CERN

Vacuum Challenges

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Agenda:

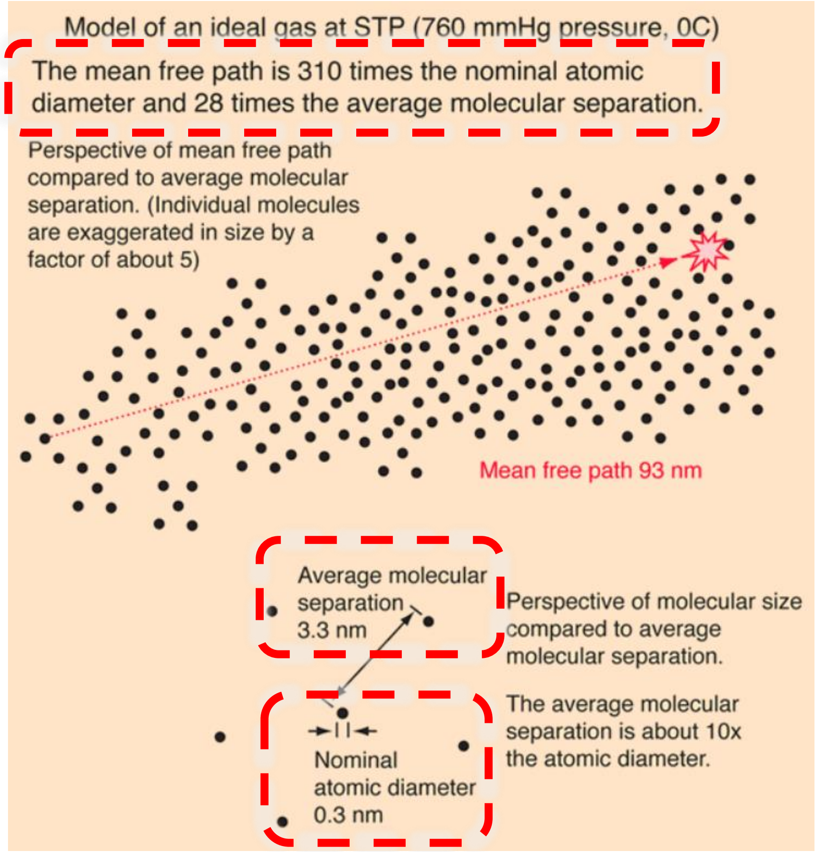
- Vacuum for accelerators: a primer
- Synchrotron radiation and vacuum: a primer
- Beam instabilities due to effects happening in vacuum: impedance, e-cloud, ion-instabilities, ion-induced desorption, etc…
- p-p circular colliders: FCC-hh, HE-LHC
- e^--e+ circular colliders: FCC-ee
- e^--e+ linear colliders: CLIC
- Future plasma-wake accelerators? AWAKE – what has vacuum technology to do with it?
- e-p colliders: LHeC
- Summary and conclusions

Vacuum for accelerators: **a primer**

- **Definition of vacuum**: “*a given space or volume filled with gas at pressures below atmospheric pressure*”;

- **Mean-free path**: average distance travelled by a molecule before hitting another molecule;

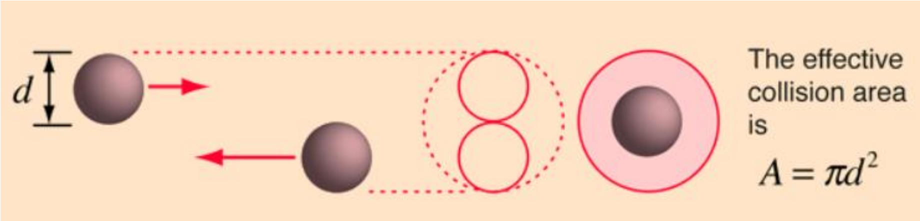
- At STP conditions (101325 Pa, 1013.25 mbar, 760 Torr, 1 atmosphere, 0 ºC), in air, the average molecular separation and distance are **3.3 nm** and **93 nm**, respectively

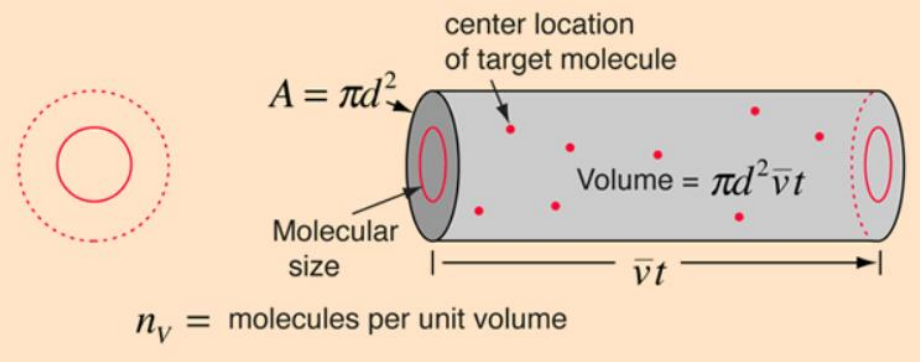


http://hyperphysics.phy-astr.gsu.edu/hbase/Kinetic/menfre.html

Vacuum for accelerators: **a primer**

- **Mean-free path (MFP) λ**: average distance travelled by a molecule before hitting another molecule;





Abbrev.	Gas	$C^* = \lambda \cdot p$ [cm · mbar]
H_2	Hydrogen	$12.00 \cdot 10^{-3}$
He	Helium	$18.00 \cdot 10^{-3}$
Ne	Neon	$12.30 \cdot 10^{-3}$
Ar	Argon	$6.40 \cdot 10^{-3}$
Kr	Krypton	$4.80 \cdot 10^{-3}$
Xe	Xenon	$3.60 \cdot 10^{-3}$
Hg	Mercury	$3.05 \cdot 10^{-3}$
O_2	Oxygen	$6.50 \cdot 10^{-3}$
N_2	Nitrogen	$6.10 \cdot 10^{-3}$
HCl	Hydrochloric acid	$4.35 \cdot 10^{-3}$
CO_2	Carbon dioxide	$3.95 \cdot 10^{-3}$
H_2O	Water vapor	$3.95 \cdot 10^{-3}$
NH_3	Ammonia	$4.60 \cdot 10^{-3}$
C_2H_5OH	Ethanol	$2.10 \cdot 10^{-3}$
Cl_2	Chlorine	$3.05 \cdot 10^{-3}$
Air	Air	$6.67 \cdot 10^{-3}$

Table III: Mean free path l
Values of the product c of the mean free path λ (and pressure p for various gases at 20 °C (see also Fig. 9.1)*

Mean free path

$$\lambda = \frac{RT}{\sqrt{2}\pi d^2 N_A P}$$

R=8.3145 J/K/mole

http://hyperphysics.phy-astr.gsu.edu/hbase/Kinetic/menfre.html

Flow regimes:

In gas dynamics literature flow regimes are defined by the so-called "Knudsen number", which is defined as:

$$Kn = \frac{\lambda}{D}$$

And the different flow (pressure) regimes are identified as follows:

FREE MOLECULAR FLOW	:	Kn >1
TRANSITIONAL FLOW	:	0.01< Kn< 1
CONTINUUM (VISCOUS) FLOW	:	Kn< 0.01

Practically all accelerators work in <u>the free-molecular regime</u> i.e. in a condition where the MFP λ is bigger than the "typical" dimension of the vacuum chamber (e.g.its diameter, for a circular tube), and therefore <u>intra-molecular collisions can be neglected</u>.

Flow regimes:

82 | 4 Gas Flow

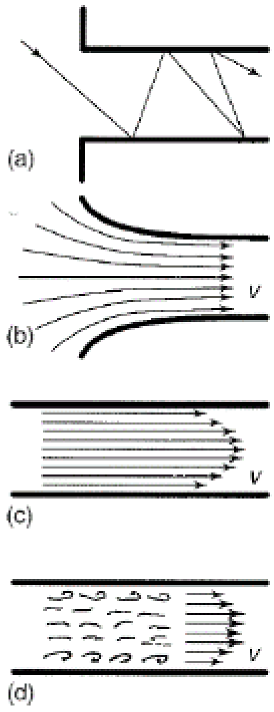
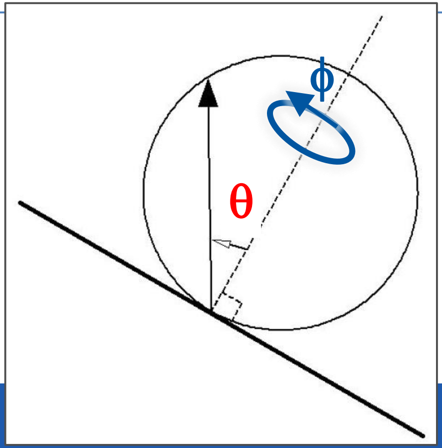


Fig. 4.2 Different types of gas flow. Top: molecular flow. Below and further down: different types of viscous flow: gas-dynamic (intake flow), laminar, and turbulent.

<u>IMPORTANT:</u> in molecular flow regime, the absence of collisions between molecules translates into the fact that high-vacuum pumps DO NOT "SUCK" GASES, they simply generate some probability <u>s</u> that once a molecule enters into the pump it is permanently removed from the system.

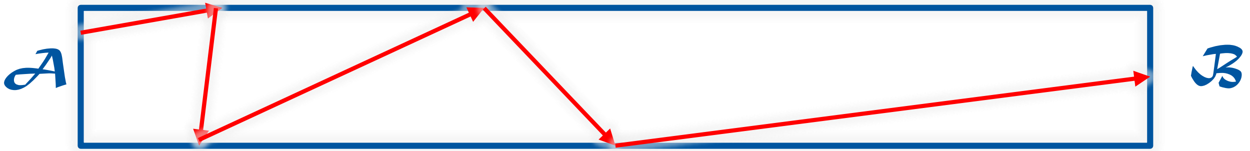
<u>s</u> can be identified as the <u>equivalent sticking coefficient.</u>

In molecular flow regime, molecules move around randomly (diffusion process): the probability of being re-emitted in a specific direction follows the <u>cosine distribution</u> (or <u>Lambertian distribution</u>). The azimuthal angle ϕ about the normal to the point of desorption follows a uniform distribution, while θ follows the cosine one:



Conductance:

- In molecular flow regime, the concept of conductance is a very important one. It is a geometric property of a vacuum system related to the distribution of the gas load and the pumping system. It tells us how "easy" molecules move from point A to B;
- For single vacuum components, like a tube or a valve, typically it is explained in terms of the transmission probability for molecules entering from one side (the inlet *A*) and being removed from another side (the outlet *B*):



- N_{tot} molecules are generated according to the cosine distribution in A and the ratio of those which reach (are transmitted to) the outlet B, N_{TR}, $P_{TR}=N_{TR}/N_{TOT}$ is called the transmission probability;
- The conductance C_{TR} in l/s is given by $C_{TR} = P_{TR} \cdot A(cm^2) \cdot 11.77$: this expression is valid for a mass 28 gas (like CO or N_2) at 20 °C (i.e. 293.15 K); for different gas mass M or temperature T, C_{TR} should be scaled with $\sqrt{T/293.15} \cdot \sqrt{28/M}$
- A higher T and smaller M gives a bigger C_{TR}

• Vacuum for accelerators: **Pressure profiles;**

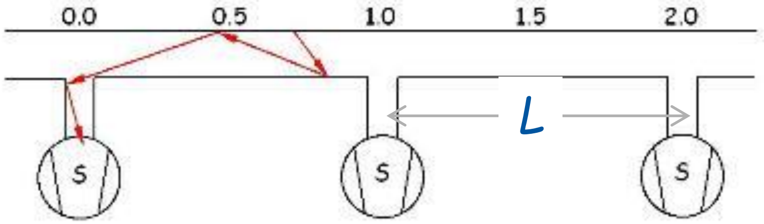
- All future high-energy colliders will have very large bending radii, and therefore a **first-guess model of their pumping system** can be thought of as having lumped pumps S installed at (possibly large) equal distance L from each other (in order to minimize the number of such pumps);
- The large radius of curvature in the dipoles will also mean a rather "constant" synchrotron radiation-induced outgassing rate (if present, see below);
- In this case, a simple analytical model for the pressure profile is the following:

$$P(x) = \frac{AqL}{2c}\left(Lx - x^2\right) + \frac{AqL}{S}$$

$$P_{AVERAGE} = \frac{1}{L}\int_0^L P(x)dx = AqL\left(\frac{L}{12c} + \frac{1}{S}\right) = AqL(1/S_{EFF})$$

$$P_{MAX} = AqL\left(\frac{1}{8c} + \frac{1}{S}\right); \quad \mathrm{AqL} = \mathrm{Q_{tot}}; \quad S_{EFF} = \left(\frac{L}{12c} + \frac{1}{S}\right)^{-1}$$

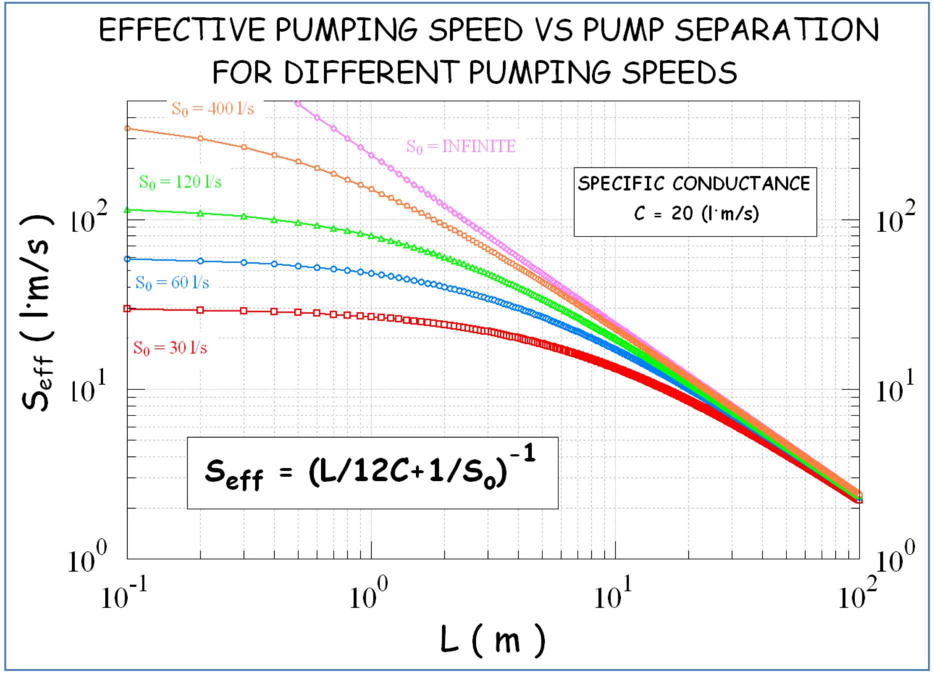
AqL=gas load Q along one segment L of the accelerator



Ref. : R. Kersevan, CAS School Vacuum Technol., 2017, Glumslöv (SWE), https://indico.cern.ch/event/565314/timetable/

• Vacuum for accelerators: **a primer**

- The effective pumping speed S_{eff} vs the installed pumping speed S_o is **limited by the specific conductance**, i.e. the size and shape of the vacuum chamber cross-section;
- There is a conflict between the vacuum need to have a large cross-section (to maximize S_{eff} by maximizing the conductance) and the **need for compact magnets** with small inscribed circles(especially true for the p-p colliders due to the large cost increase vs SC coil diameter);
- For a given specific conductance c (in this case 20 l·m/s, S_{eff} vs L and S_o is as follows →:



$$P_{AVERAGE} = \frac{1}{L}\int_0^L P(x)dx = AqL\left(\frac{L}{12c} + \frac{1}{S}\right) = AqL(1/S_{EFF})$$

$$P_{MAX} = AqL\left(\frac{1}{8c} + \frac{1}{S}\right); \quad \mathrm{AqL} = \mathrm{Q}_{tot}; \quad S_{EFF} = \left(\frac{L}{12c} + \frac{1}{S}\right)^{-1}$$

Lesson: It doesn't "pay" to install large pumps, as c limits S_{eff}: vacuum-wise, all particle accelerators are "**conductance-limited systems**";

Synchrotron radiation and vacuum: a primer

- Synchrotron radiation (SR) affects vacuum directly and indirectly: directly via **photo-desorption**, indirectly via **photo-electron emission** and the chain of events which may be originated by it (e.g. **e-cloud**, **pressure bursts with ion-trapping or ion-induced desorption and related instabilities**, etc…);
- SR can be expressed with simple formulae as a function of the **relativistic factor** γ, $\gamma = 1/\sqrt{1-\frac{v^2}{c^2}}$, valid for both e-e+ and p-p colliders:

Integrated Photon Flux, F : $F = 4.1289 \cdot 10^{14} \cdot \gamma \cdot I(mA) \cdot k_F$ (ph/s/mA)

Integrated Photon Power, P: $P = 6.0344 \cdot 10^{-12} \cdot \frac{\gamma^4}{\rho(m)} \cdot I(mA) \cdot k_P$ (W/mA)

Critical Energy, e_{crit} : $e_{crit} = 2.9596 \cdot 10^{-7} \cdot \frac{\gamma^3}{\rho(m)}$ (eV)

k_f, k_p = fraction of photons with energies above given threshold (typically 4 eV);

- Synchrotron radiation and vacuum: a primer

Typical textbook representation of the radiation cone

Introduction and Overview 9

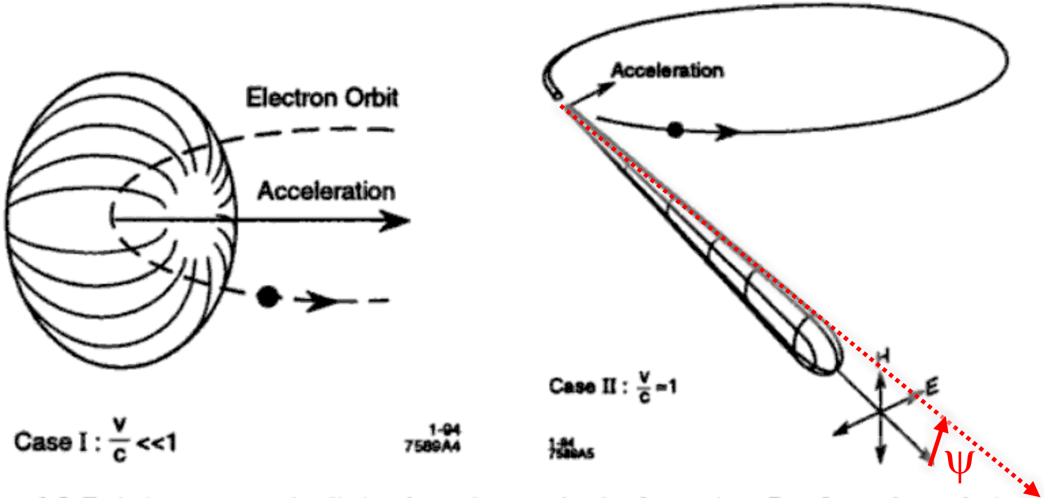


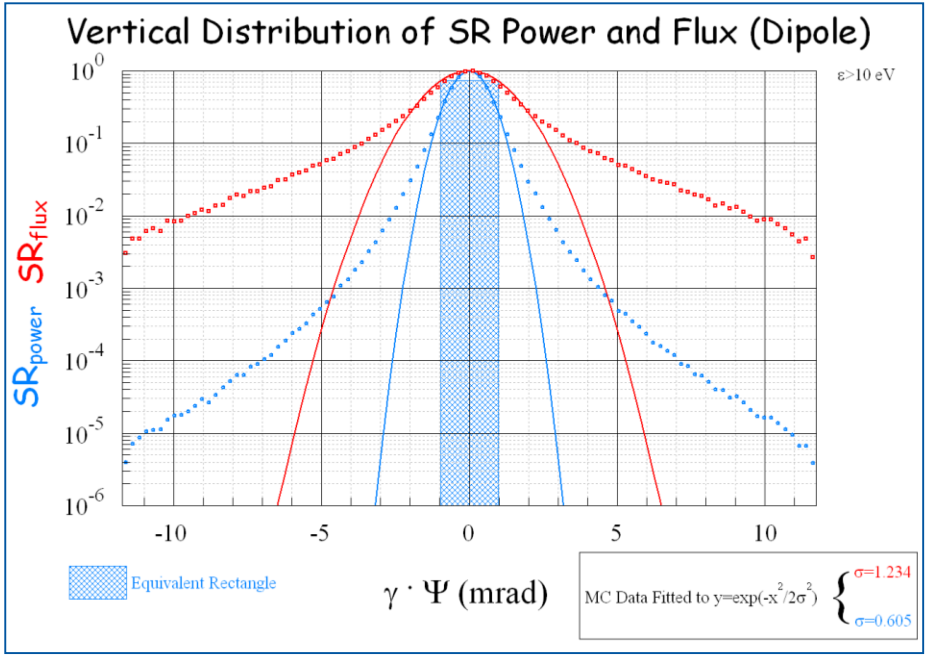
Figure 1.5. Emission patterns of radiation from electrons in circular motion; Case I: at a low velocity compared to the velocity of light; and Case II: approaching the velocity of light.

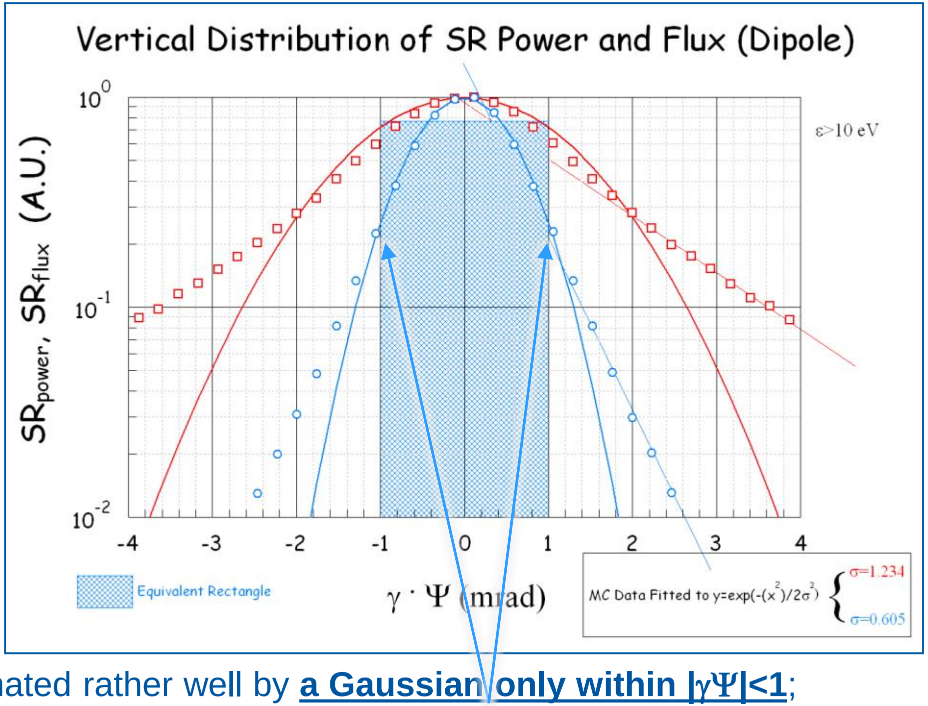
- It is usually assumed that most of the power is generated within a **narrow cone** $\psi=1/\gamma$;
- While this is not too far from reality for SR power, it is **rather inaccurate for SR flux** (see next slide);

• Synchrotron radiation and vacuum: **Vertical distribution of SR**

- Red/blue symbols: MC data (SYNRAD+);
- Thick lines: Gaussian fits and extrapolations

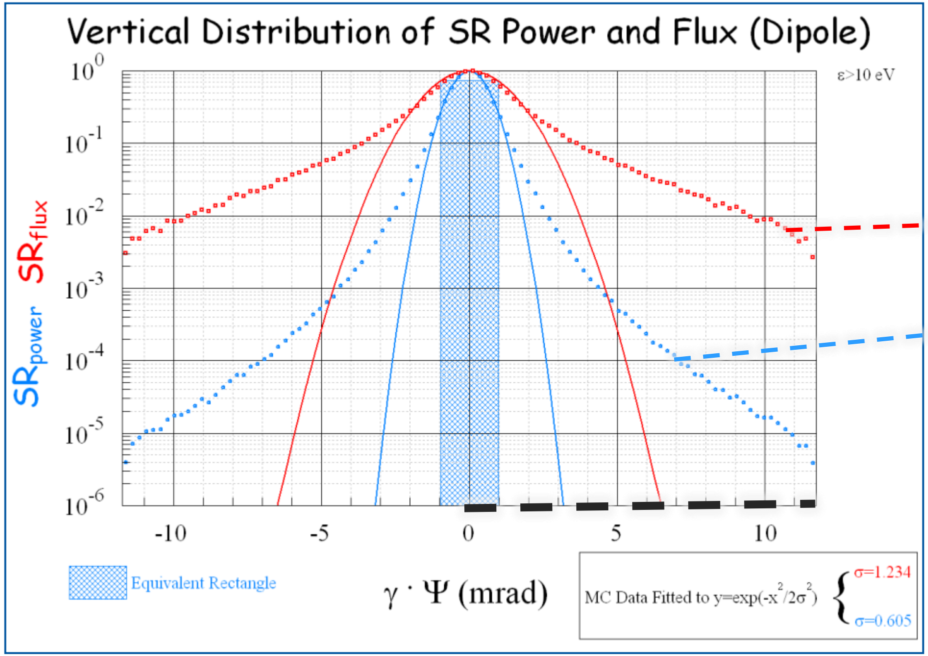
Calculated with SYNRAD+
https://molflow.web.cern.ch/content/synrad-downloads

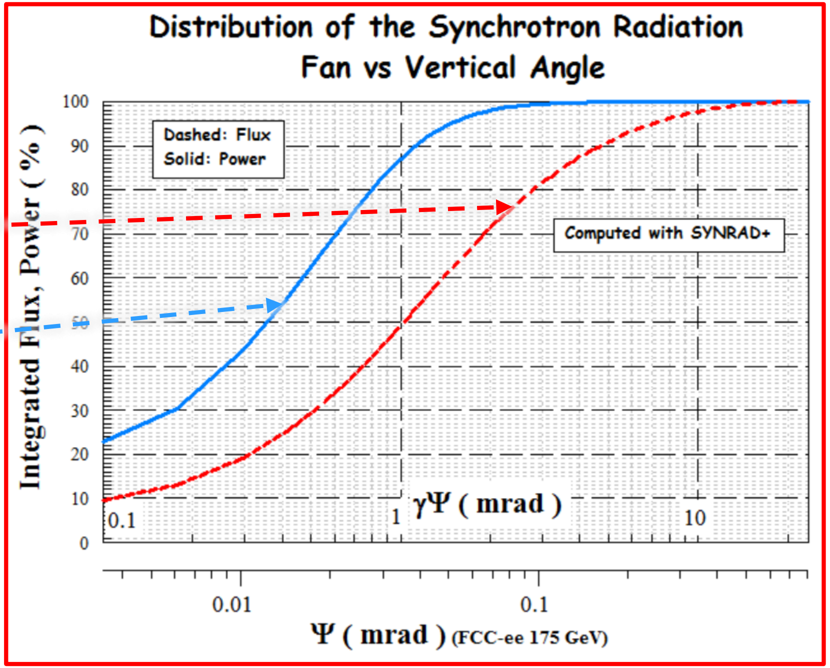




- The SR power distribution in the vertical direction is approximated rather well by **a Gaussian only within |γΨ|<1**;
- The SR flux distribution **is not** well approximated even within that small angular range; ~ 50% of the photon flux is generated outside **of |γΨ|<1;**

- Synchrotron radiation and vacuum: **Vertical distribution of SR**



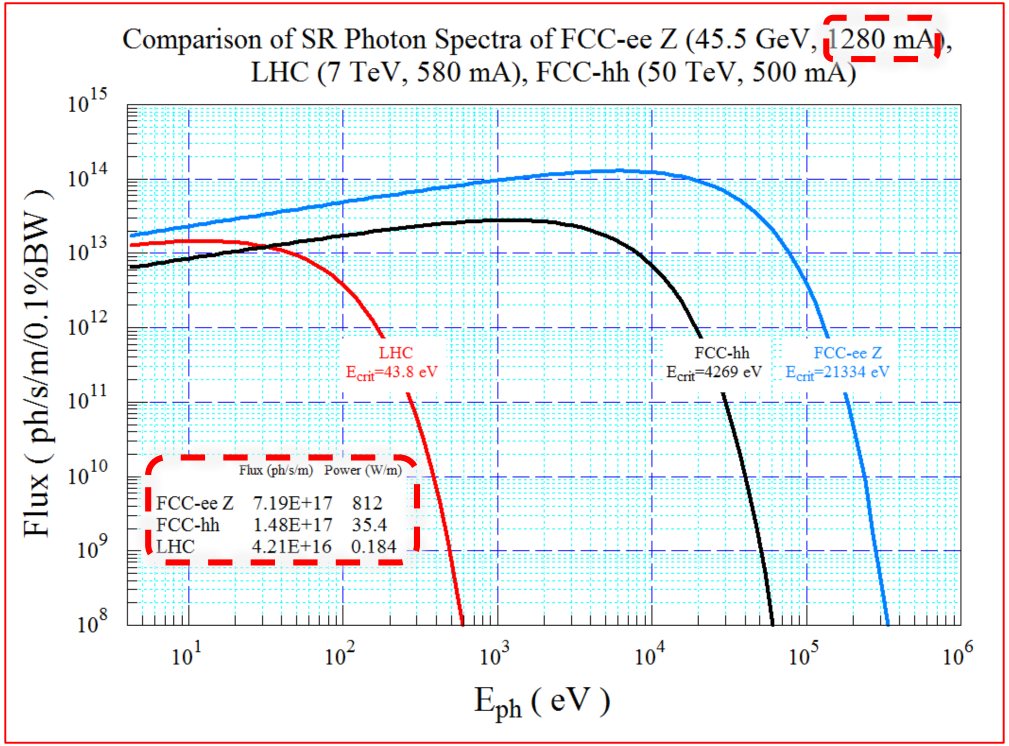


The vertical distribution of the SR fan is extremely collimated (~1/γ for power): for the T-pole at 175 GeV the vertical footprint at 20 m distance is only ~ ±0.2 mm (ideal, zero-emittance beam); **Extremely high SR power/flux density follows**

- Synchrotron radiation and vacuum: a primer

Example: FCC-ee vs FCC-hh vs LHC

Spectra calculated with SYNRAD+
https://molflow.web.cern.ch/content/synrad-downloads

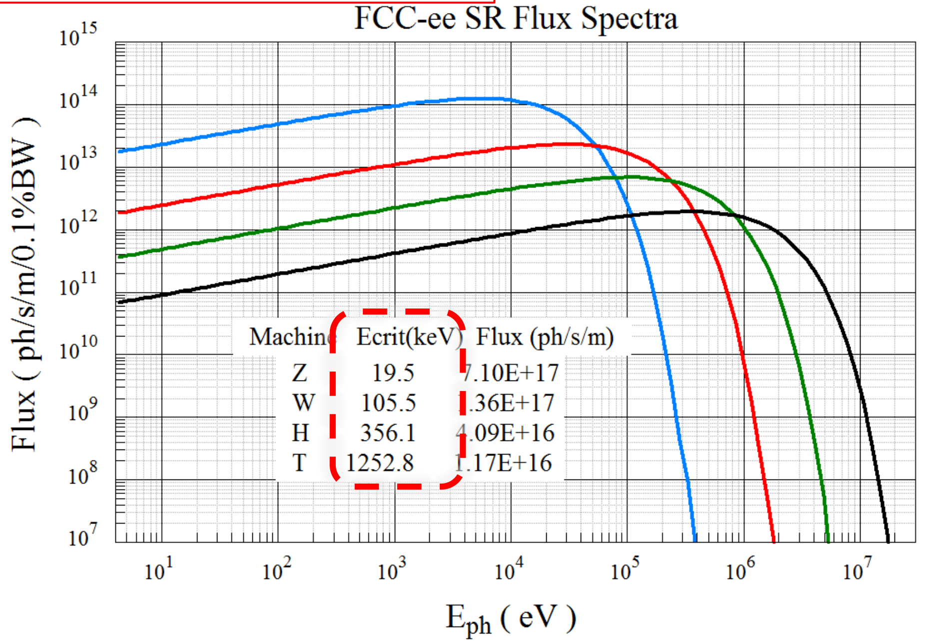


- Synchrotron radiation and vacuum: a primer

Example: FCC-ee vs FCC-hh

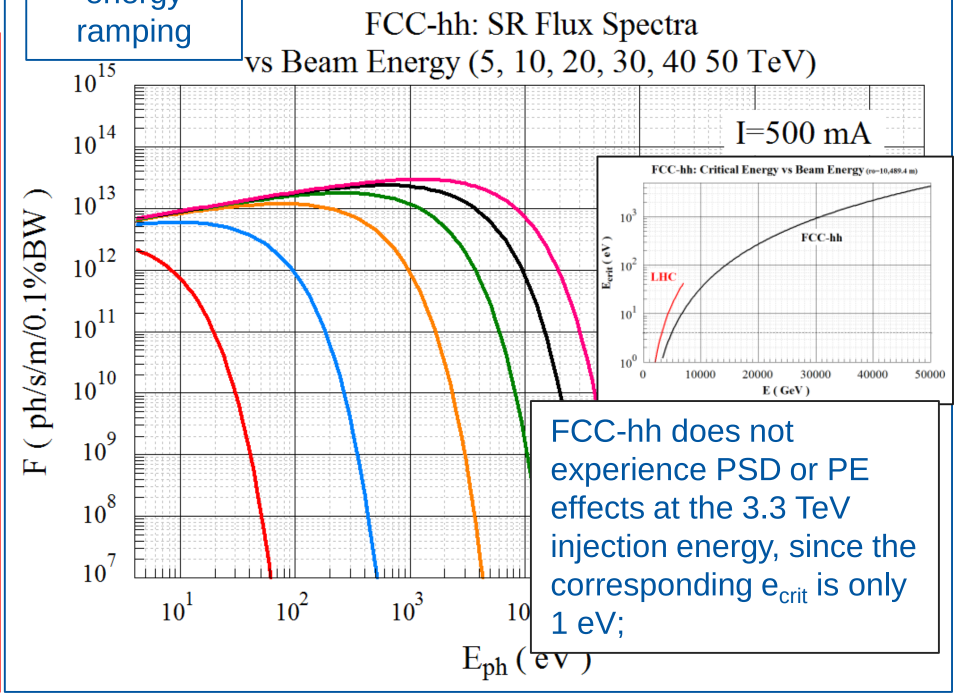
Spectra calculated with SYNRAD+
https://molflow.web.cern.ch/content/synrad-downloads

FCC-ee: full energy injection



Machine	Ecrit(keV)	Flux (ph/s/m)
Z	19.5	7.10E+17
W	105.5	1.36E+17
H	356.1	4.09E+16
T	1252.8	1.17E+16

FCC-pp: energy ramping



FCC-hh does not experience PSD or PE effects at the 3.3 TeV injection energy, since the corresponding e_{crit} is only 1 eV;

The W, H and T versions of FCC-ee have much higher critical energies than the FCC-hh's: **very penetrating gamma rays**!
The photon flux of the Z-pole is 2.5 orders of magnitude higher than that of the T-pole: **Z is high current**!

• Vacuum for accelerators: **SR and vacuum**

- Synchrotron radiation (SR) in a particle accelerator generates molecules, the so called **photon-stimulated desorption** effect (PSD) (see below);
- **PSD coefficients vary from material to material**, and also depend on the **surface treatment** (bake-out, roughness, thin-film coatings, photon angle of incidence, etc…), photon energy, angle of incidence, and more…;
- PSD is usually **determined experimentally**: many data exist in literature; a typical PSD curve looks like this →
- It can be modelled as a **power-law dependence vs accumulated photon dose (in ph/m)**, see fits
- It is evident that **photons clean the surface with time** and generate a decreasing amount of gas;
- Theoretically, PSD is believe to be **mediated by emission of photo-electrons (PE)**;
- These PEs are one of the seeds of the e-cloud effect, the other source being beam ionization (see below);

Ref.: JVST A 14 no.3 (1996) p1273-1276

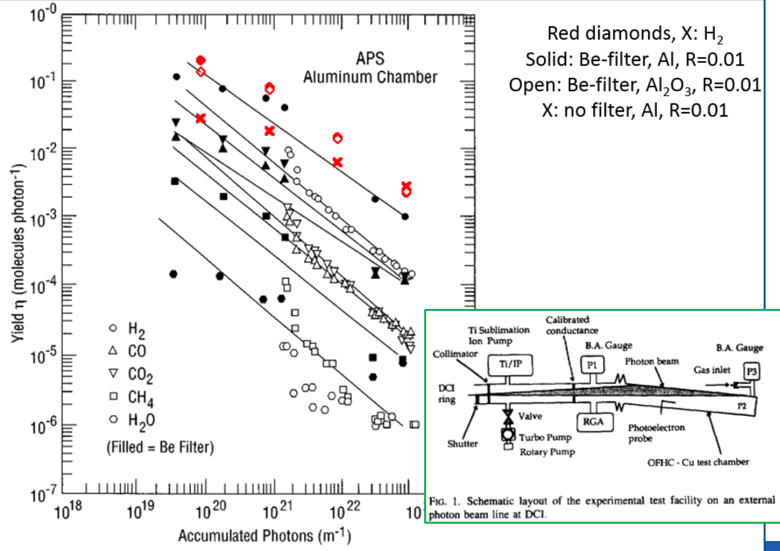
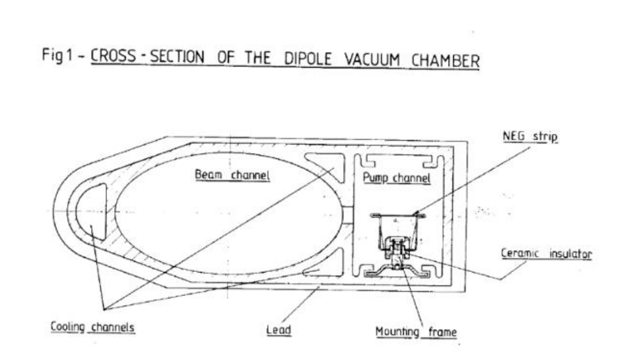


FIG. 3. Molecular desorption yields for the APS extruded storage ring chamber. Filled gas molecule symbols indicate that the beryllium filter was in the photon beam path.

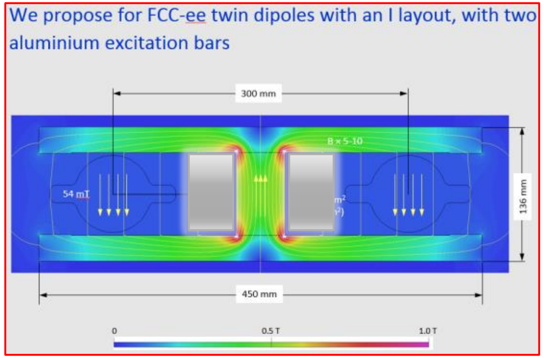
• Vacuum for accelerators: **Interfacing with the magnets**

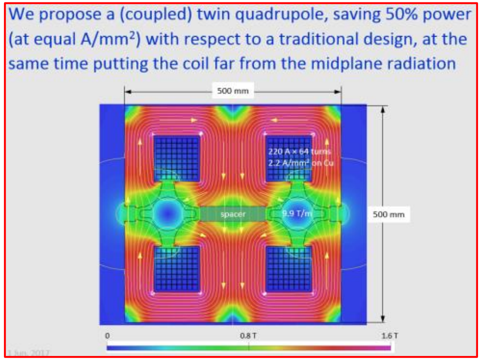
- Given the size of the **FCC-ee machine**, in order to reduce the number of pumps to reasonably small numbers one would need to use some "**distributed pumping**", like done in the past for LEP;
- Unfortunately FCC-ee is a **twin-ring machine**, while **LEP was a single-ring** one: a chamber-antechamber design like LEP is not compatible with the intra-beam distance (300 mm) and the shape of the **common-yoke dipoles and quadrupoles** proposed for FCC-ee:



Beam chamber cross-section: 131x70 mm^2 ellipse

LEP dipole extrusion: NEG strip in antechamber gives distributed pumping (few 100s l/s/m)



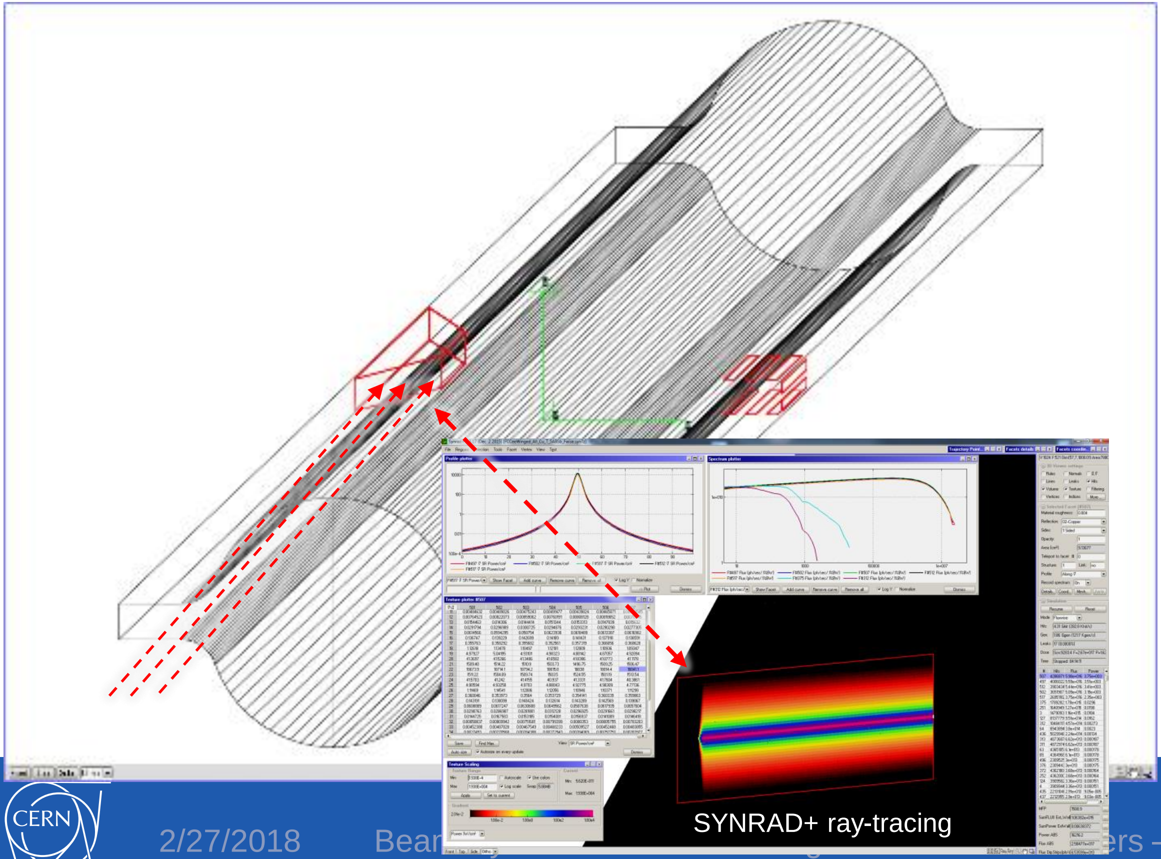


Beam chamber cross-section: 70 mm ID with "winglets" (SUPERKEKB-type)

FCC-ee: cross-section of dipoles (left) and quadrupoles (right) with SUPERKEKB-type vacuum chamber profiles (A. Milanese, CERN)

• Vacuum for accelerators: **FCC-ee vacuum chamber concept**

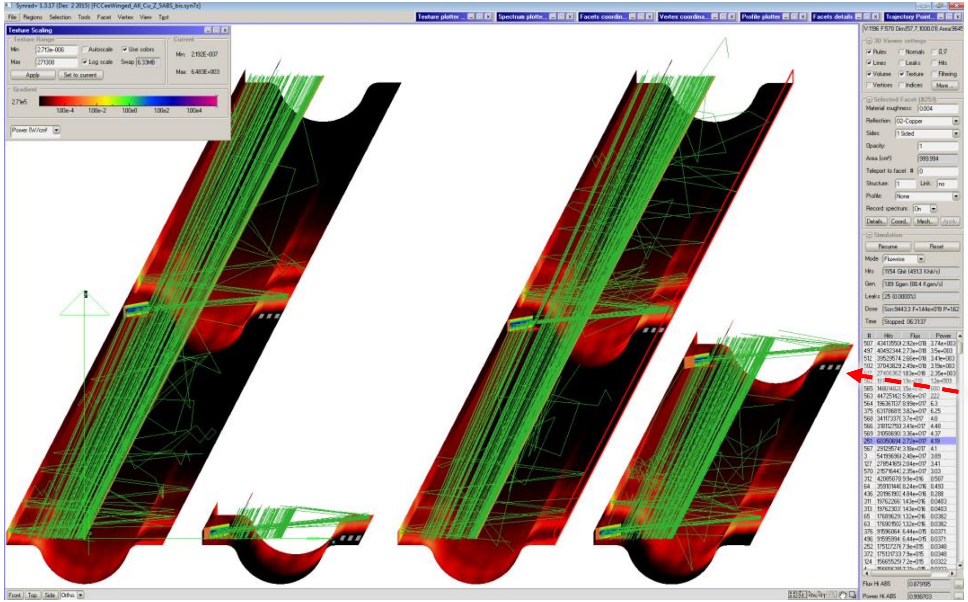
- The SUPERKEKB e+e- B-meson collider vacuum chamber geometry has been identified as a good starting point

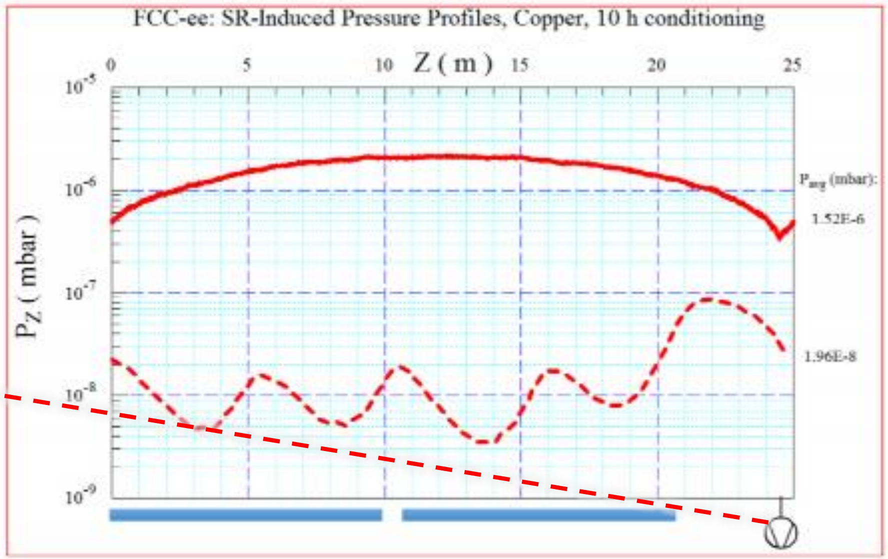


- Schematics of beam chamber extrusions (OFC copper): **70 mm ID with "winglets"** (**SUPERKEKB-type**);
- **Discrete water-cooled absorbers** are placed along the external winglet, in order to intercept **100% of the primary SR fans**; total power absorbed **4~7 kW**;
- A **pumping port** is connected via **slots machined on the opposite winglet** (see next slide);
- If the surface of the absorber is vertical (as in this draft) then the **power density is too high** (almost 19 kW/cm^2 for the T-pole at 175 GeV);
- A **"V"-shaped surface** (not shown) is machined on the absorbers' face in order to increase the surface and reduce the aerial power density to reasonable levels

• Vacuum for accelerators: **FCC-ee: coupled MC simulations**

Coupled montecarlo ray-tracing along ½ cell of FCC-ee: SR (SYNRAD+), and molecular flow (Molflow+)





½ cell model: 2x 10m-long dipoles with 60 cm-long drift between them and 4.4 m-long quad/sextupole drift; 5 lumped SR absorbers intercept 100% of the primary SR photon fan; the 4 parts are connected to each other, sequentially

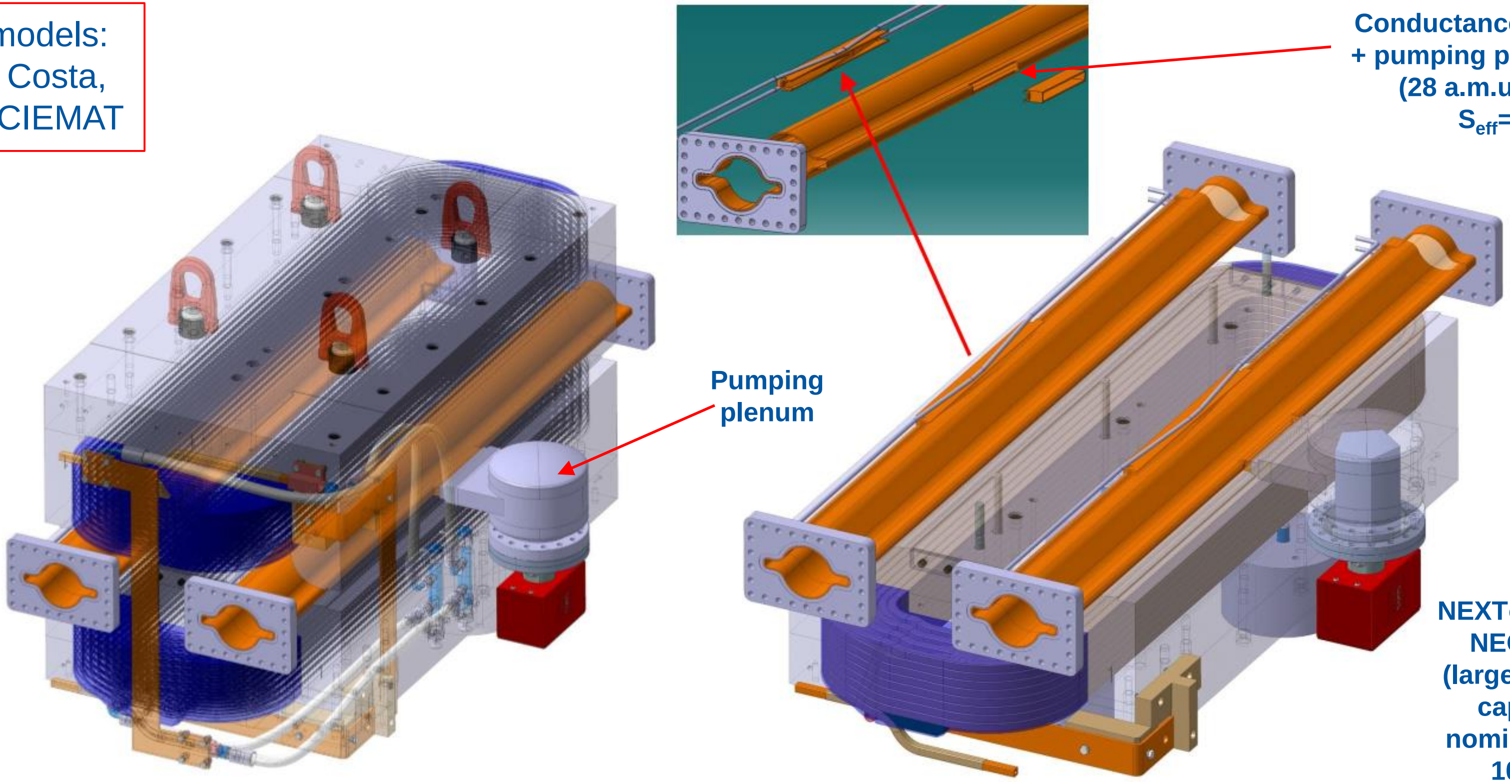
- The average pressure is ~ **1/77** of the one without distributed pumps: very effective!

Comparison of pressure profiles with only 1 lumped pump and with pump plus NEG strips (like in SUPERKEKB)

- Vacuum for accelerators: example **FCC-ee twin-ring vacuum chamber prototype**

Design of a prototype of SUPEKEKB-type vacuum chamber with lumped SR absorber and pumping port:

CAD models:
M. Gil Costa,
CERN/CIEMAT



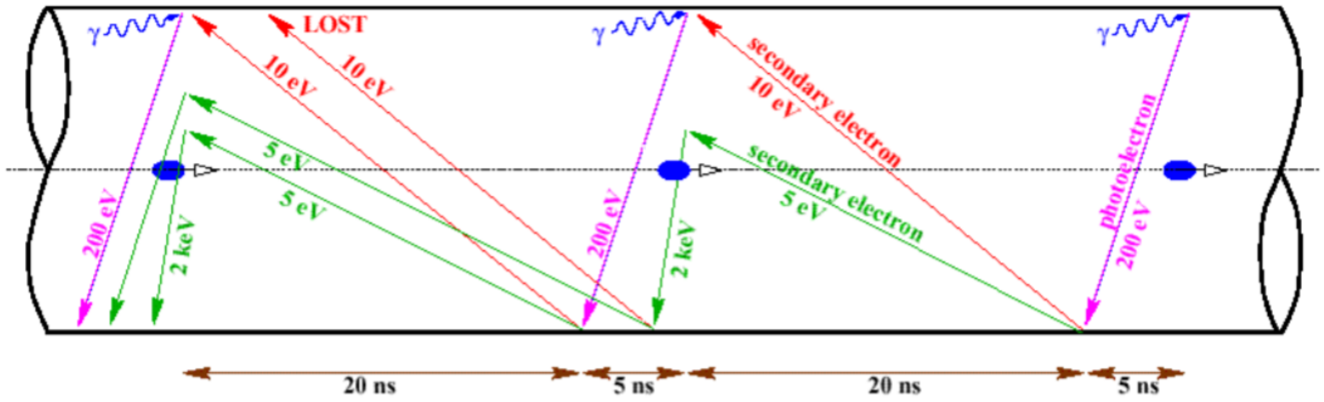
Conductance pumping slot + pumping plenum: ~110 l/s (28 a.m.u. gas, 20 C)
S_{eff}=100 l/s

NEXTorr D-1000 NEG pump (large pumping capacity), nominal speed 1000 l/s

Vacuum for accelerators: **e-cloud in the LHC**

- **Depends on bunch spacing, bunch charge, secondary electron yield (SEY), surface cleanliness (especially carbon layers), magnetic field, and other machine parameters.**

LHC mechanism



Schematic of electron-cloud build up in the LHC beam pipe.

F. Ruggiero *et al.*, LHC Project Report 188 1998, EPAC 98

• Vacuum for accelerators: **e-cloud in the LHC vs Future Colliders**

- Misses one multiplicative factor which accounts for the **fraction** of SR photons capable of extracting photoelectrons;
- The **cut-off photon energy is typically 4 eV**, i.e. the **work function** of metals used for the fabrication of vacuum components, see next slide;

➢ Total number of photoelectrons per particle per meter $N_{ph} = N_\gamma \cdot Y$
- ❑ Photoelectron Yield Y
- ❑ Number of SR photons per particle per meter $N_\gamma = \frac{5\alpha}{2\sqrt{3}} \frac{\gamma}{\rho}$

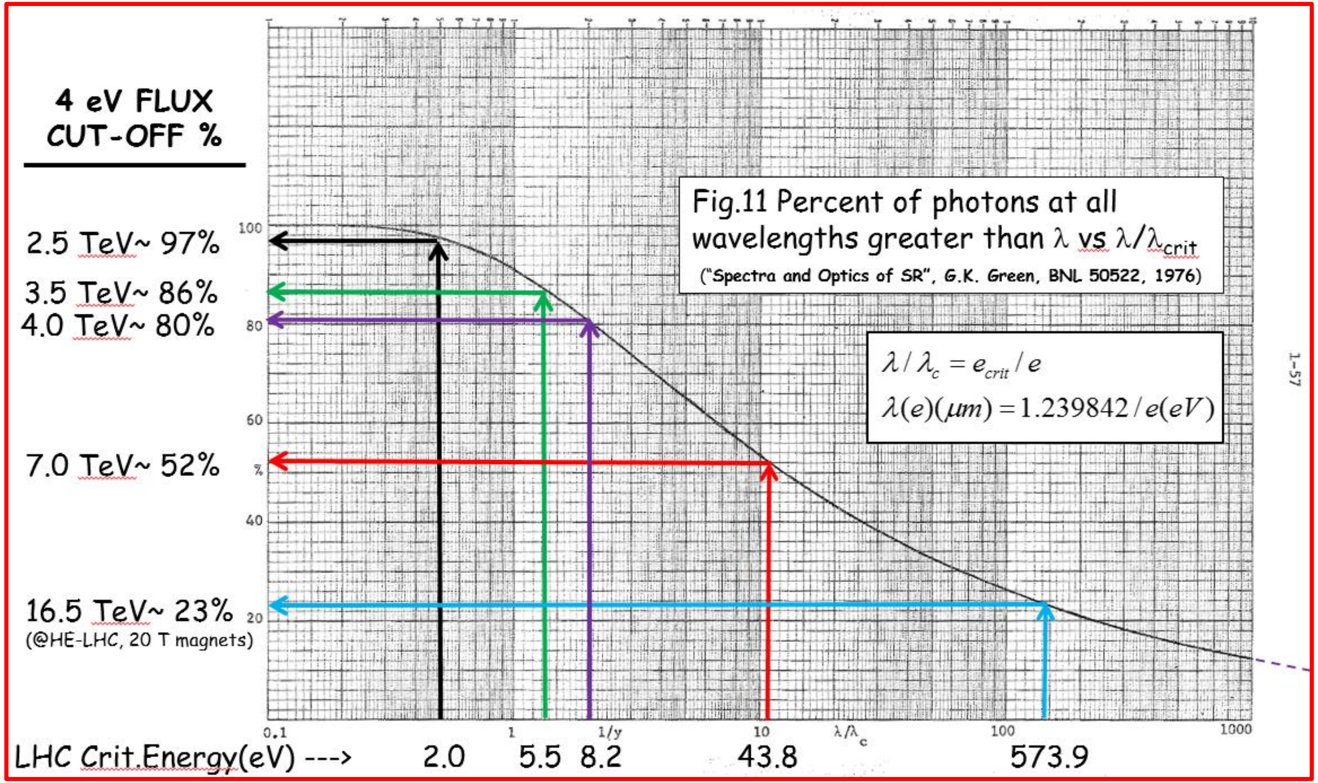
	LHC	FCC-hh	FCC-ee
E [GeV]	7000	50000	45.6
γ	7400	53300	89236
ρ [km]	2.8	11.3	11.3
N_γ/p^+m	0.028	0.05	0.085

➢ Photoelectrons produced by scattered photons
- ❑ Photon reflectivity R
  - ❑ Electrons from direct photons : $N_{ph,d} = N_{ph} \cdot (1 - R)$
  - ❑ Electrons from scattered photons: $N_{ph,rf} = N_{ph} \cdot R$

➢ No experimental data for photoelectron yield and photon reflectivity
- ✓ **Scan of Y and R**

Ref.: “Trapped modes and Electron Cloud in the Interaction Region of FCC-ee”, E. Belli et al., FCC-ee MDI Workshop 2017, https://indico.cern.ch/event/596695/contributions/

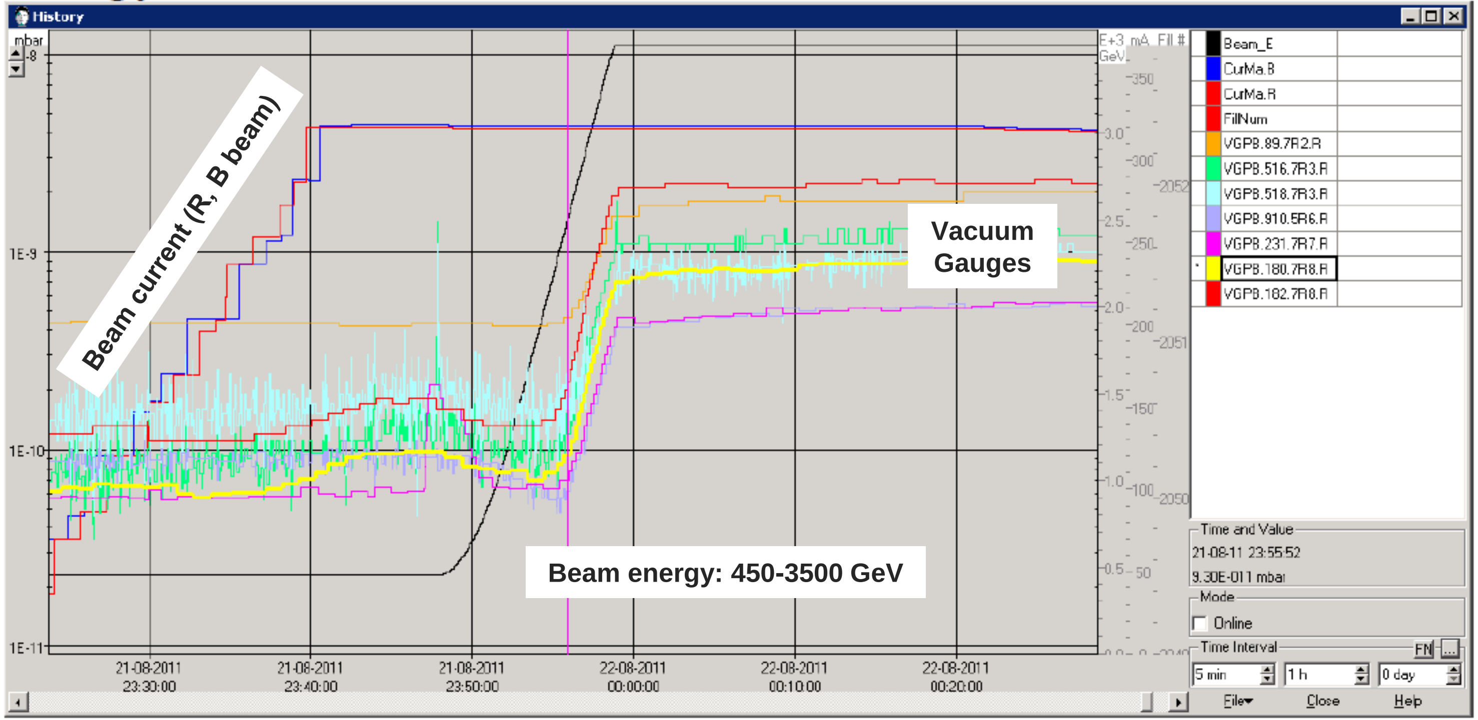
- Vacuum for accelerators: **SR photon cut-off vs beam energy: LHC case**



Ref.: R. Kersevan, **Tutorial 2 on Synchrotron Radiation**, JUAS 2018, https://indico.cern.ch/event/683638/timetable/

- Vacuum for accelerators: **SR-induced (PSD) pressure rise in the LHC vs beam energy at ramping**

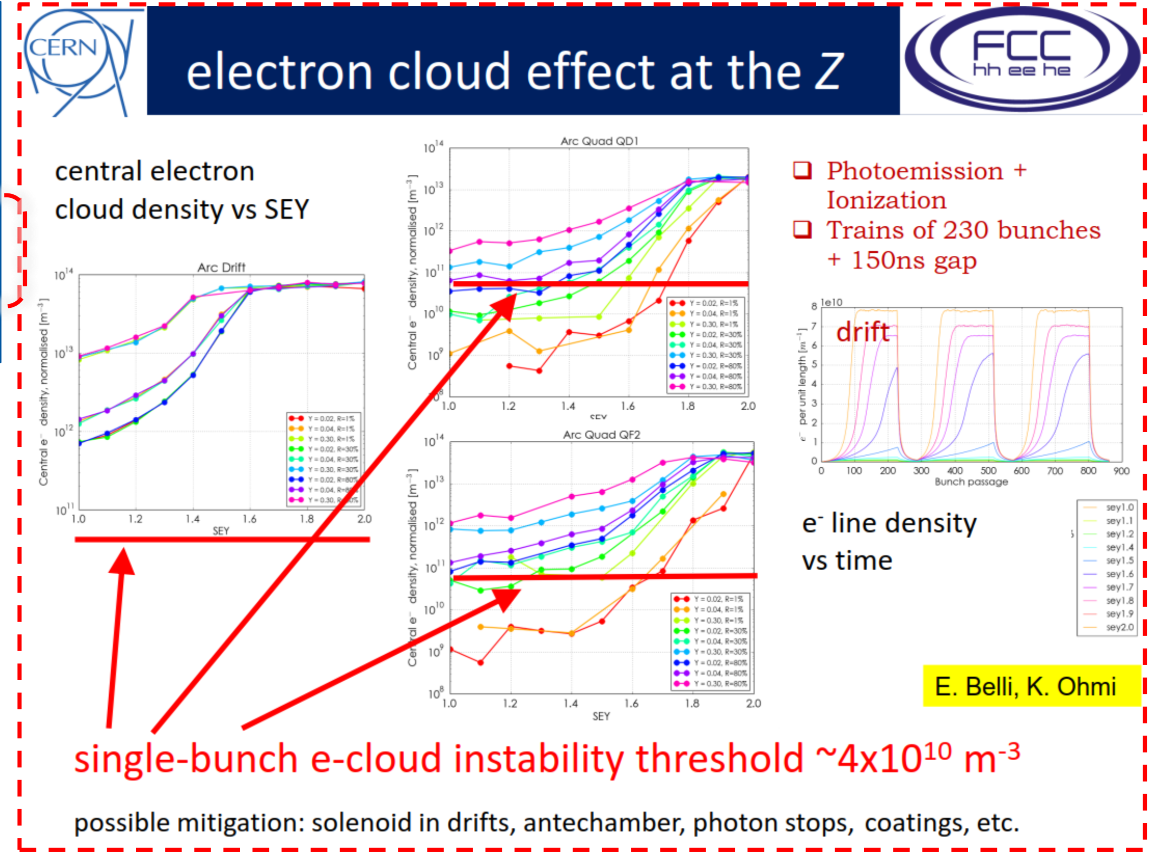
Ref.: R. Kersevan, **Tutorial 2 on Synchrotron Radiation**, JUAS 2018, https://indico.cern.ch/event/683638/timetable/



The pressure gauges start reacting to the energy ramp as soon as E_{beam}=2~2.5 TeV, i.e. e_{crit}>1~2 eV

Vacuum for accelerators: **FCC-ee e-cloud strategy**

- **The amount of photo-electrons "seeding" the e-cloud must be minimized (see beam-ionization and PSD effects);**
- **The use of "anti e-cloud" thin films is envisaged (see next slide);**



• Vacuum for accelerators: **FCC-ee impedance instabilities and contributions**

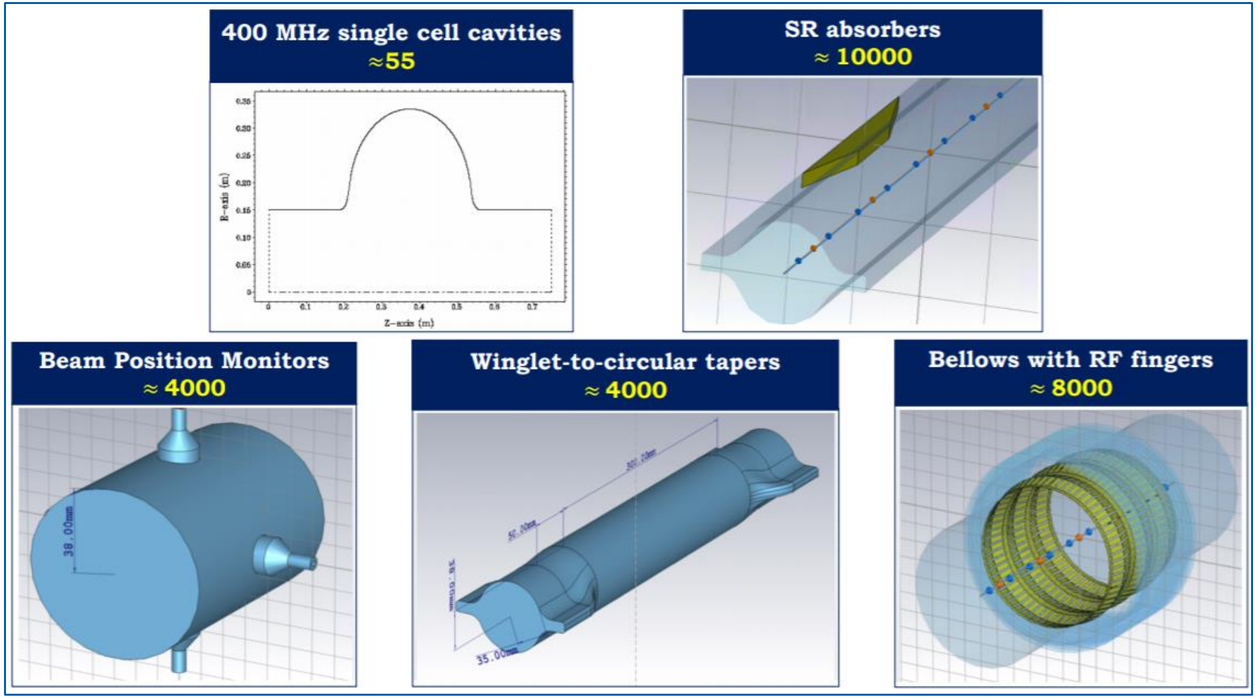
THPAB020 Proceedings of IPAC2017, Copenhagen, Denmark

COUPLING IMPEDANCES AND COLLECTIVE EFFECTS FOR FCC-ee

"Impedance model and collective effects for FCC-ee", E. Belli, FCC Week 2017, Berlin

In the following, we will focus on the main single bunch effects due to the RW on the beam dynamics, by considering a 35 mm radius vacuum chamber with three layers (a first layer of copper with 2 mm thickness [5], then 6 mm of dielectric and finally iron with resistivity $\rho = 10^{-7}\Omega m$) and different coatings of the pipe walls:

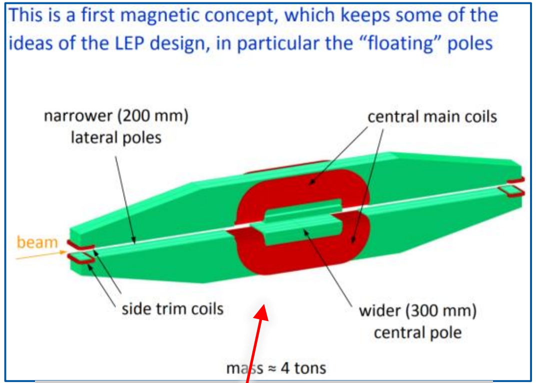
- Amorphous Carbon (AC)
  thk = 200 nm, $\rho = 10^{-4}\ \Omega m$ [5]
- Non-Evaporable Getter (NEG)
  thk = $1\mu m$, $\rho = 10^{-6}\ \Omega m$ [6]
- Titanium Nitride (TiN)
  thk = 200 nm, $\rho = 0.5 \cdot 10^{-6}\ \Omega m$ [7, 8]

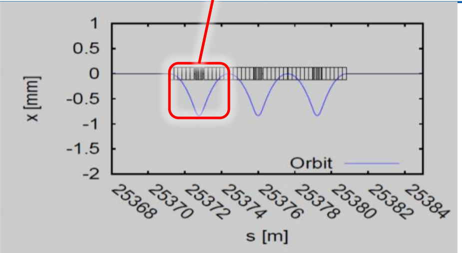


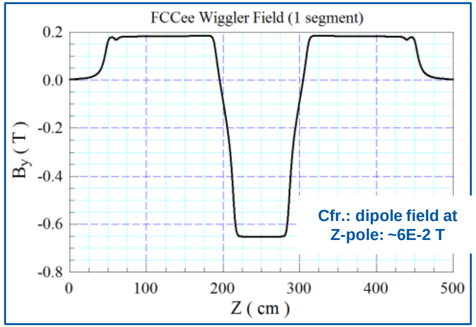
Tapers, BPMs, sliding RF fingers and other components must be carefully designed and analysed

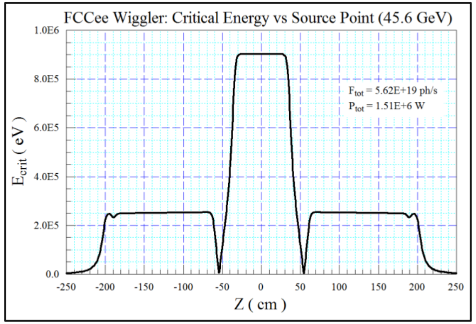
- Synchrotron radiation and vacuum

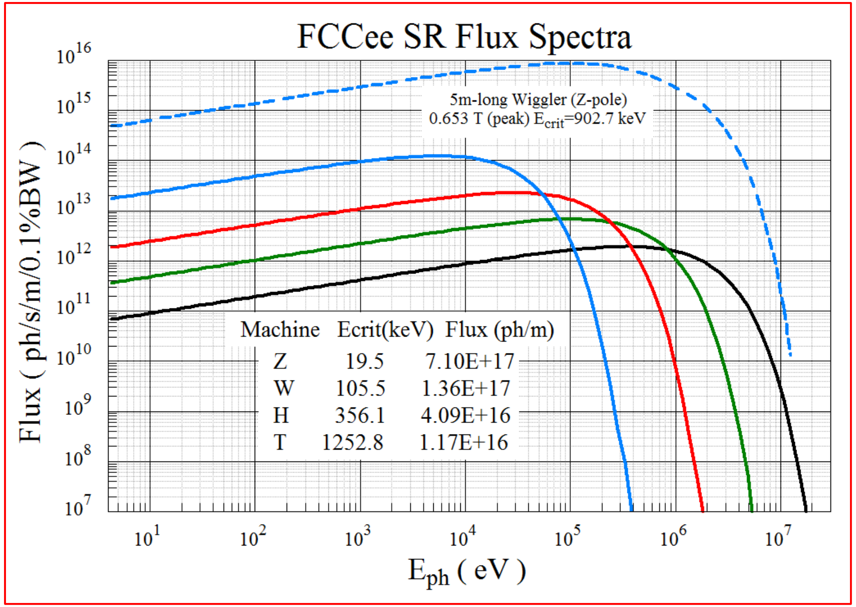
Special case: **polarization wigglers for FCC-ee**











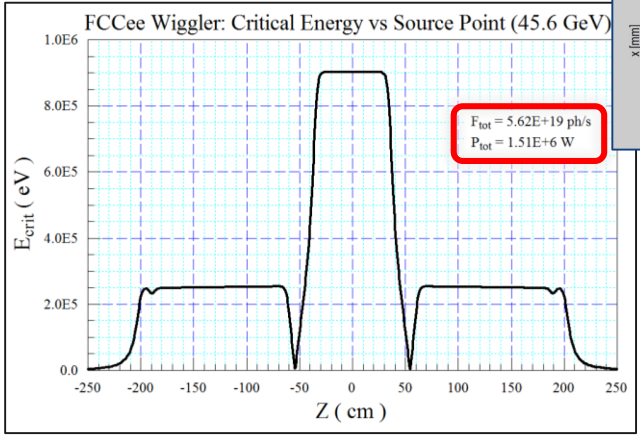
Model and field data: A. Milanese, CERN
https://indico.cern.ch/event/616602/
personal commun.

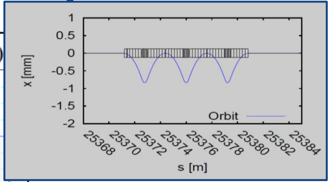
Note: Flux curve above for wiggler is for entire 5 m length, not normalized to 1 m; Total flux over 5 m equivalent to ~80 m of dipole radiation

Spectra, orbits and critical energy calculated with SYNRAD+

• Synchrotron radiation and vacuum

Special case: **polarization wigglers for FCC-ee**





- 1.5 MW/5m segment: careful design of all vacuum components downstream of such wigglers **mandatory**;
- Wigglers were one of the major sources of downtime due to **vacuum leaks during LEP operation** (see ref. →);
- The beam current during LEP 1 times at 45 GeV was limited to few 10s mA: **FCC-ee Z-pole aims at 1390 mA, almost 2 orders of magnitude more.**

EPAC-98 conference:

SYNCHROTRON RADIATION EFFECTS AT LEP

R. Bailey, B. Balhan, C. Bovet, B. Goddard, N. Hilleret, J.M. Jimenez, R. Jung, M. Placidi, M. Tavlet, G. von Holtey, CERN, Geneva, Switzerland

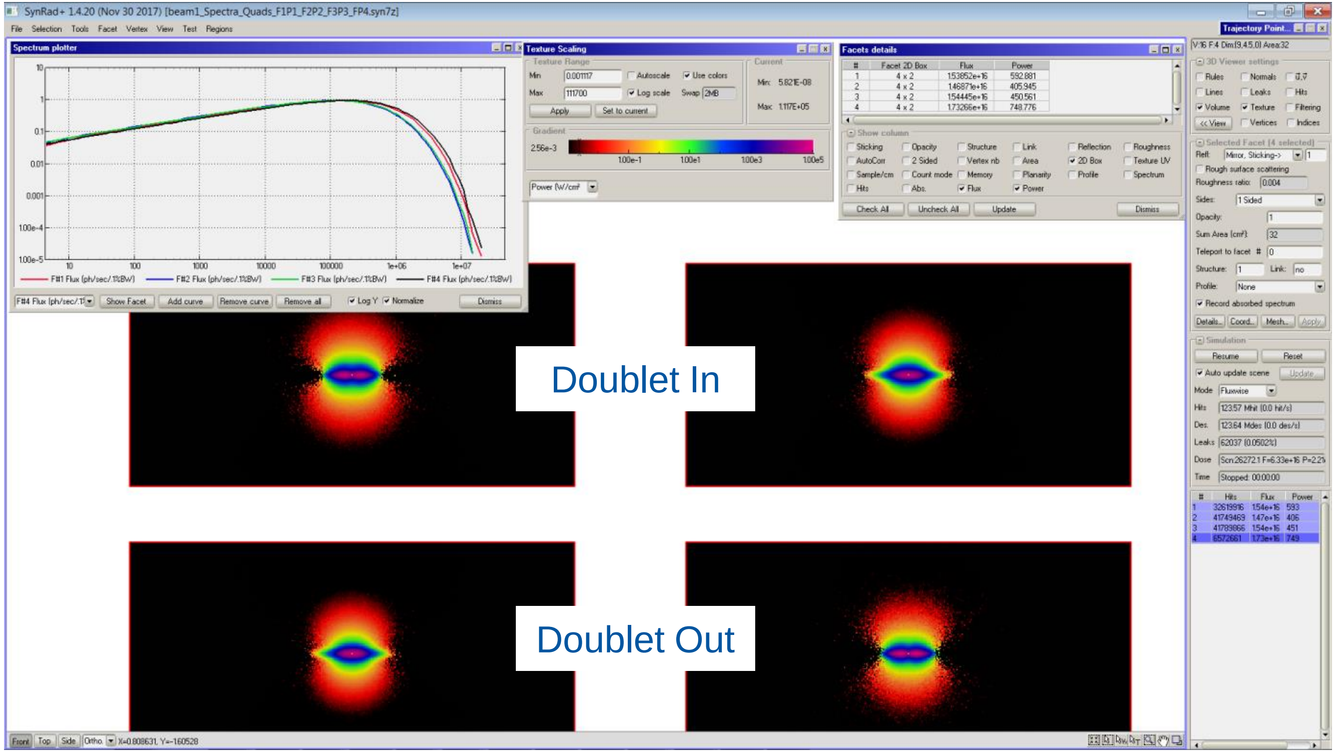
Table 1 - Emitted synchrotron radiation power from various sources in LEP, for a 6mA beam at 93GeV

Magnets	Bending Radius [m]	dP/ds [kW/m]	Magnetic Length [m]	P [kW]	Number of Magnets	Ptot [kW]
Weak arc dipole	30960	0.0066	6	0.04	64	2.536
Standard arc dipole	3096	0.6604	6	3.96	3376	13377
Injection dipole, octant 1	1548	2.6416	6	15.8	32	507.2
Quadrupole (QL6, QS4)	4500	0.3126	2	0.63	16	10
Damping wigglers	282	79.599	0.8	63.7	4	254.7
Emittance wigglers	282	79.599	0.8	63.7	4	254.7
Polarisation wigglers	227	122.84	0.75	92.1	12	1106
miniwigglers	1223	4.2321	2.12	8.97	2	17.94

- Synchrotron radiation and vacuum

Special case: **focusing doublets at IP**

- Even for the 175 GeV T-pole, the SR generated along the 2 focusing doublets is **extremely hard**;
- The screen-shot on the right shows the SR photon power density of each quadrupole magnet, ray-traced onto 4x2 cm^2 screens at 63 m distance from the IP (shown side by side for clarity, in reality the fans would overlap each other);
- **The critical energy is above 2 MeV** (>>pair-creation and Compton edge);



Spectra, ray-tracing, and orbits calculated with SYNRAD+

• Synchrotron radiation and vacuum: **masking photons in the Interaction Region**

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH
CERN – SL DIVISION
CERN SL/91-23 (DI)

PROCEEDINGS OF THE FIRST WORKSHOP ON LEP PERFORMANCE
Chamonix, January 13–19, 1991

Edited by
J. Poole

Presentation 39

Particle Backgrounds at LEP Detectors

By G. von Holtey

The synchrotron radiation photon background is much more difficult to estimate. The number of radiated photons and the photon energy spectrum depend strongly on the beam energy. Furthermore, as most of the background stems from SR in quadrupole fields, the rate of photons at the detectors becomes a strong function of the transverse beam dimensions, in particular in the horizontal plane. In addition, elastic and inelastic scattering of SR photons along the LEP vacuum chamber walls and on collimator surfaces must be taken into account. A special simulation program has been developed for this purpose [4]. Simulations for the LEP I optics have shown that the collimator protection system must provide photon reduction factors of the order of 10^7 in order to reduce the very high photon flux to an acceptable level. Due to the complexity of the problem and the fact that most of the photon background is radiated by electrons populating the edges of the gaussian beam core (the beam halo), absolute predictions of photon rates are very difficult to obtain and could be wrong by an order of magnitude.

CERN-SL-98-058 (EA)

Synchrotron Radiation Power from Insertion Quadrupoles onto LEP Equipment

A. Butterworth, G. Cavallari, M. Jimenez, G. von Holtey

Abstract

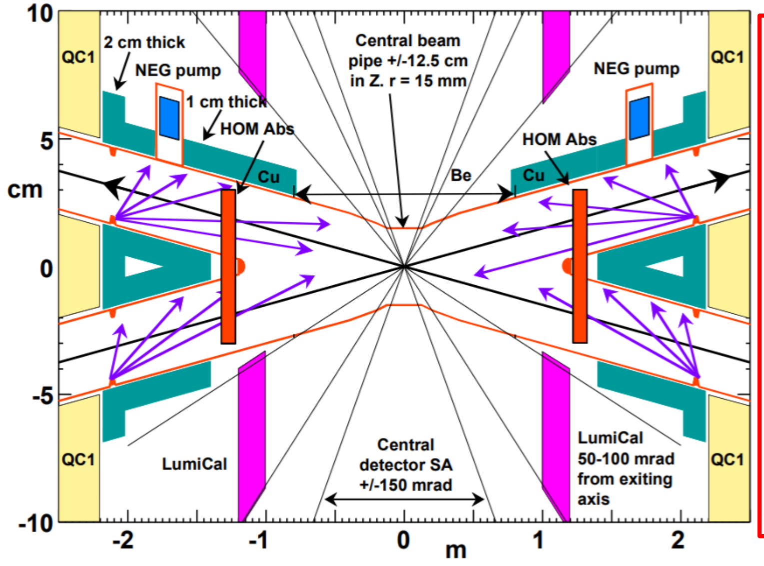
Hot spots and leaks at vacuum transition pieces in the experimental straight sections at high beam energy have been shown experimentally as well as by simulation to be due to synchrotron radiation from the low-beta quadrupoles. The transition pieces can be effectively protected by collimators. However, when closed, the collimators themselves are hit by a very high flux of synchrotron radiation photons, amounting to several hundreds of Watts per mA of beam current. The power seen by the collimator jaw surface is strongly dependent on the horizontal closed orbit amplitude through the quadrupoles. Upper limits for asymmetric horizontal orbits in the even IP's are given in order to keep the incident power onto collimators below design values.

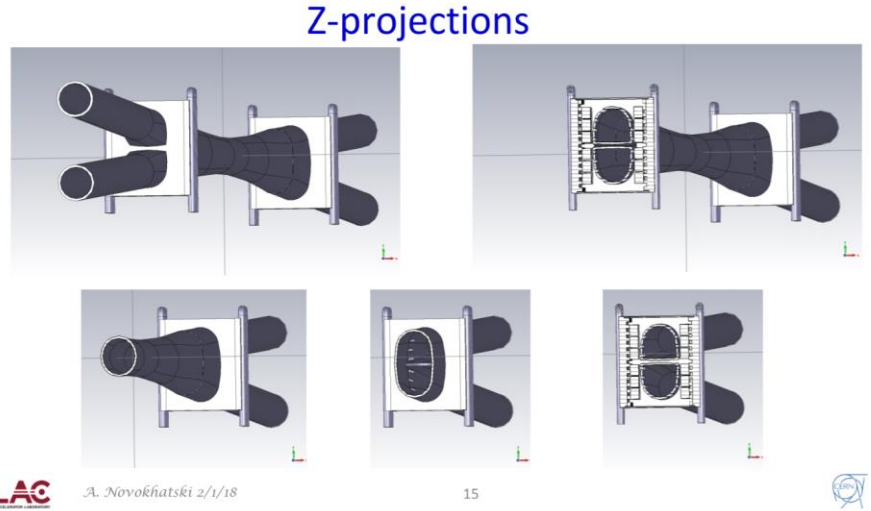
- Synchrotron radiation and vacuum: **masking photons in the Interaction Region**

Given the much increased beam current in FCC-ee with respect to LEP, the issue of masking the IR will be even more important; An ad-hoc working group on **M**achine **D**etector **I**nterface looks at this: https://indico.cern.ch/event/694811/timetable/?view=standard

Workshop on the mechanical optimisation of the FCC-ee MDI
30 Jan 2018, 08:30 → 9 Feb 2018, 17:30 Europe/Zurich

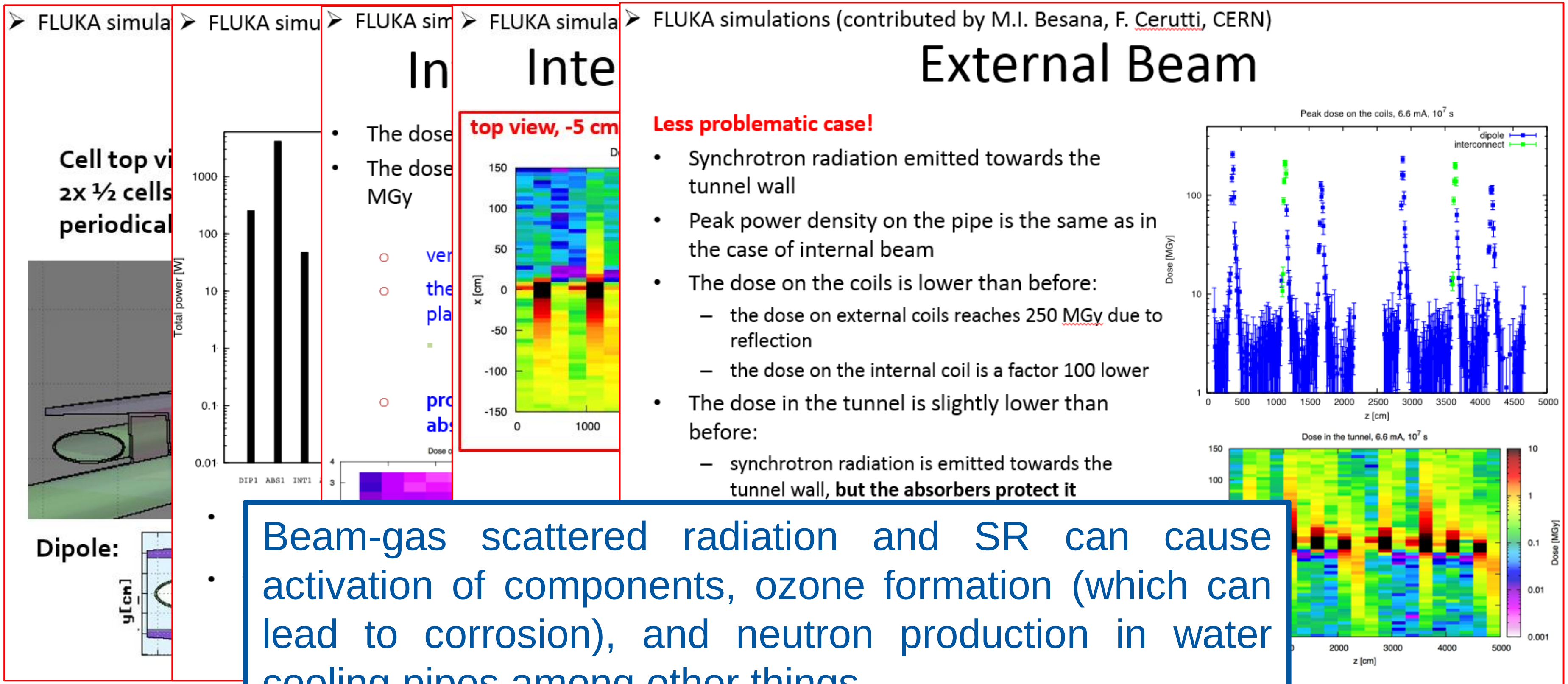
CAD model is based on the M. Sullivan design (FCC 2017, May 2017)





CAD model: M. Gil Costa, CERN/CIEMAT

• FCC-ee SR and beam-gas scattering radiation damage and tunnel activation



Old, superseeded v

Beam-gas scattered radiation and SR can cause activation of components, ozone formation (which can lead to corrosion), and neutron production in water cooling pipes among other things…

The geometry of the vacuum system and its performance are very important

• Vacuum for accelerators: **Beam Ionization (Bethe theory)**

M², C from Rieke and Prepejchal, Phys. Rev. A6, 1507 (1972)

LHC-VAC/AGM

Beam-C

At energies greater than 100 keV the ionisation cross section σ for a gas by a particle of charge Ze is given by:

$$\sigma = 4\pi Z^2 \left(\frac{\hbar}{mc}\right)^2 \frac{1}{\beta^2}\left(M^2 x + C\right) \qquad m^2 \qquad (2)$$

where σ is the ionisation cross section for the gas molecule (m^2)
c is the speed of light=2.998 10^8 ($m\ s^{-1}$)
v is the speed of the ionising particle ($m\ s^{-1}$)
β=v/c=0.99999998203 for 7.0 TeV protons
m is the mass of the electron=9.109 10^{-31} (kg)
M^2 and C are constants depending on the molecule

and the function x is given by:

$$x = \ln\left(\frac{\beta^2}{1-\beta^2}\right) - \beta^2 \qquad (3)$$

since β is ~1 this expression is more useful in the following form:

$$x = 2\ln(\gamma) - \beta^2 \qquad (4)$$

where

$$\gamma = \frac{\beta}{\sqrt{1-\beta^2}}$$

and γ is the ratio of the energy of the proton relative to its rest mass
the rest mass of the proton =0.9383 GeV

and the rest mass of the electron =5.11 MeV

$$\sigma = 1.874\ 10^{-24} \frac{Z^2}{\beta^2}\left(M^2 x + C\right) \qquad m^2$$

Table 2

Gas	M^2	C
H_2	0.695	8.115
He	0.752	7.571
CH_4	4.23	41.85
CO	3.70	35.14
CO_2	5.75	55.92

M^2+C

LHC 7 TeV	FCC-hh 50 TeV	FCC-ee Z
19.82	22.55	23.27
20.23	23.19	23.96
113.06	129.69	134.06
97.43	111.98	115.79
152.72	175.33	181.26

Table 4

Gas	Calculated σ x 10^{-18} cm^2 (26 GeV)	Calculated σ x 10^{-18} cm^2 (7 TeV)	Correction Factor	Corrected σ x 10^{-18} cm^2 (7 TeV)
H_2	0.226	0.371	1.2	0.445
He	0.225	0.382	1.2	0.458
CH_4	1.23	2.12	1.5	3.18
CO	1.05	1.83	1.5	2.75
CO_2	1.66	2.86	1.5	4.29

P_{gas}/kT=n (gas density)

$$I_p = \sigma_p \frac{P_{gas}}{kT} I_{beam}$$

e.g. LHC arc: I_p~ 20 nA/m at nominal current and density (10^{15} H_2/m^3)

Scaling the **20 nA/m linear ionization current density of LHC** with beam current and molecular density n=2·10^{14} H_2/m^3 for FCC-hh and n=1.24 ·10^{12} H_2/m^3 for FCC-ee (e.g. at a pressure of 5.0 ·10^{-9} mbar, 20 ºC), we estimate **3.43 nA/m for FCC-hh** and **60 pA/m for FCC-ee Z**: **negligible**

• Vacuum for accelerators: **nuclear scattering on residual gas**

Ref.: O. Grobner, CAS School “Vacuum in Accelerators”, 2006, Platja d’Aro, Spain

Power loss by nuclear scattering

Particles lost by nuclear scattering along the arcs of a machine can not be collimated and their losses occur uniformly distributed around the arcs

$$P(w/m) = \frac{1}{c}\frac{IE}{\tau} = 0.93\frac{I(A)E(TeV)}{\tau(h)}$$

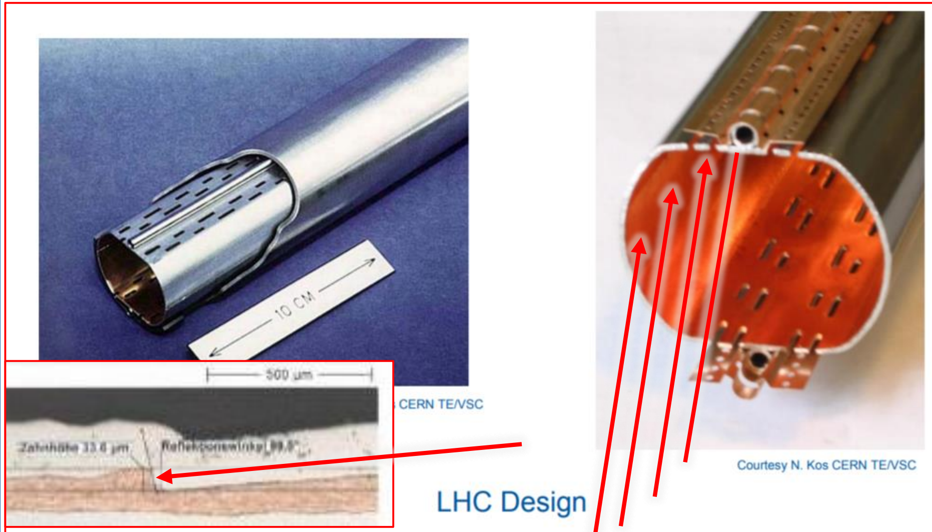
LHC design requires a nuclear-scattering life time of ~ 100h

LHC -> 0.1 W/m for two beams at ultimate current required gas density equivalent to 10^{15} H_2/m^3

Each W at 1.9 K ~ 500 W at RT ← Carnot Efficiency

The saw-tooth profile minimizes the photon scattering/reflection probability and localizes the resulting photon-stimulated desorption and photo-electron production

This is why we need to intercept the SR in FCC-hh at a relatively **higher temperature than that of the cold-bore** (1.9 K): a dedicated **beam-screen** has been devised; **SR load at LHC ~ 0.18 W/m/beam**



Sawtooth profile

(CERN LHC Vacuum group)

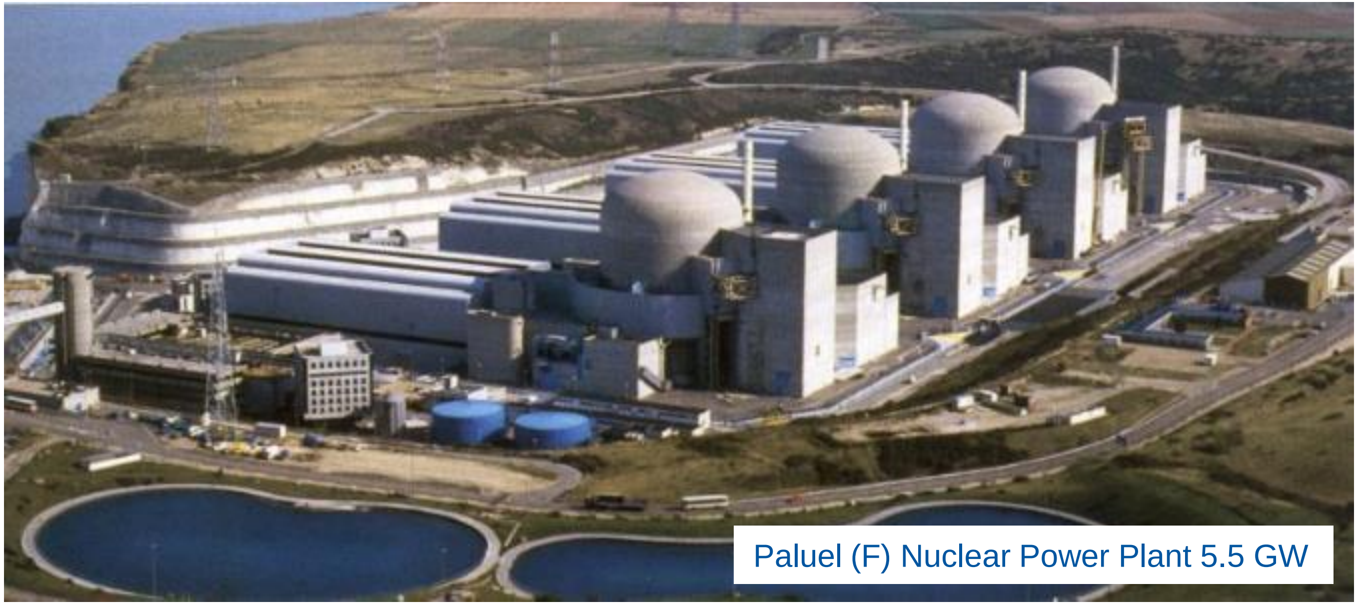
• Perforated Cu colaminated beam screen to intercept the SR power protecting the 1.9 K cold bore and to allow a distributed pumping

Ref.: V. Baglin, JUAS 2018, Lecture 4

- Vacuum for accelerators: **Carnot efficiency: why is it important?**

What does it mean to transfer 30 W/m **from 1.9 K to 300 K** in FCC?

$$P_w = 30\frac{W}{m}\cdot\frac{300}{1.9}\cdot\frac{1}{0.3}\cdot 2\cdot 85000\,m \approx 3\,GW \rightarrow\approx 5GW_{el}$$



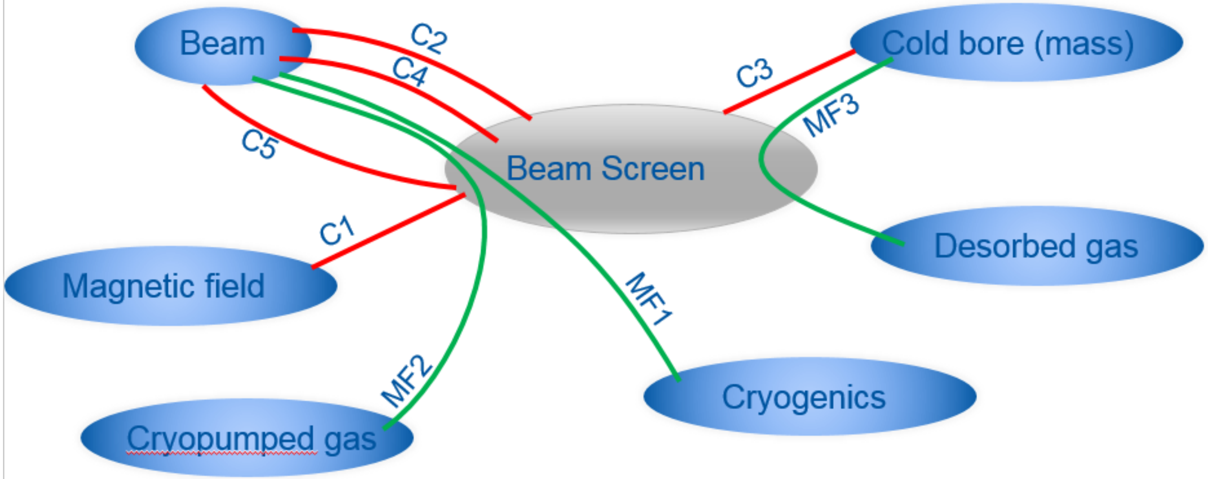
Paluel (F) Nuclear Power Plant 5.5 GW

The electricity bill of CERN would be unmanageable!

Ref.: R. Kersevan – Workshop "Beam Dynamics meets Vacuum, Collimations, and Surfaces", KIT 3/9/2017

- Vacuum for accelerators: **Why do high-energy pp colliders need a beam-screen?**

Beam Screen functions



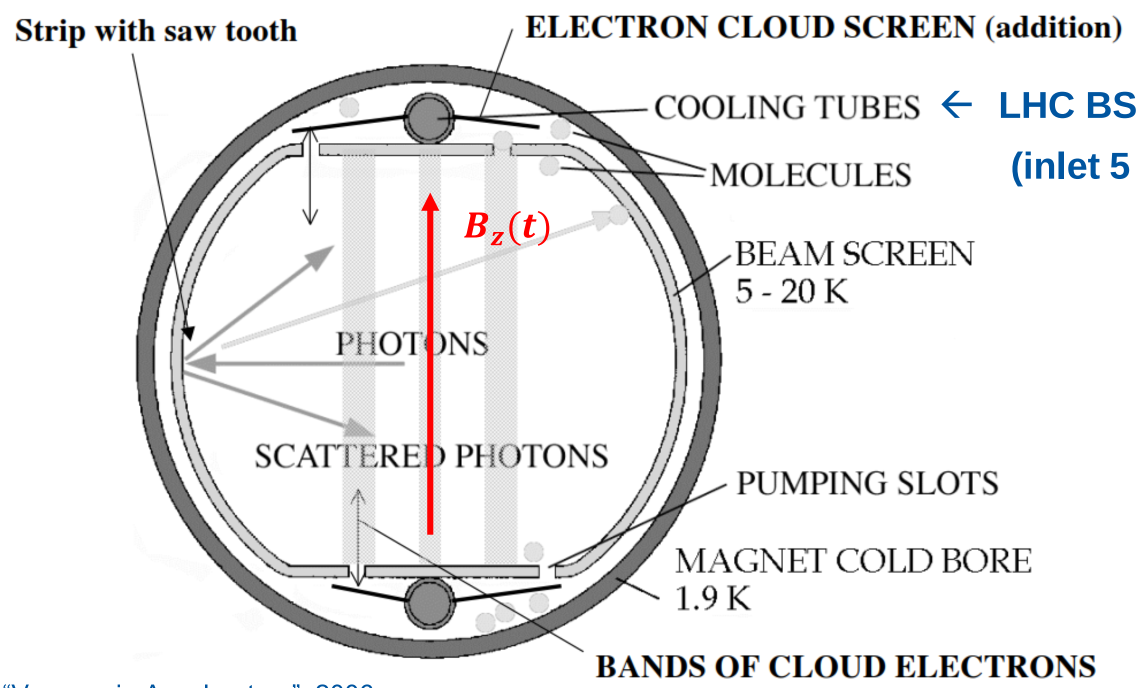
MF1 : Intercept beam induced synchrotron power and transfer it to cryogenic cooling fluid
MF2 : Hide the cryopumped gas from beam induced photon impingement
MF3 : Provide sufficient pumping speed of desorbed gas toward the cold bore
C1: Withstand the Lorentz's forces during a quench
C2: Fulfil impedance requirements
C3: Minimise the heat loads to the cold bore
C4: Mitigate electron cloud
C5: Maximize the beam aperture

Main **F**unctions and **C**onstraints

Ref: C. Garion, FCC Week 2016, Rome

• Vacuum for accelerators: **counteracting the e-cloud in the LHC**

Beam screen in an LHC dipole



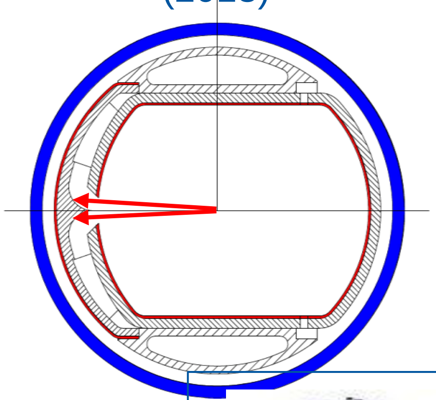
← **LHC BS temperature:**

(inlet 5 K, outlet 20 K)

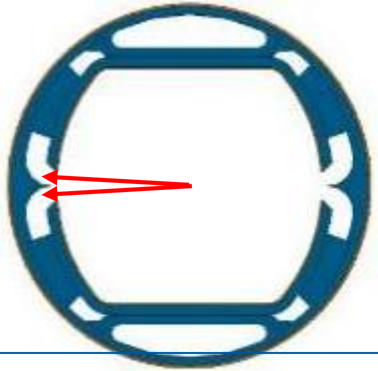
Ref.: O. Grobner, CAS School "Vacuum in Accelerators", 2006, Platja d'Aro, Spain

• Vacuum for accelerators: **FCC-hh beam-screen design evolution**

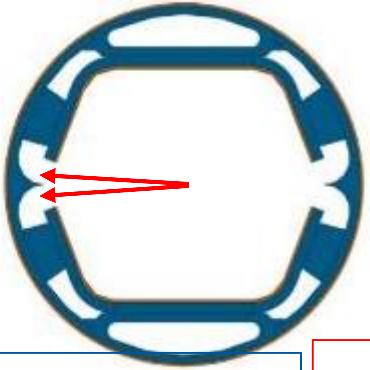
Conceptual design with antechamber (2013)



Orsay 09/2015
3th WP4 meeting

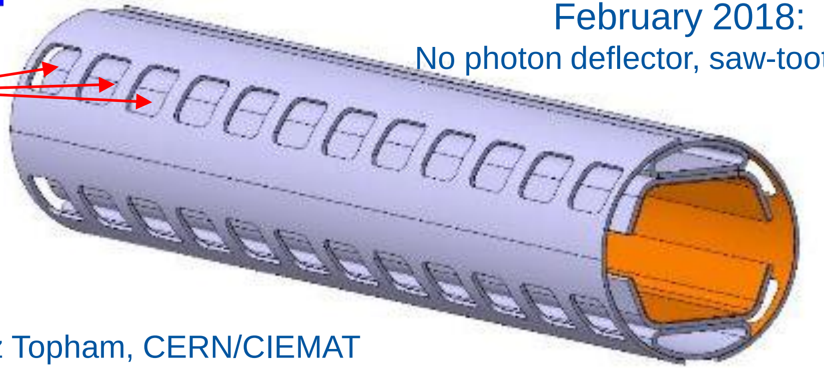


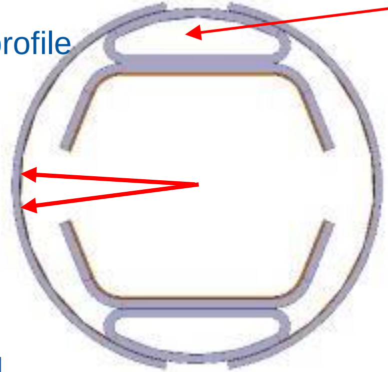
Barcelona 11/2016
5th WP4 meeting



pumping slots along ante-chamber; minimized impedance effect

February 2018:
No photon deflector, saw-tooth profile





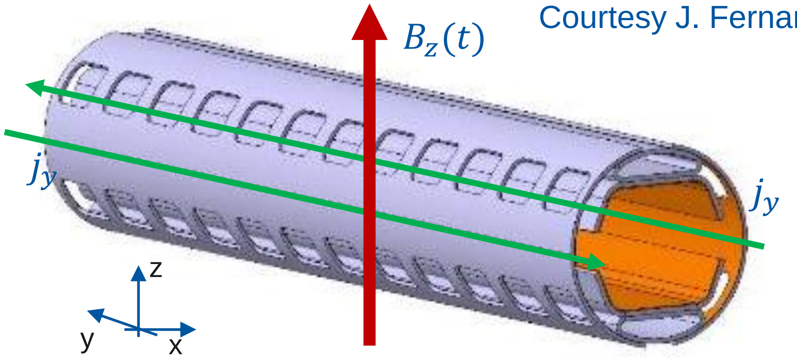
40~60 K SC He cooling channel: Improved Carnot Efficiency

Courtesy J. Fernandez Topham, CERN/CIEMAT

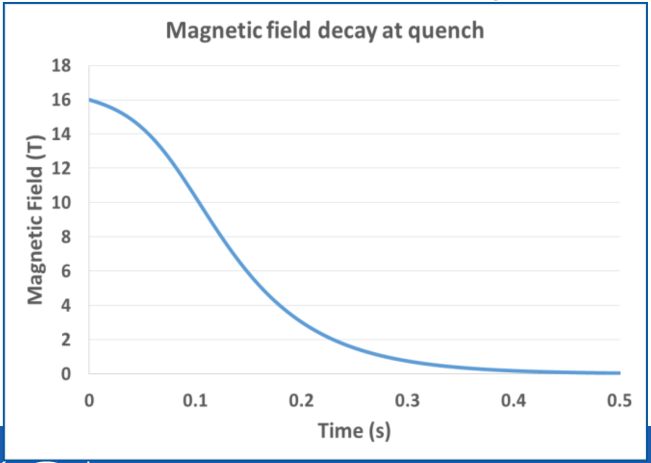
• Vacuum for accelerators: **FCC-hh BS design – Mechanical Stress During Quench**

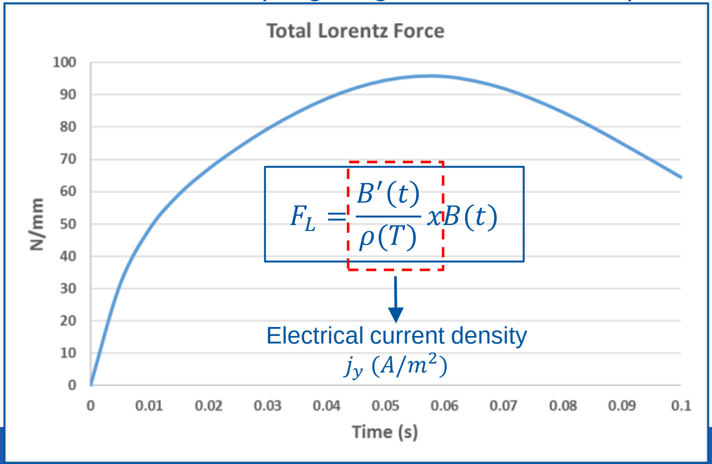
- Variation of magnetic field at quench produces currents all along the beam screen.
- These currents produce Lorentz forces that have to be correctly withstand by the beam screen.

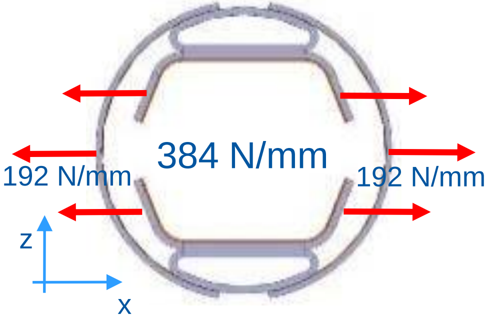
Courtesy J. Fernandez Topham, CERN/CIEMAT



3D simulations are carried out taking into account the Joule effect coupling magnetic field and temperatures ($\rho C_p \frac{\partial T}{\partial t} - \nabla(k\nabla T) = Q_e = JE$).







> 38 tons/m!

Ion stability in a bunched beam

Positive ions can be trapped in a bunched electron beam-> successive bunches give kicks to the ions

$$\begin{pmatrix} y \\ \dot{y} \end{pmatrix}_{after} = M \begin{pmatrix} y \\ \dot{y} \end{pmatrix}_{before}$$

α attractive kick given by a bunch, n number of bunches, T revolution time

$$M = \begin{pmatrix} 1 & t \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ \alpha & 1 \end{pmatrix}$$

Drift * Kick

$$\alpha = \frac{4cr_0}{b(a+b)} \frac{1}{A} \frac{N_b}{n} = \frac{2cr_0}{a^2} \frac{1}{A} \frac{N_b}{n}$$

The ion motion is stable if

$$-2 < Tr(M) < 2$$

Ions with masses larger than a critical mass A_c accumulate

$$-1 < (1 - \alpha \frac{T}{2n}) < 1 \quad \Rightarrow \alpha_c = \frac{4n}{T}$$

$$A_c = \frac{cr_0}{2a^2} \frac{N_b}{n} \frac{T}{n} = \pi r_0 \frac{RN_b}{a^2 n^2}$$

LHC: A_c ~10 -> electrons are ejected
LEP: 4 intense e- bunches $A_c > 200$
e^- rings all require a 'clearing gap'

Future circular collider with e- beams will need a careful design so as to reduce/eliminate the ion-trapping effect; **Minimizing the number of ions is done by minimizing the residual gas density and its ionization by the beam;**

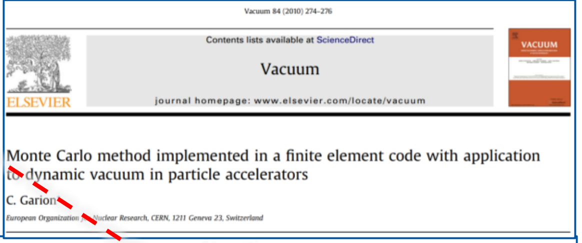
Ref.: O. Grobner, CAS School "Vacuum in Accelerators", 2006, Platja d'Aro, Spain

• Linear colliders: **CLIC: high-voltage discharge inside an accelerating cell**

- A factor limiting the performance of the RF cavities is the **breakdown rate** occurring at high gradients (typically of the order of 100 MV/m).
- The breakdown is due to high surface electric field that can lead to the **development of an electrical arc and therefore to a local melting and a degradation of the cavity surface**.
- From an operational point of view, **a breakdown releases a large amount of gas in the cavity**.
- To avoid disturbing the beam, **it has to be pumped before the next bunch of particles comes**.
- The amount of gas released has been estimated at **$2\cdot10^{12}$ H_2 molecules**.
- The time between two bunches is **4 ms**.
- The **maximum pressure**, 4 ms after a breakdown, **is limited to 10^{-6} Pa.**

Finite-Elements method analysis

Typical dimensions of the cavity are **3 mm** and **10 mm** for the inner and outer radius of the iris, respectively.


Vacuum 84 (2010) 274–276

Contents lists available at ScienceDirect

Vacuum

journal homepage: www.elsevier.com/locate/vacuum

Monte Carlo method implemented in a finite element code with application to dynamic vacuum in particle accelerators

C. Garion

European Organization for Nuclear Research, CERN, 1211 Geneva 23, Switzerland

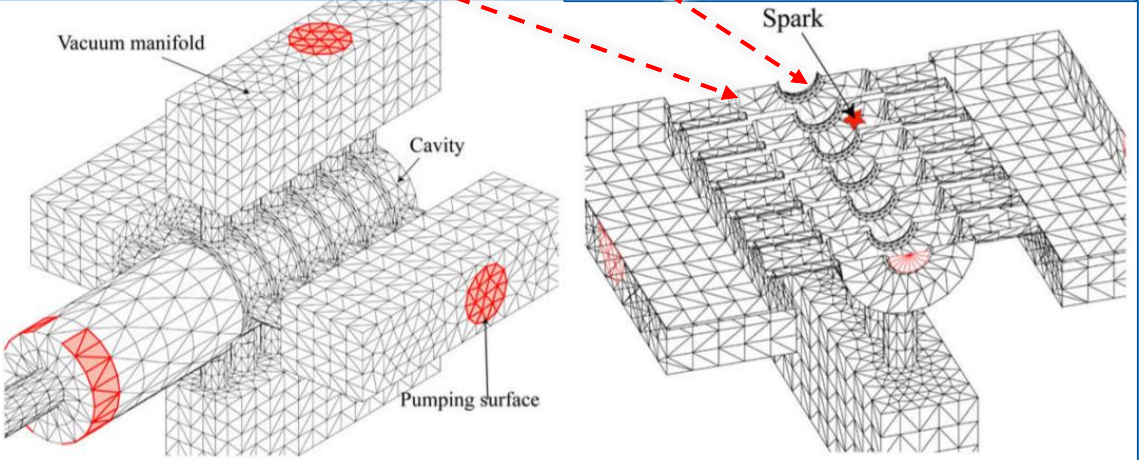
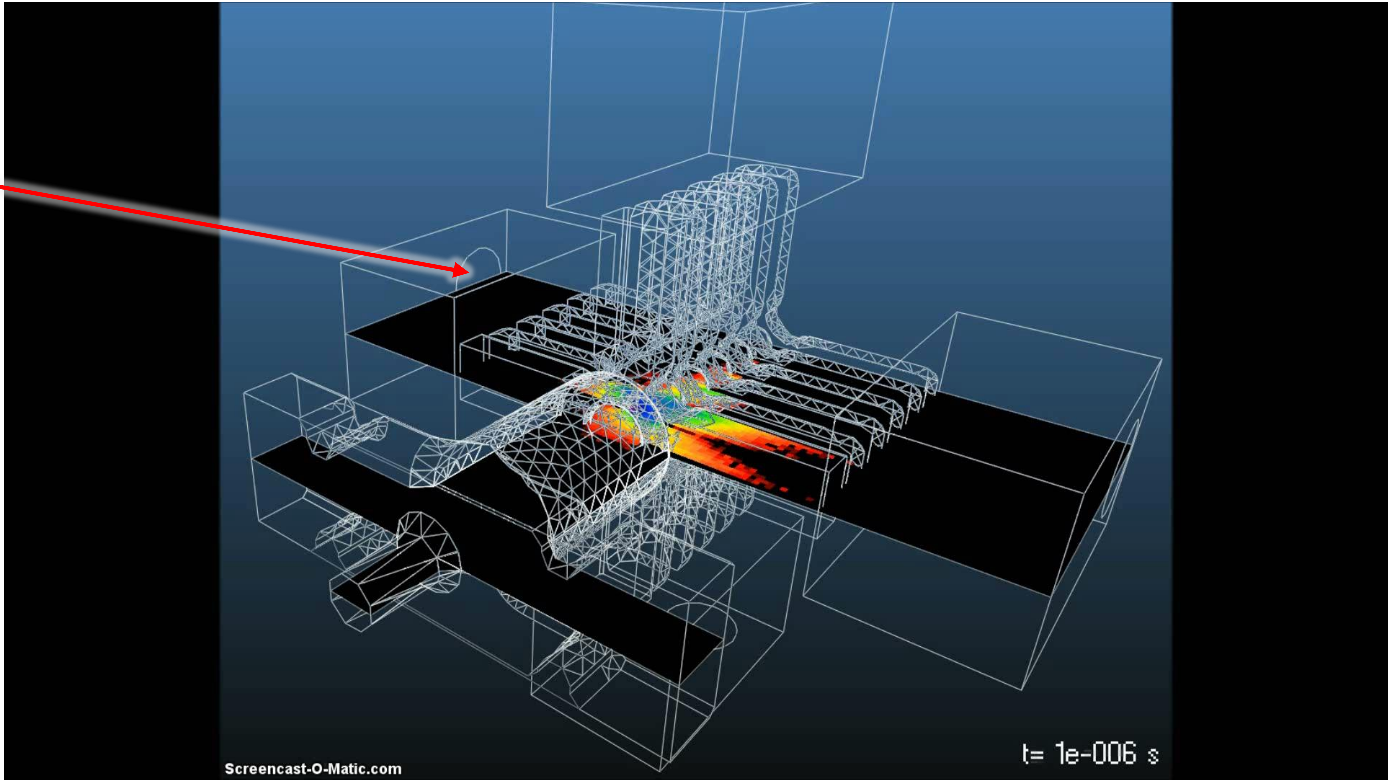


Fig. 2. Mesh geometry of the CLIC accelerating structures.

Ref. "Monte Carlo method implemented in a finite element code with application to dynamic vacuum in particle accelerators", C. Garion, Vacuum 84 (2010) 274-276

- Linear colliders: **CLIC: high-voltage discharge inside an accelerating cell**

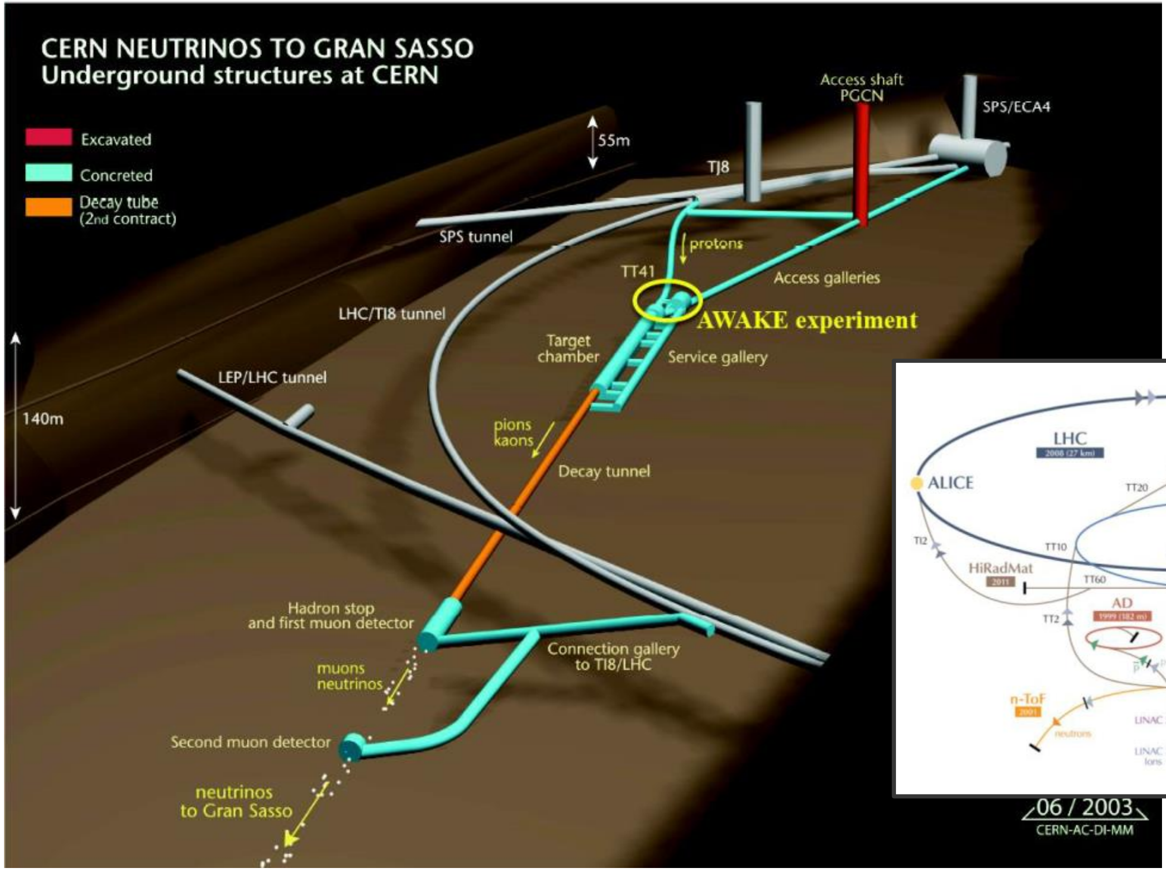
Pumping surface

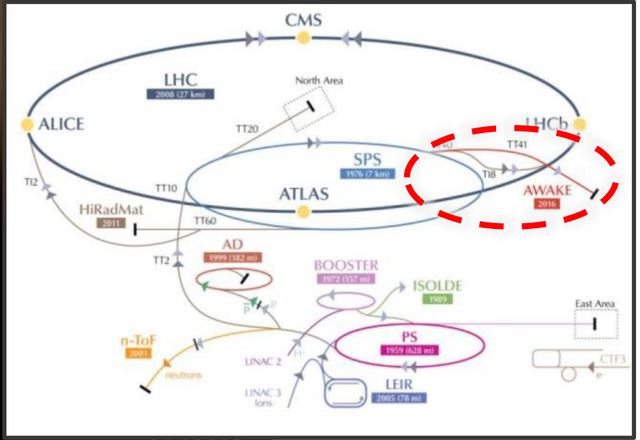


Time-dependent Test-Particle Montecarlo simulation (Molflow+): the aim is to ascertain whether the gas burst generated by (e.g.) an RF discharge can be pumped before the next bunch comes in and it is affected (4 ms); OK

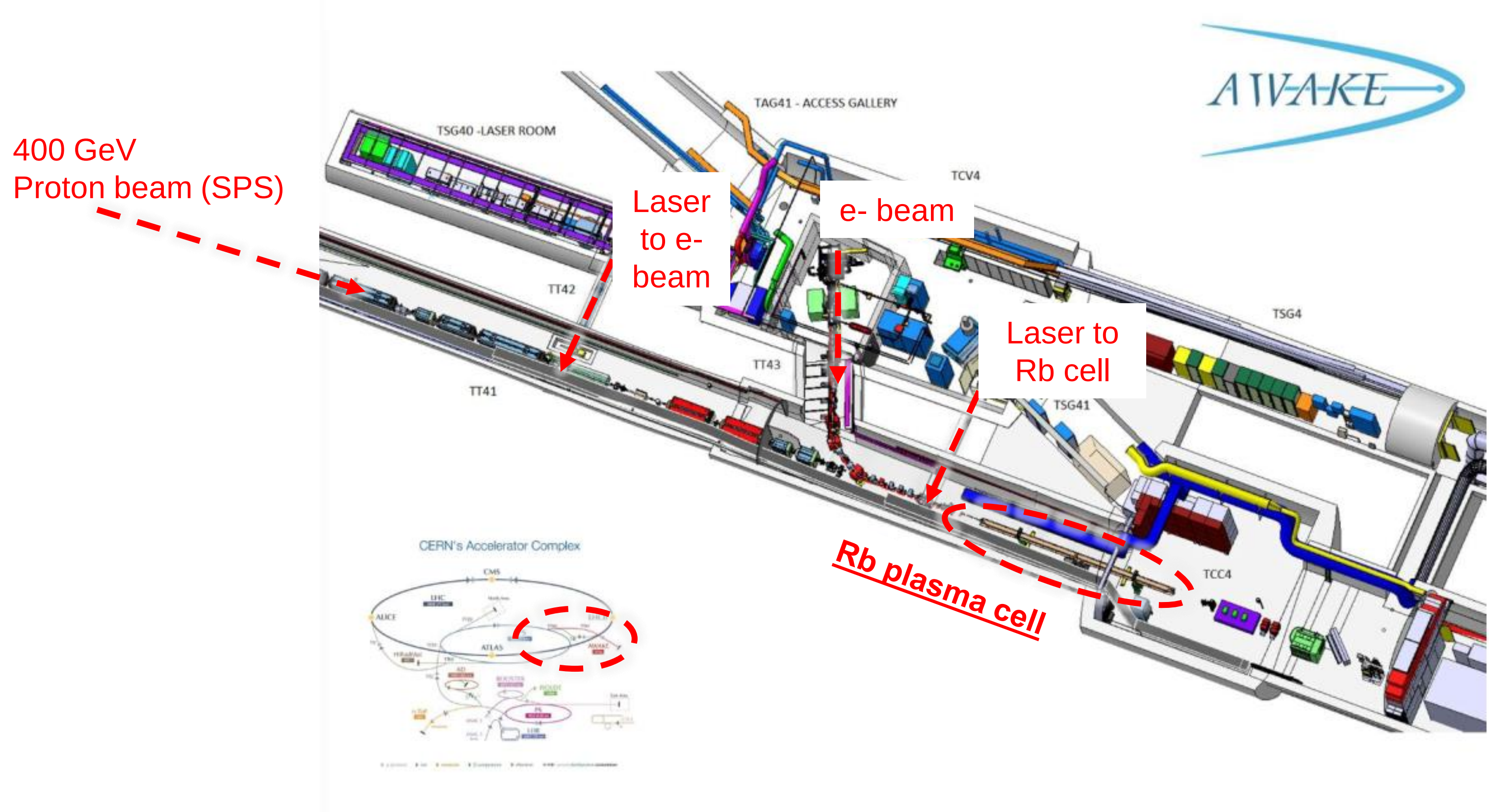
- **Future plasma-wake accelerators? AWAKE** – what has vacuum technology to do with it?

Aim:
accelerating fields of ~ 1 GV/m





- **Future plasma-wake accelerators? AWAKE** – what has vacuum technology to do with it?



- # **Future plasma-wake accelerators? AWAKE** – what has vacuum technology to do with it?

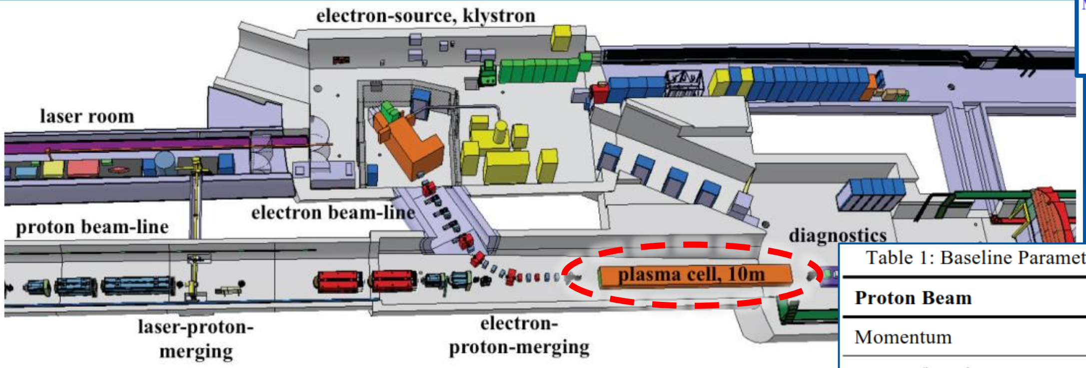


Figure 2: Integration of the AWAKE experiment in the experimental area. The 10 m lon
installed at the downstream part of the proton beam-line.

MOPRI005 Proceedings of IPAC2014, Dresden, Germany

THE AWAKE EXPERIMENTAL FACILITY AT CERN

The **rubidium plasma cell** is at the heart of the experiment;

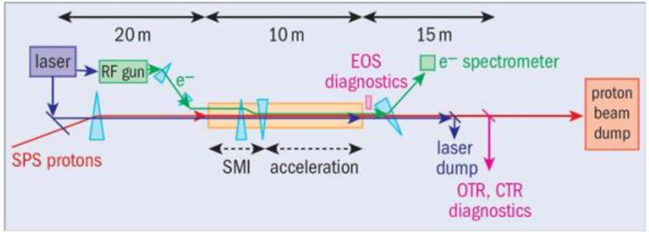


Fig. 2. Baseline design of the AWAKE experiment at CERN.

close or Esc Key

Table 1: Baseline Parameters of the AWAKE Beams

Proton Beam	
Momentum	400 GeV/c
Protons/bunch	3 E11
Bunch extraction frequency	0.5 Hz (ultimate: 0.14 Hz)
Bunch length	σ_z = 0.4 ns (12 cm)
Bunch size at plasma entrance	$\sigma_{x,y}$ = 200 μm
Normalized emittance (r.m.s.)	3.5 mm mrad
Relative energy spread	$\Delta p/p = 0.35\%$
Beta function	$\beta^*_x = \beta^*_y = 4.9$ m
Dispersion	$D^*_x = D^*_y = 0$
Electron Beam	
Momentum	16 MeV/c
Electrons/bunch (bunch charge)	1.2 E9 (0.2 nC)
Bunch length	σ_z = 4 ps (1.2 mm)
Bunch size at focus	$\sigma_{x,y}$ = 250 μm
Normalized emittance (r.m.s.)	2 mm mrad
Relative energy spread	$\Delta p/p = 0.5\%$
Beta function	$\beta^*_x = \beta^*_y = 0.4$ m
Dispersion	$D^*_x = D^*_y = 0$
Laser Beam to Plasma Cell	
Laser type	Fiber Ti:Sapphire
Pulse wavelength	λ_0 = 780 nm
Pulse length	100-120 fs
Pulse energy (after compr.)	450 mJ
Laser power	2 TW
Focused laser size	$\sigma_{x,y}$ = 1 mm
Energy stability	±1.5% r.m.s.
Repetition rate	10 Hz
Laser Beam for Electron Source	
Laser type	Ti:Sapphire Centaurus
Pulse wavelength	λ_0 = 260 nm
Pulse length	10 ps
Pulse energy (after compr.)	32 μJ
Electron source cathode	Copper
Quantum efficiency	3.00 E-5
Energy stability	±2.5% r.m.s.

• **Future plasma-wake accelerators? AWAKE** – what has vacuum technology to do with it?

IOP Publishing — Journal of Physics D: Applied Physics

J. Phys. D: Appl. Phys. **51** (2018) 025203 (10pp) — https://doi.org/10.1088/1361-6463/aa9dd7

A rubidium vapor source for a plasma source for AWAKE

- TPMC and DSMC study of the Rb plasma source;
- DSMC is TPMC with molecular collisions

- We present the scheme for a rubidium vapour source that is used as a plasma source in the AWAKE plasma wakefield acceleration experiment.
- The plasma wakefield acceleration process requires a number of stringent parameters for the plasma:
  - electron density adjustable in the $(1 \div 10) \times 10^{14}$ cm^{-3} range;
  - 0.25% relative density uniformity;
  - sharp (<10 cm) density ramps at each end;
  - density gradient adjustable from −3 to +10% over 10 m;
  - %-level density step near the beginning the plasma column;
- We show with analytical and direct simulation Monte Carlo results that the rubidium density in the proposed source should meet these requirements.
- **Laser ionization then transfers the above neutral vapor parameters to the plasma.**

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A rubidium vapor source for a plasma source for AWAKE

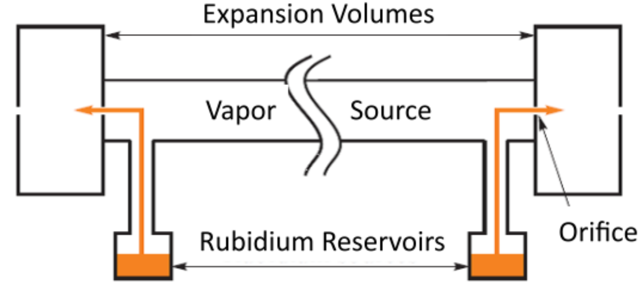


Figure 1. Schematic of the AWAKE vapor source. The orange arrows indicate the Rb vapor flow from the Rb reservoirs to the expansion volumes (not to scale).

$$\lambda_{mfp} = \frac{k_B T}{\sqrt{2}\pi d^2 p} = \frac{\mu}{p}\sqrt{\frac{\pi k_B T}{2m}}$$

$$\mu = \frac{1}{\pi^{3/2}}\frac{\sqrt{m k_B T}}{d^2}$$

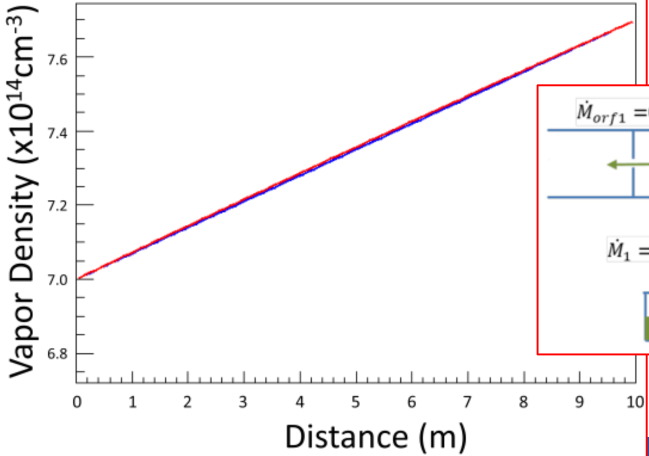
At a temperature of 500 K, with the Rb atom mass $m=1.419\times10^{-25}$ kg and diameter d=496 pm, the viscosity is $\mu=2.3\times10^{-5}$ Pa · s;

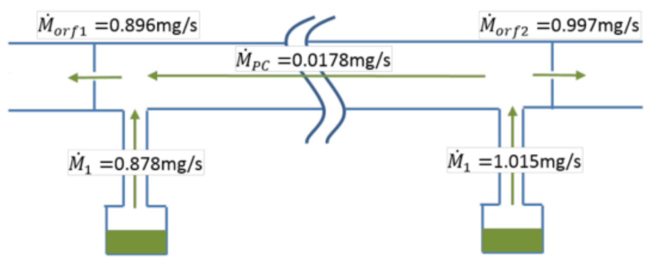
The mean free path for a density of 7×10^{14} cm^{-3} is thus λ_{mfp} =1.31 mm;

We are in the so-called "**transition regime**", where molecular collisions cannot be neglected;

TPMC method may not be accurate enough, DSMC has been used;

Rb plasma cell:
L=10 m; Dia.= 4 cm;





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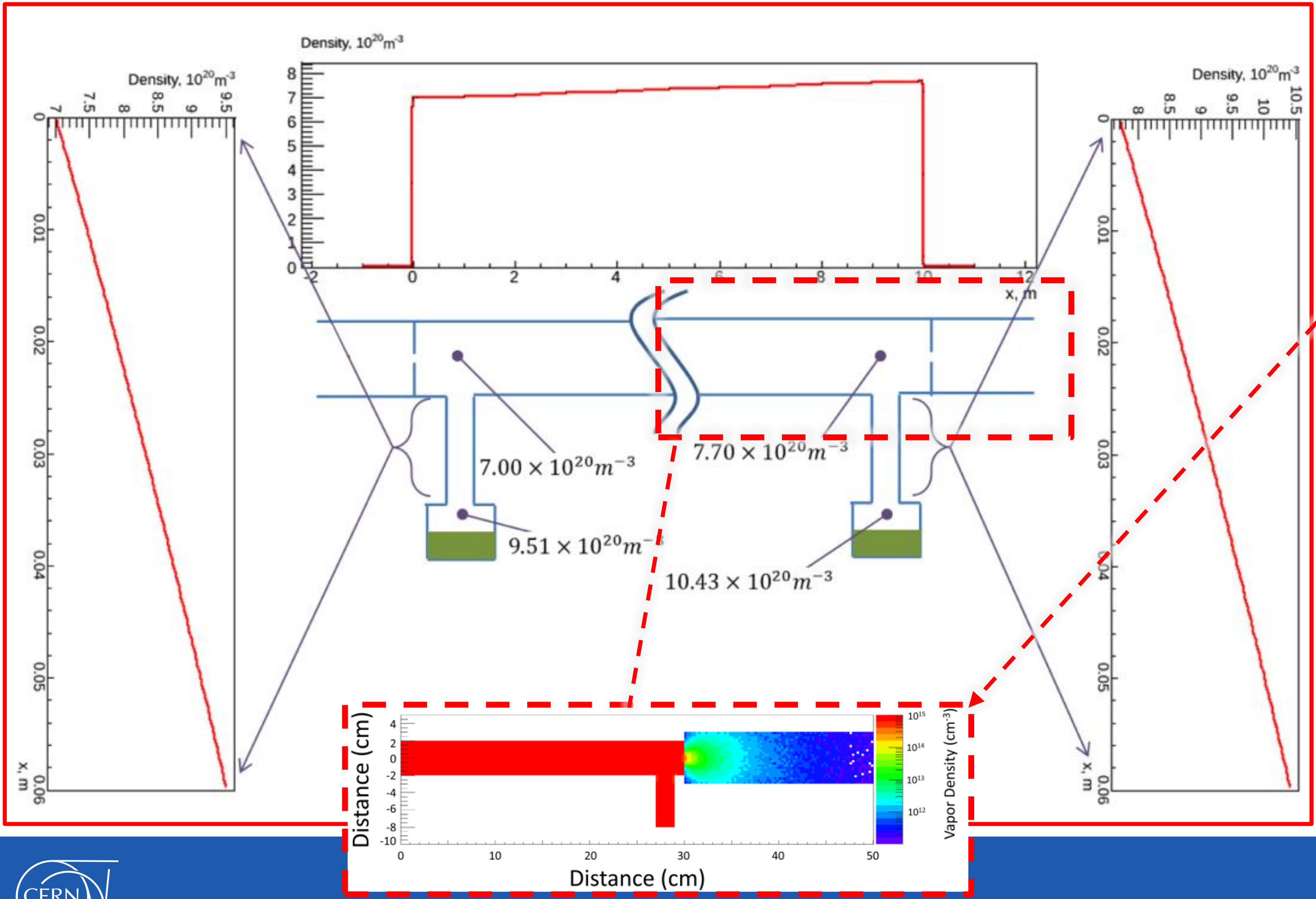
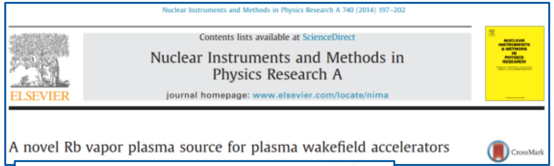


- The **required density gradient** with **sharp rise/fall at both extremities** can be obtained as shown in this figure;
- The sharp rise/fall can be obtained using **expansion chambers with reduction orifices (10 mm dia.)**;
- The Rb density in the various parts of the plasma cell is precisely **controlled by local temperature variations**;
- Therefore, the plasma cell must be extremely well characterized in terms of its temperature distribution: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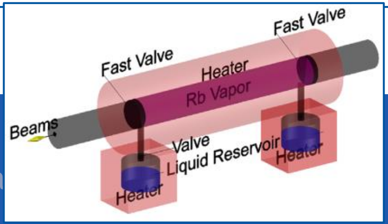
A novel Rb vapor plasma source for plasma wakefield accelerators



• e-p colliders: LHeC

“Mixed” colliders, where an electron beam is brought into collision with a proton beam, like HERA was at DESY, or LHeC is designed to be, will face vacuum problems mainly in the experimental areas, where **the electron beam is deflected and focused by the final-focus quadrupoles and dipoles** (and eventually stray fields of the experiment’s main solenoid), thus **creating powerful fans of high critical energy synchrotron radiation**;

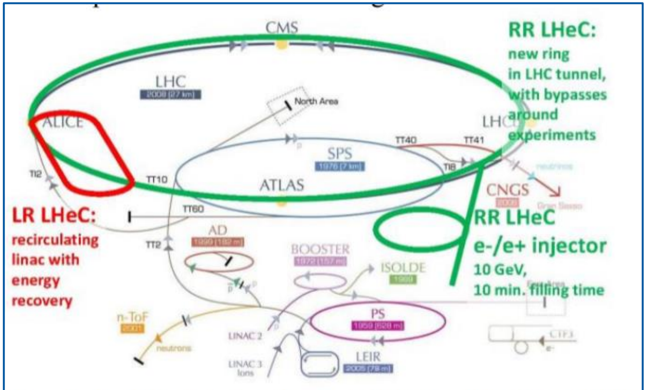


Fig. 1: Schematic of a Large Hadron electron Collider (LHeC) based on the LHC: option 1 consists of a new lepton ring in the LHC tunnel together with a 10-GeV injector complex (green color), option 2 of a Racetrack-shape multiple-pass recirculating energy-recovery linac placed in a new, smaller separate tunnel (red).

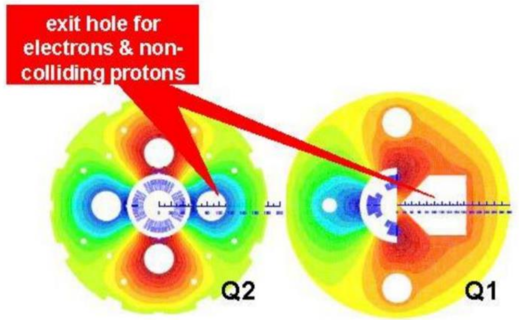


Fig. 6: Cross section of final two proton quadrupoles of the linac-ring LHeC with parameters as listed in Table 3 [S. Russenschuck].

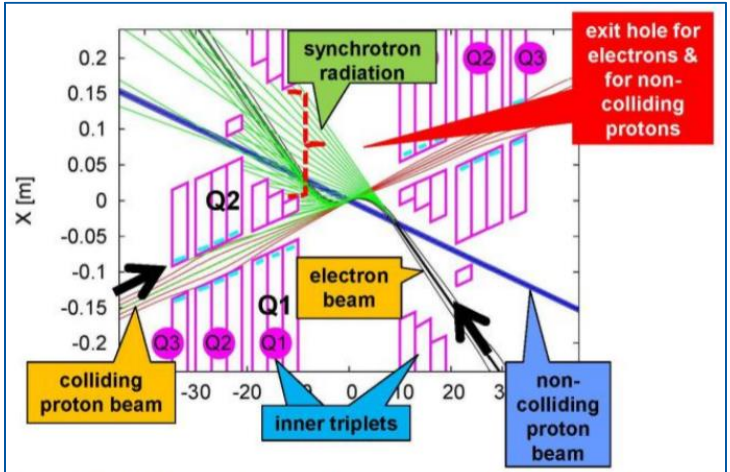


Fig. 5: Schematic of linac-ring 3-beam LHeC IR including synchrotron radiation fan from detector-integrated dipole magnet [R. Tomas].

Ref. “LHeC and HE-LHC: Accelerator Layout and Challenges”, F. Zimmermann, Chamonix 2012, https://indico.cern.ch/event/164089/timetable/#all.detailed

Summary, main points

- In high-energy colliders, **vacuum is affected by several physical phenomena, and it affects the performance of the machines**
- Keeping the **residual gas density as low as possible** is important in order to reduce these detrimental effects, such as **e-cloud**, **ion-trapping**, **nuclear gas scattering and energy deposition on SC magnets**, **radiation damage** and **activation of components**, **radiation dose to personnel**, etc…
- Future pp collider of higher beam energy are characterized by **copious generation of synchrotron radiation**, with **power levels orders of magnitude higher than today's LHC**
- The **main vacuum element of pp colliders** will be the **beam-screen**: a careful analysis and design of its characteristics must be carried out
- High energy **e-e+ colliders are characterized by extremely strong synchrotron radiation**, large photon fluxes and/or critical energy, and high power densities on lumped absorbers; for high-current rings (e.g. FCC-ee Z-pole) the vacuum conditioning time may be long compared to the experimental program duration (→ this pushes for a reduced-PSD coating, like NEG, in order to speed-up the commissioning);
- Considering the large sizes of the future colliders, **new fabrication technologies and materials capable of reducing the capital costs are sought**
- In parallel, **computational tools must be developed and improved** in order to allow proper simulation of all vacuum effects