The LIEBE Project
-status report -

L. Popescu for the LIEBE collaboration

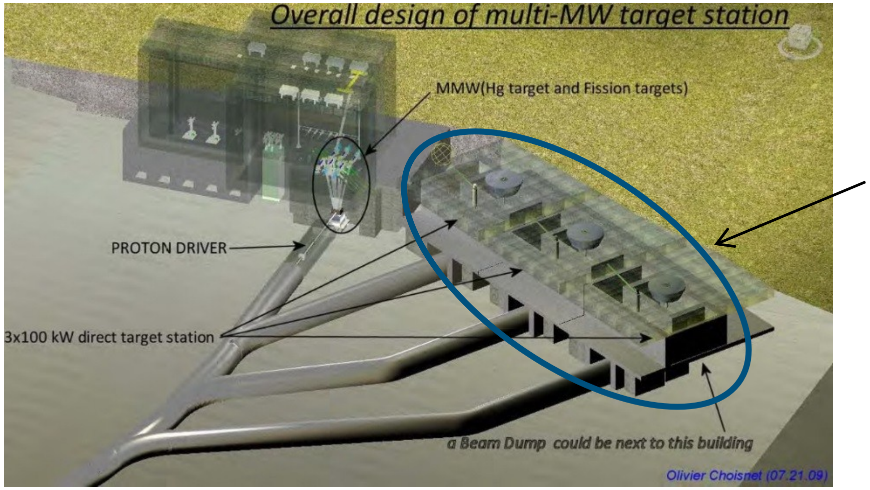
STUDIECENTRUM VOOR KERNENERGIE
CENTRE D'ETUDE DE L'ENERGIE NUCLEAIRE

Outline

- The LIEBE project
- Target design & Preliminary optimization analysis
- Prototype and tests at CERN-ISOLDE
- Conclusions and Outlook

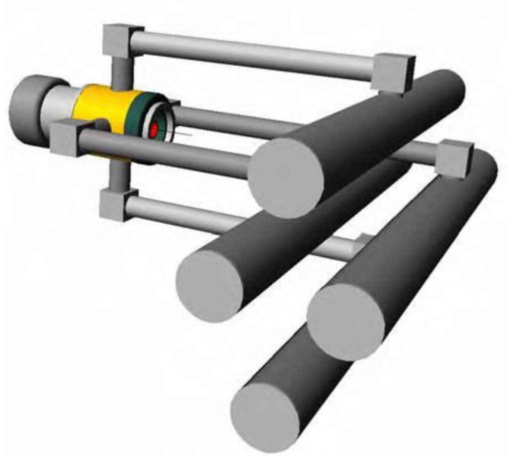
Direct Targets for EURISOL

EURISOL
Design Study

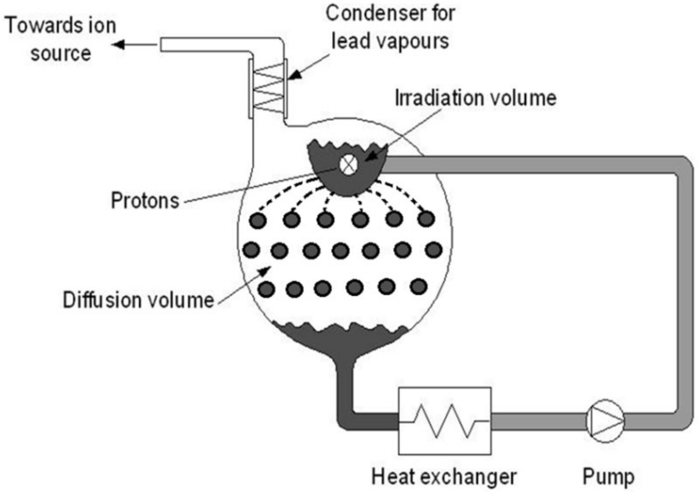


100-kW direct targets

Concept of solid-target units



Concept of molten-metal target

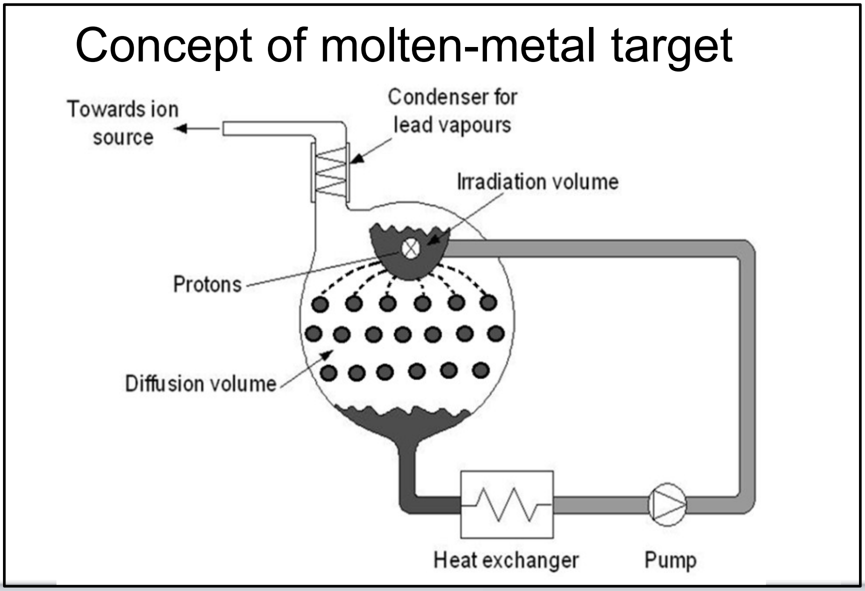


The LIEBE Project

- LIEBE : **Li**quid **E**utectic Lead **B**ismuth Loop Target for **E**urisol

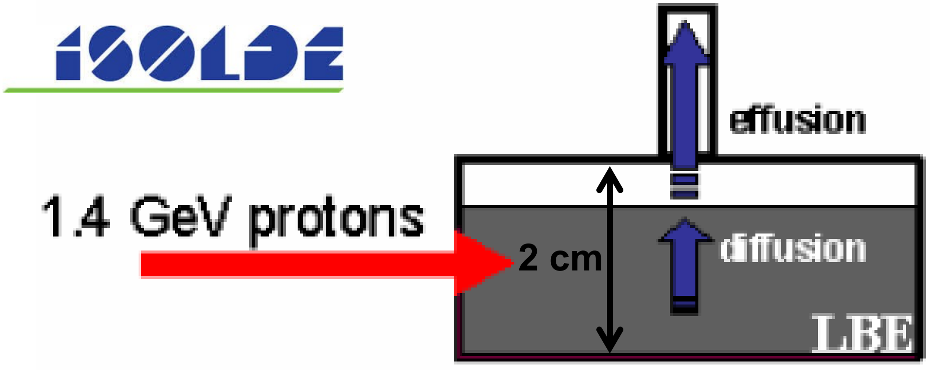
- Aim:
  - Detail the conceptual design of the EURISOL molten-metal direct target
  - Develop a prototype for tests at CERN-ISOLDE
  - Offline + online tests at ISOLDE

- Collaboration between 6 institutes
  - CEA
  - CERN – ISOLDE
  - IPUL
  - PSI
  - SCK•CEN – ISOL@MYRRHA
  - SINP
- Project leader: Thierry Stora (CERN)



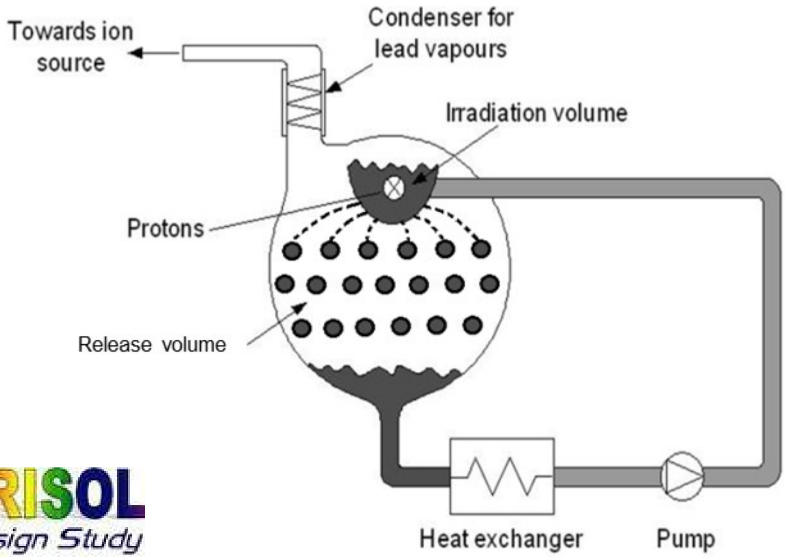
Concept of molten-metal target

Molten-Metal Target



Limitations

- Slow diffusion process → significant decay losses for short-lived isotopes (~ ms)
- Difficult heat management when increasing beam power



Advantages

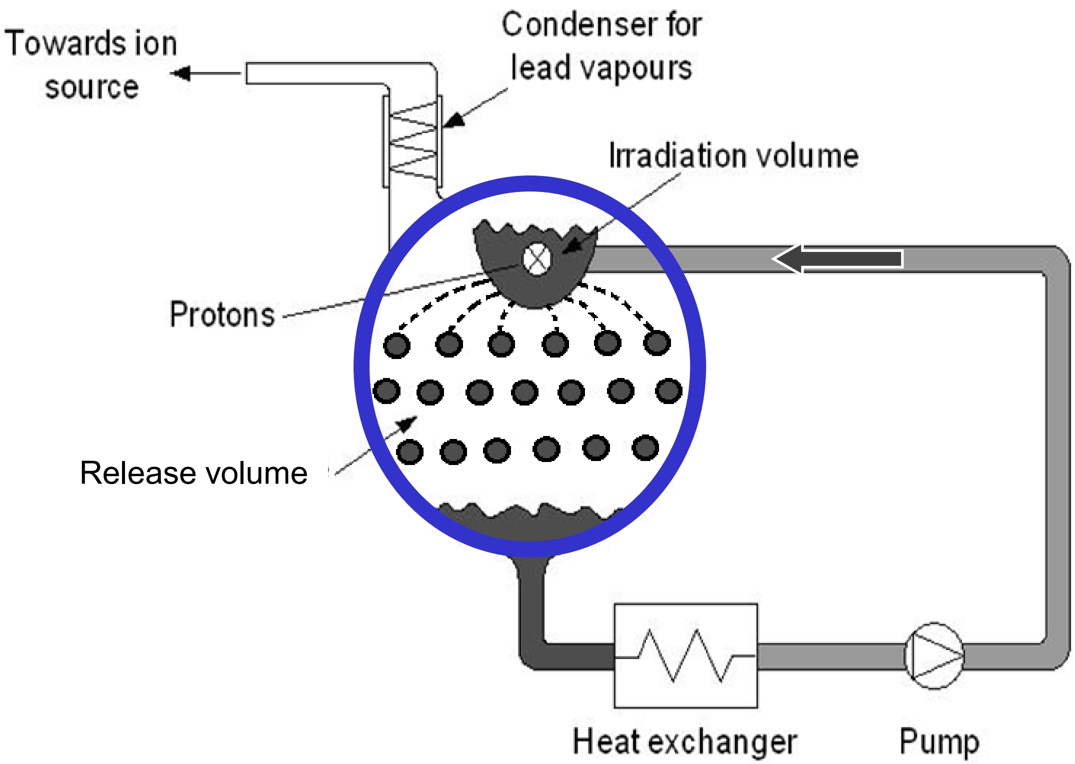
- Improved diffusion efficiency (LBE spread in a shower of small droplets)
- Loop-type design with HEX → good heat management
- Capability to operate at high beam-powers (~ 100 kW)

Target Design & Optimization

Computational Fluid Dynamics Analysis

Calculations by D. Houngbo (SCK•CEN and UGent)

Design Requirements



Fast evacuation of irradiated LBE (t ~ 100 ms) *to* *minimize decay losses of short lived Isotopes*

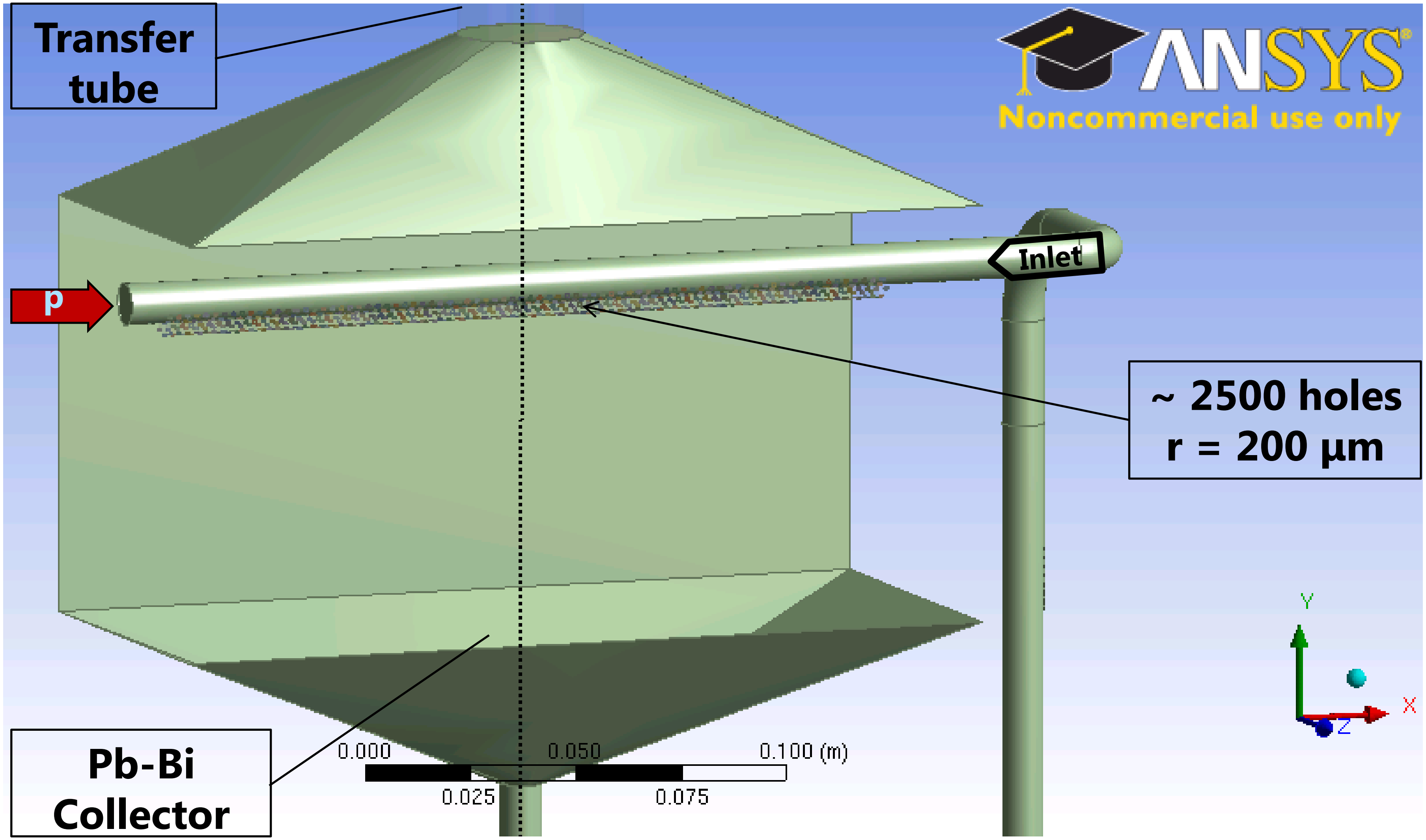
Small droplets (r ~ 100 μm) *to* *reduce diffusion length*

Sufficient fall time *to* *increase overall diffusion efficiency*

RIB intensity $= \phi \sigma N_{target} \varepsilon$

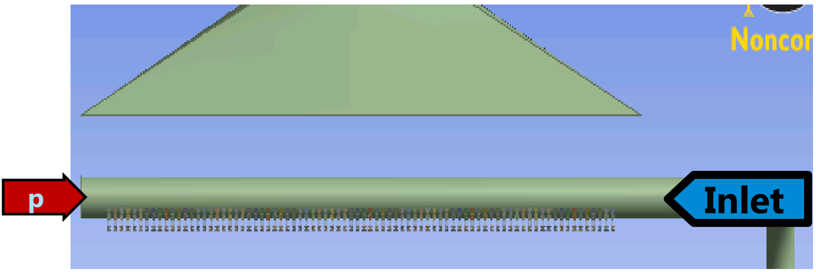
$$\varepsilon = \varepsilon_{diffusion}\, \varepsilon_{effusion} \varepsilon_{ionisation} \cdots$$

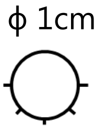
Starting Case



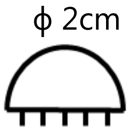
Initial Concepts

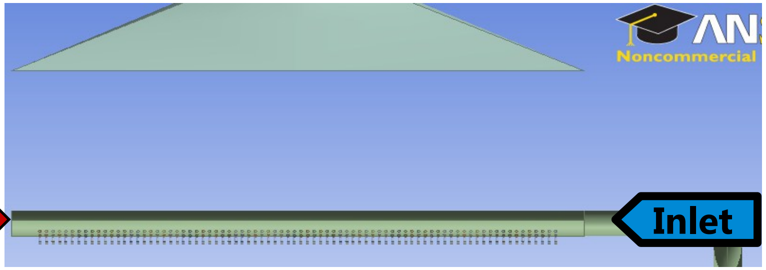
Concept 1

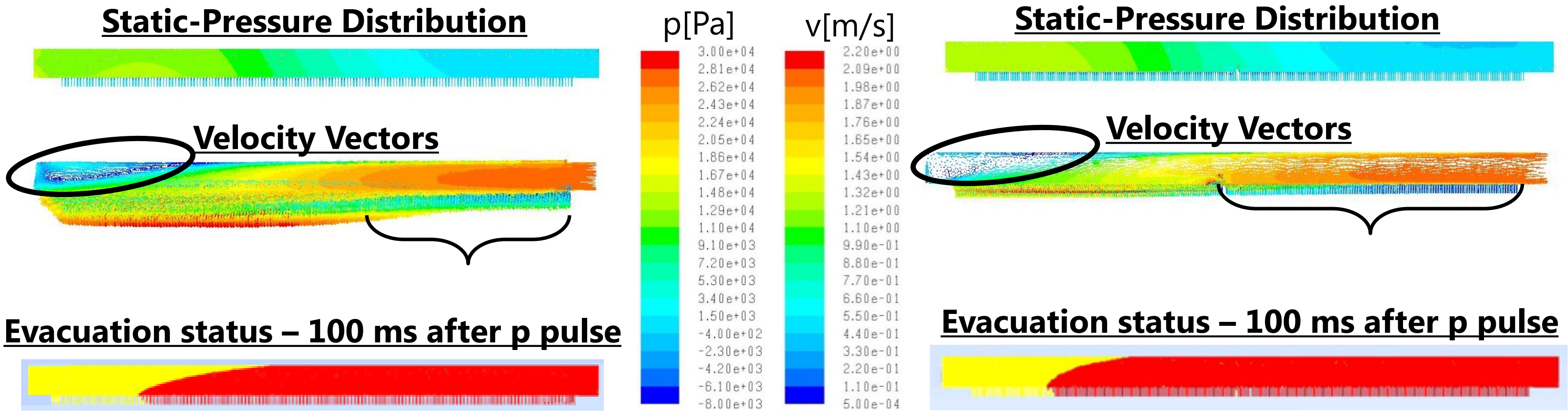




Concept 2



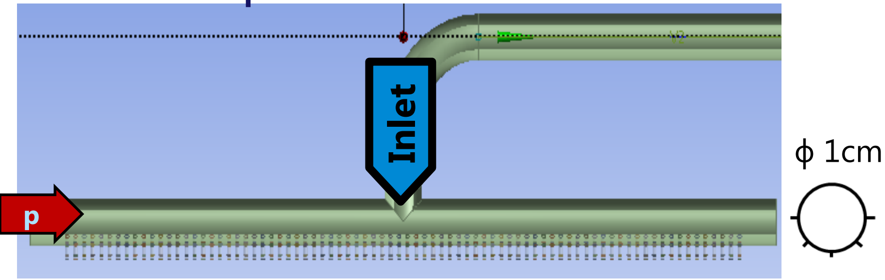




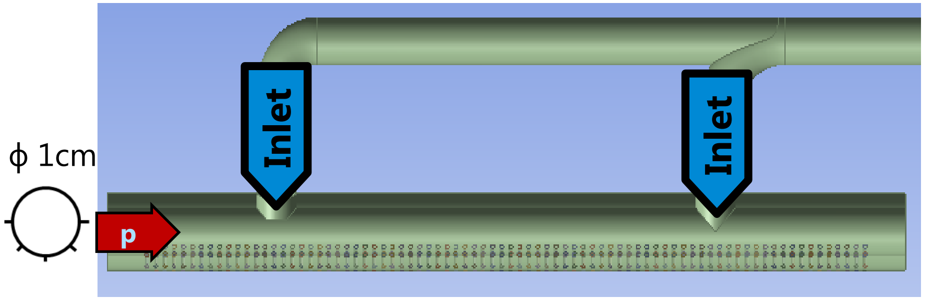
- Bending over small curvature radii → low pressure zones & cavitation risks
- Horizontal axial inlets → non-uniform evacuation velocities & droplet formation
- Recirculation in irradiation cylinder → long evacuation times
  → risks of overheating

Transverse – Inlets Concepts

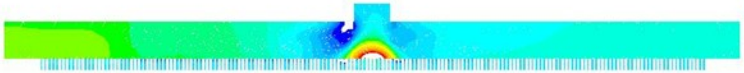
- Concept 3



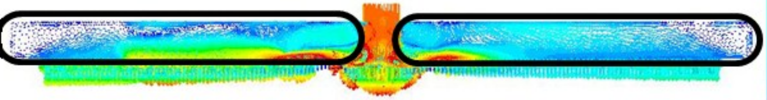
- Concept 4



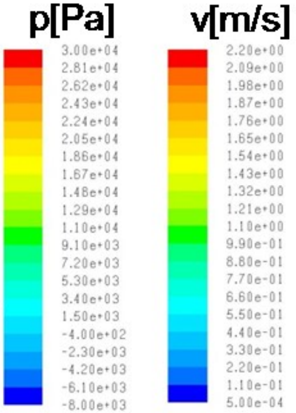
Static-Pressure Distribution



Velocity Vectors

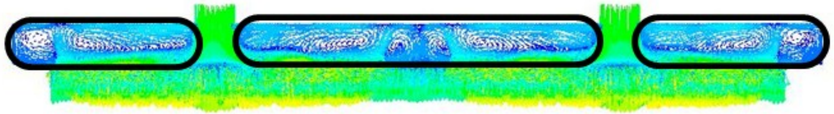


Evacuation status – 100 ms after p pulse



Static-Pressure Distribution

Velocity Vectors



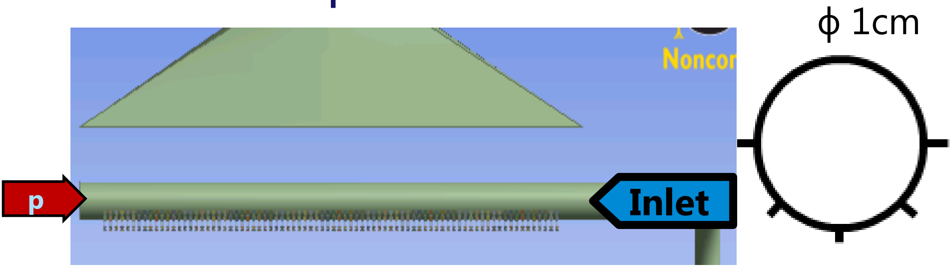
Evacuation status – 100 ms after p pulse

- Multiple transverse inlets → more uniform distribution of evacuation velocities.

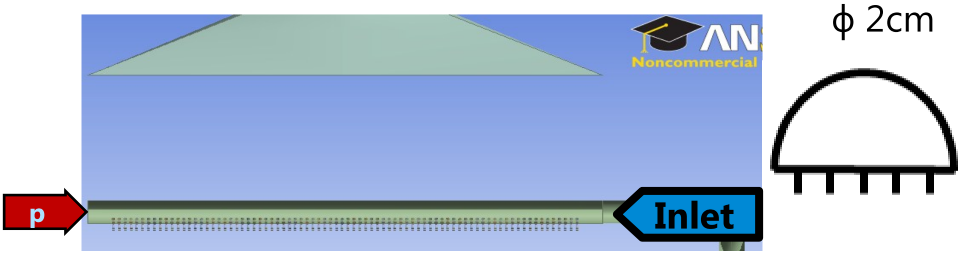
  → large recirculation zones still present.

Optimized Concepts

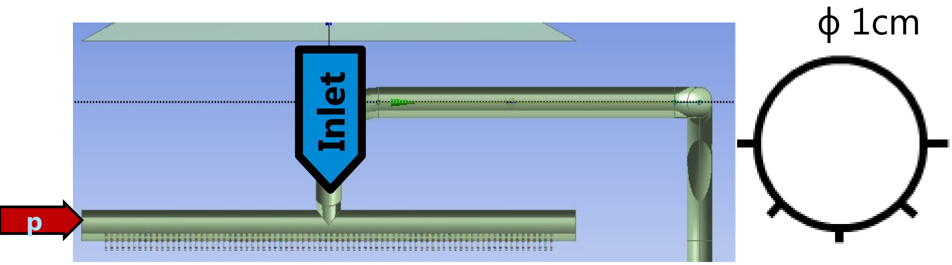
- Concept 1



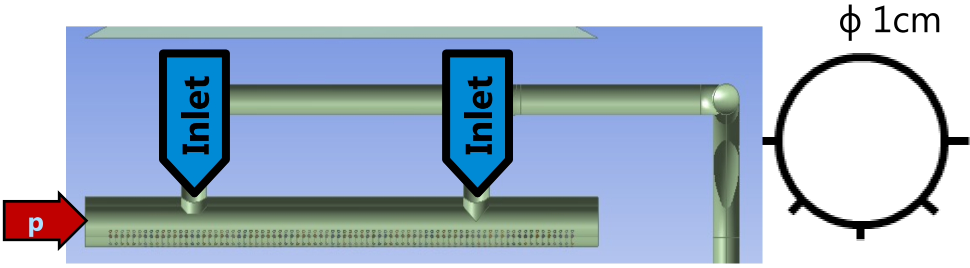
- Concept 2



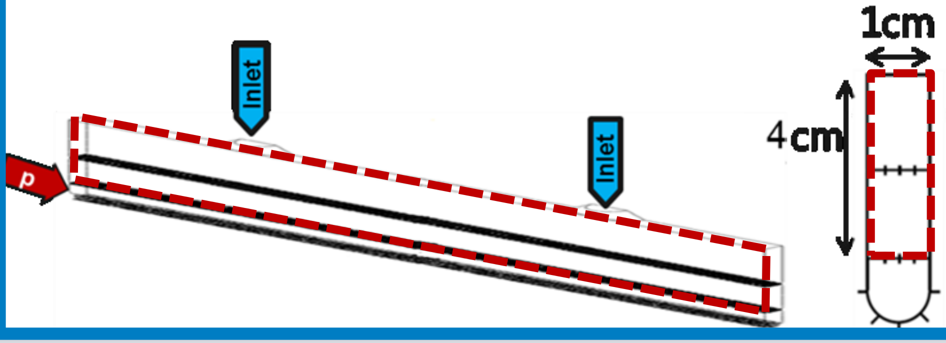
- Concept 3



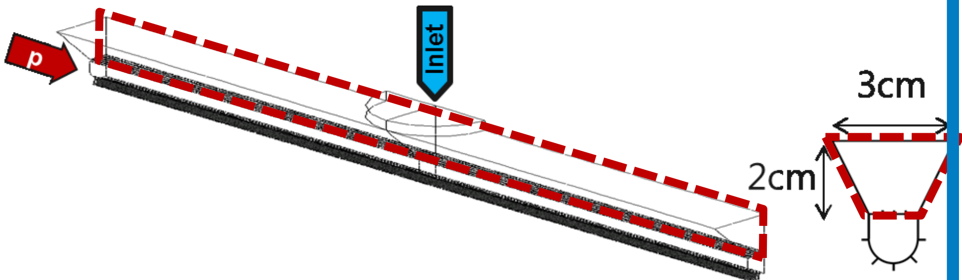
- Concept 4



- Concept 5

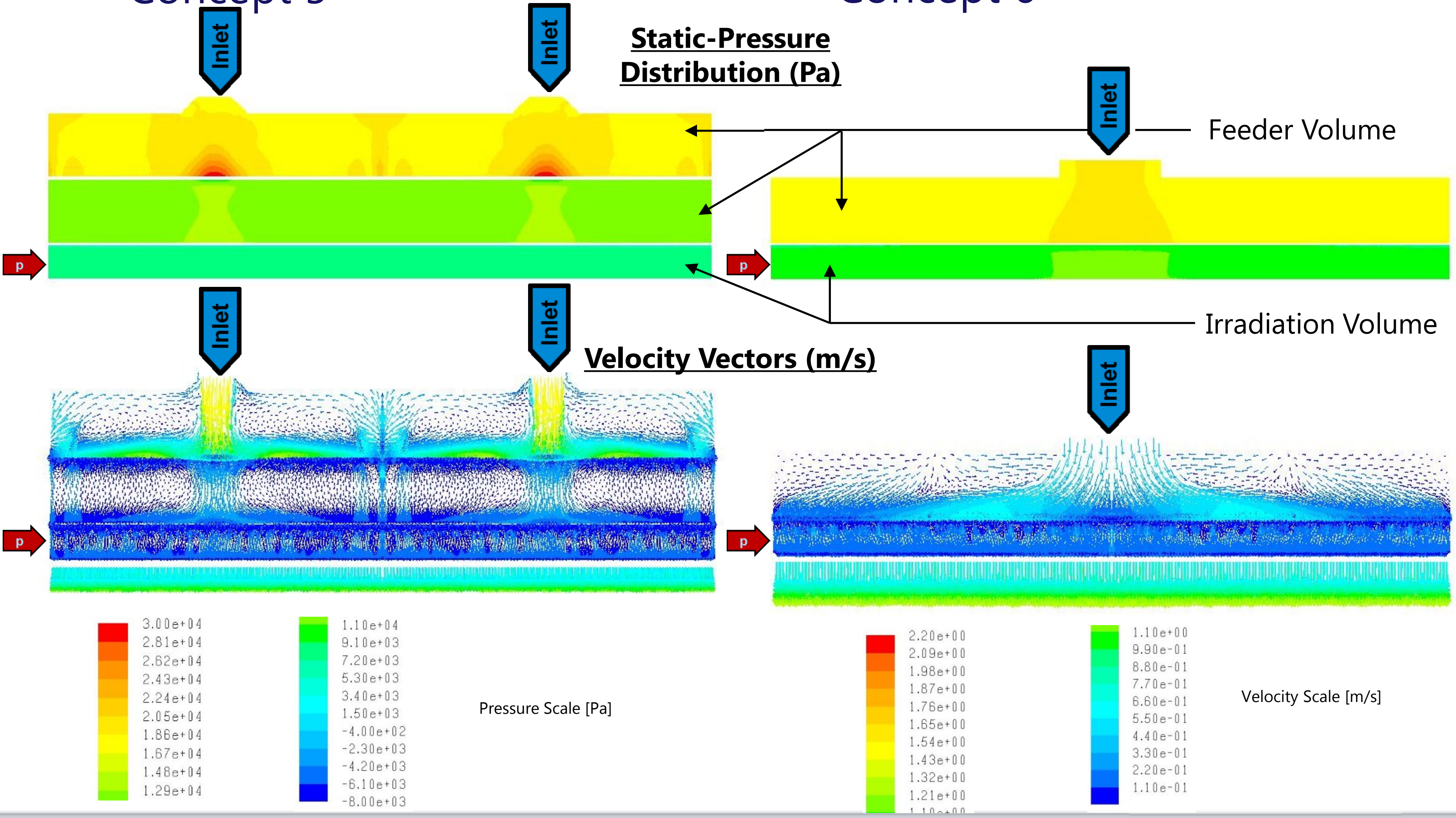


- Concept 6



Optimized Concepts - Results

- Concept 5
- Concept 6



Static-Pressure Distribution (Pa)

Feeder Volume

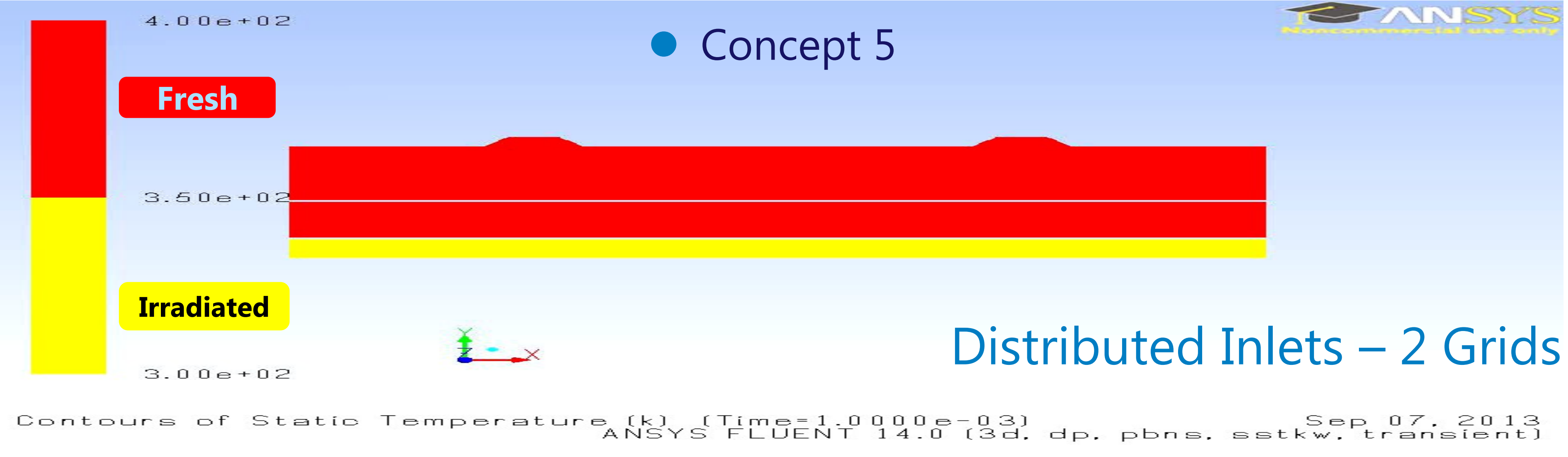
Irradiation Volume

Velocity Vectors (m/s)

Pressure Scale [Pa]

Velocity Scale [m/s]

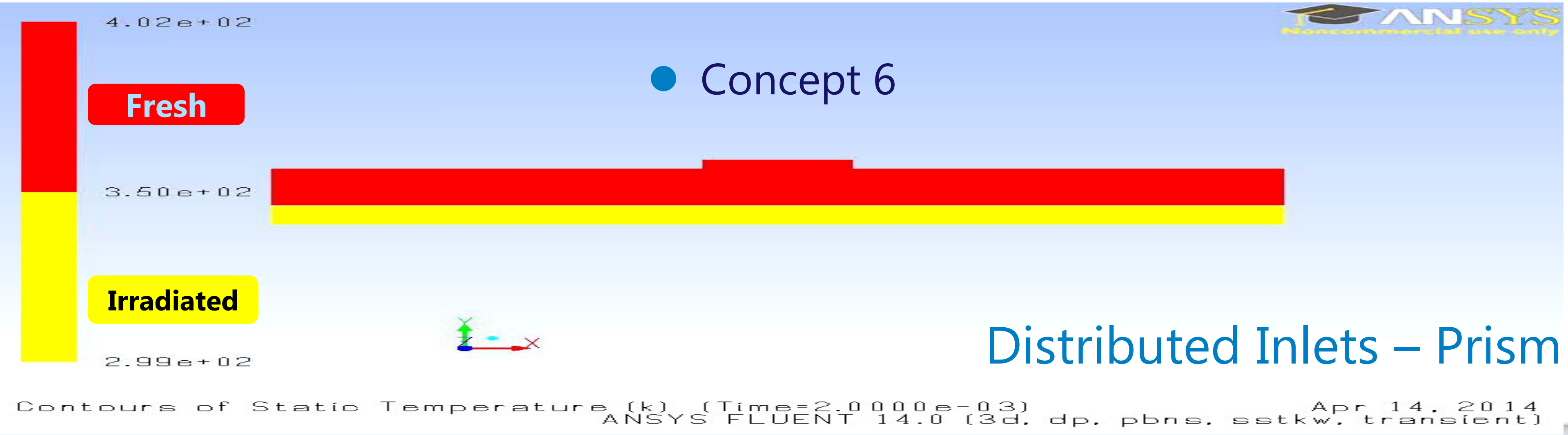
Animations showing the full evacuation of irradiated LBE from the irradiation volume within ≤ 100 ms



- Concept 5

Distributed Inlets – 2 Grids

```
Contours of Static Temperature (k)  (Time=1.0000e-03)                     Sep 07, 2013
                                   ANSYS FLUENT 14.0 (3d, dp, pbns, sstkw, transient)
```



- Concept 6

Distributed Inlets – Prism

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Contours of Static Temperature (k)  (Time=2.0000e-03)                     Apr 14, 2014
                                   ANSYS FLUENT 14.0 (3d, dp, pbns, sstkw, transient)
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2^{nd} Requirement – Small & Spherical Droplets

Requirements

- 🟦 Fast evacuation of irradiated LBE (t ~ 100 ms) *to minimize decay losses*
- 🟨 Small droplets (r ~ 100 µm) *to reduce diffusion length*
- 🟩 Sufficient fall time *to increase release efficiency*

Why Small ?

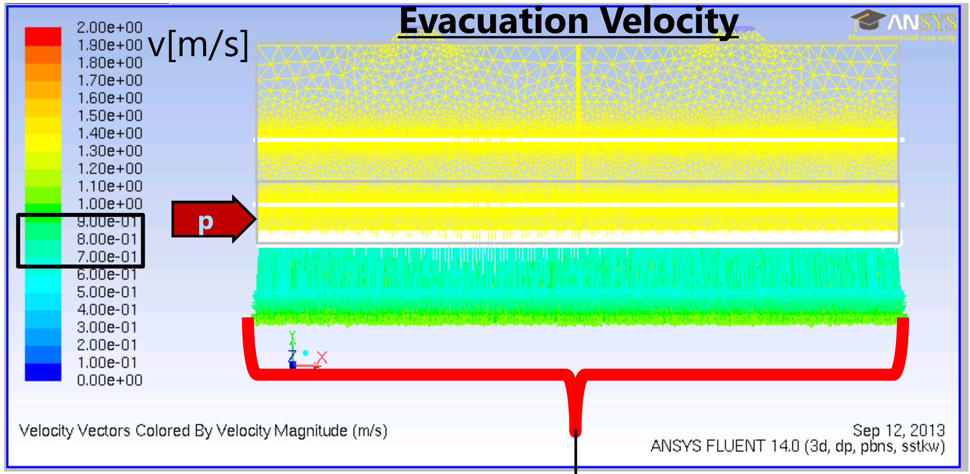
Fick's Second law : $\frac{\partial}{\partial t}C_i = \mathrm{Div}(\mathrm{DGrad}C_i)$

Diffusive flux : $J_i = -D\,\nabla C_i = -D\frac{\partial C_i}{\partial r}$

Spherical Droplet - Condition

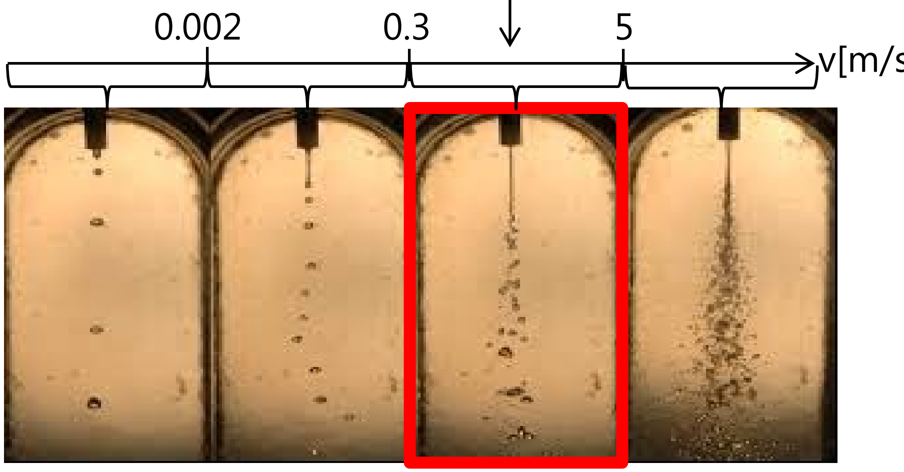
$$r \ll \sqrt{\frac{\gamma}{g\left(\rho_{liq} - \rho_{vap}\right)}}$$

For LBE, $r = 200\mu m$, with 1% deviation from perfect sphere



Velocity Vectors Colored By Velocity Magnitude (m/s)

Sep 12, 2013
ANSYS FLUENT 14.0 (3d, dp, pbns, sstkw)



Jetting Regime (r=100 µm)

Christophe CLANET , Juan C. LASHERAS, Transition from drippin
jetting, J. Fluid Mech. (1999), vol. 383, pp. 307-326

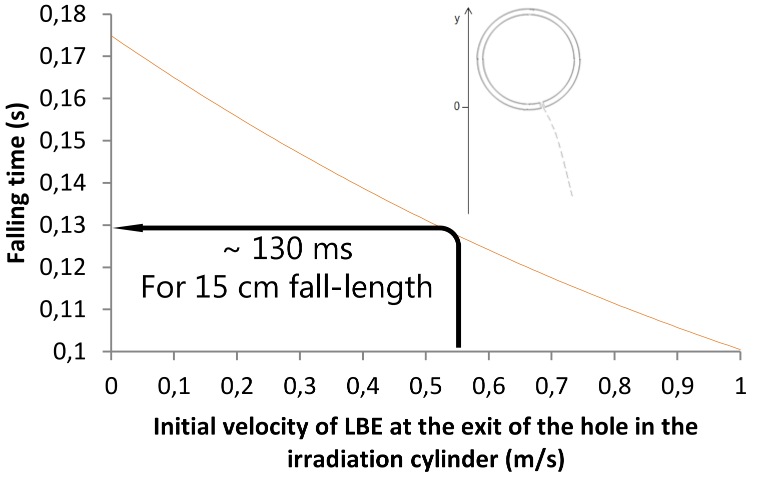
3rd Requirement – Sufficient fall time

Requirements

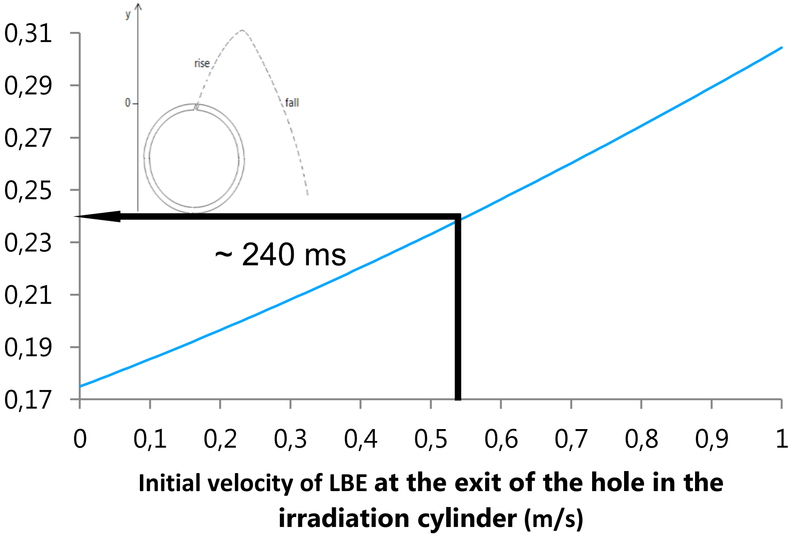
Fast evacuation of irradiated LBE (t ~ 100 ms) *to minimize decay losses*

Small droplets (r ~ 100 µm) *to reduce diffusion length*

Sufficient fall time *to increase release efficiency*



~ 130 ms
For 15 cm fall-length



~ 240 ms

Isotope-Release Efficiency

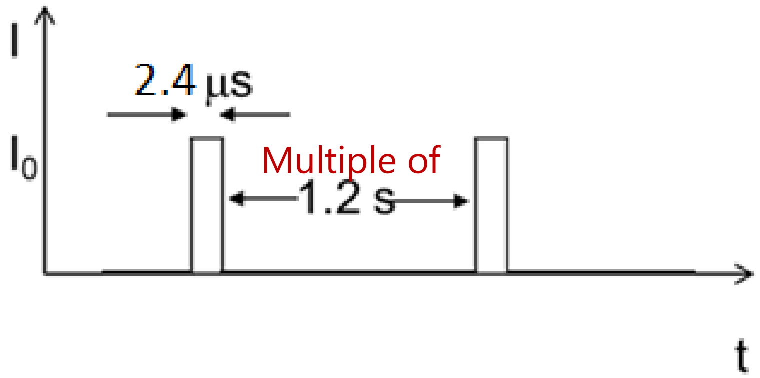
Preliminary estimations for the prototype test at ISOLDE

Calculations by D. Houngbo (SCK•CEN and UGent)

Production and Release of Short-Lived Hg Isotopes

- Proton-beam duty cycle at ISOLDE:

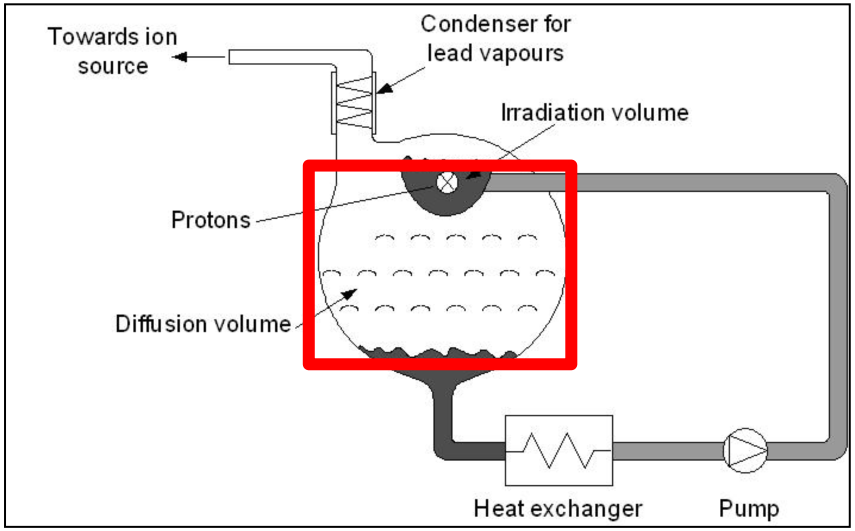
Pulsed Beam
E_p =1.4 GeV
Integrated current: ~ 2 µA



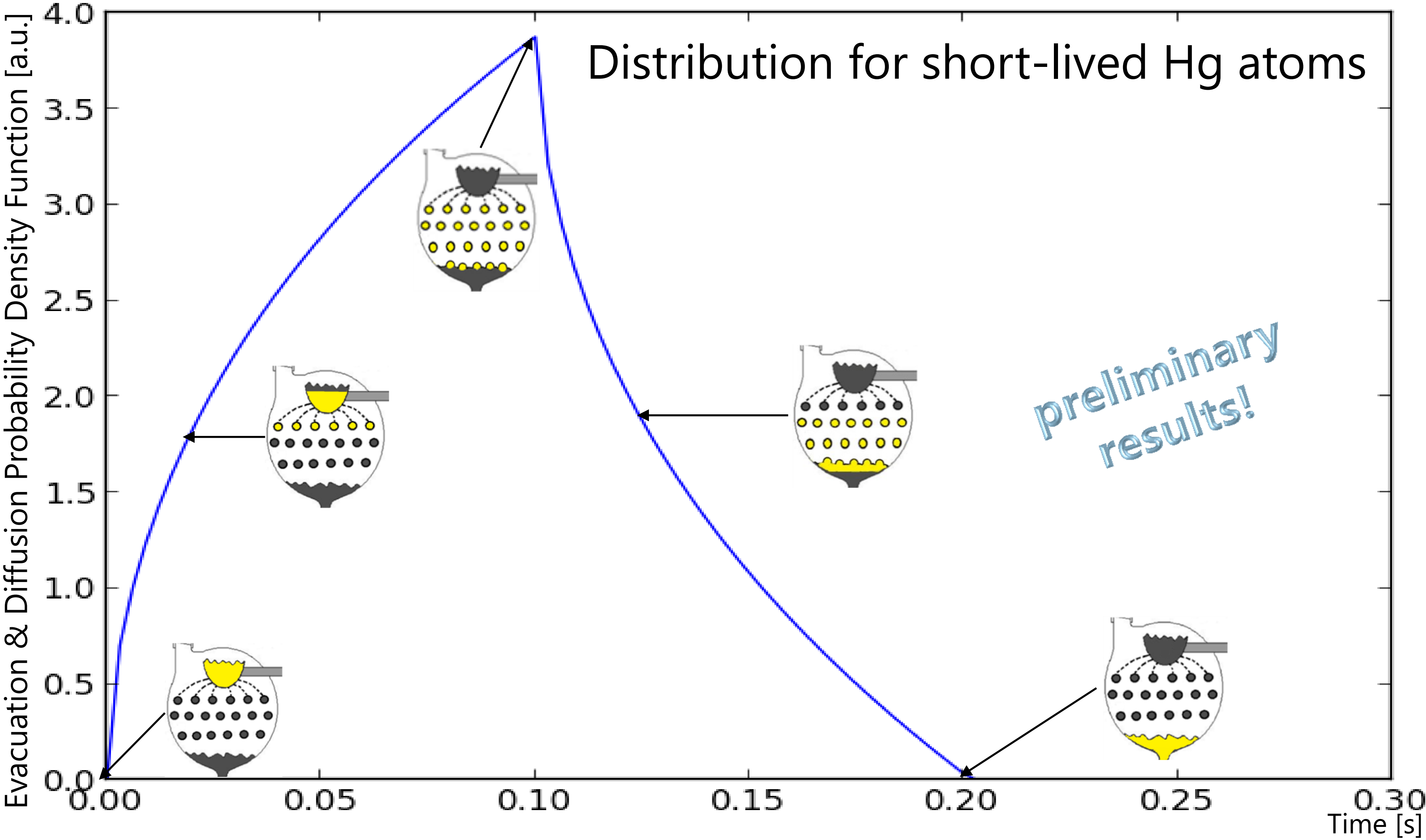
- ^{177}Hg → $T_{1/2}$ = 118 ms
- ^{178}Hg → $T_{1/2}$ = 267 ms

- In the diffusion volume:

^{177,178}Hg atoms created in 1 proton-beam pulse only!

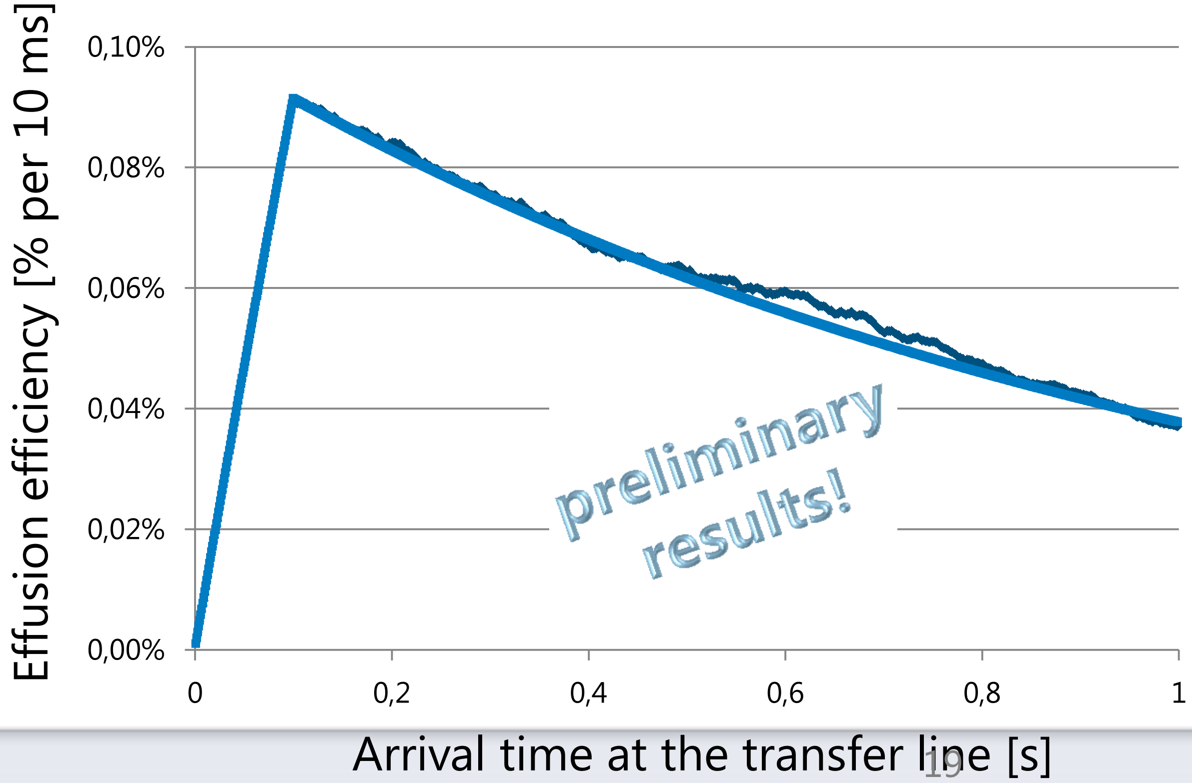


Delay-Time Distribution of Atoms at Droplets Surface (fall time ≈ evacuation time)

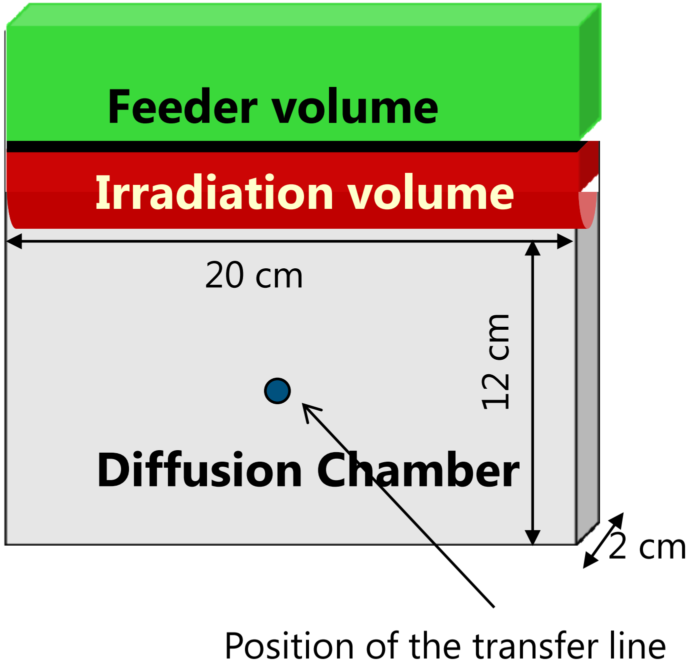


Effusion Efficiency

- MolFlow calculations for Hg
- Atoms generated randomly in the LBE shower
- 50-µm radii LBE droplets
- Irrad. & Diff. Chamber dimensions as in fig.



1.4 GeV, 10^{13} prot.



Feeder volume

Irradiation volume

20 cm

12 cm

2 cm

Diffusion Chamber

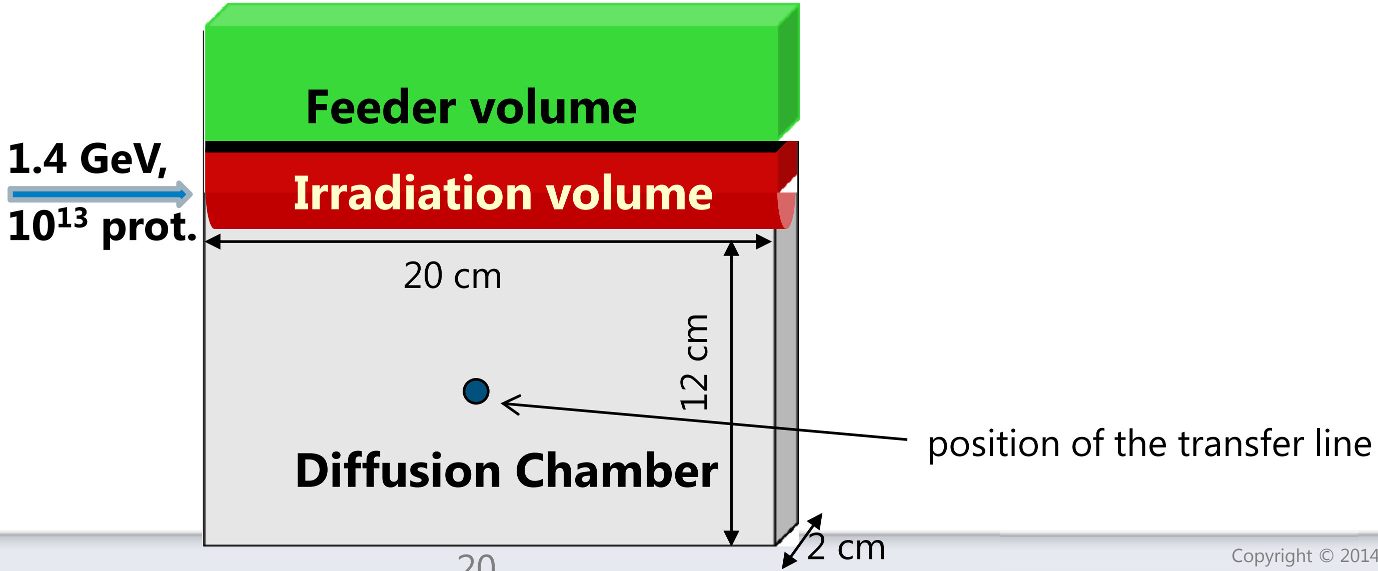
Position of the transfer line

60,10% of the Hg atoms desorbed from the droplets arrive at the transfer line within 1 s

Preliminary Release Estimations

- Release efficiencies for different lengths of irradiation and diffusion chamber - LIEBE target

Diffusion Chamber Length [cm]	**5**	**10**	**15**	**20**	**25**	**30**	**35**
Release efficiency (177Hg)	5.78%	3.55%	2.58%	2.02%	1.65%	1.42%	1.19%
Release efficiency (178Hg)	12.95%	9.13%	7.09%	5.76%	4.86%	4.23%	3.63%

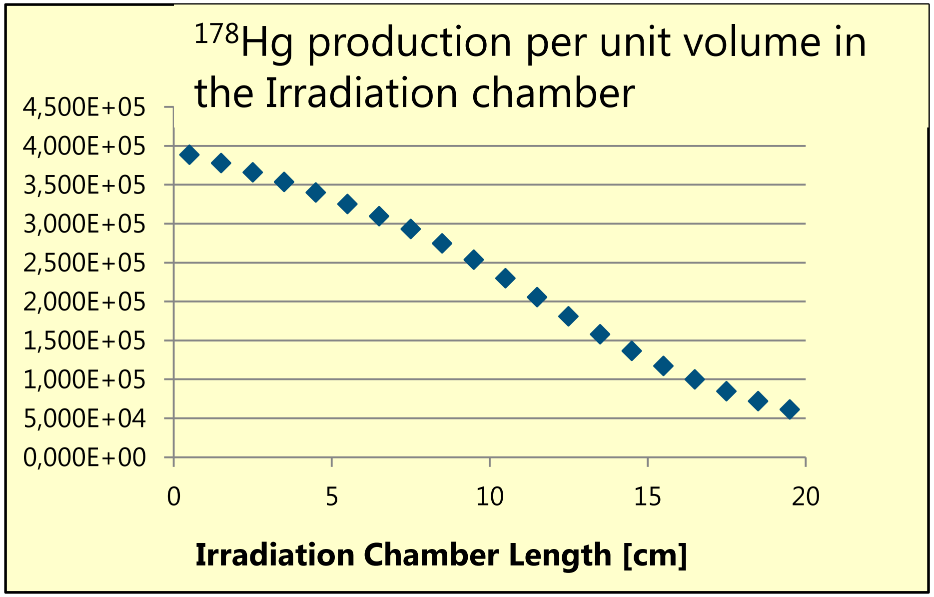


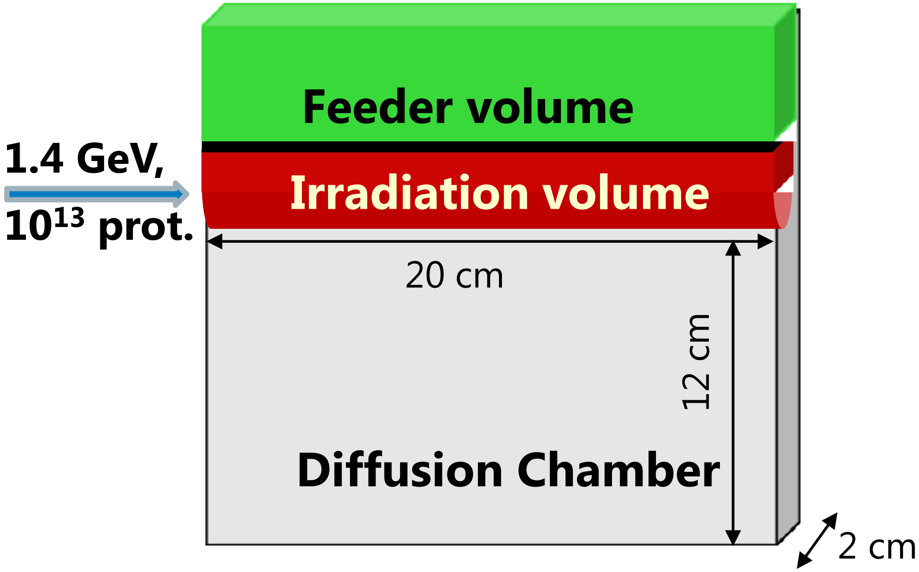
RIB Yield Optimization

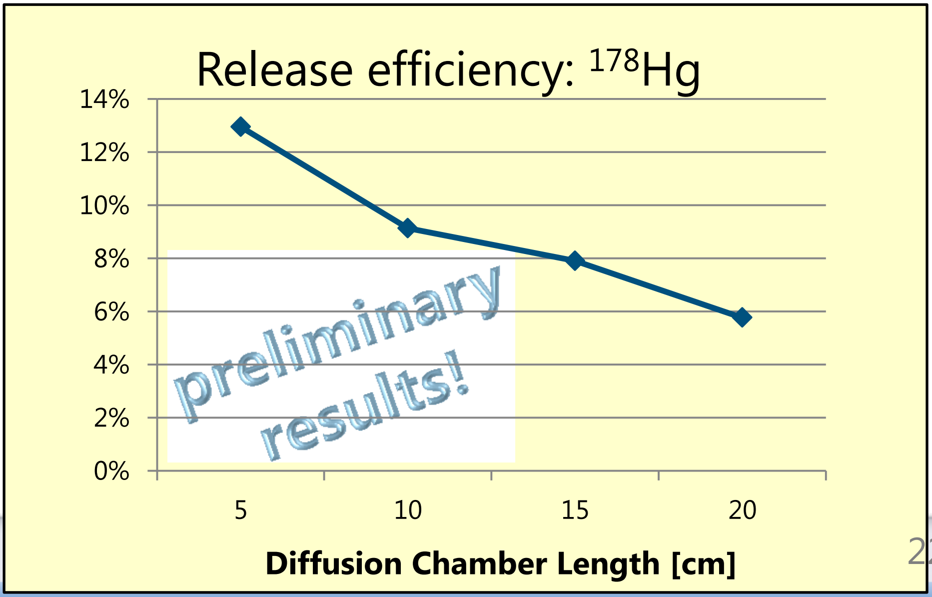
First exercise towards an optimized target

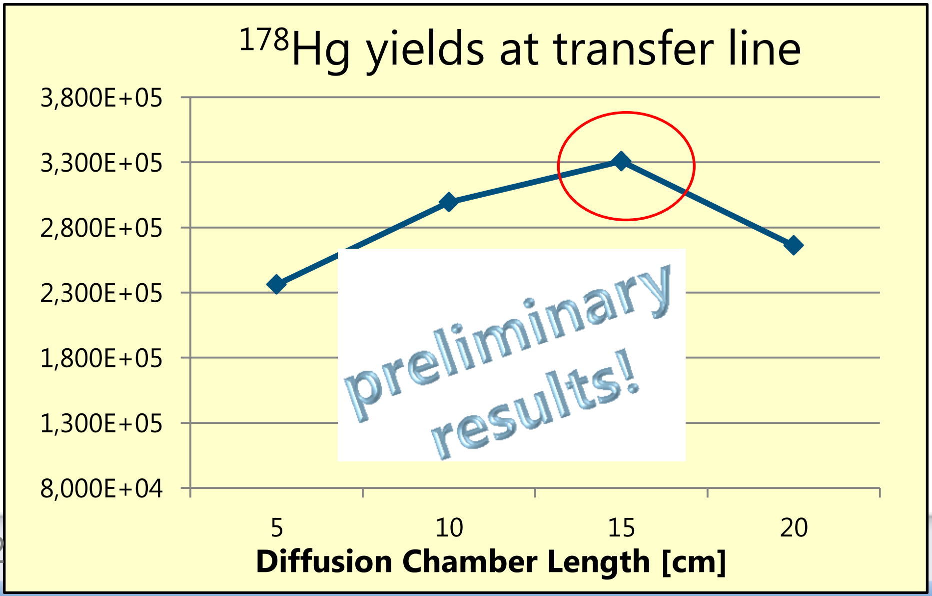
Calculations by Alexey Stankovskiy (SCK•CEN)
& D. Houngbo (SCK•CEN and UGent)

RIB Yield Optimization: ^{178}Hg

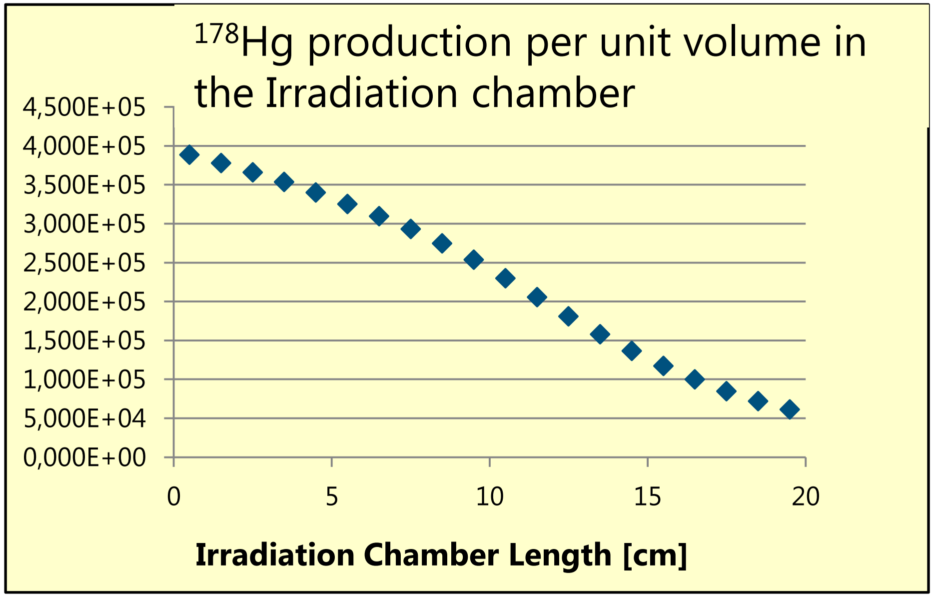


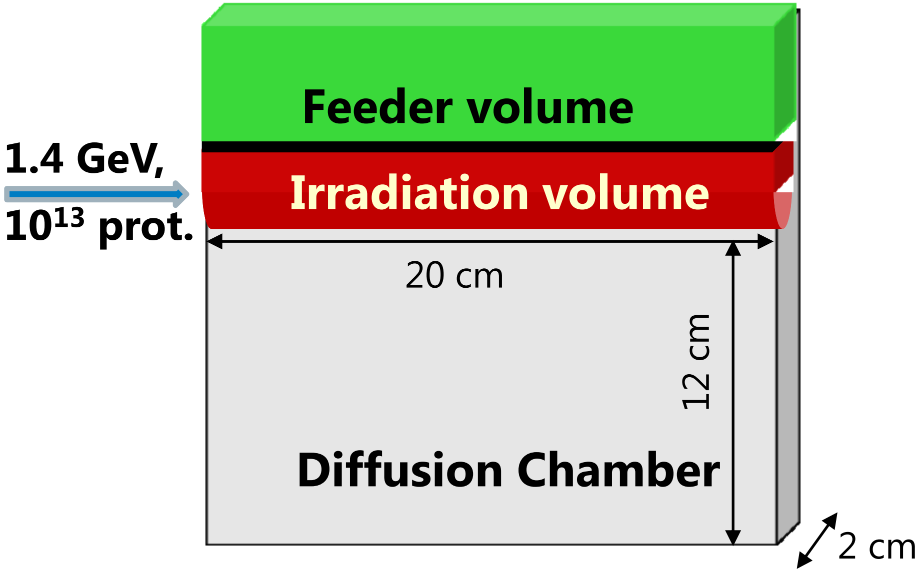






RIB Yield Optimization: ^{177}Hg


^{178}Hg production per unit volume in the Irradiation chamber


1.4 GeV,
10^{13} prot.

Feeder volume

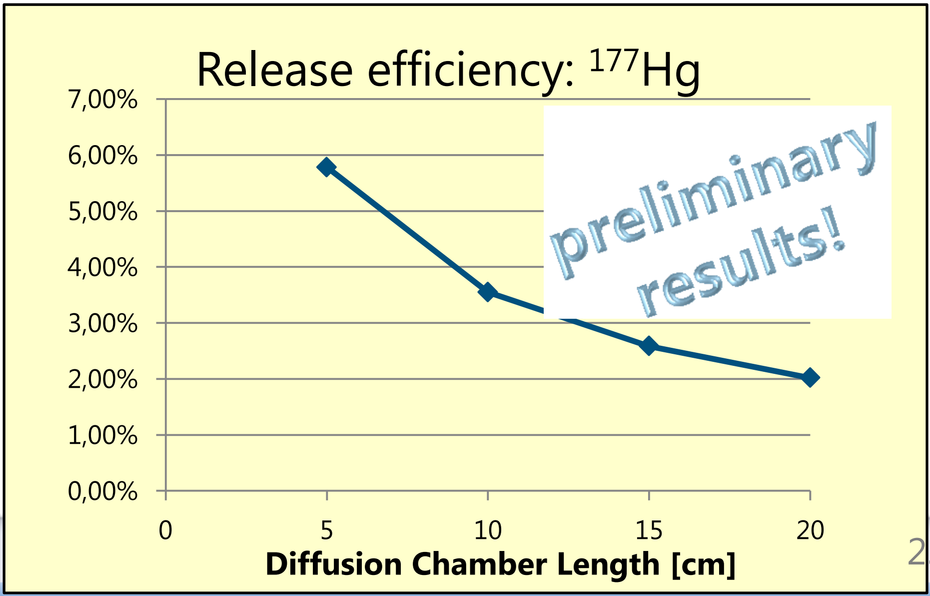
Irradiation volume

20 cm

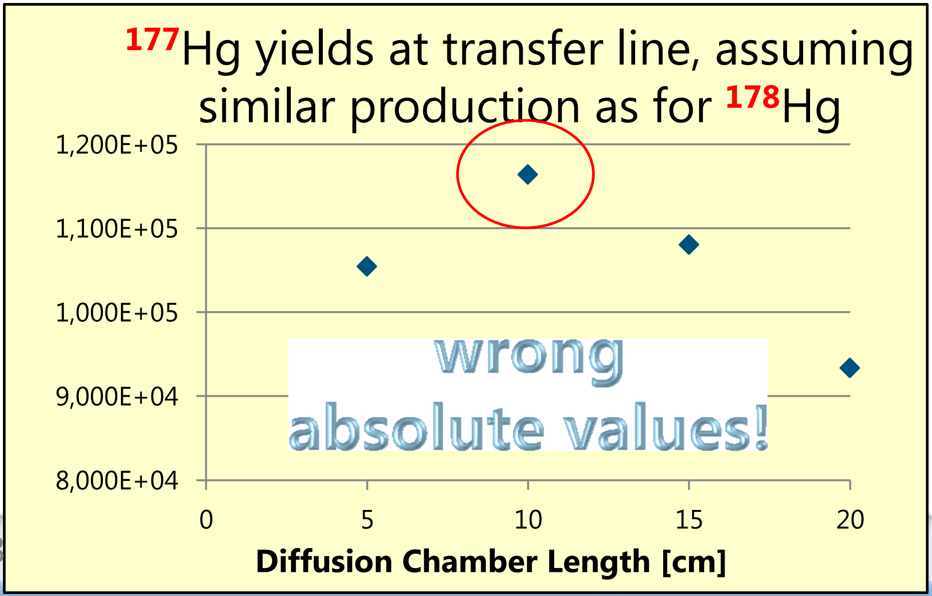
12 cm

Diffusion Chamber

2 cm


Release efficiency: ^{177}Hg

preliminary results!


^{177}Hg yields at transfer line, assuming similar production as for ^{178}Hg

wrong absolute values!

RIB Yield Optimization

- There is room for further optimization!
  - test different droplet-fall lengths
  - test different droplet sizes
  - test different target sizes
  - test different placement of the transfer line

- Target design adapted to the isotope of interest

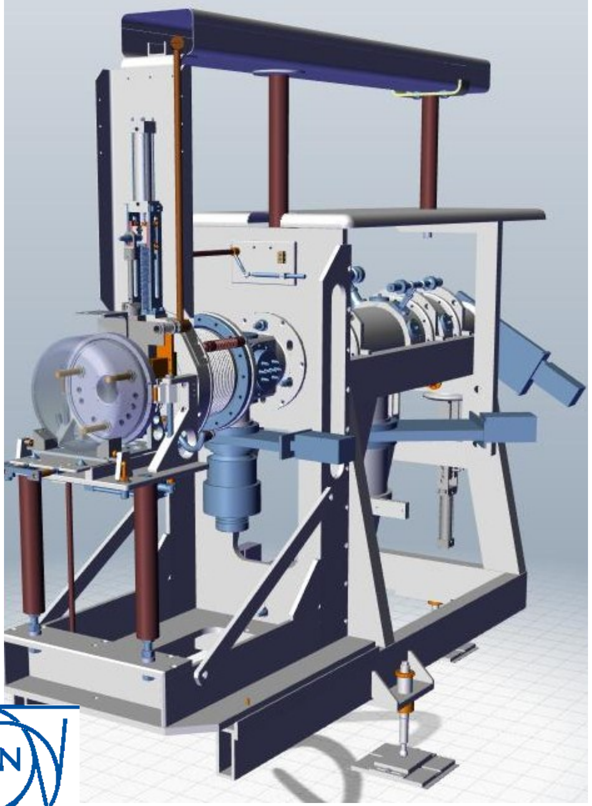
Realization of the LIEBE prototype

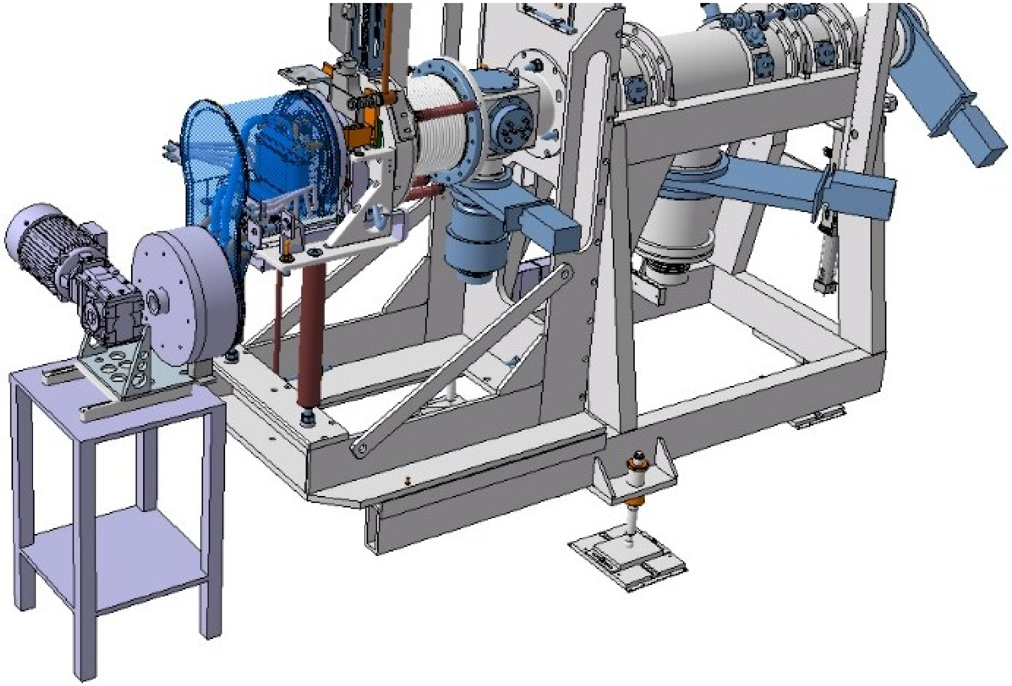
Main contributor: CERN
(V. Barozier, A.P. Bernardes, M. Delonca, S. Kelpentidjian,
F. Loprete, C. Maglioni, T. Mendonca, T. Stora, H. Znaidi)

LIEBE Prototype Considering the ISOLDE Front-End

ISOLDE Front-end

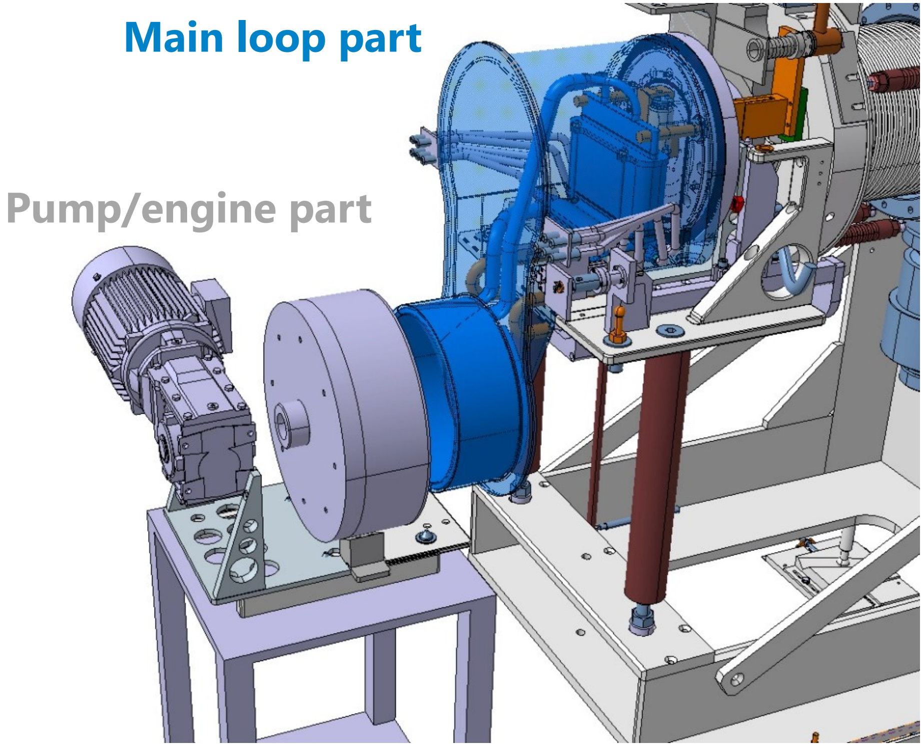
LIEBE prototype



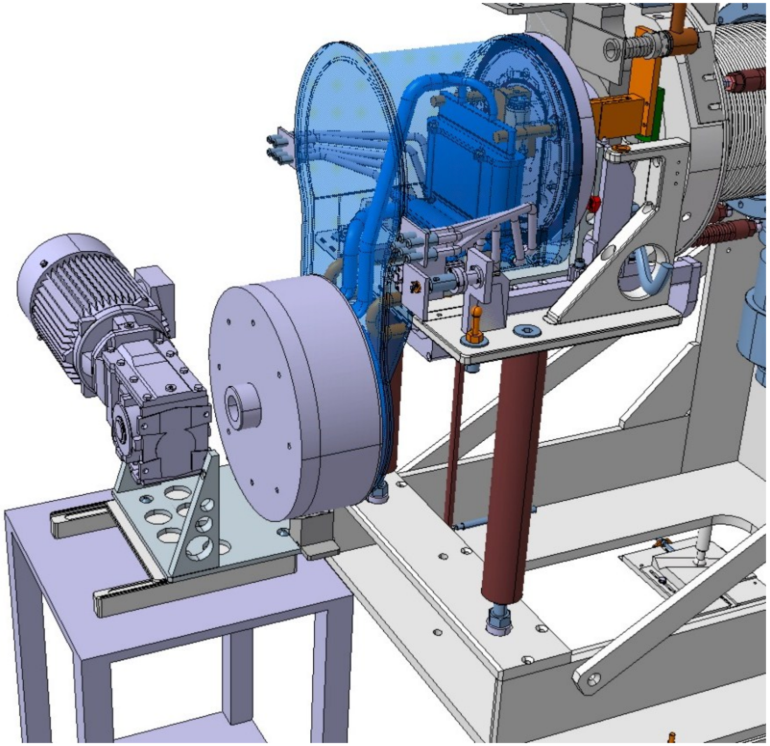


LIEBE Prototype

- Proposed LIEBE design: a « two parts plugged » principle
  - *Allow the confinement of the LBE while keeping the total weight below the limit fixed by the robot at ISOLDE*



Unplugged position

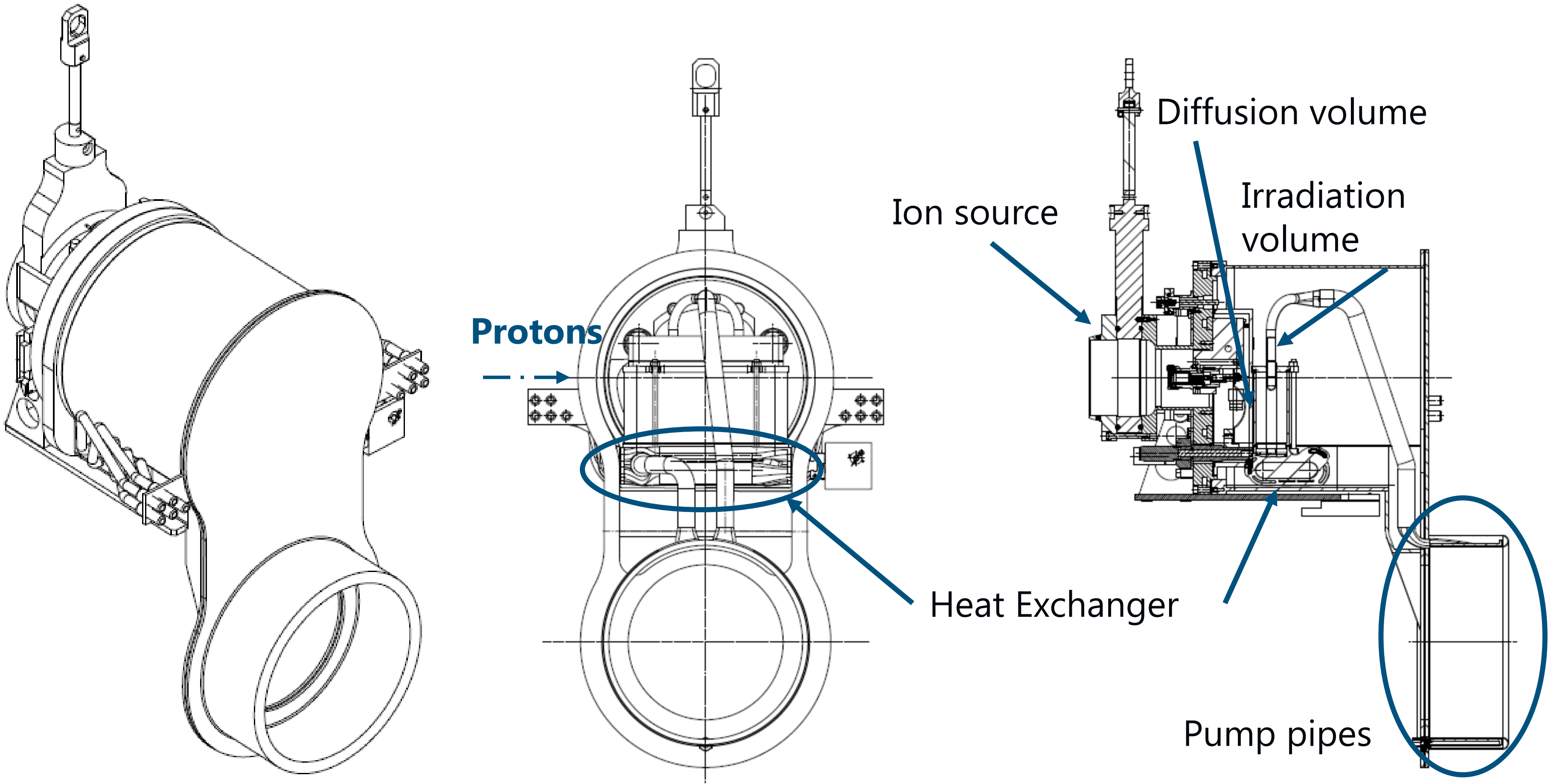


Plugged position

Slide from M. Delonca (CERN)

LIEBE: design of the prototype loop

- Main loop part: some details



Protons

Ion source

Diffusion volume

Irradiation volume

Heat Exchanger

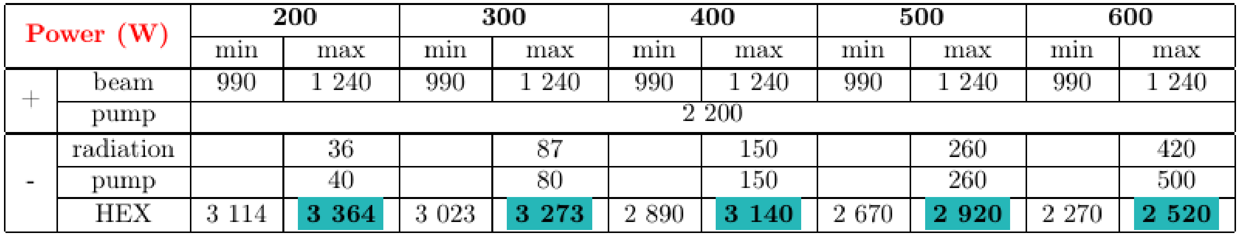
Pump pipes

+ heating elements all along the loop and filling system

Slide from M. Delonca (CERN)

HEX: a curious design (1)

- **He**at **Ex**changer (HEX): what for?
  - To extract the power brought by the beam and the pump (electromagnetic pump)
  - To allow a proper thermal equilibrium of the target



Power (W)		200		300		400		500		600	
		min	max	min	max	min	max	min	max	min	max
+	beam	990	1 240	990	1 240	990	1 240	990	1 240	990	1 240
	pump	2 200									
-	radiation		36		87		150		260		420
	pump		40		80		150		260		500
	HEX	3 114	**3 364**	3 023	**3 273**	2 890	**3 140**	2 670	**2 920**	2 270	**2 520**

Dimensioning of an HEX:

$$P = H * S * \Delta T_{lm}$$

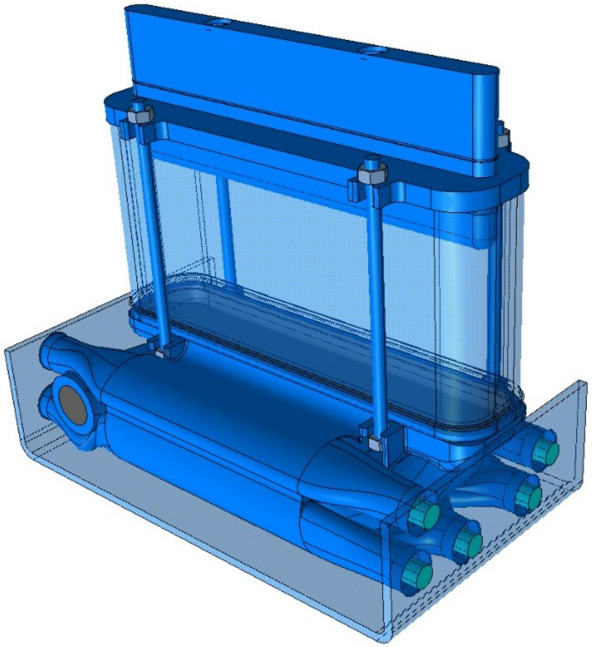
with $\Delta T_{lm} = \frac{\Delta T_2 - \Delta T_1}{\ln\left(\frac{\Delta T_2}{\Delta T_1}\right)}$ and $H = \frac{1}{\frac{1}{h_1} + \frac{1}{h_2}}$

- Specificity of the design:
  - The HEX must extract less power @ 600 °C than at 200 °C BUT the power extracted depends on the surface of exchange, the average heat exchange coefficient and the temperature of both fluids involved -> **need of a variable HEX**!

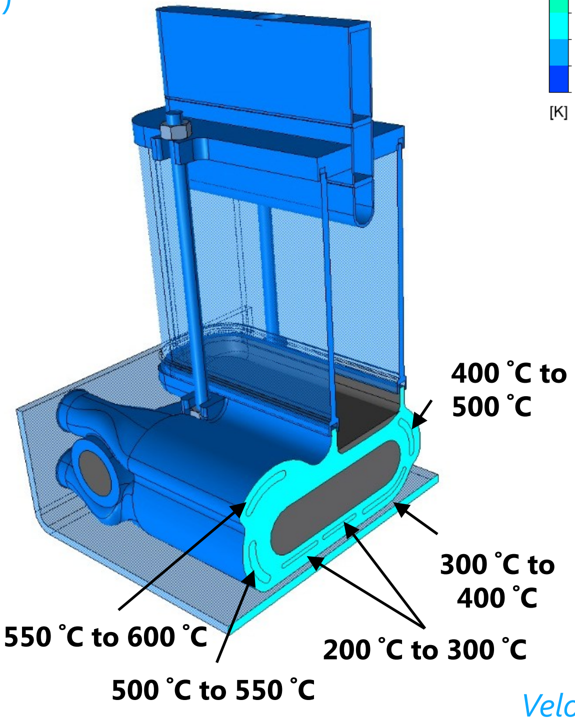
Slide from M. Delonca (CERN)

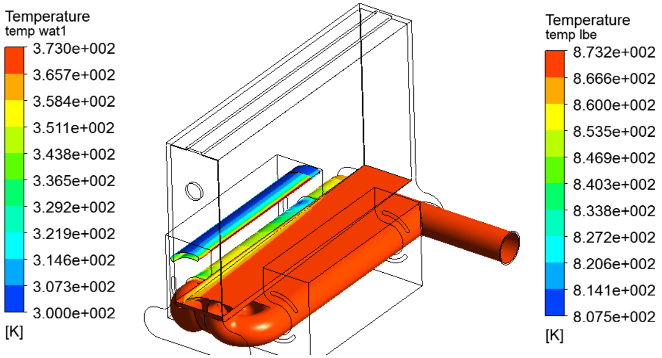
HEX: a curious design (2)

- HEX: proposed design

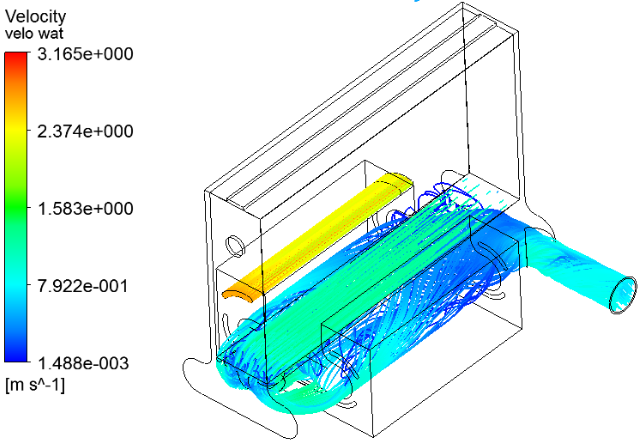


6 water inlets, 4 alimented separately and independently (one per 50˚C or 100 ˚C) + 2 together (from 200 ˚C to 300 ˚C)





Temperatures repartitions for LBE and water @ 600 ˚C – CFX analysis



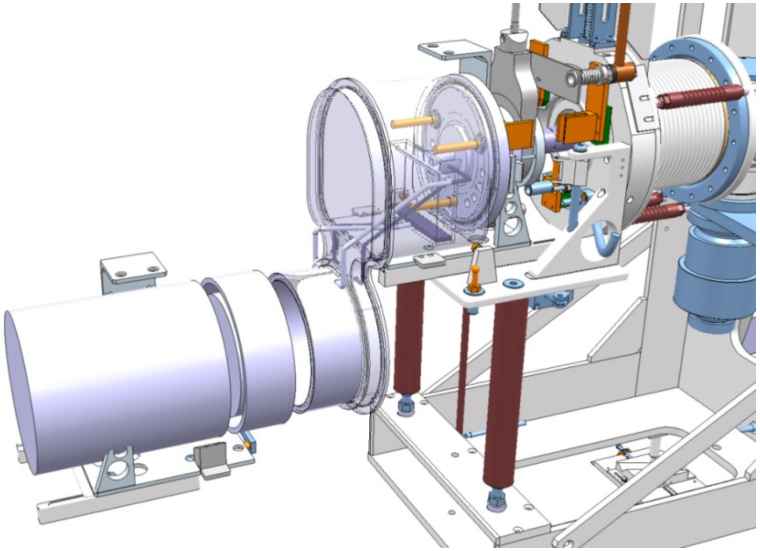
Velocity streamlines for LBE and water @ 600 ˚C CFX analysis

Isolde parameters	Water	LBE
Flow rate (l/s)	0.22	0.23
T_{inlet} (ºC)	27	Variable
T_{outlet} (ºC)	< 90	Variable

The *full part will be produced by 3D printing (around 6 000 €/piece)*

Slide from M. Delonca (CERN)

Permanent-Magnet Pump



Flow rate = 0.23 l/s

Max Total Pressure drop in the loop = 1.54 bar

Pressure head required at pump = 2.3 bar

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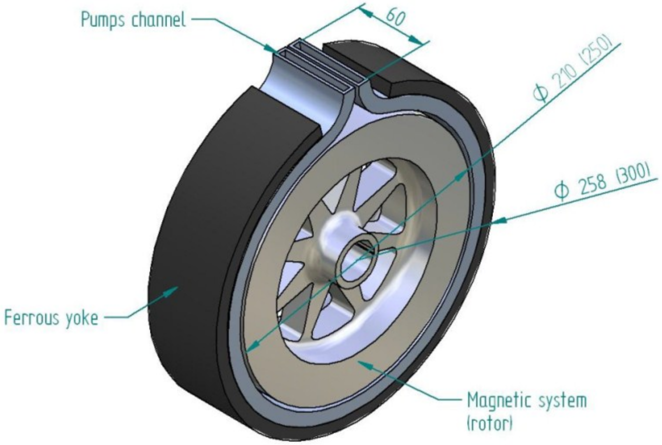
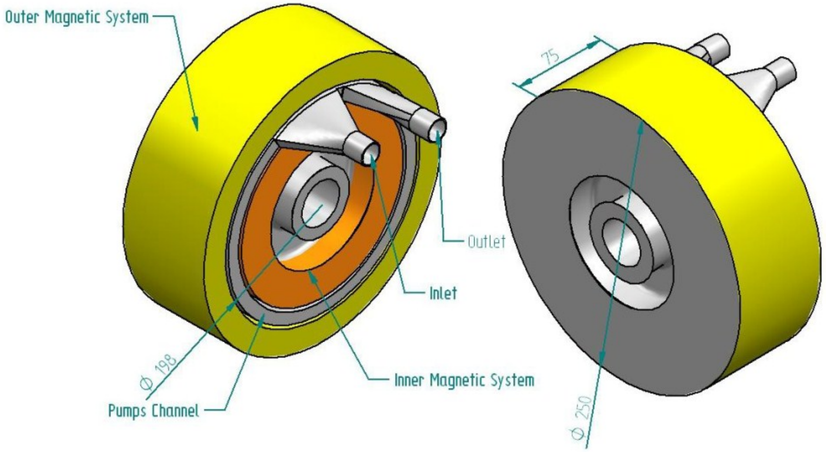
Flow rate up to 0.5 l/s

Pressure head up to 2.5 bar



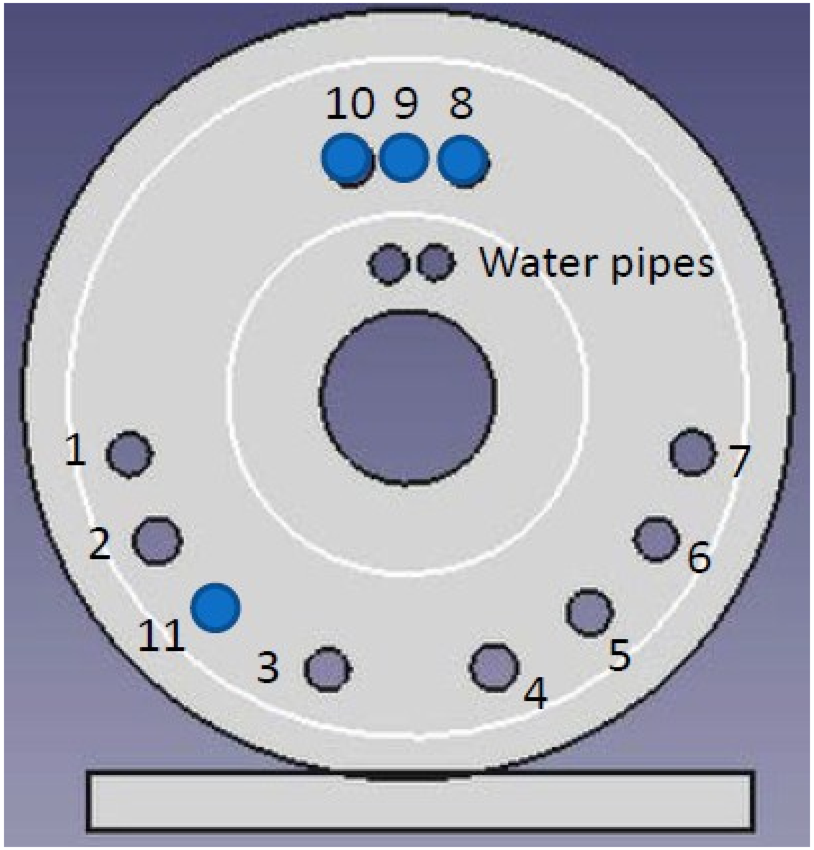
Cylindrical PMP with passive laminated ferrous yoke



Cylindrical PMP with two active magnetic systems

Monitoring & Instrumentation

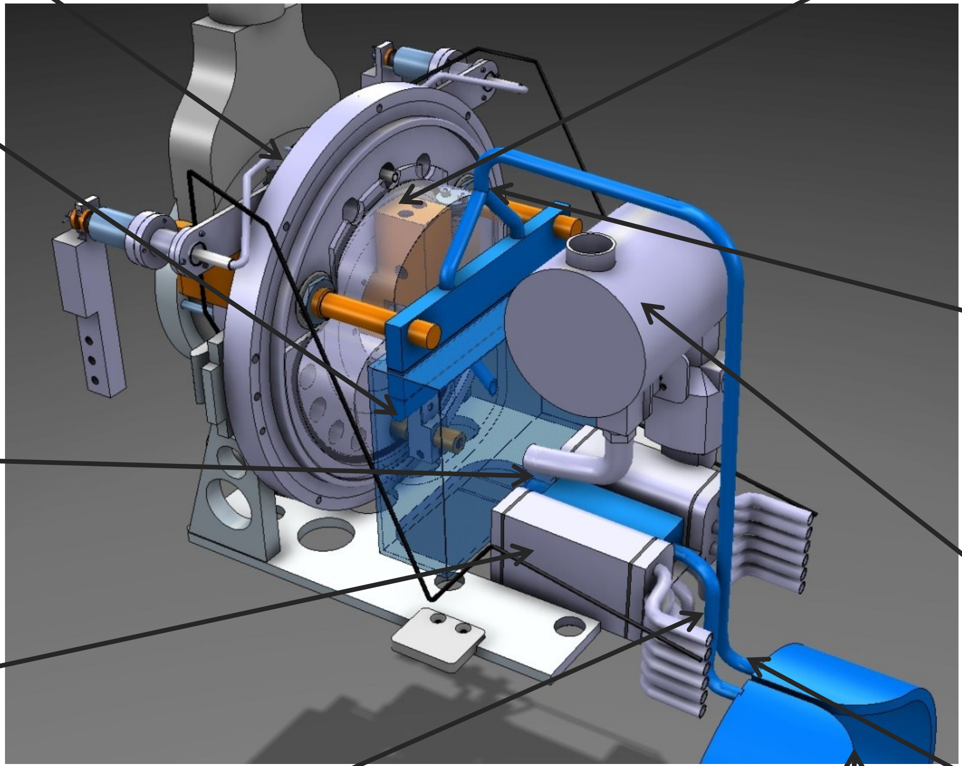
Parameter	Number & type of sensors
Temperature	15 thermocouples
Pressure	1 pressure gauge
Level	4 Level meters



1. Ion source (Magnet)
2. Ion source (Anode)
3. Chimney heating
4. Transfer line heating
5. Gas line
6. Power supply inlet
7. Thermocouples
8. Thermocouples
9. Pressure sensor
10. Level meters

Monitoring & Instrumentation

Thermocouple location



Ambient vessel

Transfer line and chimney: 2x

Diffusion chamber

Inlet irradiation Container : x2

Outlet diffusion chamber: 2x

LBE filling tank

Heat exchanger: x3

Inlet pump

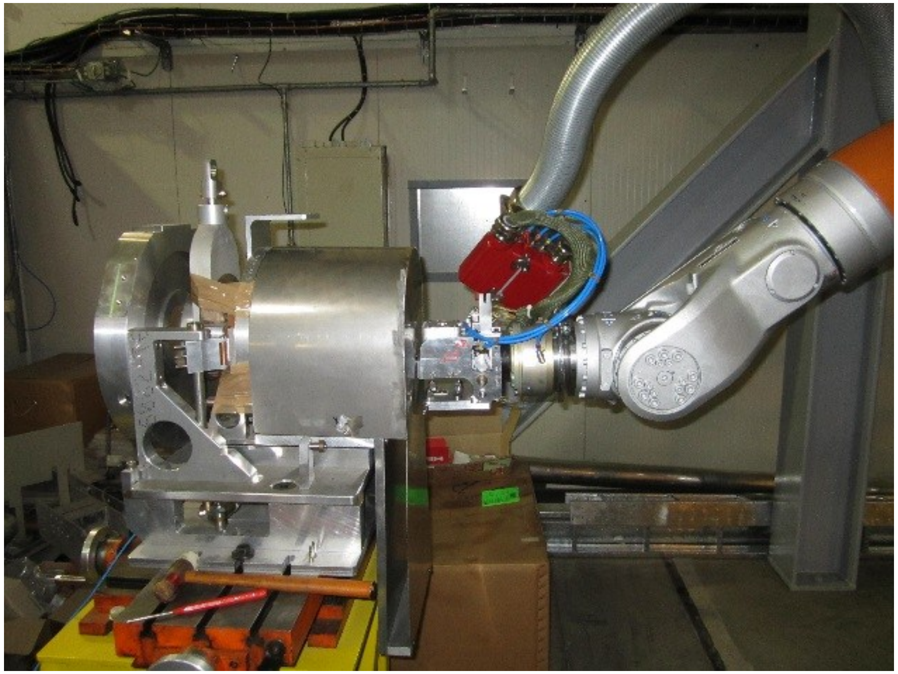
Pump: 3x

Outlet pump: 2x

Slide from A.P Bernardes (CERN)- Acknowledgement T.M. Melo Mendoca(CERN)

Prototyping phase of the LIEBE target – First tests (1)

- Maximum weight that can be carried out by the ISOLDE robot?

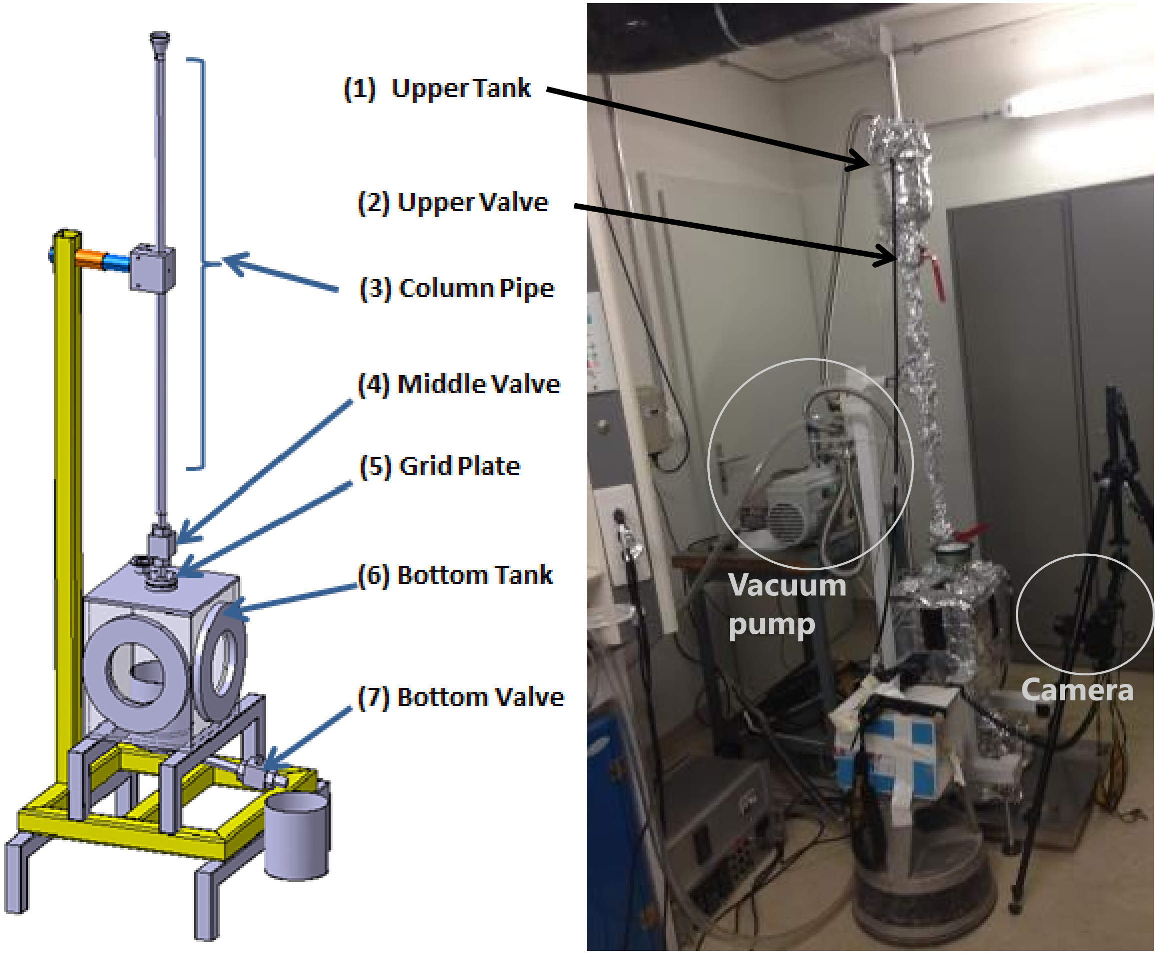


- *To be tested: Robot handling of the target when center of gravity changes*

Slide from M. Delonca (CERN)

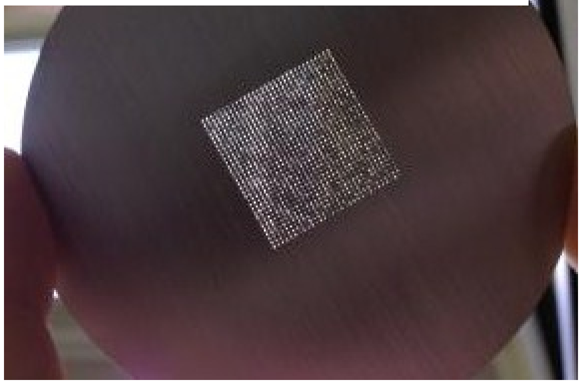
Prototyping phase of the LIEBE target –First tests (2)

- What is the proper spacing of evacuation apertures?



- 4 grids tested (different spacing from 1 mm up to 0.4 mm), holes diameter of 0.1 mm.
- 6 tests with each grid

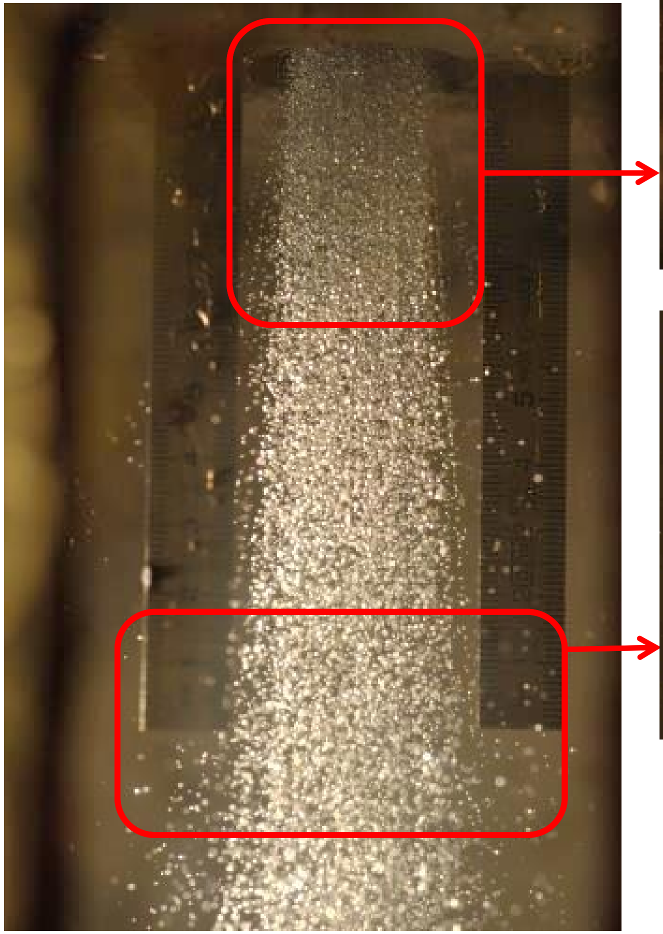
Grid samples

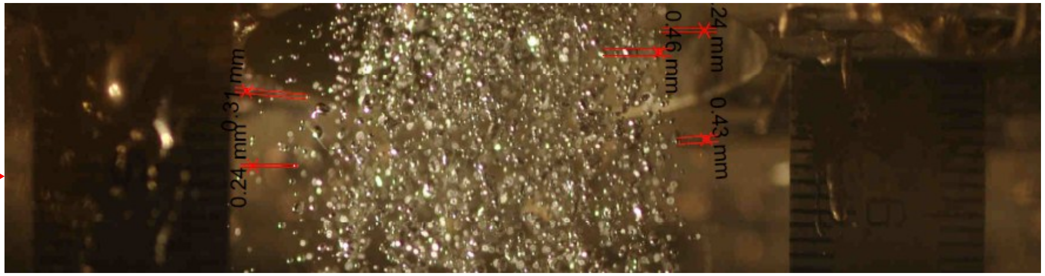


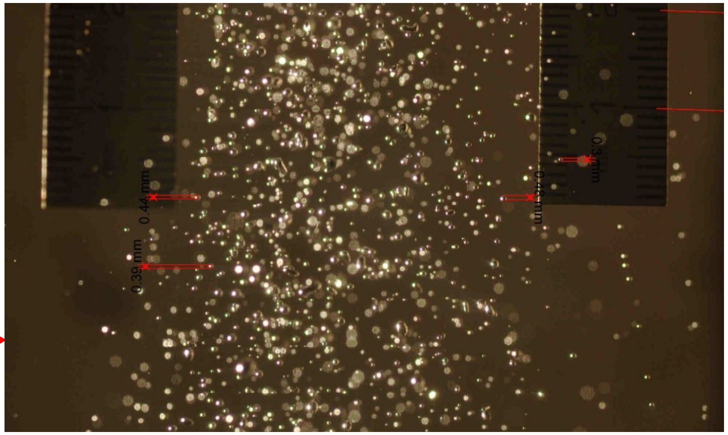
Slide from M. Delonca (CERN)

Prototyping phase of the LIEBE target – First tests (3)

- Smallest spacing allowing a proper shower: **0,6 mm**





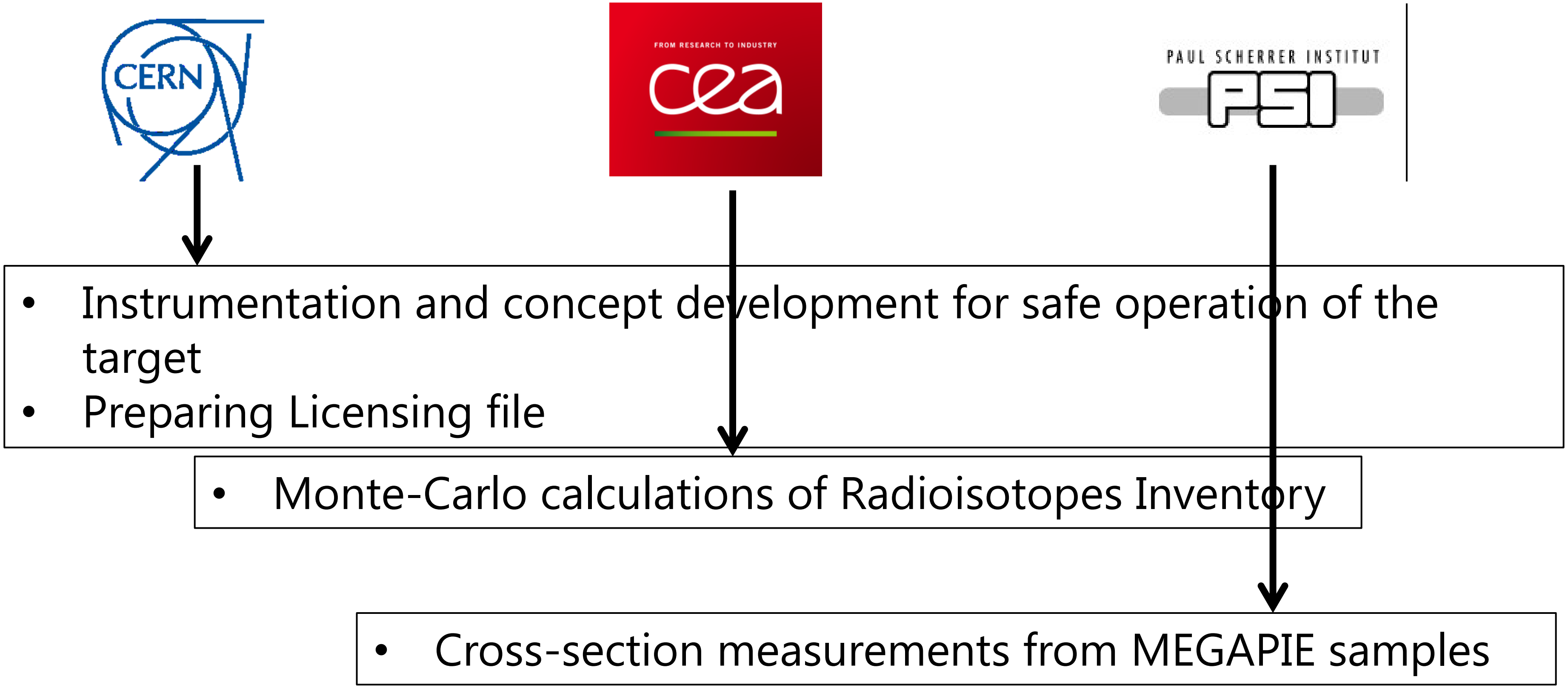


The data are currently being studied.

Slide from M. Delonca (CERN)

Safety Study– Licensing the Target at ISOLDE

- Main contributors:



- Instrumentation and concept development for safe operation of the target
- Preparing Licensing file

- Monte-Carlo calculations of Radioisotopes Inventory

- Cross-section measurements from MEGAPIE samples

I apologize to different contributors for not having space to include their slides !

Conclusion and Outlook

- LIEBE project: development of a liquid Pb-Bi target loop for the 100-kW target station of EURISOL
  - Improved isotope-release efficiencies for short-lived isotopes
  - Capability to operate at high primary-beam powers
  - Detailed design in an advanced stage
- Finalization of target design:
  - *coupling between the two parts of the target, controlling system for the thermal equilibrium of the target, evaluation of the impact of pressure-waves due to the pulsed beam structure at ISOLDE and prototype design optimization,…*
  - Design optimization to maximize RIB Yields
- Prototyping phase to be pushed further:
  - *HEX test (prototype being currently assembled); Pump test; Coupling procedure; Leak-tightness system test; Off-line test of the loop*
- *Off-line tests of the operating loop (2015)*
- *On-line tests at ISOLDE (2016)*

Beyond LIEBE

- Post-irradiation analysis of the prototype
- Benchmark of simulations codes with experimental data from online test & PIE
- Detailed Target-optimization analysis for RIB-yields maximization (production & release)
- Yields estimation and design optimization for EURISOL primary-beam conditions
- Preparing the safety file for EURISOL 100-kW target

LIEBE++

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