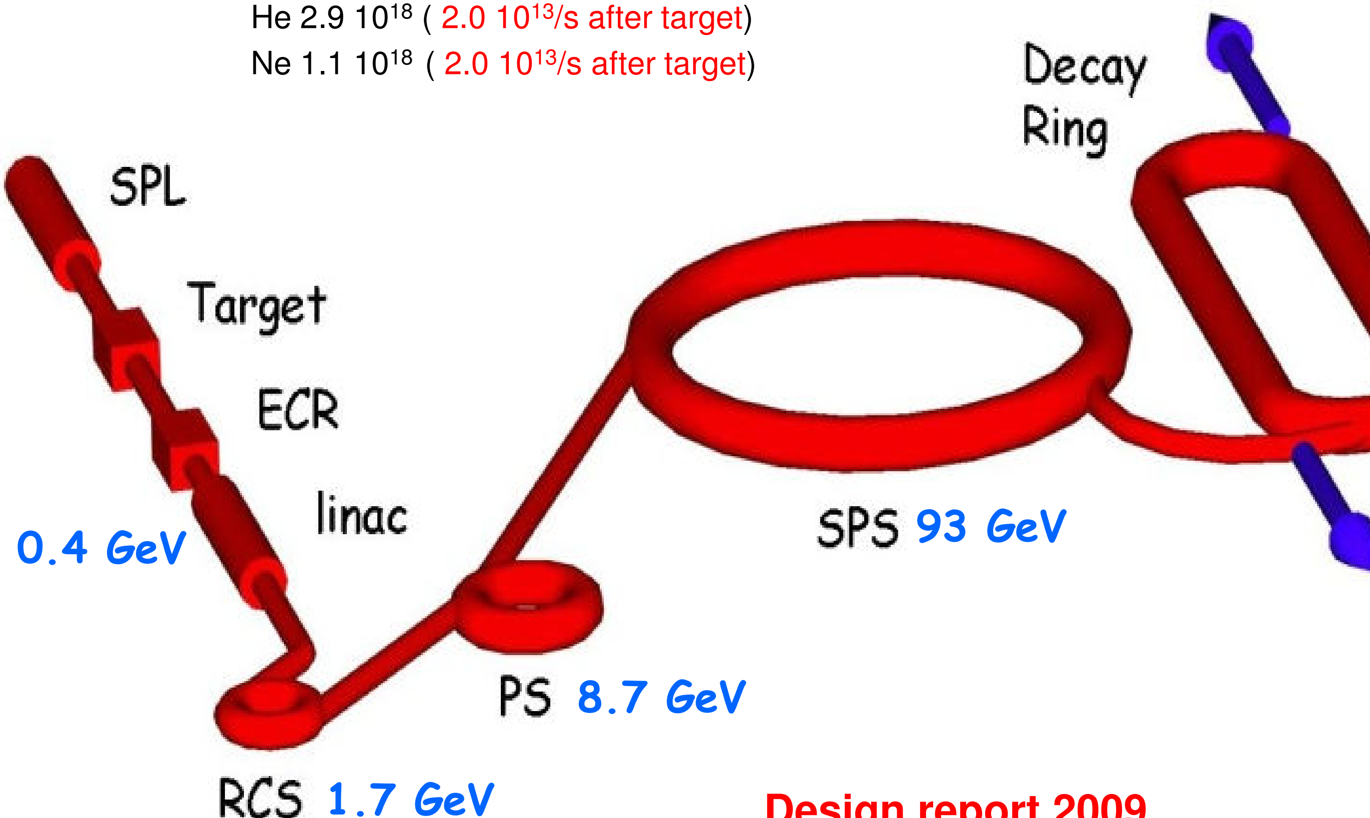
Ne 1.1 10^{18} (2.0 10^{13}/s after target)

Decay ring

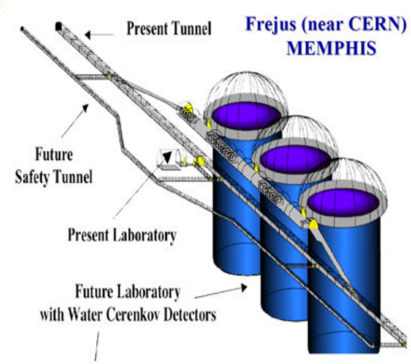
$B\rho$ = 1500 Tm

B = ~6 T
C = ~6900 m
L_{ss}= ~2500 m

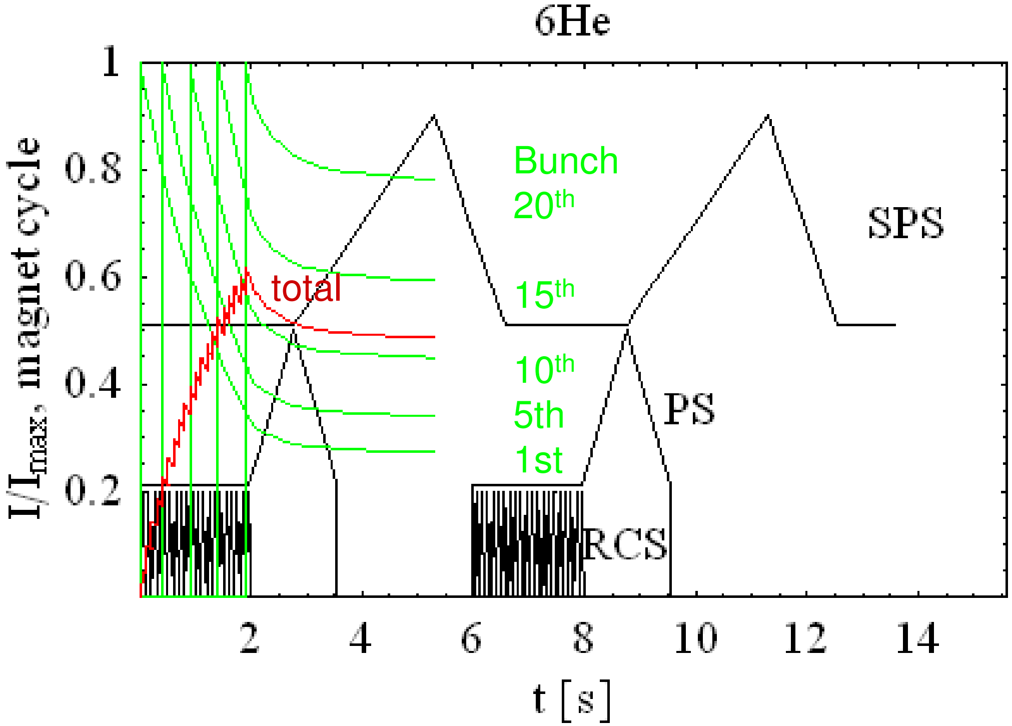
^{6}He: γ = 100
^{18}Ne: γ = 100



Design report 2009



Intensity evolution during acceleration



Cycle optimized for neutrino rate towards the detector

30% of first ^{6}He bunch injected are reaching decay ring
Overall only 50% (^{6}He) and 80% (^{18}Ne) reach decay ring

Normalization
Single bunch intensity to maximum/bunch
Total intensity to total number accumulated in RCS

Radioprotection

Residual Ambient Dose Equivalent Rate at 1 m distance from the beam line (mSv h^{-1})				
	RCS (quad - ^{18}Ne)	PS (dip - ^{6}He)	SPS	DR (arc - ^{18}Ne)
[illegible]	[illegible]	[illegible]	-	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
1 week	2	2	-	1.4

Not a show stopper

Annual Effective Dose to the Reference Population (μSv)			
RCS	PS	SPS	DR
0.67	0.64	-	5.6 (only decay losses)

Stefania Trovati, Matteo Magistris, CERN

CERN-EN-Note-2009-007
STI
EURISOL-DS/TASK2/TN-02-25-2009-0048

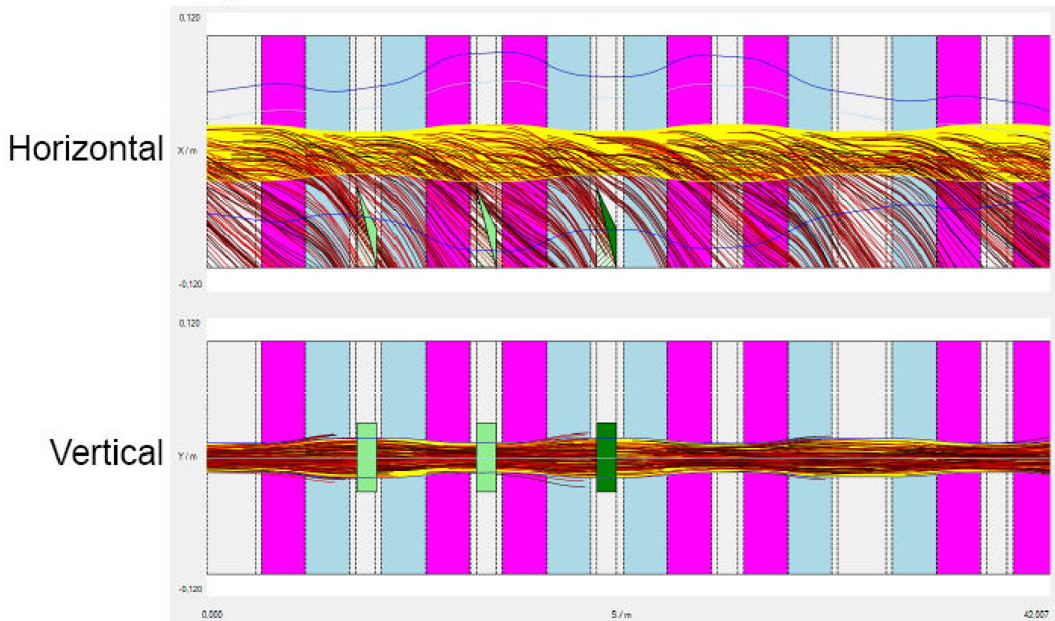
Yacin Kadi et al. , CERN

Activation and coil damage in the PS

StrahlSim: Losses

Beta Beams in EURISOL

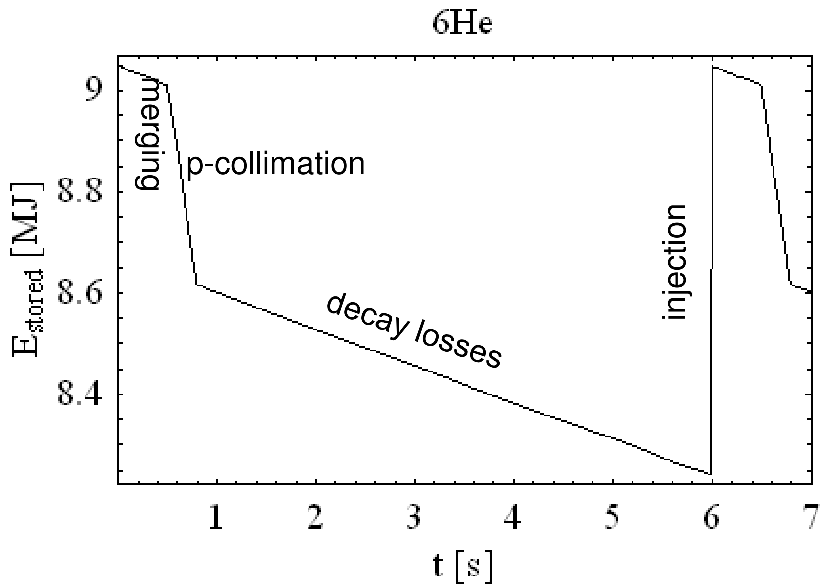
He-beam. Decay products tracked to the collimator and beampipe (red & black curves).

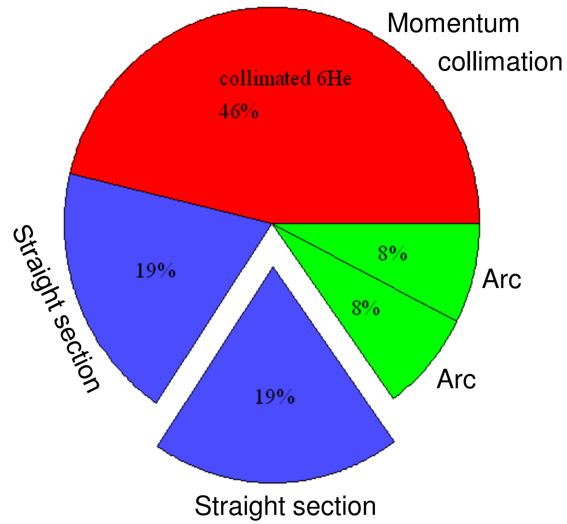


M. Kirk et. al GSI

The coils could support 60 years operation with a EURISOL type beta-beam

Particle turnover in decay ring

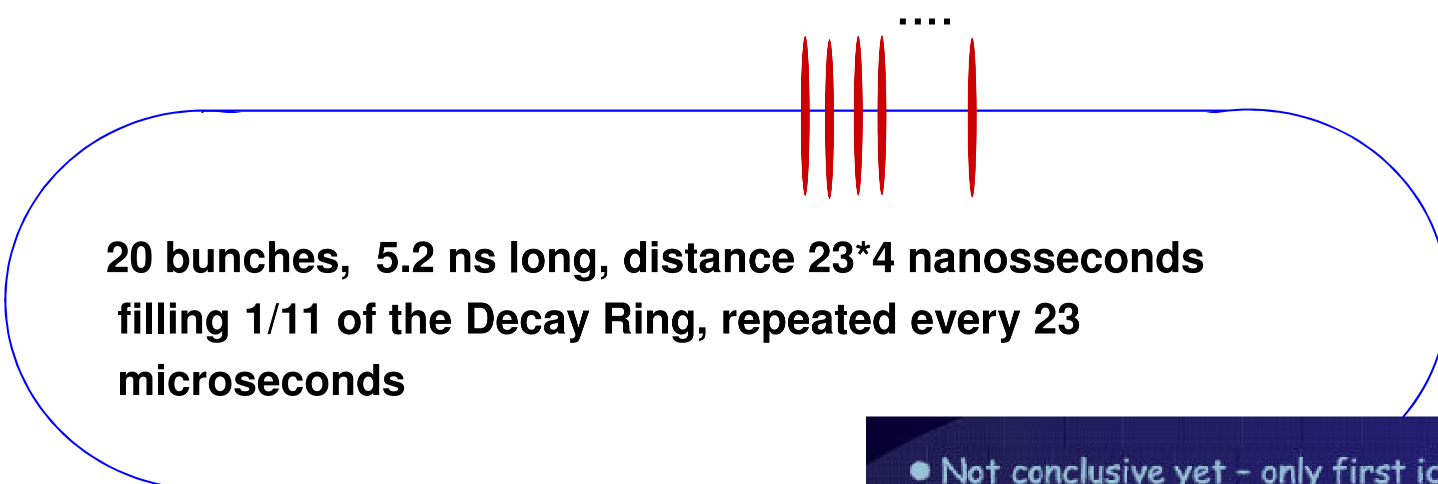




- Momentum collimation (study ongoing):
  - ~5*10^12 ^6He ions to be collimated per cycle
  - Decay: ~5*10^12 ^6Li ions to be removed per cycle per meter
- Dump at the end of the straight section will receive 30kW
- Dipoles in collimation section receive between 1 and 10 kW (masks).

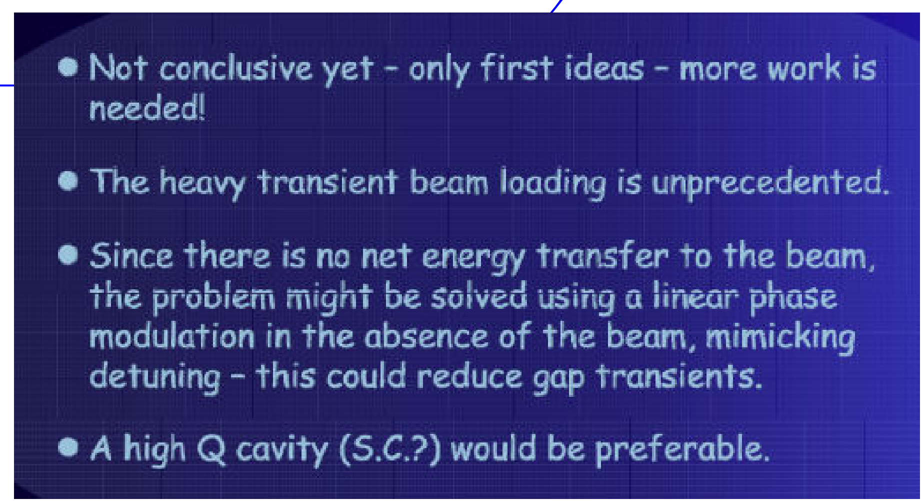
Duty factor and Cavities for He/Ne

10^{14} ions, 0.5% duty (supression) factor for background suppression !!!



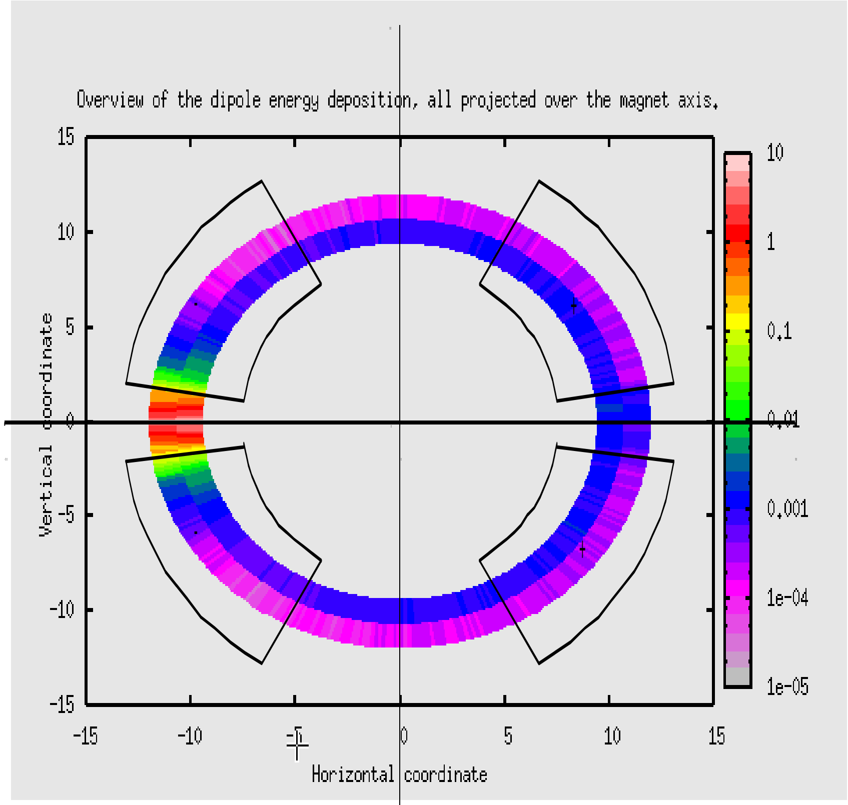
20 bunches, 5.2 ns long, distance 23*4 nanosseconds filling 1/11 of the Decay Ring, repeated every 23 microseconds

Erk Jensen, CERN


- Not conclusive yet – only first ideas – more work is needed!
- The heavy transient beam loading is unprecedented.
- Since there is no net energy transfer to the beam, the problem might be solved using a linear phase modulation in the absence of the beam, mimicking detuning – this could reduce gap transients.
- A high Q cavity (S.C.?) would be preferable.

Open Midplane Dipole for Decay Ring

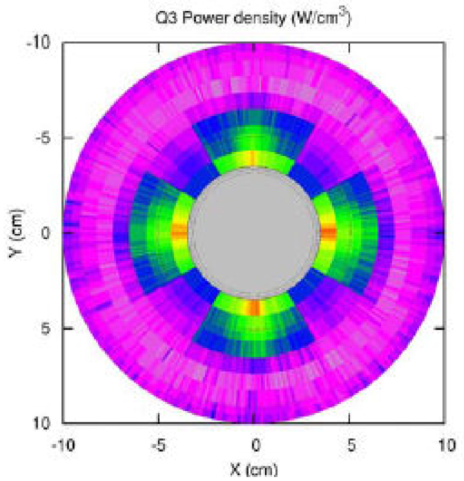
Cosθ design open midplane magnet

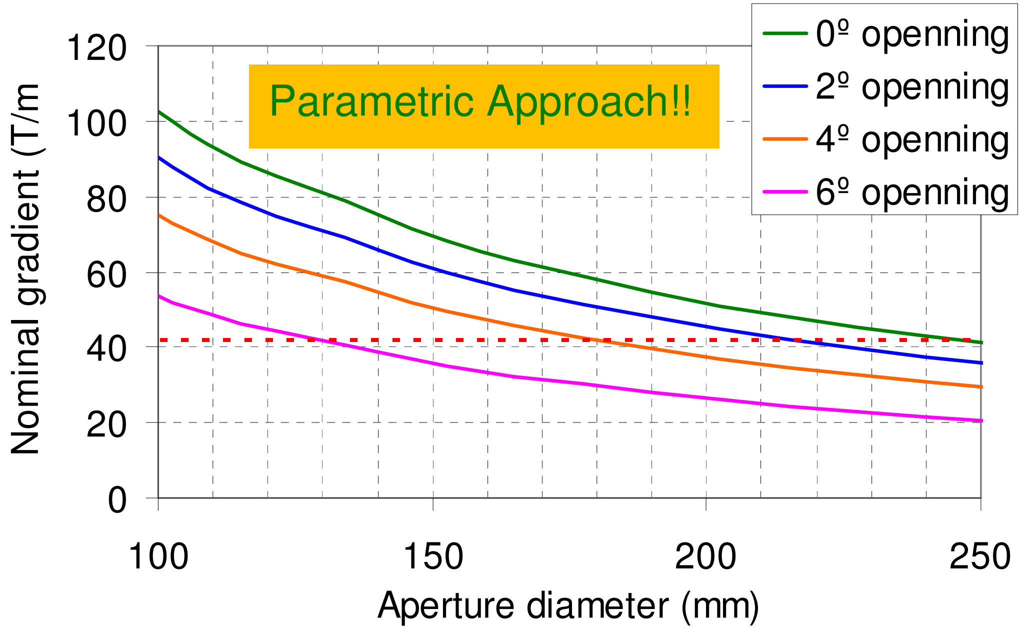


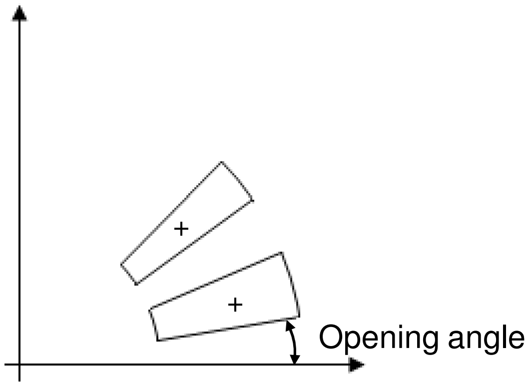
- Manageable (7 T operational) with Nb -Ti at 1.9 K
- Aluminum spacers possible on midplane to retain forces: gives transparency to the decay products
- Special cooling and radiation dumps may be needed inside yoke.

J. Bruer, E. Todesco, E. Wildner, CERN

Open mid-plane Quadrupole







Acknowledgments (magnet design):
F Borgnolutti, E. Todesco (CERN)

Options for production

- ISOL method at 1-2 GeV (200 kW)
  - 2 10^{13} ^{6}He per second
  - <8 10^{11} ^{18}Ne per second
  - Studied within EURISOL
- Direct production
  - >1 10^{13} (?) ^{6}He per second
  - 1 10^{13} ^{18}Ne per second
  - Studied at LLN, Soreq, WI and GANIL
- Production ring
  - 10^{14} (?) ^{8}Li per second
  - >10^{13} (?) ^{8}B per s
  - Studied Within EUROν

Difficult Chemistry

Aimed:

He 2.9 10^{18} (2.0 10^{13}/s)

Ne 1.1 10^{18} (2.0 10^{13}/s)

See talks by T. Stora and S. Mitrofanov

N.B. Nuclear Physics has limited interest in those elements => Production rates not pushed!

Try to get ressources to persue ideas how to produce Ne!

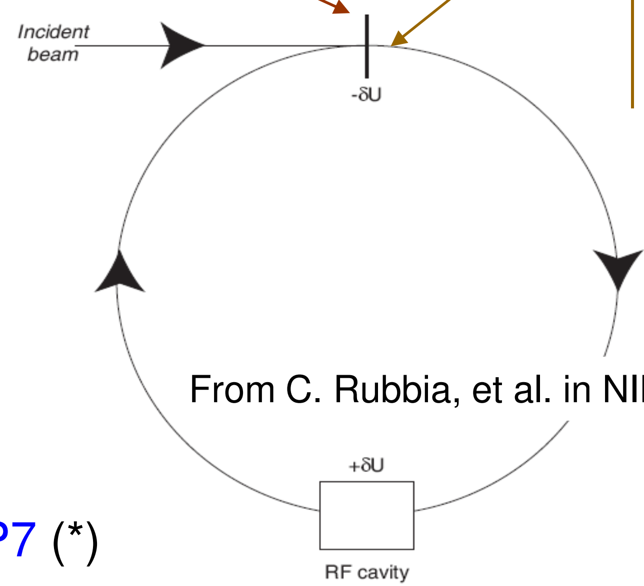
New approaches for ion production

"Beam cooling with ionisation losses" – C. Rubbia, A Ferrari, Y. Kadi and V. Vlachoudis in NIM A 568 (2006) 475–487

"Development of FFAG accelerators and their applications for intense secondary particle production", Y. Mori, NIM A562(2006)591

Supersonic gas jet target, stripper and absorber

^{7}Li
^{6}Li



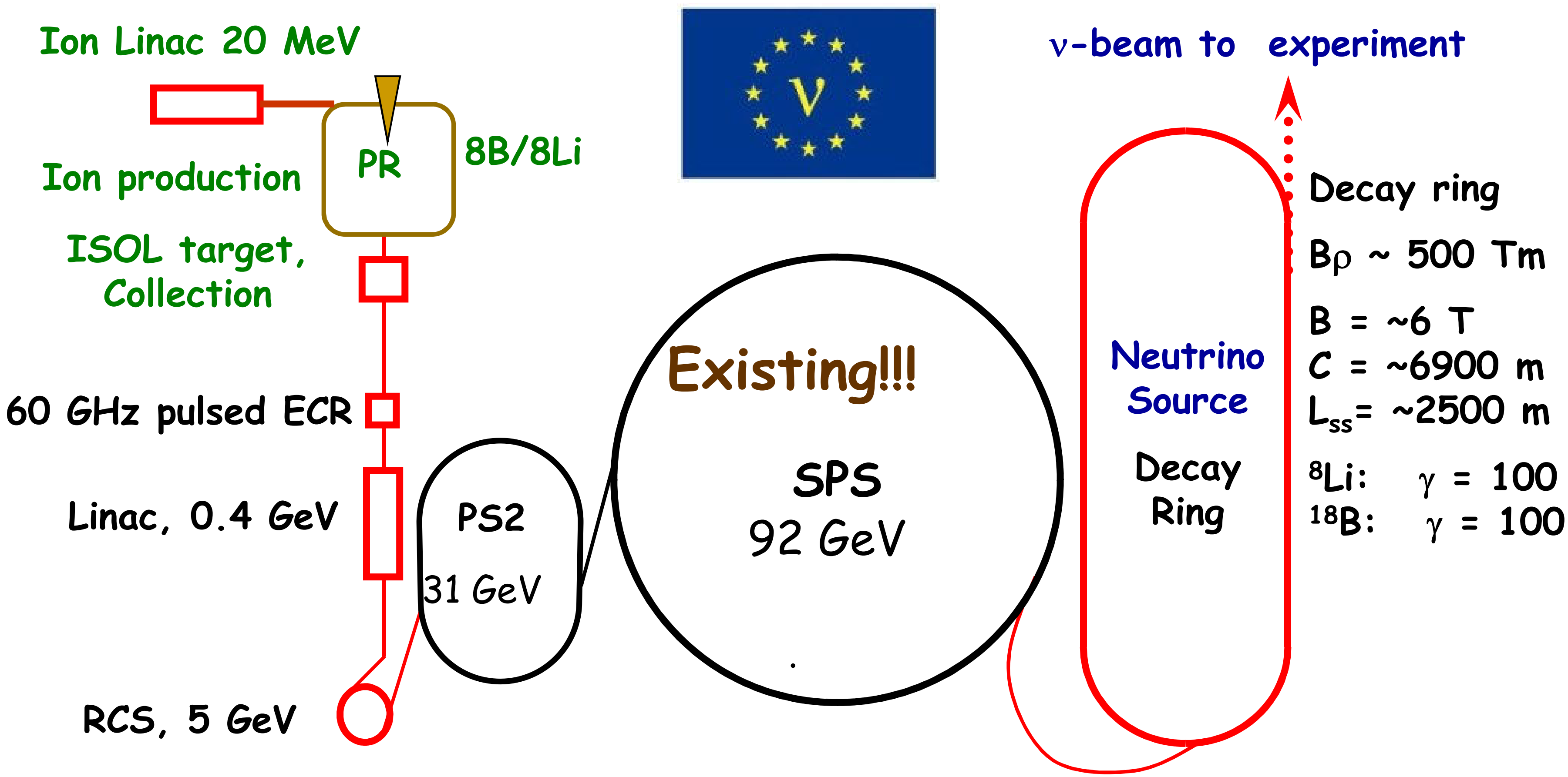
$^{7}Li(d,p)^{8}Li$
$^{6}Li(^{3}He,n)^{8}B$

From C. Rubbia, et al. in NIM A 568 (2006) 475–487

Studied within Euroν FP7 (*)

(*) FP7 "Design Studies" (Research Infrastructures) EUROnu (Grant agreement no.: 212372)

Beta Beam scenario EUROnu, FP7



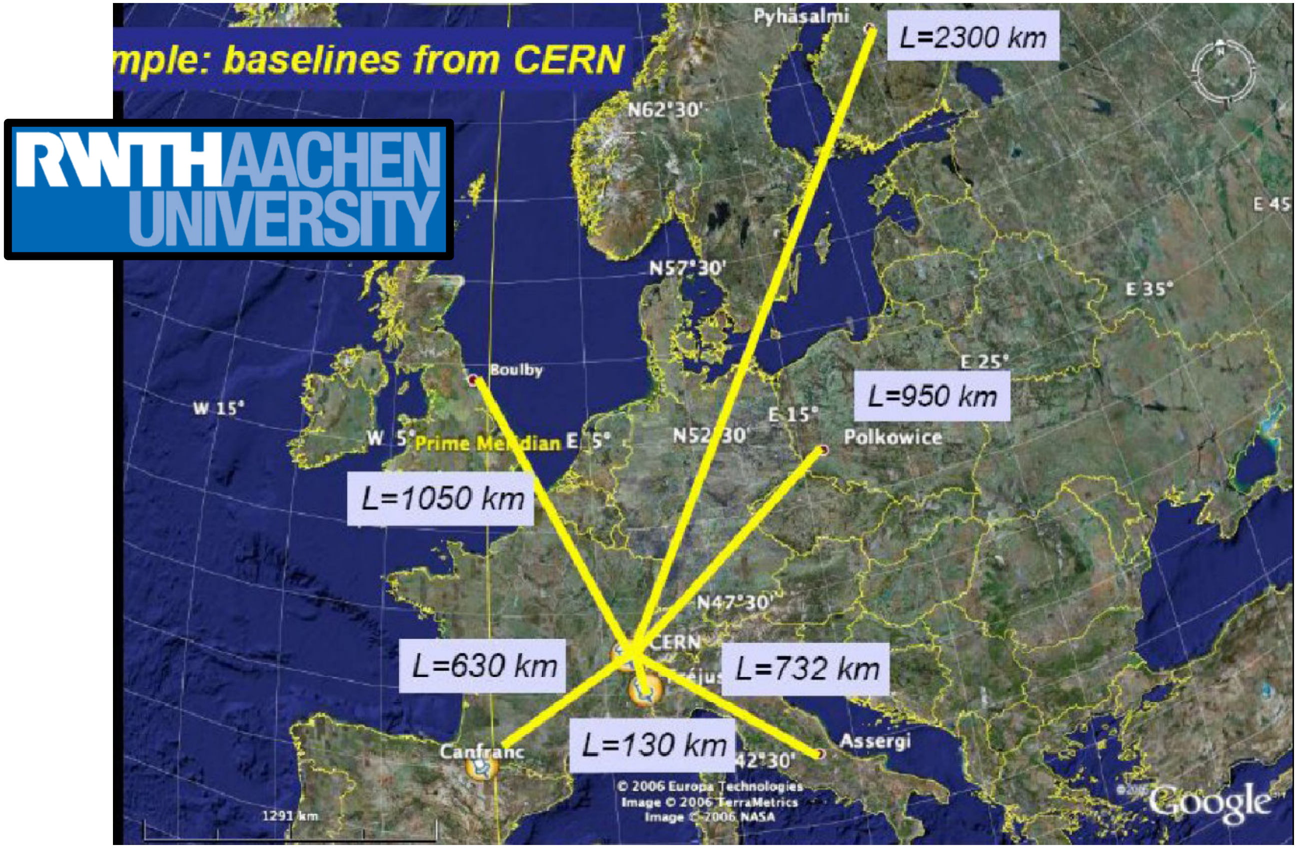
Detector Gran Sasso (~ 5 times higher Q)

The beta-beam in EURONU DS (I)

- The study will focus on production issues for ^{8}Li and ^{8}B
  - ^{8}B is highly reactive and has never been produced as an ISOL beam
  - Production ring: enhanced direct production
    - Ring lattice design (CERN)
    - Ionization Cooling (CERN +)
    - Collection of the produced ions, release efficiencies and cross sections for the reactions (UCL, INFN, ANL)
    - Sources ECR (LPSC, GHMFL)
    - Supersonic Gas injector (PPPL + ?)
- CERN Complex
  - All machines to be simulated with B and Li (CERN, CEA)
  - PS2 presently under design (requirements for beta beams)
  - Multiple Charge State Linacs (P Ostroumov, ANL)

Associated partners in EURONU DS

3-Flavor Oscillation needs two significantly different baselines to disentangle CP and matter effects



Possible realization with one detector only (price)

ν_μ-beam:

SPL: $\langle E_\nu \rangle$ = 260 MeV

L_{opt} = 134 km

CERN – Frejus: 130 km

ν_e-beam:

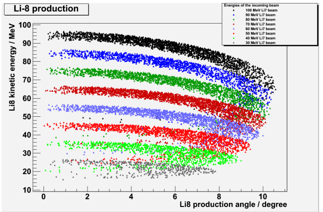
γ = 100 Lopt = 130 km

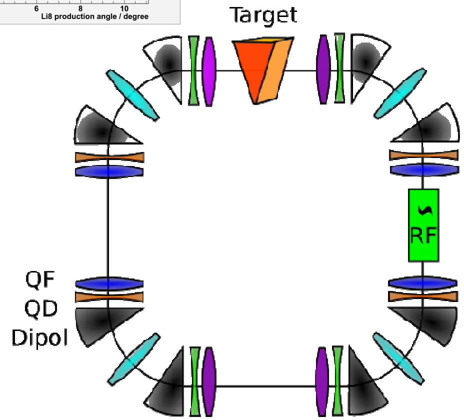
γ = 500 Lopt = 1000 km

CERN – Frejus: 130 km

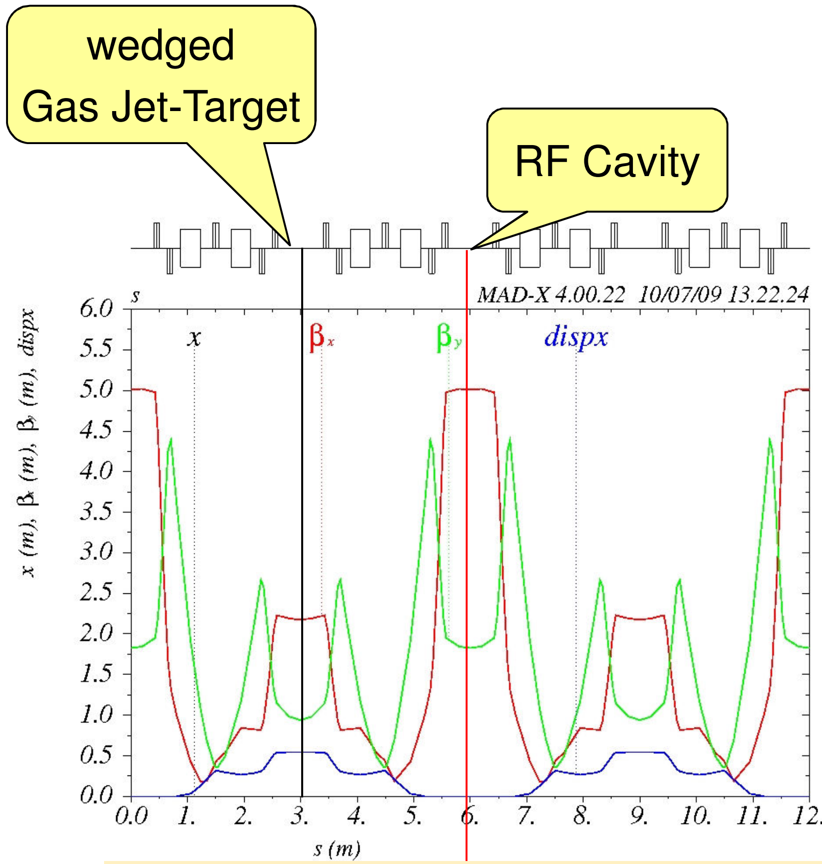
DESY – Frejus: 960 km

The production Ring: Ion Source for Beta Beams





- 12m circumference
- mirror symmetrical structure
- 1.5T dipoles
- 5 quadrupole-families
- Dx = 0 in cavity-section
- best choice of Dx in target-section depends on wedge angle of the target

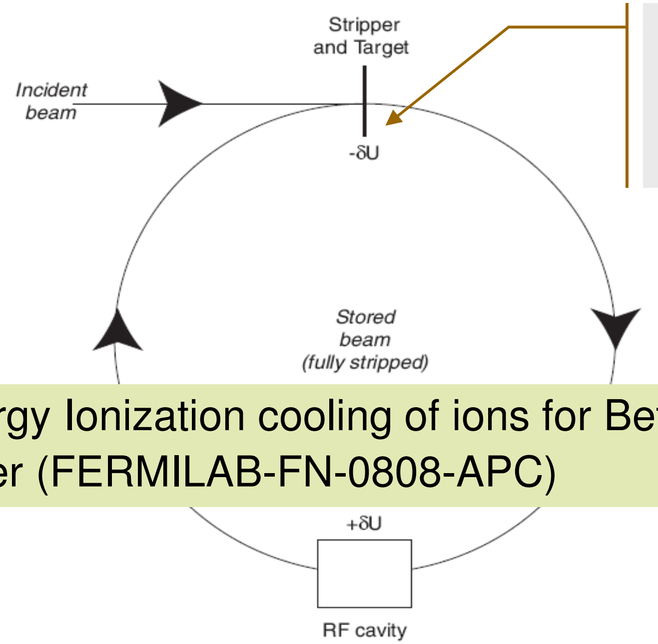


Michaela Schaumann , Aachen/CERN, 2009
Jakob Wehner, Aachen/CERN, 2009
Elena Benedetto, CERN, 2009
See Poster session

The production ring cooling: review

^{7}Li

^{6}Li



$^7Li(d,p)^8Li$

$^6Li(^3He,n)^8B$

Low-energy Ionization cooling of ions for Beta Beam sources – D. Neuffer (FERMILAB-FN-0808-APC)

Mini-workshop on cooling at Fermilab summer 2009
(David Neuffer)
joining teams from CERN and Fermilab

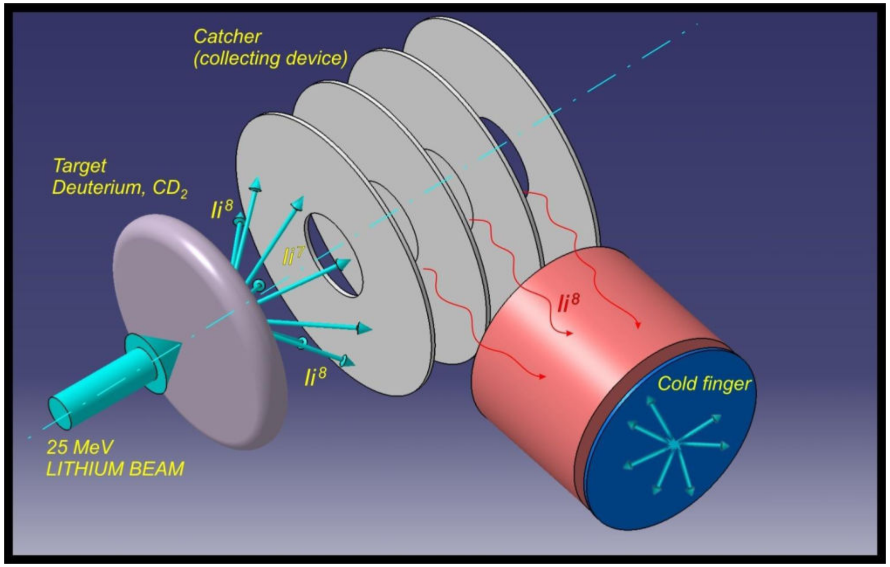
Challenge: collection device

- A large proportion of beam particles (^{6}Li) will be scattered into the collection device.

- Production of ^{8}Li and ^{8}B:

  $^{7}Li(d,p)\,^{8}Li$ and $^{6}Li(^{3}He,n)\,^{8}B$ reactions

  using low energy and low intensity ~ 1nA beams of ^{6}Li(4-15 MeV) and ^{7}Li(10-25 MeV) hitting the deuteron or ^{3}He target.



CRC
Louvain-la-Neuve

- **Semen Mitrofanov**
  (See next talk)

- Thierry Delbar
- Marc Loiselet

Cross section measurements at Laboratori Nazionali di Legnaro

M.Mezzetto (INFN-Pd)
on behalf of
INFN-LNL: M. Cinausero, G. De Angelis, G. Prete

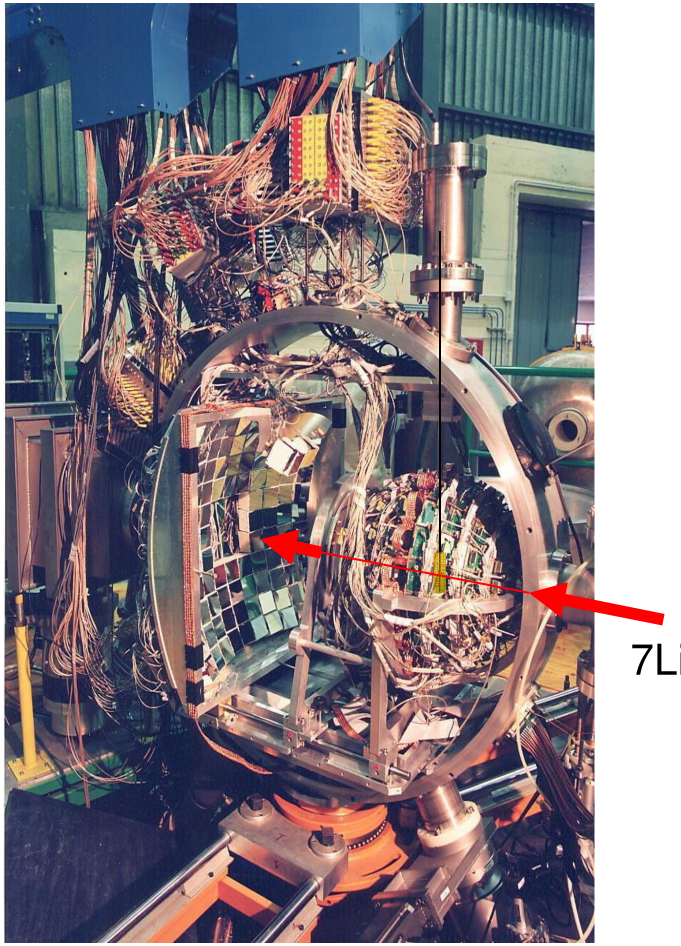
First Experiment performed in July 2008

Inverse kinematic reaction:

$^{7}Li + CD_2$ target E=25 MeV

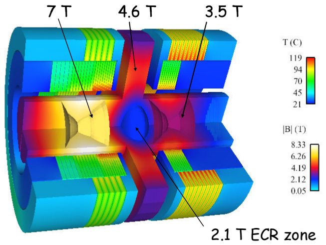
Data reduction in progress

Future: reduce contamination

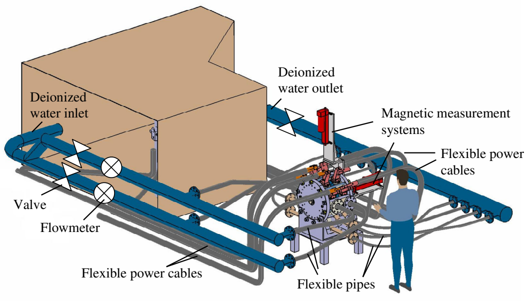


7Li

ECR 60 GHz Source



Courtesy: Thierry Lamy, LPSC



- Source Assembly for October 2009
  - Magnet field measurements at half intensity
- Tests of source at 28 GHz expected in 2010
- Scientific collaboration
  - ISTC (IAP NN, LPSC, LNCMI, CERN, Istituto di Fisica del Plasma)
  - 490 k€ EU + 225 k€ LPSC
  - Gyrotron manufacturing, 60 GHz plasma and beams developments

Associates

- Weizmann Institute of Science, Revohot
  - Michael Hass
  - Partners: GANIL and Soreq
  - Collaboration with Aachen (exchange of students)
- Work Focus
  - produce light radioactive isotopes also for beta beams
  - secondary neutrons from an intense, 40 MeV d beam (6He and 8Li) and direct production with 3He or 4He beams (18Ne).
  - Use of superconducting LINACs such as SARAF at Soreq (Israel) and the driver for SPIRAL-II (GANIL).
- Added Value
  - To produce strong beta beam ion candidates or production methods not in EUROnu

Courtesy Micha Hass

Relaxed Duty Factors for more neutrinos

0.5% duty factor for background suppression could be relaxed for higher neutrino energies.

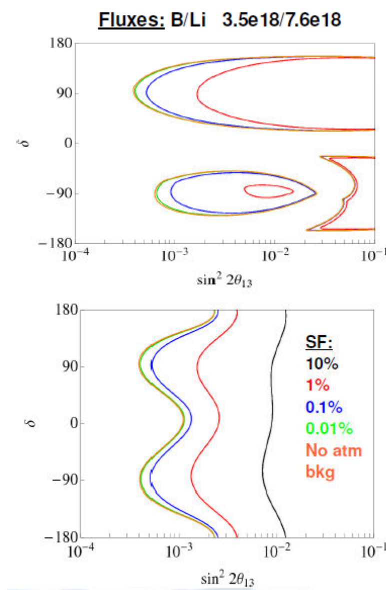
....

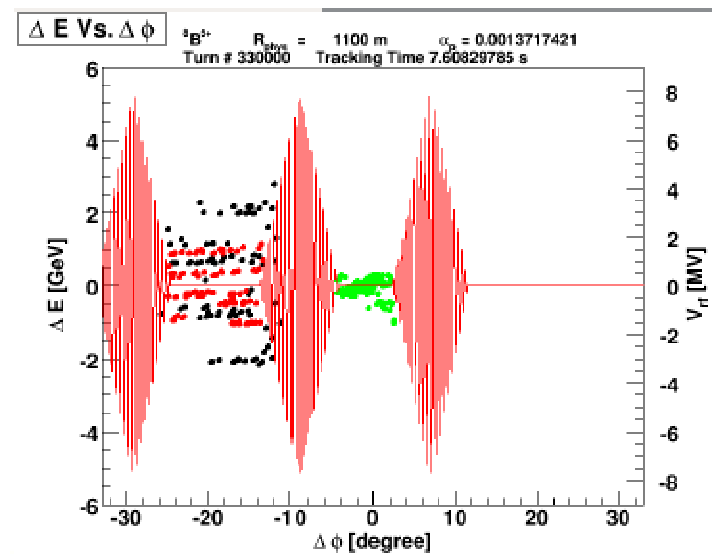
But not enough to profit of Barrier Buckets for B and Li!
We need in addition more flux for high-Q ions.

Christian Hansen

Enrique Fernandez-Martinez

See Poster session





High γ and decay-ring size, ^{6}He

Gamma	Rigidity [Tm]	Ring length T=5 T f=0.36	Dipole Field rho=300 m Length=6885m
100	938	4916	3.1
150	1404	6421	4.7
200	1867	7917	6.2
350	3277	12474	10.9
500	4678	17000	15.6

Magnet R&D

Example : *Neutrino oscillation physics with a higher γ β-beam*, arXiv:hep-ph/0312068
J. Burguet-Castell, D. Casper, J.J. Gomez-Cadenas, P.Hernandez, F.Sanchez

Beta Beams at Fermilab

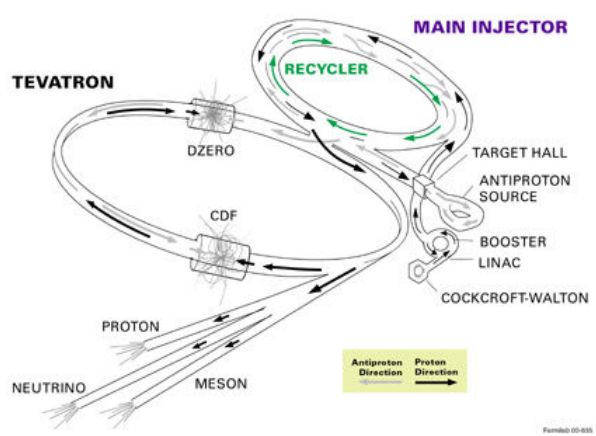
Jansson, Mena, Parke & Saoulidou hep-ph/0711107

Combining CPT-conjugate neutrino channels at the same E/L to determine only the neutrino mass hierarchy

$$P(\nu_\mu \to \nu_e) > P(\bar{\nu}_e \to \bar{\nu}_\mu) \quad \text{for Normal Hierarchy}$$

$$\text{and} \quad P(\nu_\mu \to \nu_e) < P(\bar{\nu}_e \to \bar{\nu}_\mu) \quad \text{for Inverted Hierarchy,}$$

The neutrino channel, nu_mu -> nu_e, would use the existing NuMI beamline
Whereas the anti-neutrino channel, nubar_e -> nubar_mu, would come from 6He or 8Li Beta beams



For 6He the Tevatron (1 TeV) gives a gamma=350 and one can use the NOvA detector (810 km)
Whereas for 8Li the Main Injector (120 GeV) is used for a gamma=55 and baseline needs to be 300 km (new detector)

Optimized Two-Baseline Beta Beam

Courtesy: Sandhya Choubey

- Beams from He/Ne with $\gamma = 350$ sent to a 500 kton WC detector at $L = 650$ km (CERN-Canfranc) for 2.5 years each
- Beams from Li/B sent to a 50 kton iron calorimeter at $L = 7000$ km (CERN-INO) for 2.5 years each
- The magic baseline option requires a storage ring with dip angle 34°; that is a challenge for a very large storage ring

Choubey, Coloma, Donini, Fernandez-Martinez (2009)

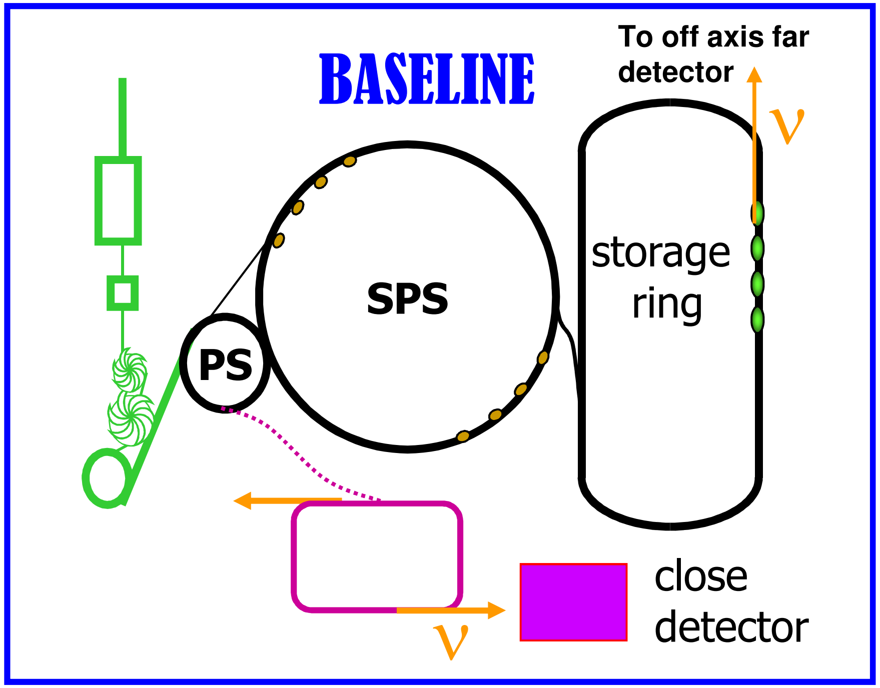
Outperforms the Neutrino Factory for $\sin^2 2\theta_{13} \gtrsim 10^{-3}$

Low energy Beta Beams

Christina Volpe:

A proposal to establish a facility for the production of intense and pure low energy neutrino beams (100 MeV).

J Phys G 30 (2004) L1.



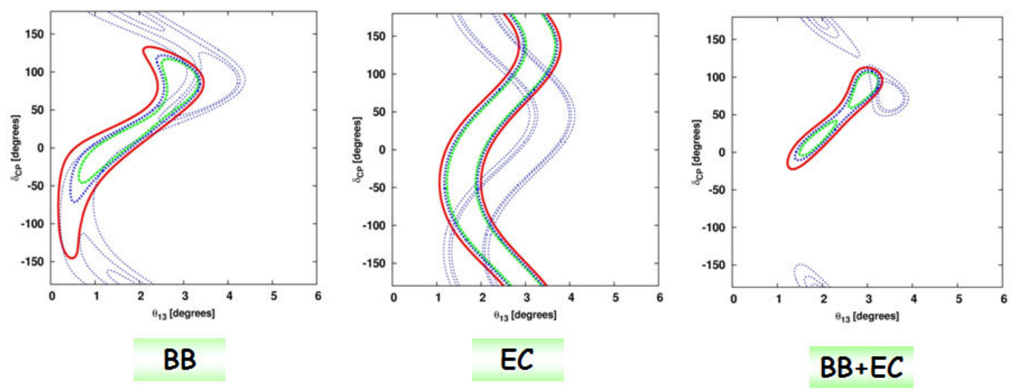
PHYSICS POTENTIAL

- ν-nucleus cross sections (detector's response, r-process, 2β-decay)
- fundamental interactions studies (Weinberg angle, CVC test, μ_ν)
- astrophysical applications

PHYSICS STUDIED WITHIN THE EURISOL Design Study (FP6, 2005-2009)

The virtues of combining energies from BB and EC

- Sensitivity to θ_{13} and δ (CERN to Gran Sasso or Canfranc)



$^{156}_{70}Yb$ Long lifetime, difficult to make, space charge ?

J. Bernabeu, C. Espinosa, C. Orme, S. Palomares-Ruiz and S. Pascoli
based on JHEP 0906:040, 2009

Summary (i)

- **The EURISOL beta-beam conceptual design report will be presented during 2009**

  (^{6}He and ^{18}Ne , gamma 100)
  - First coherent study of a beta-beam facility
  - Top down approach
  - 18Ne shortfall as of today
  - Duty Factors are challenging:

    Collimation and RF in Decay Ring

Summary (ii)

- A beta-beam facility using ^{8}Li and ^{8}B (EUROnu) (gamma 100)
  - Experience from EURISOL
  - Production issues (pay attention to 18Ne)
  - Optimize chain
  - Revisit Duty Factors, RF and bunch structures
  - Acceptance of PS2
  - (Complete) simulation of beta beam complex
  - Costing
  - **First results will come from Euronu DS (2008-2012)**

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FP6 "Structuring the European Research Area" programme (CARE, contract number RII3-CT-2003-506395) and FP7 “Design Studies” (Research Infrastructures) EUROnu (Grant agreement no.: 212372)

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…

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