Pressure Profile in the experimental area of FCC-hh and FCC-ee calculated by an analytical Code

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Objectives

Ultra high vacuum (UHV) is a basic requirement for the Future Circular Colliders (FCC). The dimension of the FCC and the high energy of the particles make this requirement challenging. Therefore good simulation codes are required, that gives us knowledge about how, why and where specific factors may impact on the vacuum quality. A low residual gas particle density (described in the following by the variable **n**) means a good vacuum quality. Density and pressure (meassured by the gauges) are related with the ideal gas law.

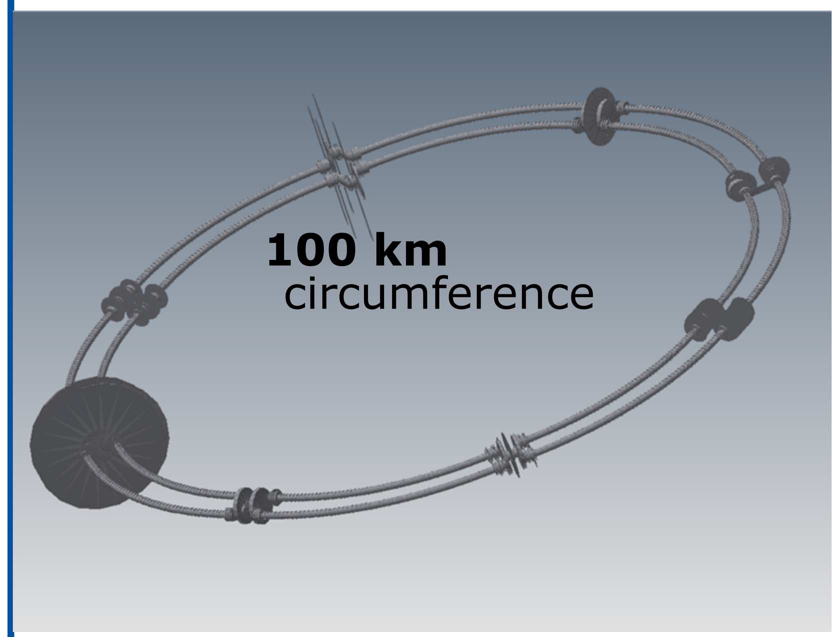
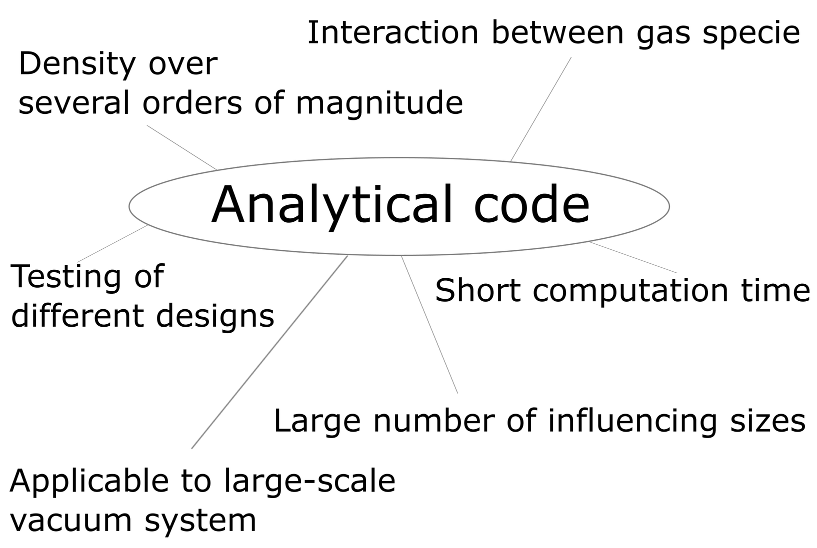


Fig. : Sketch of a circular accelerator.



Simulation Code

The model is implemented in a Python environment, embedded in a graphical user interface (PyQT) and cross-checked with:

- a Monte Carlo code (Molflow+ [3])
- real case scenarios of the LHC (by comparison to gauges values)

Qt

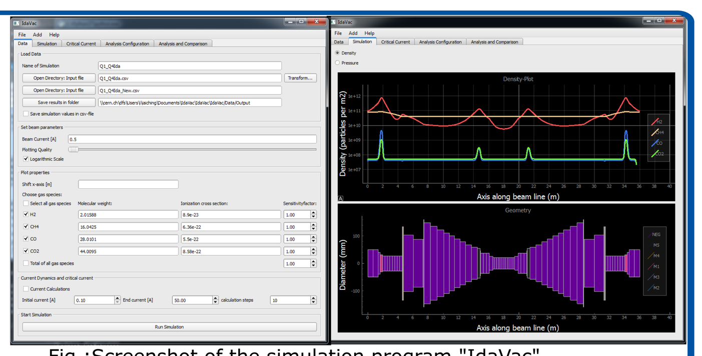


Fig.:Screenshot of the simulation program "IdaVac".

56 variables influence vacuum

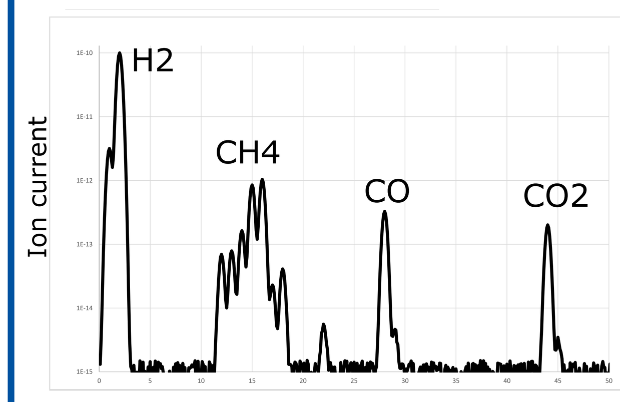


Fig.: Mass spectrum in an UHV.

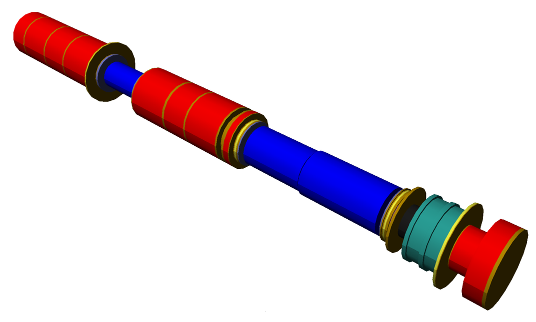


Fig.: Sketch of a vacuum chamber; different colors correspond to different materials.

Four dominating gas species in an UHV-system:
H_2, CH_4, CO, CO_2

Temperature 293K 10K
Magnets operate at cryogenic temperatures: 1.5-20K
Everywhere else: room temperature: 293K

Geometry
Diameter and length of vacuum chamber influence conductance and beam induced effects. The diameter varies between 50 and 250mm in the room temperature area and is about 30mm in the cryogenic area (compare to LHC: 41.6mm)

Material NEG
The material specification defines desorption yields and thermal outgassing.
- A beamscreen is implemented in the cryogenic area with pumping holes.
- Vacuum chambers are made out of copper with an additional coating of Non Evaporable Getters (NEG).
- Between NEG coated parts are beam instrumentaion and collimator equipment installed.

The pipe close to the detector is made out of beryllium.

Pumps and gassources
Surface pumping occurs through holes in the beam screen and through NEG. Lumped pumps are mainly provided by sputtered pumps (ion pumps, turbomolecular pumps).
Simualtion of gas sources provide testing of potential leaks.

Beam-induced effects
Energetic particles bombard the chamber and may provoke desorption from:
(a) Synchrotron radiation (SR)
(b) Electron Cloud phenomena (EC)
(c) ionized resiudal gas particles

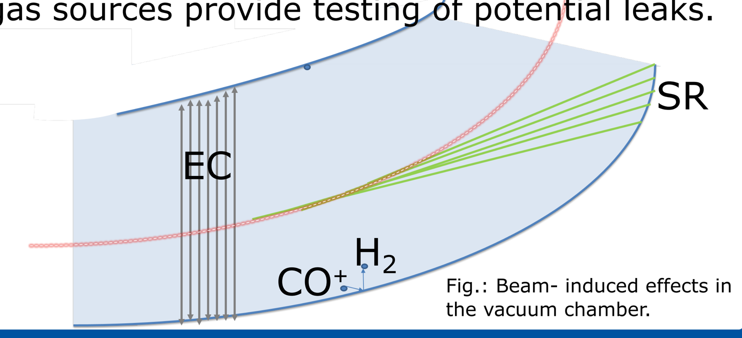


Fig.: Beam- induced effects in the vacuum chamber.

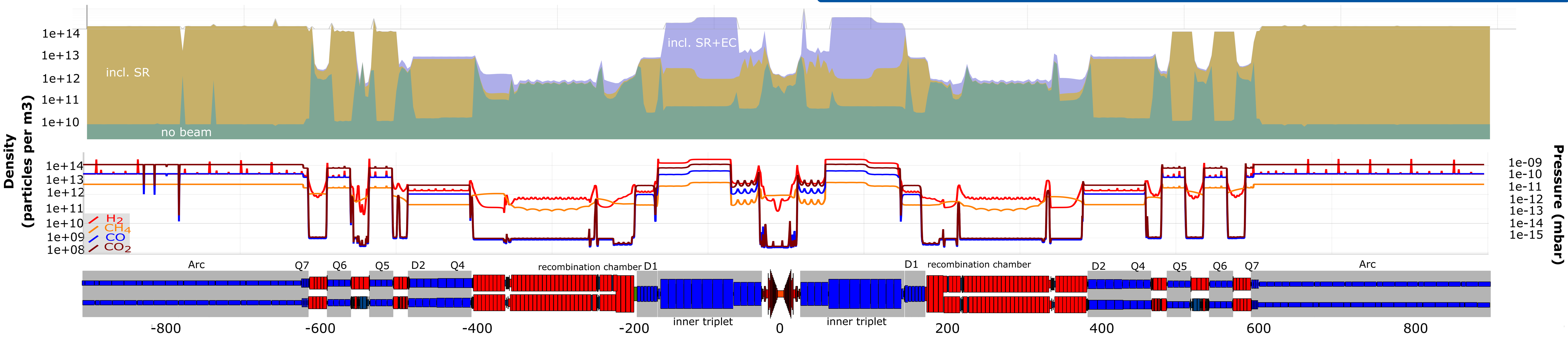


Fig. 1: Simulation example of the Long Straight Section of the FCC-hh with an experiment in the middle. First plot presents a parameter variation of the total density in the case of (a) no beam, (b) with SR and (c) with SR and EC. Second plot presents the density profile of the four gas species H_2, CH_4, CO amd CO_2 in the presence of EC and SR.
Further description below in the FCC-hh textbox.

FCC-hh

The design of the FCC is close to the LHC with:
- magnets that are stronger and 4 times longer,
- inner triplets with a bigger aperture
- a smaller beamscreen in the cryogenic area,
- seperation dipoles operate at cryogenic temp.
- distance between IP and magnets increased.

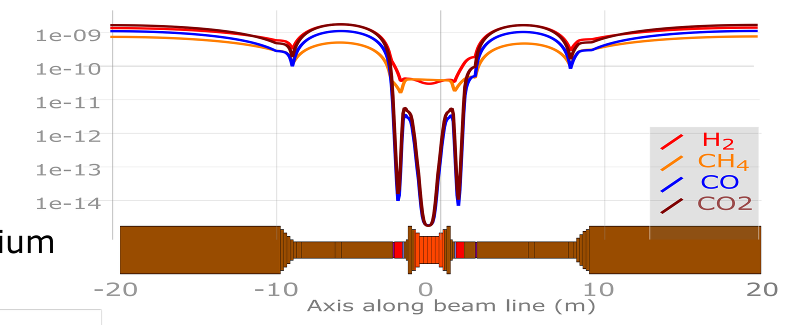
--> aiming to have a
5 times better vacuum quality.
(corresponds to a density of 2. 10^{14} particles/m³)

10K 293K NEG

Main observations of Fig.1.:
- 4 gas specie result in 4 different density profiles.
- Density limit of 2.10^{14} part./m³ is nearly reached.
- H_2 constitutes the major part of the gas load.
- CH_4 is not pumped by NEG.
- H_2 peaks in the arcs visualize the interconnects, where H_2 is not pumped anymore.
- biggest density gradient in the transient areas from room temperature area to cryogenics.
- beam induced effects occur mainly in the arcs and in the inner triplet.

FCC-ee

- operates at room temperature on the whole ring
- Vacuum chamber is mainly made out of copper.
- Coating as NEG might not be possible.
- Layout of pumping system consists only of lumped pumps.
- very short common chamber; made out of Beryllium
- asymmetric layout close to the experiment for the two beams (see Fig.)
- Absorbers are installed to shield the interaction point (IP) from SR.



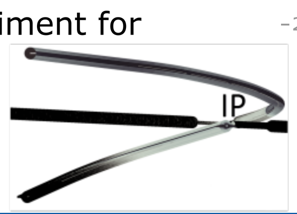


Fig. top: an example pressure profile of IP region
Fig. left: asymmetric layout of IP region

293K

Mathematical Model

Ficks's first and second laws of diffusion define the fundamental balance equation of the kinetics in an UHV system. Considering additionally the flow into and out of the system, gives us the following mass-balance equation with the particle density **n** = (n_{H2}, n_{CH4}, n_{CO}, n_{CO2}) as unknown (detailed description in[1]):

$$\underbrace{\frac{\partial \mathbf{n}}{\partial t}}_{\substack{\text{Time variation}\\ \text{of particles}}} = \underbrace{\mathbf{a} \circ \frac{\partial^2 \mathbf{n}}{dx^2}}_{\text{Diffusion}} + \underbrace{\eta_{ph} \cdot \dot{\Gamma}_{ph}}_{\substack{\text{Desorption}\\ \text{by photons}}} + \underbrace{\eta_e \cdot \dot{N}_e}_{\text{by electrons}} + \underbrace{\boxed{\underbrace{\mathbf{H}_{ion} \cdot \dot{I}_{\text{ion}} \circ \mathbf{n}}_{\substack{\text{Ionization by beam}\\ \text{and desorption by ions}}}}}_{\textit{Multigasmodel}} + \underbrace{A \cdot \mathbf{q}_{\text{th}}}_{\substack{\text{thermal}\\ \text{outgassing}}} - \underbrace{\alpha \circ \frac{A \cdot \bar{\mathbf{v}}}{4} \circ (\mathbf{n} - \chi_{\text{cryo}} \mathbf{n_e})}_{\text{wall distributed pumping}} - \underbrace{\mathbf{p}_l \circ \mathbf{n}}_{\text{linear pumping}}$$

Two key ideas to solve the equation system:

1) The beam pipe usually provides constant coefficients over a specific domain. Hence, split the domain into a finite number of elements and compute on each element the solution function. The local solution functions are combined then by boundary conditions to a global solution.

The following boundary conditions describe density and flux continuity:

$$\begin{aligned} \mathbf{n}_{k-1} &= \mathbf{n}_k \\ -\frac{D\mathbf{n}_{k-1}}{Dt} + \frac{D\mathbf{n}_k}{Dt} &= \mathbf{s}_k \mathbf{n}_k - \mathbf{g}_k \end{aligned}$$

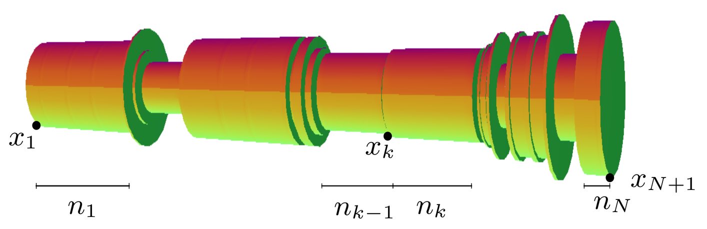


Fig. Schematics of splitted beam chamber. n_k defines the particle density for element k.

2) Transform equation system to an equation system of first order, by using the transformation identitiy $\mathbf{y} := \begin{pmatrix} \mathbf{n} \\ \mathbf{n}' \end{pmatrix}$. The fundamental Theorem of Picard Lindelöf poses then a solution by:

$$\mathbf{y}(x) = \underbrace{e^{(x-x_0)\mathbf{M}}}_{\text{fundamental solution}} \mathbf{y_0} + \underbrace{\int_{x_0}^{x} e^{(x-t)\mathbf{M}} \mathbf{b} dt}_{\text{particular solution}}$$

Where $\mathbf{M} \in \mathbb{R}^{8\times8}$ and $\mathbf{b} \in \mathbb{R}^8$ are determined by material, beam and geometry specifications. $\mathbf{y_0} \in \mathbb{R}^8$ is the integration constant and can be determined by the boundary conditions.

Vacuum Surface & Coating Group
Technology Department

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3. R. Kersevan and M. Ady: *Molflow - A test-particle Monte Carlo simulator for ultrahigh vacuum systems,* Geneva 2009.
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