Future options for the beta-beam with a focus on production issues

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on behalf of the Beta-beam Study Group
http://cern.ch/beta-beam

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Acknowledgements

- All colleagues in EURISOL
- My CERN colleagues working on beta-beams:
  - Michael Benedikt, Adrian Fabich, Steven Hancock, Elena Wildner
- Prof. Carlo Rubbia
- Yacine Kadi, Vasilis Vlachoudis, Alfredo Ferrari
- Mauro Mezzetto and Pierro Zuchelli
- Andreas Jansson at FNAL
- All other colleagues who helped with and supported this work
- My colleagues at ANL
- Prof. Dave Casper, UCI
- My wife and children

Guideline to ν-beam scenarios

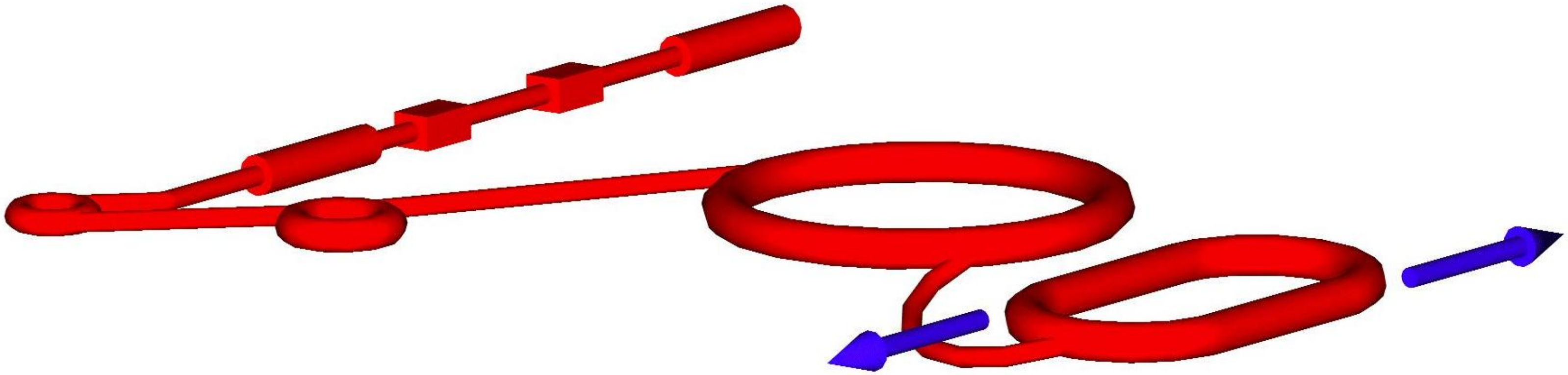
based on radio-active ions

- Low-energy beta-beam: relativistic $\gamma < 20$
  - Physics case: neutrino scattering
- Medium energy beta-beam: $\gamma \sim 100$
  - EURISOL DS
  - Today the only detailed study of a beta-beam accelerator complex
- High energy beta-beam: $\gamma > 350$
  - Take advantage of increased interaction cross-section of neutrinos
- Monochromatic neutrino-beam
  - Take advantage of electron-capture process
- High-Q value beta-beam: $\gamma \sim 100$

Accelerator physicists together with neutrino physicists defined the accelerator case of γ=100/100 to be studied first (EURISOL DS).

What would we like to improve in the beta-beam conceptual design?

- Production of radioactive nuclei
  - Limit of the ISOL method
  - Production ring
  - Direct production
- Highly efficient bunching and ionization of the ions
  - Should it be a Preglow ECR…
  - …or and Afterglow ECR?
- High(er) energy in the decay ring
  - Fast (and cheap) acceleration to high energies
  - Affordable high gamma decay ring
- Magnet protection and collimation for higher intensity beams
  - Open mid plan SC dipoles



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

Where are we today?

- 2 10^{13} atoms/s of ^{6}He -> **1.8 10^{13} ions/s $^{6}He^{q+}$** *(90%!!)*
- 8 10^{11} atoms/s of ^{18}Ne -> **2.7 10^{11} ions/s $^{18}Ne^{q+}$** *(30%)*
- He-6 and Ne-18 beams are presently available at
  GANIL, DUBNA, ISOLDE, ISAAC, ….LLN
- After the ion source, the available intensity is at maximum

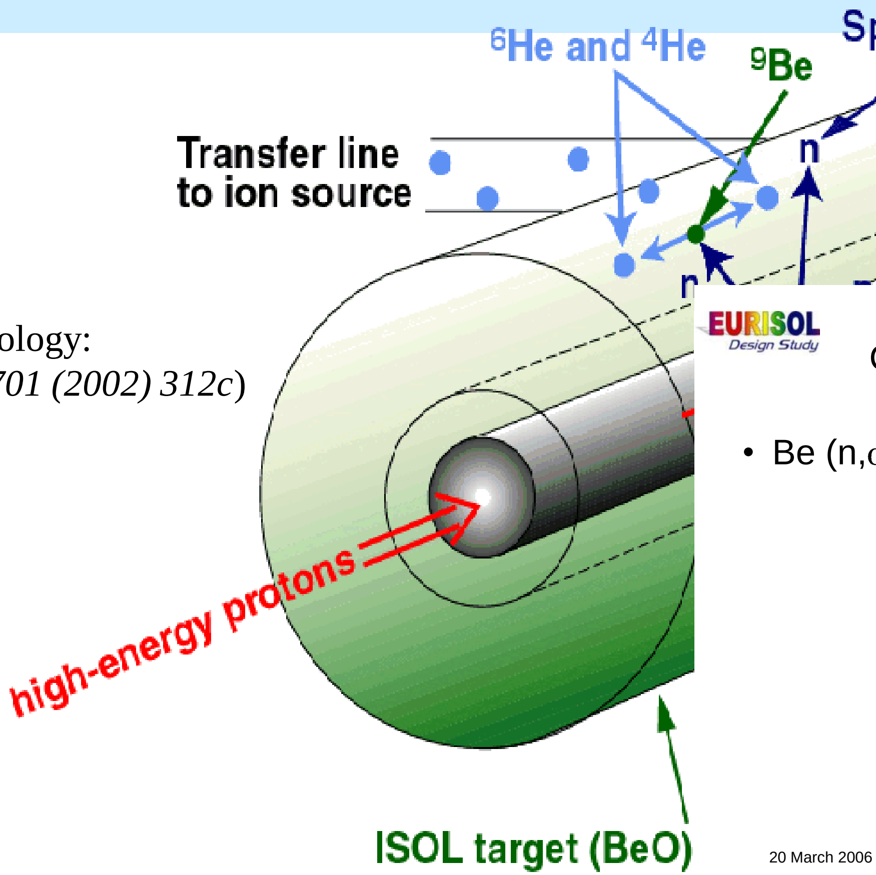
  3 10^{8} ions/s for **$^{6}He^{1+}$**
  3 10^{8} ions/s for $^{18}Ne^{10+}$

Production shortfall

	Nominal production rate [ions/s]	Required production rate [ions/s]	Missing factor
6He	2×10^{13}	2×10^{13}	1
18Ne	8×10^{11}	1.9×10^{13}	24

- Major challenge for ^{18}Ne
- New production method proposed by C. Rubbia and Y. Mori
- Direct production

^{6}He production from ^{9}Be(n,α)

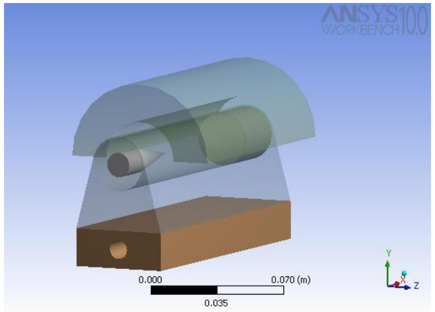


Converter technology:
(*J. Nolen, NPA 701 (2002) 312c*)

EURISOL Design Study

Conceptual design of the dual converter-BeO target

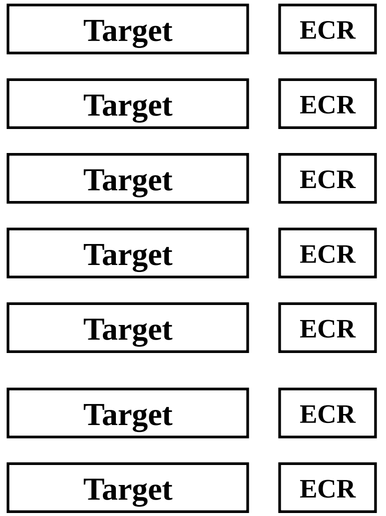
- Be (n,α) ^{6}He



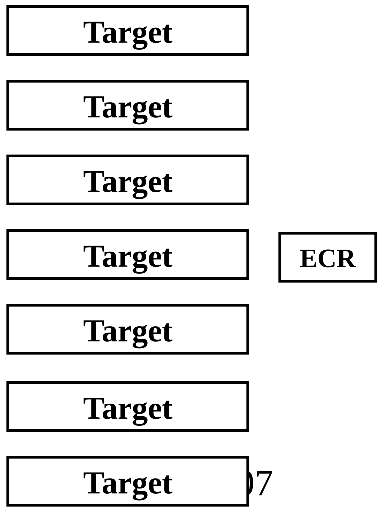
20 March 2006 T. Stora, CERN EURISOL – Task #3

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

Multiple targets and ECR sources with accumulation ring



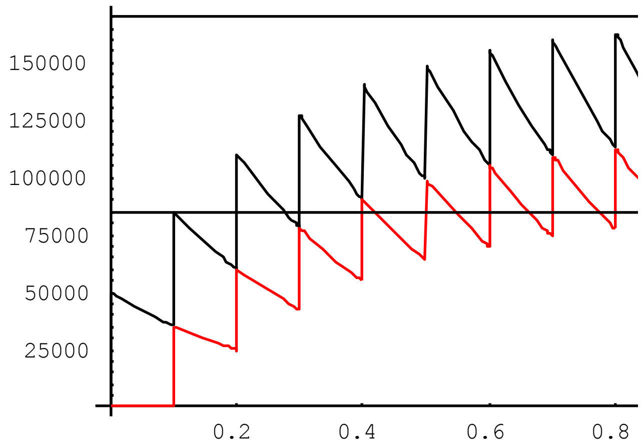
- Multiple target and multiple ECR sources
  - Proton beam split between 7 targets i.e. 1.4 MW of protons in total on all targets
  - 1 second accumulation time in the ECR source
  - 0.1 seconds between injections into linac and Accumulation ring
  - Accumulation of 10 bunches in SPS
  - ECR pulse: 2 10^{11} ions per pulse
  - Annual rate: 1 10^{18} (without accumulation ring 4 10^{17})
  - Drawback: Expensive and complicated!

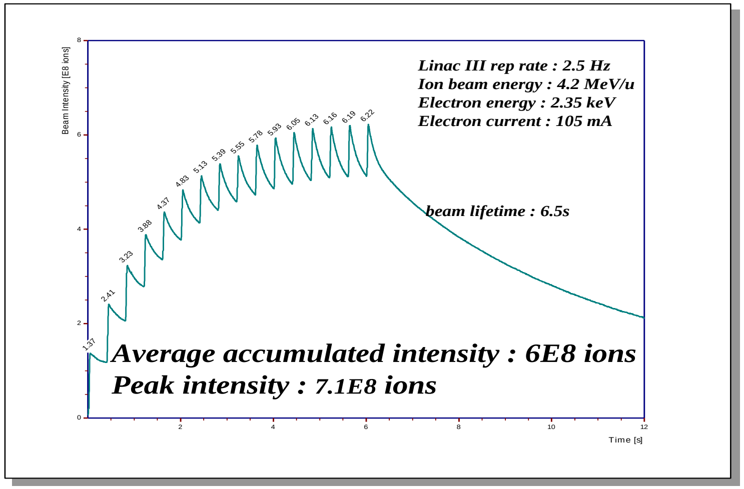


- Multiple target and single ECR sources
  - Proton beam split between 7 targets i.e. 1.4 MW of protons in total on all targets
  - 0.1 second accumulation time in the ECR source
  - 0.1 seconds between injections into linac and Accumulation ring
  - Accumulation of 10 bunches in SPS
  - ECR pulse: 1.4 10^{11} ions per pulse
  - Annual rate: 1 10^{18} (without accumulation ring 4 10^{17})
  - Drawback: Efficiency in the transport from target to ECR!

Use of a storage ring at low energy

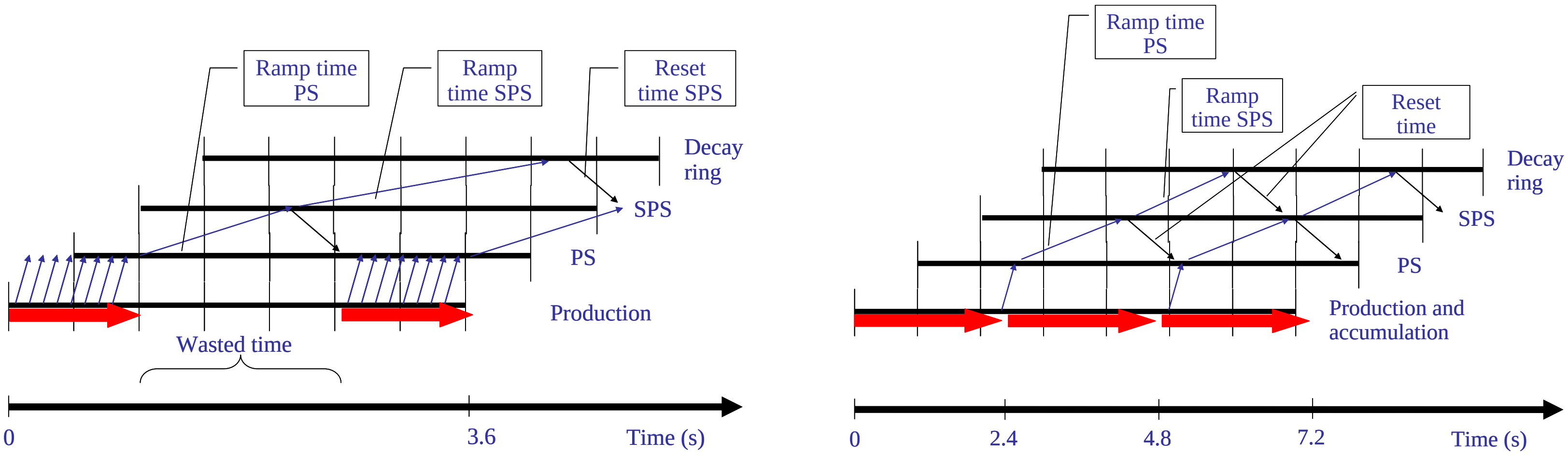
Multiturn injection with electron cooling





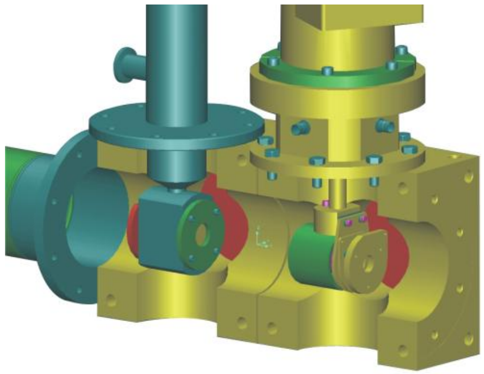
Half life [s]	0.1	1	10
T_{vacuum} [s]	30	30	30
Intensity ions [every 100 ms in 30 microsceonds]	10^4	$5\ 10^5$	$5\ 10^5$
T_{cool}[ms]	100	100	100
Number of turns	10	10	10
Final emittance [micrometer]	0.1	0.1	0.1
Final number of particles in stack	$3\ 10^4$	$3\ 10^7$	$3\ 10^8$

Why do we gain with such an accumulation ring?



- Left: Cycle without accumulation
- Right: Cycle with accumulation. Note that we always produce ions in this case!

- Measurements at Louvain-La-Neuve (CRC) of cross section



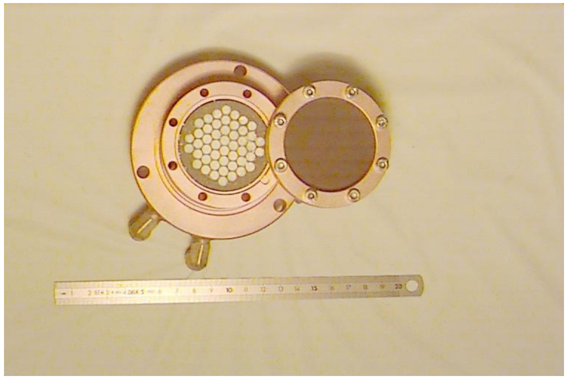
- The gas target was constructed like a cell with thin entrance foils
- In experiment the target pressure and the ^{3}He beam energy was changed

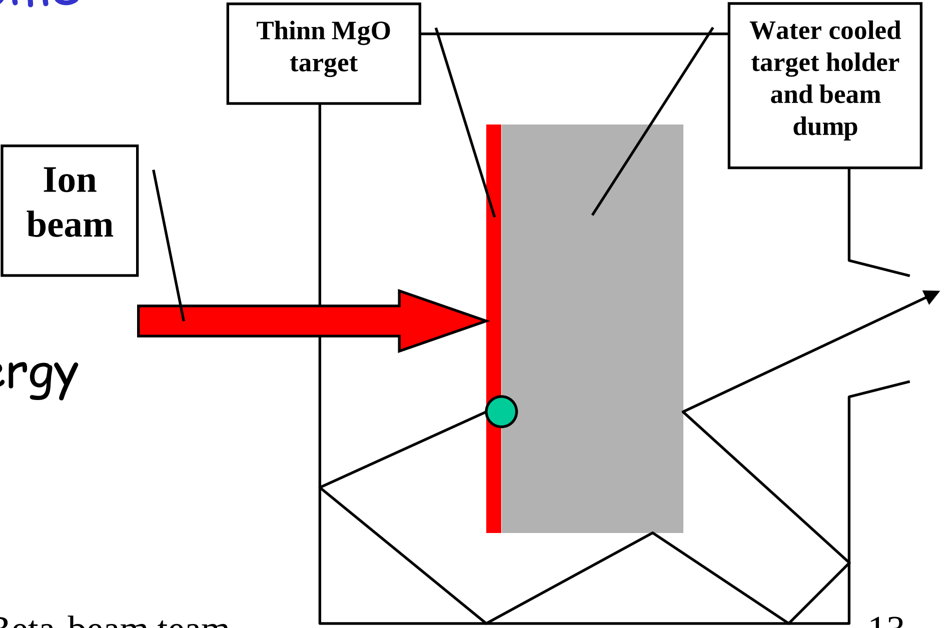
Beam energy, MeV	Target pressure, mbar (torr).	E_{loss},MeV
13	900 (675)	2
14.8	1200 (900)	2.4

Courtesy to Semen Mitrofanov and Marc Loislet at CRC, Belgium

Preliminary results from CRC

- Production of 10^{12} ^{18}Ne in a MgO target:
  - At 13 MeV, 17 mA of ^{3}He
  - At 14.8 MeV, 13 mA of ^{3}He
- Producing 10^{13} ^{18}Ne could be possible with a beam power (at low energy) of 1 MW (or some 130 mA ^{3}He beam).
- To be studied:
  - Extraction efficiency
  - Optimum energy
  - Cooling of target unit
  - High intensity and low energy ion linac
  - High intensity ion source

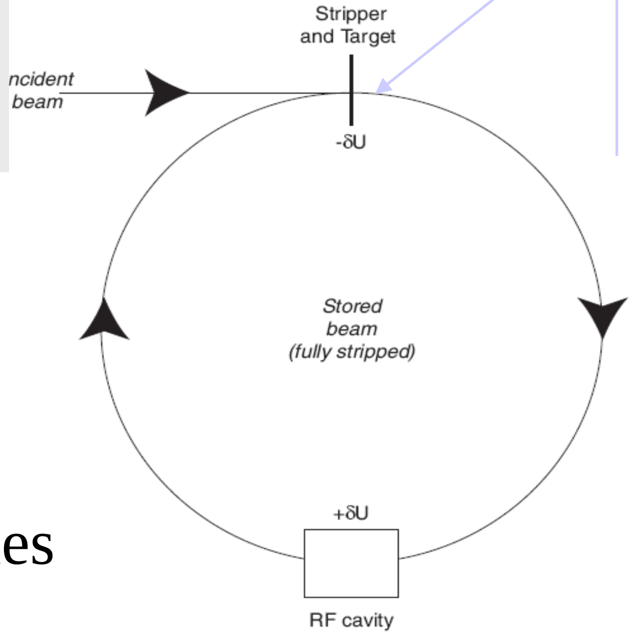




Beam cooling with ionisation losses – C. Rubbia, A Ferrari, Y. Kadi and V. Vlachoudis in NIM A 568 (2006) 475–487

^{7}Li

^{6}Li



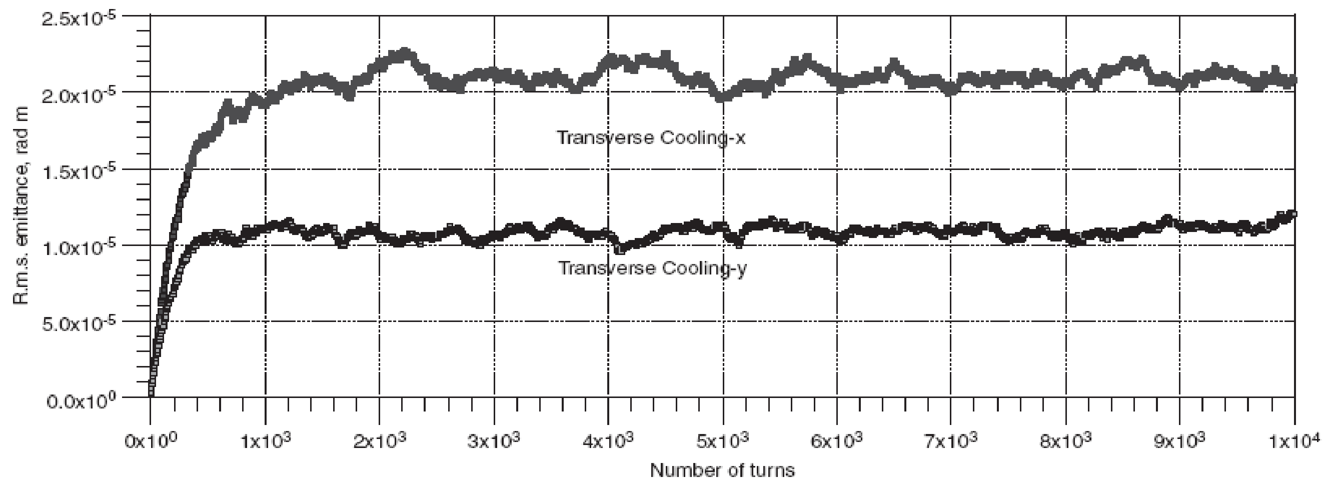
$^{7}Li(d,p)^{8}Li$

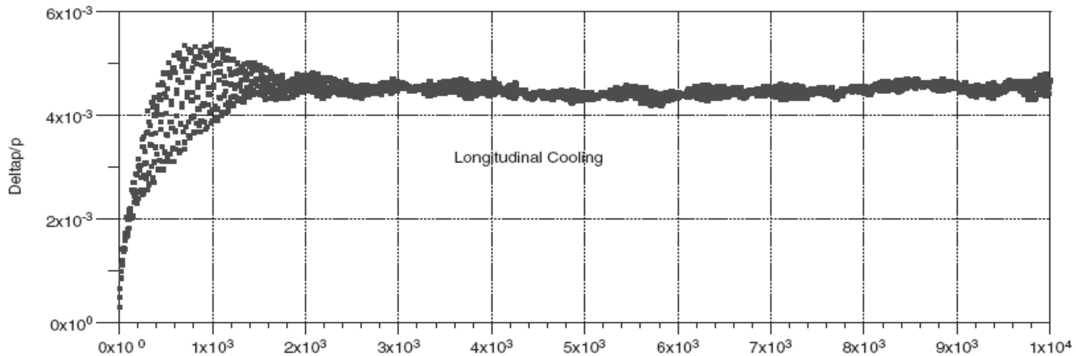
$^{6}Li(^{3}He,n)^{8}B$

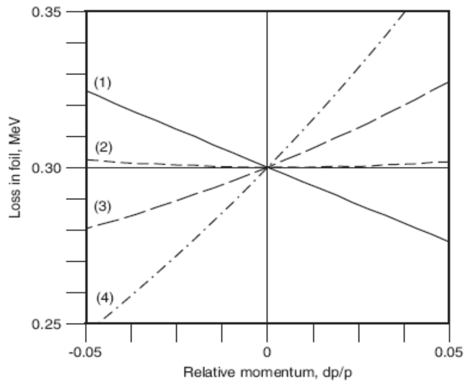
Missed opportunities

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

Transverse and longitudinal cooling in paper by Carlo Rubbia et al.



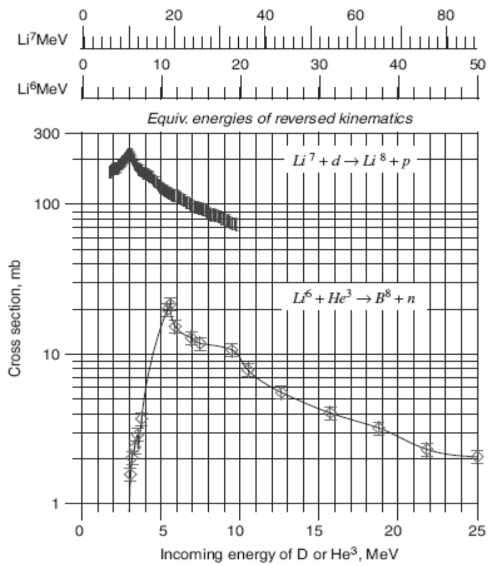


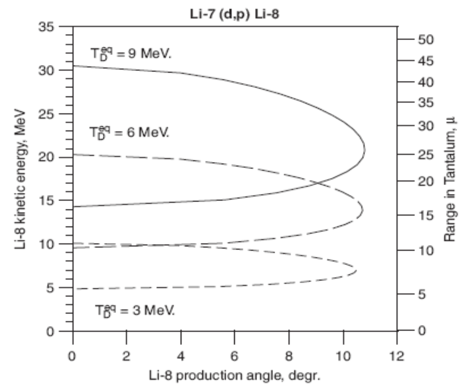


Inverse kinematics production and ionisation parameters in paper by Carlo Rubbia et al.

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

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





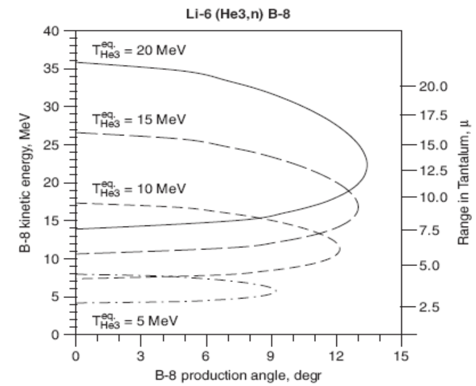
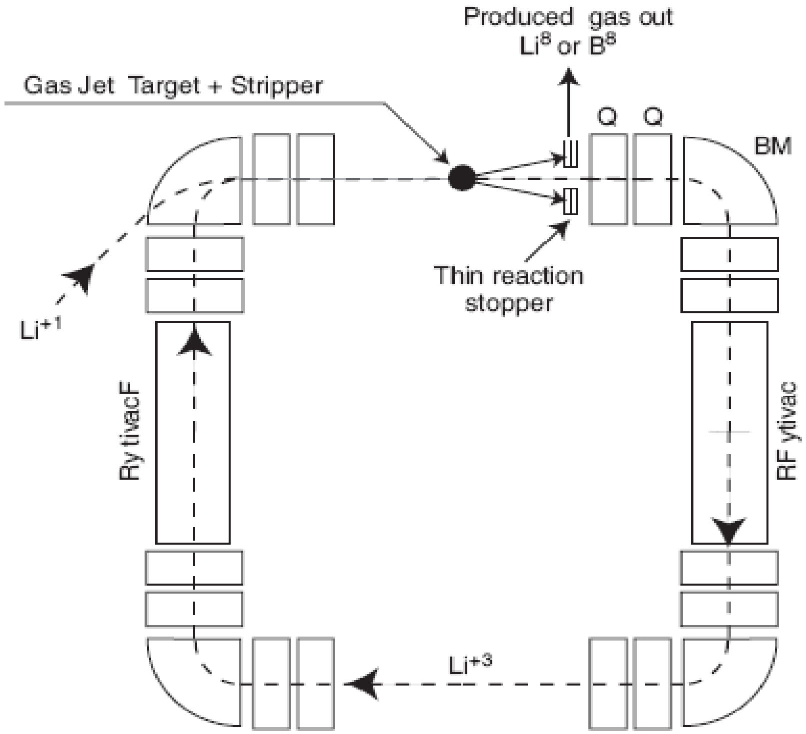


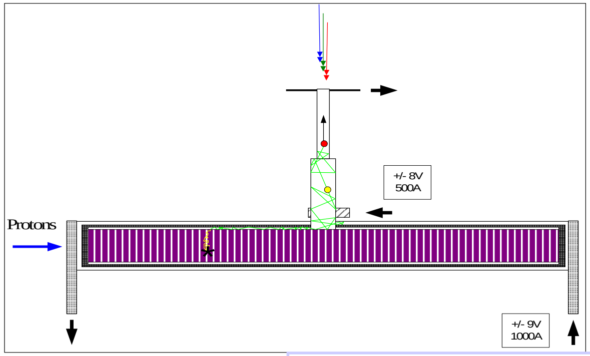
Table 1
Some ionisation parameters for ^{6}Li and ^{7}Li in the energy interval of interest

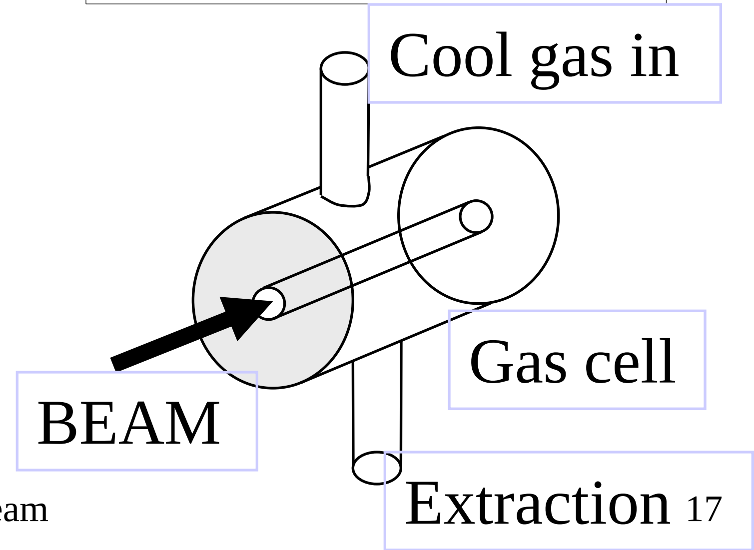
Energy, T (MeV)	dE/dx (MeV/(mg/cm^2))		$\sqrt{\langle Z \rangle^2}$		δE (keV) for loss of 0.3 MeV	
	^{6}Li	^{7}Li	^{6}Li	^{7}Li	^{6}Li	^{7}Li
5	3.356	3.355	2.94	2.89	10.646	9.866
10	2.120	2.014	3.00	3.00	11.751	10.205
15	1.660	1.573	3.00	3.00	13.340	11.714
20	1.356	1.329	3.00	3.00	14.752	12.999
25	1.116	1.092	3.00	3.00	16.102	14.174
30	0.965	0.890	3.00	3.00	17.331	15.323
35	0.861	0.778	3.00	3.00	18.428	16.309

Collection in paper by Carlo Rubbia et al.

"The technique of using very thin targets in order to produce secondary neutral beams has been in use for many years. Probably the best known and most successful source of radioactive beams is ISOLDE."

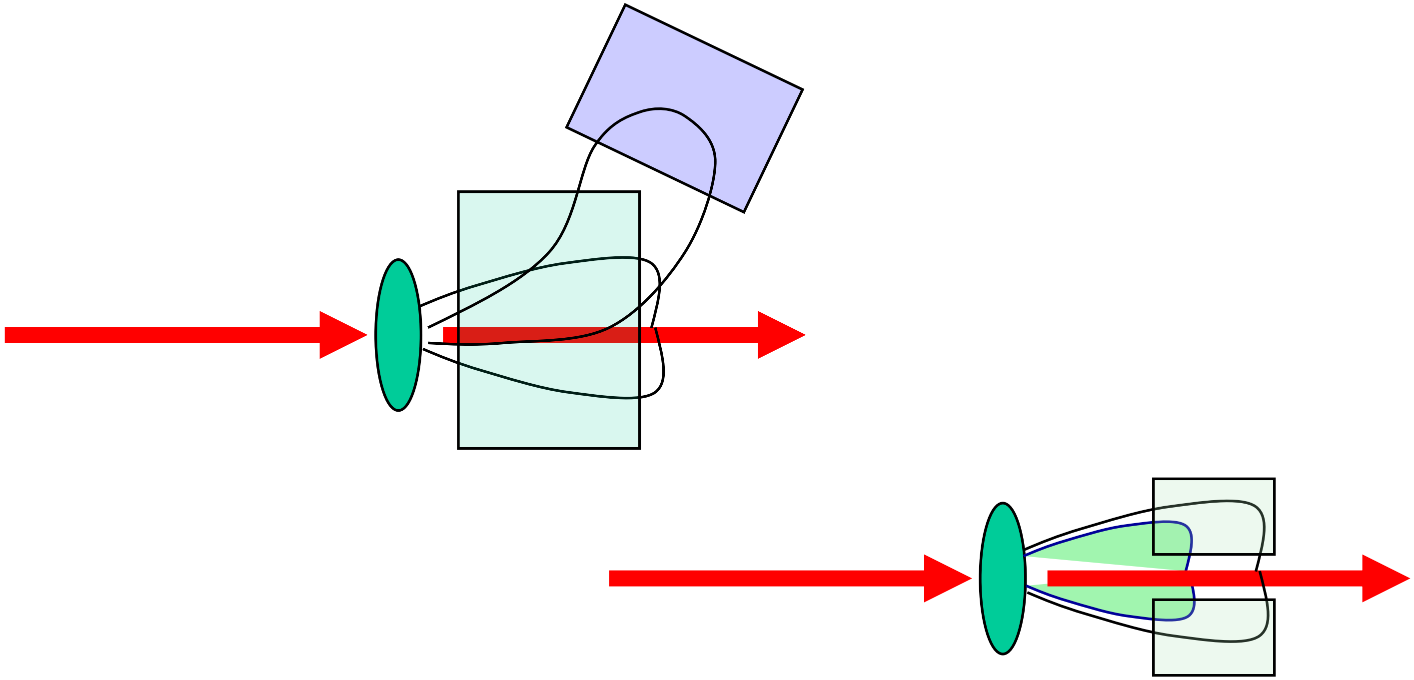






Problems with collection device

- A large proportion of beam particles (^6Li) 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 ^8B ions are produced in a cone of 13 degree with 20 MeV ^6Li ions with an energy of 12 MeV±4 MeV (33% !).



Reactions to study for the EURISOL beta-beam

- $^{20}Ne(p,t)^{18}Ne$
  - H.Backhausen et al, RCA,29(1981)1
- $^{16}O(^{3}He,n)^{18}Ne$
  - V.Tatischeff et al, PRC,68(2003)025804
- $^{6}C(CO_2,{}^{6}He)^{18}Ne$?
  - K.I.Hahn et al, PRC,54(1996)1999
- $^{7}Li(T,A)^{6}He$

Critical review of the production ring concept

- Low-energy Ionization cooling of ions for Beta Beam sources - D. Neufer (To be submitted)
  - Mixing of longitudinal and horizontal motion necessary
  - Less cooling than predcited
  - Beam larger but that relaxes space charge issues
  - If collection done with separator after target, a Li curtain target with ^{3}He and Deutron beam would be preferable
    - Separation larger in rigidity

Gamma 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	935	4197	3.1
150	1403	6296	4.7
200	1870	8395	6.2
350	3273	14691	10.9
500	4676	20987	15.6

New SPS

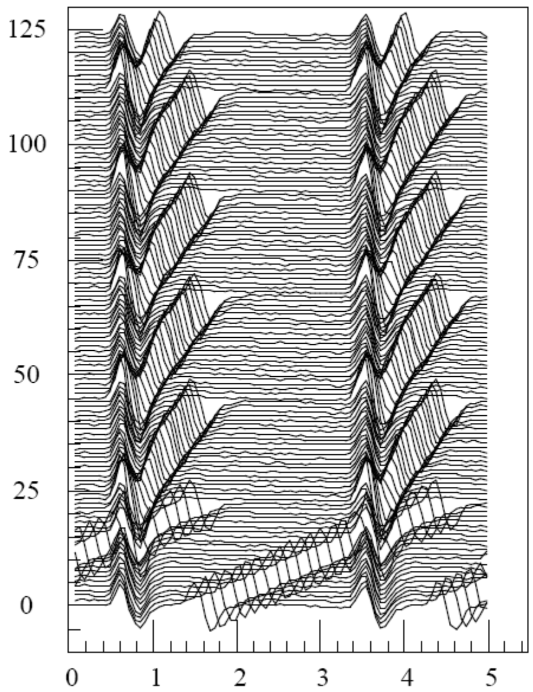
Civil engineering

Magnet R&D

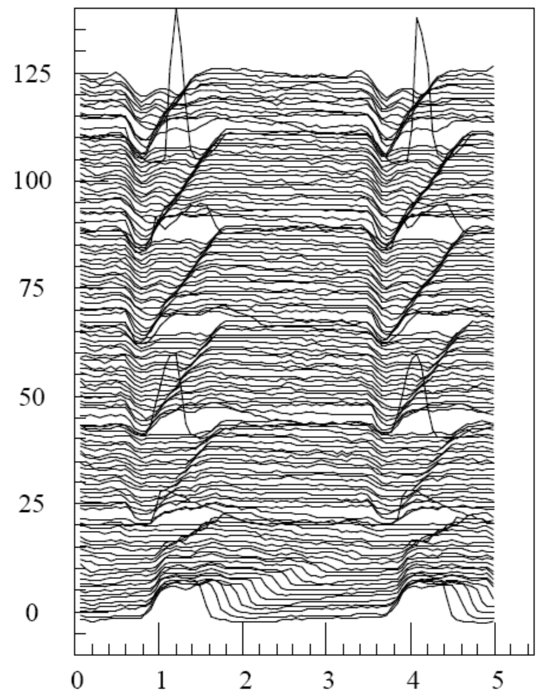
Accumulation with Barrier buckets (no duty cycle)

A Barrier Bucket Experiment for Accumulating De-bunched Beam in the AGS*

M. Blaskiewicz, J.M. Brennan
AGS Dept. Brookhaven National Laboratory
Upton, NY 11973-5000 USA

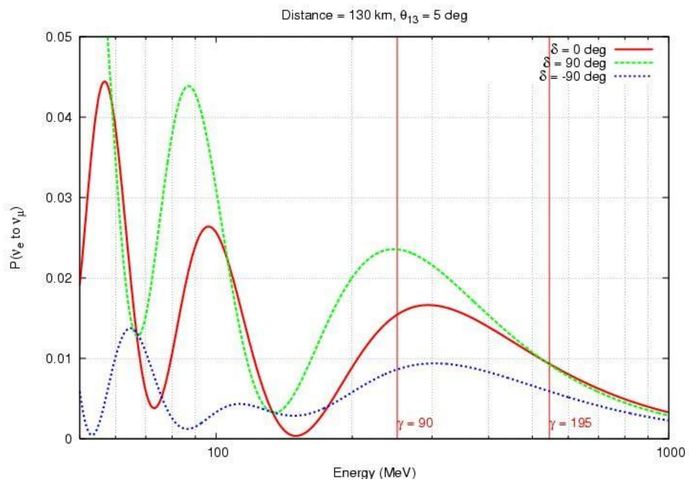


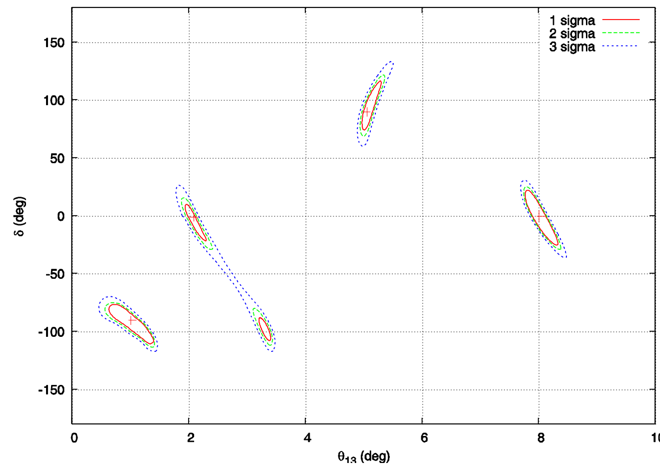
RF voltages (Barriers)



Beam current

EC: A monochromatic neutrino beam





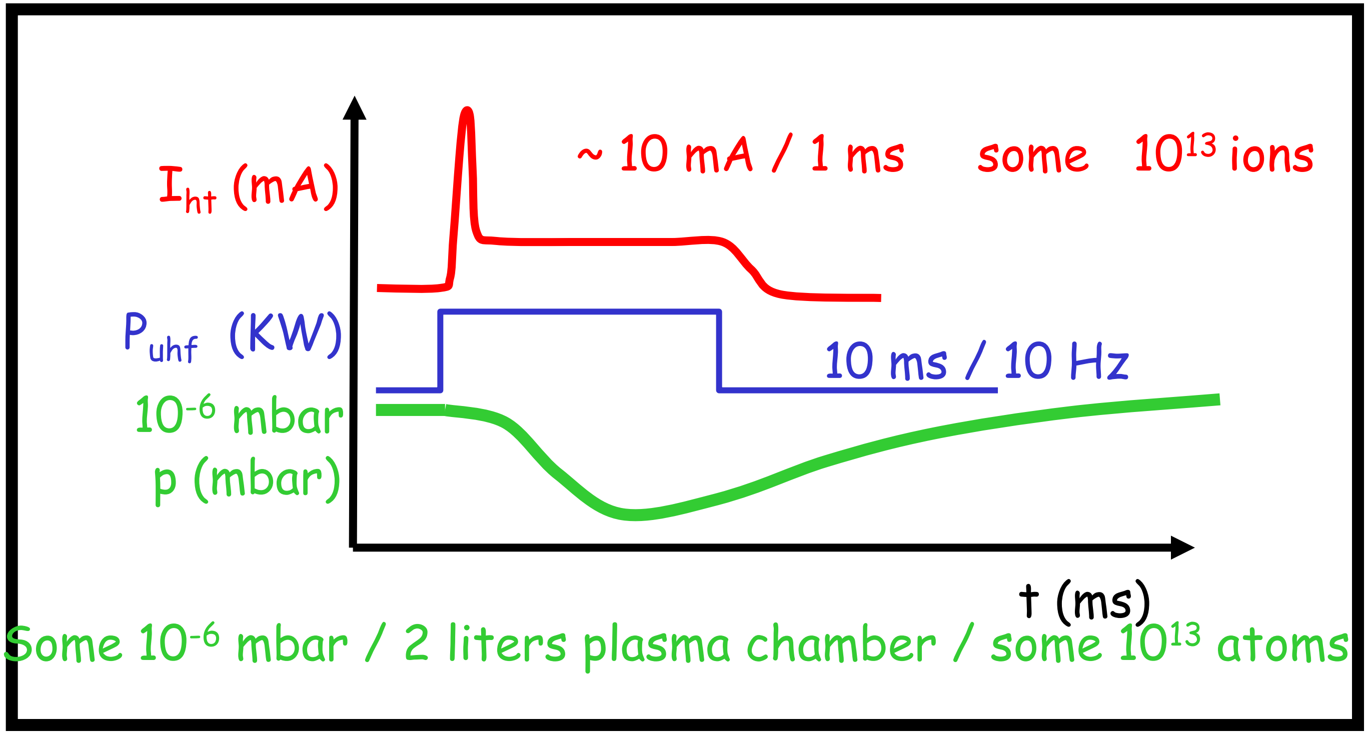
Decay	$T_{1/2}$	BR_ν	EC/ν	I^{β}_{EC}	B(GT)	E_{GR}	Γ_{GR}	Q_{EC}	E_ν	ΔE_ν
$^{148}Dy \to {}^{148}Tb^*$	3.1 m	1	0.96	0.96	0.46	620		2682	2062	
$^{150}Dy \to {}^{150}Tb^*$	7.2 m	0.64	1	1	0.32	397		1794	1397	
$^{152}Tm2^- \to {}^{152}E_T^*$	8.0 s	1	0.45	0.50	0.48	4300	520	8700	4400	520
$^{150}Ho2^- \to {}^{150}Dy^*$	72 s	1	0.77	0.56	0.25	4400	400	7400	3000	400

Long half life – high intensities

- At a rate of 10^{18} neutrinos using the EURISOL beta-beam facility:

Acccelerator Isotope	RCS [10^{12} C]	PS [10^{13} C]	SPS [10^{13} C]	DR [10^{14} C]	DR Peak Current [kA]
^{148}Dy	120	102	828	87.6	3.74
^{150}Dy	139	117	948	97.8	4.18
^{150}Ho	86.1	74.0	602	68.7	2.93
^{152}Tm	28.3	23.2	162	27.5	1.17
^{18}Ne	2.71	4.35	4.29	7.47	1.60

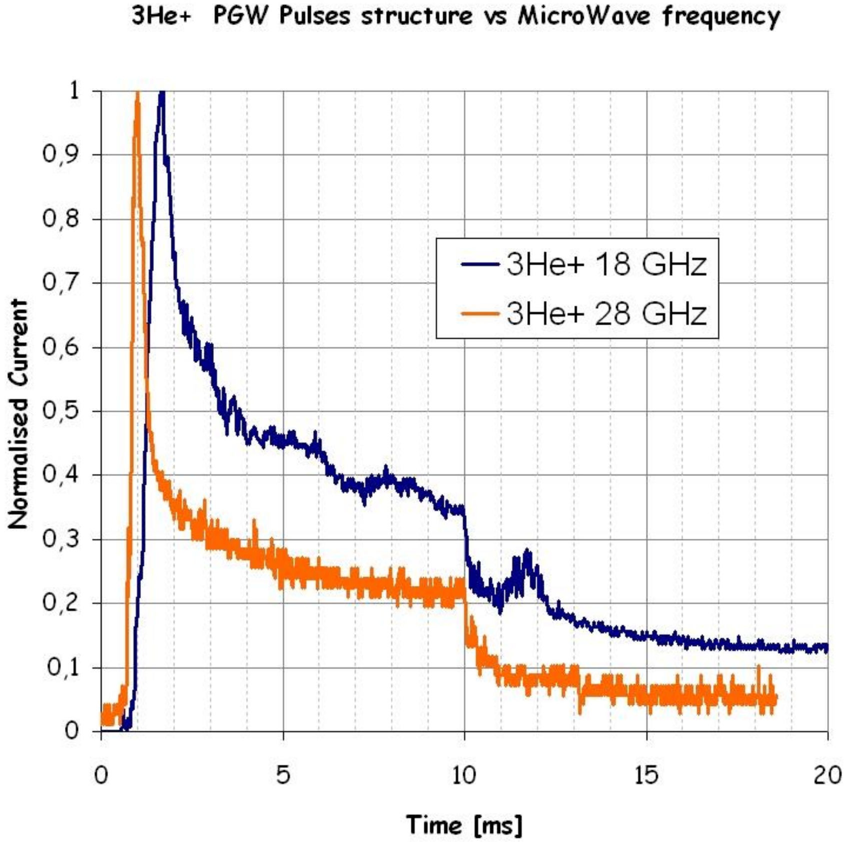
- Pulsed modes of the ECRIS: afterglow and preglow
  - Afterglow: well-known from 10 to 18 GHz (Pb^{27+} LHC beam)
  - Preglow: experimental evidence at LPSC, predicted by a simple model, data analysis under progress.

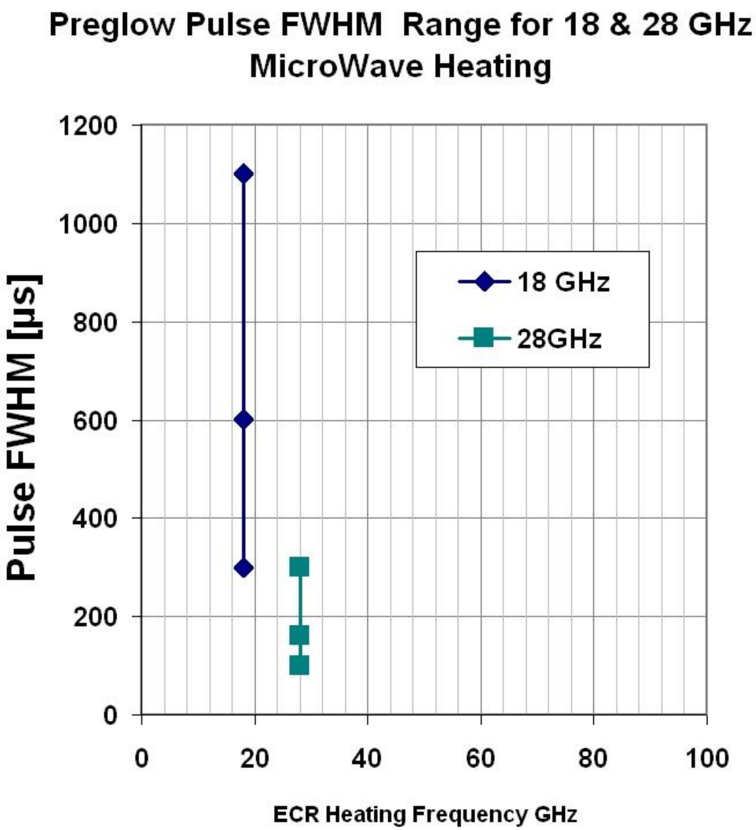


Present status

- Preglow experiments at 18 and 28GHz for ^{3}He and ^{22}Ne gases have been achieved, still under analysis (background suppression ^{12}C, ^{14}N, ^{16}O)
- Collaboration with the Grenoble HMFL for the 60GHz magnetic structure
- 60GHz ion source + Gyrotron funding: **CPER accepted, under final negociation** ~1M€
- Collaboration with the IAP of **Nizhniy Novgorod** (2006-2008) 37.5 GHz and 75 GHz plasma studies

Pre-glow performance





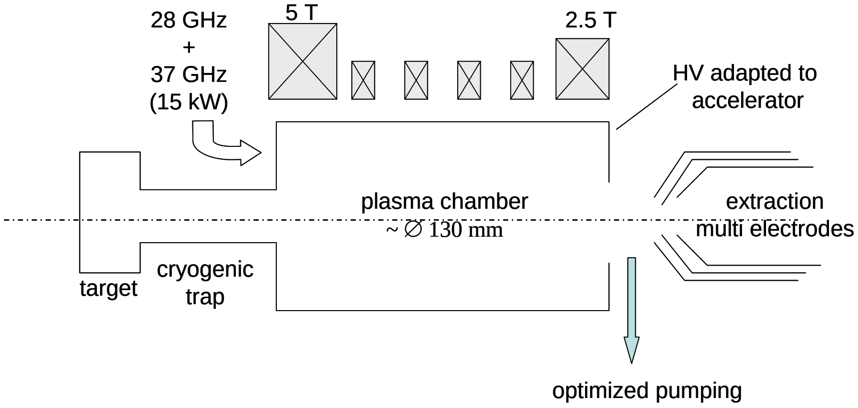
18 GHz : high Magnetic confinement => "large" FWHM (300<T<1100 µs)

28 GHz : low magnetic confinement => "short" FWHM (150<T<300 µs)

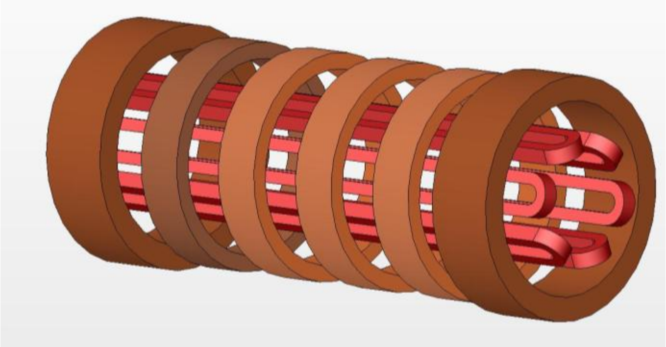
60 GHz T< 50 µs ?

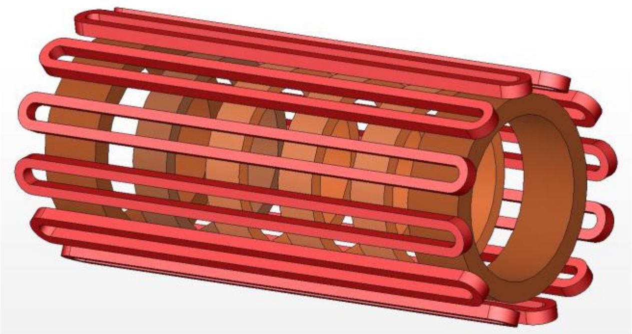
Denis Hitz, CEA Grenoble

- Strong confinement
- Large plasma chamber
- No gas mixing 1 charge state ($^{18}Ne^{10+}$?)
- Different frequencies 28+35 GHz
- Afterglow only
- Original method for pulsing



several central coils for a good confinement at injection
and a weaker confinement at extraction

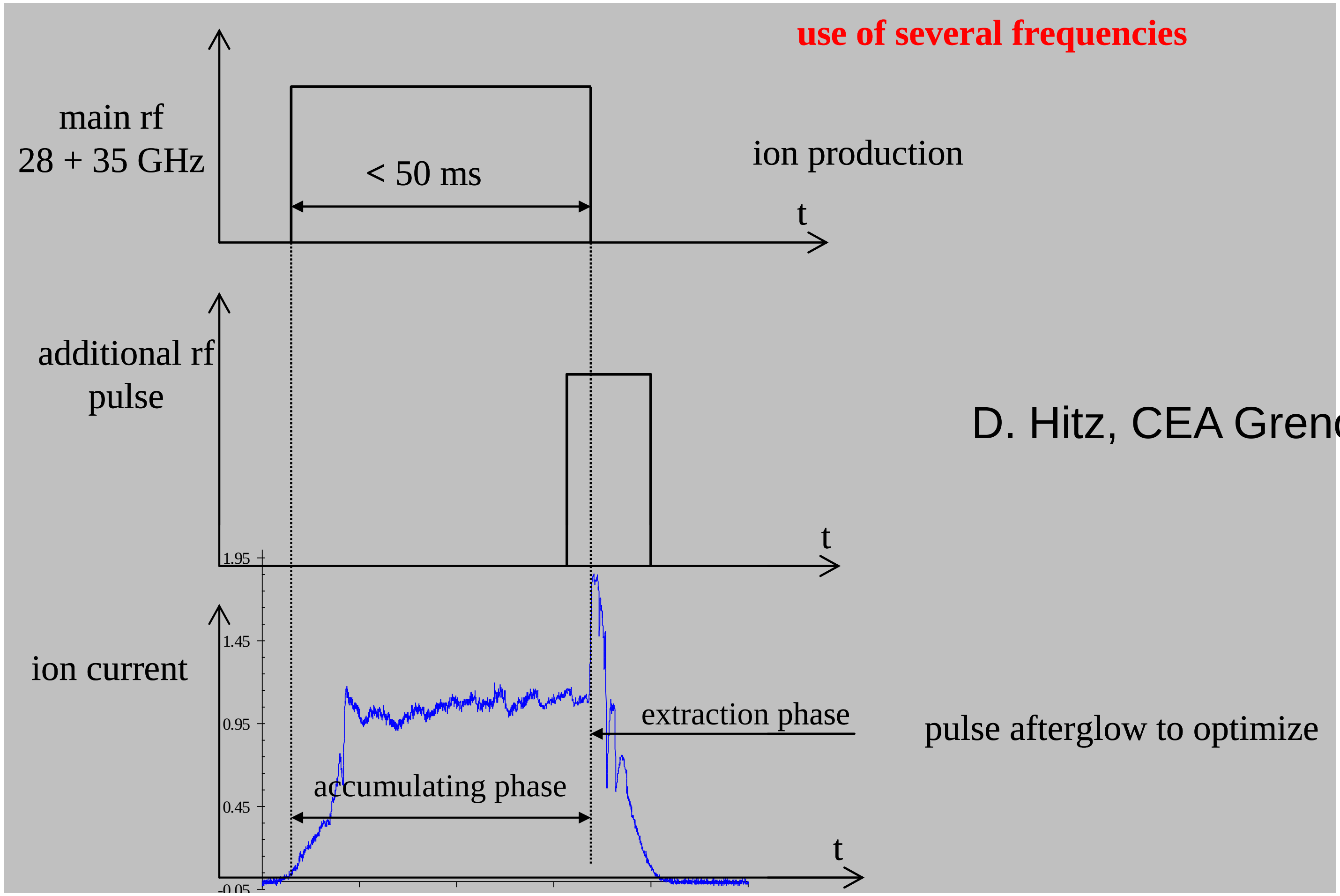




Injection

Extraction

Pulsing



D. Hitz, CEA Grenoble

Open issues

- The physics made possible with the new production concept proposed by Rubbia and Mori needs to be explored
  - The production ring concept and the production cross sections will be measured in EURONU DS
- The collection of the radioactive ions seems to be a critical aspect of this proposal
  - Would it be possible to use a gas cell combined with a separator?
  - Can we extract Boron as BF_3?
- The efficiency of the initial ionization and bunching
  - Continued R&D on 60 GHz ECR source
  - Proposal to use afterglow in VENUS/GTS type source
  - Proposal to use basic duo-plasmatron source
- The stacking and low duty cycle is a major constraint on the beta-beam
  - Can we live with a DC neutrino beam at higher neutrino energies?
  - Can one use Barrier buckets to fill the decay ring?
- These issues will be addressed in the Euroν Design Study

Finally, a reflection…

- If the beta-beam facility could start with anti-neutrinos…

  …we could start early with a neutron converter target or direct production target producing ^{6}He or ^{8}Li to measure θ_{13}…

  …and later upgrade the facility for higher intensities and isotopes giving us neutrinos (^{18}Ne or ^{8}B) to measure CP violation.

If we do it today, couldn't we make use of the Main injector at Fermi lab, build a new decay ring (with acceleration) and an experiment in Soudan?

Thank you for you attention!