A HIGH HARMONIC CAVITY FOR CONTROLLED LONGITUDINAL PHASE SPACE DILUTION IN THE AGS*

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Abstract

A harmonic cavity at 93 MHz is being built that will be used in the Brookhaven AGS to perform a controlled blow up of the longitudinal phase space in order to facilitate lossless passage through the transition energy. The phase space area will be increased from 1.0 eV-s to as much as 4.0 eV-s on two 50 ms magnetic field flattops. The cavity is a shorted quarter wave TEM mode cavity that provides 30 kV of gap voltage for less than 10 kW of drive power. When the cavity is not in operation it will be switched to a low-impedance state by a PIN diode switch.

Introduction

The fundamental limit to the achievable proton intensity in the Brookhaven AGS is space charge tune shifts near injection.[1] When the machine is injected from the 1.5 GeV (kinetic) booster synchrotron, which is scheduled for completion in 1991, the limit will be increased by a large factor. With typical operating intensities much higher than present values, beam loss rates that are now tolerable will become excessive. In particular, some 3% to 5% of the beam is now lost in passing through the transition energy. With much higher intensity, this fractional loss rate will cause unacceptable irradiation of the machine. Furthermore, the higher particle density at increased intensity is likely to cause the rate of loss to increase. It is imperative, therefore, to decrease the particle density by increasing the longitudinal phase space area up to a value approaching the area of the stable rf bucket. This will be done by adding a new cavity to the rf system that operates at a high harmonic of the revolution frequency and injects a pseudo-random perturbation to the rf potential seen by the beam This will cause a controlled blow-up and dilution of the phase space area. In order to make full use of the available phase space area, the dilution process will be performed twice during the cycle, once at injection where the bucket area is ~ 2 eV sec/bunch and later at about 4.3 GeV/c where the bucket area is ~ 4 eV sec/ bunch. The technique has been in use for several years at the CERN PS.[2]

The dilution may prove to be very beneficial even after transition. A fast transition-jump scheme is also planned for the AGS as a complement to the dilution process. Tests have shown that the jump is very effective in eliminating the uncontrolled blow-up that invariably happens at transition. Indications have already been seen that without the controlled blow-up from the cavity, the very high longitudinal density after a transition jump will drive fast growing transverse instabilities that destroy the beam.

When the dilution cavity is not in use it will be switched to a low-impedance state by a PIN diode switch that is tightly coupled to the gap.

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Controlled Blow-Up

Blow-up of the phase space area is fundamentally a non-adiabatic process and therefore tends naturally to lead to distributions that are not matched to the bucket. The goal of a controlled blow-up is to create a new distribution in phase space with a larger area and whose boundary is still matched to the trajectories of the bucket. The result is a lower density in phase space (consequently, a lower charge density in coordinate space) and no apparent coherent motion of the bunch within the bucket. The action of the high harmonic cavity is to make the trajectories of phase space extremely complicated on a microscopic scale. The enclosed area may not literally be increased. But when the appropriate phase modulation program is applied to the cavity voltage, and the modulation frequency is significantly greater than the synchrotron frequency, the local structures of the boundaries become diffuse and effectively disappear. The resulting distribution is larger in area and is matched to the bucket.

The parameters for the harmonic cavity that minimize the time required for a 100% increase in phase space area were obtained in a computer simulation and are listed in Table I.[3] The harmonic number is a multiple of the revolution frequency, not the rf frequency, since the absolute phase of the harmonic cavity with respect to a bunch is not important. There is a technical advantage to choosing harmonics that are not multiples of the rf frequency because this minimizes the beam induced voltage on the cavity. The cavity frequency is fixed (there is no dynamic tuning of the cavity) so when the cavity is used at different points in the cycle, the harmonic number will be changed. The harmonic numbers have been restricted to values at 1/3 and 2/3 of the separation between the rf harmonics because there may be significant Fourier strength elsewhere since the AGS will be filled with four batches (not necessarily exactly equal) of three bunches from the booster. The frequency of the modulation is stated as a range because the optimal dilution program exploits a parametric resonance between the synchrotron frequency and the phase modulation frequency. Because there is a spread of synchrotron frequencies in the beam, the modulation frequency is swept repeatedly (in 4 ms) through a range that overlaps the parametric resonance of all the particles in the bunch.

Table I

Harmonic Numbers	268, 272
Cavity Frequency	93.15 MHz
Cavity Voltage	30 kV (= 1/3 of main rf voltage)
Dilution Duration	50 ms
Frequency of Phase Modulation	6.7 to 7.3 kHz
Duration of Modulation Sweep	4 ms
Phase Deviation	$\pm \pi$ (@ 93 MHz)
Maximum Impedance	60 kOhms

The Harmonic Cavity

The choice of harmonic number for optimal dilution is not critical. This made it possible to choose a cavity frequency that is overlapped by the commercial FM broadcast band and led to a savings in the cost of the power amplifier to drive the cavity. At 93 MHz, the most practical type of cavity is the shorted quarter-wave TEM mode cavity. The cavity is illustrated in Figure 1. The through bore of the inner conductor is given by aperture requirements of the AGS to be 140 mm. The overall flange-to-flange length of the cavity is 1100 mm. The length of the inner conductor is 740 mm and the gap is 76 mm. The diameter of the outer conductor, which determines the R/Q, is 305 mm.

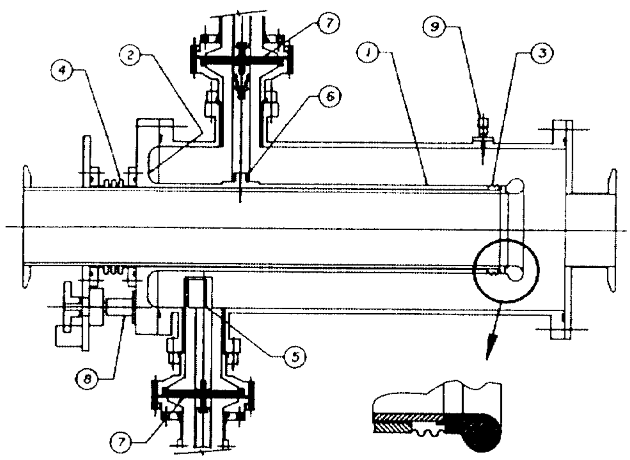

Figure 1. The 93 MHz cavity; (1) inner conductor, (2) shorting plate, (3) rf bellows, (4) vacuum bellows, (5) power feed loop, (6) connection to PIN diode switch, (7) ceramic window, (8) tuner power screw, (9) monitor probe.

The choice for R/Q of the cavity (R here is defined as V^2_{peak}/2Power) is driven by two considerations. First is that the bandwidth of the cavity must be greater than the power spectrum that is applied when the phase modulation program is on. This bandwidth is given approximately by Carson's rule, $BW=2f_m(1+\Delta)$, where f_m is frequency of phase modulation and Δ is the deviation in radians. This implies the bandwidth should be greater than 60 kHz, so the loaded Q must be 1500 or less. The second consideration is that gap impedance must be below the threshold for exciting a coupled-bunch instability in the beam. For this cavity frequency, the mode m=21 is dominant and it has a threshold value, Z/n < 220 Ohms. This sets the maximum value for R/Q at 40 Ohms. The R/Q for a TEM quarter-wave cavity is $(4/\pi)Z_o$, where Z_o is the characteristic impedance of the line. When the PIN diode de-Qing switch is added, the R/Q is reduced by the factor $[1 + 3(Z_o/Z)\sin^2(kl)]$, where Z is the impedance of the line to the switch, k is $2\pi/\lambda$, and l is the distance from the shorted end of the cavity to the point where the switch line connects to the center conductor. The factor 3 enters because the line is three quarter wave lengths long. The parameter l determines the Z/n when the cavity is de-Qed by the PIN diode switch. To obtain Z/n < 10 Ohms, l was taken to be 170 mm. The R/Q, then, for the cavity plus de-Qing switch is 38 Ohms. When the cavity is in the de-Qed state, the Q is reduced to less than 70, making the Z/n < 10 Ohms at the resonance frequency.

Power is fed into the cavity via a drive loop located near the shorted end. The loop has an area of 18 cm^2 and gives a coupling coefficient,[4] $\beta > 1$. The loaded Q is given by $Q_l = Q_o/(1 + \beta)$ and can be adjusted to the desired value of 1500 by rotating the loop to vary β. The power needed to achieve the required gap voltage is less than 10 kW.

The cavity is equipped with a mechanical tuner that can very the resonance frequency over a range of ± 300 kHz. This range is large enough to span the revolution harmonics of the AGS so that the cavity could, in principle, be used at any point in the cycle. The restriction mentioned above, of using only certain harmonics, or the need to use the cavity more than once per cycle, are added constraints that are satisfied by the specific choice of the center frequency. In order to keep the higher order mode spectrum of the cavity as simple as possible, the tuner was designed to not introduce a large perturbation on the cavity symmetry. The tuner functions by varying the length of the center conductor by ± 2.5 mm via a short copper bellows. The moveable end of the inner conductor is driven by a pipe connected to three power screws outside the vacuum space. The copper bellows is not a vacuum seal. Power dissipation in the bellows is negligible because the rf current is very low at the open end of the inner conductor.

The inner conductor and the shorting plate are made of OFHC copper and fused by electron beam welding. The outer conductor is made of mild steel and electroplated with copper. The cover plate at the gap end of the cavity is made of stainless steel. The demountable joints at the ends of the outer conductor are equipped with spring rings to make the rf connection and a metal O-ring for the vacuum seal The inner conductor is water cooled and the overall thermal design is such that the cavity could be operated continuously at 100 kV.

PIN Diode Switch

The PIN diode switch is connected to the cavity via a 3-1/8 inch EIA coaxial transmission line whose length is three quarter wave lengths at the operating frequency. For the high Q state, the switch is closed, making a short that is reflected back to the cavity as an open and does not load the cavity. For the low Q state, the switch is open. A 50 Ohm load is placed after the switch so that the cavity is heavily loaded at all frequencies by the 50 Ohms. The point where the line to the switch connects to the cavity was chosen to provide the necessary reduction in gap impedance when the cavity is not in operation. This point cannot be arbitrarily close to the gap because the rf current that flows in the switch when the cavity is in operation increases according to sin(kl) and can become excessive.

The switch is made from 48 MA-4P506 diodes (MA/COM Silicon Products, Inc.), arranged radially in the coaxial line. A short section of the outer conductor is d.c. isolated by bypass capacitors so that the bias voltage can be applied to control the rf conduction in the diodes. One hundred volts reverse bias is used to turn off the diodes and a forward current of 145 mA (per diode) is used to turn them on. A real diode is not, of course, a perfect switch. To study the effects on the cavity of a real diode switch, a computer program[5] was written that treats the cavity and switch as a circuit of transmission lines terminated with lumped impedances. Figure 2 shows the circuit models used for the diodes in the forward and reverse biased states. Values for the parameters of the models were obtained from the manufacturer's data sheets. Network analyzer measurements of the final assembled switch gave good agreements with calculations using these parameter values. Each diode will carry 4.1 A (rated maximum is 7.8 A) with 30 kV on the gap. The combined impedance of the open switch and the 50 Ohm load is (53 + j68) Ohms at the cavity, which gives the desired de-Qing of the cavity.

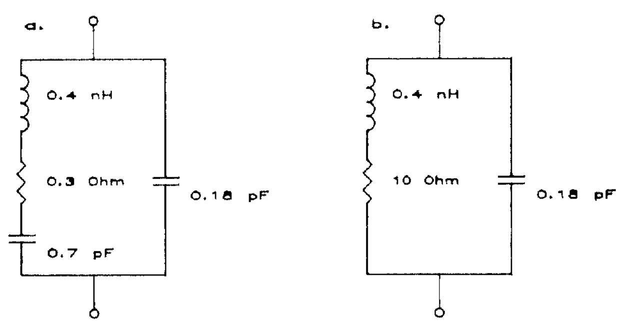

Figure 2. Circuit models of PIN diodes; a. reverse biased, b. forward biased. There are 48 such diodes in the switch.

RF Measurements

A full-scale cold model of the cavity was made using the final cavity inner conductor and an adjustable shorting plate with spring fingers and a dispensable outer conductor. The precise length for the inner conductor was found by moving the shorting plate. The range, resolution and backlash of the tuning mechanism were measured to be, ± 325 kHz, 88 Hz/step, and less than one step, respectively.

The R/Q was measured for the operating mode and several higher order modes by the perturbing bead-pull technique.[4] A 1/2-inch diameter bead of Al_2O_3 was used because the high dielectric constant improves the measurement sensitivity. The generator (HP8656A) frequency was locked to the cavity resonance frequency by a servo loop from the phase across the cavity. Data analysis was expedited by using the computational capabilities of the LeCroy 9400 digital oscilloscope. Figure 3 shows a typical R/Q measurement. Trace 1 is the position of the bead. Trace 2 is the frequency control voltage to the generator. Trace 3 is the square root of trace 2, which is proportional to the electric field at that position. Trace 4 is the integral of trace 3, which is proportional to R/Q. The proportionality constant is calculated from the speed of the bead (trace 1), the dielectric constant of the bead, and the frequency control constant of the generator.

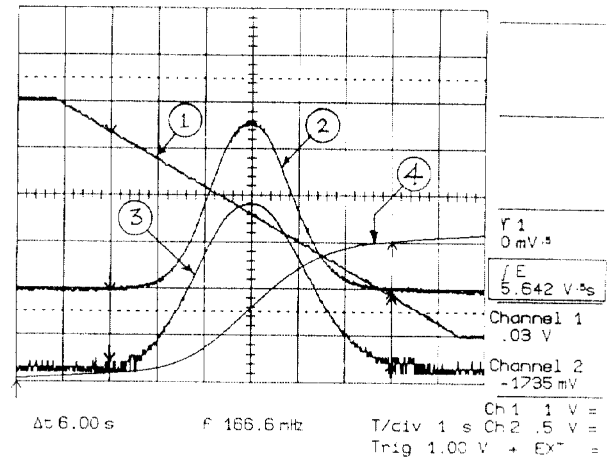

Figure 3. Digital oscilloscope display of bead-pull signals and computed results; 1. bead position, 2. frequency deviation, 3. electric field, 4. R/Q.

The R/Q of the bare cavity (no PIN diode switch) was measured to verify the validity of the technique for a case that is directly calculable. A SUPERFISH calculation gave 46 Ohms. The transmission line calculation mentioned above (when the measured length of the inner conductor was used to estimate the capacitive loading at the gap) gave 41 Ohms. The measured value was 42 Ohms. When the PIN diode switch was connected, the measured value was 32 Ohms. The transmission line calculation gave 37 Ohms.

A study of the higher order modes of the cavity is in progress at the time of this writing.

Conclusion

A 93 MHz harmonic cavity for use in the AGS to perform controlled blow-up of the longitudinal phase space has been designed, modeled, and tested. RF measurements show the design to be sound and compatible with the machine requirements. The construction of the final cavity is well advanced because a large fraction of the components of the final cavity were used in the model.

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