A NEW 500 MHZ FIFTH HARMONIC RF SYSTEM FOR SUPER-ACO[1]

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Abstract

A new 500 MHz fifth harmonic RF system has recently been installed on the Super-ACO storage ring primarily for bunch length reduction for Free-electron laser (FEL) and time resolved synchrotron radiation experiments. This system, intended for neutral phase operation, uses an ELETTRA cavity and a 35 kW CW, tetrode-based, television amplifier fabricated by Thomson. Maximum RF voltage is about 300 kV. Other major components, including power supplies and a modular 1 kW MOSFET solid-state preamplifier optimised for fixed frequency operation, were designed and realised in-house. Each module furnishes 10 dB of gain and up to 150 W maximum output power. The RF amplitude and phase feedback loops were optimised to respect the very stringent requirements necessary for stable FEL operation. They maintain 1% amplitude/1° phase stability with 1 kHz bandwidth. We present a detailed description of this RF system as well as the first year's operating experience.

1 INTRODUCTION

The performance of the Super-ACO FEL has been limited by its low gain per passage with the nominal machine specifications, which are shown in Table 1.

Table 1: Super-ACO parameters

Parameter	Value	Unit
Revolution frequency: f_0	4.1614	MHz
Energy: E_s	800	MeV
Loss per turn	20	keV
Energy dispersion	$5.32\ 10^{-4}$	1
Longitudinal damping time: τ_s	9.28	ms
Momentum compaction: α	$1.48\ 10^{-2}$	1
Principal harmonic number: h	24	1
Principal RF voltage: V_p	170	kV
Nominal bunch length: σ_r	87	ps
Nominal synchrotron freq.: f_s	14	kHz
Higher harmonic number: k	120	1
Harmonic voltage: V_h	0-300	kV

Since the gain is directly proportional to the electronic bunch density, one means of increasing it is to reduce bunch length by increasing the RF accelerating slope with a higher harmonic cavity. Using a single additional cavity operating at the fifth RF harmonic of 500 MHz, a reduction in bunch length by a factor of 2 to 3 is feasible in principle. Such a reduction, in addition to its benefits for FEL operation is also of interest in order to increase the resolution of several types of time-resolved synchrotron radiation experiments. In this paper, we present the operating principles and technical aspects of this RF system. Other papers presented at this conference will discuss results obtained in terms of collective beam dynamics[1] and FEL performance[2].

2 GENERAL CONSIDERATIONS

The dynamics of longitudinal motion are determined by the vectorial sum of all RF voltages applied to the beam whatever their frequencies as long as these are harmonics of the revolution frequency. Fixed points in the phase plane are determined by the condition that the total RF voltage be equal to the turn-by-turn losses. Stable fixed-points, around which bunching tends to occur, correspond to local minima of the longitudinal potential well, and bunch-length as well as synchrotron frequency are proportional to the square root of the curvature of the potential function in the vicinity of these points. In this paper we will consider bunch length only in relative terms because the absolute values are determined by collective effects. Of course even in relative terms the effect of an harmonic cavity is likely not to be given exactly by the zero-current analytic formulae however we expect these to be much closer to the reality than the absolute expressions.

2.1 Choice of parameters

Our harmonic cavity system has been designed for neutral-phase operation. That is, the harmonic cavity voltage at the stable fixed points is intended to be zero. In this case, there is no average energy exchange between the beam and the harmonic cavity and all RF power supplied is available for maintaining the cavity voltage. In this configuration the bunch shortening factor is given by the expression:

$$r = \sqrt{1 + \frac{V_h f_h}{V_p f_p \cos(\phi_s)}} \qquad (1)$$

where V and f refer to the voltages and frequencies of the harmonic and principal RF cavities as indicated by the subscripts and ϕ_s is the synchronous phase.

From this expression, we see that the effectiveness of the harmonic cavity in reducing bunch length is determined by the product of voltage by frequency. A

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frequency of 500 MHz was chosen because of the extensive experience in other laboratories with RF systems at this frequency.

Once the harmonic frequency is determined, expression (1) provides a one to one relationship between cavity voltage and bunch-length reduction. For example, with the nominal Super-ACO parameters, a reduction factor of 3 would require 270 kV of harmonic cavity voltage. The necessary voltage increases as the square of the reduction factor and the RF power, which largely determines the cost of the system, with the square of this value. Since this strong dependence on r prohibits much larger reduction factors, we chose r=3 as a starting point for cost-performance optimisation of the system. In any case, since Touschek lifetime is inversely proportional to bunch length, reduction factors larger than about 3 are also excluded because of the unacceptable beam-lifetimes they would imply (<1 hour).

2.2 *Injection*

One problem particular to Super-ACO results from the fact that the machine is injected with a LINAC which provides pulses of approximately 5 ns duration.. We would thus expect to fill roughly 2 to 3 500 MHz buckets instead of a single one. In addition the pulse length of the RF knockout system is also too long for efficiently eliminating the undesired bunches.

The solution to this problem is provided by the fact that the number of stable fixed points depends on the harmonic voltage applied. It is obvious that if this voltage is very small compared to the principal RF voltage, new fixed points cannot be created. However even for relatively large harmonic voltages, the new fixed points which are created do not represent stable solutions because no potential barrier separates them from the principal fixed points. This effect is shown in figure 1 where the longitudinal potential is drawn for neutral phase operation at three different harmonic voltages. Calculations show that the limiting voltage for producing a potential barrier is about 150 kV. Injection is therefore performed with a voltage inferior to this value. Once the beam has been injected and the bunches damped to their nominal lengths, it should be possible to raise the voltage without trapping particles in the parasitic buckets because a significant asymmetrical potential barrier (indicated H_a in figure 1) separates the stored particles from these undesired fixed points. In our case the energy acceptance corresponding to this potential barrier is on the order of 1 %. Of course Touschek scattering will provide sufficient energy for certain particles to overcome this barrier. We therefore expect filling of these parasitic bunches on a time scale given by the Touschek loss rate for the corresponding energy acceptance (of the order of 1 hour).

Note that it should be possible to prevent this phenomenon by removing Toushek scattered particles with a horizontal scraper in a section with dispersion.

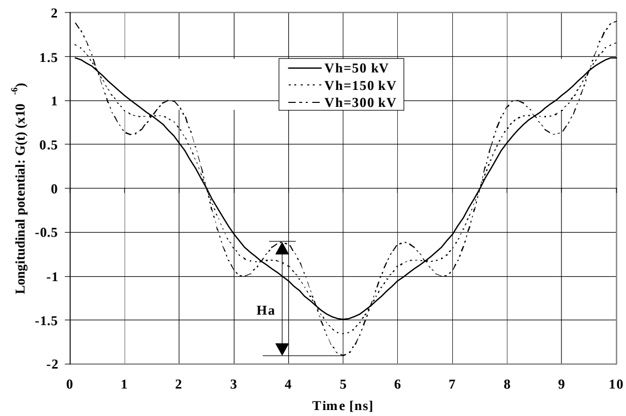

Figure 1: Longitudinal potential for 3 harmonic voltages

3 SYSTEM DESCRIPTION

3.1 *Cavity*

The cavity as well as the main RF power coupler and window, manufactured by Sincrotrone Trieste, are identical to those used on the ELETTRA storage ring[3]. The primary parameters of the fundamental mode are presented in table 2. In order to ensure the possibility of rapid switching between operating modes, we have replaced the cavity stretcher tuning system used at ELETTRA by a mobile plunger mounted on one of the cavity's 3 equatorial CF-100 vacuum flanges. This plunger provides a full tuning range greater than 2 MHz and an average sensitivity of about 50 kHz/mm. The cavity mechanical support also provides the possibility of manual stretching. This could thus serve as a second parameter for the control of higher order modes (HOM's) although this possibility has not been needed to date.

Cooling and temperature control of the cavity and plunger are provided by a semi-closed water circulation loop equipped with an 18 kW heating coil and a regulation valve separating the loop from the general machine cooling system. This system allows temperature regulation in the range 35-70°C with a precision of 0.1°C.

Table 2: Harmonic cavity fundamental mode parameters

Parameter	Value	Unit
Resonant frequency: f_r [2]	499.04	MHz
R/Q[3]	85	Ω
Measured Q_0	39 600	1
Measured coupling factor: β	0.99	1

[2] Under vacuum at 25°C without plunger.
[3] Our definition is: $P_d=V^2/2(R/Q)Q_0$.

3.2 High power RF circuit and power-supplies

The final stage of the RF amplifier chain consists of a Thomson TH 563 tetrode mounted in a TH 18550 UHF television type coaxial cavity circuit assembly. This stage provides approximately 16 dB of gain and a maximum output power of 30 kW. The filament, screen and grid are all powered by standard commercially available switch-mode power supplies. The anode is fed by a house-built 9 kV, 9 A power supply using thyristor regulation on the primary. The secondary is equipped with a double-cell low-pass filter having a 75 Hz cut-off frequency. In addition to standard interlocks, the tube is protected by a spark-gap based crowbar circuit on the anode secondary.

RF power is fed to the cavity via an EIA 6-1/8" coaxial transmission line equipped with a 35 kW circulator presenting a reflection coefficient of less than -20 dB.

A house-built two-stage MOSFET preamplifier, described in another paper presented at this conference[4], feeds the tetrode with 20 dB of gain and up to 1 kW of output power. The preamplifier is in turn fed by a commercial 40 dB, 25 W solid-state amplifier.

3.3 Low level RF circuit and feedback loops

The fifth harmonic RF signal is generated by frequency multiplication of the 100 MHz RF reference signal using a comb generator followed by a band-pass filter. The resulting signal serves simultaneously as a 500 MHz phase reference which represents the phase of the harmonic cavity relative to that of the principal one and as the input signal for the amplifier chain.

Feedback loops are provided for cavity voltage, phase, tuning angle/plunger position and temperature (described in section 3.1). The voltage loop compares the detected cavity voltage with a user specified reference voltage and then adjusts an electronically variable attenuator to minimise the difference between these. This loop provides amplitude stability of about 1 % with a 3 dB rolloff of 1.5 kHz. The cavity phase loop error signal is derived by mixing the cavity signal with the 500 MHz reference, the phase of which can be adjusted in a range greater than 360° by an electronic phase shifter. Another electronic phase shifter is then adjusted to minimise this error. The loop precision is of the order of 1° with a 3 dB rolloff of 1.5 kHz.

In practice the cavity phase is adjusted by measuring and minimising the variation in cavity incident power as a function of beam current. In fact this condition defines 2 solutions. The desired solution corresponds to a single bunch at the neutral phase point while a parasitic solution exists for a split bunch with density maxima slightly above and slightly below the neutral phase (one is slightly accelerated, the other slightly decelerated). It is in fact easy to distinguish between these as the desired solution gives a smooth variation of power transfer with phase in its vicinity while the parasitic solution is located at a discontinuity in power transfer.

The tuning angle loop uses the same principal as the cavity phase loop except that the compared signals are cavity voltage versus the cavity incident RF signal. The error signal then modulates the frequency of a pulse generator which actuates the stepper motor controlling the plunger. In this case precision is again of about 1° but with a 3 dB rolloff of 1.7 Hz. This loop can also be used to control plunger position in absence of RF using a linear potentiometer position signal.

4 OPERATING EXPERIENCE

At present 3 operating modes are defined for the harmonic RF system. For all non-FEL runs, the cavity is detuned by about 1 MHz from the fifth RF harmonic. This configuration results in an accidental, but beneficial, modification in the longitudinal dynamics of 24 bunch beams due to an HOM which appears to convert the large amplitude (>1 ns) phase oscillations previously observed into smaller amplitude bunch-length oscillations which result in a 20% improvement in total beam lifetime due to the increase in average bunch-length.

A second inactive mode with 2 MHz of fundamental mode detuning allows us to recover the pre-installation beam behaviour. This configuration is used for FEL runs which do not use the active mode in order to avoid bunch-lengthening due to the aforementioned HOM.

Finally the active, bunch shortening mode is now used for most FEL runs (roughly 20 hours per week). To date up to 150 mA have been stored in a 2 bunch beam with harmonic voltages as high as 300 kV. Although instantaneous bunch-length reduction factors greater than 3 have been measured in this mode, such strong bunch shortening results in single-bunch longitudinal and transverse instabilities which are currently under study.

REFERENCES

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