Production and bunching of RIBs for beta-beams

Pierre Delahaye, ISOLDE

For beta-beams

The beta-beam concept

P. Zucchelli, PLB 2002

- A pure beam of ν_e to study the $\nu_e \rightarrow \nu_\mu$ oscillation
  - A beam of ν_e, $\overline{\nu}_e$ from β-decaying nuclides
- A Lorentz boost for a collimated beam (high γ)
  - From Wikipedia:

For a boost in an arbitrary direction with velocity $\vec{v}$ it is convenient to decompose the spatial vector $\vec{r}$ into components perpendicular and parallel to the velocity $\vec{v}$: $\vec{r} = \vec{r}_\perp + \vec{r}_\|$. Then only the component $\vec{r}_\|$ in the direction of $\vec{v}$ is 'warped' by the gamma factor:

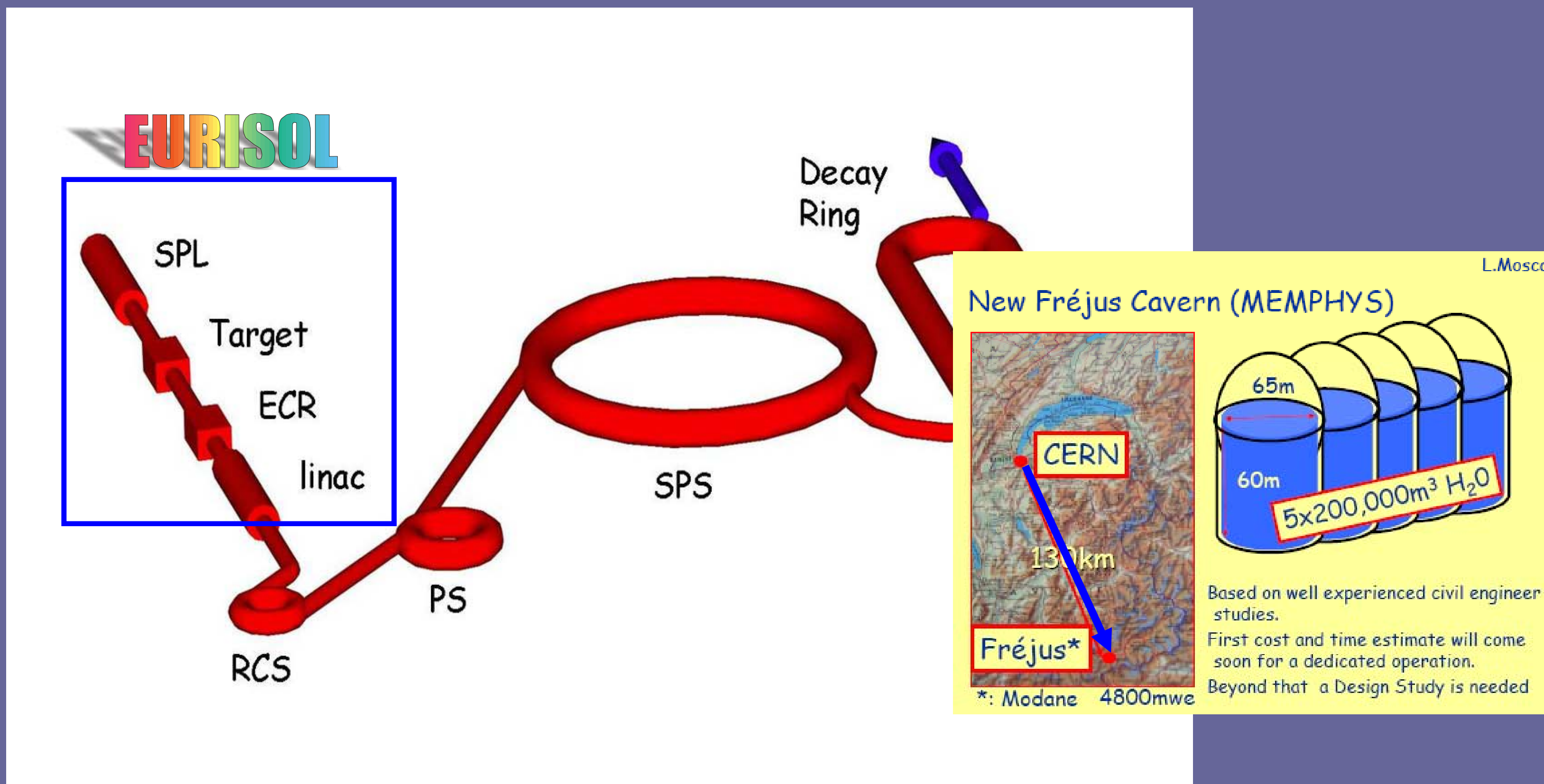
$$\begin{cases} t' = \gamma\left(t - \dfrac{\vec{r}\cdot\vec{v}}{c^2}\right) \\ \vec{r'} = \vec{r}_\perp + \gamma(\vec{r}_\| - \vec{v}t) \end{cases}$$

where now $\gamma \equiv \dfrac{1}{\sqrt{1 - \vec{v}\cdot\vec{v}/c^2}}$

θ→1/γ

Beta-beams and EURISOL

- CERN baseline scenario



Production of the beta-beams

- **Different candidates, ^{6}He and ^{18}Ne as preferred ones**
- **Factors influencing ion choice**
  - Need to produce reasonable amounts of ions
  - Noble gases preferred - simple diffusion out of target, gaseous at room temperature.
  - Not too short half-life to get reasonable intensities.
  - Not too long half-life as otherwise no decay at high energy.
  - Avoid potentially dangerous and long-lived decay products.
- **Best compromise**
  - Helium-6 to produce antineutrinos:

$$ {}^{6}_{2}He \rightarrow {}^{6}_{3}Li\ e^{-}\ \overline{\nu} $$
$$ \text{Average } E_{cms} = 1.937 \text{ MeV} $$

  - Neon-18 to produce neutrinos:

$$ {}^{18}_{10}Ne \rightarrow {}^{18}_{9}F\ e^{+}\ \nu $$
$$ \text{Average } E_{cms} = 1.86 \text{ MeV} $$

- **New ideas**
  - **^{8}Li, ^{8}B Rubbia et al**
  - **EC decays for monochromatic beams J. Bernabeu et al**

The requirements

- The first beta-beams study was aiming for:
  - A beta-beam facility that will run for a "normalized" year of 10^7 seconds
  - An annual rate of 2.9 10^{18} anti-neutrinos (^{6}He) and 1.1 10^{18} neutrinos (^{18}Ne) at γ=100

with an Ion production in the target to the ECR source:

- **^{6}He= 3.3 10^{13} atoms per second**
- **^{18}Ne= 2.1 10^{13} atoms per second**

- The often quoted beta-beam facility flux for ten years running is:
  - Anti-neutrinos: 29 10^{18} decays along one straight section
  - Neutrinos: 11 10^{18} decays along one straight section

State of the art

Production

$^{6}He^{+}$

GANIL 2E8/s

2.5kW ^{13}C 75 MeV/u on C target, ECR source

ISOLDE 1E7/s

5kW 1.4GeV p on MgO target, FEBIAD source

LLN, DUBNA, ISAC…

$^{18}Ne^{+}$

GANIL ~2E8/s

1 kW ^{20}Ne 95 MeV/u on C target, ECR source

ISOLDE 1E6/s

5kW 1.4GeV p on CaO target, FEBIAD source

LLN, DUBNA, ISAC…

Factor 10^{5} missing

Ionization and bunching

CW

Phoenix 18GHz Grenoble

25% in one charge state Ne

>50% on one charge state He

Bunching

Afterglow with GTS, Phoenix, MINIMAFIOS

Preglow at LPSC

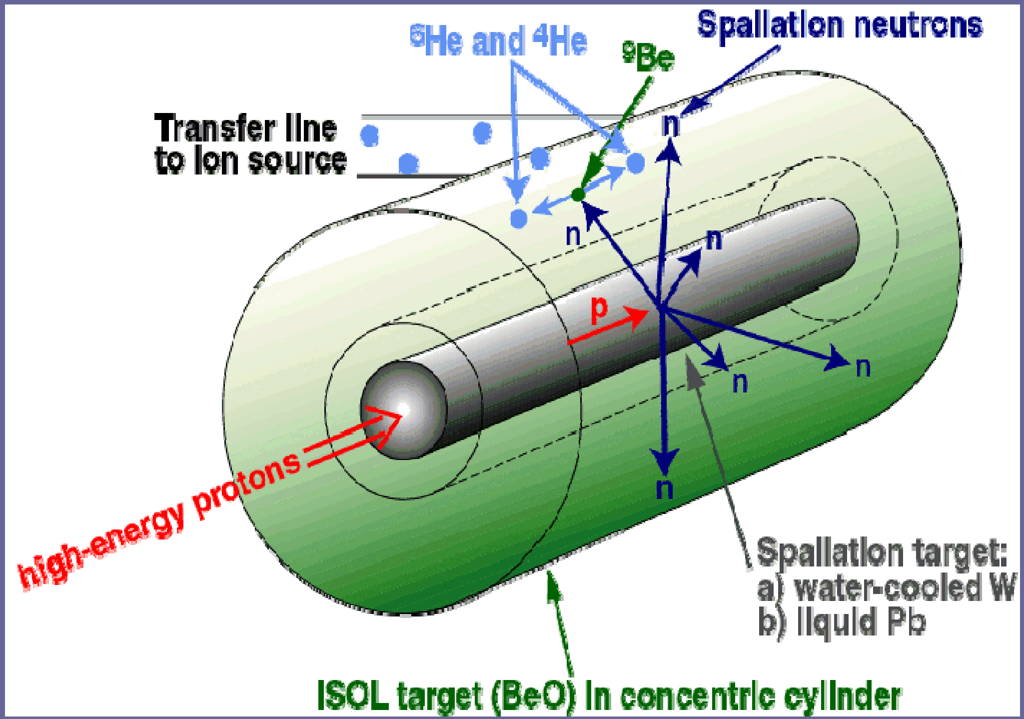
>200µs pulses

- **Efficiencies to be optimized**
- **Bunch length to shorten**

^{6}He production from ^{9}Be(n,α)

- Using the converter technology

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

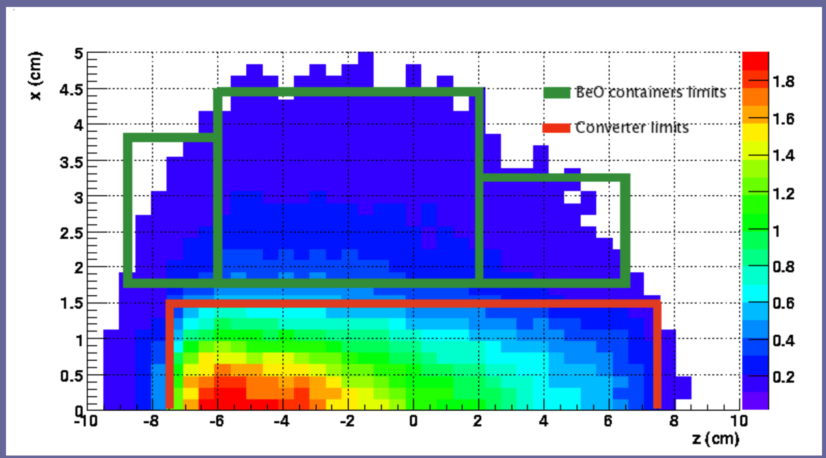


- **Preferred to direct irradiation (heat transfer and efficient cooling allows higher power compared to insulating BeO).**
- **^{6}He production rate is ~2x10^{13} ions/s (dc) for ~200 kW on target**
- **Use of a 4MW target is a priori possible**

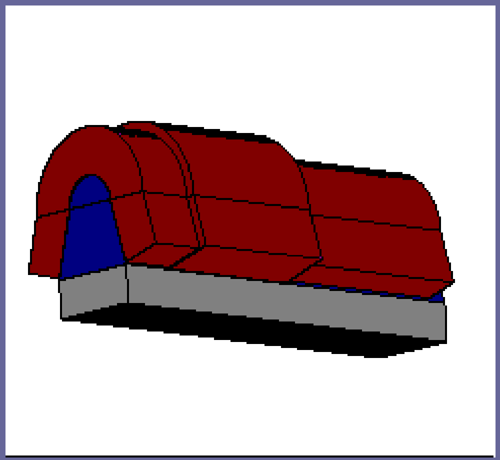
Optimized geometry

- **Original geometry: T. Stora, E. Bouquerelle, J. Lettry, task 3 internal note**
- **Optimized geometry: N. Thiollière, J.C. David, V. Blideanu, D. Doré, B. Rapp, D. Ridikas**

Soon available as a preprint DAPNIA, CEA Saclay (November 2006) at http://www-dapnia.cea.fr/Documentation/Publications/index.php



Neutron flux selection versus x and z-dimension superposed with converter and BeO containers limits.



The optimized (in terms of in target yields) target geometry to produce ^{6}He beams.

Using MCNPX

2 GeV 200 kW → 10^{14} in target production
~ fulfills the requirements

EURISOL Design Study

^{18}Ne from a MgO or Al_2O_3 target

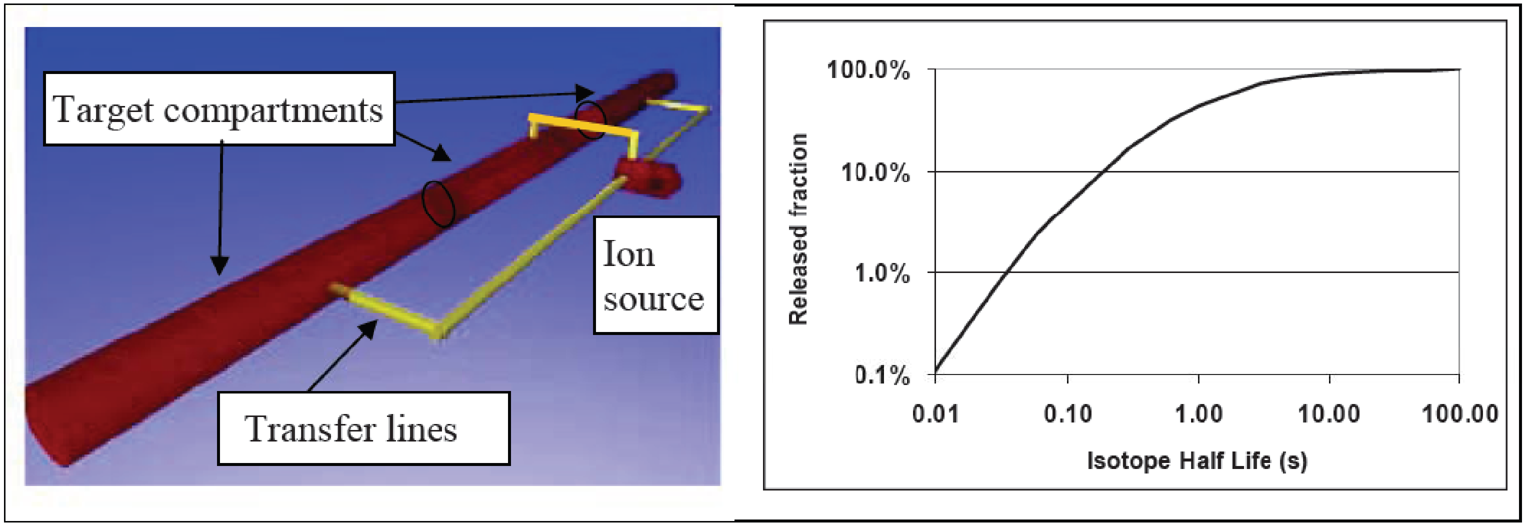


Figure 4: Ne released fraction computed with RIBO for 1 m long Al_2O_3 target with two separation walls and three transfer lines geometry [28].

Task 3 internal note from T. Stora et al, feasibility study of the 100kW targets

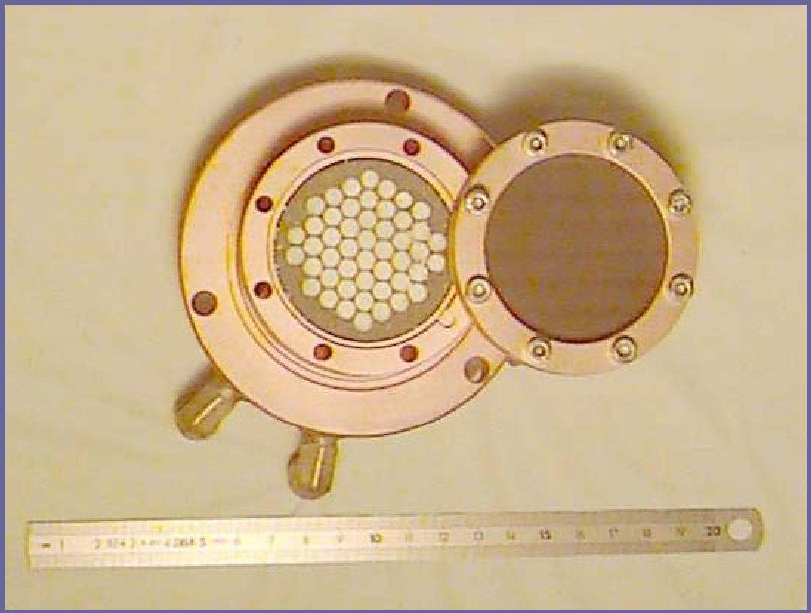
About 8 10^{11}/s instead of 2.1 10^{13}/s out of the target

A factor of ~24 missing

Dedicated experiments for alternative production methods

- ^{7}**Li** (p,2p)^{6}**He**
- ^{19}**F** (p,n)^{19}**Ne**
- ^{19}**F** (p,2n)^{18}**Ne**
- ^{16}**O** (^{3}He,n) ^{18}**Ne**

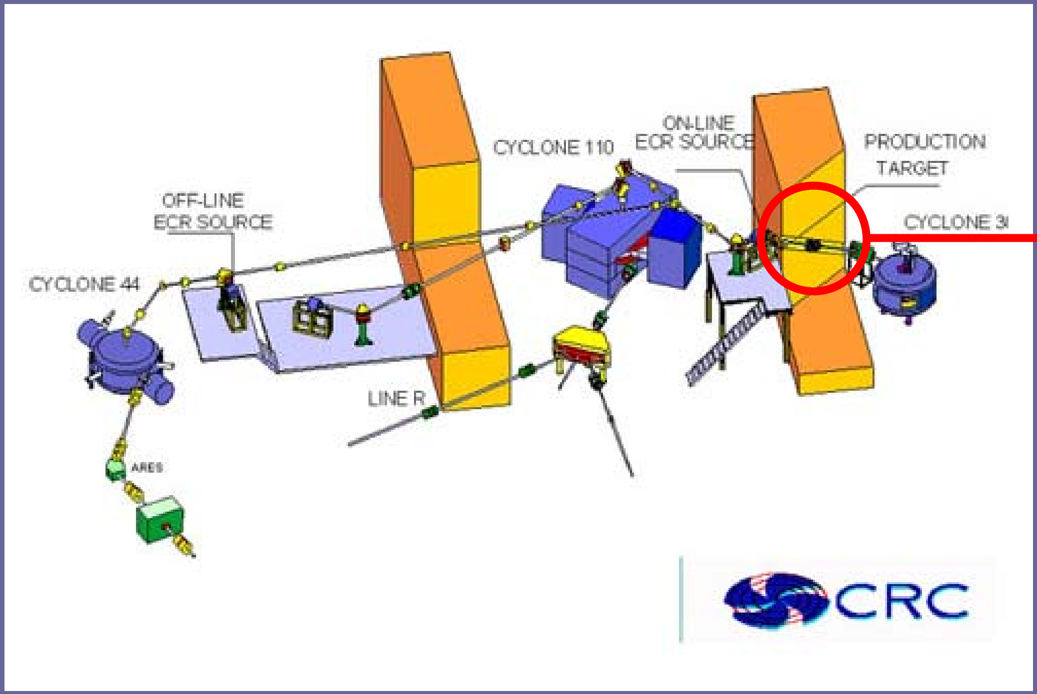
> 300 μA, 30 MeV protons



LLN: Marc Loiselet, Semen Mitrofanov

Light particles at low energy, “cleaner” production

Tests at Louvain-La-Neuve



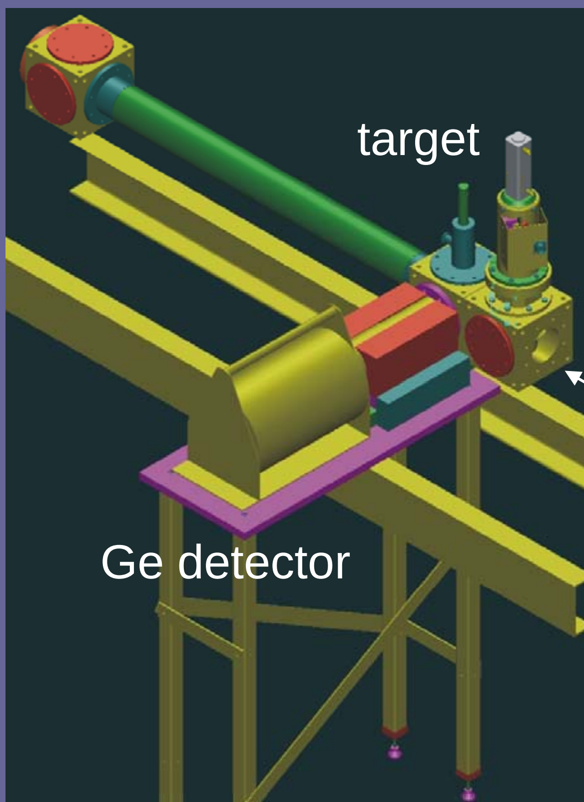
Routinely 200µA, 30MeV protons

Work in progress

^{19}F (p,2n)^{18}Ne

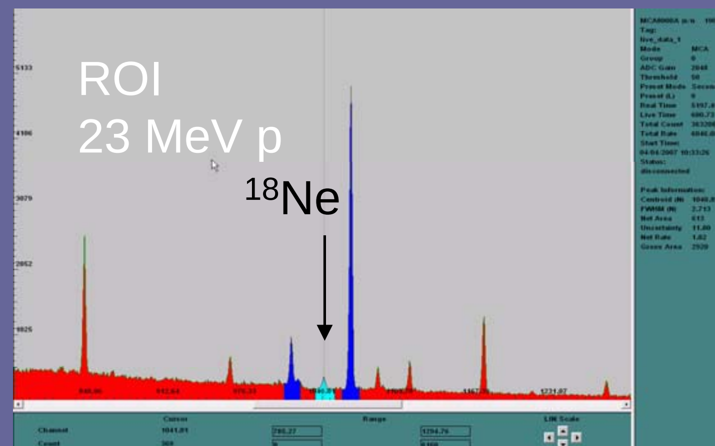
Proton beam: 1 nA 23,30,45 and 65 MeV

Beam dump



FC

p beam



Remains to be tested:

- ^{19}F(p,2n)^{18}Ne 65 MeV protons
- ^{16}O (^{3}He,n) ^{18}Ne

Semen Mitrofanov, Marc Loiselet LLN

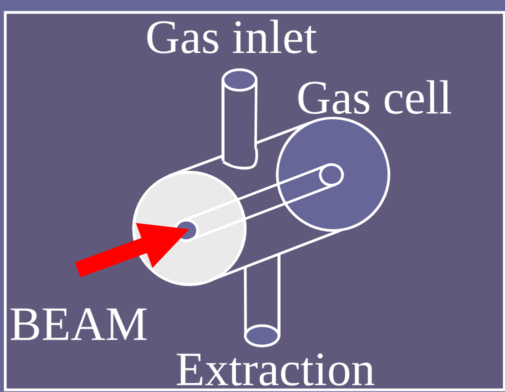
A new approach

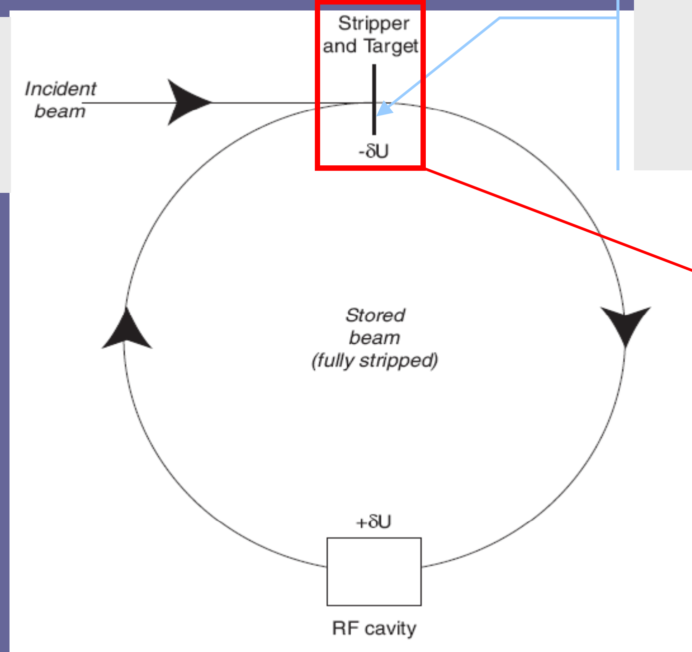
Beam cooling with ionisation losses – C. Rubbia, A Ferrari, Y. Kadi and V. Vlachoudis in NIM A, 568 (2006) 475

“Many other applications in a number of different fields may also take profit of **intense beams of radioactive ions**.”

^{7}Li
^{6}Li

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





ISOL or IGISOL extraction
M. Lindroos et al, NIC-IX proceedings

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

Other reactions of interest

- $^{20}Ne(p,T)^{18}Ne$
  - H.Backhausen et al, RCA,29(1981)1
- $^{16}O(^{3}He,n)^{18}Ne$
  - V.Tatischeff et al, PRC,68(2003)025804
- $^{12}C(CO_2,^{6}He)^{18}Ne$?
  - K.I.Hahn et al, PRC,54(1996)199
- $^{7}Li(T,A)^{6}He$

Multi-ionization and bunching

- **Even if the charge breeding is not mandatory, the bunching of a high intensity beam is mandatory**
  - 50µs pulses, 10-20Hz repetition

- A high frequency ECR source may do the job

- Preliminary preglow and afterglow studies at 18 and 28GHz at LPSC Grenoble

Multiple targets and ECR sources with accumulation ring

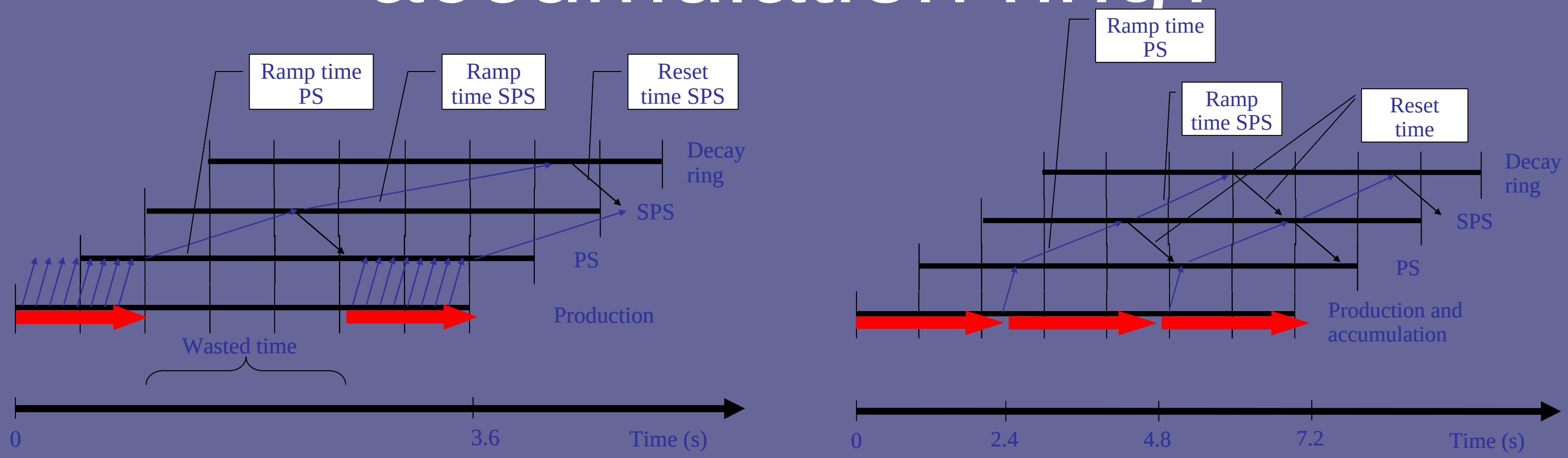
- Multiple target and multiple ECR sources
  - Proton beam split between 7 targets i.e. 1.4 MW of protons in total on all targets
  - 1 second accumulation time in the ECR source
  - 0.1 seconds between injections into linac and Accumulation ring
  - Accumulation of 10 bunches in SPS
  - ECR pulse: 2 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!

Mats Lindroos

EURISOL Design Study

Why do we gain with an accumulation ring?

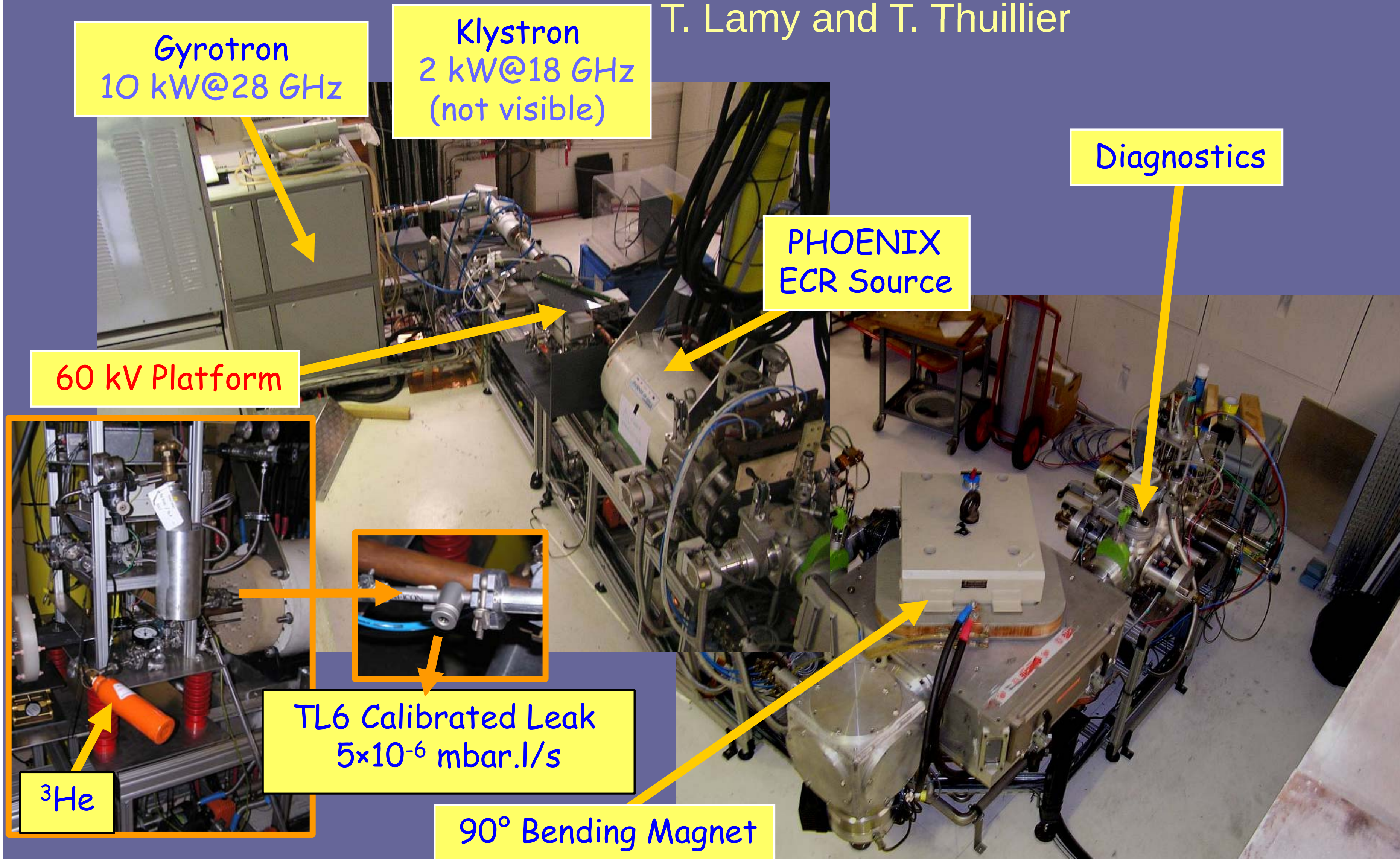


- Left: Cycle without accumulation
- Right: Cycle with accumulation. Note that we always produce ions in this case!

Mats Lindroos

Experiments at LPSC Grenoble

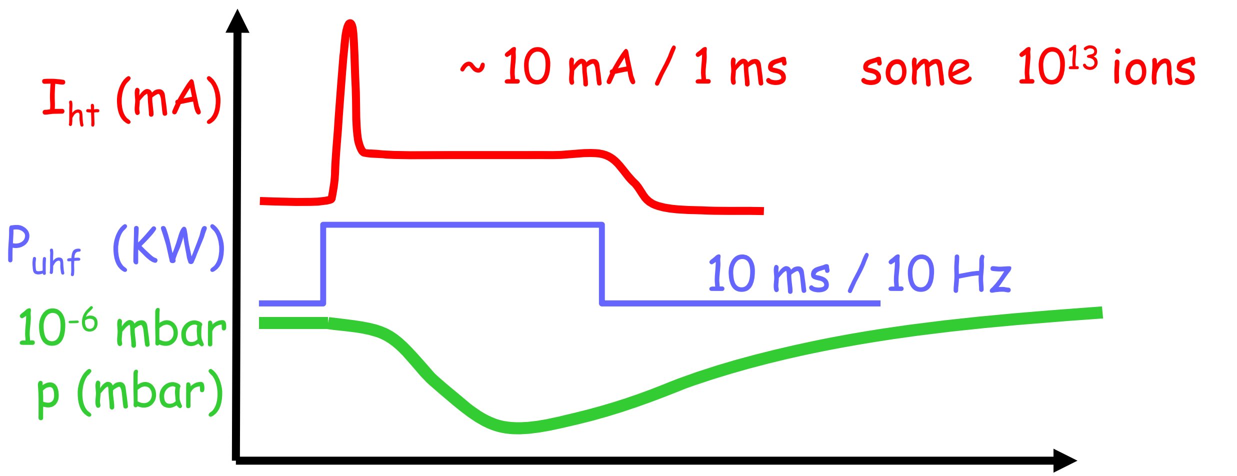
T. Lamy and T. Thuillier



ECRIS capabilities

- 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.

Pumping effect during the preglow - of high interest!



Some 10^{-6} mbar / 2 liters plasma chamber / some 10^{13} atoms

Present status

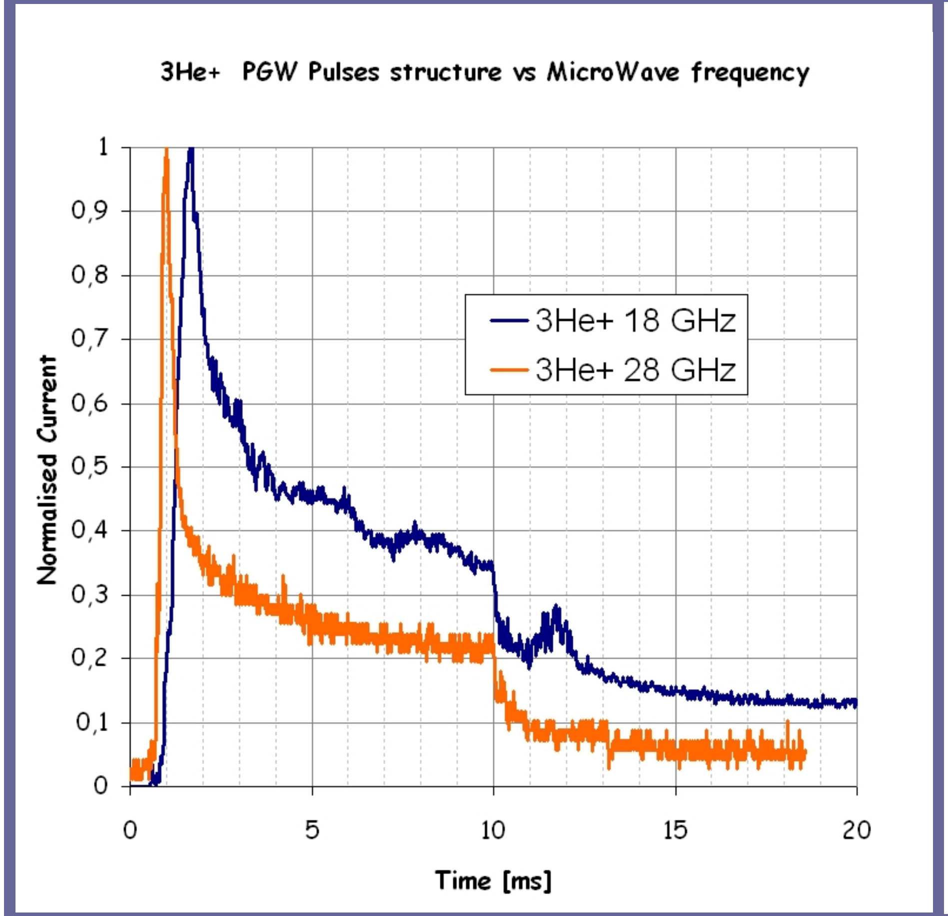
- Preglow experiments at 18 and 28GHz for ^{3}He and ^{22}Ne gases have been achieved, still under analysis (background suppression ^{12}C, ^{14}N, ^{16}O)

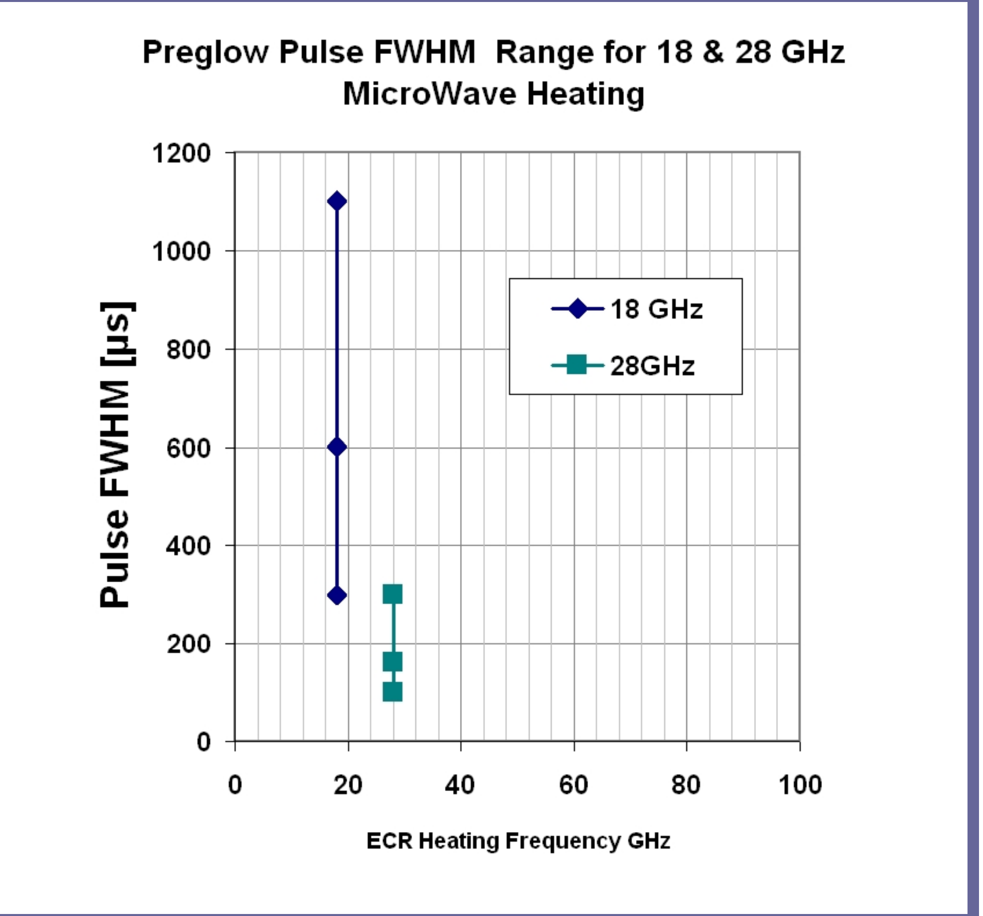
- Collaboration with the Grenoble HMFL for the 60GHz magnetic structure

- 60GHz ion source + Gyrotron funding: ANR refused - **CPER accepted, under final negociation** ~1M€

- Collaboration with the IAP of **Nizhniy Novgorod** (2006-2008) 37.5 GHz and 75 GHz plasma studies

Preglow pulse time structure with PHOENIX V2 ECR Ion Source

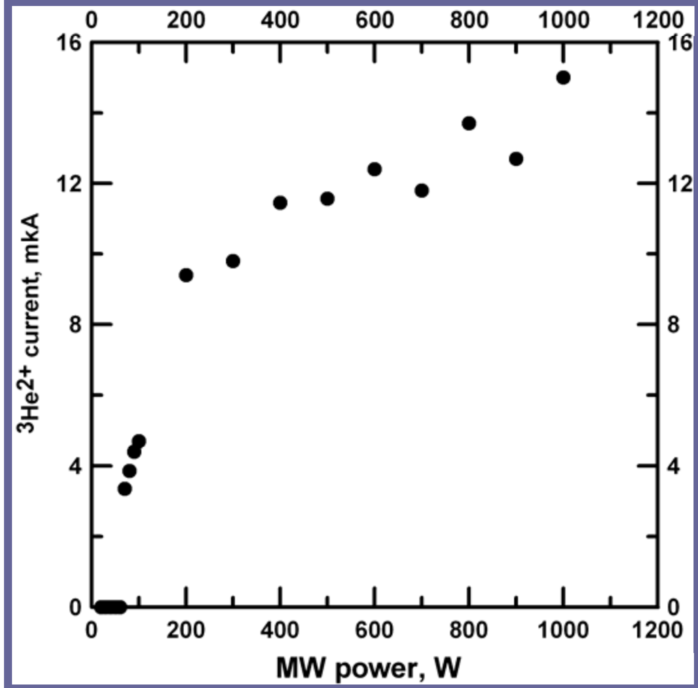


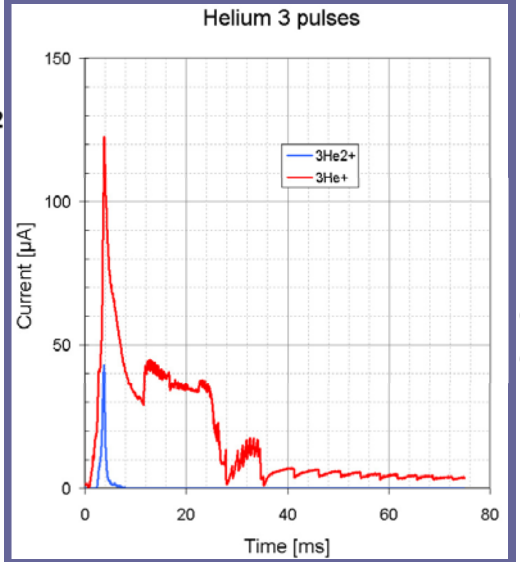


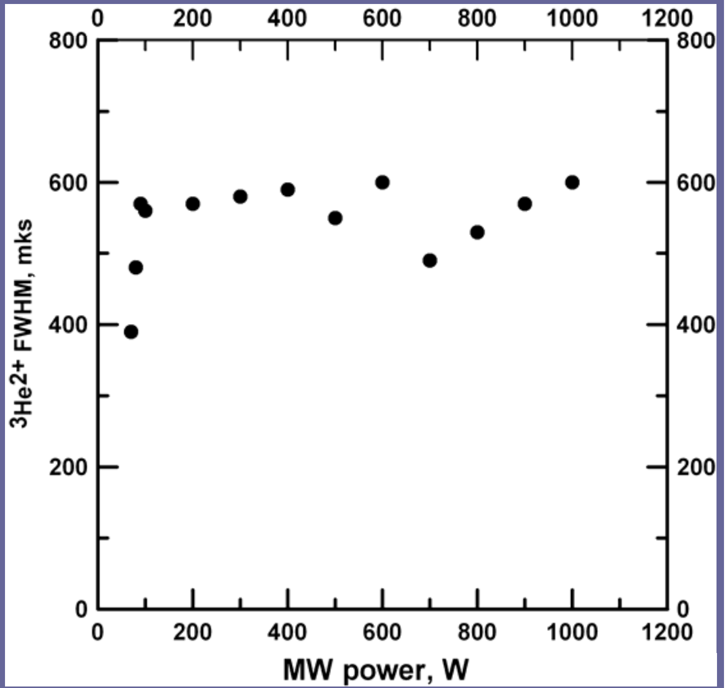
18 GHz : high Magnetic confinement => "large" FWHM (300<T<1100 µs)
28 GHz : low magnetic confinement => "short" FWHM (150<T<300 µs)
60 GHz T< 50 µs ?

Preglow Intensity and FWHM with PHOENIX V2 ECR Ion Source

Frequency 18 GHz, Pulse length 10 ms, Pulse frequency 10 Hz



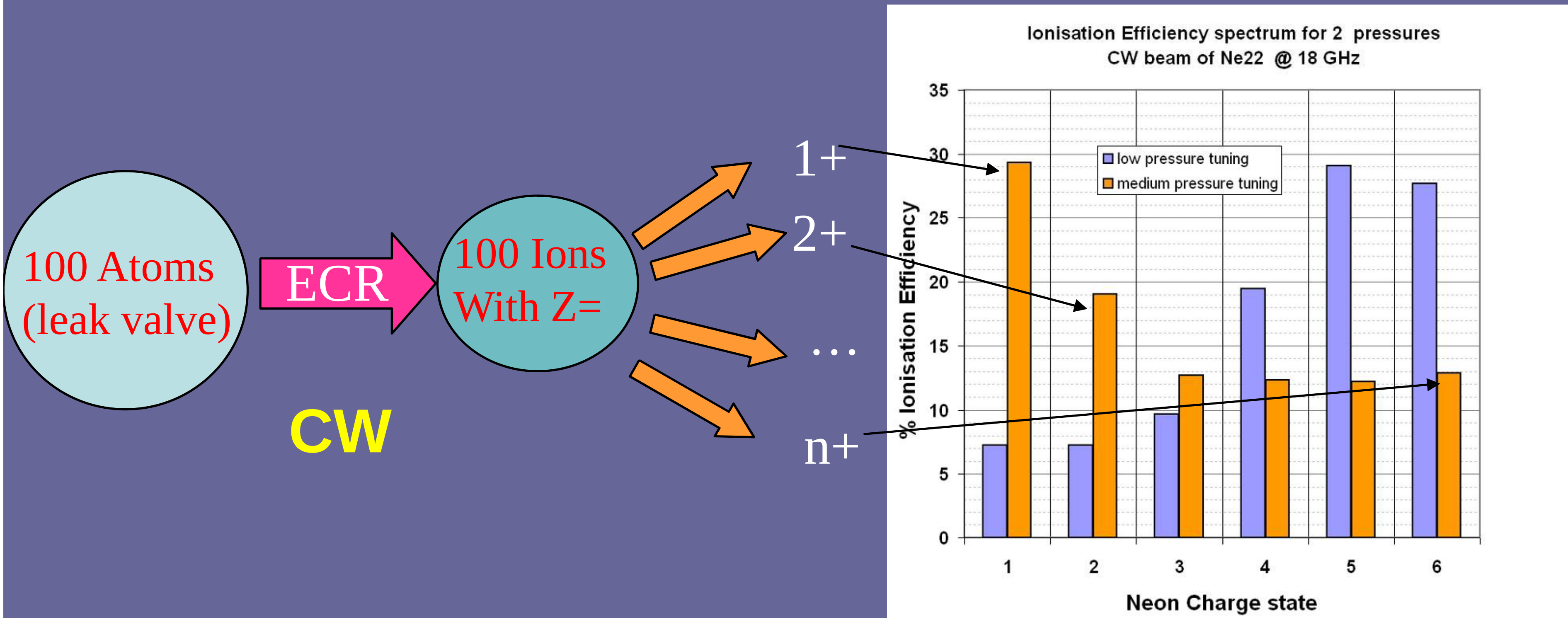




Preglow intensity increases with Power, Preglow FWHM remains constant

Neon Ionization Efficiency Study with PHOENIX V2 ECR Ion Source

- calibrated leak TL6 = $5*10^{-6}$ mbar.l.s-1
- CW operation @ 18 GHz
- 0_2 buffer Gas



⇒Global Ionization Efficiency of Neon is ~100%

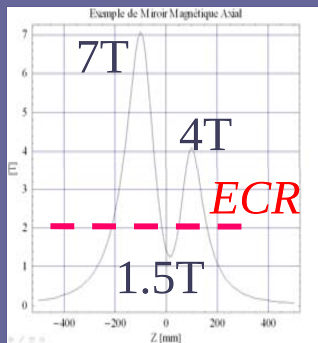
⇒Max CW efficiency on one charge state is ~25%

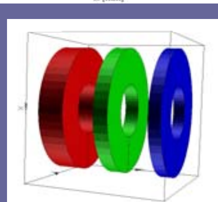
EURISOL Design Study

60 GHz ECR Ion Source Prototype (Preliminary Design)

High Axial magnetic confinement

4 T radial magnetic confinement





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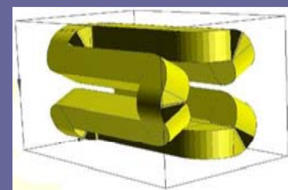

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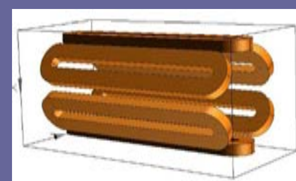
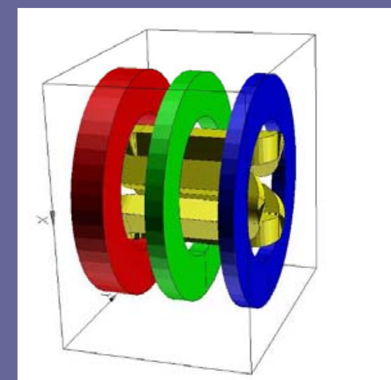
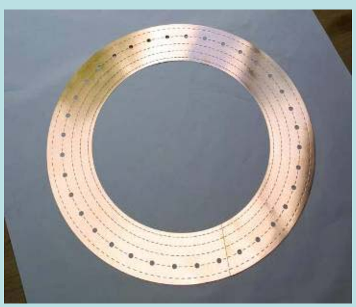
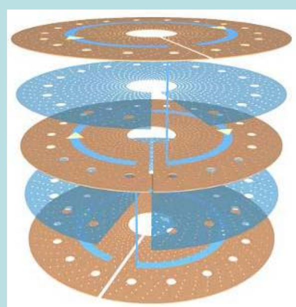




High Magnetic Confinement for optimal 60 GHz Microwave injection

GHMFL





Using Bitter Coil (or PolyHelix) Technology

Will enable pulse study in :

- Afterglow mode
- 1+ n+ ECRIT mode
- Preglow mode

International Scientific Collaboration Program

PICS CNRS - LPSC Grenoble / RAS - IAP Nizhny Novgorod Russia (2006-2008)

- Experimental and theoretical collaboration on pulsed Gyrotron generated ECR plasmas
- Gas dynamic regime with cusp or simple magnetic mirror geometry at IAP (37.5, 75 GHz)
- Classic ECR magnetic bottles (i.e. radial field) at LPSC (18, 28, future 60 GHz)
- He and Ne Efficiency measurements and time structures with different configurations and parameters

LPSC outlook

Objectives: Bunching capabilities for CW gas injection

- Afterglow time structure: 60GHz <50µs ?
- Preglow time structure: 60GHz <50µs ?
- Efficiencies He, Ne?

– Performed: Phoenix (1.6T axial, 1.3 T radial)
  - 18 GHz (good confinement) preglow and afterglow regimes
  - 28 GHz (low magnetic confinement vs RF) preglow only

– Summer 2007: A-Phoenix (3T axial, 2T radial) built
  - 18 GHz: B influence on preglow and afterglow regimes
  - 28 GHz: (good confinement) preglow and afterglow regimes
  - 28+18 GHz higher charge states

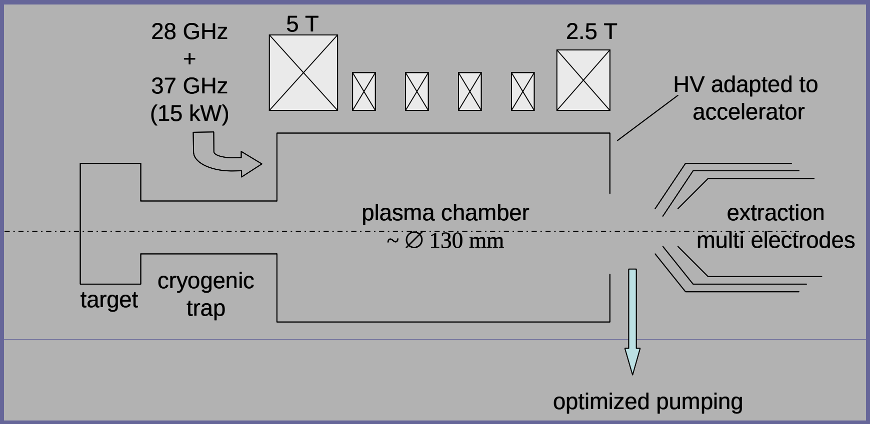
– Winter 2007: 60 GHz Bitter coils based prototype design (7T axial)
  - Magnetic field influence

– 2008: 60 GHz magnetic bottle
  - Afterglow, preglow regimes in tunable magnetic field confinement
  - End of 2008: 60 GHz injection

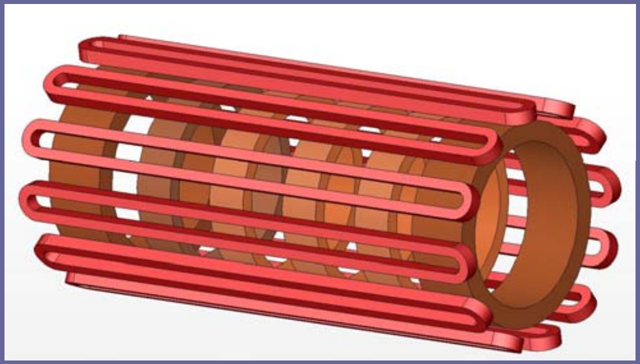
Alternative design

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

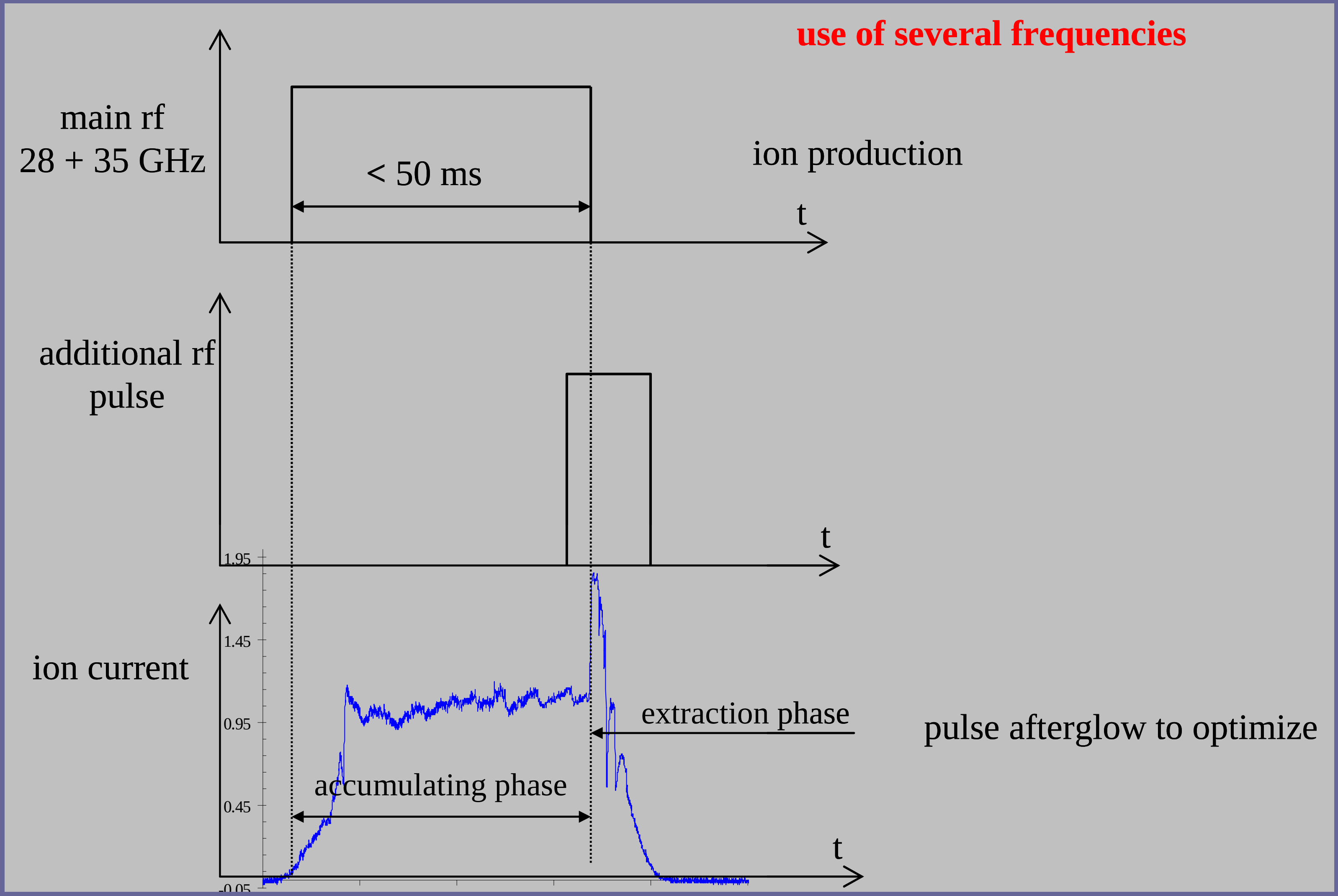


Injection

Extraction

Pulsing

D. Hitz, CEA Grenoble



Conclusions (1)

- The production of the antineutrinos from the decay of ^{6}He seems feasible ~2 10^{13}/s
- The production of the neutrinos from the decay of ^{18}Ne seems difficult
  - – In target production too low with the standard techniques (factor 24 missing)

Alternative production techniques
- tests at LLN - Marc Loiselet
- magnetic ring with target/stripper - C. Rubbia et al

Alternative candidates

Several target-ion sources units (M. Lindroos)

Conclusion (2)

- High intensity beam bunching
  - The length of the afterglow and preglow pulses from an ECR source is decreasing rapidly with the frequency (18GHz / 28GHz tests). Is it still true from 28 to 60GHz?
  - In CW mode, gas injection, the efficiencies are compatible with those accounted for. He:100% Ne: ~30% in one charge state. Is it possible to reach the same efficiencies with any of the two bunching modes?

The 60 GHz prototype is on the way to be funded - it should answer to these questions!

Summary

Present

Production
- kW targets
- simple plasma ion sources
- DC current

→ **2.10^{8} $^{6}He^{+}$ $^{18}Ne^{+}$/s**

Bunching
- **14-28 GHz** ECR sources
- minimum B confinement
- relatively low B field

→**DC >50% He^{+}; 25% Ne^{x+}**
→ **Afterglow and preglow pulses with time spread >200μs, efficiency to be optimized**

Future

Production
- **100 kW** targets
- Or **Ring with target/stripper**

→ 3.10^{13} ^{6}He
? → 3.10^{13} ^{18}Ne atom/s

Bunching
- **60GHz** source directly coupled
- High B field and power

? → ~100% He^{+} ~30% Ne^{x+}
? → 50µs pulses

Option
Several targets coupled to several ion sources **(M. Lindroos)**

Thanks a lot for your attention!

Special thanks to

- Marc Loiselet, S. Mitrofanov, Louvain-La-Neuve
- Thierry Lamy, Thomas Thuillier, Louis Latrasse LPSC Grenoble
- Thierry Stora, Mats Lindroos, CERN-ISOLDE
- Danas Ridikas, Nicolas Thiollière, Jean-Christophe David, CEA Saclay
- The beta-beams collaboration

Open possibilities for the beam bunching

Afterglow:	Preglow:	Continuous
18GHz 1ms	18GHz 1ms	
28GHz 150µs	28GHz 150µs	
60GHz – ?<50µs?	60GHz – ?<50µs?	
1+→n+ 10 - 14 GHz a few % for Kr, Rb, Xe	1+→n+ ??	1+→n+ 14GHz a few % per charge state
Gas injection Under investigation	Gas injection Under investigation	Gas injection 18GHz ~ 100% He ~ 30% Ne on 1 charge state

Rappeler les efficacités demandées