Studies on the beam induced effects in the FCC-hh

Ignasi Bellafont

WP4 Meeting 05

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OUTLINE

1. Previous status
2. Expanded thesis proposal
3. High power density issue in the beam screen - Absorber design
4. Low pumping speed issue - Beam screen optimization
5. Roughness role in the reflector design
6. Heat load on the cold bore
7. Pumping speed improvement
8. Reflectivity and PSD future studies
9. Conclusions, next steps

LAST MEETING STATUS

- ✓ The **6 months training** of the resource allocated at CERN was **already completed**, according to the foreseen plan
- ✓ ANKA setup synchrotron **radiation power distribution**, slits aperture, and **pressure** level **were studied and found**, including its variants, in a preliminary way. **No major issues were found**, and the pressure levels it will achieve were found to be adequate for the experiments
- ✓ The **power and flux distribution** and the **vacuum status** of the FCC-hh **bending magnets** were studied, and the first simulations were performed. Some **major issues were identified**, as some high power density areas and a low pumping speed, meaning a high scrubbing time of operation until being able to achieve the necessary molecular density levels

THESIS PLAN DETAILED PROPOSAL

- After the received training, the project necessities were better identified and therefore the working plan and **necessary studies were further detailed**:
  - **FCC-hh cryogenic vacuum system** - The **pressure contribution** of the beam induced effects will be studied, resulting in one total **equivalent molecular density inside the BS** for different system conditions of the FCC-hh

Beam induced vacuum effects

- Photon stimulated desorption
- Electron cloud
- Ion induced desorption

Total Pressure (P) = *Photon-stimulated desorption + Ion induced desorption + Electron induced desorption + Thermal outgassing*

THESIS PLAN DETAILED PROPOSAL

- A final **viability report** regarding the vacuum status due to the beam induced effects, for the steady state status, will be then written, mainly focusing in the PSD effect

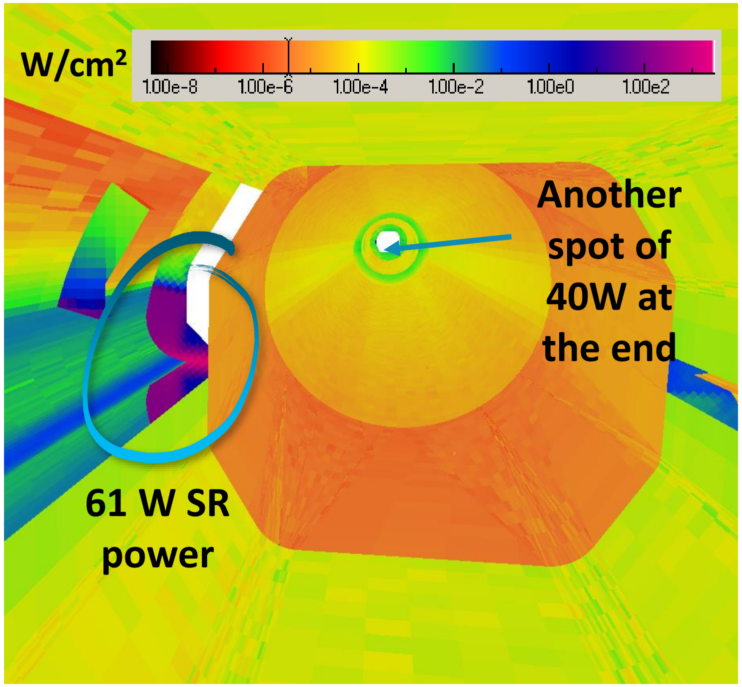
- **ANKA prototype -** The pressure evolution and the photon flux distribution will be analyzed for different prototype configurations and design options. These simulated results will be thus **compared with the experimental ones**, allowing their correctness a higher confidence with the simulations of the FCC-hh vacuum system

- General suggestions for the **future work**, **mitigating measures** for the identified issues and a comparison with the LHC cryogenic vacuum system will be included in the final report

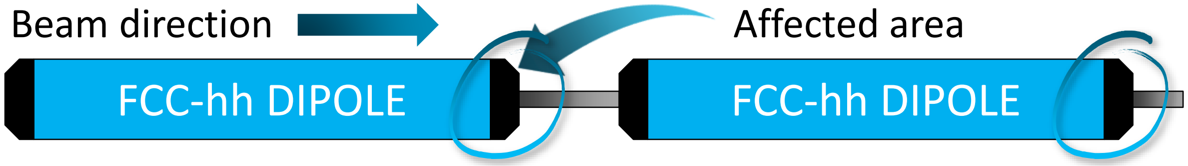
RADIATION ABSORBER

- Due to the **secondary chamber design and angle between dipoles**, there is one region at the end of the beam screen where the radiation could reach power **densities higher than 3kW/cm²**, due to the forward reflection and direct radiation impact (for ideal beam). This could raise **too much the temperatures** and generate an **excessive thermal stress**

- To deal with this high density, **an absorber has been designed**. Focusing the SR on this absorber would also improve the **cooling efficiency** and would **lower the PSD**

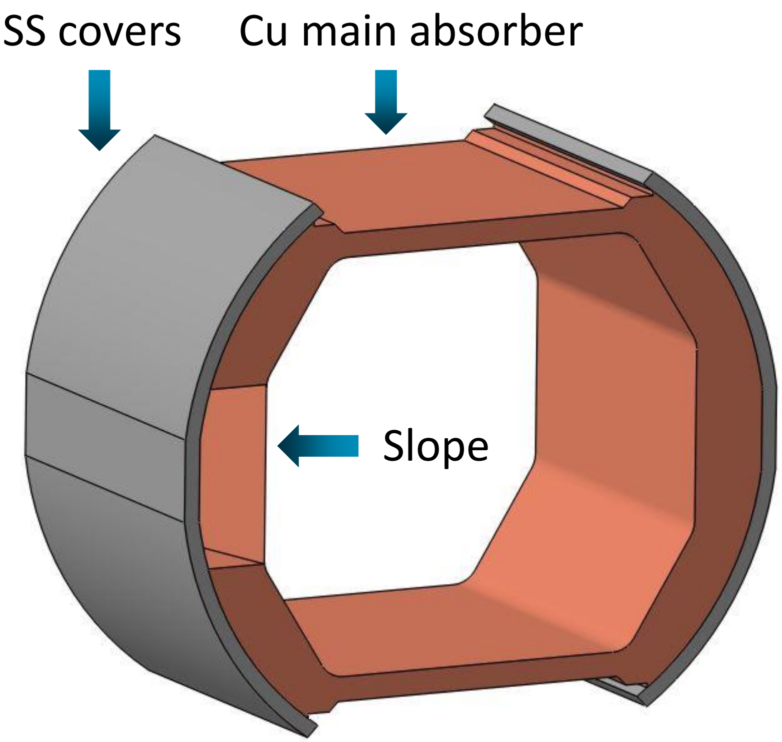


Power distribution at the end of the FCC-hh beam screen



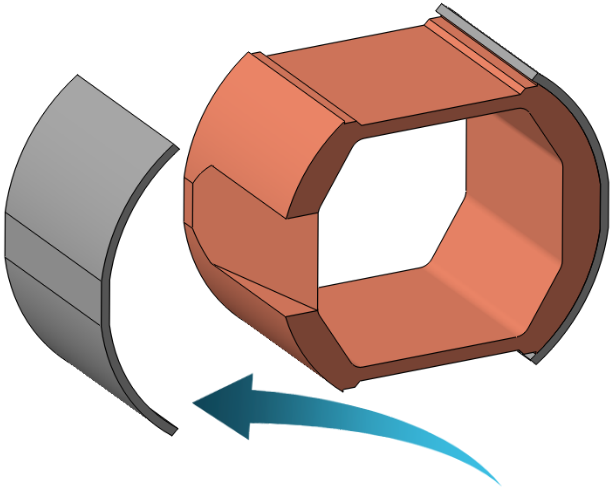
RADIATION ABSORBER

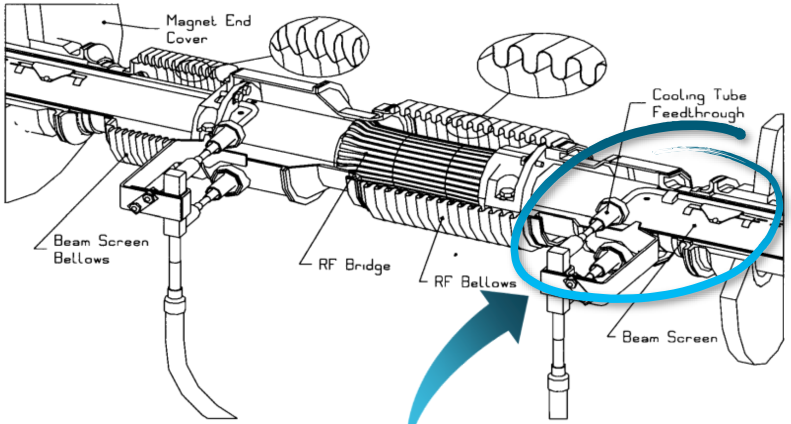
- This 22mm long Cu/Glidcop absorber, would be placed out of the cryogenic region, at the beginning of the **bending magnets interconnection**
- Its design and final position is still tentative, **the final geometry of the interconnection still has to be defined**
- It can be **symmetrical** to avoid reverse mounting errors



Main idea proposed by C. Garion

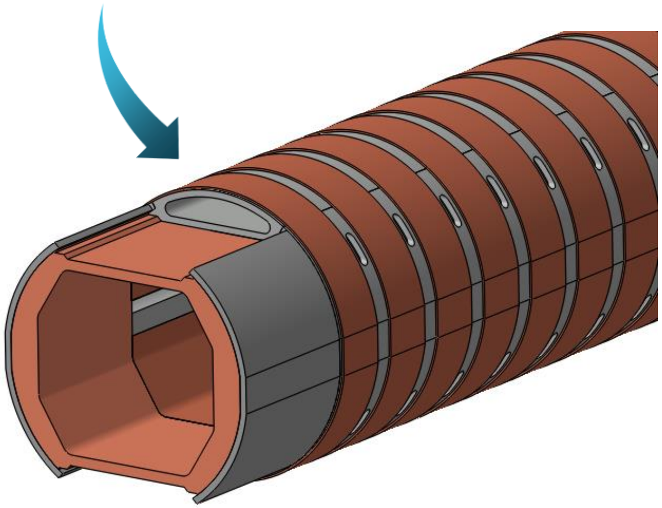
RADIATION ABSORBER



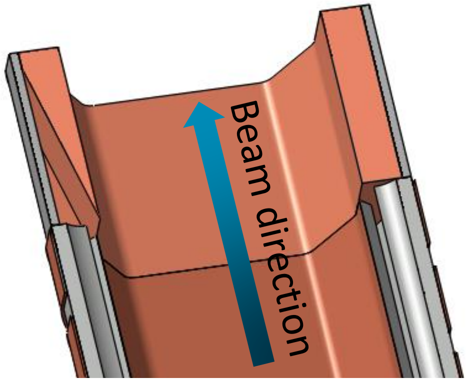


S. steel, welded to the BS and brazed to the Cu

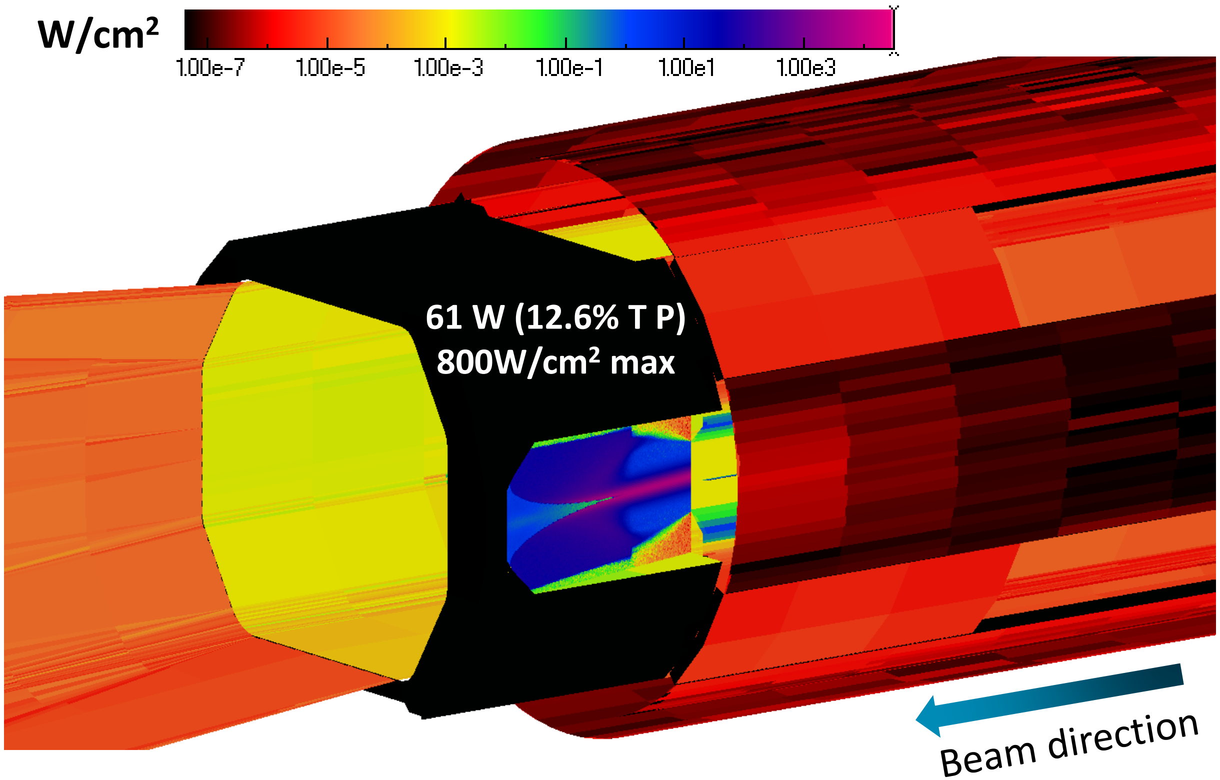
Possible absorber location



22mm long,
12.8^{o} slope



RADIATION ABSORBER



- ✓ For an ideal beam, this end absorber can reduce the maximum power density **more than 4 times on the slope area**, reducing the possibility to have a **thermomechanical failure**

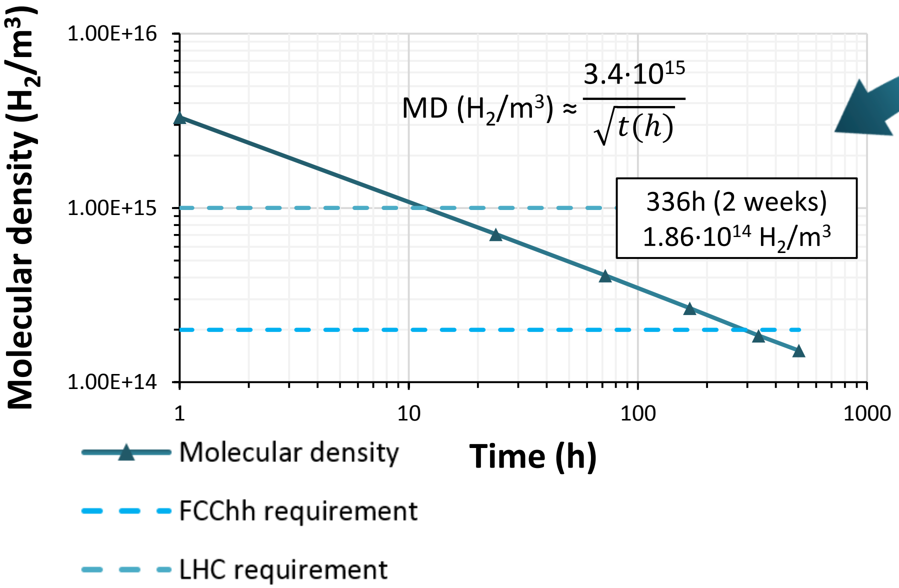
$$K(T) = \frac{T_C}{T_H - T_C}$$

Carnot efficiency of refrigerators

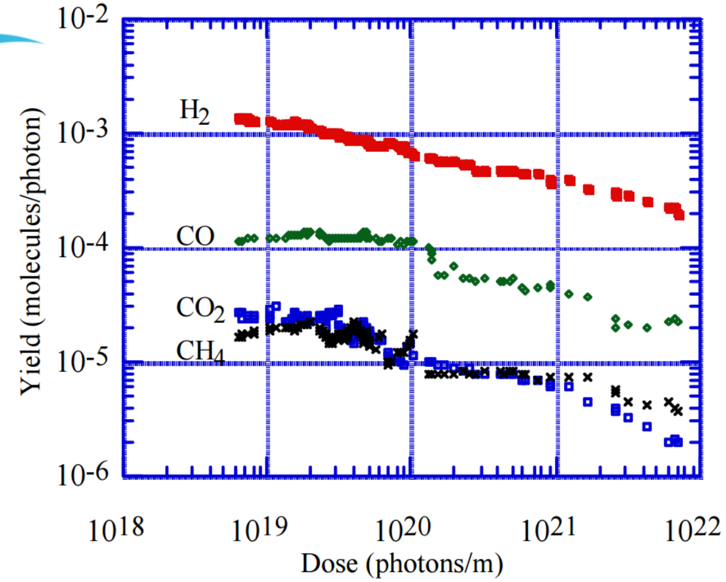
- ✓ Redirecting as **much SR as possible** to the absorber, not only the **cooling efficiency** improves, the **total outgassing is also decreased.** It can be done changing the reflector's shape or reducing its roughness

LOW PUMPING SPEED ISSUE

Dynamic H_2 PSD molecular density over time, for FCChh 50 TeV 500mA



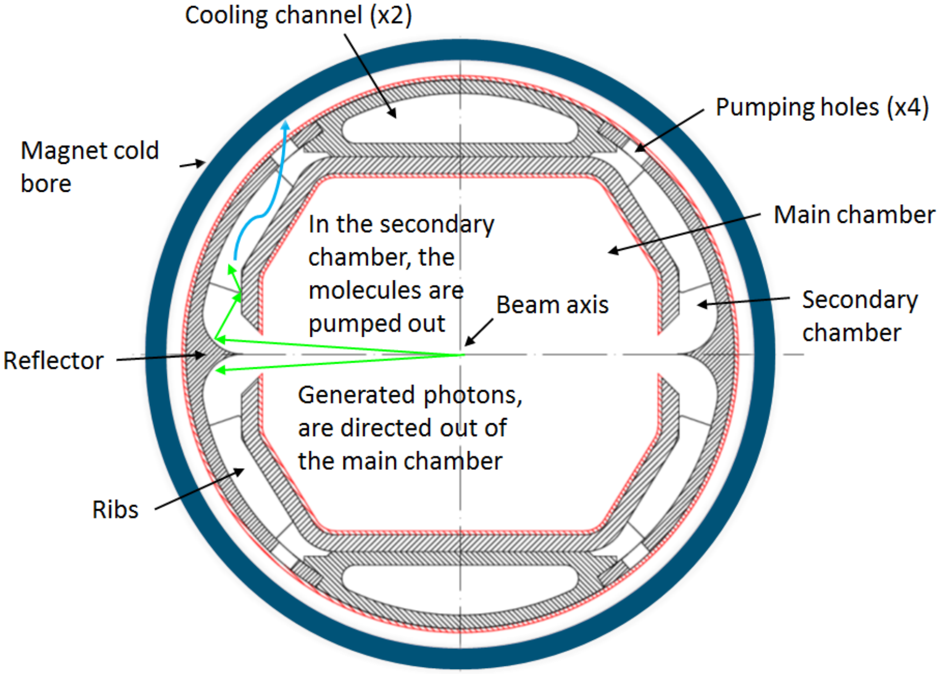
Molecular desorption yield tendency example



- ✓ In the last meeting we saw the molecular density coming from the PSD **effect was too high**, and the time to achieve the pressure requirements would take **longer than acceptable**
- ✓ We had then to **optimize the system** to reduce the molecular density

BS PUMPING SPEED OPTIMIZATION

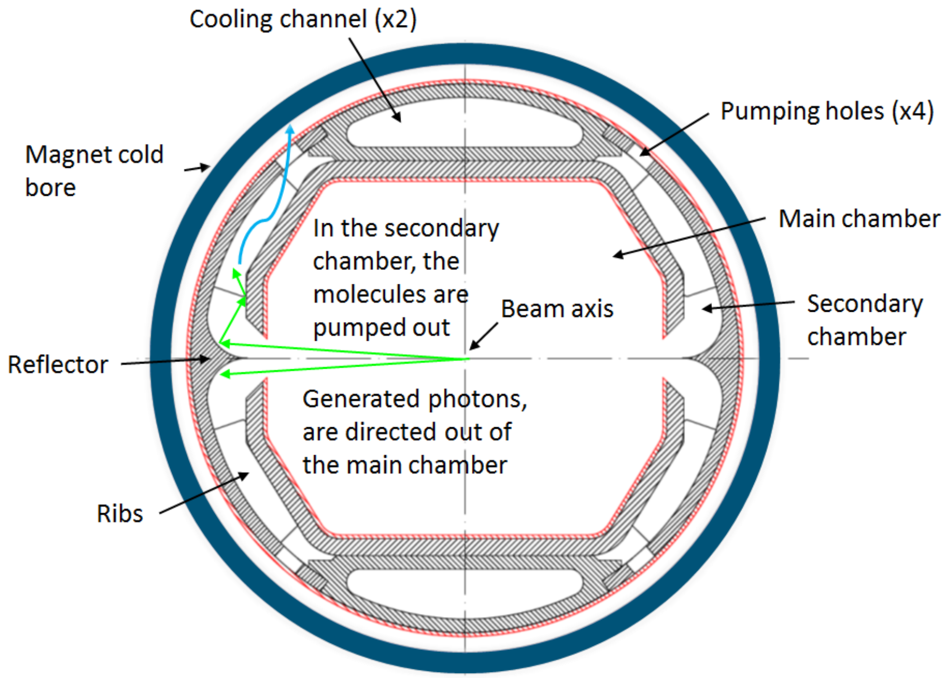
- ✓ To **reduce the total molecular density** inside the beam screen coming from the PSD contribution, we can:
  - Trigger the PSD effect as **far as possible from the main chamber**
  - **Lower the outgassing,** by redirecting the radiation to be absorbed in **high flux density areas**, or using low PSD yield materials
  - **Increase the conductance** of the main chamber to the cold bore, **increasing the pumping speed**



One of the initial FCC-hh BS cross sections

BS PUMPING SPEED OPTIMIZATION

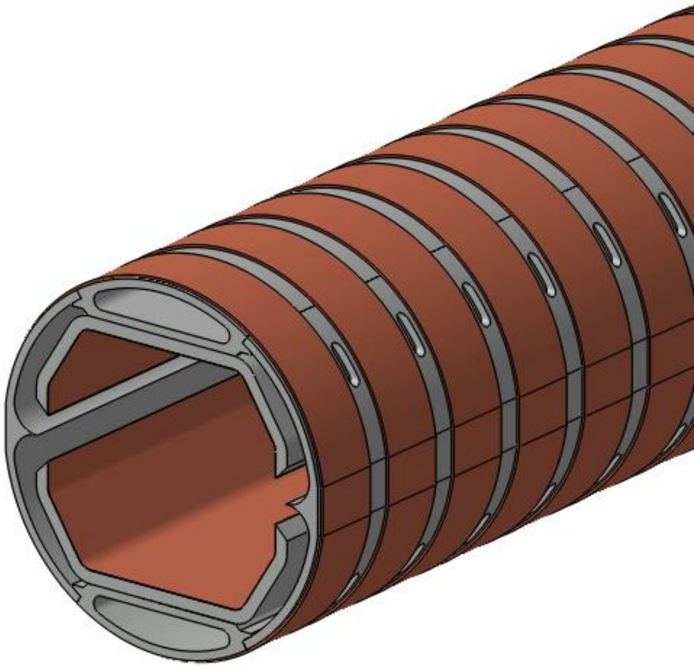
- ✓ For now, the most effective and with most potential solution is to **increase the pumping speed of the system**, easing the pass of the molecules to the cold bore:
  - Increasing **the size of the slot which divides the primary chamber and the secondary one**, where photons are absorbed
  - Increasing the **size of the pumping holes**. This size has a limit, since **too much radiation can be leaked towards the cold bore** surpassing its limit



One of the initial FCC-hh BS cross sections

PUMPING HOLES OPTIMIZATION

- The **bigger** they are, the **higher the pumping speed**, as the molecules have more probability to pass trough them towards the cold bore, were they are pumped.
- However, we have three limitations:
  - The **beam cannot see the pumping holes**, they have to be screened, as this could increase the **impedance**
  - We can't have asymmetry and make bigger the side where we don't have SR, **to reduce the risk of mounting the BS in a wrong way**
  - The bigger they are, **the more radiation is also leaked and reaches the cold bore**. So we had to find a **maximum thermal radiation budget** which will limit the slots shape and aperture



A previous FCC-hh beam screen geometry, with the pumping holes distribution

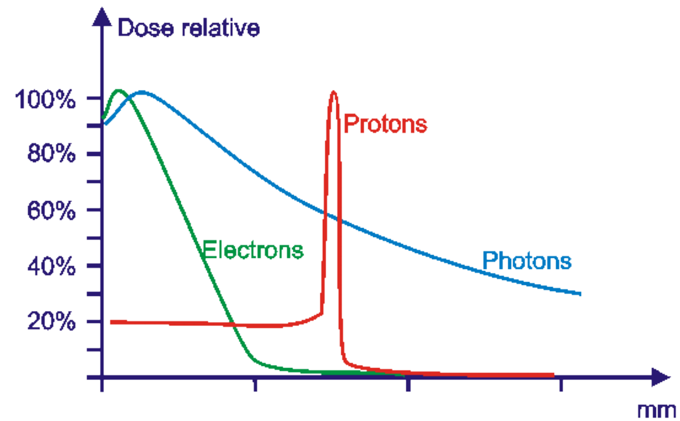
PUMPING HOLES OPTIMIZATION

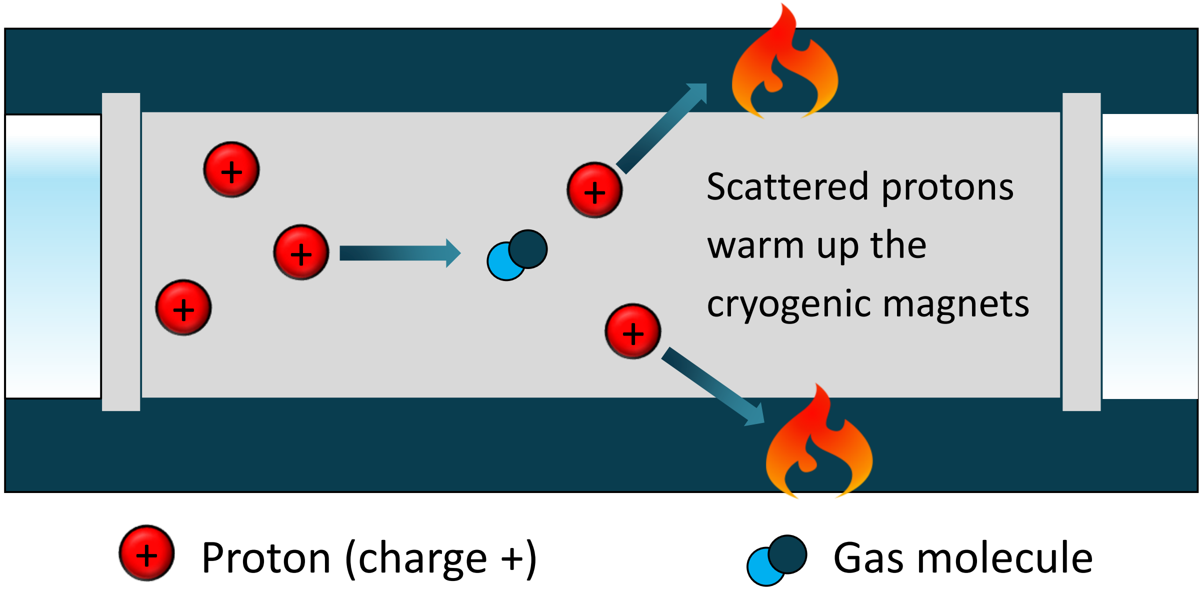
	LHC cold bore heat load	FCC-hh cold bore heat load
Beam gas scattering, average	0.035 W/m	0.046 W/m
Max conduction, sliding rings	0.0043 W/m	0.049 W/m
Leaked radiation power	< 0.001 W/m	?
Gray body thermal radiation	< 0.0001 W/m	0.0023 W/m
Total heat load	**< 0.05 W/m**	**< 0.1 W/m**

- ✓ The **total thermal budget for the 1.9K cold bore is the 0.1W/m/aperture**, (given by C. Kotnig, cryogenics team, internal communication)
- ✓ Due to the electron shield in the LHC and the design of the FCC-hh BS, the thermal load due to the **electron cloud in the CB has been neglected**
- ✓ For the leaked radiation, we have **around 0.0027 W/m** budget left, around **0.038W per dipole and beam**

PUMPING HOLES OPTIMIZATION

- For a hydrogen equivalent density of $2{\cdot}10^{14}$ H_2/m^3, **the total amount of scattered power is 0.05 W/m,** with a beam gas lifetime of 463h
- Around the 8% of this power **is absorbed in the beam screen**, though (M.I Besana, 2015), so the resulting power in the cold bore is **0.046 W/m**





$$\tau = \frac{1}{\sigma\, c\, n}$$

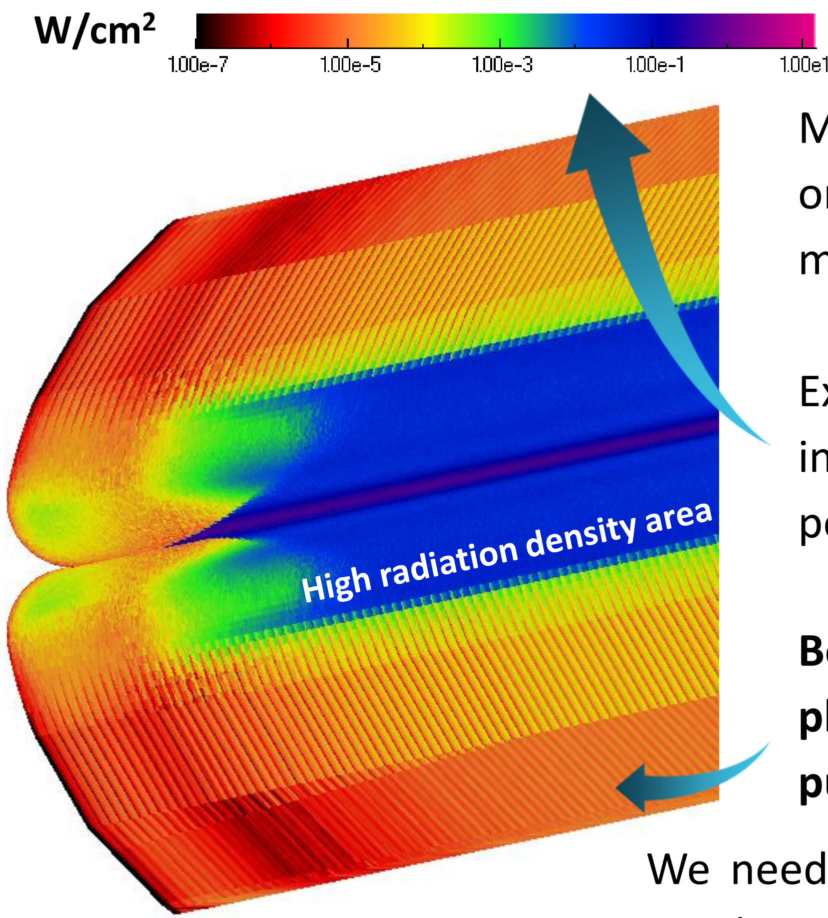
← Molecular density

↑ Cross-section area, around 100mbarn for H_2

$$P_{cold\ mass} = \frac{I\,E}{c\,\tau}$$

← Beam energy

PUMPING HOLES OPTIMIZATION



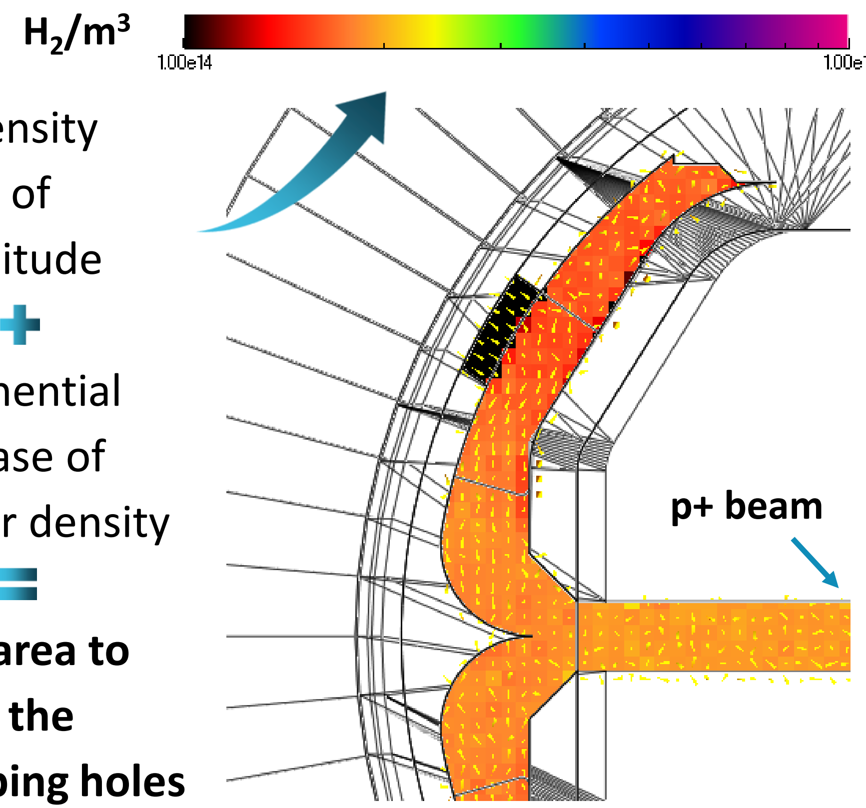
M. density order of magnitude

+

Exponential increase of power density

=

Best area to place the pumping holes

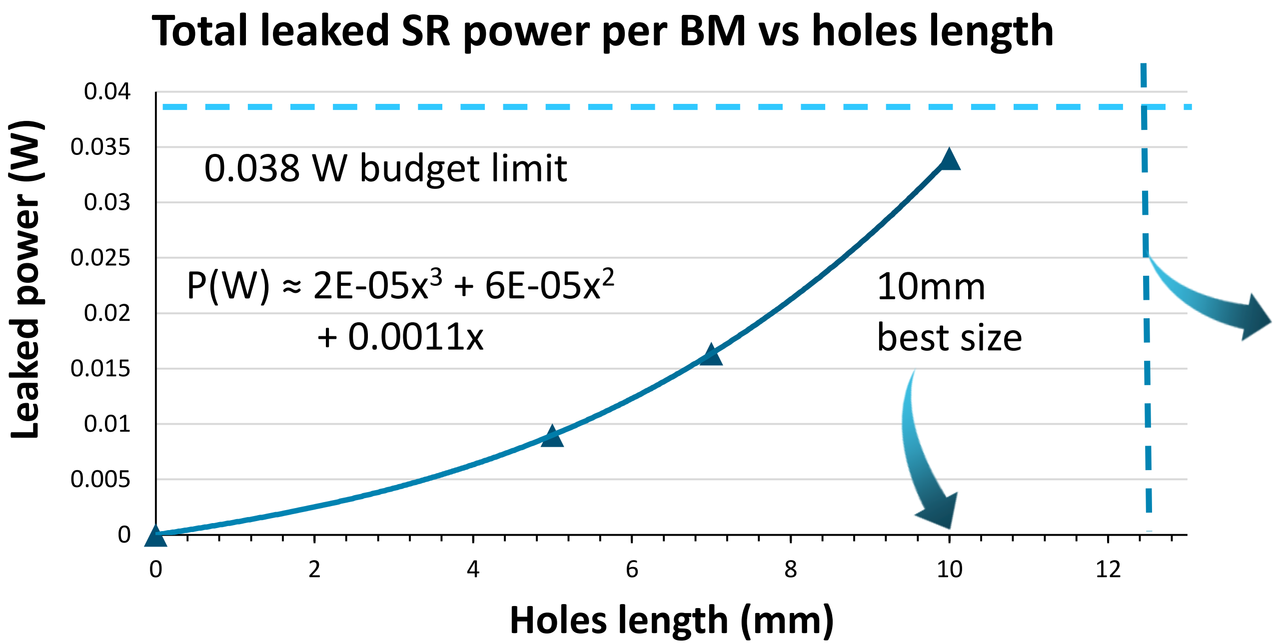


We need to reduce the number of Cu rings!

Molecular density, in H_2/m^3

Power distribution in the reflector, in W/cm^2

PUMPING HOLES OPTIMIZATION



Limit to the **high radiation area**, where there is no shadow from the ribs, **change of slope**

- ✓ Taking advantage as much as possible of the thermal budget we found, the resulting holes found size has been **10mm**, with a changed and optimized copper ring distribution allowing a 23.75mm length
- ✓ Making the **holes axially longer** takes advantage of the space more efficiently

REFLECTOR ROUGHNESS IMPACT

- ✓ Increasing the roughness in the reflector, makes the **radiation to be scattered** in a more diffuse way, **not being stopped by the ribs** and being leaked to the cold bore
- ✓ With **higher reflector roughness**, the budget is surpassed! So it should be **polished**

	σ	T	σ/T	Cold bore P
Reflector roughness	10nm	3100nm	0.0032	**2.38 mW/m**
Other areas	200nm	5500nm	0.036	
Reflector roughness	200nm	5500nm	0.036	**5.31 mW/m**
Other areas	200nm	5500nm	0.036	

(2.7mW/m budget)

- ✓ Reflectivity used data
  - Pure Fe/Cu

$$P_{spec}(y,\lambda) = exp\left[-\left(\frac{4\pi\sigma y}{\lambda}\right)^2\right]$$

Specular probability of the incident radiation

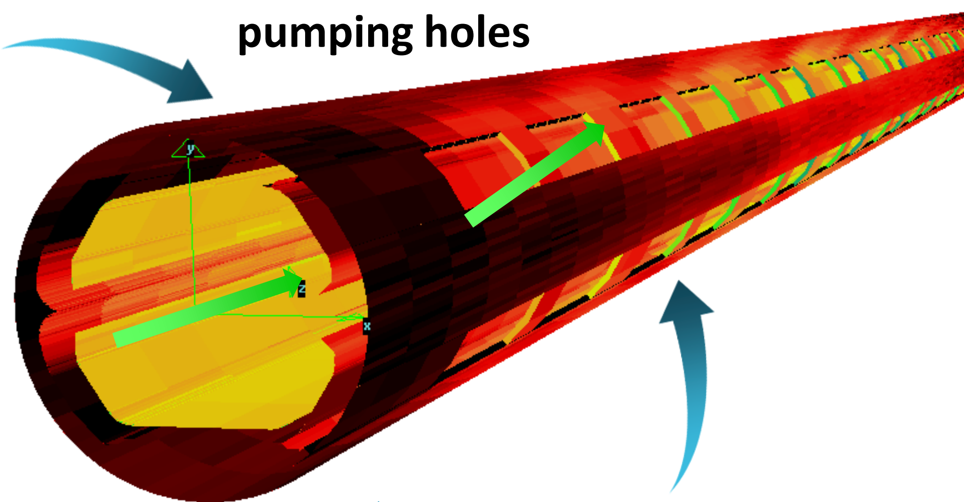
Better polished reflector → Higher pumping speed / Lower BS temperature → Less pressure, less heat leaked to the cold bore and **reduced operating costs**!

- ✓ A recommended manufacturing roughness shall be fixed!

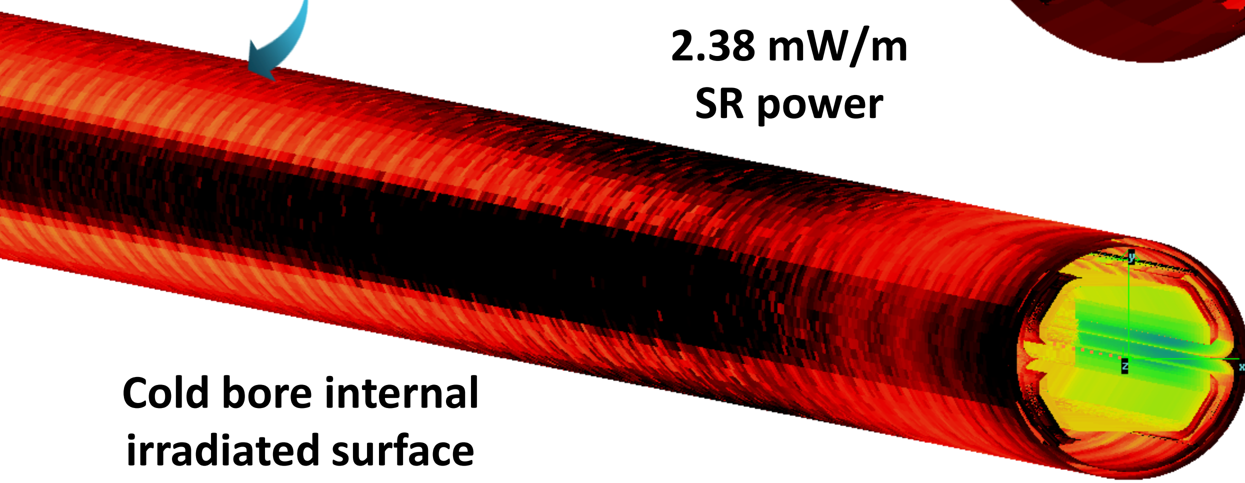
LEAKED RADIATION TO THE CB

- On the other hand, **increasing the roughness of the ribs**, could reduce the leaked radiation, **decreasing their reflectivity**
- Cold bore **leaked radiation** ray tracing - The **openings marks of the pumping slots** are easily noticeable

BS external surface, with the pumping holes



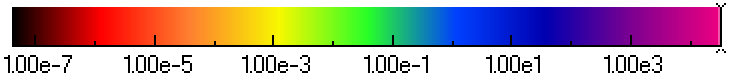
2.38 mW/m SR power



Cold bore internal irradiated surface

- The transversal sides of the drilled holes act **as a 2nd barrier to the radiation,** as it hits them perpendicularly, keeping safer the cold bore

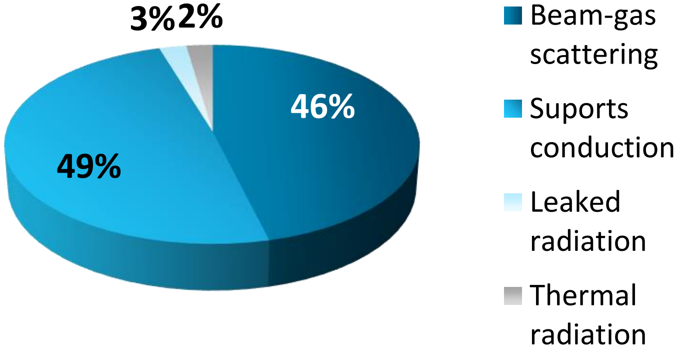
W/cm^2



TOTAL HEAT LOAD DISTRIBUTION

	FCC-hh cold bore heat load
Beam gas scattering, average	0.046 W/m
Max conduction, sliding rings	0.049 W/m
Leaked radiation power	0.00238 W/m
Gray body thermal radiation	0.0023 W/m
Total heat load	**0.09968 W/m**

1.9K Heat load distribution

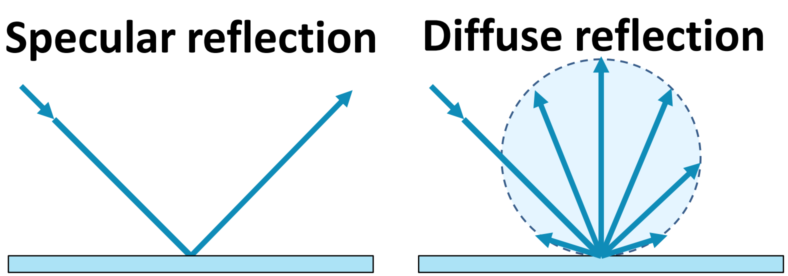


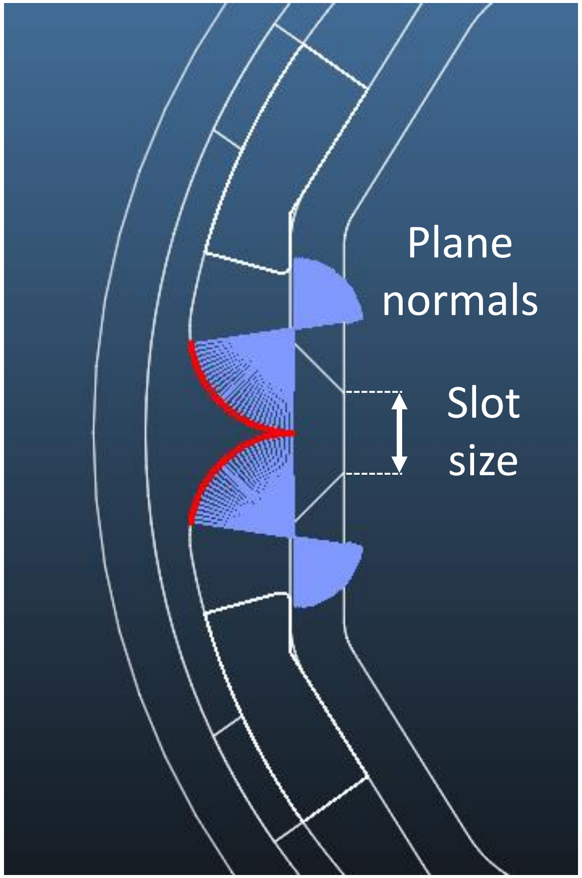
Under 0.1W, OK! ✔

- ✓ The first estimations **show it is possible to achieve reasonably the maximum budget**
- ✓ The heat load with the highest potential to be reduced is the **conduction of heat** from the beam screen to the cold bore through the metallic supports, as it is **highly geometry and material dependent**

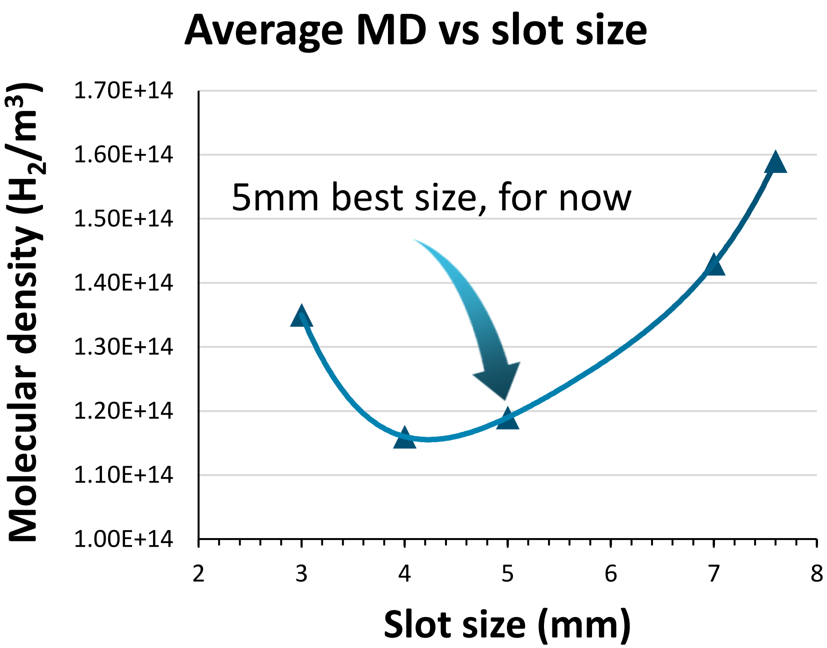
MAIN BEAM SCREEN SLOT SIZE

- The slot can't be indefinitely increased, as opening it too much would result in **an excess of radiation being backscattered** to the main chamber
- Besides, opening it worsens the impedance and the **mechanical resistance during a quench**
- It has to cover, at least, **most part of the main reflected radiation**, while guaranteeing an optimal conductance
- Monte Carlo simulation tools can help us to find an optimal size





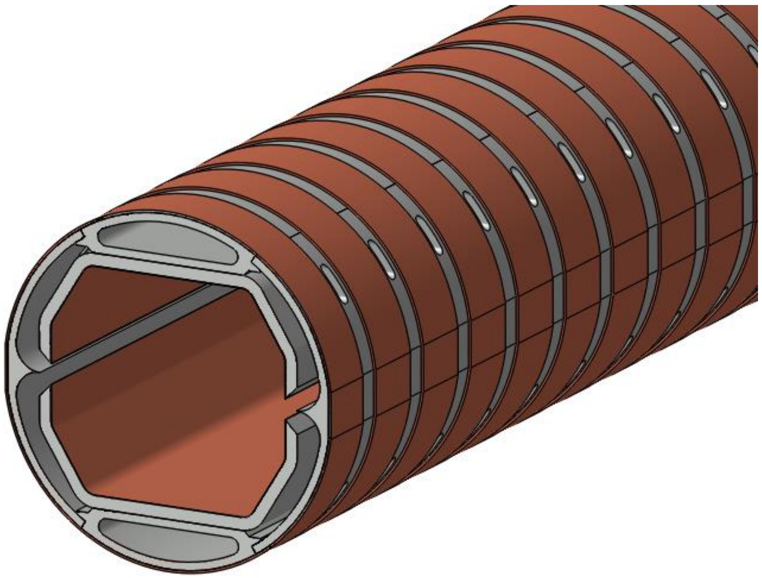
MAIN BEAM SCREEN SLOT SIZE



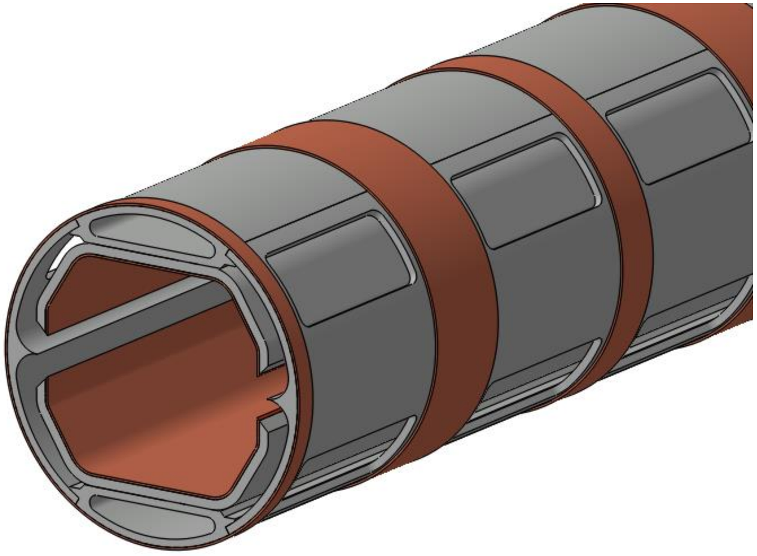
PSD data	Bk. 316SS H_2 293K 4 keV
Pumping holes size	7mm
Time lapse	72h
Reflector roughness	σ/T = 0.0032

- ✓ After testing many configurations, it was seen the optimal size for a 72h max photon dose is **around 4.2mm**
- ✓ However, as Synrad does not take into account the photon energy, and the scattered radiation to the main chamber has low one, **the effect of the backscattered radiation is in fact lower**. Taking also into account possible misalignments, we would recommend a **5mm slot**

GEOMETRY COMPARISON



Previous geometry, July 2016



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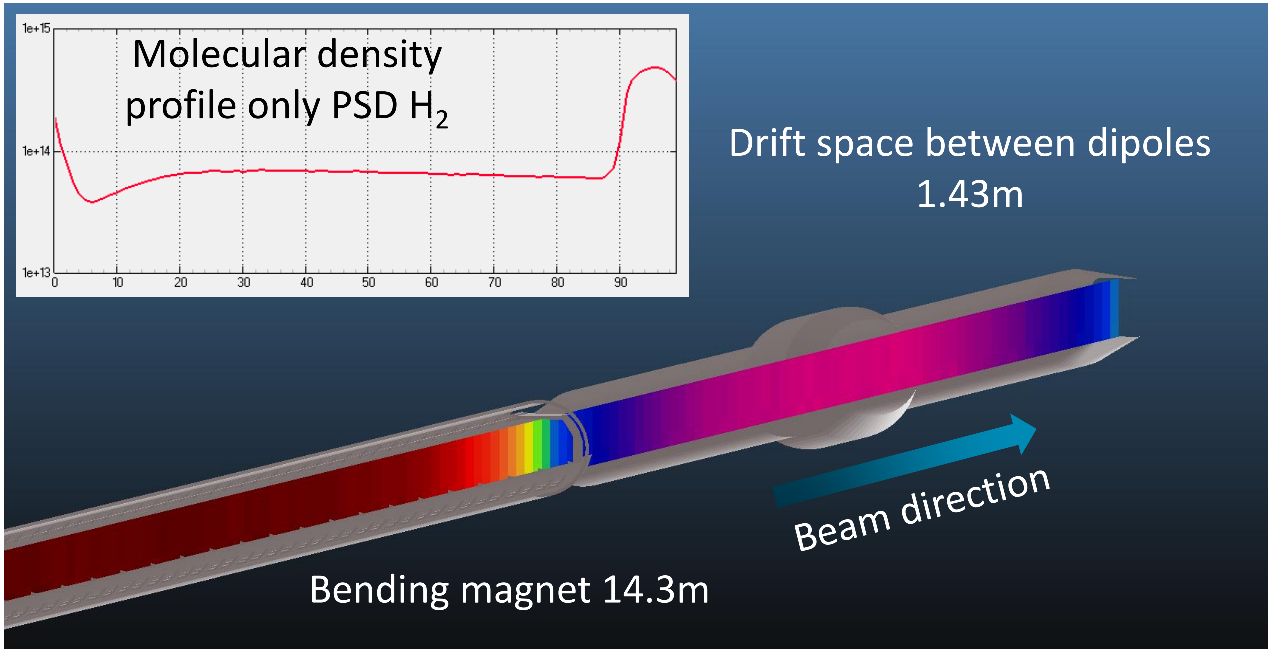
	Previous	Current
Holes length	~5.3mm	10mm
Holes width	1.5mm	23.75mm
Central slot	2.28mm	5mm
Av. H_2 p. speed 50K	**~127 l/s/m**	**~ 530 l/s/m**

x4!

$$S_{av}[l/s] = \frac{Q\ const[mbar \cdot l/s]}{P\ [mbar]}$$

MOLECULAR DENSITY RESULTS

Main slot aperture	Pumping Holes length	Holes area coverage	Reflector roughness
5mm outwards	10mm	67’6 %	σ/T = 0.0032



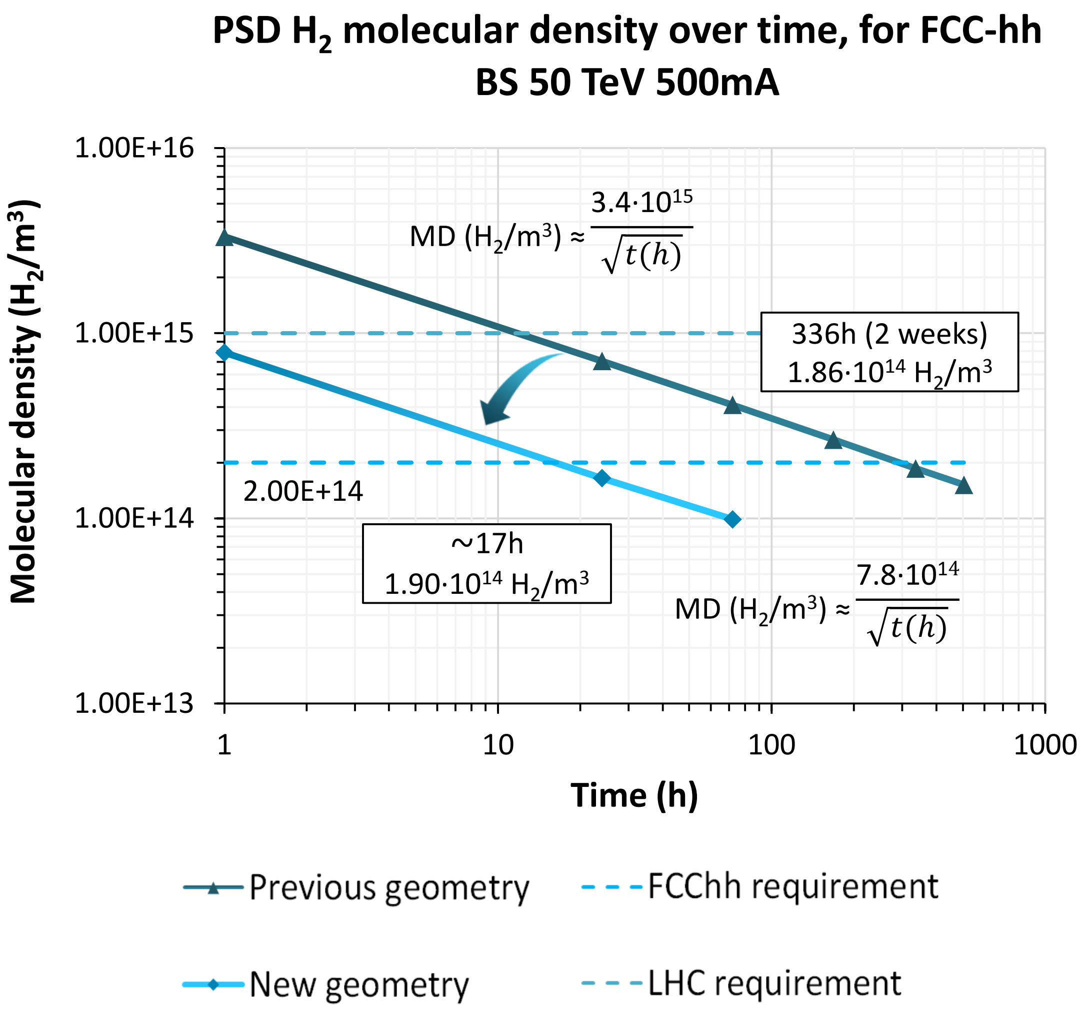
Temperatures	
Ribs	60K
Main reflector	60K
Cold bore	1.9K
Inner copper	47K
End absorber	100K
Other areas	50K

Outgassing per BM
$4.97 \cdot 10^{-6}$ mbar·l/s

Average arc density	$9.88 \cdot 10^{13}$ H_2/m^3
Average arc pressure	$6.56 \cdot 10^{-10}$ mbar
Time lapse	72h

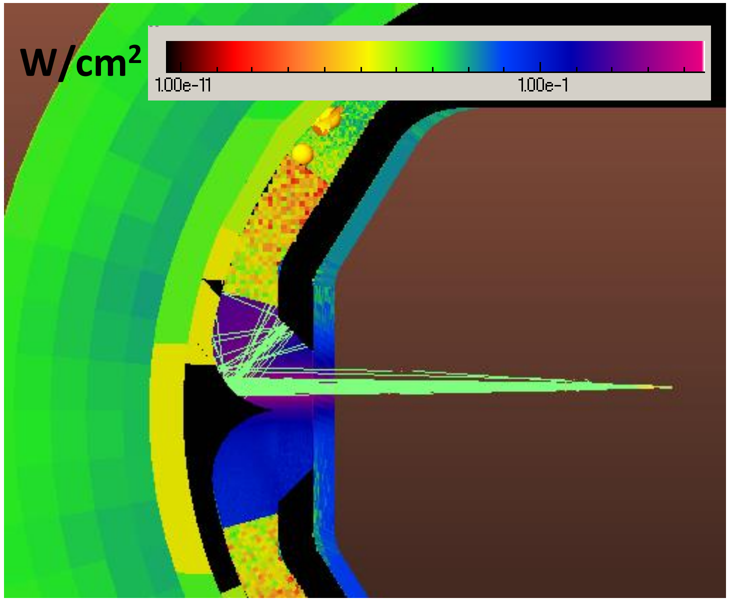
PSD data
Bk. 316 SS H_2 293K 4 keV

PUMPING SPEED IMPROVEMENT



- ✓ Due to the cleaning effect, the **PSD decreases gradually with time**
- ✓ If only this effect was rising the pressure, and counting only hydrogen, in **less than one day of maximum dose** in nominal conditions, the required density would be met (SS room temperature PSD data)
- ✓ **Further studies** with all gases and the remaining effects will be carried out

MISALIGNEMENT STUDY

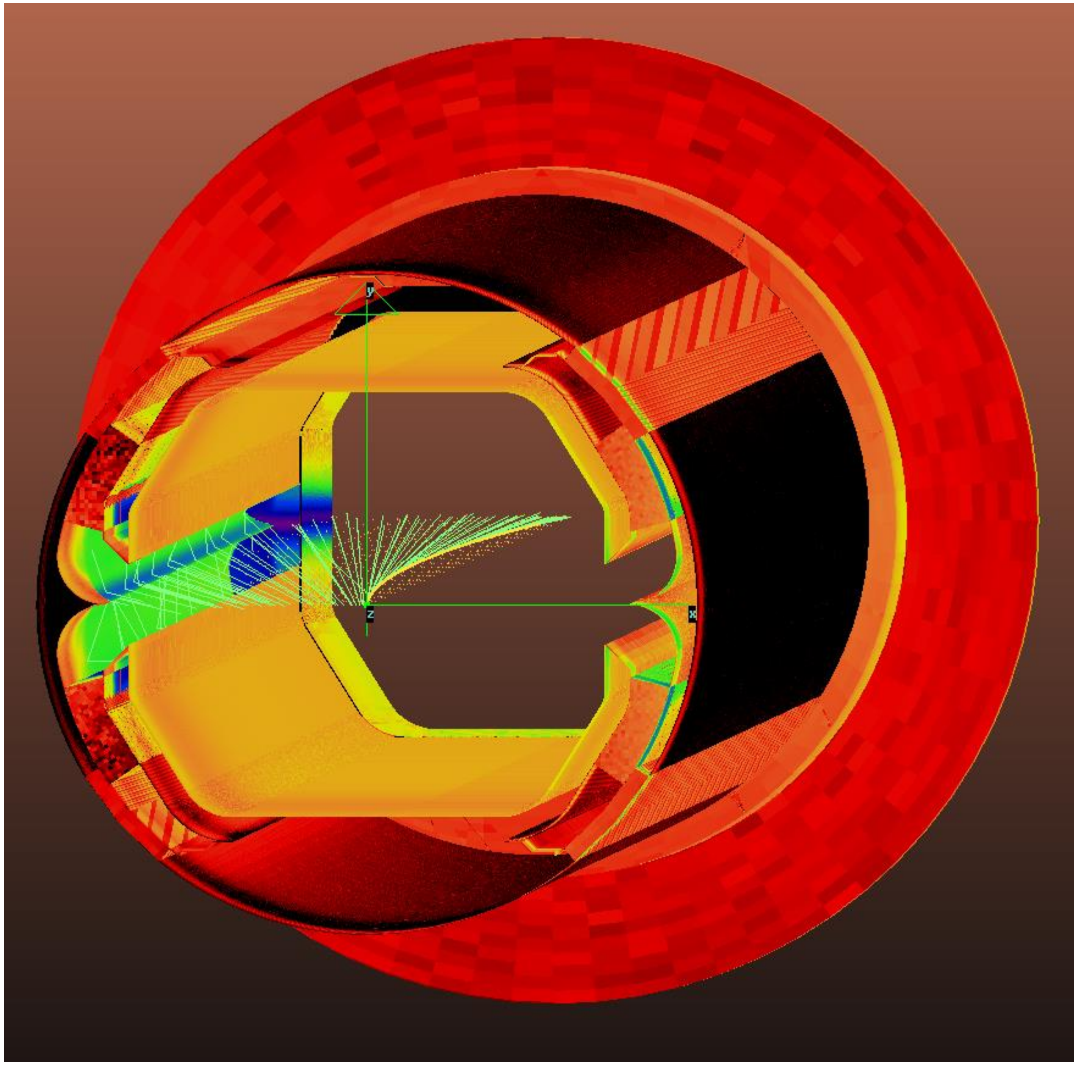


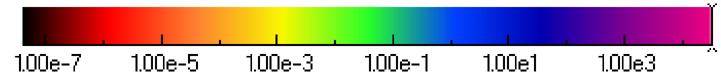
- ✓ To perform an approach to the real geometry conditions, a **misalignment study** has been carried out, moving the beam **1mm upwards**
- ✓ The **leaked power is slightly lower**, while the molecular density is slightly worse
- ✓ The radiation is directed forward **with a narrower angle**, increasing the absorber power

	Aligned	Misaligned
Molecular density 72h	$9.88 \cdot 10^{13}$ H_2/m^3	$9.93 \cdot 10^{13}$ H_2/m^3
Cold bore power	0.034 W	0.032 W
Absorber power	63 W	86 W
Inner copper power	3.3 W	3.7 W
Ribs power	165 W	73 W

- ✓ **Stretching the sharp point** of the reflector can produce the same effect in ideal conditions

RAY TRACING FAST RESULTS



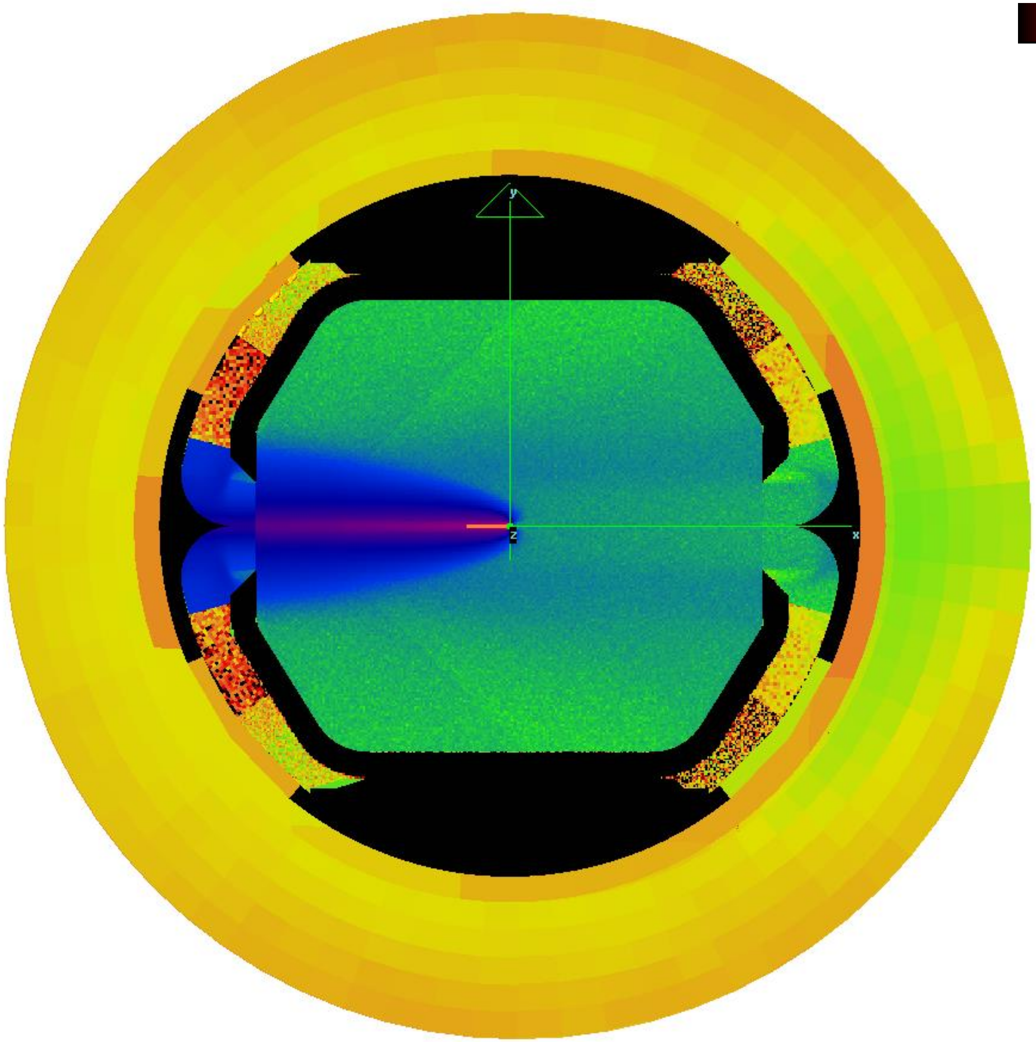


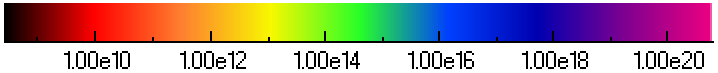
W/cm²

% of Total BM Power, 502W	
Ribs	32.9%
Reflectors	29.3%
Cold bore	0.007%
Inner copper	6.56%
End absorber	12.6%
Drift space	8.1%

- ✓ **68% of the incident power** is reflected on the reflector

RAY TRACING FAST RESULTS





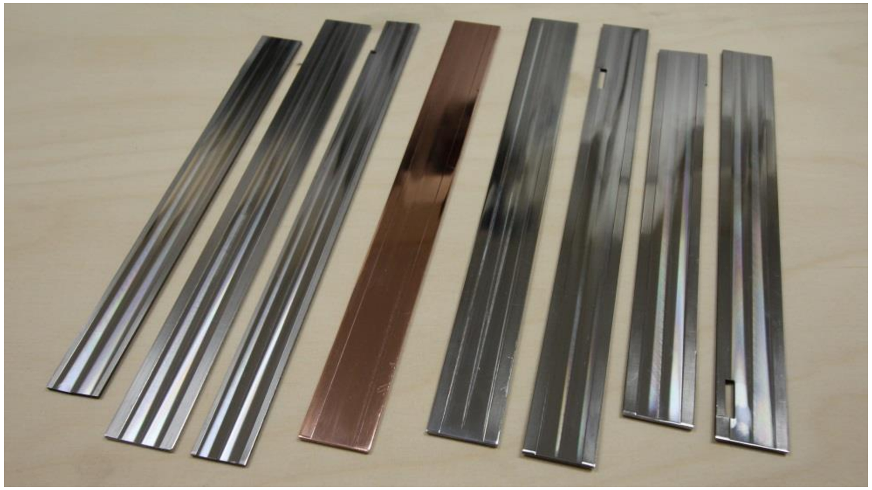
Photons/s/cm²

% of Total BM Flux, 2.1E18 ph/s	
Ribs	29.6%
Reflectors	21.4%
Cold bore	0.27%
Inner copper	4.9%
End absorber	12.8%
Drift space	5.9%

- ✓ **78% of the incident flux** is reflected on the reflector

REFLECTIVITY STUDIES

- There is no experimental data of the reflectivity of the FCC-hh's beam screen steel in the X-Ray range. Knowing accurately its reflectivity properties **would increase the reliability of the performed simulations**

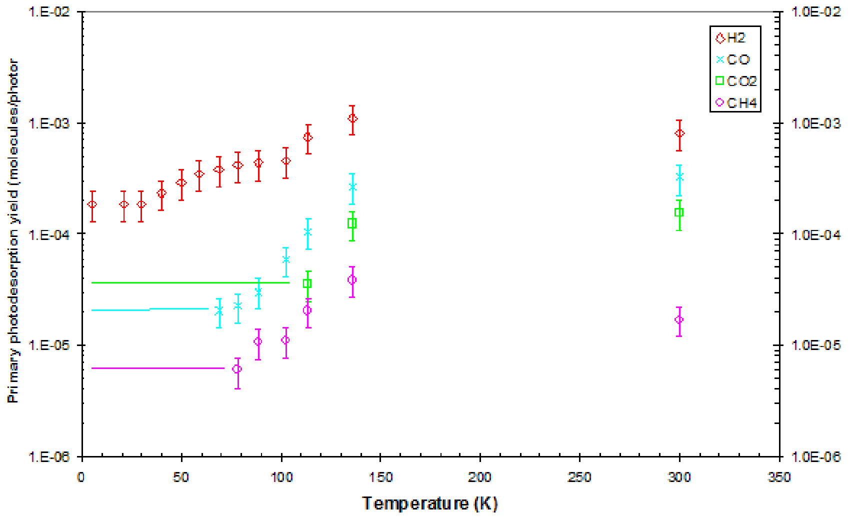


Special thanks to H. Kos for the machining

- Some measurements are foreseen to be performed **at BESSY II,** Germany, by the end of the year by R. Cimino with the **samples provided by CERN,** and if allocated the beamtime, more measurements will be done next year
- Three materials with different roughness will be analyzed: **SS P506** (FCC and LHC steel, most important one), 316LN (ANKA steel) and copper with SALT treatment

PROJECT NEEDS - FURTHER DATA

- All these molecular density simulations have been performed with the SS data for room temperature, so they are still not very accurate
- As done for the LHC, we should characterize the **PSD yield at the BS cryogenic temperatures**, around 40K-70K, for stainless steel (P506 better..)! The difference could be of **an order of magnitude**
- Ideally, the critical energy should be as close as possible to 4.3keV
- The **initial yield would be lower**, but the cleaning rate would be slower, too



PSD yield dependence of temperature example
(V. Baglin et al, Vacuum 67, 421-428)

CONCLUSIONS

- ✓ The FCC-hh beam screen pumping speed **has been increased**, being the new design capable of meeting the pressure requirements for nominal conditions in a much shorter amount of time
- ✓ The **heat load on the cold bore** has been analyzed, still existing potential to reduce it
- ✓ The surface finishing plays an important role in the manufacturing specifications, it should be rough were the radiation has to be absorbed, and smooth were reflected
- ✓ The future reflectivity measures, and a possible PSD yield measurement for P506 stainless steel, **will allow a higher reliability and accuracy** in the simulations

NEXT STEPS

- ✓ **Detailed design of the end absorber**, and the drift space design, to deal with the directly irradiated areas

- ✓ The total pressure contribution of the **electron and ion induced desorption shall be studied, as done with the PSD,** to completely study all the beam induced vacuum effects

- ✓ The beam screen design will be **further improved** and reanalyzed, following possible future geometry changes, to maximize the pumping speed and thus reducing the pressure

- ✓ The **pressure contribution** of the outgassing generated when warming up some possible beam screen coatings will be studied

THANK YOU FOR YOUR ATTENTION !