# Status of Beta Beam R&D: Radioactive ion production

Etam NOAH

(October 21, 2009)

On behalf of EURISOL-DS*/ISOLDE-CERN

Acknowledgements: Mats Lindroos, Thierry Stora, Elena Wildner and Beta-beam team

*Project supported by the European Commission under the FP6
"Research Infrastructure Action- Structuring the European Research Area"
EURISOL-DS Project Contract no. 515768 RIDS


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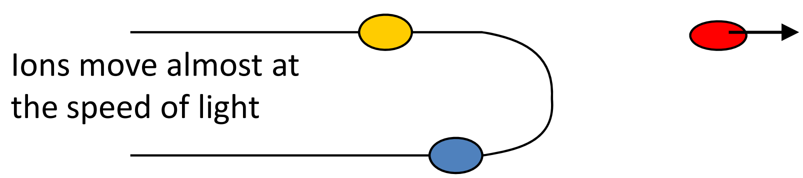
# Outline

- Beta-beams:
  - Neutrino beams
  - EURISOL-DS beta-beam
- Ion production issues:
  - Production options
  - The ISOL method
  - Production and extraction of $^{6}He$
- EURISOL-DS 100 kW targets:
  - 100 kW liquid metal target
  - 100 kW oxide target

# Introduction to beta-beams

- Beta-beam proposal by Piero Zucchelli
  - *A novel concept for a neutrino factory: the beta-beam*, Phys. Let. B, 532 (2002) 166-172.
- AIM: production of a pure beam of electron neutrinos (or antineutrinos) through the beta decay of radioactive ions circulating in a high-energy ($\gamma \sim 100$) storage ring.




- First study in 2002
  - Make maximum use of the existing infrastructure.

# Beta-beam basics

Book: Beta Beams: Neutrino Beams, Mats Lindroos, Mauro Mezzetto, Imperial College Press (24 Sep 2009).

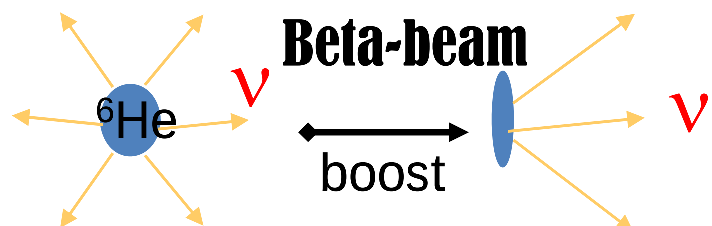
Aim: production of (anti-)neutrino beams from the beta decay of radio-active ions circulating in a storage ring

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

Beta-decay at rest

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

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

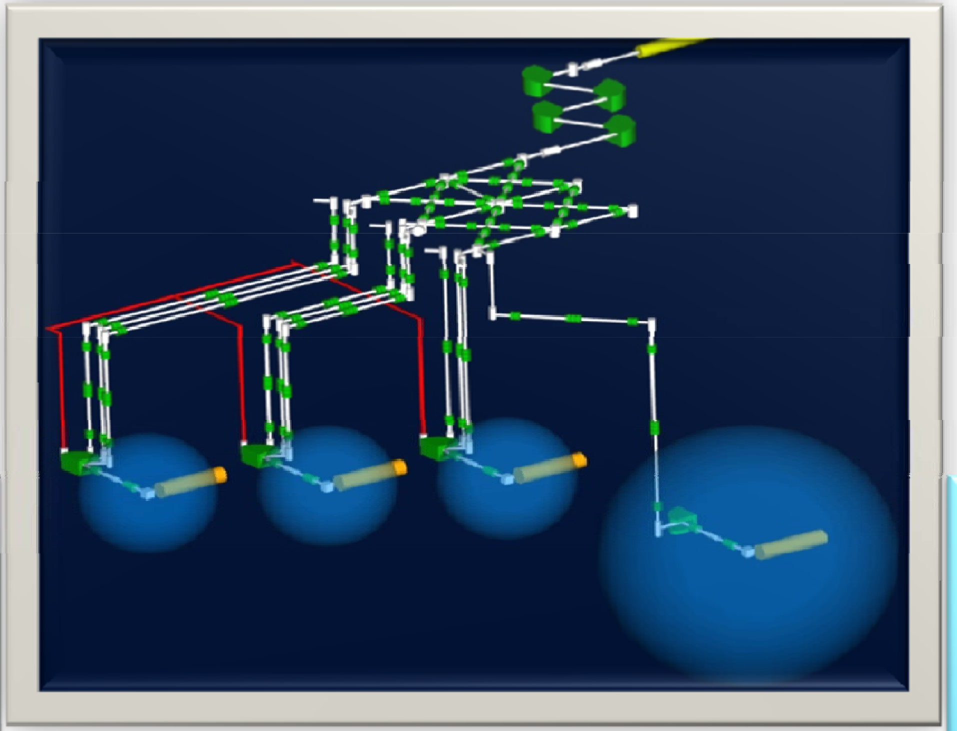



- Pure electron (anti-)neutrino beam!
  - Depending on $\beta^+$- or $\beta^-$- decay we get a neutrino or anti-neutrino
  - Two different parent ions for neutrino and anti-neutrino beams
- Physics applications of a beta-beam
  - Primarily neutrino oscillation physics and CP-violation (high energy)
  - Cross-sections of neutrino-nucleus interaction (low energy)

# The Beta-beam Options

- Low energy beta-beams
  - Nuclear physics, double beta-decay nuclear matrix elements, neutrino magnetic moments
- The medium energy beta-beams or the EURISOL beta-beam
  - Lorenz gamma approx. 100 and average neutrino energy at rest approx. 1.5 MeV (P. Zucchelli, 2002)
- The high energy beta-beam
  - Lorenz gamma 300-500 and average neutrino energy at rest approx. 1.5 MeV
- The very high energy beta-beam
  - Lorenz gamma >1000
- The high Q-value beta-beam
  - Lorenz gamma 100-500 and average neutrino energy at rest 6-7 MeV
- The Electron capture beta-beam

# The EURISOL-DS



## 100 kW direct targets

RIB production:
- Spallation-evaporation
- Main: P-rich
  (10 to 15 elements
  below target material)
- Residues: N-rich
  (A few elements
  below target material)

Target materials:
- Oxides
- Carbides
- Metal foils
- Liquid metals

**Participants:**
**~20 institutions**

**Contributors:**
**~20 institutions**

**EU suport (~30%):**
**~9.2 MEuros**

**Duration:**
**2005-2009**

**12 Tasks**

## mMW fission target

RIB production:
- Fission
- N-rich
- Wide range
  Z = 10 to Z = 60

Target material:
- U (baseline)
- Th

Converter:
- Hg

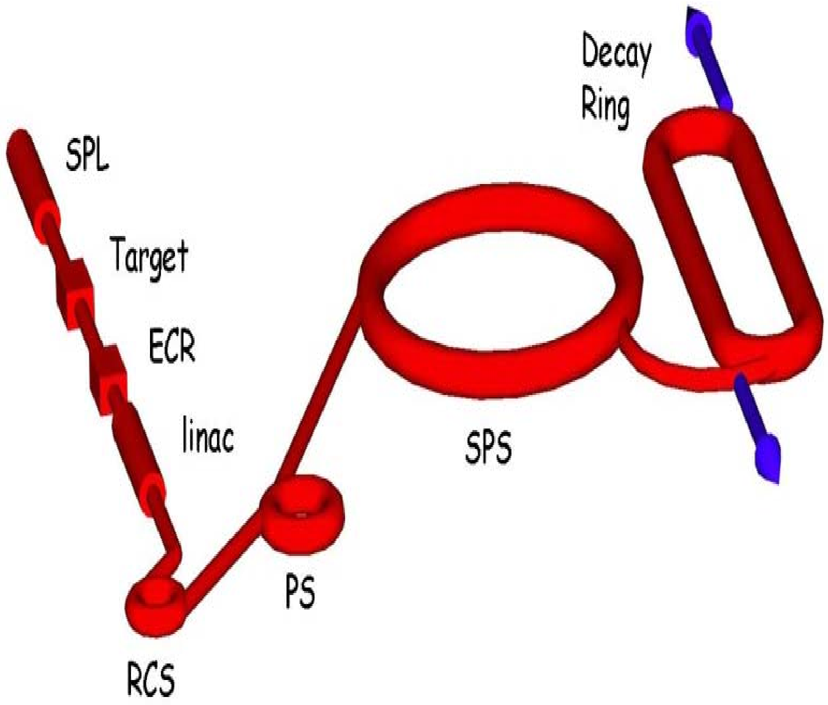
# The EURISOL Scenario

- Based on CERN boundaries
- Ion choice: $^{6}He$ and $^{18}Ne$
- Relativistic gamma=100/100
  - SPS allows maximum of 150 ($^{6}He$) or 250 ($^{18}Ne$)
  - Gamma choice optimized for physics reach
- 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

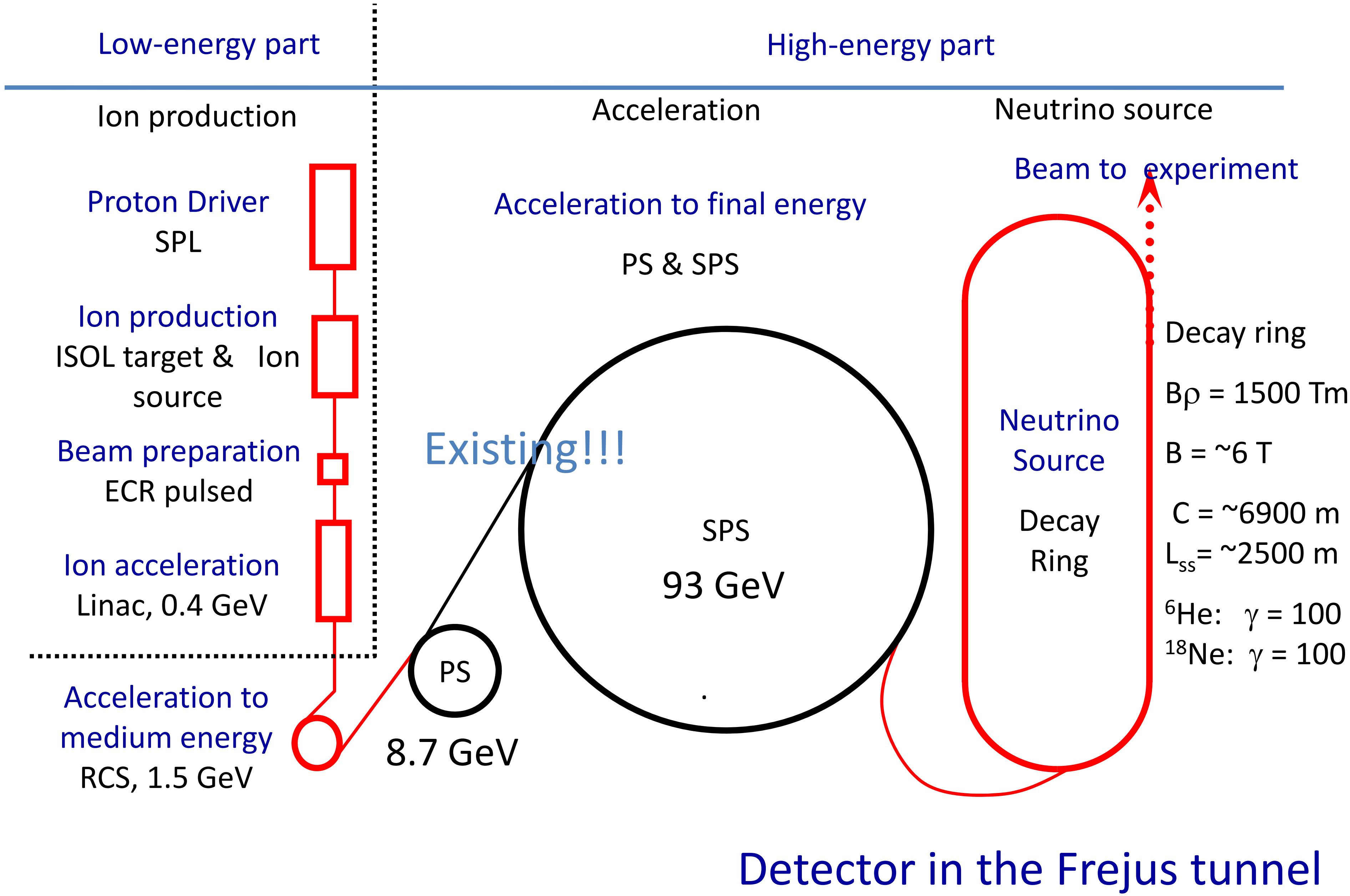
- Opportunity to share a Mton Water Cerenkov detector with a CERN superbeam, proton decay studies and a neutrino observatory

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

EURISOL scenario



# Possible beta-beam complex



# 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 lifetime 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 problem
- EURISOL choice in 2002
  - $^{6}$He to produce antineutrinos
  - $^{18}$Ne to produce neutrinos

$$ {}^{6}_{2}He \rightarrow {}^{6}_{3}Li\ e^{-}\ \overline{\nu} $$

Average $E_{cms} = 1.937$ MeV

$$ {}^{18}_{10}Ne \rightarrow {}^{18}_{9}F\ e^{+}\ \nu $$

Average $E_{cms} = 1.86$ MeV

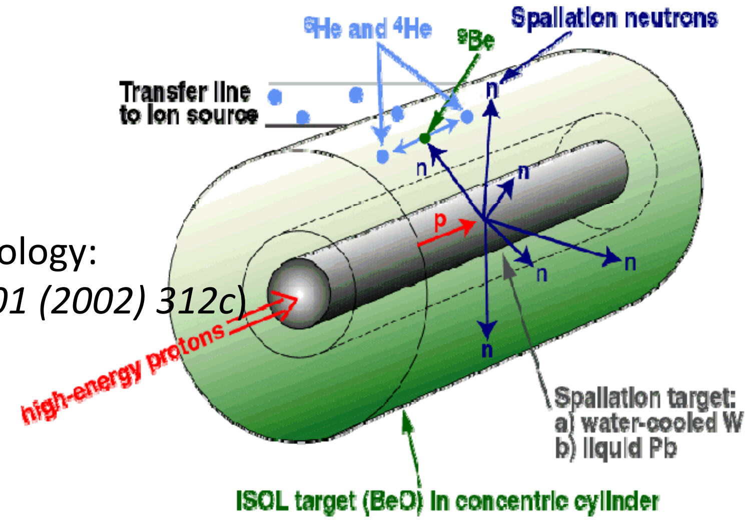
# Production of beta-beam isotopes

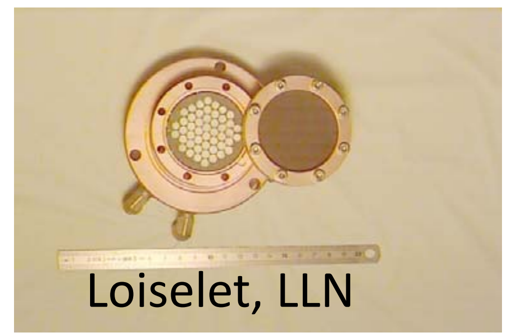
- The Isotope Separation On-Line (ISOL) method at medium energy
  - EURISOL type production, uses typically 0.1-2 GeV protons with up to 100-200 kW beam power through spallation, fission and fragmentation
- Direct production
  - Uses low energy but high intensity ion beams on solid or gas targets. Production through compound nuclei which forms with high cross section at low energies
- Direct production enhanced with a storage ring
  - Enhancing the efficiency of the direct production through re-circulation and re-acceleration of primary ions which doesn't react in the first passage through the target.
  - Possible thanks to ionization cooling!

# Intensities at source

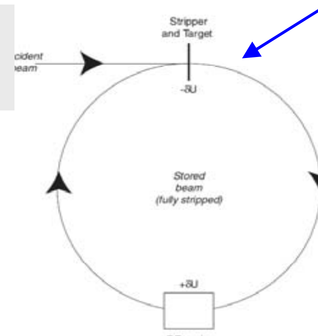
- ISOL method at 1-2 GeV (200 kW)
  - >1 $10^{13}$ $^{6}He$ per second
  - <8 $10^{11}$ $^{18}Ne$ per second
  - $^{8}Li$ and $^{8}B$ not studied
  - Studied within EURISOL
- Direct production
  - >1 $10^{13}$ (?) $^{6}He$ per second
  - 1 $10^{13}$ $^{18}Ne$ per second
  - $^{8}Li$ and $^{8}B$ not studied
  - Studied at LLN, Soreq, WI and GANIL
- Production ring
  - $10^{14}$ (?) $^{8}Li$
  - >$10^{13}$ (?) $^{8}B$
  - $^{6}He$ and $^{18}Ne$ not studied
  - Will be studied in the future

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




$^{7}Li$
$^{6}Li$



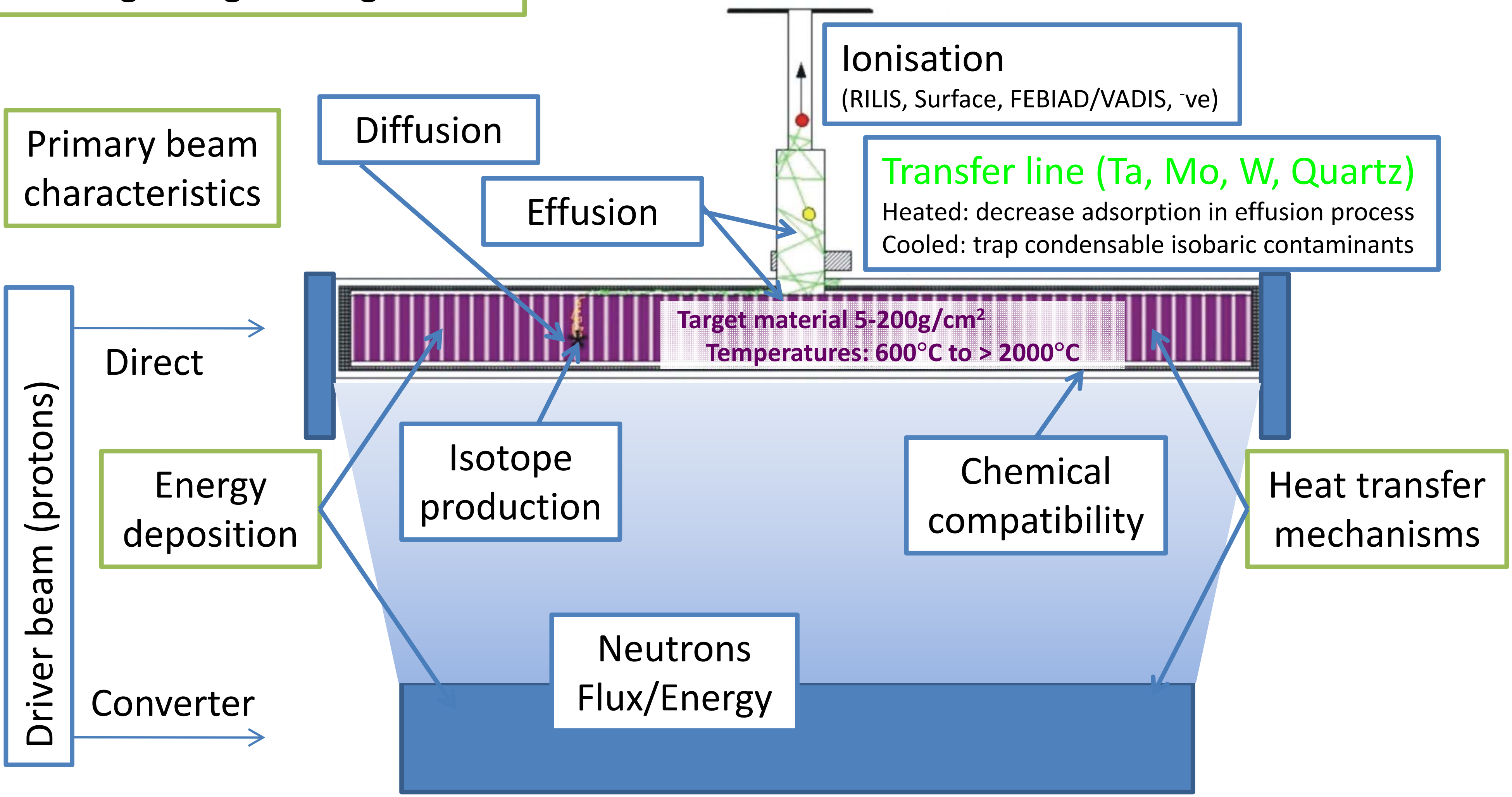

$^{7}Li(d,p)^{8}Li$
$^{6}Li(^{3}He,n)^{8}B$

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

# The ISOL method

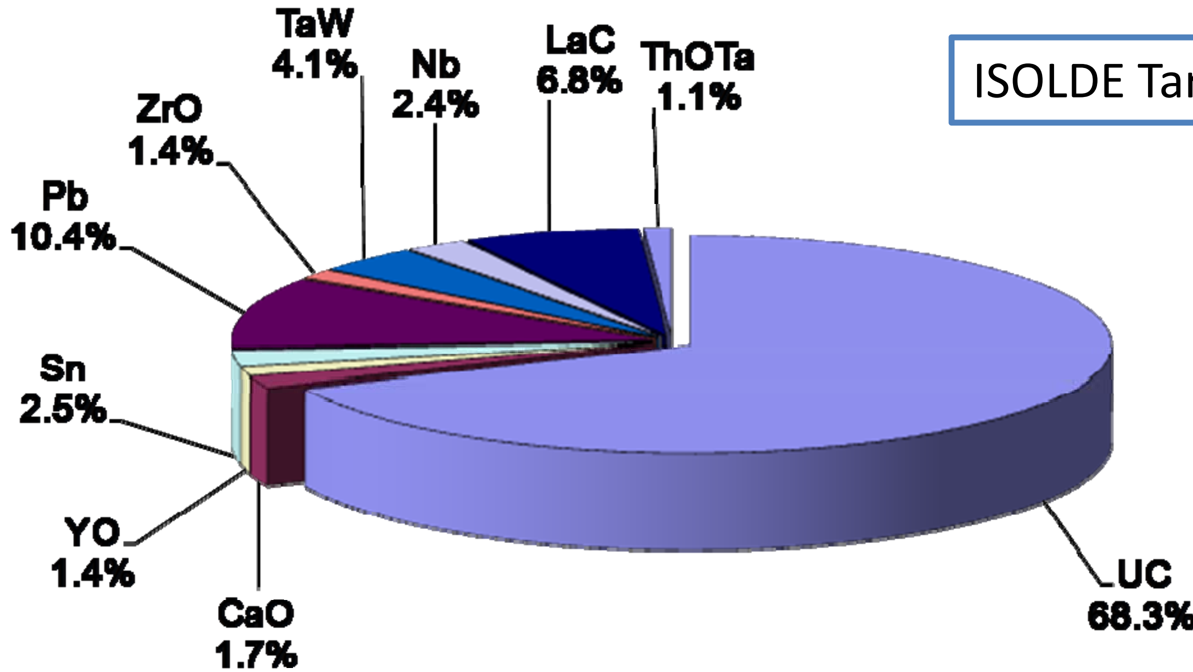
RIB production and release

RIB target engineering isssues



# Typical target materials and RIBs

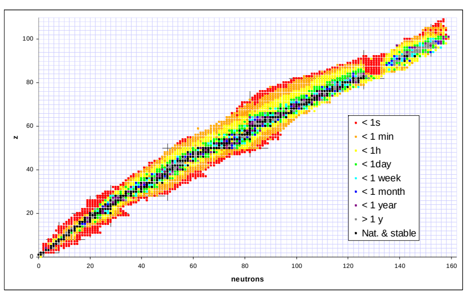
ISOLDE Targets 2008

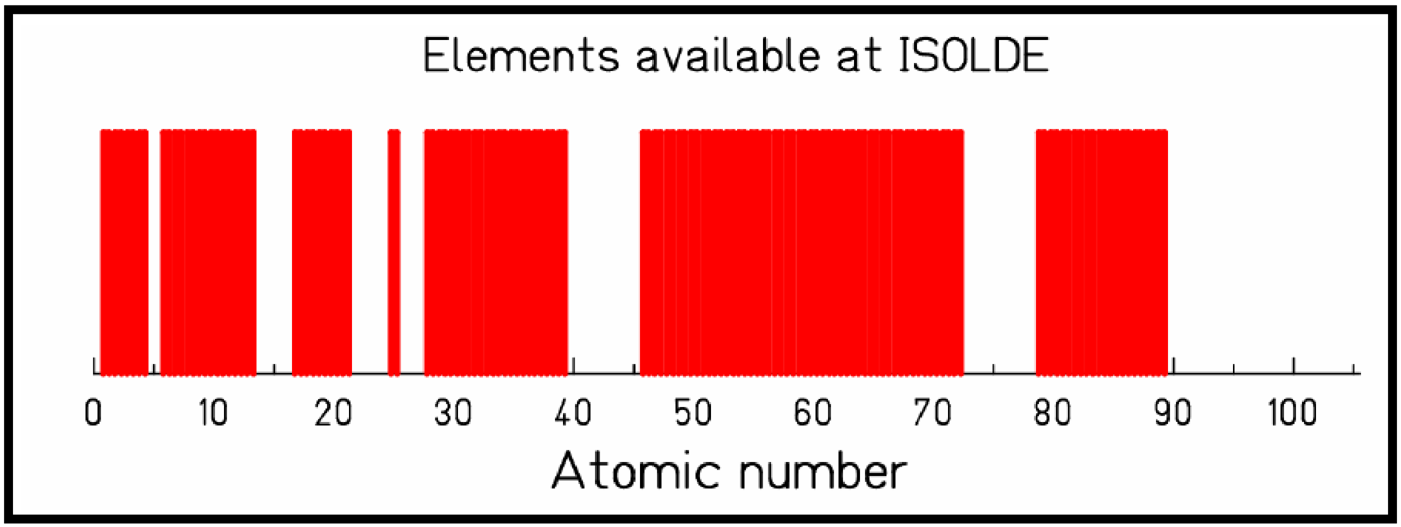



## Target elements

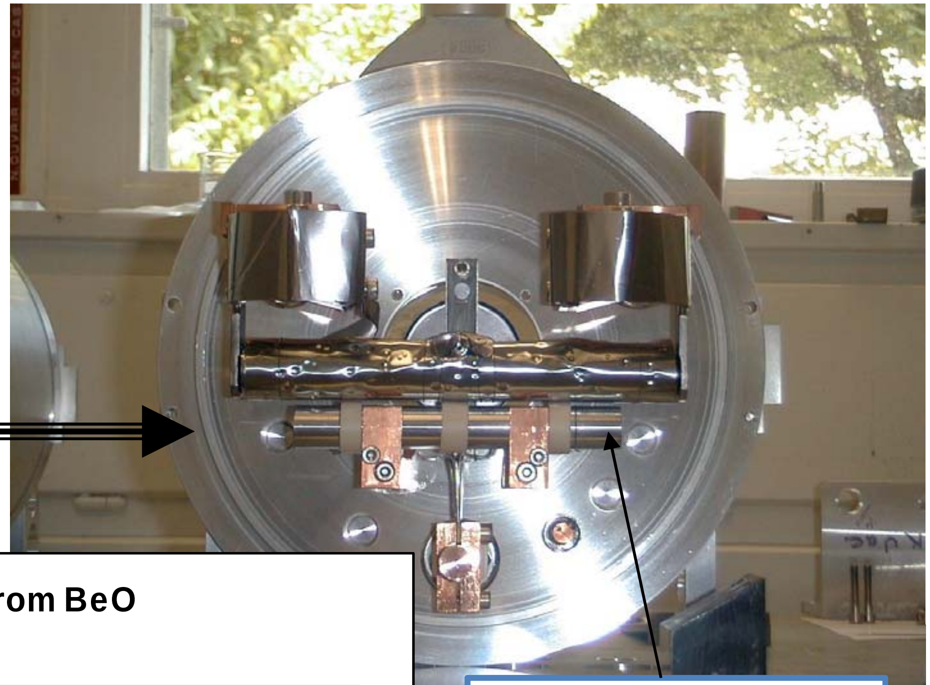
- UCx, ThCx
- CaO, MgO, $Al_2O_3$, ZrO
- Ta, Nb
- Sn, Pb, La
- SiC, $LaC_2$

## RIBs



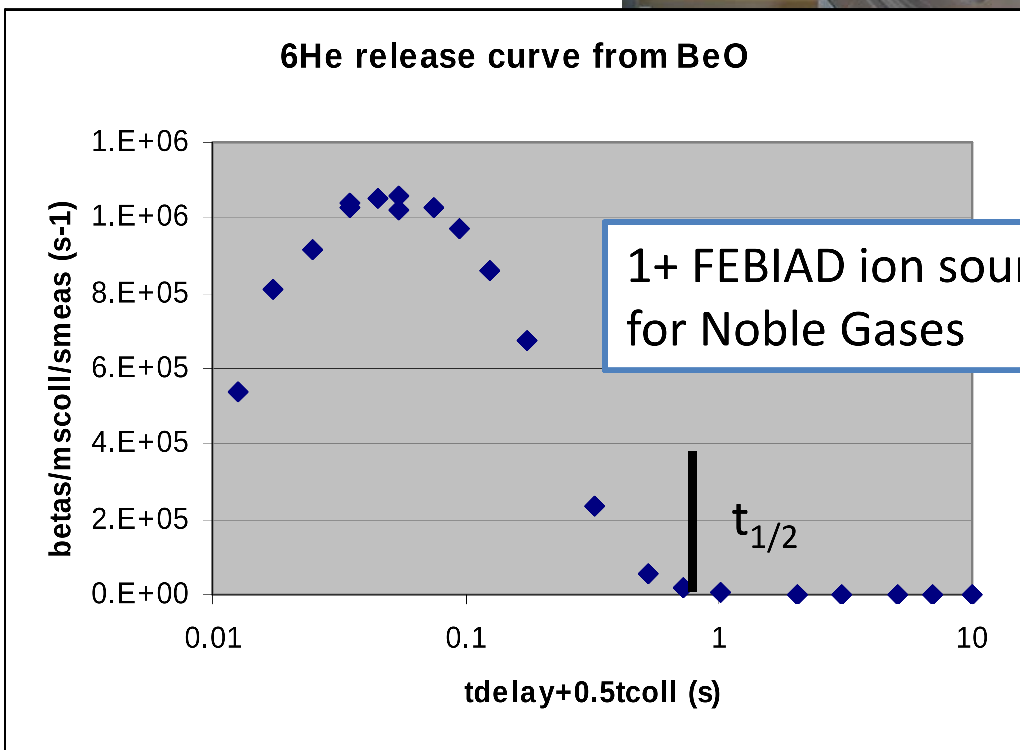
# $^{6}$He production at ISOLDE-CERN in 2009

1.4 GeV from PSB

p-n W converter

80 porous BeO pellets



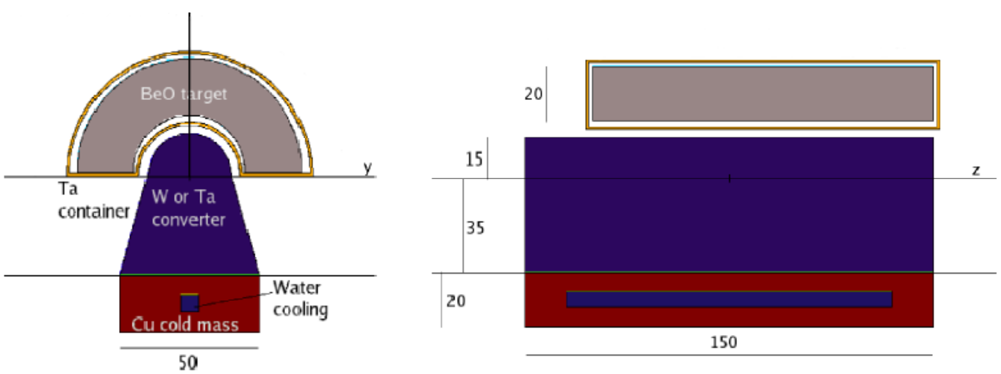

1+ FEBIAD ion source, cold line for Noble Gases

>85% released

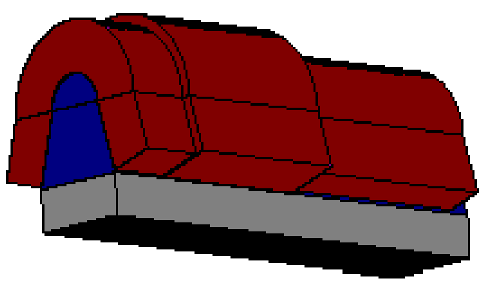
Release efficiency
operation temperature
outgasing
materials compatibility
ageing, etc…

# Reaching required ion intensities

- $^{6}He$ can be achieved:
  - Isotope production tested at ISOLDE
  - 1.3 $10^{13}$ $^{6}He/s$ 100 kW, 40 MeV deuteron beam
  - 2 $10^{13}$ $^{6}He/s$ 100 kW, 1 GeV proton beam
  - $10^{14}$ $^{6}He/s$ 200 kW, 2 GeV proton beam
- $^{18}Ne$ challenging:
  - $^{3}He$, 30 MeV, 200 mA direct on oxide target, 600 kW!
  - p, 70 MeV, 30 mA on $Al_2O_3$ target.

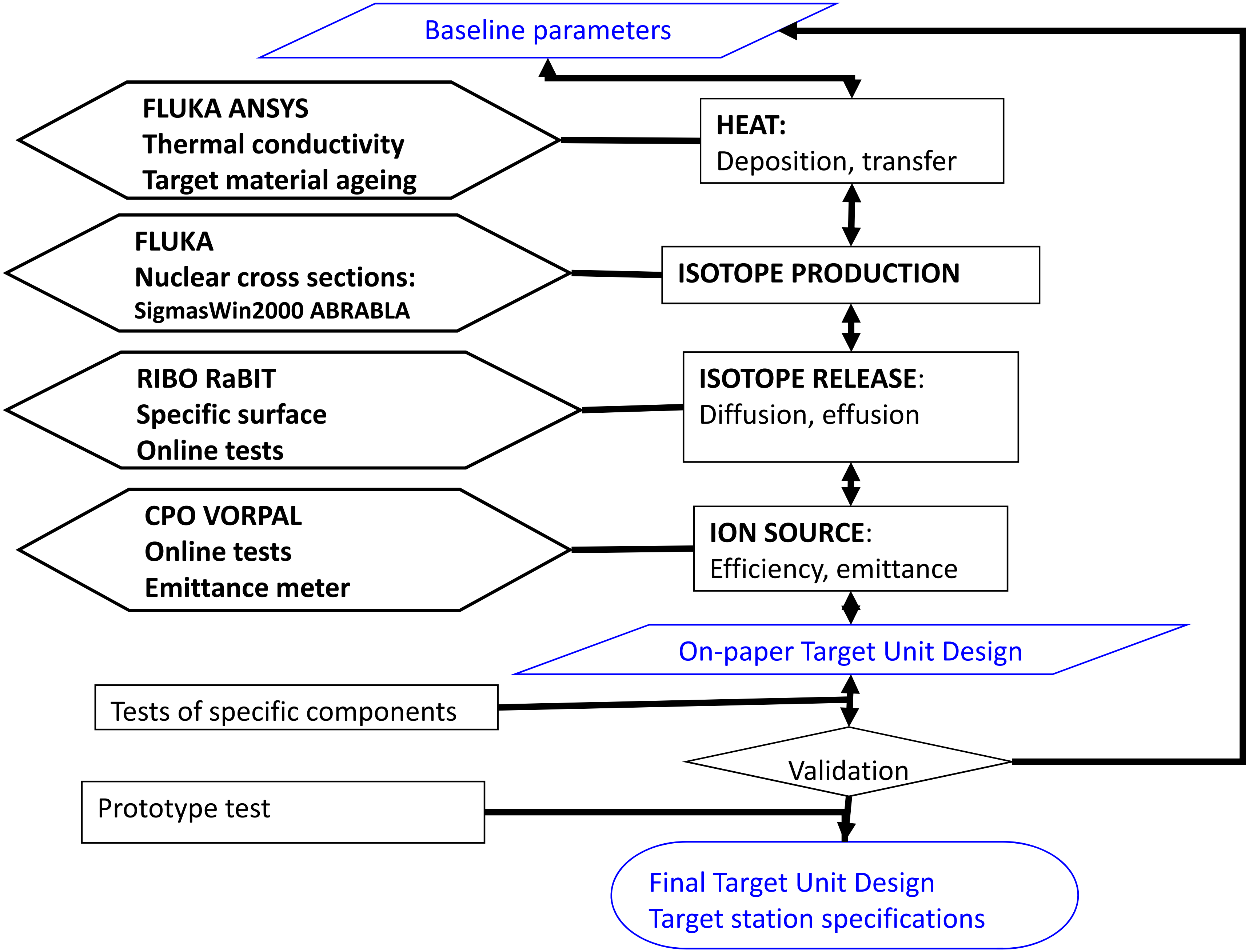



Ø3cm , 15cm



Ø3cm , 24cm

# EURISOL 100 kW Direct Target Design

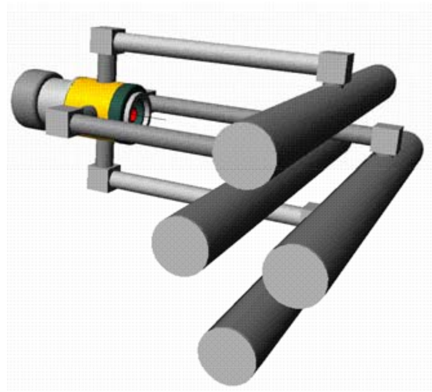


# EURISOL 100 kW target baseline parameters

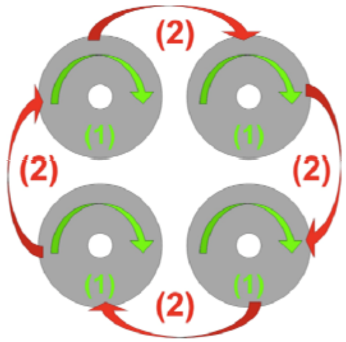
| Parameter | Symbol | Units | Nval | Range |
|---|---|---|---|---|
| Target material | $Z_{targ}$ | - | SiC, Ta, BeO, Pb (molten) | Be-U |
| Beam particles | $Z_{beam}$ | - | Proton | Deuterium – $^{12}C$ |
| Beam particle energy | $E_{beam}$ | GeV | 1 | 0.5 – 3 |
| Beam current | $I_{beam}$ | μA | 100 | 100 – 1000 |
| Beam time structure | - | - | dc | ac<br>50Hz 1ms pulse |
| Gaussian beam geometry | $\sigma_{beam}$ | mm | 7 | 3 – 20 |
| Beam power | $P_{beam}$ | kW | 100 | 100-1000 |
| Target thickness | X | $g/cm^2$ | 200 | 10 – 250 |
| Target radius (cylinder) | $r_{targ}$ | mm | $3\sigma_{beam}$ | $3\sigma_{beam} - 5\sigma_{beam}$ |
| Target temperature | $T_{targ}$ | ºC | 2000 | 500-2500 |
| Number of target containers | $j_{targ}$ | - | 4 | 1 – 10 |
| Plasma ionization outlet diameter | $Ø_{out}$ | mm | 3 | 2 – 6 |

# EURISOL 100 kW direct target issues

- Heat dissipation + target temperature profile optimisation are main drivers of 100 kW direct target design:
  - Uniform high temperature for fast diffusion and effusion
  - Avoid cold spots where isotopes could condense
  - Heat dissipation by conduction/thermal radiation $T^4$
  - Compact target geometries to minimise effusion losses
- Solid targets: Oxides and Carbides
  - Oxides: thermal insulators (e.g. $ThO_2$ 0.4 W/mK @1673 K)
  - Relatively low operation temperature (e.g. CaO 1673 K)
  - Composite target pills
  - Multibody target concept + neutral beam merging
- Solid targets: Metal foils
  - Foil thickness optimisation for mechanical properties/diffusion
- Liquid metal targets:
  - Loop required to dissipate factor x20 more heat than can be accomodated classically
  - Diffusion chamber required to optimise release efficiency of short-lived isotopes



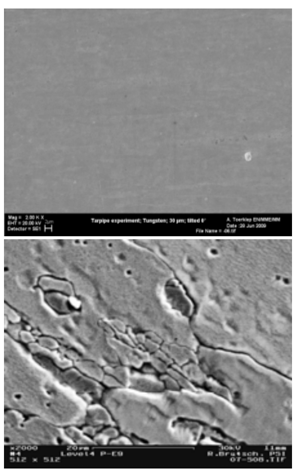
Multi-body target




Beam sharing between sub-units of one target station

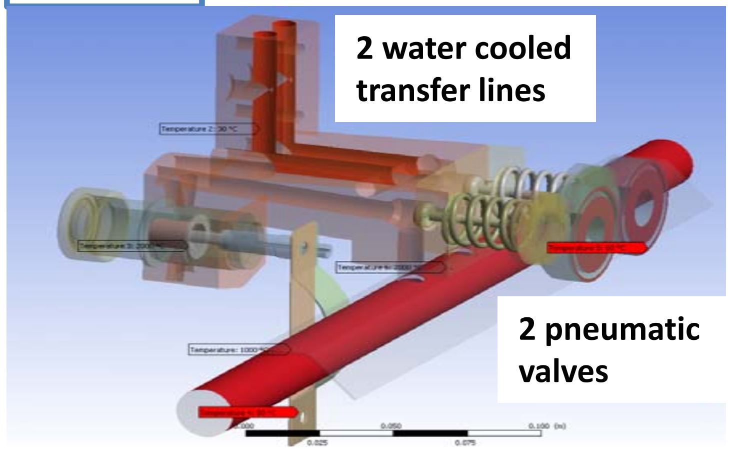
# EURISOL 100 kW target developments

## TARPIPE



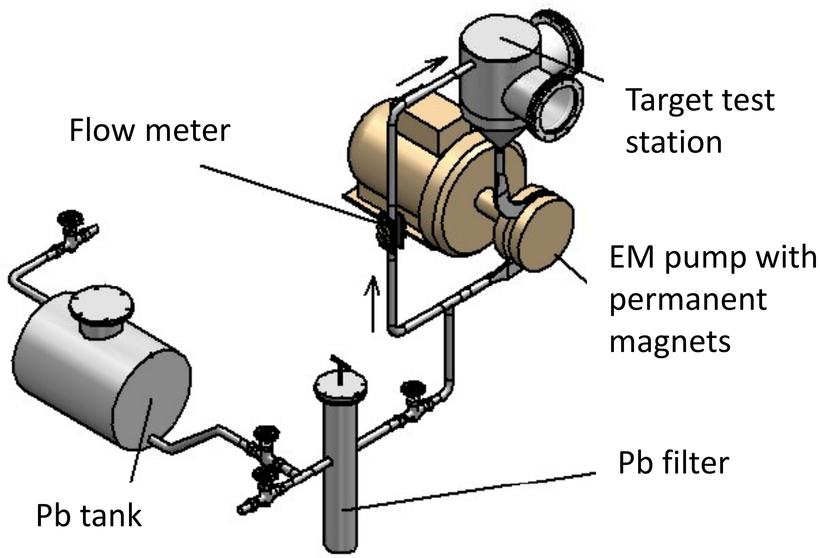
W - 30μm foil

## Bivalve

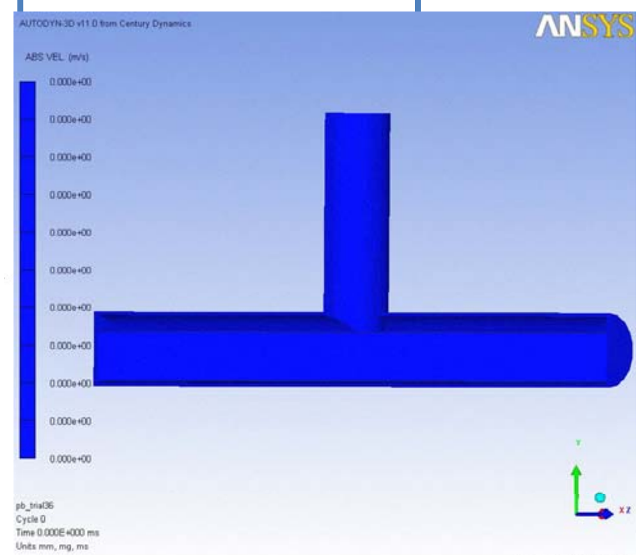



## Oxide target prototype ($Al_2O_3$)

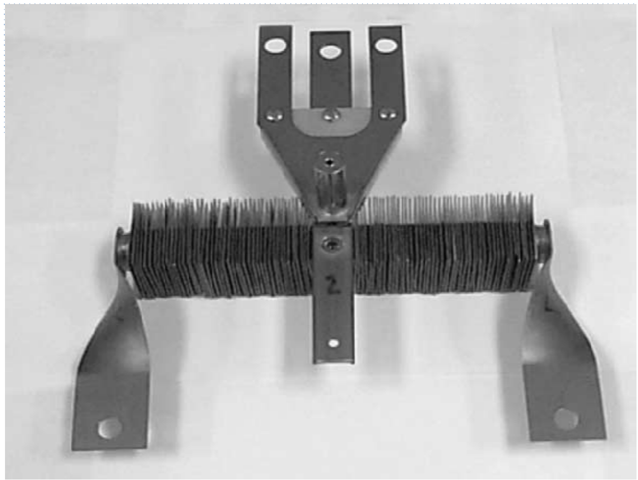

## Liquid metal direct target

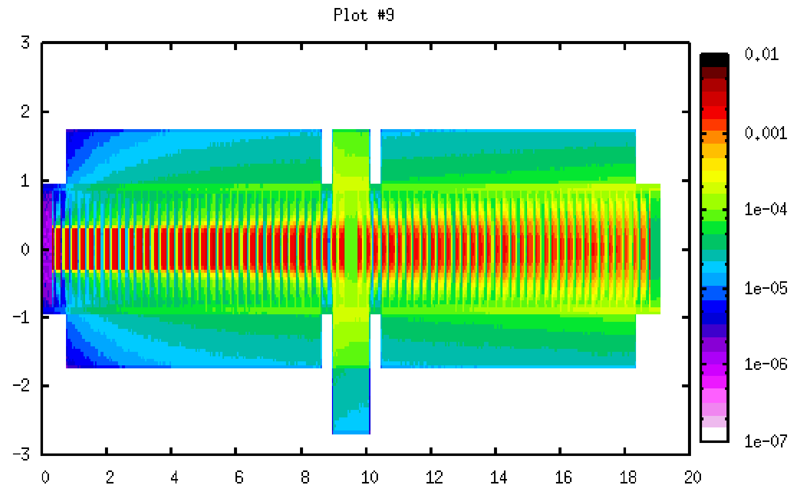


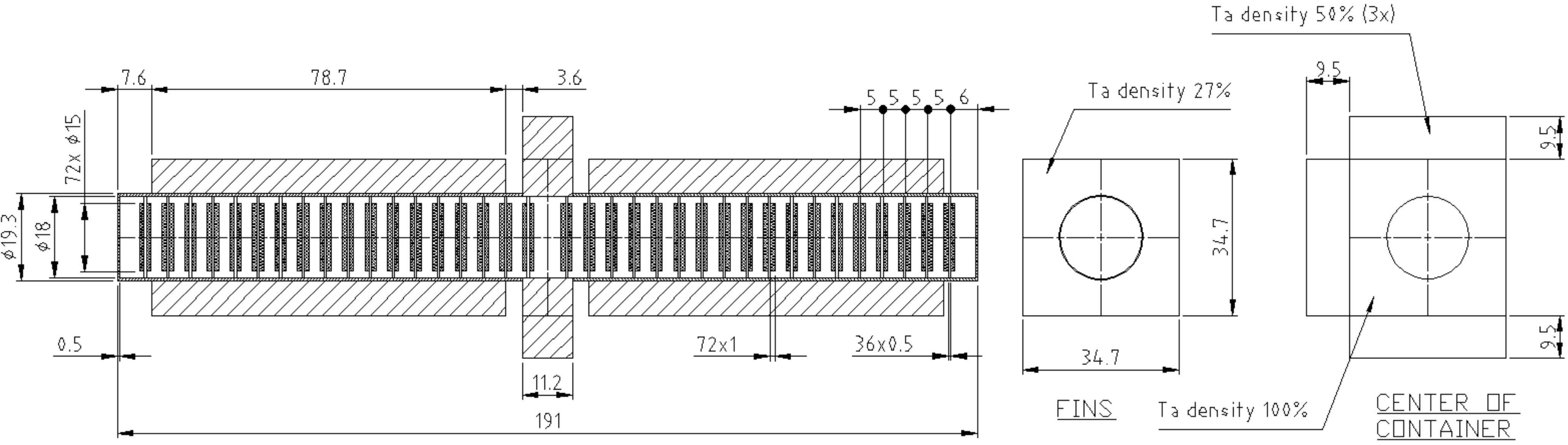

## Transient effects



# High power oxide direct target prototype



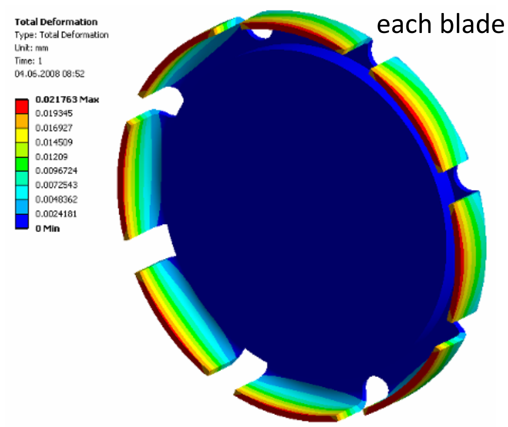


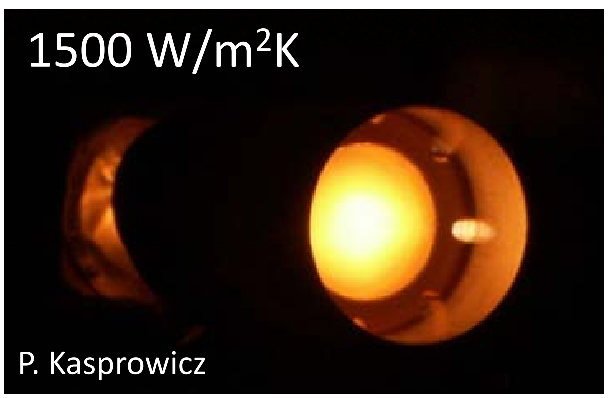
# $Al_2O_3$/Nb composite target

S. Marzari

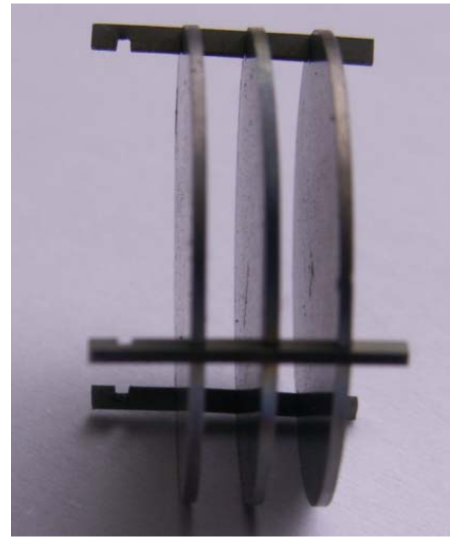
## Earlier concept

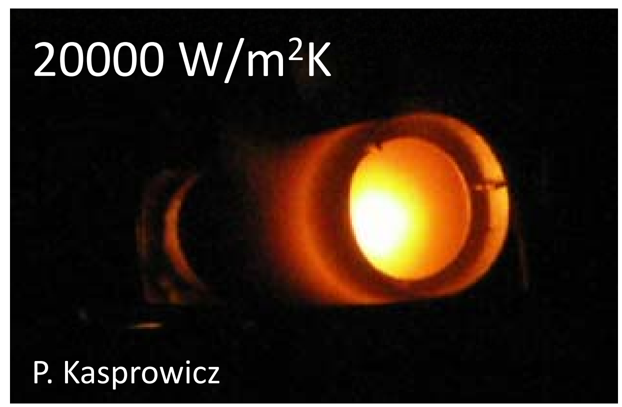



**Deformation** = 0.022 mm on each blade

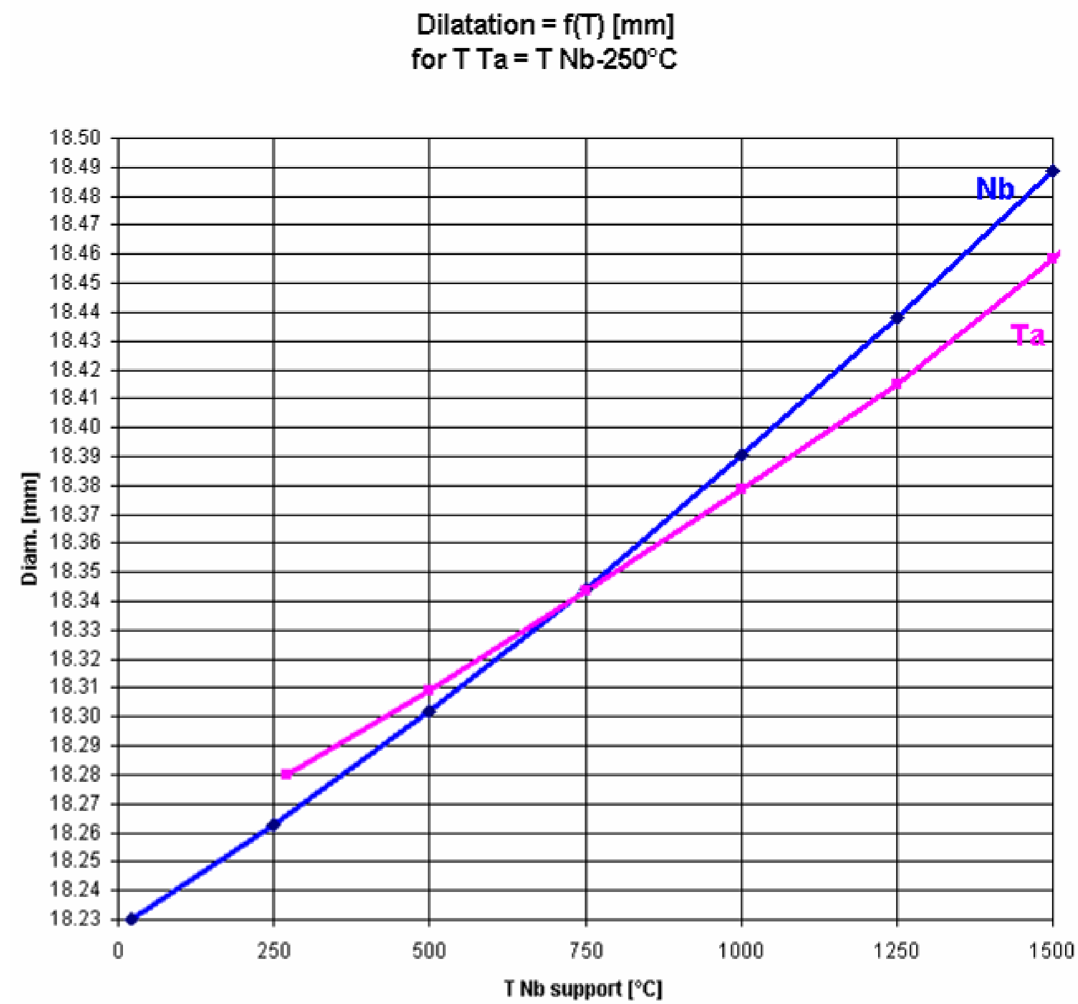



## Final concept

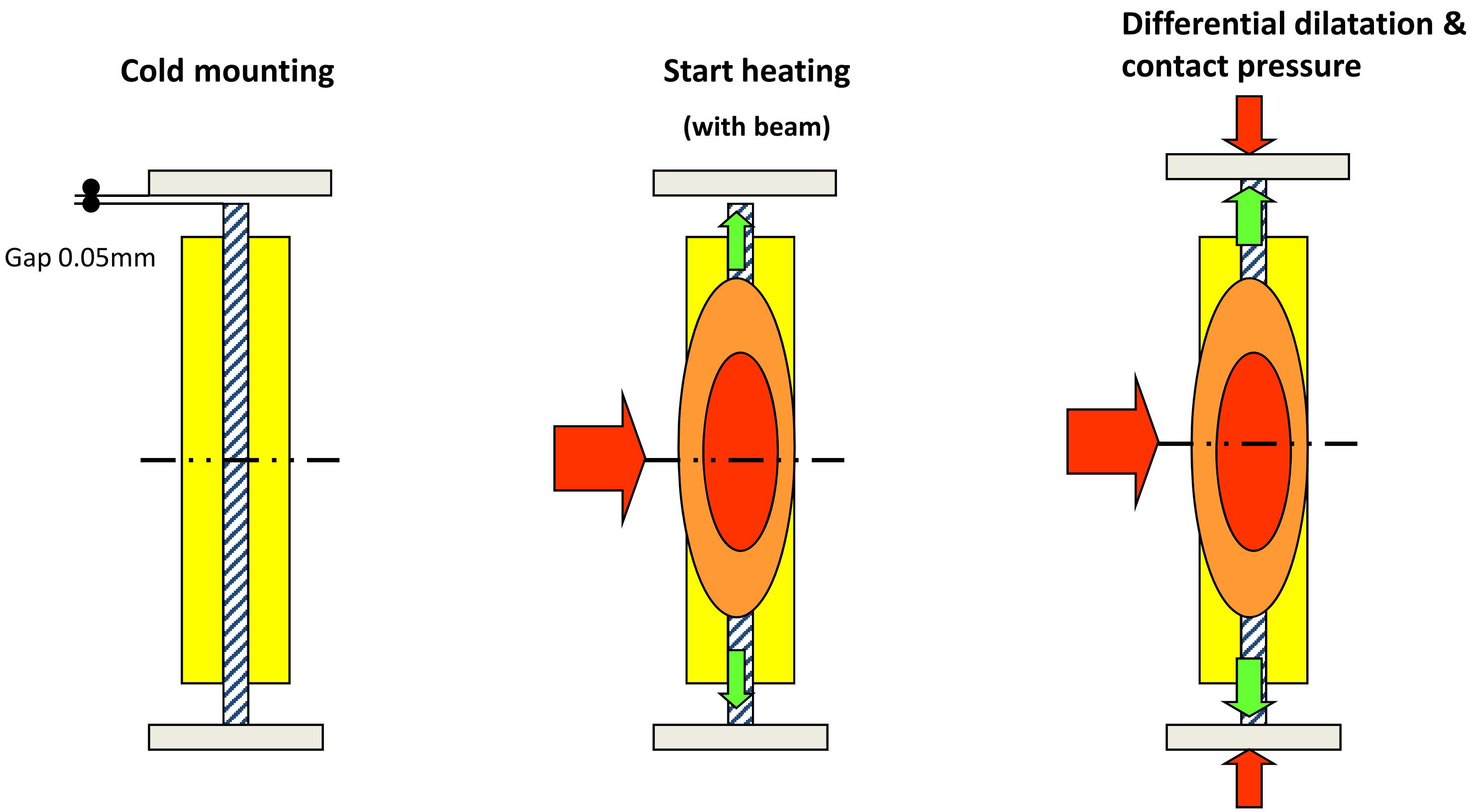




# Differential dilatation Ta/Nb



# Differential dilatation Ta/Nb



# Nb thickness choice

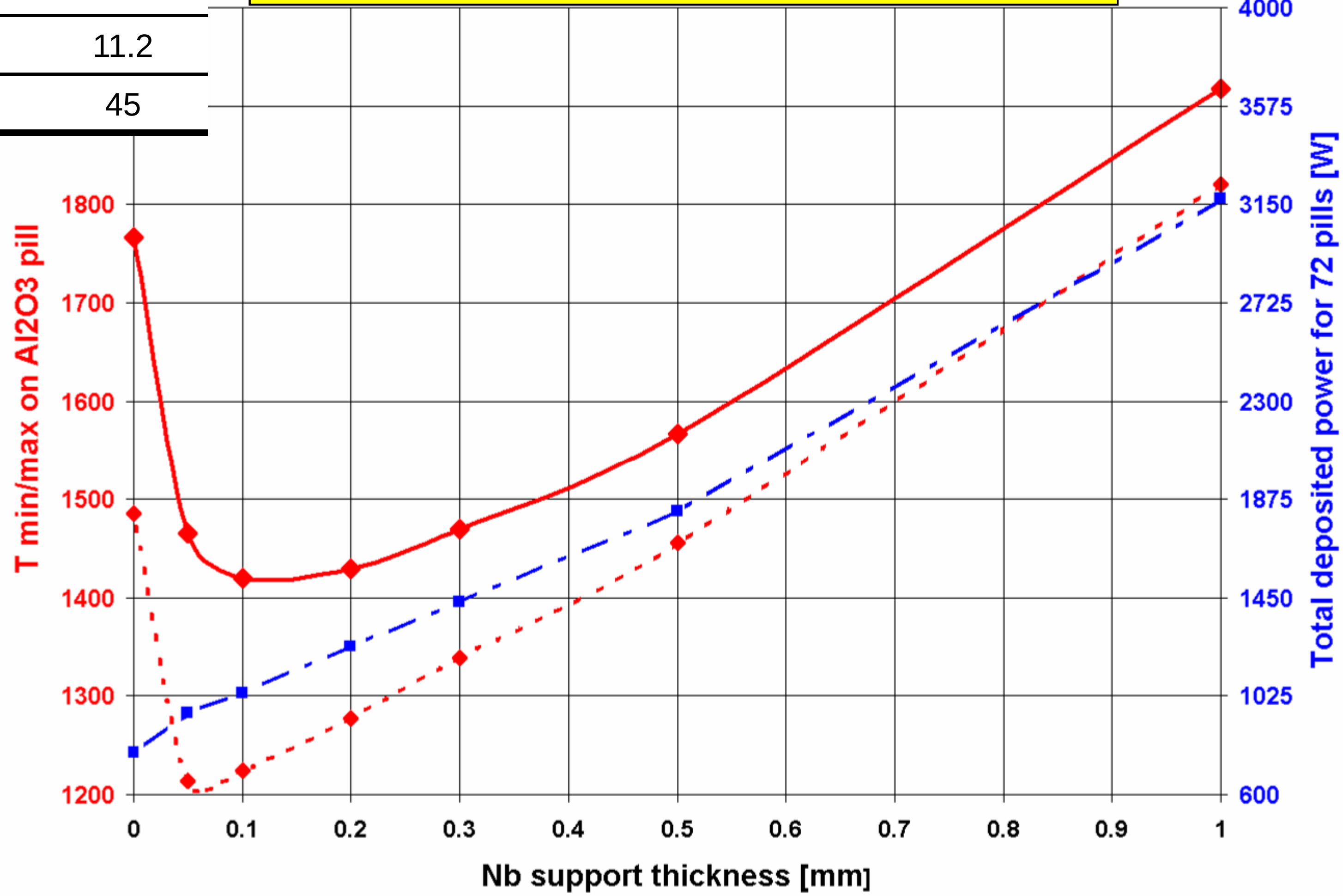
Power deposited by 10 kW beam in 1 composite pill, 1.0 mm thick $Al_2O_3$ brazed onto Nb, as a function of Nb thickness.

| | Nb Thickness | | |
|---|---|---|---|
| | 0.2 mm | 0.5 mm | 1.0 mm |
| Nb [W] | 6.36 | 16.5 | 33.8 |
| $Al_2O_3$ [W] | 10.8 | 11 | 11.2 |
| Total [W] | 17.16 | 27.5 | 45 |

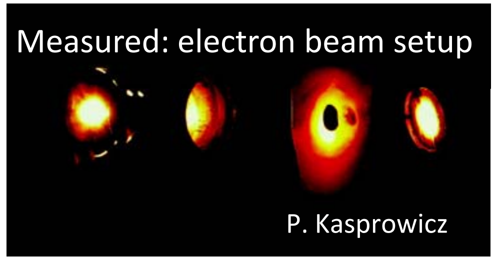
=> 0.3mm is a good compromise between max/min ratio temperature and Nb support construction

FLUKA

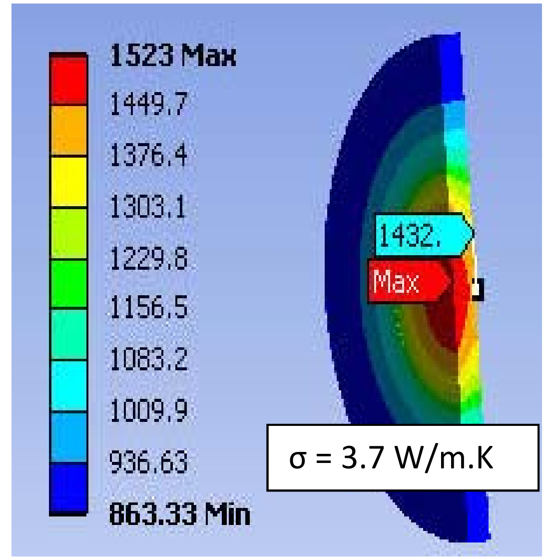
ANSYS WB



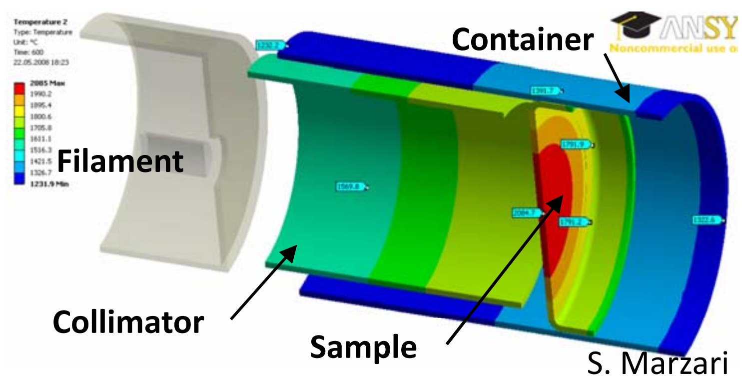
# $Al_2O_3$ thermal conductivity



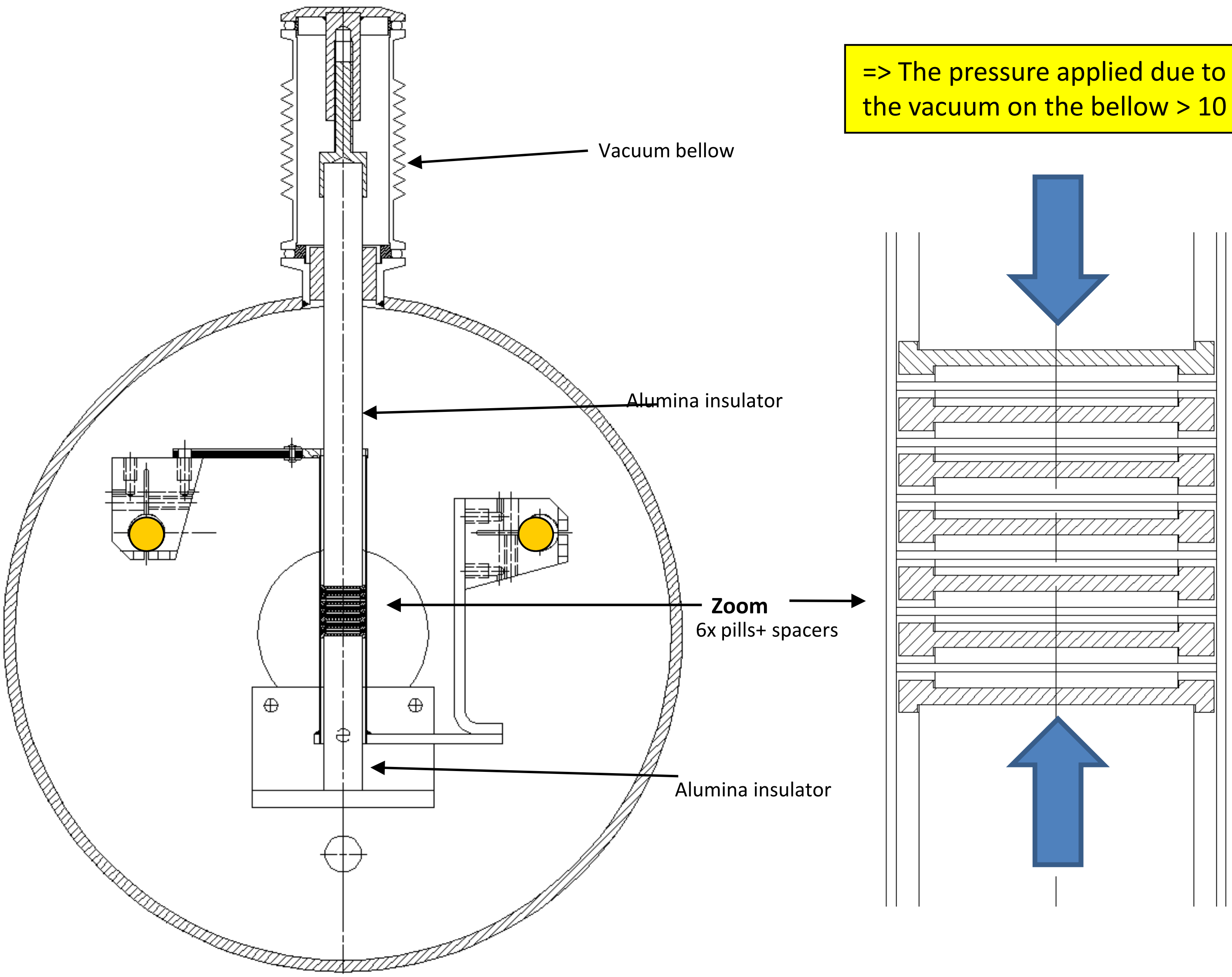

Power on sample = 28 W
Beam spot < 8 mm
Front = 1524 °C
Back = 1432 °C




Pill-container thermal contact conductance



# Brazing equipment

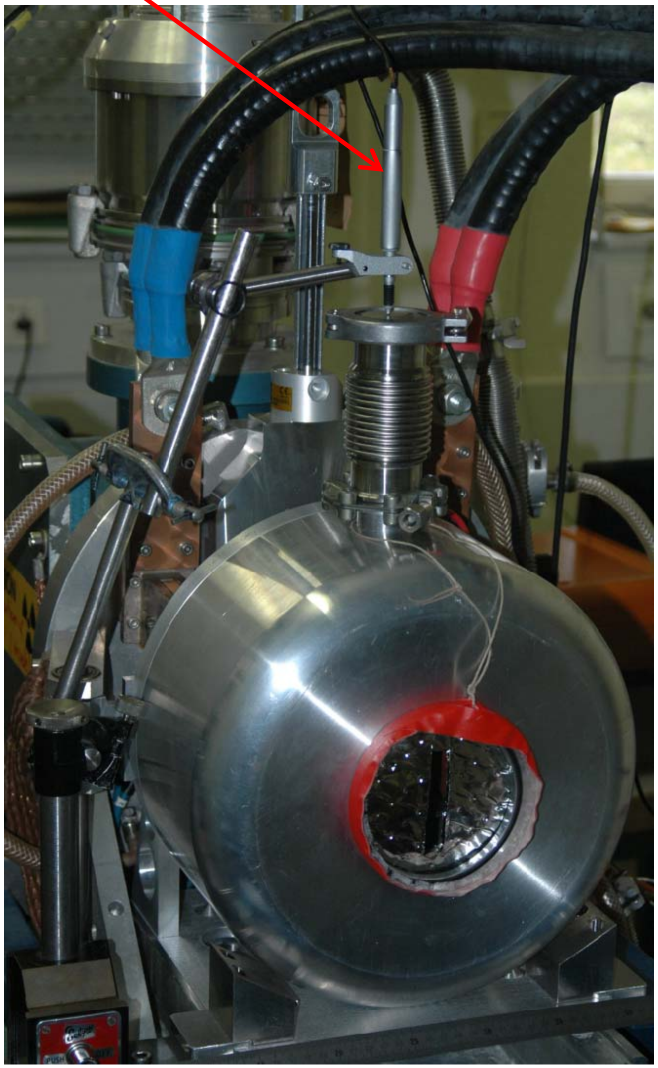


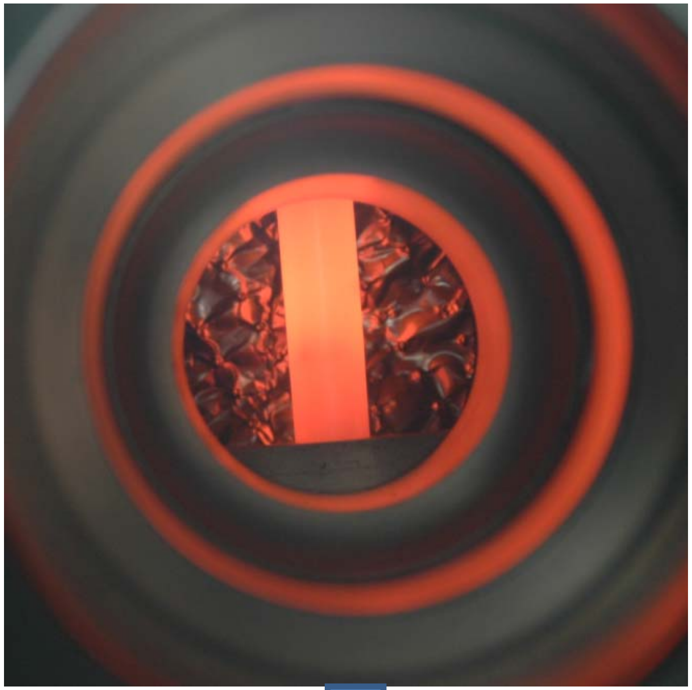

=> The pressure applied due to the vacuum on the bellow > 10 kg

# Brazing equipment

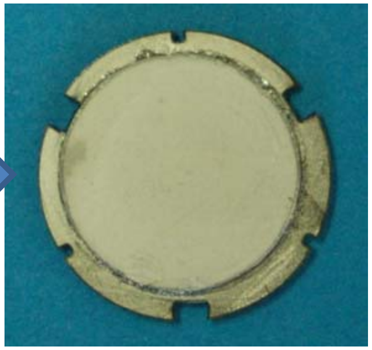
- Varying temperature and time to obtain the parameters for optimal brazing

Micron meter for dilatation monitoring



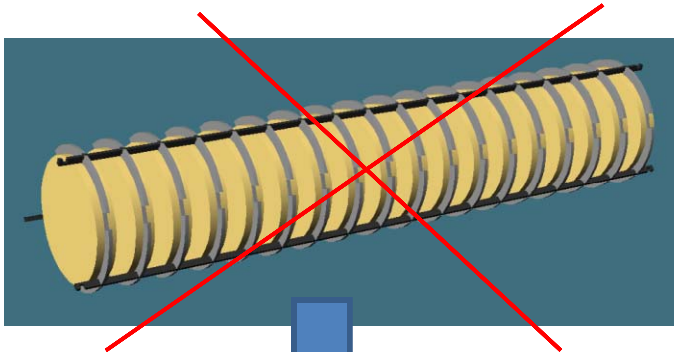


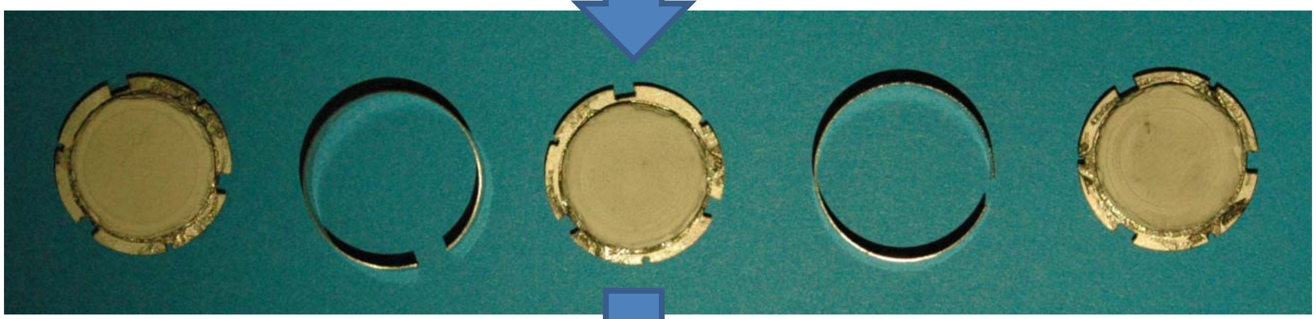
Brazed pills after final laser cutting

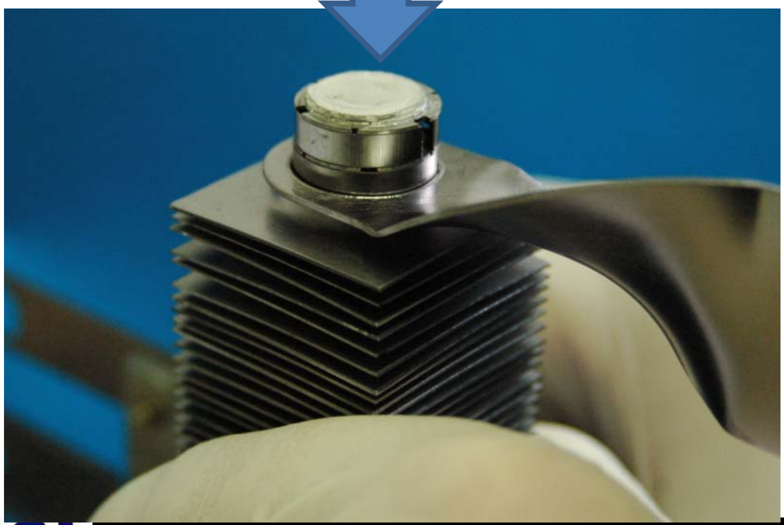


# $Al_2O_3$ target final assembly

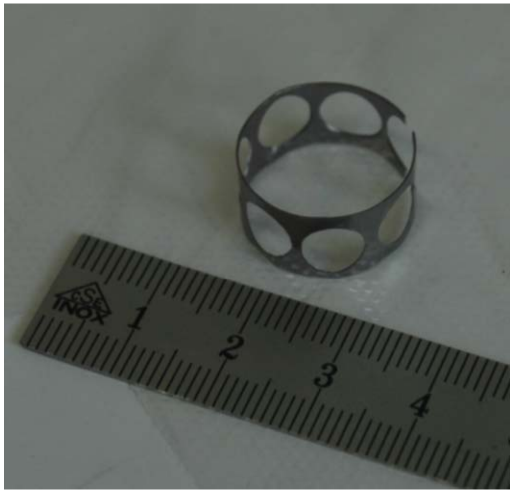
- During mounting we decide to replace the gap spacers for ring spacers



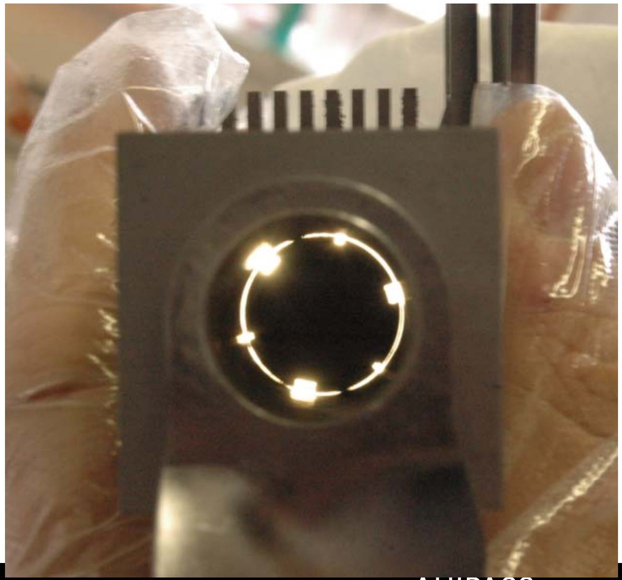




Central spacer

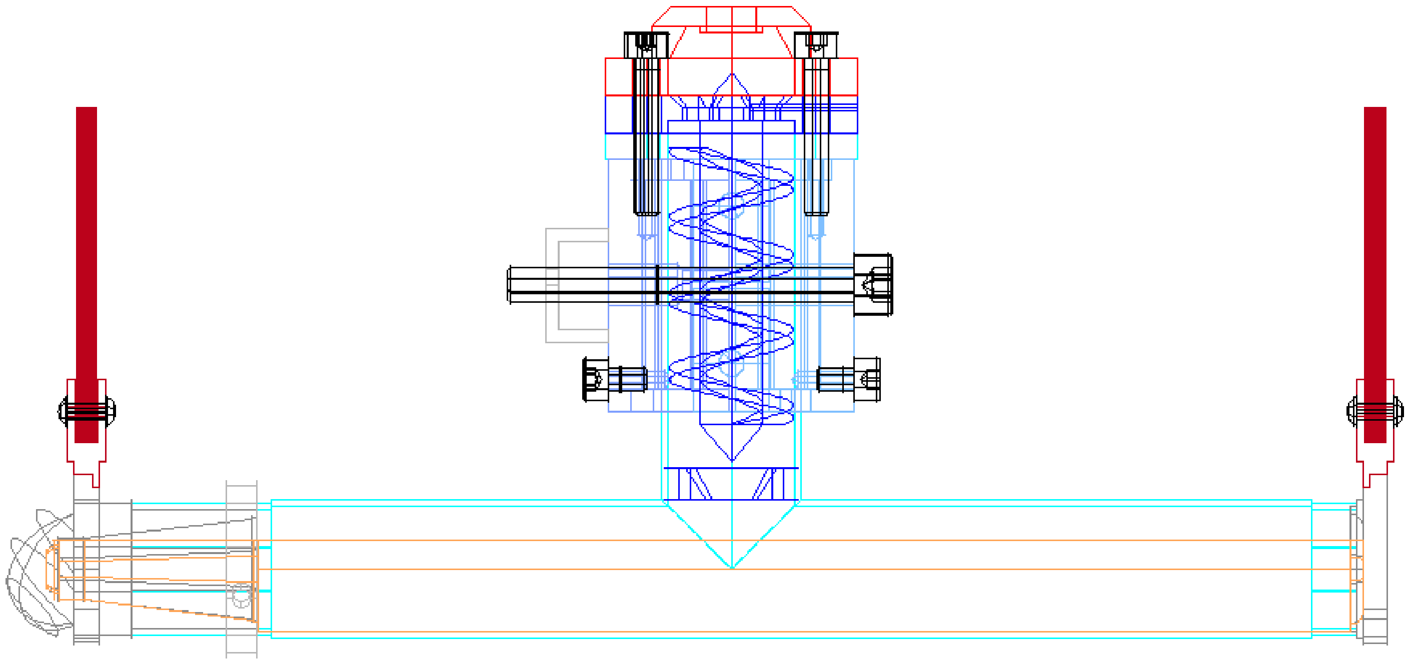


Average gap ~0.03 mm



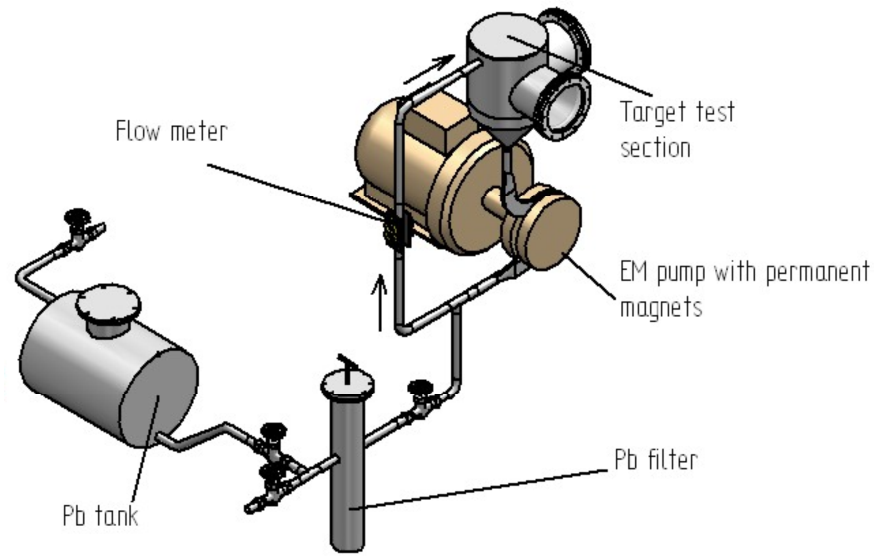
# March tests at TRIUMF: 12 kW

# Direct liquid metal targets



- Today's state of the art [ISOLDE]:
  - Release fraction < 2% for short-lived Hg
  - Diffusion $\tau$ >> 10s
  - Max. power deposition 1 kW !!!

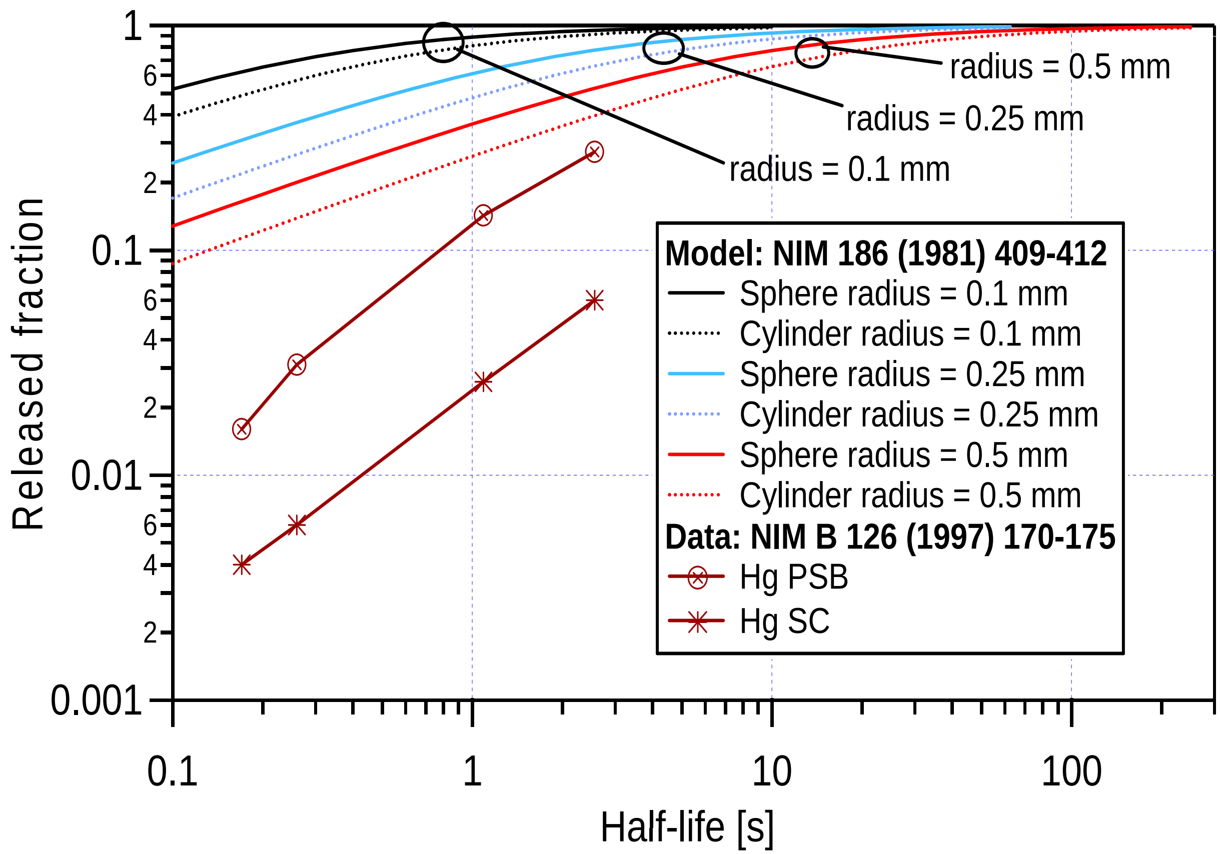
# 100 kW liquid metal: loop for heat removal



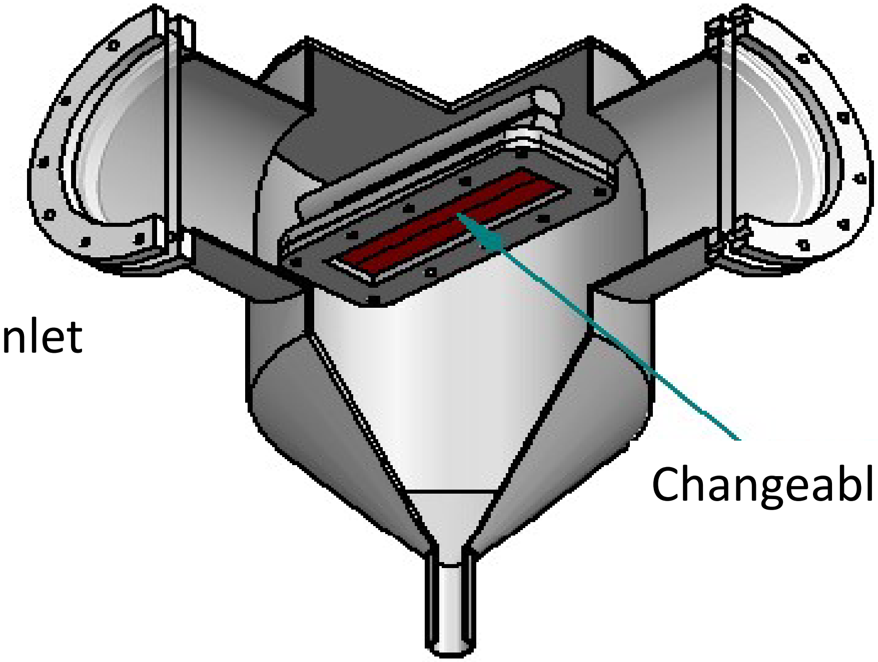

- Loop=Target material: Pb, LBE
  - Operating temperature: 1100 K
  - $\Delta T$: 100 K
  - Flow rate: 0.2 l/s
- Beam: 1 GeV $H^+$
  - 100 $\mu$A, $\sigma_x/\sigma_y$=0.3/0.7 cm
  - 30 kW deposited in target

# Diffusion chamber concept

Minimise decay losses due to diffusion times

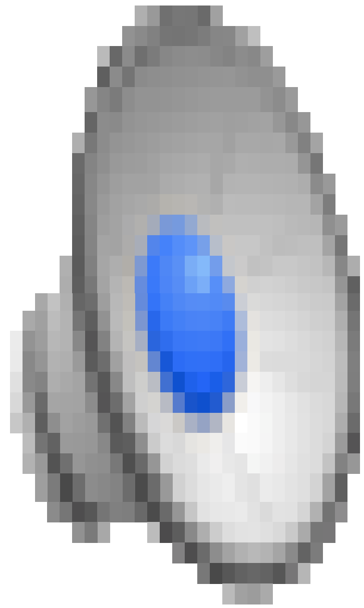


# PbBi loop prototype at IPUL Latvia



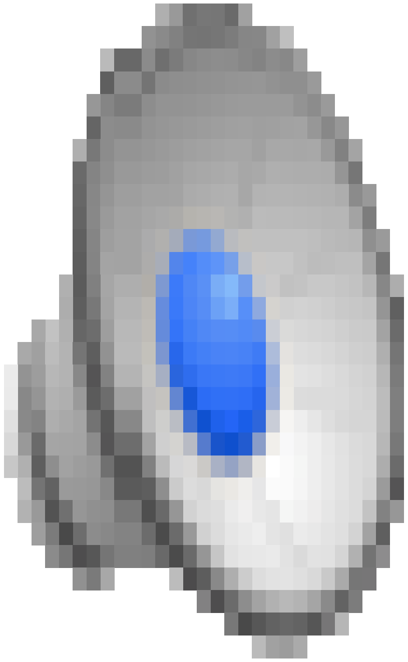
# Diffusion chamber prototype at IPUL

PbBi 600°C



# Diffusion chamber prototype at IPUL

PbBi $600^{o}$C



# Summary

- The EURISOL-DS beta-beam:
  - Conceptual design report presented during 2009
  - High power target R&D for $^{18}$Ne required
  - Full converter-BeO target for $^{6}$He to be tested
- EUROnu DS, FP7 (2008-2012):
  - A beta beam facility using $^{8}$Li and $^{8}$B
  - Production issues (experience from EURISOL-DS)
  - Accelerator issues (duty factors, RF and bunch structures)
  - Costing
- Clear synergies with Radioactive Ion Beam facilities: SPIRAL2, HIE-ISOLDE phase 2 (100 kW), EURISOL

# Back up

# 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 | [illegible] | [illegible] | - | [illegible] |
| 1 day | 3[illegible] | [illegible] | - | [illegible] |
| 1 week | 2 | 2 | - | 1.4 |

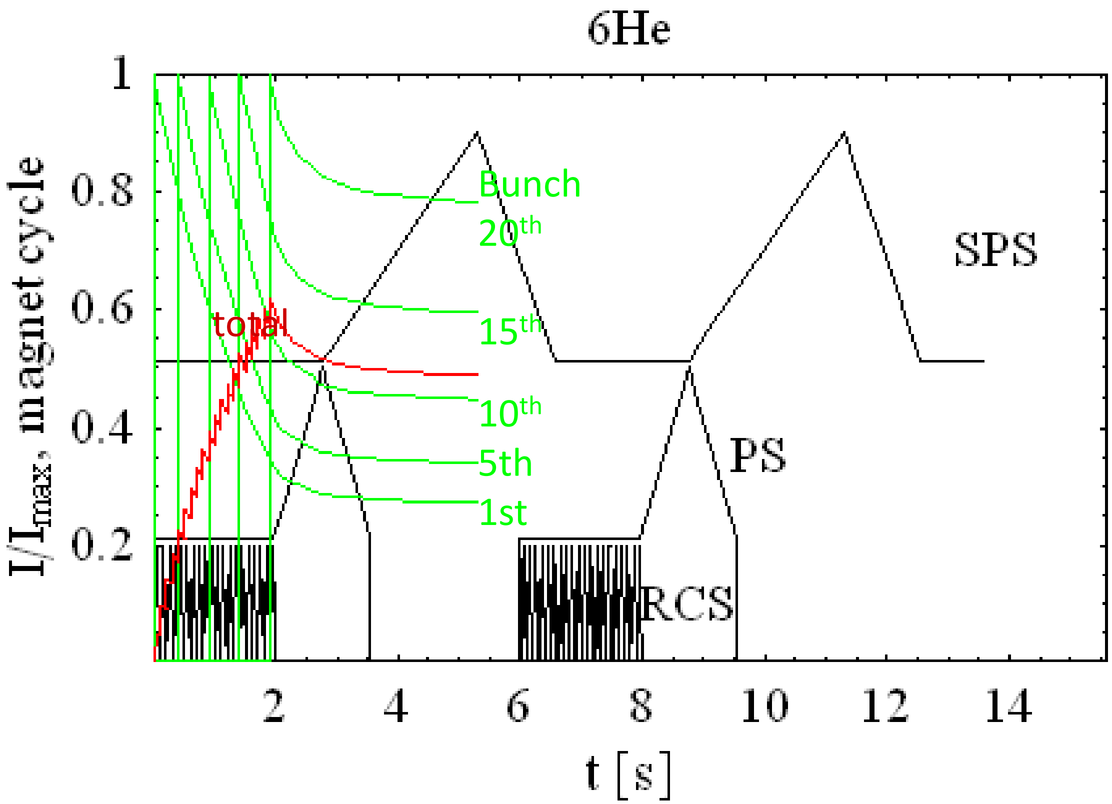
**Not a show stopper**

| 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

Yacin Kadi et al. , CERN

# Intensity evolution during acceleration



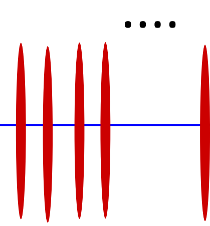

Cycle optimized for neutrino rate towards the detector

30% of first $^{6}He$ bunch injected are reaching decay ring
Overall only 50% ($^{6}He$) and 80% ($^{18}Ne$) reach decay ring

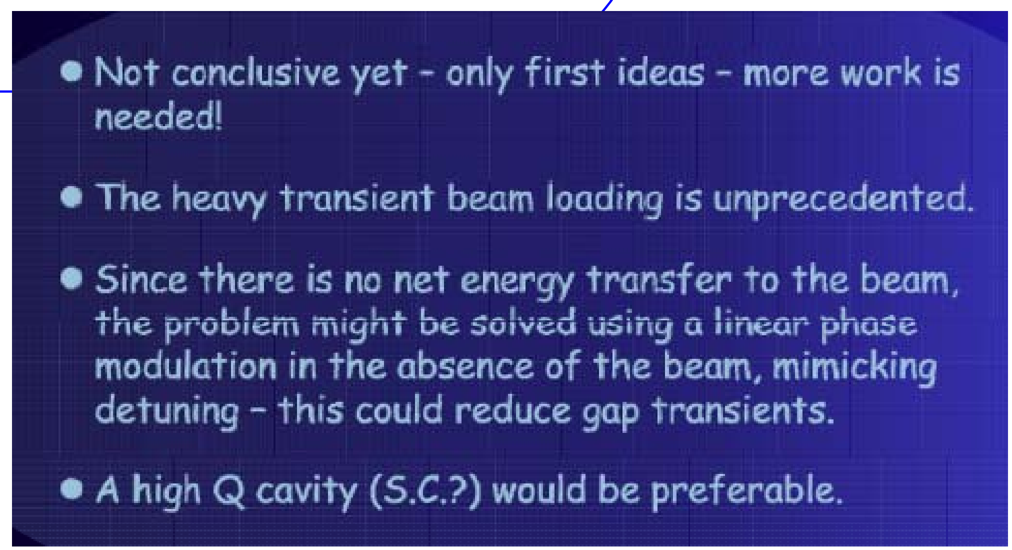
Normalization
Single bunch intensity to maximum/bunch
Total intensity to total number accumulated in RCS

# Duty factor and Cavities for He/Ne

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

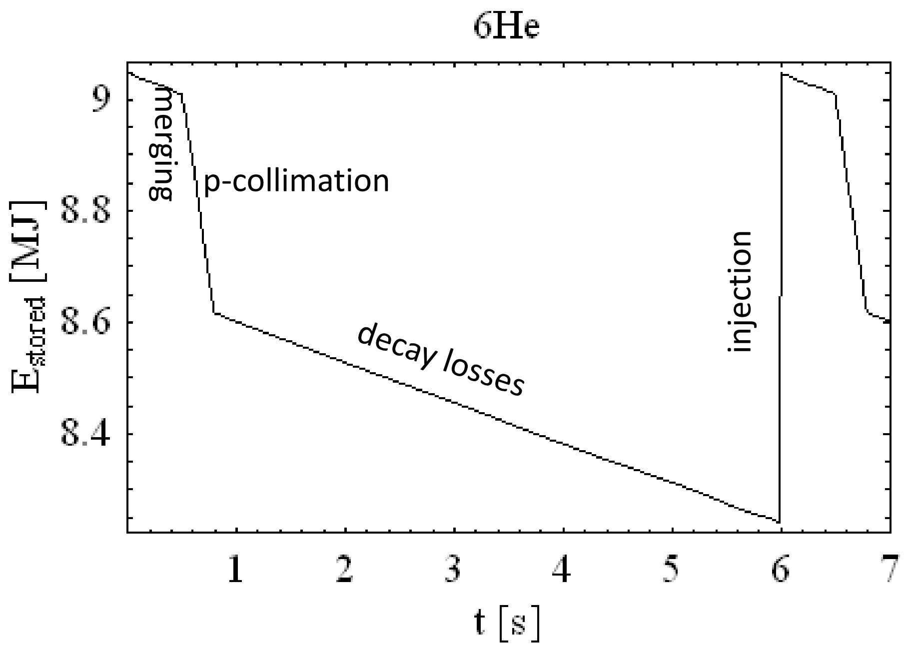


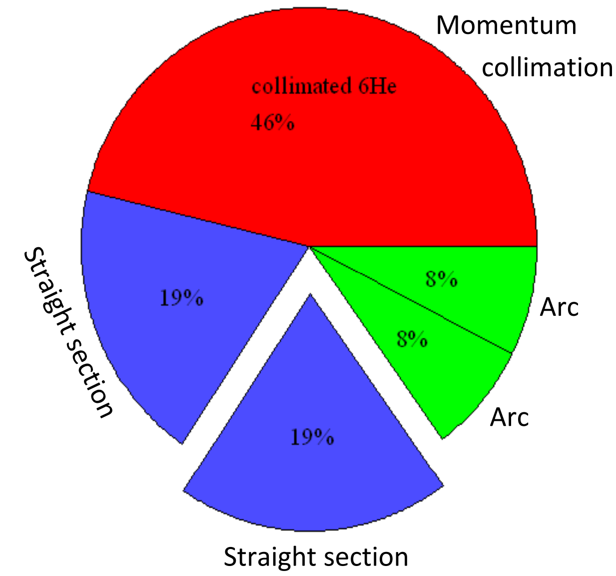

**20 bunches, 5.2 ns long, distance 23*4 nanosseconds filling 1/11 of the Decay Ring, repeated every 23 microseconds**


- 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.

Erk Jensen, CERN

# 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
- Dump at the end of the straight section will receive 30kW
- Dipoles in collimation section receive between 1 and 10 kW (masks).

# EURONU-DS Objectives

- A High Intensity Neutrino Oscillation Facility in Europe
  - CDR for the three main options: Neutrino Factory, Beta-beam and Super-beam
  - Focus on potential showstoppers
  - Preliminary costing to permit a fair comparison before the end of 2011 taking into account the latest results from running oscillation experiments
  - Total target for requested EU contribution: 4 Meuro
    - 1 MEuro each for SB, NF and BB WPs
    - 1 MEuro to be shared between Mgt, Phys and Detectors WPs
    - 4 year project which started 1st September 2008
- First EURONU Town meeting at CERN, 25-26 March 2009

# Alternative ions

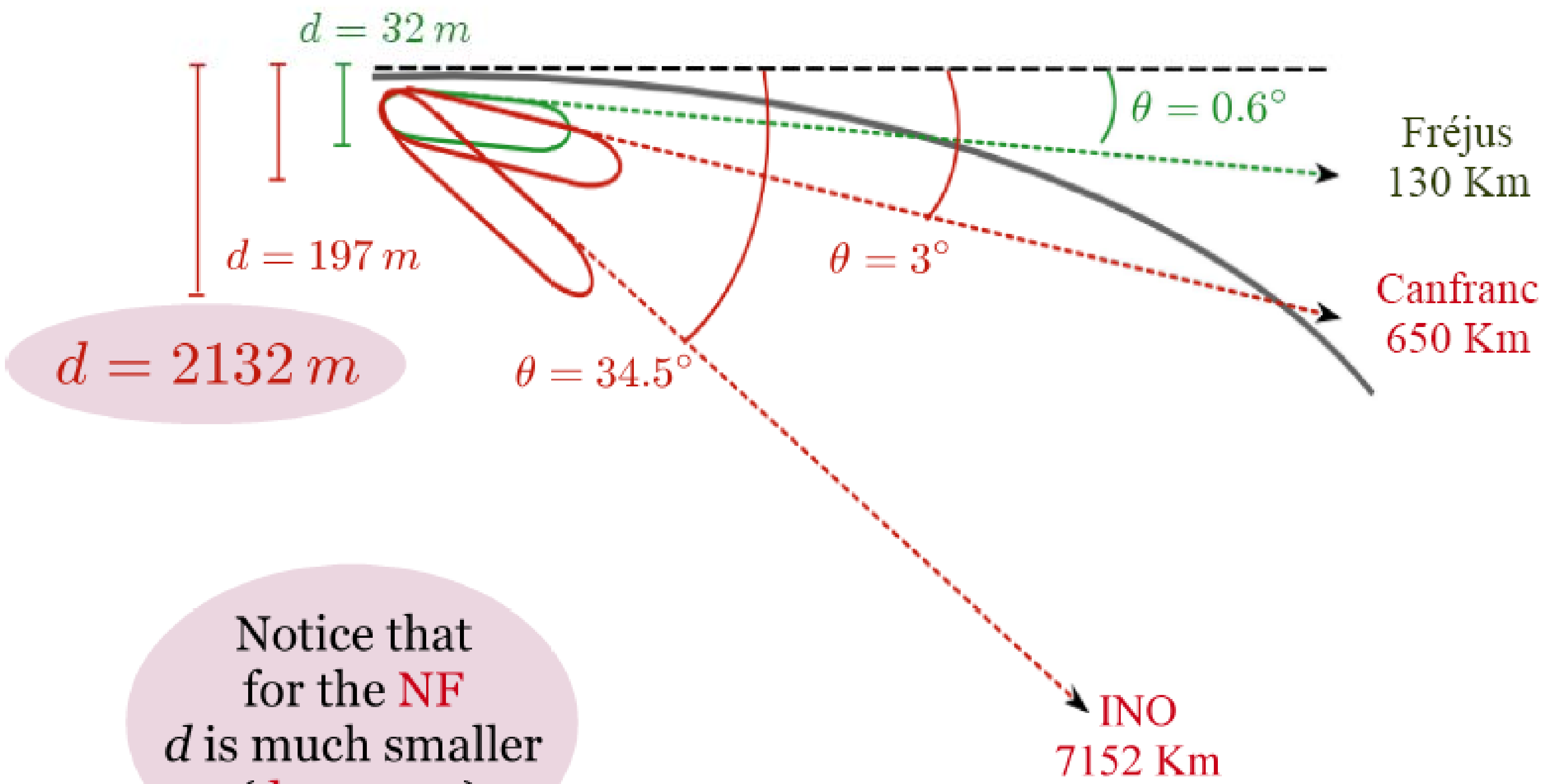
Table 2.1 Some possible isotopes which are $\beta^-$ emitters, from [84]

| Isotope | A/Z | $T_{1/2}$ (s) | $Q_\beta$ g.s. to g.s. (MeV) | $Q_\beta$ effective (MeV) | $E_\beta$ average (MeV) | $E\nu$ average (MeV) |
|---|---|---|---|---|---|---|
| $^6$He | 3.0 | 0.80 | 3.5 | 3.5 | 1.57 | 1.94 |
| $^8$He | 4.0 | 0.11 | 10.7 | 9.1 | 4.35 | 4.80 |
| $^8$Li | 2.7 | 0.83 | 16.0 | 13.0 | 6.24 | 6.72 |
| $^9$Li | 3.0 | 0.17 | 13.6 | 11.9 | 5.73 | 6.20 |
| $^{11}$Be | 2.8 | 13.8 | 11.5 | 9.8 | 4.65 | 5.11 |
| $^{15}$C | 2.5 | 2.44 | 9.8 | 6.4 | 2.87 | 3.55 |
| $^{16}$C | 2.7 | 0.74 | 8.0 | 4.5 | 2.05 | 2.46 |
| $^{16}$N | 2.3 | 7.13 | 10.4 | 5.9 | 4.59 | 1.33 |
| $^{17}$N | 2.4 | 4.17 | 8.7 | 3.8 | 1.71 | 2.10 |
| $^{18}$N | 2.6 | 0.64 | 13.9 | 8.0 | 5.33 | 2.67 |
| $^{23}$Ne | 2.3 | 37.2 | 4.4 | 4.2 | 1.90 | 2.31 |
| $^{25}$Ne | 2.5 | 0.60 | 7.3 | 6.9 | 3.18 | 3.73 |
| $^{25}$Na | 2.3 | 59.1 | 3.8 | 3.4 | 1.51 | 1.90 |
| $^{26}$Na | 2.4 | 1.07 | 9.3 | 7.2 | 3.34 | 3.81 |

Table 2.2 Some possible isotopes which are $\beta^+$ emitters, from [84]

| Isotope | A/Z | $T_{1/2}$ (s) | $Q_\beta$ g.s. to g.s. (MeV) | $Q_\beta$ effective (MeV) | $E_\beta$ average (MeV) | $E\nu$ average (MeV) |
|---|---|---|---|---|---|---|
| $^8$B | 1.6 | 0.77 | 17.0 | 13.9 | 6.55 | 7.37 |
| $^{10}$C | 1.7 | 19.3 | 2.6 | 1.9 | 0.81 | 1.08 |
| $^{14}$O | 1.8 | 70.6 | 4.1 | 1.8 | 0.78 | 1.05 |
| $^{15}$O | 1.9 | 122. | 1.7 | 1.7 | 0.74 | 1.00 |
| $^{18}$Ne | 1.8 | 1.67 | 3.3 | 3.0 | 1.50 | 1.52 |
| $^{19}$Ne | 1.9 | 17.3 | 2.2 | 2.2 | 0.96 | 1.25 |
| $^{21}$Na | 1.9 | 22.4 | 2.5 | 2.5 | 1.10 | 1.41 |
| $^{33}$Ar | 1.8 | 0.17 | 10.6 | 8.2 | 3.97 | 4.19 |
| $^{24}$Ar | 1.9 | 0.84 | 5.0 | 5.0 | 2.29 | 2.67 |
| $^{35}$Ar | 1.9 | 1.77 | 4.9 | 4.9 | 2.27 | 2.65 |
| $^{37}$K | 1.9 | 1.22 | 5.1 | 5.1 | 2.35 | 2.72 |
| $^{80}$Rb | 2.2 | 34 | 4.7 | 4.5 | 2.04 | 2.48 |

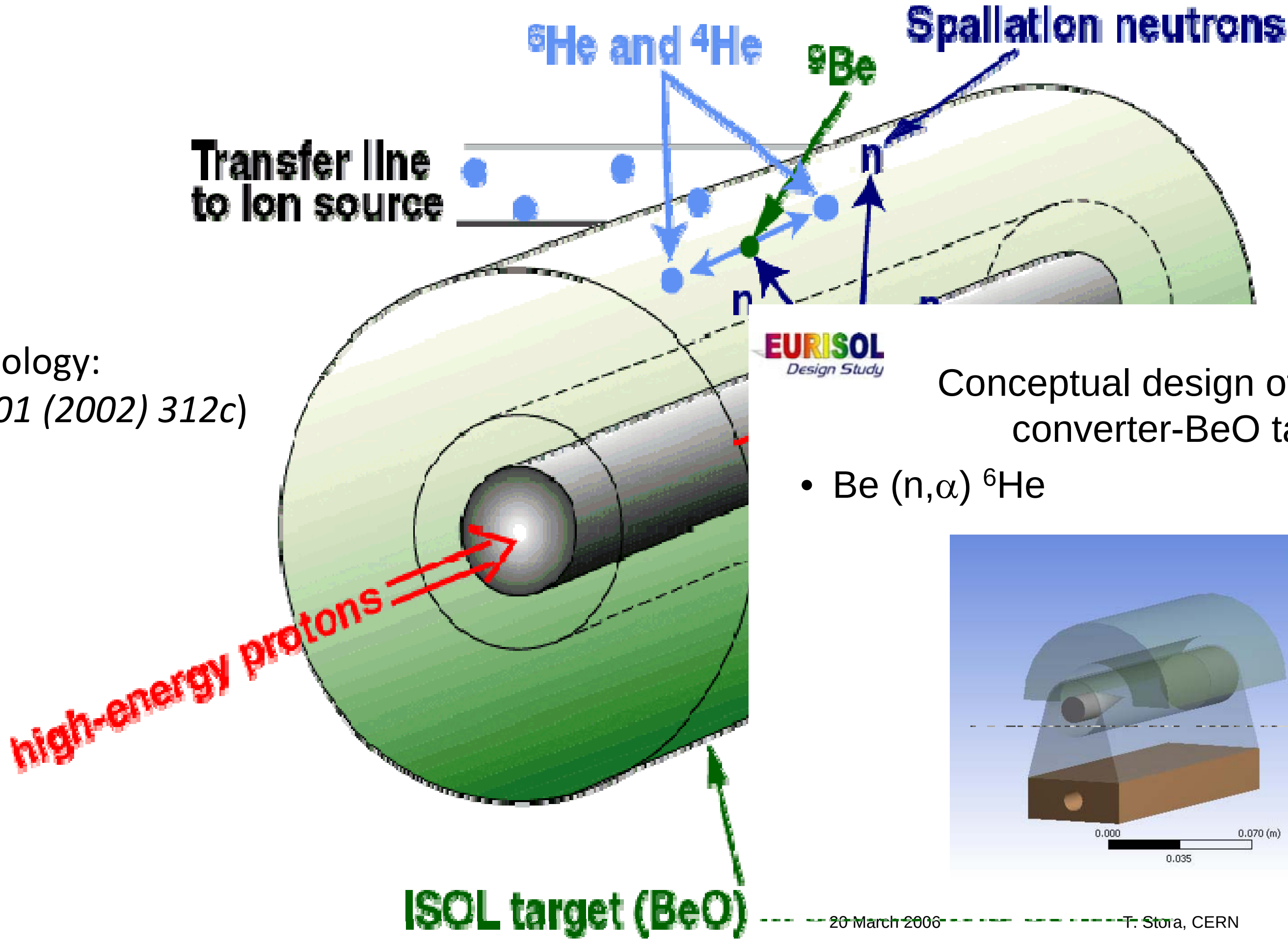
# Baseline options: Detectors




Notice that
for the NF
*d* is much smaller
(d= 423 m)

Pilar Coloma
Optimization of the Two-Baseline β-Beam

# $^{6}$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

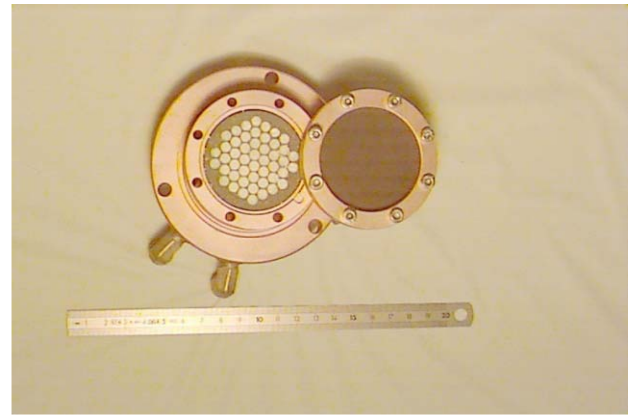


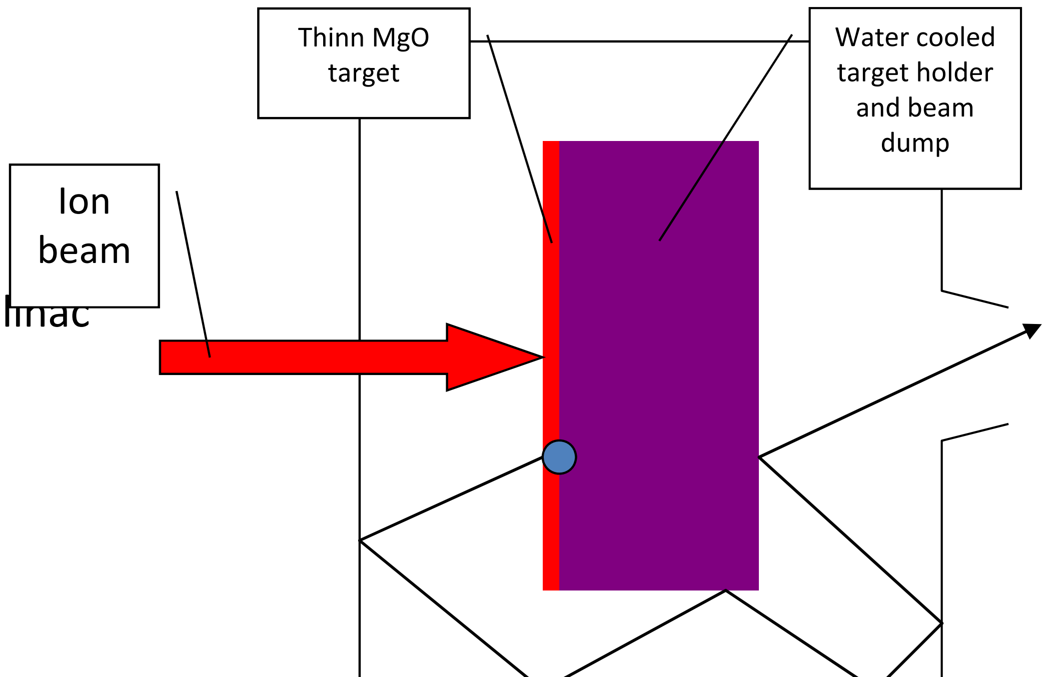
20 March 2006 T. Stora, CERN EURISOL – Task #3

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

# Direct production: $^{16}O(^{3}He,n)^{18}Ne$ at LLN

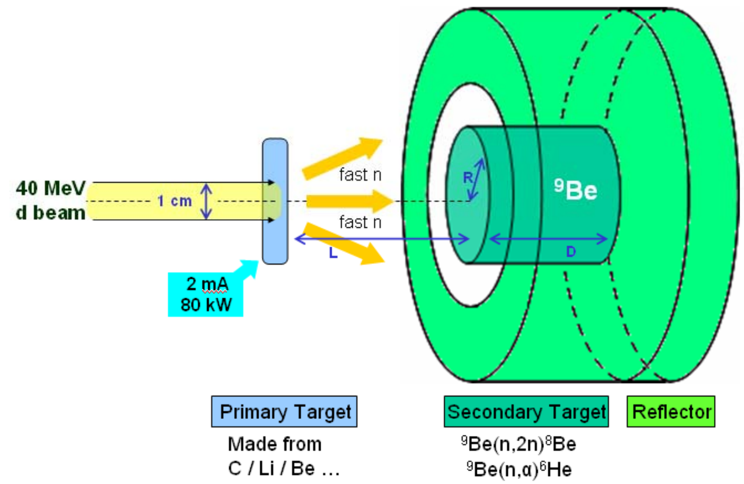
- Production of $10^{12}$ $^{18}Ne$ in a MgO target:
  - At 13 MeV, 17 mA of $^{3}He$
  - At 14.8 MeV, 13 mA of $^{3}He$
- Producing $10^{13}$ $^{18}Ne$ could be possible with a beam power (at low energy) of 1 MW (or some 130 mA $^{3}He$ beam).
- To keep the power density similar to LLN (today) the target 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

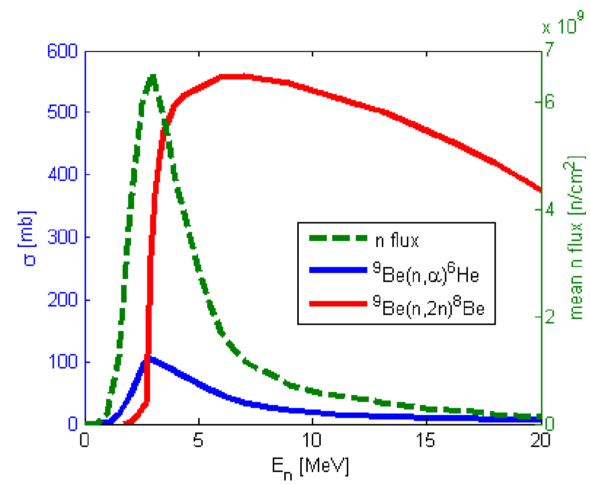




# Light RIB production: 40 MeV Deuteron beam

- **T.Y.Hirsh, D.Berkovits, M.Hass (Soreq, Weizmann I.)**
- **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 ~$6 \cdot 10^{13}$ atoms per second.**

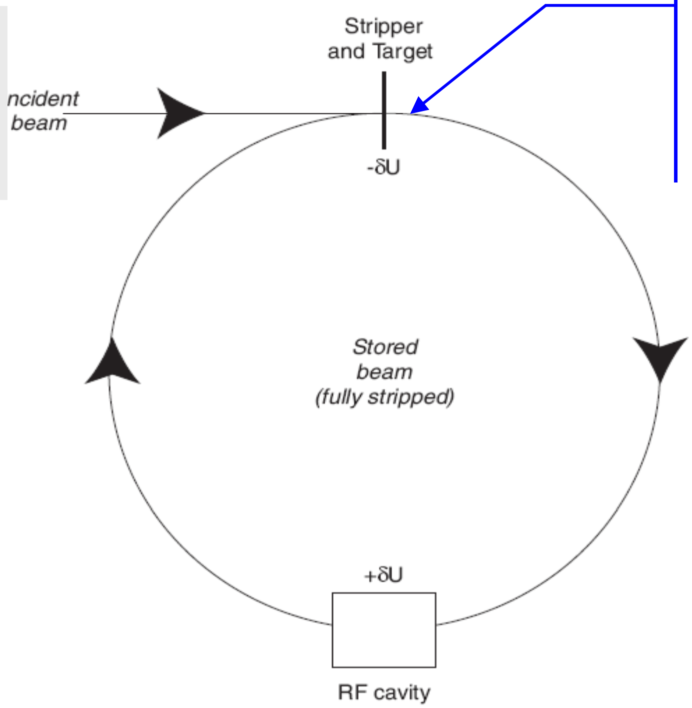


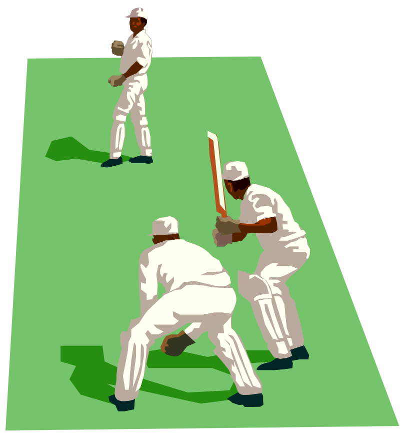
# A new approach for the production

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

$^{7}Li$
$^{6}Li$



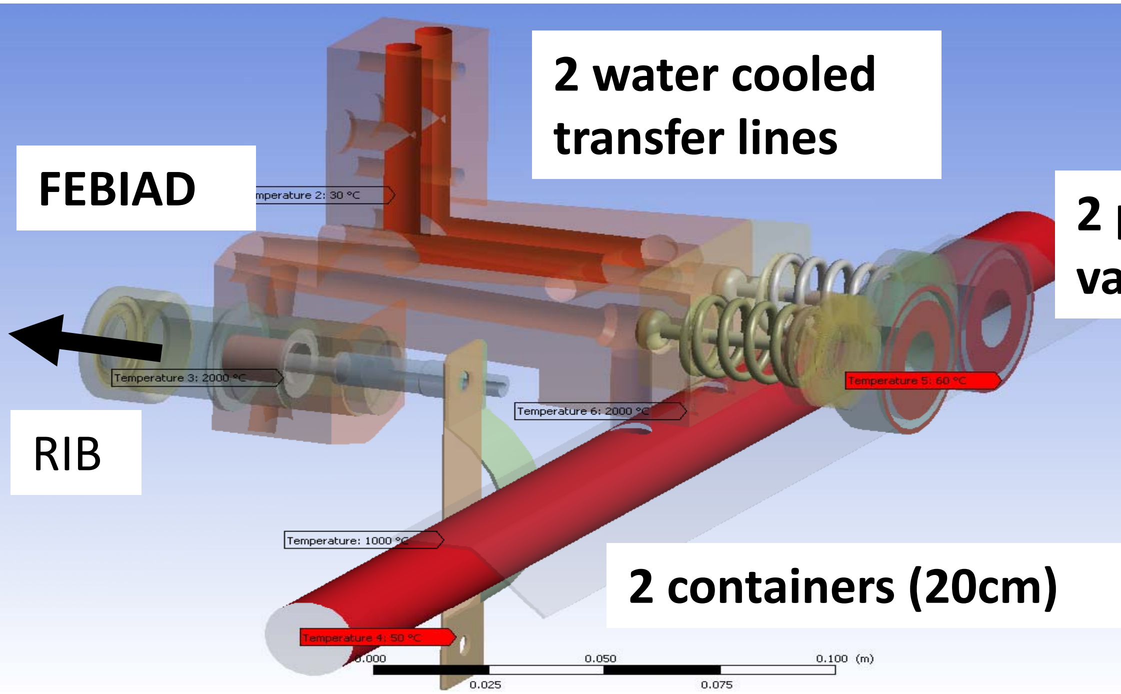

$^{7}Li(d,p)^{8}Li$
$^{6}Li(^{3}He,n)^{8}B$

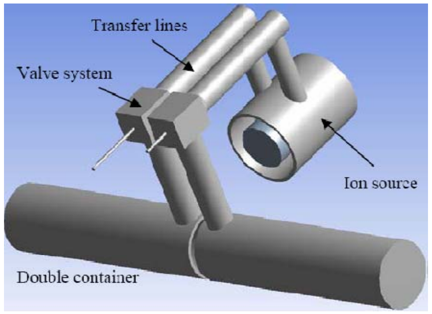


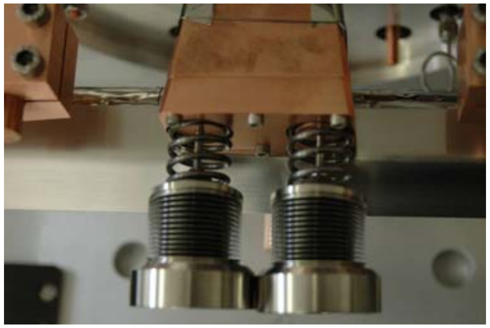
See also: Development of FFAG accelerators and their applications for intense secondary particle production, Y. Mori, NIM A562(2006)591

# Bivalve

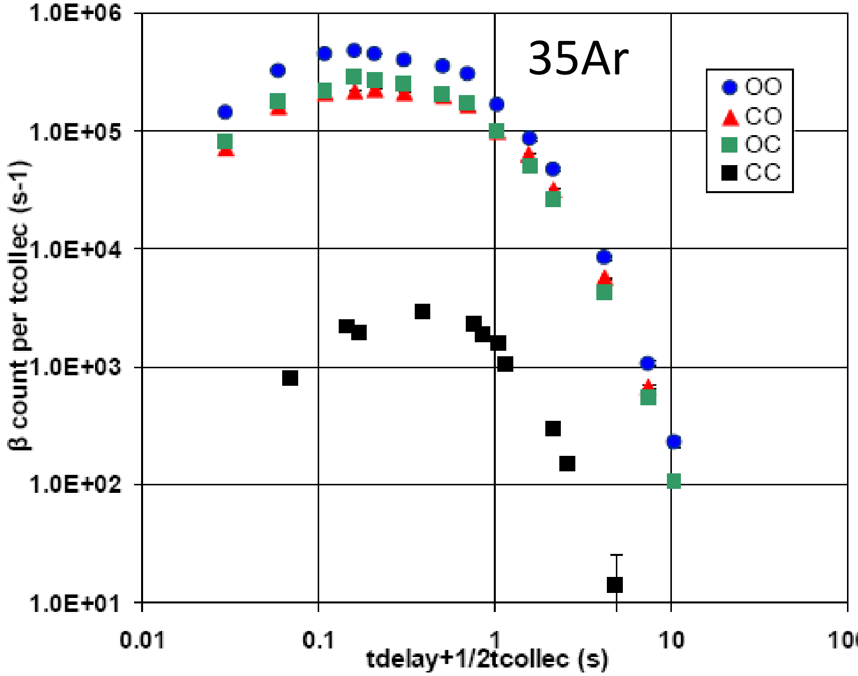
- <u>Bivalve:</u> merging of a double-transfer line system into a single FEBIAD ion source: Elian Bouquerel.



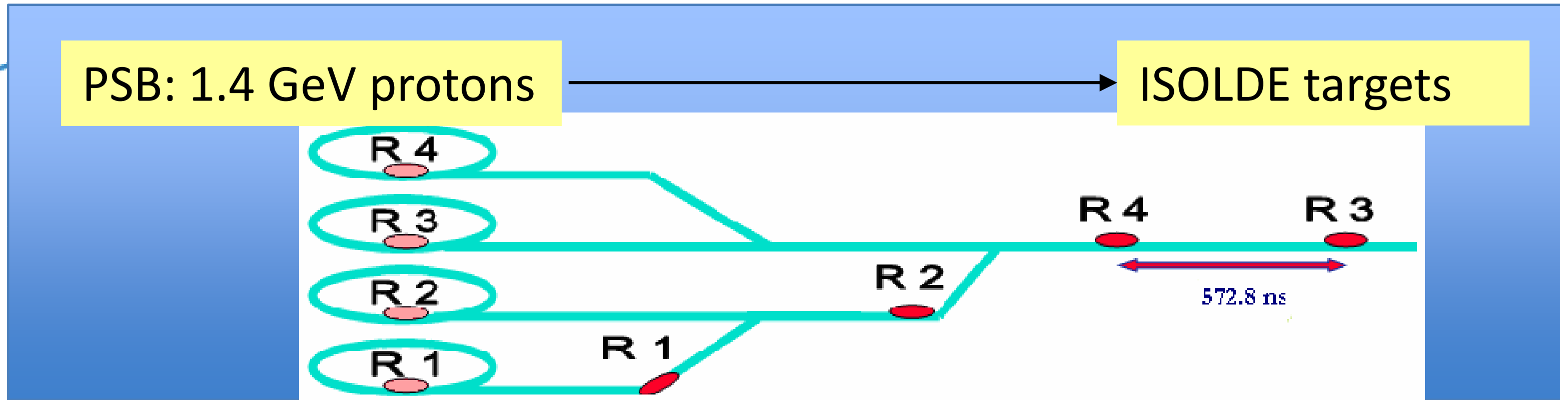



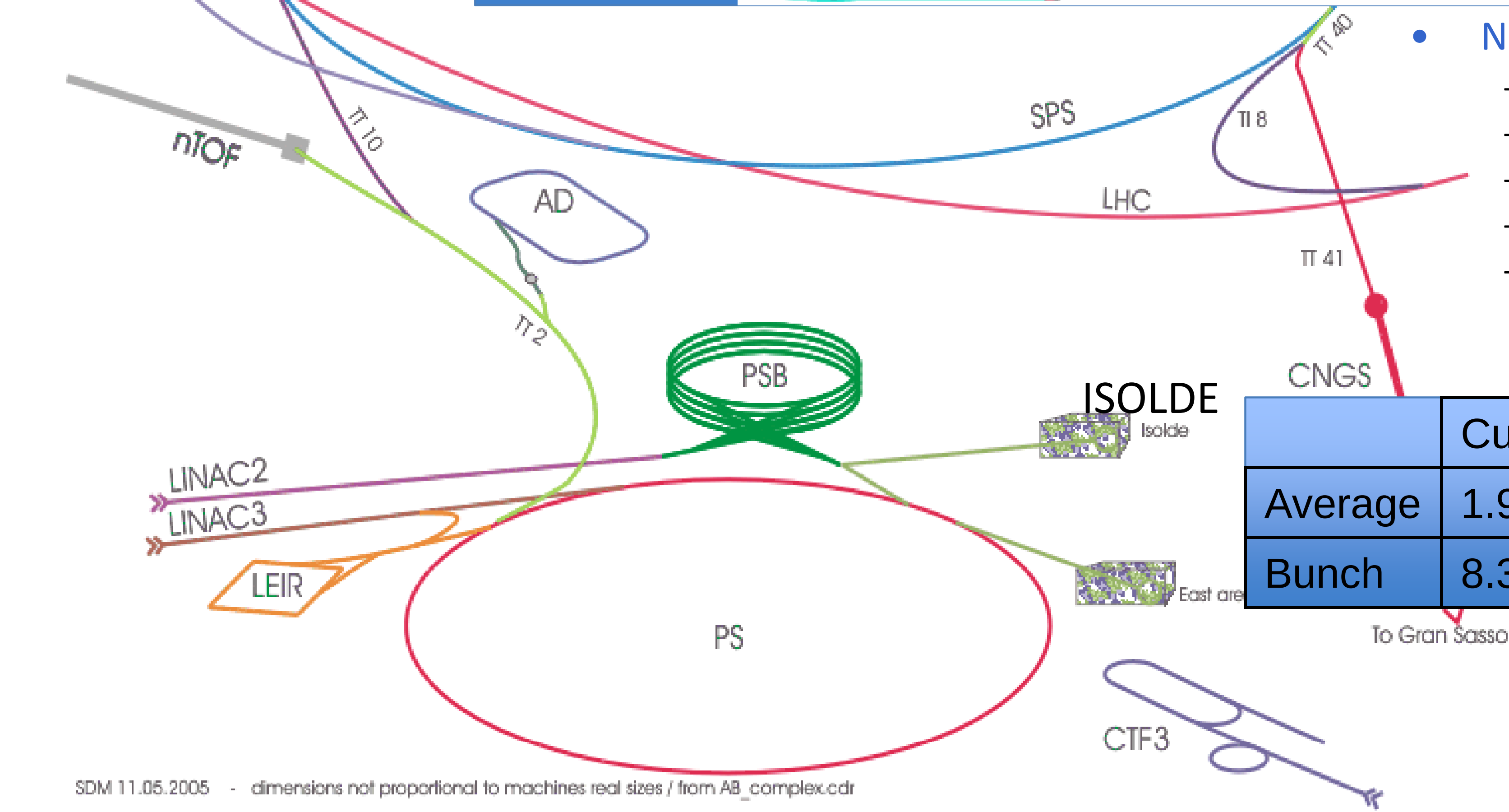



Online Tests: ISOLDE, April 2007



# Proton beam to ISOLDE




- Normal PSB beam
  - 4 bunches.
  - 230 ns bunch width.
  - 573 ns bunch spacing.
  - 1.2 s repetition rate.
  - Most ISOLDE targets.

| | Current | Power |
|---|---|---|
| Average | 1.92 μA | 2.7 kW |
| Bunch | 8.36 A | 11.7 GW |