DAΦNE TECHNICAL NOTE

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Terahertz Coherent Synchrotron Radiation at DAΦNE

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Abstract

We investigate the phenomena related to the emission of coherent synchrotron radiation (CSR) in the Terahertz frequency range at the DAΦNE collider. In particular, we calculate the threshold for the synchrotron radiation (SR) induced single bunch instability, usually referred as microbunching instability (MBI) [1-4]. The MBI can potentially have some effect at very high current in DAΦNE as well as in the foreseen strong RF focusing mode presently under investigation [5]. We also study the possibility of using DAΦNE as a high stability broadband CSR source in the Terahertz frequency. The cases for the existing normal-conductive RF system and for the super-conductive one proposed in [6] are evaluated following the optimization scheme of references [7, 8]. Such special mode of operation requires a quasi-isochronous lattice. Two possible solutions, with wigglers ON and OFF respectively, are also presented.

Introduction

An important issue for the high current operation of DAΦNE and for the proposed strong RF focusing experiment is the evaluation and understanding of the effect of the machine impedance on the bunch length and energy spread. One effect which has not yet been considered is a microbunching instability (MBI) driven by the radiation impedance. We would like to determine the importance of the MBI for these modes of operation. In fact, when the current per bunch is above the MBI threshold, the longitudinal dynamics of the bunch starts to be perturbed by the instability. For most storage rings and just above the MBI threshold, the perturbation is weak and shows measurable effects only as bursts of CSR in the far infrared (FIR). For currents much higher than the MBI threshold the effects could be relevant inducing average bunch lengthening and strong transient modulation of the longitudinal distribution.

In this note, a preliminary evaluation of the MBI effects on DAΦNE is presented. The threshold for the MBI is calculated and some considerations are done. A more careful and detailed analysis of the instability effects should include simulations of the longitudinal dynamics as the ones presented in reference [2]. Experimental characterization of the MBI in DAΦNE remains the most direct way for approaching the issue. To this end we suggest some experiments.

If the current per bunch is kept below the MBI threshold, DAΦNE could become an interesting source of stable CSR in the terahertz frequency range. In fact, generating CSR requires relatively short bunches and according to the criteria of references [7, 8], several beneficial features are simultaneously present in the Frascati collider: the relatively low energy contributes to obtaining short bunches; the small bending radius and the large dipole gaps reduce the shielding of the vacuum chamber that tends to suppress the CSR emission; the aluminum vacuum chamber minimizes the contribution of the resistive wall impedance that induces bunch lengthening; the several families of sextupole and octupole magnets allow for a precise control of the linear and nonlinear terms of the momentum compaction, which is a fundamental requirement when tuning the machine to vanishing α_C and short bunches; last but not least, DAΦNE has SINBAD [9], a beamline optimized for the far-infrared (FIR) in the electron ring. The only non-ideal feature is represented by the existing RF system which allows for relatively small voltage in the cavities. However, with the proposed strong focusing RF scheme using a 1.3 GHz superconducting cavity operated at several megavolts, DAΦNE could become an outstanding source of CSR.

In the following analysis the contribution of the wigglers in the arcs to the CSR wakefield is not considered. While the wiggler effect is small for most existing storage rings, it could not be the case for DAΦNE, where the SR power radiated from the wigglers is comparable with that radiated from the dipole magnets. This situation makes DAΦNE an interesting machine for studying the wiggler wakefield effects experimentally. If the effect of the wigglers is significant, the results of the optimization of DAΦNE as a CSR source can still be used for a lattice with the electromagnetic wigglers OFF. Two lattices, with wigglers ON and OFF respectively, are examined in paragraph 2.

Another interesting point that could be studied in DAΦNE is the effect of the beam-beam on the MBI. In fact in DAΦNE, the strong beam-beam regime could have significant effects on the MBI dynamics.

1. The microbunching instability in DAΦNE.

According to references [1, 3] the threshold for the MBI is given by :

$$I_b > \frac{\pi^{1/6}}{\sqrt{2}} \frac{ec}{r_0} \frac{\gamma}{\rho^{1/3}} \alpha_C \delta_0^2 \sigma_z \frac{1}{\lambda^{2/3}} \tag{1}$$

where I_b is the average current per bunch, e the electron charge, c the speed of light, r_0 the electron classical radius, γ the beam energy in rest mass units, ρ the dipole bending radius, α_C the momentum compaction, δ_0 the relative energy spread, σ_z the rms bunch length and λ the SR wavelength.

Expression (1) has been calculated for $\sigma_z >> \lambda/2\pi$ and for a gaussian longitudinal distribution. The largest values that λ can assume is limited by the vacuum chamber cutoff.

The MBI is associated with the appearance of temporary structures in the longitudinal distribution with characteristic length smaller than the bunch length. These microbunches radiate CSR with a spectrum limited roughly to wavelengths as short as the characteristic length of the microbunch. For this reason, the SR wavelength λ appearing in Eqn. 1, can be also interpreted as the characteristic length of the microbunch itself. Shorter structures can be generated only at higher currents per bunch.

The experimental results in references [8, 9] have clearly shown that Eqn. 1 can be used for careful predicting the MBI absolute threshold (first appearance of the instability) when the natural bunch length is used as the value for λ.

In DAΦNE the microwave ibnstability threshold appears at very low currents (~below 1 mA/bunch), while the MBI threshold is higher, as shown in Fig. 1, where calculations have been done assuming natural bunch length and energy spread.

The microwave instability lengthens the bunches and increases energy spread and therefore also the MBI threshold.

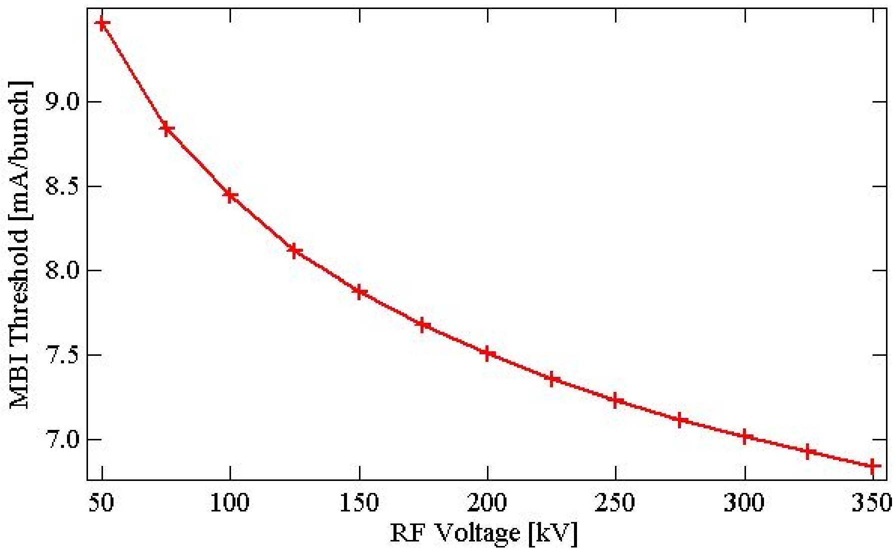

Figure 1: Single bunch average current threshold for the MBI calculated for DAΦNE with E = 510 MeV, ρ = 1.4 m, α_C = 0.02.

At very high currents per bunch both instabilities could appear, and this could be experimentally verified at the SIMBAD FIR beam line. In fact, the CSR bursts associated with the appearance of the MBI, can be easily detected by a bolometer with sensitivity in the THz frequency range.

Figure 2 shows an example of such a measurement at the Advanced Light Source in Berkeley. The signal from a bolometer is observed at the oscilloscope for three different current values all above the MBI threshold of ~ 8 mA.

Streak camera measurements of the longitudinal distribution in the MBI regime are also very interesting even if somehow difficult.

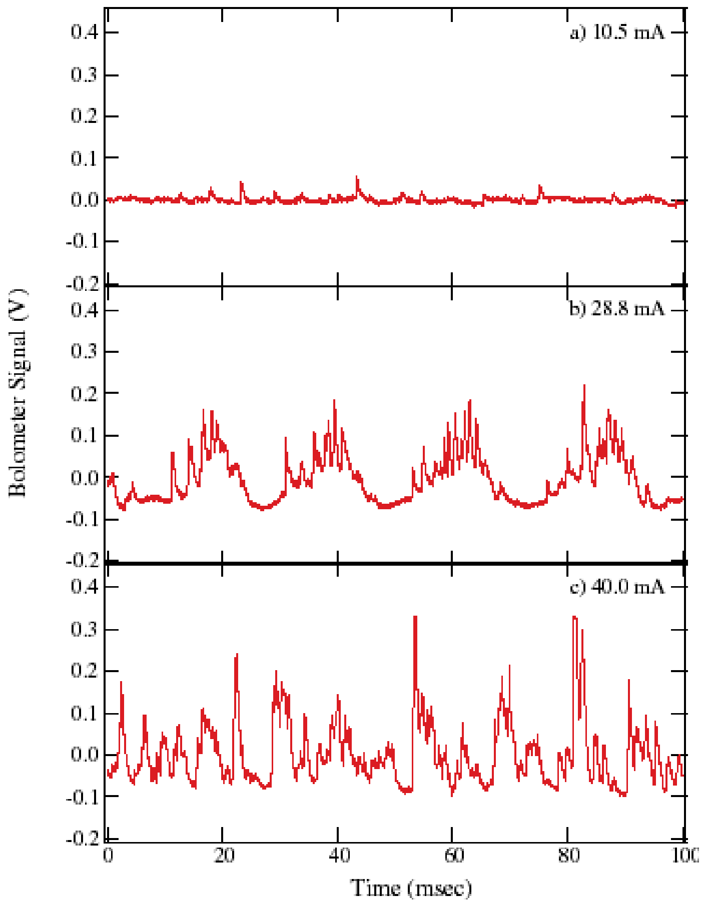

Figure 2: Measurements of the CSR burstings associated with the MBI at the Advanced Light Source in Berkeley.

In the proposed strong focusing RF scheme for DAΦNE, shorter bunches are foreseen. According to Eqn.1, shorter bunches lead to lower MBI thresholds, but because of the very peculiar characteristics of this mode of operation, Eqn. 1 cannot be directly used and a new expression accounting for the new situation should be instead derived. Nevertheless, the MBI effects should be carefully investigated in order to evaluate the presence of undesired effects, such as bunch lengthening for example, that could limit the performance of this special mode of operation.

2. DAΦNE as an ultra-stable source of CSR.

Recently it has been experimentally demonstrated at the BESSY II synchrotron light source that electron storage rings can be operated in a special mode where the CSR emission in the terahertz frequency is extremely stable and powerful [10, 11]. Afterward works [7, 8] presented a physical model that explains the results of BESSY II and that allows to optimize new and existing storage rings for the CSR performance [12]. In this special mode, the momentum compaction is tuned to significantly lower values than in normal operation. As a consequence, the bunch shortens and the SR becomes the dominant wake. In such a situation, the SR wake induces a stable distortion of the bunch longitudinal distribution from Gaussian to a sawtooth-like shape with a sharp leading edge. This distortion significantly extends the CSR emission towards shorter wavelengths. For a stable emission, the current per bunch must be maintained below the MBI instability threshold that decreases for decreasing momentum compaction. We have applied such a model to DAΦNE for the two cases with the existing RF system and with the 1.3 GHz superconductive system, foreseen in the proposed strong RF focusing scheme.

2.1 DAΦNE as a CSR source with the existing 368 MHZ RF system.

Table 1 shows the relevant parameters of DAΦNE, while Table 2 presents the principal characteristics for three possible CSR modes of operation. The minimum momentum compaction of SET 1 is ~ 270 times smaller than the normal operation one and the (very small) currents per bunch for all the three modes are ~ 0.5 times the threshold for the MBI.

Table 1: DAΦNE relevant parameters.

Energy [MeV]	510	Ring Length [m]	97.7
Bend Radius [m]	1.4	Harm. Number	120
RF freq. [MHz]	368.26	RF Voltage [kV]	250
Natural Relative Energy Spread (rms)	4.0×10^{-4}	Normal Momentum Compaction	0.02
Vacuum Chamber Height [mm]	50	Vacuum Chamber Material	Al

Table 2: Three possible sets for DAΦNE in the ultra-stable CSR mode. The CSR power is integrated between 1 and 30 cm^{-1} over an horizontal acceptance of 40 mrad. The sets correspond to the three curves shown in Figures 3, 4 and 5.

	Nat. bunch rms length [mm]	Momentum compaction	Total Current [mA]	Current per bunch [µA]	Total CSR Power [mW]
SET 1	0.5	7.5×10^{-5}	0.52	4.3	2.27
SET 2	1.0	3.0×10^{-4}	2.92	24.3	15.6
SET 3	2.0	1.2×10^{-3}	19.2	160	31.9

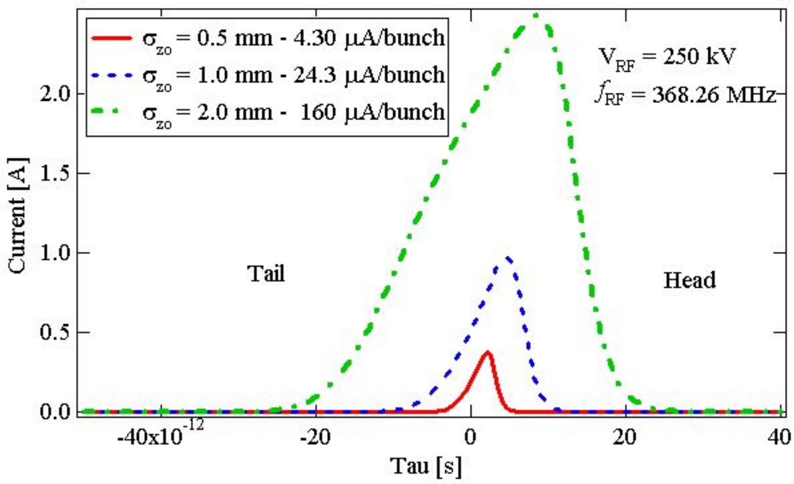

Figure 3: Calculated longitudinal distribution of the bunch for three different modes of DAΦNE as ultra-stable source of CSR.

Figure 3 shows the equilibrium distributions for the three sets of Table 2. All the calculations include also the shielding effects of the vacuum chamber and the resistive wall impedance contribution. The effect of the geometric impedance of the vacuum chamber is negligible in this short bunch regime. The sawtooth like distortion due to the SR wakefield is clearly visible. The curve for the 2 mm length case, shows a hump-like shape on the trailing edge. This is an indication that for such a bunch length (and longer ones), the shielding effect of the vacuum chamber starts to be significant.

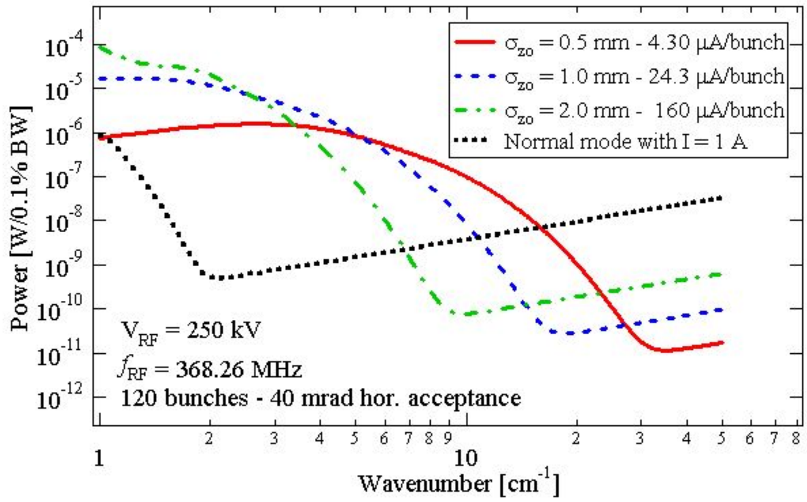

Figure 4: Calculated SR Spectra for three different sets of DAΦNE as ultra-stable source of CSR.

Figure 4 shows the SR power spectra for the three sets. The lower limit of the spectra has been set to 1 cm^{-1} that roughly corresponds to the DAΦNE vacuum chamber cutoff. Also shown as a dotted line, is the spectrum for DAΦNE in the normal mode of operation with 1 A of stored current. If we normalize the other spectra with respect to this last one, we obtain the curves in Figure 5 where the gain in power, for the three CSR sets with respect to the normal mode with 1 A, is shown. As Figure 5 shows, several order of magnitudes increase in power are obtained in the bandwidth from 1 to ~ 15 cm^{-1}. Shorter bunch lengths extend the bandwidth but decrease the peak power. The small difference in the peak gain between the 1 and 2 mm cases, is due to the stronger shielding effect that the vacuum chamber has in the longer bunch case.

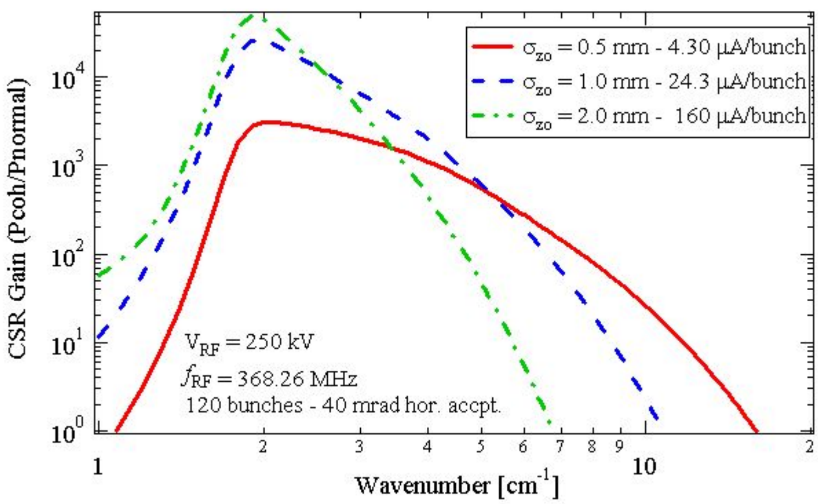

Figure 5. Calculated CSR gain for the three different sets of DAΦNE as ultra-stable source of CSR. The curves have been obtained dividing the power spectra by the spectrum of DAΦNE in the normal operation mode with 1 A stored.

2.2 DAΦNE as a CSR source with the 1.3 GHz superconductive RF system.

In the proposed strong RF focusing scheme, a 1.3 GHz superconductive RF system is considered. Such a system will be capable of a RF voltage of up to ~ 10 MV. In what follows, we have repeated the analysis of the previous paragraph for the case with this more powerful RF system and assuming an RF voltage of 1 MV. The presented configuration has not been optimized with respect to the RF voltage and it is shown only as example of the better performances that can be obtained with such a RF system. Again the currents per bunch have been kept at ~ 0.5 the MBI threshold. The number of bunches used is 60, the maximum compatible with the present DAΦNE injection system. Table 3 and 4 show the parameters for this new mode of operation, while Figures 6, 7 and 8 the obtained results.

Table 3: New parameters for DAΦNE with the superconductive RF system.

RF freq. [GHz]	1.3	RF Voltage [MV]	1.0
Harm. Number	424		

Table 4: Three possible sets for DAΦNE in the ultra-stable CSR mode with the superconductive RF system. The total current is distributed among 60 bunches. The CSR power is integrated between 1 and 60 cm^{-1} over an horizontal acceptance of 40 mrad. The sets correspond to the three curves shown in Figures 6, 7 and 8.

	Nat. bunch rms length [mm]	Momentum compaction	Total Current [mA]	Current per bunch [μA]	Total CSR Power [mW]
SET 4	0.25	2.5×10^{-4}	0.68	11.3	25.0
SET 5	1.0	1.0×10^{-3}	3.40	56.7	220
SET 6	2.0	4.0×10^{-3}	18.48	308	1506

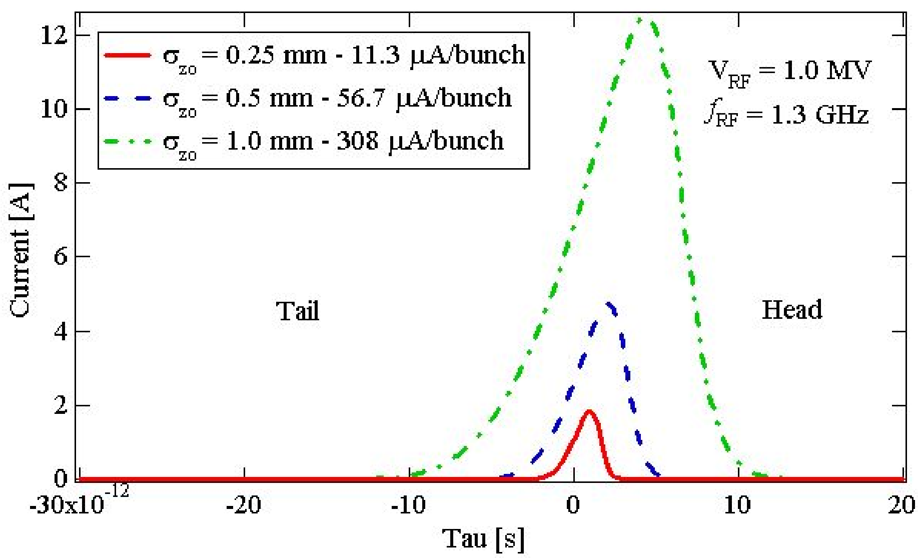

Figure 6: Calculated longitudinal distribution of the bunch for the three different modes of DAΦNE with the superconductive RF system.

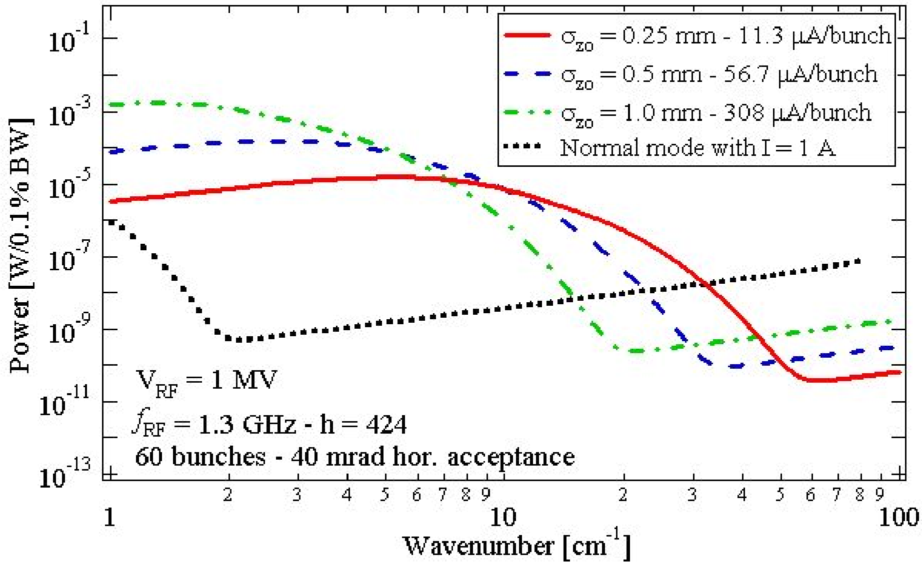

Figure 7: Calculated SR Spectra for the three different sets of DAΦNE with the superconductive RF system.

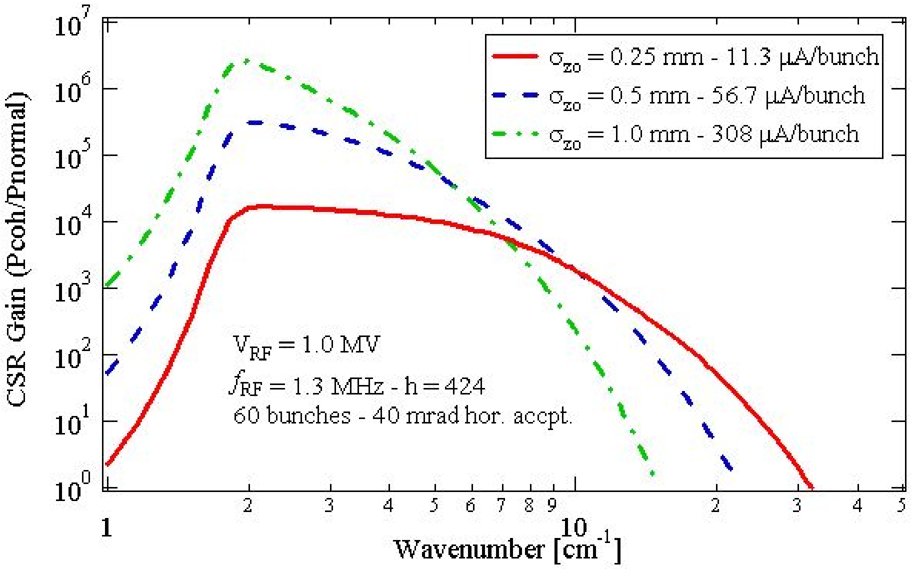

Figure 8: Calculated CSR gain for the three different sets of DAΦNE with the superconductive RF system. The curves have been obtained dividing the power spectra by the spectrum of DAΦNE in the normal operation mode with 1 A stored.

Figure 8 shows the impressive performances of DAΦNE with the superconductive RF system. The power gain greatly increased in both bandwidth and absolute value.

2.3 Two low alpha lattices for DAΦNE as a CSR Source.

DAΦNE lattice can be flexibly tuned in the momentum compaction factor by modifying the behavior of the dispersion in the dipoles facing the short and the long sections. By keeping zero dispersion and derivative dispersion at both Interaction Points, the dispersion behavior in the dipoles near to the Interaction Regions is in fact almost fixed. The range of tunability is wide: measurements with negative momentum compaction of the order of few 10^{-2} have been already done [13]. Lattices with high momentum compaction (near 10^{-1}) have been also designed in view of the strong rf focusing experiment [6]. The lattice can also be tuned to the isochronicity condition straightforwardly. In this situation the maximum dispersion along the ring is of the order of 2 m.

A quasi-isochronous lattice has been defined for two cases: one with the wigglers ON in the arcs on and the other with the wigglers OFF. Figures 9 and 10 refer to the first case and show respectively the betatron functions and the dispersion along the ring, while Figures 11 and 12 refer to the wigglers OFF solution. Table 5 summarizes the main parameters for the two configurations. The main differences between the two lattices are essentially the damping times, which differ by more than a factor 2, and of course the energy lost per turn. The emittance is almost the same and this has been obtained by increasing the synchrotron radiation integral I_5 in the wigglers-OFF solution by a factor 2, for counteracting the halving of the synchrotron radiation integral I_2. The betatron vertical tune is one integer lower in the case of wigglers OFF and in both cases the tunes can be varied in the usual range of ± 0.2 with the short section working point knob. The revolution frequency with wigglers OFF is 1 kHz higher, since the wiggling trajectory is longer by 7 mm per wiggler.

Table 5: Relevant parameters of the lattices for DAΦNE as a CSR source.

	Wigglers ON	**Wigglers OFF**
C (m)	97.68	97.66
α_c	5 10^{-4}	5 10^{-4}
Uo (keV)	9.6	4.3
τ_x **(msec)**	37	85
ε_x **(mm mrad)**	0.26	.33
Qx	5.16	5.08
Qy	5.22	4.22

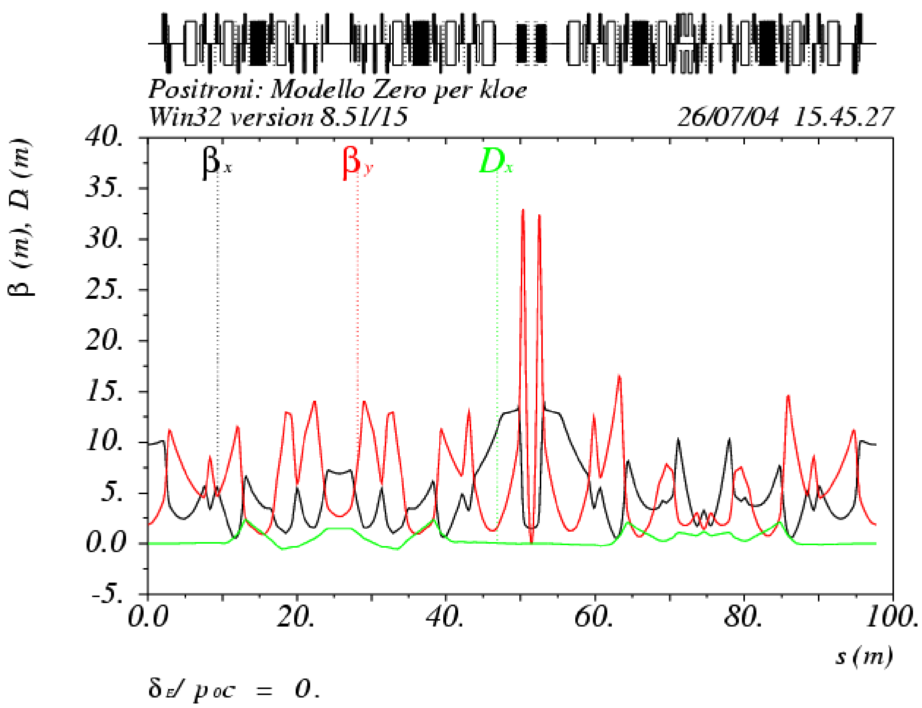

Figure 9: Betatron functions along the ring with wigglers ON.

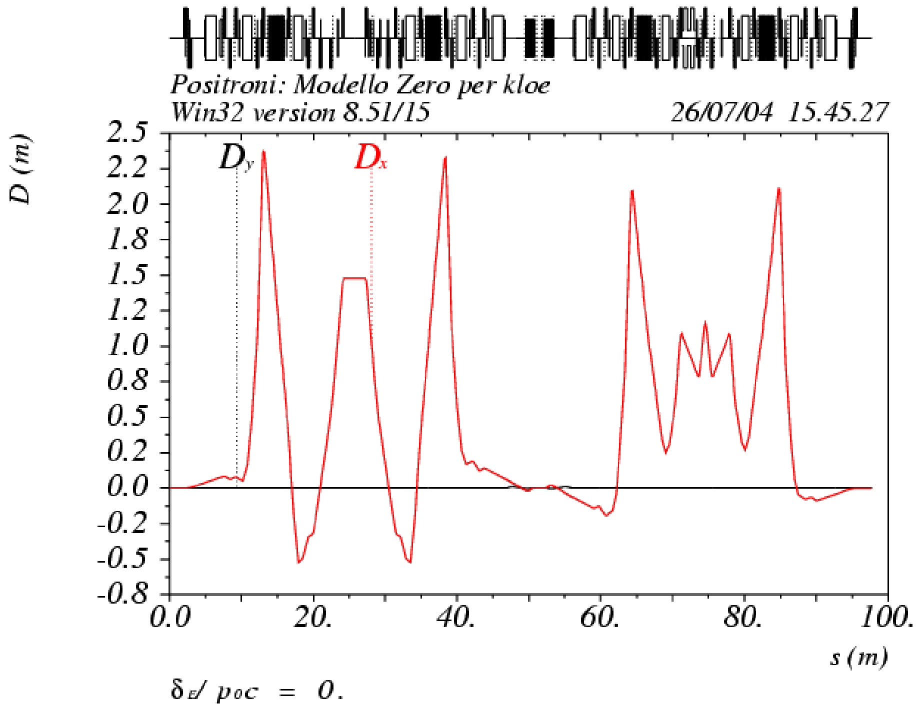

Figure 10: Dispersion function along the ring with wigglers ON.

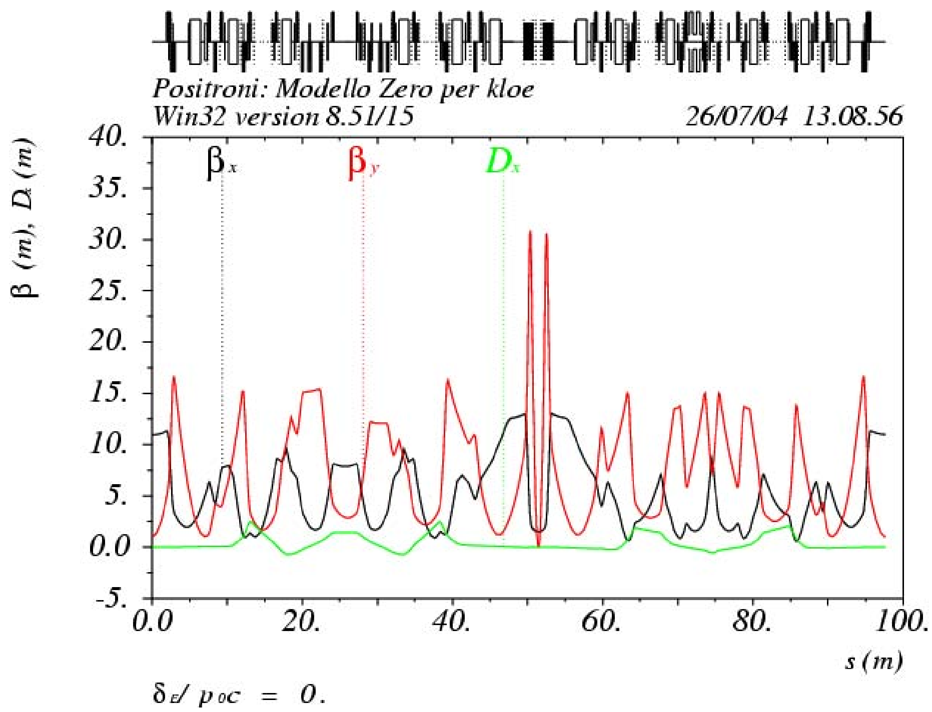

Figure 11: Betatron functions along the ring with wigglers OFF.

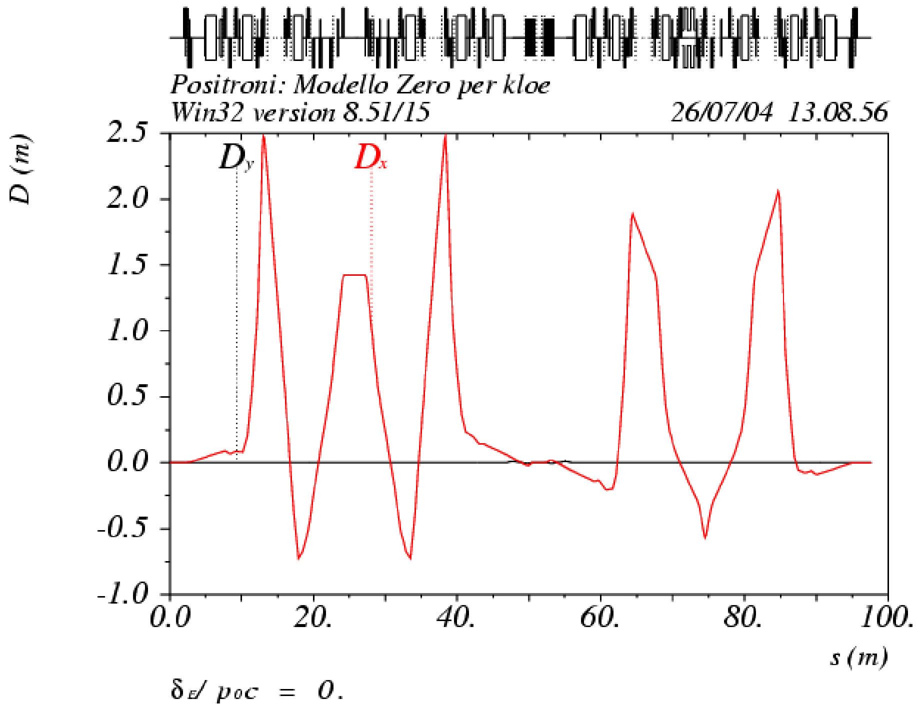

Figure 12: Dispersion function along the ring with wigglers OFF.

When tuning the lattice into small values of the momentum compaction, particular attention must be put on the energy dependent high order terms of the momentum compaction. For example, special care must be used in minimizing the second order term that directly affects the momentum acceptance of the machine. In DAΦNE the presence of several families of sextupole and octupole magnets should ensure a direct control of the energy dependent terms of the momentum compaction up to the third order.

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Conclusions.

The CSR issues associated with DAΦNE have been analyzed. The threshold for the MBI has been calculated. The results showed that MBI is not a concern in the present high current collision operation while it could appear at very high current per bunch. Analogously, the MBI could be important in the proposed strong RF focusing scheme, where shorter bunches are foreseen. Experimental characterization of the MBI in DAΦNE, well above the single bunch threshold, will help to better define the question.

Additionally, a detailed analysis of DAΦNE optimized as a powerful source of ultra-stable CSR in the terahertz frequency region has been performed. Two cases, one with the present RF system, the other with the superconductive 1.3 GHz one foreseen in the strong RF focusing scheme, were investigated. The results are very interesting and show the high potentiality of DAΦNE as a CSR source.

References

[1] S. Heifets. And G. Stupakov., Phys. Rev. ST Accel. Beams **5**, 054402 (2002).

[2] M. Venturini and R. Warnock, Phys. Rev. Letters **89**, 224802 (2002).

[3] J. M. Byrd, *et al*. Phys. Rev. Letters **89**, 22, 224801 (2002).

[4] M. Abo-Bakr, *et al*., Proc. 2003 IEEE Part. Accel. Conf., Portland, OR, 2003, p. 3023.

[5] A. Gallo, P. Raimondi and M. Zobov, DAΦNE Technical Note G-60, August 18,2003.

[6] Gallo, *et al*., "Strong RF focusing experiment at DAΦNE", EPAC04, Lucerne, Switzerland, July 2004.

[7] F. Sannibale *et al.*, Proc. 2003 IEEE Part. Accel. Conf., Portland, OR, 2003, p. 863.

[8] F. Sannibale *et al.*, accepted for publication on Phys. Rev. Letters.

[9] A. Marcelli, *et al.*, Journal of Synchr. Radiation **5**, 575 (1998).

[10] M. Abo-Bakr *et al*., Phys. Rev. Letters **88**, 254801 (2002).

[11] M. Abo-Bakr *et al*., Phys. Rev. Letters **90**, 094801 (2003).

[12] J. M. Byrd, *et al*., "CIRCE the Coherent InfraRed CEnter at the ALS", EPAC04, Lucerne, Switzerland, July 2004.

[13] M. Biagini, *et al.*,. DAFNE Technical Note BM-15, July 12, 2004.