CERN-ACC-2015-113

Future Circular Collider

PUBLICATION

Beam Dynamics Challenges for FCC-ee

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07 October 2015

The research leading to this document is part of the Future Circular Collider Study

CERN-ACC-2015-113

1.1 Beam Dynamics Challenges for FCC-ee

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1.1.1 Introduction

The goals of FCC-ee include reaching luminosities of up to a few 10^{36} cm^{-2}s^{-1} per interaction point at the *Z* pole or some 10^{34} cm^{-2}s^{-1} at the *ZH* production peak, and pushing the beam energy up to ≥175 GeV, in a ring of 100 km circumference, with a total synchrotron-radiation power not exceeding 100 MW. A parameter baseline as well as high-luminosity crab-waist options were described in [1] and [2], respectively. The extremely high luminosity and resulting short beam lifetime (due to radiative Bhabha scattering) are sustained by top-up injection. The FCC-ee design status and typical beam parameters for different modes of operation are reported in [3].

One distinct feature of the FCC-ee design is its conception as a double ring, with separate beam pipes for the two counter-rotating (electron and positron) beams, resembling, in this aspect, the high-luminosity B factories PEP-II, KEKB and SuperKEKB as well as the LHC. The two separate rings do not only permit operation with a large number of bunches, up to a few 10,000's at the *Z* pole, but also allow for a well-centered orbit all around the ring as well as for a nearly perfect mitigation of the energy sawtooth, e.g. by tapering the strength of all magnets according to the local beam energy, and for an independent optics control for the two beams. A side benefit at low energies is a reduction of the machine impedance by a factor of twos.

A long list of optics and beam dynamics challenges for FCC-ee includes the following: (1) final focus optics design with a target vertical IP beta function of 1 or 2 mm, 50 or 25 times smaller than for LEP2, incorporating sextupoles for crab-waist; (2) synchrotron radiation in the final focus systems and the arcs, with effects on the detector (background, component lifetime) and on the beam (vertical emittance blow up and dynamic aperture); (3) beam-beam effects, including single-turn and multi-turn beamstrahlung; (4) design of the interaction region with a strong detector solenoid with possible compensation solenoids, a large crossing angle and a pair of final-focusing quadrupoles; (5) compatibility of the layout with the design of the hadron collider sharing the same tunnel; (6) RF acceleration system for high voltage (ZH, tt) and high current (Z, WW) with possible staging scenario; (7) impedance, HOM losses and instabilities, especially for high-current "low-energy" operation at the *Z* pole; (8) the top-up injection scheme; (9) achieving the dynamic aperture required for adequate beam lifetime and for the top-up injection, comprising the optimization of the arc optics; (10) vertical emittance control, including alignment and field errors, lattice nonlinearities, as well as beam-beam effects; (11) energy calibration and transverse polarization; (12) adapting to a non-planar tunnel; and (13) the development of a mono-chromatization for direct *H* production in the *s* channel. In the following we consider some of these challenges.

1.1.2 Collider Layout

Figure 1 presents one possible FCC-ee collider layout, with two collision points. The latter are located at diametrically opposed positions of the ring. The incoming beam line is less bent than the outgoing beam line in order to minimize the synchrotron radiation emitted in the direction of the experimental detector. This leads to a rather large separation of the inner and outer beam lines on each side of each interaction point (IP), most likely necessitating two separate tunnels over a distance of 5-6 km around each IP. The outer tunnel might accommodate the detector-bypass for the booster ring, as sketched in the figure, and it might later host the hadron collider. The outer and inner beam lines cross in the long straight sections half way between the two experiments. This provides a perfect two-fold symmetry of the FCC-ee collider ring, with a correspondingly decreased number of systematic resonances.

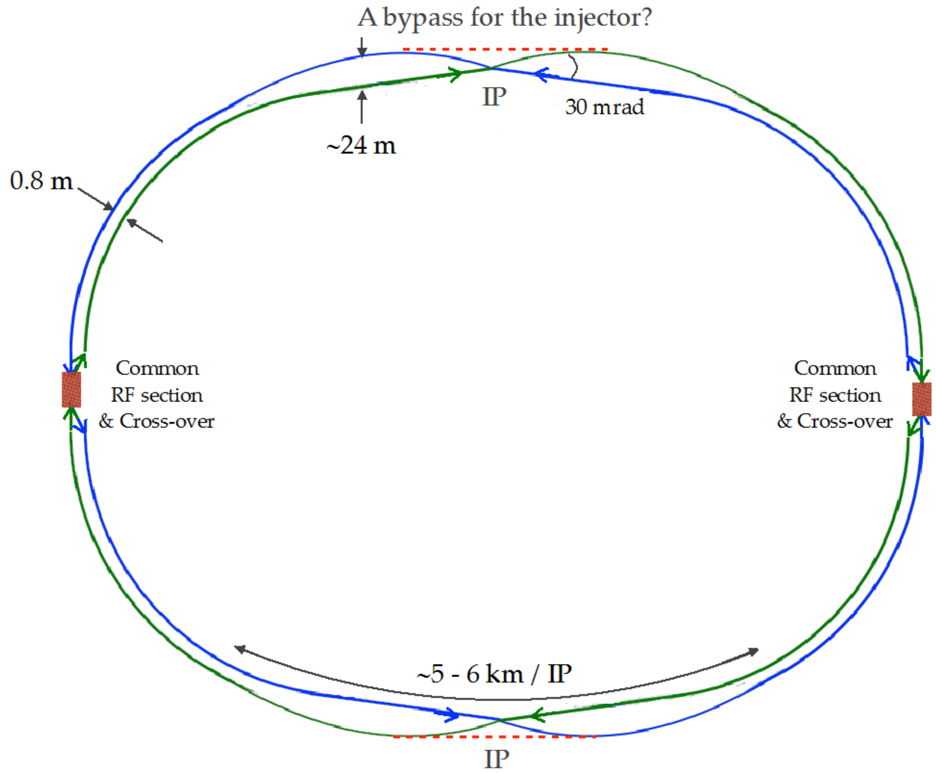

Figure 1: One possible FCC-ee layout (K. Oide).

1.1.3 Staging

Staging scenarios are being considered, in which the RF system is varied in steps, starting at low energy, e.g. *Z* pole operation (45.5 GeV/ beam), with fewer cavities (and correspondingly lower impedance), installing the full 400-MHz RF system for *ZH* running (120 GeV/beam), and later, for $t\bar{t}$ operation (175 GeV per beam) sharing the RF cavities for both beams, as indicated in Fig. 1, or adding higher harmonic 800 MHz cavities [4,5]. Complementary staging possibilities exist for the arc optics (varying cell length, or emittance) and for the vertical IP beta function, β_y^*.

1.1.4 Final-Focus Optics

Various final-focus optics for FCC-ee have been developed and evaluated [6,7]. A recent design is illustrated in Fig. 2, which shows the incoming half of one possible final focus optics, corresponding to the layout of Fig. 1 at a total crossing angle of 30 mrad. As indicated at the bottom, the critical photon energies for this design are below 100 keV over the last 900 m before the IP, and less than 1 kW of synchrotron radiation power is emitted here, so that all design requirements inferred from LEP experience [8,9] appear to be met. The crab waist collision scheme can be realized by a dedicated crab-waist sextupole [7] or by a “virtual” crab-waist sextupole as in Fig. 2 (based on the odd-dispersion scheme for chromaticity correction [10], where only one of two vertical chromatic correction sextupoles is located at a place with nonzero dispersion).

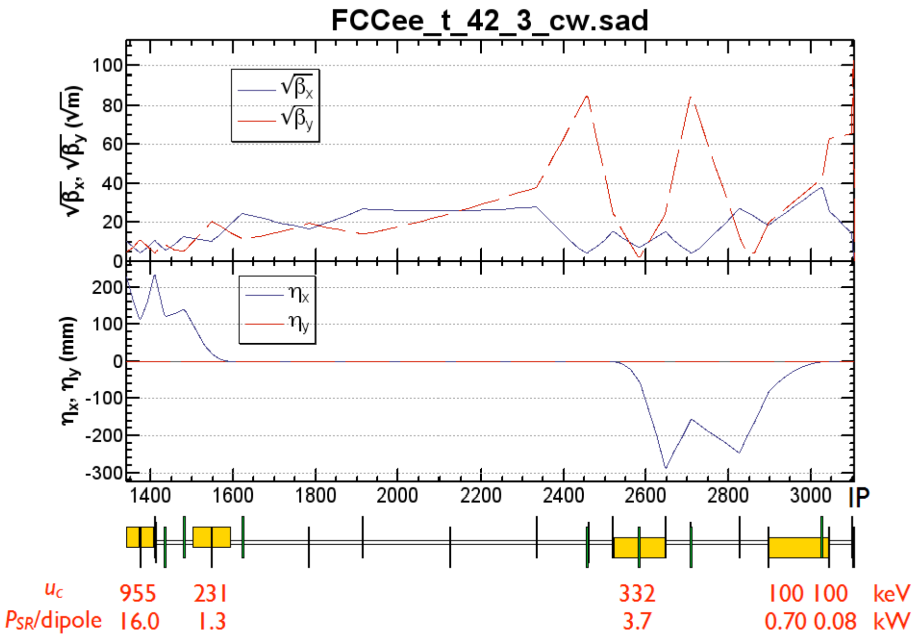

Figure 2: Incoming FCC-ee IR optics with low synchrotron radiation (K. Oide).

1.1.5 Interaction Region

The part of the interaction region closest to the IP is particularly challenging, due to the combination of a small β_y^* of 1-2 mm and a large crossing angle of 30 mrad, which enhances the effect of fringe fields, kinematic nonlinearities, and synchrotron radiation. Additional complications arise from the detector solenoid field, and the need for shielding solenoids (around the final quadrupoles) as well as for an anti-solenoid (to compensate the solenoid-induced betatron coupling), together with synchrotron radiation emitted in these elements, and especially in their fringe fields [7]. Figure 3 shows one proposed configuration.

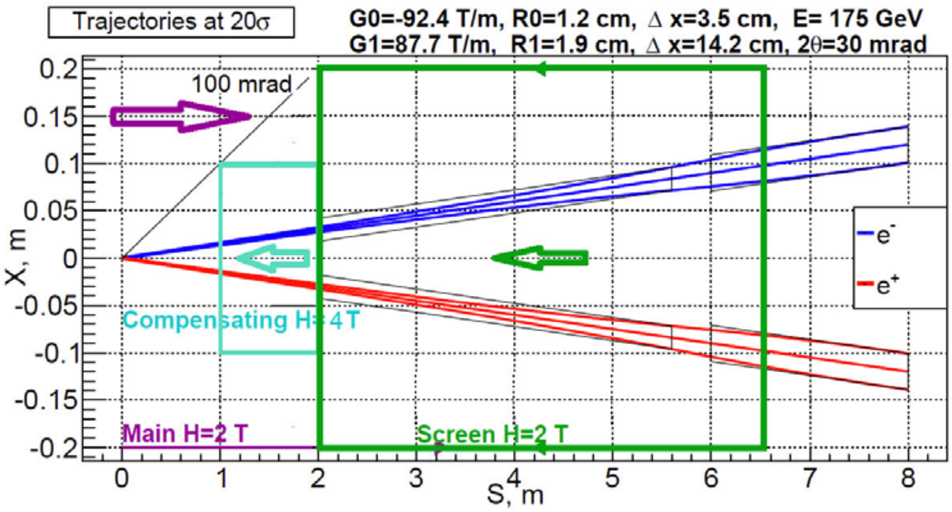

Figure 3: Example IR layout including main, compensating and screening solenoids (A. Bogomyagkov, S. Sinyatkin).

1.1.6 **Machine Detector Interface and IR Synchrotron Radiation**

Tools based on GEANT have been developed to model the machine detector interface and beam-related detector background in FCC-ee [8,9]. LEP Experiences call for critical photon energies below 100 keV and total power levels below 1 kW emitted in the direction of the particle-physics detector.

1.1.7 **Dynamic Aperture**

Off-momentum dynamic aperture is an important design constraint. A large acceptance improves the beam lifetime at the top threshold where beamstrahlung is important [11], and also provides space for off-momentum (top-up) injection.

The minimum required momentum acceptance, in view of beamstrahlung, is ±1.5% at 175 GeV and ±1.0% at 120 GeV, for the presently assumed beam parameters in case of crab-waist collisions.

Over the past years, the off- and on-momentum dynamic aperture of several alternative collider optics have been steadily improved, e.g. by optimizing the arc-cell phase advance and by adjusting the strengths of the arc sextupoles.

Synchrotron-radiation damping must be taken into account when simulating the dynamic aperture. Figure 4 shows an example result.

The dynamic aperture and the dynamic energy acceptance are almost acceptable in the latest optics designs. The radiation damping plays an important role for the dynamic aperture. The quadrupole fringe fields and kinematic terms can be compensated by two IR octupoles. The dynamic aperture is limited by the combined effect of IR sextupoles and arc sextupoles.

A potential issue is the energy sawtooth due to synchrotron radiation, varying from a negligible value to about 2% per half-turn from the Z energy to the $t\bar{t}$ beam energy. In the two-ring scenario based on separated magnetic systems, this effect can be mitigated by varying the magnet strengths according to the local beam energy. Detailed studies of possible powering schemes are required to ensure that the momentum aperture remains sufficiently large. If during $t\bar{t}$ running the RF sections are combined for both beams, the two optics in the common regions can be matched simultaneously, as is routinely done for energy-recovery linacs.

Synchrotron radiation in the quadrupole magnets is another important effect for FCC-ee as it already was for LEP2 [12]. Indeed, this effect sets a minimum length for the arc quadrupoles. For large-amplitude particles it also leads to a breakdown of the geometric and chromo-geometric cancellations between paired sextupoles.

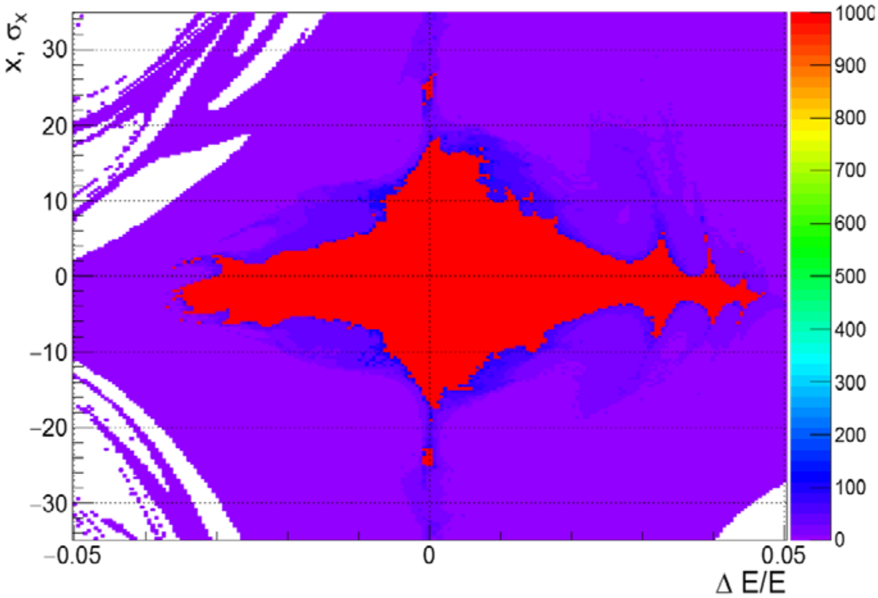

Figure 4: Simulated horizontal dynamic aperture as a function of initial relative momentum offset, ranging from -5% to +5%, for one FCC-ee candidate optics at 175 GeV beam energy, obtained by tracking over 1000 turns, including synchrotron motion, radiation damping, and crab-waist sextupoles. The color code indicates the number of turns survived (P. Piminov, A. Bogomyagkov).

1.1.8 Beam-Beam Effects

The crab-waist collision scheme is predicted to increase the maximum value of the vertical beam-beam tune shift at which the vertical beam size starts to blow up by about a factor of two, as compared with a standard (head-on) collision scheme.

A novel phenomenon for circular colliders is beamstrahlung, which at high energies affects the beam lifetime [11], and at low beam energies increases the bunch length and the energy spread [13,14]. Both effects are taken into account in the FCC-ee design optimization.

According to LEP experience and confirmed by some simulations, the beam-beam limit for classical head-on collisions increases with beam energy or damping decrement [15]. For FCC-ee crab-waist collisions, reducing the number of IPs from 4 to 2 may increase the maximum tune shift per IP only by a moderate 5-10% and the corresponding luminosity per IP by a similar factor [16].

1.1.9 Top-Up Injection

Top-up injection is an integral part of any high-luminosity circular collider [17]. Longitudinal injection can profit from faster damping and may have less impact on the particle-physics detector (since the design dispersion at the collision point is zero). Longitudinal injection has successfully been used at LEP [18,19]. Initial design considerations for the FCC-ee longitudinal injection include multipole kicker injection and septum-less injection schemes [20]. An alternative vertical injection scheme could potentially take advantage of the extremely small vertical emittance.

1.1.10 Mono-Chromatization

An interesting options presently under study is the possibility of direct Higgs production in the *s* channel, at a beam energy of 63 GeV. In order to obtain an acceptable Higgs event rate and to precisely measure the width of this particle mono-chromatization will be required. The mono-chromatization can be realized, e.g., by introducing horizontal IP dispersion of opposite sign for the two colliding beams [21,22]. The mono-chromatization factor should be larger than 10.

1.1.11 Impedance and Instabilities

Impedance effects are a concern, in particular for the high-current operation at the *Z* pole. The energy loss at the RF cavities can be as large as the energy loss due to synchrotron radiation [23]. Fortunately, most of the power will be dissipated in the tapers outside the low-temperature cavity cells. Higher-order mode (HOM) heating of the cavities is a related concern, calling for efficient HOM dampers operating at room temperature. As this has the potential to limit the beam current—thus the maximum luminosity achievable at the Z pole—we will continue to investigate means to reduce the loss factor.

In addition the heavy-beam loading and residual HOM-driven instabilities require strong longitudinal feedback loops, perhaps similar to those for PEP-II, while a transverse bunch-by-bunch feedback must suppress resistive-wall, HOM-driven, and ion instabilities. Both the B factories as well as the LHC have demonstrated transverse damping times on the order of 10 turns, which gives a measure of the maximum undamped growth rate allowable.

At LEP the transverse mode coupling instability at injection limited the achievable bunch intensity. By contrast, at FCC-ee the beam is always at full collision energy.

1.1.12 Polarization and Energy Calibration

Scaling from LEP some natural transverse polarization due to the Sokolov-Ternov effect is expected up to the *W* threshold (80 GeV / beam) or above. In this energy range resonant depolarization of a few dedicated non-colliding bunches will provide an exquisite measurement of the average beam energy [24]. Extrapolation to the beam energy at the IPs, taking into account the energy sawtooth as well as possible beam-beam effects, may lead to some systematic uncertainties. For higher beam energy and as a cross-check other techniques, such as Compton backscattering schemes and also measuring the spin precession of an injected polarized beam [25], are being considered. These techniques would also allow for a cross calibration.

The potentially harmful effect of an orbit kink on the polarization and on the vertical emittance can be avoided by a special orbit inclination technology [26]: Twists between arc segments match the horizontal plane of oscillations with the bending planes of the segments. Spin matching is provided by weak solenoids which produce roughly half of the full twist. The other half of the twist is obtained from a unity/minus-unity insertion appropriately rotated around the longitudinal axis [26].

1.1.13 Conclusions and Outlook

Over the past years the optics development and beam dynamics studies for FCC-ee have made great progress. A double ring collider with crab waist collisions promises superb performance over a large range of beam energies, and allows for an elegant staging.

The primary design challenges arise from the tight focusing, the large energy acceptance required, the wide range of beam parameters and beam energies to be accommodated, severe constraints on the final-focus synchrotron radiation, the effects of the detector solenoids and their compensation, polarization issues, and the required compatibility with the layout of the FCC-hh hadron collider.

We expect to arrive at a complete design, meeting all constraints, by the end of 2016.

1.1.14 Acknowledgements

This work was supported, in parts, by the European Commission under the Capacities 7th Framework Programme project EuCARD-2, grant agreement 312453, and the HORIZON 2020 project EuroCirCol, grant agreement 654305.

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