VACUUM SYSTEM REQUIREMENTS FOR A HIGGS FACTORY e+e- COLLIDER

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Abstract

Several proposals for a new class of accelerators called Higgs Factories (HF) have been made in the recent years. The LEP machine, formerly installed in what is today the 26.7 km LHC tunnel, had already given a glimpse of the issues which such machines would have to face. Since the stop and dismantling of LEP, big advancements have been made by the accelerator physics community to develop smart ways of increasing the luminosity. At the same time, the synchrotron radiation (SR) community has worked towards the development of so called "ultimate light sources", which have lately been grouped under the name of "ultra-low emittance" light sources. The merging of the two fields has allowed the development of new magnetic lattices which would allow a HF machine to obtain a very low beam emittance, which in turn would generate, with proper design of the interaction regions (IRs) unprecedented values of the luminosity at center of mass energies in excess of several hundred GeVs. These state-of-the-art accelerators necessarily need state-of-the-art implementation of technologies for their sub-systems, such as radio-frequency (RF), vacuum, feedback and control, etc…

The paper looks into the specific vacuum system requirements stemming from the large size of any HF, its high beam energy, its rather large beam currents and attendant synchrotron radiation losses and loads, just to name a few. It is shown that an optimization of the vacuum system based on discrete, localized absorbers would allow a minimization of the number and size of the pumps, especially if implemented in conjunction with distributed pumping along most of the machine, like was done in LEP. Localized absorbers would also allow concentrating the radiation background generated by the MeV-range critical energy of the SR, and minimizing the radiation damage and material activation in the tunnel.

Delving into the details, and taking into account what has been done for the Long Straight Sections (LSS) of the LHC, it becomes clear that a cost-optimization of the vacuum system is possible under the assumption that an industrial-scale development of the vacuum chamber fabrication and preparation could be carried out.

In principle, there seems to be no major technological show-stopper, since modern B-factories and light sources have already found solutions for dealing with extremely high linear photon flux and power densities.

Based on LEP experience, particular care must be taken in case damping- and beam-polarization- wigglers are installed on the rings.

This paper does not address any specific vacuum issues relevant to the IR regions or to the injectors, which are treated in separate talks.

BACKGROUND

A wealth of information on the vacuum issues relevant to very high energy e- e+ accelerators has been accumulated during the 12 years of operation of LEP, under its various forms ([1-10], and references therein). In addition to those seen on LEP, a new class of vacuum issues can be expected in HFs due to the extremely low emittance specifications for these machines, which call for narrower gaps in the magnets and stronger focusing gradients. These effects have already appeared in all their magnitude in B-factories, in particular the electron-cloud generated in the e^+ ring, an effect which had not affected LEP since it hosted both e^- and e^+ beam in the same vacuum chamber.

For the sake of clarity, the well documented case of LEP is taken as a guideline for the discussion, and extrapolations to the design and performance of future HFs are made.

SYNCHROTRON RADIATION AND GAS LOADS

Synchrotron Radiation

Any multi-GeV e^+ and/or e^- accelerator is bound to generate a huge amount of synchrotron radiation (SR). Standard formulae [11] show that the total flux varies linearly with the beam energy, while the total power varies with the 4^{th} power of the energy and is inversely proportional to the radius of curvature. For reasons related to obtaining a very low emittance, the radius of curvature of the dipoles for the proposed HFs is always very large, as is the number of dipoles. In the case of the FCC-ee versions proposed by CERN (FCC-ee Z, W, H, tt), the radius of curvature is presently ~ 11 km, i.e. ~3.5x that of LEP (3096 m) [12]. This helps with keeping down the linear flux and power densities, in ph/s/m and W/m respectively, which dictate the local vacuum conditions along the ring. As explained in the nice retrospective review paper [4], SR-induced desorption is the main source of residual gas in the vacuum chamber of a LEP-like accelerator, and is also the source of other different problems. All photons with energies above 4 eV are considered capable of inducing the emission of molecules from the surface of the vacuum chamber, and migration/diffusion from the bulk of it. These molecules in turn move randomly around the chamber until either they reach a pump and are removed or are hit by one of the circulating e^-/e^+. In that case the collision can lead to beam losses following different well known mechanisms, and energy deposition, both locally and away from the

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point of collision, as explained in [13]. HFs, in comparison with the higher linear power density of the B-factories, are characterized by the extremely high critical energy of their SR spectra. The critical energy varies with the third power of the beam energy, and is inversely proportional to the bending radius. LEP2 had reached, at 104 GeV, critical energies in excess of 800 keV, and had shown clear signs of additional heating and outgassing loads due to Compton scattered radiation, which becomes a major source as soon as the photon energy reaches few hundreds keV [3]. It becomes therefore mandatory to design the vacuum system in concert with the people dealing with radiation deposition, like has been done in [14].

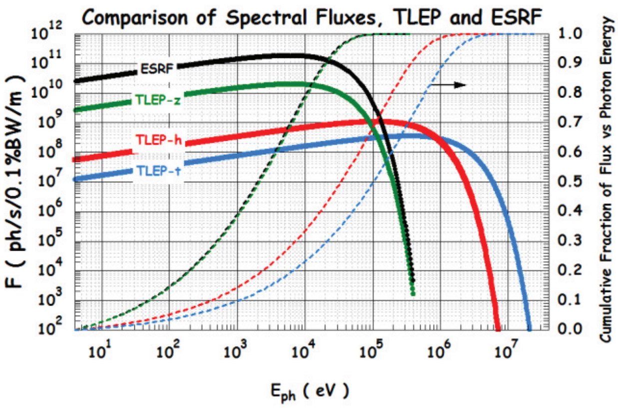

Figure 1: Comparison of the SR spectral fluxes, per meter of dipole length, for various "TLEP" flavours (now called FCC-ee), compared to that of a well-known SR light source, the ESRF. Dotted lines: scale on the right.

Gas Loads

Depending on the solution chosen for the SR absorbers, distributed vs discrete, the gas load of a HF will change a lot. It will also depend on the pumping choice made, since if the NEG-coating solution is employed, the SR-induced desorption yield will be substantially lower as compared to a non-coated solution [15], as indicated in figure 2:

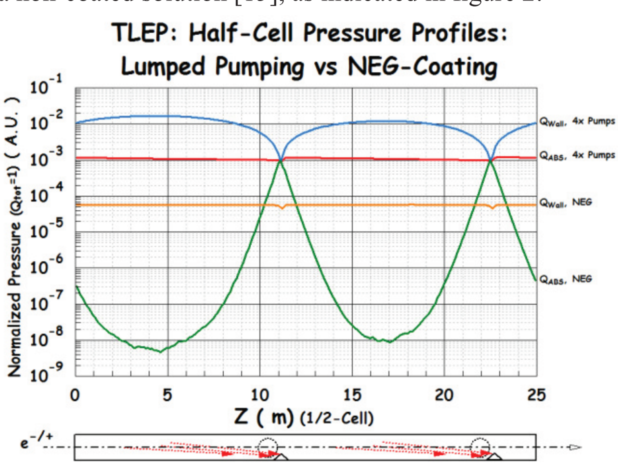

Figure 2: Comparison of calculated normalized pressure profiles for a lumped pumping with distributed SR absorption vs distributed NEG-coating with discrete absorbers. Same total flux [16]. The lower SR-induced desorption yield of NEG-coating has not been taken into account [14].

For some of the HFs under study at this time [12], gas loads of relevant magnitude should only be expected for the high-current, 45.5 GeV Z-pole version, with its 1450 mA beam. Looking at figure 1, it can be seen that the spectrum of such a HF is almost identical to the one generated by the SR light source ESRF, in Grenoble. With a critical energy of about 20 keV, practically all of its photon flux would be capable of desorbing molecules (limited amount of photons escaping the vacuum chamber via Compton scattering, see [2], Sec.5). The linear photon flux, in ph/s/m, at nominal current I and energy E is given by the formula

$$F' = 8.08E+17 \cdot E(GeV) \cdot I(mA) / (2\pi\rho(m)) \quad (1)$$

where ρ(m) is the bending radius of curvature.

Inserting the appropriate values in (1) yields the value of F'=8E+17 ph/s/m. This can be converted into practical vacuum outgassing units, for instance mbar·liter/s, via the conversion unit k, 1 mbar·liter = 2.47E+19 molecules (at 20 ºC temperature).

Dividing F'(ph/s/m) by k and multiplying by the photo-desorption yield (PDY) η(molecules/ph) we can obtain a reasonable estimate of the specific gas load Q', in mbar·liter/s/m: Q'=3.24E-2·η.

Commissioning Scenarios

For a non vacuum-conditioned accelerator, η can initially be as high as 0.01 mol/ph. Experimentally it conditions with a slope proportional to $D^{-\alpha}$, with D being the integrated beam dose in mA·hour, and α a coefficient typically ranging between -1 and -0.5 [17]. What is important to notice here, is that the initial η, at machine start-up, can vary by more than 2 orders of magnitude, depending on: 1) the choice of the material of the vacuum chambers; 2) their cleaning procedure; 3) bake-out cycle (or lack of it); 4) eventual presence of low-PDY coatings [15]. These parameters could, in principle, be combined in many different ways, and each combination would yield a different conditioning curve. The time to condition the vacuum system, which in literature is typically obtained when η decreases to 1.0E-6 mol/ph, also has a strong dependence on the combination chosen.

It is of course the responsibility of the vacuum scientists and engineers, to implement the best combination, in agreement with the project team, plan, budget and schedule.

It is important here to notice that there are clear implications of the chosen combination also on the operational constraints in case of vacuum failure, such as the time to recover the conditions prior to the failure, costs associated with the recovery, etc.

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Examples

Example 1: Just to clarify this last point, recovering a large vacuum leak in a NEG-coated section would need bake-out and activation of the full sector. Therefore, it would be important to have vacuum sector which are not too long (LEP had ~ 500 m long sectors), but the additional capital and operational cost of a large number of all-metal gate valves (GVs) with RF-contacts has to be weighted in. An 11 km bending radius HF with 200 m vacuum sectors would need of the order of 350 GVs per ring, excluding those installed in the LSS, and those around special non-vacuum equipment (SRF cavities, pulsed magnets, diagnostics, etc...).

Example 2: The equations above give a worst case initial value of the specific gas load Q' of ~3.0E-4 mbar·l/s/m and a best case, "fully conditioned" value of ~3.0E-8 mbar·l/s/m. Setting a target average pressure of ~1.0E-9 mbar for being able to run the HF with reasonably low beam-gas scattering levels (~100 hours beam-gas scattering lifetime, [13]), the former value of Q' would need the implementation of an effective specific pumping speed S' of 300,000 l/s/m, which is physically impossible to obtain, while the latter value would imply S'=30 l/s/m, which can certainly be obtained even taking into account the conductance limitations of the chambers, as can be seen in figure 3. In particular, it has been shown that NEG-coating, once activated, can provide an initial η of the order of 1.0E-5 mol/ph [15], meaning that initially a HF like FCC-ee-Z could store beams of the order of ½ its nominal current in a very short time. This simplified numerical estimate does not take into account the additional, and possibly large, gas load generated by any non NEG-coated components facing vacuum which would be hit by stray, scattered photons. This is clearly the case for present day design of sliding contact fingers inside the bellows, an item which has been under close scrutiny by the vacuum community since several decades.

VACUUM HARDWARE

Vacuum Chamber Materials

LEP had been built using aluminium alloy, mainly for ease of fabrication (good extrusion and machining) and cost, but this choice had a strong impact on its vacuum performance .

First of all, SR-induced desorption from aluminium is well known to be higher compared to that of austenitic steels or copper alloys [3], and therefore needed a more efficient pumping mechanism. Aluminum is also more transparent to high-energy photons, and therefore lets a larger fraction of the SR spectrum escape the vacuum chamber, deposit energy, and create radiation damage and activation on components outside of the vacuum chamber [1-4]. This in turn may generate a higher concentration of ozone in the tunnel, which may provoke corrosion. In order to reduce these effects, a lead cladding had to be installed all around the vacuum chamber [7], and this in turn created other unexpected problems (de-polarization of the beams due to nickel in the Al-to-Pb bonding layer, and localized heating of the chamber). Aluminium chambers also dictated, in LEP, a low bake-out temperature and the need to develop custom sealing flanges based on soft, pure aluminium, with diamond-shaped rings, which could only be baked at low temperatures. This low temperature bake-out, maximum 150 ºC via super-heated water, reduced the effectiveness of the bake-out procedure.

On the other hand, modern B-factories have accumulated experience with copper for the fabrication of their vacuum chambers (typically for the high-energy ring), and therefore a natural choice would be to employ Cu, due to its superior mechanical strength, better electrical conductivity and thermal dissipation higher density and attenuation factor. On the other hand, copper alloys cannot be extruded as easily as aluminium ones, and are more expensive. They can be baked to higher temperatures as compared to aluminium ones, and this may help for the passive activation of NEG-coatings during bake-out (see sections below).

Austenitic stainless steel is the best known material and the one most used for the fabrication of vacuum components. It has strengths and weaknesses as compared to aluminium and copper, though. In particular it has a very low electrical conductivity, and has a low thermal conductivity as well. On the other hand, it is easily weldable and via the ConFlat design of the flanges, can be baked at high temperatures, therefore assuring water vapour-free residual gas composition, and passive activation of NEG-coatings (see sections below).

Vacuum Hardware

Contrary to LEP, the proposed HFs have all in common a very low emittance target, which demands a very careful design of all components such as bellows, flanges, tapered transitions, beam-position monitors (BPMs), feed-back and control instrumentation (horizontal or vertical electrostatic separators, stripline monitors, injection and ejection kickers and septa, beam scrapers, SR-light monitors, low-gap wigglers or undulators, etc…). The analysis and design of such components must be carried out in close collaboration with people doing impedance studies, as there is ample evidence that adverse effects take place in low-emittance machines whenever there is a change of cross-section of the vacuum chamber, or material properties change (e.g. with regards to coatings of surfaces). Also, the bake-out cycle demands a careful placement of a sufficient number of low-impedance bellows, in order to take care of the elongation of the chamber, and possible misalignment, during bake-out. In particular, LEP suffered a number of failures at bellows, especially when affected by high-order mode (HOM) radiation leaking from RF cavities or other components capable of trapping HOMs, and stray SR from strong quadrupoles in the LSS [4]. Clearly, all vacuum hardware components must be carefully integrated into the CAD model and a series of ray-tracing runs, taking into account any possible positioning tolerances for the beam orbits and

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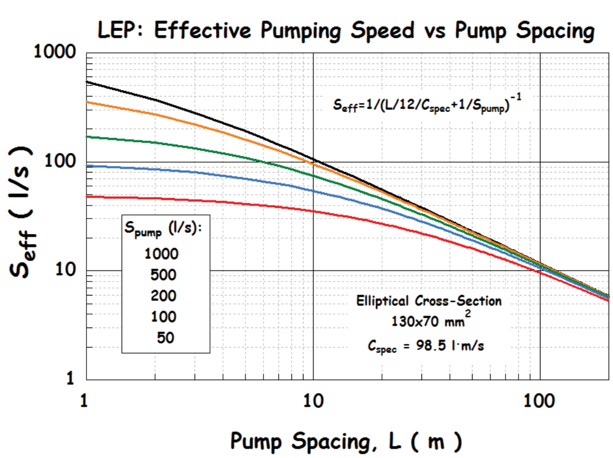
vacuum chambers, must be carried out. Modern computing tools allow to do this, either open-domain software [18, 19], or commercial ones.

Another accelerator hardware category to mention is the RF cavities. For reasons of energy conservation and needed acceleration gradients, superconducting RF technology (SRF) is mandatory whenever high beam energies are to be reached. This was the case for the LEP-2 upgrade, which more than doubled the initial energy of 45 GeV. SRF cavities need a very good vacuum in the sections between different cryomodules, and those preceding and following them, in order to minimize the possibility of polluting the surface of the cavities, which is kept at liquid He temperatures. For the HFs under study now, the LSS seem to be sufficiently long so as to guarantee the possibility of placing the SRF cavities sufficiently far from the nearest dipoles and their powerful SR fans. Alternatively, the SRF cavities must be protected by carefully designed SR absorbers with large-conductance pumping systems. This kind of analysis and technology has already been developed for high-current B-factories and SR light sources, and therefore it should not constitute a major hurdle towards the design and construction of a HF.

Pumping System

Contrary to the custom of the times, which employed either lumped pumps or distributed ion-pumps inside the dipoles, a novel pumping solution was proposed and finally adopted for LEP [20]. The NEG strip, combined with the possibility to extrude complicated shapes out of aluminium, allowed the implementation of distributed pumping along the arcs of LEP. Distributed pumping is much more effective than lumped pumping in conductance-limited vacuum systems [21]. The St101 NEG strip of LEP installed in the ante-chamber generated about 260 l/s/m of average pumping speed along the dipole chambers: in order to obtain the same average pumping speed using lumped pumps of 500 l/s, they should be installed at ~2 m spacing from each other, which would be impractical and extremely expensive. For LEP, with its ~ 3 km radius of curvature, it would have meant of the order of 8,800x 500 l/s pumps (as a best case, without considering further restrictions coming from the conductance limitation at the pumps' throats, e.g. RF-shielding grids).



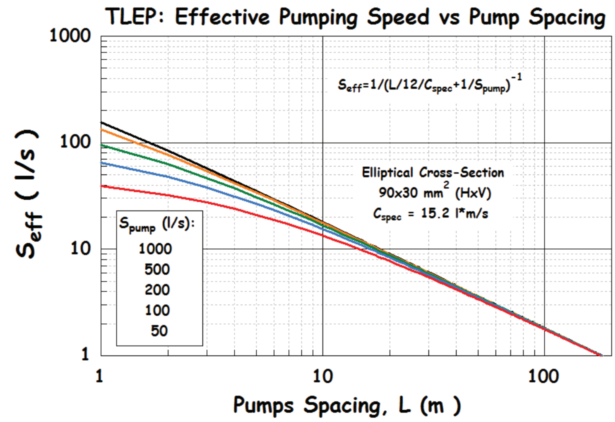


Figure 3: (top) LEP elliptical chamber: effective pumping speed vs pump spacing for different pump sizes; (bottom) same for the proposed FCC-ee chamber [10, 14].

Trying to obtain the same pressure inside of a FCC-ee-like machine would be physically impossible even using 1000 l/s pumps installed at 1 m spacing, as figure 3 (bottom) shows: an effective pumping speed slightly above 150 l/s/m would be obtained. This is the consequence of the fact that the specific conductance of the proposed FCC-ee chamber is ~ 6.5 times smaller than that of the elliptical LEP chamber. This demonstrates once more the effectiveness of distributed pumping vs discrete pumping in conductance-limited vacuum systems.

The importance of the specific conductance is evident when comparing the value for different cross-sections. In figure 4 the parabolic pressure profiles obtained along 5 different 5 m-long chambers is shown. We have chosen the two cross-sections of the KEK-B machine [22], the 130x70mm^2 elliptical chamber of LEP (without antechamber), and the proposed FCC-ee elliptical 90x30mm^2. The KEK B chambers are round 94 mm ID,and racetrack 150x94 (HxV) mm^2.

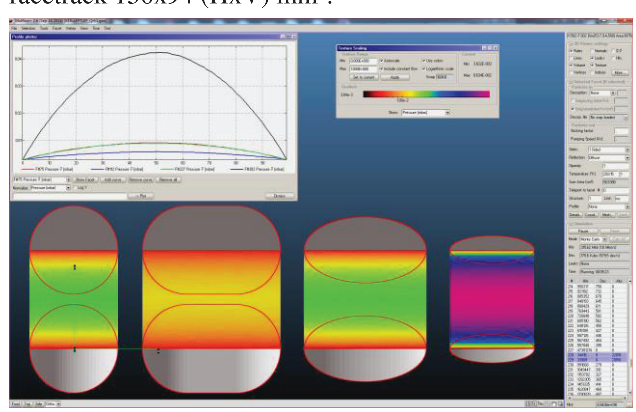


Figure 4: Parabolic pressure profiles along the 5m-long chambers. From left to right: KEK B round and racetrack, LEP, FCC-ee. 160 l/s pumps are assumed at each extremity of the chambers. A unitary outgassing rate is also assumed. The colour-coded pressure along the rectangular transparent facet on the plane of the orbit is in logarithmic scale.

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It has already been shown [16] that for an effective reduction of the outgassing rate and effective pumping to take place, a discrete absorber design of the vacuum system should be preferred as compared to a distributed absorption of SR along all chambers (as had been the case for LEP). It is interesting to note that the LEP design team had, in effect, considered the possibility of implementing such a discrete absorber design (page 30 of [9], and [10]), but their estimation of needing a ~1.5 m spacing between adjacent absorbers led them to the conclusion that it was not practical to do it. Although not clearly stated in their report, it is our impression that the 1.5 m spacing was dictated by the fact that LEP was a two-beams-in-one-chamber accelerator, with need to accommodate future changes in the pretzeled orbits. Clearly, a separated-ring design, where the e^- and e^+ have each dedicated arc chambers, with a larger bending radius would help in this direction, as is the case for the FCC-ee study machine. As shown in [14,16], a single-beam HF with ~ 9 km bending radius of curvature would need a spacing of about 12 m, in order to absorb all primary photons [16] (i.e. except those scattered on discrete absorbers), see figure 5, and ~6 m for minimizing the amount of radiation scattered on the magnet coils and in the tunnel (creation of ozone) [14], see figure 6. On the other hand, the e^+ beam would suffer from the e-cloud effect, as seen in all machines dedicated to e^+, and appropriate mitigation mechanisms should be envisioned in that case (low secondary electron yield – SEY– coatings or solenoids).

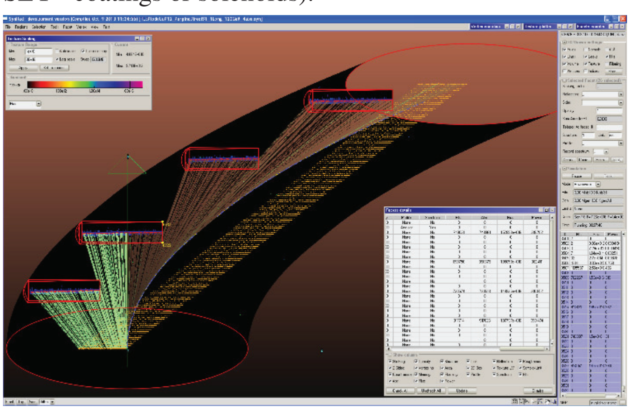

Figure 5: Ray-tracing (SYNRAD+ code [18]), of a half-cell FCC-ee arc chambers, with 4 discrete absorbers [16]. 100 percent of the primary SR fan is intercepted by the Cu absorbers. Elliptical chamber, 90x30 mm^2 (HxV).

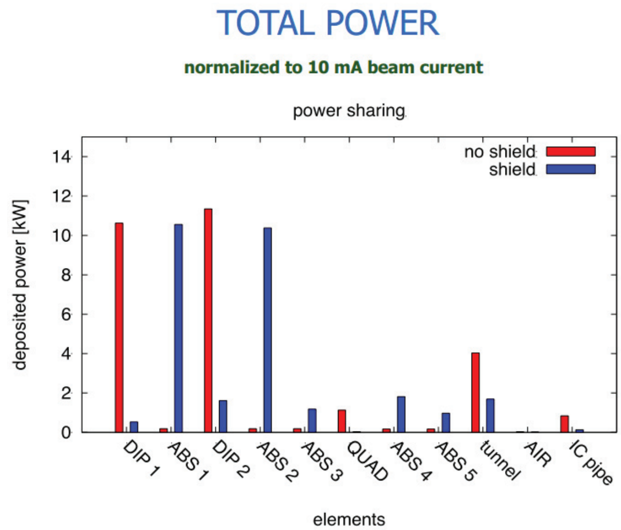

Figure 6: Four absorbers per 25 m section of the FCC-ee FODO arc elements. Copied from [10]. In addition to covering 100% of the primary photon hits, the additional 4 absorbers/half-cell minimize also the Compton-scattered radiation to the coils of the magnets and to the tunnel.

CONCLUSIONS

General Remarks

This paper has used a retrospective view and analysis of data of the operation of the vacuum system of LEP, as the natural ancestor of today's high-energy Higgs Factories. It has been shown that the vacuum technology available today is adequate to deal with the demands of such machines. This good news does not, in any way, eliminate or alleviate the need for a careful analysis, based on all available software tools and literature bibliography, of the design of the vacuum system of a HF. In particular, careful 3D ray-tracing, i.e. employing real CAD models of the vacuum chambers, is mandatory, in order to avoid the appearance of hot-spots during the operation of the machine.

Also, the paper has given indication of possible choices which could be made in terms of vacuum equipment (materials, treatments, sectorization, bake-out cycle, NEG-coatings, etc…) which would lead to different commissioning scenarios, or scenarios to recover from vacuum leaks/problems, and including rather wide budget envelopes for the total cost of the vacuum system.

Just to stress this important point once more, a ~66.5 km arc section (FCC-ee, [8]) pumped by lumped pumps installed every 12 meters would mean the need for 5500 pumps per ring, with most of the pumps needing a cable (like in the case of ion-pumps) subject to radiation damage by the high-critical energy SR beams, and an additional couple of flanges plus a spool piece to connect each pump to the beam chamber, in contrast to a NEG-coating solution which has an initial non-negligible capital cost for the coating plant or contract to industry, but then does not need more than one "holding" ion-pump per 50~100 m (depending on the conductance of the chamber).

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Requirements

- Cross-section of the vacuum chamber as big as possible (to maximize the specific conductance)
- Implementation of distributed pumping scheme
- Choice of a combination of vacuum chamber material and treatments which assure the lowest possible photon-induced desorption
- Careful analysis and design based on 3D ray-tracing
- Optimization of the vacuum sector length
- Capability to bake-out the vacuum chamber to, at least, 200 ºC
- Implementation of e-cloud suppression measures in case of separated-rings option

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