APS Storage-Ring RF System Capabilities And Preparation in Support of 200mA/10.5MV User Operation

10/13/08

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This document outlines the present capability of the APS storage-ring RF systems to support routine 200mA user beam operation at a total gap voltage of 10.5MV, with available options for optimizing rf system performance and reliability. Available rf system operating modes for 200mA/10.5MV operation will be discussed, and the impact on overall rf system reliability for various modes of operation will be estimated. Recommended measures to improve and insure consistent overall rf system reliability will be provided.

I. RF Power Requirements to Support 200mA Operation

Using data from past high-current runs as a guideline, shown below are estimates for rf power required to support 200mA operation at 10.5MV total rf gap voltage:

→ Total rf power required ≈ 2.32MW

→ Total rf power to beam ≈ 1.44MW

→ RF power per cavity ≈ 145kW

→ RF power at injection ≈ 55kW/cavity

II. Available Operating Modes

Past operating experience has shown that the maximum stored beam current possible with single-ended operation (two klystrons operating into eight cavities each) is approximately 150mA, assuming a total rf gap voltage of 9.4MV. Under these conditions, each klystron would be operating at approximately 1MW CW output power, with the klystrons, power supplies, and AGC control loops near the end of their dynamic range. Therefore, 200mA operation would require at least two klystrons operating in parallel mode driving two sector pairs (eight cavities). Compatible rf operating modes in the 420 waveguide switching system that fulfill this requirement are shown below, with details:

a) <u>RF1/RF4 and RF2/RF3 in parallel mode, each station at ~ 600kW output power</u>
   → RF Test Stand down
   → No redundancy for RF5

b) <u>RF1 single-ended at full power, RF2/RF3 in parallel mode</u>
   → RF Test Stand down
   → RF4 down
   → No redundancy for RF5

c) <u>RF2 single-ended at full power, RF1/RF4 in parallel mode</u>
   → RF Test Stand down
   → RF3down, or available for Booster

d) <u>RF3 single-ended at full power, RF1/RF4 in parallel mode</u>
   → RF Test Stand down
   → RF2 down
   → No redundancy for RF5

e) <u>RF4 single-ended at full power, RF2/RF3 in parallel mode</u>
   → RF1 down, or available to power the RF Test Stand
   → No redundancy for RF5

Of the five operating modes available, mode "a" above is the preferred mode, as it would allow the klystron power outputs to remain balanced at the present operating level of approximately 600kW each. While modes "b" through "e" are all possible alternatives, the single-ended rf stations in these modes would be required to operate at full power (~ 1-1.1MW). This would have a negative effect on reliability and would most likely require occasional testing and conditioning periods to verify that each rf station is capable of full-power operation as the klystrons age. Sustained operation of the 352-MHz CW klystrons at 1MW will reduce their average life expectancy considerably, possibly reducing it to the previously-recognized 30,000-hour useable life. This would increase the burn rate of spare klystrons, which may trigger the purchase of more spares sooner than expected.

It is also very important to point out the fact that operation of the 350-MHz RF Test Stand during 200mA operation is severely limited unless operating mode "e" is used, as RF1 is presently required to supply rf power to the test stand.

III. Effect on Present RF System Reliability

For this analysis, the rf systems will be divided into two discrete parts, [1] the individual rf stations up to and including the circulators, and [2] the rf cavities and associated waveguide.

The rf stations themselves are all designed for and capable of producing 1-1.1MW CW rf power output. As a general rule of thumb, operation of the rf stations below approximately 700kW requires less attention to critical parameters. Routine operation of each rf system at power levels of 800kW and above will require optimization of many operating parameters relating to the klystrons, such as cathode voltage, heater power, and rf drive power, and will also result in increased stress on the power supplies and circulators. I roughly estimate that our routine downtime would increase by approximately 0.5% to 2% under full-power operating conditions. Therefore, it is expected that rf system reliability will be optimized if all four storage-ring rf systems are utilized in parallel mode to support 200mA operation (operating mode "a" above).

Utilizing RF1-RF4 for routine storage ring operation will reduce the degree of redundancy built into the 420 Waveguide Switching System in the event one rf station becomes inoperative. For instance, RF3 would be available to back up RF5 in Booster service only in mode "c", and all rf stations will need to be capable of trouble-free operation at full power for modes "b" through "e" to be available. However, the expected overall effect on reliability due to this loss of redundancy is relatively low, based on the number of times that we have actually needed to switch rf systems to maintain operation in the last couple of years. I estimate that we require on average three waveguide switches per year to maintain operation after a non-recoverable rf system fault at the rf station level, with each switch requiring approximately one hour of downtime. Assuming 4,558 hours of operation per year, downtime related to three waveguide switch operations is 0.065%.

Assuming constant operation of RF1-RF4 in parallel mode to support operation (mode "a"), downtime as a result of three non-recoverable rf system faults per year is estimated at approximately 30 hours. Again, assuming 4558 hours of operation per year, downtime related to three non-recoverable rf system failures per year is 0.658%.

Based on these estimates, it is expected that the average rf system downtime will increase by approximately 0.6-0.8% when RF1-RF4 are used in parallel mode to support operation. This estimate assumes that rf system faults are efficiently diagnosed and repaired, which will require adequate manpower and spare parts support.

The impact on reliability at the rf cavity and waveguide level is expected to be a dominant contributor to the decrease in overall rf system reliability. It is well known that the weakest component in the rf cavity system is the input coupler, which has a generally-accepted maximum rf power capability of 100kW under matched conditions. Therefore, it is estimated that operation at the higher power levels required for 200mA operation will increase rf downtime by approximately 2-3% annually if no steps are taken to reduce stress on the couplers.

If the rf systems are utilized as-is to support 200mA/10.5MV operation, the combined estimated increase in downtime due to all of these factors would be approximately 2-4%.

NOTE: The 350-MHz RF Test Stand presently utilizes RF1 as a source of rf power, and only mode "e" (RF4 single-ended, RF2/RF3 in parallel mode) makes RF1 available to power the test stand. This restriction will affect both operations reliability and our ability to develop and condition spare parts for the rf cavities. This will increase the risk of significant downtime in the event we suffer an abnormally high number of coupler, tuner, or HOM damper failures.

IV. Five-Year Plan Options to Maintain Reliability and Performance at 200mA/10.5MV Operation

Reducing the potential for increased downtime is the dominant requirement in preparation to support routine 200mA operation. Several options are considered to achieve this over the next five years:

1. <u>Maintain rf system design as-is, and routinely condition the cavities to increased power levels required</u>.

   This action would call for conditioning all cavities to ~ 65-70kW/cavity coming out of all shutdowns, and also require that we build up our spare coupler supply in anticipation of increased coupler failures. We would require approximately five days of extra conditioning time per start-up, and an additional $50-$75k per year of additional funding to produce more spare couplers. ***An increase in downtime due to coupler failures should be assumed.***

2. <u>Re-design of cavity input couplers to provide more power handling capability</u>.

   Develop a new coupler of more robust design that would be capable of sustained 150-200kW input power under poorly-matched conditions. I roughly estimate the cost of developing the first article of a new coupler design at approximately $200k. The expected cost of producing 20 units of the new design is $500k. The new couplers could be installed one sector at a time per shutdown, thereby completing the installation in approximately 15 months. The total cost of this action is estimated at approximately $800k. ***To meet the 5-year timetable, work on this action should begin immediately.***

3. <u>Modify all cavities to use two input couplers</u>.

   Based on the results of the Two-Coupler Test, the existing storage ring cavity and related components are capable of 200kW CW operation if the input power is delivered to the cavity utilizing two input couplers properly phased. I roughly estimate the cost of installing the "two-coupler" configuration on all sixteen storage- ring cavities at $1.6M. ***This action would require significant downtime to implement. Work on this action should begin sometime in FY09 to meet the 5-year timetable.***

4. <u>Add one additional feedback card channel to the "slave" rf stations to improve phase noise performance</u>.

   Operational tests of the parallel-klystron configuration at APS indicates that the amplitude of 360-Hz phase noise sidebands on the output of the combined rf stations is approximately -30dBc, which is 20dB higher than levels when the rf stations are operating in single-ended mode. This increase in phase noise occurs because the power-phase loop at the slave station in each parallel-pair is utilized for phase control of the parallel station outputs, leaving the slave station to operate without a functioning power-phase loop. ***This condition can be corrected by installing an additional feedback card at RF3 and RF4 to provide a separate power-phase loop. The cost of this action is estimated at $15k.***

5. <u>Development of turn-on scripts to provide fast rf system recovery by operations</u>.

   Operational experience with the parallel-klystron operating mode indicates that re-start of the rf systems is significantly more complicated than in single-ended mode. Therefore, it will be necessary to develop and implement start-up scripts for the rf systems that will allow the operators to restore injection-level rf system operation in a timely fashion. It is estimated that implementing this action would require approximately six months of script development and study time to verify correct operation.

6. <u>Develop a new HOM damper design as soon as possible to enable implementation at the end of five years in the event dampers prove necessary for storage ring beam stability</u>.

   *The installation of effective HOM dampers on all storage ring rf cavities may be required to guarantee beam stability at currents greater than 103mA and over the entire range of possible fill patterns. Effective dampers may also reduce the stress on the rf system components by preserving beam stability at lower total rf gap voltage**. It is recommended that development of a new HOM damper design be started as soon as possible to enable implementation of HOM dampers on all storage ring cavities within 5 years. The estimated cost for this effort is $1.125M.***

   NOTE: A funding request for development and implementation of new HOM dampers is presently submitted under a separate project proposal.

7. <u>Begin work as soon as possible to find and implement a replacement for the now-obsolete LAND IR meters presently used to monitor coupler ceramic temperatures</u>.

   The ability to monitor the temperature of coupler ceramics is a critical diagnostic tool, and the LAND IR meters presently used for this application are obsolete and *no longer available. Work should begin as soon as possible to find a replacement unit and implement it.* ***The estimated cost for this effort is $100k***.

8. Develop and implement fast vacuum interlocks on the storage ring power monitor systems to increase the survival rate of input couplers during vacuum and arcing events.

   It is felt that removing rf power as fast as possible at the first sign of high pressure in an rf cavity is crucial to preventing irreversible damage to input couplers. ***Work should begin immediately to develop a re-design of the present vacuum rf interlock system to increase the speed of the interlock response, and implement the re-design as soon as possible. The estimated cost for this effort is $50k.***

9. Develop and implement the use of our existing arc detectors to detect light inside the cavities as a way to prevent coupler damage during vacuum and arcing events.

   Optical detection of arcs at power couplers is recognized as one of the most effective ways to prevent irreversible damage to rf power windows due to the very fast reaction time to the detection of arcs. Work should begin immediately to investigate the feasibility of using this method to protect the storage ring cavities, and implement a system that proves to be functional and reliable. The estimated cost for this effort is $60k

V. Recommended Course of Action

Operating experience with the storage-ring rf systems indicates that the dominate failure modes related to operation at 200mA/10.5MV are associated with the cavity couplers and not with the rf stations themselves. Based on reliability, cost, and schedule considerations, I recommend the following plan to provide reliable operation at 200mA/10.5MV:

1. The preferred mode of operation is RF1/RF4 and RF2/RF3 in parallel pairs.

   → *It should be recognized that four other operating modes exist that would also support 200mA/10.5MV operation and do provide rf system operational redundancy, but at reduced rf system reliability and component lifetime.*

2. Start an aggressive program to design a new cavity input coupler that will reliably operate at 150-200kW input power and implement the new design as soon as possible.

→ *This is the most cost-effective approach to improving the robustness of The rf systems where it is needed most. It also requires minimum dark time to implement.*

→ ***Estimated Cost = $800k***

3. Begin conditioning the existing input couplers to higher power levels, and step-up production of spare couplers.

→ *This step will be necessary to prepare for routine 200mA/10.5MV operation, and provide increased headroom against damage with the existing couplers until a new coupler design is available and ready to implement.*

→ ***Estimated Cost = $100k***

4. Develop control scripts for auto-startup of the storage-ring rf systems when in all five applicable parallel modes.

→ *This step will be necessary to prepare for routine 200mA/10.5MV operation.*

5. Install additional feedback cards in RF3 and RF4 in order to improve the Nx60Hz phase noise levels when operating in parallel mode.

→ *This step will be necessary to reduce 360-Hz phase noise on the rf voltage to specified levels when operating the rf systems in parallel mode.*

→ ***Estimated Cost = $15k***

6. Schedule and perform sufficient beam studies in RF1-RF4 parallel modes to better understand and optimize system performance in each mode.

→ *This step will be necessary to prepare for routine 200mA/10.5MV operation.*

7. Make the 350-MHz RF Test Stand autonomous so that it does not need to rely on RF1 for dc input power.

→ *This step is crucial to preserve our ability to develop and test new high-power rf components such as cavities, input couplers, tuners and HOM dampers. The ability to operate the test stand independent of operations is absolutely necessary for work relating to high-power components to progress at an acceptable rate.*

→ *This step will allow full-power testing of spare APS klystrons into the 1MW rf test load independent of storage ring operations.*

→ *This step will require construction of a dedicated dc power supply for the test stand rf power system so that reliance on RF1 is no longer required. The present configuration of the test stand rf system design includes a 350-MHz/1MW CW klystron amplifier, and a dc power supply capable of producing up to 95kV@20A would be required to operate the klystron at full power.*

→ ***Estimated Cost = $1M***

<u>ESTIMATED TOTAL COST</u> = $1.915M