Neutrino Production: Beta Beams

Elena Wildner, LIS meeting 24/03/09

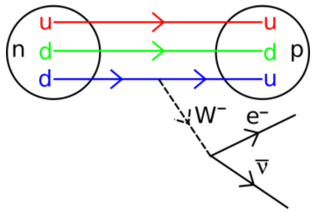
Layout of talk

- What is a beta beam?
- The EURISOL Design Study
  - Overall layout
  - Specific challenges & shortfalls
- FP7
  - The collaborators' tasks
  - Decay Ring RF
  - The Production Ring
  - Radio Protection
  - The Parameter Data Base

Team Work

- Many Collaboration Institutes, CNRS, CEA, LPSC, UCL…
- Mats Lindroos, the driving force
- Michael Benedikt, the FP6 task leader
- Adrian Fabich, parameters and organizing
- Steve Hancock, the decay ring RF
- …and many others

Beta-beam Basics

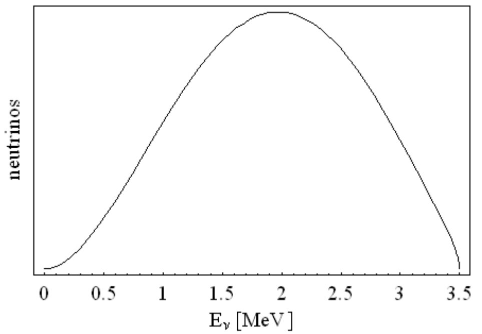


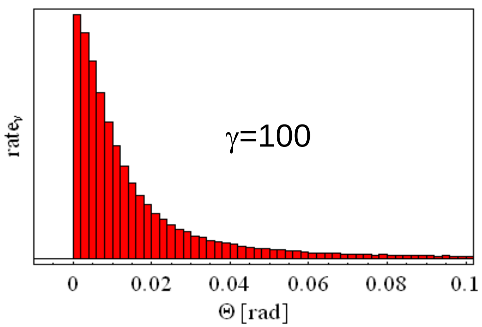
Aim: production of (anti-)neutrino beams from the beta decay of radio-active ions circulating in a storage ring (race track).

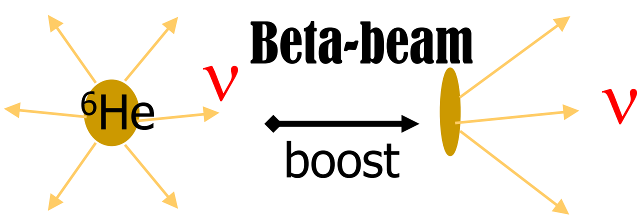
- Similar concept to the neutrino factory, but parent particle is a beta-active isotope instead of a muon.
- Both neutrinos and antineutrinos are needed

- Beta-decay at rest
  - ν–spectrum well known from electron spectrum
  - Reaction energy Q typically of a few MeV (neutrino energy)
  - Only electron (anti-)neutrinos

- Accelerated parent ion to relativistic γ_{max}
  - Boosted neutrino energy spectrum: $E_\nu \leq 2\gamma Q$
  - Forward focusing of neutrinos: $\theta \leq 1/\gamma$



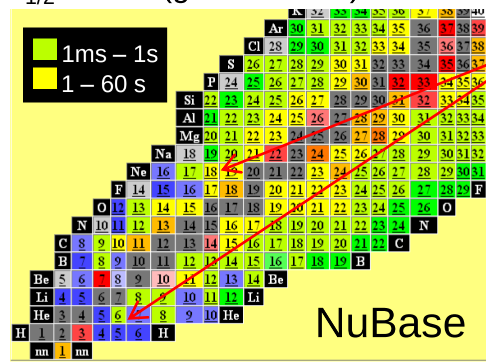




Choice of radioactive ion species

- Beta-active isotopes
  - Distance from stability
    - Production rates
    - Life time
- Reasonable lifetime at rest
  - If too short: decay during acceleration
  - If too long: low neutrino production
  - Optimum life time given by acceleration scenario and neutrino rate optimization
  - 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

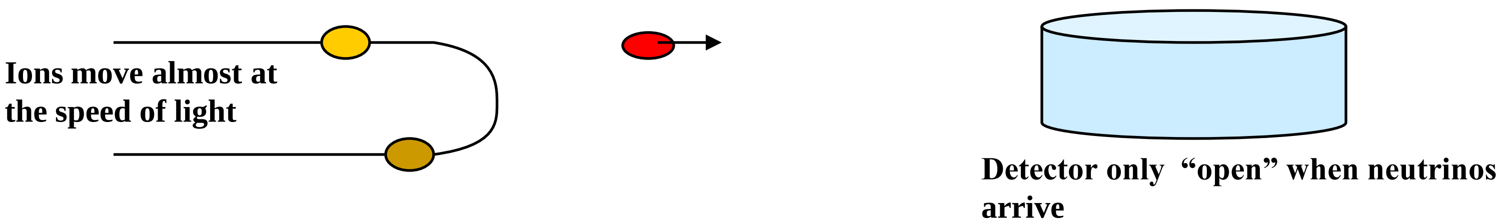
EURISOL DS

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	2.6	0.64	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	$9\cdot10^{11}$	$3\cdot10^{8}$	$2\cdot10^{8}$

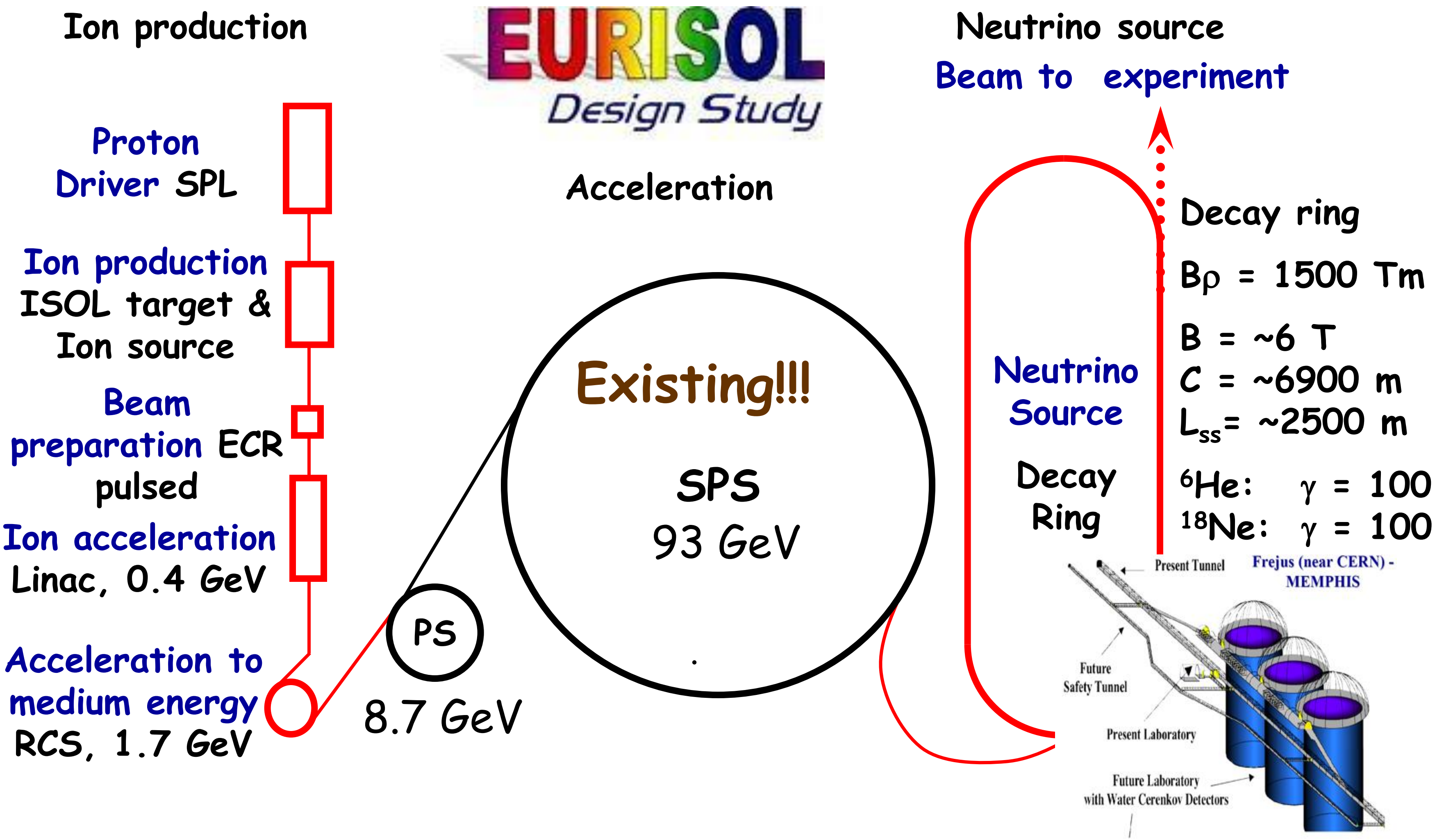
What is important for the experiment?

- Gamma 100 chosen for CERN accelerator complex
- The atmospheric neutrino background is large at 500 MeV, the detector can only be open for a short moment every second, unfortunate for an otherwise good choice…
  - The decay products move with the ion bunch which results in a bunched neutrino beam



  - Low duty cycle – short and few bunches in decay ring
  - Accumulation in decay ring to make use of as many decaying ions as possible from each acceleration cycle

Recall of Beta Beam scenario, FP6

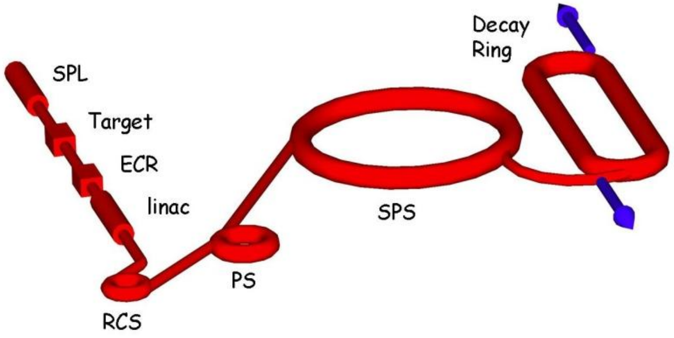


Detector in the Frejus tunnel

The EURISOL scenario

- 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 is 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

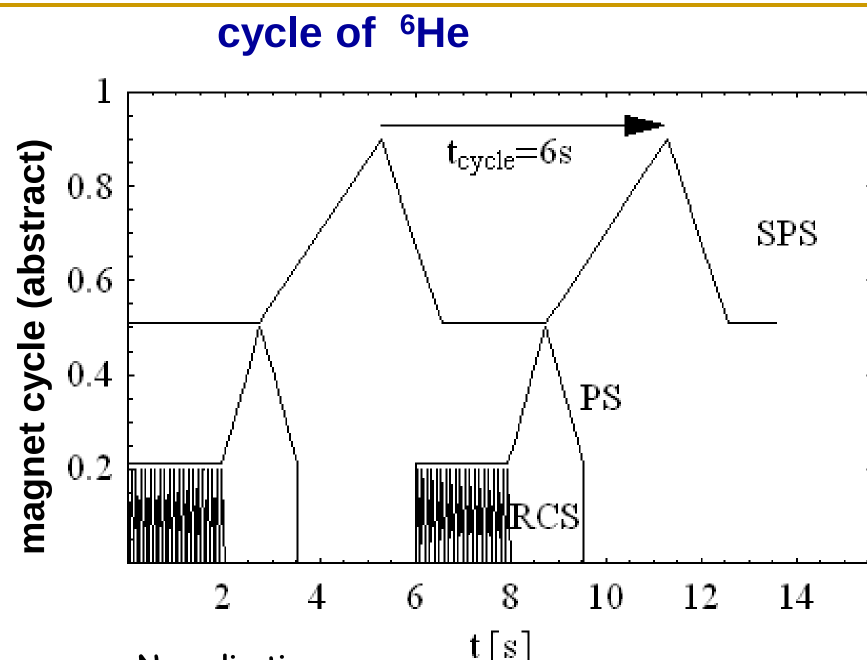


- Achieve an annual neutrino rate of
  - 2.9×10^{18} anti-neutrinos from ^{6}He
  - $1.1\ 10^{18}$ neutrinos from ^{18}Ne

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

Machine cycle

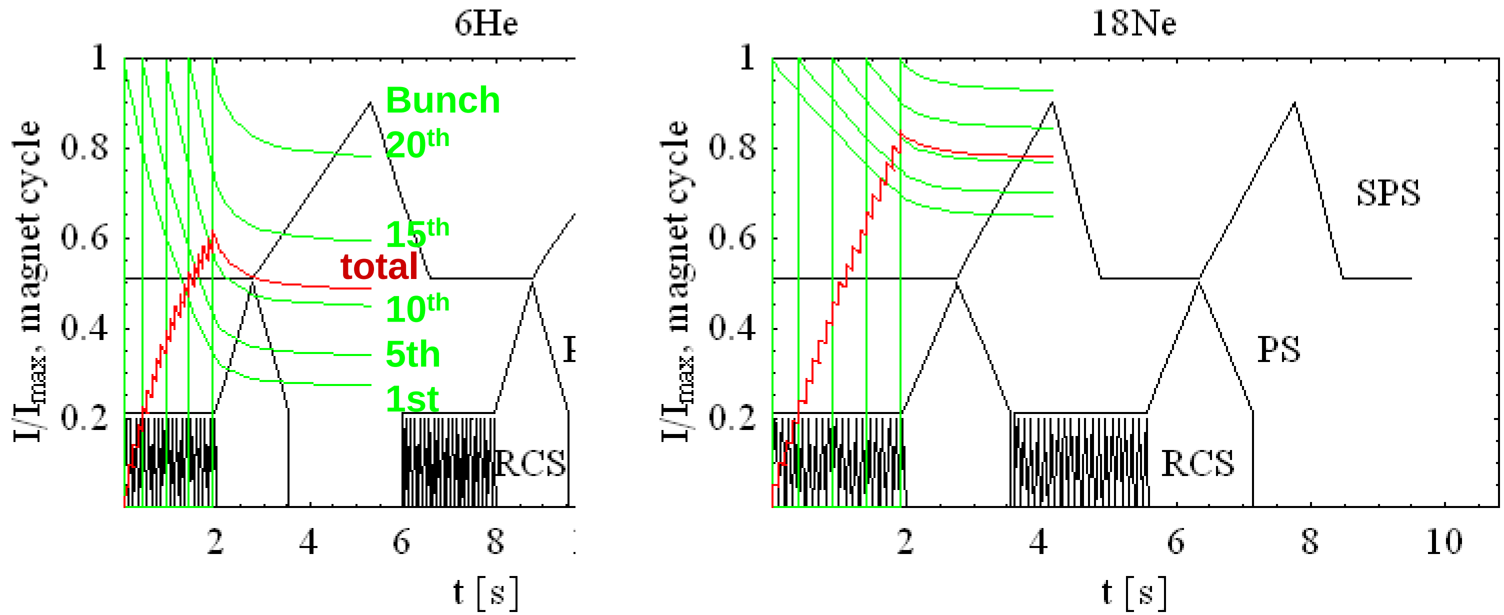


Normalization
Single bunch intensity to maximum/bunch
Total intensity to total number accumulated in RCS

Baseline version:

- Production
  - ^{6}He, ^{18}Ne
- ECR, Linac and RCS
  - Cycling at 10 Hertz
- Accumulation in the PS
  - Accumulation of 20 RCS bunches (~2 seconds)
- Acceleration through PS and SPS as fast as possible
  - γ_{top} = 100 for both isotopes
- Injection into decay ring
  - Merging with circulating bunches
  - Every 6 s for ^{6}He and every 3.6 s for ^{18}Ne

Ion intensities

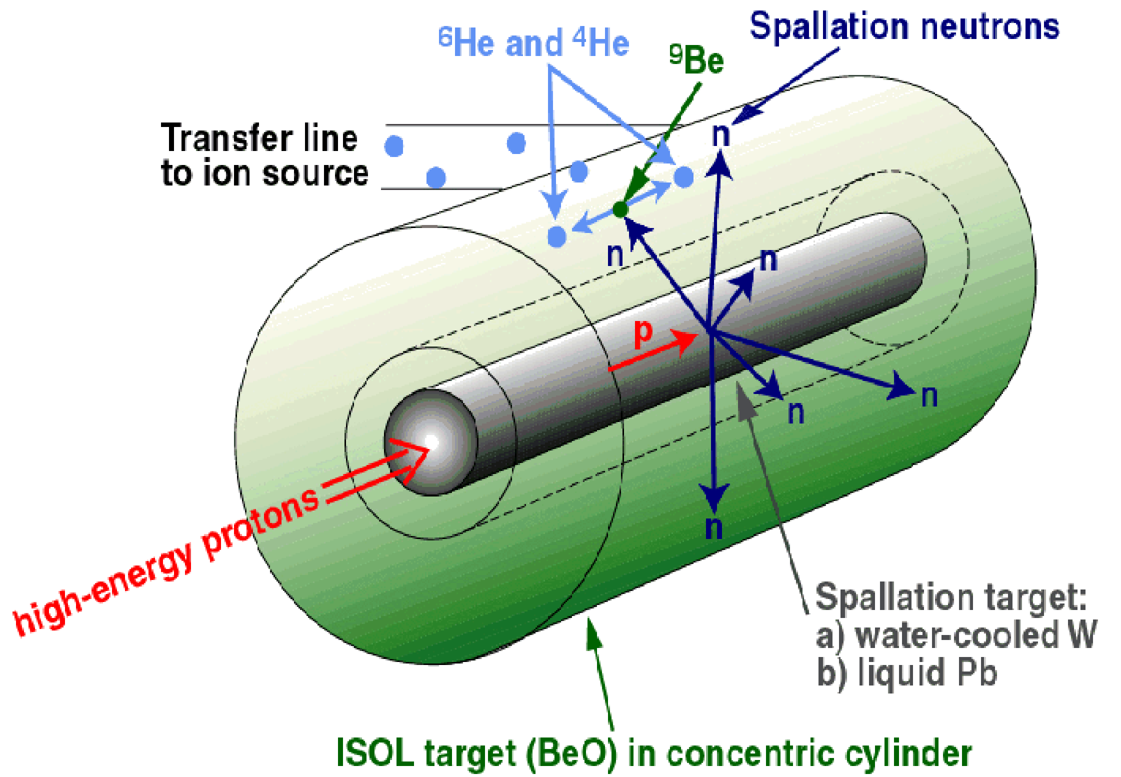


Cycle optimized for neutrino rate.

- 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

^{6}He (ISOL)



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

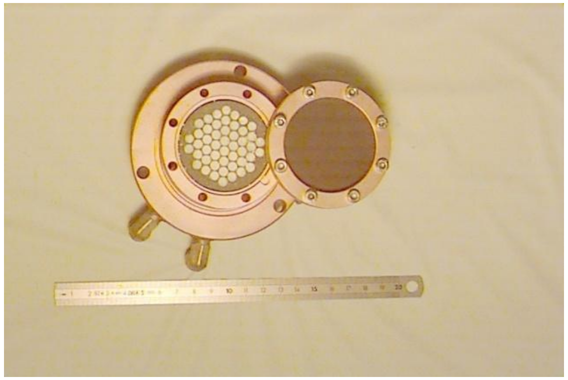
T. Stora, N. Thollieres, CERN

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

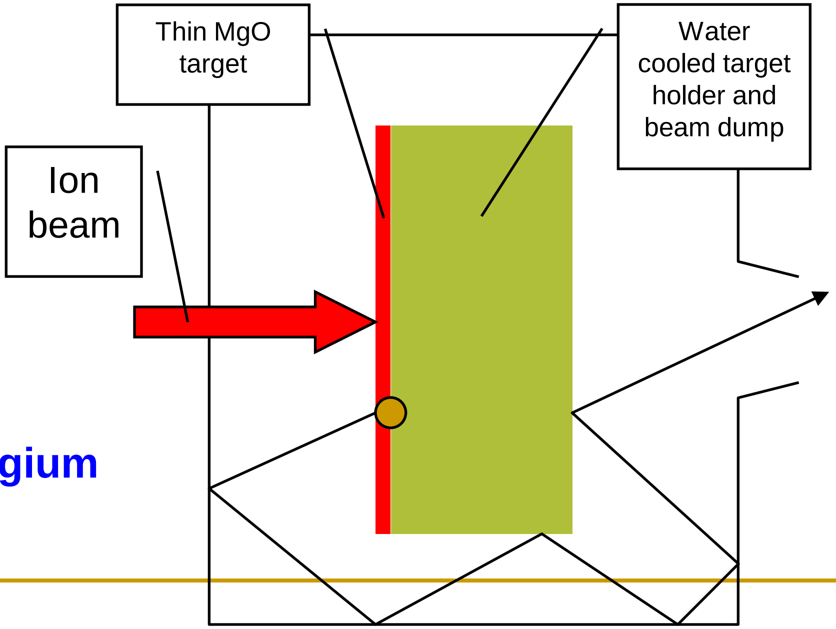
Projected values, known x-sections!

^{18}Ne (Direct Production)

Geometric scaling



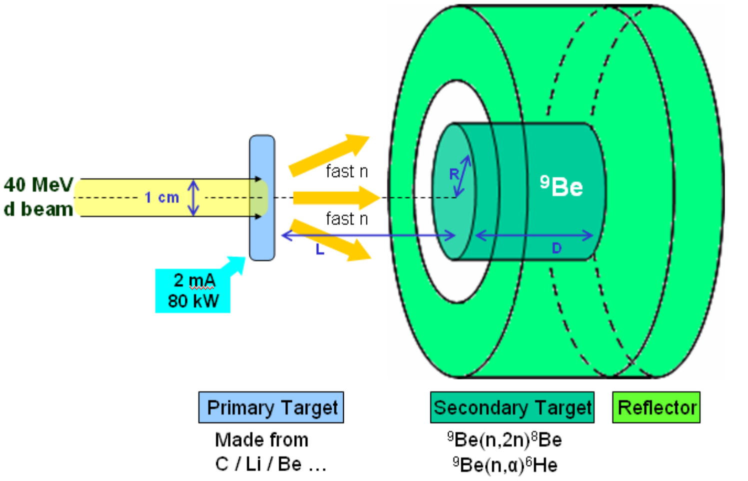
- Producing 10^{13} ^{18}Ne could be possible with a beam power (at low energy) of 2 MW (or some 130 mA ^{3}He beam on MgO).
- To keep the power density similar to LLN (today) the target has to be 60 cm in diameter.
- To be studied:
  - Extraction efficiency
  - Optimum energy
  - Cooling of target unit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



S. Mitrofanov and M. Loislet at CRC, Belgium

^{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.



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

Ion 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
  - ^{8}Li ?
  - 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!

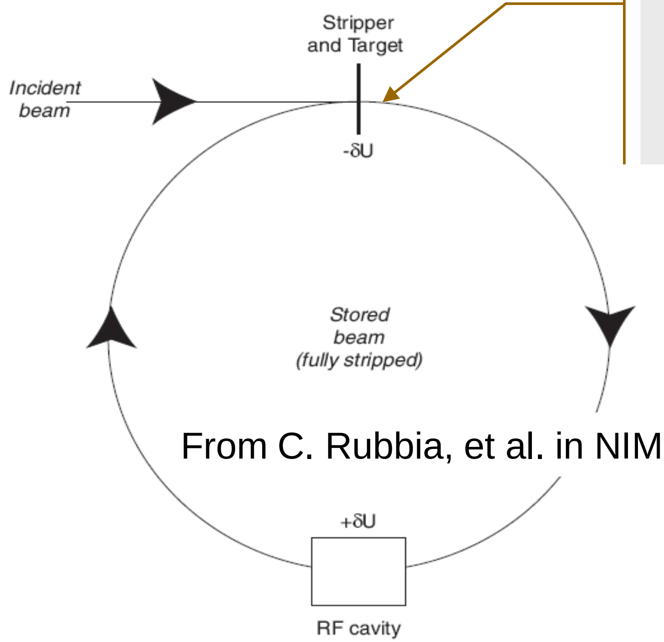
New approach for ion production

"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

^{7}Li
^{6}Li

20-30 MeV

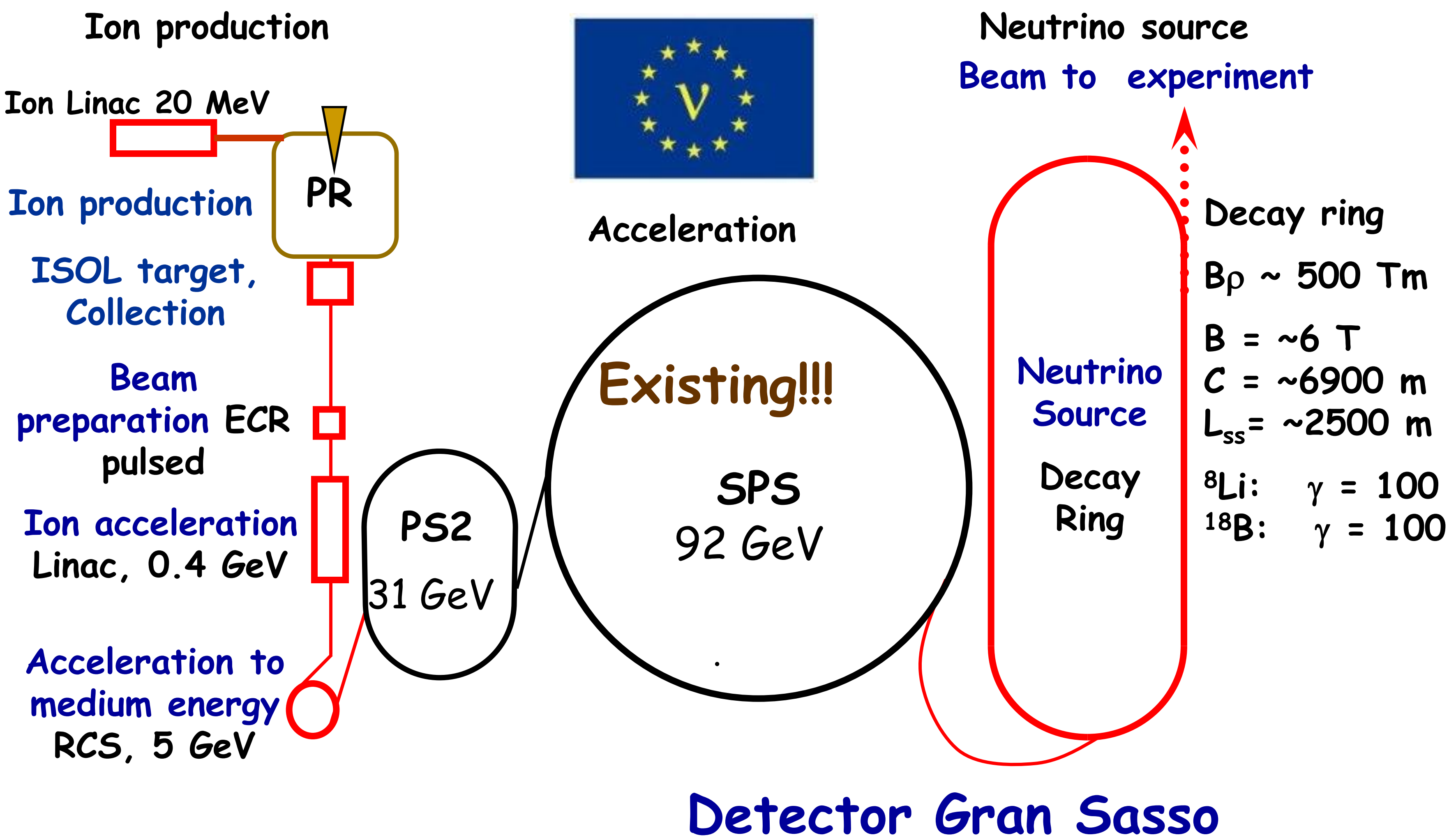


$^{7}Li(d,p)^{8}Li$
$^{6}Li(^{3}He,n)^{8}B$

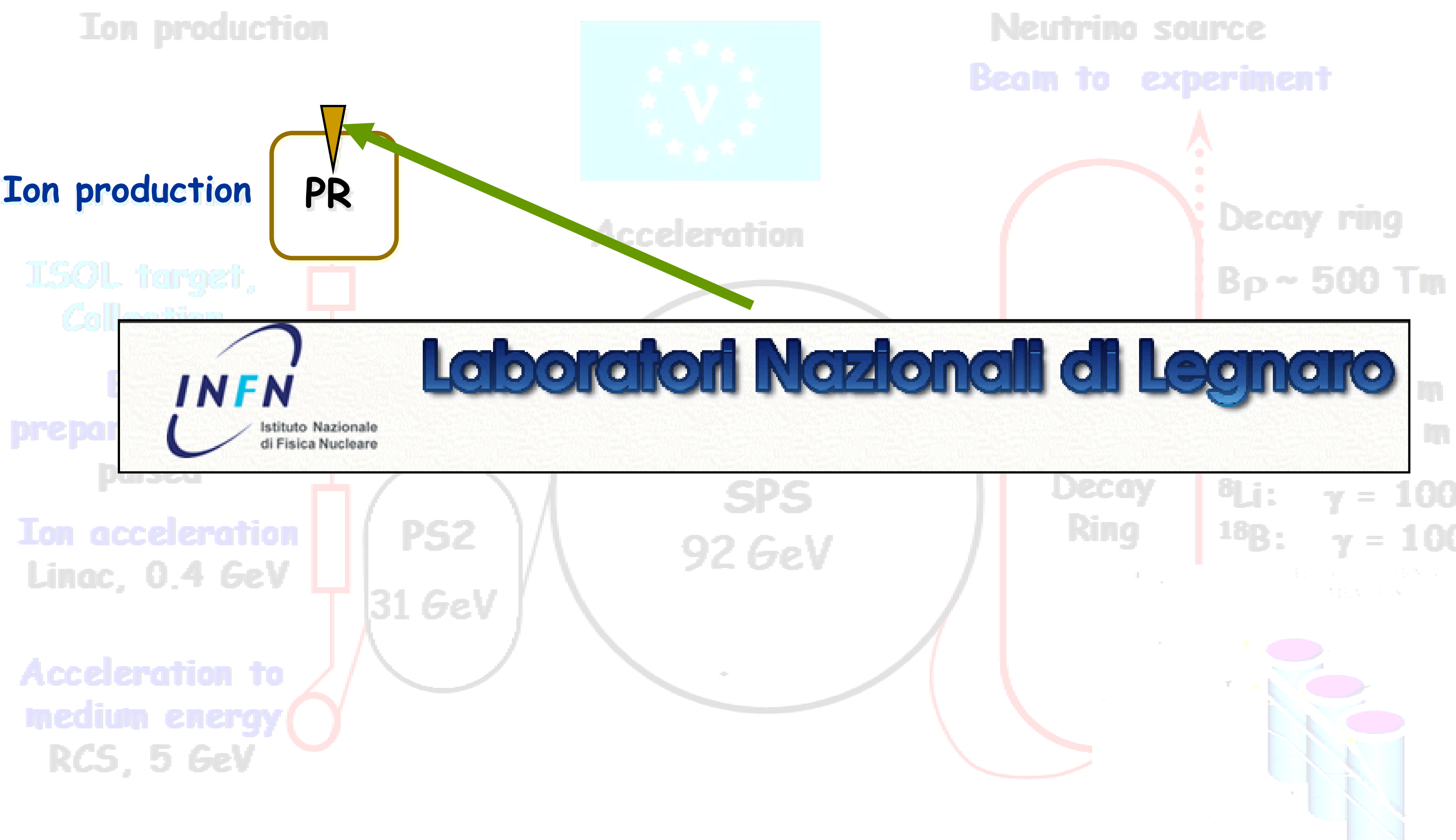
From C. Rubbia, et al. in NIM A 568 (2006) 475–487

Chemistry with Boron?

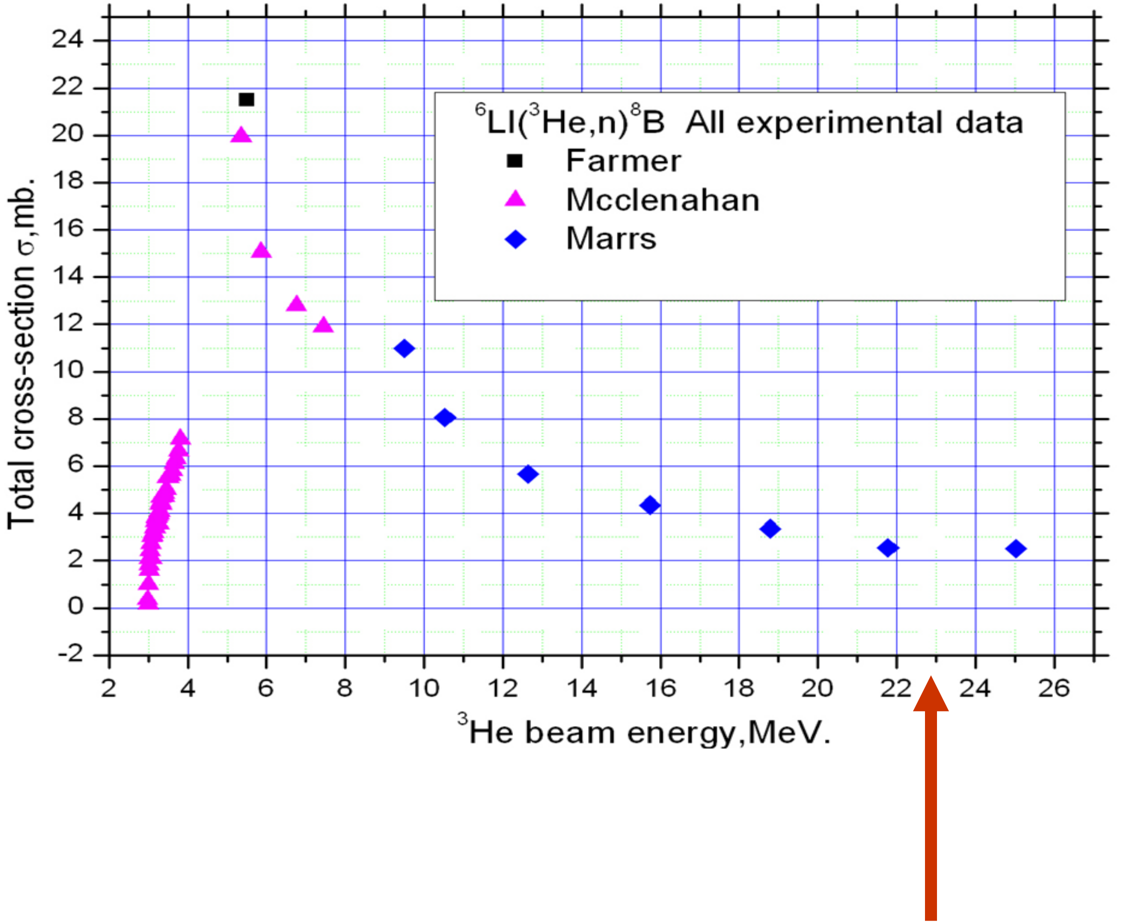
WP4, Beta Beam scenario EUROnu



WP4, Beta Beam scenario EUROnu



Cross Section Measurements, INFN LNL

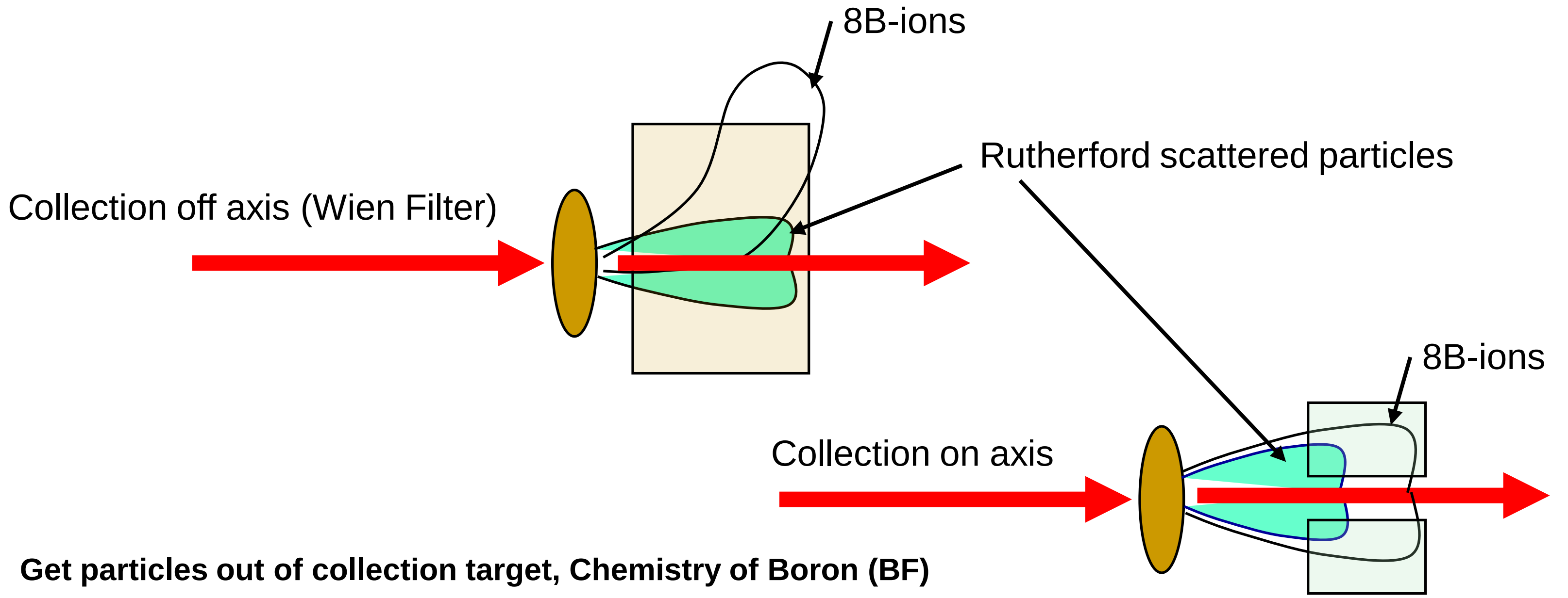


Beam Energy needed for stripping

WP4, Beta Beam scenario EUROnu

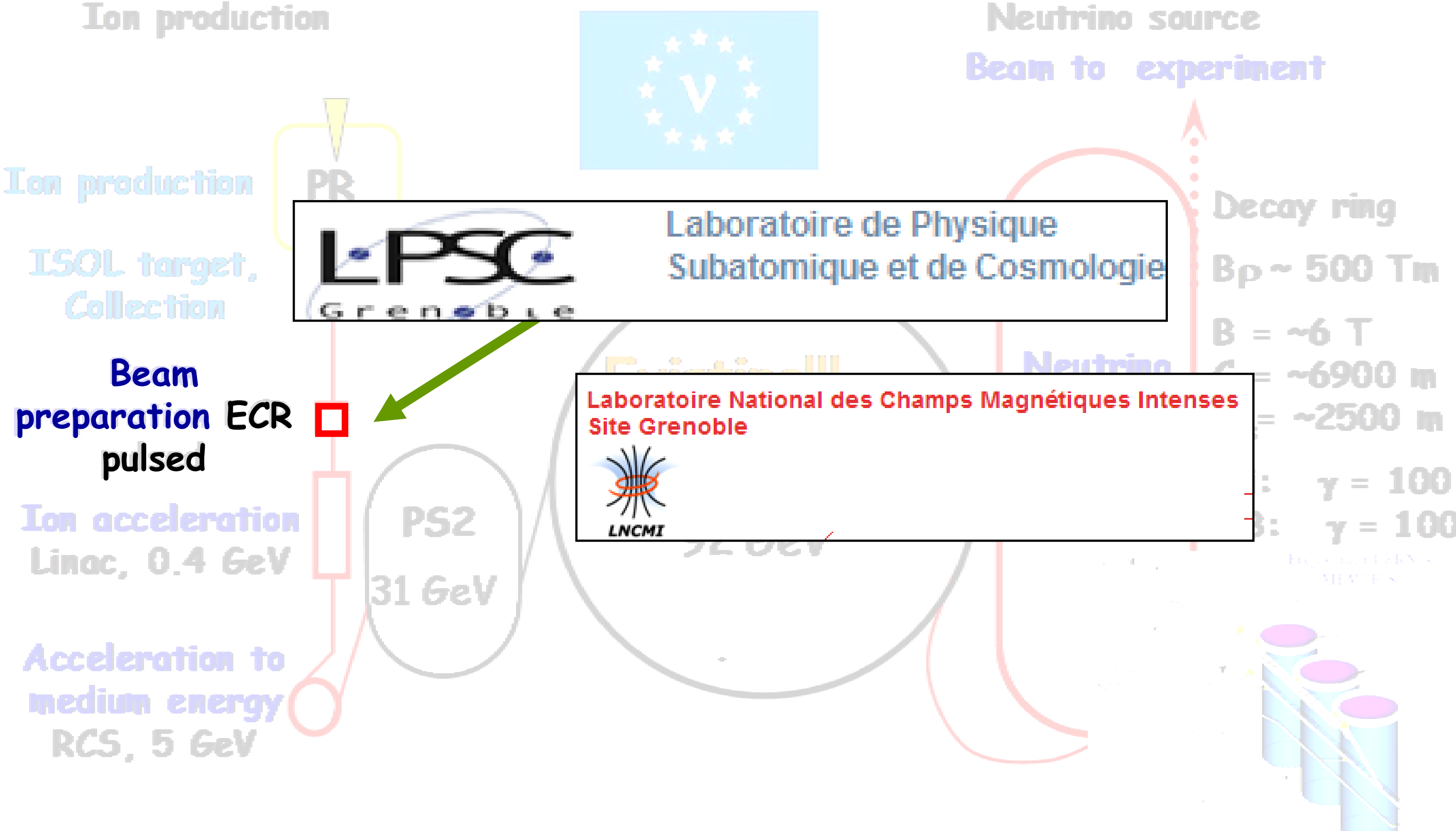
Collection device, UCL

- A large proportion of the primary beam particles (^{6}Li) will be scattered into the collection device.
  - The scattered primary beam intensity could be up to a factor of 100 larger than the RI intensity for 5-13 degree using a Rutherford scattering approximation for the scattered primary beam particles (M. Loislet, UCL)
  - The ^{8}B ions are produced in a cone of 13 degree with 20 MeV ^{6}Li ions with an energy of 12 MeV±4 MeV (33% !).

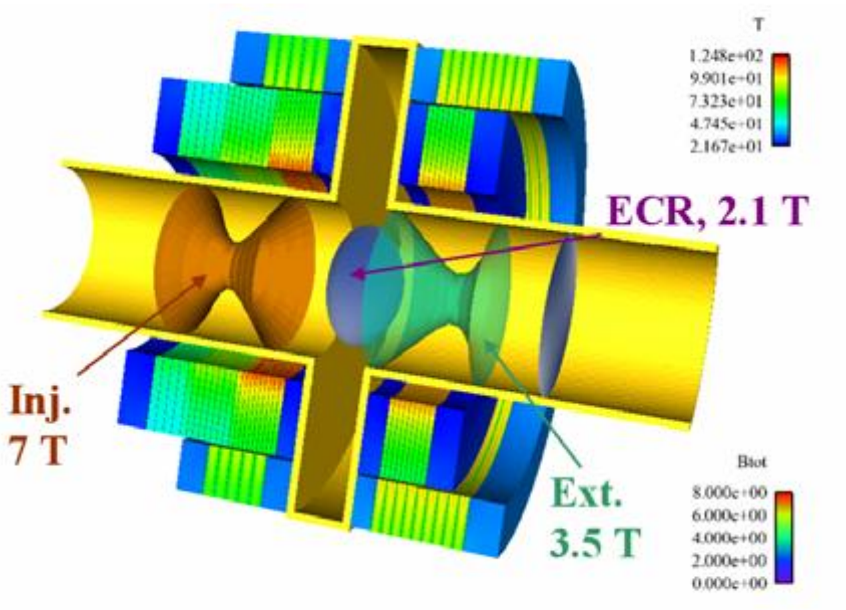


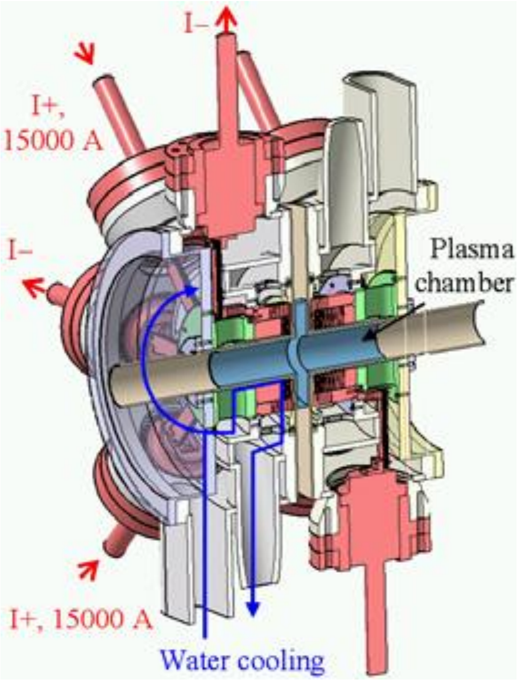
Get particles out of collection target, Chemistry of Boron (BF)

WP4, Beta Beam scenario EUROnu



ECR Source



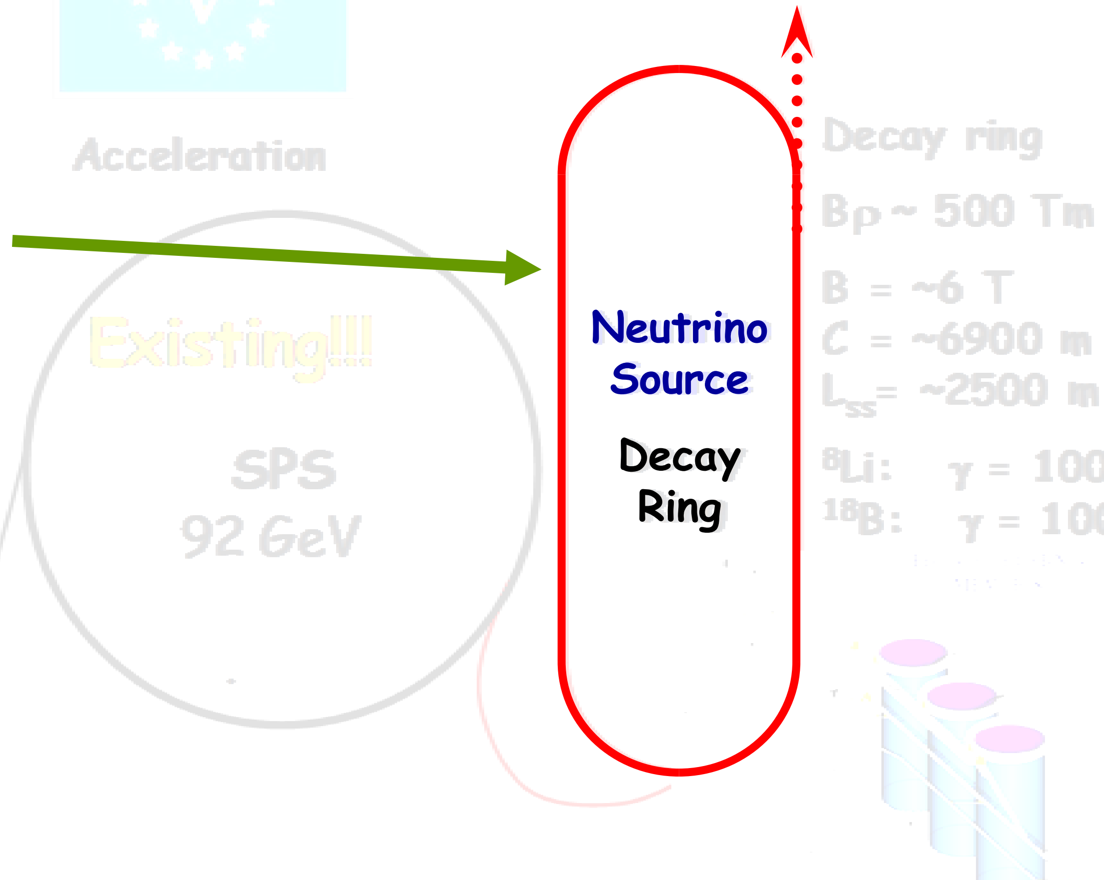


Short pulses (50 μsec) of radioactive ion beams
60 GHz ECR Ion Source
Prototype using room temperature coils

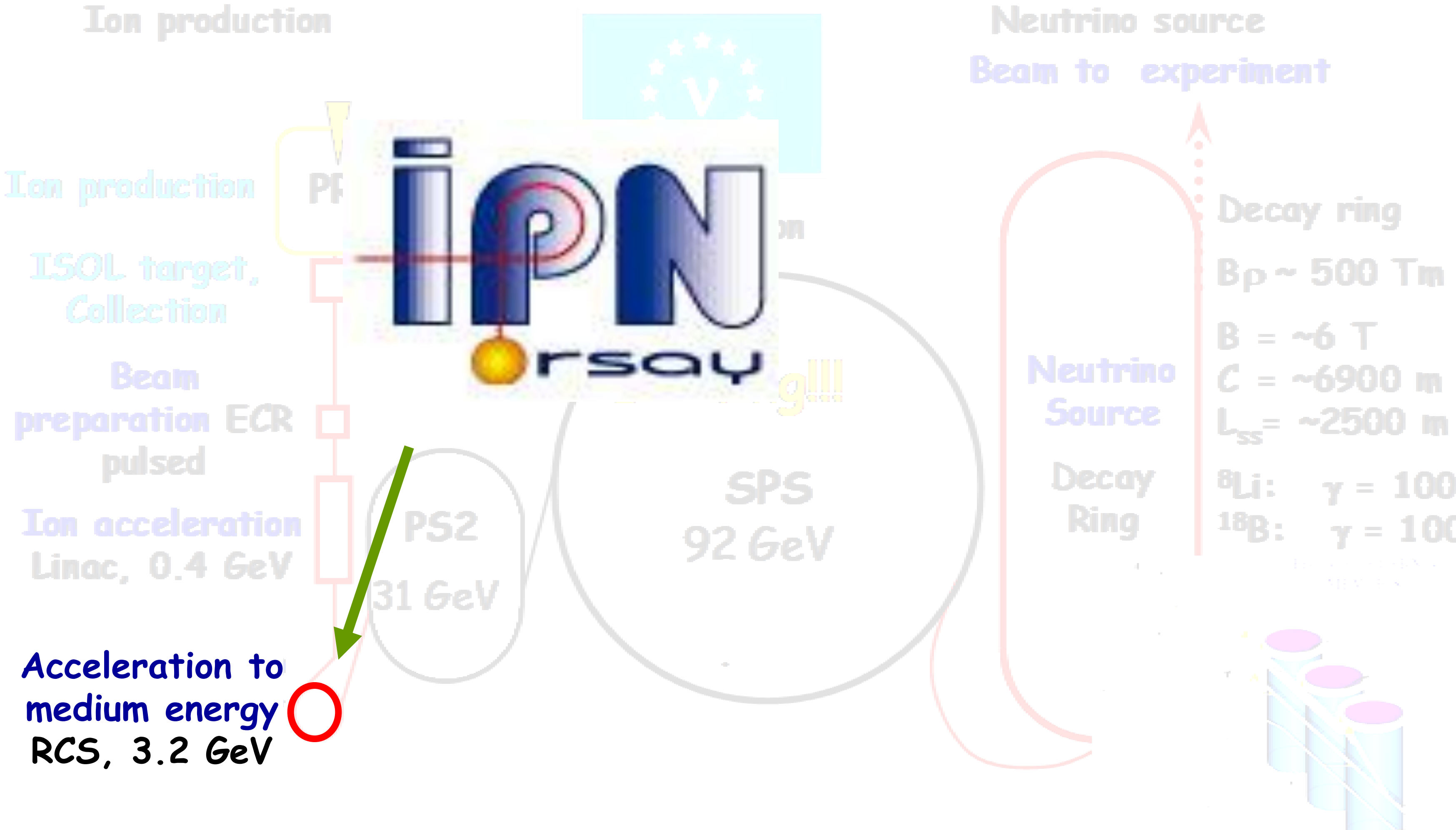
The 3D magnetic field structure to confine plasma
Experiments at 60 GHz may start in 2010.

WP4, Beta Beam scenario EUROnu

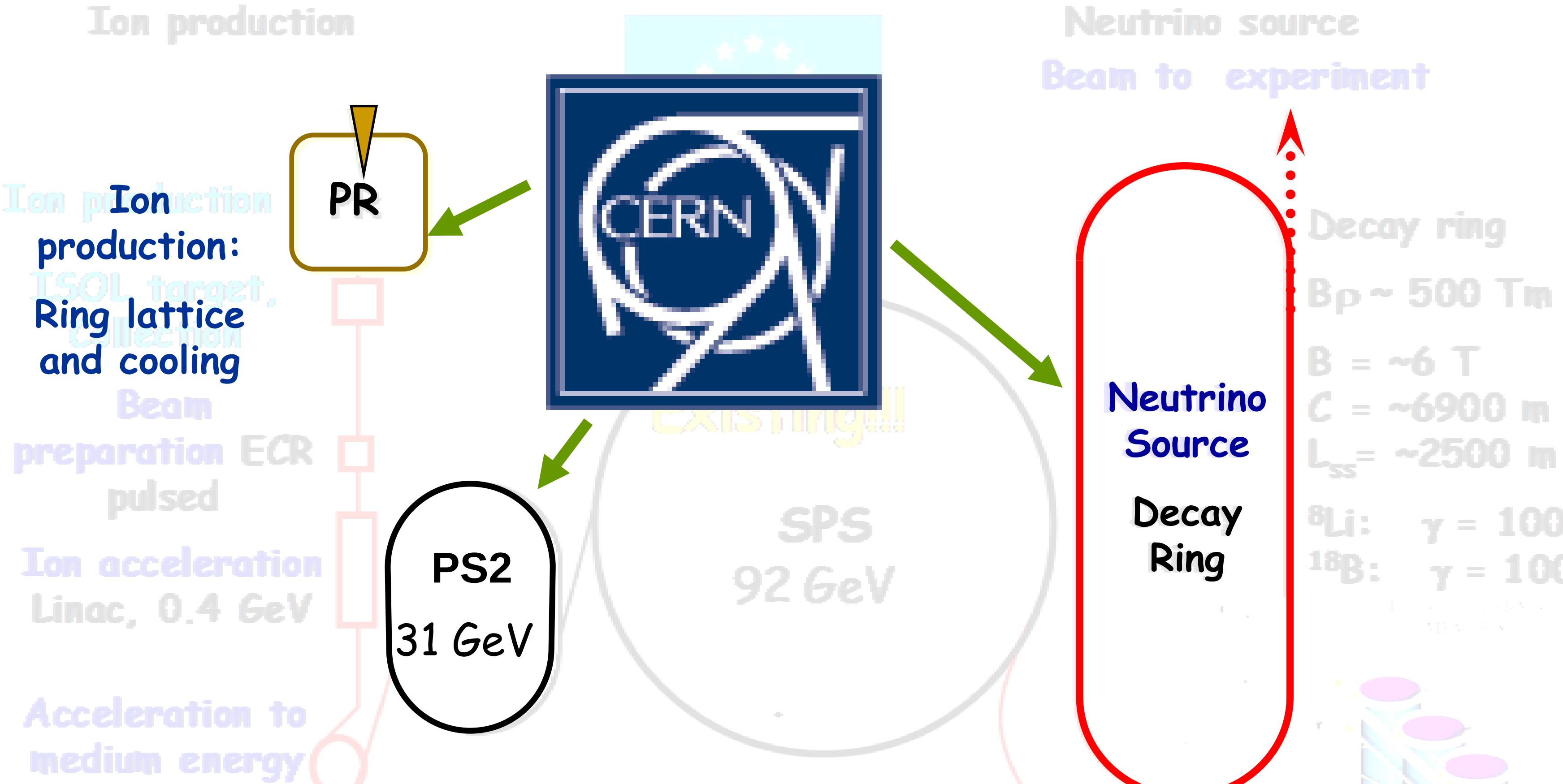
CEA, L'Irfu, Institut de Recherches sur les lois Fondamentales de l'Univers



WP4, Beta Beam scenario EUROnu

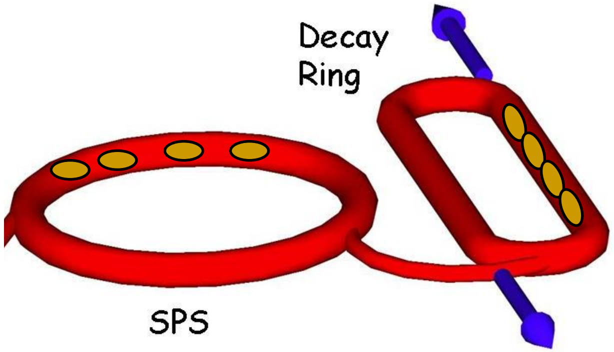


WP4, Beta Beam scenario EUROnu



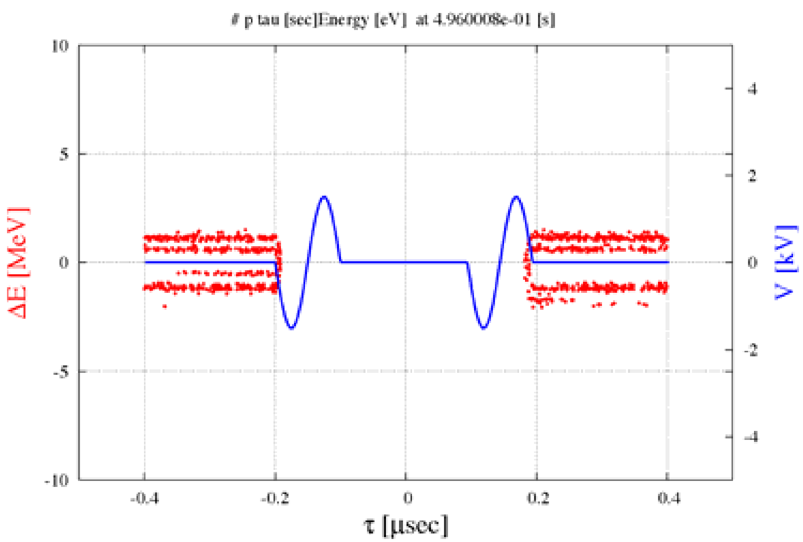
Overall accelerator & parameter data base
Radio Protection

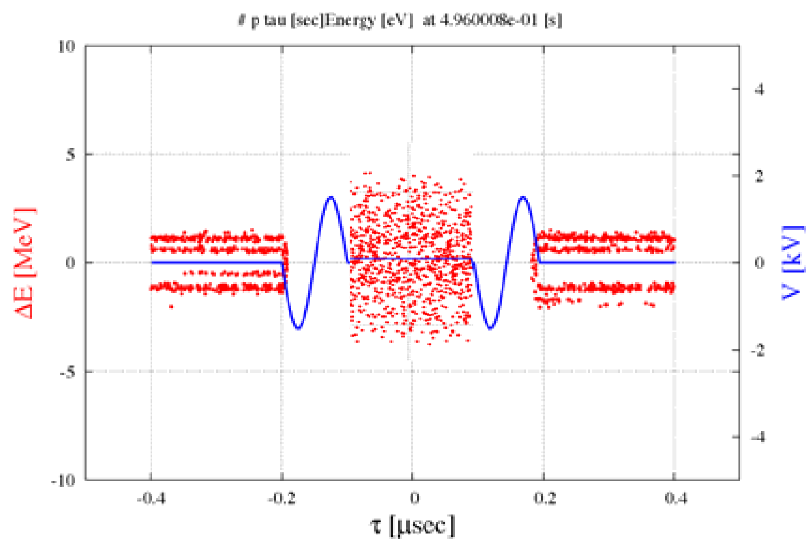
Relaxing the duty-cycle for higher energy neutrinos



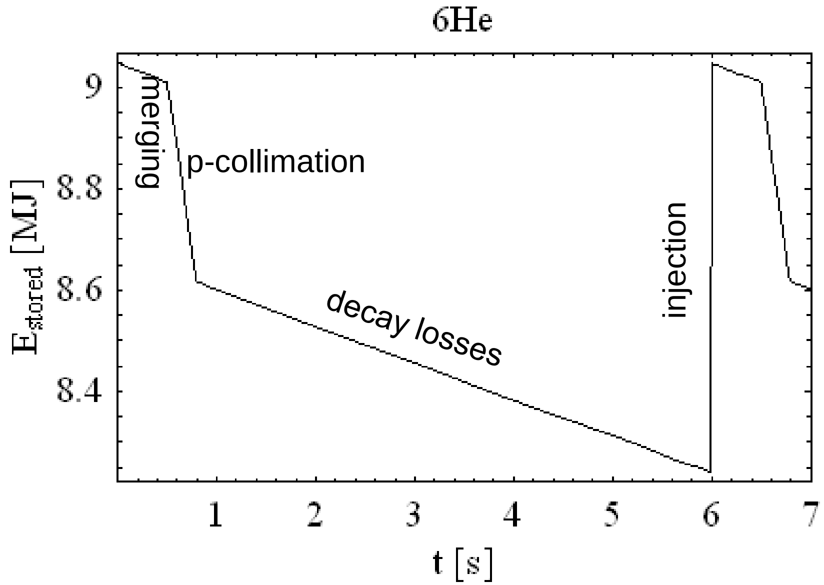
Neutrino atmospheric background for Ne and He (gamma = 100)

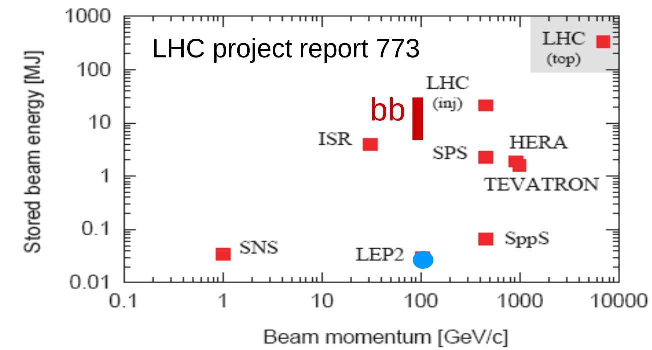
For 8Li and 8B, filling of decay ring using barrier buckets

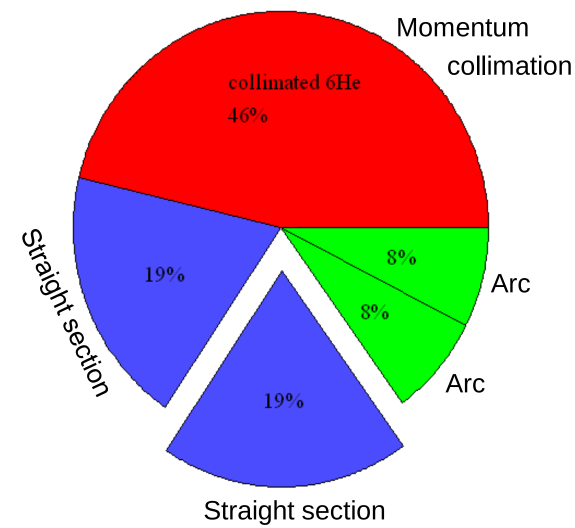




Particle turnover in decay ring (FP6)







- Momentum collimation: ~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

Progress and Plans CERN

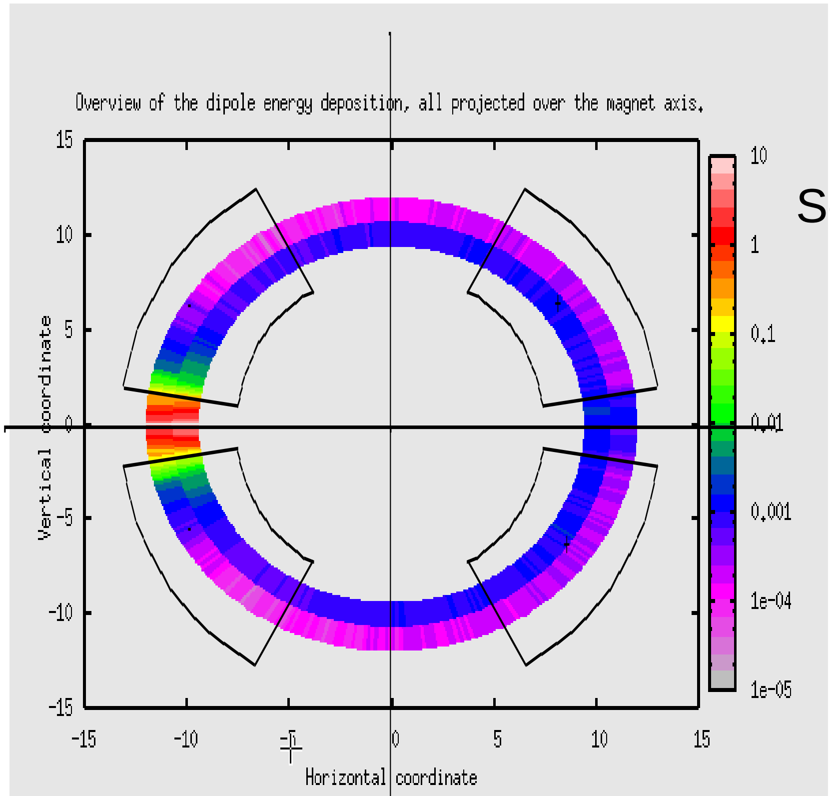
- Review of baseline design, ongoing
  - PS2 integration (minimum)
    - RCS
    - Overall cycle and bunch structure
- Relax of requirements of bunch structure in the Decay Ring
  - Barrier buckets in Decay Ring
  - Bunch structure of preceding accelerators
- Production ring
  - Selection of staffing ongoing
- Parameter list
  - Database structure and setup, ongoing
  - Filling, depending on baseline review, being prepared
- Decay Ring Superconducting Magnets
  - Open mid-plane dipole and quadrupole design has been done (energy and radiation checks with beam remaining)

Welcome Christian Hansen

Dependencies

- ECR source
  - Specification of beam parameters after source
- RCS
  - Depends on PS2 integration, extraction energy, bunching and cycling
- Decay Ring Layout
  - Magnet layout
  - Injection (barrier buckets)
  - Collimation (barrier buckets)
- Collection device
  - Production Ring Simulations
- Radio Protection Studies
  - Decay Ring Layout and RF
  - RCS design (Injection Chopper)
  - PS2

Open midplane magnets for decay ring



Scale arbitrary

Design ok for the present design of the decay ring, check for energy deposition and radio resistance (B and Li, check if larger apertures with liner a better option)

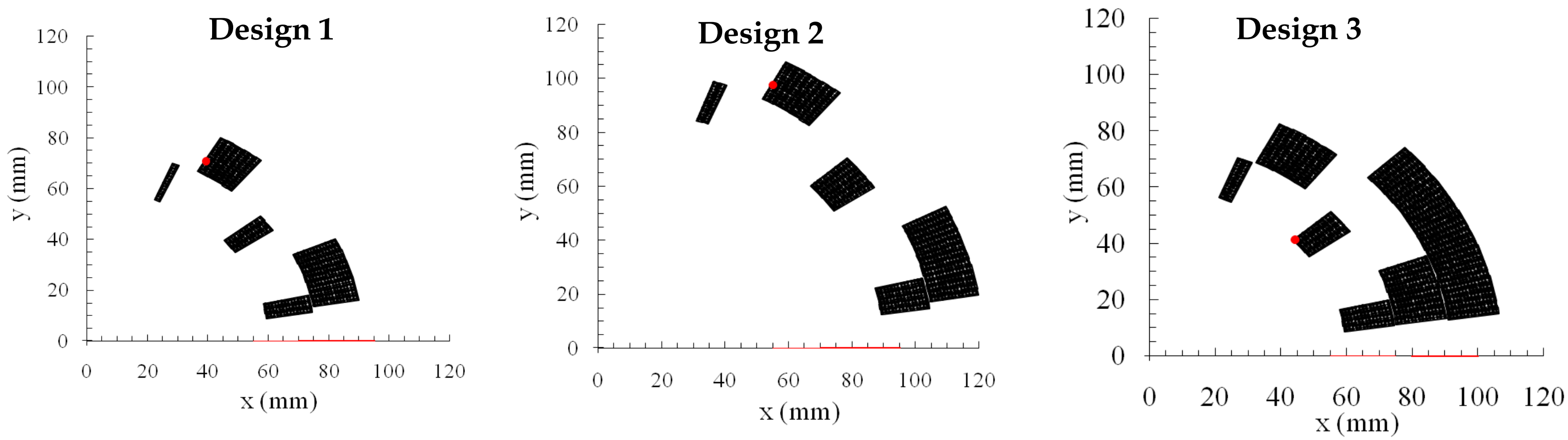
Acknowledgments (magnet design, cryostating, cryogenics):

Jens Bruer, F Borgnolutti, P. Fessia, R. van Weelderen , L. Williams and E. Todesco (CERN)

Three designs, Decay Ring Dipole

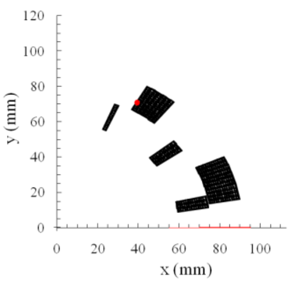
Design	1	2	3
Aperture radius (mm)	60	90	60
B_{ss} at 1.9 K (T)	6.5	6.8	8.7
Operational field at 1.9 K (T)	5.2	5.5	7.0
B_{ss} at 4.2 K (T)	4.9	5.3	6.7
Operational field at 4.2 K (T)	4.0	4.2	5.4
Gap in midplane (mm)	8.9	12.5	8.7
Yoke (mm)	180	270	240

Courtesy Jens Bruer

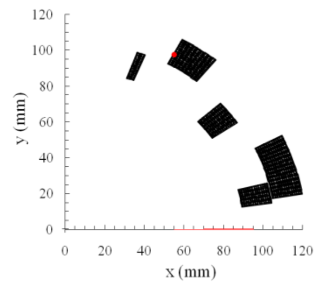


Cost estimation, Decay Ring Dipole

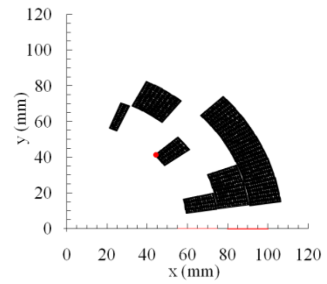
- For magnet fabrication and assembling, calculated for a 13 m long dipole



Design 1



Design 2



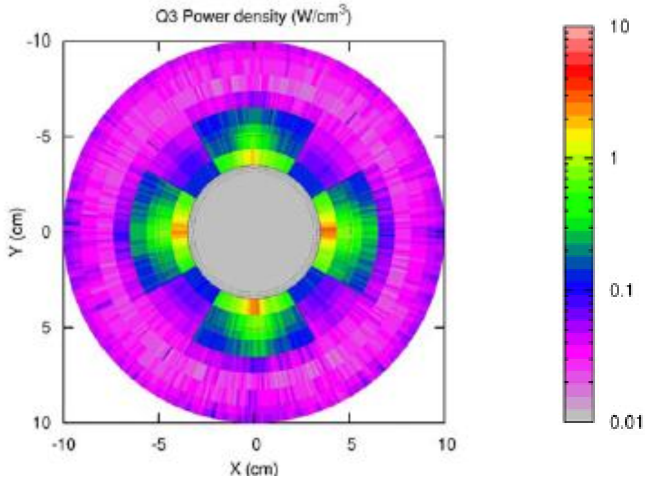
Design 3

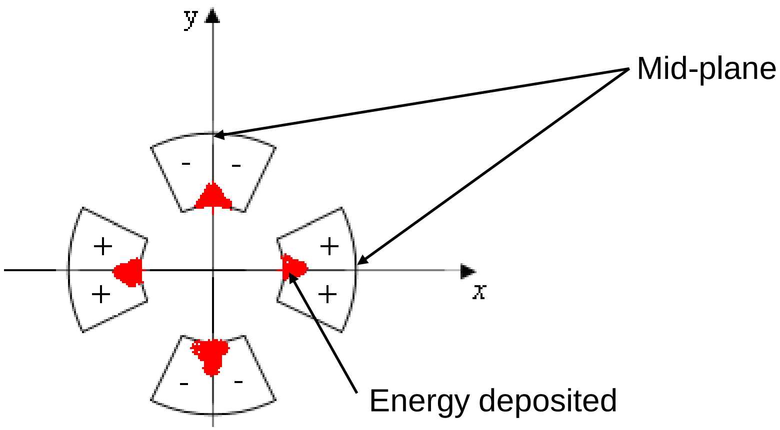
Requires 1.9K !!

Cost (MCHF per unit)	Design 1	Design 2	Design 3
Magnet (material + fabrication)	0.71	0.76	0.82
Cryostat	0.1	0.1	0.1
Cryoplants at 1.9 K	0.3	0.3	0.3
Cryoplants at 4.5 K	0.2	0.2	0.2
Total at 4.5 K	1.01	1.06	1.12
Total at 1.9 K	1.11	1.16	1.22

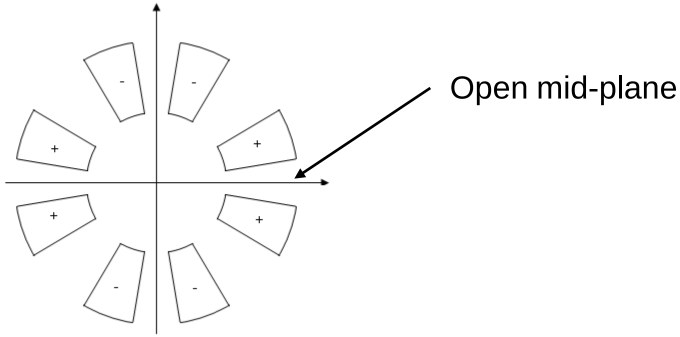
Open mid-plane quadrupole

- In a quadrupole beam losses are mainly located in the mid-plane:
  - Damage the superconducting cable
  - Might lead to a quench





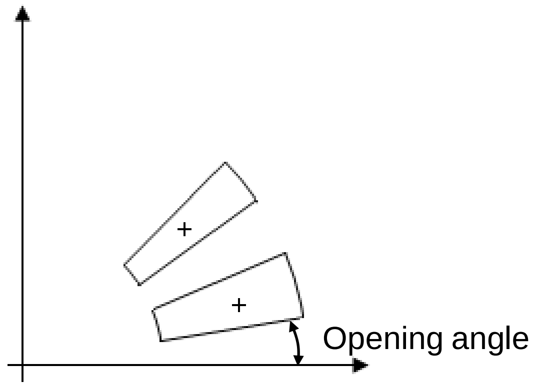
- To avoid the peak of the heat deposition an open mid-plane can be inserted
  - How is the field strength affected by insertion of an open mid-plane?

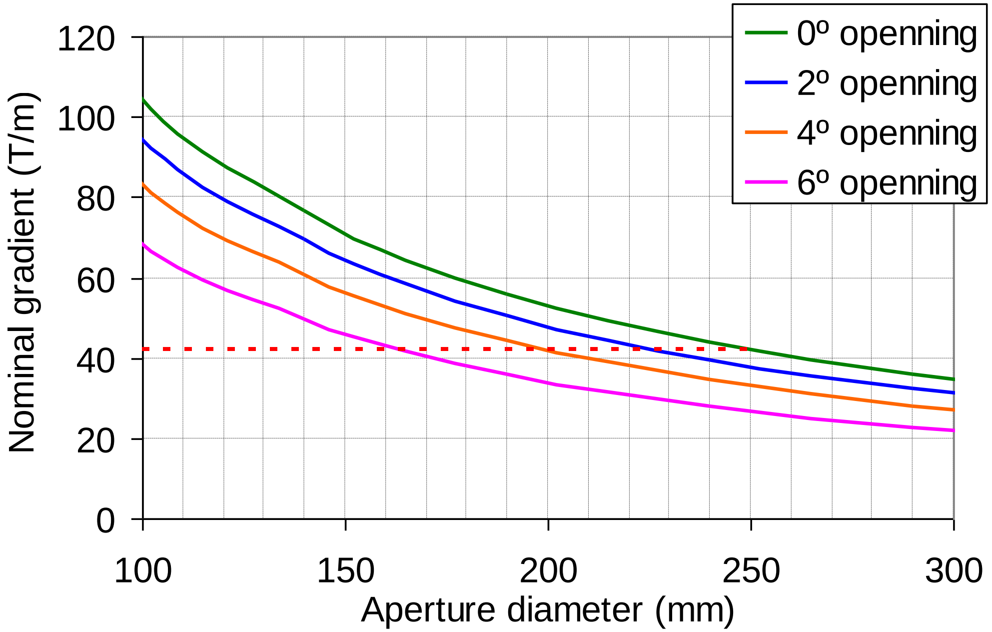


Courtesy Franck Borgnolutti

Open mid-plane quadrupole

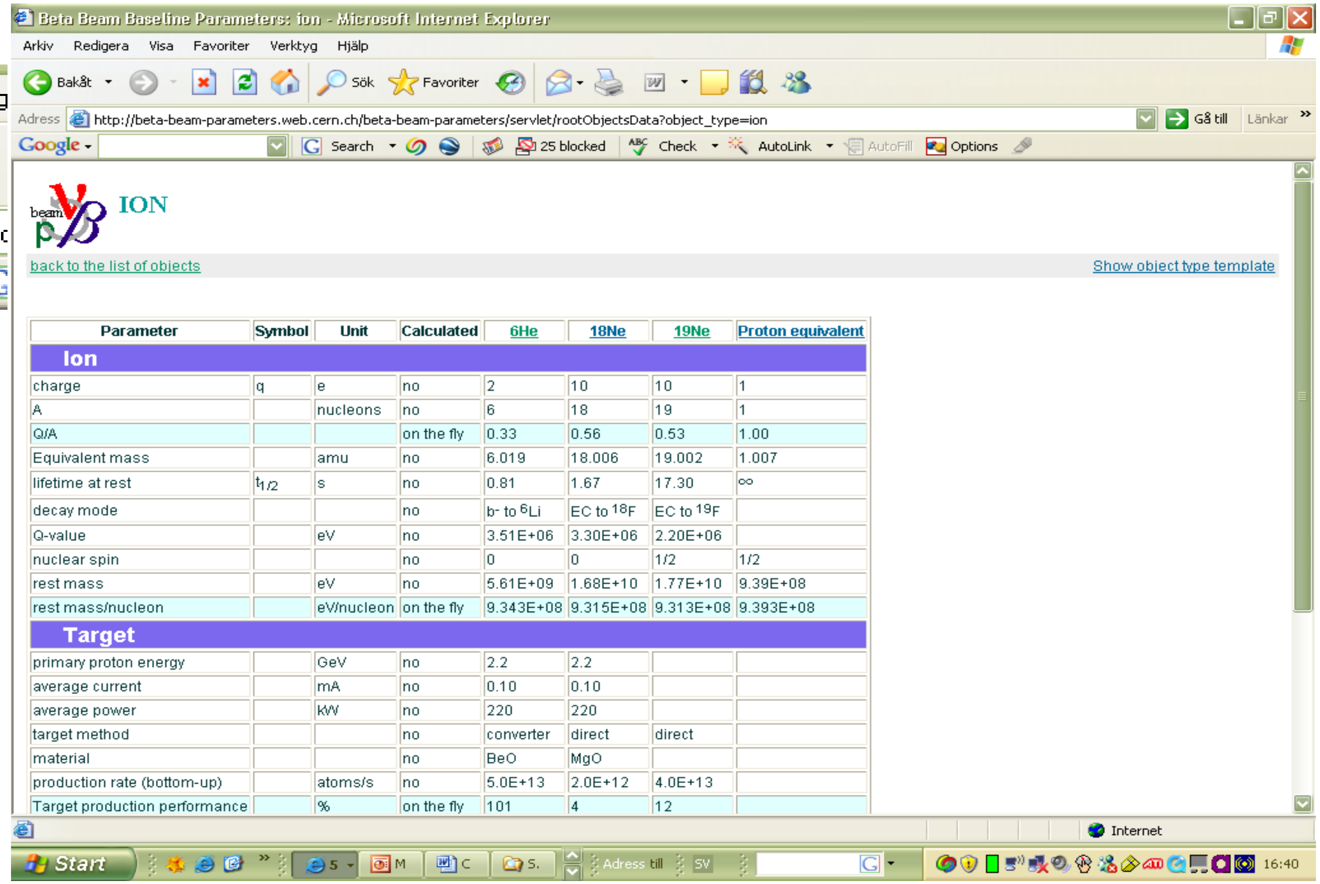
- We consider a quadrupole made of 2 pure sector blocks of the LHC main dipole cable.
- Ironless coil is assumed.





- Aperture diameter corresponding to a nominal gradient of 42 T/m with 20 % margin from the quench:
  - 2º opening : 230 mm
  - 4º opening : 200 mm
  - 6º opening : 160 mm
- Alternative to open midplane: thick liners

Parameters on the Web for 8B and 8Li



Parameter	Symbol	Unit	Calculated	6He	18Ne	19Ne	Proton equivalent
Ion							
charge	q	e	no	2	10	10	1
A		nucleons	no	6	18	19	1
Q/A			on the fly	0.33	0.56	0.53	1.00
Equivalent mass		amu	no	6.019	18.006	19.002	1.007
lifetime at rest	$t_{1/2}$	s	no	0.81	1.67	17.30	∞
decay mode			no	b- to ^{6}Li	EC to ^{18}F	EC to ^{19}F	
Q-value		eV	no	3.51E+06	3.30E+06	2.20E+06	
nuclear spin			no	0	0	1/2	1/2
rest mass		eV	no	5.61E+09	1.68E+10	1.77E+10	9.39E+08
rest mass/nucleon		eV/nucleon	on the fly	9.343E+08	9.315E+08	9.313E+08	9.393E+08
Target							
primary proton energy		GeV	no	2.2	2.2		
average current		mA	no	0.10	0.10		
average power		kW	no	220	220		
target method			no	converter	direct	direct	
material			no	BeO	MgO		
production rate (bottom-up)		atoms/s	no	5.0E+13	2.0E+12	4.0E+13	
Target production performance		%	on the fly	101	4	12	

Conclusion

For the first annual meeting of FP7 there seems to be no major danger of not meeting the milestones and the deliverables

Annual meeting this week

Christian, Elena and Elena… in SPC panel for neutrino's it **may** be considered to propose additional support to the project (and the other neutrino projects)

We need advice from RF experts, cooling experts… and there are many interesting subjects to work on…