Study on the beam induced vacuum effects in the FCC-hh

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FCC Week

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Contributions from L. Mether

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OUTLINE

Beam induced vacuum effects

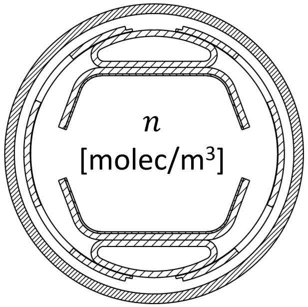
1. General expression
2. Synchrotron radiation in the FCC-hh. 160 times higher linear power density
3. Photon stimulated desorption
4. Electron stimulated desorption
5. Ion stimulated desorption

The FCC-hh beam screen

6. Main features. Functional map
7. Comparison with the LHC BS

Molecular density results, conclusions and future work

GENERAL EXPRESSION



η depends on the material properties

thermal outgassing, negligible in dynamic mode

$$n = \frac{P}{kT} = \frac{Q}{SkT} = \frac{\overbrace{(\eta_{ph}+\eta'_{ph})\,\dot{\Gamma}_{ph}}^{\textit{photon-stimulated desorption (PSD)}} + \overbrace{(\eta_e+\eta'_e)\,\dot{\Gamma}_e}^{\textit{electron-stimulated desorption (ESD)}} + \overbrace{(\eta_i+\eta'_i)\,\sigma_i\,\frac{I}{e}n}^{\textit{ion-stimulated desorption (ISD)}} + Aq}{S}$$

- The FCC-hh beam energy and consequent **SR power levels are unprecedented for hadron colliders**, and a thorough study had to be carried out to determine its impact on the vacuum level
- In order to guarantee an affordable conditioning time before meeting the **molecular density requirement**, a new beam screen had to be designed, including new beam induced effects mitigation measures

Parameter	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]	0.22	35.4
Critical energy [eV]	43.8	4286
Cold bore aperture [mm]	50	44
Circumference [km]	26.7	97.75

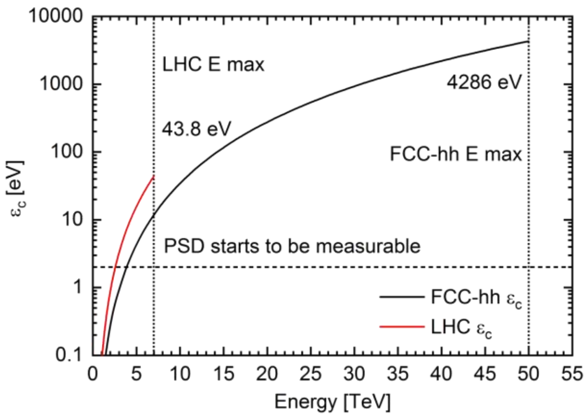
$$P_{cold\ mass} = k_c\,(1-k_w)\frac{IE}{c\,\tau_{bg}} < 0.2\ W/m$$

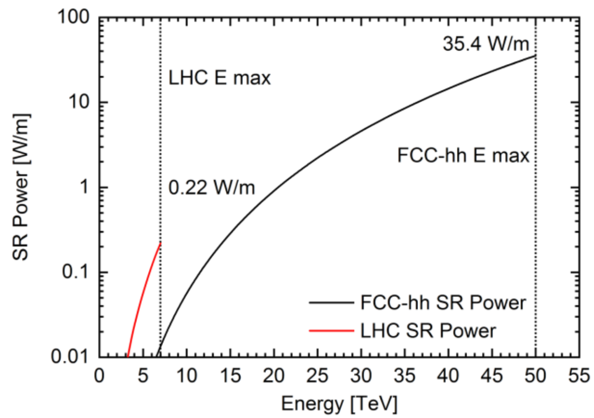
$$\tau_{bg} = \frac{1}{\sigma_g\,c\,n} > 100\ h$$

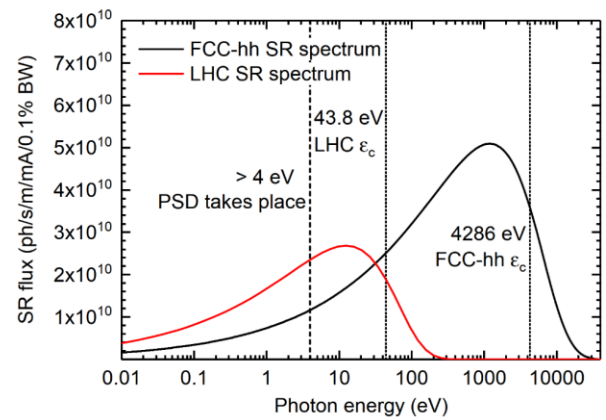
$$n \leq 10^{15}\ \mathrm{H_{2\ eq}}/\mathrm{m^3}$$

Molecular density requirement to reach 100 h of nuclear scattering beam lifetime whilst keeping the related heat load to the cold mass within the budget

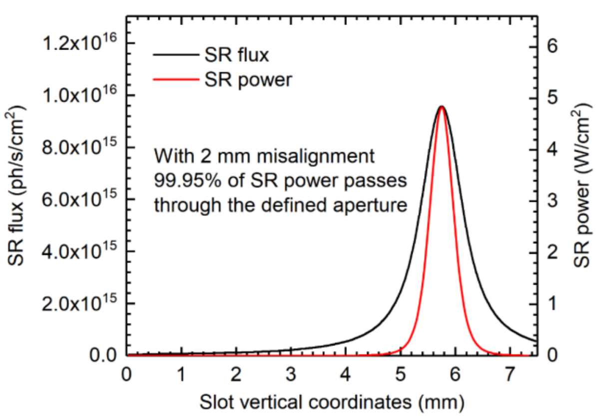
SYNCHROTON RADIATION IN THE FCC-hh





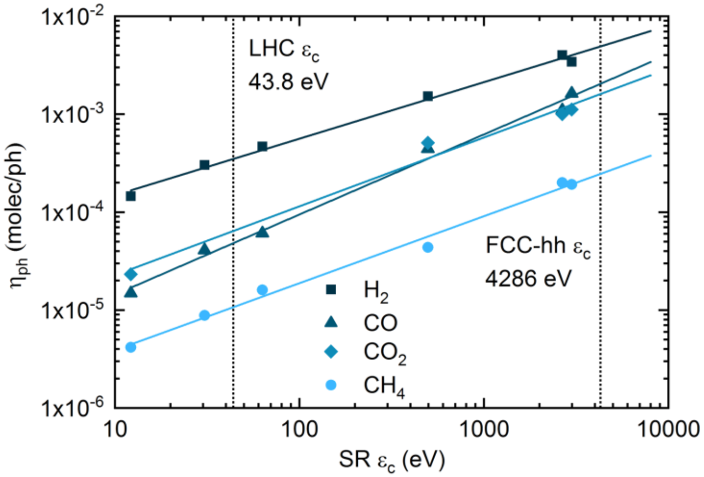


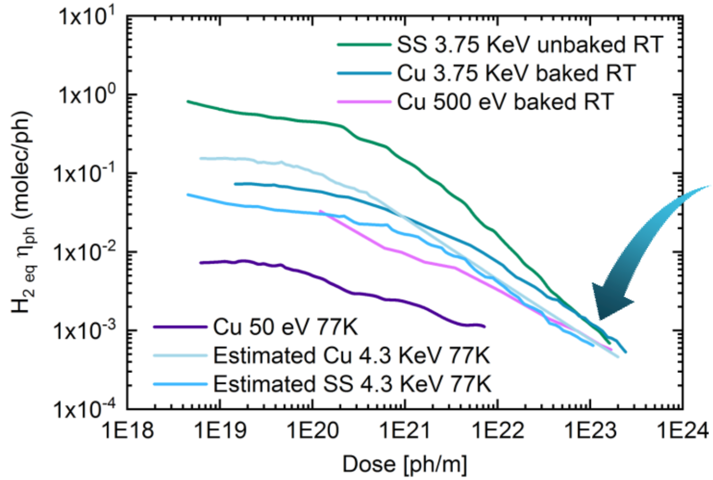
$$\varepsilon_c\ [eV] = 3.583 \times 10^2\,\frac{E^3[TeV]}{\rho[m]} \qquad P\ [W/m] = 1.239\,\frac{E^4[TeV]}{\rho^2\ [m]}\ I[mA] \qquad \dot{\Gamma}_{ph}\left[\frac{ph}{m\cdot s}\right] = 7.007 \times 10^{16}\,\frac{E[TeV]\ I[mA]}{\rho[m]}$$



- The beam energy increase, from 7 TeV to 50 TeV, entails a **SR linear power density 160 times higher**, and a SR critical energy (ε_c) around 100 times higher
- This increment not only has direct consequences to the cooling system, but also to the vacuum system, since **the higher SR power and flux are expected to increase the gas load in the vacuum chamber**. Meeting the vacuum requirement of 10^{15} $H_{2\ eq}/m^3$ is considerably more challenging

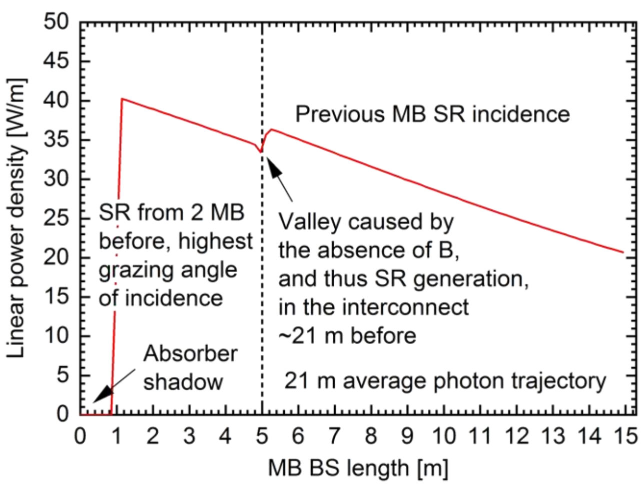
PHOTON STIMULATED DESORPTION

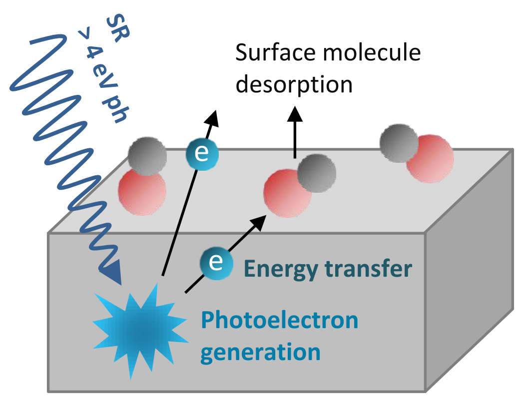




For high photon doses, all common technical materials have a similar η. The **main concern is the machine commissioning** (low photon doses)

- The amount of released gas molecules per photon **depends on the photon energy**
- Lacking experimental data, the molecular yield for the FCC-hh conditions has been estimated

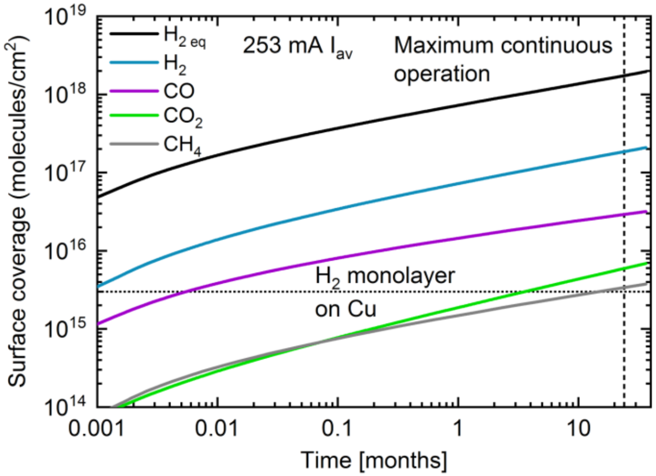




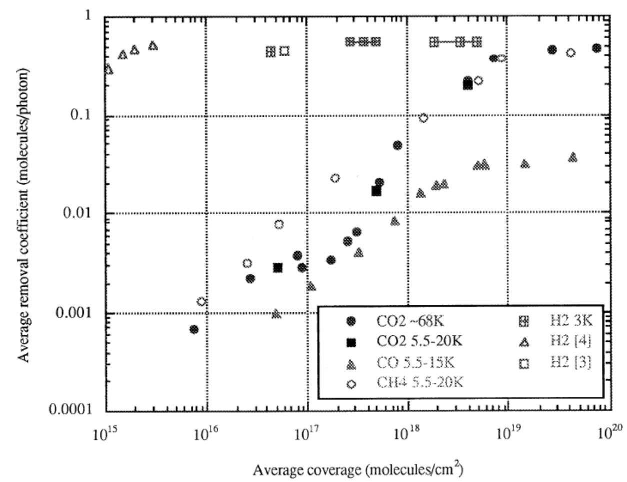
$$Q_{PSD} = (\eta_{ph} + \eta'_{ph})\ \dot{\Gamma}_{ph}\ kT$$

- Owing to the higher SR power and the implemented SEY mitigation, **PSD** is expected to be the cause of the **highest gas load**, as opposed to the LHC, where it plays a secondary role with respect to e-cloud effects

PHOTON STIMULATED DESORPTION

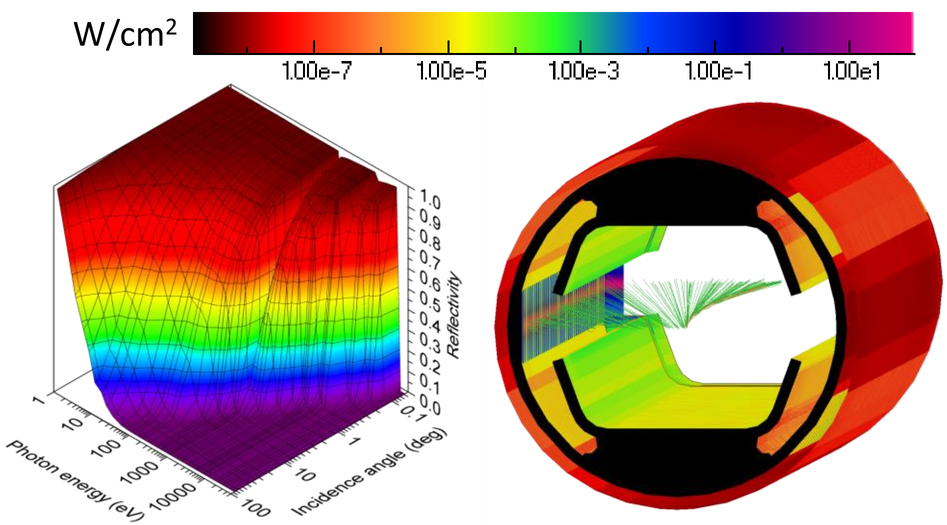


Gas coverage evolution over time on the 1.9 K CB



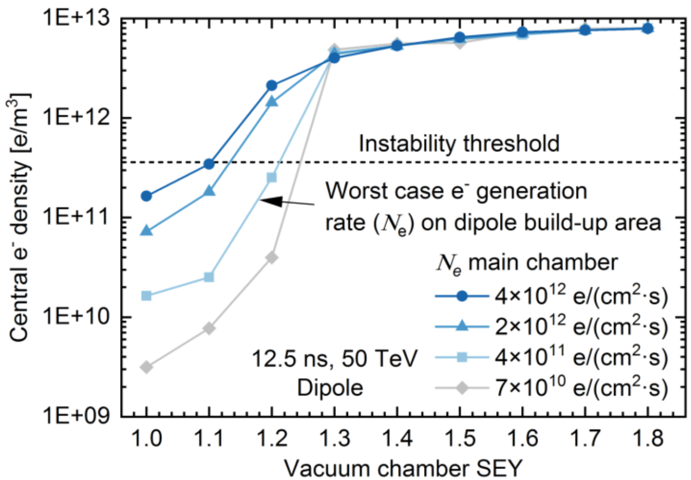
V. Anashin, O. Malyshev. Vacuum 53, 269-272

If the SR impacted directly on the cold mass, the recycling effect would not allow the gas to condense and the pumping speed would be drastically reduced



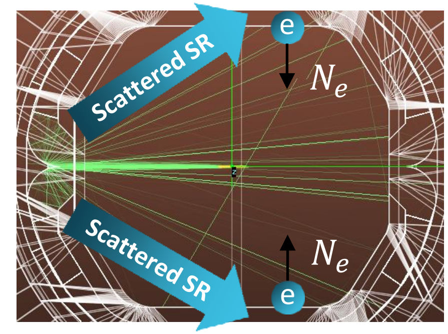
- The **ray tracing simulations** give us information of the SR flux and power distribution
- More than **95% of the SR power** hitting the BS is **absorbed** in the first hit
- Less than 0.01 % of the emitted power reaches the cold bore, **allowing the generated gas to condense** onto the cold bore and the coverage to grow over time, with a low gas recycling rate

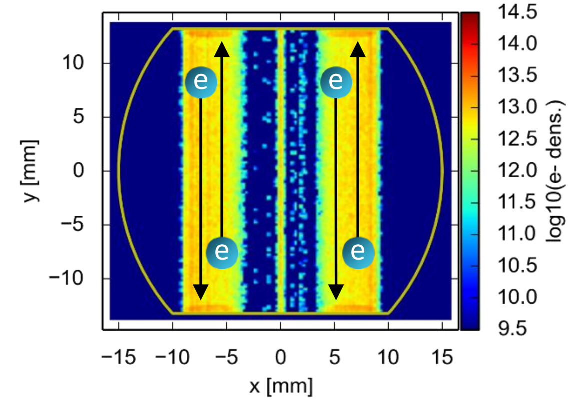
ELECTRON STIMULATED DESORPTION



$$N_e = \int_{E_{min}}^{E_{max}} \dot{\Gamma}_{ph}(E)\, Y_{ph}(E)\, dE$$

- The **electrons** accelerated by the beam's positive potential **desorb non-negligible amounts of gas** when hitting the chamber walls, therefore increasing the gas density in the vacuum chamber
- The **e⁻ density is proportional to the e⁻ generation rate** (N_e) depending in turn on the SR arriving to the critical areas

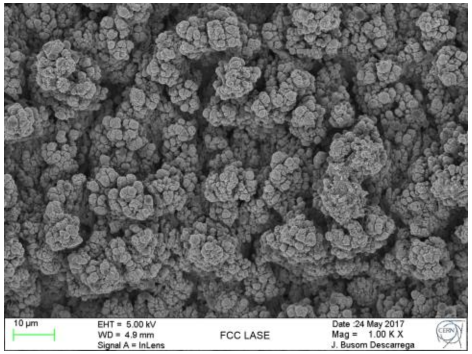




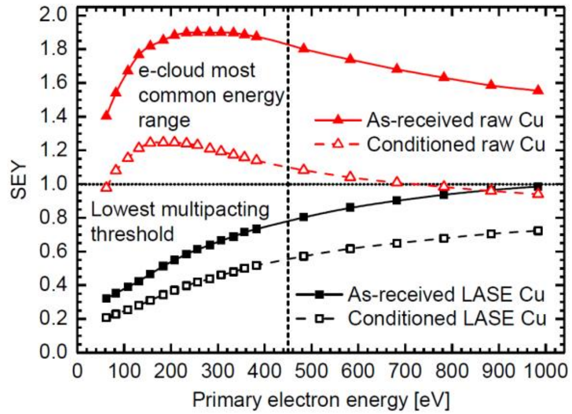
- In order to avoid **instabilities** and **keep a good vacuum quality**, N_e should be kept well below 10^{12} e⁻/(cm²·s)

Absorbing surface	SR power absorption	SR power on CB	SR power on inner Cu	N_e if Cu [e/(cm²·s)]	N_e if LASE [e/(cm²·s)]	Assessment
Rounded SS tip	43%	$7.1\cdot10^{-2}$ %	18.7 %	$3.1\cdot10^{13}$	$1.6\cdot 10^{12}$	Non-viable
Flat OFHC Cu	46%	$1.8\cdot10^{-3}$ %	5.3 %	$3.2\cdot10^{12}$	$3.7\cdot 10^{11}$	Non-viable
LHC sawtooth	96%	$4.4\cdot10^{-4}$ %	0.27 %	$3.1\cdot10^{11}$	$7.1\cdot 10^{10}$	Acceptable
FCC-hh sawtooth	98%	$3.4\cdot10^{-4}$ %	0.14 %	$1.0\cdot10^{11}$	$2.3\cdot 10^{10}$	High performance

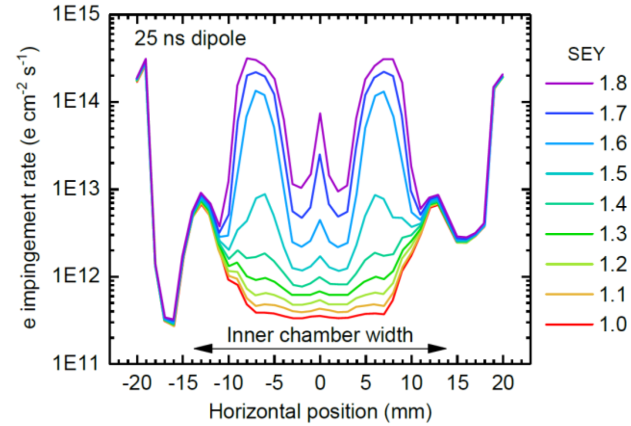
ELECTRON STIMULATED DESORPTION



- Using LASE or carbon coating is expected not only to lower the SEY but also Y_{ph}, further improving the vacuum quality



LASE and Cu SEY comparison
R. Valizadeh, O. Malyshev et al.



For additional information, see L. Mether's presentation in this conference, *Electron Cloud*

$$Q_{ESD} = (\eta_e + \eta_e')\ \dot{\Gamma}_e\ kT$$

e⁻ imping. rate ← $\dot{\Gamma}_e \propto N_e$ ← PyECLOUD

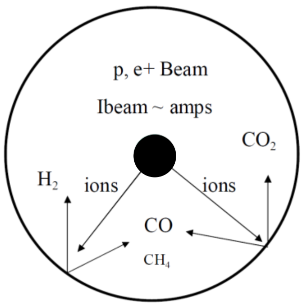
$$N_e = \int_{E_{min}}^{E_{max}} \dot{\Gamma}_{ph}(E)\ Y_{ph}(E)\ dE$$

Low, thanks to high SR absorption implementation

Experimentally measured. See *R. Cimino* talk

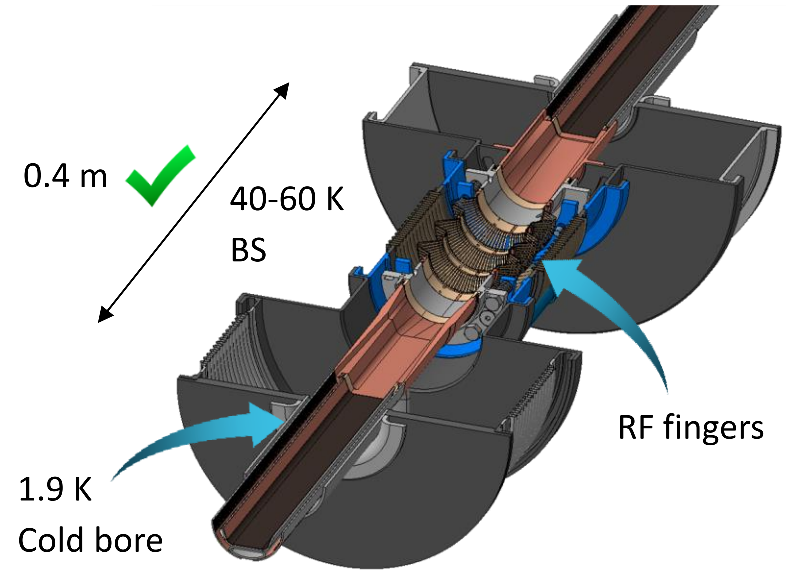
- As long as the SEY is effectively mitigated, **the ESD is expected to be relegated to a secondary role**, representing around 10% of the total gas load. In the LHC, it is estimated to represent 90%
- For dipoles with 25 ns of bunch spacing , where there are no so strict SEY requirements (< 1.5), it is possible to use **scrubbed copper** in the main chamber without any further SEY mitigation treatment. Nevertheless, it would imply an **ESD outgassing two times higher** than using LASE
- Using LASE on the sawtooth finishing would lower N_e in the inner chamber

ION STIMULATED DESORPTION



- The ions generated by the **beam ionization** are repelled by the positive potential and **desorb gas** upon colliding with the chamber's wall
- The maximum beam currents to avoid a pressure overrun have been found
- Thanks to the **high pumping speed of the BS** and the **short interconnect**, the ISD gas load is minor

$$I_c\,(A, B^+) = \frac{C_A\, e}{\eta_{A,B^+}\, \sigma_B} \qquad \Delta n\,(\%) = \frac{100\, I}{I_c - I}$$



MB interconnect, with 0.4m without active pumping

$$L_{max} \approx \pi \sqrt{\frac{ue}{\sigma_i\, I\, \eta_{i+}}} \qquad u \approx \frac{A \cdot d}{3} \sqrt{\frac{8RT}{\pi M}}$$

Infinitely long tube, two gases system at He = 40 K				
Area	H_2 + CO	Δn	CO + CO_2	Δn
Magnet BS	37 A	1.4 %	19 A	2.7 %

Length w/o BS between BS's, two gases at He = 40 K				
Area	H_2 + CO	Δn	CO + CO_2	Δn
Interconnect	12.8 A	4.1 %	6.8 A	7.9 %

Interconnect maximum length at 40 K				
Gas	H_2	CO	CO_2	CH_4
Max length	18.6 m	2.0 m	2.2 m	9.0 m

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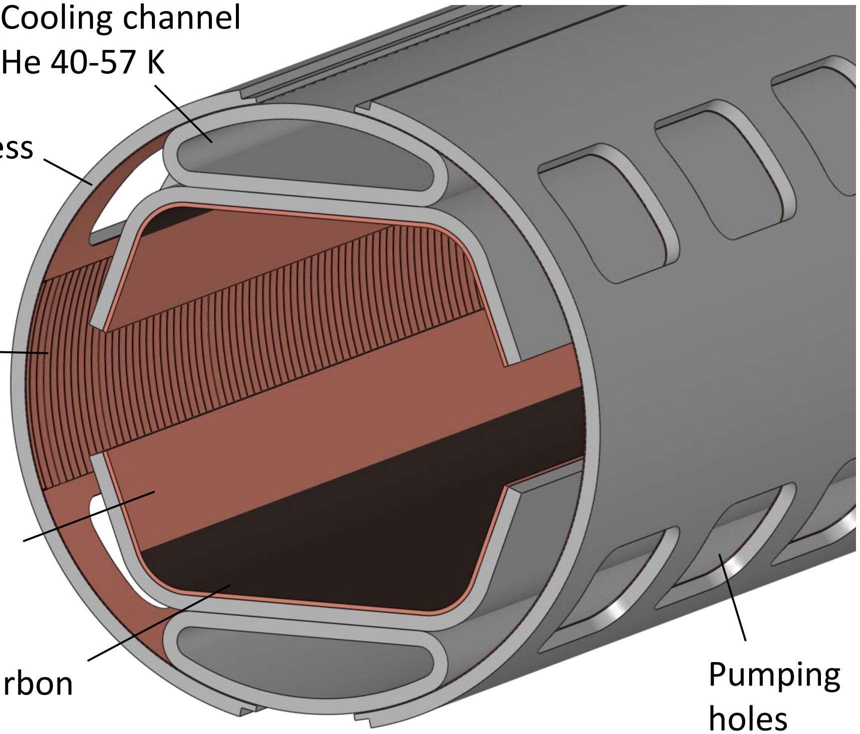
THE FCC-hh BEAM SCREEN

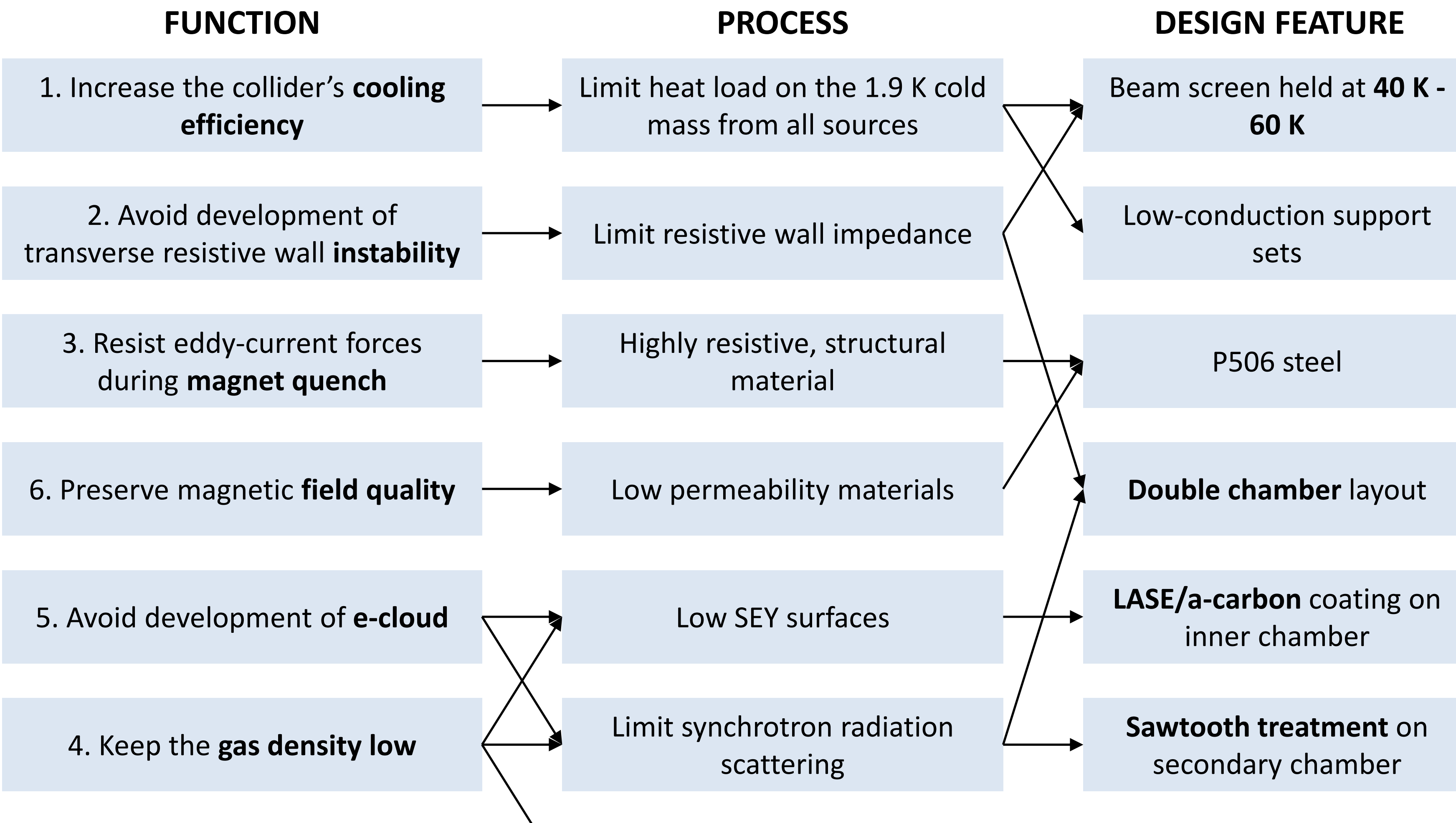
The FCC-hh beam screen has been designed with a series of new features to reduce the impedance and mitigate the beam induced effects:

- A **double chamber layout**, hiding the pumping holes from the direct sight of the beam. Apart from neglecting the holes contribution to the total impedance budget, it prevents the SR to directly hit the cold mass and lowers the SR reflected towards the inner chamber
- An **SEY mitigation solution**, LASE/a-carbon, which lowers the electron density in the beam's path and improves the vacuum quality
- An **improved sawtooth finishing**, aiming to lower the residual **gas density**, the SR reflectivity and the electron cloud seeds in the inner chamber



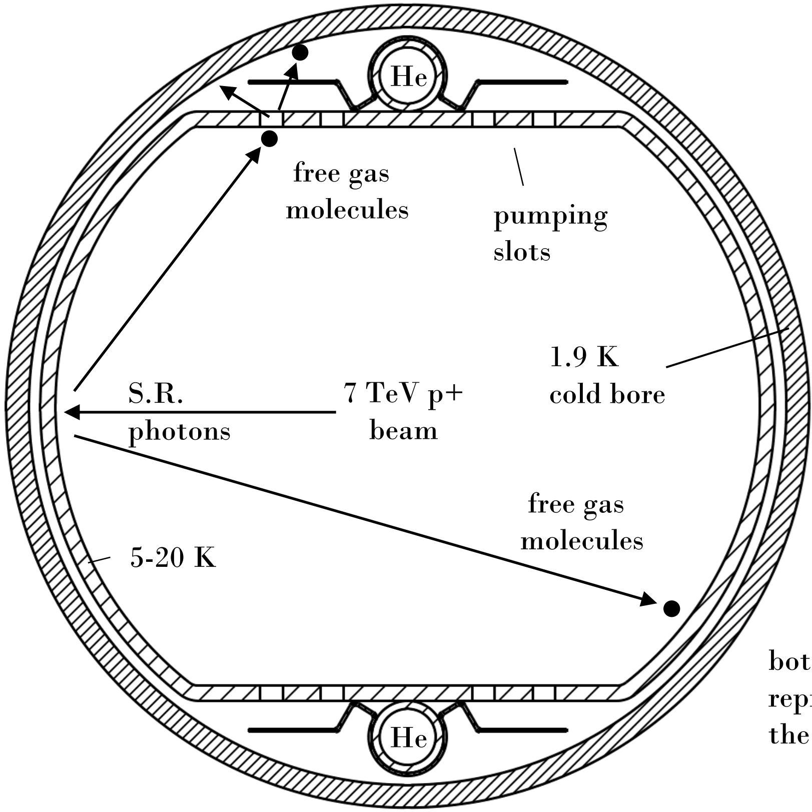
See M. Morrone's presentation in this conference, *Update of the design and thermomechanical study of the FCC-hh beam screen* for more information about the mechanical design

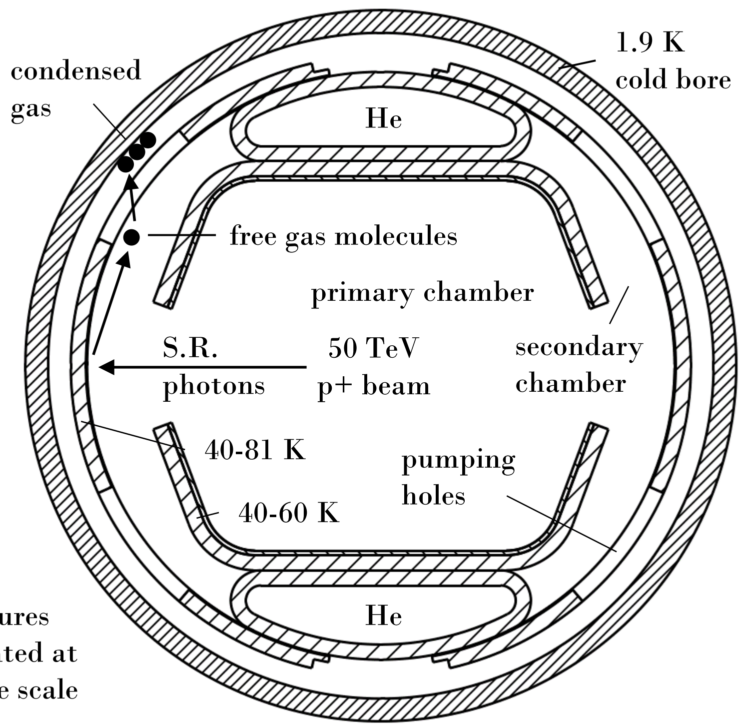
FCC-hh BS FUNCTIONAL MAP



Updated from *P. Lebrun et al. ICEC 2012*

BEAM SCREEN COMPARISON





both figures represented at the same scale

LHC - 173 l/(s·m) for H_2 at 5 K
0.22 W/m emitted SR

FCC-hh - 898 l/(s·m) for H_2 at 40 K
35.4 W/m emitted SR

- At the expense of a **higher complexity** (translated into a higher, but still affordable, cost) the beam induced vacuum effects are mitigated and the **pumping speed** and cooling capacity have been **considerably increased**

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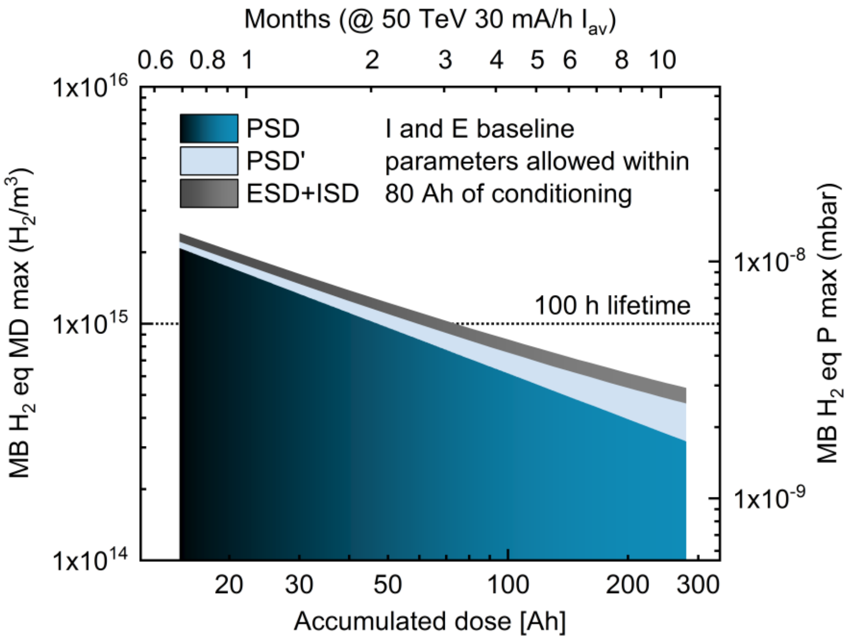
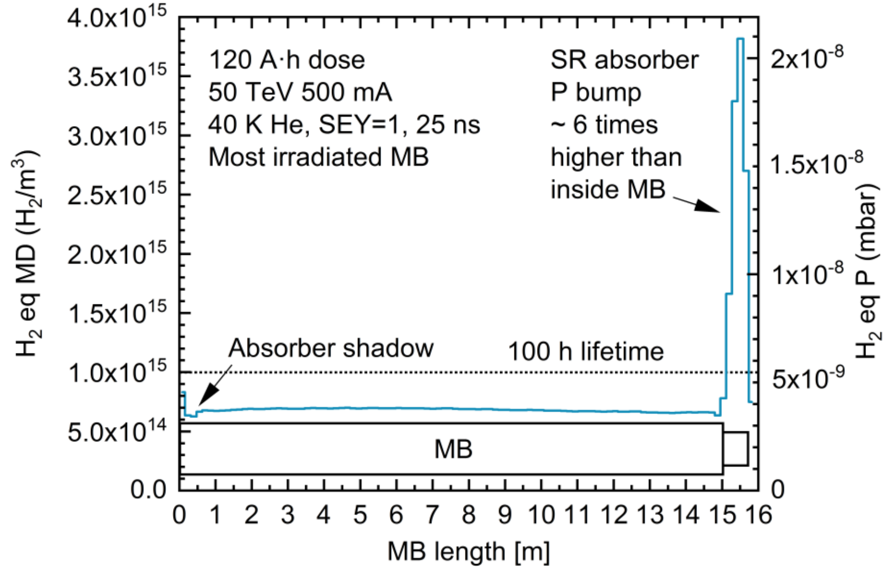
MOLECULAR DENSITY EVOLUTION





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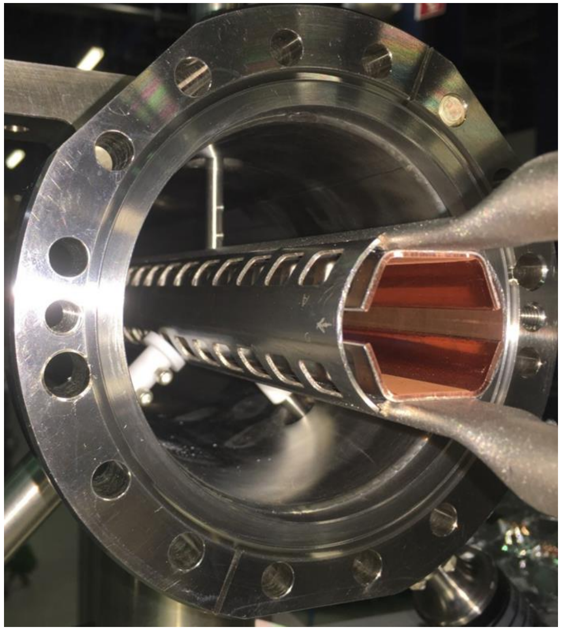
Contributions to the total gas load at 36 Ah				
Effect	PSD	PSD'	ESD	ISD
%	80%	10%	8%	< 3%

- For **50 TeV and 500 mA**, the gas density in the arcs is expected to be below the requirement of 10^{15} $H_{2\,eq}/m^3$ **within 80 Ah**. The current shall be kept lower than 500 mA before the BS is conditioned to keep the lifetime above 100 h
- **H_2** would be the **most abundant** gas species, whilst **CO** would be the one with the **highest impact on beam lifetime**

R&D FOLLOW UP PROPOSAL



BESTEX set-up with the latest BS inserted for measuring.
See L. A. González's presentation in this conference, *Photodesorption Studies on FCC-hh Beam Screen Prototypes at KARA*

- Several **experimental inputs shall be acquired** to increase the accuracy and **reliability** of the **computational models**
- **BESTEX** set-up is expected to acquire η_{ph} at 77 K, ε_c = 4.3 - 6.2 keV, for copper, Cu LASE and sawtooth. These data, representing 80% of the total gas load, will be directly used to refine the models
- The properties and **exact specifications of LASE** or a-carbon shall be properly **studied**. Currently, the studied laser treatment presents a large safety margin on the SEY, but there are many unknowns about its surface resistance. This treatment is specially interesting for the vacuum system owing to its low cost and high potential in **reducing the gas load and photoelectron generation** inside the beam screen. The carbon coating is being studied in parallel in the framework of the HL-LHC project
- A dedicated experiment to measure the **recycling effect** (η'_{ph}) of the gas condensed on the cold bore, for low photon doses, and η_e of the BS materials, shall also be carried out, owing to the lack of literature data
- Detailed e-cloud studies should be carried out in the **interconnect region** taking into account the residual magnetic field. The optimal location of the SEY mitigation treatments in this region should be defined

STUDY CONCLUSIONS

- A **new beam screen** has been proposed for the FCC-hh. It is intended to **overcome the challenges** derived from the increase of beam energy, from the 7 TeV of the LHC up to the 50 TeV of the FCC-hh, which raises the linear power density from 0.22 W/m up to 35.4 W/m.

- The impact of the **beam induced vacuum effects** on the beam vacuum level of the FCC-hh **has been assessed**. It is concluded that, despite the much higher synchrotron radiation power and beam screen temperature, the proposed **vacuum system shall be adequate**. The **conditioning time** needed to run the collider with baseline beam parameters and above 100 h of nuclear scattering lifetime **is acceptable**, i.e. **lower than 80 Ah**, equivalent to around 4 months of escalated commissioning

- These favorable previsions would be possible **thanks to the new beam screen geometry**, which features a pumping speed more than four times higher than the one of the LHC, and on the other hand, thanks to the expected **SEY mitigation**, relegating ESD to a minor cause of gas release

- That being said, **despite the good forecasts**, the high uncertainty of these estimations derived from the **lack of data in the literature** leaves these results as mere tentative. To completely assess the viability of the proposed FCC-hh vacuum system, **dedicated experiments** will have to be carried out in the future as those proposed at KARA light source (see L. A. González's talk, this conference)

THANK YOU FOR YOUR ATTENTION

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Ignasi Bellafont

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