ACCELERATOR RESEARCH ON THE RAPID CYCLING SYNCHROTRON AT IPNS*

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INTRODUCTION

The Rapid Cycling Synchrotron (RCS) at IPNS is a six-period combined function synchrotron with a magnet structure of D00FDF0 which was commissioned and demonstrated operation up to $1x10^{12}$ protons/pulse in 1979[1]. Operation was intermittent over the next couple years during which the extraction was changed to provide beam to the present IPNS target. Initial attempts to increase the charge/pulse in 1981 were limited by a head-tail instability that had a threshold just under $1x10^{12}$ protons/pulse. Tune measurements revealed that the horizontal chromaticity became slightly positive near the end of the acceleration cycle. The trim-sextupole power supplies were changed from dc to programmable to adjust the chromaticity, allowing an intensity increase to $2x10^{12}$ protons/pulse[2]. Limited experiments of adding 2^{nd}-harmonic rf to spread the bunch longitudinally were performed in early 1983 and it was proposed to add a 3^{rd} rf cavity to improve beam handling as a route to higher charge per pulse[3]. Between 1983 and 1985, improvements to control loops[4] and the introduction of a cavity-to-cavity phase modulation (PM) or "scrambler" to broaden the bunch longitudinally[5] provided another intensity increase to slightly greater than $3x10^{12}$ protons per pulse.

Funding problems prevented development of a third rf cavity and the "scrambler" proved a low-cost cure to the instability threshold at $2x10^{12}$ protons/pulse. Thus by 1985, the RCS had reached its original design goal of operating at $3x10^{12}$ protons pulse. Funding constraints indefinitely postponed further attempts to get closer to the RCS's space charge limit for a uniformly distributed beam of $5.6 x10^{12}$ protons/pulse.

Funding for U.S. DOE user facilities improved in the late 1990's and operational imperatives at IPNS changed from year-to-year survival to ensuring operation for the indefinite future with ever-increasing scientific capabilities.

Neutron-scattering instrument improvements offered the most cost-effective route to significant gains, several of which have achieved data-rate increases of more than a factor of ten through adding detectors, neutron guides and other enhancements. For the accelerator system the goals were more modest, increase beam-on-target by increasing operating time (to ~ 30 weeks/year) and increase protons/pulse while maintaining or improving reliability. Initially, the emphasis had to be on updating or replacing those subsystems that were becoming obsolete (spares no longer available or nearing end-of-life) and controlling losses so that operating hours could increase without increasing the activation of components. Calculations[6] showed that improving synchrotron rf system capabilities could reduce beam losses, and had the further advantage of providing redundancy to improve reliability. Thus, fifteen years after the original proposal, work started on a third rf system[7] for the RCS. More recently, improvements in diagnostics and better computer modeling have let us take a more detailed look at what limits the charge-per-pulse in the RCS and begin studies to increase the threshold current of the instability.

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THIRD RF SYSTEM

The third rf cavity is installed in the L6 straight section of the RCS (see Fig. 1), replacing a set of vertical scrapers that proved redundant to the vertical scrapers in the S4 straight section.

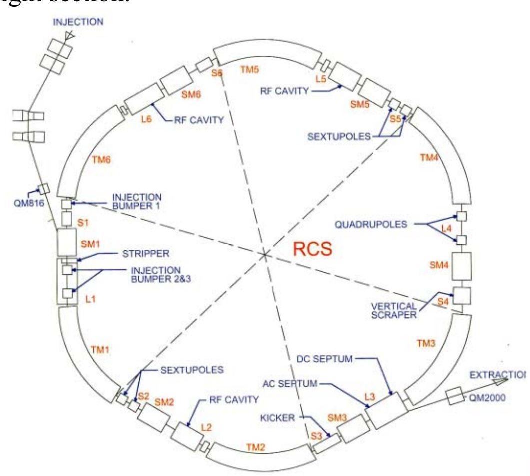

Figure 1: IPNS Rapid Cycling Synchrotron Layout

Installation was completed during the two-month shutdown that ended in early February 2006, and initial beam experiments with it began in mid-March. The cavity ferrite limits the maximum frequency to about 6 MHz. The present plan is to operate the 3^{rd} cavity at the 2^{nd} harmonic for capture and initial acceleration (<4 ms), then switch it to the fundamental frequency for additional fundamental rf during the middle of the acceleration cycle when acceleration requirements are greatest. To date, it has only operated in the fundamental mode because the low-level rf changes for dual-mode operation are still being developed. Having the third cavity increases the available gap voltage per turn to over 32 kV (up from the previous 21.5 kV of the original two cavities). Preliminary tests seem to show that additional fundamental rf is not in itself a replacement for the "scrambler." Additional fundamental plus "scrambler" has not proven statistically superior to "scrambler" alone although it appears marginally better at controlling losses when operating just below the stability threshold.

IMPROVED DIAGNOSTICS

Horizontal and vertical pie-electrode diagnostic devices are located in several of the RCS straight sections. The electrodes behave as short striplines giving a signal proportional to di/dt. Data from these can be digitized using a fast oscilloscope to give position information. An FFT analysis of this data then yields the fundamental bunch frequency and sideband information from which the betatron tune can be obtained. Sideband data can also be used to infer the onset of an instability as will be discussed later. A recently installed pinger magnet system[8] can give small horizontal and vertical kicks (fractions of a milliradian) to the beam at any desired time in the acceleration cycle, setting up betatron oscillations that can be detected and analyzed from the pie-electrode signals. They provide a convenient method to measure tune and chromaticity.

RESULTS

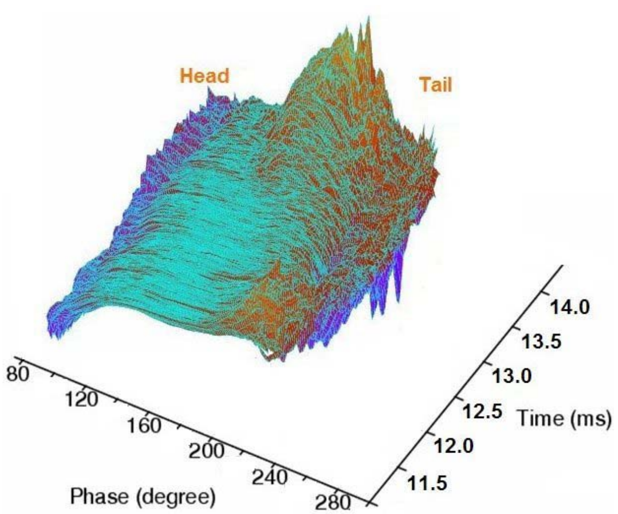

Figure 2: Position data from vertical pie electrodes showing vertical motion over the length of the bunch during the final quarter of the acceleration cycle.

We have earlier reported [9] data on how the "scrambler" tends to suppress the instability by setting up a quadrupole oscillation that increases the rms momentum spread in the charge bunch. Beginning in late 2005, we modified our operating schedule to include several additional days for machine research each month, with the aim of first characterizing the RCS and then moving on to find ways to overcome the instability. The instability has to date limited peak accelerated current to about 3.2 x 10^{12} protons per pulse, little changed in the last 15 years. Figure 2 shows an analysis of vertical pie-electrode data during the latter third of the acceleration cycle when the charge-per-pulse is above the stability threshold and the "scrambler" is turned off. The head of the bunch appears to be relatively stable, while the tail of the bunch oscillates vertically. As charge-per-bunch increases the sidebands and tail oscillations continue to grow until the bunch is hitting the chamber walls. When this happens the tail is lost, leading one to observe a shortening of the longitudinal bunch length. The early tune data reported was taken when the RCS extraction energy was 500 MeV and the acceleration cycle lasted 16.3 ms (injection at B_{min} and extraction at B_{max}). Since early 1982 we have operated with a peak magnetic field corresponding to about 470 MeV and have extracted almost 2 ms before B_{max} at an extraction energy of 450 MeV (injection to extraction period of ~14.5 ms).

Tune measurements were not repeated when the operation changed, and the sextupoles have been "tweaked" empirically over the years to give minimum losses and maximum stability. Over the last few months, we have remeasured the tunes to compare with the earlier data and to see if we had reasonable matches with our modeling codes. Horizontal and vertical chromaticity versus time in the acceleration cycle is shown in Figure 3. Vertical chromaticity is negative throughout the cycle, but approaches zero at about 9 ms after injection.

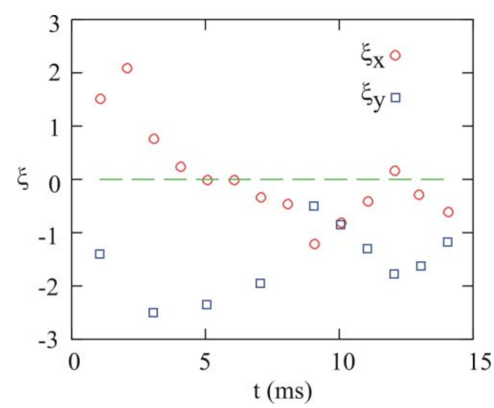

Figure 3: Horizontal and vertical chromaticity over the acceleration cycle.

Horizontal chromaticity starts off positive but then goes negative at about 6 ms. However, it again goes positive at about the 12 ms point, a couple of ms after the "scrambler" begins its work. It's possible that we have tuned ourselves back into the condition for a head-tail instability that Cho and Rauchas[2] cured 25 years ago. If so, the new threshold is at a charge-per-pulse that is higher than that reached after their fix.

The sextupole power supplies do not have sufficient capacity to make large negative changes to the x-chromaticity, ξ_x at 12 ms, but we were able to increase the current from the nominal 82A to 99A which can be seen in Figure 4 to change the x-chromaticity from +0.02

to -0.65. This had no significant effect on the peak current we could accelerate. We found cases where changes to both horizontal and vertical chromaticitys could lower the threshold.

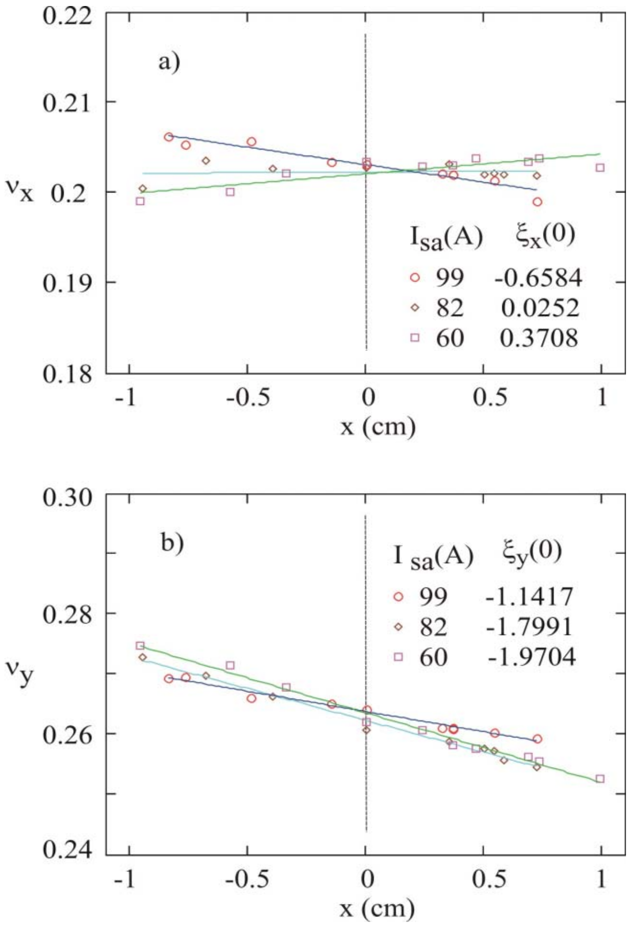

Figure 4: Horizontal and vertical betatron tunes at 12 ms in the acceleration cycle

FUTURE PLANS

To date in our chromaticity studies we have been able to make changes that significantly lower the instability current threshold (to below $1x10^{12}$ protons/pulse), but have been unable to increase it. We are now in the process of modifying the sextupole power supplies to provide higher output to permit more systematic studies of the effect chromaticity on the threshold level. We are also proceeding with changes to the low-level rf controls with the aim of using second-harmonic rf to help shape the beam pulse at injection and provide more fundamental rf at the mid-point in the acceleration cycle.

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