PROBING SOME OF THE ISSUES OF FOURTH GENERATION LIGHT SOURCES AT THE ESRF

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ABSTRACT

The successful operation of the first third generation light sources at performances beyond target specifications has demonstrated the capability of pushing design considerations even further [1]. Among the new challenges to be met by the next generation of storage rings, the achievement of diffraction limited beams and the production of very short pulses whilst keeping a reasonable lifetime and adequate beam stability deserve detailed attention.

The flexibility of the ESRF storage ring lattice enables the investigation of these problems when running the ring at 1 GeV to obtain very small transverse emittances or operating in a quasi isochronous mode with a small positive or negative momentum compaction. This paper will summarize the results achieved so far.

1 MOTIVATION

The recent ICFA Workshop on Fourth Generation Light Sources [2] emphazised in its conclusions that, for the light sources to come, there is an excellent scientific case for even more coherence and shorter pulses than already achieved with the light sources of the third generation which started scientific production about two years ago.

In comparison with storage rings of the generation before, third generation light sources aimed at gaining a factor of 10^4 on the brilliance. Since routine operation started in 1993, the ESRF has dramatically surpassed its target goals with a best achieved brilliance of 2 10^{20} at 12 keV and 200 mA, a factor 100 higher than the 2 10^{18} initially targeted [3]. In the medium term, we plan a further upgrade towards the 10^{21} range. This would place the ESRF two orders of magnitude below the ultimate 10^{23} brilliance achievable with a diffraction limited ring.

The ESRF is an ideal bench to evaluate the limits of circular machines in terms of brilliance and to test the possible achievement of short and intense bunches. An R&D program has been launched with the objective of studying some of the adverse effects which are likely to develop (HOM driven instabilities in multibunch mode, intrabeam scattering, bunch lengthening,...).

2 HOW FAR ARE WE FROM DIFFRACTION LIMITED EMITTANCES?

More transverse coherence can be achieved by means of smaller emittances. The key figure of merits for users then lies in the brilliance, i.e. the photon flux drawn from the source point divided by the product of the transverse beam sizes and divergences. Since the effective dimensions result from the convolution between the electron beam emittances and the photon beam emittances associated with the single electron, the ultimate prospects in brilliance would correspond to horizontal and vertical electron emittances of the order, or even smaller than the radiation emittance.

The ESRF source is routinely operated at 6 GeV with transverse emittances which have been significantly decreased with respect to the design goals. The original Chasman-Green lattice has been retuned so that, by introducing a finite dispersion along the circumference, the horizontal emittance was reduced from 7 nm down to 4 nm [4]. This is still far from the diffraction limit which for a typical undulator wavelength of 0.86 Å (or 14.4 keV) is 0.014 nm for a 5 m long device. In the vertical plane, the diffraction limit is almost reached thanks to the reduction of the coupling from 10 % down to 0.4 %.

Achieving ultimate performances at the ESRF would require gaining a factor of about 300, mainly on the horizontal emittance. The scaling down of horizontal emittances with the square of the energy suggests that operating the ESRF at lower energy could provide a solution to approach the diffraction limit. Given the fact that the photon energy also scales with the square of the energy, the adequate energy range can easily be found (Figure 1). Ideally the ESRF would be diffraction-limited below 1.5 GeV.

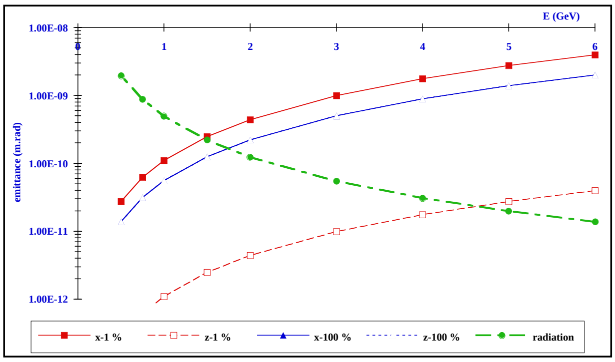

Figure 1: Electron and radiation emittances versus energy

Unfortunately, with such a combination of very small beam sizes, high intensity and low energy, interactions between particles are likely to affect ideal performances. In particular intrabeam scattering (IBS) will ultimately determine the electron beam emittances. As shown in Figure 2, the ESRF operated at low energy cannot reach the expected super brilliant regime. IBS limitations appear well before diffraction limits are reached.

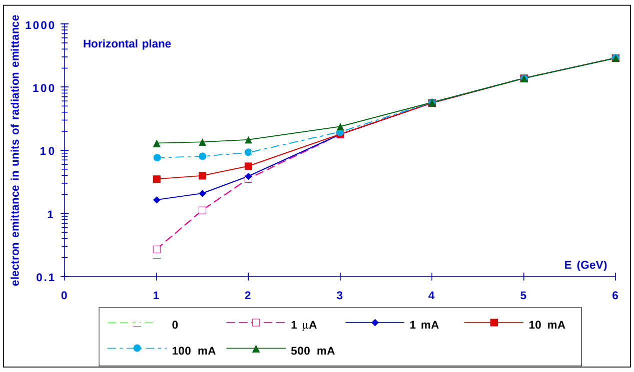

Figure 2: Electron beam emittance blow-up with current

3 OPERATING THE ESRF AT LOW ENERGY

3.1 Tuning of the source

In order to define reproducible settings, the applied strategy consisted in ramping down the energy of the storage ring with stored beam on. This was performed by driving a software loop which linearly scales the dipole and sextupole currents with energy and applies a constant Kl law, as defined from the modelling, to the quadrupole currents. On the injector side, the booster is run in the standard 6 GeV mode. Extraction and transfer line magnets are scaled down according to the energy and the extraction time is adjusted to get the correct energy matching between the two machines.

It took about one shift to establish ramping tables in 1 GeV steps and tune the source at the different energies. Lattice performances (tunes, closed orbit corrected in the 100 µm rms range in both planes, dispersion, β-functions deduced from response matrix measurements) are very similar to those of the nominal optics.

3.2 Achievements

Up to now, the emphasis has been put on peak intensity. Performances are summarized below.

E (GeV)	V_{RF} (MV)	I_{max} (mA)	Lifetime (h)
6	8	200	40
5	5	100	25
4	5	80	
3	3	13	3
2	0.4	13	1
1	0.58	1	1

Table 1

Intensity limitations are due to the excitation of longitudinal coupled bunch instabilities driven by the Higher Order Mode resonances of our LEP type normal conducting cavities. These instabilities experimentally show up in the following way: large longitudinal oscillations recorded by the streak camera, spurious lines at 500 MHz on the spectrum analyzer, spoiling of the tune signals, distortion of the filling pattern in permanent injection with creation of a hole. This distortion enables the achievement of currents significantly higher than predicted.

At 6 GeV, the adopted solution to avoid the excitation of instabilities consists in a non uniform filling of the ring with a gap extending over 2/3 of the circumference. The antidamping induced by HOMs (which limits the current to about 80 mA in the uniform filling mode) is compensated by the damping due to the modulation of the RF voltage induced by the beam loading of the cavities at the passage of the bunch train. The resulting spread in synchrotron frequency provides additional damping.

When running the machine at low energy in multibunch mode, we no longer benefit from this beam loading and subsequent Landau damping. Strong intensity limitations are therefore expected. The growth rate for longitudinal coupled bunch instabilities is given by the imaginary part of the frequency shift Δω:

$$\Delta\omega = j\,\frac{m\,\omega_s}{m+1}\;\frac{4\,I}{\pi^2 B^2 V_{RF}\, h \cos\varphi_s}\left(\frac{Z}{p}\right)_{//} F(\Delta\varphi)$$

The instability (and therefore the maximum intensity) occurs when Im (Δω) is equal to the inverse of the longitudinal damping time τ_{sync} which scales like E^{-3}. Figure 3 gives the intensity scaling law (at fixed RF voltage) with respect to the 6 GeV reference.

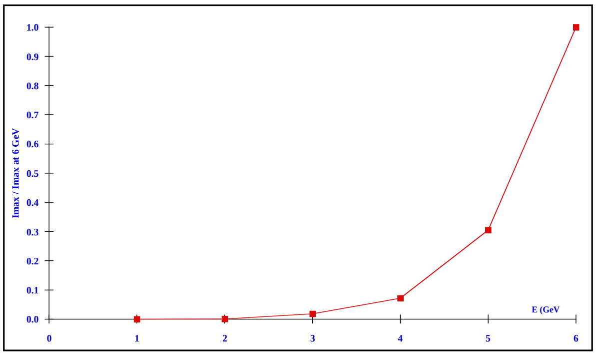

Figure 3: Dependence of maximum intensity on energy

Solutions to overcome these limitations could be envisaged since, at low energy, the RF power required to compensate for radiation losses can easily be provided by two out of the four RF cavities fed by one transmitter. The other pair of cavities and the second transmitter could therefore be tuned one revolution harmonic away from the nominal RF frequency to provide the required Landau damping [5]. Preliminary tests look promising.

4 COULD A CONVENTIONAL STORAGE RING PRODUCE INTENSE BUNCHES IN THE SUB PS RANGE ?

4.1 Available parameters

Very attractive time resolved experiments requiring short and intense pulses make the production of short pulses increasingly fashionable. In a third generation light source like the ESRF, the achievement of a low horizontal emittance is obtained by minimizing the dispersion of trajectories with energy at locations where particles radiate, thus leading to small orbit length deviations as a function of energy deviation, i.e. a small momentum compaction and short bunch lengths.

At the ESRF, the lattice is routinely tuned to have a linear momentum compaction α_1 of 1.9 10^{-4}. This corresponds to a rms zero-current bunch length of 15 ps. Since the natural bunch length σ_L scales like $\sqrt{\frac{\alpha E^3}{\omega_{RF} V_{RF}}}$, possible ways to decrease the bunch lengths could be to decrease the energy (σ_L = 0.75 ps at 1 GeV) or to run the machine in a quasi isochronous mode (σ_L = 1 ps with α_1 of the order of 9 10^{-7}). Given the factor to gain, increasing the RF gradient only looks unrealistic.

4.2 The ESRF lattice tuned to a low α_1 value

The flexibility of the ESRF Chasman-Green lattice gives large tuning possibilities. Figure 4 shows the optical functions of the adopted low α version of the lattice. It can be seen from the dispersion path that the zero-crossing point in the dipole can easily be displaced by varying the focusing elements on both sides of the dipole, thus changing the value and the sign of α.

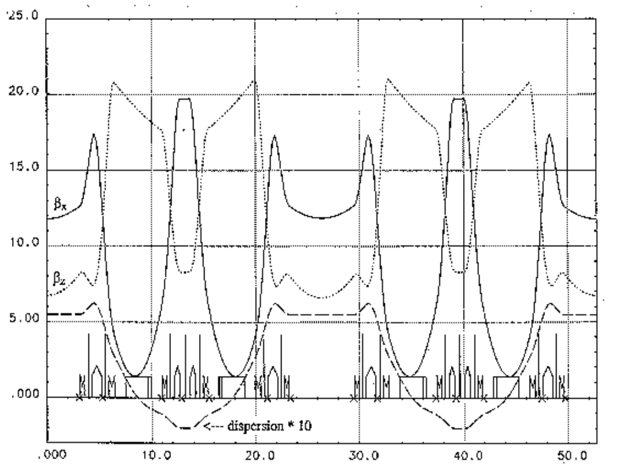

Figure 4: Optical functions of the low α lattice

Tests have been performed with the storage ring tuned to υ_x = 28.2, υ_z = 12.4 and α_1 ranging from -2 10^{-4} to 2 10^{-4}. To date, the best achieved results [6] correspond presumably to the shortest zero-current bunch lengths ever achieved in a circular machine with α_1 = 1.5 10^{-5}, i.e. σ_L = 4.3 ps. With such low values, we experienced limitations due to the non-compensated α_2 and RF noise in the few hundred Hz band of the synchrotron frequency. Clearly, efforts to reduce these effects would be required if further reduction of α would be beneficial.

4.3 Bunch lengths

The evolution of bunch lengths measured with the streak camera [7] as a function of the bunch current is compared in Figure 5 for various α values. They show that, for positive α, all curves have a common asymptote. The smaller the momentum compaction, the quicker the asympote is reached with increasing current. In the high intensity regime, bunch lengths become independent of the momentum compaction. The theoretical mechanism [8] is the following: at high current, the wake field induced by the interaction of the bunch with the environment has a strong defocusing effect on the bunch which lengthens with increasing current in the potential well regime.

It could be imagined that with negative α, the effect of the wake field would be reversed, thus increasing the effective RF voltage and leading to shorter bunches. Again simulations show that this beneficial effect is limited. Below the negative mass instability current threshold, a minor shortening is observed. As was already the case for $\alpha > 0$, bunch lengths are independent of α above threshold in the high intensity regime.

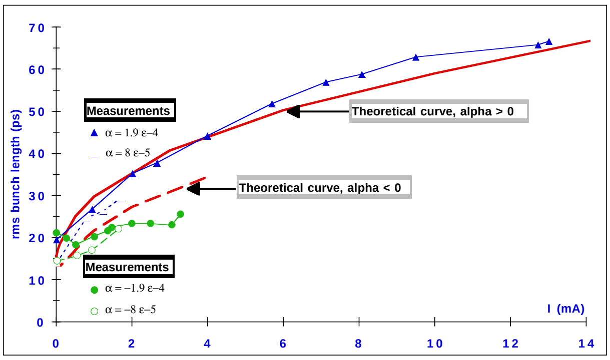

Figure 5: Bunch lengthening with current

5 CONCLUSIONS

As illustrated by ESRF experience, quasi isochronous storage rings look inadequate for producing short and intense pulses and competing with linac FELs.

In terms of brilliance, one of the challenging issues for future machines lies in the intrabeam scattering limitations which could prevent from reaching the diffraction limit.

REFERENCES

[1] L. Farvacque, these Proceedings
[2] 10th ICFA Beam Dynamics Panel Workshop on 4th generation light sources, Grenoble, January 1996
[3] J. M. Lefebvre, these Proceedings
[4] L. Farvacque, J. L. Laclare, P. Nghiem, J. Payet, A. Ropert, H. Tanaka, ESRF/MACH-LAT-93/08
[5] C. David, J. Jacob, A. Panzarella, J. P. Perrine, J. L. Revol, these Proceedings
[6] T. Günzel, A. Hofmann, J. L. Laclare, C. Limborg, A. Ropert, ESRF Technical Note 53/95-MDT
[7] K. Scheidt, these Proceedings
[8] G. Besnier, J. L. Laclare, C. Limborg, Proceedings of the Micro Bunches Workshop, Sept 1995, BNL