THE IPNS SECOND HARMONIC RF UPGRADE*

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Abstract

The Intense Pulsed Neutron Source (IPNS) rapid cycling synchrotron (RCS) is used to accelerate protons from 50 MeV to 450 MeV, at a repetition rate of 30 Hz. The original ring design included two identical rf systems, each consisting of an accelerating cavity, cavity bias supply, power amplifiers and low-level analog electronics. The original cavities are located 180 degrees apart in the ring and provide a total peak accelerating voltage of ~21 kV over the 2.21-MHz to 5.14-MHz revolution frequency sweep.

A third rf system has been constructed and installed in the RCS. The third rf system is capable of operating at the fundamental revolution frequency for the entire acceleration cycle, providing an additional peak accelerating voltage of up to ~11 kV, or at the second harmonic of the revolution frequency for the first ~4 ms of the acceleration cycle, providing an additional peak voltage of up to ~11 kV for bunch shape control.

We describe here the hardware implementation and operation to date of the third rf cavity in the second harmonic mode.

INTRODUCTION

IPNS was commissioned in 1981. With operational experience, it was quickly realized that the RCS was space-charge limited and the ring rf was voltage starved. Studies made in 1983 suggested the addition of a third cavity capable of operating at the second harmonic of the revolution frequency for the first ~4 ms of the acceleration cycle would lengthen the bunch and, thereby, increase the space-charge limit of the machine. In addition, it was proposed that the third cavity be capable of switching to the fundamental revolution frequency after capture and early acceleration, to provide additional fundamental acceleration voltage through the remaining acceleration cycle [1].

Because of budget and personnel constraints it was not until the late 1990s that IPNS was able to actually consider the addition of a third cavity. Design and construction of a new predriver amplifier for a third rf system began in 1998. Simulation studies performed in 1999 suggested that a 20 to 40 percent increase in the extracted beam current could be realized with the addition of a second harmonic system capable of operating over the entire frequency sweep [2]. Funding was not available to develop a full second harmonic cavity, but adequate spare parts were available to assemble a third cavity identical to the original two cavities. The three-stage power amplifier system, cavity bias supply and cavity were completed and installed in the RCS in late 2005 and early 2006. Operation in fundamental mode to full voltage as an integral part of the RCS rf system began in February 2006. Second harmonic mode was implemented in early 2006, and the third cavity was operated with beam in second harmonic mode in September 2006 with modest increase in beam on target. Since then, operation of the third cavity in the second harmonic mode has become the operational mode of choice. Work continues to implement the mid-cycle second harmonic to fundamental switch.

RCS RF SYSTEM DESCRIPTION

The original RCS rf system has been described elsewhere [3] as well as the third cavity upgrade [4], so only a brief description of the rf systems will be given here. Table 1 summarizes the operational parameters of the IPNS RCS.

Table 1: IPNS RCS Machine Parameters

Ring Cirumference	42.9m
Injection	H^-, multi-turn
Injection Energy	50 MeV
Protons Injected	~3.5 x 10^{12}
Injection Frequency	2.21 MHz
Extraction	Single Turn
Extraction Energy	450 MeV
Protons Extracted	~3.2 x 10^{12}
Extraction Frequency	5.14 MHz
Harmonic Number	1
Typical Average Beam Current	~15 µA

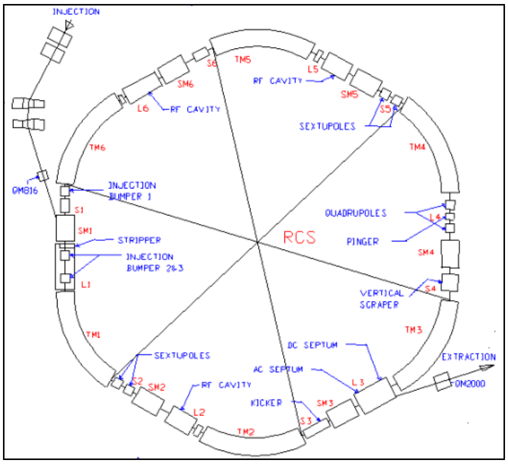

Figure 1: Schematic diagram of IPNS RCS.

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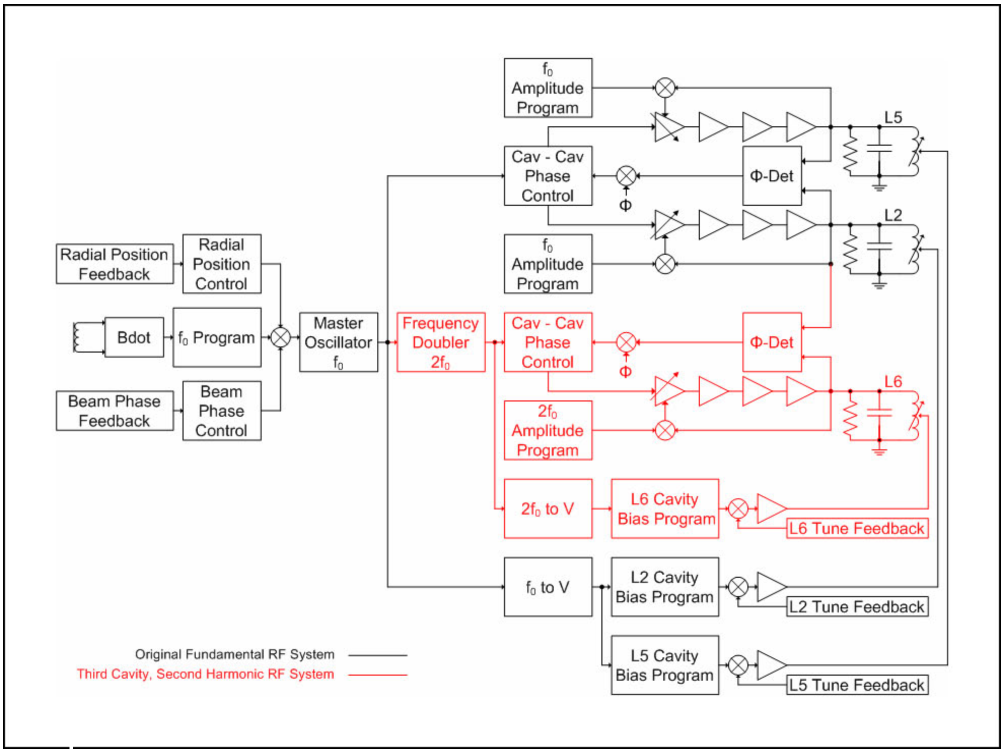

Figure 2: Block diagram of the IPNS rf system.

Cavities are located in the L2, L5 and L6 straight sections as indicated in Figure 1. Figure 2 shows a block diagram of the RCS rf system. Each rf system consists of a single-gap, ferrite-loaded, coaxial cavity and close-coupled final amplifier located in the ring, and a driver, predriver, solid-state line driver, and analog low-level electronics located outside the radiation shield. Variable DC current supplies (0 to 1000 A) coupled to the cavities via two parallel, single-turn, figure-eight, water-cooled bias conductors provide the required bias field for the ferrite to tune the cavities over the revolution frequency sweep.

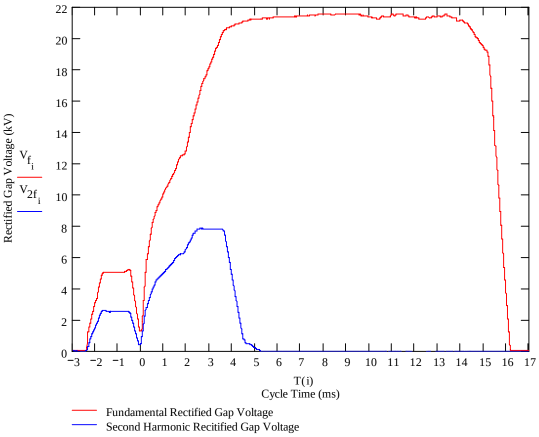

Figure 3: Rectified fundamental and second harmonic gap voltages.

Each cavity has cavity tune, amplitude, and cavity-to-cavity-phase control loops. The L5 and L6 cavities are phase controlled with respect to the L2 cavity. The L2 and L5 cavities share the same amplitude control program. The L6 cavity has an independent amplitude control program when running in the second harmonic mode. Figure 3 shows typical rectified fundamental and second harmonic gap voltages.

Although identical in function to the original rf systems, there are minor differences in the medium and high power hardware. The third-cavity predriver amplifier uses two Eimac YU-106 water-cooled power triodes in a grounded-grid, cathode-driven, push-pull topology and is operated in class A. Plate power is provided by a 5-kV, 4-A DC supply. At the typical operating point (V_{plate} = 5-kV, V_{grid} = +35-V), the tubes conduct ~1-A per tube of zero-signal plate current. The predriver has proven to be a highly reliable amplifier. Two additional predrivers are currently under construction to replace those in the L2 and L5 rf systems.

The third-cavity driver amplifier is identical to the driver amplifiers in the L2 and L5 rf systems. It uses two Eimac 4CW25000A water-cooled tetrodes in a grid-driven, push-pull topology and is operated in class A. Plate power is provided by a 5-kV, 10-A DC supply. At the typical operating point (V_{plate} = 5-kV, V_{screen} = 1.5-kV, V_{grid} = -300-V) the tubes conduct ~3-A per tube of zero-signal plate current.

The third-cavity final amplifier uses two Eimac 3CW150000H3 water-cooled power triodes in a grounded-grid, cathode-driven, push-pull topology and is operated in class A. Plate power is provided by a 8-kV, 24

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A DC supply. At the typical operating point V_{plate} = 8-kV, V_{grid} = -320-V) the tubes conduct ~5-A per tube of zero-signal plate current.

Inputs and outputs on the predriver and driver amplifiers and the inputs on the final amplifier, are transformed to 50-ohms, making troubleshooting convenient with readily available 50-ohm instrumentation.

RESULTS

Best operation for capture and initial acceleration is with the second harmonic at approximately zero phase relative to the fundamental (physically, the L6 cavity is 240 degrees around the ring from the reference cavity L2) and with the second-harmonic to fundamental voltage amplitude ratio equal to approximately 0.5. This agrees well with simulations [2]. Single-turn fundamental and second harmonic voltages, and the vector sum, at ~1.8 ms after injection, are shown in Figure 4.

Figures 5 and 6 show pie electrode-derived bunch profiles at ~1.8ms after injection with and without second harmonic, for equal injected charge. A modest increase in the bunch length can clearly be seen.

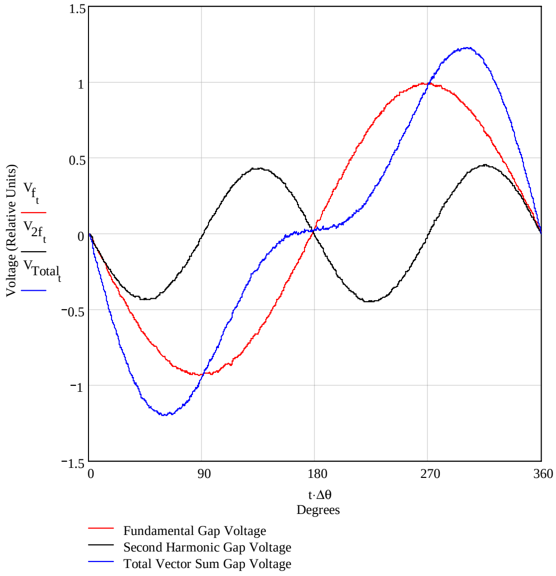

Figure 4: Single turn, vector sum of the gap voltages.

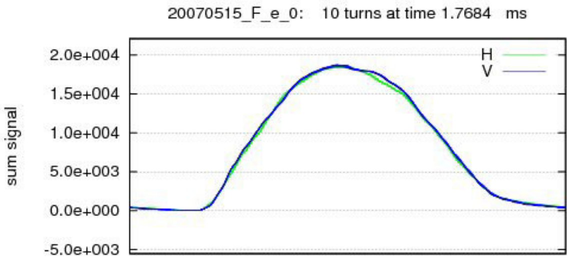

Figure 5: Bunch profile without second harmonic cavity.

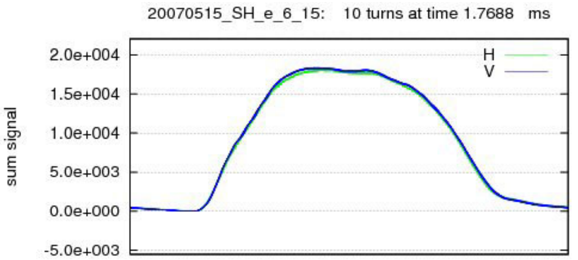

Figure 6: Bunch profile with second harmonic cavity.

A current-dependent instability in the RCS is the primary factor limiting the charge-per-pulse level at which the RCS can be operated [5]. The addition of second harmonic during the capture and initial acceleration phase presently increases the stability threshold nearly 10 %. The details of how it does this are being studied.

SUMMARY

The addition of the third cavity, operating in the second harmonic mode for the first ~4 ms of cycle time, has provided modest increases in the bunch length. Work continues to implement the ability to switch from second harmonic mode to fundamental mode mid-cycle.

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