Studies on the beam induced effects in the FCC-hh

Ignasi Bellafont

EuroCirCol WP4 Meeting

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Contributions from C. Garion, R. Kersevan, L. Mether

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OUTLINE

Introduction

1. Previous status

Beam screen design updates

2. SR power redirection
3. Design comparison and new geometry proposal
4. LASE in the beam screen

Interconnections and CELL

5. Interconnection design updates
6. Half-CELL modelling and PSD pressure profile
7. Updated heat load to the cold mass

Summary and Outlook

PREVIOUS STATUS

- The **molecular density requirements** in the arcs were reviewed, being **$1.0 \cdot 10^{15}$ $H_{2\,eq}$ /m^3** for 100h lifetime and to cope with the allocated thermal budget
- The **synchrotron radiation** (SR) behavior inside the beam screen was **extensively studied**. To allow a proper operation, complex manufacturing procedures were recommended to be used
- The **temperatures** achieved due to SR both in the beam screen and magnet interconnections were found to be **higher** than desired, nevertheless this being **easy to solve**. The total heat load to the cold mass is found to be **well below the budget**
- For the bending magnets length the photon stimulated desorption (PSD) **pressure profile** was found, identifying a pressure bump in the interconnection area, as it was expected, which doubled the average pressure
- The amount of **leaked photons to the main chamber** (the one directly seen by the beam), from the secondary one (out of the main one, with the pumping holes), was found to be potentially dangerous, surpassing the instability threshold for worst cases
- Due to the calculated **beam sagitta** along the straight dipoles, and the beam-stay clear requirements at injection, the initial beam aperture was increased and interfering with the space allocated for the tolerances, being necessary to review them

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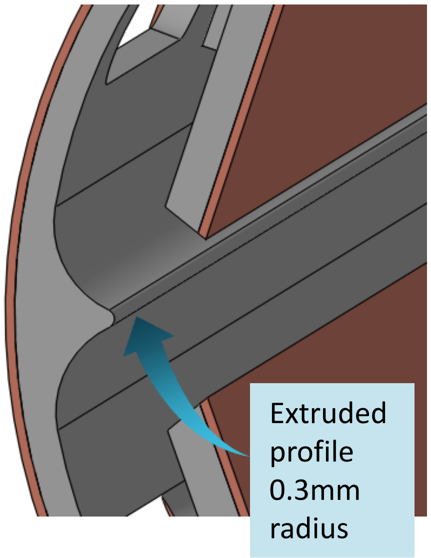
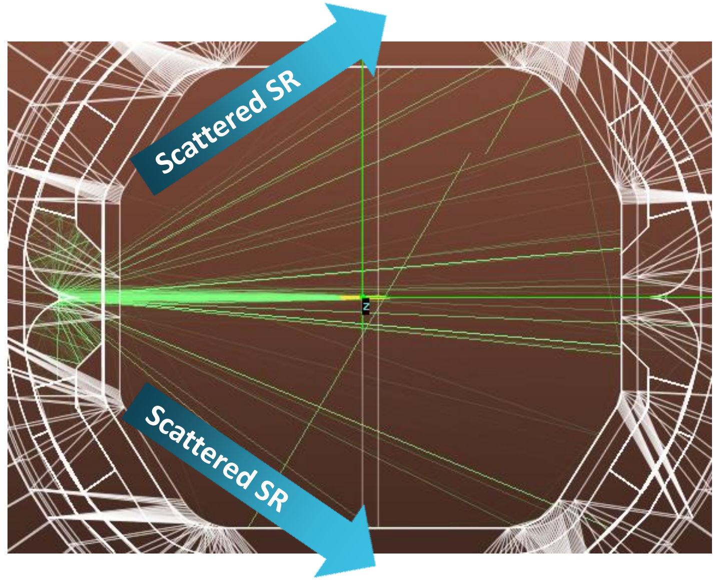
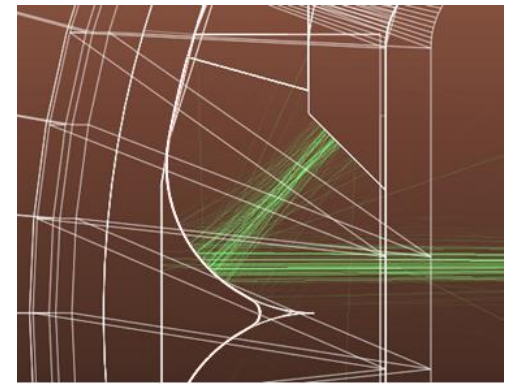
SR POWER REDIRECTION





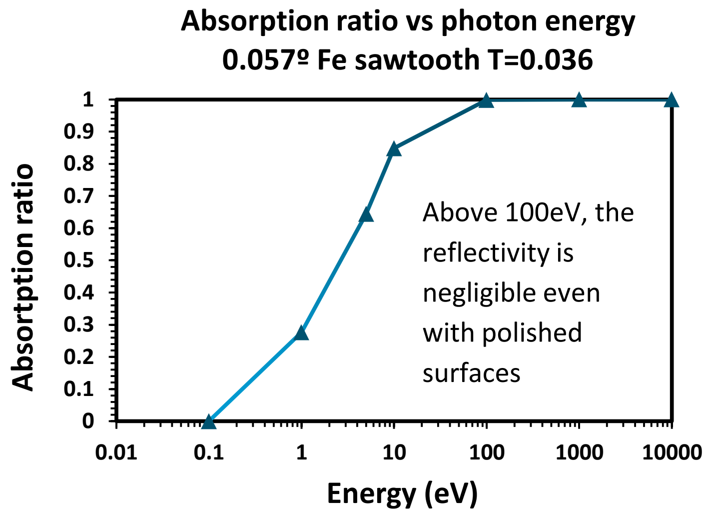


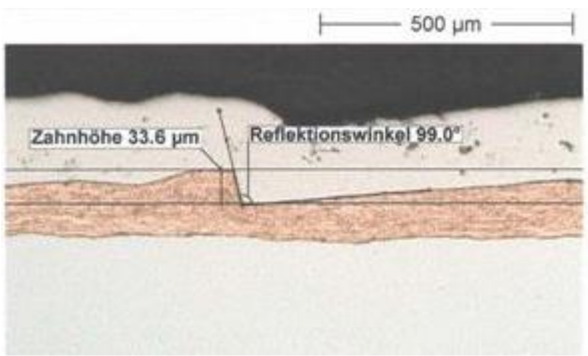
SR ray tracing simulation

- The reflector, with a **V shape**, was **aimed to redirect the radiation** towards the **ribs**, in order to avoid scattering photons back to the main chamber and to improve the conductance of molecules towards the cold bore
- Nevertheless, the chosen manufacturing methodology (**extrusion**) would always leave a **rounded edge** instead of a perfectly sharp one. Even being as small as 0.3mm (best found supplier), if the beam is centered, and without machining it afterwards, makes a **huge amount of SR go back to the main chamber** where it was originated
- Besides, to work properly even being perfectly sharp, the beam **can´t be misaligned more than 1mm**, otherwise the beam sees a flat surface. And, as previously studied it **has to be very polished** to work efficiently, **rising the costs**

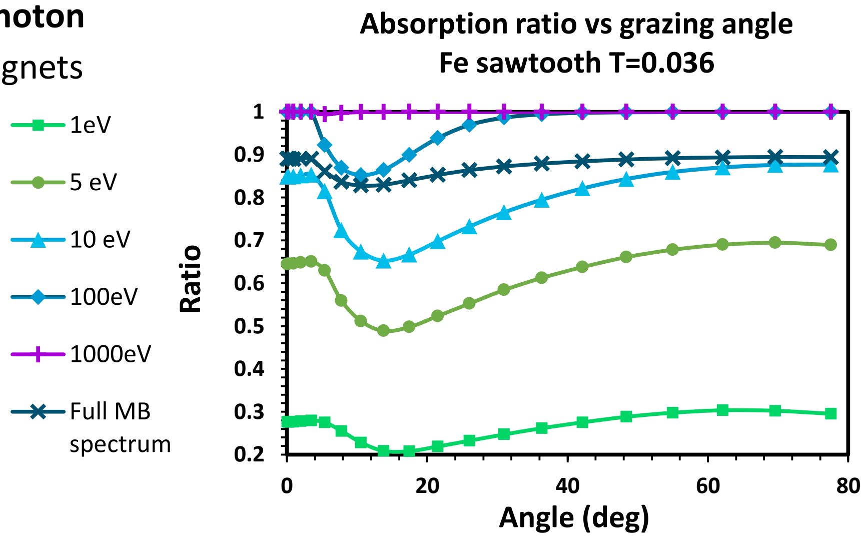
SAWTOOTH SURFACE PROPERTIES

- Owing to the difficulties of **effectively reflect** the synchrotron radiation with the reflector and within an **affordable complexity**, the **approach has been changed to maximize the absorption** on the first impact area, along the beam screen walls
- For this, a **sawtooth profile has been proposed**, because of its proved efficacy in absorbing X rays with a relatively low manufacturing cost whilst besides **decreasing** the photoelectron yield (PEY) and **light scattering**
- According to the carried out simulations, even with a polished copper surface, **it can absorb more than the 90%** of the **photon flux** and **99.5% of the power** coming from the bending magnets



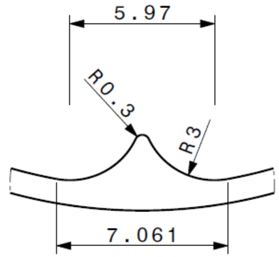


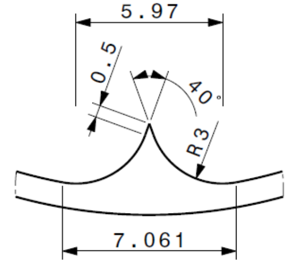
Sawtooth profile of the LHC's BS

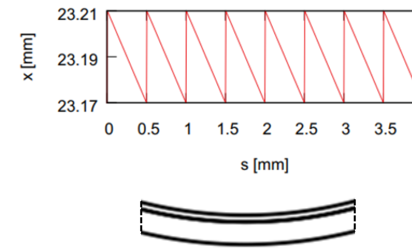


REFLECTOR PROFILE COMPARISON

- With the former beam screen dimensions, a **comparison of three possible reflector profiles** has been performed, with polished surface and the beam aligned, for **50 TeV, 500 mA,** SR > 4eV



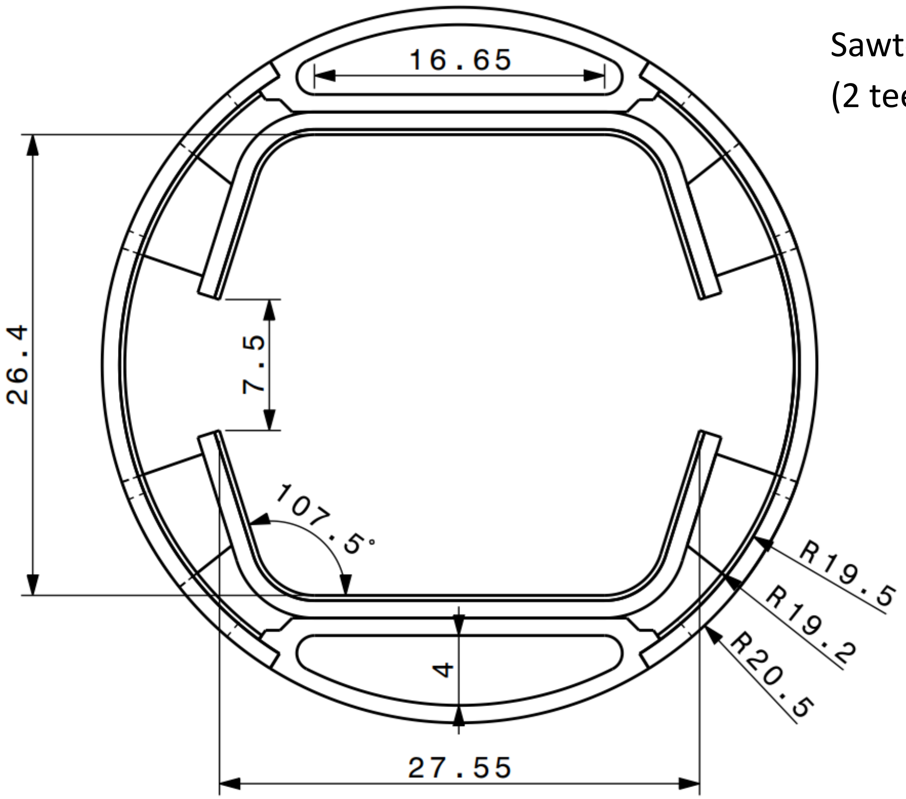


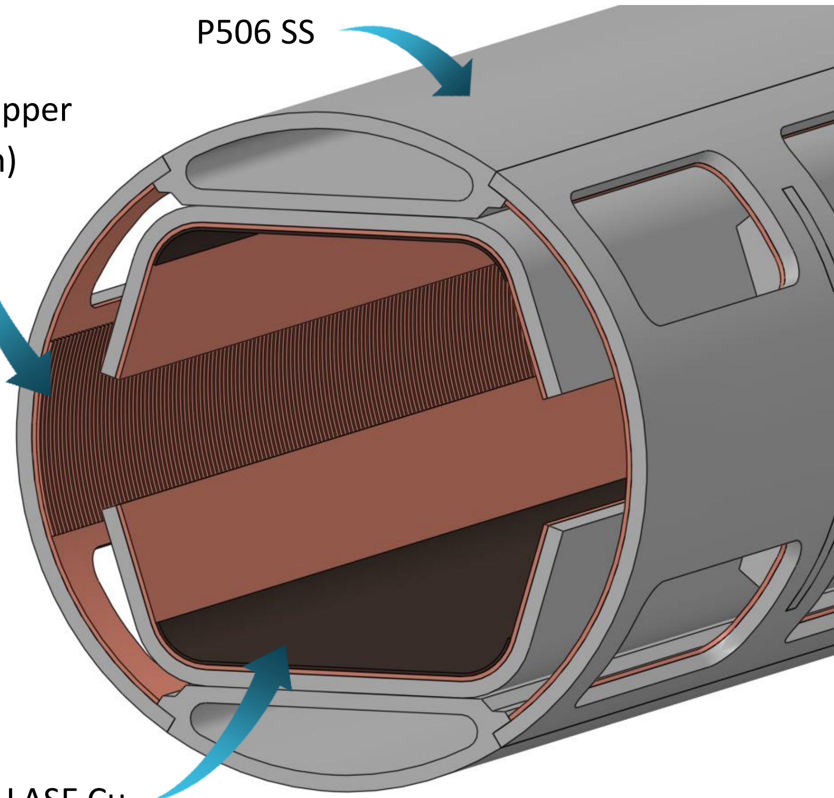


	Extruded profile	Extr.+ machined profile	Cu sawtooth
Leaked SR power to cold mass (σ=1)	0.035 W	0.045 W	0.002 W
Inner beam Cu chamber SR power	80.1W (16% of MB)	3.6 W (0.8% of MB)	0.18 W (0.04% of MB)
Power on flat area of the inner Cu	13.2 W (2.7% of MB)	0.3W (0.06% of MB)	0.006W (0.0013% MB)
Leaked % SR power through main slot	20%	1%	0.01%
Ribs SR absorbed power	25 W	91.2 W	0.0025 W
% Power absorption on the reflector	49%	49%	99.5%
H_2 molecular density PSD 36 A·h	$1.7 \cdot 10^{14}$ H_2/m^3	$1.2 \cdot 10^{14}$ H_2/m^3	$4.8 \cdot 10^{13}$ H_2/m^3
Manufacturing complexity	Low	Medium	High

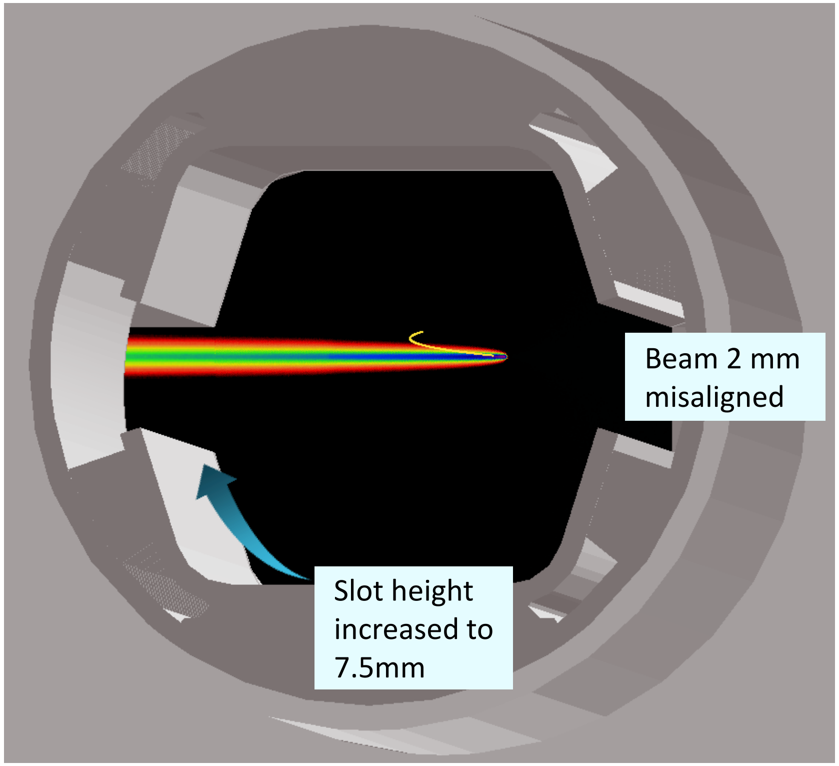
- **Best numbers are given by the sawtooth profile in all critical fields**, redirecting **400 times less power** to the inner Cu chamber, also **lowering** the total PSD generated **outgassing.** Shown numbers are per MB, for the previous design

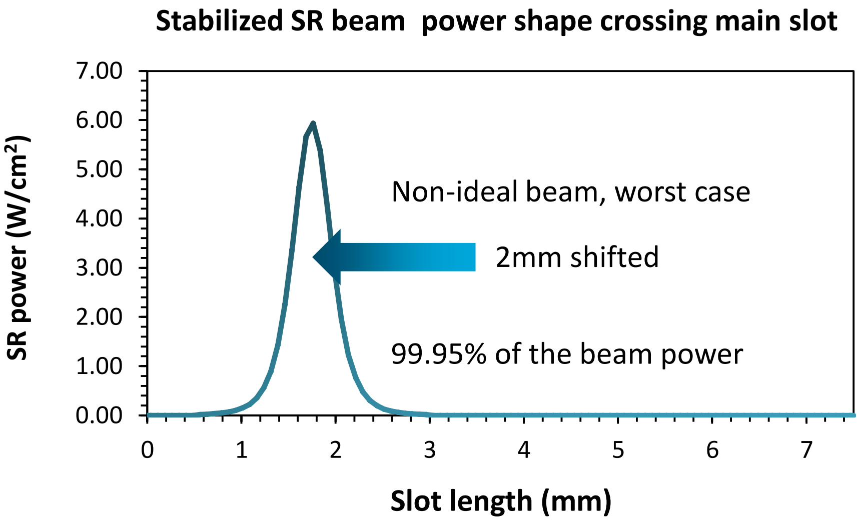
NEW BEAM SCREEN PROPOSAL

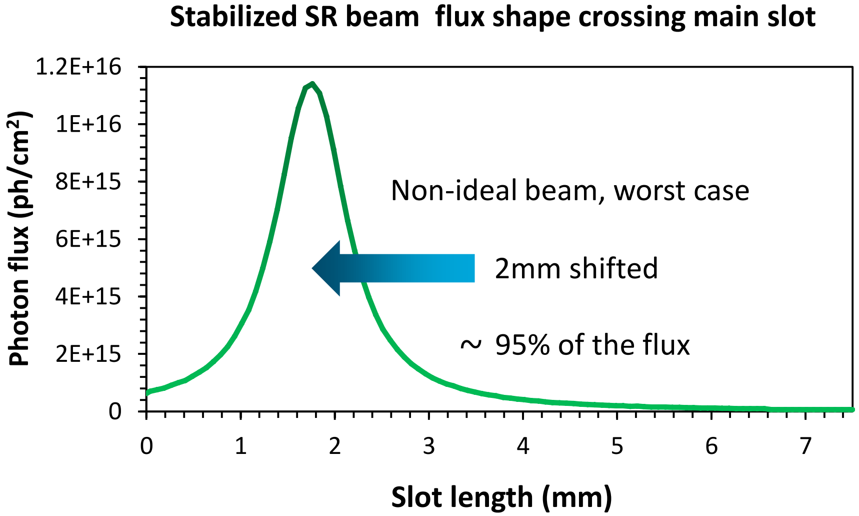




SR BEAM PROFILE







- The main slot size has been increased **to 7.5mm**, to allow a **2mm beam misalignment**, and because the secondary chamber no longer needs to contain as much **scattered radiation** thanks to the **sawtooth**
- The **pumping speed** is therefore **increased**

ADVANTAGES OF CURRENT DESIGN

- Thanks to the higher photon absorption, derived from the almost perpendicular SR impact on the sawtooth, there is **less leaked flux to the primary chamber**, decreasing then the **electron density** and thus having less beam interaction with the electrons and less **ESD outgassing** (main gas source in the LHC) ✔

- Also, **less outgassing** from PSD owing to the less scattered radiation, the PSD is therefore triggered on areas which are already cleaned and yield less molecules per photon ✔

- **Lower global and localized temperatures** *(J. Fernández),* since the copper layer of the inside of the secondary chamber improves considerably the cooling performance. As a consequence, the outer copper rings, are then no longer necessary, **further reducing the manufacturing costs** ✔

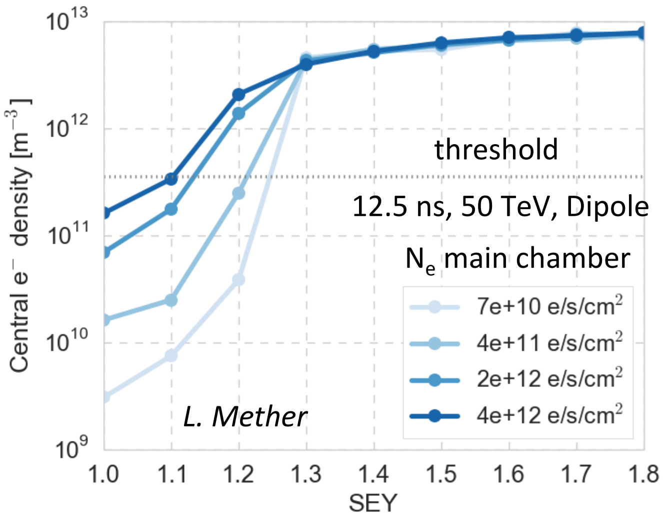
- Higher **robustness against beam misalignments**, since it is no longer needed to make an effort to align the radiation on the reflector edge ✔

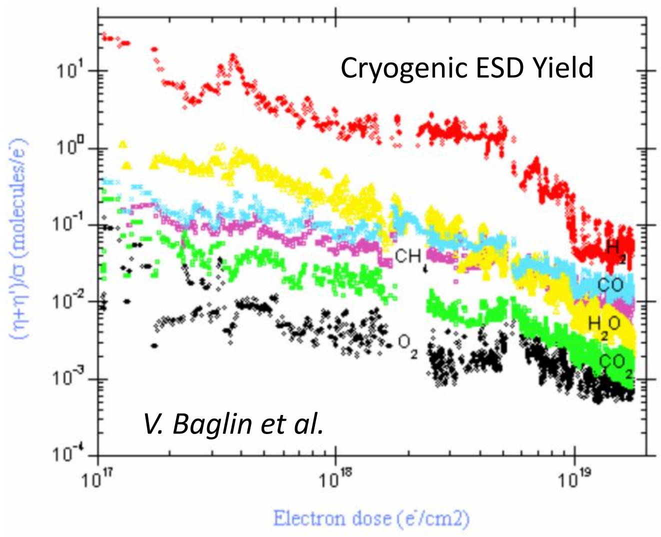
- Compared with the previous beam screen design, **beam impedance is little affected** (*D. Astapovych)* even after increasing the main slot size ✔

LASE BEAM SCREEN COVERAGE

- For the **most restrictive** bunch spacing and beam energy (12.5ns, 3.3 TeV), **SEY** has to be lower than **1.0 in the quadrupoles** and **1.2 in dipoles** and **drift spaces** (*L. Mether*) to avoid electron multipacting. For 25ns (baseline) it would be 1.6 for dipoles, 1.2 quadrupoles and 1.8 drift spaces, not so demanding
- This very low SEY requirement, along with the high amount of chambers to be treated, makes **LASE the preferred option** from the **manufacturing** point of view to achieve these values (max SEY < 1) since it can be applied during **series production**
- Due to its high surface aspect ratio, and the low SEY, LASE is also an option which **would lower considerably the pressure inside the beam screen**, since ESD contribution is directly proportional to **SEY and PEY**
- Compared to the previous design, the proposed sawtooth profile **reduces 10 times the flux** (around $1\cdot10^{12}$ ph/s/cm^2, 1% of the flux > 4eV) and 40 times the power to the **areas** with the **highest electron** impingement rate, therefore **reducing** considerably the **electron density** inside the main chamber

$$P_{ESD} \propto e_{density} \propto PEY, SEY$$





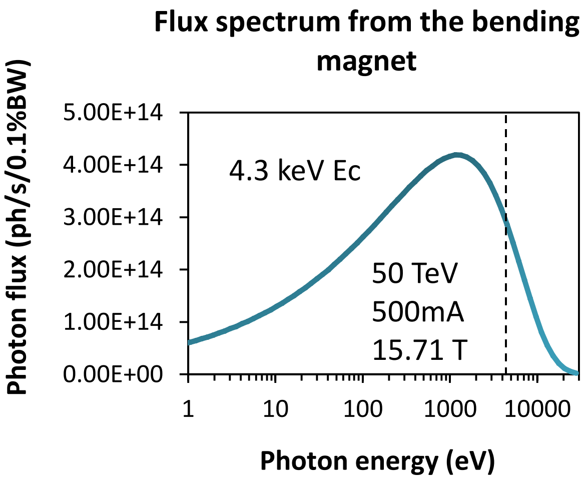
LASE BEAM SCREEN COVERAGE

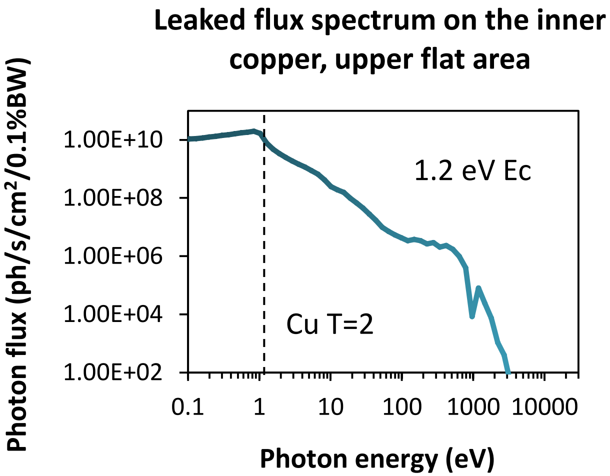
- With regard to the global flux in the primary chamber, it is around **$7 \cdot 10^{11}$ ph/s/cm²** (> 4eV) with a sawtooth profile in the reflector. The number of generated photoelectrons is then **under the calculated instability threshold** if using LASE, even for Cu PEY values
- Due to the high radiation absorption of the sawtooth, the **flux** arriving to the **cold bore** and the inner chamber **has very low power**, this yielding less electrons per photon
- To accurately determine **LASE's PEY**, some **tests** are foreseen to be carried out at **BESSY II,** Germany (October-November 2017) for different photon energies, as well as its **reflectivity properties**

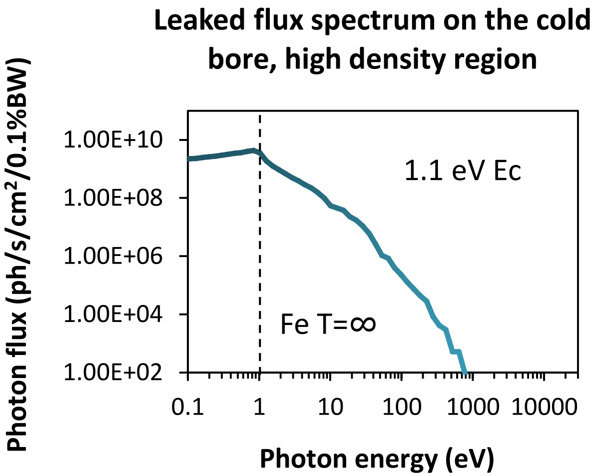
$$N_e = \dot{\Gamma}[ph/s/cm^2] \cdot Y$$

Surface	Status	R (%) 45 eV	Y* (e/ph) 45 eV
Cu co-lam.	as-received	80.9	0.114
	air baked	21.7	0.096
Cu elect.	as-received	5.0	0.084
Cu sawtooth	as-received	1.8	0.053
	150°C, 9h	1.3	0.053
	150°C, 24h	1.3	0.040

V. Baglin et al.

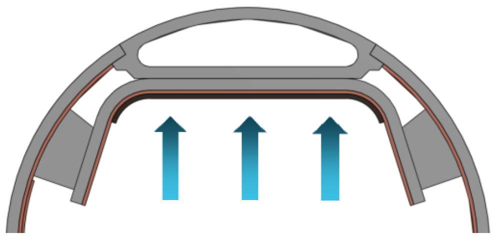




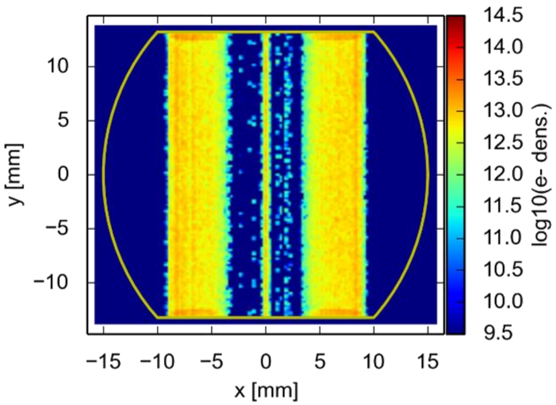


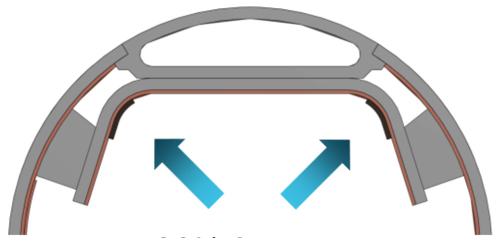
LASE BEAM SCREEN COVERAGE

Dipole 25ns LASE regions	Quadrupole 25ns LASE regions	BS drift space 12.5ns LASE regions

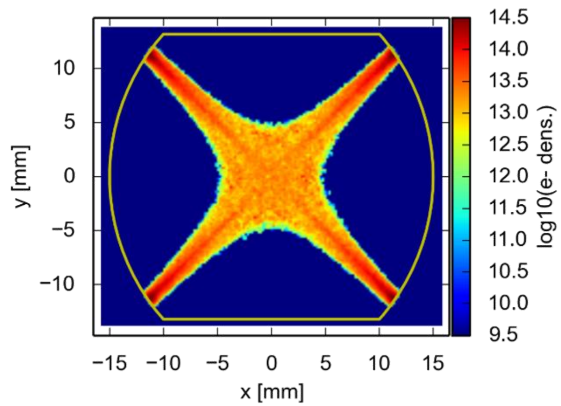


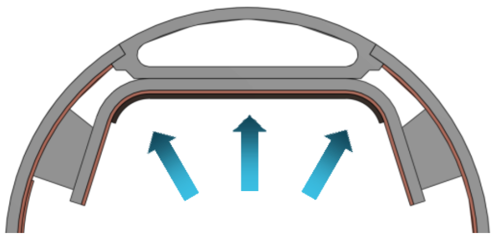
60% Cu area



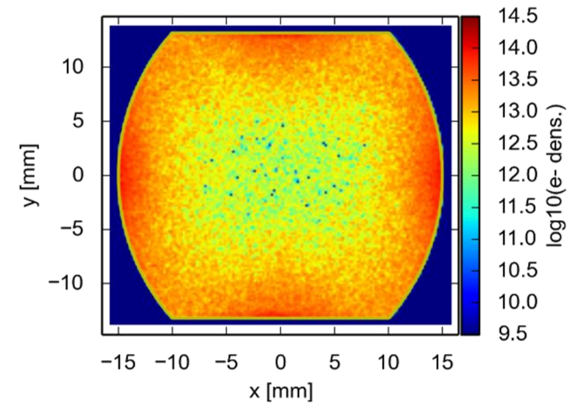


20% Cu area





20-60% Cu area



Electron density distributions courtesy of L. Mether

- In dipoles, the LASE coverage shall be extended to take into account the allowance for a **2mm** horizontal **misalignment**
- In **drift spaces**, without magnetic field, the fraction of coverage has not been studied yet. Nevertheless, extending the **coverage of the magnet they belong** might be sufficient to keep the e density within acceptable levels

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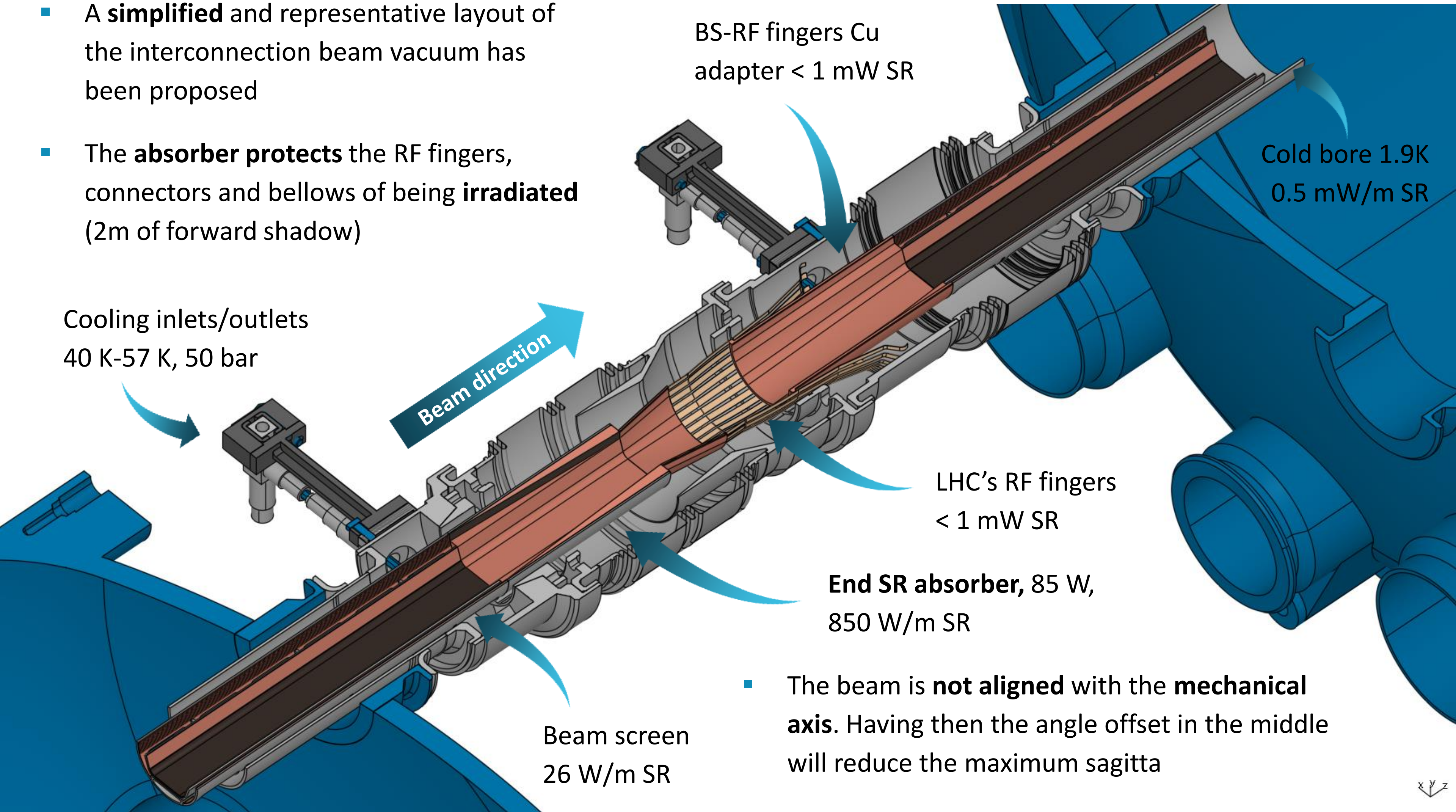
MB INTERCONNECTION UPDATES

- A **simplified** and representative layout of the interconnection beam vacuum has been proposed
- The **absorber protects** the RF fingers, connectors and bellows of being **irradiated** (2m of forward shadow)

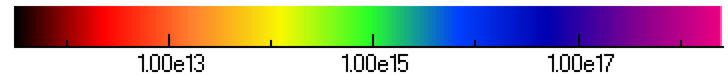


- The beam is **not aligned** with the **mechanical axis**. Having then the angle offset in the middle will reduce the maximum sagitta

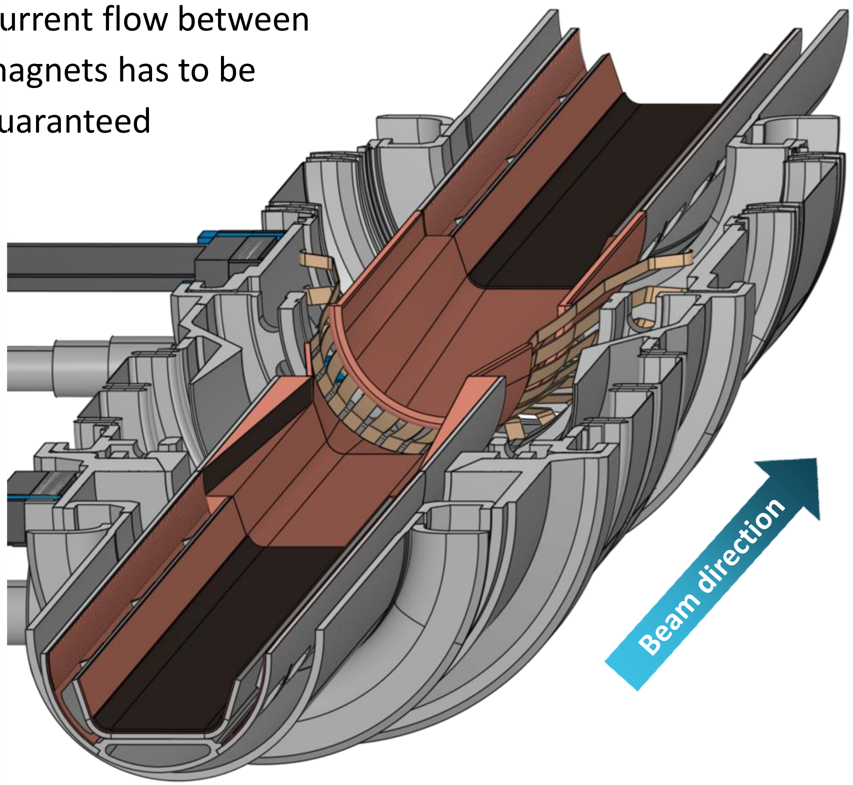
MB INTERCONNECTION UPDATES

Reflectivity SR 50TeV vs treatment	
Flat Cu T=0.036	38%
Sawtooth T=0.006	19%
LASE estimation T=0.9	10%

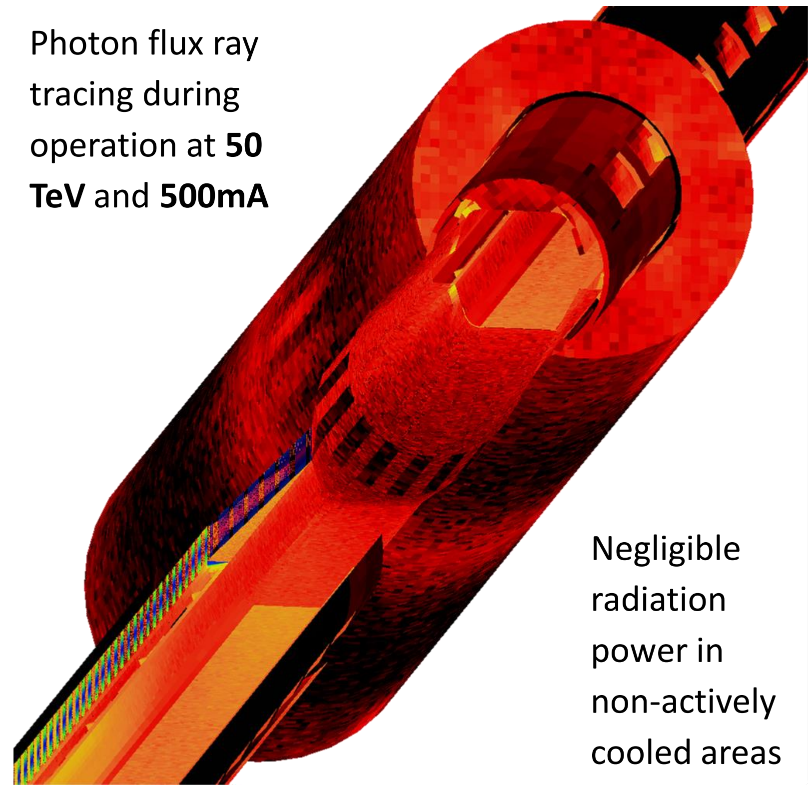
Treating the absorber's slope with **LASE** improves the absorption and could **reduce the PE yield**



Current flow between magnets has to be guaranteed



Photon flux ray tracing during operation at **50 TeV** and **500mA**



Negligible radiation power in non-actively cooled areas

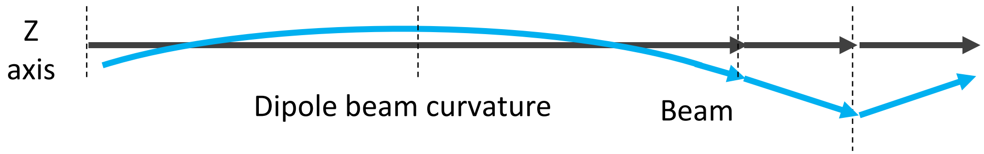
HALF-CELL MODELING

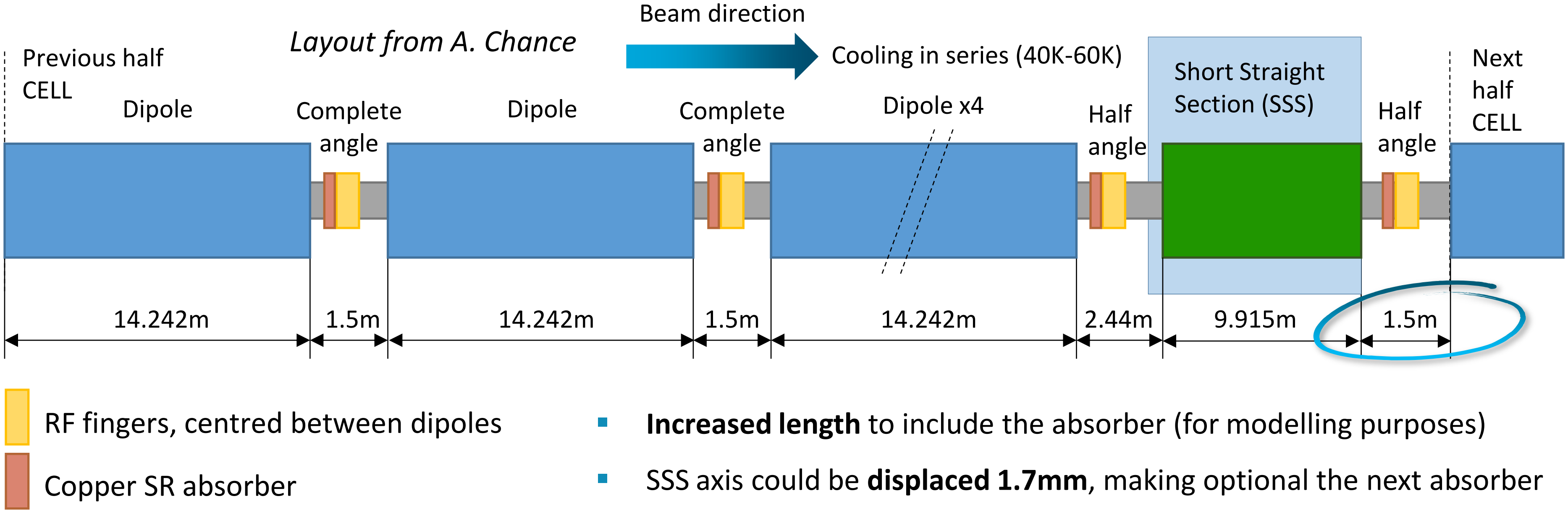
Used parameters	
Angle between dipoles	0.077º
Average photon trajectory length	22.5m
Average power along the BS	26 W/m
Av. pumping speed inside the CB	860 l/s/m
No-pumping L per interconn.	0.4m
% of pumping length per CELL	97%

- Using data from the optics layout, a **simplified model** of the half **CELL** has been created to perform the **SR ray tracing** along it and in order to calculate the pressure profile

1.2 mm sagitta in the middle and at extremities, if the beam is centred

Almost 1.7mm offset in the interconnect

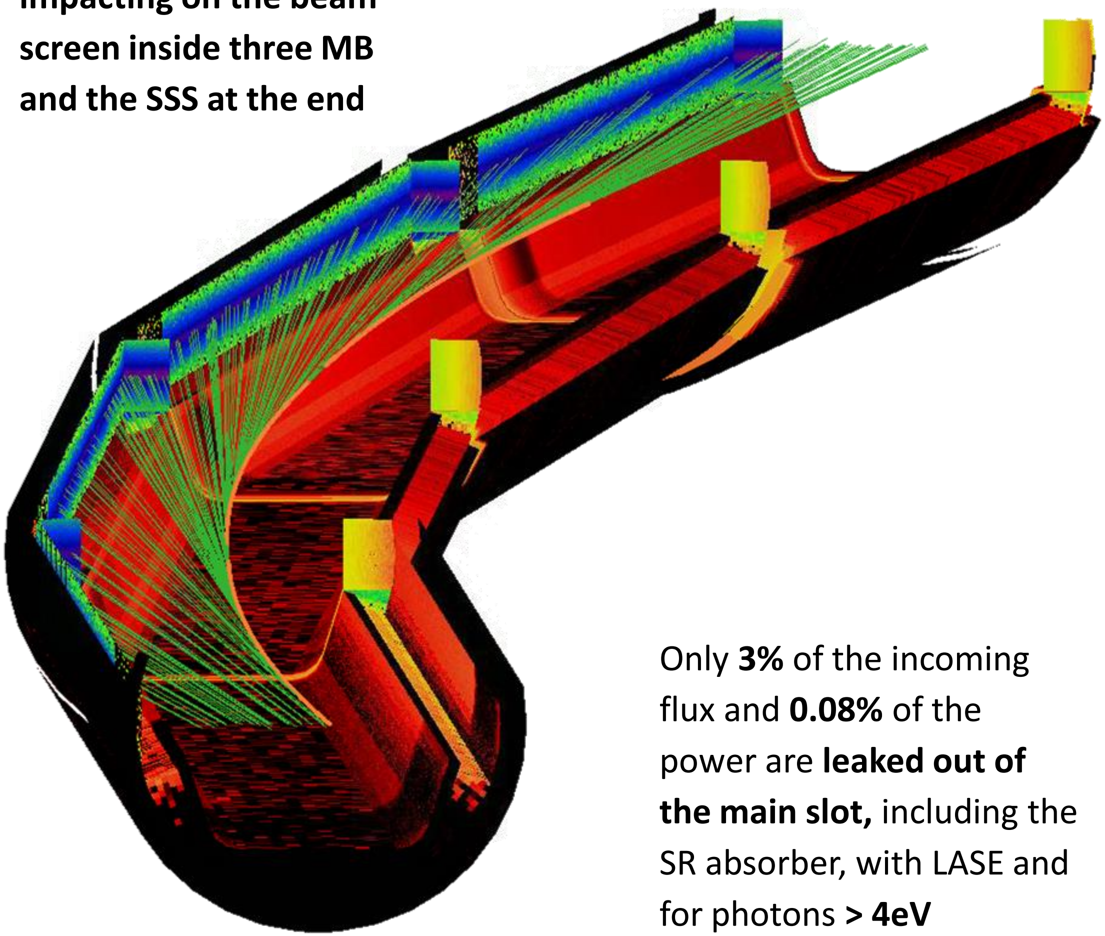


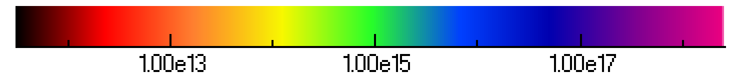


- **Increased length** to include the absorber (for modelling purposes)
- SSS axis could be **displaced 1.7mm**, making optional the next absorber

SR RAY TRACING COMPARISON

Visualization of the SR impacting on the beam screen inside three MB and the SSS at the end





Photons/s/cm²

% of Total BM Flux > 4eV, 2.1E18 ph/s		
Ribs	51%	0.04%
End absorber	19%	17%
Cut main slot	8.4%	0.06%
Reflectors	7.1%	81%
Drift space	5.7%	0.5%
Inner copper	< 5%	1.2%
Cold bore	< 0.3%	0.05%

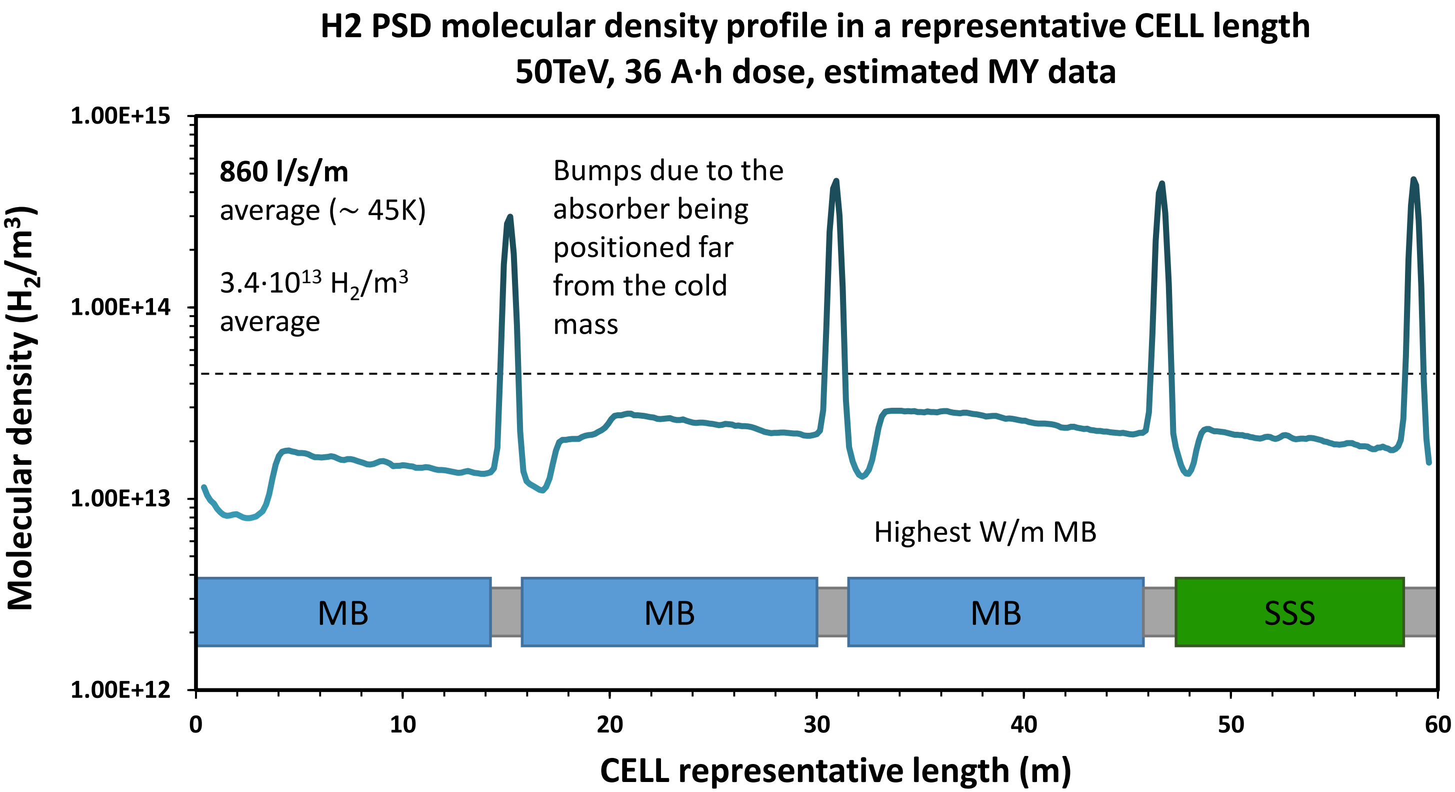
Current design, sawtooth walls

Previous design, reflector

Only **3%** of the incoming flux and **0.08%** of the power are **leaked out of the main slot,** including the SR absorber, with LASE and for photons **> 4eV**

- 50 TeV 500 mA, 15.78 T non ideal beam
- Sawtooth profile T=0.006, aligned beam
- Absorber Cu T=0.9

HALF-CELL PSD MD PROFILE



Decreasing the shadow of the absorbers (2m now), their **power load would be lower** so would be the **pressure bumps**, meaning nevertheless slightly tighter alignment tolerances

*R. Kersevan	LHC	LHC-HL trip	FCC-hh
T window [K]	5-20	40-60	40-60
S at 50K, H_2 [l/s/m]	765*	1236*	905
Relative complexity	Low	Medium	High

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

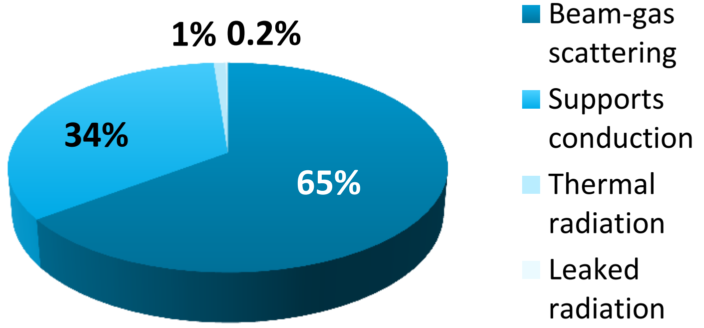
$$S_{av}[l/s] = \frac{Q\ const[mbar \cdot l/s]}{P\ [mbar]}$$

UPDATED COLD MASS HEAT LOAD

	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	100 mW/m*
Gray body thermal radiation from 50K BS	3 mW/m*
Leaked radiation power through p. holes	0.5 mW/m
Total heat load	**294.5 mW/m**

**J. Fernández*

Heat load from inside the 1.9K cold bore



Under 300 mW ✔

- The thermal conduction has been risen mainly due to an increase of the number of beam screen supports. Nevertheless, the numbers shown correspond to the temperature profile of the former 'spiked' reflector, and the **updated ones are expected to be lower**. Using a sawtooth profile in the secondary chamber implies the need of a co-laminated copper surface, thus **reducing the temperature and the leaked heat** through conduction
- **Leaked SR** to the cold mass has been reduced to **negligible levels**
- Having, in the current analysis, a shorter length without pumping in the interconnects, the heat load due to beam loss is expected to be more **distributed along the arcs**

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SUMMARY AND OUTLOOK

- A **new BS design has been proposed**, replacing the spiked reflector with a sawtooth flat Cu surface. It would lower the generated outgassing due to the beam induced effects, it would ensure a **higher tolerance to misalignments**, and it would improve the cooling efficiency, with relatively low manufacturing costs

- The **interconnection design has been updated**, stopping the radiation efficiently without strict manufacturing and alignment tolerances, being in principle able to be cooled in series with the BS without further issues. The amount of stopped radiation on the **absorber** will be adjusted to **lower** as much as possible the **pressure bumps** in the area

- The chamber design **complies with the received constraints** of maximum leaked photon flux, setting the electron density under the instability threshold. Using **LASE** inside the beam screen would also comply with the SEY specifications

- The **updated heat load** is still **under the thermal budget** maximum values for worst cases

- As next step, a detailed calculation of the conditioning time will be written, which will include the final generation of the pressure profile in the arcs for **all the beam induced effects**, with ecloud inputs from the WP2

- Experiments in **BESSY II** would confirm the simulated reflectivity parameters and the photoelectron yield for the materials used in the beam screen, further **validating the design** and ensuring an accurate ESD **outgassing calculation**

THANK YOU FOR YOUR ATTENTION

Studies on the beam induced effects in the FCC-hh

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BEAM SCREEN CROSS SECTION