Summary

In classical electromagnetism, a charged particle radiates energy in the form of electromagnetic radiation when it is subject to a force. This effect is the principle behind many useful sources of radiation such as electron synchrotrons and linear accelerators. The main figures of merit of synchrotron radiation sources are (narrow) spectral bandwidth, photon wavelength tunability and brilliance. The periodic motion of particles in a synchrotron makes these machines well-suited for a stable emission at high repetition rate. However, in addition to the synchrotron radiation and complementary to that, a strong need has emerged over the last few years for a source of radiation with extremely high brilliance, close to full coherence, a bandwidth approaching the Fourier limit and a stable and well characterized temporal structure in the femtosecond time domain. Such a source is the single-pass Free Electron Laser (FEL) that, due to Doppler frequency up-shifting of emitted radiation by relativistic electrons, is particularly well-suited to generate short wavelength X-ray pulses with peak brilliance many orders of magnitude higher than that generated in modern synchrotrons and with sub-picosecond pulse lengths. There are currently no alternative sources that have such high pulse energies and short durations. The investigation domain opened by the new FEL sources covers essentially all basic science fields giving access to explorations of matter in practically unexplored regimes. The scientific opportunities will in fact impact studies of a large number of disciplines encompassing material and biomaterial science, nanoscience, plasma physics, molecular and cluster femto- and nano- physics and chemistry, as well as having various connections to life, environmental, astrophysical and earth science.

The FEL high brilliance, high intensity and shot-to-shot stability strongly depends on the electron beam source. Delivering a high quality electron beam and machine flexibility to serve a broad range of potential applications imposes severe requirements on the final electron beam parameters and the machine design. To meet these requirements, the need of a linac design based on extensive studies of possible perturbations that may affect the electron beam dynamics, of means to correct them and of parameter optimization has emerged. In this sense,
the realization of a valid machine design is a fundamental and critical step for the success of a FEL project. Because of the special sensitivity of the FEL generation to the electron beam emittance, relative energy spread and trajectory control [15, 16], this Thesis has focused on the design strategies to control these parameters. Some aspects of the machine study have been developed for the specific FEL scheme known as harmonic generation. In fact, we can identify two general ways to generate X-rays with a FEL. The Self Amplified Spontaneous Emission (SASE) [22–25] relies on the interaction of electrons and photons that are emitted by the electron beam itself. Since the electron bunching starts to grow from the natural noise of the initial electron distribution, the SASE output radiation is relatively poor in longitudinal coherence. In the High Gain Harmonic Generation (HGHG) scheme [5–9, 26, 27], instead, the initial energy modulation is driven by an external seed laser. It is then transformed into density bunching in a dispersive section inserted in the undulator chain. In this case, the output FEL properties reflect the high longitudinal coherence of the seed laser. The machine design of a single-pass linac-based FEL and the related electron beam dynamics has been presented in this Thesis. The specific case of a HGHG FEL has been treated. Then, the general principles have been applied, for a quantitative analysis, to the FERMI@Elettra FEL case study. Some experimental results of the recent FERMI commissioning have been discussed and compared with the model predictions.

The FERMI@Elettra single-pass linac-based FEL at the Elettra Laboratory of Sincrotrone Trieste [28, 29] is one of the FEL based European projects, designed to become the international user facility in Italy for scientific investigations with ultra high brilliance X-ray pulses of ultra-fast and ultra-high resolution processes in material science and physical biosciences. With a peak brightness of about 6 orders of magnitude greater than third generation sources, full transverse coherence, (close to) transform limited bandwidth, pulse lengths of the order of a picosecond or less, variable polarization and energy tunability, the FERMI source is a powerful tool for scientific exploration in a wide spectrum of disciplines. The coherence properties will open up new perspectives for single shot imaging, allowing to study the dynamics of chemical reactions and other phenomena through single pulse coherent diffraction imaging with a spatial resolution in the nanometer domain. The high peak power will allow studying nonlinear multi-photon processes in a regime never explored before, dilute samples that are of paramount importance in atmospheric, astrophysical and environmental physics as well as in the characterization of nano-size materials. The short pulse duration will open the door to visualizing ultra-fast intra-atomic and electronic dynamics. So, the ultra-bright, ultra-short pulses will allow single photon pulse experiments to collect images at time scales faster than radiation damage. This in turn will open the possibility of studying the morphol-
ogy and the structure of bio-systems unstable under X-ray radiation exposure. Last but not least, the choice of harmonic generation by an external seed laser is dictated by the scientific applications and the flexibility that such choice entails. As the seed laser determines the duration, bandwidth, and wavelength of the output radiation, all are tunable and controllable, covering a wide spectral range. The seed laser furthermore provides a reference signal throughout the FERMI facility (including the experimental beamlines) to facilitate the femtosecond level precision timing and synchronization of all systems. The seeded FEL driven by an external laser is therefore particularly suitable for pump-probe synchronization at time scales well below one picosecond. The choice of design parameters allows FERMI to generate FEL radiation with a wide range of characteristics tailored to match a diversity of experimental requirements, ranging from single shot, short (≤50 fs), high brilliance, time-resolved experiments to ultra-fast pump-probe experiments, to high resolution experiments with close to transform-limited radiation on the 10’s fs time scale.

This thesis starts from the assumption that a high brightness electron beam is generated in a photo-injector at energies lower than 100 MeV. The primary goal of the machine design is that of preserving the 6-D electron beam emittance as at the injector level. The emittance is a measure of the phase space domain occupied by the beam. The transverse emittance has to be small enough to allow the production of a spatially coherent photon beam at the desired wavelength. The longitudinal emittance or more precisely the energy spread, for a given electron bunch duration, has to be small enough to permit the saturation of the FEL intensity within a reasonable undulator length. A small energy spread also ensures a small bandwidth of the output photon pulse and a high harmonic content. Typical electron beam parameters of the fourth generation – very high brightness – linac-based FELs (from infrared to X-rays spectral range) are listed in the following and the FERMI@Elettra nominal parameters are put in parenthesis: 0.2–1 nC charge (0.8 nC), 1–3 mm mrad normalized emittance (1.5 mm mrad), 0.5–3 kA peak current (0.8 kA), 0.05–0.1 % relative energy spread (0.1%) and 1–50 GeV final electron energy (1.5 GeV). In contrast to linear colliders, where particle collisions effectively integrate over the entire bunch length, the X-ray FEL concerns only very short fractions of the electron bunch length. The integration length is given by the FEL slippage length that is the electron-to-photon longitudinal slippage over the length of undulator, prior to FEL power saturation. The slippage length is typically in the range 1–30 μm, a small fraction of the total bunch length.

The original contributions of this Thesis are structured as follows. Chapter 2 is an introduction to the FERMI@Elettra layout based on the FERMI Technical Design Study. Apart from little manipulations of some formulas, Chapter 3 introduces for the Reader’s convenience well-established theoretical tools which
are used in the following Chapters to describe the electron beam dynamics and the 6-D emittance degradation. The validity of the theoretical models for the FERMI case study is discussed. Chapter 4 deals with the machine design from the point of view of the single particle dynamics, including the specification of the magnetic field tolerances and alignment, the optics design of diagnostic and production lattice and geometric collimation. Chapter 5 describes the impact of collective effects on the electron beam dynamics such as wake fields, space charge forces and emission of coherent synchrotron radiation. Chapter 6 is focused on the determination of the machine working point in terms of bunch length compression factor and final electron beam parameters. Finally, Chapter 7 reports about the FERMI@Elettra commissioning results that are highly relevant for a comparison with the theoretical and simulation studies carried out in the previous Chapters.

In Chapter 2, the main parameters and layout of the FERMI@Elettra single-pass FEL have been introduced. Due to the relatively low energy of the electron beam, ranging from 0.9 GeV to 1.5 GeV, the harmonic up-shifting of an initial seed signal is an obliged choice for FERMI in order to reach the FEL fundamental emission at wavelengths as short as 4 nm. However, the seeding interaction puts a tight constraint on the maximum slice energy spread of the electron beam at the undulator entrance that is approximately 150 keV (rms value), only a factor of 5 bigger than the minimum theoretical uncorrelated energy spread expected after bunch length compression. Peak power saturation at the fundamental wavelength is ensured by the several hundred’s Ampere electron beam with a normalized slice emittance equal or smaller than 1 mm mrad. The S-band, normal conducting Elettra linac has been upgraded with other 7 accelerating structures from CERN. Only the Elettra structures should be able to provide the remarkable accelerating gradient of 25 MV/m, instead of 15 MV/m in the others, by virtue of the SLED system for RF pulse length compression. Unfortunately, the BTW structures have irises with inner radius of only 5 mm, instead of the 9 mm in the TW structures. Such a small radius excites strong longitudinal and transverse wake fields that have to be carefully considered in the machine design and study of the electron beam dynamics. A movable, achromatic, four dipoles magnetic chicane has been designed to manage the magnetic bunch length compression. Two of these chicanes, BC1 and BC2, are integrated in the linac magnetic lattice. A 30 m long transfer line brings the high energy electron beam to the parallel undulator lines of FEL1 and FEL2. The electron beam is finally dumped in the horizontal plane, while the emitted photons are transmitted to the downstream photon beam lines for experiments.

Chapter 3 contains the theoretical tools for describing the single particle and electron beam collective motion in a single-pass linac; their applicability to the FERMI case study has been discussed. Liouville’s theorem illustrates the pri-
mary goal of 6-D electron beam emittance preservation as at the injector level. The high beam quality that is required from the FEL process is expressed in terms of the Liouville transverse emittance and energy spread. In reality, the applicability of Liouville’s theorem to the beam transport and bunch length compression in a linac-based FEL is invalidated by several single particle and collective frictional forces. These degrade time-projected or local (in the z-coordinate) beam parameters. To investigate such different effects, the concept of projected and slice emittance has been introduced for the transverse motion. The definition of correlated, uncorrelated and slice energy spread has been given for the longitudinal motion. The rms emittance has also been introduced as a statistical measure of the particle spread in the phase space. In fact, most of the measurements of the electron beam parameters deal with that, not with the Liouville one. Unfortunately, unlike the latter, the former is diluted by chromatic filamentation. Because of the relatively high energy spread required for the magnetic bunch length compression, chromatic filamentation might develop in the presence of beam optics mismatch or magnetic field errors. Nevertheless, the beam matrix formalism allows one to determine the design tolerances in terms of mismatch parameter, magnet alignment and field quality to avoid an emittance dilution beyond the specifications. As for the longitudinal dynamics, the theory of magnetic bunch length compression has been expanded up to the second order in the particle coordinates. It has been shown how the second order energy chirp and path length-to-energy correlation term limit the compression efficiency and, therefore, the minimum bunch length achievable with a magnetic chicane. A higher harmonic RF cavity has therefore been introduced in order to cancel out the second order terms in the longitudinal particle motion.

The analytical treatment of the most important collective effects has also been given. The interaction of the electron beam with the image charge field in the accelerating structures has been described in terms of the longitudinal and transverse wake potential. The beam dynamics in the presence of the electromagnetic self-field has been investigated through the laminarity parameter. This could be used to identify the linac regions in which short range space charge forces corrupt the quasi-laminar particle motion due to very high charge density. This is expected to happen, for example, during the bunch length compression, even at high energy. The space charge forces are then modeled with a longitudinal wake function that induces an energy modulation at wavelength much shorter than the bunch length. It is transformed into density modulation in the chicanes’ dispersive region, thus enhancing the emission of coherent synchrotron radiation that, in turn, amplifies the initial energy modulation. This self-amplifying process is called the microbunching instability and degrades both the energy and the particle density distribution. Formulas for the computation of the linear gain, in the one- and two-stage compression scheme have been given. A very
similar process is at the basis of the FEL instability. The 1-D modeling of the FEL generation has been sketched and the requirements on the electron beam quality have been deduced from the basic formulas, essentially for the peak current, transverse emittance and relative energy spread.

The analytical evaluation of the effect of the magnetic field errors, magnet misalignments and chromatic aberrations in the presence of linear and nonlinear fields on the transverse beam dynamics in the FERMI@Elettra linac has been presented. Using the beam matrix formalism and theory of field expansion introduced in Section 3.2, the specifications for the magnets field quality and alignment have been given in order to limit the emittance dilution to 1% for each individual error source. Then, in the assumption of linear optics transport, the design of a dispersion-free, straight diagnostic line and of a dispersive diagnostic line has been presented. With particular attention to the FERMI@Elettra lattice, the BC1 region for electron beam diagnostic and transport has been discussed. The optics requirements coming from the beam diagnostic performance have been integrated in the optics design. So, the intrinsic resolution of the mean energy and energy spread measurement has been evaluated. The possibility of measuring the correlated, uncorrelated and slice energy spread at all the dispersive lines of the FERMI@Elettra lattice has been investigated. The measurement of several beam parameters has been simulated with particle tracking. Finally, a two-stage station for beam geometric collimation, integrated into the straight diagnostic line, has been discussed. The collimation efficiency has been analytically defined and the theoretical prediction for the BC1 case study agrees well with the result of particle tracking.

Analytical evaluations and simulations with particle tracking of electron beam collective effects in a single-pass, S-band linac have been carried out. A quantitative study for the FERMI@Elettra electron beam delivery system from the injector end to the undulator, including the magnetic bunch length compression has been done. The effect of the structural longitudinal and transverse wake field on the electron beam energy distribution and projected emittance, respectively, has been studied. Shaping of the initial current profile has been proposed to alter the longitudinal wake potential and make it almost linear. In this way, the longitudinal wake field can be used to cancel out the linear energy chirp required for magnetic compression; moreover, nonlinear contributions to the energy chirp are minimized. It has been proposed to suppress the head-tail instability induced by the transverse wake with trajectory manipulation along the linac (emittance bumps). Then, a trajectory jitter study has been done in order to specify the magnet alignment and vibration tolerances that do not affect this correction scheme. Finally, the CSR effect on the transverse emittance and the microbunching instability linear gain has been computed and compared with particle tracking results. The optics design allows the compensation of the CSR.
effect by means of a suitable optics arrangement in the magnetic chicanes and in the Spreader. As for the microbunching instability, it enters into the nonlinear regime when a two-stage compression is adopted. This study therefore justifies the implementation of a laser heater to Landau damp the instability and to keep the slice energy spread within the FEL specifications.

Some guidelines for the design of the magnetic compressor scheme have been given, according to the requirements based on the FEL performance goal. The principles depicted in this Chapter refer to the specific case of a seeded X-ray FEL and only magnetic compression of the bunch length has been considered. The design parameters for the FERMI magnetic compressors have been made explicit as a case study of the previous theory. After that, the effect of the magnetic bunch length compression on the microbunching instability development in a linac-based FEL has been investigated. In particular, the reduction of the instability gain by particle longitudinal phase mixing has been demonstrated analytically. It has been shown that the efficiency in removing the beam microbunching is much more sensitive to the initial modulation wavelength than to the amplitude. The natural consequence of this dynamics is the adoption of a single stage of compression. The feasibility of this scheme has been demonstrated by means of 3-D particle tracking for the FERMI@Elettra FEL, with promising results for the preservation of the beam quality. In addition to this, a different promising configuration shows up. If the linear energy chirp at the exit of BC1 could be removed by dedicated accelerating structures, then particle longitudinal crossover is enhanced in BC2. The effect is optimized by two chicanes, BC1 and BC2, with the same sign of \( R_{56} \). As a result, the energy modulation is damped, together with the associated current spikes. The FERMI@Elettra case study has been analyzed in some details. The 1-D beam transport has been verified against the 3-D particle tracking performed with \texttt{elegant}, including collective effects, for a compression factor of 10 in BC1. The study shows that this alternative scheme of compression is successful and even more efficient than the single compression for initial modulations whose wavelength is of the order of tens of \( \mu \)m. It may even be applicable to longer wavelengths and/or higher compression factors, although these more extreme situations need to be confirmed by further investigations.

We have reported about the commissioning of the FERMI@Elettra electron beam delivery system. Methods and experimental results concerning the control of the longitudinal (acceleration, energy distribution, bunch length compression and microbunching instability) and transverse (optics matching, transport and trajectory control) electron beam dynamics in FERMI have been shown. The longitudinal phase space of the electron beam has been characterized at the beginning of the FERMI commissioning with a simple spectrometer line. Optics has revealed to be an important ingredient for the characterization of the electron
beam energy distribution since it optimizes the resolution of the energy measurement. Starting from experimental Twiss parameters of the electron beam, the optics matching and transport through the whole line has been performed with the \texttt{elegant} code, which includes the description of the real accelerating gradients and the RF edge focusing of the structures. The mismatch parameter usually describes a projected emittance growth smaller than 1\% in both planes. \texttt{elegant} has also been used to generate trajectory theoretical response matrices to correct the real beam trajectory in the linac and in the high energy transfer line. The matrices are imported in a trajectory feedback tool. This is also able to measure experimental response matrices. The theoretical and the experimental ones can be merged for a global trajectory correction along the whole line. The BPMs integrated into the feedback tool read the beam position at the frequency of 10 Hz and their reading is by the corrector magnets forced to the value determined by the user. In this way, the feedback works as a trajectory correction tool as well. It has been verified that the magnetic chicane BC1 does affect neither the trajectory nor the dispersion in the succeeding lattice. The dispersion bump in the chicane has been measured and agrees well with the theoretical expectation. An important horizontal emittance growth appears during the magnetic bunch length compression, especially for compression factors larger than 3. Offline simulation studies indicate that CSR might be the main responsible of this emittance degradation, especially in the presence of nonlinear compression (the X-band cavity to linearize the longitudinal phase space during compression has not been installed yet) and potential slice optics mismatch. Some evidence of the microbunching instability has been detected for compression factors larger than 3. They are COTR emission downstream of BC1 and an energy modulation of the compressed electron beam. At the end, a comparison of the theoretical expectation and measured values for many electron beam parameters has been produced and summarized in Table 7.2. The transverse beam dynamics suffers of a normalized emittance degradation during compression in BC1, as mentioned before, and of a further growth due to the transverse wake field effect in the last part of the linac, as predicted by the model. On the other hand, the beam optics seems to be pretty well under control since the mismatch parameter is usually very close to 1. The particle energy distribution is manipulated according to the model along the entire linac. An energy jitter beyond the specification has been measured at the entrance of BC1 and this could be related to the trajectory jitter also observed in a range larger than the specification. So, further investigations are needed to accomplish a full understanding of the physics developing in BC1. Nevertheless, the electron beam quality has revealed to be more than sufficient to generate the first coherent harmonic generation in seeded configuration at 43 nm (FEL fundamental output) in December 2010, after one year (calendar time) of machine commissioning.