0.1 Injection and extraction

The technical straight section in point B (PB) of the FCC is dedicated to the beam transfer from the booster to the collider and to the dump systems. In total, 8 systems are installed in this area and this section focuses on the collider system and the top-up injection and dump concepts for the lattice `V24.4_GHC` [**?**].

Top-up injection

The integrated and peak luminosity targets of the collider necessitate a continuous injection scheme from a full-energy booster, as the beam lifetime during collisions is well below $1\,\mathrm{h}$. Due to the high bunch charge in the collider and the limitations of the injector complex, a swap-out scheme is not feasible; thus, a top-up injection scheme is required.

Among the four operation modes, the Z mode is particularly challenging, with approximately $18\,\mathrm{MJ}$ of stored beam energy per collider ring at an energy of $45.6\,\mathrm{GeV}$. As such, the Z mode is the current focus of the injection scheme design. In this mode at each injection occurring every $3\,\mathrm{s}$, up to $10\,\%$ of the collider's maximum bunch intensity and up to 1120 bunches are injected totalling up to $1\,\%$ of the collider nominal intensity. This is considered to be a reasonably safe intensity to be transferred from the booster to the collider, provided that a series of collimators is installed in the booster extraction region and also along the transfer line to the collider to intercept mis-kicked bunches.

Several possible schemes have been explored to implement top-up injection at the FCC-ee collider [**?**]. The longitudinal schemes, which require an individual kick to each injected bunch trailing circulating bunches, have been excluded due to complexity of the required kicker system. For the traditional off-axis injection scheme, the impact of the SR cone originating from the beamlet on the SR (Synchrotron Radiation) mask and aperture limitation around the experimental insertion was modelled and showed an unacceptable level [**?**].

On axis injection

For on-axis injection, the beam is placed onto the chromatic closed orbit, where the energy offset together with the ring's optics dispersion provides the horizontal separation between the injected and circulating beams. The beamlet undergoes synchrotron oscillations, and around IPs it overlaps with the circulating beam due to the zero dispersion, thus preventing any increase in the SR cones or of the experiment background.

The beamlet benefits from faster damping compared to off-axis injection since synchrotron oscillations damp twice as fast as betatron oscillations. Another advantage of on-axis injection was observed at the LEP collider, where this scheme provided higher efficiency and lower sensitivity to errors at the injection point [**?**]. Therefore, the conventional on-axis injection has been selected for the present baseline concept.

The distance between injected and circulating beams establishes the requirements on the energy offset and dispersion at the injection septum:

$$|D_x\Delta| = 5\sigma_{cir} + S + 5\sigma_{inj} \tag{1}$$

where D_x is the dispersion at the injection point, Δ is the relative energy offset of the injected beam, S is the blade thickness of the septum, σ_{cir} and σ_{inj} are the beam sizes of the circulating and injected beams at the injection point.

As shown Eq. 1, the required energy offset increases with the septum blade thickness. Hence, an initial concept aimed at using an electrostatic septum to minimise its thickness but there are significant uncertainties on the reliability of such a system in the presence of synchrotron radiation. Therefore, the present concept focuses on thin magnetic septa with $S = 2.8\,\mathrm{mm}$.

During injection the circulating beam closed orbit is placed at $5\sigma_{cir}$ from the septum blade (see Eq. 1). This condition must be fulfilled for the shortest possible duration because the septum, or a protection absorber placed immediately upstream, becomes the primary aperture of the ring. Therefore, the baseline concept features a fast bump to bring the circulating beam close to the injection septum for one single turn. Two sets of fast bumper magnets placed at a relative phase advance of π are used to produce the orbit bump with a height of $10\sigma_{inj} + S$ at the injection point. The nominal position of the circulating beam is $15\sigma_{cir}$ from the edge of the injection septum. paragraph commented-out in .tex on bump failure to be re-located in machine protection? question from Yann for Anton

The collider ring baseline optics for technical straight sections have been optimised to include the on-axis injection requirements in its most recent `V24.4_GHC` [**?**]. This collider optics in the PB straight section is shown in Fig. 1 with the injection region on the right side of the IP and the crossing dipoles in the centre. The injection point is located at $s = 800\,\mathrm{m}$ where it achieves a dispersion of $D_x = -1.5\,\mathrm{m}$ and $\beta_x = 1000\,\mathrm{m}$. This allows on-axis injection with an energy offset of $\sim 1\,\%$, providing sufficient space for the magnetic septum blade of approximately $3\,\mathrm{mm}$.

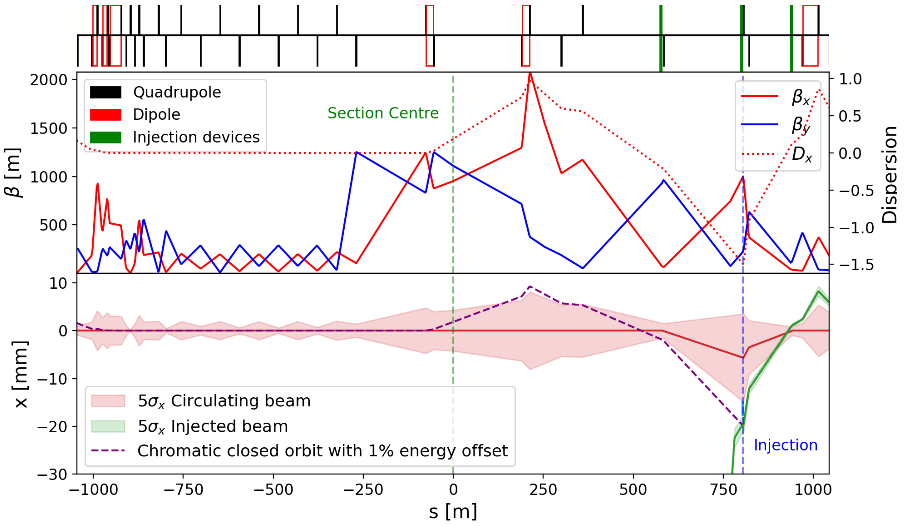

Fig. 1: The collider optics in the PB straight section with the longitudinal position relative to the IP.

The hardware requirements for the baseline injection scheme are summarised in Tab. 1.

Table 1: Collider injection hardware requirements.

System	Value	unit
Beam energy	45.6 – 182.5	GeV
Thick septum apparent thickness	10	mm
Thick septum deflection	0.1	mrad
Thin septum apparent thickness	2.8	mm
Thin septum deflection	100	µrad
Fast bump kicker angles	40 and 60	µrad
Fast bump kicker max. rise/fall time	600	ns
Fast bump kicker flattop	304	µs
Fast bump kicker maximum ripple	1.5	%

While the zero-dispersion condition was introduced to simplify the solution of Eq. 1 and to reduce the size of the injected beam at the injection septum, it also causes a mismatch between injected and circulating beams. The distance of the injected beam from the septum is constrained by the energy offset. In the Z and W modes in particular, the lattice momentum acceptance limits the energy offset of the injected beam to approximately $1\,\%$. On the other hand, the dispersion mismatch causes betatron oscillations in the injected particles away from the chromatic closed orbit. This effect remains moderate, as the momentum spread of the injected beam δ_{inj} is small. Additional studies will be needed to quantify this effect and investigate different matching for each operation mode.

For the transfer from the booster to the collider, a complete design of the line will need to be developed. Presently, this line is approximately $450\,\mathrm{m}$ long from the booster extraction at the centre of the straight section to the collider injection point (see Fig. **??**). Since the booster ring is $1030\,\mathrm{mm}$ above the collider plane, particular attention must be paid to preserving the small vertical emittance and precisely matching the vertical optics to the collider ring. In the horizontal plane, immediately upstream of the thin collider injection septum, a thicker magnetic septum is considered for the beam trajectory with specifications listed in Tab. 1.

Both booster and collider beam parameters depend on the operation mode. ref to hannes table In the present concept, the lattice configuration of the injection straight section as well as the injection devices' specifications remains the same for all operation modes. With fixed optics and septum thickness, it is the energy offset that is optimised at every energy mode to adapt to the different beam characteristics and ring momentum acceptance. The baseline injection settings for the four operation modes are shown in Fig. 2.

(a) Z mode, $\Delta = 0.95\,\%$.

(b) W mode, $\Delta = 1\,\%$.

(c) H mode, $\Delta = 1.4\,\%$.

(d) $t\bar{t}$ mode, $\Delta = 1.6\,\%$.

Fig. 2: Normalised horizontal phase space at the collider injection point for each operation mode. Beam distributions and associated $5\,\sigma$ envelopes around the injection septum are shown for each mode.

In order to maintain a clearance of $5\,\sigma$ for both the injected and circulating beam a larger energy offset is required for modes with higher beam emittance (see Eq. 1), and the energy offset in H and $t\bar{t}$ mode is increased to $1.4\,\%$ and $1.6\,\%$, respectively. This remains compatible with the large momentum acceptance in Higgs and $t\bar{t}$ modes, which are $\pm 1.6\,\%$ and -2.8/+2.5 %, respectively [?]. For Z mode, the RF acceptance is $1.06\,\%$ and the momentum acceptance is approximately $1\,\%$, so the baseline injected beam energy offset is set to $0.95\,\%$ to ensure the entire injected beam fits within the ring acceptance.

The collider's and booster's equilibrium emittances in the W mode are significantly larger, but the energy acceptance of the ring is still limited to $1\,\%$. This prevents increasing the energy offset as in the higher energy modes and makes the on-axis scheme unable to provide sufficient clearance for the $2.8\,\mathrm{mm}$ septum blade. The present concept proposes to introduce a small betatron offset to the scheme and moving towards a hybrid injection for the W mode. The purple dashed line in Fig. 2b represents the chromatic orbit for the energy offset considered, and the injected beam is further offset by $1\,\mathrm{mm}$ away from the septum, which corresponds to $0.5\,\sigma_{\mathrm{cir}}$.

The hybrid injection scheme increases the separation between injected and circulating beams without increasing the energy offset, making it partially on-axis and off-axis. While the off-axis injection is not possible for the FCC collider, a small betatron oscillation is not incompatible with the SR absorption around the experimental IPs [?]. Other effects discussed earlier, such as experimental background sensitivity and errors, may still play a significant role and will need to be quantified.

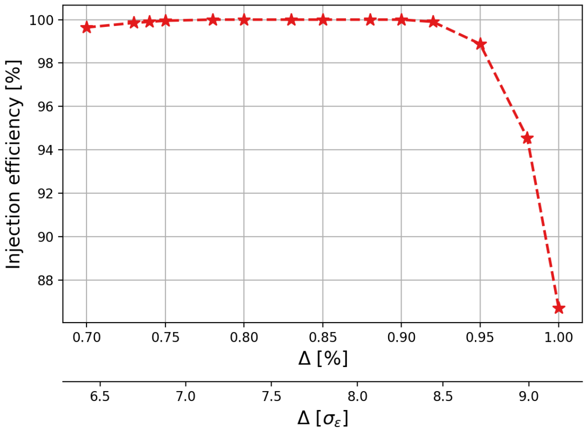

Fig. 3: Injection efficiency versus injected beam energy offset for the Z mode.

Presently, the injection efficiency is modelled using particle tracking of the injected beam in the collider ring lattice. The tracking consists of a Gaussian 6D distribution of 2500 injected particles, which are tracked for 3000 turns using the Xsuite code [?]. The synchrotron radiation model used accounts for quantum excitation to accurately predict the behaviour of particles injected near the edge of stability. Additional studies including strong-strong beam-beam effects, yet based on a simplified lattice model, did not show any additional detrimental effect of the beam-beam interaction on the injection efficiency [?]. Further comprehensive studies will need to include beam-beam interaction, collective effects and lattice errors.

The evolution of the simulated injection efficiency for on-axis and hybrid injection schemes is shown in Fig.3. The energy offset of the baseline on-axis injection is $0.95\,\%$, with an injection efficiency of $99\,\%$. This confirms the baseline injection scheme is achievable with the present lattice and the injected beam is within the acceptance of the ring.

At other injection offsets, only the energy of the injected beam is adjusted but the optics is not optimised and the physical beam position is unchanged. Below the baseline on-axis scheme energy offset, the injection efficiency remains high, which indicates that the DA and MA are sufficient to capture an injected beam with some betatron offset. At an energy offset below about $0.7\,\%$ the injection efficiency decreases, which shows that a maximum betatron offset is reached and part of the injected beam is outside the lattice DA. Due to the energy acceptance of the lattice, of $\pm 1\,\%$, the injection efficiency drops quickly for energy offset above the baseline scheme.

Collider dump

The stored beam energy can reach 18 MJ per beam during Z mode operation, which is the highest stored energy among the lepton machines worldwide. Due to the synchrotron radiation damping, the beam sizes in the FCC-ee will be much smaller than in typical hadron machines, leading to a much higher energy density. The vertical beam size, in particular, is on the order of tens of micrometres, corresponding to energy densities around $5\,\mathrm{GJ/mm^2}$, which cannot be absorbed safely [**?**]. The design and operation of the beam abort system have to account for such destructive potential and several safety levels have to be implemented to avoid damaging accelerator components in case of hardware failure. Protection elements, typically located at a precise phase advance from the extraction kickers, have to be installed to intercept any mis-kicked beam in case of a spurious firing of the kickers that is not synchronised with the abort gap. The voltage of the kickers, as well as the current of the septa and ring dipoles, must be constantly monitored to ensure they remain within tight thresholds relative to the reference value for a fixed energy.

Machine protection consideration commented-out, question about moving it from Yann for Anton

The collider dump design is implemented at the entrance of the PB straight section and extracted outwards with the dump placed on the other side of the IP. The beam dump is located 5 m away from the ring to allow sufficient space for shielding and to limit radiation to the ring equipment [**?**]. The present geometry uses a small deflection angle to achieve the required separation and a long transport line of 1200 m from the ring extraction point.

In order to reduce the energy density on the dump, the present design aims for a large beta function and dispersion in both horizontal and vertical plane, to maximise the beam size. Despite the significant length of the line, the natural divergence of the beam at the extraction point is insufficient to produce a large enough beam spot on the dump. Therefore, a dedicated set of four quadrupole magnets is installed in the transfer line to further increase the beam divergence. In the horizontal plane, the dump kicker and septa provide the deflection to reach the dump but also a significant dispersion that is further amplified by the dump line quadrupoles to reach 20 m at the dump. Along with the beta function of 121 km and the beam parameters in collision, the present design achieves a horizontal beam size on the dump of 10 mm for the Z mode [**?**].

For the vertical plane, a 1 mrad vertical dipole is placed at the start of the dedicated dump line to create a vertical dispersion that is further amplified by the dump line quadrupoles to reach 23 m at the dump. Between the betatron and dispersive contribution, this scheme also provides a large beam size in the vertical plane of 10 mm for the Z mode using the beam characteristics expected in collision. The vertical deflection also places the dumped beam at the height of the booster.

The extraction design follows a traditional fast extraction scheme in the horizontal plane. The circulating beam is extracted in one turn so that the kicker flattop must be 304 ţs and its rise time should be smaller than the filling scheme abort gap of 0.6 ţs. The dump design hardware requirements are summarised in Tab. 2.

Table 2: Summary of the collider dump scheme hardware requirements

	Kicker	Septum
Beam energy (GeV)	$45.6 - 182.5$	
Deflection angle per system (mrad)	0.3	5
Maximum repetition frequency (Hz)	0.3	0.3
Kicker pulse flatness (%)	±20	N/A
Rise/fall time (ţs)	0.6	N/A
flattop time (ţs)	304	N/A
Blade thickness (mm)	N/A	25
Aperture (H×V mm)	N/A	30×10
Longitudinal available space (m)	20	20