Photon ray tracing and gas density profile in the FCC-hh

Ignasi Bellafont

FCC Week

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OUTLINE

Introduction

1. Updated molecular density requirements
2. Beam screen operation principles

Photon ray tracing

3. Synchrotron radiation in the bending magnets
4. Updated derived heat loads to the cold mass

Vacuum features

5. Expected PSD pressure profile in the bending magnets and yield evolution
6. ANKA setup expected pressure values

Conclusions

VACUUM REQUIREMENTS

	LHC	FCC-hh
Energy [TeV]	7	50
Current [mA]	580	500
Photon flux [ph/m/s]	$1 \cdot 10^{17}$	$1.7 \cdot 10^{17}$
SR power in BM [W/m]	0.2	35
Critical energy [eV]	44	4300

- **Vacuum** is required in particle accelerators to **minimize beam-gas interactions**, thus ensuring an acceptable beam lifetime and minimizing the heat load to the 1.9K cold mass due to the scattered beam particles
- **Being the flux and critical energy higher** than in the LHC, we expect higher pressures for the same current mainly due to the interaction of the radiation with the walls

- Knowing the updated **restrictions**, we can define the maximum recommended **molecular density requirement**:

$$P_{cold\ mass} = k_{abs} \frac{IE}{c\tau_{bg}}$$ → < 0.2 W/m per beam *C. Kotnig*

$$\tau_{bg} = \frac{1}{\sigma\ c\ n}$$ → > 100h *LHC requirement*

n = $1.0 \cdot 10^{15}$ $H_{2\,eq}/m_3$

- Meaning $H_{2\,eq}$ the amount of H_2 MD equivalent to the **main gas species.** Same level as for **the LHC!**

σ: **Cross section**, 90 mbarn for H_2

τ_{bg}: Beam lifetime due to residual gas

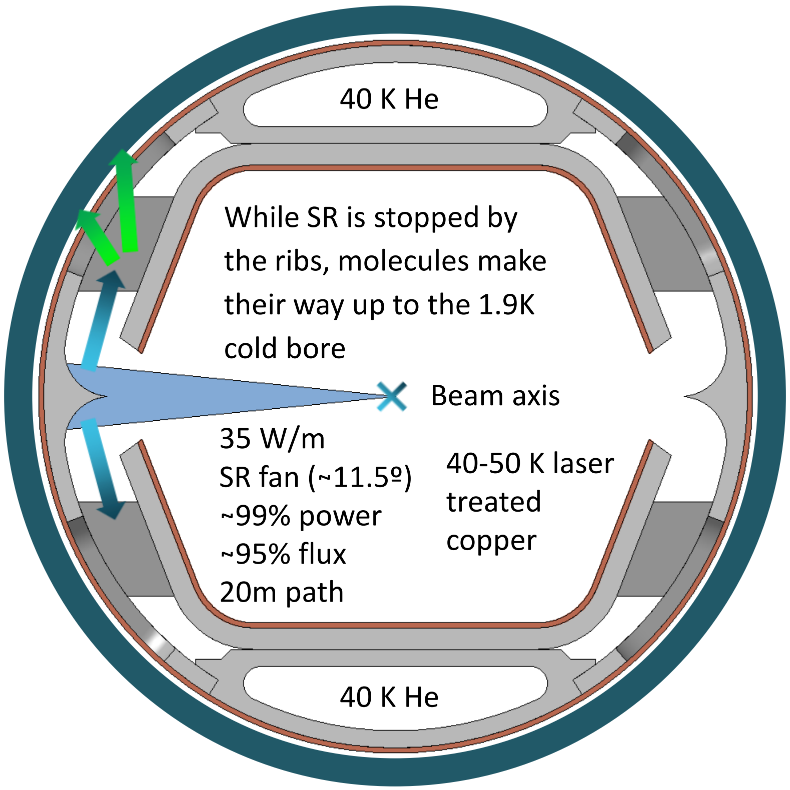
k_{abs}: Ratio of **total scattered protons** absorbed by the **cold mass**, ~0.85, *A. Infantino*

Photons contribution

$$n = \frac{P}{kT} = \frac{Q}{S \cdot kT} \approx \frac{\eta_{ph}\Gamma_{ph} + \eta_e\Gamma_e + \sum \eta_{j^+}\sigma \cdot \frac{I}{e} n_g + a \cdot q}{S \cdot kT}$$

BEAM SCREEN FEATURES

- As done in the LHC, we need one 'warm' element to set the **cooling efficiency within affordable numbers**, being the temperature window 40-60K, avoiding crossing vapor pressure limits and setting the copper resistivity low
- In spite of **losing pumping performance** due to its complexity, setting the pumping holes out of the main chamber ensures good impedance, avoids triggering a high number of photoelectrons in the beam region and **direct leakage of photons and e cloud electrons** up to the cold mass
- Being 5mm the main slot, an aperture of 4mm at that position contains **97% of flux and 99.9% of power** (ideal beam), leaving margin for **< 1mm misalignment** in the y axis

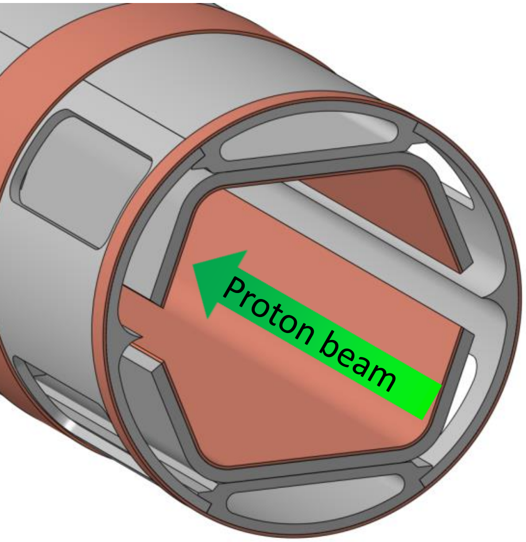


	LHC	LHC-HL tripl	FCC-hh
T window [K]	5-20	40-60	40-60
S at 50K, H_2 [l/s/m]	765*	1236*	540**
Relative complexity	Low	Medium	High

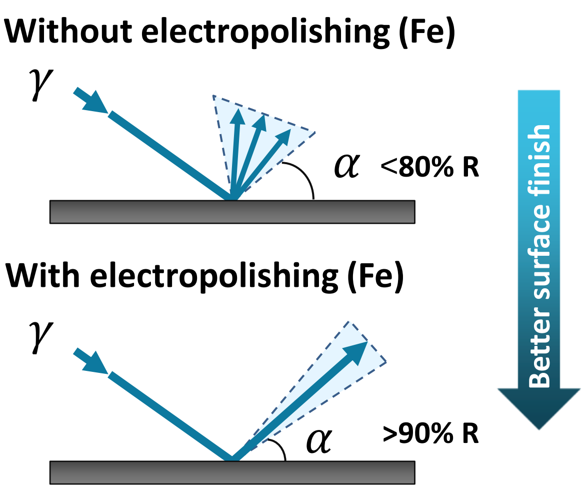
**R. Kersevan **Non updated geometry*

$$K(T) = \frac{T_c}{T_H - T_C}$$ **Carnot efficiency of refrigerators**

BEAM SCREEN FEATURES

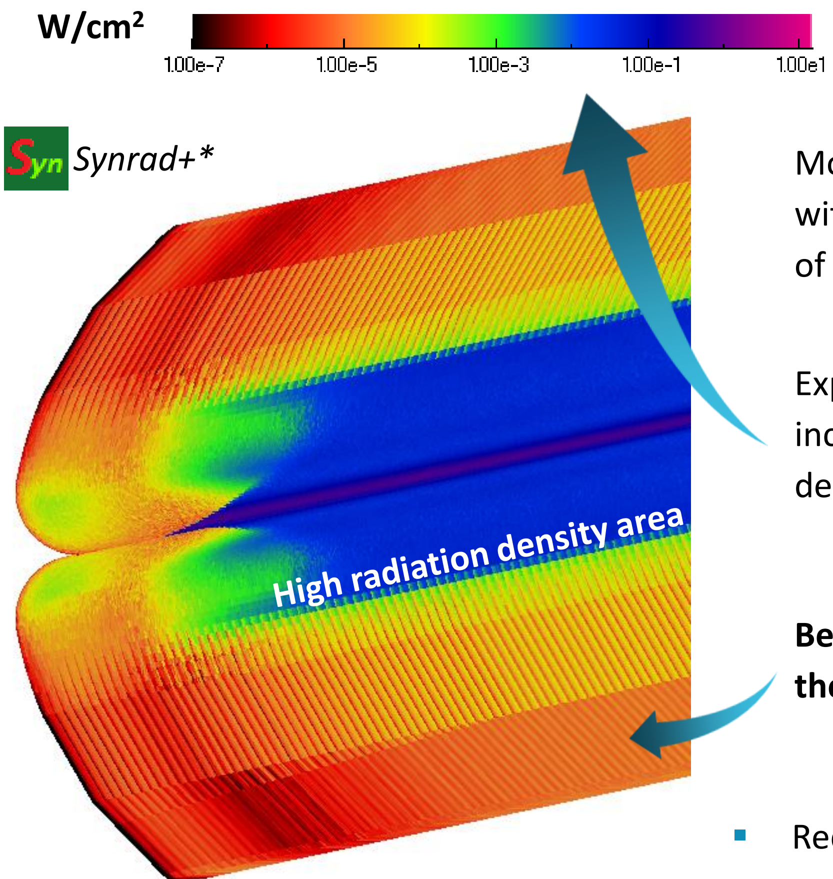


Element	Recommended surface finish
Reflector (irradiated)	R_q < 0.1µm, T > 300µm
Inner copper	R_q > 5µm, default by LASE
Cold bore, ribs support facets	R_q < 0.3µm, T > 30µm
Ribs	R_q > 0.3µm, T < 30µm



- The reflector has been determined **to be electropolished**, in spite of increasing **manufacturing costs**, due mainly to the following reasons:
  - With a standard roughness, the reflecting capacity is **not high enough**, and a considerable amount of power is absorbed on its surface (~10 W/m) **raising the temperature above the defined window** (~80K)
  - More flux is directed toward the ribs (>50%) and less to the main chamber, **increasing the pumping speed** and lowering the amount of photoelectrons in the beam region (Fe reflectivity data)
  - Due of the uncertainty of reflectivity properties with very small **grazing angles** (< 0.1º), an extra margin is needed for **safety reasons,** since the real reflectivity could be much lower

RAY TRACING AND MD CALCULATION



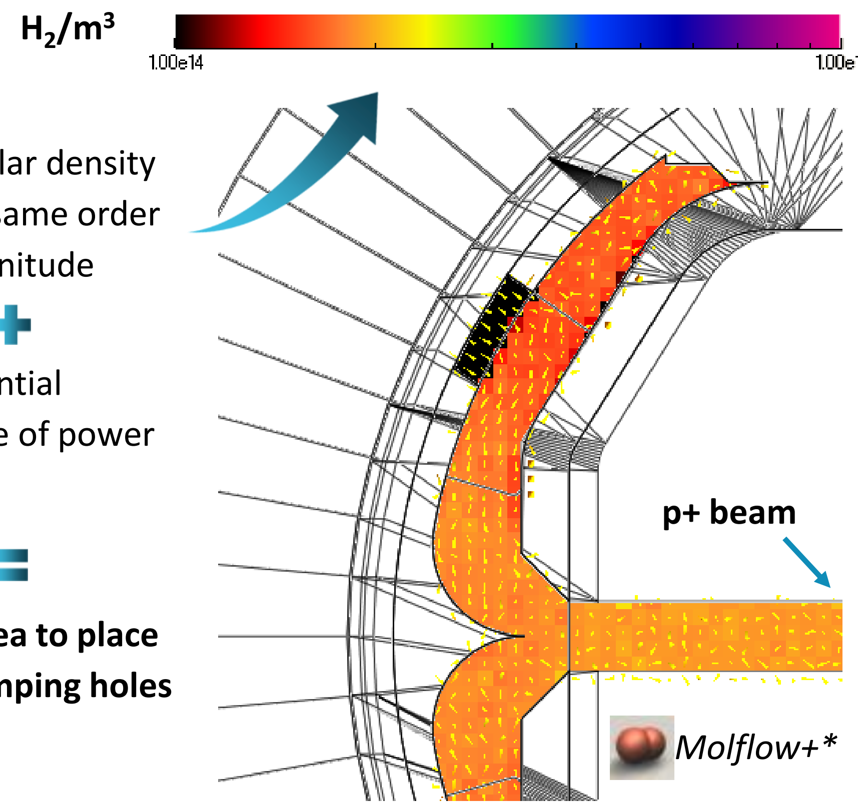
Molecular density within same order of magnitude

+

Exponential increase of power density

=

Best area to place the pumping holes



Power distribution in the reflector, in W/cm²

**R. Kersevan, M. Ady - CERN*

- Reducing the external number of Cu rings allows higher holes area and higher pumping speed

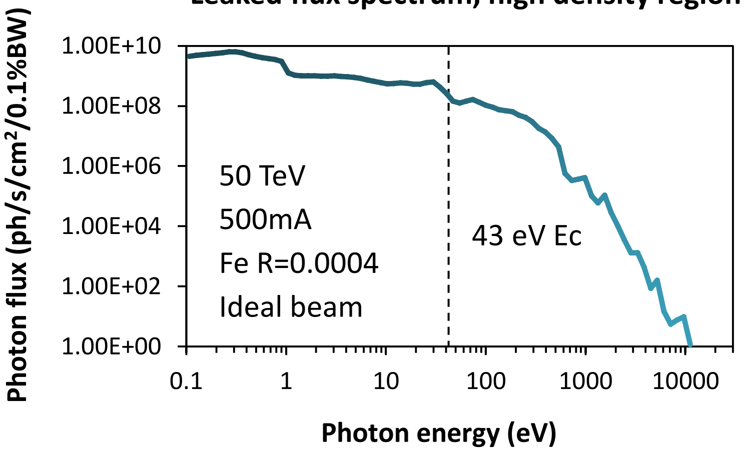
Molecular density, in H_2/m^3

50 TeV, 500 mA
Ideal beam

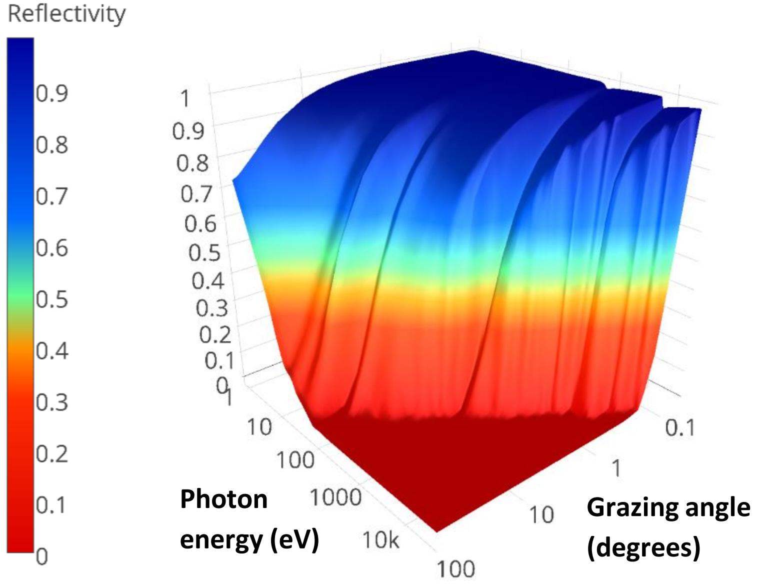
RAY TRACING AND MD CALCULATION

- The present design is very effective **minimizing the leaked power to the cold mass** (main purpose of the BS), since less than the **0.01%** of the total emitted power is leaked
- For the 4.3keV Ec and above, almost **all the incident power** above 1º grazing angle **is absorbed**

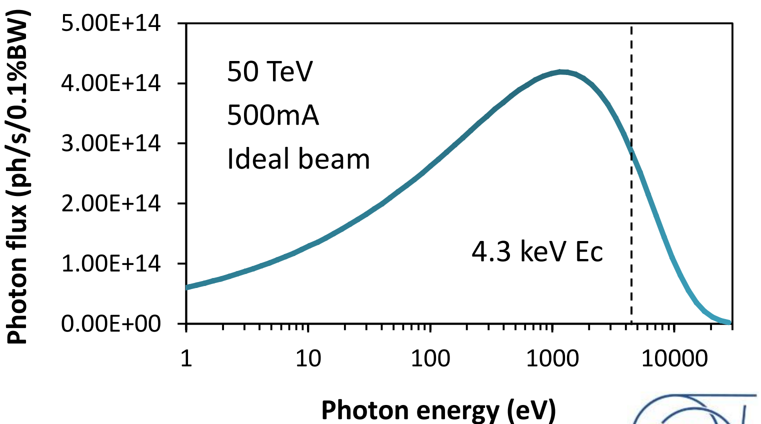
Leaked flux spectrum, high density region



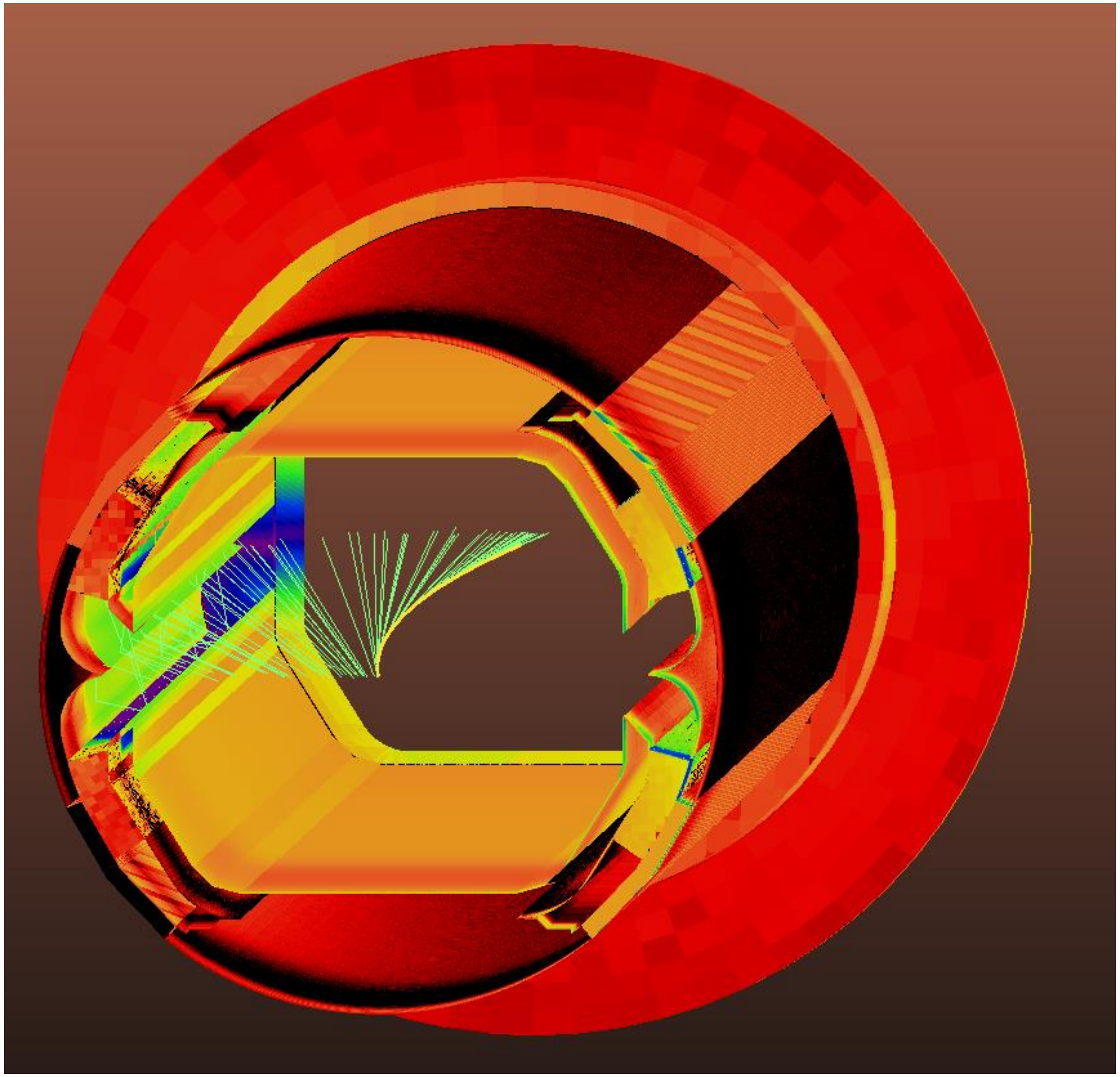
Pure iron reflectivity vs E and Angle
Ideally polished surface



Flux spectrum from the bending magnet



RAY TRACING GENERAL RESULTS

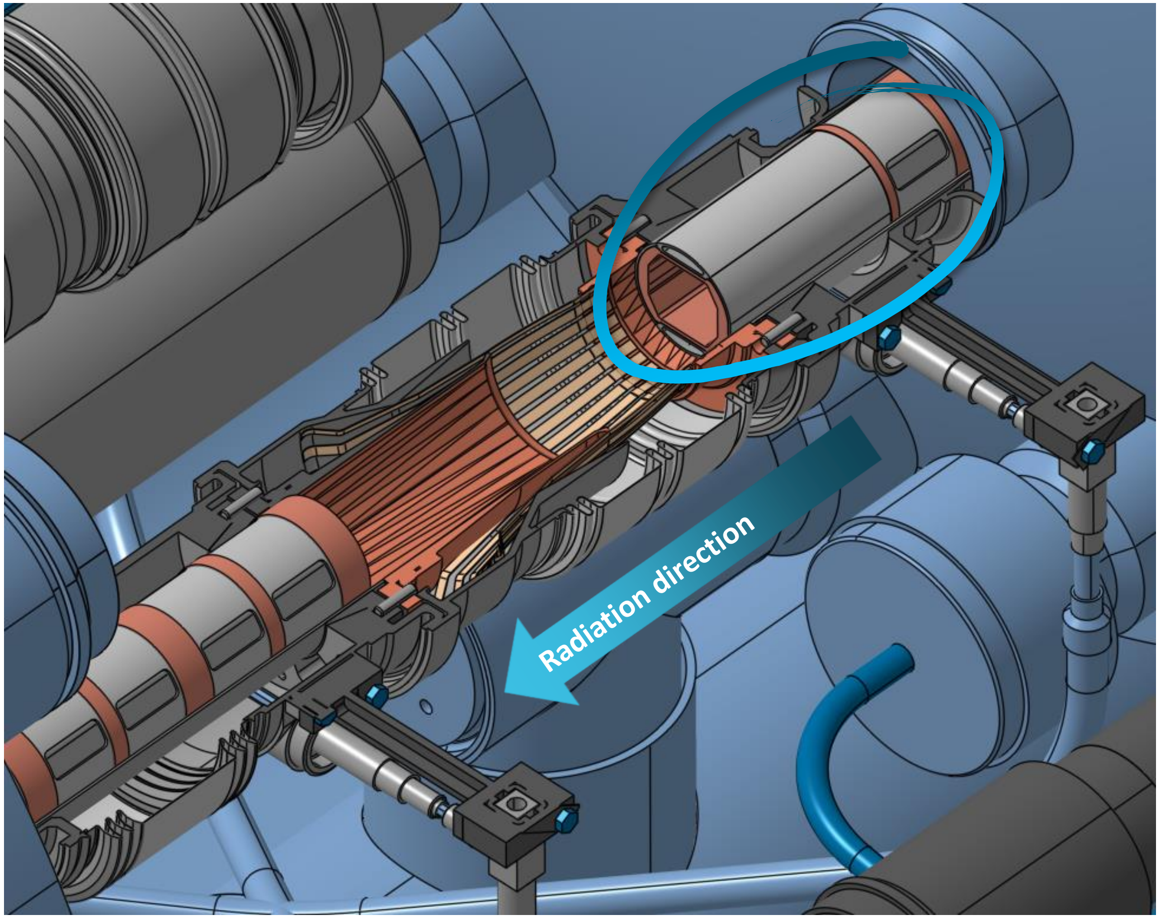


Photons/s/cm²

% of Total BM Flux > 4eV, 2.1E18 ph/s	
Ribs	51%
End absorber	19%
Cut main slot	8.4%
Reflectors	7.1%
Drift space	5.7%
Inner copper	< 5%
Cold bore	< 0.3%

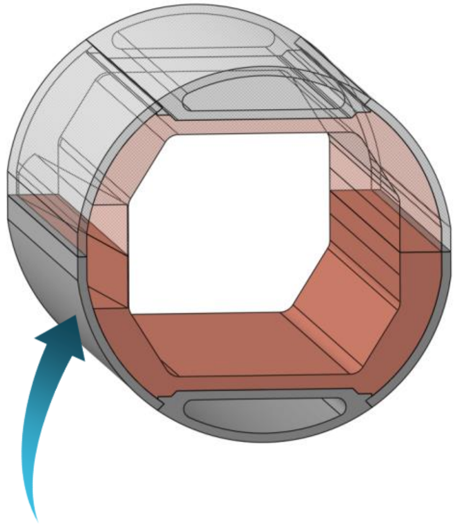
- **> 90% of the incident flux** is reflected on the reflector (pure Fe reflectivity data)
- **50 TeV 500 mA,** 15.9 T ideal beam
- Reflector Rq = 0.1µm, T = 300µm
- Perfect beam **alignment**

PHOTON ABSORBERS



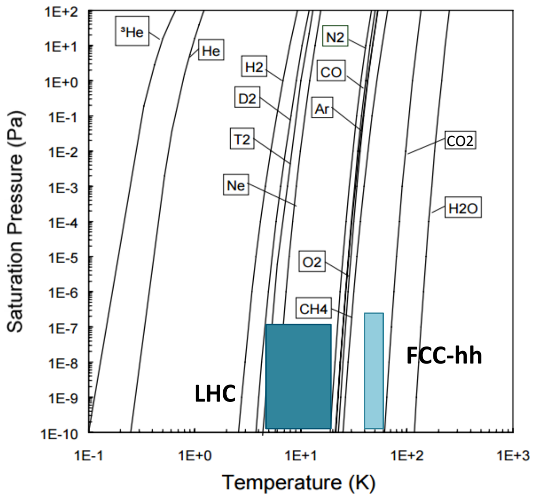
Representation of the possible position of the photon absorber in an LHC's-like BM interconnection

- Placing a photon absorber **out of the magnet** just before the RF fingers and where the angular transition between BM is applied, **it would protect** not actively cooled regions of being **directly irradiated** and would improve cooling efficiency

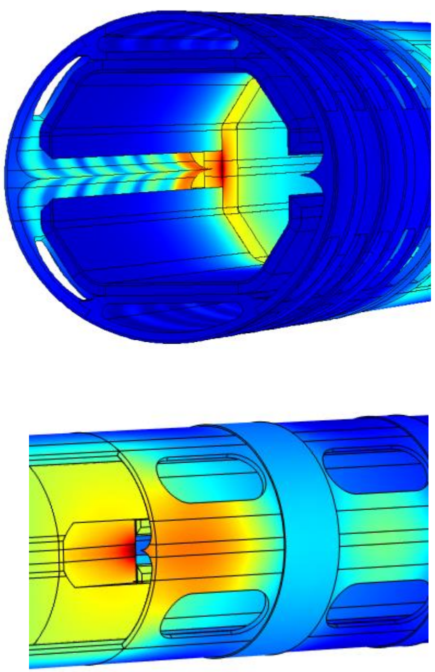


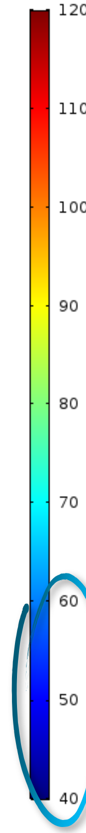
The longitudinal cut can lower power density by >10

VACUUM THERMAL ISSUES



- At some points*, the baseline T window is surpassed, increasing the risk of triggering **pressure peaks** due to an increased desorption rate
- The ribs **can exceed 100K** (above H_2O's saturation curve). Using **copper plated steel** (2-0.5 mm Cu) is an effective solution to increase the cooling performance and **lower the temperature**





Courtesy of J. Fernandez

- With a maximum absorbed power of **100W in the absorber**, and peaks of very high power density (>3000 W/cm^2, ideal beam, at the edge) its temperature easily exceeds the recommended one **being challenging** to keep it cold
- To solve this, its **slope could be oriented facing the beam**, achieving **higher sections of material** but reflecting some radiation forward to the next magnet
- Being placed **out of the cold mass**, a cooling line separated from the one feeding the BS could be also implemented, avoiding overheating the He. A **higher temperature window** (77K-100K) would be also possible from the vacuum point of view

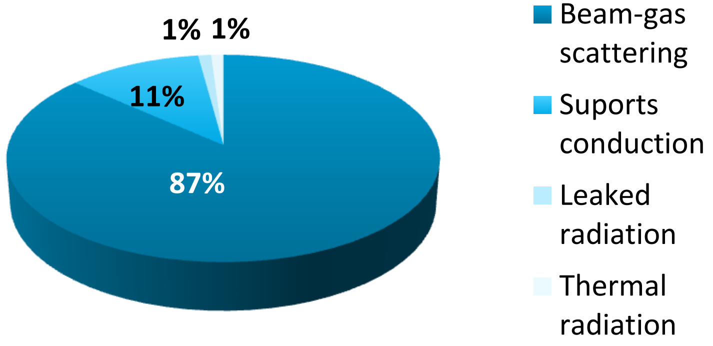
** See Special Technologies,* Thermo-mechanical simulation of the FCC-hh beam screen

TOTAL HEAT LOAD DISTRIBUTION

	FCC-hh cold bore heat load, 50 TeV 500 mA
Beam gas scattering for baseline MD	191 mW/m
Thermal conduction BS 50K-CB 1.9K	25 mW/m
Leaked radiation power through PH	2.4 mW/m
Gray body thermal radiation from 50K BS	2.3 mW/m
Total heat load	**220.7 mW/m**

Under 300 mW

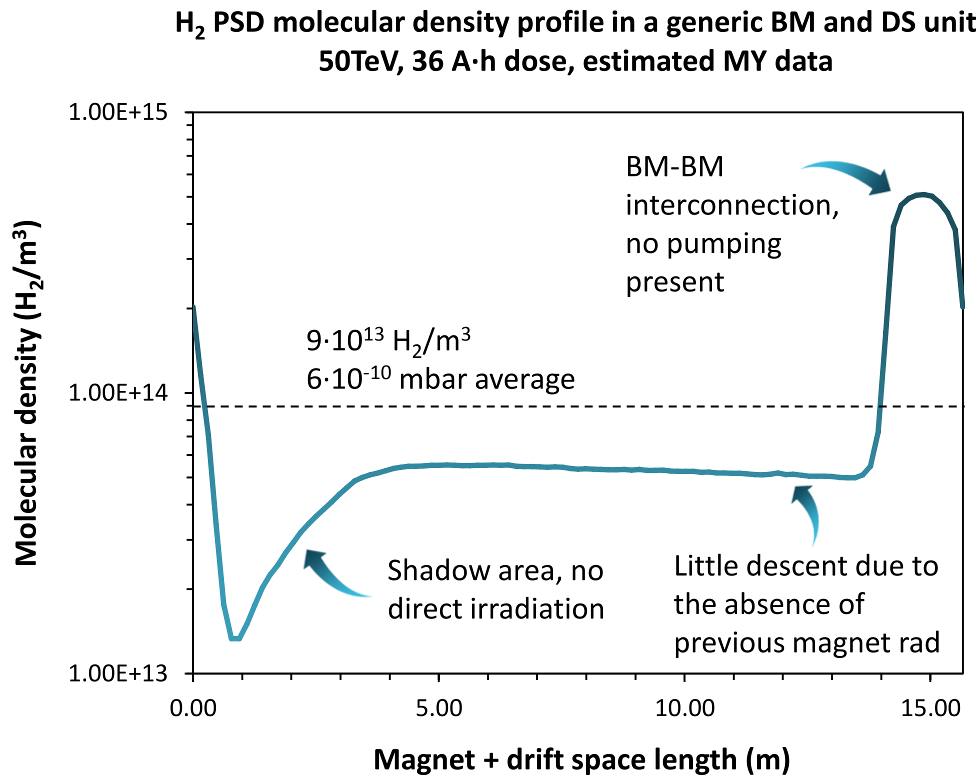
Heat load from inside the 1.9K CB



- In the latest revision *(C. Kotnig, 2016*), **0.3 W/m/beam** have been allocated as the **maximum average heat load to the cold mass** coming from **inside the cold bore elements** in the magnets. 0.2W/m can be allocated for beam scattering and 0.1 W/m for other sources, like thermal radiation, leaked SR and **conduction between BM and CB**
- Since all this heat sources depend on the beam current, **average loads during normal operation are expected to be much lower than the shown number**, estimated for maximum current, energy and nominal molecular density
- Being low the loads coming from conduction and leaked radiation, **it allows some margin for exceptional pressure peaks** (+30% baseline), although losing some lifetime in the process due to higher scattering

PRESSURE PROFILE IN THE BM

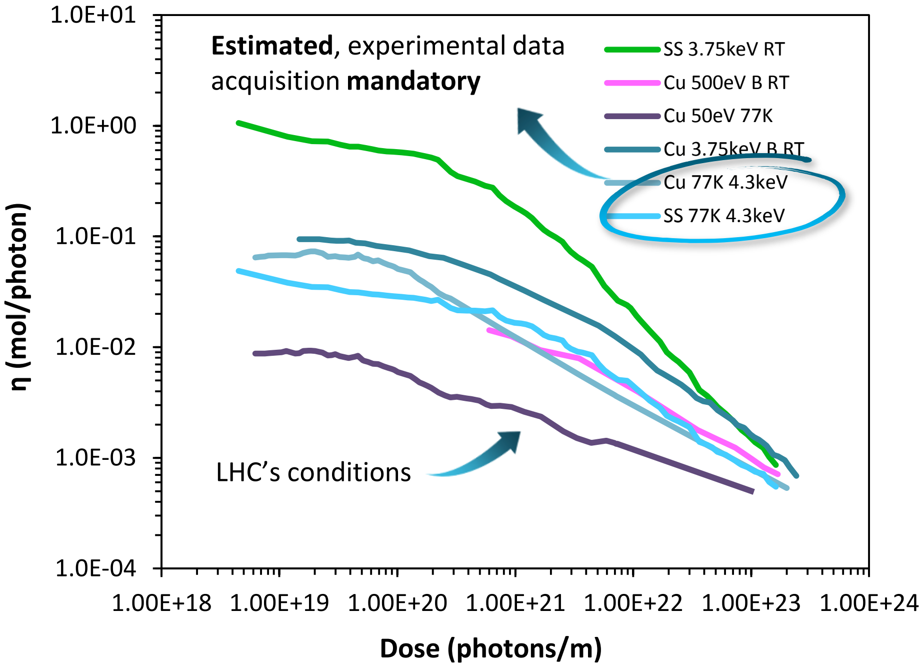
- The **pressure profile** coming from PSD effect, (the main expected pressure contributor for low doses) can be determined for different dose states and for different gases
- Average pressure in the CELL length will be **highly affected by lengths without a 1.9K cold mass**. In the shown example, the presence of 1.36m drift space between a cell composed exclusively by dipoles could **double the average pressure** which would exist without it, for a worst case scenario of no pumping present in this area
- Other **CELL elements** have to be contemplated to obtain an **accurate pressure profile** in the arcs



Higher temperatures than in the LHC yield in the FCC-hh lower molecular densities but higher pressures, due to the thermal transpiration $\frac{n_2}{n_1} = \frac{P_1}{P_2} = \sqrt{T_1/T_2}$

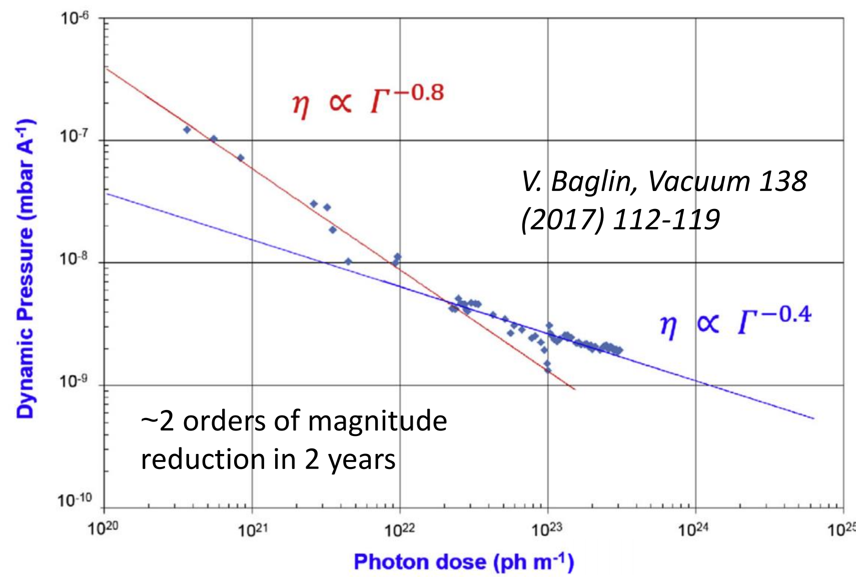
EXPECTED CLEANING DOSE

Total H2 equivalent MD Yield of different samples



Data from V. Baglin, O. Gröbner, C.L. Foerster et al.

LHC arc's extremity dynamic pressure due to SR during Run 1



GAS	Nuclear scattering cross section(cm^2)
H_2	9.5 10^{-26}
CH_4	5.66 10^{-25}
CO	8.54 10^{-25}
CO_2	1.32 10^{-24}

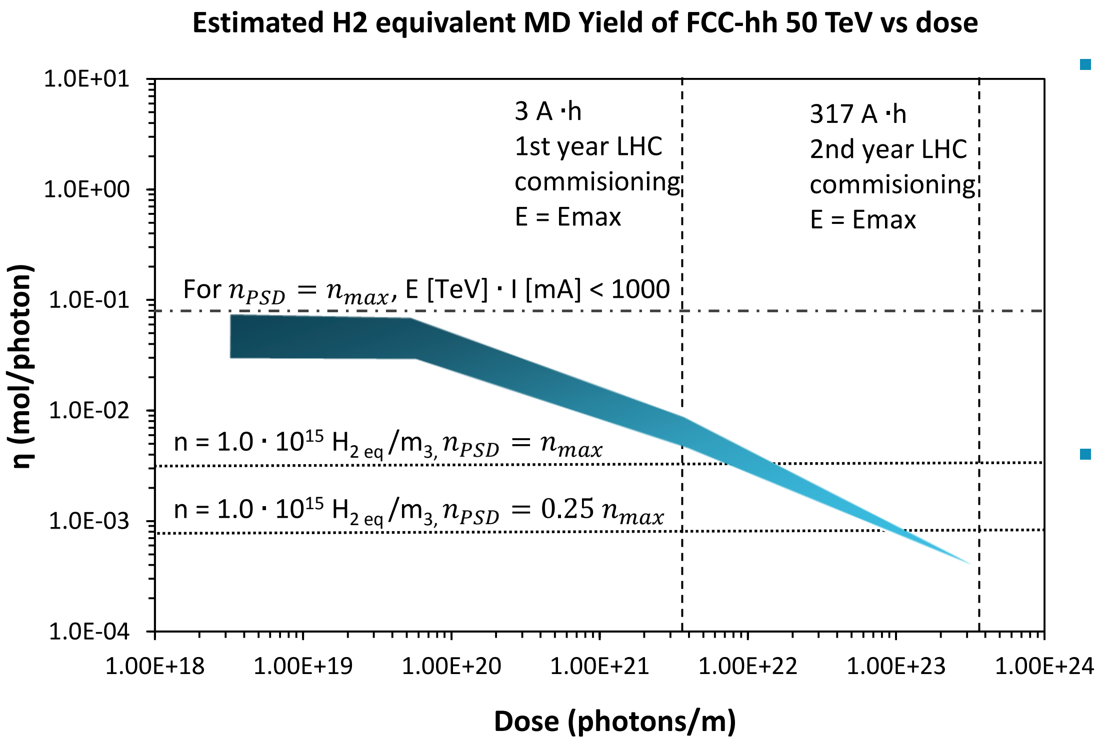
LHC-DES-REP 2004

$$\eta_{H_2eq} = \sum \eta_g \cdot \sigma_{g\ H_2rel} \cdot S_{g\ H_2rel}$$

$$\approx \sqrt{M_g/M_{H_2}}$$

- The high desorption yield for low photon doses **will severely limit the maximum current and/or energy** during the beginning of the first run
- A **higher cleaning rate than the one in the LHC is expected**, due to the higher critical energy (almost 100 times higher)

EXPECTED CLEANING DOSE



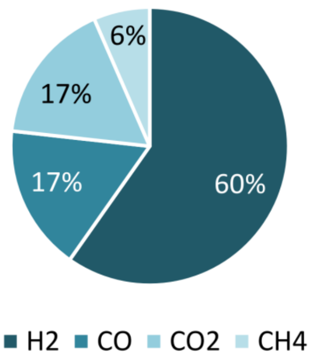
$$\eta_{av}\ [molec/ph] = \frac{n_{PSD}\ [molec/m^3\ ] \cdot S\ [m^3/s/m]}{Ph\ flux\ [ph/s/m]}$$

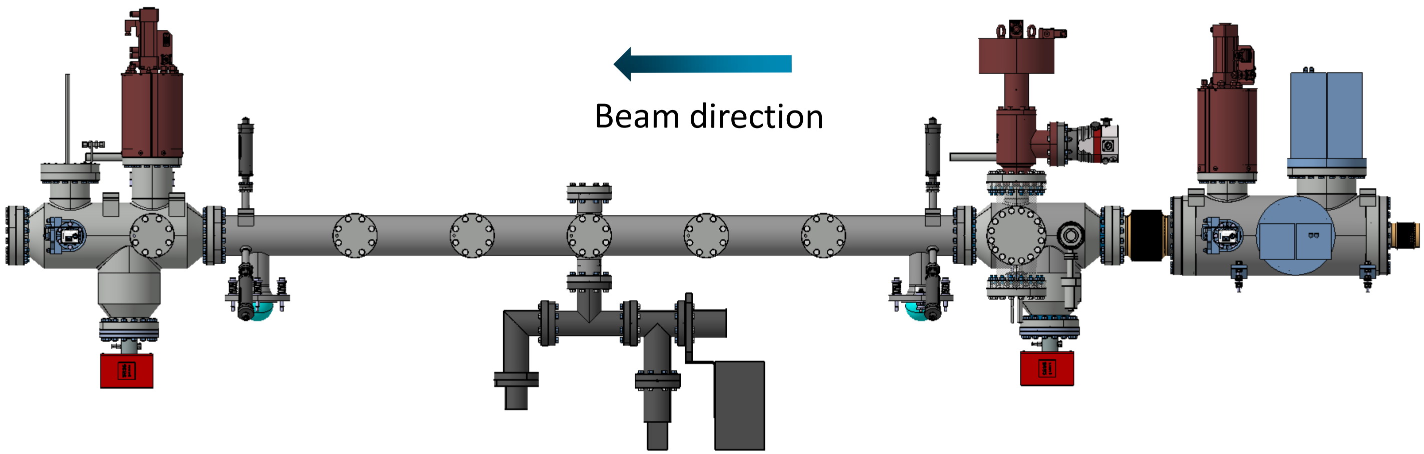
$$n_{PSD} = n_{max} - n_{ESD} - n_{others}$$

- Knowing the molecular yield the new machine could have, we can **estimate for each accumulated dose the maximum flux** we can allow in the machine to avoid surpassing the lifetime and scattered power limits, in an **stationary state** (no recycling desorption yield contribution)
- Nevertheless, future estimations of the **pressure contribution of the e cloud** will be needed, as well as an accurate study of the pressure peaks triggered by the **temperature transients** and **recycling yields** with the beam screen conditions
- In the **beginning of the commissioning**, since the beam screen won't be conditioned, for 50 TeV and ideal case the max current should be **<<20mA**

PREDICTED ANKA SETUP PRESSURES

Predicted gas composition after 100 A·h





Final BA gauge | Residual Gas Analyzer (RGA) | Initial BA gauge

Dynamic mode
2.5 GeV 130mA beam

	Final BA gauge 3 A·h	Final BA gauge 9.5 A·h	RGA 3 A·h	RGA 9.5 A·h	Initial BA gauge 3 A·h	Initial BA gauge 9.5 A·h
H_2 (mbar)	$9.9\cdot10^{-10}$	$6.3\cdot10^{-10}$	$7.0\cdot10^{-09}$	$4.3\cdot10^{-09}$	$1.5\cdot10^{-09}$	$9.6\cdot10^{-10}$
CO (mbar)	$7.1\cdot10^{-10}$	$3.4\cdot10^{-10}$	$6.8\cdot10^{-09}$	$3.2\cdot10^{-09}$	$9.4\cdot10^{-10}$	$5.2\cdot10^{-10}$
CO_2 (mbar)	$8.0\cdot10^{-10}$	$3.6\cdot10^{-10}$	$7.9\cdot10^{-09}$	$3.4\cdot10^{-09}$	$1.1\cdot10^{-09}$	$6.4\cdot10^{-10}$
CH_4 (mbar)	$1.3\cdot10^{-09}$	$6.7\cdot10^{-10}$	$1.8\cdot10^{-09}$	$9.0\cdot10^{-10}$	$1.2\cdot10^{-09}$	$6.9\cdot10^{-10}$
Total	**$3.8\cdot10^{-09}$**	**$2.0\cdot10^{-09}$**	**$2.3\cdot10^{-08}$**	**$1.2\cdot10^{-08}$**	**$4.7\cdot10^{-09}$**	**$2.8\cdot10^{-09}$**

CONCLUSIONS AND FUTURE WORK

- From the vacuum point of view, and thanks to the updated requirements, the **cryogenic vacuum system** of the FCC-hh seems to be for the time being **feasible** since **no critical showstopper** has been identified**,** however **much work still needs to be done** in order to guarantee it

- Due to the **high radiation power** in the arcs**,** the **temperatures** are **higher than expected** and an update of the design has to be performed. The power dissipation in the interconnection, out of the cold mass, seems to be promising to achieve **higher cooling efficiencies**

- A good prediction of the pressure contribution coming from the **electron cloud effect is mandatory** to predict more accurate conditioning evolutions. Low SEY materials will be critical to meet the molecular density requirements of the machine. Future vacuum simulations taking into account all **CELL elements** are also expected to be carried out

- Predicted pressures in the **ANKA setup** seem to be **adequate** for the future experimental plans

- Future **experimental plans** regarding **PSD yields** measurement and **reflectivity** are mandatory to ensure a proper validation of the vacuum system and ray tracing

THANK YOU FOR YOUR ATTENTION !