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# DESIGN OF THE VACUUM SYSTEM OF THE FCC-ee ELECTRON-POSITRON COLLIDER

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*Abstract*

The Future Circular Collider (FCC) Design Study includes a high-luminosity, low-emittance, two-ring storage ring (FCC-ee) where electrons and positrons are stored and made to collide inside two detectors.

The vacuum system of FCC-ee must be designed in order to deal with a lower-energy (45.6 GeV), high-current (1390 mA) Z-pole machine and at a final stage with a higher-energy (175-182.5 GeV) low-current (6.4-5.4 mA). Two intermediate energies are also envisioned. The lower-energy machine turns out to be the most challenging one from the point of view of vacuum, since the photon-stimulated desorption (PSD) generated by the copious synchrotron radiation (SR) fans is quite large.

Optimization of the pressure profiles has been carried out by means of extensive coupled monte-carlo simulations and optimization, for SR and molecular flow.

For the higher energy versions of the machine, for which the SR spectra are characterized by critical energies well above the Compton edge, the localized absorbers facilitate also shielding the tunnel and any radiation-sensitive machine components from scattered gamma-ray photon damage, by installing short high-Z shielding material around the absorbers.

## SYNCHROTRON RADIATION SPECTRA AND GAS LOADS

The FCC-ee machine detailed in the Conceptual Design Report (CDR) is a twin-ring 100 km circumference, room-temperature collider. It aims at accumulating very large integrated luminosities at energies corresponding to the resonances of the Z, $W^{+-}$, and H bosons, and the top quark (ttbar). The corresponding beam energies are 45.6, 80, 120, 182.5 GeV [1]. The plan is to incrementally increase the beam energy, starting with several years of operation at the Z-pole, and then increasing the beam energy in parallel with the installation of superconducting RF cavities. Like for the single-ring LEP predecessor, one of the main limitations of such a circular e-e+ collider is the emission of SR. For practical purposes, it has been decided to limit to 50 MW the amount of SR power P generated by each beam. Since P scales as the $4^{th}$ power of the beam energy, the common 50 MW limit means that the corresponding beam currents vary a lot. They are 1390, 147, 29, 5.4 mA, respectively (see Machine Parameters on Table S.1 in [1]).

While several concepts have been considered at the beginning, the design retained for the Conceptual Design Report (CDR) is one where the cross-section of the vacuum chamber (VC) in the arcs is a scaled-down version of the one implemented in the SUPERKEKB collider [2].

Contrary to SUPERKEKB tough, the SR fans are absorbed by many short absorbers, with average spacing of ~6 m. This allows localizing the PSD gas load and placing lumped pumps in front of the SR absorbers, thus maximizing the pumping efficiency and radiation shielding [3, 4].

The VC design is compatible with the design adopted for the common-yoke dipoles and quadrupoles. The VC material is OFS copper alloy, with stainless steel (SS) flanges as beaseline (also considering CuZrCr as in [2]).

On the other hand, the linear SR photon flux F' scales linearly with the beam current, and therefore the corresponding total photon flux (arc dipoles only), varies linearly with the currents: $7.10 \cdot 10^{17}$, $1.36 \cdot 10^{17}$, $4.09 \cdot 10^{16}$, and $1.17 \cdot 10^{16}$ ph/s/m, respectively.

The critical energy $\varepsilon_c$ of the SR spectrum (median of the power spectrum) scales as the cube of the beam energy, i.e. 19.5, 105.5, 356.1, 1252.8 keV, respectively. When $\varepsilon_c$ is above 100 keV the Compton effect becomes predominant with respect to the photoelectric one [5]. Compton-scattered photons are generated within a very broad solid angle, contrary to the primary SR photon fan which is highly directional and contained within a very narrow (vertically) pseudo-gaussian distribution with FWHM scaling as $1/\gamma$, with $\gamma$ the relativistic factor. For the H and ttbar versions of the machine pair-creation is also a factor to consider.

It is a well-known fact, that SR photons are capable of generating molecular desorption from the vacuum chamber (VC) surfaces. Neglecting for a moment the Compton photons, which would increase the total outgassing load [5], it is generally assumed that the corresponding linear outgassing load Q', expressed in mbar·l/s/m, is proportional to the linear SR photon flux F'.

The corresponding linear gas loads Q' (assuming that each primary SR photon has a molecular desorption yield of $2 \cdot 10^{-6}$ mol/ph, i.e. a well-conditioned machine), are $5.74 \cdot 10^{-8}$, $1.10 \cdot 10^{-8}$, $3.30 \cdot 10^{-9}$, and $9.48 \cdot 10^{-10}$ mbar·l/s/m, respectively, within arc dipoles.

We aim at stably running the collider at nominal currents at an average arc pressure $\langle P \rangle$ around $2.0 \cdot 10^{-9}$ mbar, in order to reduce beam-gas scattering and residual gas ionization, which could lead to ion-instabilities in the e- ring, and electron-cloud (EC) in the e+ ring, in addition to beam blow-up and emittance degradation [6].

As a rule of thumb, the values for Q' indicated above mean that we need to have effective linear pumping speeds S' of the order of $S' = Q'/\langle P \rangle = 28.7$ l/s/m at the Z-pole.

The W, H, and ttbar beam energies are less demanding in terms of vacuum specifications, except possibly for the experimental interaction-regions [7], which are not detailed here for lack of space.

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## VACUUM SYSTEM DESIGN

### *VC Geometry and Materials*

The design of the VC must comply with the choices made for the lattice magnets. For FCC-ee a novel design has been proposed [8], which utilizes a common-yoke for both dipoles and quadrupoles, see Fig. 1 and 3. It consists of twin-bore cross-sections, see Fig. 1, 2, and 3. For such a large machine, almost 200 km in length for the two rings, cost-containment issues push us to try and utilize the same cross-section as much as possible. A 70 mm ID circular cross-section fits both the arc dipole and quadrupole magnets. On the other hand, the experience accumulated over many SR light sources and lepton colliders, tells us that it would be advantageous to try and intercept all primary SR photons on short, localized water-cooled SR absorbers.

The advantages of this choice would be many: localization of the outgassing load; increased linear photon flux density leading to a shorter conditioning time; possibility to shield locally the absorbers with high-Z material, in order to diminish the amount of scattered high-energy photons (secondary Compton effect and gamma rays in the primary SR fan), which could lead to radiation damage and activation of machine component and the tunnel itself [4].

All these requirements have led us to try to implement the successful VC cross-section adopted by the SUPERKEK-B collider [2], whereby two small rectangular "winglets" are placed on either side of the circular chamber in the plane of the orbit. In our design, the winglet on the external side is used to locate short (~ 250 mm) SR absorbers [3].

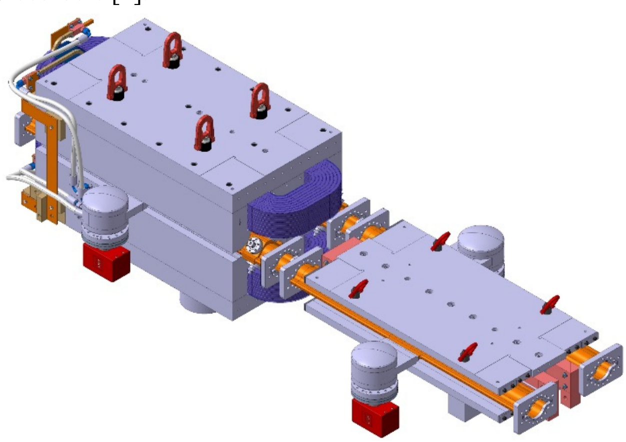

Figure 1: CAD model of 1m-long quadrupole and dipole twin-bore magnets with VC and pumping ports. The connecting bellows are not shown. Real dipole chambers can be 8-9 m-long, while quadrupole/sextupole ones are around 3.5 m. Courtesy A. Milanese, M. Gil Costa, CERN.

The other winglet can be used to install the pumping port of localized pumps. For the external beam, the pumping port along dipoles is on the same side as the absorber, since the yoke of the dipole does not allow its installation opposite to the SR absorber. There is no possibility to install the pumping ports along the short interconnects between adjacent magnets, since these can barely fit the bellows used to take care of VC expansion and alignment.

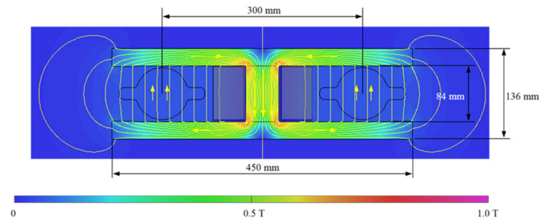


Figure 2: Cross section of the common-yoke dipole [9], with stylized VC cross-sections.

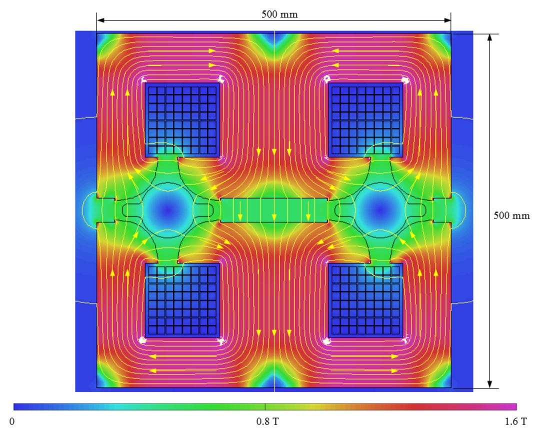


Figure 3: Cross section of the common-yoke quadrupole [9] with stylized VC cross-sections. The sextupoles, with conventional single-bore design, are not shown here.

As long as materials are concerned, OFS copper alloy for the chamber extrusions, and SS for the flanges have been selected, as the materials of choice (considering CuZrCr alloy for flanges as in [2]).

### *SR Absorbers*

Depending on their location along the arc lattice, each SR absorber can intercept between ~ 4 and 7 kW of power. Due to the extremely small vertical footprint of the SR fan, even at 20 m or so distance from the source point, the surface of the absorber should be shaped in such a way to reduce the local SR power density (W/mm$^2$). The conceptual design we have in mind implements a V-shaped surface [10], which can also take care of minor vertical displacements which could take place especially along the dipole magnet, where the VC is not centred with the beam orbit as it happens in the quadrupoles, where they are constrained by the support/fiducialization of the BPM blocks.

### *Flanges, Bellows, Gate Valves, BPM Blocks*

The very short distance between magnetic elements in the arc lattice does not allow us to use standard ConFlat flanges. We have therefore adapted the design of the SUPERKEK-B collider, which allows bake-out, and is also good in terms of beam-impedance, since it leaves no gap between facing flanges [2]. The copper gasket is of Matsumoto-Ohtsuka type [11].

The bellows are racetrack-shaped, and adopt the low-impedance "comb-type" design for the RF contact fingers [2] that have to compensate for the thermal expansion of the VC during the bake out and NEG activation.

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The gate valves (GVs) also adopt similar "comb-type" RF contact fingers [2]. Sector GVs will be placed every 500 m or so (LEP-case), in order to have manageable vacuum sectors. This length should offer a balance between length to vent and re-bake and re-condition, and electrical power and ancillary pre-pumping equipment during bake-out and leak-check prior to re-opening the GVs to connect the adjacent vacuum sectors.

The BPM blocks are 4-button ones, with electrodes connected via small SS flanges brazed on a copper body which is then welded to the VC extrusion, see Fig. 4. They are always protected from primary SR photons by one absorber appropriately placed upstream of each of them.

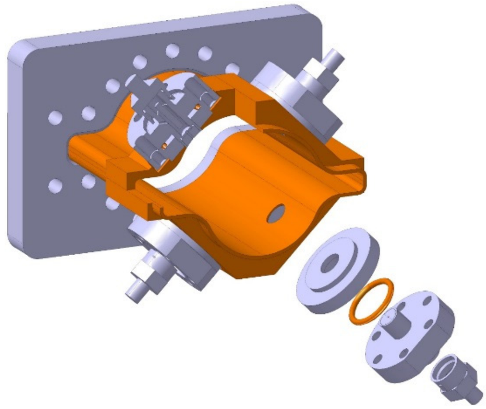

Figure 4: Exploded view of one BMP block, with electrodes (courtesy M. Gil Costa, CERN).

### *NEG-Coating*

During the past 20 years, NEG-coatings have been successfully used on numerous SR light sources (e.g. SOLEIL and MAX-IV) and colliders (e.g. the Long Straight Sections of the LHC and RHIC). Their main feature is a very low PSD yield, together with a very low secondary electron yield (SEY) as well. The former is directly linked to the amount of gas to be pumped, while the latter feature is mainly implemented in order to mitigate the EC-effect.

Extensive modelling simulations [3, 10] suggest that without NEG-coating the number of lumped pumps required to meet the average pressure and conditioning time specifications would be very large. In addition, without NEG-coating we would need to implement another EC-mitigating surface treatment (e.g. titanium nitride or laser ablated surface texturing).

A distributed pumping based on NEG strips, like adopted at SUPERKEK-B or the LEP ring, cannot be adopted here because of space constraints along the magnets. A collaborating team [12] has determined that a *thinner-than-usual* NEG-coating (only 200 nm instead of the "standard" 1~2 mm) would still retain its properties even after 10 venting-activation cycles. The measurements made on small coupons have been validated by additional experiments at the PF light source [13]. A 200-250 nm-thick NEG-coating would not increase the resistive-wall impedance budget above the critical instability threshold [12].

### *Lumped Pumps*

For ease of installation and operation, and due to space limitations, we have decided to use integrated NEG-ion pumps of the NEXTorr family [14]. The pumps are installed vertically inside a larger pumping dome, which is in turn connected to the beam chamber via a thin rectangular slotted wall, in order to reduce its impedance and high-order mode trapping. Ideally there should be one such pumping dome in front, or near, each SR absorber: this would mean something like ~13,600 pumps/ring (arc sectors only, long straight sections excluded). Cost-containment considerations suggest to skip some of them. Installing 1 pump every 5 absorbers (~30 m) roughly doubles the average pressure [3, 10].

### *Short Prototypes*

Figure 5 shows the two 1m-long prototypes. The two prototypes have been built using 3D printing techniques, in order to check the compatibility with the 1m-long prototypes of the arc dipoles and quadrupoles.

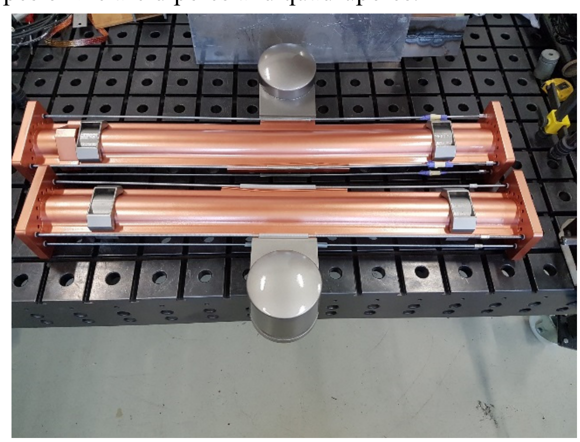

Figure 5: Short prototypes with pumping domes, Matsumoto-Ohtsuka-type flanges, and dummy BPM block.

## CONCLUSION

We have briefly outlined the main concepts leading to the design of the vacuum system of the arc sections of the FCC-ee collider. The design rests on solid grounds, based on the experience gained by the accelerator community during the 3 past decades.

Extensive modelling results, alongside with experimental data, indicate that the twin-ring machine can be built and run efficiently in spite of the large photon flux and power generated at beam energies unprecedented for circular colliders.

According to the simulations, the conditioning time is compatible with the planned time dedicated at each beam energy to study a particular particle resonance [1].

Development of alternative manufacturing technologies to reduce the cost and the prototyping of relevant vacuum components will be carried out in the near future as soon as funding is made available, pending decisions at the upcoming European Particle Strategy, and CERN Council meetings.

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