ON POSSIBILITY OF SUPPRESSION OF MICROWAVE INSTABILITY AND PRODUCTION OF FEMTOSECOND PULSES OF RADIATION IN STORAGE RINGS

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Abstract

The microwave instability appears to be main limiting factor in both longitudinal brightness of electron beam and achievement of very short bunches. It causes anomalous bunch lengthening and energy spread growth.

The 6D brightness of electron beam is the main figure of merit for their applications for generation of coherent X-rays. In this paper a possibility to suppress or to eliminate the microwave instability using advanced RF system based on inverse sub-mm FEL is discussed [1].

We present the theoretical developments of strong focusing in longitudinal direction and discuss results of computer simulations. A possibility of storage ring operating with femtosecond high peak current electron bunches and natural energy spread is discussed. This beams can be used to generate both coherent and spontaneous X-ray beams with femtosecond duration.

We discuss a possibility of the storage ring based FEL X-ray light source with average spectral brightness of 10^{27} -10^{28} ph/sec/mm2/mrad2/0.01%BW. This value exceeds existing 3rd generation light sources by 6-9 orders of magnitude, making it a 5th generation light source.

1 INTRODUCTION

The microwave instability has been observed in almost all operational storage rings. It causes anomalous bunch lengthening and energy spread growth limiting both longitudinal brightness of the electron beam and the achievement of very short bunches [2]. The 6D brightness is defined as number of particles divided by the 6D phase space volume occupied by them:

$$B_{6D} = \frac{N_e}{\varepsilon_x \varepsilon_y \varepsilon_s} \tag{1}$$

where $\varepsilon_x, \varepsilon_y, \varepsilon_s$ are the horizontal, vertical and longitudinal emittances of electron beam. The longitudinal emittance for weak longitudinal focusing is the product of RMS bunch length and RMS relative energy spread:

$$\varepsilon_s = \sigma_s \frac{\sigma_E}{E}. \tag{2}$$

Modern storage rings, are capable of providing horizontal emittance of the order of ~0.1-1 nm*rad and sub-angstrom vertical emittance at modest energies E~ 1-2 GeV [3]. A lattice of low emittance storage rings has a large number of cells and also low value of momentum compaction factor α_c. For Chasman-Green lattice value of the momentum compaction factor [4]:

$$\alpha_c = \frac{\pi^3}{3N^2}\frac{\rho_b}{C} \tag{3}$$

where C is the circumference of the ring and ρ_b is the bending radius and N is the number of cells. One of most common conclusions (see Ref.[5]) drawn from this fact is the impossibility of achieving both low transverse emittances and a low longitudinal emittance simultaneously because of microwave instability. The Keil-Snell and Boussard criteria for threshold of longitudinal (microwave) instability [6] is:

$$I_{peak} = \frac{2\pi\alpha_c E}{e\left(Z_n / n\right)}\left(\frac{\sigma_E}{E}\right)^2 \tag{4}$$

where Z_n is the longitudinal coupling impedance at the *n*th harmonic of revolution frequency and σ_E is the RMS energy spread. The $\left(Z_n / n\right)$ is usually evaluated at the frequency σ_s / c for bunched beams, where σ_s is RMS bunch length and *c* is the speed of light. Best values of $\left(Z_n / n\right)$ achieved up-to-date are about 0.5 Ohm. It means that longitudinal emittance starts to blow up starting from few amps or few tens amperes of the e-beam peak current.

It is remarkable that formulae (4) has been derived for coasted beams works very well for bunched beams as well. This can be explained by the fact that in most existing storage rings frequency of synchrotron oscillations is much smaller than increment of microwave instability or decrement of Landau damping, i.e. Q_s<<1, where Q_s is tune of synchrotron oscillations. When synchrotron motion is so slow that it does not effect process of development and saturation of the microwave instability.

We suggest that a strong longitudinal focusing with Q_s~1 will provide for the suppression of microwave instability and attainment of high longitudinal beam brightness. The results of our computer simulations provide some evidence that this may be the case.

2 STRONG LONGITUDINAL FOCUSING

Let’s consider a storage ring comprised of N achromatic bends with RF cavities located in a dispersion-free straight section (Fig.1). The achromatic bend provides for full linear de-coupling between vertical, horizontal and longitudinal motion

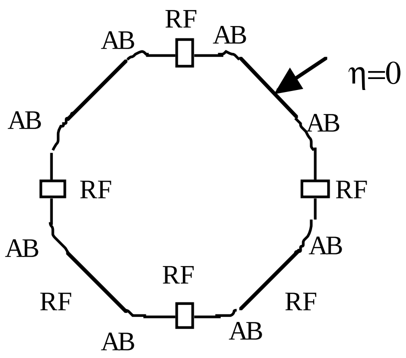

Fig.1 A schematic of a storage ring with achromatic bends (AB) and RF system (RF) located in dispersion-free straight section. The number of RF systems could be smaller than number of straight sections.

In differentials, the synchrotron motions is described by well known equations:

$$l_{n+1} = l_n + \alpha_c L \delta_n;$$

$$\delta_{n+1} = \delta_n - \frac{eV_{rf}}{E_o}\sin\left(k_{rf} l_{n+1}\right) = \delta_n - \frac{eV_{rf}}{E_o}\sin\left(k_{rf}\left(l_n + \alpha_c L \delta_n\right)\right)$$

where $k_{rf} = \dfrac{2\pi}{\lambda_{rf}} = \dfrac{2\pi h_{rf}}{C}$, $L = C/M$, M is number of RF cavities. The linear part of motion (small synchrotron oscillations) is described by the cell matrix and Courant-Snyder parametrization [1]:

$$\mu_s = 2\pi Q_s; \cos\left(\mu_s / M\right) = Tr[M_{s/cell}] =$$
$$1 - k_{rf}\alpha_c L \frac{eV_{rf}}{2E_o}; \; \beta_s = \alpha_c L / \sin(\mu_s / M); \quad (5)$$

with obvious limitation known from matrix optics that maximum tune advance per cell is 1/2. When the RF focusing parameter X= $k_{rf}\alpha_c L \dfrac{eV_{rf}}{2E_o}$ is larger than 2, small oscillations become unstable. This situation called over-focusing in periodic optics. It means that ring with one M RF systems could have longitudinal tune Q_S up to M/2. In order to obtain a large value of X~1 (for a given storage ring energy lattice of the storage ring, i.e. $\alpha_c L / E_o$ is fixed) one should either increase the RF voltage (which is impractical) or increase value of k_{rf} by reducing the RF wavelength. The short wavelength RF is very attractive. For a typical storage ring with E_o=1 GeV, L=50 m, α_c =10^{-3} it is sufficient to provide voltage of

$$V_{rf}[MV] = 10 \cdot \lambda_{rf}[mm]; \qquad (6)$$

to get X =1.57 and Qs=1.387 with four RF systems. It means that 10 MV of 1 mm RF or 1 MV of 0.1 mm RF is sufficient for strong longitudinal focusing. Short wavelength RF provides for rather small energy acceptance. For 10 MV of 1 mm RF energy acceptance will be 1.13% and for 1 MV of 0.1 mm RF is only 0.113%. Last value is comparable with a typical energy spread in the storage rings. Addition of standard (long-wavelength) RF can provide for necessary energy acceptance and reasonable life time. It also should be used for compensation of energy losses for synchrotron radiation. For short wavelength RF it leaves only the focusing function and does not require any energy transfer to the electron beam. A typical separatrices in this case are shown on Fig.2.

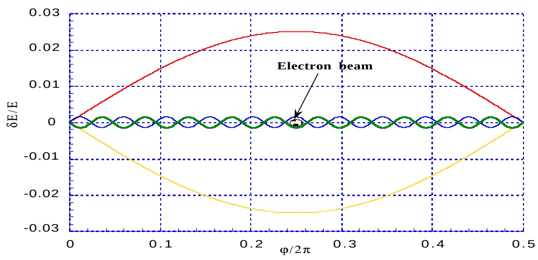

Fig.2 . A combination of long wavelength RF and short wavelength RF provide both large energy acceptance and strong focusing.

It looks very problematic or even impossible to have a RF cavity for 0.1mm wavelength. Nevertheless, it is possible to arrange a short wavelength RF system using inverse FEL mechanism. Let's consider a helical wiggler providing an interaction of electrons with TEM circular polarized 0.1 mm wave. For 1 GeV energy, a helical wiggler with a period of 40 cm and magnetic field of 11.7 kGs will provide the resonant conditions for 0.1 mm wavelength:

$$\lambda_{rf} = \frac{\lambda_w}{2\gamma^2}(1 + K_w^2); \; K_w = \frac{eH_w}{2\pi mc}.$$

Interaction of an electron with a TEM wave in a wiggler is a standard FEL problem. The result of the optimization of such "RF system" gives a simple ratio between the peak power and accelerating voltage:

$$\hat{P}[GW] \cong \frac{V^2[MV]}{3N_w} e^{\frac{1}{\pi N_w}}; \qquad (18)$$

where N_W is the number of wiggler periods. It means, that for 1 MV accelerating voltage in a wiggler with two periods (Lw=80 cm) one will need 196 MW of peak power.

The mm-wave power should be reactive with no energy transfer to the electron beam but only focusing. It means it can be the intracavity power of an FEL with average power smaller by a Q-factor of the optical cavity (Q~100). In addition, the power can be modulated in time to exist only during the pass of the electron bunches. All this can bring average power requirements for such RF system ~1 kW. Interestingly enough, FEL this levels of power far above 1 kW are already under development for a number of applications.

3 NUMERICAL SIMULATIONS OF LW SUPPRESSION OF MICROWAVE INSTABILITY

We have developed a macroparticle model and selfconsistent code to simulate longitudinal dynamics of electron beam in storage rings. We have used the wave-field calculated for SLC damping ring as the model. Results of this studies were reported elsewhere [7] and here we present a brief summary. Main parameters used in simulations are shown in Table I.

Table I. Storage ring parameters

Energy [GeV]	1.0
αc	0.0001
Natural energy spread	0.0004
Circumference [m]	200
Peak Wake [V/pc]	-600

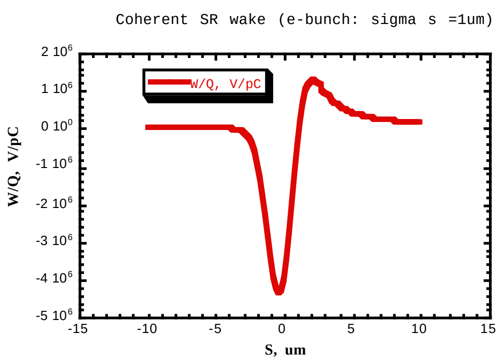

Fig. 3 Coherent SR Wake-field for electron bunch with RMS bunchlength of 1 micron.

The RF system was assumed to have two RF cavities: first with 1 MV accelerating voltage and 2 m wavelength, second - 1 mm IFEL. Without mm-wave RF system, we have observed typical development of the microwave instability starting from few amps of peak current. With 8 MV of mm-RF (Qs~0.15) we did not observed any indications of microwave instability with peak currents up to 10 kA. The energy spread did not increase as well as the natural bunch length. Because of very strong focusing, the bunch length if only few microns (~7 for quoted parameters). In this situation one should take into account coherent synchrotron radiation as the main factor. Typical "wake-field" (actually forward field) caused by coherent synchrotron radiation of 1 GeV beam with 1 micron RMS bunchlength is shown on Fig.3 (for bending radius of 2 meters).

At present time, we have included coherent synchrotron radiation in our model. Preliminary results show that electron beam is still stable at the level of few hundreds amperes. The results of this studies will be published elsewhere [8].

4 CONCLUSIONS AND PLAN

Results of our numerical simulations confirmed our expectations that strong longitudinal focusing (LW effect) suppresses microwave instability. The main limiting factor is, as expected, the coherent synchrotron radiation. Full scale numerical studies, which are underway, will provide us with answer about ultimate performance of this scheme. We also soliciting money to test this concept at the Duke storage ring.

If our expectations turn to be true, the proposed scheme will provide for very natural production of femtosecond pulses of X-ray radiation in both spontaneous and coherent (X-ray FEL modes) with typical average spectral brightness of 10. The coherent synchrotron radiation, which is a limiting problem for very high peak currents, will be on the other side a very unique source of IR coherent radiation with kW of power.

There is large number of interesting effects and possible instabilities which can occur with very short bunches. We plan to study some of them after conclusion of existing simulations.

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