The FCC-ee design study

Proposal and simulation of the FCC-ee vacuum system

R. Kersevan, CERN-TE-VSC-VSM

Agenda:

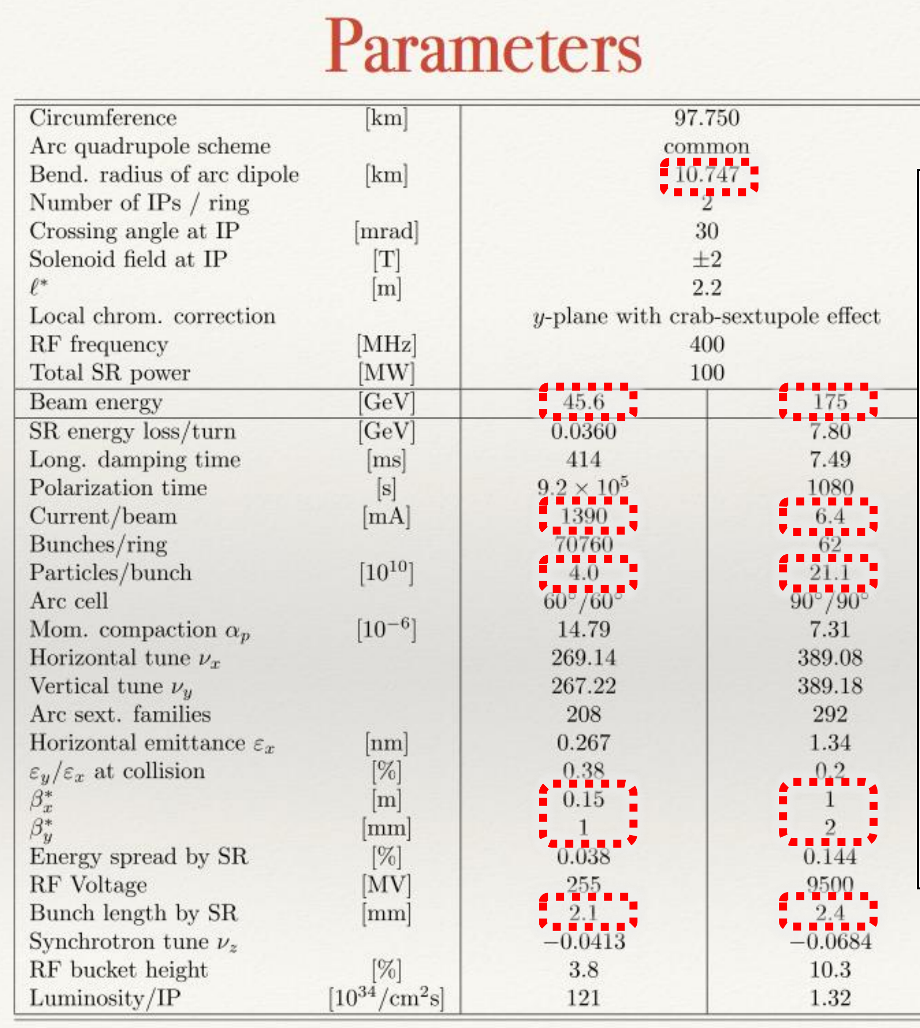
1. Introduction
2. FCC-ee parameter list
3. SR spectra, photon flux and power densities
4. Vacuum specifications
5. Vacuum chamber geometries: different options and SR ray-tracing
6. Pumping system options: pressure profiles
7. Considerations about background in the interaction region
8. Other vacuum components
9. Conclusions and future work

1. Introduction

- The FCC-ee is a very challenging vacuum study, since it aims at designing a vacuum system capable of accommodating 4 different machines, the Z-, W-, H- and T-pole, running at 45.6, 80, 120, and 175 GeV, respectively;
- It has become immediately evident that, vacuum-wise, **the Z-pole is the most challenging one**, with its B-factory-like currents of almost 1.4 A, compared to the 10 mA or so that LEP stored at the time;
- FCC-ee is conceived as a **very low-emittance, high-luminosity machine**, and therefore **all impedance issues and related beam instabilities must be avoided**: this requirement calls for a very careful design of its vacuum system, with very low-loss components, such as flanges, synchrotron radiation (SR) absorbers, tapers, resistive wall, etc… see companion presentations at this conference;
- We have tried our best to take advantage of the lessons learned in the last 2 decades on B-factories (SLAC, KEK, Cornell) and the legacy studies on LEP, trying to combine different features, design, and material choices into a reasonable solution applicable to a twin ~100 km ring;
- This talk discusses and motivates the main choices made, and highlights some of the results achieved so far, and the work to be done in the incoming months.

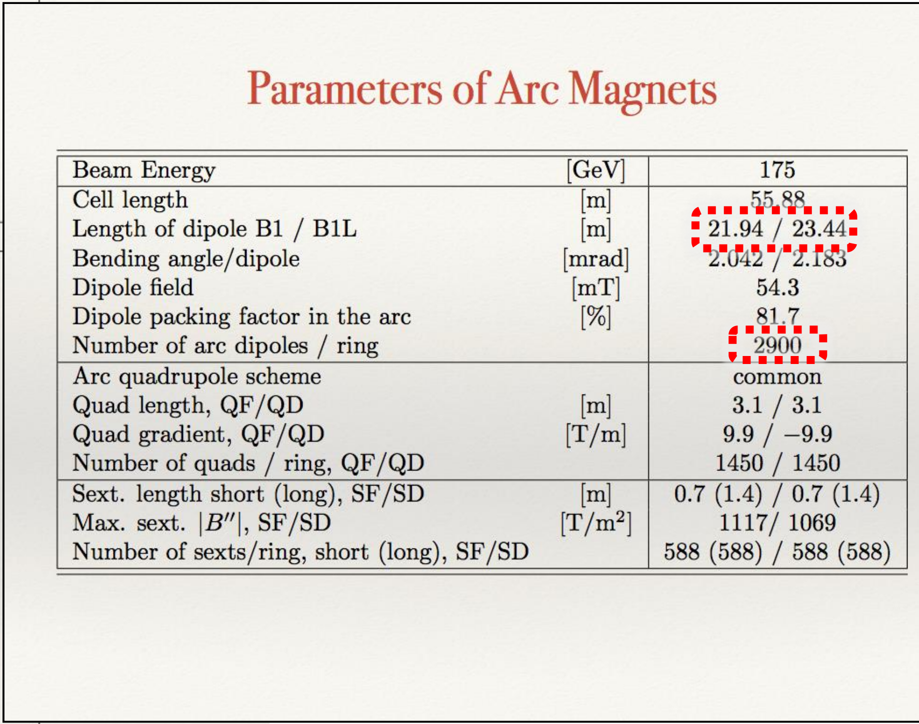
2. FCC-ee parameter list

- The list of machine parameters for the Z- and T-pole machines is shown here below (courtesy K. Oide); Highlighted in red are those which may affect vacuum;



Parameters

Circumference	[km]	97.750	
Arc quadrupole scheme		common	
Bend. radius of arc dipole	[km]	10.747	
Number of IPs / ring		2	
Crossing angle at IP	[mrad]	30	
Solenoid field at IP	[T]	±2	
ℓ^*	[m]	2.2	
Local chrom. correction		y-plane with crab-sextupole effect	
RF frequency	[MHz]	400	
Total SR power	[MW]	100	
Beam energy	[GeV]	45.6	175
SR energy loss/turn	[GeV]	0.0360	7.80
Long. damping time	[ms]	414	7.49
Polarization time	[s]	9.2×10^5	1080
Current/beam	[mA]	1390	6.4
Bunches/ring		70760	62
Particles/bunch	[10^{10}]	4.0	21.1
Arc cell		60°/60°	90°/90°
Mom. compaction α_p	[10^{-6}]	14.79	7.31
Horizontal tune ν_x		269.14	389.08
Vertical tune ν_y		267.22	389.18
Arc sext. families		208	292
Horizontal emittance ε_x	[nm]	0.267	1.34
$\varepsilon_y/\varepsilon_x$ at collision	[%]	0.38	0.2
β_x^*	[m]	0.15	1
β_y^*	[mm]	1	2
Energy spread by SR	[%]	0.038	0.144
RF Voltage	[MV]	255	9500
Bunch length by SR	[mm]	2.1	2.4
Synchrotron tune ν_z		−0.0413	−0.0684
RF bucket height	[%]	3.8	10.3
Luminosity/IP	[10^{34}/cm^{2}s]	121	1.32



Parameters of Arc Magnets

Beam Energy	[GeV]	175
Cell length	[m]	55.88
Length of dipole B1 / B1L	[m]	21.94 / 23.44
Bending angle/dipole	[mrad]	2.042 / 2.183
Dipole field	[mT]	54.3
Dipole packing factor in the arc	[%]	81.7
Number of arc dipoles / ring		2900
Arc quadrupole scheme		common
Quad length, QF/QD	[m]	3.1 / 3.1
Quad gradient, QF/QD	[T/m]	9.9 / −9.9
Number of quads / ring, QF/QD		1450 / 1450
Sext. length short (long), SF/SD	[m]	0.7 (1.4) / 0.7 (1.4)
Max. sext. $\|B''\|$, SF/SD	[T/m^2]	1117/ 1069
Number of sexts/ring, short (long), SF/SD		588 (588) / 588 (588)

3. SR spectra, photon flux and power densities

- **FCC-ee will be a very powerful and intense source of highly-collimated synchrotron radiation** (SR);
- Its critical energy, photon flux and power are given by the well-known formulae:

$$E_c = \frac{2218 \cdot E^3(GeV)}{\rho(m)}$$

$$F(ph/s) = 8.08 \cdot 10^{17} \cdot E(GeV) \cdot I(mA) \cdot k_F$$

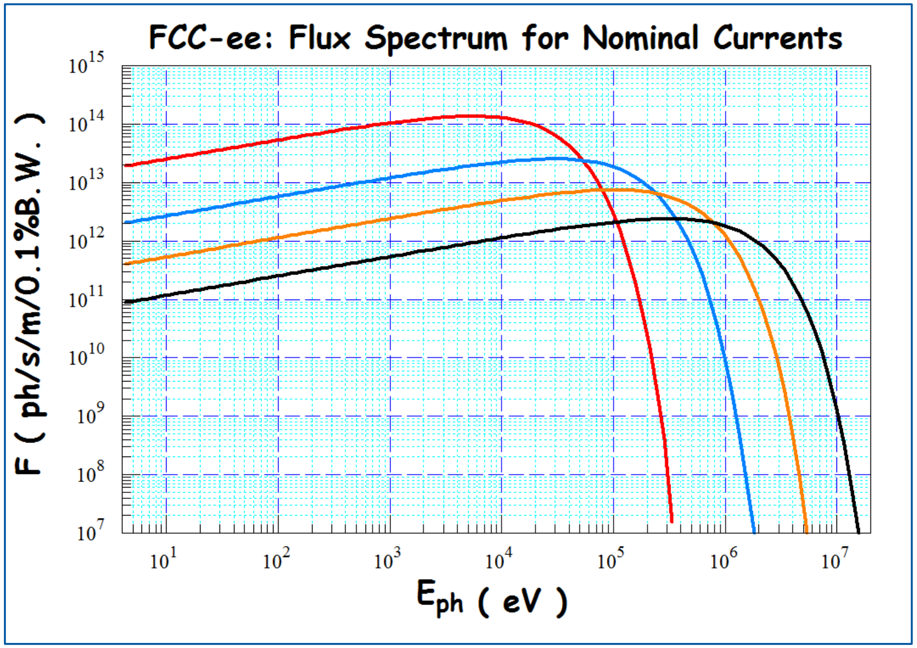
(k_F and k_P account for photons with energy e>4 eV)

$$P(W) = 88.46 \cdot \frac{E^4(GeV) \cdot I(mA)}{\rho(m)} \cdot k_P$$

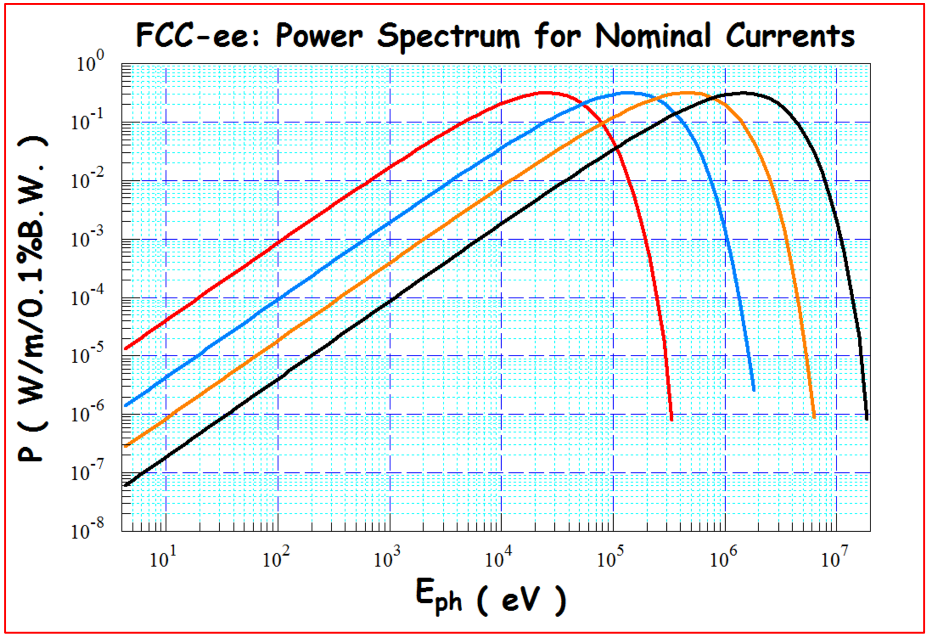
→ limited by design at 50 MW/beam

E (GeV)	E_c (keV)	I (mA)	F (ph/s)	P (MW)
45.6	19.57	1390	$4.85 \cdot 10^{22}$	~ 50
80	105.69	147	$9.30 \cdot 10^{21}$	~ 50
120	356.63	29	$2.79 \cdot 10^{21}$	~ 50
175	1106.08	6.4	$9.07 \cdot 10^{20}$	~ 50

SR flux (left) and power (right) spectra:



I (mA)
1390
147
29
6.4



- For photon energies above 100~200 keV creation of Compton photons takes place: supra-linear increase of the photon flux inside of the vacuum chamber → increased photon-induced outgassing (see bonus slides)

4. Vacuum Specifications

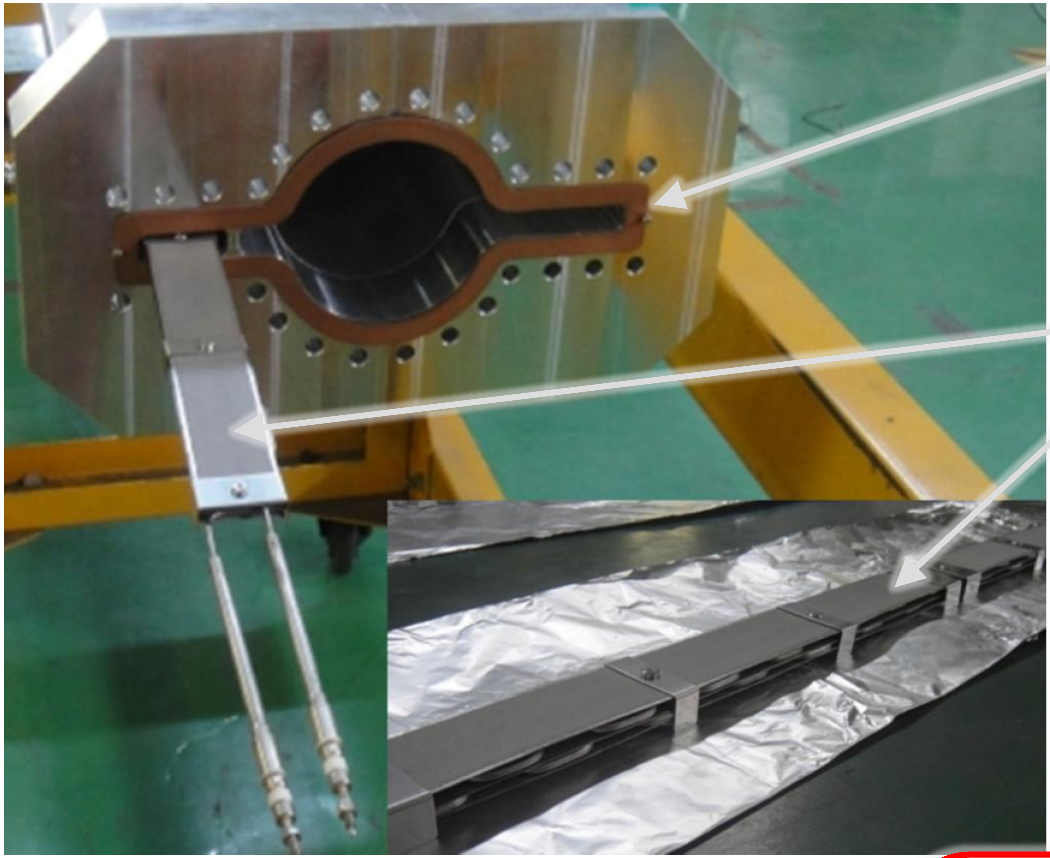
- Sufficiently long beam-gas scattering lifetimes, longer than the luminosity ones:

	Z (30k bunches)	Z (90k bunches)	W	H	T
Luminosity lifetime [min]	94	185	90	67	57

- Short vacuum conditioning time: we want to reach quickly the nominal luminosity with low pressure background, low beam losses, reduced activation of machine components and tunnel, etc…
- E-cloud- and ion-trapping-free e+ and e- rings: we want to avoid beam instabilities and beam blow-up due to excessive e-cloud, beam-ionization (then low pressure requirement), fast-ion instabilities, etc…
- Optimized vacuum system, with easy to manufacture vacuum chambers (2x100 km + full energy injection booster… industrial-scale mass production needed);
- Efficient and cost-effective pumping system: again, it's a twin-ring 100 km machine, we can't install ~1 pump/m as has been done for some B-factories;
- Use existing and proven technologies as much as possible;

5. Vacuum chamber geometries: different options and SR ray-tracing

- Having hosted the only lepton accelerator running up to ~100 GeV beam energies, it has become natural at CERN to look for the applicability of the LEP geometry;
- LEP was a large, single chamber twin beam, with pretzeled orbits and relatively low currents. The only real problems due to the SR power came from areas immediately downstream of the polarization wigglers; Its beam chamber cross-section was elliptical 131x70 mm^2 (HxV);
- The FCC-ee is a very low emittance machine, and detailed studies have proven that an elliptical chamber would excite quadrupolar moments which would destabilize the stored bunches, and should therefore be avoided; **A cross-section as close as possible to that of a circle should be preferred**;
- We have therefore abandoned the first proposal (see FCC Week 2016 and earlier), which called for a rather "flat" elliptical chamber incorporating "V"-shaped SR absorbers (see previous FCC Week indico page);
- We have adopted a SuperKEKB-type of chamber, which has a round part with two small "winglets" in the plane of the orbit; At SuperKEKB such a chamber hosts on one side a distributed pumping based on multiple, stacked NEG strips, installed behind a slotted wall;



Special low-loss copper seal

3x NEG strips, with integrated heater for NEG activation

This cross section can be extruded out of aluminium (like for the 4 GeV low-energy e^+ ring), or made welding different pieces out of copper (like for the 7 GeV high-energy e^- ring);

JVSTA

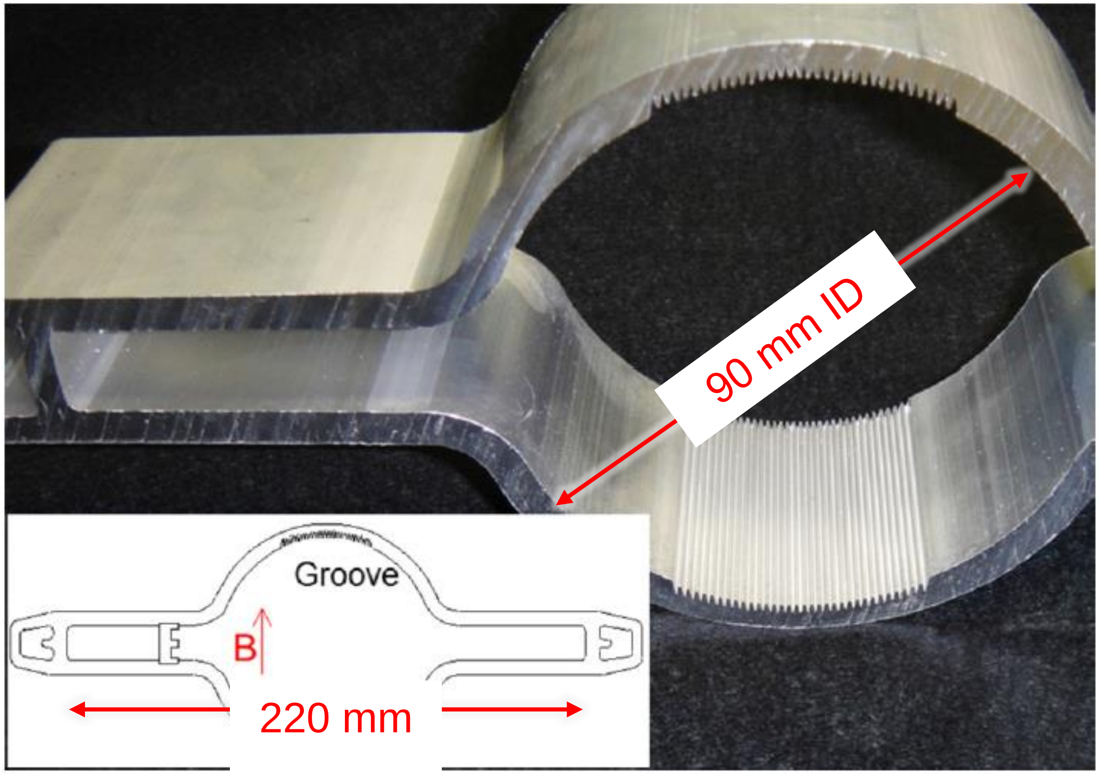
JOURNAL OF VACUUM SCIENCE AND TECHNOLOGY A

Design and construction of the SuperKEKB vacuum system

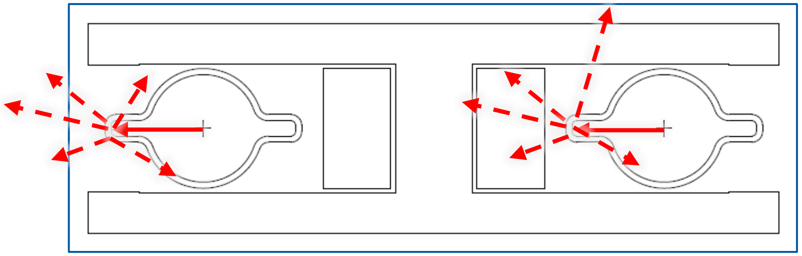
Yusuke Suetsugu, Ken-ichi Kanazawa, Kyo Shibata, Takuya Ishibashi, Hiromi Hisamatsu et al.

Citation: J. Vac. Sci. Technol. A **30**, 031602 (2012); doi: 10.1116/1.3696683

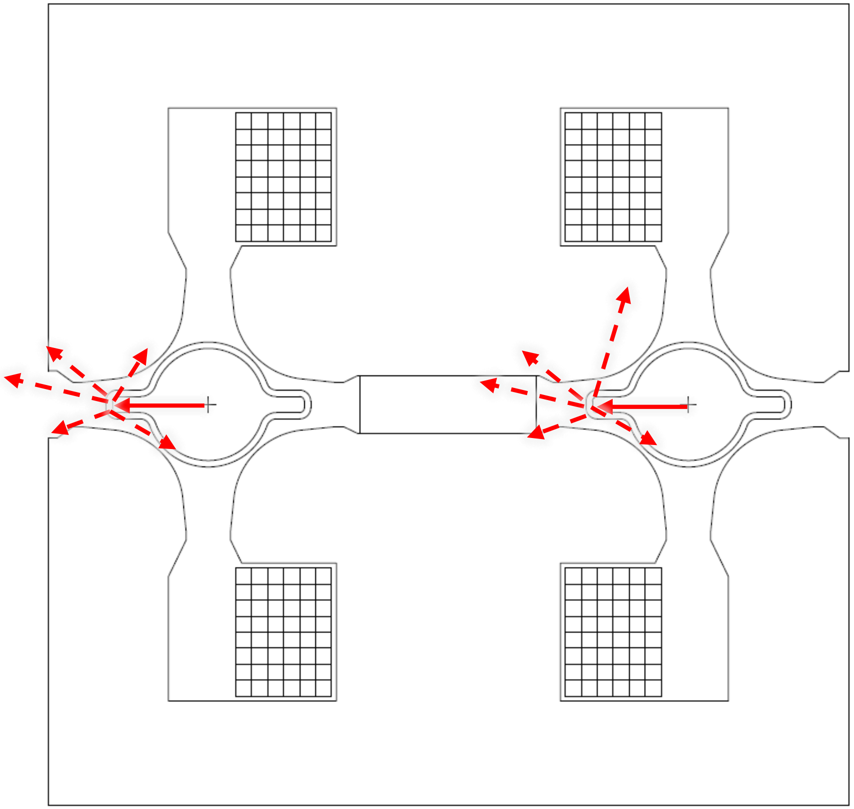
- For FCC-ee running at the T-pole, the SR critical energy is around 1.1 MeV, making an aluminium chamber not the best choice in terms of radiation leakage (see bonus slides and F. Cerutti's presentation, previous FCC Week conferences);
- A copper chamber would be preferable;



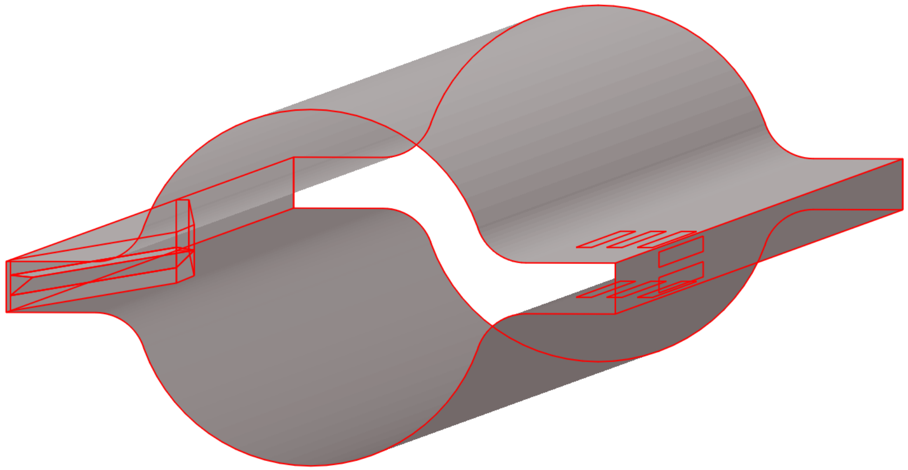
- The e+ ring, especially at the Z-pole with many short bunches and 4 ns spacing, is **expected to suffer from e-cloud**;
- **E-cloud mitigation MUST be part of the design**;
- One possibility is to use ←**grooved surfaces**, like done at SuperKEKB;
- Another possibility is to use **thin-film coatings** having a below-threshold secondary-electron yield (SEY);
- SuperKEKB has opted for TiN over NEG-coating, after having tested both on a test section of KEK-B (see “Continuing study on the photoelectron and secondary electron yield of TiN coating and NEG (Ti–Zr–V) coating under intense photon irradiation at the KEKB positron ring”, NIM A 556 (2006) 399–409);
- Based on the very positive experience on LHC’s warm sections, and on SR-light sources, we firstly proposed to use NEG-coating, but unfortunately it has recently been discovered that a 1 μm-thick NEG-coating layer would render the beams unstable due to the **resistive-wall instability** (RWI) (see E. Belli’s presentation, “Impedance model and collective effects for FCC-ee”, this conference);



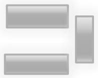
- FCC-ee main arc **dipole** and quadrupole cross-section (see A. Milanese's talk," FCC-ee Warm magnets design",this conference);
- A SuperKEKB-type cross-section has been drawn, to scale: it has a 70 mm ID circular part with two 25x10 mm^2 (HxV) "winglets" on the plane of the orbit (int. dimensions);
- The intense SR fans (←) generated by the stored beams are intercepted inside the winglet on the external side of the ring;
- At SuperKEKB the whole length of the winglet is irradiated by SR, and therefore it needs a cooling channel along it (see previous slide);
- **It becomes evident that the internal beam's SR fan irradiates the corresponding dipole coil, while the external one irradiates the tunnel components**';



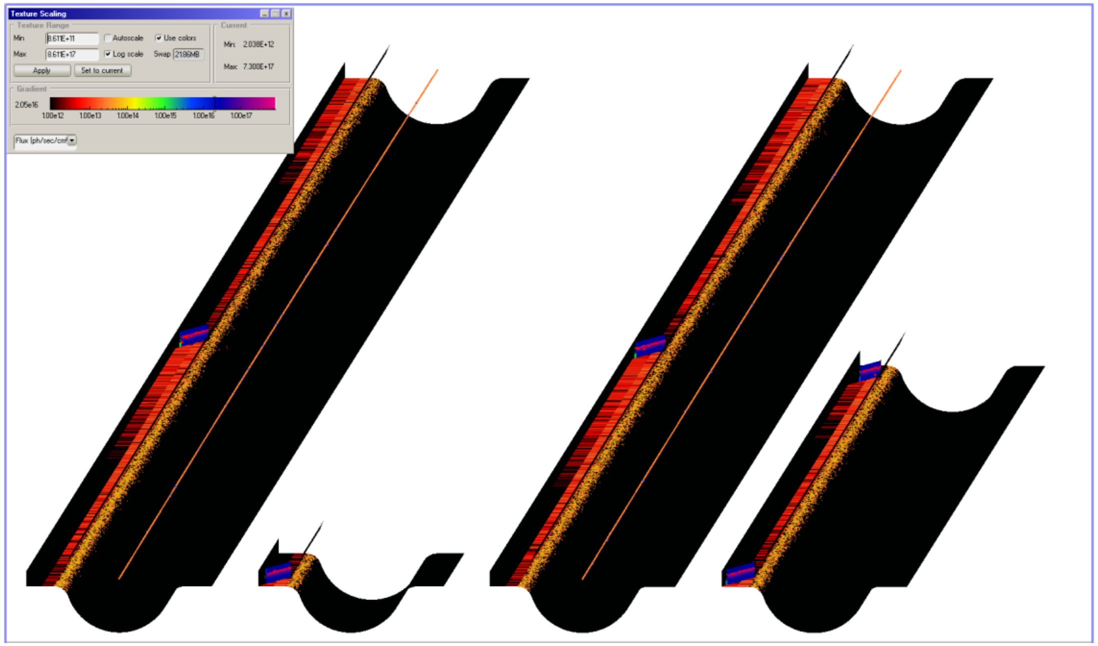
- For the **quadrupole** design, instead, the coils are in a lower-irradiation area/configuration;
- **These considerations apply mainly to the W-, H-, and T-pole machines, as the Z has a critical energy of only ~20 keV**, well below the Compton edge;



- For the selected radius of curvature of the orbit in the dipoles (10.747 km), and the 70 mm ID of the chamber, the distance between the source point of the SR and the first collision with the absorbers or the 70 mm ID wall is of the order of 35~40 m;
- This distance, combined with the natural vertical divergence of the SR fan, makes such that **only a fraction of 1% of the photons miss the 10 mm-high absorber and land on the chambers's wall** (see next slides);
- In order to limit the amount of Compton radiation leakage, and the attendant **radiation damage and components activation**, we propose to install at appropriate locations a number of lumped SR absorbers, in such a way that they cover the whole horizontal angle of the SR fan;
- **High-Z shielding could be added on the external part of the absorber** (▨);
- For geometric impedance reasons, the absorber should have a tapered shape, and do not protrude into the circular part of the vacuum chamber;
- On the opposite winglet, pumping slots could be machined, to allow molecules generated on the absorber (and elsewhere as well) to reach lumped pumps installed on a pumping plenum (not shown);



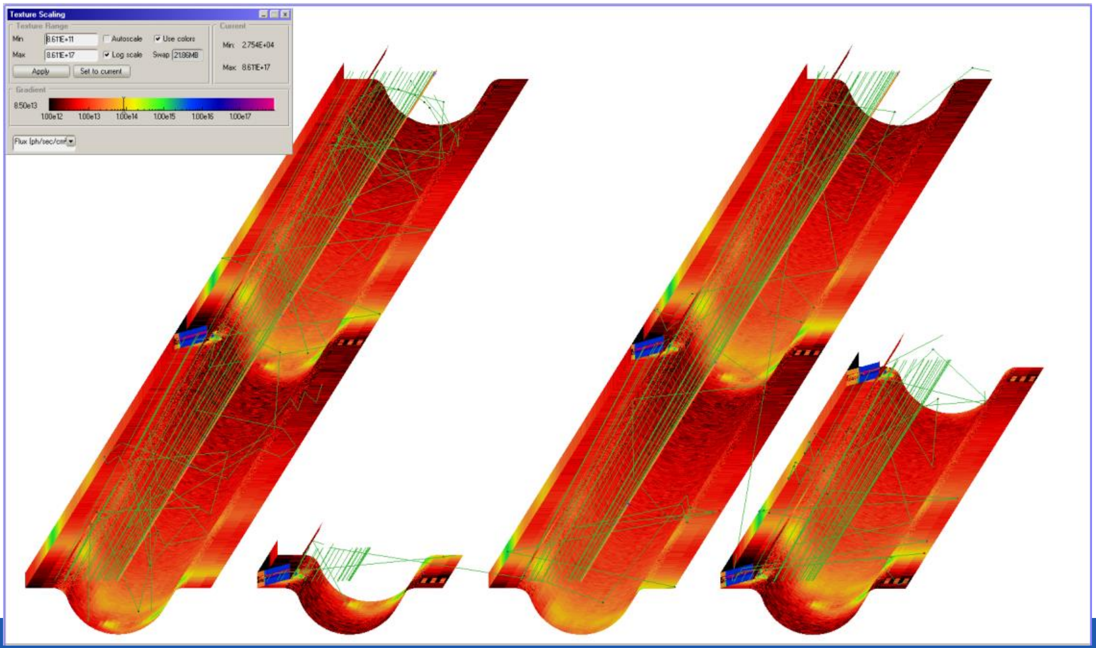
- The absorbers have a V-shaped surface where the primary SR photons impinge at a small angle thus reducing the SR power density (which for the T-pole is relevant);



Min 8.611E+11
Max 8.611E+17
☐ Autoscale
☑ Use colors
☑ Log scale
Swap 21.86MB
Current Min: 2.038E+12
Current Max: 7.300E+17
Flux (ph/sec/cm²)

- ← SR photon flux density for the no-photon scattering case (zero reflectivity);
- Less than **0.8%** of the primary photons miss the 5 absorbers and land on the vacuum chamber;
- *Note: this model shows an older version of the lattice, with 2x 10m-long dipoles (it doesn't affect the results/conclusions);*

- SR photon flux density for the realistic photon scattering case (angle&material dependent) →
- About **4.6%** of the primary photons are scattered and land on the vacuum chamber;
- **These scattered photons can generate photoelectrons which "seed" the e-cloud effect;**
- Total Power: 17.6 kW →

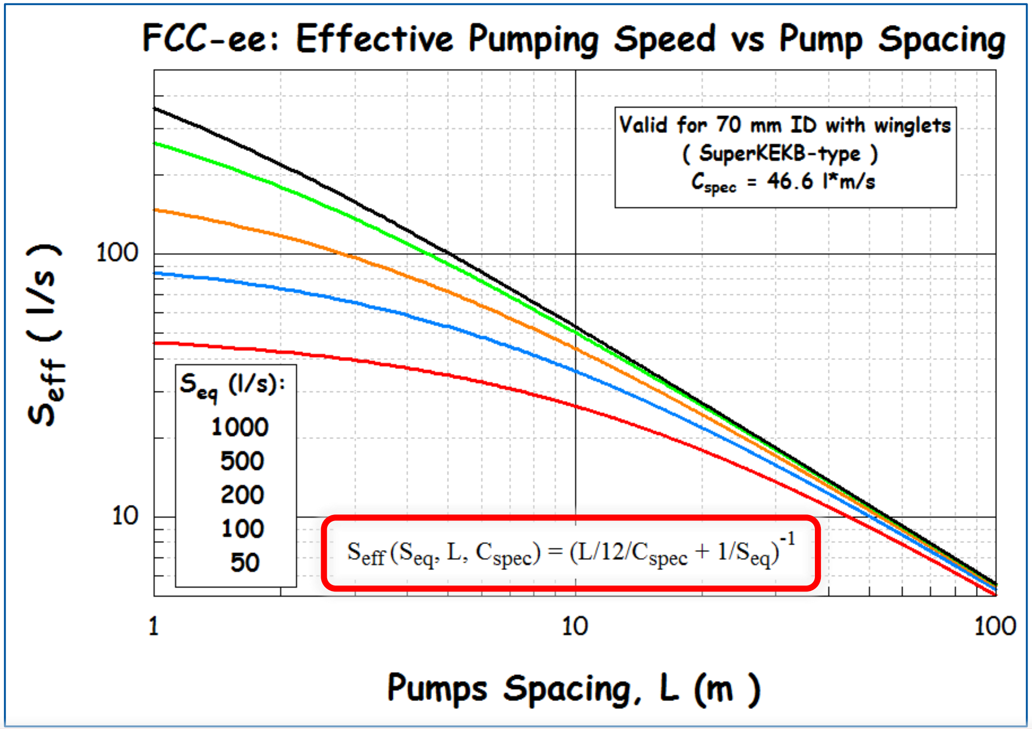


Min 8.611E+11
Max 8.611E+17
☐ Autoscale
☑ Use colors
☑ Log scale
Swap 21.86MB
Current Min: 2.754E+04
Current Max: 8.611E+17
Flux (ph/sec/cm²)

6. Pumping system options: pressure profiles

- SuperKEKB, like LEP before it, implements a distributed pumping system based on stacked strips of St707 NEG (see ref. cited above);
- Unfortunately our magnet cross-section is not compatible with a 220 mm horizontal width (internal, plus chamber wall thickness, and eventually installation tolerances): that's why we have smaller "winglets", with an horizontal dimension of only 25 mm each;
- In these 25 mm one would not be able to install the regular 30 mm-wide St707 strips, but for such a large size machine we could ask the NEG-strip manufacturer to make 20 mm-wide ones. This would reduce the pumping capacity by 33%, though;
- We have therefore explored the effect on the pressure profiles generated by different pumping configurations, taking into account the presence of the quad/dipole yokes, and coils, which would limit space for the installation of a pumping plenum;
- Out of the 5 lumped absorbers every 25 m (see previous slides), **we have calculated the pressure profile for CO when 1, 2, or 3 lumped pumps are installed in the straight part of the lattice (short dipole-dipole interconnect, and quadrupole drift area);**
- **We have also calculated the pressure when a SuperKEKB-like 20 mm-wide stacked NEG-strip pump is installed along the 2 dipoles;**

- The specific conductance of our 70 mm ID chamber with 25mm-wide winglets has been calculated to be **<u>46.6 (l·m/s), CO at 20 °C</u>**;
- For a long, constant cross-section chamber (conductance C_{spec}) with equally-spaced pumps (distance L) of the same nominal pumping speed S_{eq} the effective pumping speed S_{eff} is given by a simple formula shown in the figure:



Ref.: LEP's 131x70 mm^2 (HxV) elliptical chamber: C_{spec}=100 (l·m/s)

LEP vacuum chamber section

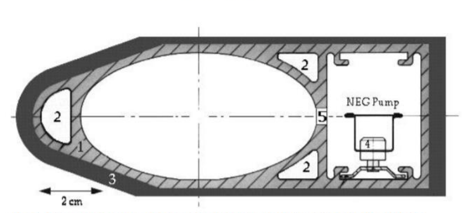
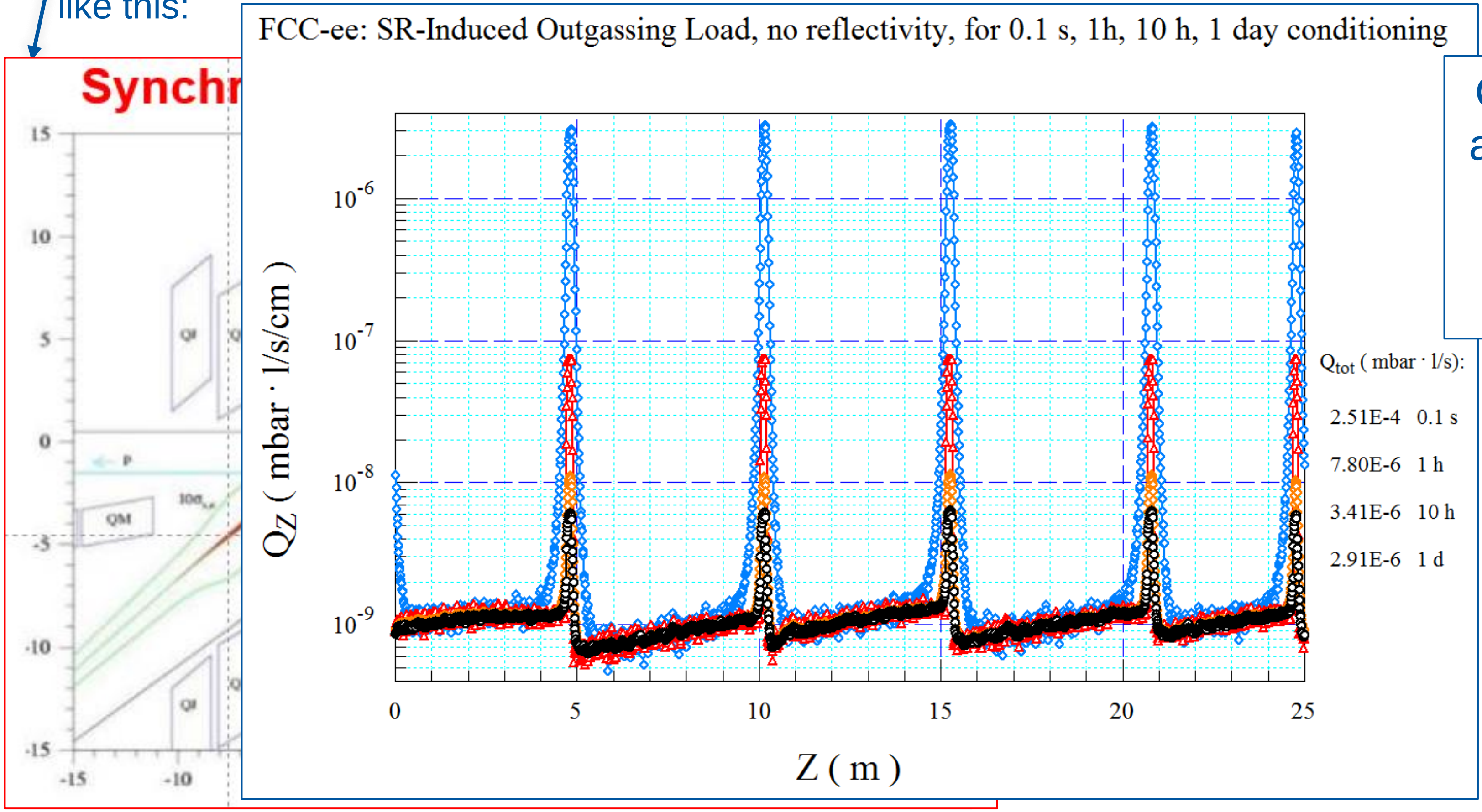


Fig. 2 : Vacuum chamber section made of (1) extruded aluminium profile with the elliptic beam channel, three cooling water ducts (2) and surrounded by 3 to 8 mm thick lead shield (3). The NEG pump (4) is housed in a separate pump channel connected to the beam channel by a row of longitudinal slots (5).

- What this means is that, unfortunately, the relatively small C_{spec} translates into the need for many pumps installed at a short distance L from each other, which <u>increases the complexity, reliability, and cost of the vacuum chamber</u> (more machining of the extruded parts, more pumping plenums, more flanges, more probable leaks, etc…)

- In order to obtain the pressure profiles (via Test-Particle Monte Carlo code Molflow+), we need to **compute the SR-induced outgassing load**;
- Sometimes a simple 2D geometric ray-tracing with a CAD system is made, essentially using a cut of the vacuum chambers in the plane of the orbit, and **assuming no photon scattering**;
- Under this hypothesis, the gas load vs beam orbit coordinate z(m) for the Z-pole machine would be like this:

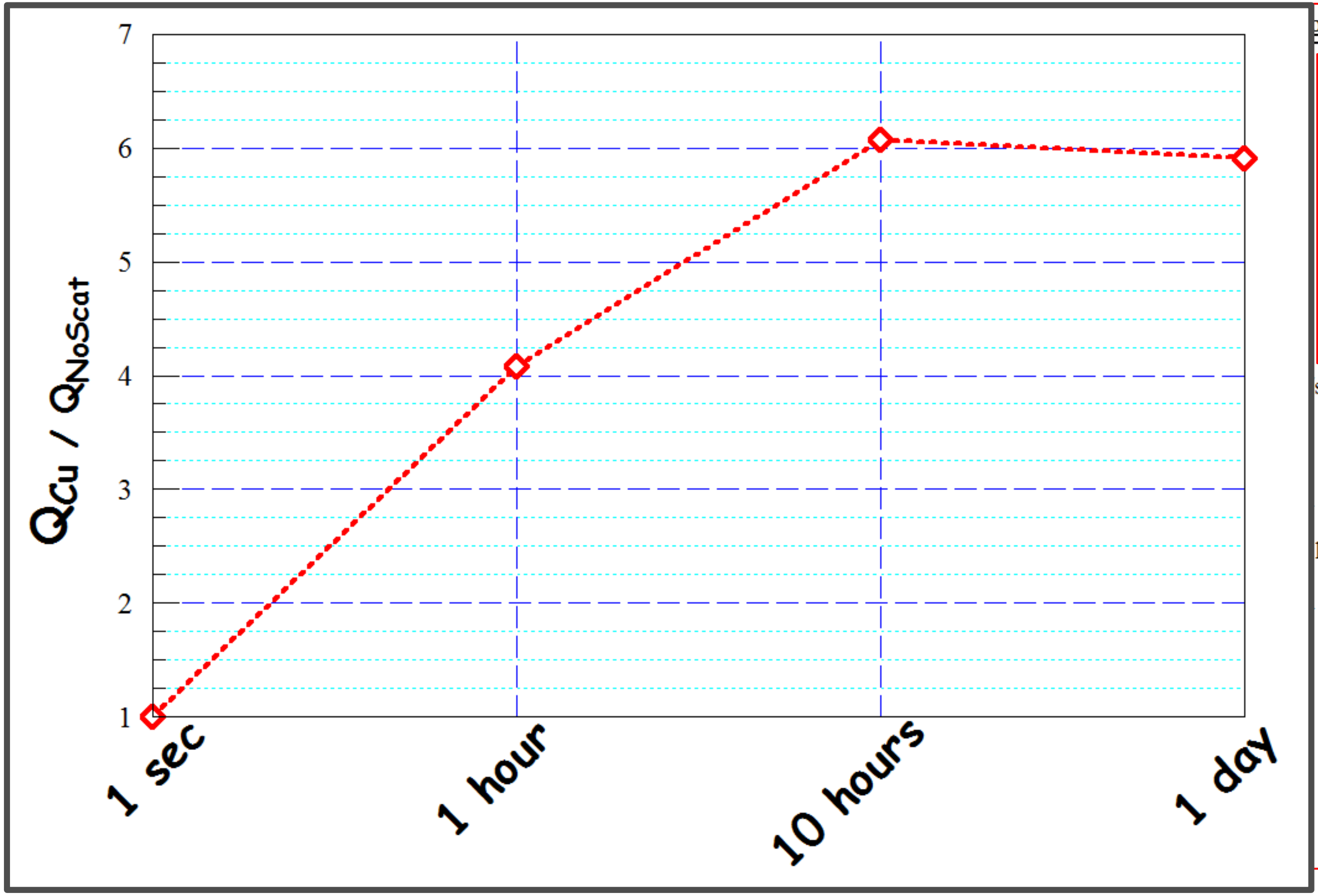

FCC-ee: SR-Induced Outgassing Load, no reflectivity, for 0.1 s, 1h, 10 h, 1 day conditioning

Computed at constant nominal current: 1390 mA

… i.e. five outgassing “spikes” corresponding to the 5 lumped absorbers;

- The integrated gas loads are shown in the table; the first one is proportional to the instantaneous absorbed photon flux distribution;

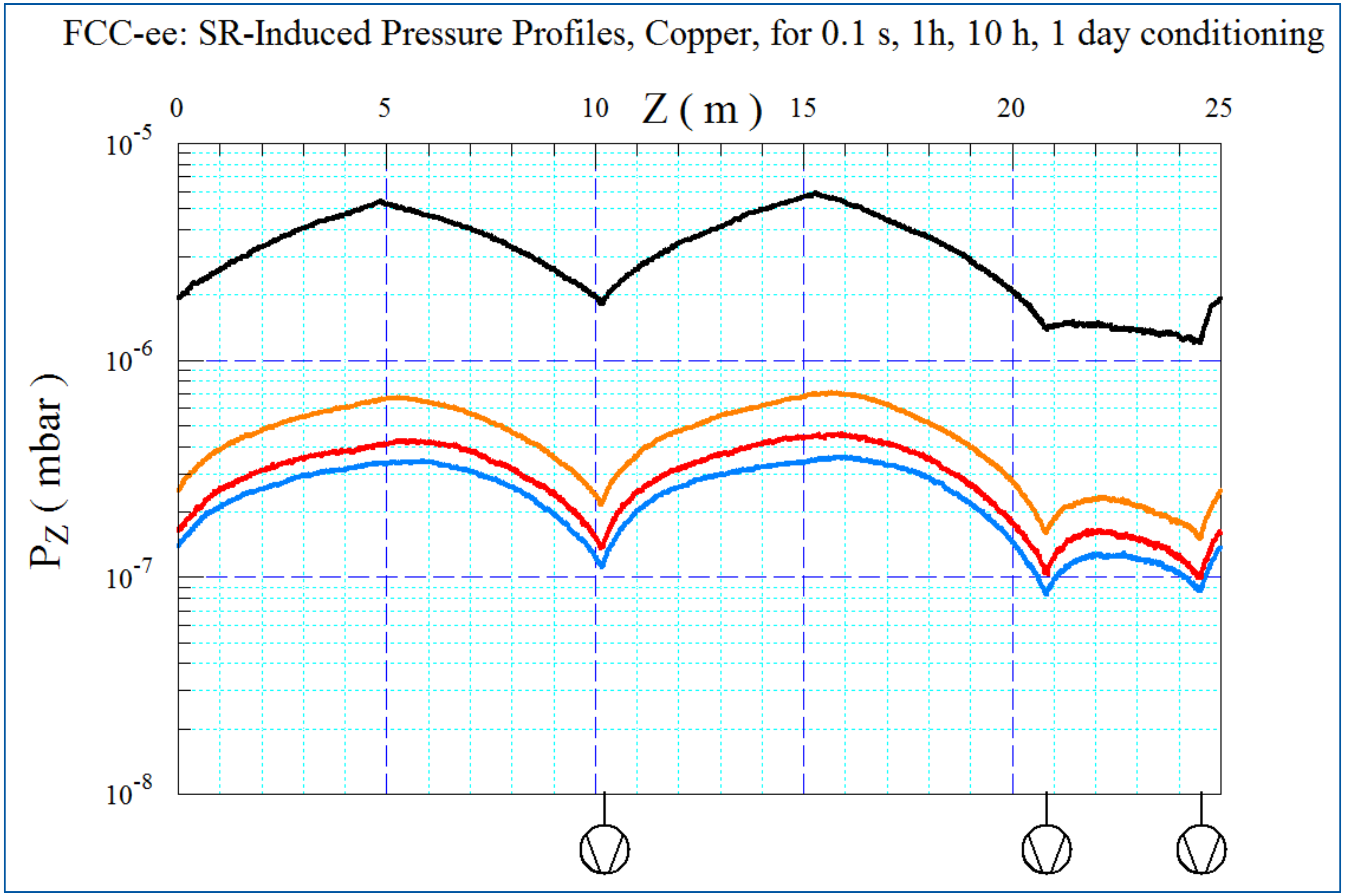
- In reality, the copper absorbers and the copper vacuum chamber will scatter most of the SR photons;
- **A realistic scattering model, with full dependence on the photon energy, angle of incidence, material, and surface roughness has been implemented recently** (see M. Ady, PhD thesis, EPFL-CERN, 2016, “Monte Carlo simulations of ultra high vacuum and synchrotron radiation for particle accelerators”, http://cds.cern.ch/record/2157666?ln=fr)



Computed at constant nominal current: 1390 mA

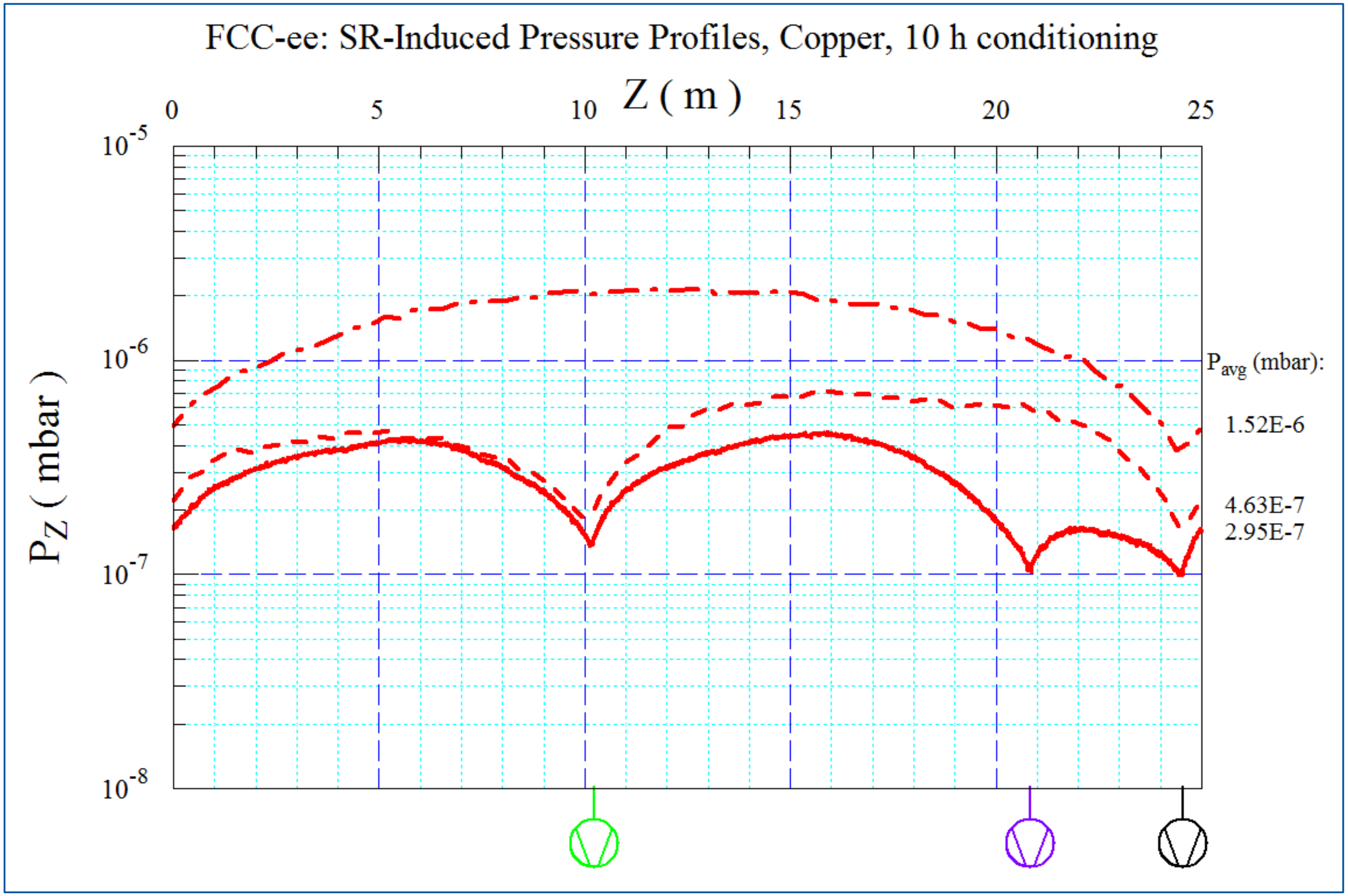
- This results in a dramatic increase of the SR-induced outgassing load profiles, and also of the integrated gas load, because the outgassing yield η(mol/ph) depends on the integrated photon dose, locally: **approximately 6 times bigger for long conditioning times**;

- Pressure profiles corresponding to the **realistic case of Cu reflectivity**, for the Z-pole are (valid for CO at 20 °C):



- They refer to the case when 3 pumps per 25 m arc length are installed, with 133 l/s effective pumping speed each;

- What if we vary the number of pumps per cell?



- Going from 3 to 2 to 1 pump per 25 m arc length we increase the average pressure by a factor of 1.6 and 5.2, respectively (note: this is valid for the 13.9 A·hr integrated dose), **a consequence of the conductance limitation**;

- It can be seen that even after 1 full day at nominal current (33.4 A·hr), the average pressure is of the order of $2 \cdot 10^{-7}$ mbar, which is very high (we aim at *low 10^{-8} range* or better)
- For CO one typically finds that the product of the beam-gas scattering lifetime τ and the pressure ***P*** follow the relationship

$$\tau P = 4.52 \cdot 10^{-8} (mbar \cdot hour)$$

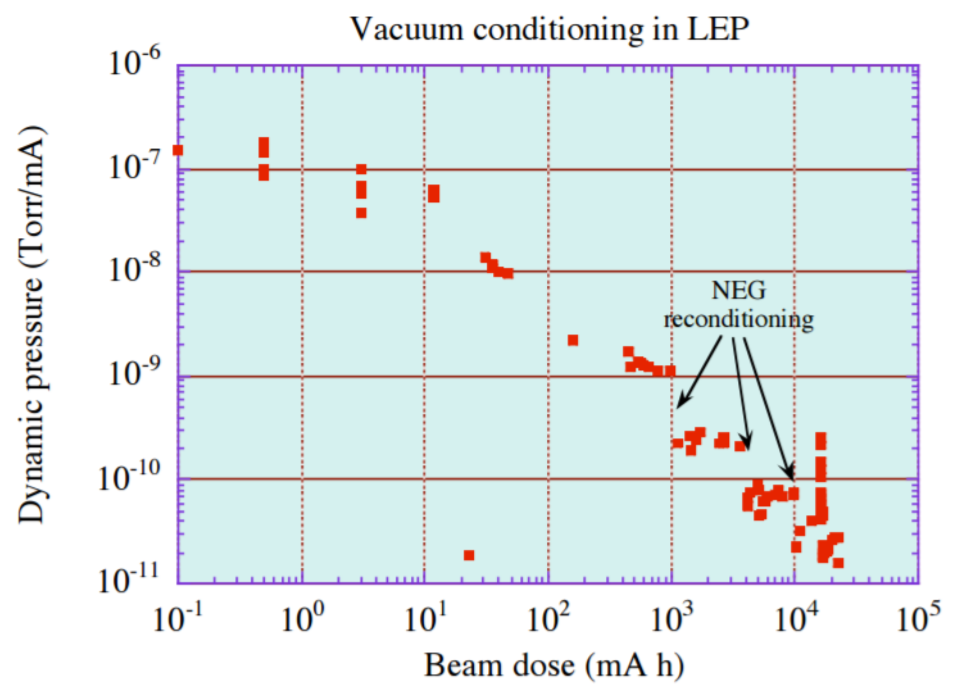
(see http://cas.web.cern.ch/cas/zakopane-2006/PDFs/Grobner.pdf)

- This means that if we want to have this lifetime contribution much longer (say 10x) than the luminosity lifetime (~100÷200 minutes for the Z-pole, depending on the number of bunches), we would need the pressure to be $\sim 1 \div 2 \cdot 10^{-9}$ mbar at least, and only when the pressure would be at least in the low-10^{-8} mbar range could we get a gas-scattering lifetime similar to the luminosity lifetime, 1.6 ~ 3.2 hours;

- **It becomes therefore apparent that for the Z-pole the vacuum conditioning time could be long, unless we are able to implement some sort of distributed pumping;**

- Ideally, a very much reduced photodesorption yield η(mol/ph) would be the best solution, for instance via massive NEG-coating of the chambers, but we have already pointed out that this seems to be incompatible with the resistive-wall instability threshold;

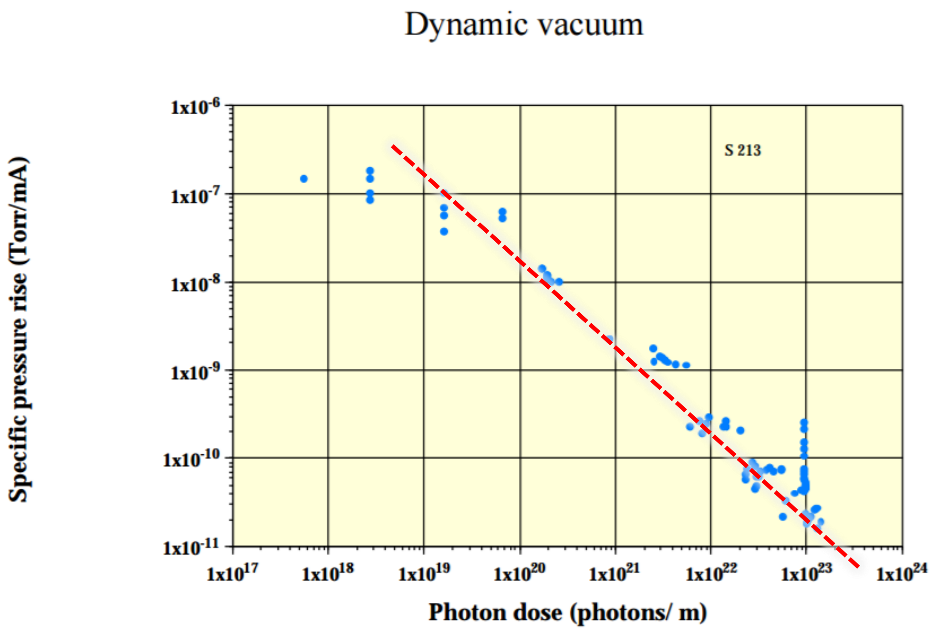
A reminder: how did LEP condition? (ref. O. Grobner, op. cit)



FCC-ee Z-pole at 1390 mA generates an average linear flux of $4.86\cdot10^{17}$ (ph/s/m);

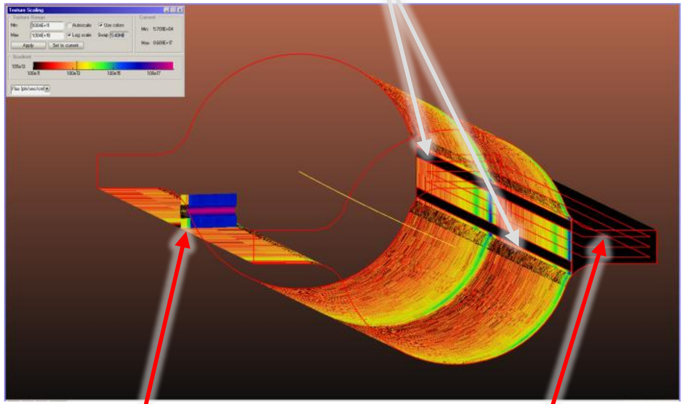
It would then need 114.3 hours in order to accumulate $2\cdot10^{23}$ (ph/m); →

The corresponding pressure would be $1.85\cdot10^{-8}$ mbar, or about 1~2 hours beam-gas scattering lifetime;



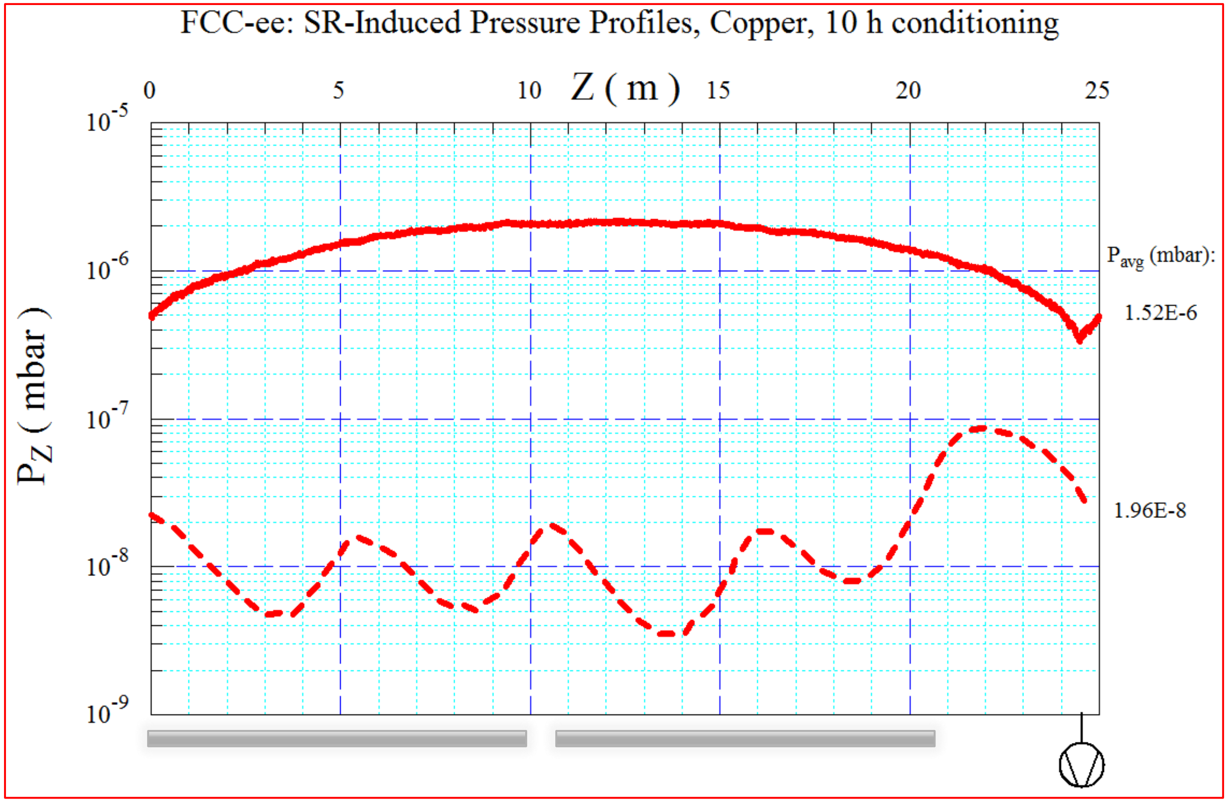
Discontinuities correspond to NEG activation/reconditioning
Data at 45 GeV during initial running of LEP

- **What is the effect of a distributed pumping?**
- We have added a 3-strip distributed NEG pump in the winglet of dipole 1 and 2, opposite to the absorbers (with only 100 l/s/m for the NEG strips (▬), a rather conservative value);
- Re-run the ray-tracing SYNRAD+ code (assuming all photons going through the 2 longitudinal pumping slots are adsorbed), then Molflow+ to get the pressure:



SR absorber
(~ in the middle of 10m-long dipole)

3x 20mm wide NEG strips

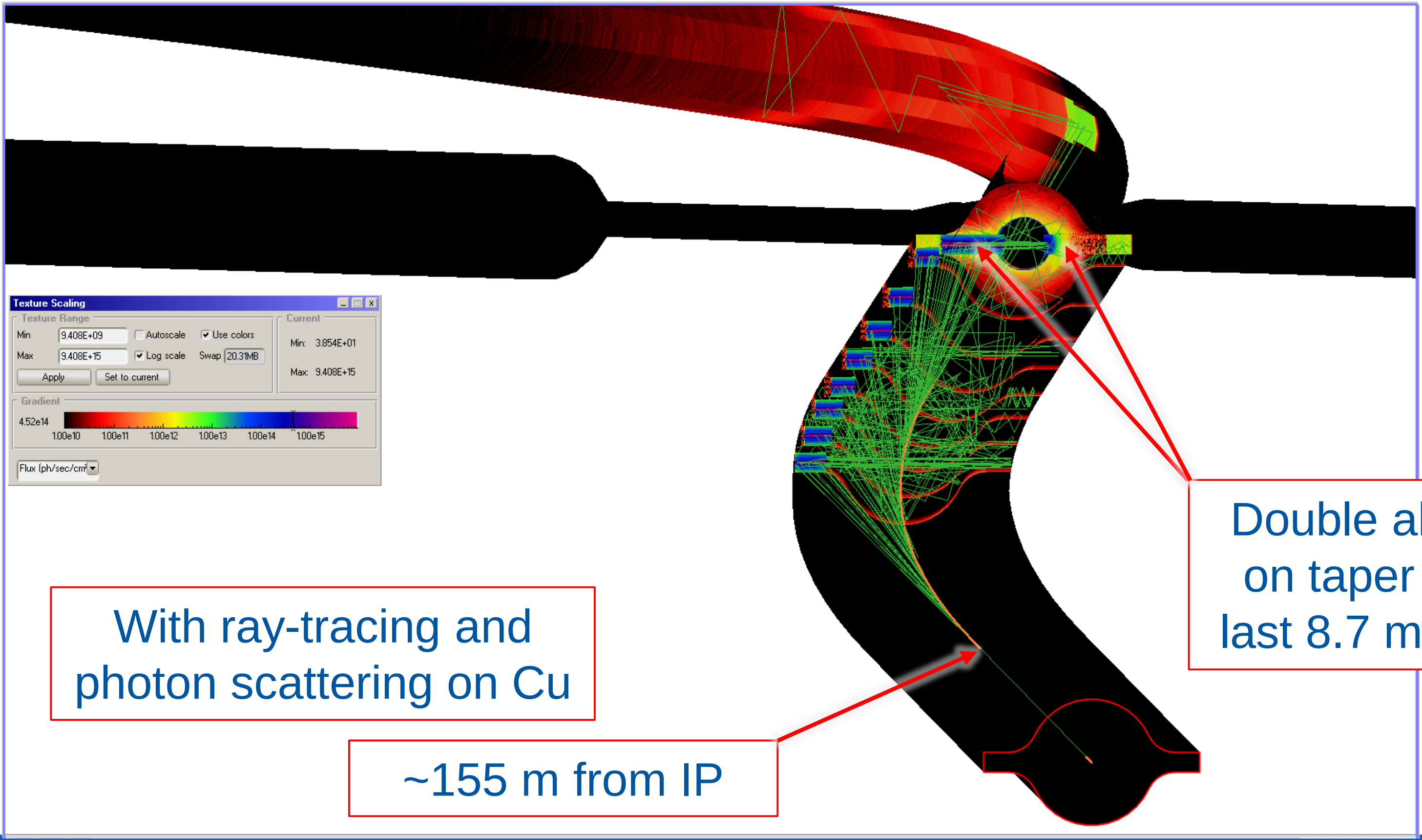


- The average pressure is **~ 1/77** of the one without distributed pumps: very effective!

7. Considerations about background in the interaction region

(see also M. Boscolo and M. Sullivan presentation on MDI, and I. Aichinger's poster, this conference)

- **The use of lumped absorbers place at strategic location to intercept all of the primary SR fan can be applied to the interaction region too;**
- Preliminary modelling results show that it would be possible to prevent most of the SR photons from reaching, either directly or via multiple Compton-scattering chain, the Be chamber, thus protecting the delicate detector electronics and detector background;



Min 9.408E+09 ☐ Autoscale ☑ Use colors
Max 9.408E+15 ☑ Log scale Swap 20.31MB

Current Min: 3.854E+01
Current Max: 9.408E+15

Flux (ph/sec/cm²)

Double absorber on taper masks last 8.7 m from IP

With ray-tracing and photon scattering on Cu

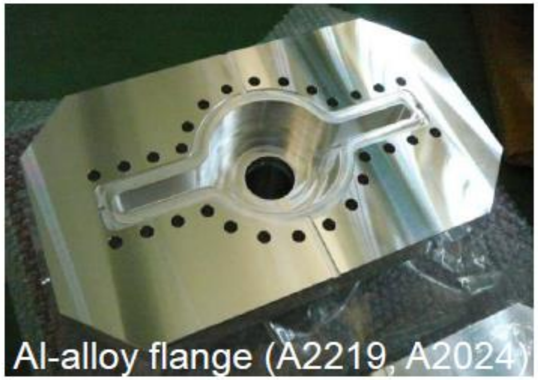
~155 m from IP

8. Other vacuum components

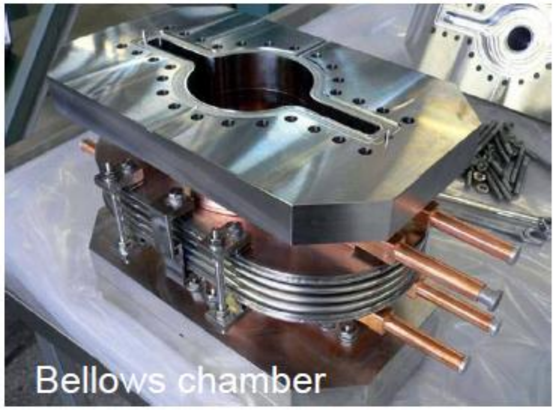
- SuperKEKB has done an excellent job at prototyping and leading to industrial production of a number of critical items for vacuum, namely low-loss bakeable metal seals, “**comb-type**” **RF contact fingers and gate valves with non-round openings**;
- **We believe that it would be worth adapting these concepts to FCC-ee;**

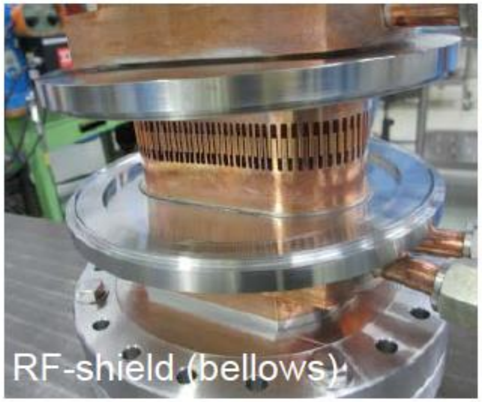
Courtesy: Y. Suetsugu, KEK

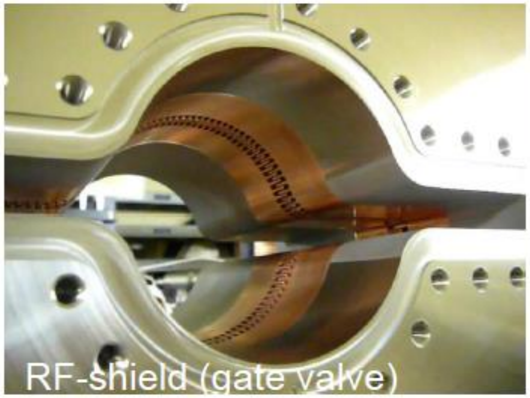

Cu-alloy flange (CrZrCu)


Al-alloy flange (A2219, A2024)


Gate valve


Bellows chamber


RF-shield (bellows)


RF-shield (gate valve)

9. Conclusions and future work towards CDR

- We propose to base the design of the vacuum system of FCC-ee on an adaptation of the design of the SuperKEKB storage rings;
- We scale down the dimensions of that chamber in order to fit our arc magnets apertures;
- We propose to install a large number of tapered SR photon absorbers, capable of covering the whole horizontal angle, masking flanges, gate valves and other components;
- We propose to adapt the design of bellows and RF contact bridges, including those of gate valves, to the “comb-type” developed at SuperKEKB;
- The vacuum chamber (VC) material of choice should be copper, rather than aluminium, in view of the its superior opacity to high-energy photons, and related radioprotection issues (see presentation of F. Cerutti at previous FCC Week);
- In order to guarantee a reasonably short vacuum commissioning time, we suggest installing distributed “stacked” NEG-strip pumps in the internal winglet of the VC (if NEG-coating is really ruled out);

- We need to re-run all simulations with the latest lattice files, and obtain the green light/validation for the final design of VC and SR absorbers from the impedance working group;
- We need to decide which e-cloud mitigation technology we want to adapt: TiN? α-carbon? Grooved surfaces? Some combination of them? (**see also M. Ady’s PhD thesis, Ch.3**);
- We need to pass the information to the FLUKA team so that they can calculate the amount of radiation leaked out of the VC;
- We need to create a realistic 3D CAD model of one arc cell vacuum system, with VCs and pumps, in order to make reasonable cost estimates;
- Attention should be also put on defining a reasonable vacuum sectoring in the tunnel, which could affect the installation and operation phases (e.g. NEG-strip re-activation);

THANKS FOR YOUR ATTENTION!

BONUS SLIDES

LEP vacuum chamber section

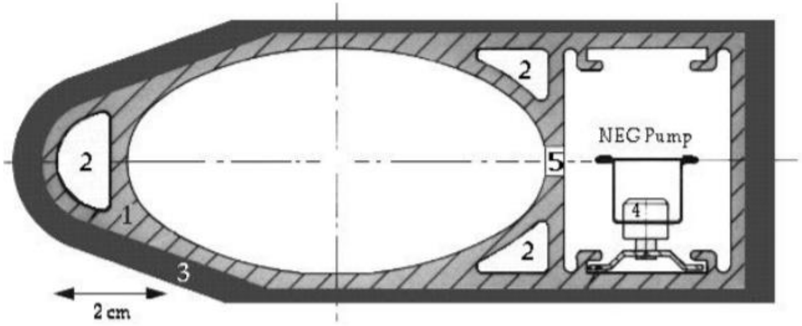
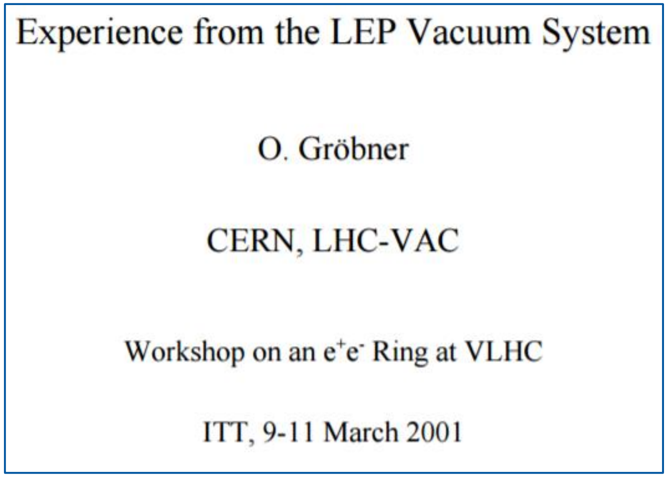


Fig. 2 : Vacuum chamber section made of (1) extruded aluminium profile with the elliptic beam channel, three cooling water ducts (2) and surrounded by 3 to 8 mm thick lead shield (3). The NEG pump (4) is housed in a separate pump channel connected to the beam channel by a row of longitudinal slots (5).



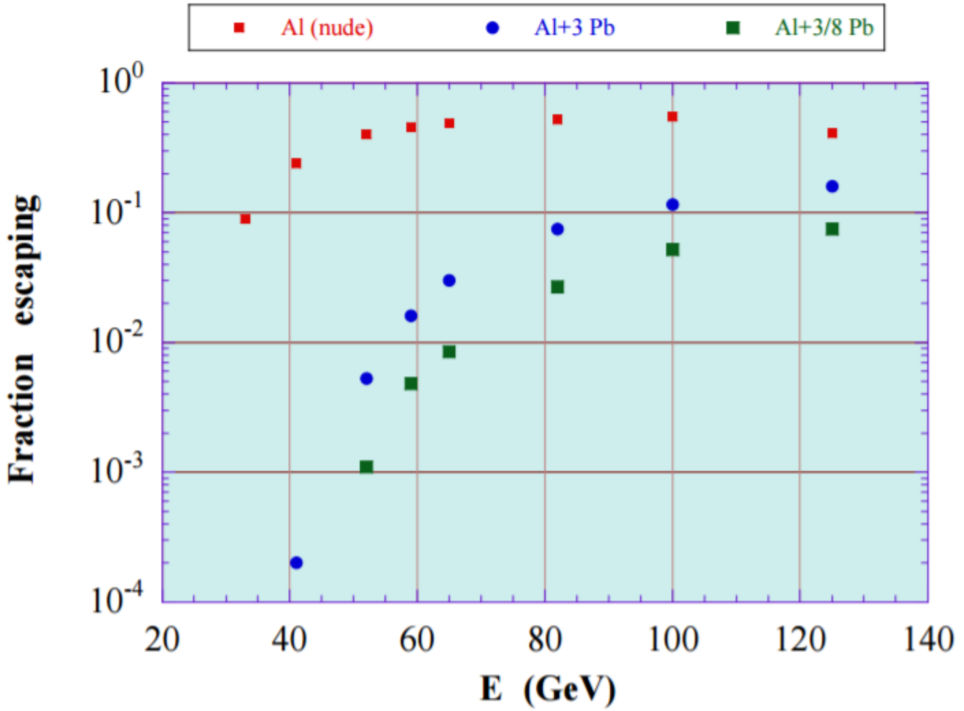
Experience from the LEP Vacuum System

O. Gröbner

CERN, LHC-VAC

Workshop on an e^+e^- Ring at VLHC

ITT, 9-11 March 2001



Fraction of s.r. escaping from LEP aluminium vacuum chamber as a function of the energy.

Cases studied:
Nude chamber
3 mm uniform lead coating
3 mm on top and bottom between dipole magnet gap and
8 mm on lateral parts

BONUS SLIDES

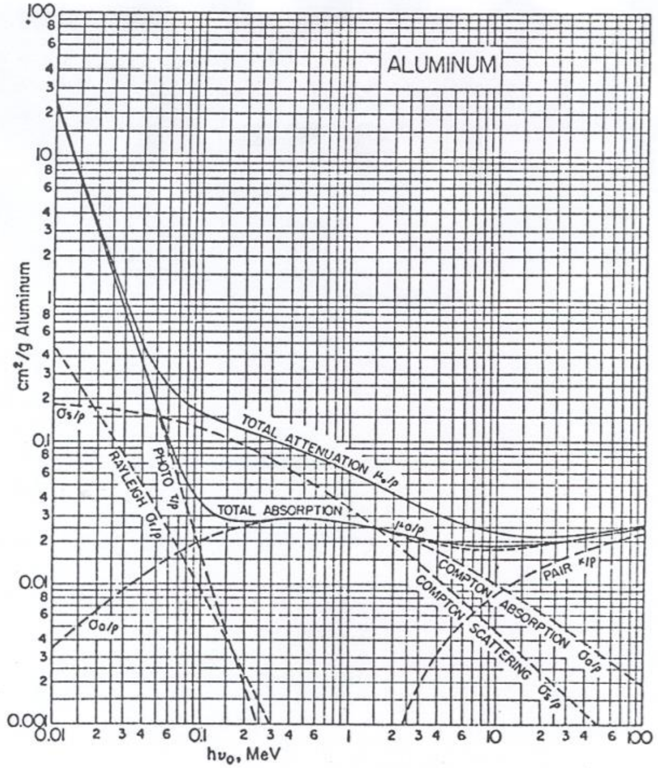
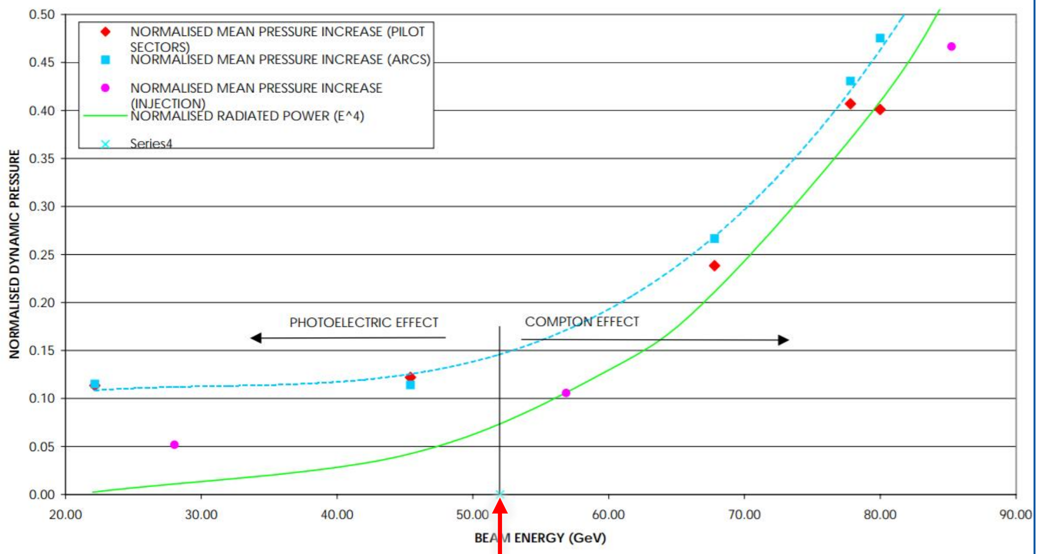


FIG. 8e-8. Mass attenuation coefficients for photons in aluminum ($Z = 13$). The dashed branch on the μ_a/ρ curve shows the effect of excluding annihilation photons [Eq. (8e-47)]. The corresponding linear coefficients for aluminum may be obtained by multiplying all curves by $\rho = 2.70$ g/cm³ Al. [*From Evans* (E1).]



NORMALISED PRESSURE INCREASE
(measured in LEP arcs 1999)

N . HILLERET - CHAM00 20/1/00

E_{crit}=100 keV