Vacuum Design for PUMA

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Data contributed by Alexandre Obertelli, Alexander Schmidt, Jonas Fischer and Anke Stoeltzel

Outline

- ☐ Introduction and motivation
- ☐ PUMA trap
- ☐ PUMA at ELENA
- ☐ PUMA at ISOLDE
- ☐ Summary

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What does PUMA mean?

antiProton
Unstable
Matter
Annihilation

Collaboration

UAM

CERN

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cea

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Laboratoire Kastler Brossel
Physique quantique et applications

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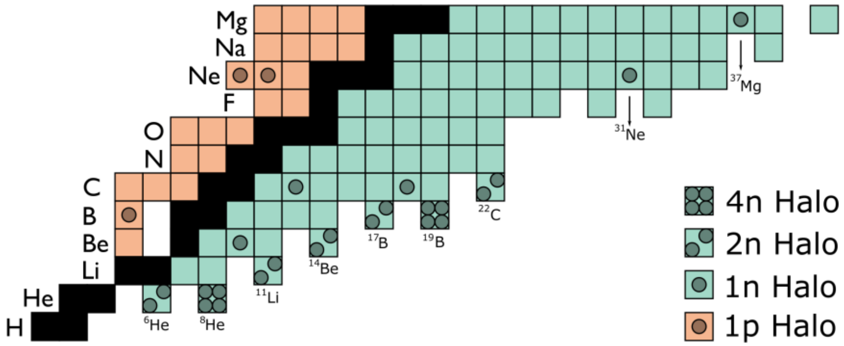
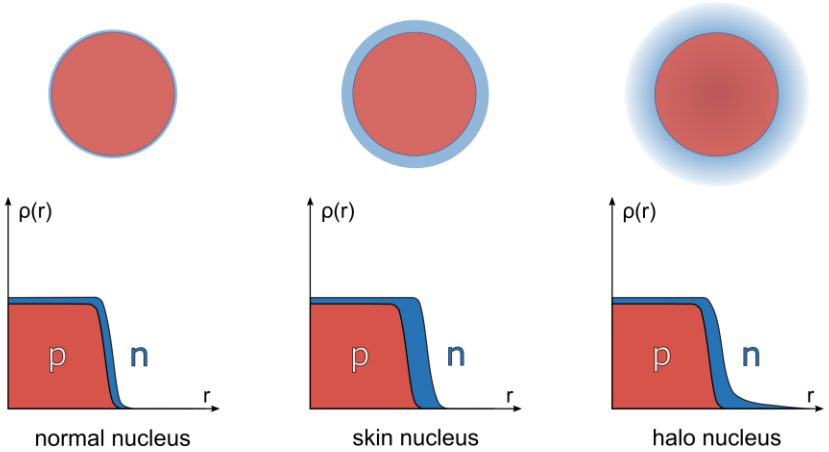
Motivation and objectives

Characterization of neutron halos and neutron skins

Objectives [1]:

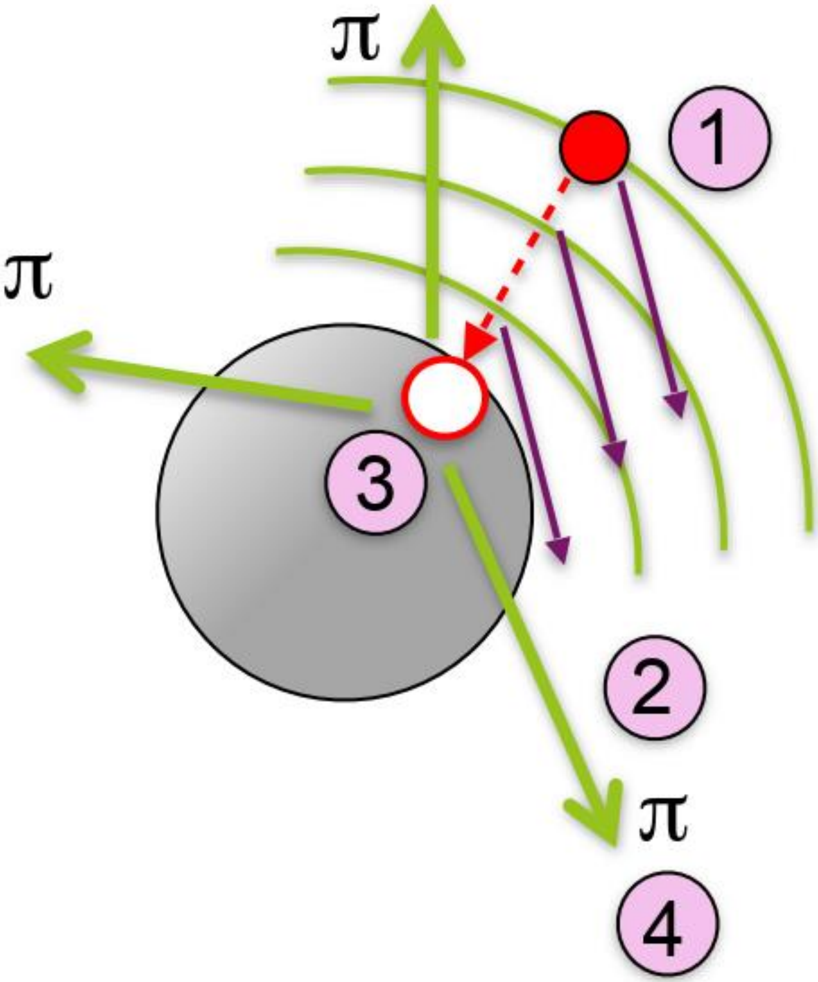
- ☐ to provide a new observable for <u>radioactive nuclei</u> that characterises the neutron to-proton asymmetry of their density tail, namely the neutron-to-proton annihilation ratio,
- ☐ to characterize the density tail of known halos and neutron skins with this new method,
- ☐ to evidence new proton and neutron halos,
- ☐ to understand the development of neutron skins in medium-mass nuclei along isotopic chains.



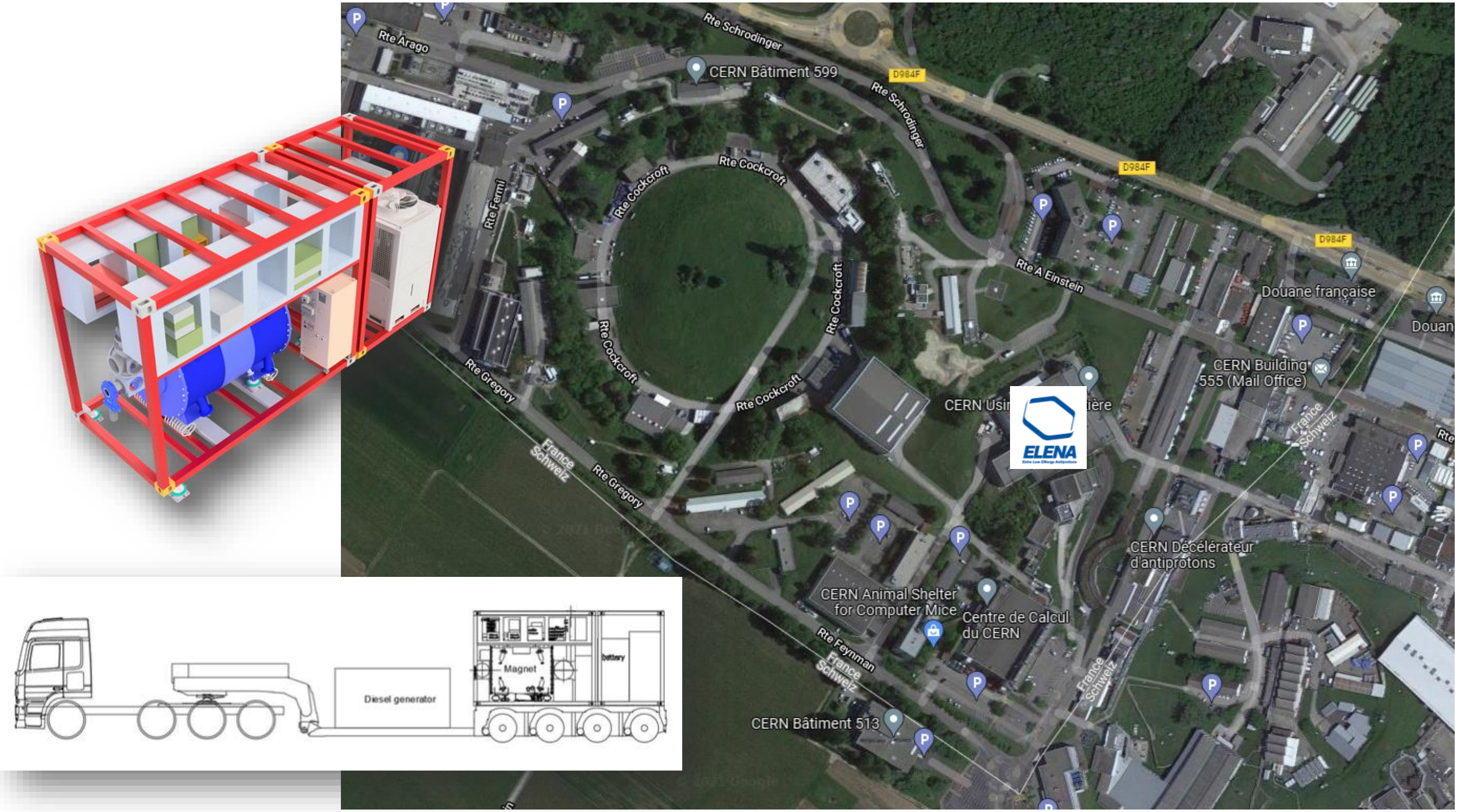


Antiproton annihilation with nuclei

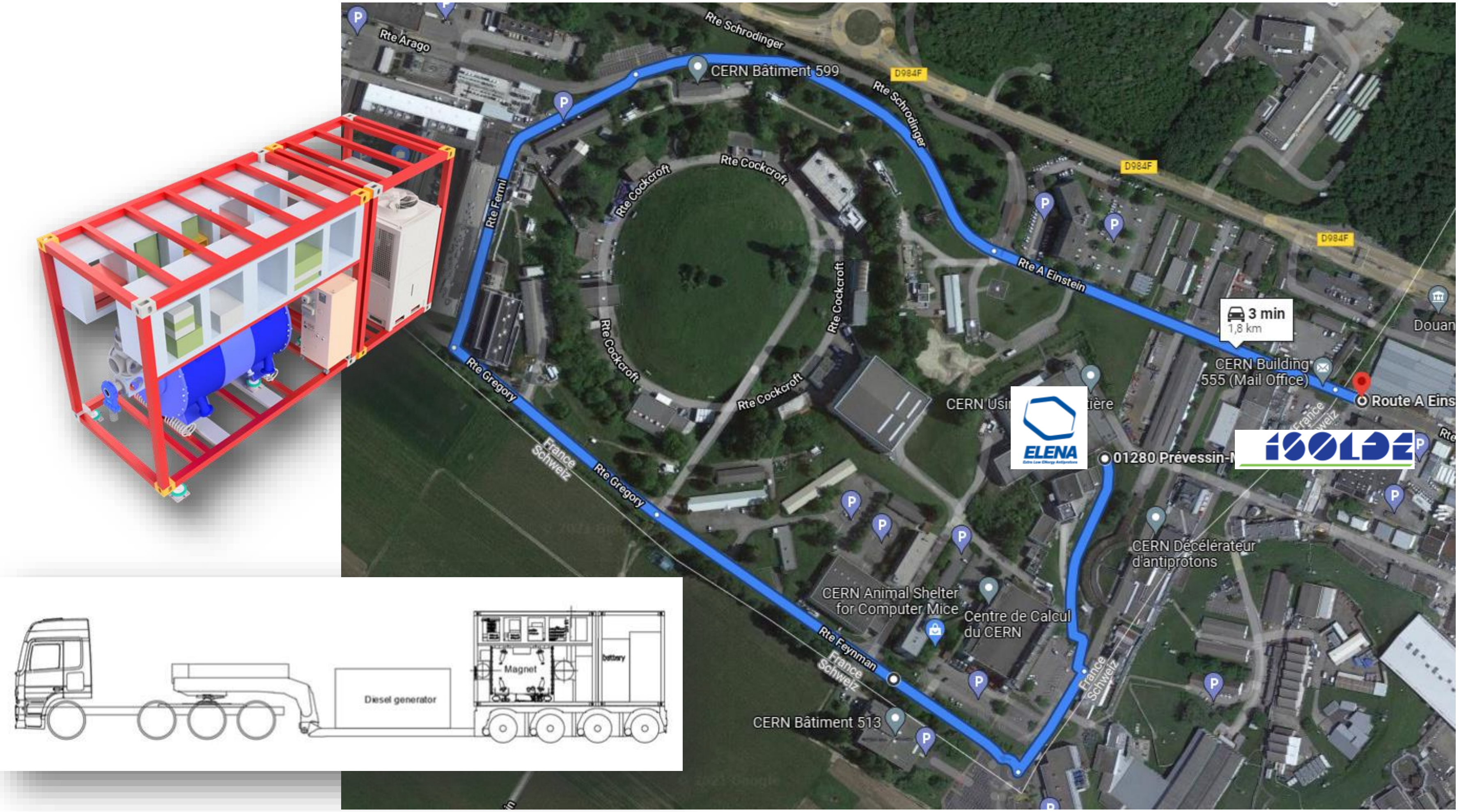
1. Antiprotons captured into atomic orbital.
2. Decay into lower atomic orbital. X-rays & Auger electrons
3. $\bar{p}$ reaches at the density tail of nuclei. Annihilate with p or n.
4. Annihilation product: Multiple pions and residual nucleus



$\bar{p}$ Trip


Rte Arago
CERN Bâtiment 599
Rte Schrodinger
D984F
Rte Schrodinger
Rte Fermi
Rte Cockcroft
Rte Cockcroft
Rte Cockcroft
Rte Cockcroft
Rte Cockcroft
Rte A Einstein
Douane française
Douan
CERN Building
555 (Mail Office)
Rte Gregory
France
Schweiz
Rte Gregory
CERN Usin
ière
ELENA
CERN Décélérateur
d'antiprotons
CERN Animal Shelter
for Computer Mice
Centre de Calcul
du CERN
Rte Feynman
CERN Bâtiment 513
Diesel generator
Magnet
battery

$\bar{p}$ Trip


Rte Arago
Rte Schrodinger
CERN Bâtiment 599
D984F
Rte Fermi
Rte Cockcroft
Rte A Einstein
3 min
1,8 km
Douan
CERN Building 555 (Mail Office)
Route A Eins
Rte Gregory
France Schweiz
CERN Usi
ière
ELENA
01280 Prévessin-M
ISOLDE
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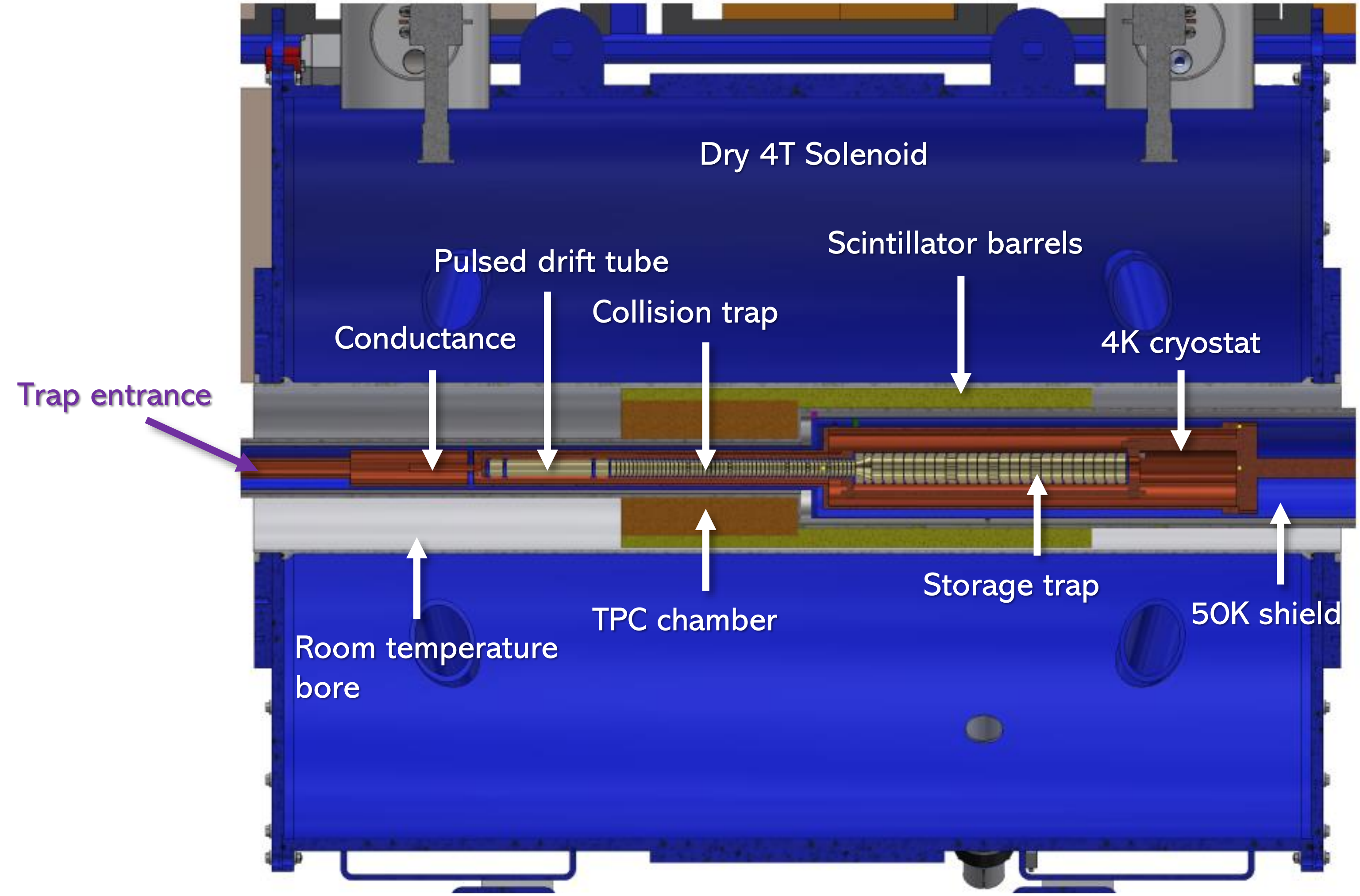
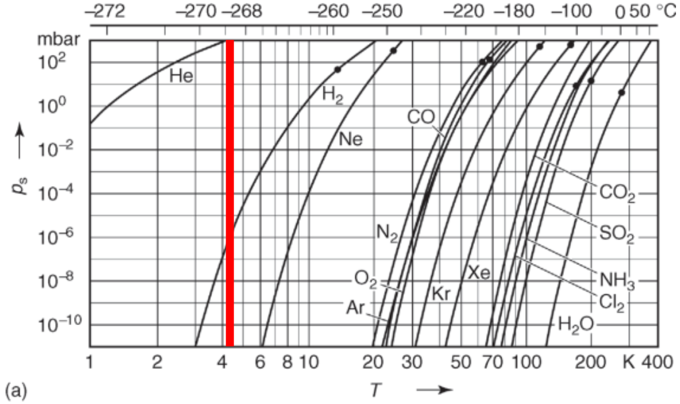
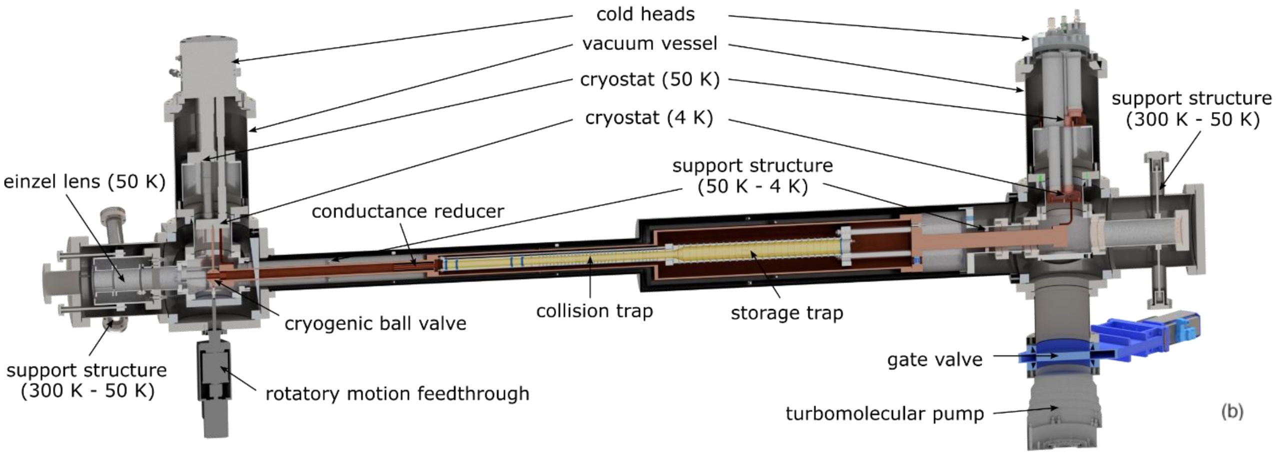
PUMA Trap

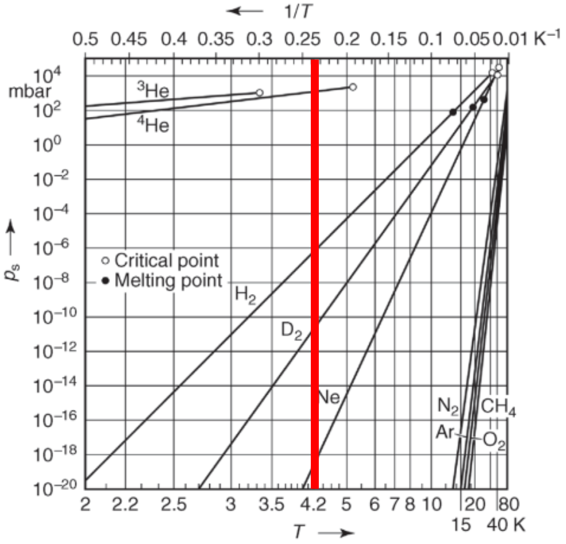

Dry 4T Solenoid
Scintillator barrels
Pulsed drift tube
Collision trap
Conductance
4K cryostat
Trap entrance
Storage trap
50K shield
TPC chamber
Room temperature bore

Pumping concept

- ❑ Pumping on cold surfaces (4.2K) of gases entering the trap
- ❑ Maximum allowed pressure at the entrance of trap ⇒ Defined by expansion of gas entering the trap
- ❑ Only H_2 and He pressure will evolve with time ⇒ Sub ML coverage
- ❑ Small conductance between the entrance and collision and storage trap.







Ref [6]

PUMA vacuum requirements

Storing 10^9 antiprotons (10^7 as first milestone)

Vacuum level:

- ❑ Antiproton lifetime (>30 days)
- ❑ Low Signal background during measurement

Specifications:

- ❑ $T = 4K$
- ❑ $\tau > 200\ days$
- ⇒ $n_{H_2} \approx 20\ cm^{-3} \rightarrow$

$$\underline{\boldsymbol{P \approx 10^{-17} mbar}}$$

- ⇒ 0.5Hz background (10^7 $\bar{p}$ in collision trap)

From [2]:

$$\sigma_{H_2} = 3\pi a_0^2 \sqrt{\frac{27.2eV}{E_{CM}}}$$

$$a_0 = 5.29 \cdot 10^{-11}\, m$$

$$\Gamma = \frac{1}{\tau} = n_{H_2} v_{rel} \sigma$$

$$v_{rel} = \sqrt{\frac{4E_{CM}}{m_p}}$$

$$n_{H_2} = \frac{\left(6\pi a_0^2 \sqrt{\frac{27.2eV}{m_p}}\right)^{-1}}{\tau} = 3.91 \cdot 10^8 s \cdot cm^{-3} \frac{1}{\tau(s)}$$

Case: ^{132}Sn:
$\sigma = 10^{-15}\ cm^2$, 10^5 ions/bunch ⇒ 100Hz

Case: ^{11}Li:
$\sigma = 10^{-16}\ cm^2$, 200 ions/bunch ⇒ 0.5Hz

Cross section for other gases (He)

Langevin cross section (ion-atom interaction) [2]:

$$\sigma = \pi\sqrt{\frac{2\alpha q_e^2}{(4\pi\epsilon_0)^2 E}} \qquad v_{CM} = \sqrt{\frac{2E}{\mu}} \qquad \mu = \frac{m_1 m_2}{m_1 + m_2}$$

$$\frac{1}{\tau} = n_{gas}\sigma v_{CM} = 2\pi n_{gas}\sqrt{\frac{2\alpha q_e^2}{(4\pi\epsilon_0)^2 \mu}} \quad \Longrightarrow \quad \boxed{n_{gas}\tau = \frac{1}{2\pi}\sqrt{\frac{(4\pi\epsilon_0)^2 \mu}{2\alpha q_e^2}}}$$

$$\alpha'_{H_2} = 0.802 \cdot 10^{-24} cm^3$$

$$\alpha'_{He} = 0.205 \cdot 10^{-24} cm^3$$

$$\tau > 200\ d$$

$$\boxed{\begin{aligned} n_{H_2}\tau &= 4500\ d/cm^3 \Longrightarrow n_{H_2} \approx 20\ cm^{-3} \\ n_{He}\tau &= 7560\ \ d/cm^3 \Longrightarrow n_{He} \approx 40\ cm^{-3} \end{aligned}}$$

- Higher tolerance to He
- No hard limit, but implications in physics program

Adsorption Isotherm

- Low temperature gas adsorption modelled with Dubinin–Radushkevich (DR) isotherm

$$\theta = \exp\left(-\beta\left(RT\ln\left(\frac{P}{P_{sat}}\right)\right)^2\right) = \exp\left(-\left(\frac{T}{T_0}\ln\left(\frac{P}{P_{sat}}\right)\right)^2\right)$$

θ relative surface coverage
T_0 adsorption energy (expressed in K)
P_{sat} Saturation vapor pressure

- Available data
  - H_2 from [3]:
    T_0=209 K ML=0.645×10^{14} cm^{-2}
  - He from [4]:
    T_0=67.8 K ML= 1.27×10^{15} cm^{-2}

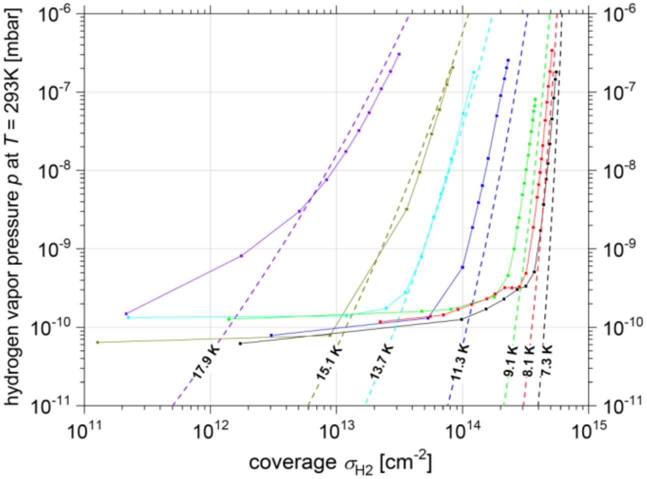
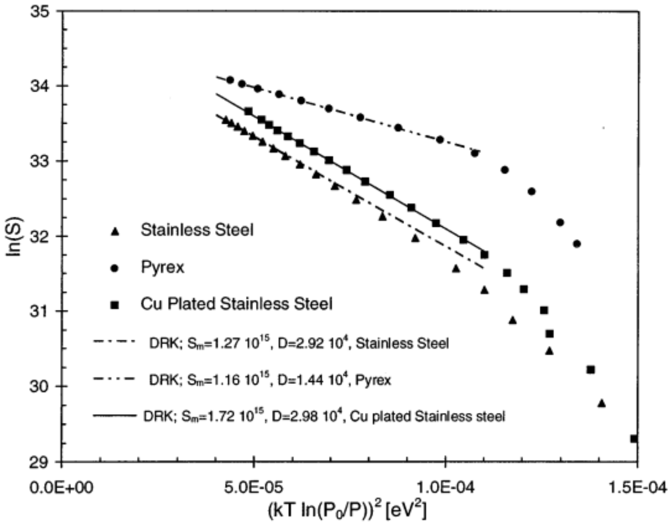


FIG. 3. Adsorption isotherms of H_2 on an electropolished stainless steel surface in the temperature range between 7.3 and 17.9 K. The dashed curves are the theoretical isotherms calculated according to the DRK [Eq. (2)] with the experimentally determined constants, $B = 3075\ \mathrm{eV}^{-2}$ and $\sigma_{mono} = 6.45 \cdot 10^{14}\ \mathrm{cm}^{-2}$.



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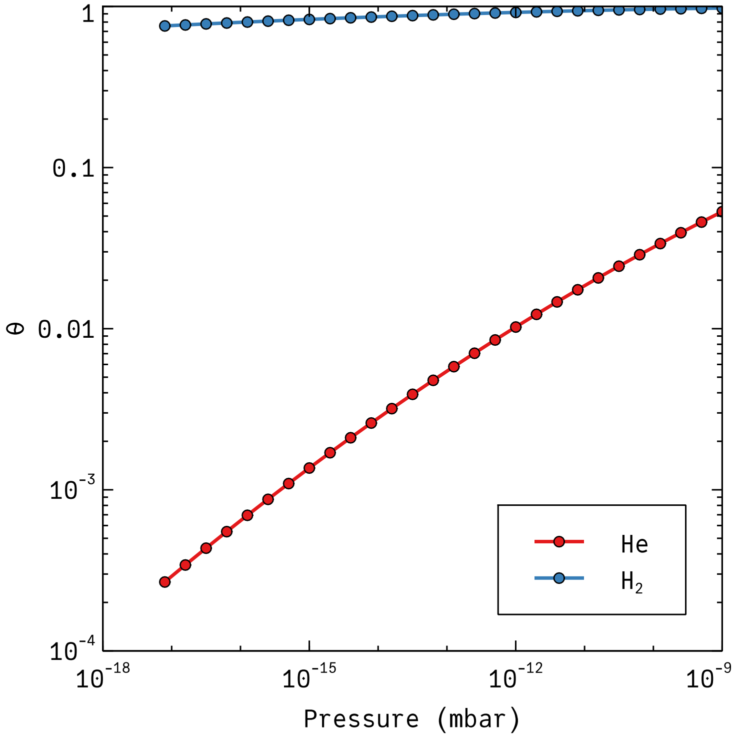


Is the extrapolation to very low equilibrium pressure valid?

COMSOL model

- Molecular flow simulation using view factors between elements to simulate the reflexion of molecules
- COMSOL allows the study of an evolving wall following the surface coverage
- Quasi-static equilibrium

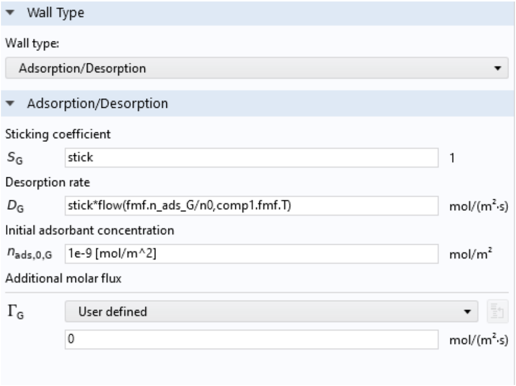
$$\frac{1}{P}\frac{\partial P}{\partial t} \ll s\frac{A}{V}\frac{\overline{v}}{4}$$

- 2D axisymmetric model
- Pressure at the entrance isotropic distribution (no beaming)
- DR isotherm model for 4.2K walls in COMSOL
  - Pumping:

$$\frac{1}{4}s_0 n_{gas} v_{th} \rightarrow \theta$$

  - Gas Desorption:

$$\frac{1}{4}s_0 n_{eq}(\theta) v_{th} \rightarrow n_{eq}(\theta) = n_{sat} \cdot \exp\left(-\frac{T_0}{T}\sqrt{-\ln(\theta)}\right)$$



Wall type: Adsorption/Desorption

Sticking coefficient

s_G: stick — 1

Desorption rate

D_G: stick*flow(fmf.n_ads_G/n0,comp1.fmf.T) — mol/(m²·s)

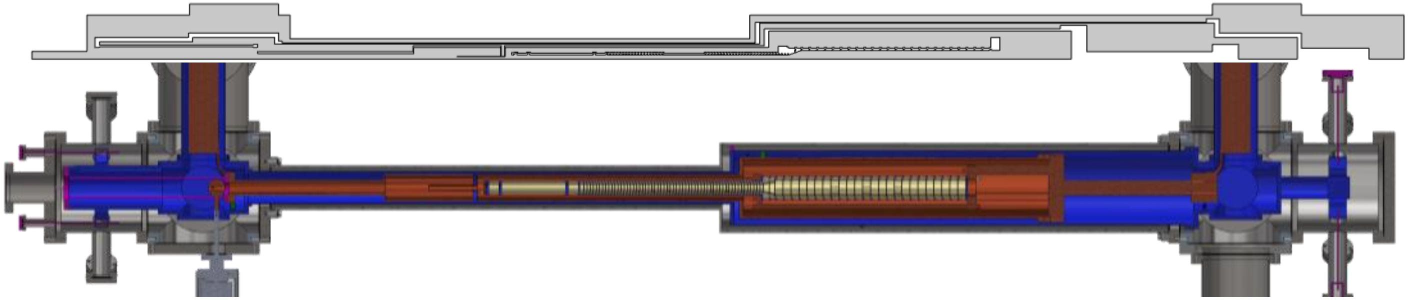
Initial adsorbant concentration

$n_{ads,0,G}$: 1e-9 [mol/m^2] — mol/m²

Additional molar flux

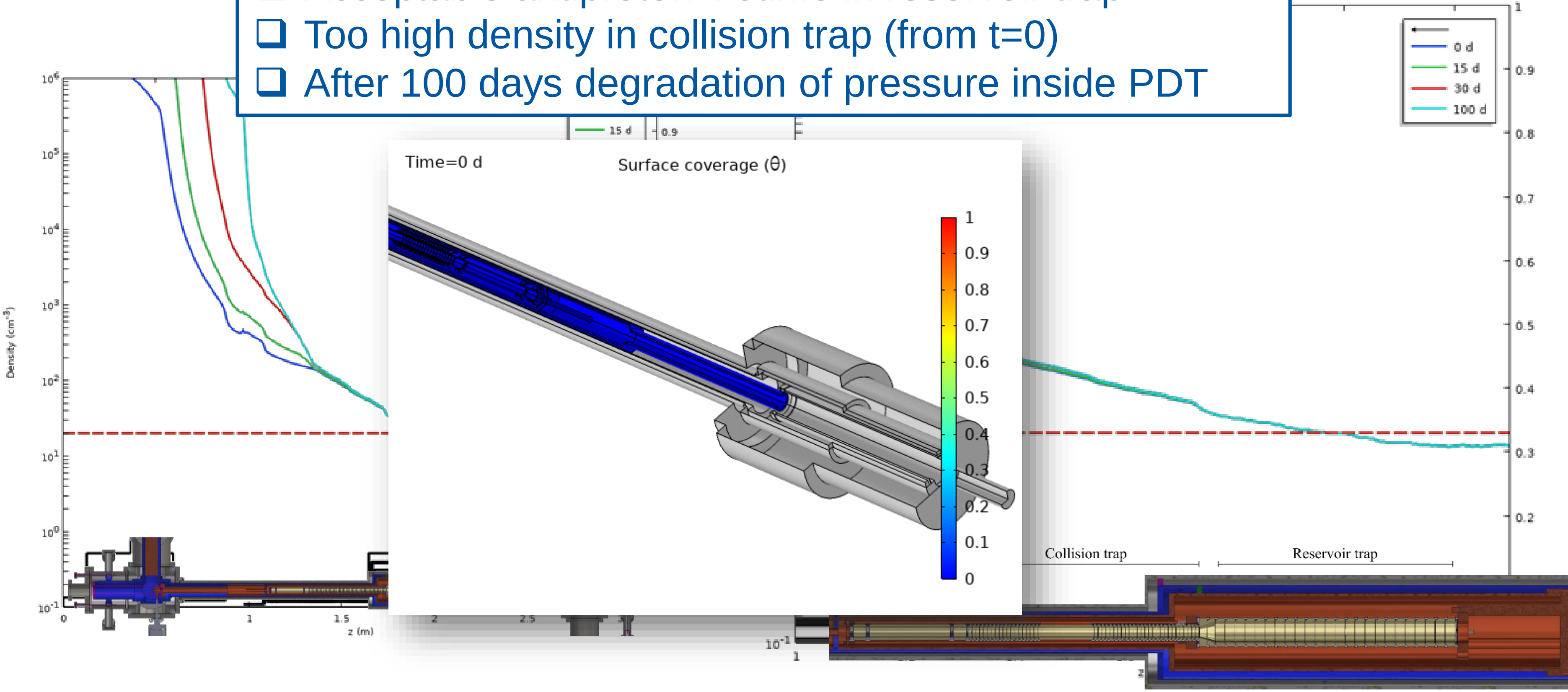
Γ_G: User defined

0 — mol/(m²·s)



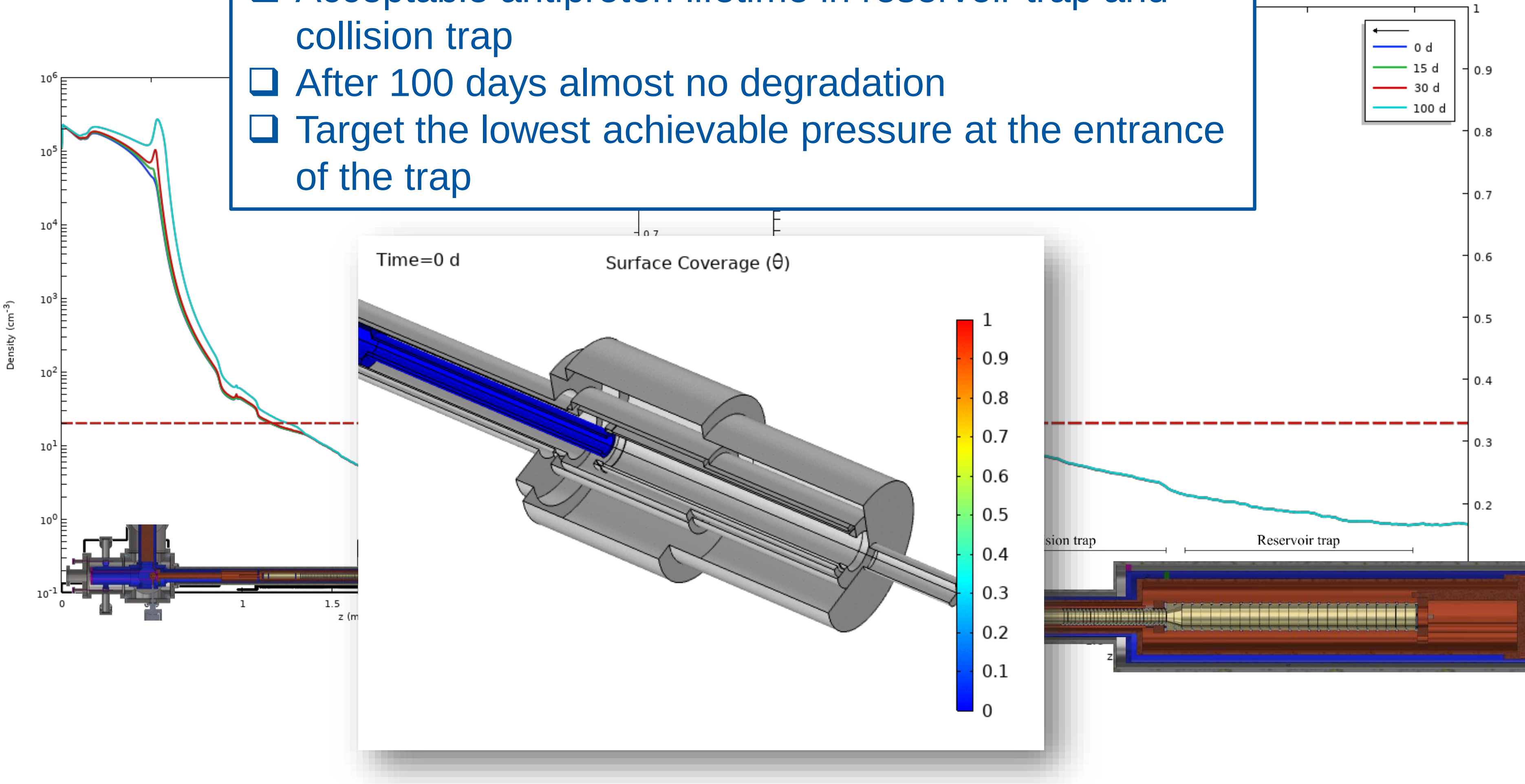
COMSOL model: $P_{H_2}=10^{-10}$mbar

- ☐ Acceptable antiproton lifetime in reservoir trap
- ☐ Too high density in collision trap (from t=0)
- ☐ After 100 days degradation of pressure inside PDT



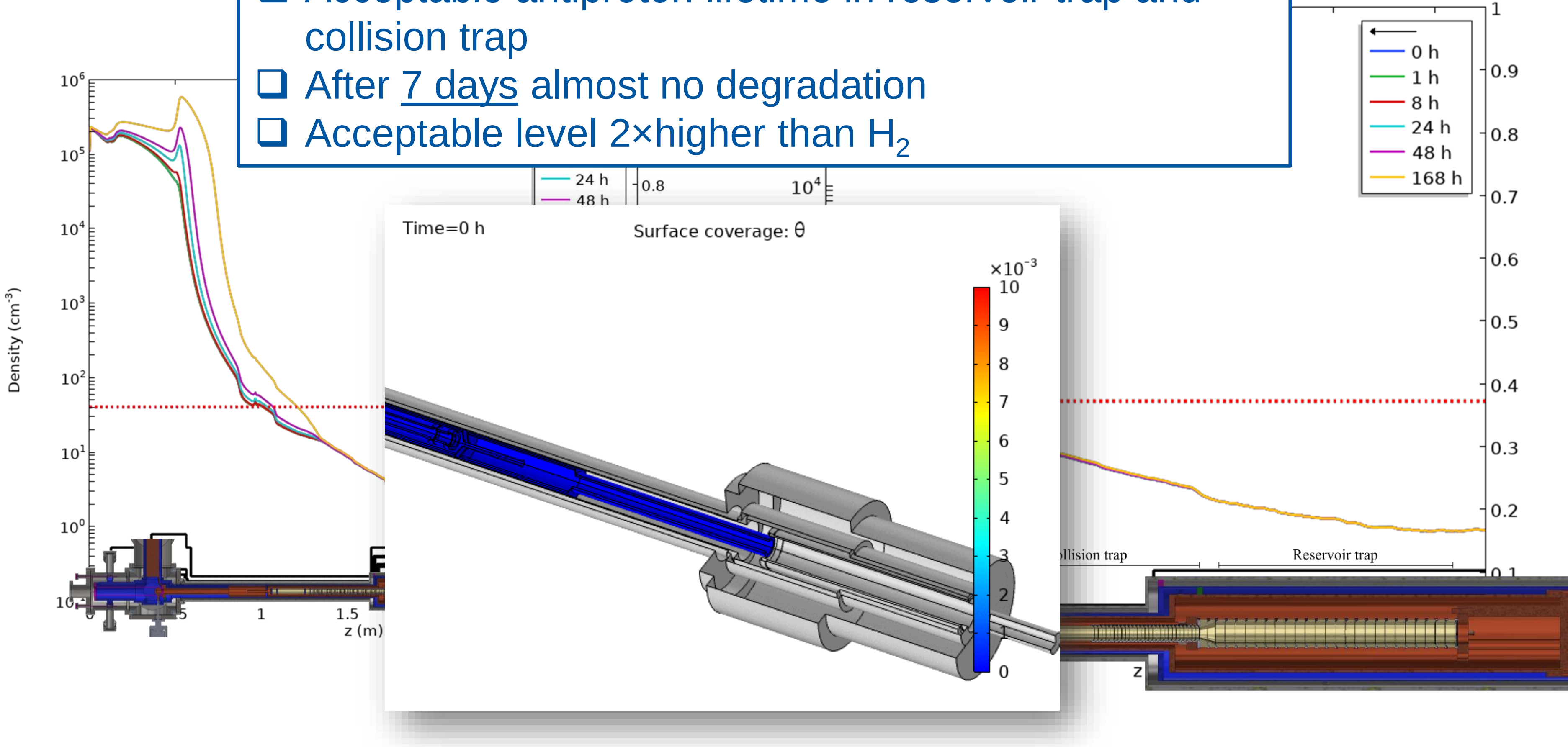
COMSOL model: $P_{H2}=10^{-11}$mbar

- ☐ Acceptable antiproton lifetime in reservoir trap and collision trap
- ☐ After 100 days almost no degradation
- ☐ Target the lowest achievable pressure at the entrance of the trap



COMSOL model: $P_{He}=10^{-11}$mbar

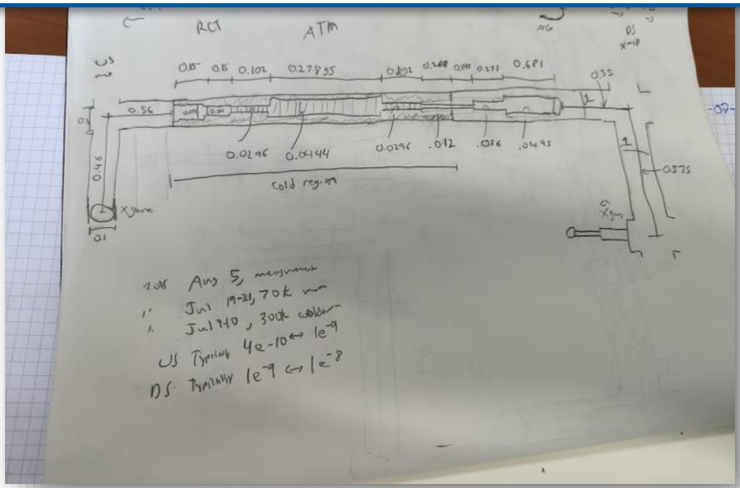
- Acceptable antiproton lifetime in reservoir trap and collision trap
- After 7 days almost no degradation
- Acceptable level 2×higher than H_2

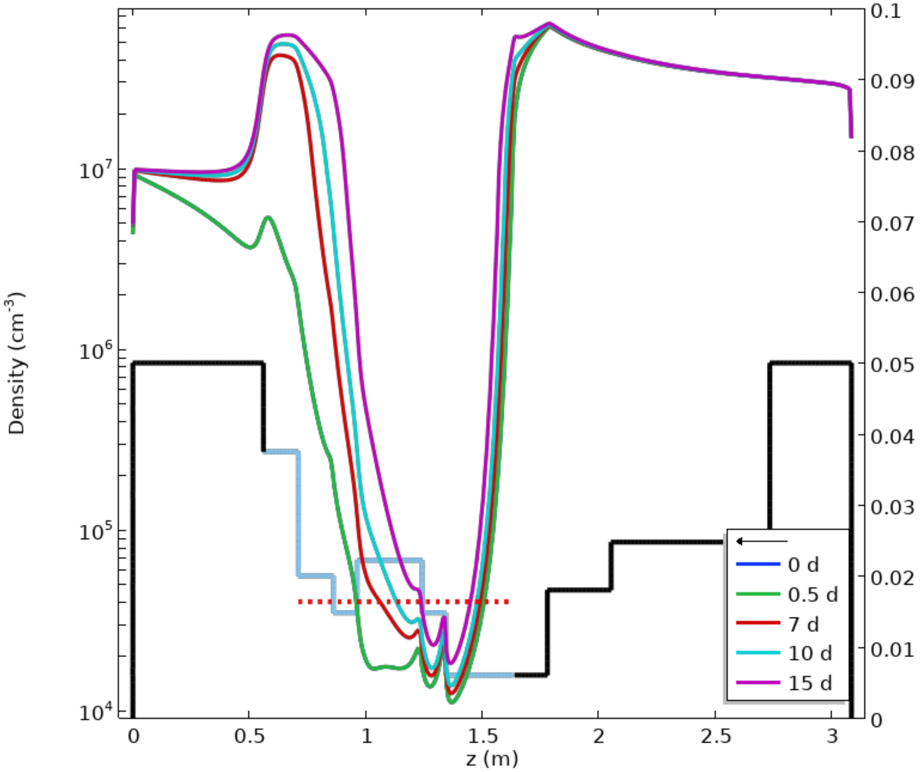


Comparison with experimental results: Alpha experiment

- Trap at 6.6K
- $P_{upstream}$ =7×10^{-10} mbar
- $P_{downstream}$=1×10^{-9} mbar
- After 15 days $\bar{p}$ lifetime estimated in 11600 s $\Rightarrow$ 3.4×10^{4} cm^{-3} or 3×10^{-14} mbar
- Model assuming 10×MLs
- s=0.3

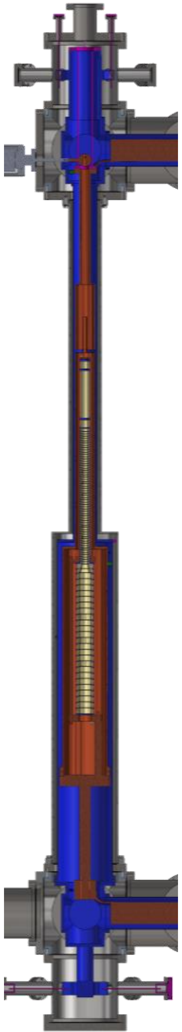
The model predicts a significant lower lifetime than observed ⇒ Conservative assumptions

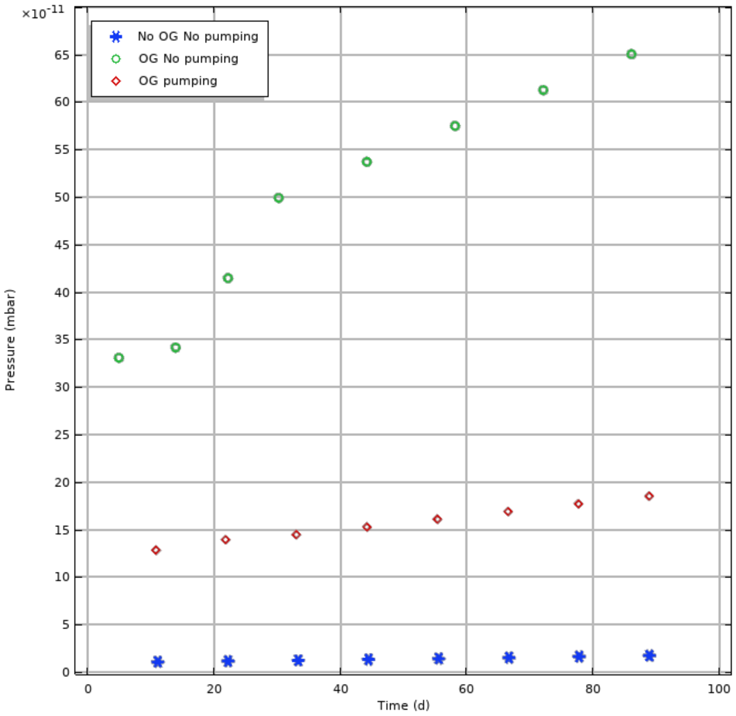




Data provided by Andrew Jordan Christensen

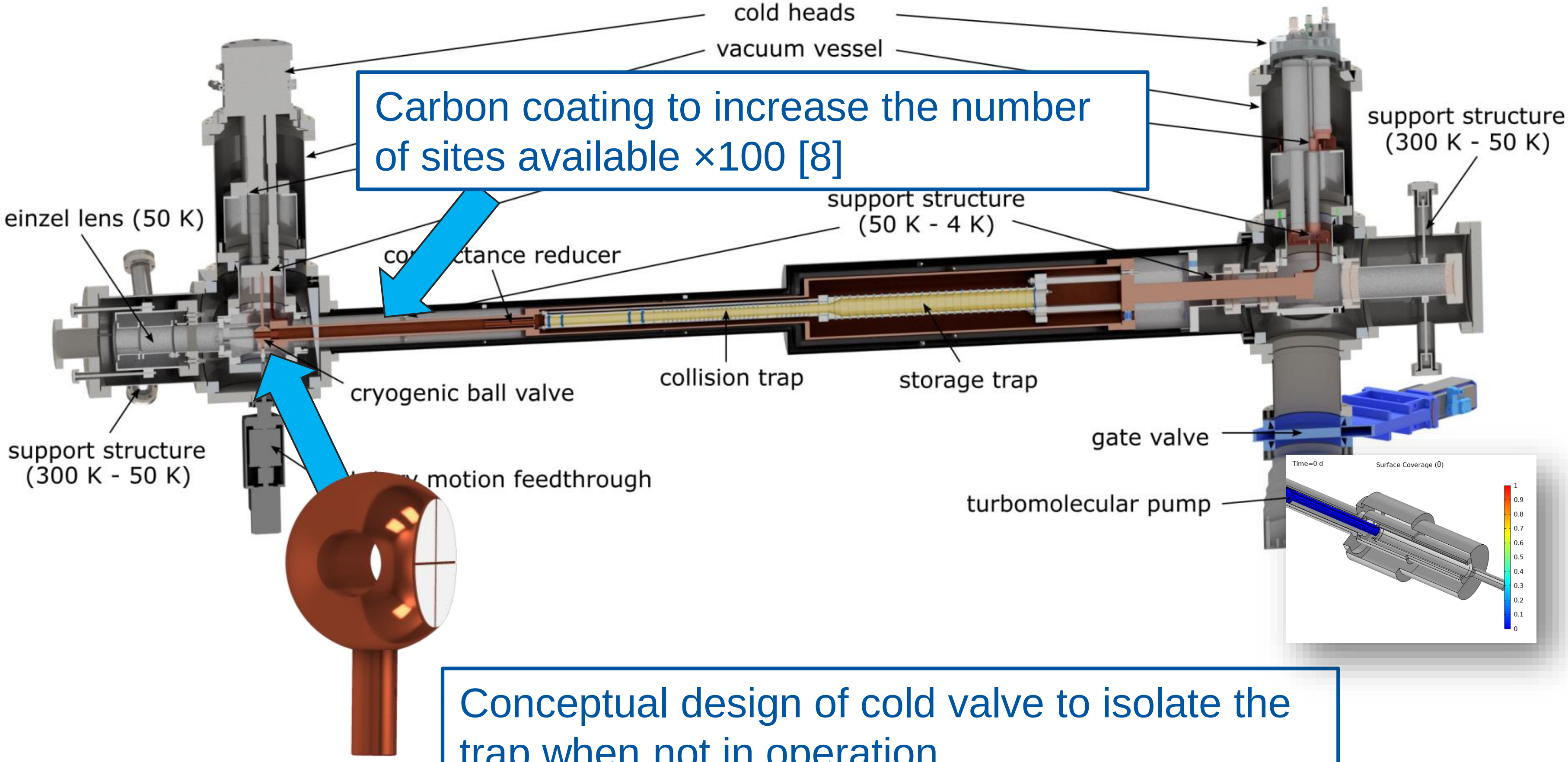
Outgassing of room temperature material





- Insulation vacuum in communication with trap vacuum.
- H_2 from room temperature materials can be the dominant gas source unless is pumped
- ➢ Reduce conductance between trap and insulation vacuum
- ➢ Add pumping

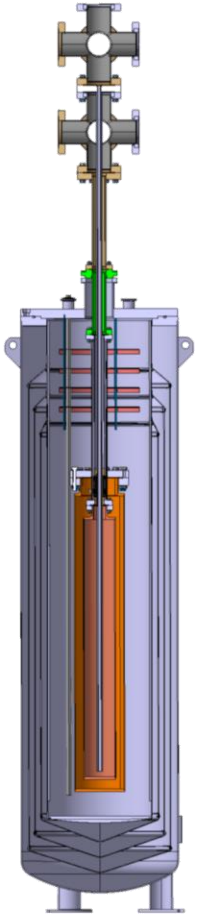
Improvements of the trap

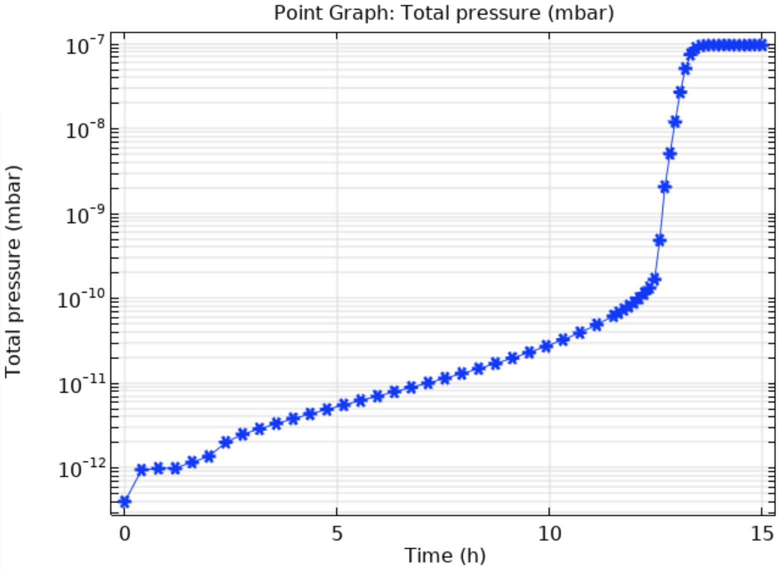


Carbon coating to increase the number of sites available ×100 [8]

Conceptual design of cold valve to isolate the trap when not in operation

H_2 and He isotherm data at low pressure





- New setup to measure isotherms at low pressure
- COMSOL to extract information from experiment
- Data to validate trap models

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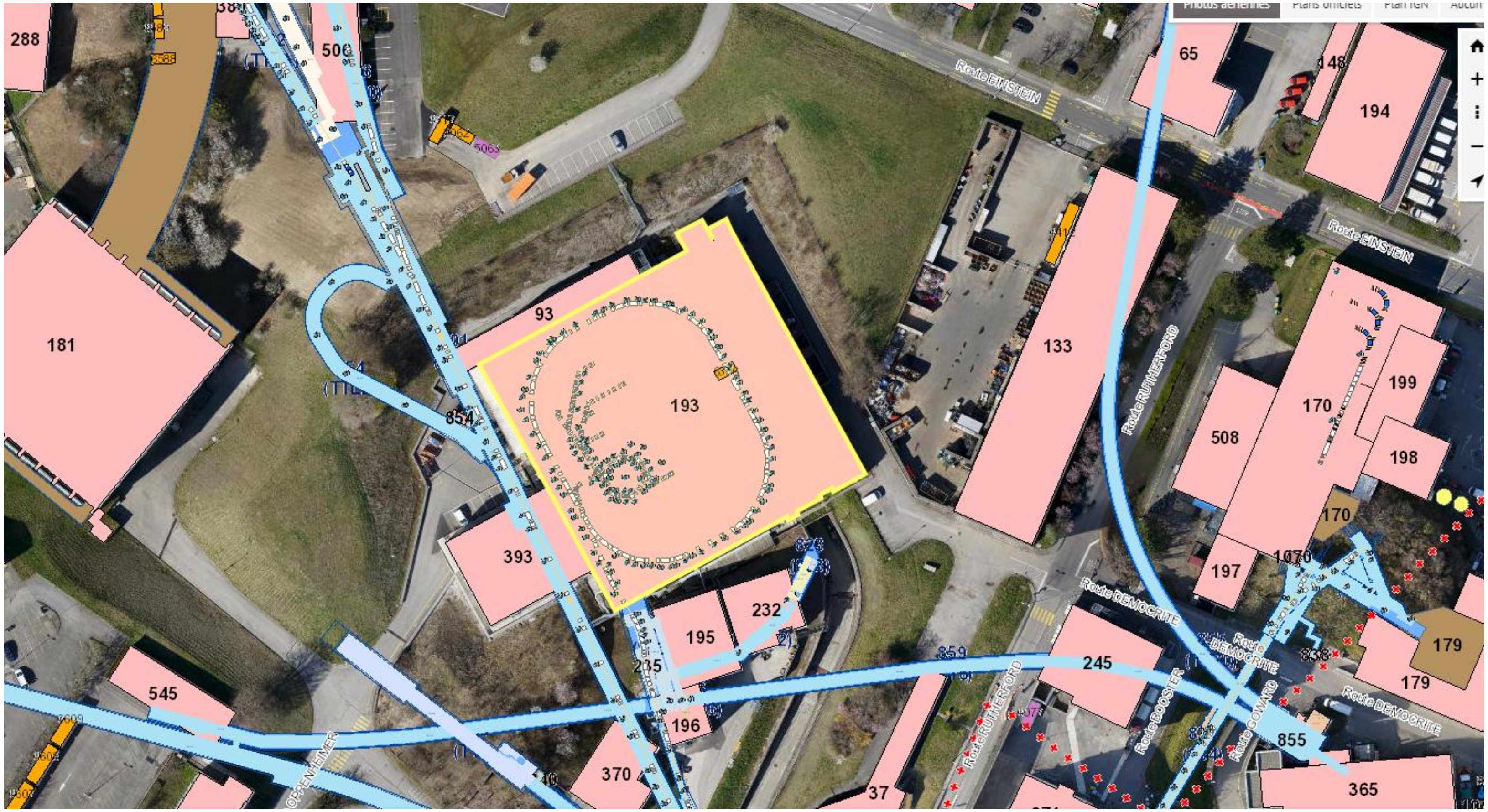
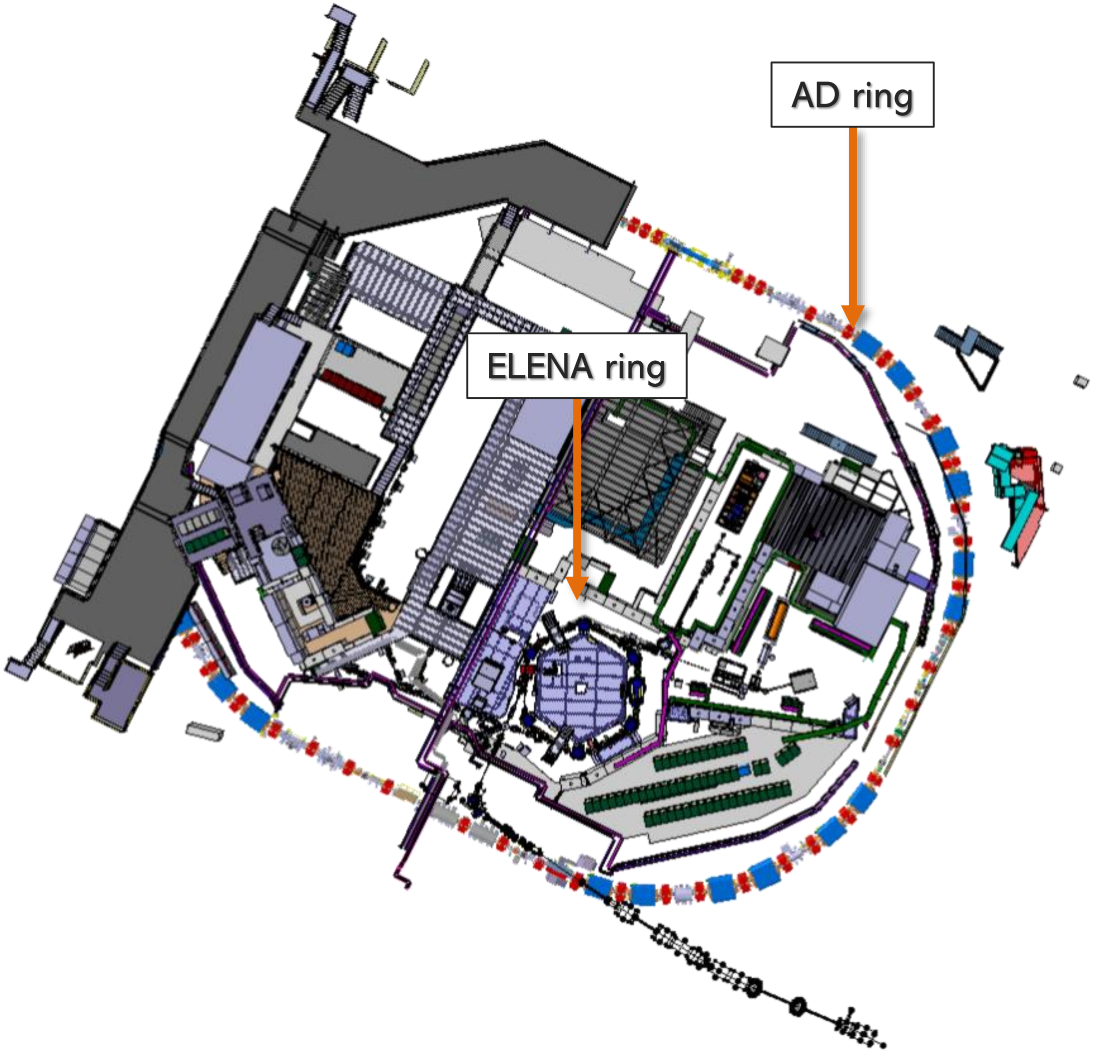
ELENA layout



ELENA layout



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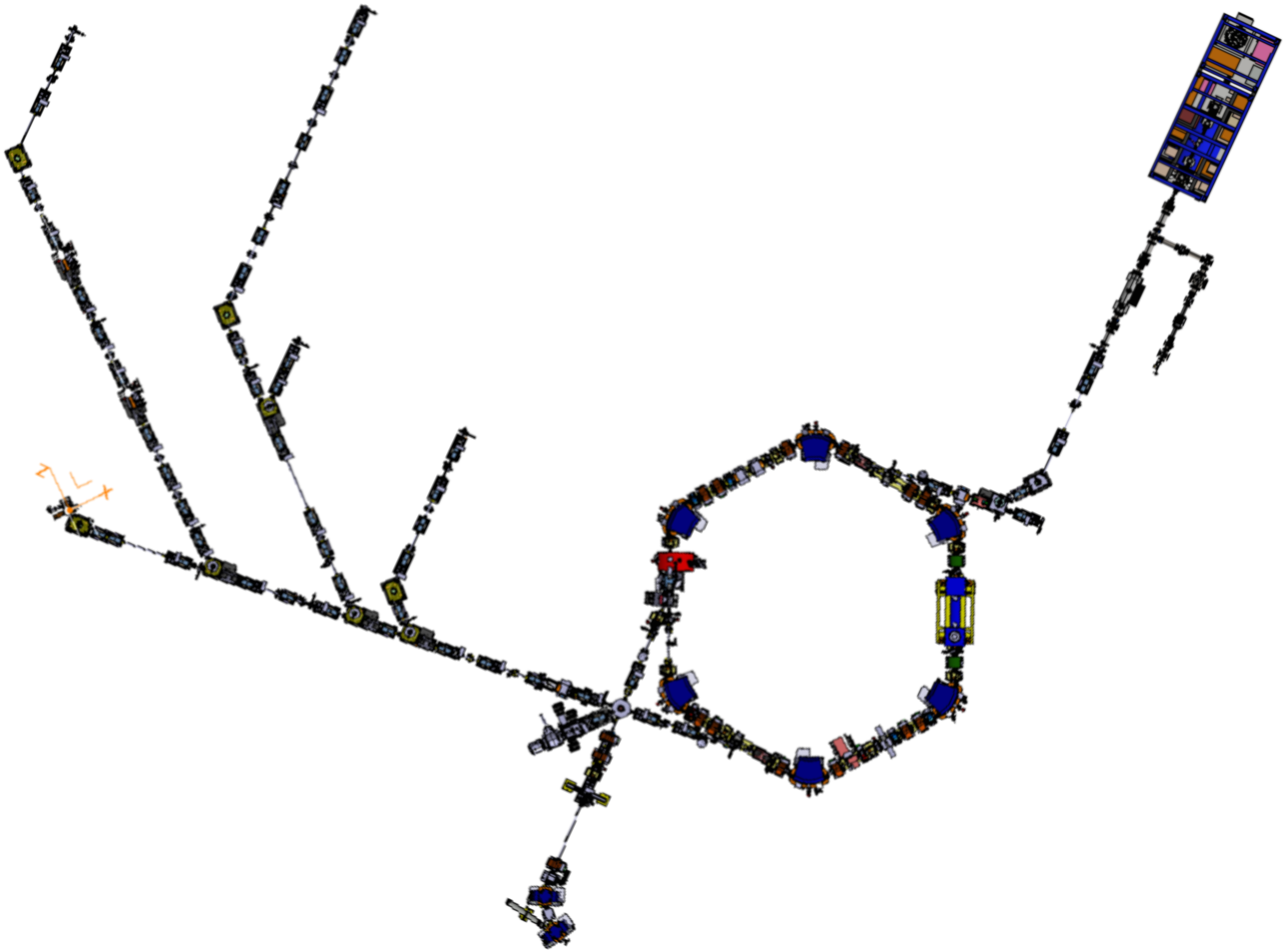
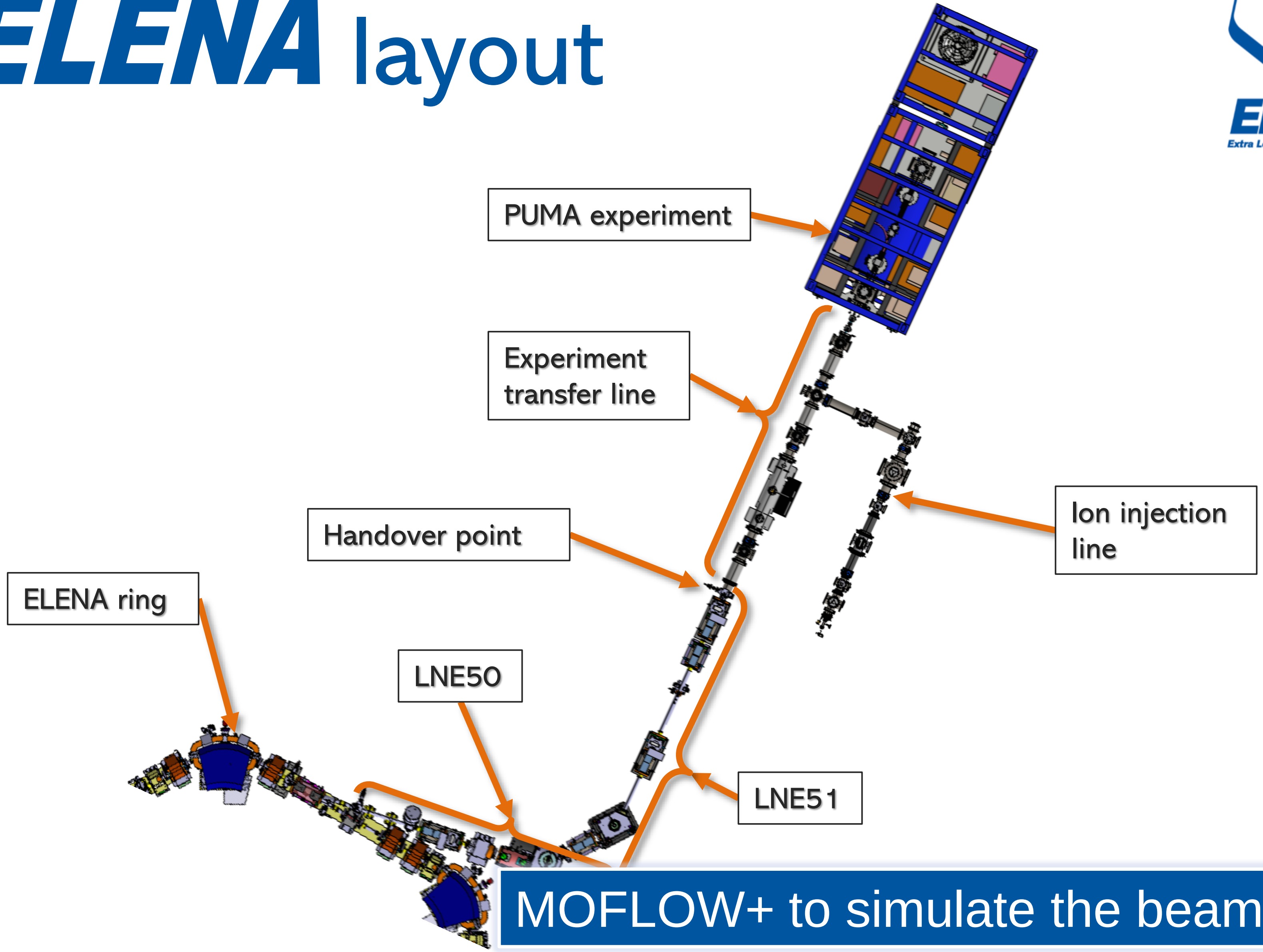


ELENA layout



PUMA experiment

Experiment transfer line

Handover point

Ion injection line

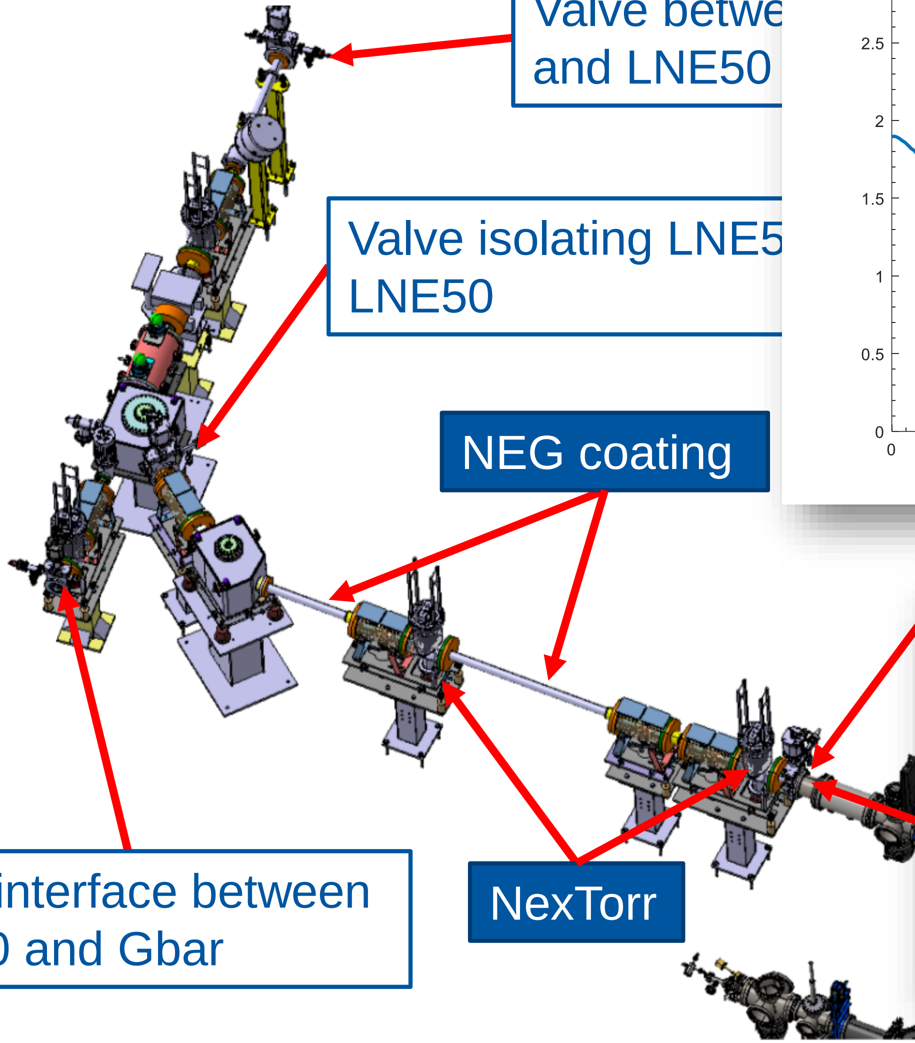
ELENA ring

LNE50

LNE51

MOFLOW+ to simulate the beam line

LNE51



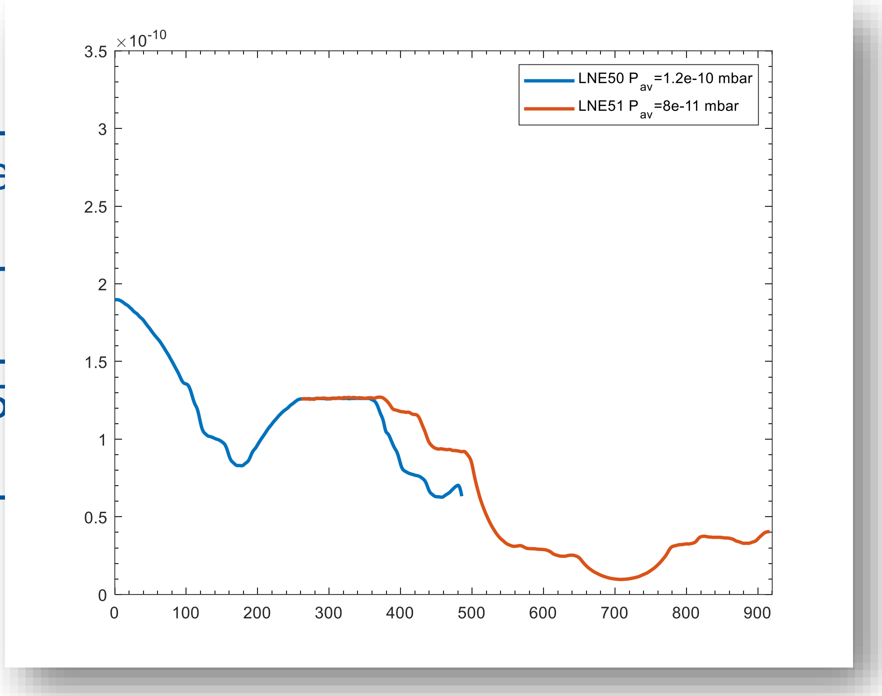
Valve betwe
and LNE50

Valve isolating LNE5
LNE50

NEG coating

NexTorr

Valve interface between
LNE50 and Gbar



Texture Scaling

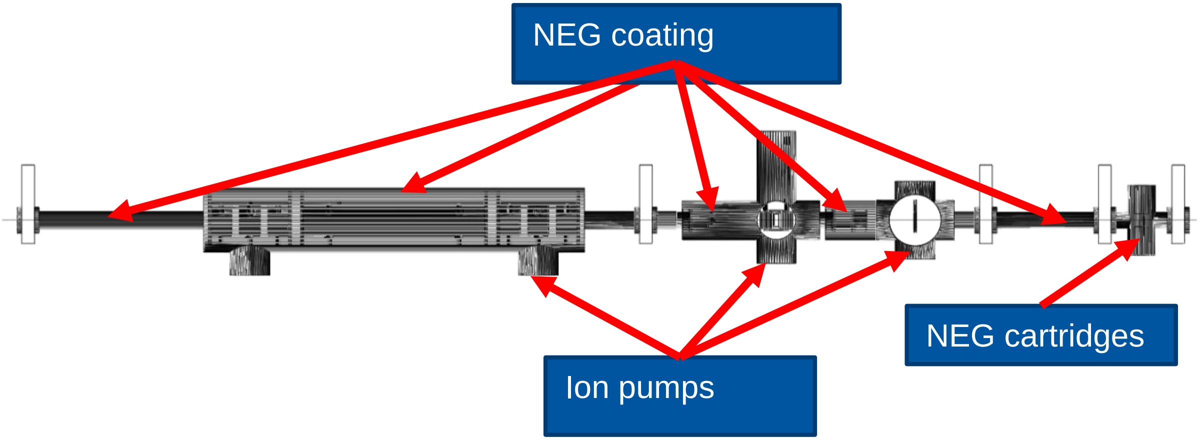
Texture Range
Min: 1.014e-15
Max: 1.997e-10
☑ Autoscale
☑ Include constant flow
☑ Use colors
☐ Logarithmic scale
Swap: 640KB

Current
Min: 1.014E-15
Max: 1.997E-10

Gradient
6.07e-11

Show: Pressure [mbar]

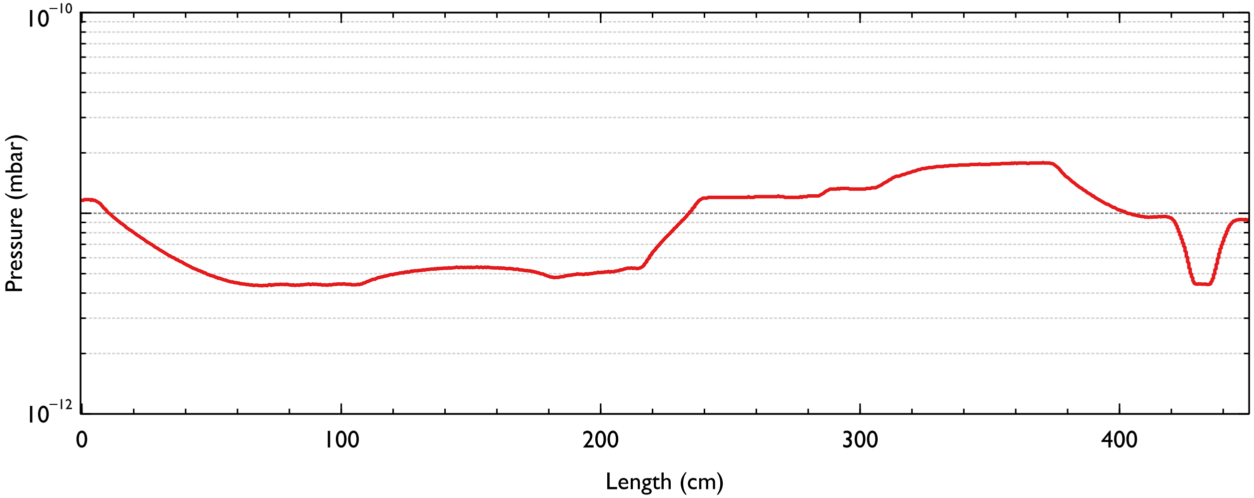
PUMA Transfer line

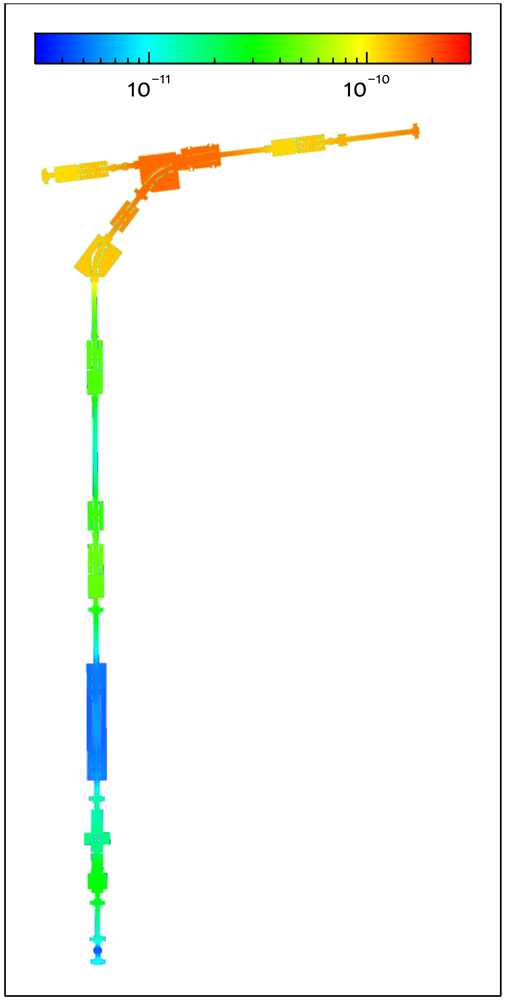


NEG coating

NEG cartridges

Ion pumps





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ISOLDE layout

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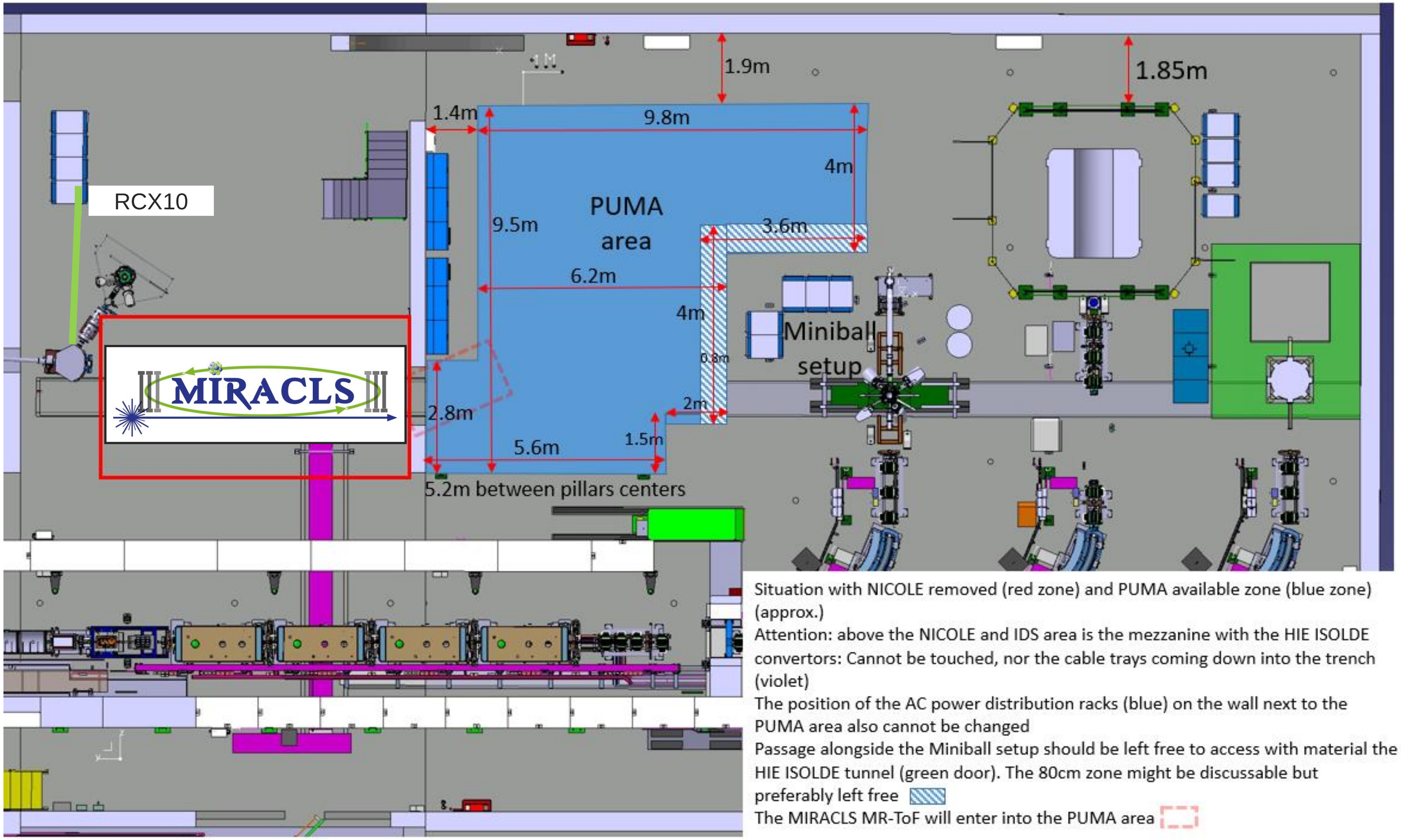


Situation with NICOLE removed (red zone) and PUMA available zone (blue zone) (approx.)

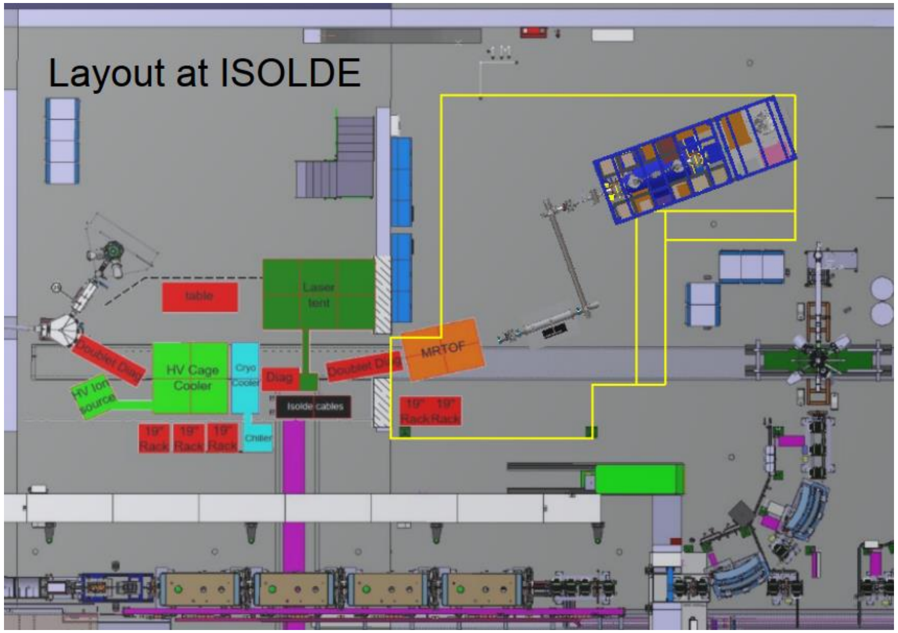
Attention: above the NICOLE and IDS area is the mezzanine with the HIE ISOLDE convertors: Cannot be touched, nor the cable trays coming down into the trench (violet)

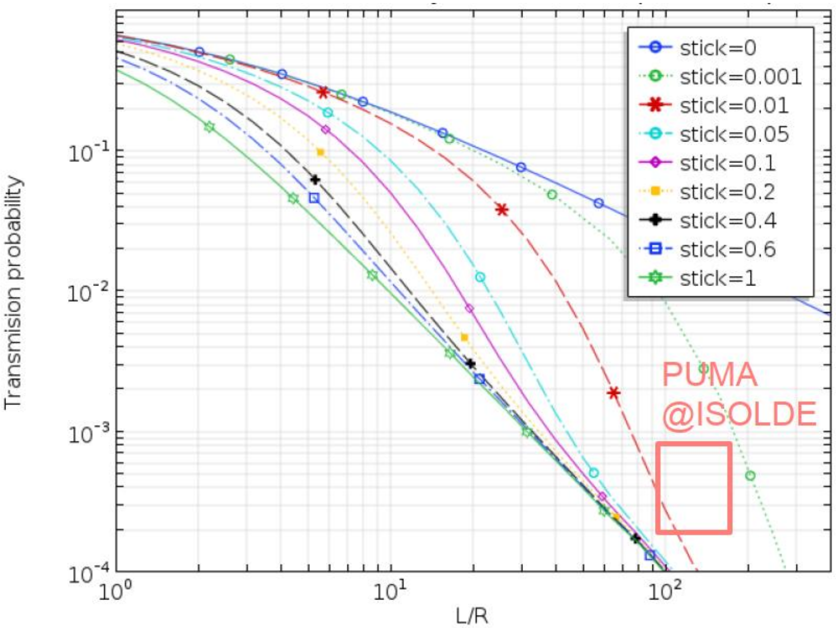
The position of the AC power distribution racks (blue) on the wall next to the PUMA area also cannot be changed

Passage alongside the Miniball setup should be left free to access with material the HIE ISOLDE tunnel (green door). The 80cm zone might be discussable but preferably left free ▨

The MIRACLS MR-ToF will enter into the PUMA area ⬚

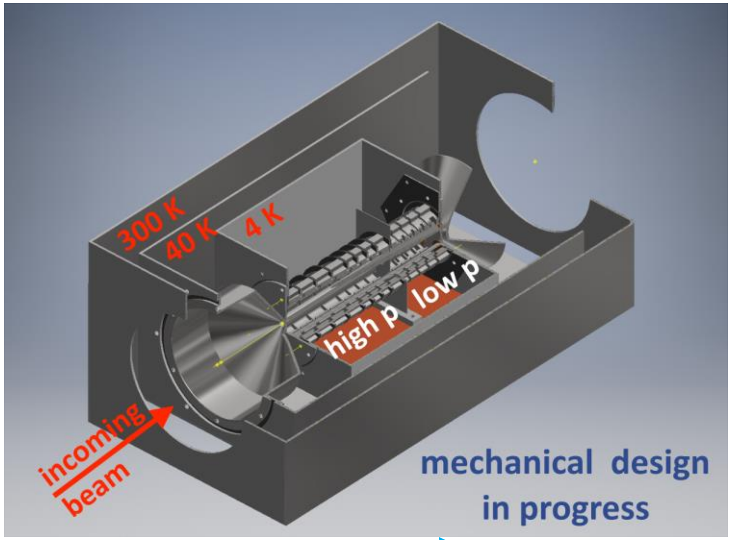
ISOLDE layout



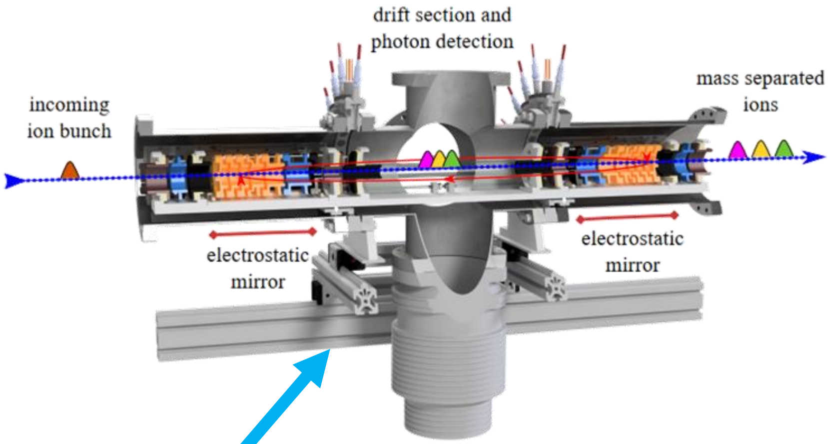


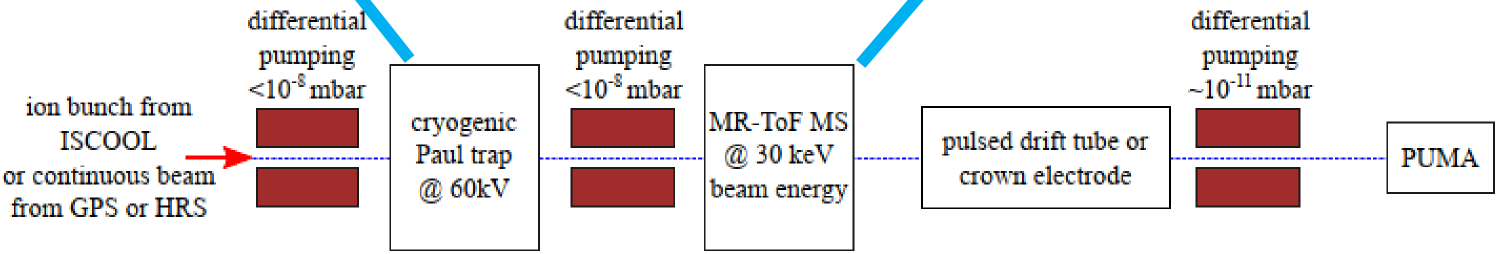
- PUMA transfer line connected to MIRACLS ⇒ Handover Point <10^{-8} mbar
- Conductance reduction over ~2 meters, smallest diameter 20 mm. Chicane to reduce beaming.
- Line still under definition

- MIRACLS: Multi Ion Reflection Apparatus for Collinear Laser Spectroscopy
- Bunches trapped in MR-ToF MS (Multi-Reflection Time-of-Flight Mass Spectrometer)
- Previous cryogenic Paul Trap for beam cooling with buffer gas for optimal longitudinal emittance.
- He gas for beam cooling!
- 30 keV final energy → Pulsed drift tube between PUMA and MIRACLS (<100 eV at PUMA)



mechanical design in progress





ion bunch from ISCOOL or continuous beam from GPS or HRS

differential pumping $<10^{-8}$ mbar

cryogenic Paul trap @ 60kV

differential pumping $<10^{-8}$ mbar

MR-ToF MS @ 30 keV beam energy

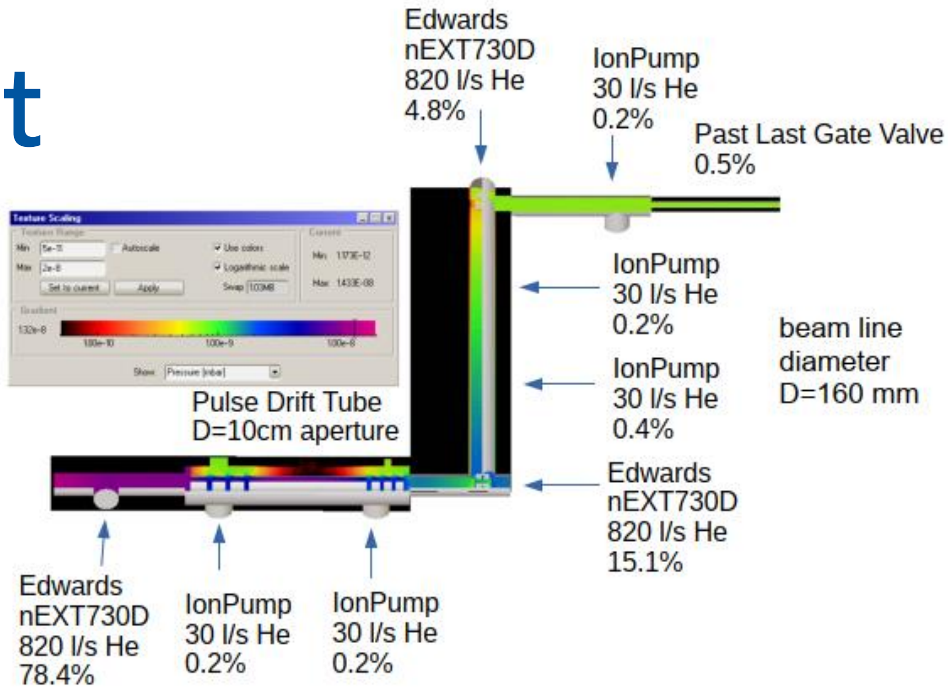
pulsed drift tube or crown electrode

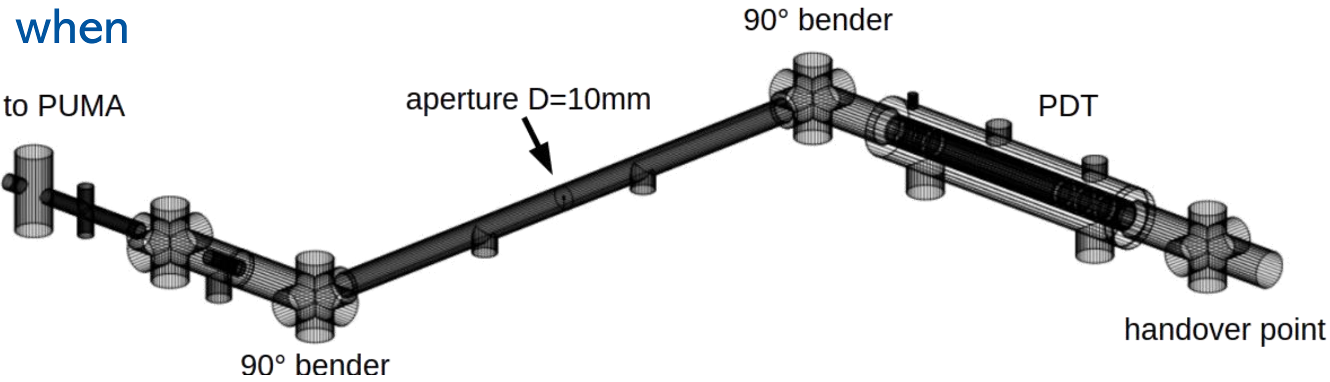
differential pumping $\sim10^{-11}$ mbar

PUMA

ISOLDE layout

- Light ions (A<15) can only be efficiently cooled down with He gas
- 0.5% transmission probability for He
- PUMA beam line at ISOLDE still to be optimised.
- Minimize the time He is injected while not in operation (open valve only when required)



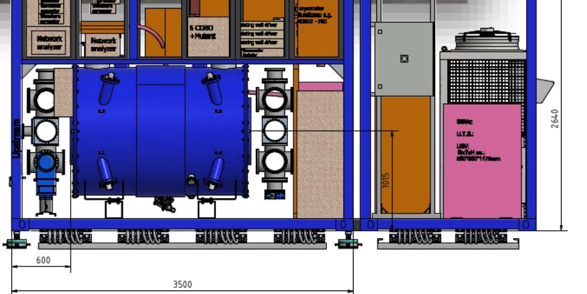


Outline

- ☐ Introduction and motivation
- ☐ PUMA trap
- ☐ PUMA at ELENA
- ☐ PUMA at ISOLDE
- ☐ Summary

Summary

- PUMA will use $\bar{p}$ as a high precision probe. The manipulation and transport of $\bar{p}$ requires extreme low vacuum only achievable with cryo-pumping
- COMSOL and MOFLOW models to design the cold trap and the transfer lines
- The pressure at the entrance of the trap is crucial to reach the objective → Extensive use of NEG coatings and strict outgassing budget
- Isotherm data at very low pressure required to refine the models
- Aspects that require further development:
  - The trap needs to be loaded with e^- using a cold field emission source. At the end of the manipulation, they should be extracted out of the trap
  - Effect of vibrations during transport
- PUMA and BASE-STEP are targeting the transport of $\bar{p} \Rightarrow$ It will open new physics opportunities



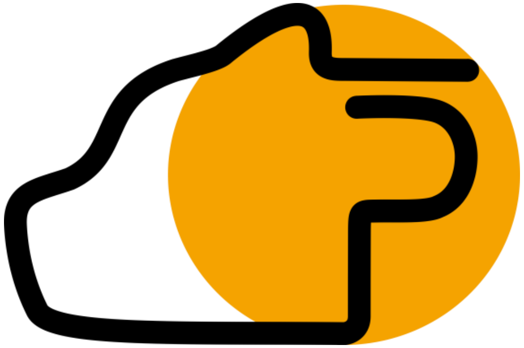
No magnet, no power supply, no special transport

0.25 g

Almost 10t, powered by diesel generator, big truck

$$0.\underbrace{000000000000001}_{\times 10^{-15}}5\ \mathrm{g}$$

Thank you for your attention!!



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Milestones

- ☐ Install and commissioning 100 kV Pulse Drift Tube at ELENA
- ☐ Build ELENA $\bar{p}$ transfer line and commissioning
- ☐ Install trap and first $\bar{p}$ trapped
- ☐ Install ion line at ELENA
- ☐ First ion trapped and $\bar{p}$ annihilation with stable ions (first physics run)
- ☐ Build ISOLDE transfer line
- ☐ Transport of $\bar{p}$ to ISOLDE
- ☐ Physics with unstable ions

Influence of thermal radiation

- H_2 desorption can be stimulated by thermal radiation [9]
- First simulations show <<10^{-3} $mW·cm^{-2}$
- Shielding of warm areas is mandatory

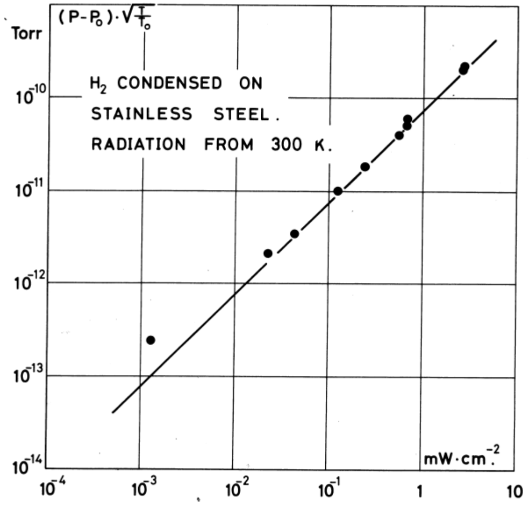
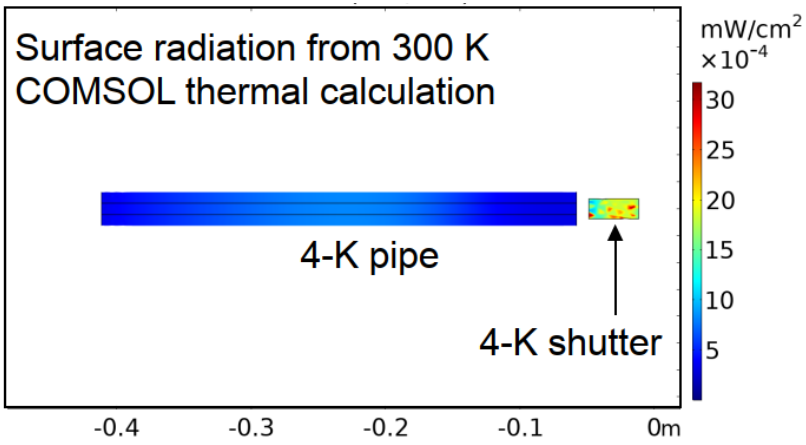
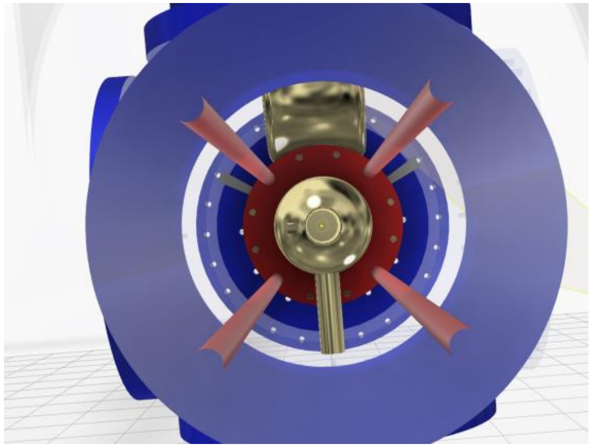


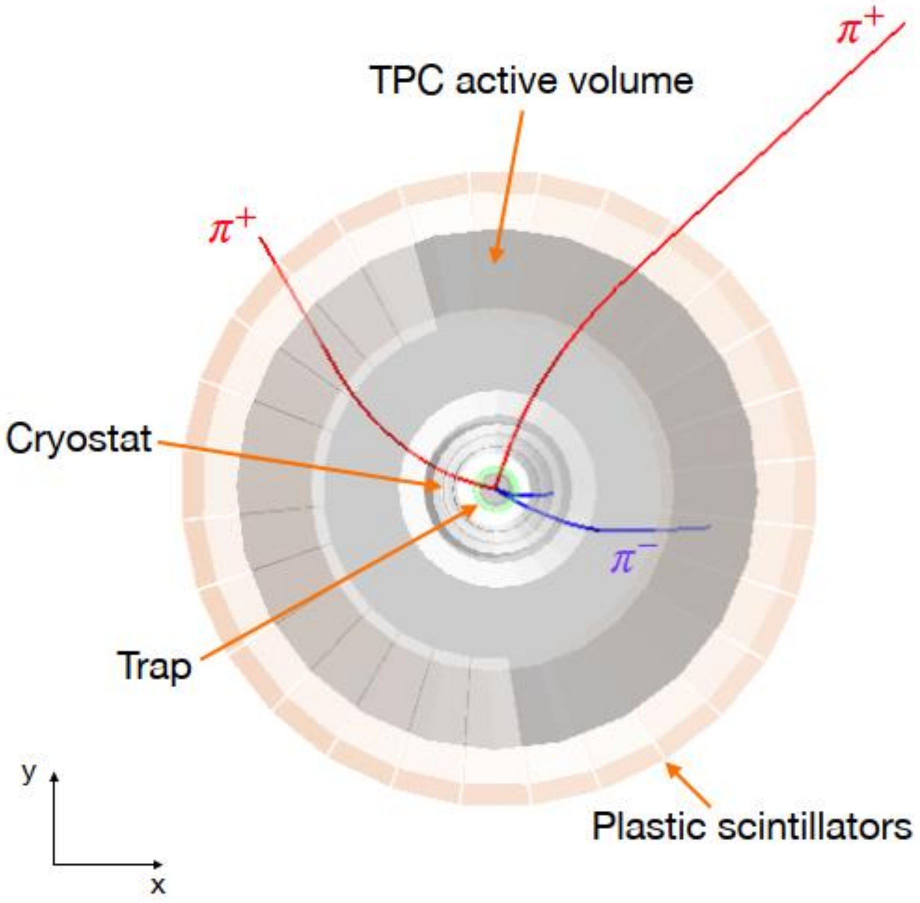
Fig. 11. Dependence of the H_2 saturated vapour pressure at 2.3 K on the thermal radiation power absorbed by the cryosurface.





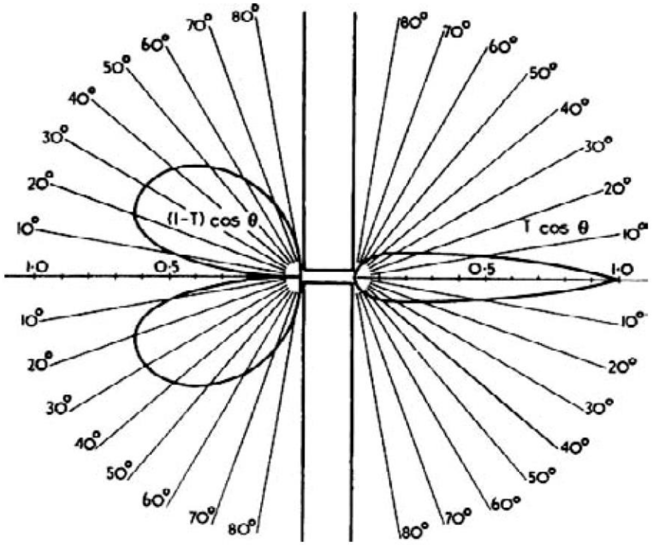
Detection

- ❑ Measure the number of annihilated neutrons to the number of annihilated proton
- ❑ Electric charge conservation during the annihilation process → total charge of pions −1 for a neutron and 0 for a proton.



Density vs Pressure

- The flow through orifices in molecular flow disturbs the speed distribution → No longer isotropic.
- $PV = nRT$ doesn't apply in those conditions
- It is preferred to use density for cryogenic systems and/or anisotropic distributions



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