NuFact09

Beta Beams

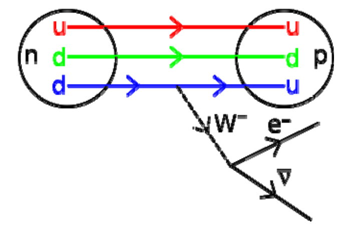
Elena Wildner, CERN

NuFact09, July 20-25, 2009 — Illinois Institute of Technology — Chicago

Outline

- Beta Beam Concepts
- A Beta Beam Scenario
- Ion Production
- Other challenges
- Conclusion

Beta-beams, recall

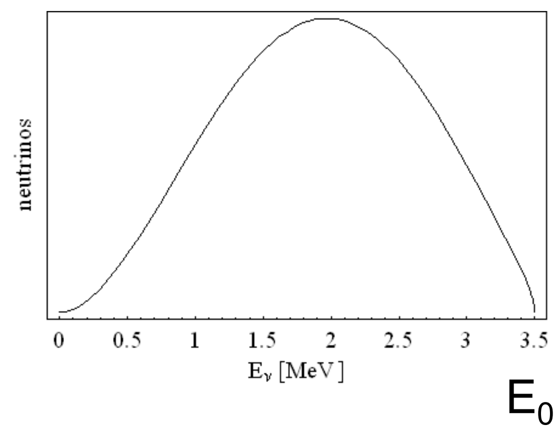


Aim: production of (anti-)neutrino beams from the beta decay of radio-active ions circulating in a storage ring

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

Beta-decay at rest

- ν–spectrum well known from the electron spectrum
- Reaction energy Q typically of a few MeV

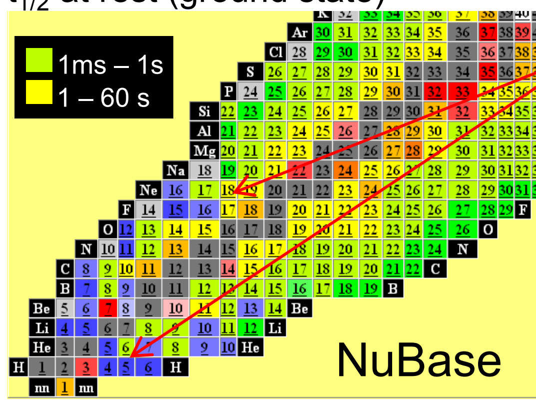


- Accelerate parent ion to relativistic γ_{max}
  - Boosted neutrino energy spectrum: $E_\nu \leq 2\gamma Q$
  - Forward focusing of neutrinos: $\theta \leq 1/\gamma$
- Pure electron (anti-)neutrino beam!
  - Depending on β^+- or β^-- decay we get a neutrino or anti-neutrino
  - Two different parent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

Choice of radioactive ion species

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

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



6He and 18Ne

8Li and 8B

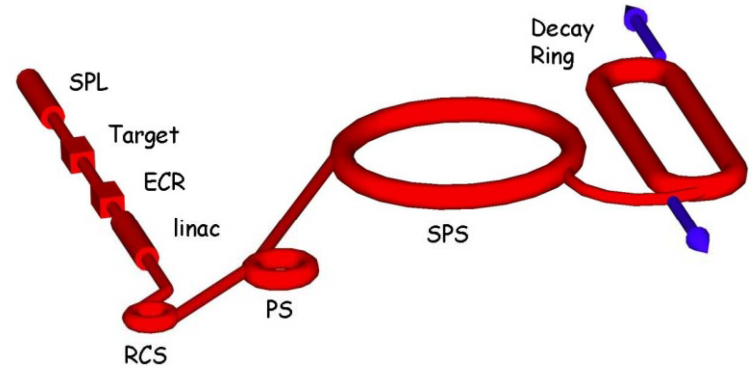
Isotope	A/Z	T ½ (s)	Q_β g.s to g.s (MeV)	Q_β eff (MeV)	E_β av (MeV)	E_ν av (MeV)	Ions/bunch	Decay rate	rate / $E_{\nu\ av}$ (s^{-1})
^{6}He	3.0	0.80	3.5	3.5	1.57	1.94	$5 \cdot 10^{12}$	[illegible]	[illegible]
^{8}He	4.0	0.11	10.7	9.1	4.35	4.80	$5 \cdot 10^{12}$	[illegible]	[illegible]
^{8}Li	2.7	0.83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

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	$2 \cdot 10^{12}$	$2 \cdot 10^{10}$	$2 \cdot 10^{9}$
^{10}C	1.7	19.3	2.6	1.9	0.81	1.08	$2 \cdot 10^{12}$	$6 \cdot 10^{8}$	$6 \cdot 10^{8}$
^{14}O	1.8	70.6	4.1	1.8	0.78	1.05	$1 \cdot 10^{12}$	$1 \cdot 10^{8}$	$1 \cdot 10^{8}$
^{15}O	1.9	122.	1.7	1.7	0.74	1.00	$1 \cdot 10^{12}$	$7 \cdot 10^{7}$	$7 \cdot 10^{7}$
^{18}Ne	1.8	1.67	3.3	3.0	1.50	1.52	$1 \cdot 10^{12}$	$4 \cdot 10^{9}$	$3 \cdot 10^{9}$
^{19}Ne	1.9	17.3	2.2	2.2	0.96	1.25	$1 \cdot 10^{12}$	$4 \cdot 10^{8}$	$3 \cdot 10^{8}$
^{21}Na	1.9	22.4	2.5	2.5	1.10	1.41	$9 \cdot 10^{11}$	$3 \cdot 10^{8}$	$2 \cdot 10^{8}$

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*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 will study ^{8}Li and ^{8}B

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

Some scaling

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

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

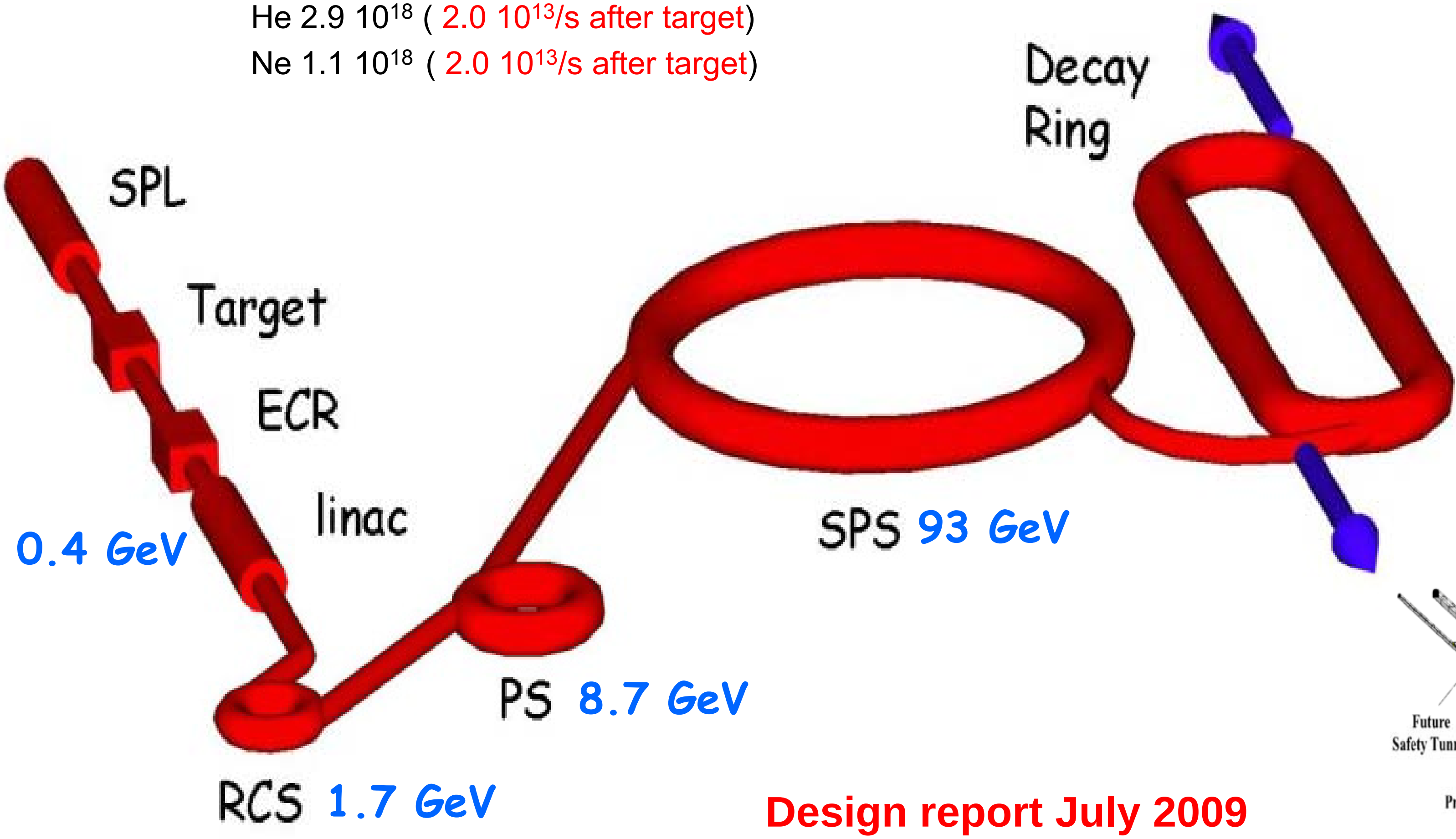
B = ~6 T

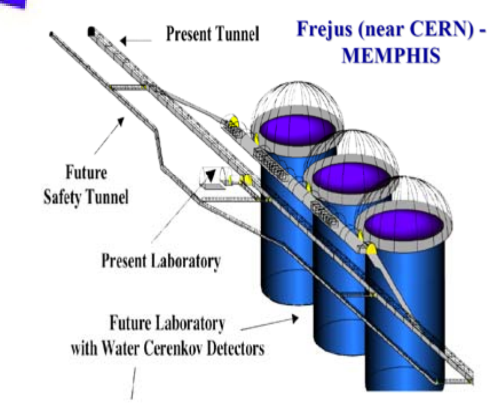
C = ~6900 m

L_{ss}= ~2500 m

^{6}He: γ = 100

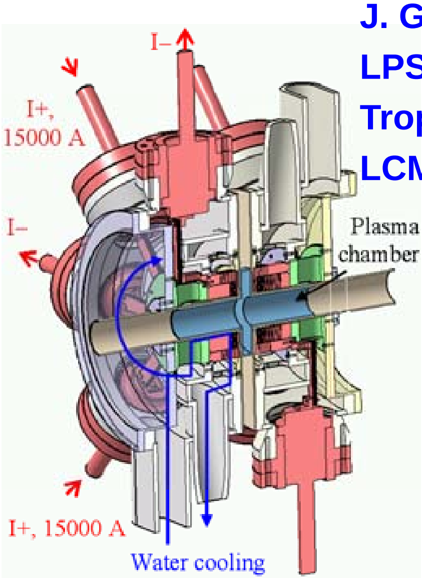
^{18}Ne: γ = 100





Design report July 2009

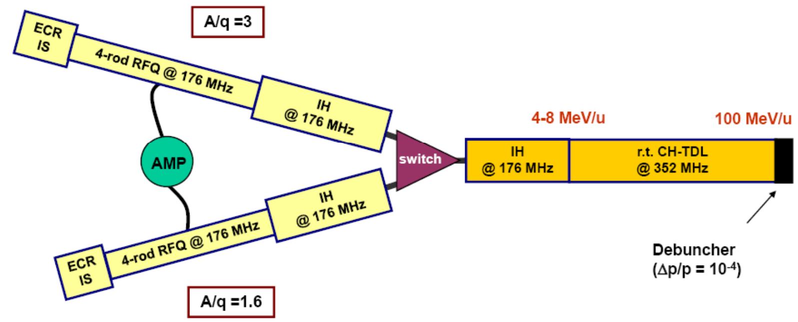
ECR, Linac, RCS, Decay Ring (Nufact08)

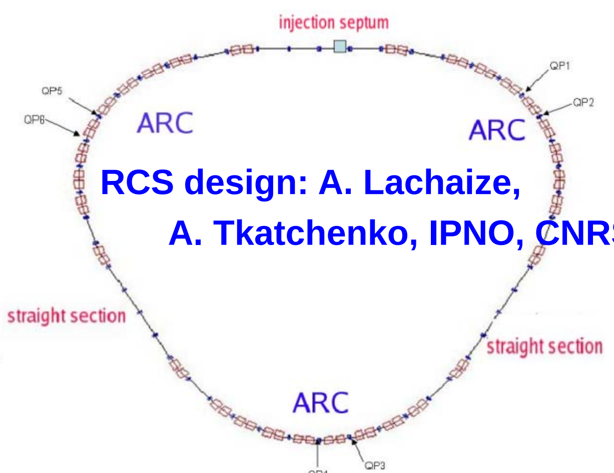


T.Thuillier, L. Latrasse, T. Lamy, C. Fourel,
J. Giraud,
LPSC, CNRS/IN2P3-UJF-INP Grenoble,
Trophime, P. Sala, J. Dumas, F. Debray
LCMI, CNRS, Grenoble

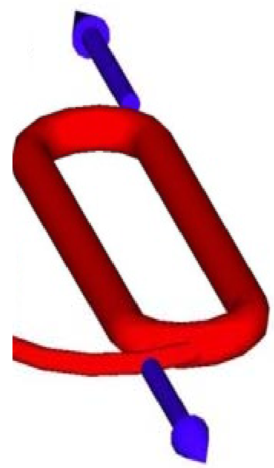
EURISOL
Design Study

LINAC Design: A. Bechtholt,
Franfurt am Main



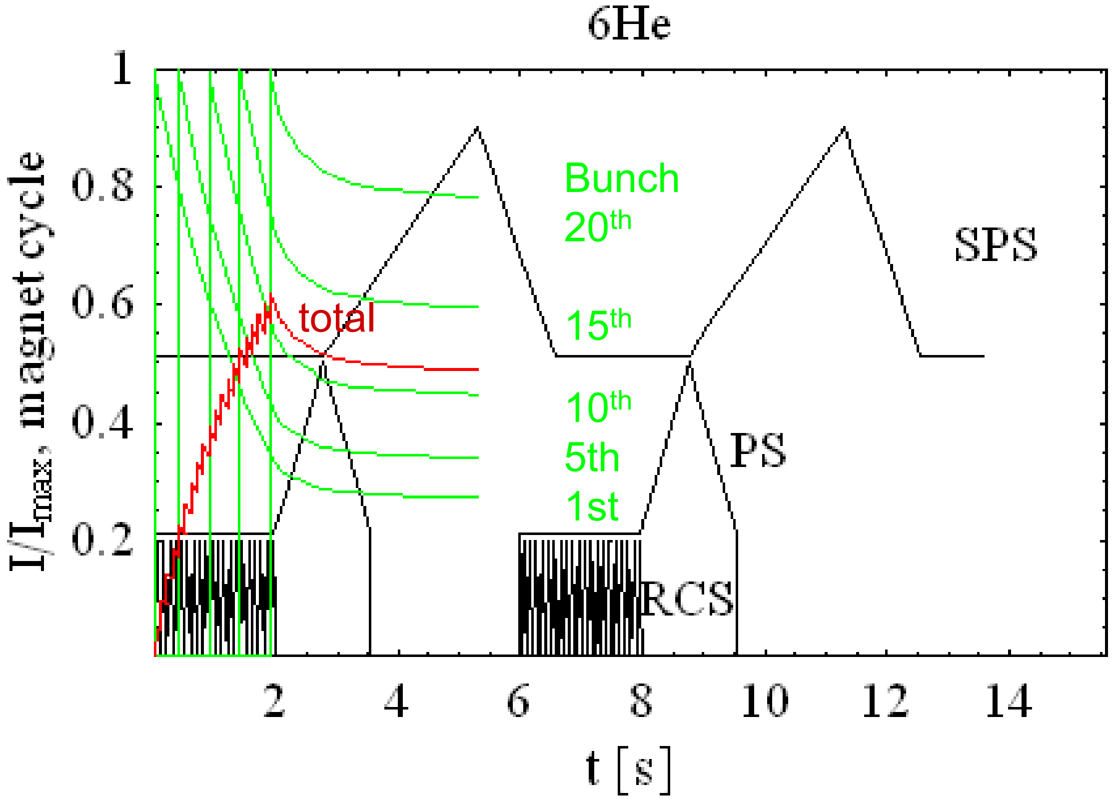


RCS design: A. Lachaize,
A. Tkatchenko, IPNO, CNRS



Antoine CHANCÉ,
Jacques Payet
CEA Saclay IRFU/SACM

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)
1 hour	15	10	-	5.4
1 day	3	6	-	2.6
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)

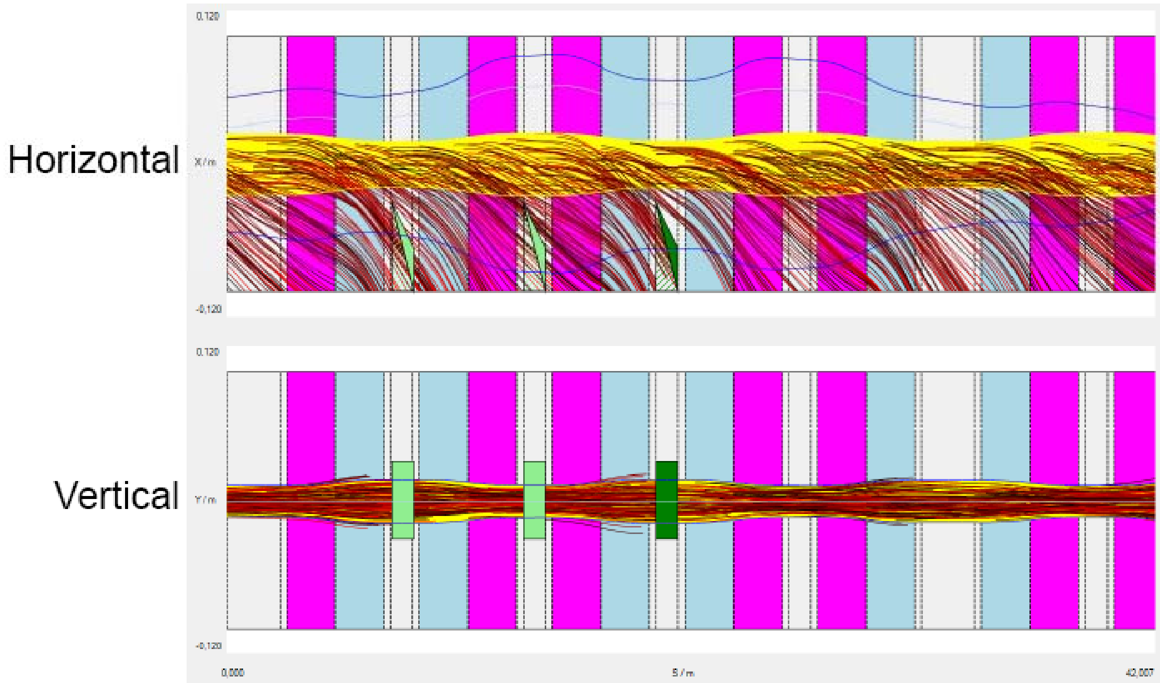
Stefania Trovati, Matteo Magistris, CERN

Activation and coil damage in the PS

StrahlSim: Losses

Beta Beams in EURISOL

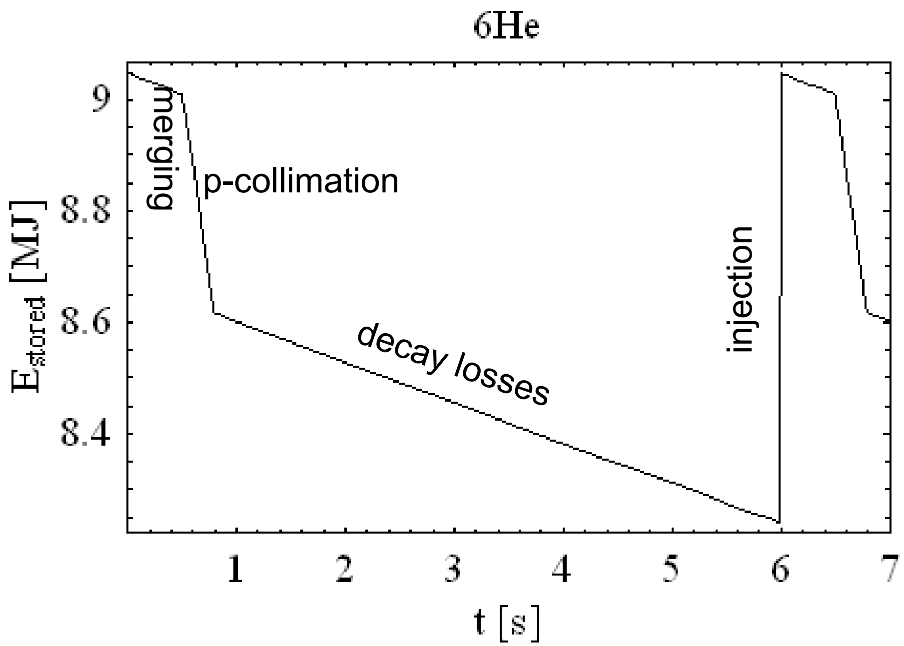
He-beam. Decay products tracked to the collimator and beampipe (red & black curves).

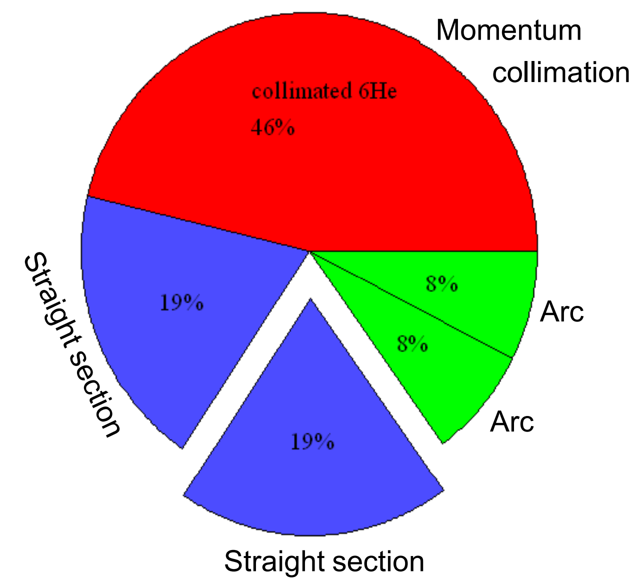


M. Kirk et. al GSI

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

Particle turnover in decay ring

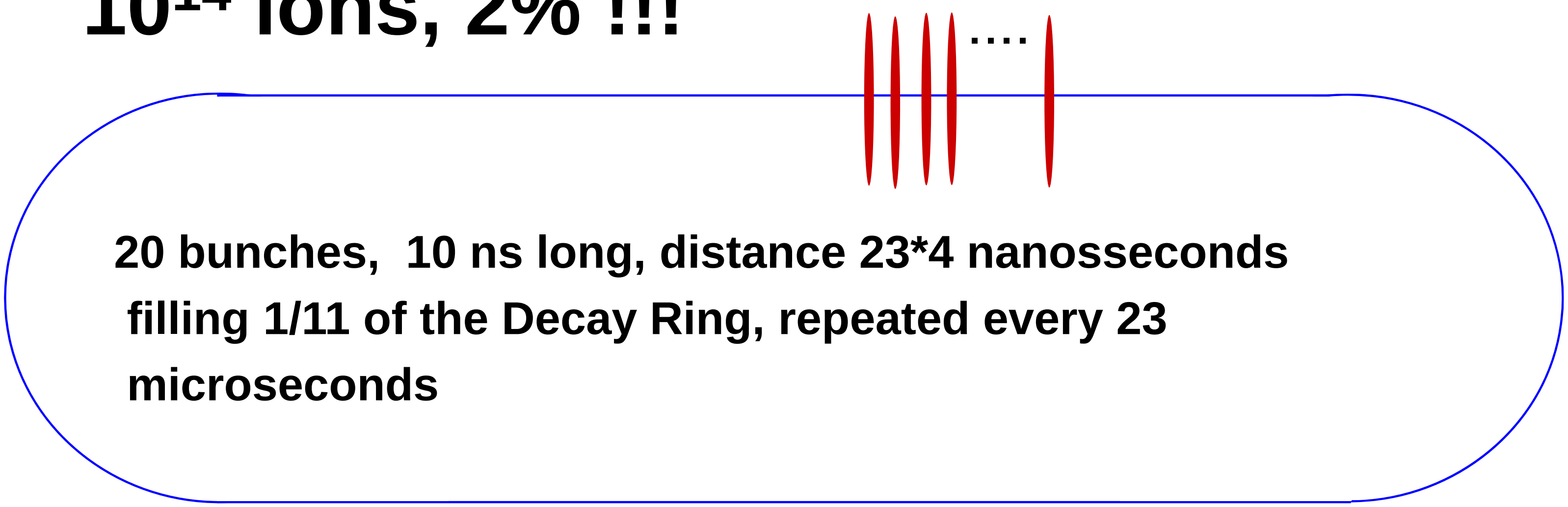




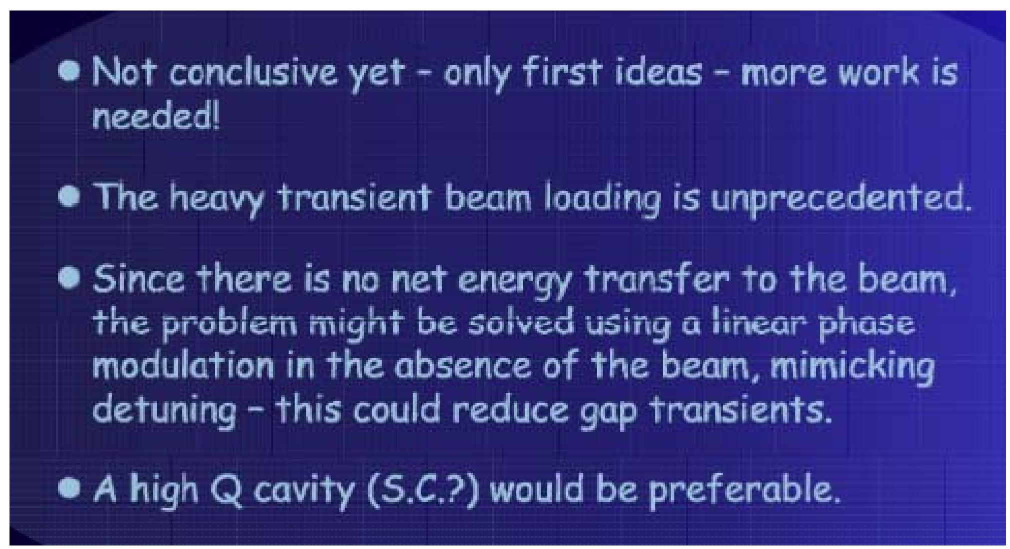
- Momentum collimation (study ongoing):
  - ~5*10^{12} ^{6}He ions to be collimated per cycle
  - Decay: ~5*10^{12} ^{6}Li ions to be removed per cycle per meter

Duty factor and Cavities for He/Ne

10^{14} ions, 2% !!!



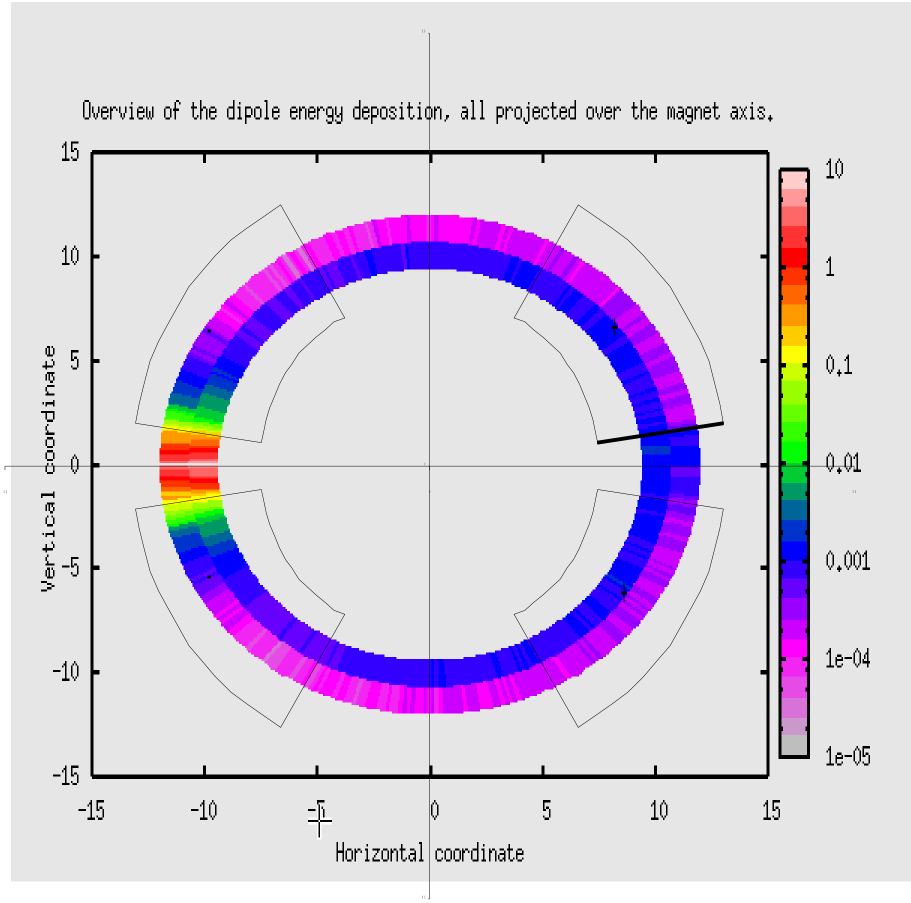
Erk Jensen, CERN



- 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

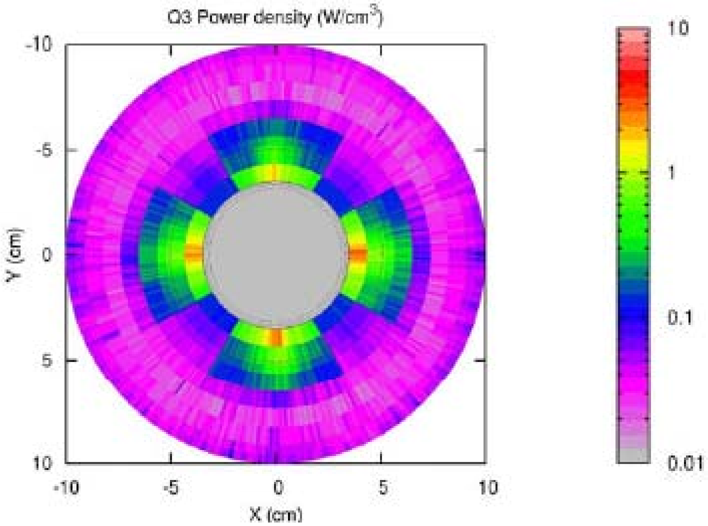
Cos2θ design open midplane magnet

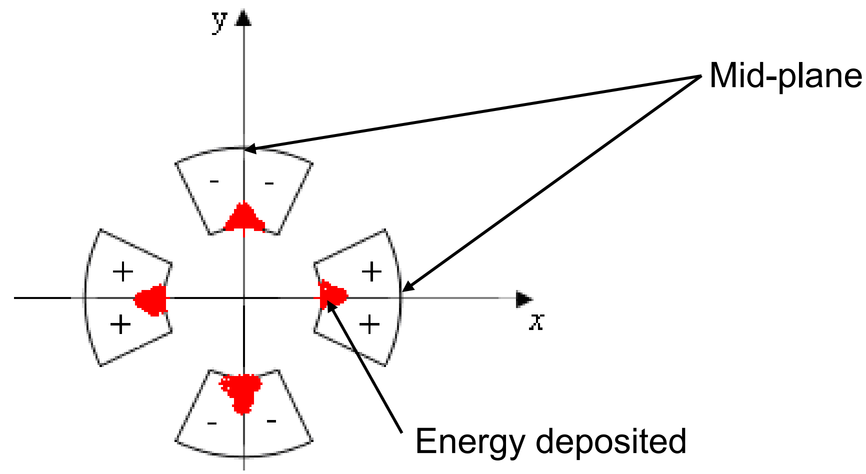


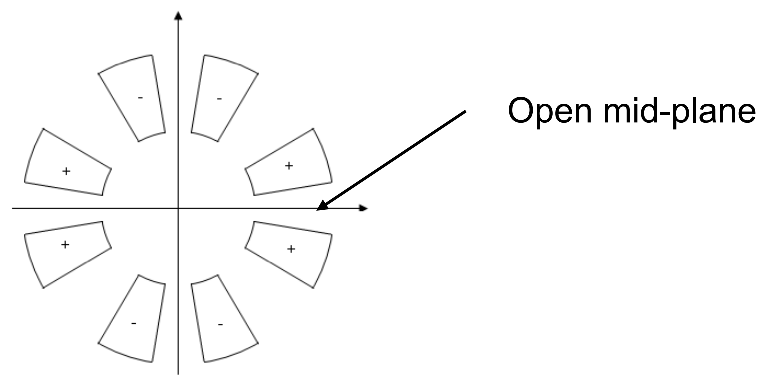
J. Bruer, E. Todesco, CERN

- 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.

Open mid-plane Quadrupole

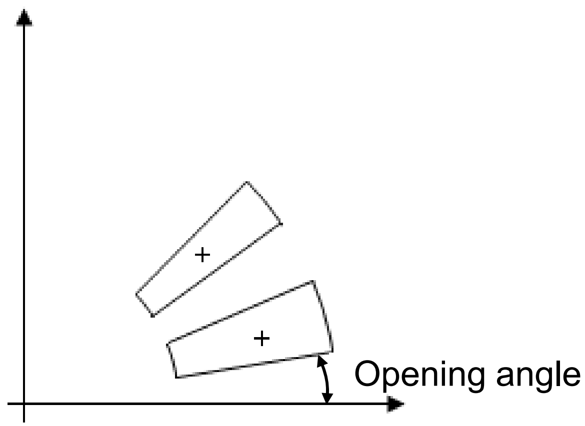


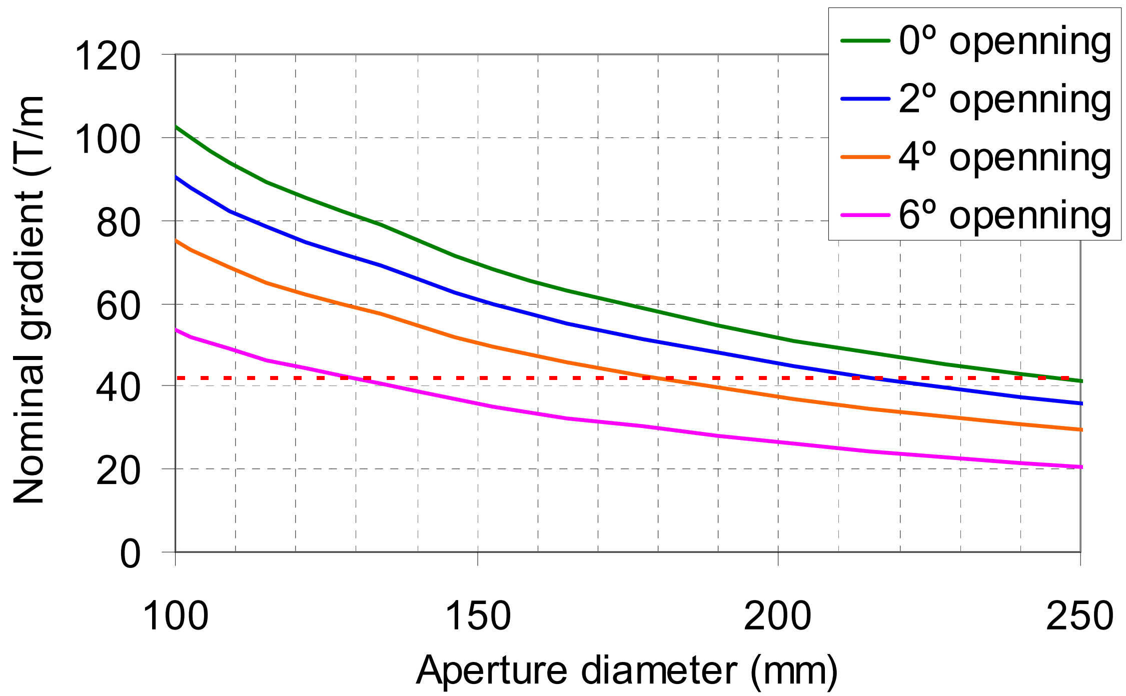




Acknowledgments (magnet design):
F Borgnolutti, E. Todesco (CERN)

Open mid-plane Quadrupole





Acknowledgments (magnet design):
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Options for production

- ISOL method at 1-2 GeV (200 kW)
  - >1 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
  - >10^{13} (?) ^{8}B
  - Will be studied Within EUROν

Aimed:

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

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

Courtesy M. Lindroos

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!

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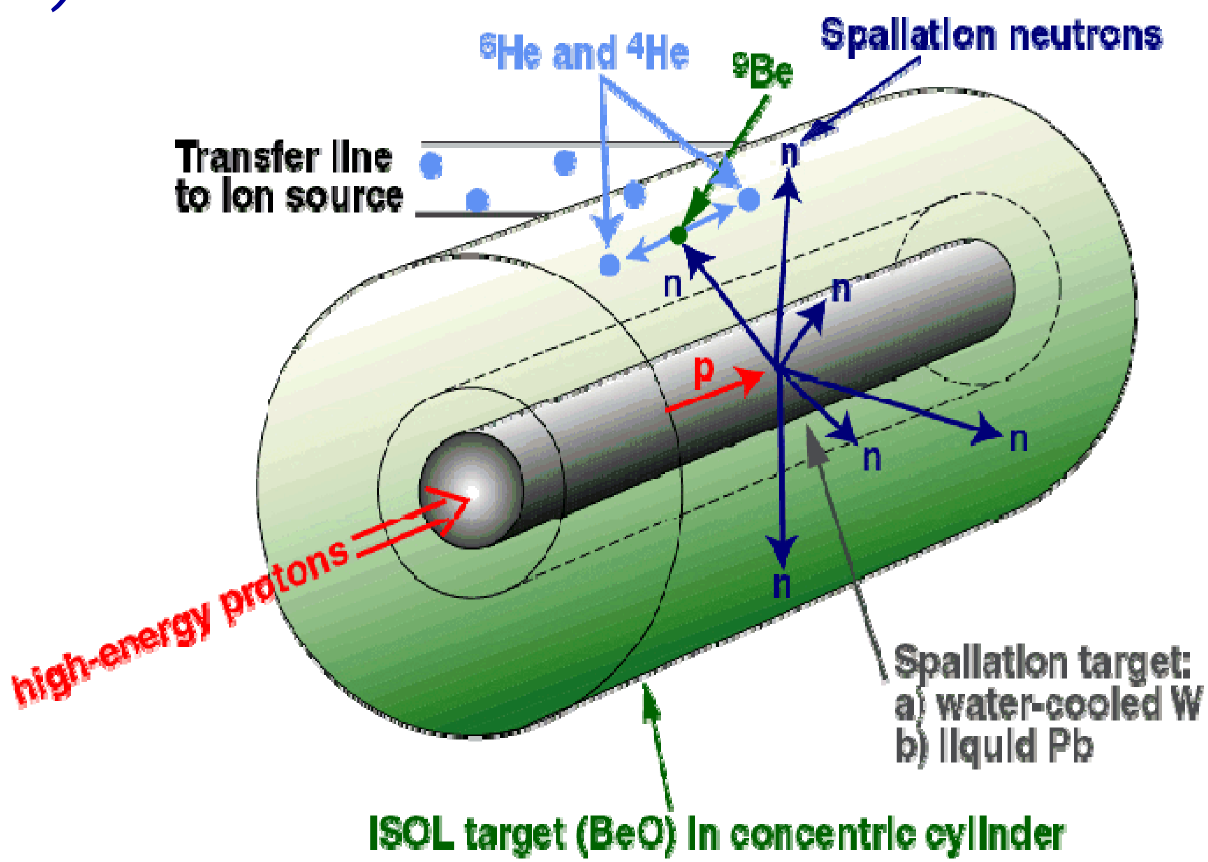
^6He (ISOL)



Converter technology:
(*J. Nolen, NPA 701 (2002) 312c*)

T. Stora, N. Thollieres, CERN

- Converter technology preferred to direct irradiation (heat transfer and efficient cooling allows higher power compared to insulating BeO).
- ^6He production rate is ~2x10^{13} ions/s (dc) for ~200 kW on target.

Recent measurements at ISOLDE

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Courtesy M. Lindroos

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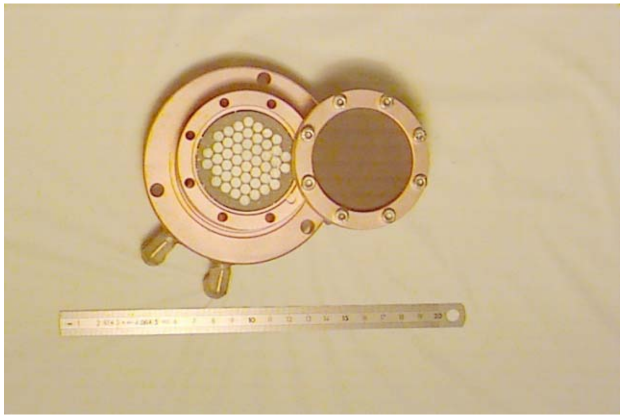
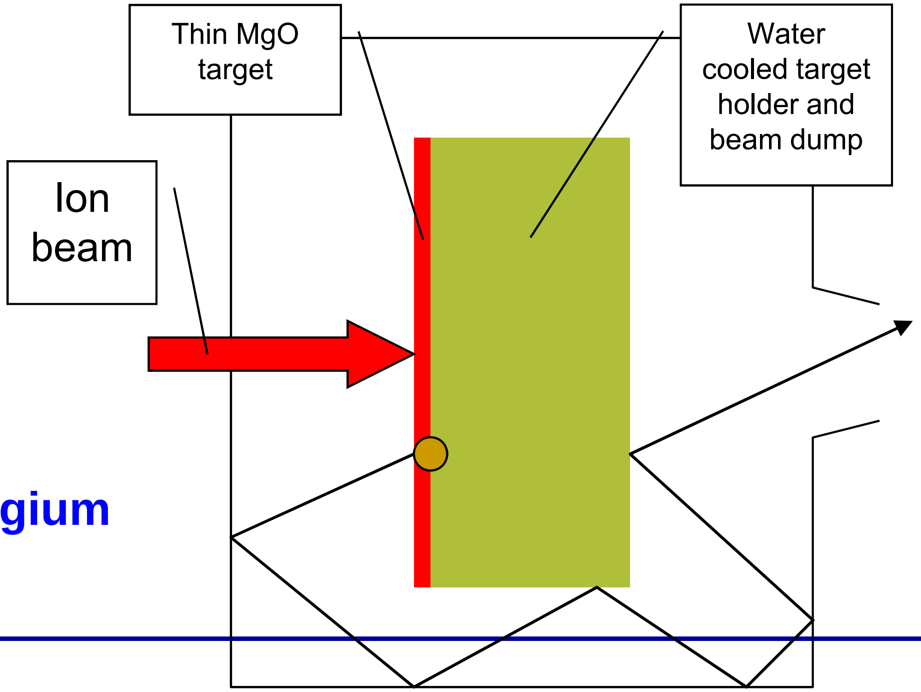
^{18}Ne (Direct Production)

Geometric scaling



- Producing 10^{13} ^{18}Ne could be possible with a beam power (at low energy) of 2 MW (or some 130 mA ^{3}He beam on MgO).
- To keep the power density similar to LLN (today) the target has to be 60 cm in diameter.
- To be studied:
  - Extraction efficiency
  - Optimum energy
  - Cooling of target unit
  - High intensity and low energy ion linac
  - High intensity ion source

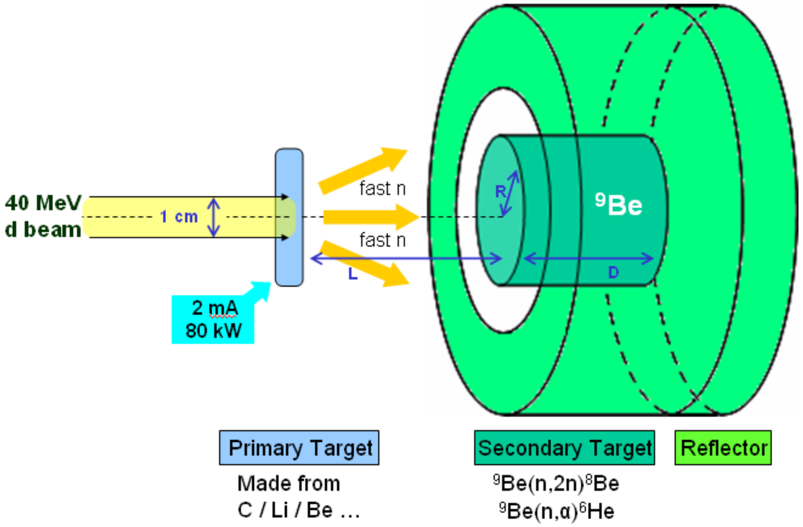


S. Mitrofanov and M. Loislet at CRC, Belgium

T. Stora, CERN, 2009 -> ?

^{6}He (Two Stage ISOL)

- Studied $^{9}Be(n,\alpha)^{6}He$, $^{11}B(n,\alpha)^{8}Li$ and $^{9}Be(n,2n)^{8}Be$ production
- For a 2 mA, 40 MeV deuteron beam, the upper limit for the ^{6}He production rate via the two stage targets setup is $\sim 6 \cdot 10^{13}$ atoms per second.
- Interesting also for ^{8}Li



T.Y.Hirsh, D.Berkovits, M.Hass (Soreq, Weizmann I.)

It seems we can produce plenty of antineutrinos…

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Difficult Chemistry

Aimed:

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Courtesy M. Lindroos

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New approaches for ion production

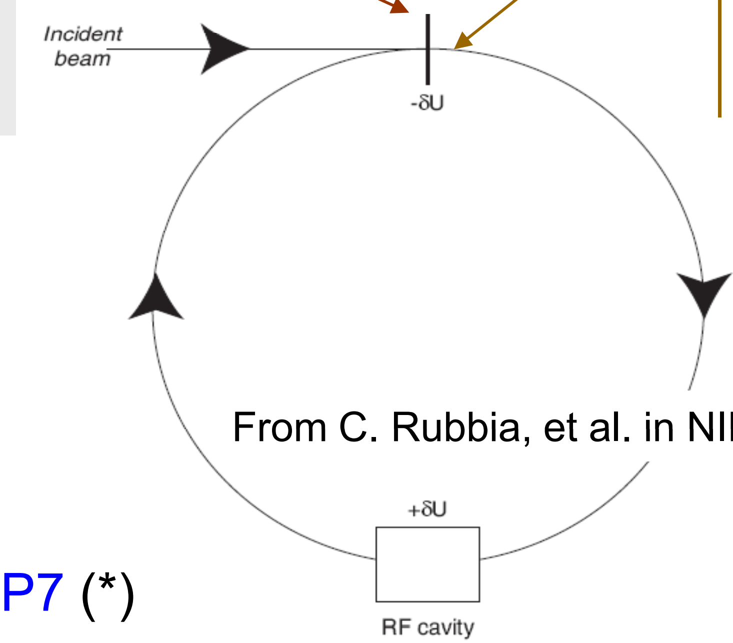
"Beam cooling with ionisation losses" – C. Rubbia, A Ferrari, Y. Kadi and V. Vlachoudis in NIM A 568 (2006) 475–487

"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

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

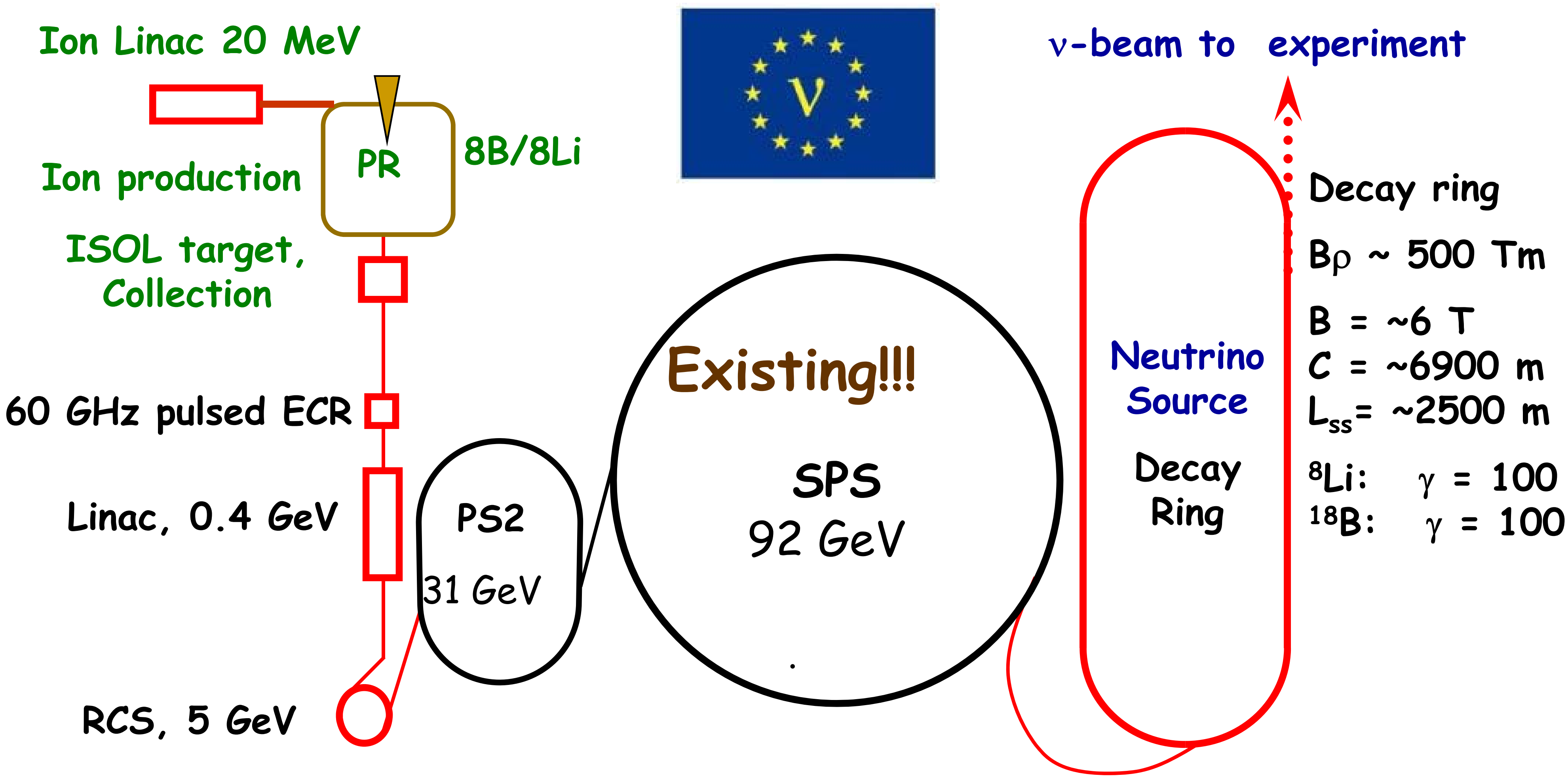


From C. Rubbia, et al. in NIM A 568 (2006) 475–487

Studied within Euroν FP7 (*)

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

Beta Beam scenario EUROnu, FP7

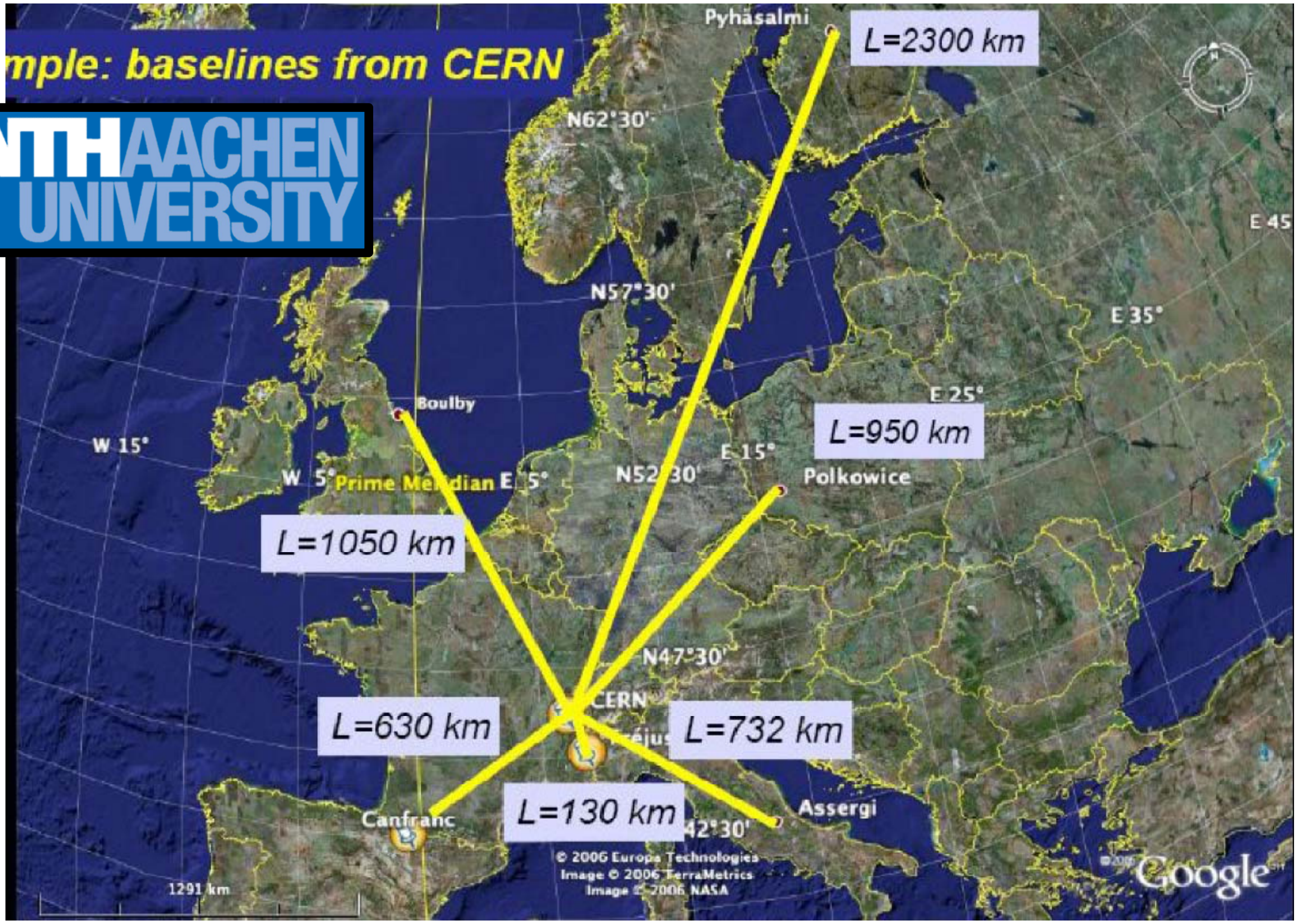


Detector Gran Sasso (~ 5 times higher Q)

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)
    - 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 (apertures!)
  - 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:

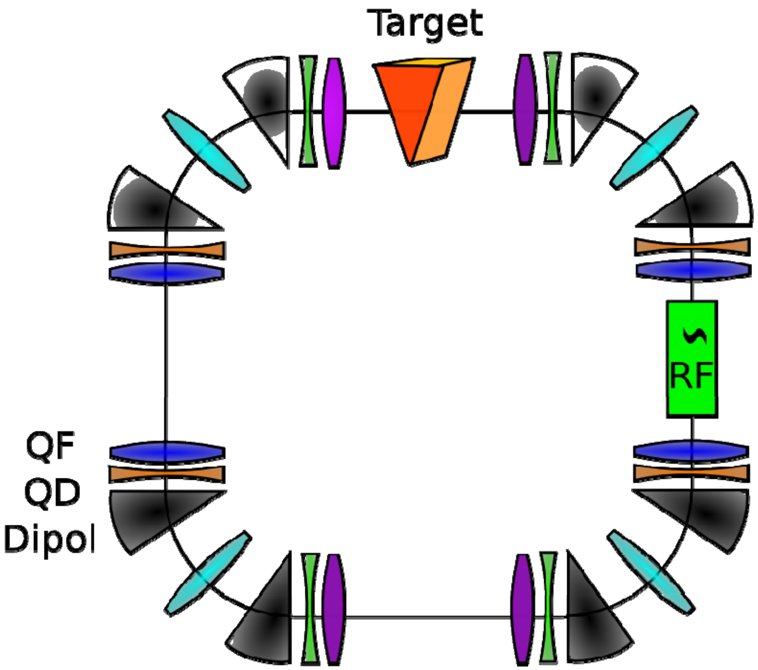
γ = 150 Lopt = 130 km

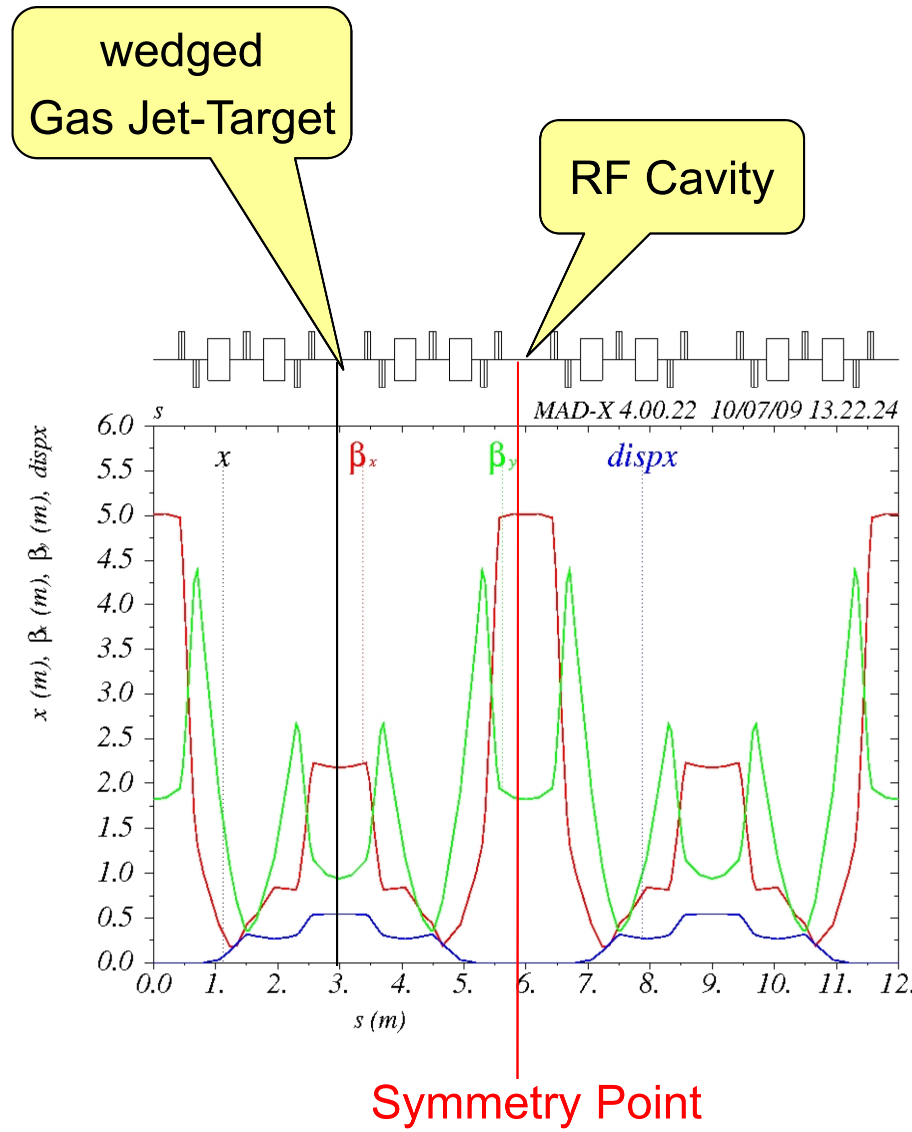
γ = 500 Lopt = 1000 km

CERN – Frejus: 130 km

DESY – Frejus: 960 km

The production Ring: Ion Source for Beta Beams

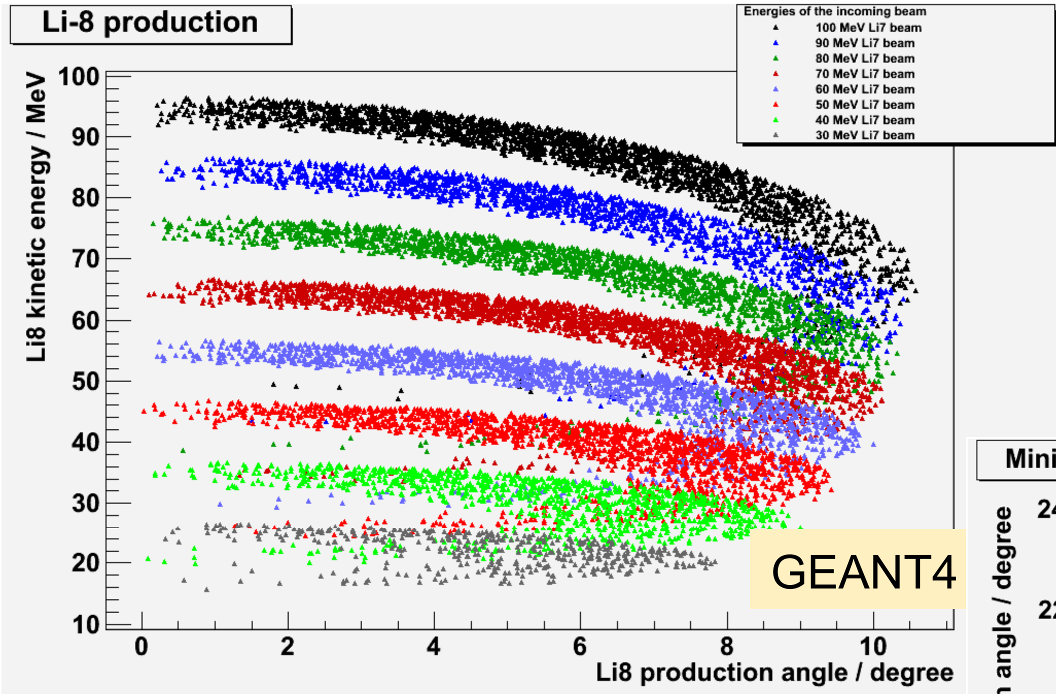




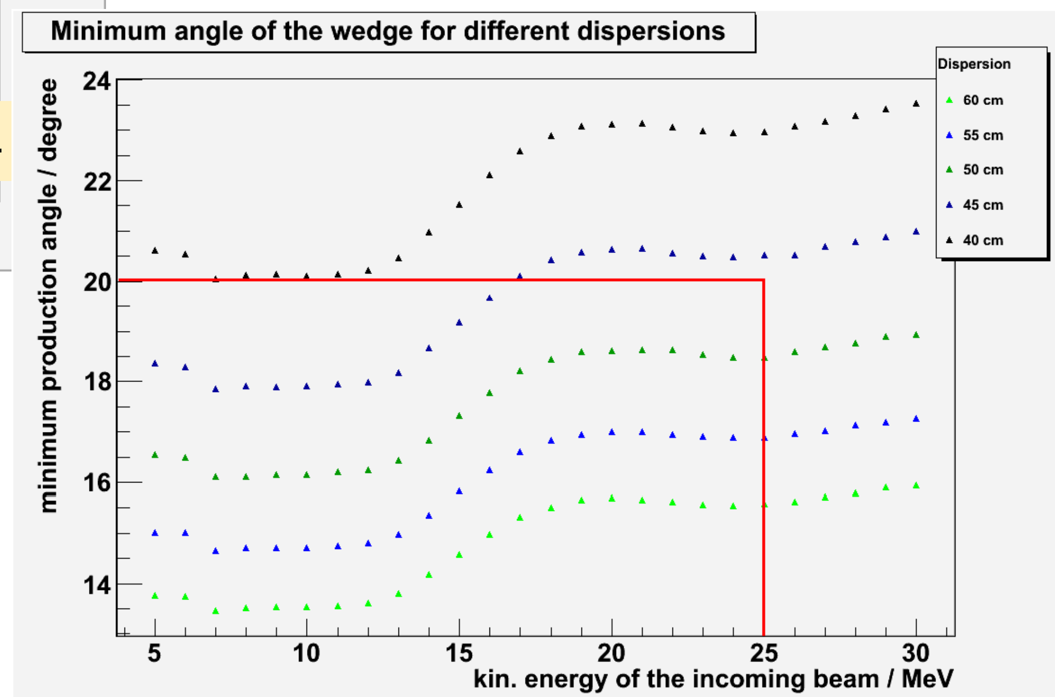
- 12m circumference
- mirror symmetrical structure
- 1.5T dipoles
- 5 quadrupole-families
- Dx = 0 in cavity-section
- best choice of Dx in target-section depends on wedge angle of the target

Michaela Schaumann , Aachen/CERN, 2009

Simulations, Production Ring (ion source)



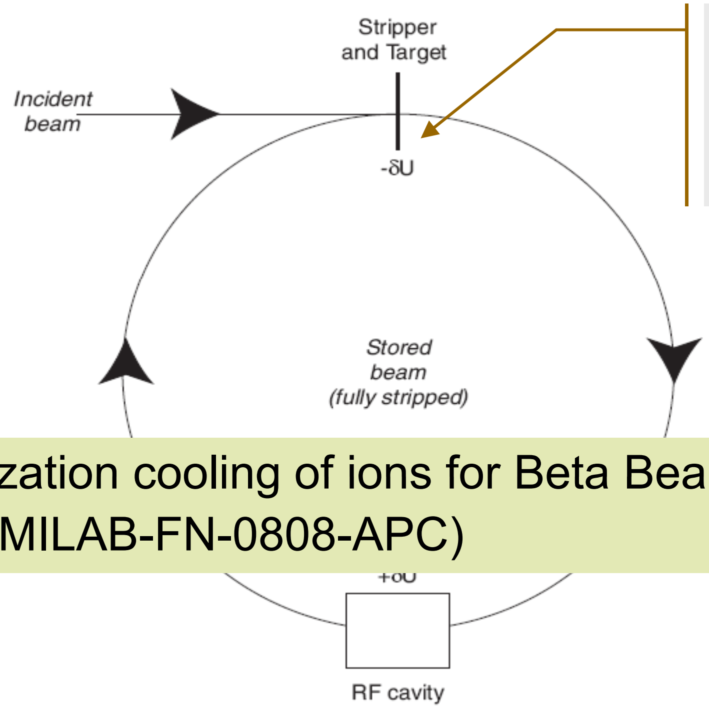
Jokob Wehner, Aachen/CERN, 2009



The production ring cooling: review

^{7}Li

^{6}Li



^{7}Li(d,p)^{8}Li

^{6}Li(^{3}He,n)^{8}B

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

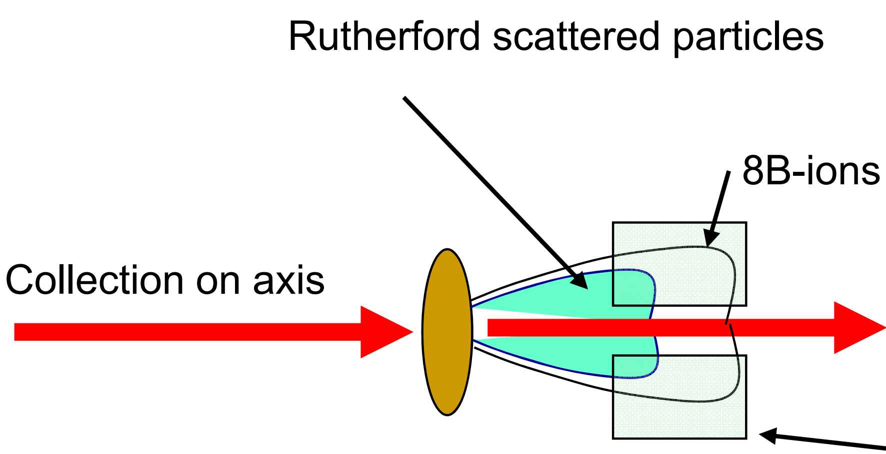
Mini-workshop Fermilab next week on Beta Beams, ionization cooling (David Neuffer)

Challenge: collection device

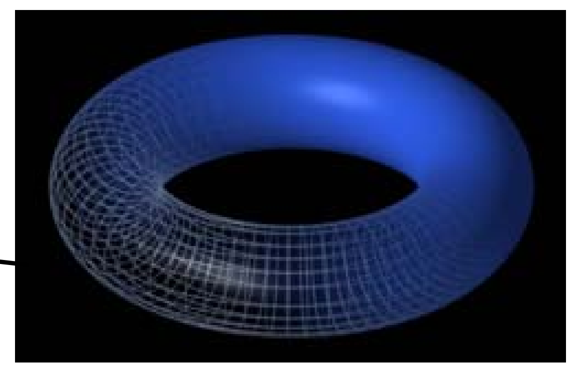
- A large proportion of beam particles (^{6}Li) will be scattered into the collection device.

- 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**
- Marc Loiselet
- Thierry Delbar



Collection Device, Schedule

CRC
Louvain-la-Neuve

- **Semen Mitrofanov**
- Marc Loiselet
- Thierry Delbar

- First beam runs – November÷December’09 – several two days runs
- Full-time beam tests - January÷February’10

- *End of the summer’10 - we hope we will finished with ^{8}Li.*

Terra Incognita:

“We have 1 years to discover how to produce ^{8}B beam of necessary intensity
and 1.5 year to develop the production technique »

Cross section measurements at Laboratori Nazionali di Legnaro

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

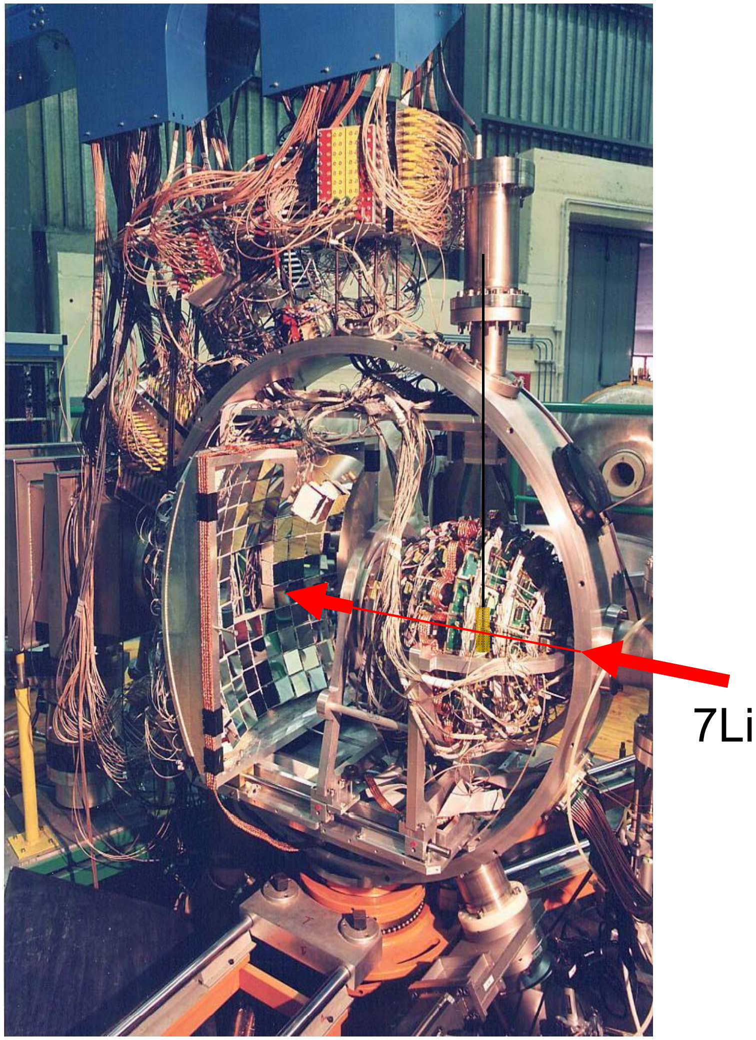
First Experiment performed in July 2008

Inverse kinematic reaction:

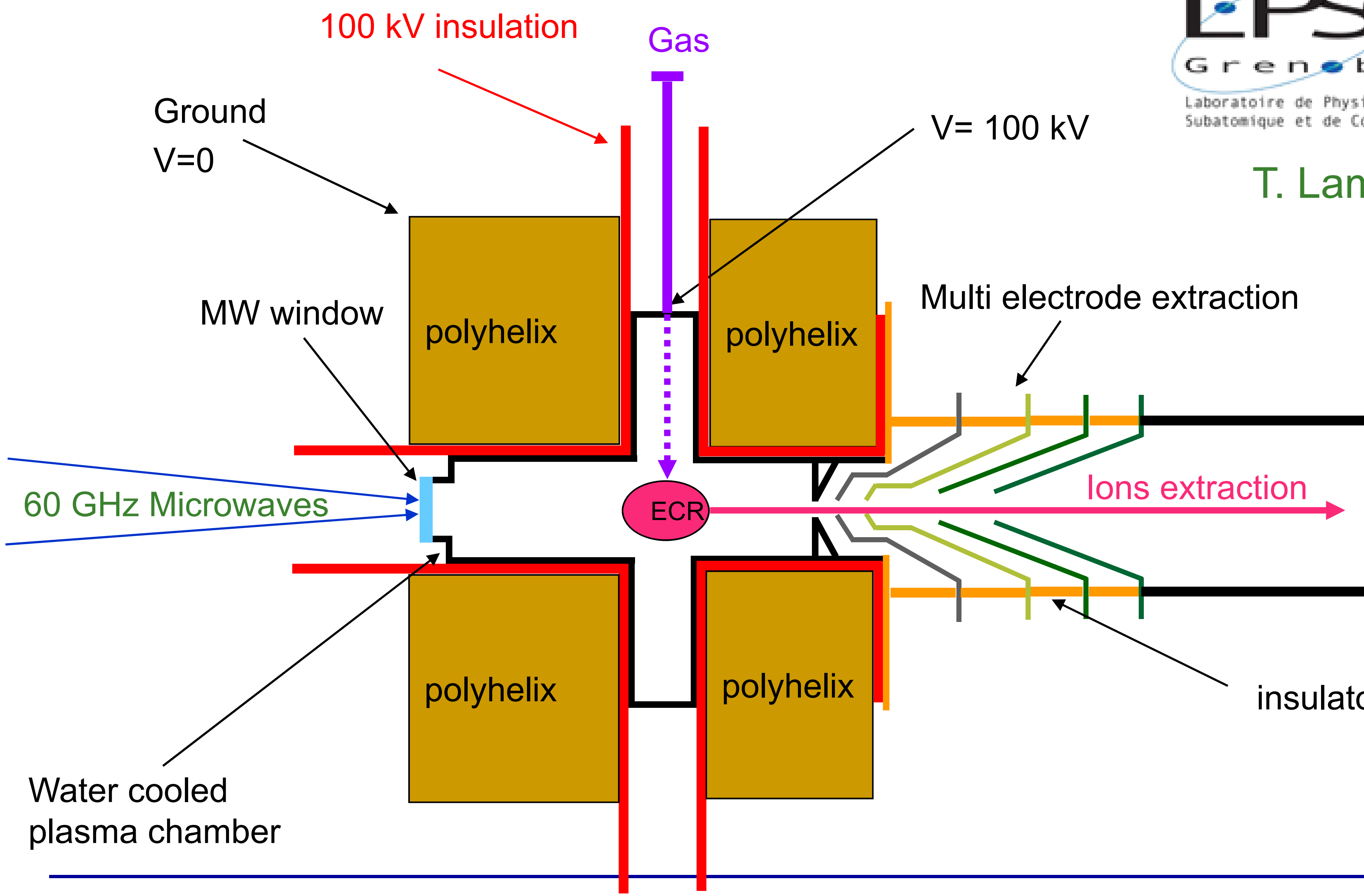
$^{7}Li + Cd_2$ target E=25 MeV

Data reduction in progress

Future: reduce contamination



ECR Source



T. Lami

How to get a 60 GHz Gyrotron and perform experiments?

Use any external resources possible (collaborate!!)

T. Lami

LPSC Grenoble
Laboratoire de Physique Subatomique et de Cosmologie

ISTC project:

IAP Nizhny Novgorod (Plasma physics theory and experiments, gyrotron manufacturing)

LPSC in this programme will be responsible of the design and construction of various ECR ion sources with the help of LNCMI.

Serge Kox
LPSC Director

LNCMI has committed itself to the magnetic characterization *(i.e. a permanent room for experiments + electrical Power!!)*

Geert Rikken
Director of the LNCMI

As the leader of one of the work packages in the EUROnu collaboration, the "Beta Beam" work package, for which CERN is the leading institute, I can only encourage the mentioned ISTC project. The ion source is one of the crucial parts for the success of the EUROnu beta beam project.

Elena Wildner, CERN/BE/ABP
Leader of the Beta Beam Workpackage (WP4), EUROnu

Estimated total cost of the project (US $)	**1 000 000**
Requested from the ISTC	**710 000**
Other financial source 1: LPSC	**290 000**

Associates

- Weizmann Institue 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

He/Ne & Li/B

- Bottom-up Exit Intensities

	# 8B Ions	# 8Li Ions	# 18Ne Ions	# 6He Ions
Source rate	$2. \times 10^{13}$	$2. \times 10^{13}$	$8. \times 10^{11}$	$2. \times 10^{13}$
ECR	5.6×10^{11}	1.69×10^{12}	2.22×10^{10}	1.85×10^{12}
RCS inj	2.79×10^{11}	8.4×10^{11}	1.11×10^{10}	9.23×10^{11}
RCS	2.73×10^{11}	8.18×10^{11}	1.09×10^{10}	8.97×10^{11}
PS inj	4.18×10^{12}	1.14×10^{13}	1.91×10^{11}	1.2×10^{13}
PS	3.84×10^{12}	$1. \times 10^{13}$	1.82×10^{11}	1.03×10^{13}
SPS	3.75×10^{12}	9.55×10^{12}	1.8×10^{11}	9.74×10^{12}
Decay Ring	1.13×10^{14}	2.41×10^{14}	3.13×10^{12}	1.04×10^{14}

Courtesy Christian Hansen May 2009

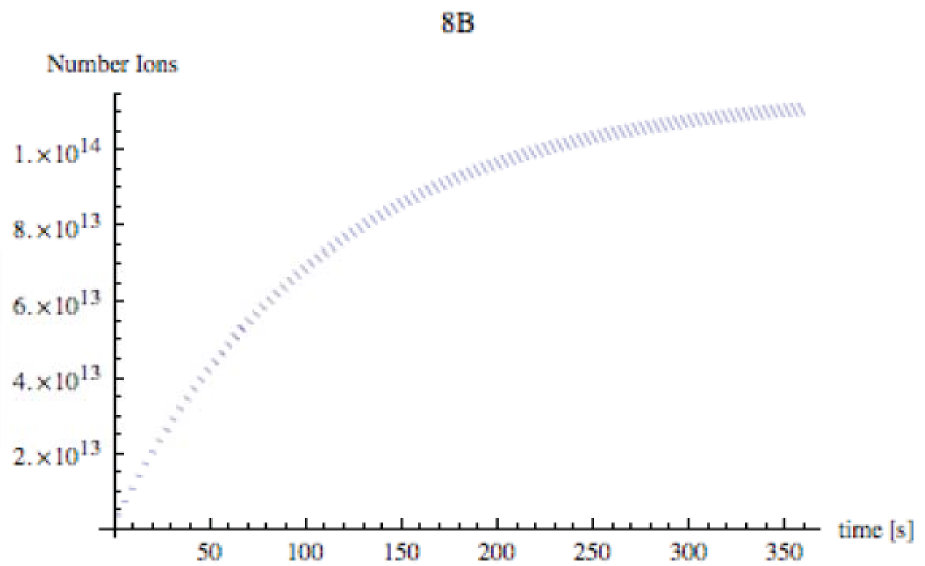
- Annual Neutrino Rates

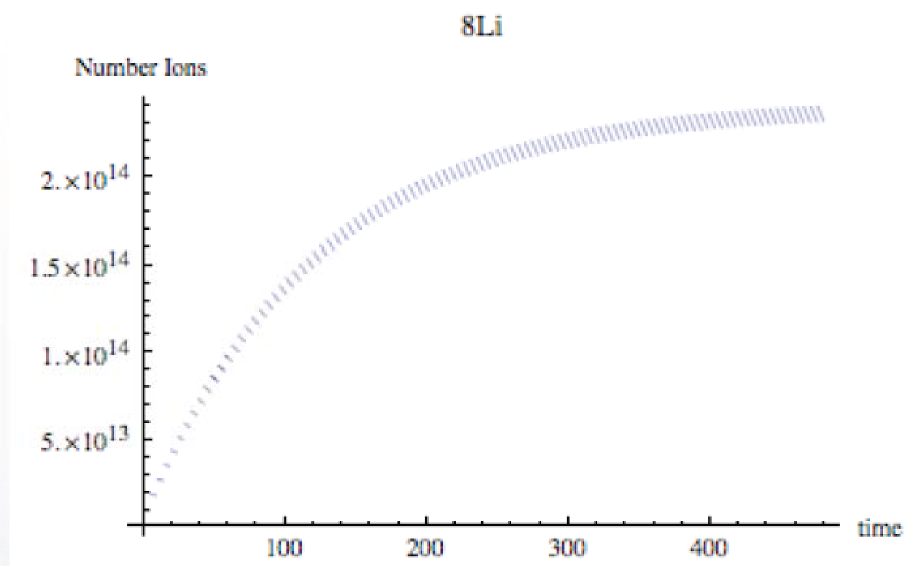
	# ν from 8B	# anti-ν from 8Li	# ν from 18Ne	# anti-ν from 6He
Annual Rate	3.75×10^{18}	7.16×10^{18}	4.64×10^{16}	3.14×10^{18}
Required Annual Rate	5.5×10^{18}	1.45×10^{20}	1.1×10^{18}	2.9×10^{19}

${}^{8}_{5}B \rightarrow {}^{8}_{4}Be + e^+ + \nu_e$ ${}^{8}_{3}Li \rightarrow {}^{8}_{4}Be + e^- + \bar{\nu}_e$ ${}^{18}_{10}Ne \rightarrow {}^{18}_{9}F + e^+ + \nu_e$ ${}^{6}_{2}He \rightarrow {}^{6}_{3}Li + e^- + \bar{\nu}_e$

No dutycycle

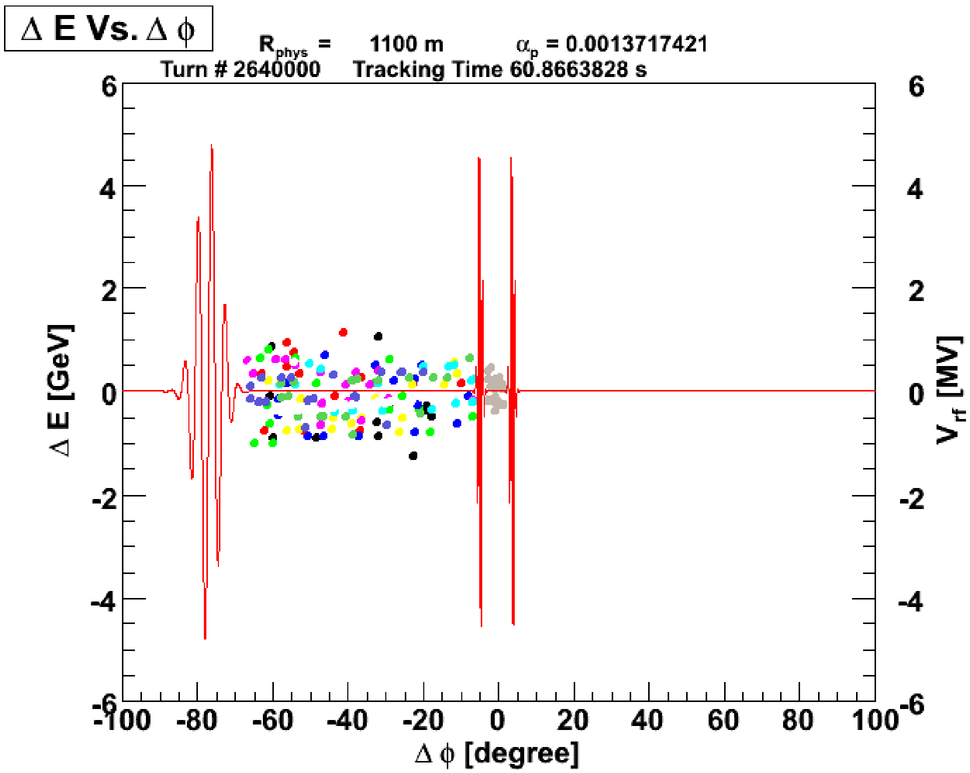
- With RF Barrier Bucket gymnastics the DR could maybe be used till full saturation (investigations ongoing)





- For the 6He and 18Ne ions however bunching was needed and merging allowed for only 15 and 20 injections respectively

Barrier Buckets, relaxed duty factor



See Poster Session today : Christian Hansen (CERN)

Gamma and decay-ring size, ^{6}He

Gamma	Rigidity [Tm]	Ring length <u>T=5 T</u> <u>f=0.36</u>	Dipole Field <u>rho=300 m</u> <u>Length=6885m</u>
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

Conclusions (i)

- The EURISOL beta-beam conceptual design report will be presented in second half of 2009
  - First coherent study of a beta-beam facility
  - Top down approach
  - 18Ne shortfall
  - Duty Factors are challenging:

    Collimation and RF in Decay Ring

Conclusions (ii)

- A beta-beam facility using ^{8}Li and ^{8}B (EUROnu)
  - Experience from EURISOL
  - Production issues (not to forget 18Ne)
  - Optimize chain
  - Revisit Duty Factors
  - Apertures of PS2
  - (Complete) simulation of beta beam complex
  - Costing (add what is not in EUROnu)
  - **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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