A COMPACT RING FOR THOM X-RAY SOURCE

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Abstract

The advantage of X-ray sources based on Compton Back Scattering (CBS) processes is to be able to develop compact devices, which can produce an intense flux of monochromatic X-rays. CBS results from collisions between laser pulses and relativistic electron bunches. Due to the relative low value of the Compton cross section, an intense electron beam with a low emittance and a strong focusing at the interaction point is required. One possible configuration combines a storage ring with a low emittance linear accelerator. An accelerator ring design for a 50 MeV electron beam, aiming at producing a flux higher than 10^{13} ph/s, will be presented.

INTRODUCTION

The high X-ray (≤ 50 keV) flux has to be of the order of 10^{13} ph/s and relatively constant over time [1]. The proposed scheme is based on a 3 GHz RF gun linac delivering 1 nC bunches at 50 MeV into a compact ring (Fig. 1). By means of beam manipulations through the transfer line, the injected bunch longitudinal parameters are 20 ps rms length and about 0.3% relative energy spread. The linac non normalized transverse emittances are around 5.10^{-8} nm. In the first part, we will present the ring lattice optics as well as the laser-electron interaction region scheme. This low energy beam being very sensitive to various kinds of perturbations, we also investigated the Compton, vacuum as well as intra beam scattering, impedance and RF cavity HOM effects that may drastically spoil the X-ray flux.

RING LATTICE

In order to meet the high flux requested, we need at the interaction point (IP) :

(1) A transverse rms size of the electron beam less or equal to 70 μm in transverse planes implying low beta functions of 0.1 m

(2) A zero dispersion at the interaction point in order to avoid beam size widening while the bunch energy spread is increasing as well as to avoid potential synchro-betatron coupling resonances.

(3) A bunch length of about 20-30 ps : short enough to achieve an efficient X-rays production with a laser crossing angle of 2°, and long enough in order to reduce the collective effects (pipe impedance, CSR, particle inner scattering ...)

Besides, general layout constraints are :

(4) A ring circumference as short as possible with enough straight sections space to accommodate the IP, the RF, the injection and possible other equipments such as kickers for longitudinal and transverse feedback systems.

(5) Some Flexibility for the optics and working point.

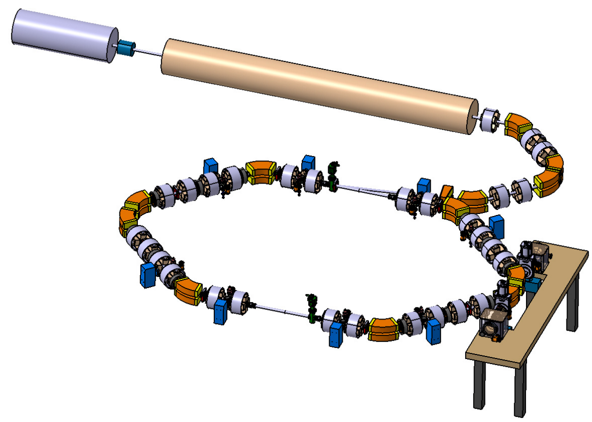

Figure 1: Thom-X layout.

To favour flexibility, the first choice turned into a ring with a four fold symmetry Double Bend Achromats (DBA) comprising eight dipoles and four long straight sections. To improve the compactness, the next step was to reduce two opposite long straight sections by removing quadrupoles and reducing the free space between the two adjacent dipoles. This optical structure has the possibility to accommodate the optical cavity in between the adjacent dipoles (Fig. 1).

Table 1: Main Parameters of the Lattice

Nominal energy	50 MeV
RF Frequency / Harm	500 MHz / 24
Circumference / Rev. Freq.	14.47 m / 21 MHz
Betatron tunes (ν_x , ν_z)	3.4, 1.4
Momentum compaction	1.48 10^{-2}
Natural chromaticities (ξ_x , ξ_z)	-3.2, -8.2
Beta, Disp @ IP	0.1, 0.1, 0
Nbr of dipoles/ Families / Field	8 / 1 / 0.5 T
Nbr of Quad / Families / Grad	24 / 6 / 3 T/m
Nbr of Sext / Families / Grad	12 / 2 / 30 T/m^2

It offers the advantages to free the two long straights and to naturally accommodate a 2D planar optical cavity inside the dipole gap [2]. In addition, the optical cavity mirrors can be easily accessed being located out of the ring and Compton extraction cone is close to IP (thank to dipole curvature). With two long (1.2 m) and two short (0.2 m) straight sections the optics presents a two fold symmetry. The focusing within the four arcs is provided by quadruplets having the advantage to allocate free space in between for sextupoles, correctors etc. Four sets of doublets complete the focusing in the long straight sections. The linear optics and non-linear optimization have been carried out with the BETA code [3]. The ring circumference is 14.57 m providing a revolution frequency of 20.6 MHz. With a 500 MHz RF frequency, the harmonic is 24.

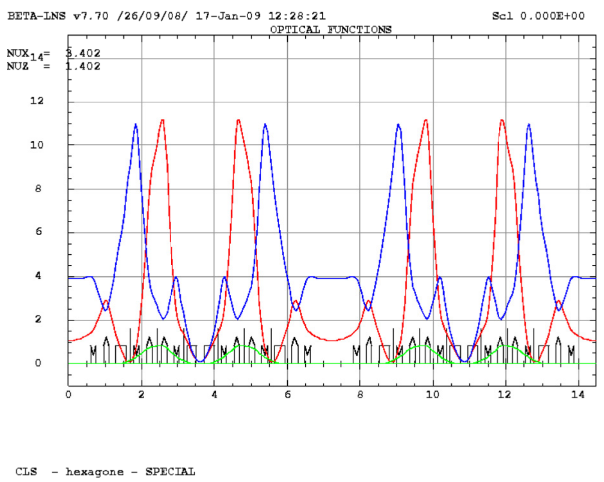

Figure 2: Horizontal (red), and vertical (blue) beta functions.

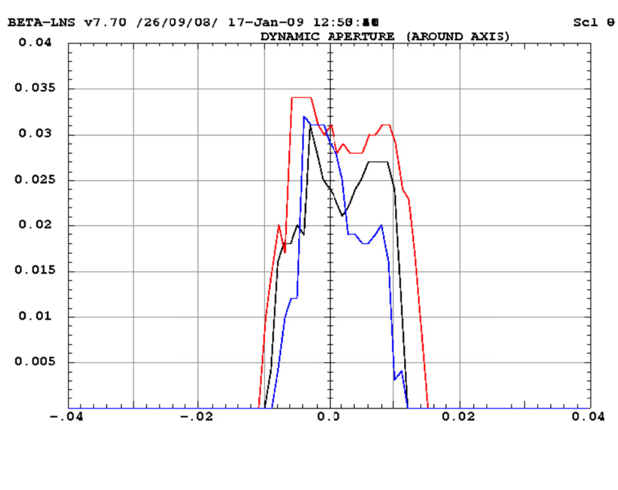

Figure 3: Dynamical aperture for on (black) and off momentum (+3% blue and -3% red) at injection point.

Natural horizontal and vertical chromaticities are respectively -3.2 and -8.3. Chromaticity corrections are achieved by means of 12 sextupoles (2 families) in the dispersive sections. Without any specific optimization, the dynamic aperture is about 50 times the rms size of the transverse injected beam (Fig. 3). In addition, it remains the same order of magnitude for ±3% off momentum particles (Fig. 3).

BEAM DYNAMICS

The electron beam dynamics that prevails in a ring under CBS interaction is similar to the one with Synchrotron Radiation (SR). CBS gives rise to quantum excitation in the transverse and longitudinal planes. It also contributes to energy losses which lead to emittance equilibrium [4]. Table 2 lists the various equilibrium values for a 1 nC electron bunch of 20 ps rms length interacting with a 25 mJ laser pulse of 5 ps rms length at 1.23 eV (1µm). The IP transverse size is 70 µm rms with 2° collision angle leading to 1.6 10^{13} ph/s X-ray flux at 50 MeV. The maximum X-ray energy is of 47 keV.

Table 2: Main Electron Bunch Equilibrium Values

	SR	***CBS***	***Both***
E-loss / turn (eV)	1.6	2.9	4.5
Longitudinal damp. time (s)	1.4	0.8	0.5
Equilibrium ΔE/E (%)	0.007	1.8	1.4
Trans verse damp. time (s)	3.3	1.6	1.1
Equilibrium emit (m.rad)	1.5 10^{-9}	7.2 10^{-8}	6.6 10^{-8}

At low energy, the synchrotron radiation is very weak, it entails about 1 second damping time and can be neglected. In the transverse planes, the equilibrium emittances turn out to be those at injection. In contrast, the CBS action is much stronger in the longitudinal plane. It gives a rapid energy spread increase from 0.3 % at injection toward several times this value over few hundreds ms storage time resulting in bunch lengthening (Fig. 4, green curve).

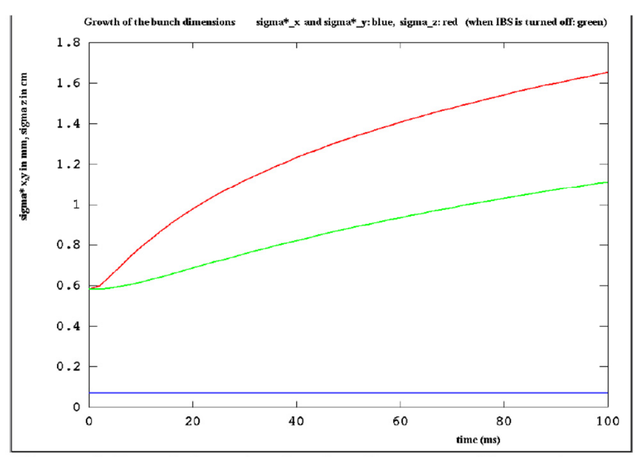

Figure 4: Bunch lengthening by Compton effect only (green) and together with IBS effect (red) versus time.

Energy transfer by collision between particles may also gives significant energy spread during the bunch storage. Based on the lattice parameters, the Touschek life time is of the order of 10 s, large enough as compared to the storage time. In counter part, the multiple Touschek effect (or IBS) plays a significant role. Simulation exhibits a large contribution as plotted in Fig. 4. With CBS effect only, the bunch length in increase by 1.8 and up to 2.8 together with IBS effect over 100 ms. Limiting the storage to 20 ms will maintain the bunch lengthening to about 60%. The transverse emittances are not affected by IBS scattering and only weakly by vacuum as long as the mean pressure is kept to few 10^{-9} Torr.

Another difficulty that is met at low energy is the high sensitivity to wakefields. As a consequence, a careful design of the vacuum chamber [5], RF cavity tapering and related questions including Coherent Synchrotron Radiation [6] (CSR) and Longitudinal Space Charge (LSC) have been investigated. The dominant longitudinal wake is clearly the CSR effect (Fig. 5). The CSR shielding configuration is not favourable with a short radius (0.352 m) and a large vertical aperture in the dipoles (40 mm). Based on these values, simulations have been carried out in order to evaluate some threshold instabilities in the short range domain. With a 1 nC charge at 50 MeV and 300 kV RF voltage, the bunch behaviour exhibits three different regimes depending on the rms bunch length :

i) For an rms length longer than 40 ps, collective effects do not affect noticeably the longitudinal behaviour.

ii) For an rms length between 20 to 40 ps, they tend to lengthen while emittance remains stable without a noticeable growth.

iii) For an rms length shorter than 20 ps, the bunch behaviour becomes unstable. It exhibits oscillations together with large emittance growth.

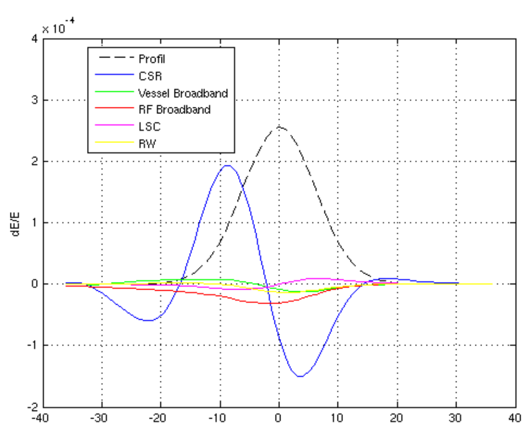

Figure 5: Wakefields distortions along a 1 nC Gaussian bunch at 50 MeV for a bunch length of 20 ps rms.

In summary, to avoid short range longitudinal instabilities with 1 nC at 50 MeV, it is advised to inject bunches longer than 20 ps rms. Note that long range or multibunch instabilities are not addressed here.

RF AND HOM CURE

The choice of 500 MHz as the RF frequency leads good compromise in terms of cavity fundamental and High Order Mode (HOM) impedances, space requirements as well as the availability of RF power sources and other components. The required accelerating voltage up to 500 kV can be provided by only one 500 MHz single cell cavity, powered by a 40 kW solid state amplifier. The choice of the cavity design is mainly dictated by the need for a strong damping of the HOM impedances in order to prevent coupled bunch instabilities (CBI). Assuming typical cavity HOM impedances (R_l . f_m = 0.1 to 1 MΩ; R_t = 0.1 to 10 MΩ/m) and the machine parameters listed in table 1, one finds that the instability growth times are very short for both longitudinal and transverse cases (10 µs as compared to the 20 ms storage time). With a large revolution frequency (21 MHz), the HOM frequency tuning by controlling the cavity temperature is well suited to cope with CBI. We have investigated (GdfidL [7]) the achievable performance by applying this technique to an ELETTRA type cavity [8], slightly modified with a cut-off pipe diameter reduced from 100 mm down to 60 mm, which fits the vacuum chamber. These preliminary results tend to confirm that it should be possible to find acceptable operating condition. It may be further improved, in a second stage, by providing additional damping, with the implementation of bunch-to-bunch feed-backs and/or a 3rd harmonic Landau cavity.

CONCLUSION

We design a compact storage ring with an original CBS interaction scheme located in between dipoles. It offers the advantages to free the long straights sections, to locate the optical mirror outside of the ring and to have the X-ray extraction cone close to IP. The ring is refilled from a 50 MeV linac at 50 Hz (20 ms storage) with a 1 nC bunch of 20 ps rms length.

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