UNIVERSIDADE ESTADUAL DE CAMPINAS
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OTIMIZAÇÃO ONLINE DA ABERTURA DINÂMICA DO SIRIUS

ONLINE OPTIMIZATION OF SIRIUS DYNAMIC APERTURE

CAMPINAS
2023

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Dissertação apresentada ao Instituto de Física Gleb Wataghin da Universidade Estadual de Campinas como parte dos requisitos exigidos para a obtenção do título de MESTRE EM FÍSICA, na Área de FÍSICA.

Thesis presented to the Gleb Wataghin Institute of Physics of the University of Campinas in partial fulfillment of the requirements for the degree of MASTER IN PHYSICS, in the area of PHYSICS.

Orientador: LIU LIN

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ESTE TRABALHO CORRESPONDE À VERSÃO FINAL DA TESE DEFENDIDA PELO ALUNO MATHEUS MELO SANTOS VELLOSO E ORIENTADA PELO PROF. DR. LIU LIN.

CAMPINAS

2023

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Abstract

Beam accumulation into the SIRIUS storage ring occurs in the off-axis scheme, for which the efficiency depends on a sufficiently large dynamic aperture (DA) - the region comprising stable transverse oscillations. In the design phase, SIRIUS DA was numerically optimized in the accelerator model using various techniques and during commissioning the optimized lattice was implemented in the machine. Recent measurements indicate that SIRIUS DA, although sufficiently large for an injection efficiency of around 85%, can be yet increased upon fine-tuning of sextupole magnets strengths, which govern the beam nonlinear dynamics and determine the DA. In this master's project, the student will carry out online optimization experiments to tune the ring nonlinear lattice and improve the DA and injection efficiency into the storage ring.

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Chapter 1

Introduction

This dissertation presents the optimization work performed on the SIRIUS storage ring sextupole mangets with the objective to improve the ring's Dynamic Aperture and injection efficiency. The text is organized as follows:

- Chapter 1 introduces syncrhotron light sources and the SIRIUS project
- Chapter 2 introduces the theoretical and scientific background of dynamics of particles in particle accelerators. Nonlinear dyanamics is presented and its consequences are presented. Particular attention is drawn to the Dynamic Aperture.
- Chapter 3 reviews optimization algorithms, introduces online optimization in accelerators and the Robust Conjugate Direction Search (RCDS) algorithm.
- Chapter 4 describes the experimental methods and experiments carried out at the SIRIUS storage ring.
- Chapter 5 concludes this dissertation presenting some final remarks.

1.1 Storage ring-based synchrotron light sources

Synchrotron radiation (SR) refers to electromagnetic radiation emitted by charged relativistic particles as a result for being accelerated. The emitted intensity is the largest along the direction perpendicular to the that of the acceleration. In a circular accelerator, this implies the emission occurs along the curved trajectory's tangent.

The phenomenon was theoretically predicted in the early 1900's when Liénard and Wiechart calculated the retarded potentials–introduced by L. Lorenz–for point particles. Liénard calculated the energy lost by the electron due to the radiation emission and recovered Larmor's famous result . Synchrotron light was firts observed experimentally at a General Electric's 70 Mev synchrotron[1] accelerator. It was named *synchrotron radiation* for this reason.

Where's Larmor in all of this?

[1]The term "synchrotron" refers to the accelerator technology based on the synchonicity between the charged particles period of revolution and the frequency of the electromagnetic fields exerting work on it to achieve and mantain high-energies.

For nuclear and particle physicists, whom the first accelerators served, SR was in fact a detrimental side-effect of achievieng high-energies. But since the light is strongly colimated and covers a broad spectrum, from infrared to hard X-rays, its potential for imaging techiniques in condensed matter physics, materials science, molecular biology and chemistry was soon realized.

The community interested in SR for these purposes first revolved around big high-energy and nuclear physics machines and obtained SR parasistically from them, in the early 1960's. These are the so-called first-generation synchrotron light sources. With the increase of experiments using SR, accelerators were built for this specific purpose, which ignaugurated the second-generation. In thses machines, light was produced at the bending magnets.

A figure of merit measuring the quality of a SR source is its *brightness*, defined as the photon flux per unit area and per unit solid angle at the source

$$B(\omega) = \frac{F(\omega)}{\Omega_{xx'}\Omega_{yy'}\Delta\omega/\omega}, \tag{1.1}$$

where $F(\omega)$ is the photon flux at energy $E = \hbar\omega$, $\Omega_{uu'}$ is the the (u, u') photon phase-space volumes, which depends on both the electron beam and photon beam distributions; $\Delta\omega/\omega$ is the frquency bandwith. The growing community based on spectroscopy and crystallography experiments soon started to require maximum flux within small phase space volume (brightness) to improve the spectral resolution and match the incident beam to the small crystal sizes

In the 1990's, the introduction of *insertion devices* (IDs) such as *wigglers* and *undulators* characterized the third-generation machines. These devices consists on arrays of alternating dipolar fields which introcue additional transverse accelerations to the beam for the light production. The additional radiation output increased radiative damping reducing emmittance and increasing brightness. IDs also allowed for control of radiation energy and polarization.

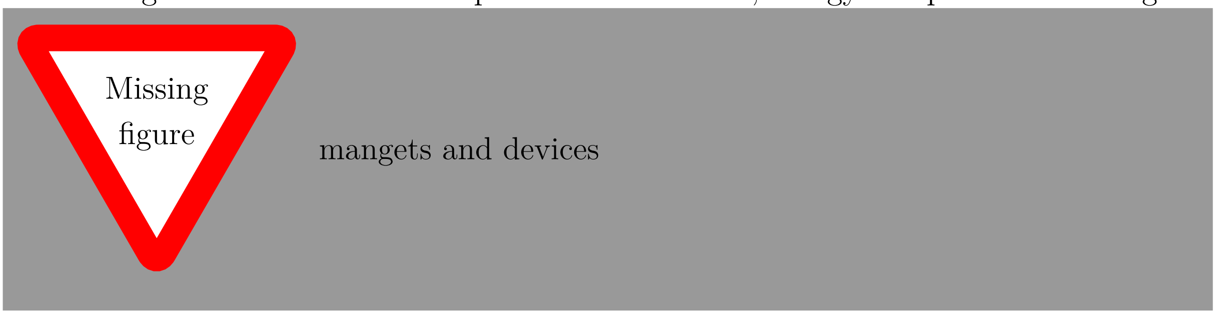
The 4th generation of SR sources was ignaugurated with the start of the comisioning of the MAX IV machine, in Lund, Sweden. The main advances with respect to the previous generatioin is the reduction by one to two orders of magnitude in the emmittance, which was made possibile due to the recent technological advances. Soon after, an upgrade of the European Synchrotron Facility (ESRF) machine redered it the second 4th generation machine in the world (when?). SIRIUS, in Campinas, is the third in the world, the first in the global-south.

what about FEL's? Why are you always making sure to clarify youre talking about storage rings?

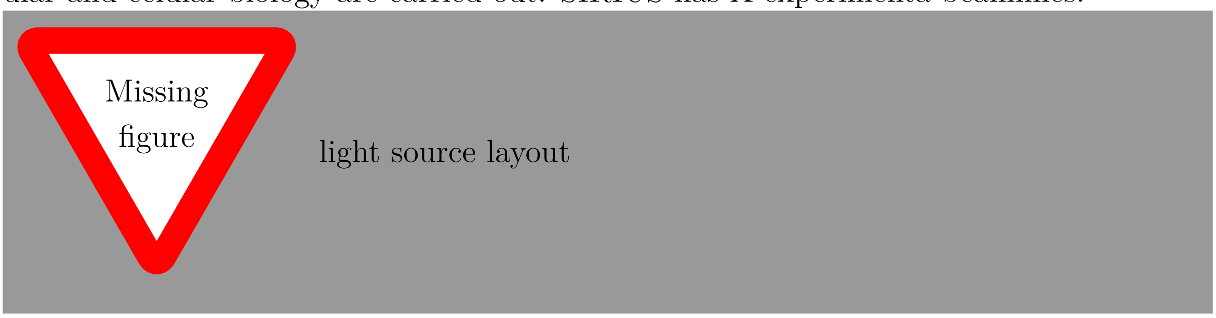
Usually, the accelerators systems of a synchrotron light source facility consists on the following devices

- electron gun (eGun): from which electrons are obtained. At SIRIUS, a cathode is used, and the electrons are ejected by thermoionic emission, at 90 keV energy.
- linear accelerator (LINAC): consisting on a array of cavities along whcih RF fields propagate with increasing group velocity, carrying the electron along with it. SIRIUS' LINAC accelerates electrons to about 150 MeV.
- booster ring: syncrhotron accelerator in which the electron energy is ramped to the storage ring's nominal operating energy of 3 GeV.
- transport lines: along which the electron is transported from the linac to booster (LTB) and from the booster to the storage ring (LTS).
- storage ring: where ultra-relativistic electrons are kept stable during hours, oscillating around a closed orbit.

Synchrotron storage rings store ultra-relativistic electrons beams close to a reference design orbit. The orbit is determined by the deflection magnets strenthgs, the dipoles. The focusing towards the closed orbit is provided by gradient fields, mostly coming from quadrupole magnets at SIRIUS. Since focusing and deflection depends on the beam energy, small energy deviations in the beam's energy can lead to differential focusing. Using an analogy from geometric optics, the beam's focusing at the lens (quadrupoles) depends on its color (energy). To correct this chromatic aberration, "glasses" are necessary. They introduce geometric aberations responsible for uniform, energy-independent focusing.



The accelerators are kept within concrete tunnels for radiation safety. Tangentially to the nominal orbits, optical beamlines direct the SR photon beams to the experimental cabins where the experiments in condensed matter physics, chemistry, molecular and celular biology are carried out. SIRIUS has X experimenta beamlines.



1.2 The SIRIUS project

SIRIUS is the 4th generation storage ring-based synchrotron light source. It was designed, built and it operated by the Brazilian Synchrotron Light Laboratory, at the campus of the Center of Resarch in Energy and Materials (CNPEM), at Campinas, Brazil. At the time of writing, SIRIUS in one of the three machines of its kind operating in the world.

SIRIUS has finished commissioning in 2022 and since 2023 is receiving its first users. It is currently operating for user's beam with a 100 mA current, but is designed to achieve 350 mA when the system of superconducting radio-frequency cavities, as well as the higher-oder-harmonic cavity are installed.

1.3 This dissertation problem

The persuit of low-emmittances and high-brightnes pushed the accelerator community towards the 4th generation of storage rings. The particular arrangement of bending magnets which allowed for such low-emmittances also requitres intese gradient fields provided by quadrupole magnets. Strong focusing, in turn, demands strong sextupolar fields for compensating chromatic effects, such as focusing dependence on the beam's small energy fluctuations. Since sextupole provide nonlinear fields, the dyamics in 4th generation storage rings has become increasingly nonlinear.

A quasi-periodic nonlinear dynamics subject to the smallest perturbations, such as small fields errors arising from rotation, alignement or excitation errors, can become unstable at large oscillation amplitudes. The instabilities result in limitations to large transverse oscillation amplitudes the machine can support. This amplitude is known as the Dynamic Aperture of the ring.

In ordinary operation condition, the equillibrium beam distribution is much smaller than the DA. One situation in which the DA is important for operation is during the injection process. The beam is extracted from the booster accelerator and enters the storage ring after passing through a transport line. It is then deflected by pulsed nonlinear magnets to make it parallel to the storage ring, but with a horizontal offset of approximately $x = -8$ mm. If the DA is smaller than that, it limits the injection efficiency for beam accumulation.

The choice of placement, symmetry and strength of sextupoles was chosen based on the optimization of the simulated dynamic aperture and beam-lifetime in the machine computer model. The average performance of the configurations in the presence of several magnets errors (simulating the expected errors in the real machine) was optimized and the obtained optimzed lattice was then implemented in the machine during the comissioning phase. The real machine, is basically a realization of such error configurations, and renders the machine a certain performance.

Prior to the optimization work, the Dynamic Aperture was measured to be , which rendered an average of injection efficiency. The main difficulty was the typycal fluctuations in the effciency .

get data

get data

get data

Since the lattice configuration implemented is in principle close to the optimum configuration, it is reasonable to assume that small nudges and adjustments on the sextupoles strengths could accomodate the lattice to the physically realized errors distribution, improving the nonlinear dynamics performance, the DA and ultimately, the injection efficiency and its stability. Online optimization consists on choosing computer-automated direct search strategies to seek the optimum sextupole configurations rendering the larges dynamic aperture.

Chapter 2

Theoretical Background

2.1 Single-particle dynamics in electron storage rings

Ultra-relativistic beams of electrons are injected into the SIRIUS storage ring with the nominal operating energy of 3 GeV. The beam is injected in the form of electron bunches, with characteristic length, width and size.

The storage ring is designed to confine the bunches and steer them along a reference closed orbit. This is achieved by specifying dipolar magnetic fields along the orbit such that the integrated effect is an angular deviation of 2π in the beam's trajectory. Additionally, to keep electrons close to the closed orbit, it is also necessary to specify gradient magnetic fields with strengths proportional the the beam's transverse deviations. These fields provide alterating focusing and defocusing of the beam in such a manner that their overall effect is to restore the beam towards the design orbit.

To correct chromatic aberrations in the beam's motion, i.e. a dependence of focusing with the beam's energy, and guarantee correct focusing despite energy deviations from the nominal value, sextupolar magnetic fields are also introduced, providing fields depending qudratically on the deviations from the nominal orbit. These fields introduce strong nonlinearities in the dynamics.

When having its trajectory bent at the dipoles and insertion devices[1], the beam loses energy in the form of synchrotron radiation. To mantain the beam stored, the energy lost must be replenished. To this aim, radio-frequency (RF) cavities are placed along the ring to provide oscilating electric fields parallel to the longitudinal direction. The work done in the beam by the fields restore its energy.

The radiated photons are emitted in a narrow cone with angular aperture of $1/\gamma$, γ being the relativistic Lorentz factor (~ 6000 at SIRIUS storage ring). The photons carry away a fraction of the beam's energy and momentum, in both the longitudinal and transverse directions, but when passing through RF cavities, only momentum in the longitudinal direction is replenished. This leads to an overall damping of transverse amplitudes.

[1] Insertion devices (IDs) consist on arrays of magnetic blocks arranged to provide additional deflection of the beam's trajectory for the production of synchrotron radiation. IDs allow for fine-tuning of the fields and as consequence of the characteristics of the emitted readiation, such as the energy and polarization.

On the other hand, the quantum nature of the emitted radiation leads to the excitation of transverse oscillations, which is known as quantum excitation. When a photon carries away energy, it depletes the electrons energy by the same amount. It thus changes the reference orbit of the electron in certain regions of the ring (dispersive regions), inducing oscillations. Eventually, equillibrium between radiative damping and quantum excitation is achieved, leading the rms values of each electron's amplitudes to reach a stationary regime.

Each one of the beam's degrees of freedom defines an acceptance: limits that when exceeded can lead to instabilities and eventually beam losses. The most obvious acceptance is the transverse acceptance: the beam motion is bounded by a vacuum chamber and collisions with the chamber's physical apperture leads to losses. Additionally, the beam also has an energy acceptance: a tolerance for energy deviations from the nominal value that when exceeded can lead to a suboptimal energetic balance, deviations from the nominal orbit and eventually collisions with the vacuum chamber.

The beam is also subject to elastic and inelastic collisions with residual gas molecules within the chamber and also the collisions between electrons within the same bunch, and other kinds of interactions with wake-fields from other bunches. The losses and their ocurrence rates define the characteristic time scale at which a given electron current survives in the ring. This is the beam lifetime and determines the rate at which injections into the storage ring are required.

Because of the nonlinearities introduced by the sextupole magnets, the transverse acceptances can be limited not by the physical aperture but rather by the amplitudes above which motion is irregular, unstable and unbounded. This limiting amplitude is known as the dynamic aperture (DA), a term that can be used to refer to amplitudes in the transverse space x, y or to the phase space coordinates x, p_x and y, p_y.

Despite the complicated physics involving the transverse oscilations as well as the energy oscillations, the damping and the excitation of amplitudes, the collective effects and the instabilities, for the purpose of this dissertation, it is sufficient to model the motion of a single electron , negletcting radiation losses and any other collective interactions. This single-particle travels along the ring at the speed of light and executes transverse oscillations in two orthogonal planes. The dynamics takes place in a 4-dimensional phase space. We neglect also coupling between the dynamics of these planes. The transverse dynamics thus consists on a quasi-periodic motion of two independent oscillators. These simplfications are justified because

- the amplitudes are ultimately damped and reach a regime equillibrium. Estimating maximum amplitudes accomodated by the dynamics neglecting radiative damping corresponds to an upper boundary

-

justify the ne- glect-

- This simplified dynamics will correspond to a linear dynamics which is used as building block upon which perturbation theory can be applied to generalize to a nonlinear, perturbated dynamics.

Next, the single-particle dynamics is presented with the aim of defining quantitavely the dynamic aperture and the characteristics of the dynamics in electron strorage rings. Throghout the modelling, optical functions and parameter for the SIRIUS storage rings are also presented.

2.1.1 Motion of charged particles in magnetic fields

An electron with charge e and momentum p follows a circular orbit of radius ρ when interacting with an uniform and time-independent magnetic field of magnitude B, perpendicular to the ortbit plane. In such conditions, Lorentz force law predicts that

$$B\rho = \frac{p}{e}. \tag{2.1}$$

Consider now an electron traveling along a curve parametrized by the arclength s with respect to an arbitrary reference point. The interaction with fields $B_x(x, y, s)$ and $B_y(x, y, s)$, both perpendicular to the electron's motion, results in deflections of the trajectory. The deflection angles are given by

$$\begin{aligned} \mathrm{d}\theta_x &= \frac{\mathrm{d}s}{\rho_x(s)} = \frac{e}{p} B_y(x, y, s)\mathrm{d}s = \frac{1}{B\rho} B_y(x, y, s)\mathrm{d}s, \\ \mathrm{d}\theta_y &= \frac{\mathrm{d}s}{\rho_y(s)} = \frac{e}{p} B_x(x, y, s)\mathrm{d}s = \frac{1}{B\rho} B_y(x, y, s)\mathrm{d}s. \end{aligned} \tag{2.2}$$

Where eq. (1) has been used to replace the p/e ratio by the *magnetic rigity* $B\rho$, which is defined as the product of the uniform field strength needed for a beam with momentum p and charge e to perform circular orbit with radius ρ. The rigidity depends solely on the electron's momentum/energy and gives the appropriate normalization to evaluate the instantaneous angular deflections in the electron's trajectory caused by magnetic fields.

Add deflection figures

2.1.2 Storage rings

draw my onw figure

Figure 2.1 sketches the typical design of a storage ring. For the porpose of storing a beam of electrons in closed orbits, magnetic fields defining a closed orbit are necessary. The angular deflections should add up to 2π, and the specification of the beam's operating energy determines the integrated field required for causing the closed orbit deflections.

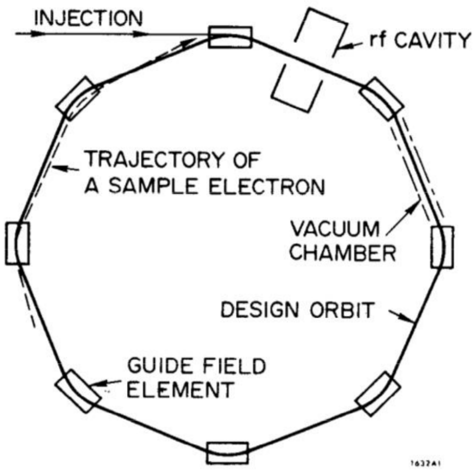


Figure 2.1: Storage ring typycal configuration. From [?]

For providing stability, focusing towards the reference closed orbit is also needed, and can be attained with the introduction of gradient fields whose strengths depend linearly on the tranverse excursions from the reference orbit. Such fields are provided mainly by quadrupole magnets, which are physically realized by specifying magnetic poles with the shape of truncated hyperbolas.

Sextupole mangets are also usually included in the design of storage rings. The fields they produce is quadratic with transverse displacement and are needed for correction of chromatic errors in the dynamics.

add magnets and field profile figures

2.1.3 The coordinate system

A convinient coordinate frame to decribe the dynamics in storge rings can be constructed by imagining a reference particle traveling along a curve drawn by the tip of a vector $\mathbf{r}_0$, as Fig. 2.2 shows. The particle travels a distance s along the ring, which can be used to parametrize the motion. The triad of direction vectors consists of a vector $\hat{\mathbf{s}}$, tangent to the trajectory, a vector $\hat{\mathbf{x}}$ normal to it, pointing in the direction at which $\hat{\mathbf{s}}$ changes and a vector $\hat{\mathbf{y}} = \hat{\mathbf{x}} \times \hat{\mathbf{s}}$, bi-normal to the trajectory. This construction leads to a Frenet-Serret reference frame.

Assuming no curvature in the y plane, i.e. that the accelerator defines a curve whose plane is parallel to the ground, then the unit vectors defining the frame can be calculated by [?]

$$\hat{\mathbf{s}} = \frac{\mathrm{d}\mathbf{r}_0}{\mathrm{d}s}, \quad \hat{\mathbf{x}} = -\rho\frac{\mathrm{d}\hat{\mathbf{s}}}{\mathrm{d}s}, \quad \hat{\mathbf{y}} = \hat{\mathbf{x}} \times \hat{\mathbf{s}}, \tag{2.3}$$

where $\rho(s) = \|\mathrm{d}\hat{\mathbf{s}}/\mathrm{d}s\|^{-1}$ is the local curvature radius[2]. The vectors evolve along s as

[2]For a circular trajectory, $\mathbf{r}_0 = (R\cos(s/R), R\sin(s/R), 0)$, $0 \leq s \leq L$ (check), in the cartesian laboratory frame. $\hat{\mathbf{s}} = (-\sin(s/R), \cos(s/R), 0)$, $\mathrm{d}\hat{\mathbf{s}}/\mathrm{d}s = -R^{-1}(\cos(s/R), \sin(s/R), 0)$ and $\rho(s) = R$

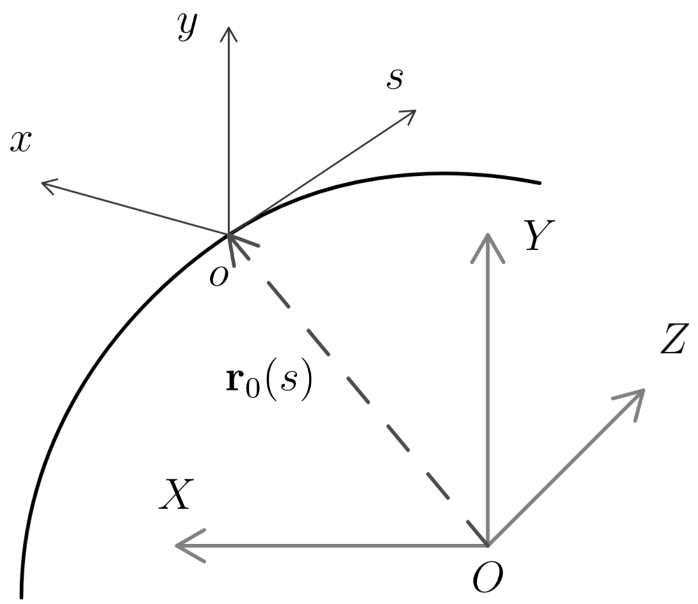


Figure 2.2: The Frenet-Serret coordinate system. From [?].

prescribed by the Frenet-Serret equations:

$$\frac{\mathrm{d}\hat{\mathbf{s}}}{\mathrm{d}s} = -\frac{1}{\rho(s)}\hat{\mathbf{x}}, \quad \frac{\mathrm{d}\hat{\mathbf{x}}}{\mathrm{d}s} = \frac{1}{\rho(s)}\hat{\mathbf{s}}, \quad \frac{\mathrm{d}\hat{\mathbf{y}}}{\mathrm{d}s} = 0, \tag{2.4}$$

The frame thus depends solely on the geometry of the specified path. Since the curvature is defined by the dipolar fields $B_0(s)$ in the y direction, then, eq. (2.2) leads to

$$G(s) \equiv \frac{1}{\rho(s)} = \frac{B_0}{B\rho}. \tag{2.5}$$

2.1.4 Hamiltonian for the relativistic electron

The dynamics of relativistic electrons influenced by electromagnetic fields $(\Phi, \mathbf{A})$ is encapsulated by the Hamiltonian

$$H = \sqrt{m^2c^4 + (\mathbf{P} - q\mathbf{A})^2c^2} + e\Phi,$$

e being the elementary charge and $\mathbf{P} = \mathbf{p} + e\mathbf{A}$ the canonical momentum. The following steps are followed to obtain equations of motion for electrons in the storage ring:

- A canonical transformation to change coordinates is applied in order to describe the motion in terms of the Frenet-Serret frame variables;
- Instead of time t, the Hamiltonian and the dynamical variables are described as functions of s, the longitudinal position along the ring;
- Geometric quantities are used: canonical momenta are the angles with respect to

the nominal orbit;

- Paraxial approximation: transverse momenta are assumed to be way smaller than longitudinal momentum

all of these steps are shown in detail in textbooks such as Refs. [?, ?, ?]. For the purpose of examining the DA, we can model the motion withouth RF cavities ($\Phi = 0$) and neglect radiation losses. The dynamics will consist solely on the transverse degrees of freedom, and takes place on a 4-dimensional phase space. In this 4D dynamics, the set of canonical variables are (x, p_x, y, p_y), where

$$\begin{cases} p_x = x'(1+\delta), \\ p_y = y'(1+\delta), \end{cases} \tag{2.6}$$

and the energy/momentum deviation is an additional parameter

$$\delta = \frac{P - P_0}{P_0} \approx \frac{E - E_0}{E_0} \tag{2.7}$$

where the ultra-relativistic approximation $E \approx pc$ was used.

Hamilton's equations for the Hamiltonian in the paraxial approximation lead to the equations of motion for 4D dynamics

$$x'' = -\frac{(1+Gx)^2}{1+\delta}\frac{B_y}{B\rho} + G(1+Gx), \quad y'' = \frac{(1+Gx)^2}{1+\delta}\frac{B_x}{B\rho} \tag{2.8}$$

where $B\rho = p/e$ and $G(s)$ defined as in Eq. (2.5).

The Magnetic Fields

Fields influencing the beam are those of dipoles, quadrupoles and sextupoles. Their functional forms are

- Horizontal Dipole:

$$B_x = 0, \quad B_y = B_0$$

- Normal quadrupole

$$B_x = B_1 y, \quad B_y = B_1 x$$

- Normal sextupole

$$B_x = B_2 xy, \quad B_y = \frac{1}{2}B_2(x^2 - y^2)$$

These are the so-called normal multipole fields. There also exists skew multipole fields, which couple the horizontal and vertical dynamics. We will neglect skew fields and coupling for now.

In the equations of motion, the magnetic rigidity normalizes all the fields. So we define the dipolar, quadrupolar and sextupolar functions by

$$G(s) = \frac{B_0(s)}{B\rho}, \quad K(s) = \frac{B_1(s)}{B\rho}, \quad S(s) = \frac{B_2(s)}{B\rho}$$

2.1.5 Linear Dynamics

Linear equations of motion

Expansion of the equations of motion up to first order in the x, y, δ variables leads to [?]

$$x'' + (G^2 + K)x = G\delta, \quad y'' - Ky = 0. \tag{2.9}$$

For on-momentum particles, $\delta = 0$, both equations reduce to Hill's equations

$$u'' + K_u(s)u = 0, \tag{2.10}$$

which are a pair of parametric oscillators for $u = x, y$, with s-dependent focusing functions

$$K_x(s) = G^2(s) + K(s)$$

$$K_y(s) = -K(s)$$

Motion in the linear approximation thus consists on oscilations around the closed orbit, known as betatron oscillations.

Pseudoharmonic description

The solutions for the equations of betatron motion can be cast in a amplitude-phase (WKB) form

$$u(s) = \sqrt{2\beta_u(s)J_u}\cos(\phi_u(s) + \phi_0), \tag{2.11}$$

where $\beta_u(s)$ must satify the boundary value problem

$$\frac{1}{2}\beta_u'' + \beta_u K_u(s) - \frac{1}{\beta_u}\left(\frac{1}{4}\beta_u'^2 + 1\right) = 0, \quad \begin{cases} \beta_u(0) = \beta_u(L) \\ \beta_u'(0) = \beta_u'(L) \end{cases} \tag{2.12}$$

and the phase advance is

$$\phi_u(s) = \int_0^s \frac{1}{\beta_u(\sigma)}\mathrm{d}\sigma. \tag{2.13}$$

The betatron functions for the SIRIUS storage ring are shown in Fig. 2.3.

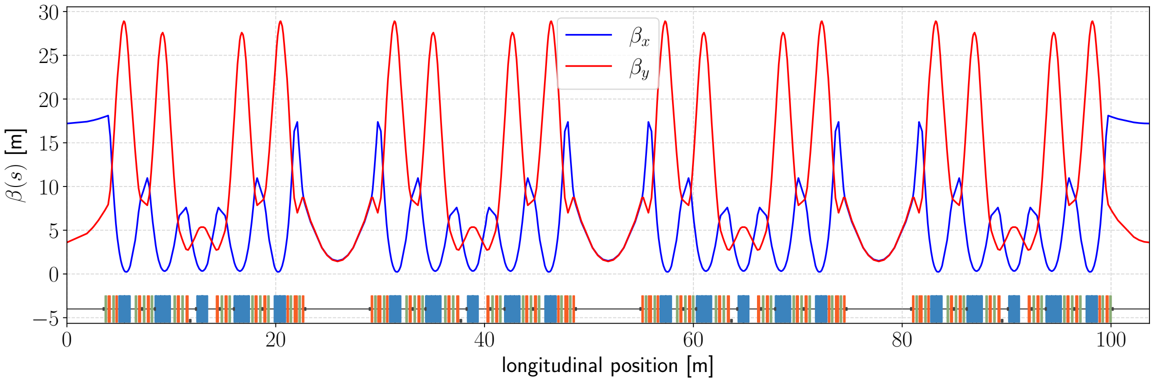


Figure 2.3: Betatron functions for the SIRIUS storage ring. Colored blocks represent the magnets of the accelerator lattice: blue for dipoles, orange for quadrupoles and green for sextupoles. The ring has a 5-fold symmetry, with the lattice and betatron function repeating the same pattern shown above five times up to $s = 518$ m

An important feature of the dynamics is the *tune*: the phase advance per ring revolution

$$\nu_u = \frac{1}{2\pi}\int_s^{s+L}\frac{\mathrm{d}\sigma}{\beta_u(\sigma)} \equiv \frac{1}{2\pi}\oint\frac{\mathrm{d}s}{\beta_u(s)}.$$

The analysis of perturbations and nonlinearities shows that the tunes are a critical variables in determining the beam's response to perturbations. More specifically, the tunes impact over disturbances amplifiction factors, which are greatest when tunes are close to integer numbers.

SIRIUS ring has tunes $(\nu_x, \nu_y) = (49.08, 14.14)$ which are very close to integers. It is desired to increase the tunes fractional parts to reduce orbit amplification factors. This is the reason why injection efficiency optimzation runs have also been carried in different machine tunes.

Turn-by-turn data

In the u, u' phase space, the quasi-periodic motion traces out ellipses. This can be verified by calculating the derivative

$$u'(s) = -\sqrt{\frac{2J_u}{\beta_u}}\left[\sin(\phi_u(s)+\phi_0) + \frac{1}{2}\beta_u'(s)\cos(\phi_u(s)+\phi_0)\right], \tag{2.14}$$

defining $\alpha_u = \frac{\beta_u'}{2}$ and $\gamma_u = \frac{(1+\alpha_u^2)}{\beta_u}$ and checking that u, u' satify the quadratic form

$$2J_u = \gamma_u u^2 + 2\alpha_u u u' + \beta_u u'^2. \tag{2.15}$$

The ellipse properties are defined by the β, α and γ functions, also known as Courant-Snyder or Twiss parameters. These parameters are functions of the position s, so at each point along the accelerator the Poincaré Section u, u' displays a different ellipse. Sampling the transverse motion at a fixed $s = s_0$ position reveals a harmonic displacement $x(t)$. Since the phase advance over a turn is $2\pi\nu + \phi_0$, the phase advance after the j-th turn is $2\pi\nu j + \phi_0$, and thus

$$x_j(s_0) = \sqrt{2\beta_0 J} \cos(2\pi\nu j + \phi_0). \tag{2.16}$$

Time of flight during a complete turn is L/c so, for j turns, $t_j = \frac{L}{c} j$. With a revolution frequency of $\omega_r = 2\pi/(L/c)$, we see that $2\pi j = \omega_r t_j$. As a function of the time elapsed over the j turns, the displacements reads

$$x_j = \sqrt{2\beta_0 J} \cos(\omega_r \nu t_j + \phi_0). \tag{2.17}$$

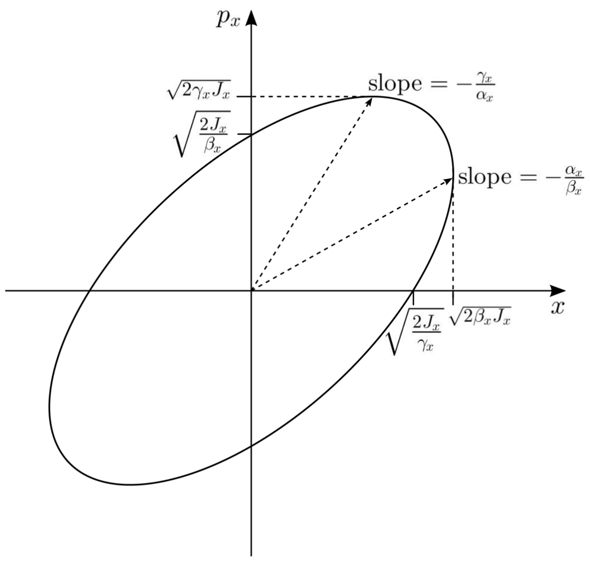


Figure 2.4: Phase space ellipse traced by tur-by-turn (TbT) motion in the (x, p_x) phase space. Optics functions determine the principal axes ratios and the inclination of the ellipse at each longitudinal position along the ring. From [?].

2.1.6 Chromatic effects

Dispersion

The equation of motion for off-momentum particles in the horizontal plane is the non-homogeneous Hill's equation. The solution consists on the linear combination of the homogeneous solutions in the phase-amplitude form plus the particular solution: $x =$

$x_\beta + x_\delta = x_\beta + \eta(s)\delta$ where $\eta(s)$ is the *dispersion function*, satisfying

$$\eta'' + (G^2 + K)\eta = G, \quad \begin{cases} \eta(0) = \eta(L), \\ \eta'(0) = \eta'(L). \end{cases}$$

The periodicity in the $\eta(s)$ function is required if we want to interpret η as closed orbit per momentum deviation. Thus, off-momentum particles perform betatron oscillations around a dispersive orbit. The dispersion function for the SIRIUS storage ring is shown in Fig. 2.5

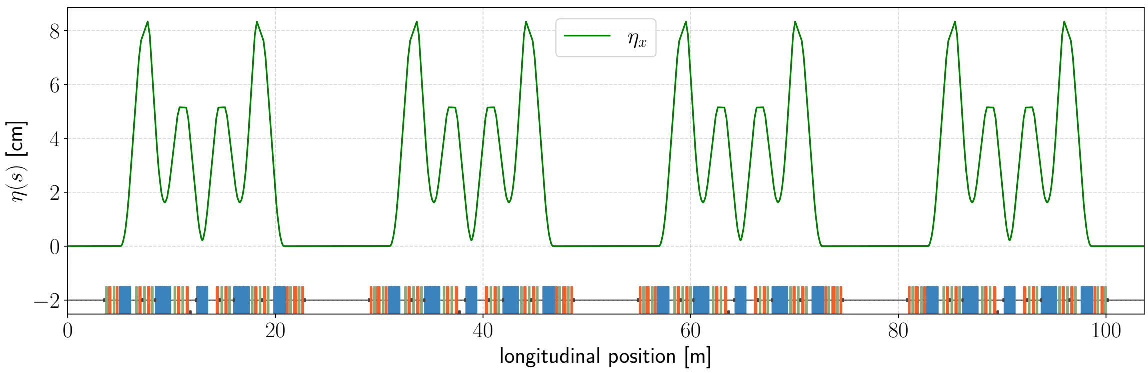


Figure 2.5: Dispersion fucntion for SIRIUS superperiod.

Chromaticity

Energy deviations affect not only the closed orbit but also the focusing. A more/less energetic beam has higer/lower rigidity and thus is focused differently when passes through quadrupoles. This chromatic aberration effect needs to be currected, which can be attained with the insertion of geometric aberrations provided by sextupolar fields. The correction comes at the expense of introducing nonlinearities in the dynamics.

The focusing errors due to energy errors cause phase advance errors and consequently tune errors, or tune-shifts. As a first order approximation,

$$\Delta\nu_u = \xi_u\delta, \tag{2.18}$$

where the tune-shift per energy deviation ξ_u is the chromaticity, which depends linearly on quadrupoles and sextupoles strengths. This linear dependence allows for the correction of chromaticity and control of the focusing for off-energy particles.

Improve: more details on the tune-shifts due to errors and the derivations on chromaticity

2.1.7 Chromaticity

As for the higher order effect on the focusing, also known as chromatic effect, we consider the motion in a straight section under a gradient, so that there is no non-homogeneous term in the horizontal equation. The equation of motion considering $x\delta$ terms reads

$$x'' + (K_x + \Delta K_x)x = 0 \tag{2.19}$$

$$y'' + (K_y + \Delta K_y)y = 0 \tag{2.20}$$

where $K_x = h^2 + K_1$, e $K_y = -K_1$ and

$$\Delta K_x = -(K_1 + 2G^2)\delta \approx K_x\delta \tag{2.21}$$

$$\Delta K_y = K_1\delta = -K_y\delta \tag{2.22}$$

The result is that an off-momentum partcile sees a different optics along the ring: different beta function and different phase advance. Thus, it deviates from nominal operation conditions, specially in the tunes, inducing the tune-shifts

$$\Delta\nu_i \approx -\frac{1}{4\pi}\oint \beta K_i \delta \, \mathrm{d}s \tag{2.23}$$

with $i = x, y$. We can define the *linear chromaticity* in the $i = x, y$ direction as the tune variation $\Delta\nu_i$ per energy deviation δ around $\delta = 0$

$$\xi_i = \frac{\mathrm{d}\nu_i}{\mathrm{d}\delta}. \tag{2.24}$$

This uncorrected chromaticity is also called natural chromaticity.

$$C_{\mathrm{nat}} \approx -\frac{1}{4\pi}\oint K\beta ds \tag{2.25}$$

To correct this chromatic effect, we need to introduce sextupolar fields in the lattice, specifically in the dispersive regions. At dispersive regions, off-energy particles should have the deviation from the design closed orbit given by $\Delta x = \eta\delta$. Since sextupolar fields are of the form

$$B_x = B_2 xy, \quad B_y = B_2\frac{x^2 - y^2}{2}$$

then the off-momentum particles “see" the fields

$$B_x = B_2(x_\beta y + \eta\delta y), \quad B_y = \frac{B_2}{2}(x_\beta^2 - y^2) + B_2 x_\beta \eta\delta + \frac{B_2}{2}(\eta\delta)^2$$

and feel the feed-down quadrupolar error

$$\Delta K_{x,y}(\delta) = \pm S\eta\delta$$

$$S = B_2/B\rho$$

The chromaticity then is

$$\xi_{x,y} = \mp\frac{1}{4\pi}\oint \beta_{x,y}(K_{x,y} - S\eta)\mathrm{d}s$$

Thus they see, at leading order, a quadrupole field $\Delta K_i(\delta) = \pm S\eta\delta$, with $i = x, y$, $+$ for x and $-$ para y, where the normalized sextupole gradient is $S = B_2/B\rho$, $B_2 = \partial^2 B_y/\partial s^2$. The other effects are of the second order on δ and on x, y. Chromaticity can then be corrected by tuning S

$$\xi_j = -\frac{1}{4\pi}\oint \beta_j(K_j \pm S\eta)\mathrm{d}s \tag{2.26}$$

with $j = x, y$.

More broadly speaking, the energy deviations induce the beam to see a completely different optics. The contributions to the changes can be of any order. For instance

$$\Delta\nu = \xi^{(1)}\delta + \xi^{(2)}\delta^2 + \dots \tag{2.27}$$

similarly

$$\Delta\beta(s,\delta) = \beta^{(1)}(s)\delta + \beta^{(2)}(s)\delta^2 + \dots \tag{2.28}$$

2.1.8 Nonlinear Dynamics and Perturbations

Action Angle Variables

Betatron motion of equation (2.10) can be obtained as Hamilton's equations for the effective Hamiltonian

$$\mathcal{H} = \frac{1}{2}u'^2 + \frac{1}{2}K_u(s)u^2. \tag{2.29}$$

A transformation $(u, u') \to (\psi, J)$ to Action-angle variables is implicitly implemented by the generating function

$$F_1(u,\phi_u) = \int u'\,\mathrm{d}u = \frac{u^2}{2\beta_u}\left(\tan\phi_u - \frac{\beta_u'}{2}\right). \tag{2.30}$$

The action variable reads

$$J_u = -\frac{\partial F_1}{\partial\phi_u} = \frac{u}{2\beta_u}\sec^2\phi_u = \frac{1}{2\beta_u}[u^2 + (\beta_u u' + \alpha_u u^2)], \tag{2.31}$$

from which we recover the pseudo-harmonic form $u = \sqrt{2\beta_u J_u}\cos(\phi_u(s) + \phi_0)$. This justifies our choice for the amplitude constant in the pseudo-harmonic description.

In the J, ϕ variables, the new hamiltonian is $H_0(\phi, J)$, given by

$$H_0 = \mathcal{H} + \frac{\partial F_1}{\partial s} = \frac{J}{\beta}. \tag{2.32}$$

Performing the change to action-angle variable in both the horizontal and vertical planes we find the new Hamiltonian for 4D dynamics

$$H_0 = \frac{J_x}{\beta_x} + \frac{J_y}{\beta_y}, \tag{2.33}$$

and Hamilton's equations read

$$\phi_u' = \frac{1}{\beta_u(s)}, \qquad J_u' = 0. \tag{2.34}$$

Perturbations and tune-shifts

Linear motion is integrable, since it can be written in terms of the action variable only (angle-independent Hamiltonian). This leads to the action variable being a constant of motion, and the phase advance behaving just as the pseudo-harmonic motion anticipated.

Linear motion, though, is only a useful first approximation. In reality, in an storage ring, there are higher order multipole magnets, such as sextupole magnets, and also multipole, alignement and excitation errors, all acting as perturbations to linear motion. Generically referring to perturbations as $V(J, \phi)$, we can write the perturbed motion Hamiltonian

$$H(J, \phi) = H_0 + V(J, \phi). \tag{2.35}$$

Hamilton's equations read

$$\phi_u' = \frac{1}{\beta_u(s)} + \frac{\partial V(J,\phi)}{\partial J_u}, \quad J_u' = \frac{\partial V(J,\phi)}{\partial \phi_u}. \tag{2.36}$$

Since the tunes consist on the phase advance per revolution, we immediately see that the presence of perturbations leads to tune-shifts.

Generically, the tunes can be expressed in terms of the tune-shifts as

$$\nu_0 = \nu_{u0} + \xi_u(\delta)\delta + \alpha_{uu} J_u + \alpha_{uv} J_v$$

where ξ_u represents the momentum-dependent tune-shifts (higher order chromaticity), and the other components consist on the amplitude-dependent tune-shifts, up to first order in the actions.

Field Errors

The dipolar contributions promote additional bendgin and thud disturb the design orbit. Assuming the perturbations are not strong enough to kill the beam, a distorted closed orbit must exist. To find it we need to find the coordinates along the ring which are mapped to themselves after a complete revolution. That is, we must find the fixed point $\mathbf{X}_{\text{co}}$ of the disturbed one-turn map:

$$\mathbf{X}_{\text{co}} = \mathbf{M}\mathbf{X}_{\text{co}} + \boldsymbol{\Delta} \tag{2.37}$$

where $\boldsymbol{\Delta} = (0, \theta)^{\intercal}$, $\theta = B_y \Delta s / B\rho$ for the (x, x') slice of the closed orbit, $\theta = B_x \Delta s / B\rho$ for the (y, y'). Solving for the closed orbit we find

$$\mathbf{X}_{\text{co}} = (\mathbf{I} - \mathbf{M})^{-1} \boldsymbol{\Delta}. \tag{2.38}$$

Using the Courant-Snyder parametrization for the one-turn map at the point s_0 immediately downstream the perturbation leads to

$$\mathbf{X}_{\text{co}} = \frac{\theta}{2 \sin \pi\nu} \begin{pmatrix} \beta_0 \cos \pi\nu \\ \sin \pi\nu - \alpha_0 \cos \pi\nu \end{pmatrix}. \tag{2.39}$$

So the closed orbit coordinates can be propagated from s_0 to any point s of the ring using the transfer matrix. For example, the propagated x coordinate reads

$$x_{\text{co}}(s) = \frac{\sqrt{\beta(s)\beta_0}}{2 \sin \pi\nu} \theta \cos(|\phi(s) - \phi_0| - \pi\nu). \tag{2.40}$$

Equation (2.40) is the closed-orbit distortion for a single perturbation. In the linear approximation, the distortion for a distribution of dipolar perturbations $\theta(s)$ along the ring reads

$$x_{\text{co}}(s) = \frac{\sqrt{\beta(s)}}{2 \sin \pi\nu} \int_s^{s+L} \theta(\sigma)\sqrt{\beta(\sigma)} \cos(\pi\nu + \phi(s) - \phi(\sigma)) \mathrm{d}\sigma. \tag{2.41}$$

Knowledge of the beam-response to perturbations allows for the inversion of the problem. We can use specified small dipole kicks to correct the orbit, bringing it closer to the nominal one. These small dipole fields are generated by corrector magnets (CM's) abd orbit correction consists on linear problem of seeking CMs strength that minimze orbit distortions.

Quadrupole errors

A quadrupole error can be represented by a thin-lens quadrupole transfer matrix [?]

$$\mathbf{M}_q = \begin{pmatrix} 1 & 0 \\ -k\Delta s & 1 \end{pmatrix}, \tag{2.42}$$

so that, immediately downstream the error, the transfer matrix reads $\mathbf{M} = \mathbf{M}_q\mathbf{M}_0$. As a consequence, the optics deviates from the nominal optics. More notouriously, the beta and the phase advances, and thus tune, changes.

The phase advance over a turn, ϕ, is related to the trace of the one-turn transfer matrix $\mathbf{M}$ as $\cos\phi = 2\,\mathrm{tr}\,\mathbf{M}$. Using the CS parametrization for $\mathbf{M}$, performing the multiplication $\mathbf{M}_q\mathbf{M}_0$ and calcualting the trace leads to

$$\cos\phi - \cos\phi_0 = -\frac{1}{2}k(s)\Delta s\beta_0 \sin\phi_0. \tag{2.43}$$

In a linear approximation (if $\sin\phi_0$ is not near zero) $\Delta(\cos\phi) = \cos\phi - \cos\phi_0 \approx \Delta\phi\ \mathrm{d}(\cos\phi)/\mathrm{d}\phi$ so the tune-shift due to a single thin-lens quadrupole error is

$$\Delta\nu \approx \frac{1}{4\pi}\beta_0 k\Delta s \tag{2.44}$$

while for a distribution of errors, we must sum over the ring

$$\Delta\nu \approx \frac{1}{4\pi}\oint \beta(s)k(s)\mathrm{d}s. \tag{2.45}$$

Besides calculating the tune-shift, the resulting transfer-matrix for the lattice with errors allows for the identification of the new optics α, β, γ, which can then be propagated to anywhere in the ring. In particular we can identify β and its fractional deviation from the nominal value along s, a parameter known as *beta-beating*

$$\frac{\Delta\beta(s)}{\beta(s)} = -\frac{1}{2\sin(2\pi\nu_0)}\int_s^{s+L} k(\sigma)\cos(2\phi(\sigma) - 2\phi(s) - \phi_0)\mathrm{d}\sigma. \tag{2.46}$$

Ressonances

4D linear unperturbed motion consists on the motion of two uncoupled parametric oscillators. The phase-space is diffeomorphic to the 2-Torus, $\mathbb{T}^2$, and there are an infinite number of such tori, corresponding to the different initial conditions J_u. Canonical perturbation theory applied to the perturbed motion fails to converge whenever the ratio of tunes is sufficiently rational. The Poincare-Birkhoff theorem states that under such conditions, almost all the periodic phase-space orbits disappear. An even number of tori survives, half of which are stable and half unstable. Unstable motion in a storage ring can eventually lead to beam loss.

The condition for sufficiently rational tunes can be expressed as

$$m\nu_x + n\nu_y = \ell,$$

for $n, m, \ell \in \mathbb{Z}$, and defines the lines in tune-space in which perturbation theory fails and motion can become unstable. These are resonance lines and $|n| + |m|$ is the order of the resonance. Figure 2.6 shows resonance lines for the resonances up to second, third and fourth order respectively. First order resonances can be excited by dipolar fields, 2nd order resonances can be excited by quadrupole fields and 3rd order resonances can be driven by sextupolar fields.

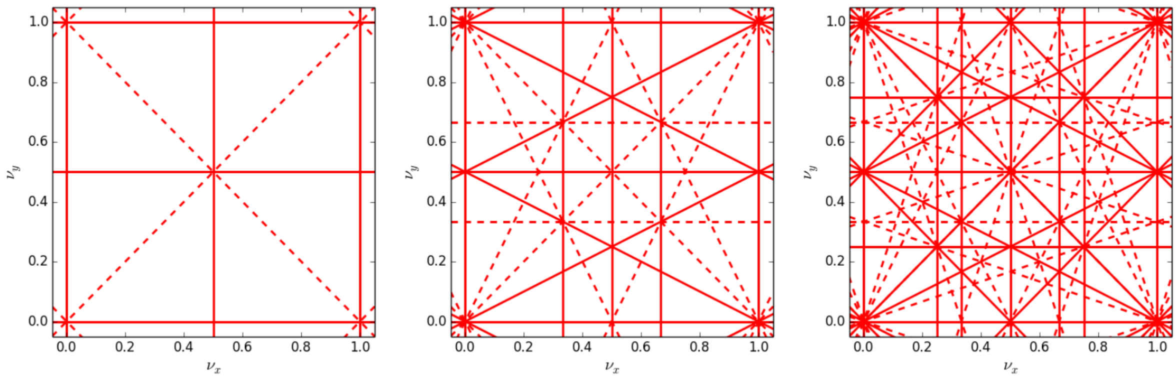


Figure 2.6: Resonance lines in tune space up to 2nd, 3rd and 4th order, respectively.

Dynamic Aperture

Nonlinear dynamics can become sensitive to initial conditions when the amplitudes are large. Because of the tune-shfits, specially the amplitude-dependent tune shifts, the tunes can wander in tune space, eventually crossing resonance conditions that may lead to instabilities, chatotic motion and beam loss. The dynamics can impose limitations to the maximum transverse deviations in which the beam can oscillate while displaying regular and bounded motion. This is a dynamic restriction to the motion known as the *dynamic aperture*.

Exceeding the dynamic aperture eventually leads to beam loss. During injection of the beam, if the transverse offsets are larger than the dynamic aperture, the beam is not captured into the storage ring. This is specially important for off-axis injection, such as in the case for SIRIUS.

2.2 The need for online optimization

2.2.1 Injection scheme for acummulation at SIRIUS storage ring

Beam acummulation into the storage ring occurs in the off-axis scheme. The beam is delivered at $x \approx -8$ mm, and receives the kick from the nonlinear kicker field. The field profile is nonlinear, with zero field and gradient at the center of the axis, so that it does not disturbs the stored beam. In the off-axis scheme, a sufficiently large dynamic aperture is desired to allow the beam to be captured into the storage ring. The predicted efficiency for SIRIUS setup, considering a dynamic aperture reaching $x = -9$ mm, was nearly 100%. What was observed during 2022 was an injection efficiency of about $88 \pm 8\%$. Lorem ipsum dolor sit amet, consectetuer adipiscing elit. Ut purus elit, vestibulum ut, placerat ac, adipiscing vitae, felis. Curabitur dictum gravida mauris. Nam arcu libero, nonummy eget, consectetuer id, vulputate a, magna. Donec vehicula augue eu neque. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Mauris ut leo. Cras viverra metus rhoncus sem. Nulla et lectus vestibulum urna fringilla ultrices. Phasellus eu tellus sit amet tortor gravida placerat. Integer sapien est, iaculis in, pretium quis, viverra ac, nunc. Praesent eget sem vel leo ultrices bibendum. Aenean faucibus. Morbi dolor nulla, malesuada eu, pulvinar at, mollis ac, nulla. Curabitur auctor semper nulla. Donec varius orci eget risus. Duis nibh mi, congue eu, accumsan eleifend, sagittis quis, diam. Duis eget orci sit amet orci dignissim rutrum.

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2.2.2 New working points

2.3 Online Optimization

This sction describes the experimental methods and analysis employed for optimizing the nonlinear dynamics and evaluating the quality of the configurations found.

2.3.1 Dynamic Aperture Optimization

Knobs

The dynamic aperture is determined by the quality of the dynamics in terms of perturbations and nonlinearities. Considering corrected quadrupoles and dipoles (linear optics), the main factors influencing SIRIUS DA are the nonlinearities introduced by the sextupoles and possbibly their field's small errors and deviations from the design parameters. The goal, thus, is to search for the sextupole configurations rendering the largest DA.

The sextupoles are the parmeters which can be tuned, the knobs. SIRIUS has 21 sextupole families: magnets powered by the same power supply. 6 of them are achromatic sextupoles. They are placed where the the dispersion is zero. The 15 other families are chromatic families. Table 2.1 shows the 21 sextupole families names. In principle, thus, the optimization parameter space is 21-dimensional. In reality, we would like to change sextupoles without changing chromaticity. Since we need at least one degree of freedom for correcting chromaticity in the horizontal plane and one degree of freedom for correcting the chromaticity in vertical plane, there are 19 available knobs. The dimensionality of the search space can be further reduced by imposing additional constraints to certain families variations. The specific choices of knobs for optimzation experiments are discussed in more details in the Results section.

Table 2.1: SIRIUS sextupole families

achromatic	SFA0, SDA0, SFB0, SDB0, SDP0, SFP0
chromatic	SDA1, SFA1, SDA2, SFA2, SDA3, SDB1, SFB1 SDB2, SFB2, SDB3, SFP1, SDP1, SDP2, SFP2 SDP3

Objective function

There is no analytical formula for relating the storage ring linear or nonlinear optics to the Dynamic Aperture. The optimization procedure must be a direct search procedure: changes are performed in the knobs and the effect over dynamic aperture is evaluated.

Also, we cannot measure dynamic aperture directly. We must choose an objective function to act as a probe to the DA: a figure of merit related to the dynamic aperture to represent it.

Two objectives usually adopted as probes are the injection efficiency and the beam's resilience to dipolar perturbations. The former is quite self-explanatory: the larger the dynamic aperture, the larger space for the beam to be captured during injection, and thus the larger the injection efficiency. The latter is related to the DA by the following: the larger the horizontal dipolar kicks the beam can survive, the larger the orbit distortions towards the positive or negative horizontal plane (depending on the kick direction). So the larger the amplitudes the beam explores as it oscillates, probing the DA borders. If the beam survives to large kicks, it means the ring can accomodate larger orbit distortions because of an increased dynamic aperture.

In summary, the dynamic aperture optimization procedure must consist on the exploration of sextupole (knobs) configurations yielding the largest dynamic aperture as accessed by as objective function such as injection efficiency or beam kick-resiliency.

Noise-Robust Online Optimization

In the optimization literature, optimization routines and algorithms are usually classified according to whether they rely on the calculation of derivatives (gradient-based) or solely on the comparison of the objective function values (gradient-free). The latter can yet be classified into direct- or indirect-search methods, depending on whether the search of the extremum relies on direct comparisons from data or from a mathematical model, respectively [?].

Both gradient-based and gradient-free strategies rely on the comparison of the objective function at different points of the parameter space. If the objective function suffers from noise this can significantly reduce the efficiency of the optimization routine [?,?]. In Chap. 7 of Ref. [?], a review of the most popular optimization algorithms shows how most of them suffer to find minima to, at least, the precision of the noise-σ the objective function is subjected to.

The Robust Conjugate Direction Search (RCDS) algorithm is a indirect-search, gradient-free optimization algorithm introduced in Ref. [?]. The algorithm consists of a main loop for constructing and managing optimal search directions along the knobs space (Powell's Method) and a one-dimensional optimizer responsible for a noise-aware search for the minimum along a given direction. The algorithm is capable of optimizing the objective function (find its local maximum/minimum) to at least the precision of the objective-function noise [?, ?], being thus adequate for online optimization problems. Specifically, for accelerator controls and optimization, the algorithm has been successfully applied to optimize beam steering and optics matching during injection [?], reducing horizontal emittance [?, ?]and optimization of dynamic aperture [?, ?, ?, ?, ?].

2.3.2 Characterization of Sextupole Magnets Configurations

Once a configuration of sextupoles (position in parameter space) is found, the nonlinear optics it provides the machine needs to be characterized. The characterizations consisted on evaluatig/measuring the followint figures of merit and desired features

- Injection efficiency in nominal off-axis conditions : this is the most desired characteristic. The sextupoles are to be optimized so the DA and the off-axis injection efficiency increase.

- Beam Kick resilience: a small current of 2 mA, concentrated in a single bucket is stored in the ring. The beam is kicked by the horizontal dipole kicker, which instantly provides a dipolar perturbation leading the beam to be displaced in the horizontal direction. The current before and after the kick is recorded by a current monitor (DCCT) and allows for the calculation of the fraction of the beam lost as a consequence of the kick and the transverse displacement. The procedure is repeated with progressively stronger kicks, and a curve of beam loss as a function of the kick can be constructed. The smaller the losses for larger kicks, the larger the resilience.

- Phase portrait area: it is expected that the optimzation procedure increases the dynamic aperture of the machine, meaning it can accomodate larger oscillations and larger phase portraits $x - x'$. Using beam position monitors (BPMs) at the two ends of a straight section, which record the positions of the beam centroid at each turn, we can calculate the position and angle of the beam in the middle of the straight section, and thus recostruct the phase-portrait from turn-by-turn (TbT) data.

- Beam lifetime: the lifetime at SIRIUS is dominated by losses due to electron-electron interactions leading to momentum transfers exceeding the energy/momentum acceptance (MA). Optimization of DA does not necessarily leads to improvements in the MA. If the MA is reduced, the rate at which the beam is lost can increase, reducing the total lifetime. It is desireble that the configurations found during DA otpimzation do not worsen the MA and beam lifetime considerably.

- Chromaticity: Sextupoles are introduced in the storage ring for correction of focusing chromatic aberretions. When changing the sextupole settings, it is desired to do so in such a manner that the chromaticity is unchanged. The methods for choosing the optimization knobs already take into account the need for keeping constant chromaticity. Still, after optimization is performed, we need to check whether chromaticity is unchanged.

The first two characterizations are quite similar to the two most immediate objective function candidates mentioned above. Indeed, in most nonlinear dynamics optimzation experiments, optimization using injection efficiency or kick resilience as objectives seemed to be completely interchangable. Improvements in injection efficiency necessarily led to improvements in kick resilience, and vice-versa. As shown in more details in the results section, for the SIRIUS storage ring this appears not to be the case. The configurations can be specialized to improvements solely on injection efficiency or solely to kick resilience. This feature was observed during the characterization of the optimized sextupole settings with respect to these two figures of merit.

Chapter 3

Optimization Experiments

Luke Skywalker has returned to his home planet of Tatooine in an attempt to rescue his friend Han Solo from the clutches of the vile gangster Jabba the Hutt. Little does Luke know that the GALACTIC EMPIRE has secretly begun construction on a new armored space station even more powerful than the first dreaded Death Star. When completed, this ultimate weapon will spell certain doom for the small band of rebels struggling to restore freedom to the galaxy [1–4].

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Chapter 4

The Phantom Menace May

4.1 Turmoil has engulfed the Galactic Republic

The taxation of trade routes to outlying star systems is in dispute. Hoping to resolve the matter with a blockade of deadly battleships, the greedy Trade Federation has stopped all shipping to the small planet of Naboo. While the Congress of the Republic endlessly debates this alarming chain of events, the Supreme Chancellor has secretly dispatched two Jedi Knights, the guardians of peace and justice in the galaxy, to settle the conflict [5, 6].

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Chapter 5

Attack of the Clones

5.1 There is unrest in the Galactic Senate

Several thousand solar systems have declared their intentions to leave the Republic. This separatist movement, under the leadership of the mysterious Count Dooku, has made it difficult for the limited number of Jedi Knights to maintain peace and order in the galaxy. Senator Amidala, the former Queen of Naboo, is returning to the Galactic Senate to vote on the critical issue of creating an ARMY OF THE REPUBLIC to assist the overwhelmed Jedi [7–11].

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Chapter 6

Revenge of the Sith

6.1 War!

The Republic is crumbling under attacks by the ruthless Sith Lord, Count Dooku. There are heroes on both sides. Evil is everywhere. In a stunning move, the fiendish droid leader, General Grievous, has swept into the Republic capital and kidnapped Chancellor Palpatine, leader of the Galactic Senate. As the Separatist Droid Army attempts to flee the besieged capital with their valuable hostage, two Jedi Knights lead a desperate mission to rescue the captive Chancellor [12–16].

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Appendix A

The Force Awakens

A.1 Luke Skywalker has vanished

In his absence, the sinister FIRST ORDER has risen from the ashes of the Empire and will not rest until Skywalker, the last Jedi, has been destroyed. With the support of the REPUBLIC, General Leia Organa leads a brave RESISTANCE. She is desperate to find her brother Luke and gain his help in restoring peace and justice to the galaxy. Leia has sent her most daring pilot on a secret mission to Jakku, where an old ally has discovered a clue to Luke's whereabouts [17].

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Appendix B

The Last Jedi

B.1 The FIRST ORDER reigns

Having decimated the peaceful Republic, Supreme Leader Snoke now deploys his merciless legions to seize military control of the galaxy. Only General Leia Organa's band of RESISTANCE fighters stand against the rising tyranny, certain that Jedi Master Luke Skywalker will return and restore a spark of hope to the fight. But the Resistance has been exposed. As the First Order speeds toward the rebel base, the brave heroes mount a desperate escape [18, 19].

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Appendix C

The Rise of Skywalker

C.1 The dead speak!

The galaxy has heard a mysterious broadcast, a threat of REVENGE in the sinister voice of the late EMPEROR PALPATINE. GENERAL LEIA ORGANA dispatches secret agents to gather intelligence, while REY, the last hope of the Jedi, trains for battle against the diabolical FIRST ORDER. Meanwhile, Supreme Leader KYLO REN rages in search of the phantom Emperor, determined to destroy any threat to his power [20–24].

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