LIEBE:

Design of a molten metal target based on a Pb-Bi loop at CERN-ISOLDE

T. De Melo Mendonca, M. Delonca, D. Houngbo, C. Maglioni, L. Popescu, P. Schuurmans, T. Stora

(May 21, 2014)

Outline

- Introduction/context
- Proposed design
- Diffusion simulations
- Numerical results
  - *Heat Exchanger (HEX)*
  - *Beam impact*
- Conclusion & next steps

Introduction/context…

Introduction/context (1)

Aim of LIEBE target: validation of conceptual design for the EURISOL direct target by developing a prototype for **CERN-ISOLDE.**

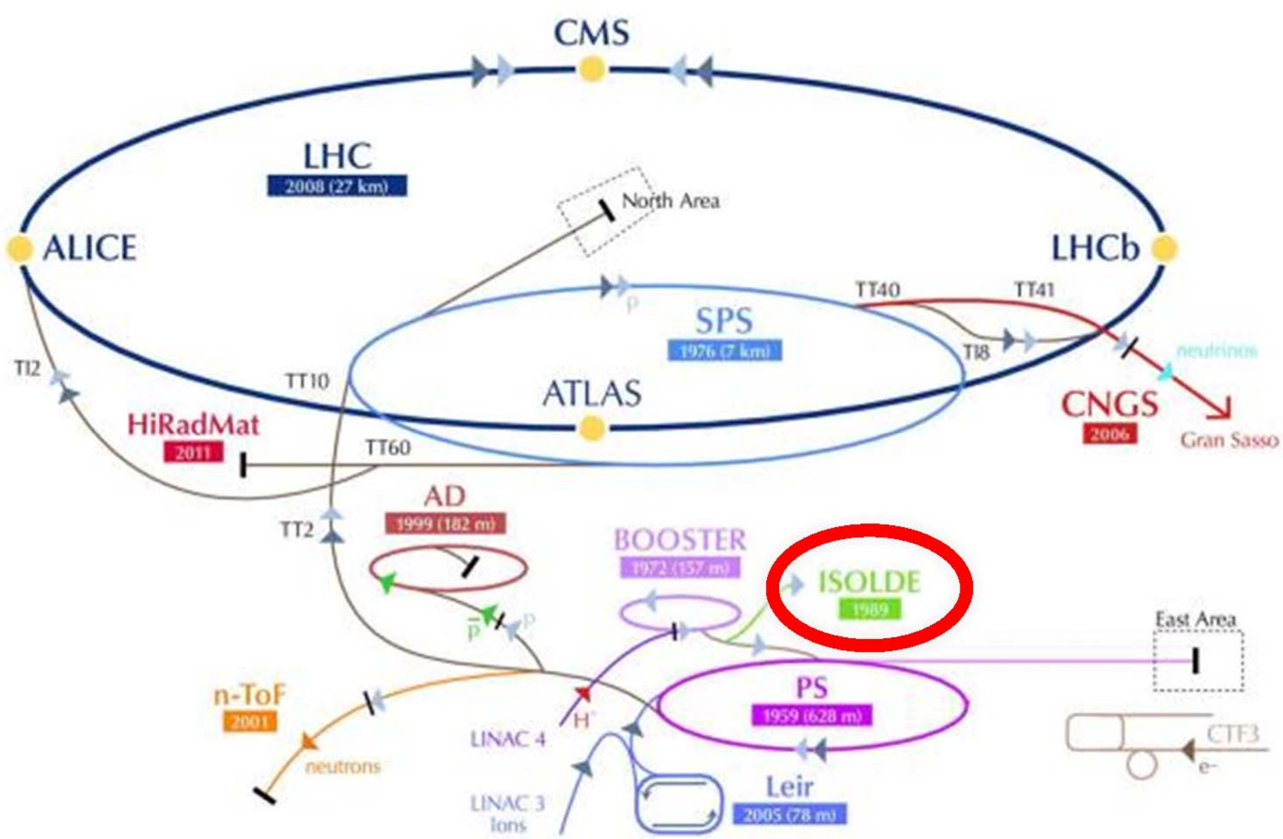
Some keywords: high power target, short-lived isotopes, …

- Collaboration started in May 2012 for the LIEBE (Liquid Eutectic Lead Bismuth Loop Target) project:

WP definition	WP holder	Coordinator
WP1 : Coordination	CERN	T. Stora
WP2 : Conceptual Design and simulations	SCK-CEN	P. Schuurmans
WP3 : Construction, assembly	CERN	M. Delonca
WP4 : Instrumentation	CERN	T. Mendonca
WP5 : Safety and Licensing	CEA	A. Marchix
WP6 : Target characterization and analysis	PSI	D. Schumann
WP7 : Radiochemistry	SINP	S. Lahiri
WP8 : Offline commissioning	IPUL	K. Kravalis
WP9 : Online operation	CERN	T. Mendonca

Introduction/context (2)

- ISOLDE: on-line isotope mass separator @ CERN



Proton beam from PSB:
1.4 GeV
2 µA
3e13 protons/pulse
Cycle: 1.2 s
3 kW average power

Instantaneous power: **≈ 1 GW**

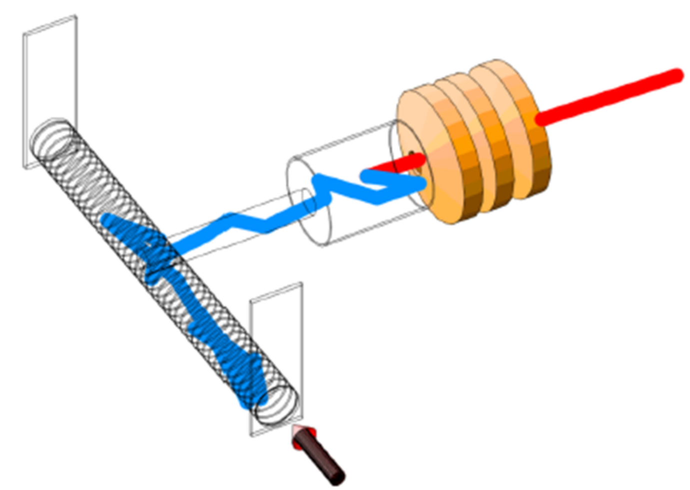
Introduction/context (3)

TRIUMF

ISOL Method

This method involves the interaction of light ion beam onto a thick high-Z target material,

The fragments are imbedded into the bulk of the target material.



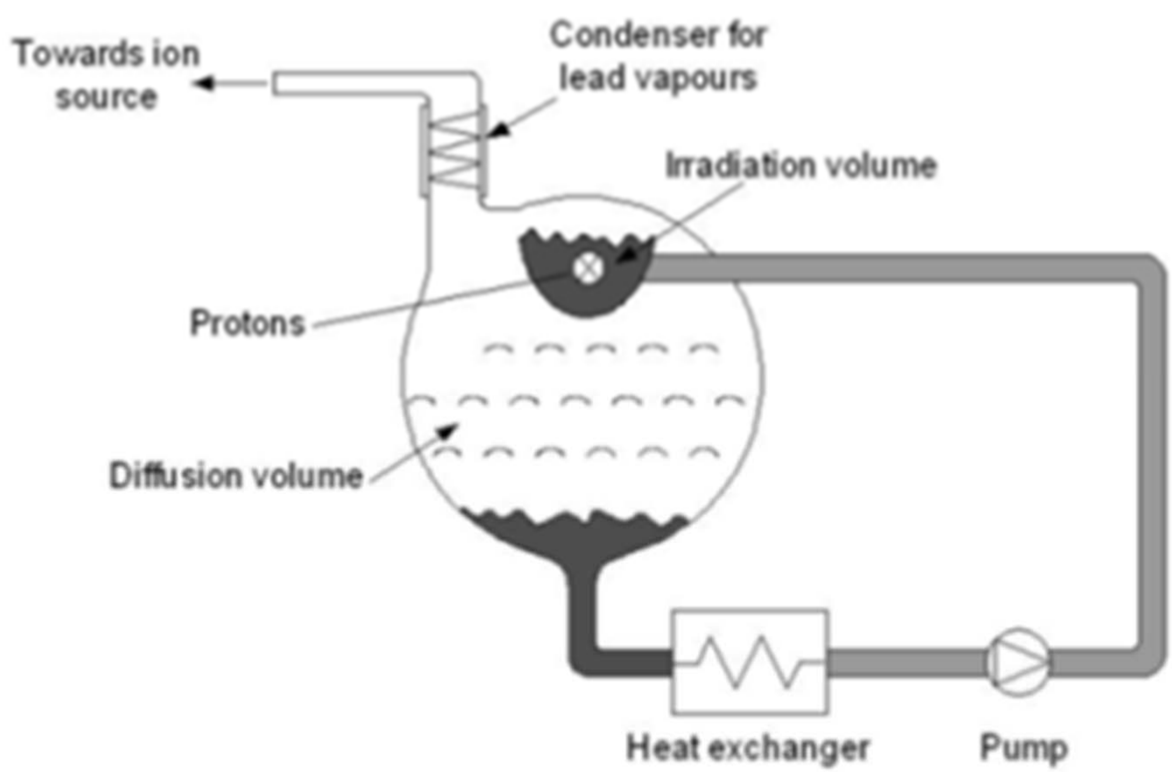
- **The radioactive atoms diffuse to the surface of the grain material,**
  - **diffusion process with efficiency ε_D**
- **Then the atom undergo desorption and move from place to place randomly until it find the exit of the target container,**
  - **effusion process with efficiency ε_E**
- **The radioactive atom enter the ion source where it is ionized,**
  - **ionization process with efficiency ε_I**

$$Y = \Phi_p\, \sigma\, (NA/A\, \tau)\, \varepsilon_D\, \varepsilon_E\, \varepsilon_I$$

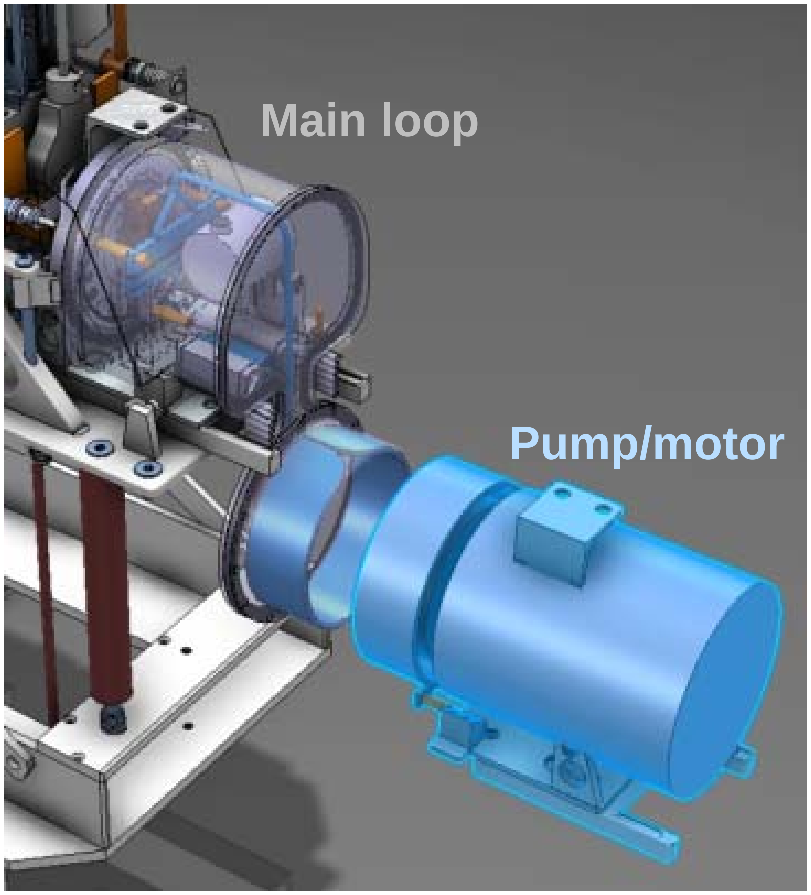
Proposed design…

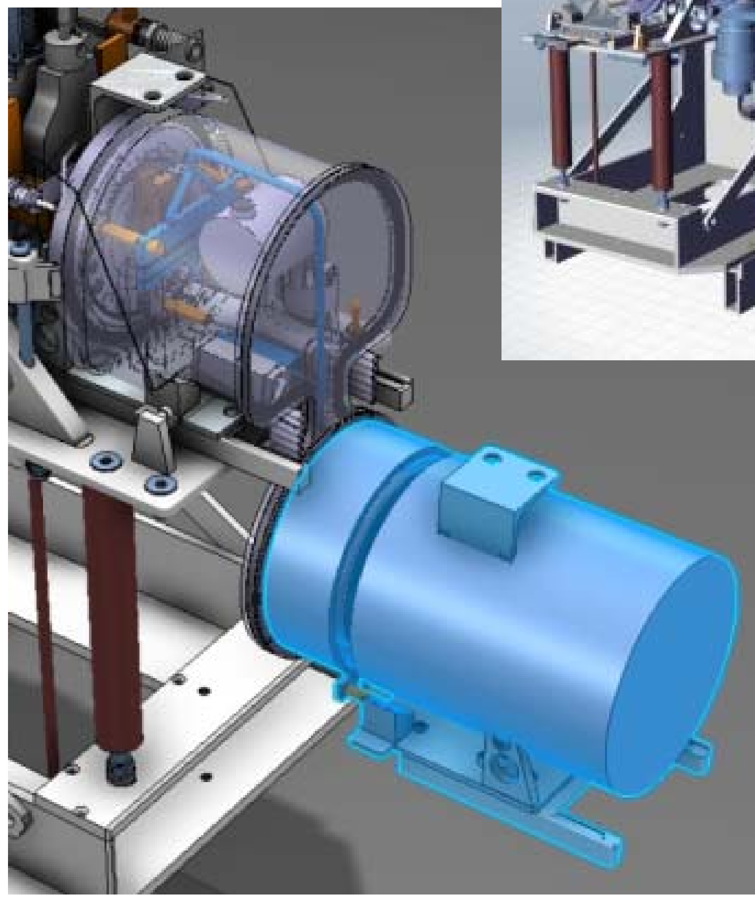
Proposed design (1)

- Proposed by EURISOL



Proposed design (2)

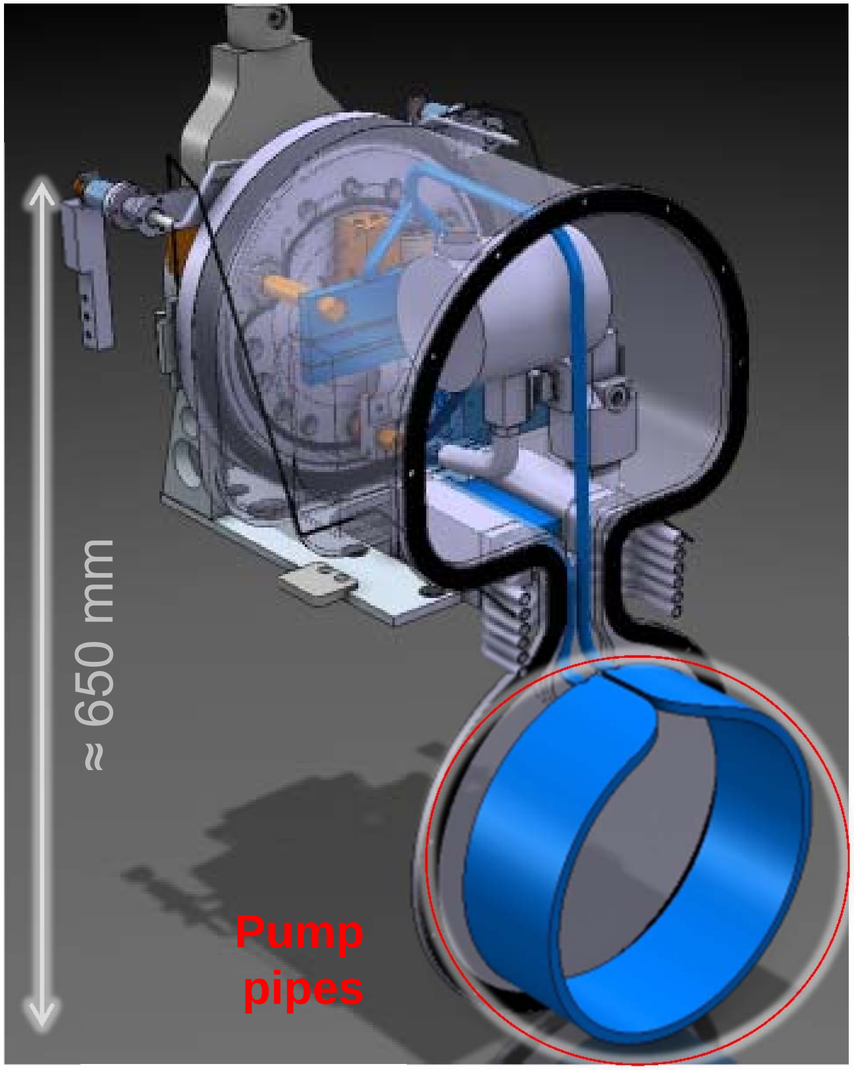


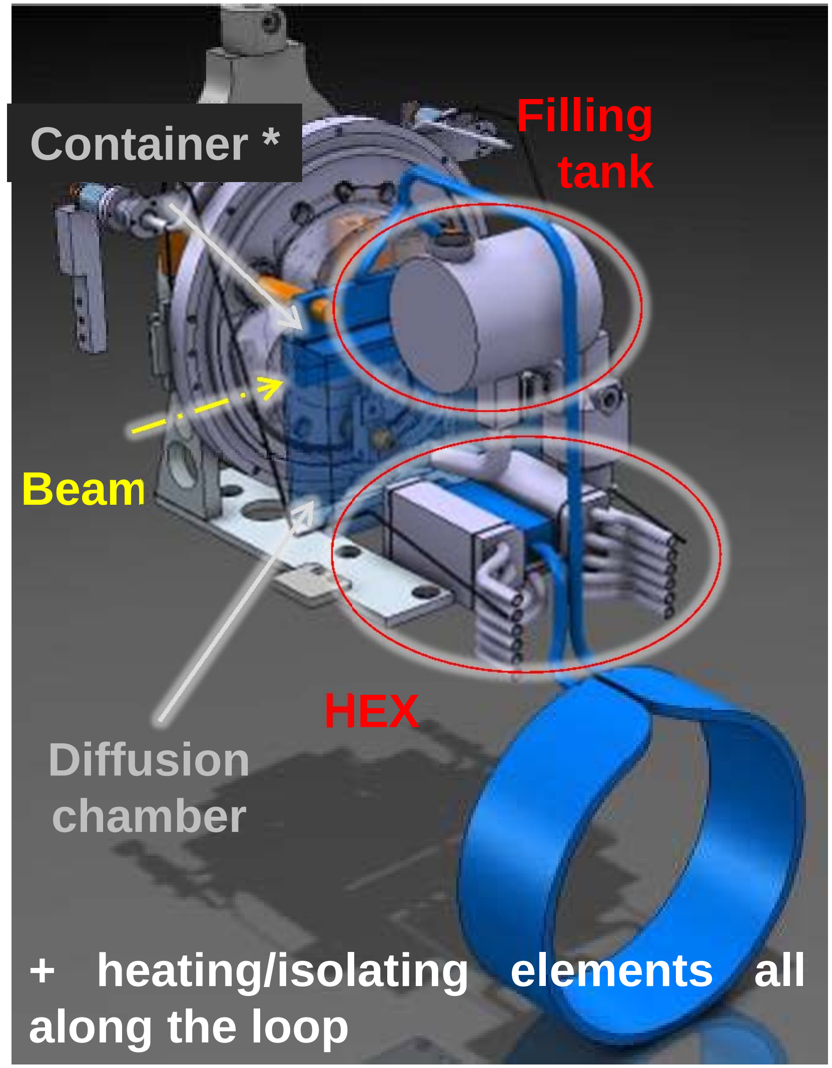


Current front end + target

Current target unit
Diameter: 300 mm

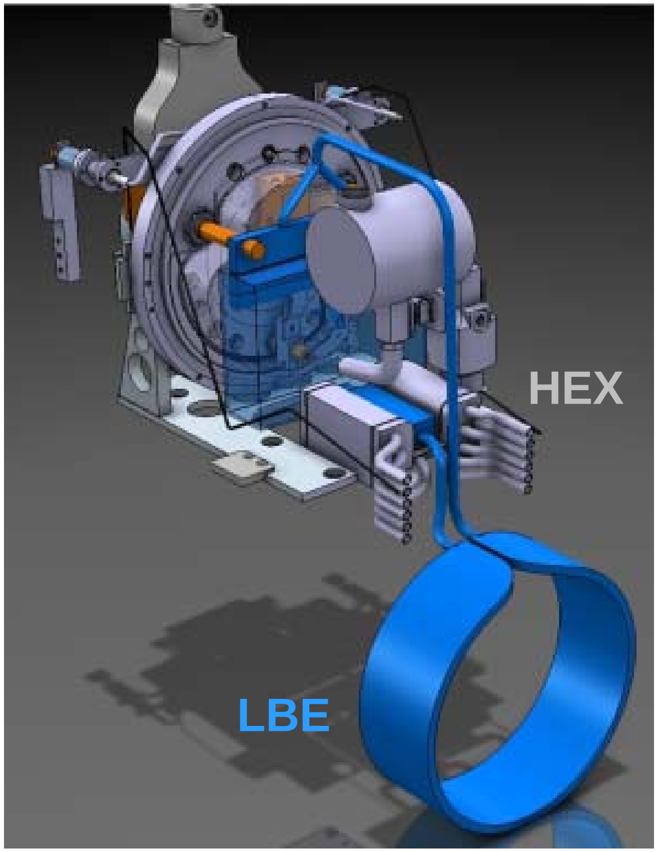
Proposed design - main part (3)

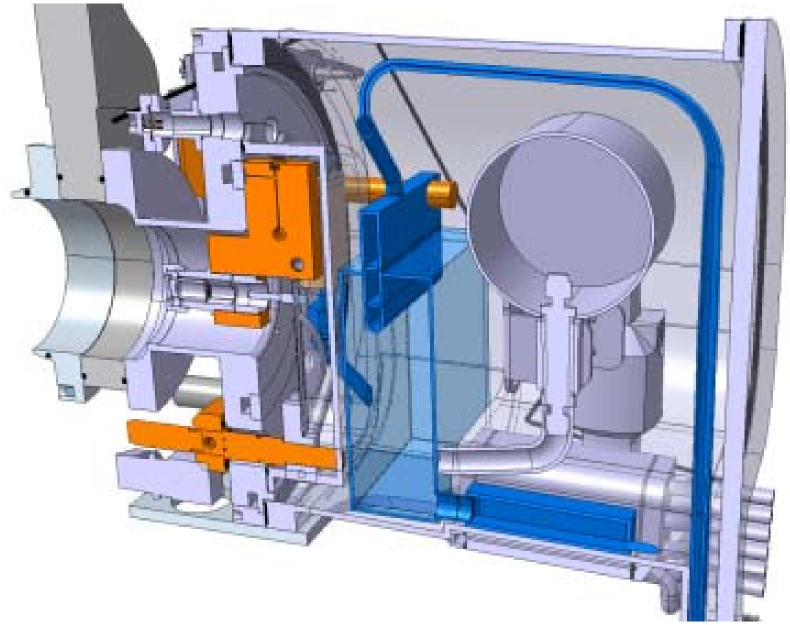




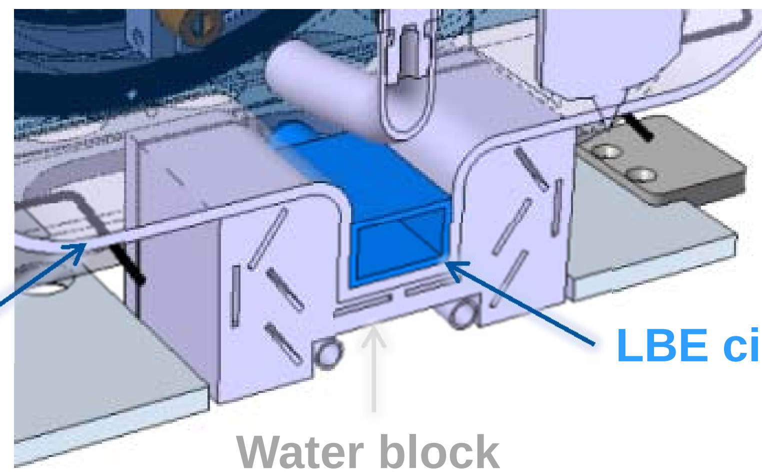
* D. Houngbo, SCK-CEN

Proposed design – HEX (4)

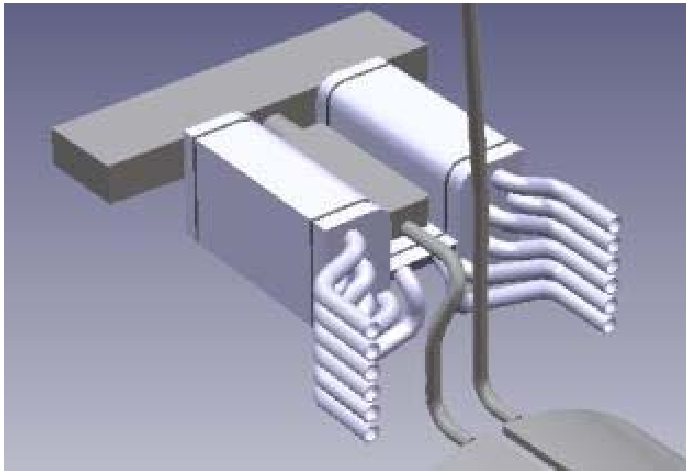


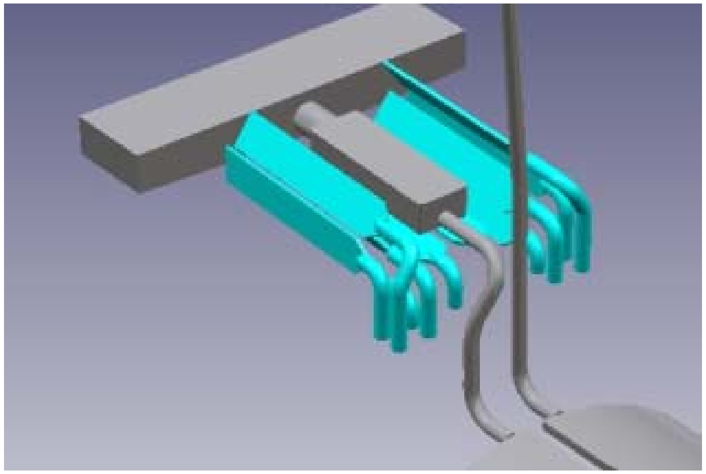


“Casserole” in between water and LBE



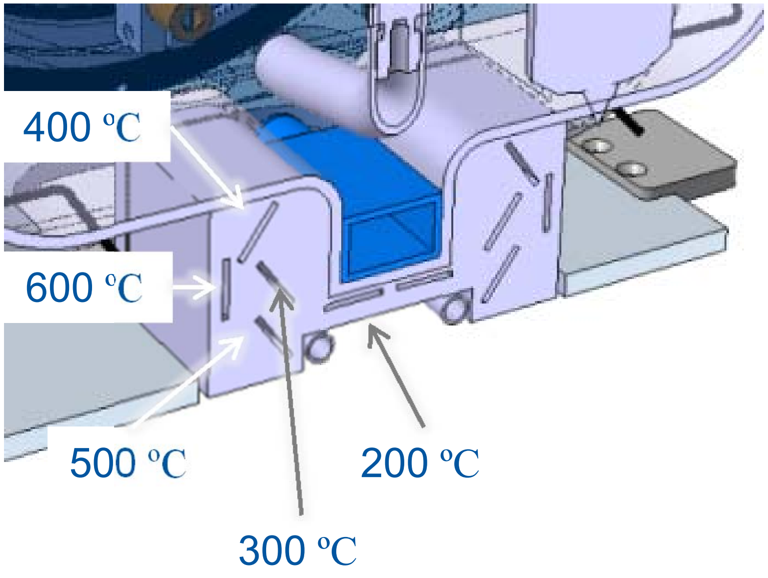
Proposed design – HEX (5)





5 working temperatures defined in step of 100 ºC
5 inlets on each side
1 outlet on each side

For each working temperature defined, only two inlets are used.



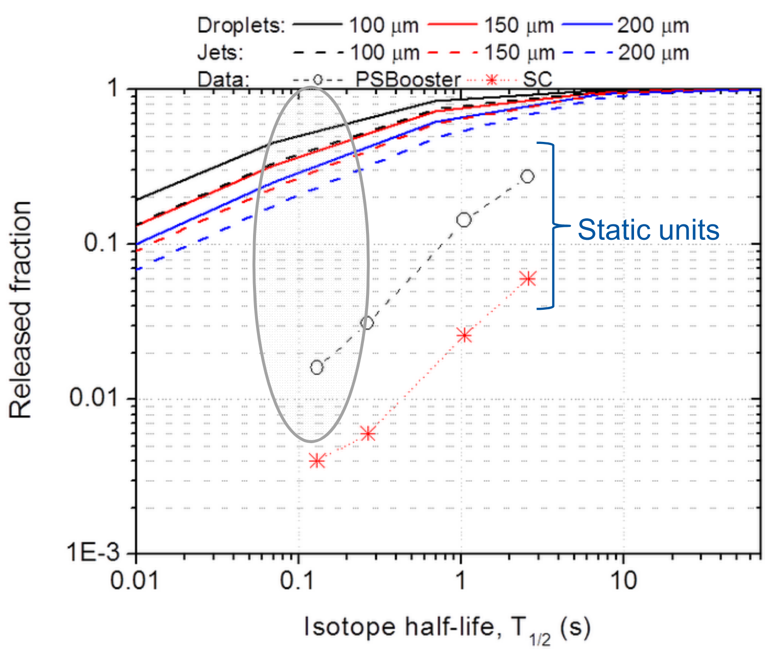
Diffusion simulations …

Diffusion simulations (1)

- Diffusion: model from Fujioka et al. (NIM 186 (1981) 409)

$$f(\hat{t}) = \frac{2.n}{\pi^2}\sum_{m=1}^{\infty}\frac{1}{c_{m+}{}^{\tau_D}/_{\tau_N}}$$

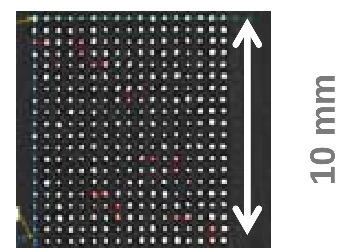
With $\tau_D = characteristic\ diffusion\ time = {}^{a^2}/_{\pi^2 * D}$
$a = radius\ of\ droplet$ $D = diffusion\ coefficient\ of\ tallium\ in\ LBE\ at\ 600\ ℃$
$\tau_N = mean\ life\ of\ isotope$



Courtesy T. Mendonca, CERN

- Diffusion optimized for droplets shape
- Need a grid on the container to create the shower

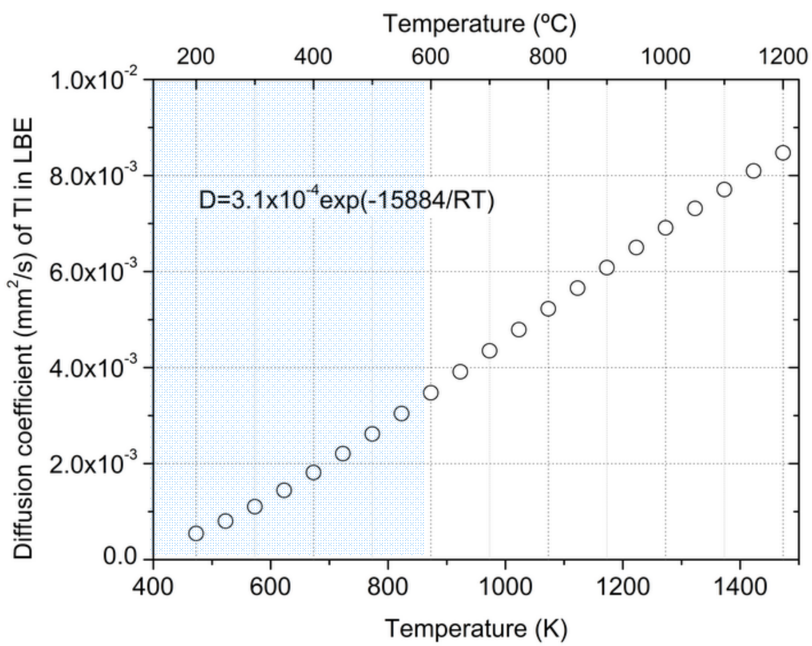
Holes diameter: 0.1 mm,
Thickness plate: 0.5 mm
Material: SS304L



Diffusion simulations (2)

- Diffusion

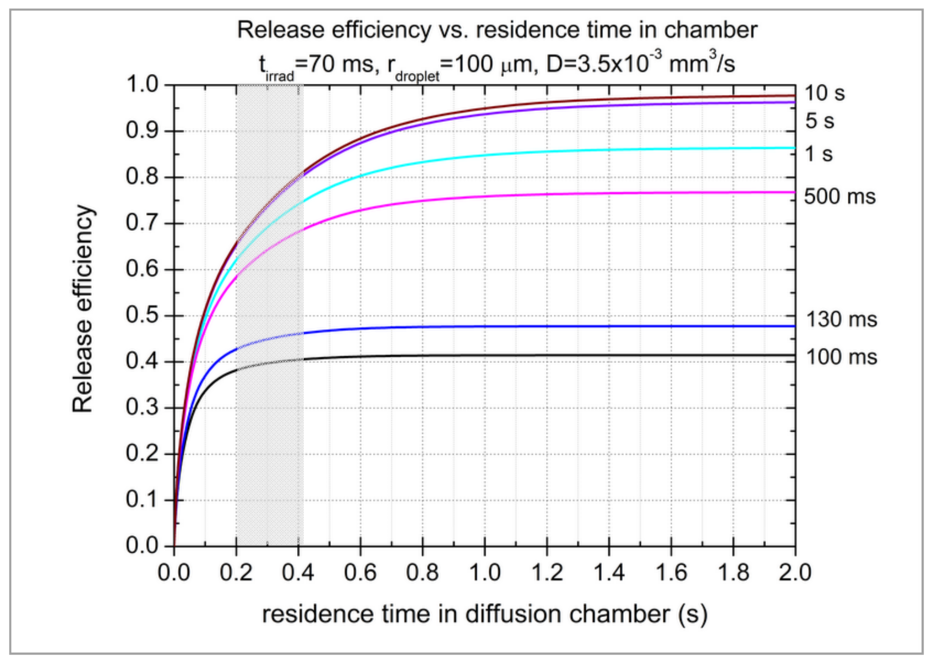
Improvement of diffusion with temperature



Maximum operating temperature limited by vapor pressure of LBE

^{177}Hg ($T_{1/2}$= 130 ms) as reference:

- ➢ Increasing droplet radius will decrease the released fraction
- ➢ Diffusion efficiency of 38% for 100 ms, 44% for 200 ms in the diffusion chamber



Courtesy T. Mendonca, CERN

Diffusion simulations (3)

- Conclusions
  - Diffusion efficiency is improved with:
    - Droplet shape
    - Temperature
    - Falling time of the droplets (lower outlet velocity, longer falling distance)

Numerical results…

Numerical results – HEX (1)

- Need to keep the target at the desired working temperature for temperature ranging from 200 ºC till 600 ºC

Power contributions:

+	-
Beam	Pump
Pump	Radiation
-	HEX

Beam	330 to 990 W
Pump	2 200 W

Pump power extraction

Temperature (° C)	**200**	**300**	**400**	**500**	**600**
Power losses (W)	40	80	150	260	500

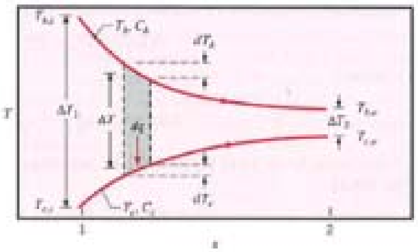
Radiation power extraction

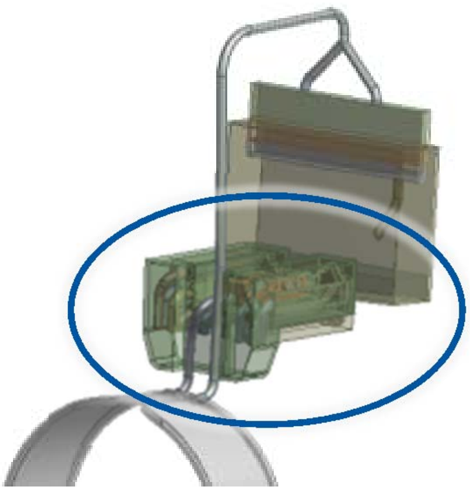
Temperature (° C)	**200**	**300**	**400**	**500**	**600**
Power losses (W)	36	87	150	260	420

Power (W)		200		300		400		500		600	
		min	max	min	max	min	max	min	max	min	max
+	beam	330	990	330	990	330	990	330	990	330	990
	pump	2 200									
-	radiation		36		87		150		260		420
	pump		40		80		150		260		500
	HEX	2 454	**3 114**	2 363	**3 023**	2 230	**2 890**	2 010	**2 670**	1 610	**2 270**

Numerical results – HEX (2)

- Assessment of HEX behavior with CFX





Dimensioning of an HEX:

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

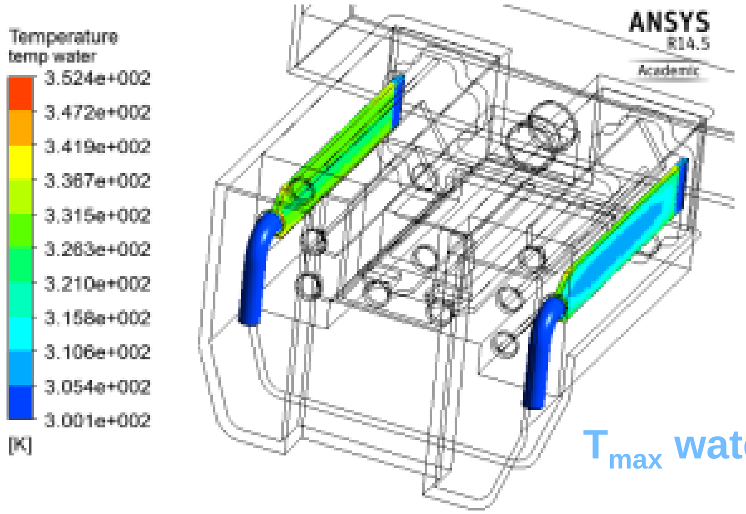
Power to be extracted by HEX									
200		**300**		**400**		**500**		**600**	
min	max	min	max	min	max	min	max	min	max
2 454	3 954	2 363	3 863	2 230	3 730	2 010	3 510	1 610	3 110

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

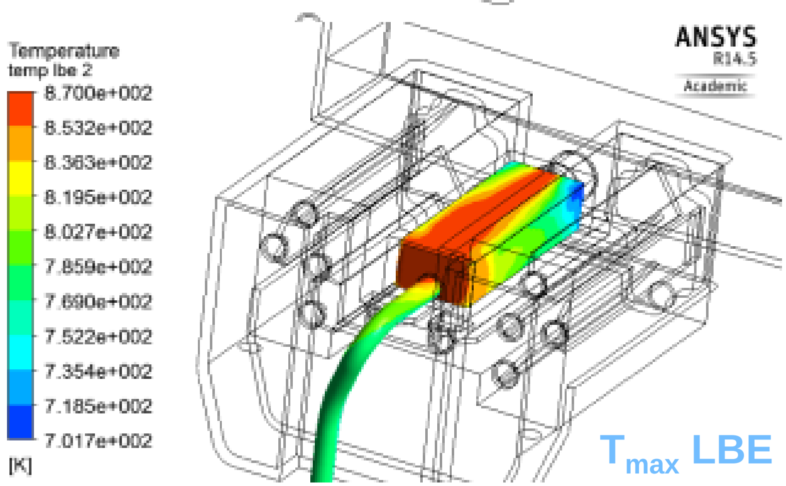
Problem: The HEX must extract less power @ 600 ºC than @ 200 ºC BUT power extracted depend on the surface of exchange, the average heat exchange coefficient and the temperature of both fluids involved -> **need of a variable HEX**!

Numerical results – HEX (3)

- Example @ **600 ºC**



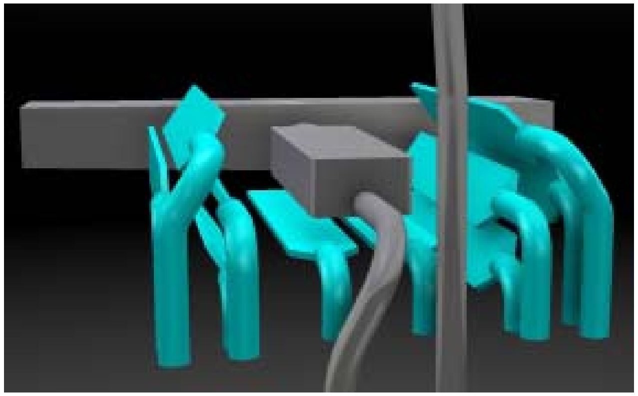
T_{max} water = 79 ºC



T_{max} LBE = 597 ºC

Summary of results:

	T_{max} water (ºC)	**$P_{extracted}$ (W)**
200 ºC	78	3 180
300 ºC	83	3 050
400 ºC	73	2 890
500 ºC	68	2 820
600 ºC	79	2 650



Numerical results – HEX (4)

- Conclusions

  - Temperature and power extraction are in the proper range (values have been checked over the full range of temperature, from 200 ºC up to 600 ºC)

  - Further analysis must be computed considering bad thermal contact between the different parts

  - Prototype will validate the design

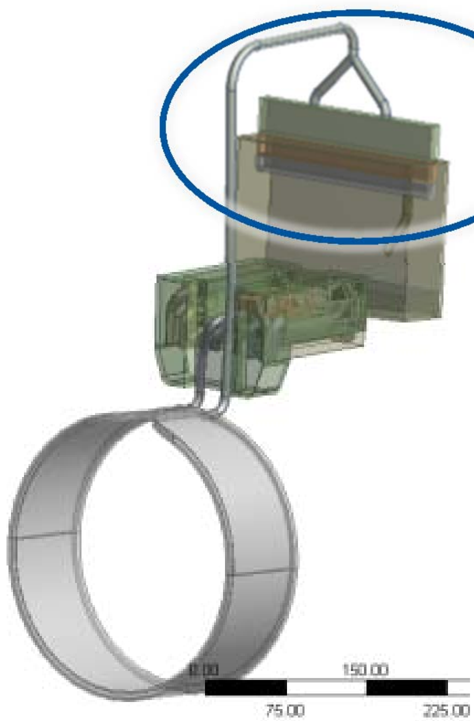
  - **Temperature controlled with heating elements installed all along the loop**

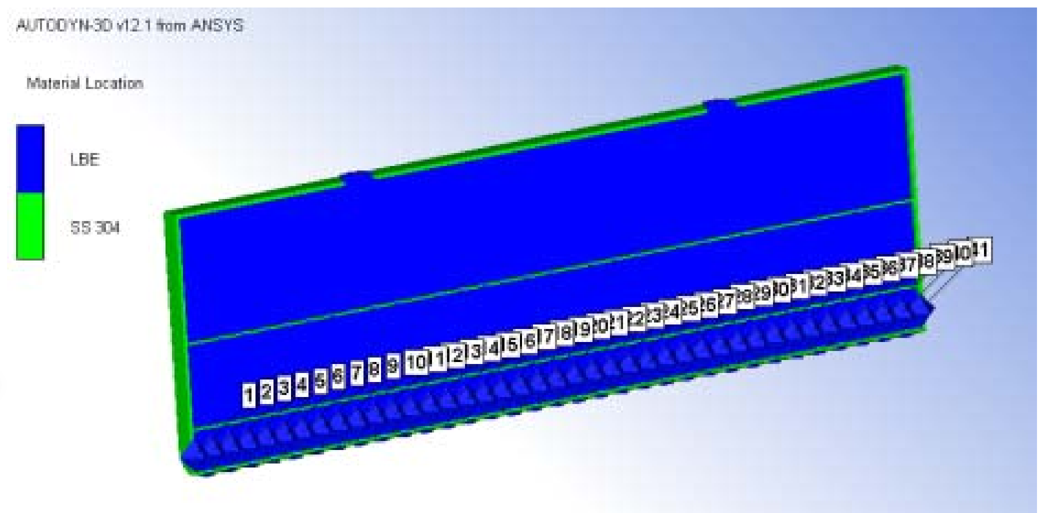
Numerical results – Beam impact (1)

- Assessment of beam impact with Fluka & Ansys Autodyn
- Geometry considered

Parameters	Units	Proton values
Energy	GeV	1.4
Frequency	Hz	0.8
Number of bunch	-	3
Bunch spacing	μs	16
Bunch width	ns	200
Total number of particles	p^+	2.4 e13
Power deposited	W	985

Isolde beam parameters



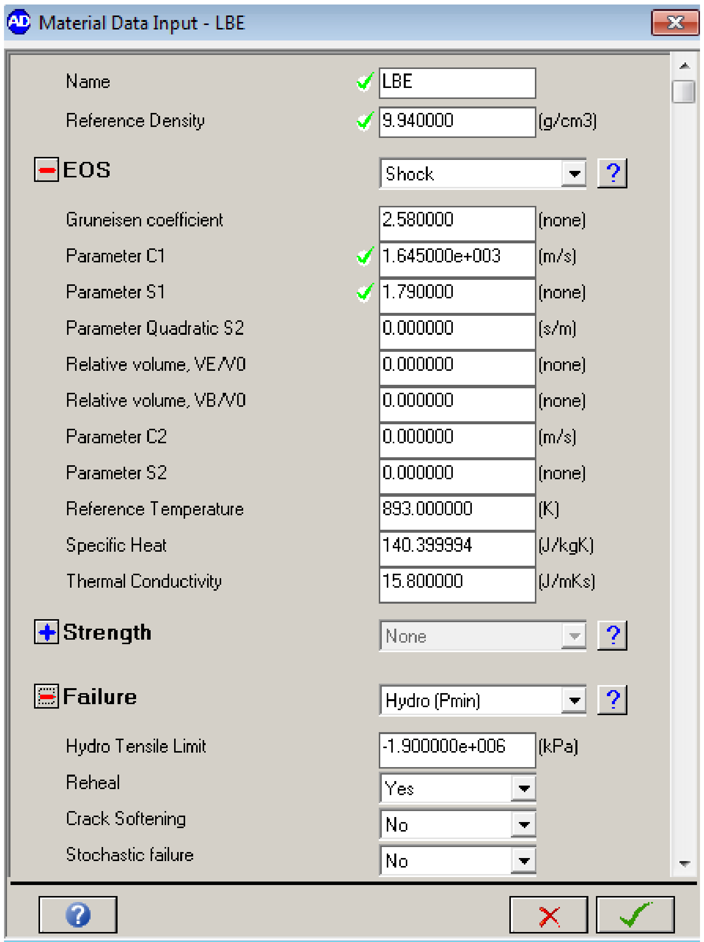


Container: Stainless Steel 304, solid part, Lagrangian part
Liquid: LBE, SPH elements

Use of 40 gauges along beam axis

Numerical results – Beam impact (2)

- Material definition



- Standard variables @ 600 ºC.
  - ρ, Cp, k

- Shock EOS (Linear model)

  Gruneisen model

$$U_S = C_0 + S * \mu_p$$
$$S = \frac{1}{2} * (1 + \Gamma)$$
$$\Gamma = \frac{\alpha * K_S}{\rho * C_p}$$

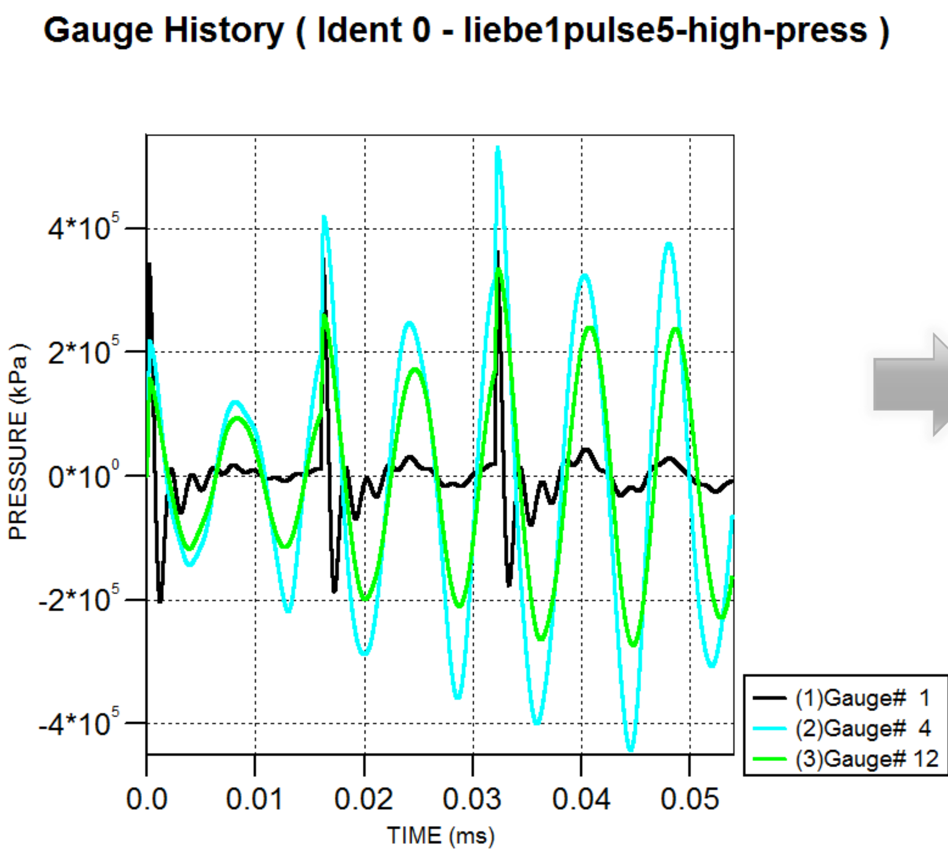
U_s = shock velocity, Γ = Gruneisen coefficient, μ_p = particle velocity, C_0 and S = fitting parameters

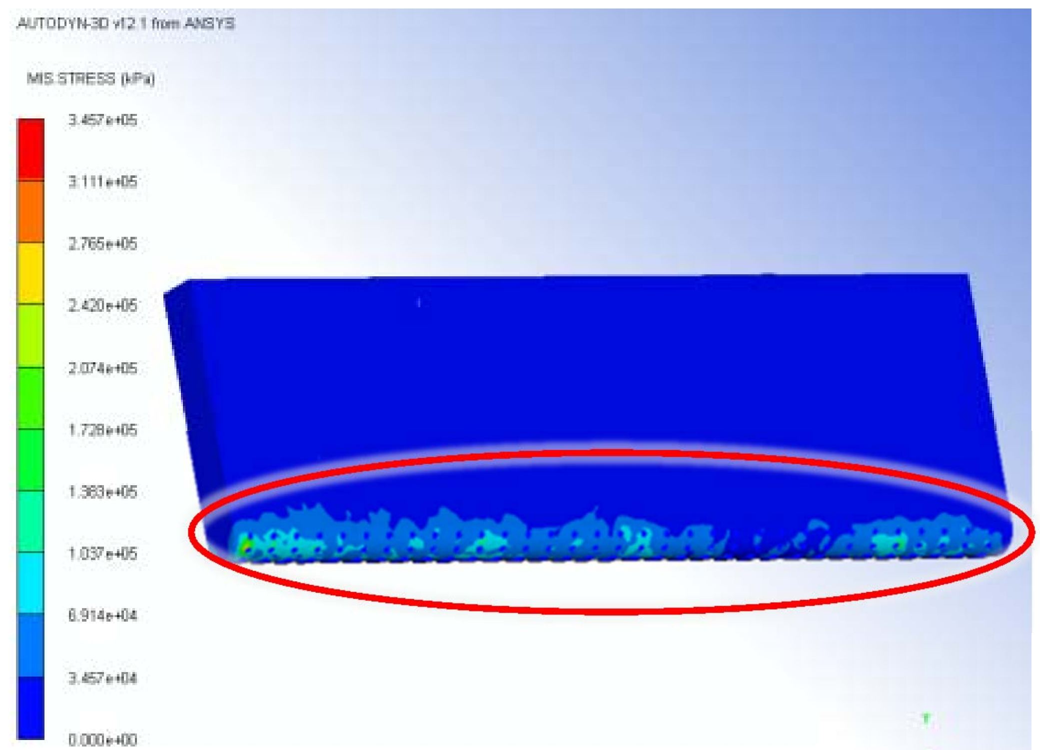
- Failure mechanism
  - Hydrodynamic tensile limit
  - 2 values considered: **-150 kPa** and **-1.9 GPa** (no value available for LBE)

Courtesy E. Noah, Un Geneva

Numerical results – Beam impact (3)

- Analysis for 50 μs (1 pulse = 32.6 μs) – **under** hydrodynamic tensile limit



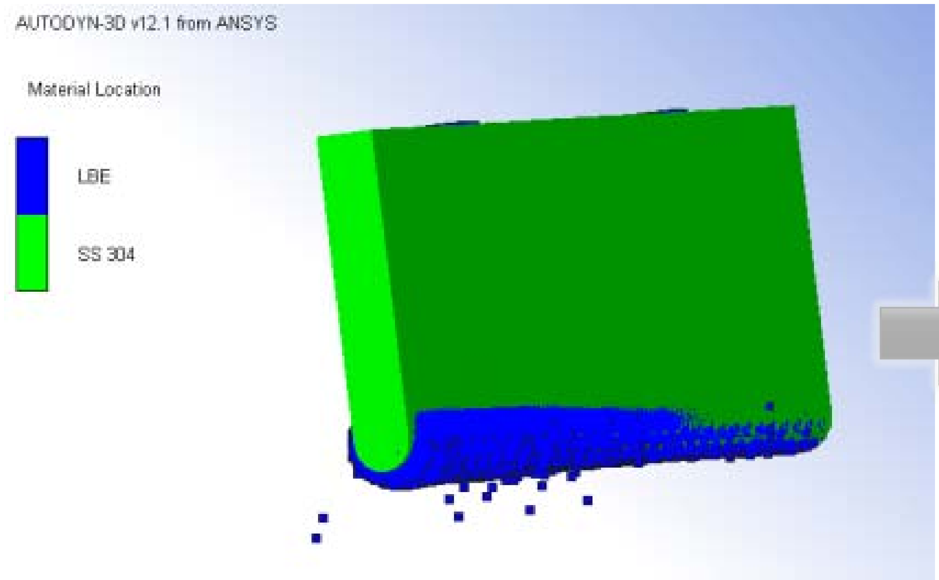


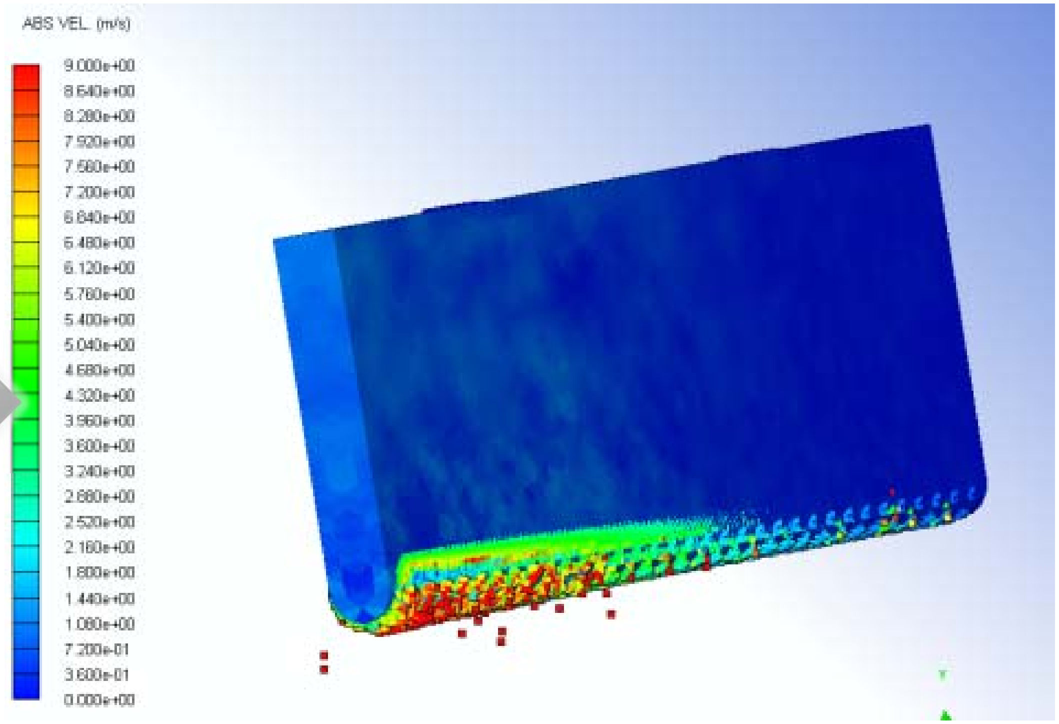
Shock waves deposit energy onto the weakest point of the container (grid part).

Stresses up to 350 MPa (Yield = 390 MPa) in less than 1 ms.

Numerical results – Beam impact (4)

- Analysis for 50 μs (1 pulse = 32.6 μs) – **over** hydrodynamic tensile limit





*Deformation scale: *9*

Cavitation in the liquid will induce splashing of the LBE and projection of droplets with very high velocity in the diffusion chamber.

Numerical results – Beam impact (5)

- Conclusions & Outlook
  - The geometry needs an improvement to avoid resonant shock waves
  - Impact of beam onto the container should be further investigated:
    - Negligible impact expected
    - Need more detailed simulation to prove it
  - Simulation must be computed for longer time

Conclusion & next steps…

Conclusion & next steps

- Preliminary design is available, under optimization
- Test of the Heat Exchanger foreseen
- Optimization of the irradiation container under beam impact on-going
- Off-line tests scheduled in the near future

Thank you for your attention!

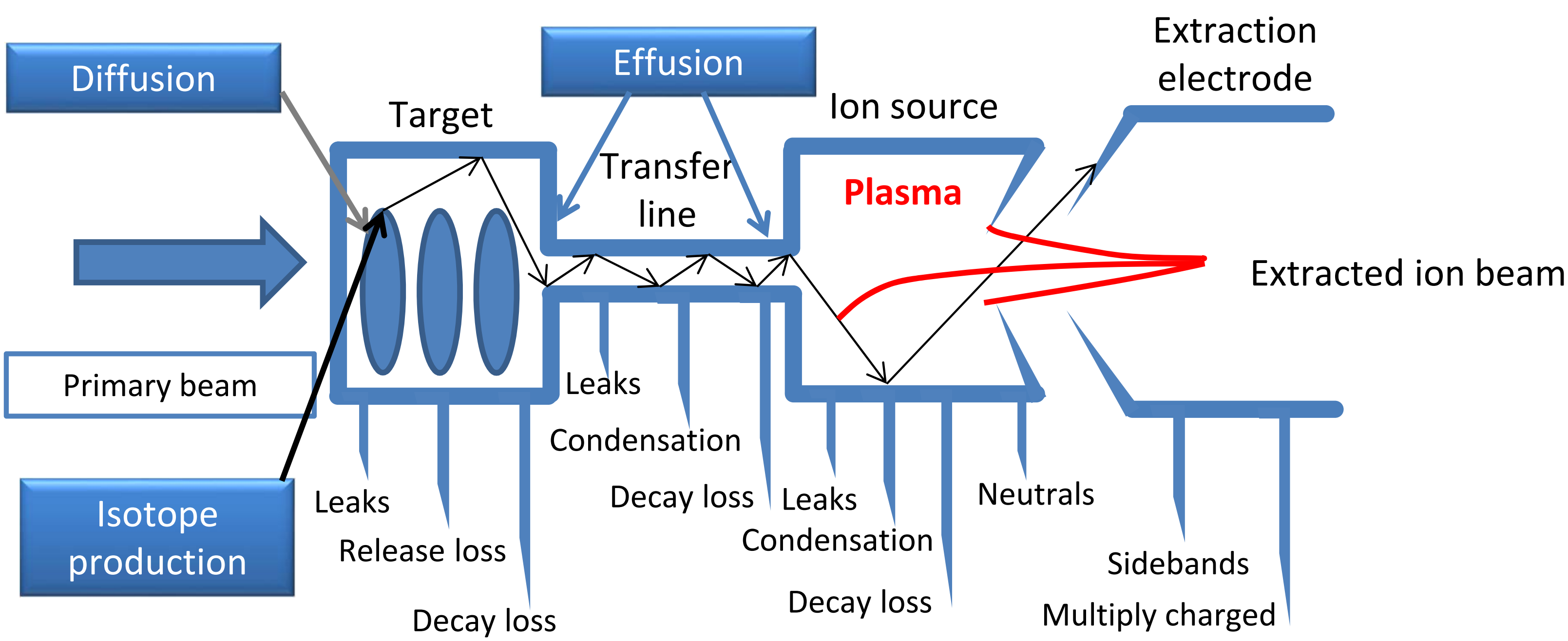
Thanks to all the contributors…

- V. Barozier
- A. P. Bernardes
- K. Kravalis
- F. Loprete
- S. Marzari
- R. Nikoluskins
- F. Pasdeloup
- A. Polato
- H. Znaidi
- … (and many others…)

Back up slides…

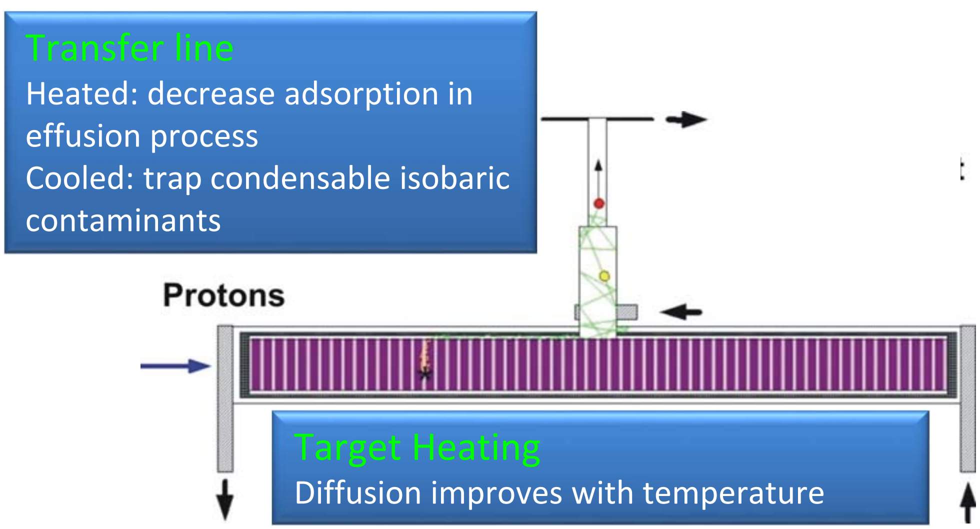
Introduction/context (4)

- **Specificity of RIBs (Radioactive Ion Beam) production via the ISOL (Isotope separation on-line) technique:** *Isolde target unit*



Introduction/context (5)

- **Specificity of RIBs (Radioactive Ion Beam) production via the ISOL (Isotope separation on-line) technique:** *Isolde target unit*



Radioactive ion beam (RIB) intensity:

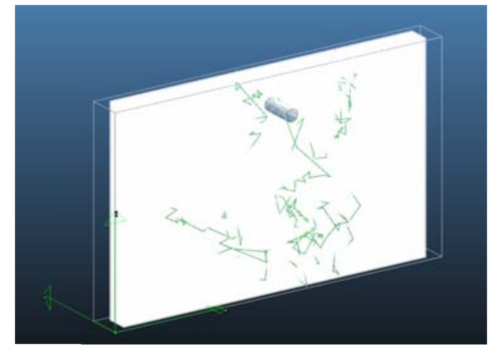
RIB intensity [$s^{-1}\,\mu A^{-1}$] — Target density [atom cm^{-2}] — Diffusion+effusion efficiency

$$I_{RIB} = \left(\sigma_{prod} \cdot N_{target} \cdot I_{prim-beam}\right) \varepsilon_{diff+eff} \cdot \varepsilon_{ion}$$

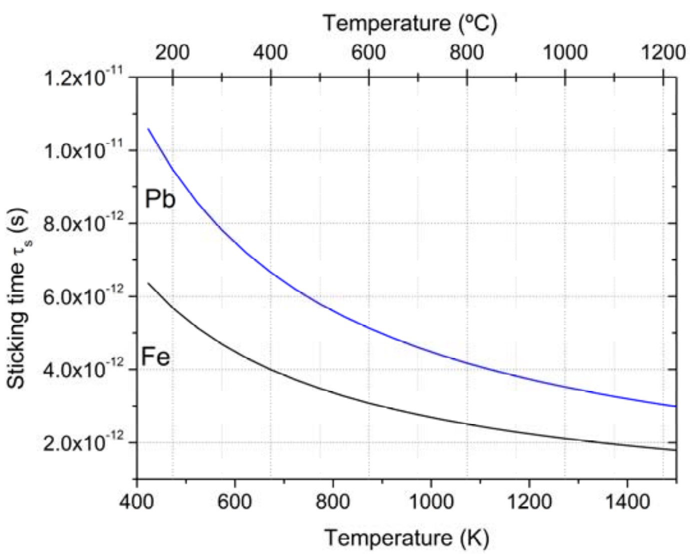
Cross section [cm^2] — Proton beam intensity [$s^{-1}\,\mu A^{-1}$] — Ionization efficiency

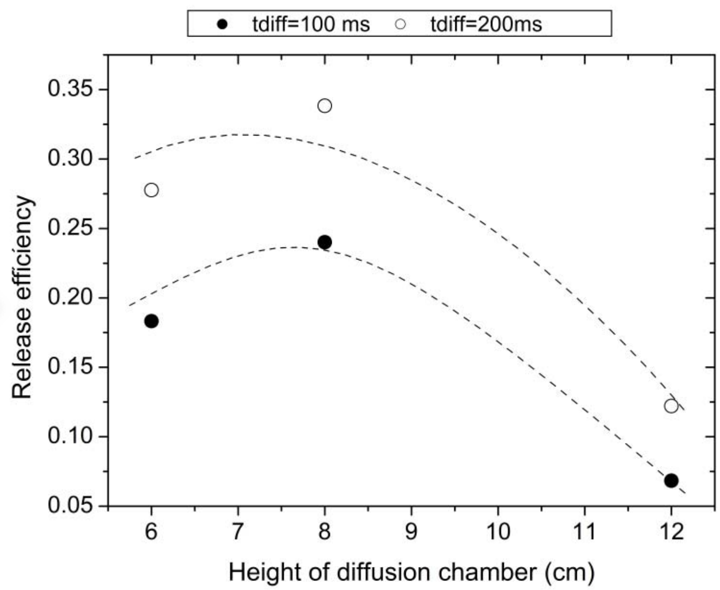
Diffusion/effusion simulations (3)

- Effusion: Monte Carlo
  - The effusion efficiency is dependent on the geometry of the container/diffusion chamber, the sticking time, the mean free path and number of collisions with droplets and surface of containment.



Sticking times of ~10^{-12} s – negligible effect in efficiency



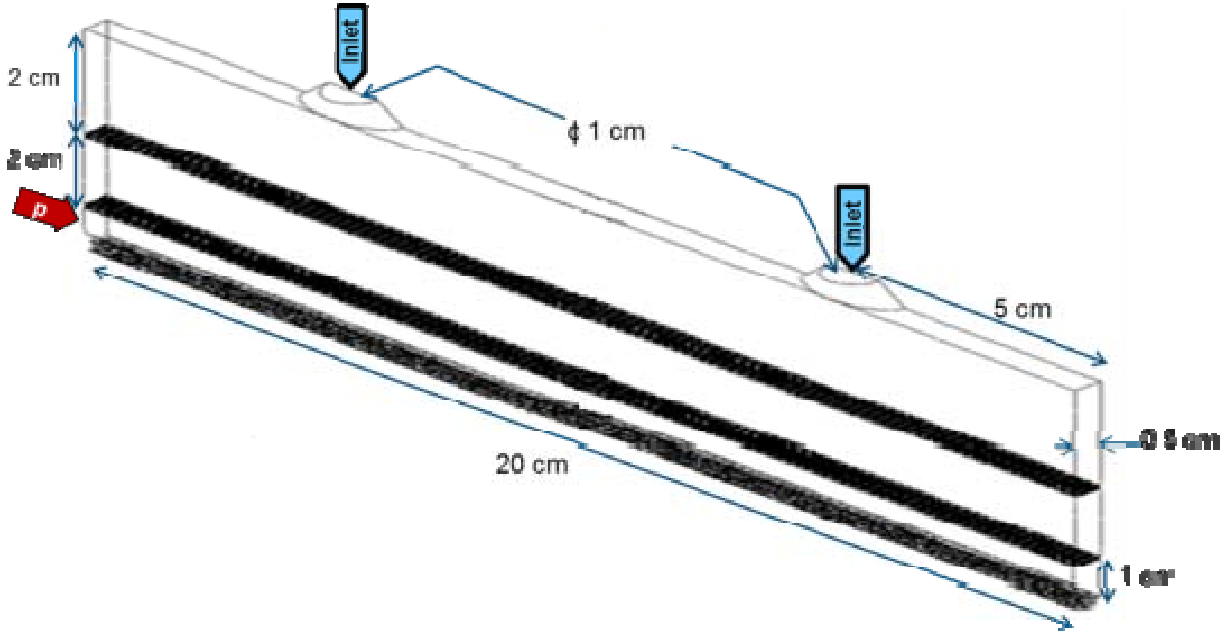


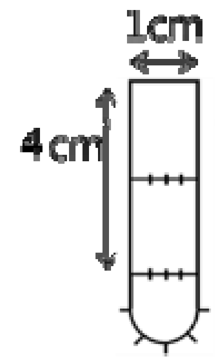
- Effusion release efficiencies between 22% and 34% for residence times in the diffusion chamber between 100-200 ms
- Estimated release efficiencies (diff+eff) of ~ 8% for 100 ms and ~ 15% for 200 ms.

Thanks to T. Mendonca

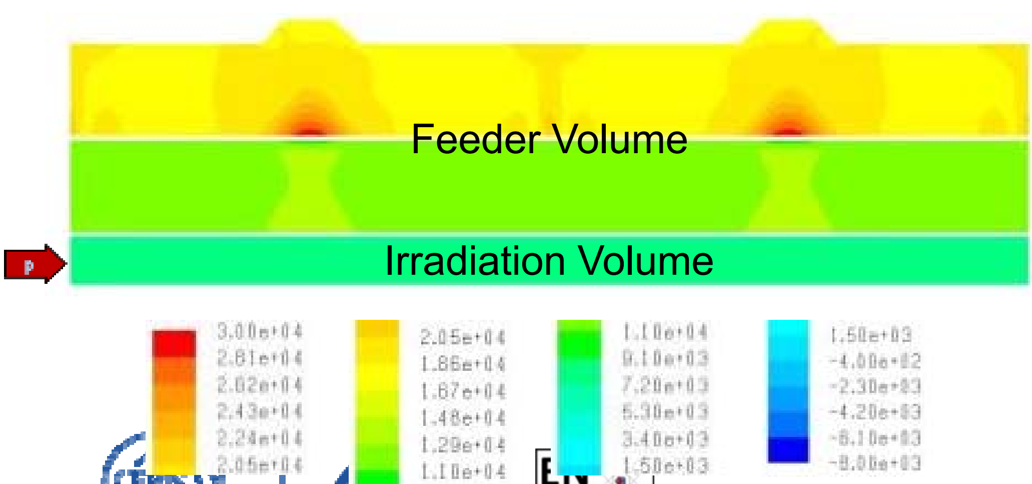
Concept 5 - Results

- 1 kg of LBE in Feeder Volume,
- 2 feeder grids of 2520 apertures
- 1-mm or 0.5-mm thick feeder grids
- 2520 evacuation apertures
- 1.5-m/s inlet velocity
- ~0.2-bar pressure drop
- Stable uniform flow between 500 K – 1500 K

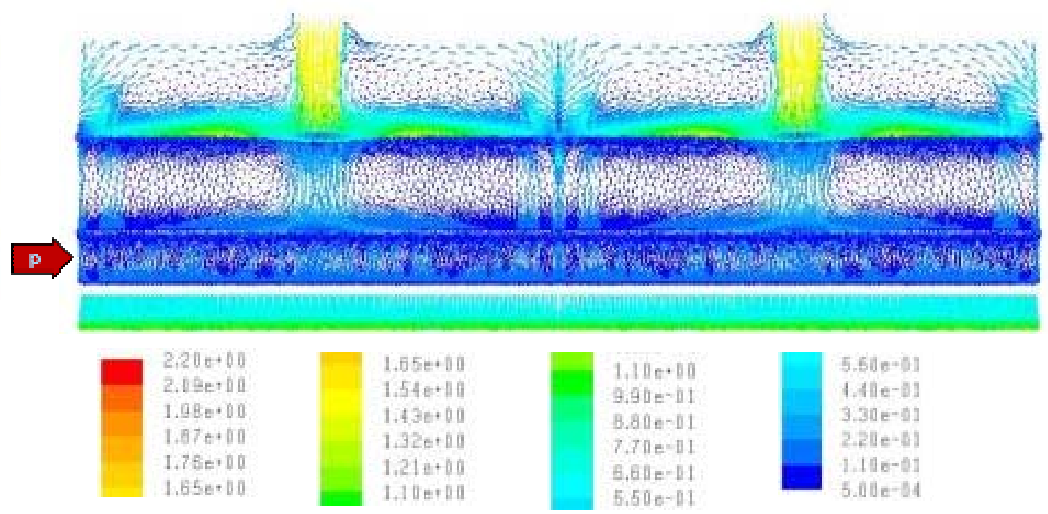




Static-Pressures (Pa)



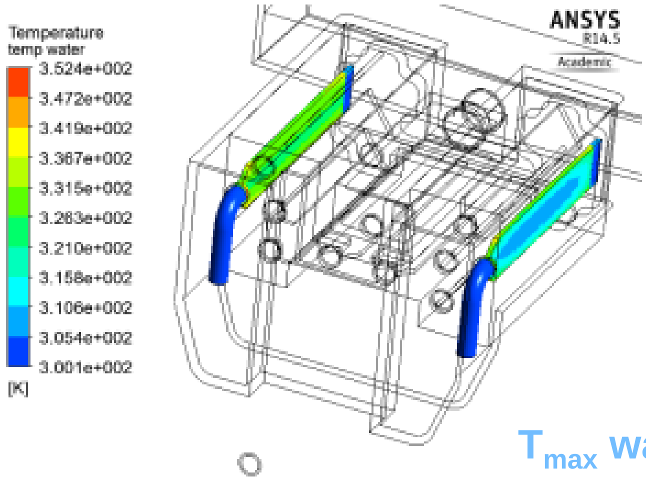
Velocity Vectors (m/s)



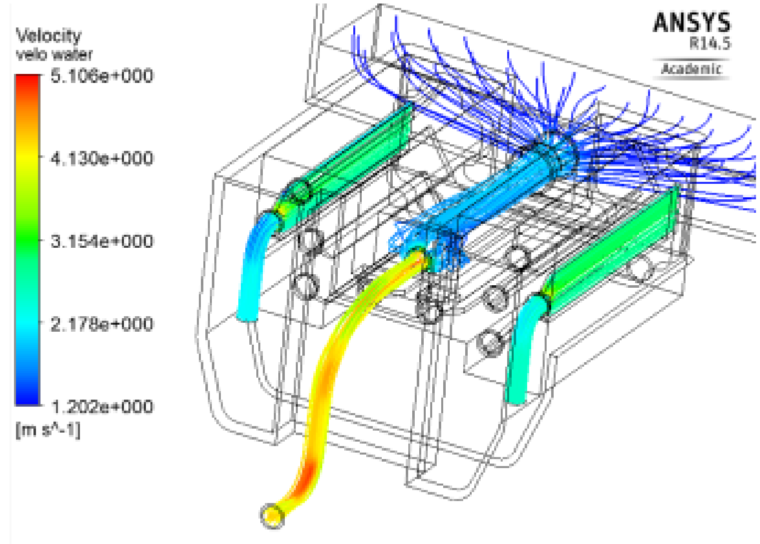
Heungbo D.- *LIEBE project, Computational Fluid Dynamics (CFD) analysis*.- Workshop on Radioactive Ion Beam Production and High-Power Target Stations.- Mol, Belgium, 16-18 September 2013.- [Presentation]

Numerical results – HEX (3)

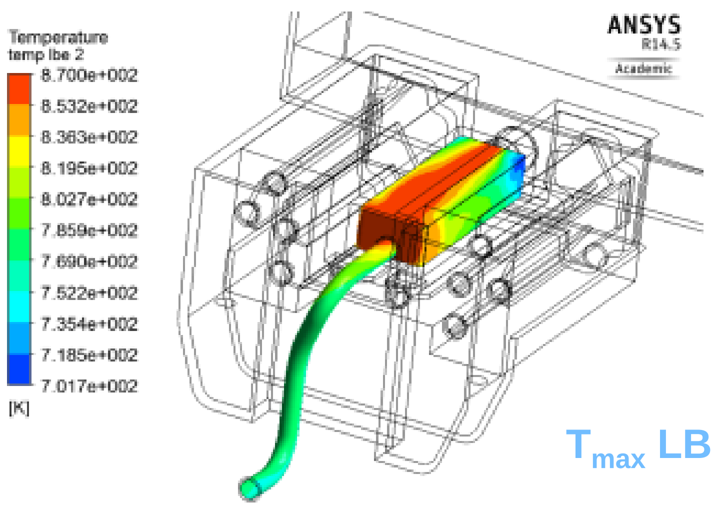
- Example @ **600 ºC**



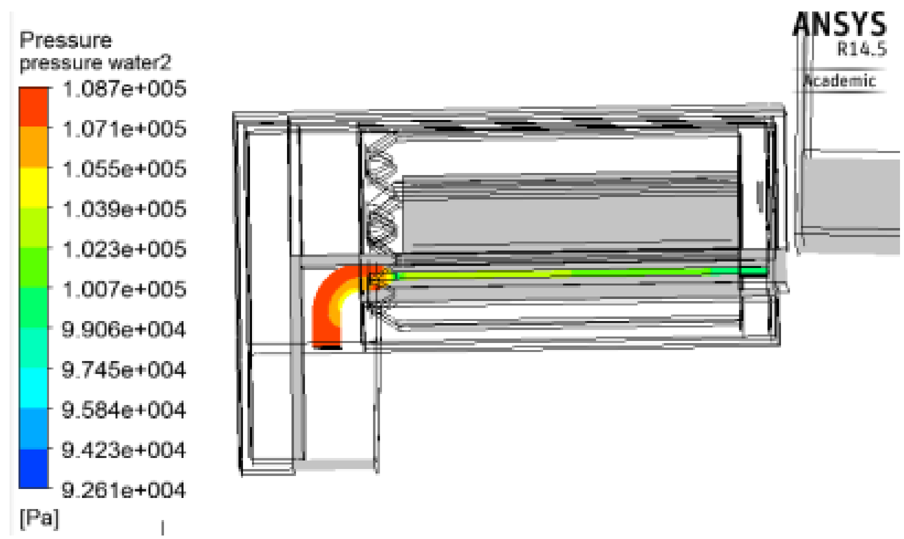
T_{max} water = 79 ºC



Velocity in water and LBE



T_{max} LBE = 597 ºC



Pressure in water for case LBE @ 200 ºC

Numerical results – HEX (4)

Summary of results:

	T_{max} water (ºC)	$P_{extracted}$ (W)
200 ºC	78	3 180
300 ºC	83	3 050
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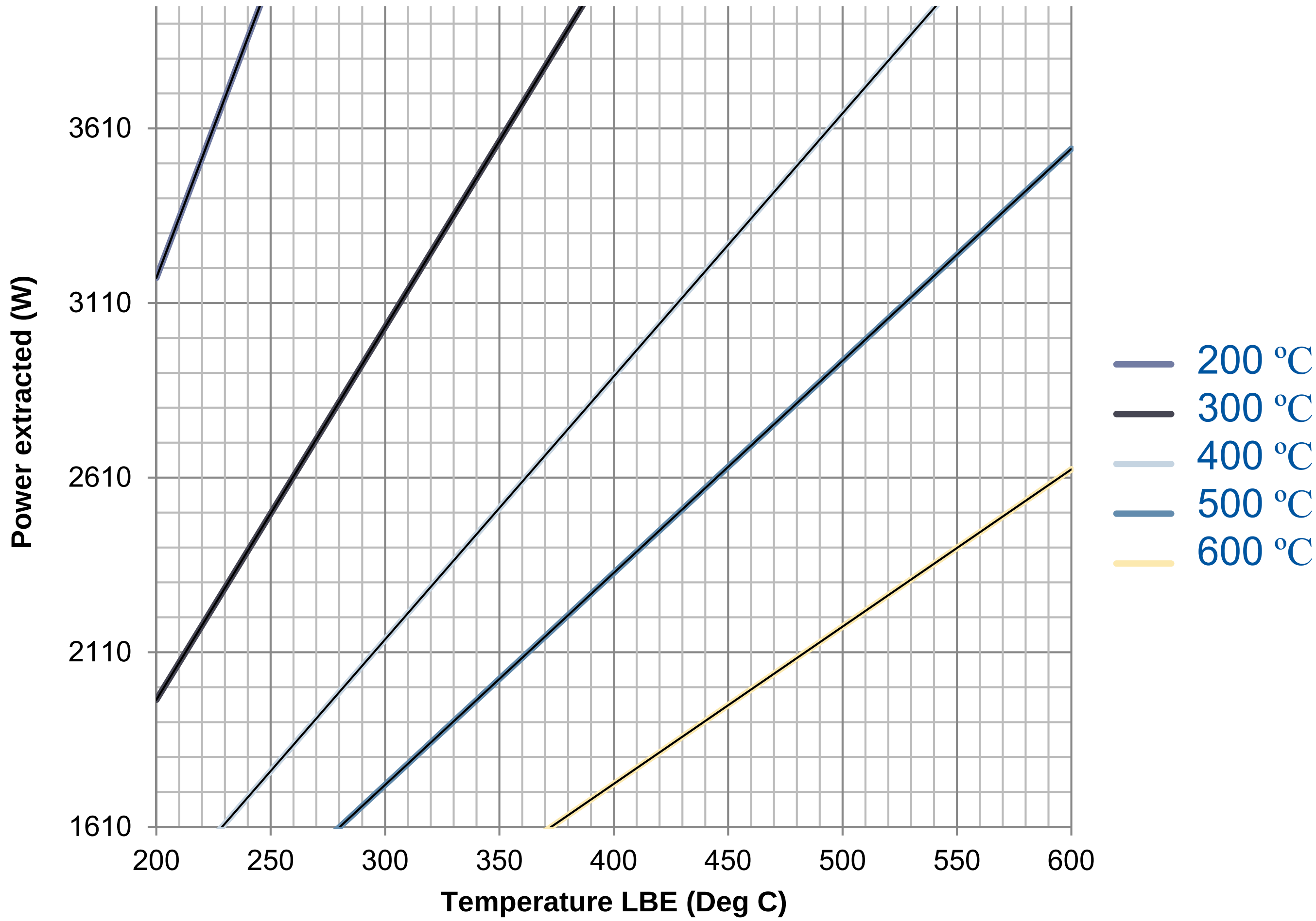

Power to be extracted by HEX									
200		300		400		500		600	
min	max	min	max	min	max	min	max	min	max
2 454	3 954	2 363	3 863	2 230	3 730	2 010	3 510	1 610	3 110