3.3 Ring to main linac transport (RTML)

3.3.1 Overview

The ring to main linac transport (RTML) connects the damping rings and the main linacs. And it is used to match beam properties like bunch length and energy from the values delivered by the damping rings to the values required by the main linacs. Accordingly, the RTML consists of beam lines for the transport of the beams from the central injector site, which is close to the surface, to the outer ends of the main linac, which is about 100 m underground. It consists of beam lines for longitudinal bunch compression, acceleration and spin rotation to match beam properties. Collimation may need to be integrated to prevent beam halo from entering the main linac. Extensive diagnostics will be needed along the entire RTML and several commissioning dumps will be installed.

Electron RTML and positron RTML each have a total length of approximately 27 km. Their lattices are very similar but not exactly the same due to geometry constraints and to the fact that positron polarization is not included in the CLIC baseline (see §3.1). A sketch of the RTML is shown in Fig. 3.6. It is a design objective to use the same RTML lattices for all different stages foreseen for CLIC, i.e. for 3 TeV, 500 GeV, nominal and conservative cases. The only change would be the reduced length of the long transfer lines at 500 GeV to adapt to the site layout.

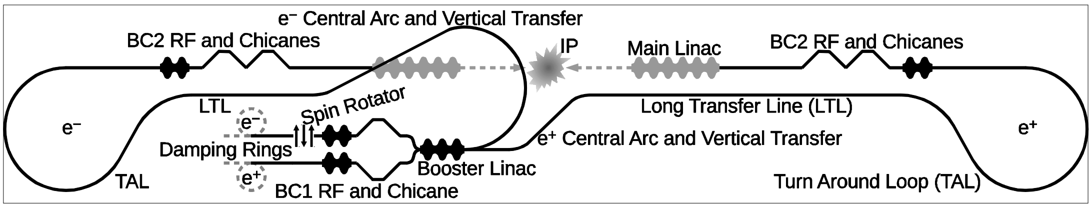

Fig. 3.6: Sketch of the RTML.

3.3.2 Beam parameters

Table 3.3 shows beam properties at the entrance of the RTML as delivered by the damping rings. Table 3.4 shows beam properties at the end of the RTML as required by the main linac. These properties are valid for conservative and nominal CLIC running scenarios except for the emittances which will be higher in the conservative case.

Table 3.3: Beam properties at the start of the RTML.

Property		Value 3 TeV	Value 500 GeV	Unit
Particle energy	E_0	2.86	2.86	GeV
Bunch charge	q_0	0.65	1.2	nC
RMS bunch length	σ_s	1800	1800	μm
RMS energy spread	σ_E	0.12	0.12	%
Normalized emittance	$\varepsilon_{\mathrm{n,x}}$	500	1800	nm rad
	$\varepsilon_{\mathrm{n,y}}$	5	5	nm rad

3.3.3 System description

The RTML consists of a variety of sub-systems. The most important ones for beam dynamics and general layout are described below following the beam path. Since the sub-systems have different requirements on beam optics they need to be connected by matching lines consisting each of a couple of quadrupoles.

Table 3.4: Beam properties at the end of the RTML.

Property		Value 3 TeV	Value 500 GeV	Unit
Particle energy	E_0	9	9	GeV
Bunch charge	q_0	> 0.6	> 1.1	nC
RMS bunch length	σ_s	44	70	μm
RMS energy spread	σ_E	< 1.7	< 1.7	%
Normalized emittance	$\varepsilon_{\mathrm{n,x}}$	< 600	< 2200	nm rad
	$\varepsilon_{\mathrm{n,y}}$	< 10	< 10	nm rad

Due to civil engineering constraints the central arcs and the transfers to tunnel differ between electron RTML and positron RTML. Currently no positron spin rotator is foreseen, but space is reserved for one. All other beam lines are identical.

Diagnostics sections are foreseen after the two bunch compression stages, BC1 and BC2. At these locations a characterization of beam properties needs to be performed as completely as possible, measuring emittances, transverse and longitudinal profiles, energy and energy spread. Additional diagnostics are required along the entire RTML for proper commissioning and operation (see §5.9).

3.3.3.1 e^+ e^+ Spin rotator

The electron spin rotator will be located at the start of the RTML. It consists of a pair of solenoids, an arc and another pair of solenoids. Each solenoid pair is intersected by a reflector beam line with the transfer matrix, $\begin{pmatrix} I_2 & 0 \\ 0 & -I_2 \end{pmatrix}$ to correct coupling. The arc has to bend by an angle which corresponds to 90° spin rotation. Such a configuration allows rotation of the spin vector to any direction by changing the solenoid strength [51].

The current layout of the electron spin rotator is described in [52]. Its total length is 134 m. The 1.3 m long solenoids have to provide a maximum field of 6 T. To achieve the necessary spin rotation the arc needs to bend by 13.9 deg. The momentum compaction factor of the arc is only 5.9 cm, which leads together with the small energy spread of 0.13% to a negligible bunch lengthening of 2 μm.

To simplify the civil engineering layout the 13.9° bend of the arc can be compensated in front of the spin rotator with an arc bending by the same amount in the opposite direction. Another possibility may be to extract the beams from the delay loop which follows the damping rings (see §3.2) under this angle. Either scheme would have no important impact on performance.

Since positron polarization is not part of the CLIC baseline, no positron spin rotator is foreseen. Nevertheless, to allow further upgrades space has been reserved for one in parallel to the electron spin rotator.

3.3.3.2 Bunch compressor 1

The first stage of bunch compression (BC1) is used to compress the initially 1.8 mm long bunches to a length of 300 μm. The RF for BC1 consists of twenty 2 GHz cavities embedded in a FODO lattice that is the same as for the booster linac. Each cavity has a length of 1.5 m. Their average gradient is 13.3 MV/m. The cavities are described in §5.5.

Since the beam passes the cavities at a phase of 90° off-crest, i.e. at zero crossing, it is on average not accelerated but trailing particles will gain a little energy while particles at the head lose energy. This leads to an almost linear energy chirp of $u_{\mathrm{BC1}} = \frac{1}{E_0}\frac{dE}{ds} = -5.9\ \mathrm{m}^{-1}$ which is required in the following chicane with $R_{56} = -14.5$ m to compress the bunches to 300 μm. The chicane consists of four equal dipoles, the outer two bend by 4.4° and the inner two by -4.4°. The total chicane length is 30 m.

The setup of BC1 and BC2 (see below) is the result of an optimization taking into account effects like coherent synchrotron radiation (CSR) and incoherent synchrotron radiation (ISR) [55]. But also constraints due to energy acceptance of the down stream arcs, beam phase stability and RF properties have been considered [53, 54].

As an alternative the use of 4 GHz cavities is being discussed. The BC1 RF would benefit from the higher gradient of the 4 GHz cavities and from the twice-as-large slope at zero crossing. wake fields are of minor importance since only a rather low voltage is required . Hence, the use of 4 GHz cavities would be preferable. But for cost reasons the frequency choice of the BC1 RF is coupled to the frequency of the booster linac cavities (see §3.3.3.3 below).

3.3.3.3 Booster linac

The booster linac is required to achieve the main linac injection energy of 9 GeV. The same linac is shared by electrons and positrons. This is made possible by shifting the two incoming bunch trains in time (see below). The booster linac consists of the same type of 2 GHz cavities as the BC1 RF. In total 276 cavities are used and run at an average gradient of 14.9 MV/m. They are embedded into a FODO lattice using 8 cavities per cell. The average beta function is about 16 m. The total length of the booster linac is about 538 m.

First studies on the impact of short-range wake fields show that dispersion-free steering can reduce vertical emittance growth to 1 nm.rad (90th percentile). An RMS misalignment of the cavities and quadrupoles by 100 μm and 100 μrad was assumed. The BPMs need a resolution of 1 μm. Including the effect of long-range wake fields in simulations doubles the vertical emittance growth. The equations derived in [56] were used to analytically study the impact of long-range wake fields in case the booster linac is perfectly aligned but the incoming beam position jitters. To safely avoid amplification of such a jitter the higher-order modes in the cavities will need to be damped to Q factors below 30.

The use of 4 GHz cavities is being discussed as an alternative. The advantage is that they would have a higher gradient and the booster linac could be shorter. On the other hand, wake fields will be lower in the 2 GHz cavities, which would be better for beam dynamics. A performance study including short-range wake fields had been performed in [57] for a booster linac consisting of 4 GHz cavities. It was found that in this case one should be able to limit vertical-emittance growth to about 2 nm rad. Long-range wake fields have not been studied. Detailed studies, especially on the impact of long-range wake fields, will have to be performed for both cases before a final decision can be made.

Electron and positron beam lines need to be merged before and split after the booster linac. Due to the opposite charge of the particles this can be done by constant-field dipoles. The layout of the merging beam line will depend on the horizontal distance between the incoming electron and positron beam lines. The layout of the splitting beam line will depend on the point where this splitting should be performed. Consequently, civil engineering will have a strong impact on the layout of both beam lines.

Bunch train timing and beam loading compensation

Electron pulse trains and positron pulse trains pass the same booster linac shortly after each other. The minimum possible timing offset of the starting points of the trains is given by the maximum pulse length of 568 ns, which is required for CLIC at 1 TeV centre of mass energy (see §8.1), plus an additional offset required for the RF beam-loading compensation. Originally it was thought that a total of 740 ns could be sufficient. This value corresponds to 221.8 m path length difference and was taken for the civil engineering layout (see §6.2).

Recent studies of the beam-loading compensation showed that this system will require more time for proper performance. Hence, the delay needs to be increased. Additionally, due to the adoption of 1 GHz RF for the damping rings and the following train combination an even longer offset is needed to fit into these beam lines (see section *****Bunch train combination*****). The minimum possible timing offset seems to be 1.1 μs, which would leave a sufficient gap for the beam-loading compensation, would improve RF efficiency and would allow the usage of a single delay loop for the train combination. That means the path length difference of electrons and positrons has to increase by at least 108 m to achieve a value of 330 m.

The optimum solution for the RF operation and the train timing would be to shift electrons and positrons by 3.6 μs with respect to each other. The booster linac could be powered by two separated RF pulses instead of the single long pulse used at the moment which would lead to a considerable increase in RF efficiency and a simplification of the beam loading compensation [58]. Also the train combination would benefit (see section *****Bunch train combination*****). The only drawback is that the path length difference would increase to 1200 m, a value that cannot easily be adopted into the current civil engineering layout.

3.3.3.4 Central arc and transfer to tunnel

The central arcs are used to direct the beams towards the outer ends of CLIC and to correct their horizontal offsets. Embedded are the transfers to tunnel level which transport the beams 100 m down. Along these beam lines the timing offset of electrons and positrons is compensated.

The direction of motion of the electrons needs to be bent by 180° in the central arc to direct them towards the correct end of the CLIC site. The lattice of the arc is copied from the lattice of the turn-around loops (see below). It is achromatic, almost isochronous and has been optimized for an acceptable emittance growth induced by incoherent synchrotron radiation (ISR). Its average radius is 305 m. A dog-leg follows this arc to correct the horizontal offset. The transfer to tunnel is placed along the straight section of the dog-leg. It is built of two vertical arcs connected by a simple periodic lattice. To limit the slope the transfer to tunnel is about 1400 m long. Horizontal and vertical bends are separated to simplify the lattices and to avoid coupling of the planes. The total length of electron arc and transfer is 2400 m.

The positron direction does not need to be changed since it is already correct. Consequently, the central positron arc is just a dog-leg with the transfer to tunnel embedded like for the electrons. To correct the bunch train timing the path length for the positrons needs to be shorter compared to the electron path length. The current baseline in the civil engineering layout shows a difference of 221.8 m. Accordingly, the transfer to tunnel has a length of about 2.1 km, which results in a total length of positron dog-leg and transfer of 2180 m. A change of the path length difference does not influence beam dynamics. It is only important for the layout.

The lattices of the arcs are either copies or variants of the turn-around loop lattice. This ensures low ISR emittances growth, achromaticity and almost isochronicity.

3.3.3.5 Long transfer line

To transport the beams to the outer ends of the site the central arcs are followed by the 21 km long transfer lines. They utilize a FODO lattice with very weak quadrupoles, $k_1 = 0.0097$ m^{-2}, resulting in a cell length of 438 m and an average beta function of 620 m. The phase advance is 45°. A beam pipe radius of 6 cm is used to reduce resistive wall wake fields [59],[60] which could otherwise lead to the development of a multi-bunch instability along these lines. Due to the fast beam-ion instability which could develop the vacuum needs to stay below 0.1 nTorr [60].

Misalignment studies show that an rms quadrupole alignment of about 100 μm rms should be sufficient even when performing only one-to-one steering [61]. Studies of magnetic stray fields, on the other hand, result in tight tolerances on their allowed dynamic variation. This only amounts to about 10 nT with a dip of 0.1 nT for periodic stray fields with a wavelength equal to the betatron wavelength are allowed [62],[53]. The acceptance of the following turn around loop for the induced beam deflection is large enough to avoid dilution of emittances. Hence, the limit on stray fields is set due to the acceptable beam deflection at the entrance of the main linac. The feed-forward system (see below) will improve requirements by about a factor ten.

3.3.3.6 Turn-around loop

The turn-around loops direct the outgoing beams into the direction of the interaction point (IP). The beams are bent by 180° and the resulting horizontal offsets are corrected by dog-legs. It was decided to use two 60° arcs per dog-leg which is a compromise between reduction of ISR and lengthening of the lattice. The arcs of a dog-leg are connected by a simple 354 m long periodic lattice. The average radius of all arcs is 305 m and the total loop length is 1944 m. Both turn-around loops consist of 50 arc cells.

Since the loops need to be achromatic and almost isochronous a rather complex lattice is used which is based on Ref. [63]. Each 31.9 m long cell bends by 6°, is achromatic and almost isochronous. To achieve this and to keep ISR emittance growth small, 5 dipoles, 7 quadrupoles and 4 sextupoles are used per cell. The phase advances are 432° in the horizontal plane and 144° in the vertical plane. Beta functions β_x, β_x, dispersion R_{16} and momentum compaction R_{56} along a single cell are plotted in Fig. 3.7. Beta functions and dispersion along the dipoles are small to avoid ISR emittance growth.

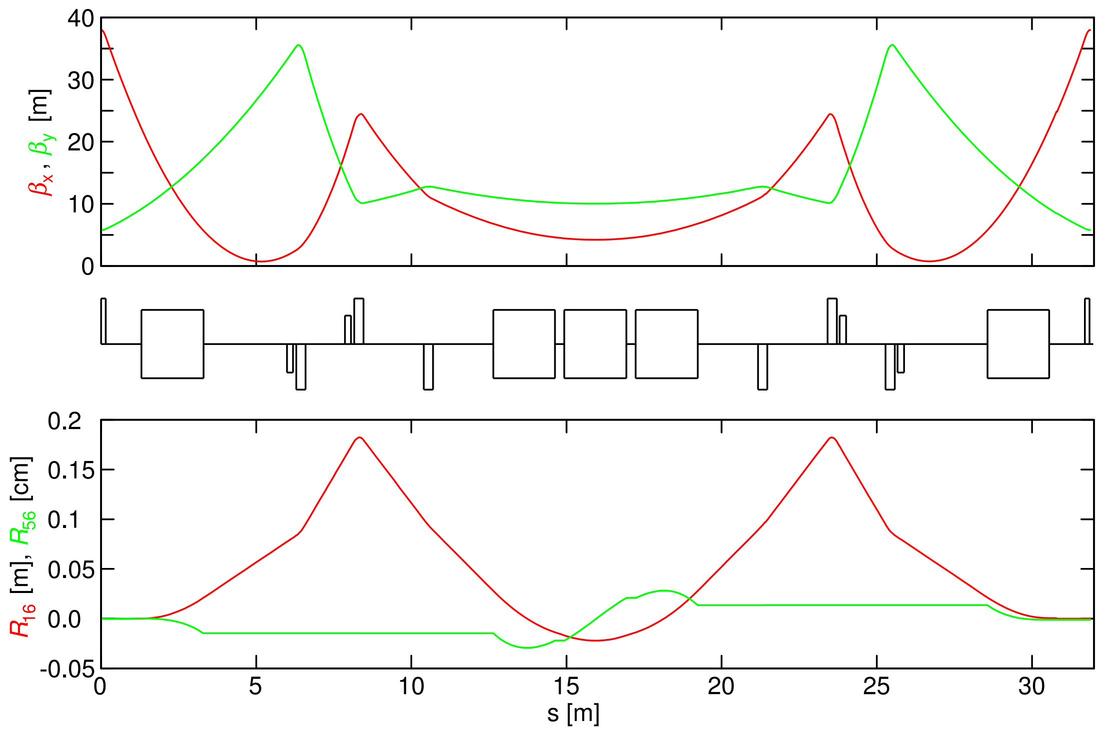

Fig. 3.7: Beta functions (top), dispersion and momentum compaction (bottom) along an arc cell.

Isochronicity is requested for the turn-around loops to avoid bunch lengthening. Bunch compressor 2 would need to be stronger to compensate for it and thus stronger synchrotron radiation would be produced. However, error tolerance studies could reveal that the chosen loop lattice is too strong and thus induces too strong emittance dilution. Hence, for an optimum solution it might be preferable to allow a small R_{56} along the loop which could reduce quadrupole and sextupole strengths considerably. The required error tolerance studies have been started. First results indicate that an alignment of the bends and quadrupoles to 100 μm and 100 μrad RMS might be sufficient when assuming a BPM resolution of 1 μm. The sextupoles might need to be aligned better. Though it is expected that coupling and dispersion correction will help to mitigate alignment tolerances further.

3.3.3.7 Feed-forward system

Around the turn-around loops there are feed-forward systems installed to mitigate beam imperfections which have been accumulated in front of the loops. Prerequisite for proper functioning is that the loop error acceptance is large enough to not let beam imperfections, e.g. beam offsets, dilute emittance. Measurements will be performed in front of the loops and corrections will be applied behind them. The feed-forward systems will correct beam orbit, energy and perhaps phase. The beam phase only has to be corrected in case external phase references are being used (see §2.6).

The feed-forward systems are expected to improve beam properties by up to a factor 10. Since most errors will influence a full bunch train, diagnostics and correctors do not have to be very fast.

3.3.3.8 Coupling and dispersion correction

Since emittances are extremely small and their ratio $\varepsilon_x/\varepsilon_y$ is large, even the slightest residual dispersion or coupling can lead to non-negligible emittance growth in the vertical plane. The turn-around loops are expected to be major sources of these kinds of imperfections. Consequently, they will be followed by coupling correction sections consisting of skew quadrupoles. Dispersion correction will be integrated in the last arcs of the loops.

3.3.3.9 Bunch compressor 2

The second bunch compression stage (BC2) compresses the bunches to their final length of 44 μm, i.e. by a factor 7. Its RF section is made of 78 12 GHz cavities which are 0.23 m long and run 90° off-crest at an average gradient of 94 MV/m. These cavities are of the same type as the main linac cavities at 500 GeV. (see §5.5). The high gradient is possible since on average no energy is extracted by the beam. Its value is sufficient to compensate for the impact of short-range wake fields, which tend to lower the induced energy chirp. To ensure that short-range wake fields do not spoil beam quality considerably, the lattice of the BC2 RF is the same as at the start of the nominal main linac.

An energy chirp of $u_{\mathrm{BC2}} = \frac{1}{E_0}\frac{dE}{ds} = -49.5\ \mathrm{m}^{-1}$ is required to fully compress the bunches in the two BC2 chicanes with $R_{56,1} = -1.38$ cm and $R_{56,2} = -0.60$ cm. Full bunch compression, i.e. compression until the longitudinal phase-space ellipse is fully upright, is required for stability reasons in the main linac. Two chicanes, each made of four dipoles, are used to reduce CSR especially when bunches are shortest. They both have a length of 30 m and are made of the same 1.5 m long dipoles. Another advantage of using two independent chicanes is that flexibility is being gained, for example to adapt the system to parameters at 500 GeV (see §9.2).

3.3.3.10 Emittance measurement

Just in front of the main linac the beam emittances in both transverse planes have to be measured. They are determined from beam size measurements performed with laser wire scanners (see §5.9.2.2). The measurement section consists of four FODO cells with a phase advance of 45° in both planes and is equipped with four laser-wire beam profile monitors placed just after the horizontally defocusing quadrupoles [64]. Each monitor includes two orthogonal laser beams scanning the bunches and is capable to measure horizontal and vertical RMS beam sizes at the micrometer level with a precision of 10%. This allows to reconstruct projected emittances with a precision of also about 10%. The Compton-scattered photons are detected either by a Cherenkov detector or a calorimeter. A weak dog-leg can be used to provide the required separation of particles and photons behind the last monitor. An offset of about 10 cm would be sufficient. The total length of the section is about 82 m, beta functions at its entrance are $\beta_x = 40$ m and $\beta_y = 18$ m.

A similar station will also be installed at the start of the RTML. Since beam energy is smaller beam sizes will be slightly larger and measurement should become simpler. But in general the same challenges have to be addressed as for the emittance measurement at the end of the RTML.

3.3.3.11 Commissioning dumps and spectrometers

For commissioning of the RTML and later for machine studies it will be necessary to have the possibility to dump the beams at various points along the RTML. Current planning is to have dumps just behind the damping rings, at entrance and exit of the booster linac, at the entrance of the turn-around loops and just in front of the main linacs.

Average beam power is 30 kW in front of the booster linac, i.e. at a beam energy of 2.86 GeV, and 90 kW behind the booster linac, i.e. at a beam energy of 9 GeV. Hence, all dumps can be rather small (see §5.11).

The beam lines leading to the dumps will also be used as spectrometers for precise energy and energy spread measurements.

3.3.4 Accelerator physics issues

Due to the large variety of sub-systems forming the RTML a large variety of accelerator physics issues has to be studied. The most important ones are described here.

3.3.4.1 Incoherent synchrotron radiation

Incoherent synchrotron radiation (ISR) is emitted in any bend. While the energy loss is a static effect, which can be easily compensated, the induced emittance growth poses a serious challenge. The emittance growth depends strongly on particle energy and bend angle [65]:

$$\Delta\varepsilon \propto E_0^5 \frac{\theta^5}{l_{\mathrm{arc}}} . \tag{3.1}$$

Consequently, all arcs behind the booster linac need to be carefully designed using long and weak bends. Additionally, ISR emittance growth can be reduced by having small beam sizes along the bends, i.e. by using small beta functions and by avoiding to place bends at locations with high dispersion. These points have been taken into account in the design of the turn-around loop lattice, which still contributes most to emittance growth in the horizontal plane along the RTML.

3.3.4.2 Coherent synchrotron radiation

Coherent synchrotron radiation (CSR) will develop along long and strong bends [66]. Like a wake field its longitudinal component will induce a non-uniform energy loss along a bunch. If this happens inside a dispersive section, e.g. a bunch compressor chicane, the dispersion cannot be compensated for all particles. Therefore, in the bend plane a transverse shift of some particles remains and the projection of the beam profile enlarges, looking like an emittance growth. Note that the emittance calculated for a sufficiently short slice of particles usually remains unchanged. A direct impact of the transverse field components of CSR on the transverse phase-space distribution is often negligible.

CSR emitted in the chicanes of the bunch compressors leads to a major contribution to horizontal emittance growth while CSR emitted in the arcs and loops is small. Only when the vertical aperture of the vacuum chambers along the bunch compressor chicanes is less than about 2 cm does the shielding effect of the conducting chamber walls [67] lowers CSR to acceptable levels [55].

3.3.4.3 Cavity wake fields

When a particle beam traverses RF cavities, wake fields will be created depending on the geometry of the cavities. As long as cavity axis and beam trajectory are perfectly aligned with respect to each other only a longitudinal field will be created which potentially changes the energy distribution along single bunches. Indeed, this effect has to be taken into account in the RF cavities of BC2.

In the BC2 RF the longitudinal wake fields induce an energy chirp opposite to the one required for bunch compression. This has to be compensated by increasing the integrated cavity voltage by 72 MV compared to the value obtained by simplified first-order calculations. Similar effects in the BC1 RF and in the booster linac are very small.

In case there is an offset between cavity axis and beam trajectory, either due to cavity misalignments or due to jitter of the incoming beam position, transverse wake field components will be created which transversely kick either particles within the same bunch (short-range wake fields) or even trailing bunches (long-range wake fields). These kicks will lead to a growth of single bunch emittances or projected emittances of the full bunch train.

Hence, on the one hand cavity design has to take into account the reduction of wake fields, e.g. by enlarging irises and by including higher order mode (HOM) damping (see §5.5). On the other hand, good cavity alignment and good control of the beam trajectory is mandatory. Also strong focusing along the cavities helps to keep wake-field effects small.

3.3.4.4 Magnetic stray fields

Contrary to magnetic field errors, which are errors of the magnets within a beam line, magnetic stray fields are produced by external sources, i.e. by sources which are not part of the beam-line lattice. These sources can be any technical installation of the accelerator itself, e.g. vacuum pumps, any technical installation near the accelerator, e.g. power lines, or even geophysical conditions of the accelerator site, e.g. fluctuations in the earth magnetic field.

The main concern in the RTML are the long transfer lines, not only due to their length, but also due to their weak focusing. The beams can easily accumulate kicks by the stray fields resulting in unacceptable beam deflections which may even dilute emittances further down stream. The study in [62] showed that stray fields periodic along the entire transfer line with a wavelength equal to the betatron wavelength are worst. In reality, such a long periodicity of stray fields is unlikely. An important function of the feed-forward system is to compensate beam deflections induced by the magnetic stray fields and thus to loosen requirements on these.

3.3.4.5 Multi-bunch resistive wall instability

The electromagnetic fields of the particle bunches interact with the walls of the vacuum chamber. In case the chamber and the bunches are not well aligned with respect to each other, transverse resistive wall wake fields are produced. Depending on radius and resistivity of the chamber these fields might persist long enough to transversely kick the following bunch and an instability might develop along a bunch train [60]. Due to the short bunch spacing within a bunch train and due to the length of the long transfer lines, wide-aperture copper beam pipeswith a radius of 6 cm will be required.

3.3.4.6 Fast beam-ion instability

Particles of the residual gas in the vacuum chambers can be ionized by the beams. The electron beam will repel the electrons of the ionized gas and trap the ions, whereas the positron beam will repel the ions and trap the electrons of the ionized gas. Since the ions have a low mobility it is possible that during the passage of an electron bunch train ions accumulate and start to defocus or transversely kick the beam particles. Onset and growth rate of this effect depend on charge density within the bunch, bunch repetition rate, vacuum pressure, i.e. number of gas particles, and gas species. In the long transfer line for the electrons a vacuum pressure of less then 0.1 nTorr is required to safely avoid the fast beam-ion instability [60]. Trapping of electrons by the positron beam is less likely due to the higher electron mobility. Hence, the vacuum pressure in the long positron transfer line could be higher. Nevertheless, current baseline is to achieve the same pressure as for the electron beam.

3.3.5 Component specifications

Due to its length and complexity the RTML consists of a variety of components. The number of magnets and cavities is summarized in Table 3.5. Details on the magnets are given in §5.2. The number of steering magnets is not yet determined but it will most likely be close to the number of quadrupoles and sextupoles. Additional magnets will be required for the diagnostics beam lines and the beam lines of the commissioning dumps.

The 12 GHz cavities of the BC2 RF are the same as the ones under study for the main linac at 500 GeV. The 2 GHz cavities of the BC1 RF and the booster linac are also used in the main beam injector complex. They are described in §5.5.

In [54] it has been evaluated within which tolerances the dipoles of the bunch compressor chicanes, the RF phases and RF amplitudes need to stay to limit beam phase jitter at the main linac entrance to 0.2°(12 GHz) and bunch energy jitter to 0.2%. A possible benefit from the feed-forward system has not yet been taken into account. The magnetic field error of the bunch compressor dipoles should not exceed a few 10^{-4}. The exact value depends on the design choice for the phase reference. The amplitude of the bunch compressor RF needs to be better than 2% to reduce bunch length jitter to less than 1% and the booster linac amplitude has to be better than 0.1%. The phase jitter of the booster linac cavities has to stay below 2°(2 GHz) whereas for the BC1 RF phase probably only 0.08°(2 GHz) is allowed. The BC2 RF phase has to be better than 0.2°(12 GHz). Final design specifications will be based on these values once the performance of the feed-forward system has been better defined.

Other requirements have not yet been fully evaluated. In general magnet stability at the 10^{-5}–10^{-4} level seems to be sufficient.

Table 3.5: Total number of magnets and cavities in the electron and positron RTML not including steering magnets.

Type	Amount
Dipoles	710
Quadrupoles	1744
Sextupoles	541
Solenoids	4
Cavities (2 GHz)	314
Cavities (12 GHz)	96