Challenges in Vacuum Design of Particle Accelerators

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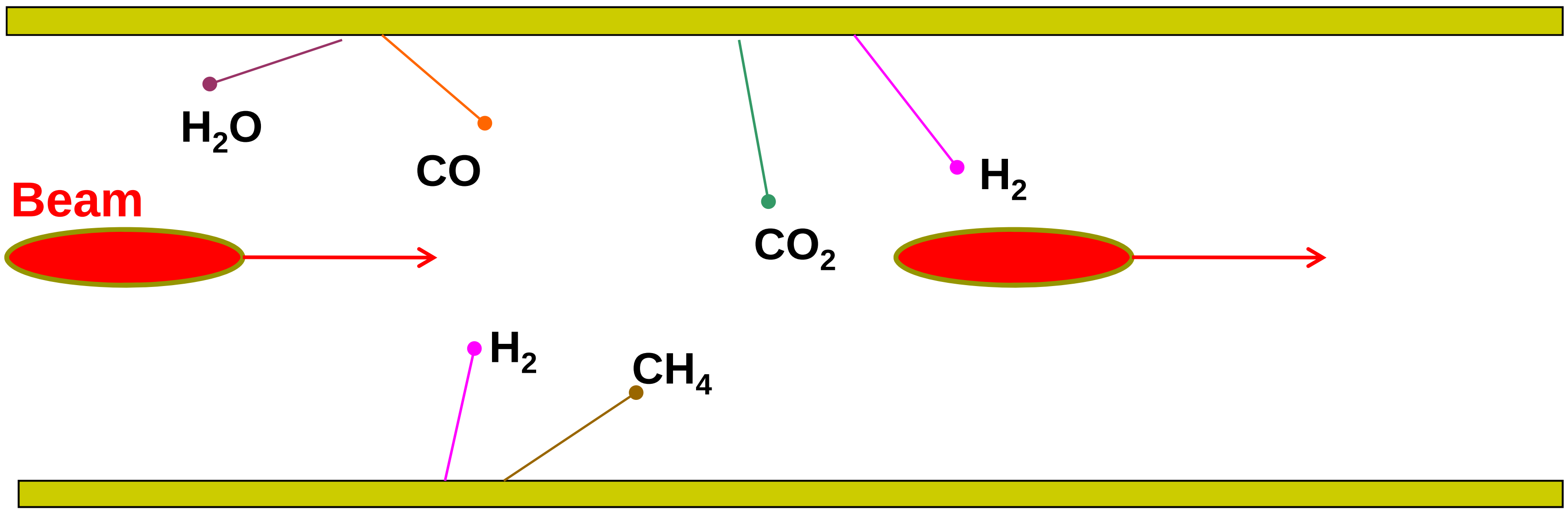
Vacuum required in the particle accelerators

High energy particles collide with residual gas molecules that results in:

- loss of particles,
- loss of the beam quality.



Sources of gas in vacuum system

- Leaks
- Residual gas from atmosphere
- Gas injection
- Thermal outgassing
- Photon, electron and ion stimulated desorption

Sources of gas in vacuum system

- Leaks —— there must be no leaks
- Residual gas from atmosphere —— It is not a source of gas for the most of UHV systems
- Gas injection —— It is usually well controlled
- Thermal outgassing
- Photon, electron and ion stimulated desorption

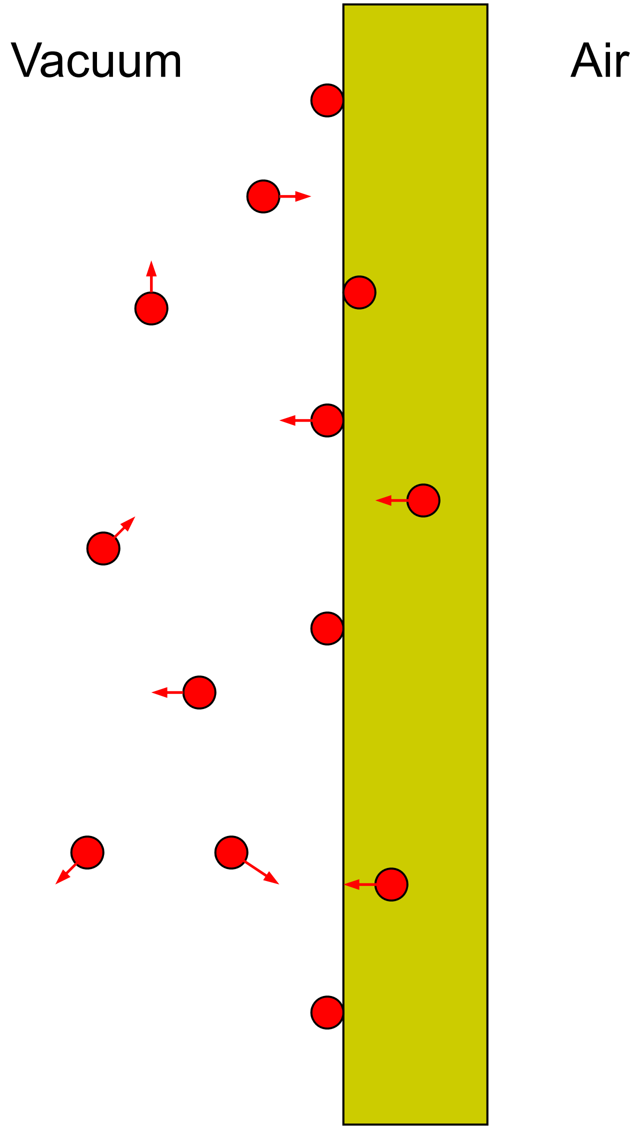
—— these are major sources of gas in UHV system

Sources of Gas in a Vacuum System: Thermal Desorption

Thermal desorption (or thermal outgassing) means:

- Molecules adsorbed on the surface (initially or after the air venting) and desorbing when vacuum chamber is pumped
- Molecules diffusing through the bulk material of the vacuum chamber, entering the surface and desorbing from it

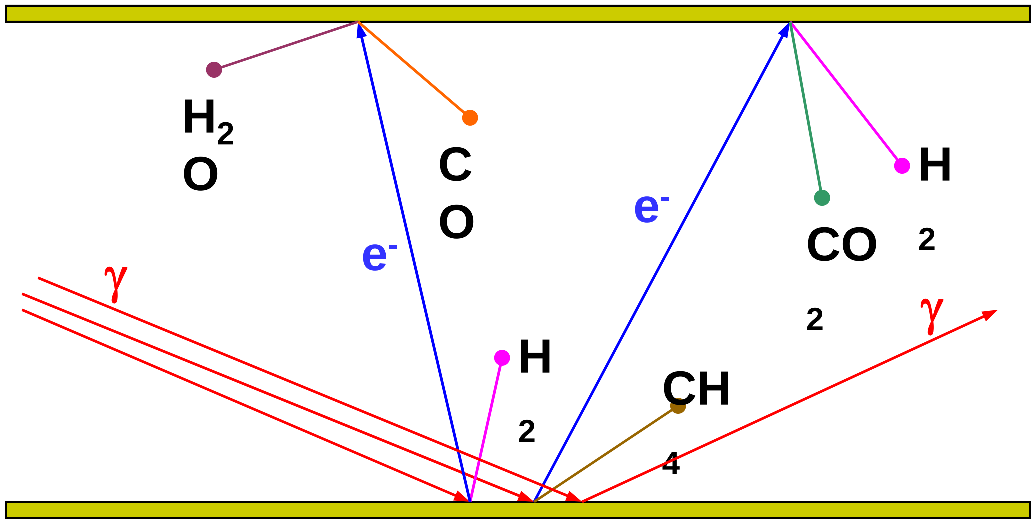
Outgassing rate depends on many factors: choice of material, cleaning procedure, pumping time, etc...



Sources of Gas in a Vacuum System: PSD

Photon stimulated desorption (PSD) is one of the most important sources of gas ***in the presence of SR***.

Gas molecules may be desorbed from a surface when and where *photoelectrons* leave and arrive at a surface



The same as thermal desorption, PSD depends on:

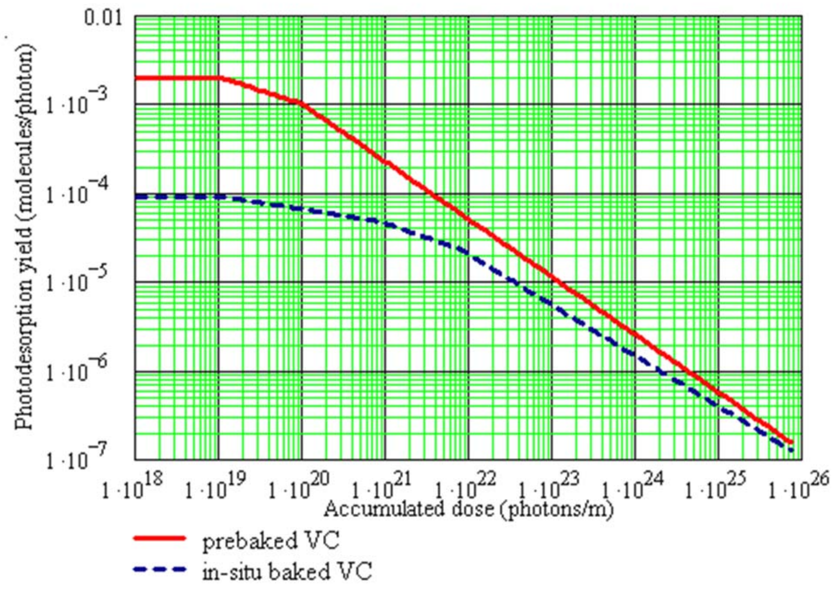
- Choice of material
- Cleaning procedure
- History of material
- Pumping time

Additionally it depends on

- **Energy of photons**
- **Photon flux**
- **Integral photon dose**
- **Temperature**

Sources of Gas in a Vacuum System: PSD

Photodesorption yields, η **(molecules/photon),** as a function of accumulated photon dose, ***D***, for different materials measured up to certain doses, these results are extrapolated for use in the design of new machines

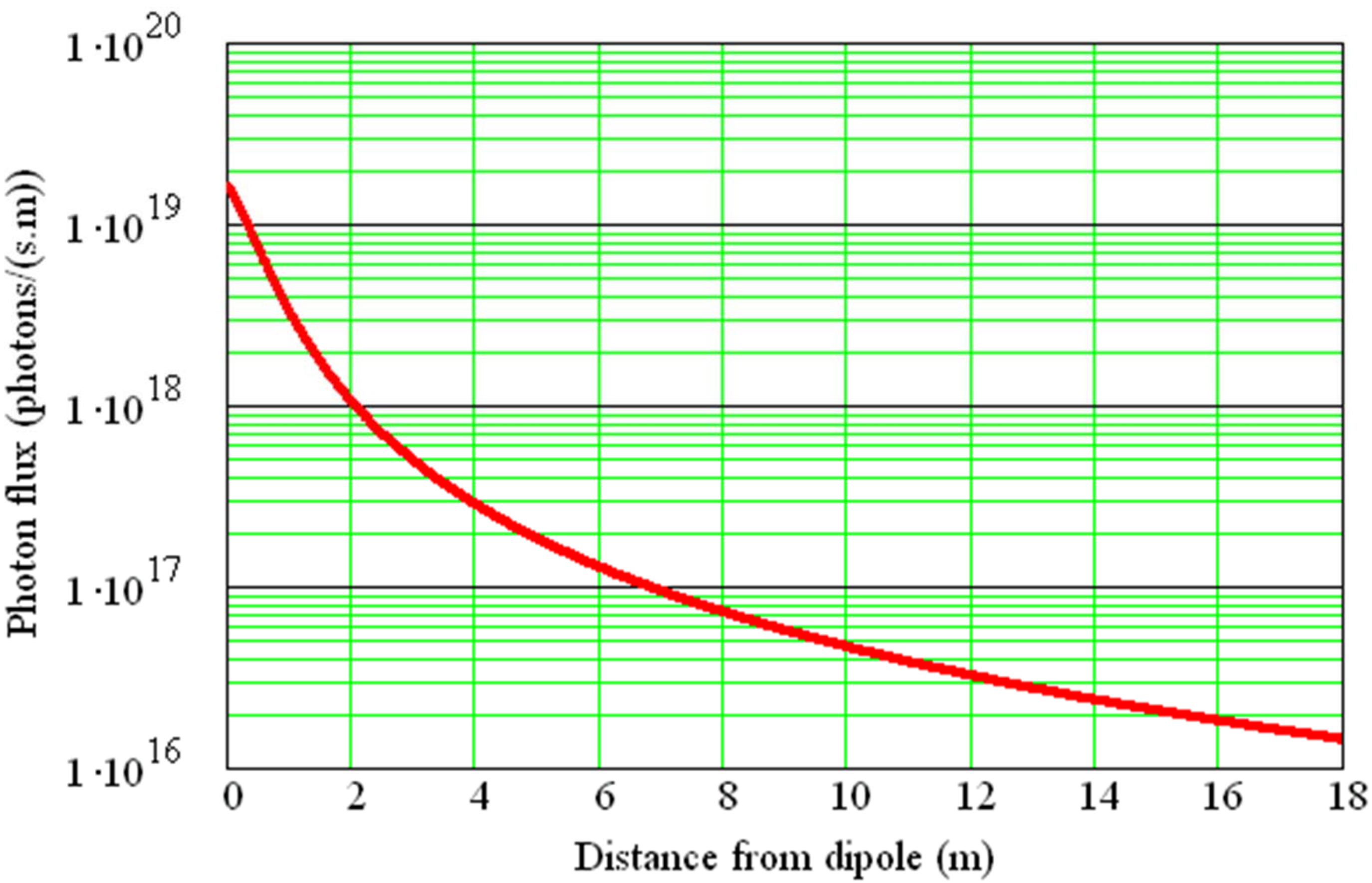


Photodesorption yield at room temperature as function of accumulated photon dose can be described as:

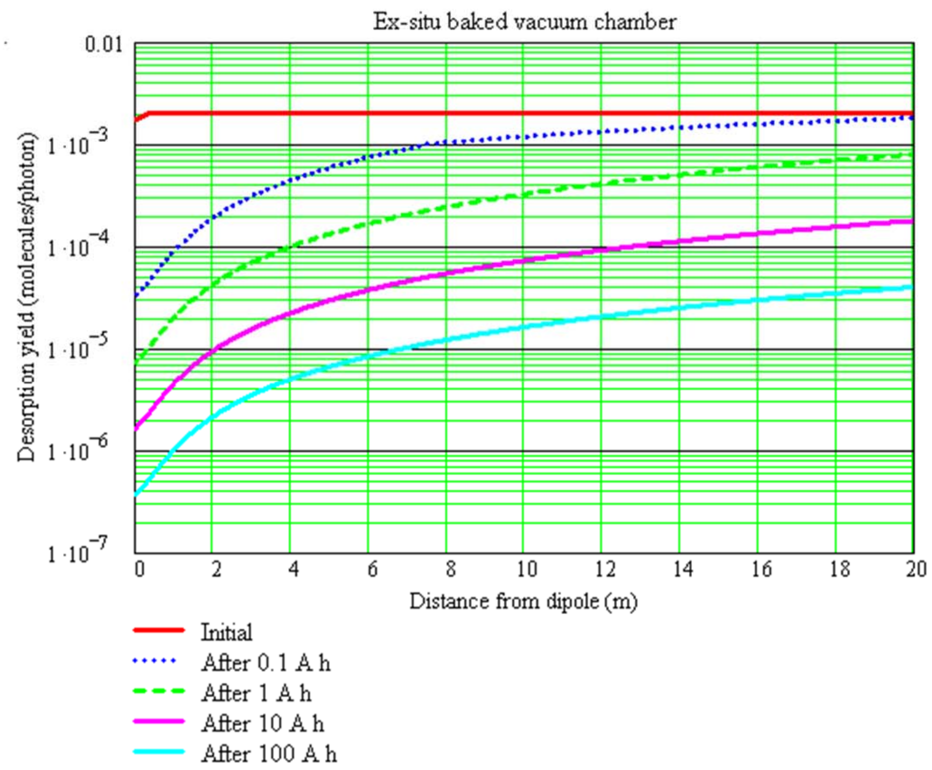
$$\eta = \eta_0 \left(\frac{D_0}{D} \right)^{\alpha}, \quad 0.65 < \alpha < 1$$

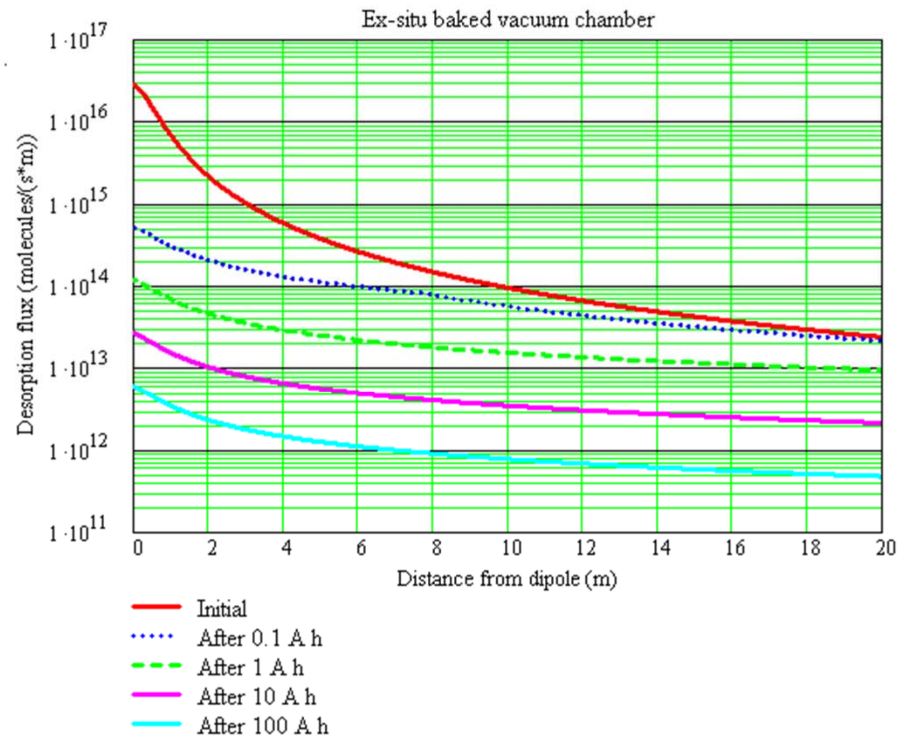
PSD yield for CO for prebaked and *in-situ* baked stainless steel vacuum chambers.
Yields for doses higher then 10^{23} photons/m (1 to 10 Amp·hrs for diamond) are extrapolations.

SR from a dipole magnet



PSD yield and flux as a function of distance from a dipole magnet





These data for each gas can be used in the gas dynamics model.

Models used in the molecular gas flow regime

- Analytical 1D diffusion model (Knudsen-Clausing)
- Monte-Carlo simulations (3D)
- Method of angular coefficient (2D and 3D)

Diffusion model

- Diffusion model is analytical one-dimensional approach
- It uses global and averaged parameters: pressure, pumping speed, uniform molecular velocity speed, etc.
- In many cases accuracy is within 0.1 to 10%
- In some cases (ex.: vacuum chamber with sorbing walls, beaming effect) the error may be times or even orders of magnitude.

A model of dynamic desorption processes in a beam vacuum chamber (1)

The equations of gas dynamic balance inside a vacuum chamber:

$$V\frac{dn}{dt} = q - cn + u\frac{d^2 n}{dz^2}$$

where
n is the gas volume density;
q is the gas desorption flux;
z is the longitudinal axis of the vacuum chamber;
V is the vacuum chamber volume;
c is the distributed pumping speed

Gas desorption q consists of two main sources: thermal and photon stimulated desorption:

$$q = \eta_t F + \eta_\gamma \Gamma$$

where

η_t is the thermal desorption yield,
F is the vacuum chamber surface area,
η_γ is the photon stimulated desorption yield,
Γ is the synchrotron radiation photon flux.

A model of dynamic desorption processes in a beam vacuum chamber (2)

In the **quasi-equilibrium state** when the condition

$$V\frac{dn}{dt}=0 \quad \text{or} \quad \left[V\frac{dn}{dt} \ll q \text{ and } V\frac{dn}{dt} \ll cn \text{ and } V\frac{dn}{dt} \ll u\frac{d^2n}{dz^2} \right]$$

is satisfied then:

$$u\frac{d^2n}{dz^2}-cn+q=0$$

This second order differential equation for the function *n(z)* has two solutions:

$$n(z)=-\frac{q}{2u}z^2+C_{1a}z+C_{2a} \qquad for \quad c=0$$

$$n(z)=\frac{q}{c}+C_{1b}e^{\sqrt{\frac{c}{u}}z}+C_{2b}e^{-\sqrt{\frac{c}{u}}z} \qquad for \quad c>0$$

where the constants C_1 and C_2 depend on the boundary conditions.

A model of dynamic desorption processes in a beam vacuum chamber (3)

All vacuum chamber along the beam can be fragmented on N elements with $c = 0$ and $c > 0$. Every i-th element lying between longitudinal co-ordinates z_{i-1} and z_i will be described by above equations with two unknowns C_{1i} and C_{2i}. The boundary conditions are

$$n_i(z_i) = n_{i+1}(z_i) \quad \text{and} \quad \partial n_i(z_i)/\partial z = \partial n_{i+1}(z_i)/\partial z$$

.

A system of 2N–2 equations with 2N–2 unknowns which can be easily solved.

A model of dynamic desorption processes in a beam vacuum chamber (4)

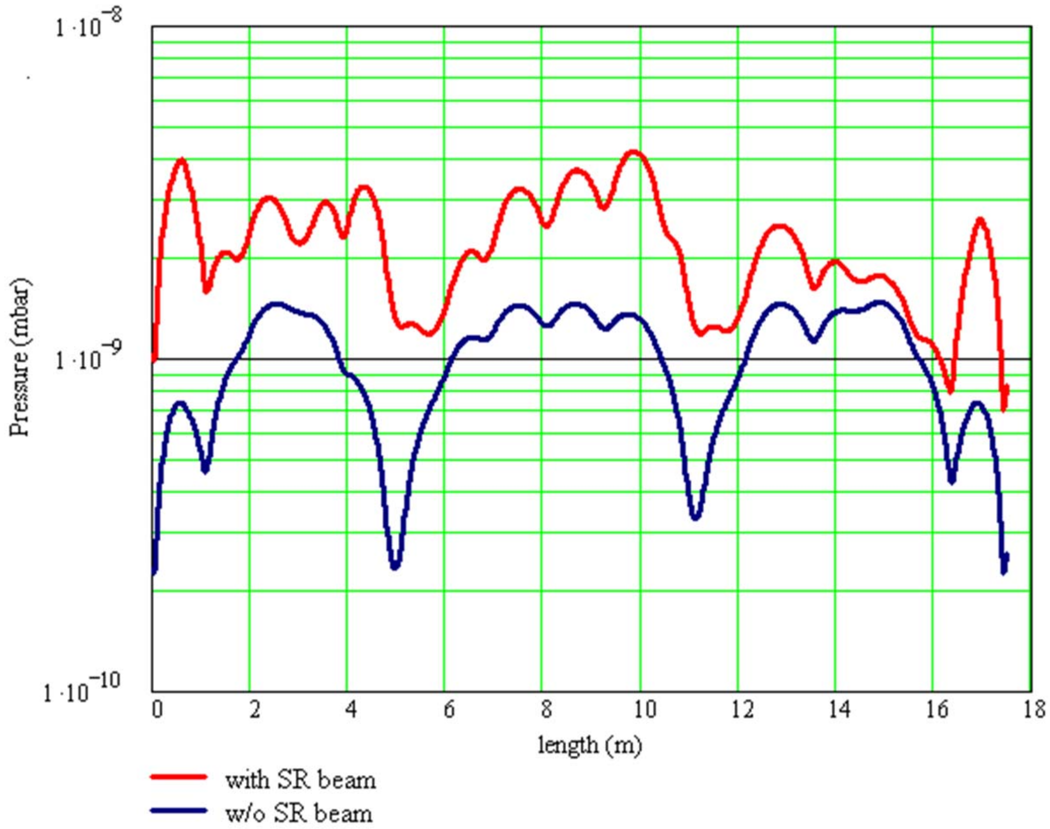
Then **the pressure along the vacuum chamber can be described <u>analytically</u>.**

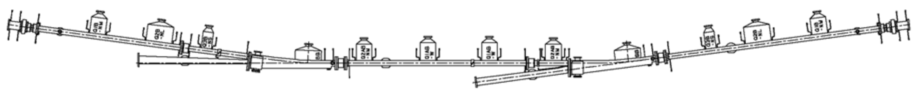
$$n_i(z) = -\frac{q_i}{2u_i} z^2 + C_{1i} z + C_{2i} \qquad for \quad c_i = 0$$

or

$$n_i(z) = \frac{q_i}{c_i} + C_{1i} e^{\sqrt{\frac{c_i}{u_i}} z} + C_{2i} e^{-\sqrt{\frac{c_i}{u_i}} z} \qquad for \quad c_i > 0$$

Pressure profile along the arc after 100 A·hrs beam conditioning





Average pressure

without a beam:

$\langle P_t \rangle = 1\cdot10^{-9}$ mbar

due to SR photons only:

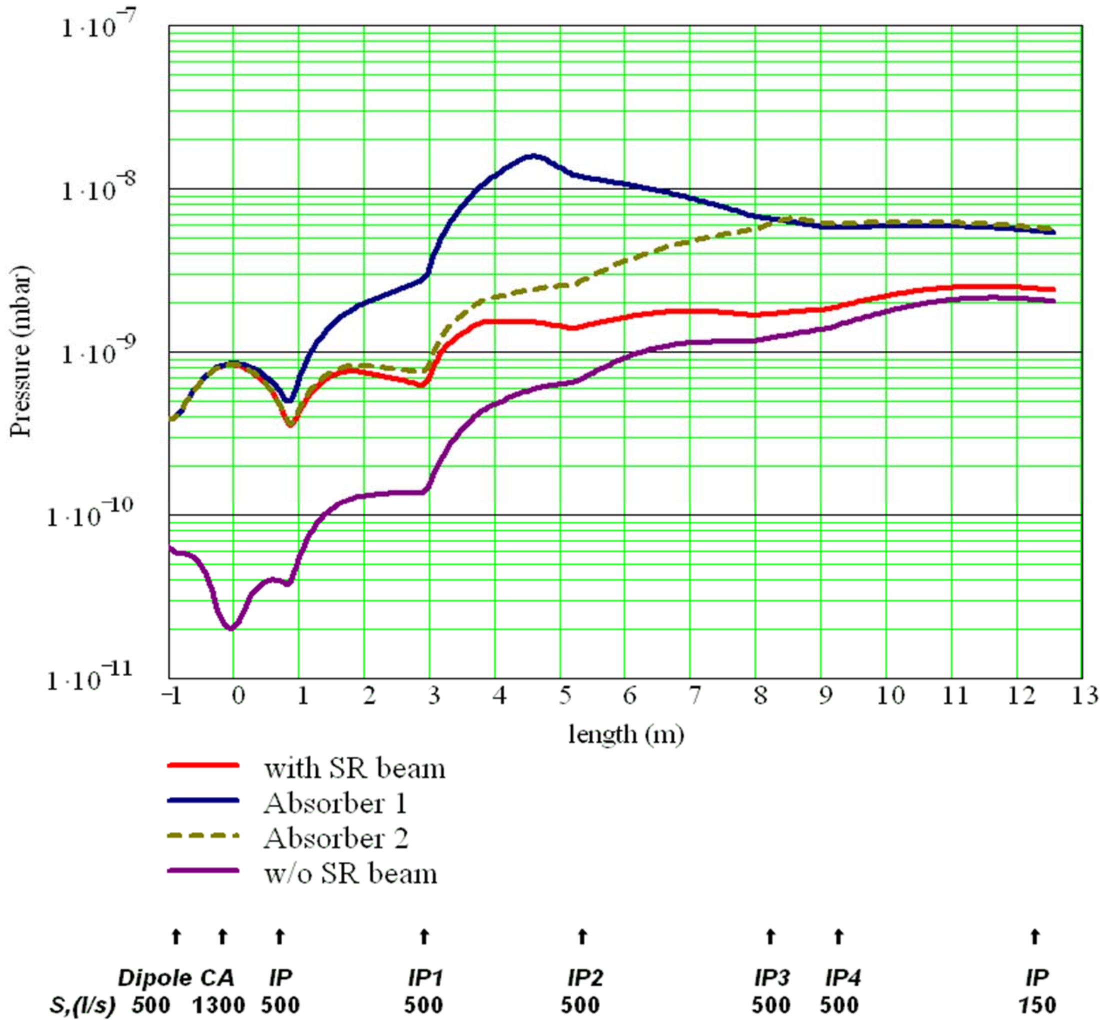
$\langle P_\gamma \rangle = 1\cdot10^{-9}$ mbar

Sum (i.e with a beam):

$\langle P_{din} \rangle = \langle P_t \rangle + \langle P_\gamma \rangle =$

$= 2\cdot10^{-9}$ mbar

Pressure profile along front ends after 30 A·hrs beam conditioning



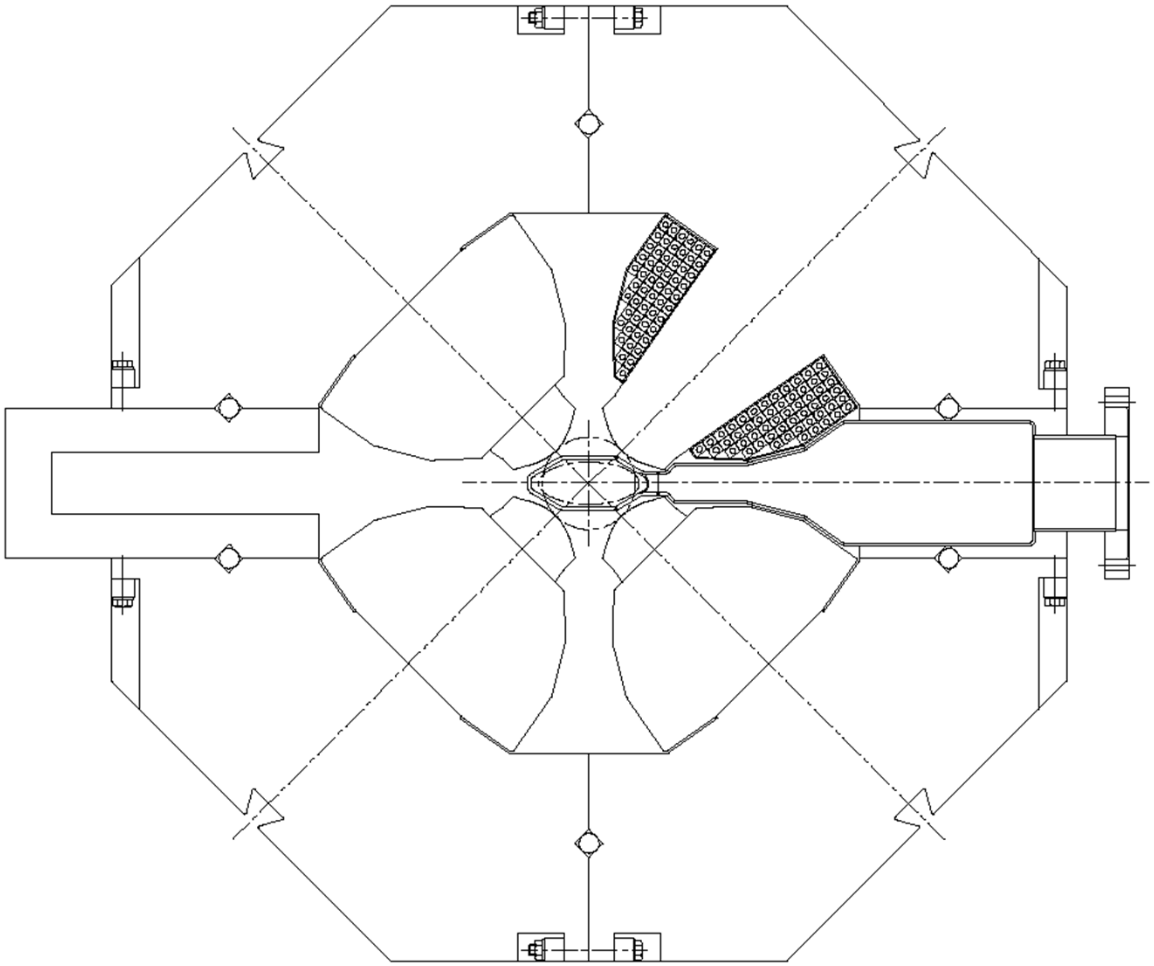
Test Particles Monte-Carlo method (TPMC)

- Three-dimensional model
- Mechanical analogy to particle movement in free molecular flow regime
- Random statistical generation of initial position, velocity direction, reflection from walls, sorption probability.
- Accuracy is proportional to number of generated particles

Test Particles Monte-Carlo method (TPMC)

- *gas load q (desorbing surfaces and angular distribution),*
- *pumping speed S (pumping surfaces sticking probability or capture coefficient)*
- *geometry of vacuum system.*

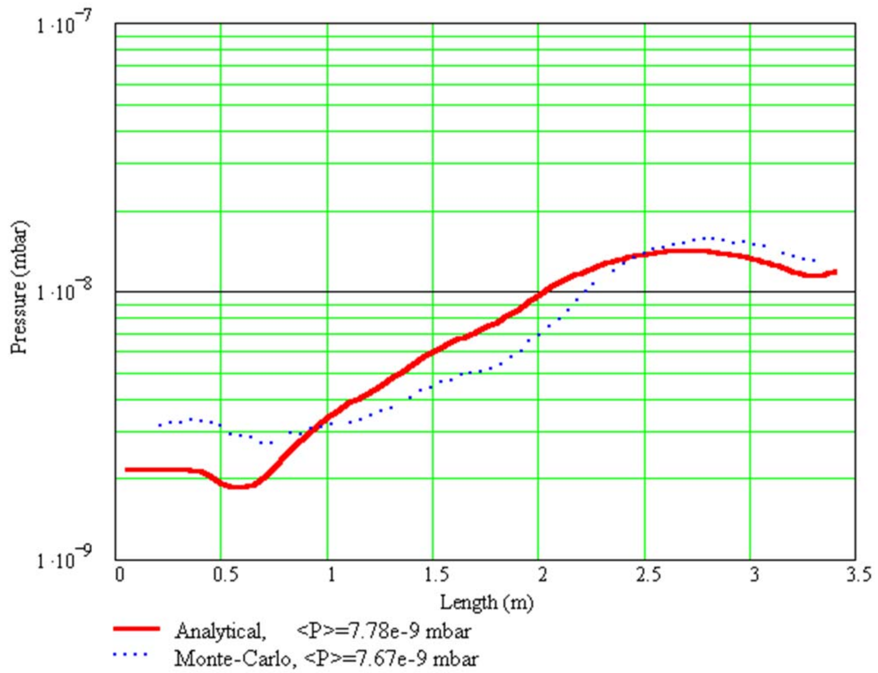
Monte-Carlo for modelling pumping port

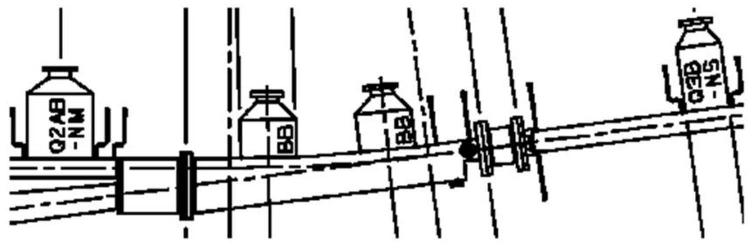


Pressure profile along the arc

Comparison between the analytical methodology and a Monte-Carlo simulation (MOLFLOW written by R. Kersevan) for some elements of the diamond vacuum

chamber





Comparison between models

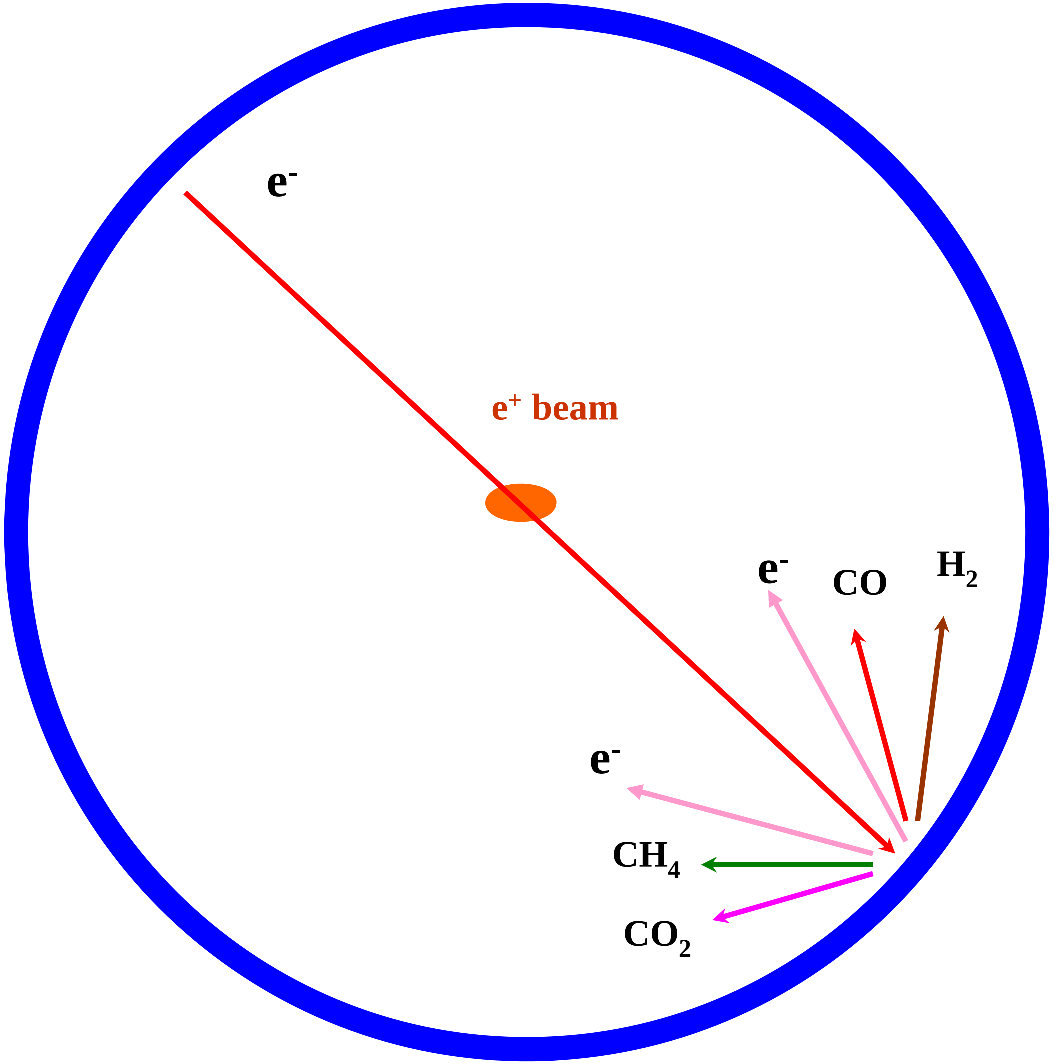
Model	Diffusion	Monte-Carlo
Accuracy	1D simplified model Global parameters: P, u, S, etc.	3D accurate model Local parameters: n, w, α, etc.
Complicate shape	Not accurate	Accurate
Long structures	Short time calculations	Very long calculations
Vacuum system optimisation	Easy to change and calculate	Time consuming modelling and calculations
Molecular beaming	Does not consider	Accurate
Use	Good knowledge of gas dynamic is essential	

Conditions

The postulated physical conditions for the following calculations of the capture factor and pumping speed of the slots are:

1. the molecular flow is stable;
2. the particles are uniformly distributed over the entrance of the pumping slots;
3. the angular distribution of particles at the entrance is uniform;
4. the mean free path of particles is much larger then the dimensions of the vacuum chamber;
5. the particles are reflected from the walls with a cosine law.

Electron cloud in the positron DR



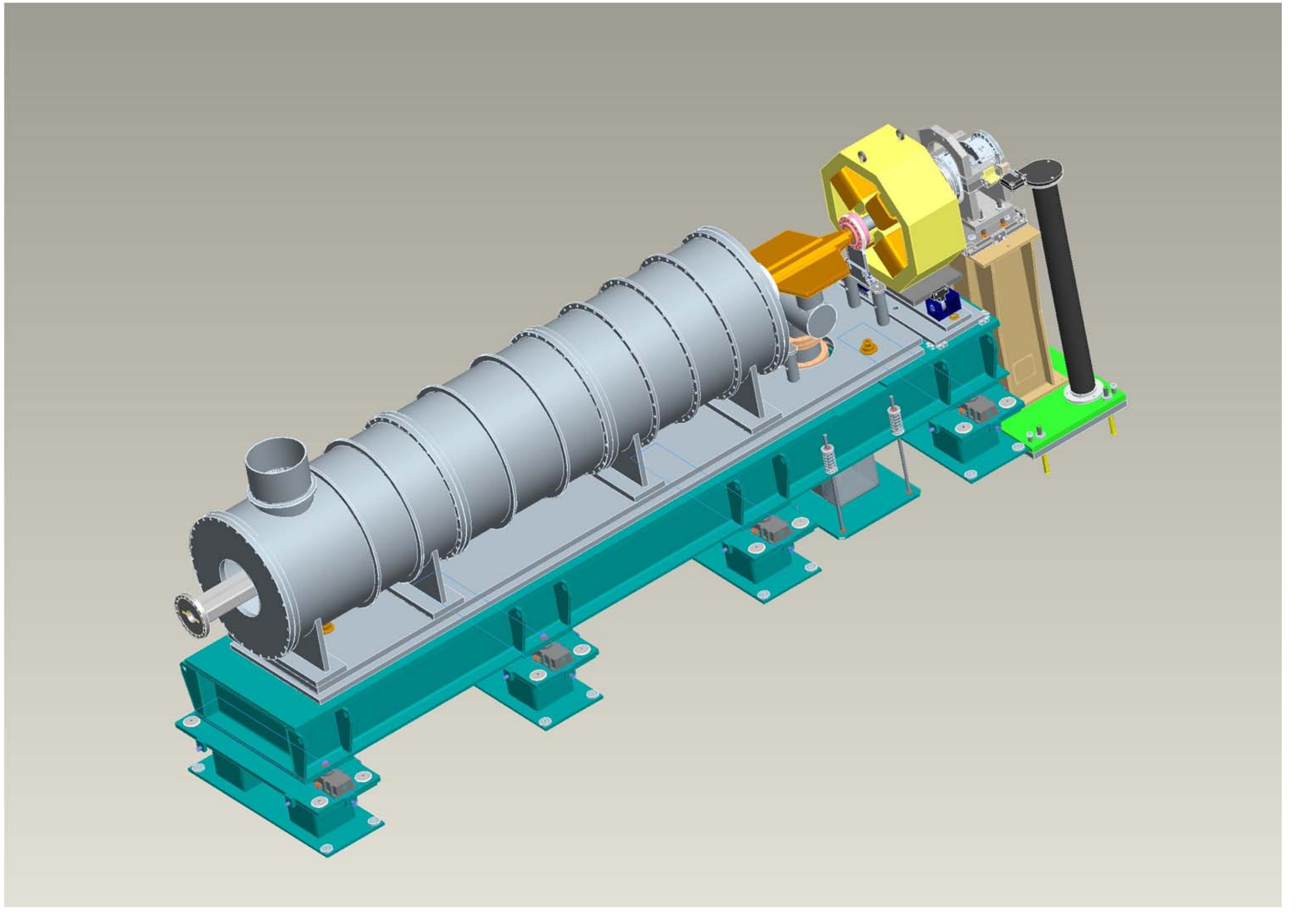
1. Electrons appear in vacuum chamber due to photoemission and electron from beam induced gas ionisation
2. They accelerated by a beam charge
3. These electrons may strike the vacuum chamber wall causing
   - Secondary electrons
   - Electron stimulated gas desorption

How the e-cloud affect vacuum

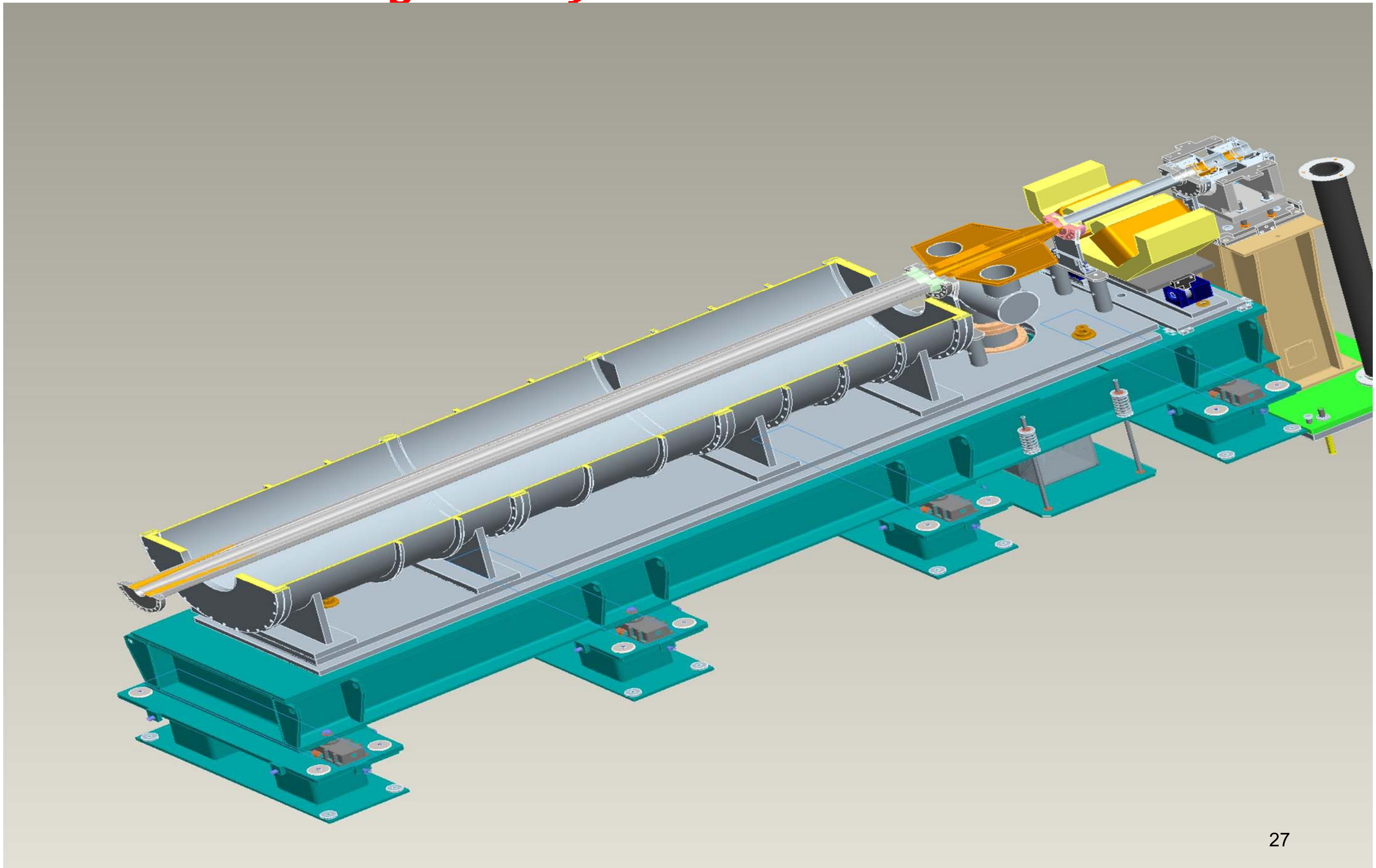
1. The electron flux ~10^{16} $e^-/(s\cdot m)$ with $E \approx 200$ eV (0.3 W) will desorb approximately the same gas flux as the photon flux of ~10^{18} $\gamma/(s\cdot m)$ from a DR dipole.
2. If the electron simulated desorption is larger than photon stimulated desorption, that should be considered in vacuum design and conditioning scenario.
3. E-cloud of DR is studied by many scientist around the globe.
4. The flux and energy of electron hitting vacuum chamber walls are needed to be found for a number of vacuum chamber designs in dipole, wigglers and straights.

Vacuum vessel geometry

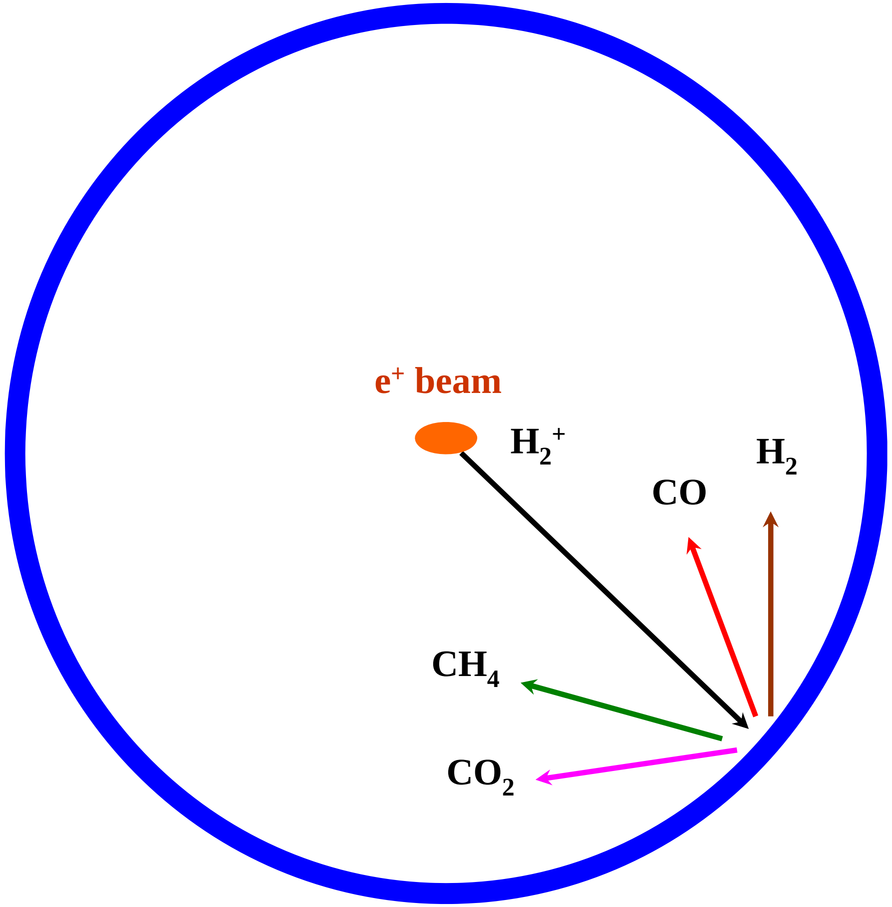
- 88 Section repetitions for 6.4-km circumference Damping Ring



Vacuum vessel geometry



Ion induced pressure instability



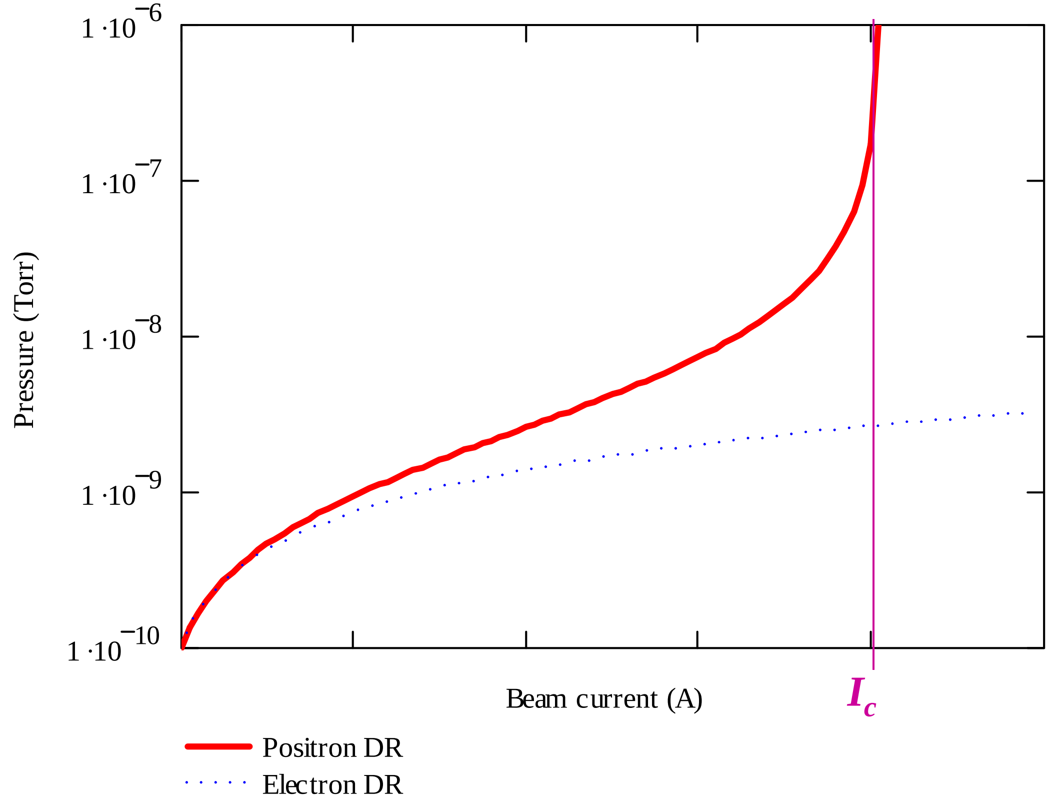
$$n = \frac{Q}{S_{eff} - \chi \frac{\sigma I}{e}}$$

where
Q = gas desorption,
S_{eff} = effective pumping speed,
χ = ion induced desorption yield
σ = ionisation cross section,
I = beam current.

$$\chi = f\left(E_{ion}, M_{ion}, material, bakeout, ...\right)$$

$$E_{ion} = f\left(N_{bunch}, \tau, T, \sigma_x, \sigma_y, ...\right)$$

Critical current



Critical current, I_c, is a current when pressure (or gas density) increases dramatically.

Mathematically, if

$$P = \frac{Q}{S_{eff} - \chi \frac{\sigma I}{e}}$$

when $S_{eff} > \chi \frac{\sigma I}{e}$

Hence $I < I_c$,

where $I_c = \frac{S_{eff} e}{\chi \sigma I}$

Multi-gas model

- the gas density of N species, A_i (i=1,2…N), are cross-correlated. A system with N equations:

$$V\frac{dn_i}{dt}=\eta_i\dot{\Gamma}+\sum_{j=1}^{N}\frac{\chi_{A_i,A_j^+}I\theta_{A_j}}{e}n_i-C_i n_i+u_i\frac{d^2 n_i}{dz^2}.$$

- Solving the system of N equations in quasi-static conditions, where $V\,dn/dt\approx 0$ and $A\,ds/dt\approx 0$, for gas densities $n_i(z)$ one can find the gas density inside the vacuum chamber.

Pressure instability thresholds:

What can be calculated for given beam parameters and vacuum chamber geometry:

- I_c – critical current
- L_c – critical length between pumps
- S_c – critical pumping speed