Progress on ion production studies for beta beams

Elena Wildner, CERN

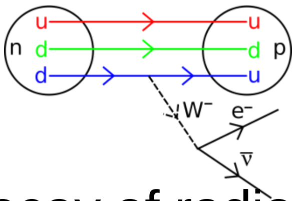
EuCARD 1st ANNUAL MEETING

Rutherford Appleton Laboratory (RAL), Oxfordshire-UK

Outline

- Beta Beam Concepts
- A Beta Beam Scenario
- Ion Production status
- Conclusion

Beta-beams, recall

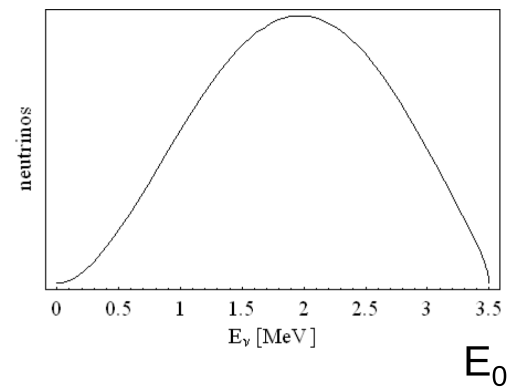


Aim: production of (anti-)neutrino beams from the beta decay of radio-active ions circulating in a storage ring

- 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

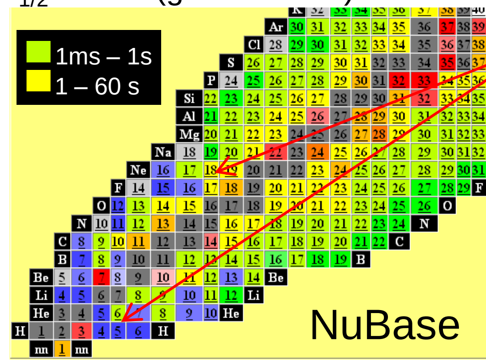


- Accelerate parent ion to relativistic γ_{max}
  - Boosted neutrino energy spectrum: $E_\nu \leq 2\gamma Q$
  - Forward focusing of neutrinos: $\theta \leq 1/\gamma$
- Pure electron (anti-)neutrino beam!
  - Depending on β^+- or β^-- decay we get a neutrino or anti-neutrino
  - Two different parent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

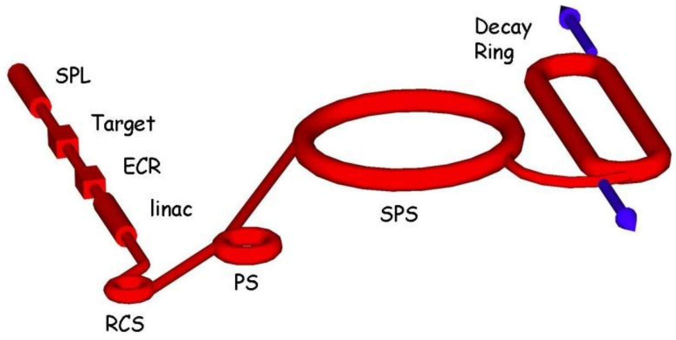
Isotope	A/Z	T ½ (s)	Q_β g.s to g.s (MeV)	Q_β eff (MeV)	E_β av (MeV)	E_ν av (MeV)	Ions/bunch	Decay rate	rate / $E_{\nu\ av}$ (s^{-1})
^{6}He	3.0	0.80	3.5	3.5	1.57	1.94	$5\cdot10^{12}$		
^{8}He	4.0	0.11	10.7	9.1	4.35	4.80	$5\cdot10^{12}$		
^{8}Li	2.7	0.83	16.0	13.0	6.24	6.72	$3\cdot10^{12}$		
^{9}Li	3.0	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]	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	$9\cdot10^{11}$	$3\cdot10^{8}$	$2\cdot10^{8}$

The EURISOL scenario(*) boundaries

- Based on CERN boundaries
- Ion choice: ^{6}He and ^{18}Ne
- Based on existing machines and technologies
  - 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



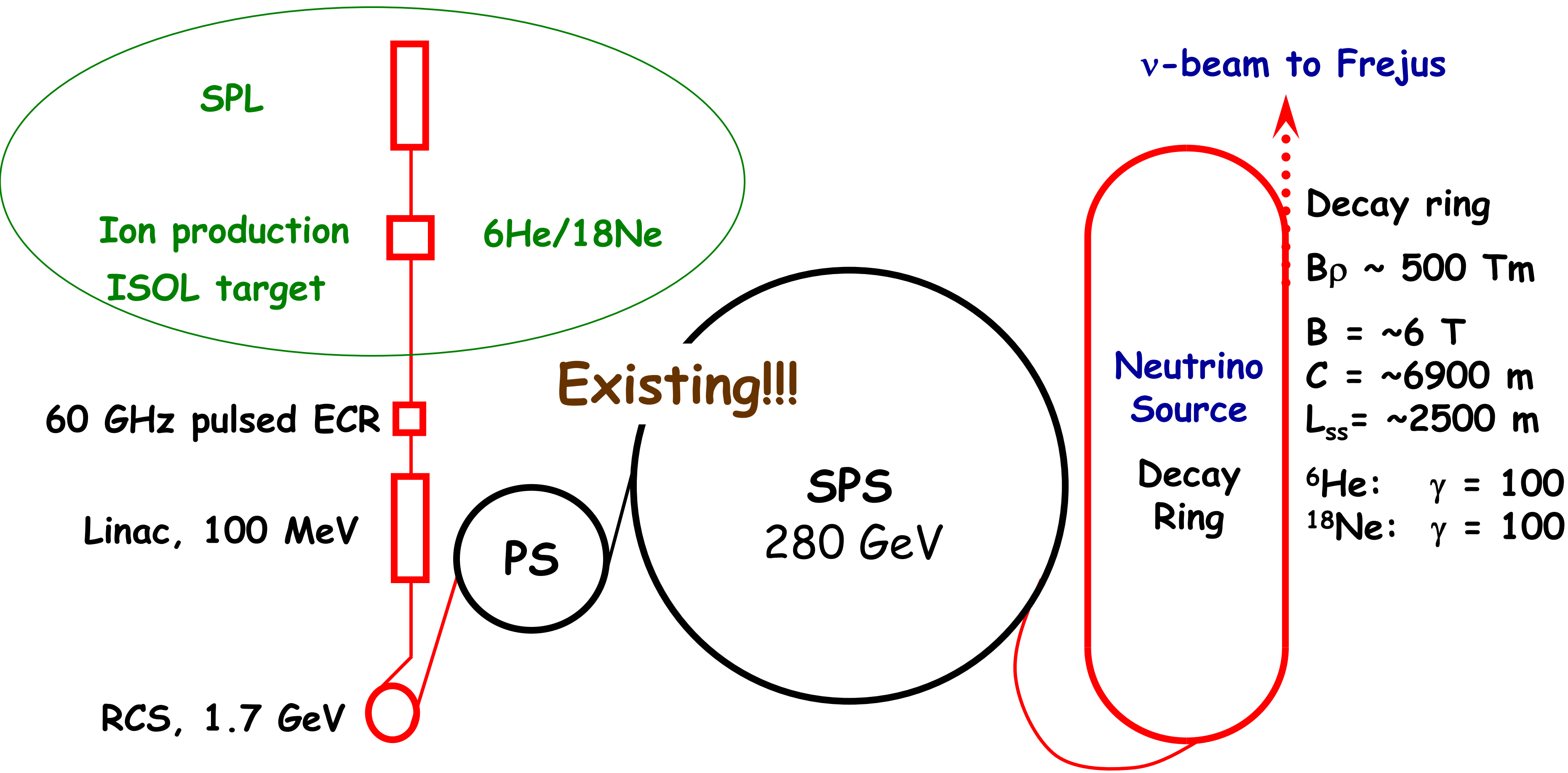
- Achieve an annual neutrino rate of
  - 2.9*10^{18} anti-neutrinos from ^{6}He
  - 1.1 10^{18} neutrinos from ^{18}Ne

top-down approach

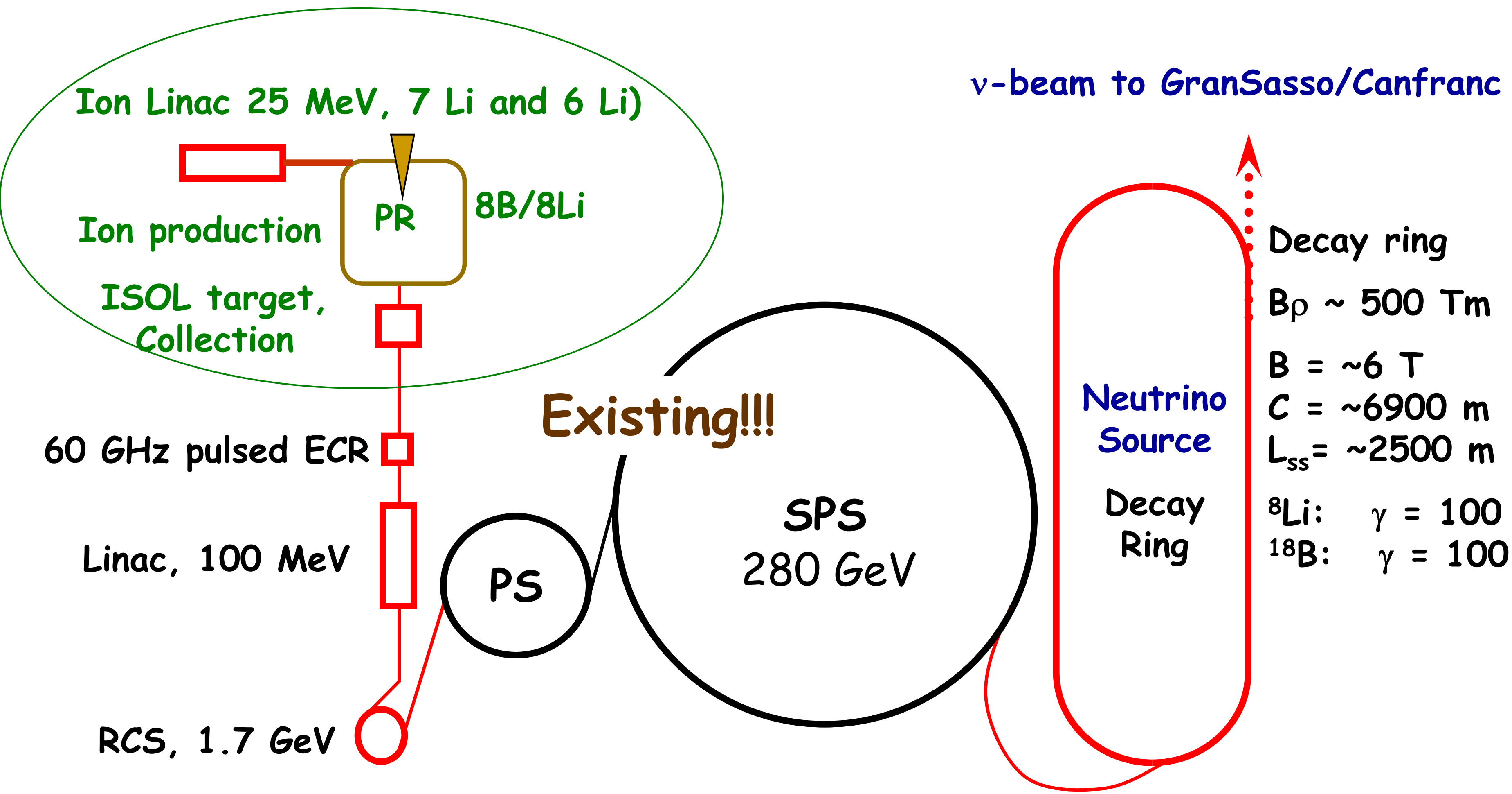
- The EURISOL scenario serves as reference for other studies and developments within Euroν (FP7) to study ^{8}Li and ^{8}B

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

Beta Beam scenario 6He/18Ne



Beta Beam scenario 8Li/8B



Options for production 2008

- ISOL method at 1-2 GeV (200 kW)
  - >1 10^{13} ^{6}He per second
  - <8 10^{11} ^{18}Ne per second Not sufficient
  - 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
- Solution (?): Production ring
  - 10^{14} (?) ^{8}Li
  - >10^{13} (?) ^{8}B
  - Will be studied Within EUROν

Aimed:

He 2.9 10^{18} (2.3 10^{13}/s)

Ne 1.1 10^{18} (2.3 10^{13}/s)

Known losses through the accelerator complex included

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!

Estimated production

	# 8B Ions	# 8Li Ions	# 18Ne Ions	# 6He Ions
After Target	$9. \times 10^{13}$	$9. \times 10^{13}$	2.3×10^{13}	2.34×10^{13}
ECR	2.07×10^{12}	6.22×10^{12}	5.23×10^{11}	1.78×10^{12}
RCS inj	1.03×10^{12}	3.1×10^{12}	2.61×10^{11}	8.85×10^{11}
RCS	1.01×10^{12}	3.02×10^{12}	2.58×10^{11}	8.6×10^{11}
PS inj	1.54×10^{13}	4.2×10^{13}	4.49×10^{12}	1.15×10^{13}
PS	1.42×10^{13}	3.69×10^{13}	4.29×10^{12}	9.89×10^{12}
SPS	1.38×10^{13}	3.52×10^{13}	4.24×10^{12}	9.34×10^{12}
Decay Ring	1.2×10^{14}	2.97×10^{14}	7.38×10^{13}	$1. \times 10^{14}$
Annual ν Rate			1.1×10^{18}	3.01×10^{18}

RCS: Multiturn 50 %

ECR efficiency: 30 %

Decay Ring fraction: 0.36 (0.42 gives 10 % more Ne 15 % more He)

Linac, beam stabilty, vacuum... May still reduce the final flux from decay ing

Aimed:

He 2.9 10^{18} (2.3 10^{13}/s)

Ne 1.1 10^{18} (2.3 10^{13}/s)

But: 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 $\sim \langle E_\nu \rangle \sim \gamma Q$

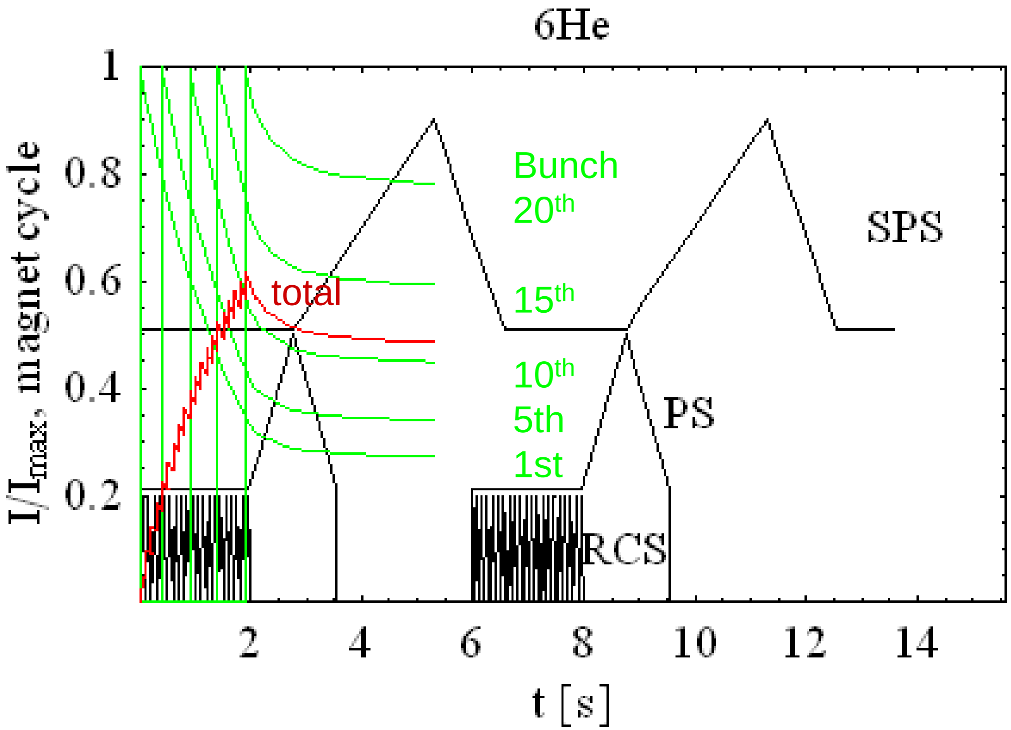
- Merit factor for an experiment at the atmospheric oscillation maximum: ***M=*** γ / Q

- Decay ring length **scales ~** γ (ion lifetime)

- B and Li have 5 time higher Q and detector needs a factor 2:

  10 times more ions have to be accelerated: (Too) High challenge

Intensity evolution during acceleration



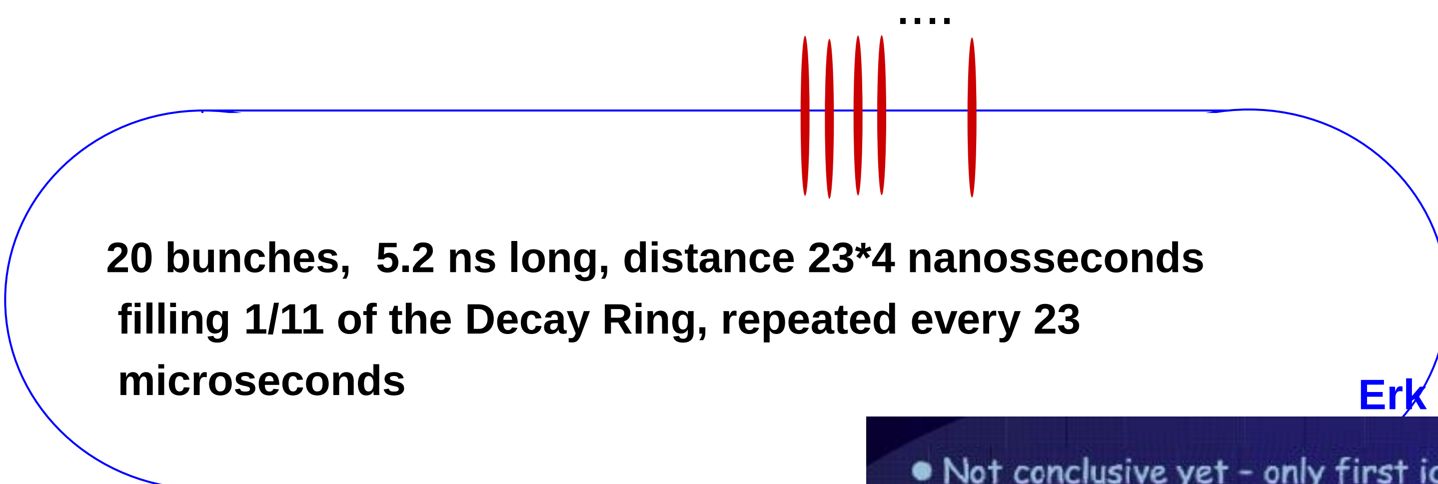
Cycle optimized for neutrino rate towards the detector

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

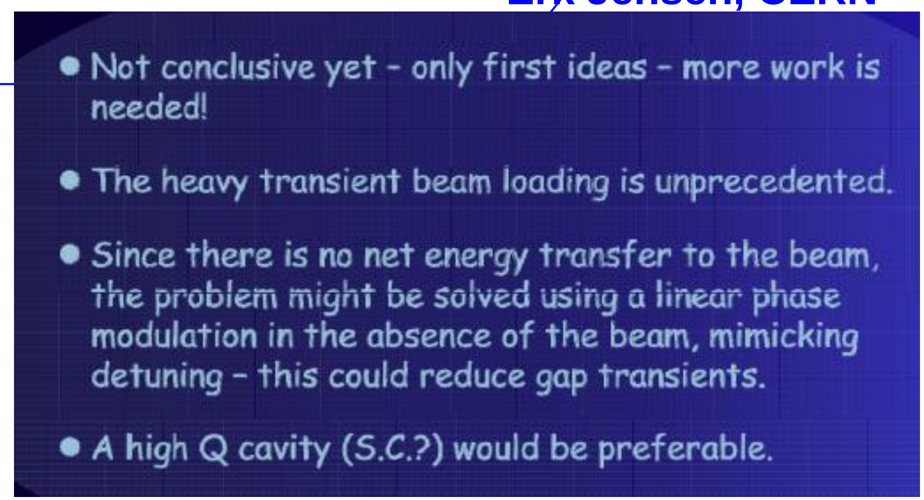
Duty factor and Cavities for He/Ne

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



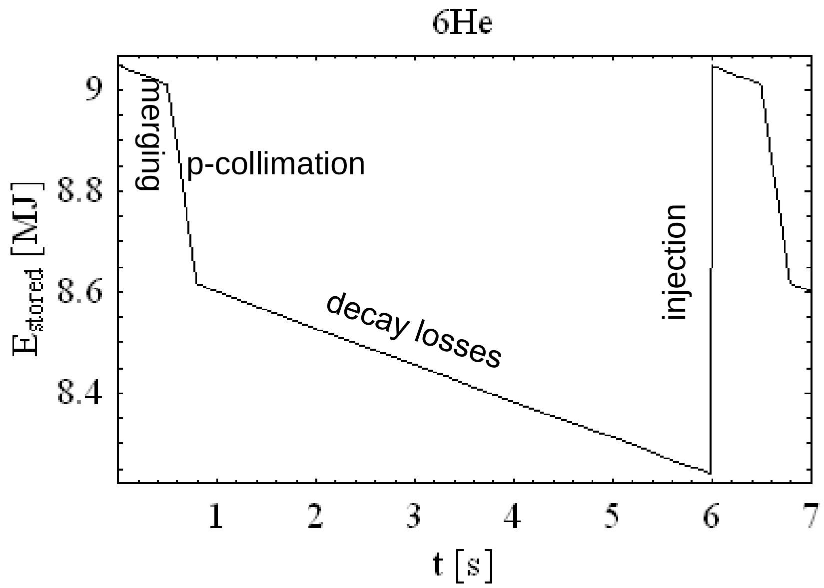
20 bunches, 5.2 ns long, distance 23*4 nanosseconds filling 1/11 of the Decay Ring, repeated every 23 microseconds

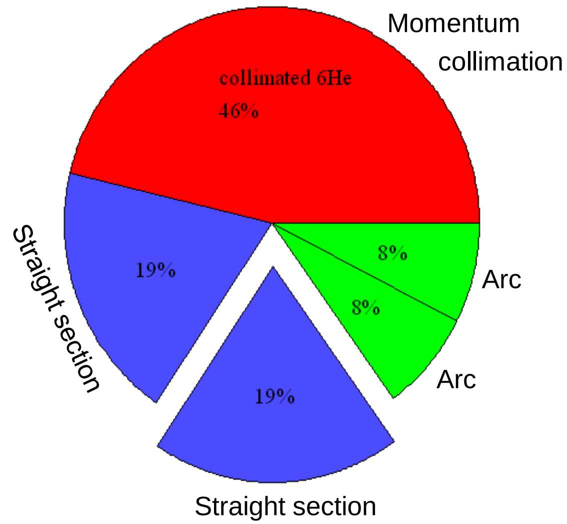
Erk Jensen, CERN


- 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.

For B and Li the duty factor can be relaxed by a factor 2!

Particle turnover in decay ring





- Momentum collimation (study ongoing):

  ~5*10^12 ^6He ions to be collimated per cycle

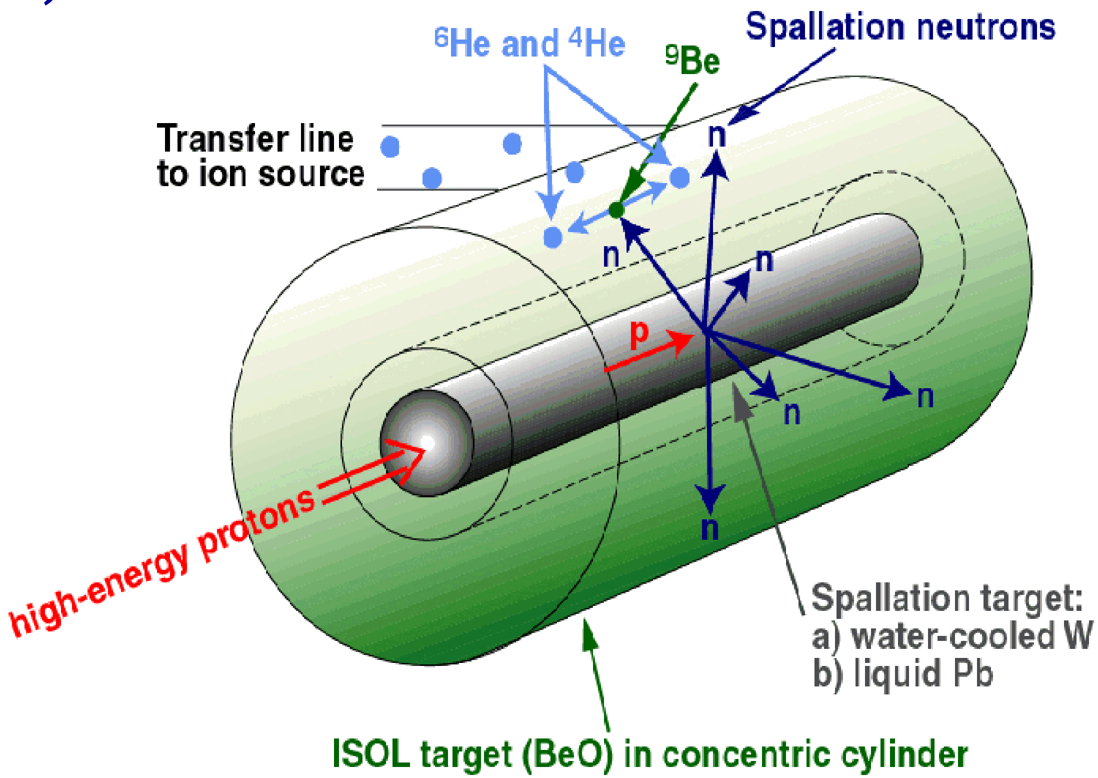
  Decay: ~5*10^12 ^6Li ions to be removed per cycle
- Dump at the end of the straight section will receive 30kW
- Dipoles in collimation section receive between 1 and 10 kW (masks).

Options for production 2010

- ISOL method at 1-2 GeV (200 kW)
  - >3 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
  - Is studied Within EUROν

Aimed:
He 2.9 10^{18} (2.3 10^{13}/s)
Ne 1.1 10^{18} (2.3 10^{13}/s)

^{6}He (ISOL)



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

T. Stora, CERN, N. Thiollieres, CEA

- Converter technology preferred to direct irradiation (heat transfer and efficient cooling allows higher power compared to insulating BeO).
- ^{6}He production rate is ~3x10^{13} ions/s (dc) for ~200 kW on target.

Options for production 2010

- 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

Difficult Chemistry

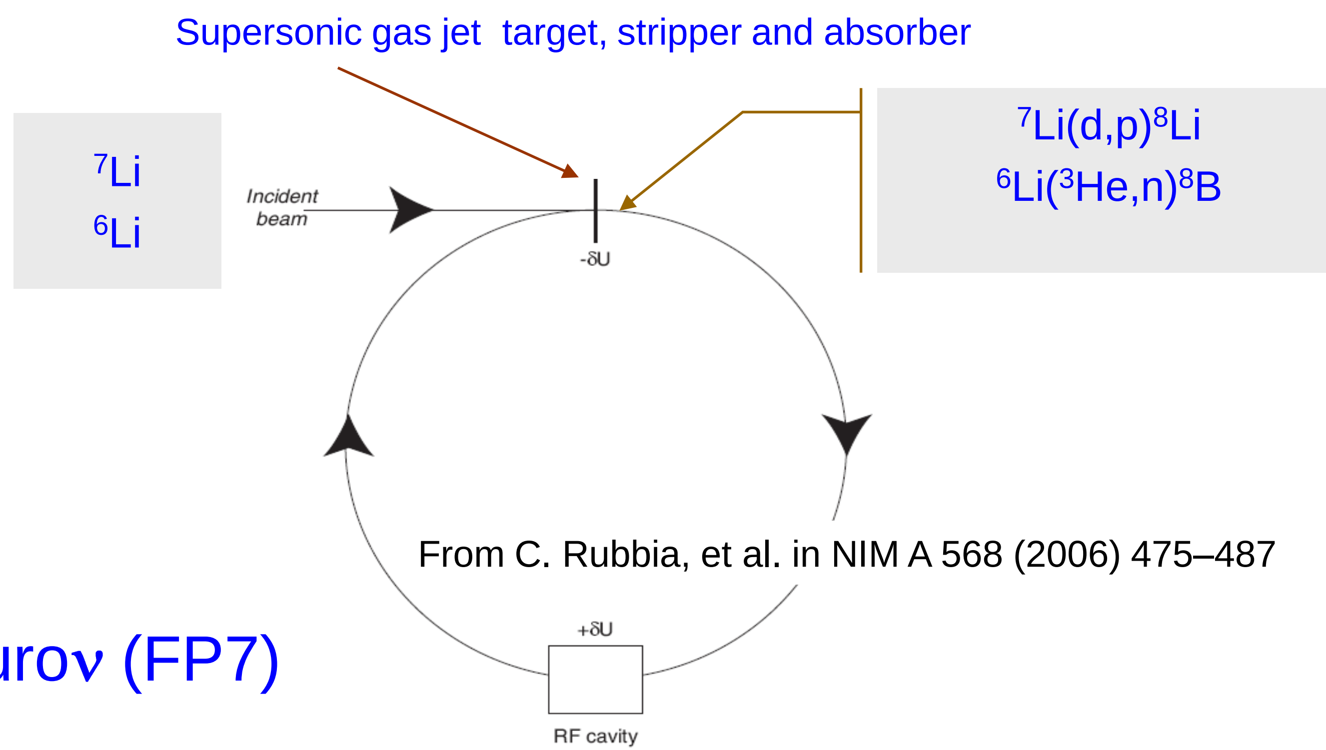
Aimed:
He 2.9 10^{18} (2.3 10^{13}/s)
Ne 1.1 10^{18} (2.3 10^{13}/s)

N.B. Nuclear Physics has limited interest in those elements => Production rates not pushed!
Try to get ressources to persue ideas to produce Ne!

8B and 8Li ion production

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

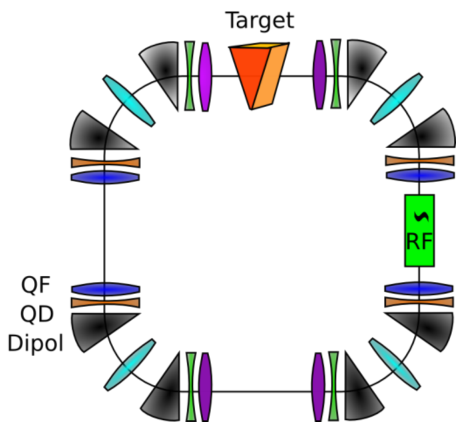
“Development of FFAG accelerators and their applications for intense secondary particle production”, Y. Mori, NIM A562(2006)591

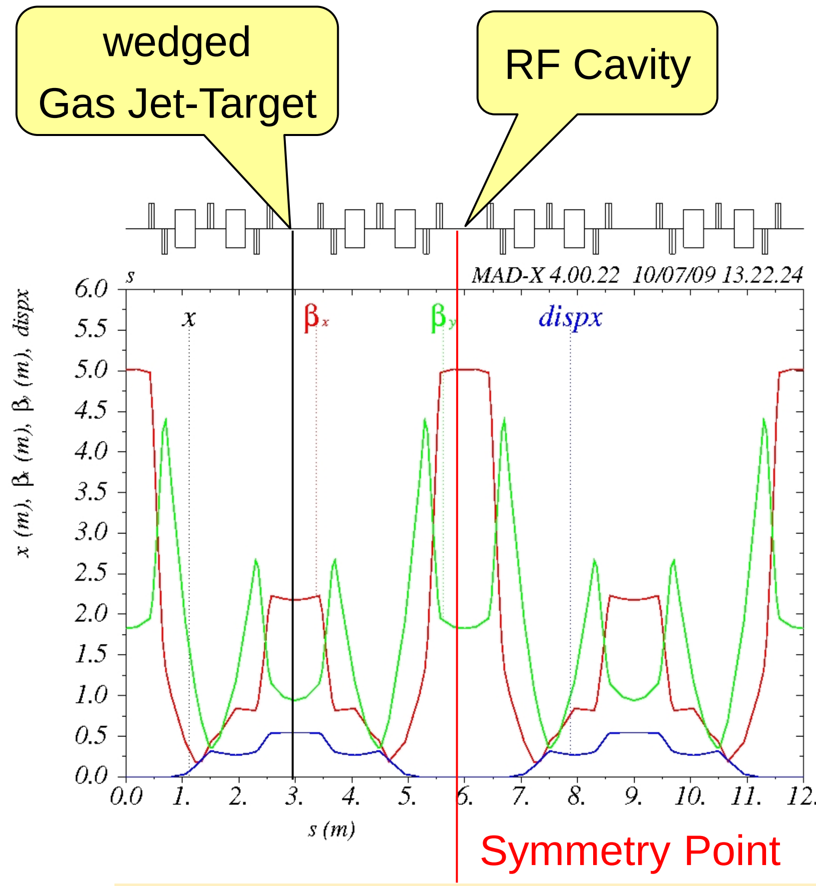


From C. Rubbia, et al. in NIM A 568 (2006) 475–487

Studied within Euroν (FP7)

The production Ring: 8Li and 8B Ion Source





- Target simulations ongoing (FLUKA)
- Cross sections will be adjusted
- Cooling could be possible (simulations)
- Existing RF technologies are ok
- Gas jet target not possible

Michaela Schaumann , Aachen/CERN, 2009
Jakob Wehner, Aachen/CERN, 2009
Elena Benedetto, CERN, 2009

Cross section measurements at Laboratori Nazionali di Legnaro

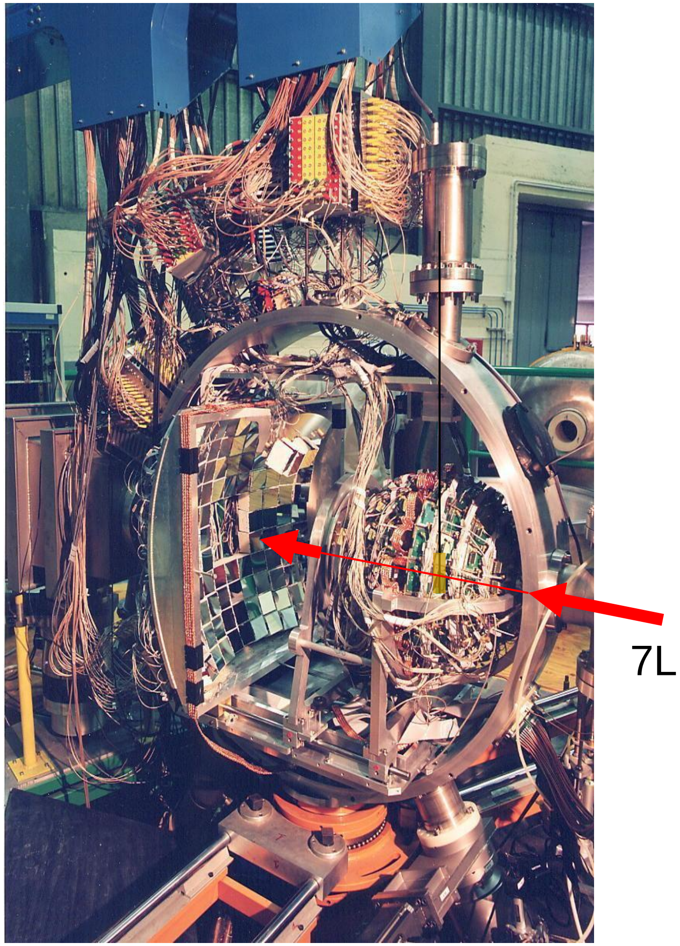
M.Mezzetto (INFN-Pd)
on behalf of
INFN-LNL: M. Cinausero, G. De Angelis, G. Prete

Results for Li available

Inverse kinematic reaction:

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

Data reduction (presented Feb. 2010) will be used for beam cooling simulations in the production ring.

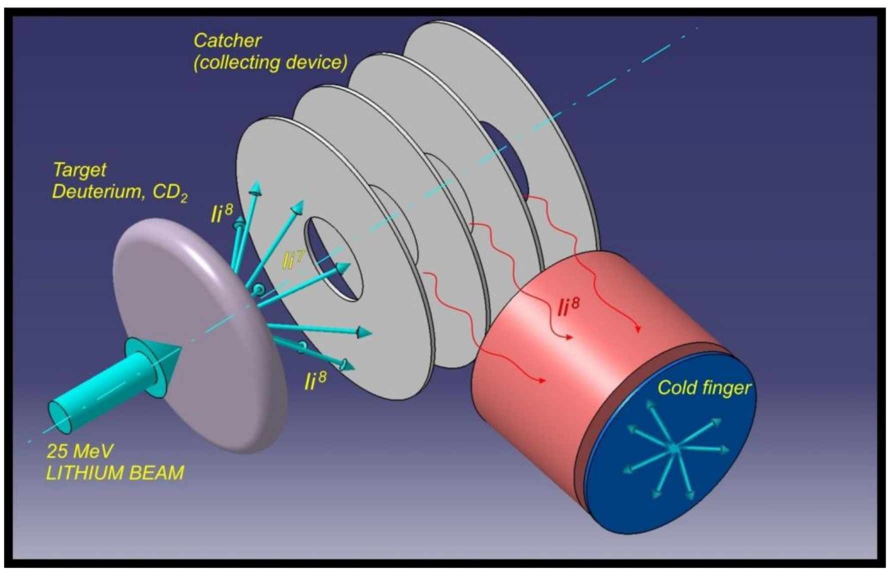


Challenge: collection device

- 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.

- First results for Li will be presented in June 2010

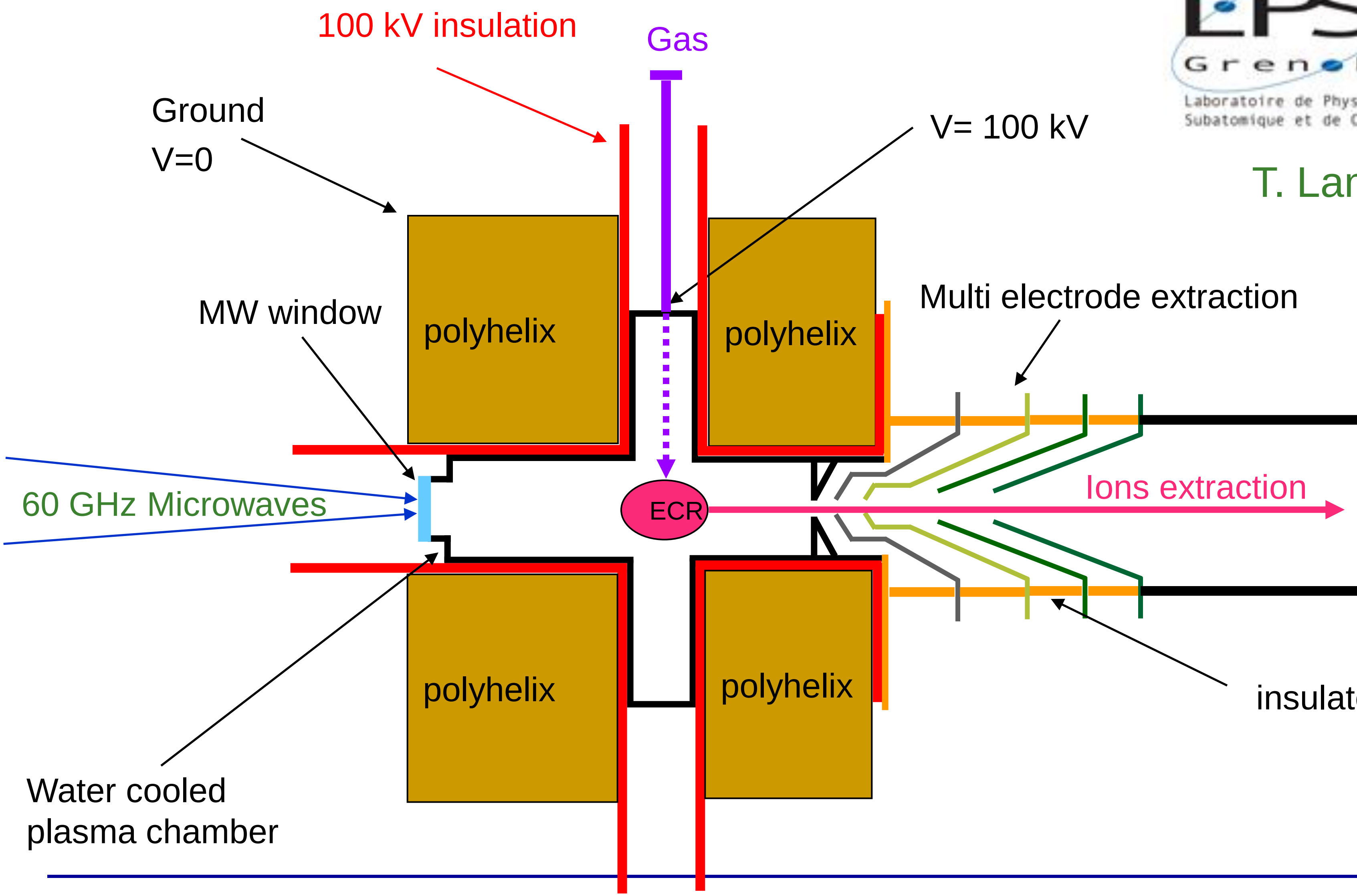


CRC
Louvain-la-Neuve

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

60 GHz ECR Source

T. Lami



Options for production 18Ne

- ISOL method at 1-2 GeV (200 kW)
  - >3 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
  - Is studied Within EUROν

Aimed:

He 2.9 10^{18} (2.3 10^{13}/s)

Ne 1.1 10^{18} (2.3 10^{13}/s)

Options for production

Courtesy Thierry Stora

Type	Accelerator	Beam	I_{beam} mA	E_{beam} MeV	P_{beam} kW	Target	Isotope	Flux s^{-1}	Ok?
ISOL & n-converter	SPL	p	0.1	2 10^3	200	W/BeO	6He	5 10^{13}	
ISOL & n-converter	Saraf/GANIL	d	15	40	600	C/BeO	6He	5 10^{13}	
ISOL	Linac 4	p	6	160	700	19F Molten NaF loop	18Ne	1 10^{13}	
ISOL	Cyclo/Linac	p	10	70	700	19F Molten NaF loop	18Ne	2 10^{13}	
ISOL	LinacX1	3He	> 170	21	3600	MgO 80 cm disk	18Ne	2 10^{13}	
P-Ring	LinacX2	7Li	0.160	25	4	d	8Li	?1 10^{14}	
P-Ring	LinacX2	6Li	0.160	25	4	3He	8B	?1 10^{14}	

Possible

Challenging

Needs some optimization

R & D !!!

Experimentally OK

On paper may be OK

Not OK yet

Work for ^{18}Ne production

- Work on ^{18}Ne production (production cross section, thermal dissipation, extraction losses, windows effects, known chemistry and corrosion effects with molten salts nuclear loops).

- Exploration up to 160 MeV to see if Linac4 would be a possible injector for beta beams.

- The goal is to provide a proposal with as close as possible technologies which are realistic. In particular, 100's kW rather than MW target dimensioning.

- Other future options for ^{8}B studies will be envisaged at CERN-ISOLDE. INTC is getting interested.

Courtesy T. Stora

Work on accelerators

- Collective effects in the SPS and the PS are studies He and Ne
- Will be used to check limits for intensities (later for B and Li)
- Deacy ring has been redesigned to increase the proportion of straight section (higher field magnets) and enhance the useful part of the Decay Ring (gives 10 for Ne)
- End to end simulations being set up to check all losses
- Check if we can run longer with Ne and less with He (increse intensity up to limit)

Choice of Beta Beam Baseline

- FP6 EURISOL Beta Beam
  - 18 Ne shortfall -> but 2009 work very encouraging
  - 6He intensities confirmed by experiment
  - Beam stability studies in FP7
  - Becoming a solid option
- FP7 EUROnu Beta Beam
  - Intensity needs multiplies by 10 (geometry, long baseline, detector)
  - Present accelerators limited
  - Detector needs another factor 2
  - Production ring not feasible (more research needed)
  - For the time being not a solid option

Conclusions

- We are coming close to a baseline for Beta Beams
  - Using 6He and 18Ne ions
  - Working hard with limited resources to achieve production
  - Now working for experimental verification (resources?)
  - Beta Beam accelerator complex beam stability studies
- Production Ring Studies pursued
  - Very difficult technologies to be developed (production)
  - Beam Stability?
  - Decay Ring Intensities not comfirmed
- Results to be presented 2012

Acknowledgements

FP6 "Structuring the European Research Area" programme (EC Contract 515768 RIDS) and

FP7 “Design Studies” (Research Infrastructures) EUROnu (Grant agreement no.: 212372)