INFN

Istituto Nazionale di Fisica Nucleare

LNF – xx/xx
Xxx xx, 20xx

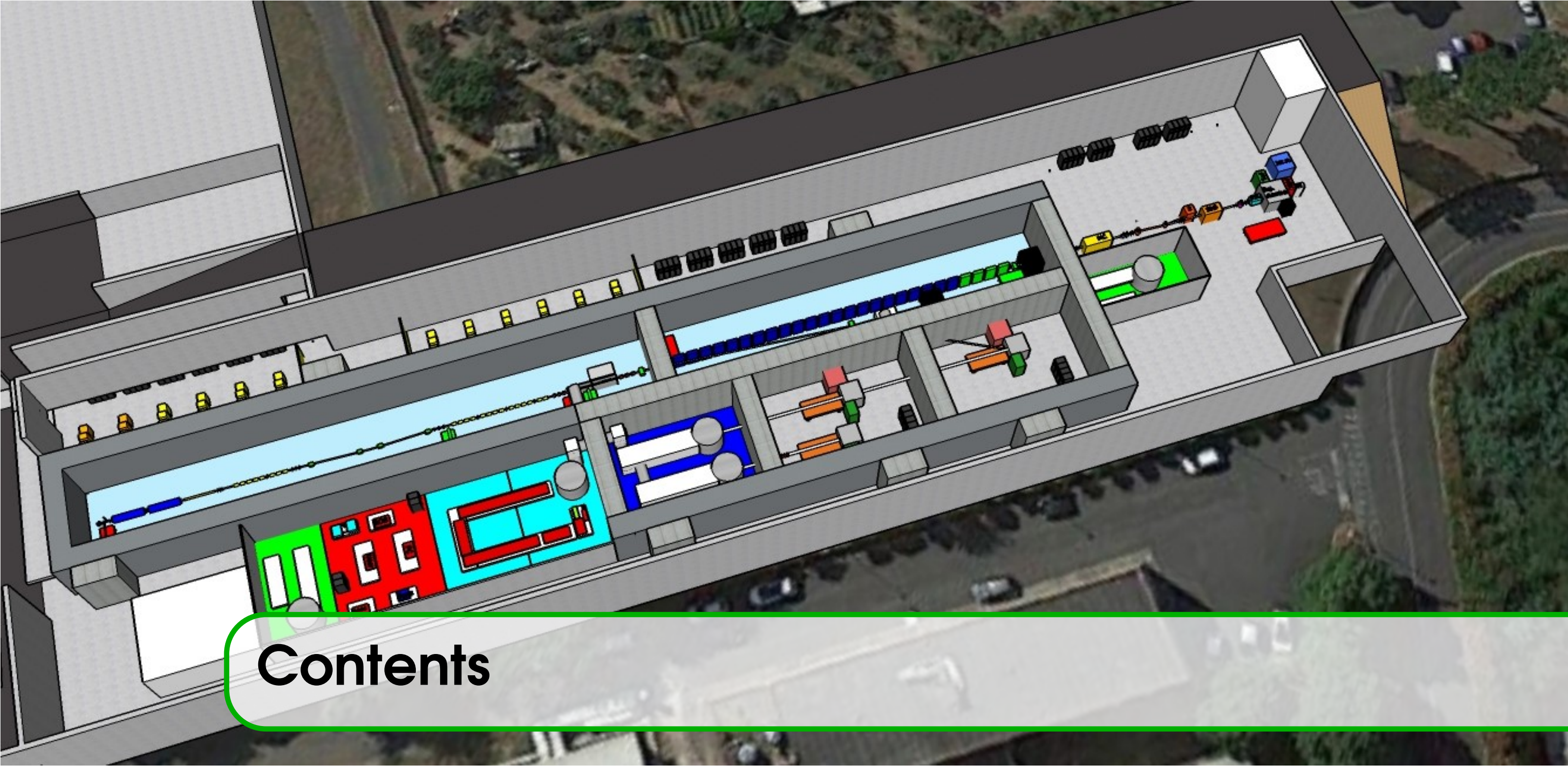
EuPRAXIA@SPARC_LAB

Technical Design Report

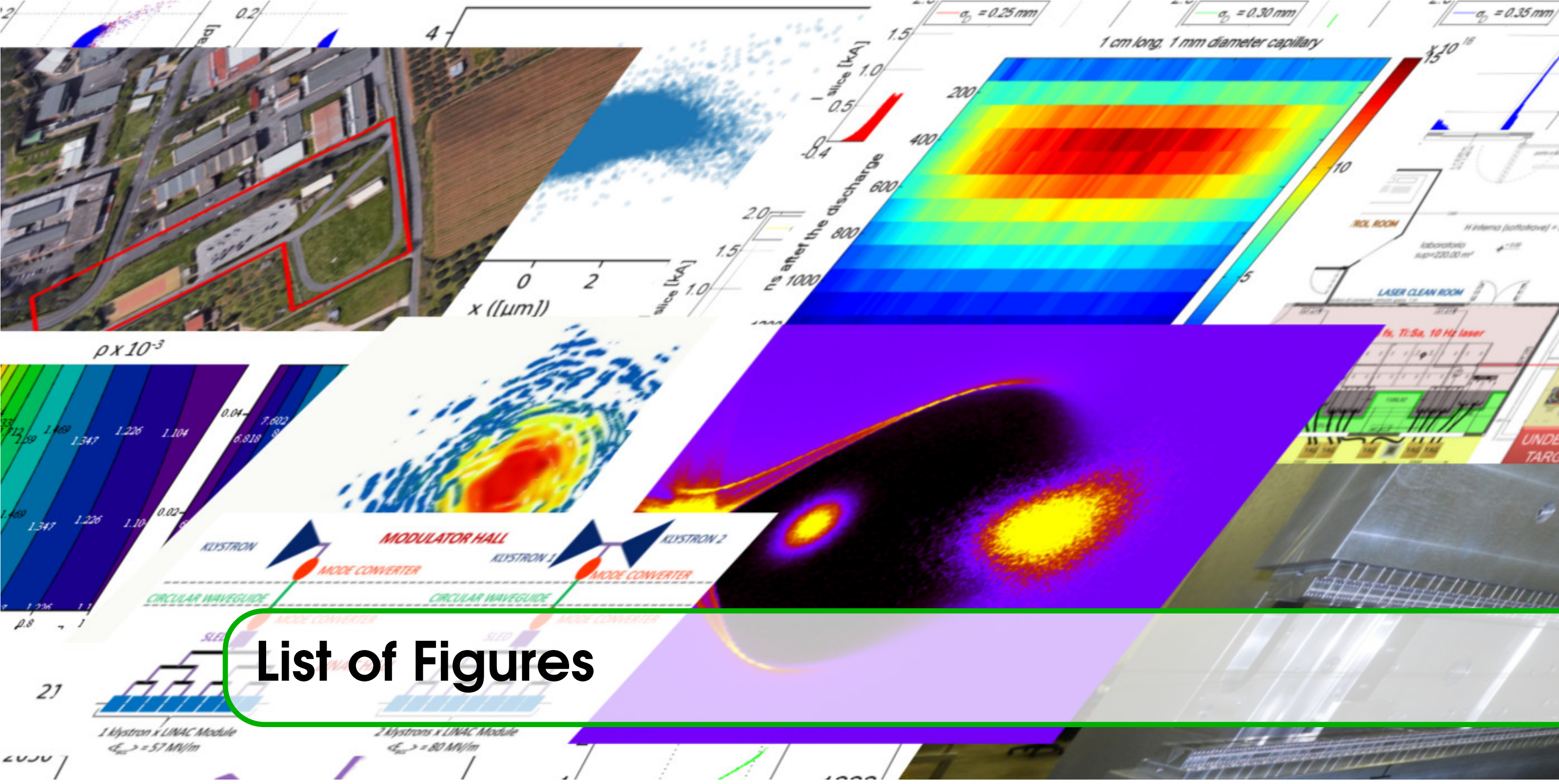
Authors

N. Cognome[a]

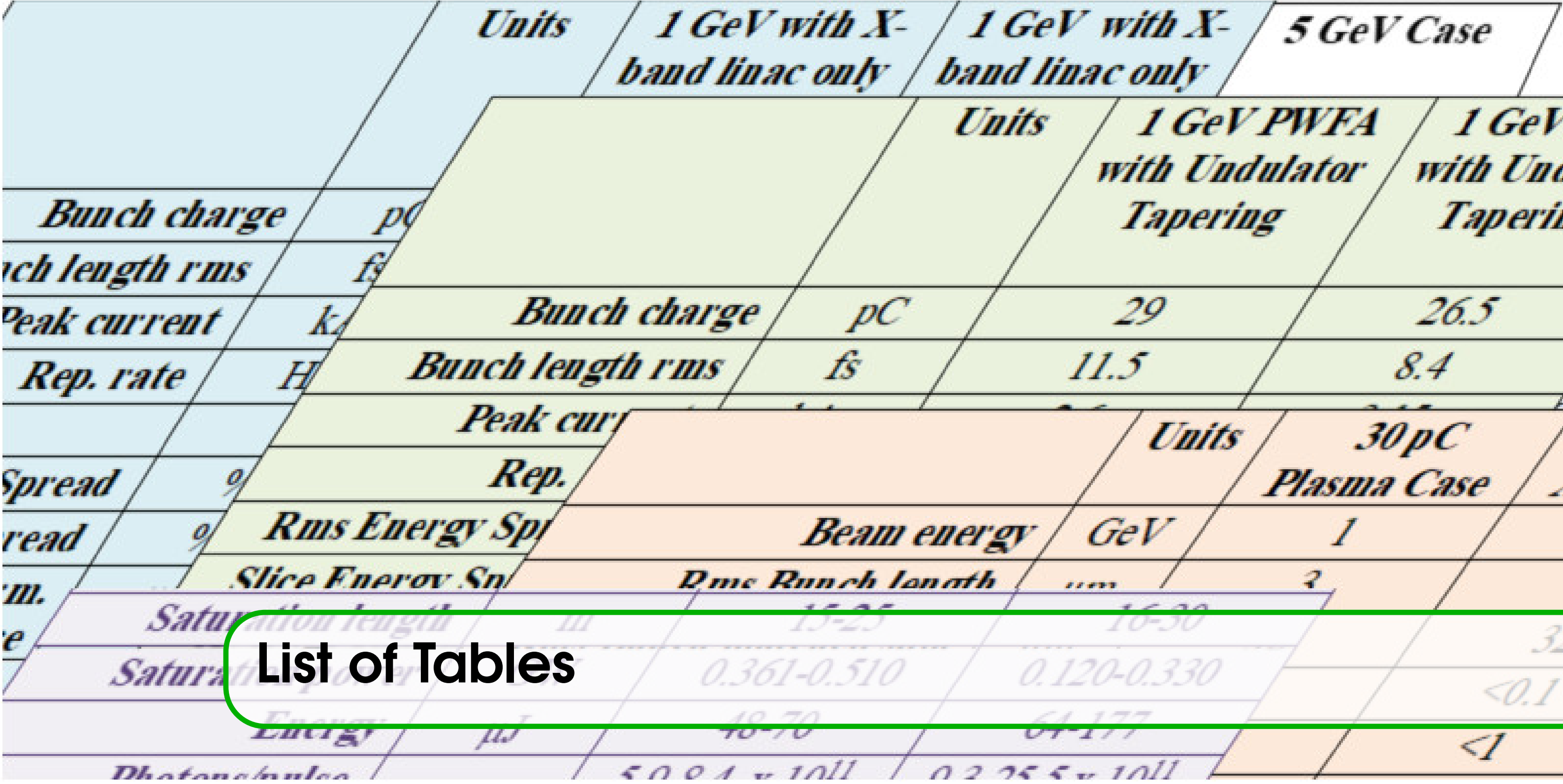
[a] *ente, indirizzo, cap città, Italy*



Contents



List of Figures



List of Tables

1. Free Electron Lasers

1.1 Introduction: layout and scope

(why two FELs - operation range and modes of operation of ARIA and AQUA. Space available, separation between the two beamlines)

The Eupraxia facility boasts two state-of-the-art free-electron lasers (FELs), driven by a 1-1.2 GeV linear accelerator (linac). This linac can be further supplemented by an innovative plasma accelerator, providing an additional acceleration stage. Together, these systems form a vanguard in FEL technology, being the first FEL facility relying on the high accelerating gradients permitted by the plasma.

The first FEL at Eupraxia, AQUA, aims at the 'water window', a critical spectral region with wavelengths as short as 4 nm. Harnessing ultrashort pulses in this domain is paramount for several reasons. At such wavelengths, researchers can delve into the microscopic world, capturing high-resolution images of biological entities and soft matter, without the need for staining or other intrusive techniques. Additionally, the ultrashort pulse duration allows for studying ultrafast dynamics, providing insights into phenomena that unfold at unprecedented time scales.

Eupraxia's second FEL, ARIA, is a seeded system with a working range in the vacuum ultraviolet (VUV) spectrum, specifically between 50 to 150 nm. Unlike SASE FELs, this one boasts full transverse and longitudinal coherence. This feature endows the FEL with an array of applications, especially in gas phase studies, atmospheric physics, and chemistry. The precise coherence of this FEL allows scientists to probe molecular dynamics, track chemical reactions in real-time, and decipher intricate processes occurring in our atmosphere.

Unique to this VUV FEL is its dual operation mode. In the short pulse mode, it delivers 10-20 femtosecond pulses, ideal for capturing the fastest of chemical and physical processes. On the other hand, the long pulse mode, stretching up to 200 femtoseconds, boasts the production of narrow linewidth pulses. This distinctive feature facilitates precise spectroscopic studies, enabling scientists to discern minute details in molecular spectra, bridging the gap between theory and observation.

The Eupraxia facility stands as a beacon for cutting-edge FEL technology, with each FEL tailored for specific groundbreaking applications, pushing the boundaries of scientific exploration.

The ensuing sections of this technical design report will delve into the intricate requirements of the two distinct FELs housed within the Eupraxia facility. To ensure optimal performance and cater to the broad scientific goals of these lasers, a meticulous understanding and design of several elements are crucial.

The subsequent analyses and discussions aim to provide a comprehensive understanding of the design considerations and requirements of the Eupraxia FELs, ensuring their unparalleled performance and reliability.

1.1.1 Layout

1.2 AQUA FEL

1.2.1 Tuning range General Requirements

General Requirements Beyond specific operational needs, certain general prerequisites ensure the stability, safety, and longevity of the FEL systems. This segment will enumerate and elucidate these requirements, laying down the foundational needs for the effective operation of the FELs.

Specific to AQUA, undulator type choice of parameters, tuning range expected performances from Xie and modified Xie.

1.2.2 Introduction to the Undulator Design for the AQUA Beamline

The heart of any Free-Electron Laser (FEL) lies in its undulator system. It is this intricate device that orchestrates the choreography of electron movements, converting their kinetic energy into coherent radiation. For the AQUA beamline, tasked with the ambitious goal of achieving self-amplified spontaneous emission (SASE) down to 4 nm wavelength, the undulator's design is paramount. Such wavelengths demand unprecedented precision, finesse, and a deep understanding of electron dynamics. The ensuing section provides an in-depth exposition of the undulator design tailored for the AQUA beamline, illustrating the careful balance of technical innovation and robust engineering needed to realize its ambitious operational parameters. Through this, the AQUA beamline is poised not only to be a marvel of modern optics but also a testament to the cutting-edge of FEL technology.

The AQUA FEL beamline, powered by an electron beam ranging between 1-1.2 GeV, presents unique challenges given its operation within the water window at such a relatively low energy. This operational domain necessitates the exploration of advanced undulator technology to achieve both a potent magnetic field strength and a compact undulator period. In pursuit of these requirements, two forefront technologies emerged as prime contenders: the superconducting undulator, boasting a period of 16 mm, and the more traditional permanent magnet undulator with a slightly longer period length of 18 mm. Naturally, each technology presents its own set of benefits and challenges. This section aims to provide a comprehensive review of the extensive research and development undertaken, encompassing magnetic and mechanical designs and delving into the prototype implementations. By the end, readers will gain insight into the meticulous process leading up to the final technology selection for the AQUA FEL line.

1.2.3 Magnetic Lattice

The undulator technology chosen for the AQUA beamline is the variable polarization permanent magnet APPLE-X. Preliminary calculations based on the average electron beam parameters show that a period length of 18mm allow to reach for the so called "water window" part of the spectrum, around 3-4nm wavelength, *i.e.* 310-410 eV photon energy with an efficient photon flux and at the same time provide:

- deflection strength $K \simeq 1$ at resonant $\lambda = $ 3-4nm ;
- selectable linear and circular polarization;
- some contingency in the total active length;
- some flexibility in the wavelength tuning range.

The design under consideration [1] envisages a 2 m long module, namely about 110 periods, with variable polarization and deflection strength parameter K that can be accordingly tuned to a maximum value: $K_{max} = 1.2$ ($K_{max} = 1.7$) in case of circular (linear) polarization. Figure 1.1 shows

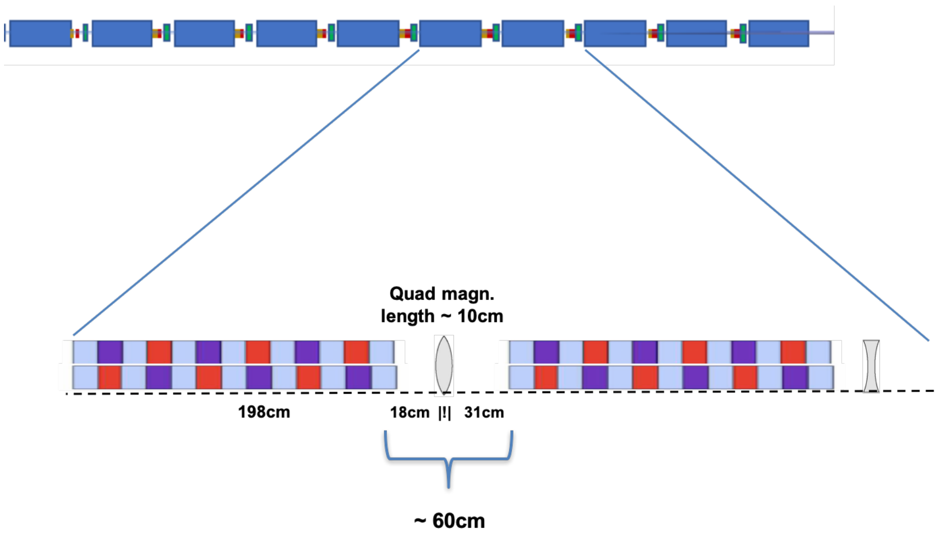


Figure 1.1: AQUA schematic layout.

the scheme of the undulator section, featuring the inset zoom of the magnetic unit cell made of the undulator and FODO sections.

For a 1GeV electron beam energy, the choice to have the intra-undulator distance of about 60cm , together with Twiss average β parameter and K values constrain the quadrupole integral gradient fields requested to operate the APPLE-X modules at 4nm wavelength, in either linear or circular polarization. For a 1GeV electron beam energy, the choice to have the intra-undulator

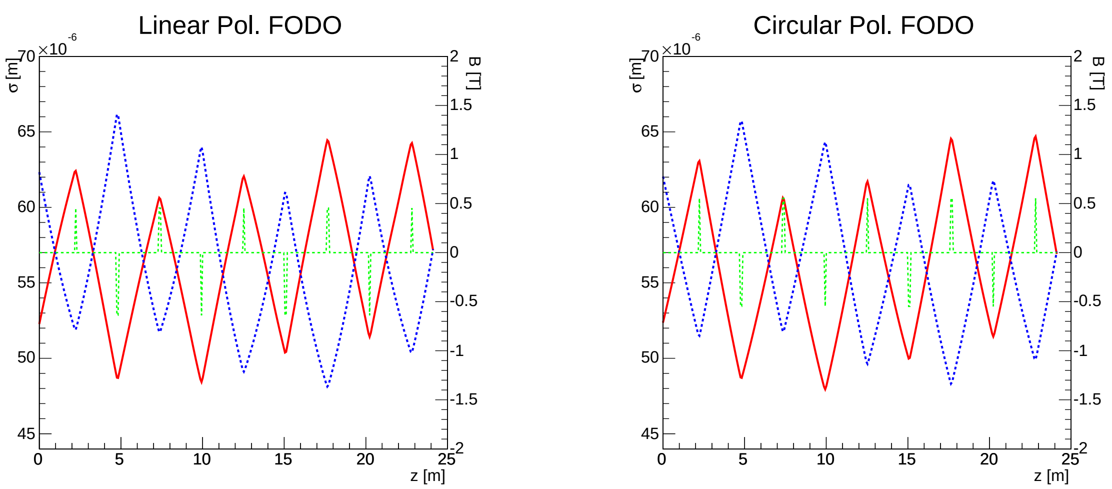


Figure 1.2: Profile of the electron beam subject to the undulator plus FODO sections in Linear (left) and Circular (right) polarization operations.

distance of about 60cm , together with Twiss average β parameter and K values, constrains the quadrupole integral gradient fields requested to operate the APPLE-X modules at 4nm wavelength, in either linear (LP) or circular (CP) polarization.

Figure 1.2 shows the transverse profile of the electron beam subject to the undulator plus FODO sections in Linear (left) and Circular (right) polarization operations with $\langle\beta_{x,y}\rangle = 8$m , and integral gradient field values on the second y-axis. These results are obtained with the Genesis1.3 simulation code for evaluating the transverse size of the nominal electron beam subject to the undulator plus FODO line sketched in Figure 1.1. The behavior of the integral gradient field values is investigated with increasing the electron beam energy, while keeping constant all other parameters. In order to accommodate the same focusing factors, integral gradient fields have to be increased. Figure 1.3

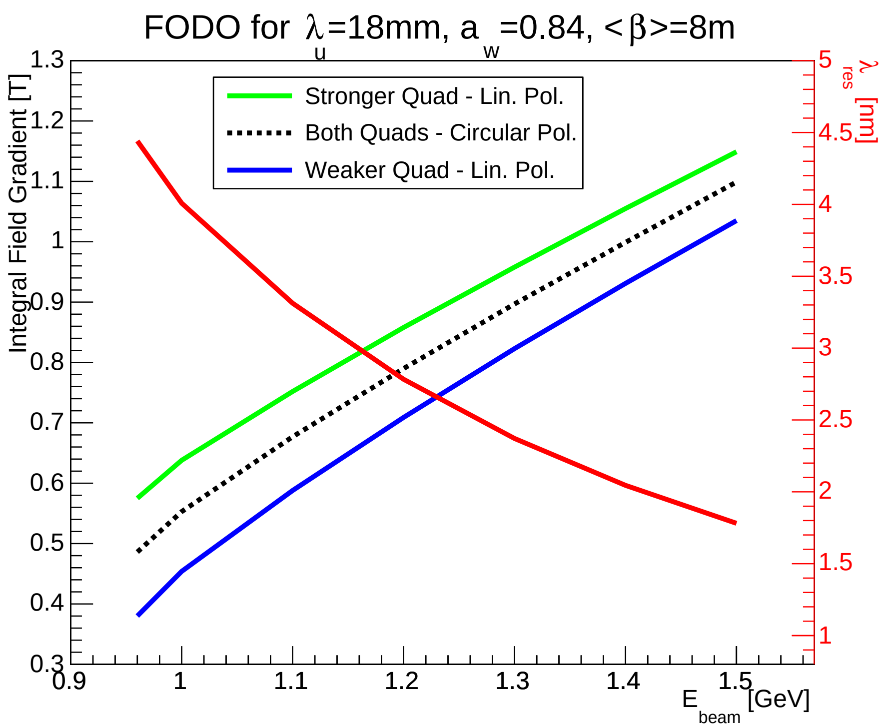


Figure 1.3: Integral gradient field values as a function of beam energy.

shows these values for both LP and CP configurations, superimposed to the achievable wavelength as a function of the electron beam energy. The field values stay on the order of about 1 Tesla or even smaller. These estimates imply that the same structure under design can operate at higher energies, in such a way to cover shorter resonant FEL wavelengths in a more efficient way.

Figure 1.3 shows these values for both LP and CP configurations, superimposed to the achievable wavelength as a function of the electron beam energy.

1.2.4 AQUA Undulator magnetic design

1.2.5 AQUA Undulator mechanical design

SC Undulator option

1.2.6 Analysis of wake fields, vacuum chamber

Wake Fields can critically impact the beam quality and overall performance of the FELs. They arise from the interaction between the charged particle beam and the structures of the accelerator. This section will present a detailed analysis of these phenomena, their potential effects on the FEL performance, and strategies to mitigate any deleterious impacts.

Longitudinal

Transverse

1.2.7 Vacuum chamber

At the heart of an FEL's operation is the vacuum chamber, ensuring that the electron beam's path is unhindered by extraneous particles. The design, material selection, and maintenance protocols for the vacuum chamber are vital. This segment will explore the considerations behind the vacuum chamber's design and the measures in place to maintain an optimal vacuum level.

1.2.8 Expected performances

Table 1.1: FEL performance summary of the 4 nm and 5.75 nm wavelengths working points for both polarizations.

working point	LP K_{max}	LP 4nm	CP K_{max}	CP 4nm
resonant λ [nm]	5.75	4.01	5.75	4.01
photon energy [eV]	215	309	215	309
matching $\langle\beta\rangle$ [m]	6	8	6	8
Pierce ρ_{1D} [10^{-3}]	1.8	1.4	2.0	1.5
gain length$_{1D}$ [m]	0.56	0.79	0.41	0.57
satur. length [m]	16.8	23.4	14.3	20.8
satur. $\langle$power$\rangle$ [GW]	0.39	0.24	0.49	0.28
exit E_{pulse} [μJ]	23.9	11.6	33.0	13.7
exit bandwidth [%]	0.15	0.09	0.22	0.12
exit pulse length$_{\mathrm{RMS}}$ [fs]	6.10	3.50	6.12	3.76
exit divergence [mrad]	0.032	0.023	0.031	0.022
exit trans. size [μm]	200	130	190	130
exit N_γ/pulse $\left[10^{11}\right]$	6.9	2.3	9.5	2.8

Simulations with average parameters, used as a reference for the specs on the various physical requirements.

High Charge (Long Pulse)

Low Charge (Short pulse)

1.2.9 Analysis of Tolerances

Energy spread, Current, Emittances, betafunctions

Use analytic model and simulations to show the effect of a variation of selected input parameters

Trajectory Injection

Nota Michele

Sensitivity to magnetic errors

Nota Vittoria

Table 1.2: Electron beam parameters

Quantity	Value
Charge Q	200 pC
Energy E_{beam}	1 GeV
Peak current I_{peak}	1.26 kA
RMS bunch length σ_z	20 μm
Proj. normalized x, y emittance ε_n	1.7 mm $\times$ mrad
Slice normalized x, y emittance ε_n	0.8 mm $\times$ mrad
Proj. fractional energy spread $\sigma_{\delta,p}$	0.95 %
Slice fractional energy spread $\sigma_{\delta,s}$	0.05 %

Table 1.3: Electron beam parameters

Quantity	Value
Charge Q	30 pC
Energy E_{beam}	1 GeV
Peak current I_{peak}	1.8 kA
RMS bunch length σ_z	2 μm
Proj. normalized x, y emittance ε_n	1.7 mm $\times$ mrad
Slice normalized x, y emittance ε_n	0.8 mm $\times$ mrad
Proj. fractional energy spread $\sigma_{\delta,p}$	0.95 %
Slice fractional energy spread $\sigma_{\delta,s}$	0.05 %

Alignment of components (undulators-quadrupoles-bpm; specs of ps

Thermal requirements

1.3 ARIA beamline

1.3.1 FEL layout and Tuning range

1.3.2 General Requirements

1.3.3 Expected performances

1.3.4 Requirements for the seed laser system

1.3.5 Modes of operation

Short pulse mode

Short pulse multicolor mode

Long pulse mode

1.3.6 Analysis of Tolerances

Jitters

Energy

Current

Emittances and matching

Trajectory

Magnetic errors

Bibliography

[1] A. Petralia et al. "Short Period Apple-X Undulator Modeling for the AQUA Line of the Future EuPRAXIA@SPARC_LAB Facility". In: *Proc. 40th International Free Electron Laser Conference* (Trieste). International Free Electron Laser Conference 40. JACoW Publishing, Geneva, Switzerland, Aug. 2022, pp. 454–457. ISBN: 978-3-95450-220-2. DOI: 10.18429/jacow-fel2022-wep38. URL: https://indico.jacow.org/event/44/contributions/473.