VACUUM AND MULTIPACTOR PERFORMANCE OF THE HERA 52 MHz CAVITIES

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Abstract

The HERA 52 MHz rf cavities must achieve the low operating pressures of the HERA proton storage ring, and stably provide accelerating voltages which will vary during the acceleration/storage cycle from 15 to 150 kV. This paper reviews material choices, treatment, cleaning, assembly and surface preparations that have resulted in achievement of those operating goals. Computer simulations, helpful in establishing those zones in the cavity most likely to be susceptible to multipactor, are also discussed, as are the vacuum and rf conditioning processes.

Introduction

Two 52 MHz radio frequency (rf) systems, including cavities and control systems, for the acceleration of protons in the main HERA ring were fabricated and tested at Chalk River Nuclear Laboratories (CRNL) as part of a contribution from Canada to the construction phase of HERA. Both systems have been delivered and installed in the ring at DESY in Hamburg, West Germany[1-3].

Specifications for the 52 MHz systems call for a total circumferential voltage range of 30 to 290 kV, or 15 to 145 kV per cavity, during capture and acceleration cycles. The high electric fields in the gap region precluded the use of a ceramic window as a vacuum envelope on the beam line and led to a choice of an evacuated cavity design. Beam lifetime in the storage ring can be in excess of ten hours, which requires vacuum pressures in the ultra-high vacuum regime. Careful attention was given to this requirement during all aspects of the design and fabrication of each of the cavities, which were fabricated entirely of aluminum alloy and feature large volumes and surface areas. Special treatment of the aluminum surface was necessary because the secondary electron yield coefficient of aluminum oxide is greater than one and this, coupled with the cavity geometry, supports resonant electron current or multipactor. Areas predicted to be problematic by the computer code NEWTRAJ[4] were flashed with titanium to lower the emission coefficient in these areas to less than one. Attempts to operate one of the cavities without the surface treatment failed.

Initial evacuation of the cavities yielded a higher than expected base pressure but the cavity had been exposed to air on several occasions after the final chemical cleaning. A subsequent moderate bakeout brought the pressure closer to that calculated for the installed pumping speed. Base pressure continued to drop with extended high-power rf conditioning cycles.

Design and Fabrication

The cavities were modelled after the Fermilab Debuncher ring rf system[5]. Figure 1 illustrates the basic outline of the cavities, which may be considered as back-to-back half-wave resonators loaded by an intermediate cylinder supported on a post at the zero-field symmetry point (TM-010 mode). The cavities were fabricated from aluminum alloy 6061-T6, which was considered a good compromise of material strength, electrical and thermal conductivity, vacuum characteristics, machining and welding characteristics, and residual activation similar to that of other materials in the HERA installation.

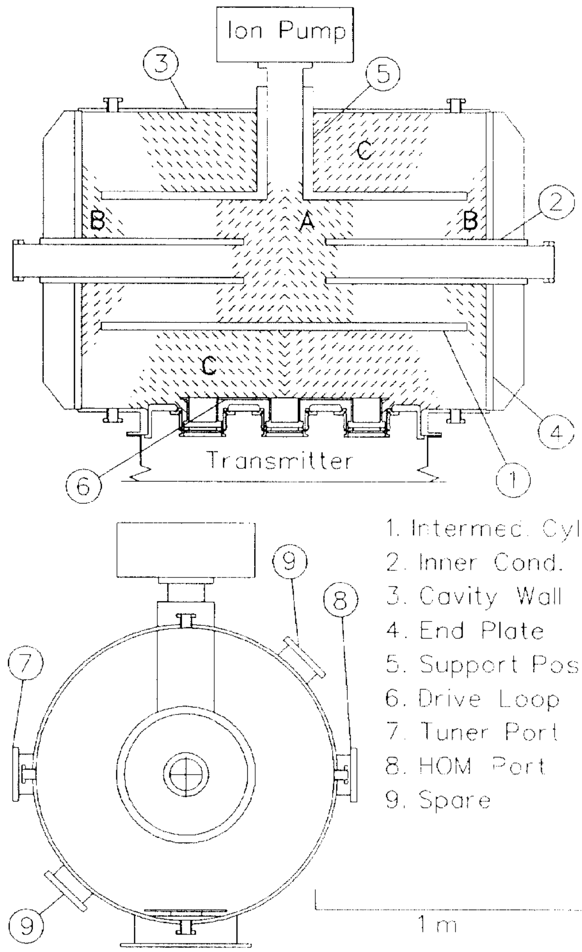

Fig. 1 Outline of HERA 52 MHz cavity. Areas A, B, and C indicate titanium deposition.

All joints are welded by the gas metal arc welding process and all welds are internal, with the exception of the end plate to cavity wall joints, the last welds to be done. The end plates have a protruding lip where they mate to the cavity wall. Here, multiple radial grooves are machined to vent trapped gases and provide good electrical joints, over which the rf current must pass. The intermediate cylinder and the inner conductor are double wall assemblies with the annulus between the walls vented to atmosphere. Aluminum cooling tubes are clipped to the walls within the annulus to avoid a water to vacuum interface. Attempts to solder the cooling tubes failed as the fluxes and active ingredients in the soldering alloys led to stress cracking on the cold-rolled aluminum surfaces.

Each cavity has five large ports with eight inch conflat flanges. Aluminum conflat flanges with titanium nitride coating on the sealing surface were used as they could be welded directly to the cavity wall. These ports are used for the tuner and higher-order mode damper coupling loop feedthrough assemblies, and the vac-ion pump. Two spare ports provide flexibility for adding additional components and access to the interior of the cavity. Four small ports on each end of the cavities provide access for rf probes, vacuum gauges and diagnostic equipment. Three rf drive loop ports are complex assemblies that allow for adjustment of the loop penetration into the cavity. Standard conflat flanges could not be used here, so specially designed flanges and helicoflex seals were employed.

The cavity fabrication was performed by CRNL workshops under tight quality control. Difficult weld joints were mocked up with test pieces to determine optimum weld preparations and procedures. Each weld was individually helium leak checked, by means of specially fabricated test assemblies, on a helium leak detector on the 10^{-8} Pa L/s scale, with the test joint flooded with a helium atmosphere (bag method) for at least 15 minutes. Sub-assemblies and final assembly were re-tested in a similar fashion. No vacuum leaks were found on any weld joints on either of the two cavity assemblies.

Immediately prior to welding the end plates to the cavity, the entire structures were wiped with an abrasive pad (3M Scotchbrite Pads) to remove gross deposits, and then cleaned with a degreasing agent. The cavities were then washed with a caustic solution to remove fatty based oils, an acidic solution to remove oxides and, finally, another weak caustic solution to neutralize the acid residue. The structures were then flushed thoroughly with clean water, wiped with alcohol and blown dry with dry nitrogen. The cavity ends were then installed and further exposure to air was minimized.

Vacuum System

Vacuum pressure in the cavities must be comparable to the vacuum in the rest of the storage ring, in order that there be no detrimental effects on the beam due to gas loading in the cavity sections. The design goal was to achieve a base pressure in the low 10-7 Pa range or better.

Assuming no vacuum leaks, the main gas load on the vacuum system will be thermal desorption from the large surface area, which exceeds 12 m^2 per cavity when all internal components are considered. Under ideal conditions and with careful baking procedures, outgassing rates of less than 10^{-10} Pa L/s/cm^2 should be achieved. During development tests, ideal conditions are not a reality, as the cavities are frequently vented and internal components often have to be handled or repaired, after which proper cleaning is not possible. A thorough bakeout is difficult because the large thermal mass and low thermal conduction paths to internal components complicate temperature control and monitoring. The strength of aluminum decays rapidly beyond 180°C, so it is important not to create hot spots that might cause the aluminum to collapse under vacuum loading. It is expected that most improvements in pressure will come with long-term rf conditioning and heating.

The installed pump is a 400 L/s Varian Star Cell vac-ion pump. The pumping speed for hydrogen is higher in this type of pump than a normal triode pump, and it has the option of adding non-evaporable getter units, which roughly double the pumping speed. The calculated pumping speed (for ideal conditions) required to reach a base pressure of 10^{-7} Pa is 125 L/s. During the developmental stage, the system was roughed out with a combination of rotary vane, sorption, and 150 L/s turbo pumps.

On initial pumpdown, the base pressure was $6.5*10^{-4}$ Pa and after baking the cavity at about 120°C for 24 hours the base pressure was reduced to $4*10^{-6}$ Pa. The cavities were then conditioned with rf, during which time large pressure transients were observed, particularly when attempting to break through multipactor. After conditioning, the cavities were subjected to about 100 hours of uninterrupted operation at close to full power (20 kW). During this time, the outside wall temperatures reached 60°C and internal components such as the coupling loops were suspected to be at temperatures much higher than this. During the extended high-power operation, pressure in the cavities approached $1.3*10^{-5}$ Pa and continued to decline slowly but steadily. Base pressure with the rf turned off was 10^{-6} Pa, probably limited by a small valve leak discovered during disassembly for shipping. All pressures were determined from ion pump current conversions.

Multipactor and RF Conditioning

Multipactor problems were anticipated from the outset of the cavity design. Aluminum oxide has a secondary yield coefficient greater than 1.5, the exact value depending on layer thickness and other factors. A substantial oxide layer would have formed on the aluminum surfaces and the secondary yield coefficient could be closer to 3 or 4. This, combined with the complex cavity geometry and electromagnetic field distribution, leads to a high probability for multipactor.

The computer code NEWTRAJ simulates the resonant electron discharge phenomena in resonators and predicts areas of strong resonant discharge under particular cavity conditions. This code has been used previously to predict problematic areas in cavities similar to the HERA cavities and has influenced cavity designs to overcome multipactor problems. The code solves the equation of motion of a charged particle in the rf fields in the cavity. The trajectory of the particle is computed and the probability of production of further backscattered particles is calculated for each impact with a surface. Figure 2 illustrates a typical plot for the HERA cavities for a gap voltage of 7.4 kV and a conservative 1.5 yield coefficient. An area of high probability of multipactor can be assumed where there are multiple overlapping paths or an increasing production rate of secondary particles.

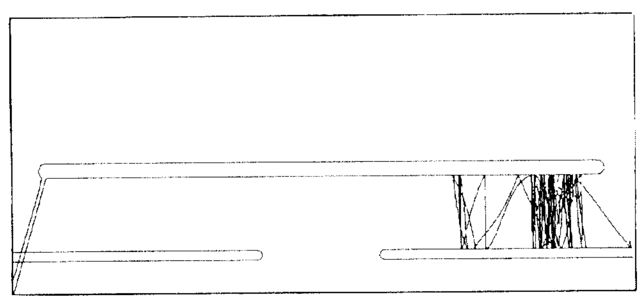

Fig. 2 Half-section model of HERA cavity showing resonant trajectory for V_{GAP} = 7.4 kV.

Multiple plots were produced for the cavities representing various conditions. As suspected, the areas between the inner conductor and the intermediate cylinder and the end walls around the intermediate cylinder were predicted as problematic for gap voltages from 5 to 35 kV, and the planned solution was to reduce the secondary yield in these areas by flashing titanium on these surfaces with Ti-Ball™ (Varian Associates) units. NEWTRAJ also predicted resonant activity between the intermediate cylinder and the outer cavity walls for higher gap voltages between 30 and 100 kV. These predictions were later proven accurate, as it was necessary to flash these areas with titanium to achieve reliable operation. The drive loop was considered a highly unlikely area for multipactor because the loop sits at the transmitter tube anode potential. However, during initial conditioning there was some discharge activity in this area, as evidenced by a blue glow in and around the loop area, which is yet unexplained.

Special filament lead extensions were made up for mini Ti-Ball units to flash the shaded area "B" shown on Fig. 1, and a rotatable extension with a regular Ti-Ball unit was inserted through the inner conductor to flash the shaded area "A". By using the four small ports on the ends of the cavities, the mini Ti-Ball units could be positioned in eight different locations between the intermediate cylinder and end wall on each end of the cavity. In the gap region, the Ti-Ball unit could be hinged up to gain line-of-sight to most of the area between the inner conductor and intermediate cylinder, and this area was also flashed in eight locations by rotating the unit on a rotatable flange. The area labelled "C" was accessed through the large ports at the centre of the cavity with the use of filament lead extensions. The units were operated at their maximum sublimation rate for five minutes at each location at a starting pressure of 10^{-3} Pa and the cavities were backfilled with dry nitrogen four times during the process while re-positioning the Ti-Ball units. Examination of the cavity surfaces after flashing revealed a gold tinge characteristic of titanium nitride in some areas, but for the most part the coating was a dull grey colour characteristic of titanium oxide. Both have a secondary yield coefficient less than 1. The second cavity was done in the same manner, with the exception that the sublimation time was increased to 12 minutes. This improved performance considerably and led to further application in the first cavity.

To condition the cavities, a fast risetime high-amplitude rf pulse was used to pass quickly through the particle energy level where the yield of secondaries is greatest (about 300 eV for Al_2O_3), and to exceed this level in all areas of the cavity. Initially, the peak rf fields in the cavity were limited to 1 kV, but after a few hours of conditioning the amplitude was raised to 8 kV and eventually to 35 kV after two days. This barrier could not be overcome until the cavity was vented and the area labelled "C" flashed with titanium. The cavity fields could then be raised to levels approaching 200 kV at a 1% duty factor. Within 48 hours, the peak amplitude could be lowered to 160 kV and cw operation was achieved. During the first stages of the conditioning process, the ion pump had to be turned off and the system pumped with a turbo pump to get through even the lowest multipactor levels. After completion of conditioning, the ion pump appears to have no effect on the operation, but as a safeguard the pump is turned off momentarily during the rf turn-on procedure.

The conditioning process was continued by gradually reducing the operating voltage in 500 V steps and pausing to let the vacuum recover if a pressure transient occurred. There were several gap voltage levels where pressure transients were much more severe as resonant discharges took place in different areas of the cavities, but these areas would eventually clean up with sustained operation, until they could no longer support a resonant condition. The conditioning process was continued for over a week, until stable cw operation was achieved over the entire operating range. Occasional discharges still occur, which result in a collapse of cavity fields to a point where the control system loses lock and shuts the system down. Nevertheless, 24-hour uninterrupted operation of both cavity systems at 160 kV has now been demonstrated. The increased titanium deposition time on the second cavity system reduced the entire conditioning process on this system to less than three days.

Although both systems now operate reliably over the full voltage range, small but distinct tuning steps which occur at some gap voltage settings indicate that the cavity is still being slightly loaded by a resonant discharge. It is expected that performance and vacuum pressure will continue to improve with operating time.

Acknowledgments

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References

1. M.S. de Jong, et al., "Final Testing, Installation and Commissioning of the HERA 52 MHz rf systems", this conference.

2. S.T. Craig and R.J. West, "Beam Loading Compensation for 52 MHz Systems", this conference.

3. M.S. de Jong and A.B. Hood, "Micro-Computer Control Systems for the HERA 52 MHz rf Systems", this conference.

4. R. Boni, et al., "Design and Operation of a Multipactor-Free 51.4 MHz RF Accelerating Cavity", Nuclear Instruments and Methods in Physics Research, A274 (1989) 49-55, North Holland, Amsterdam.

5. J.E. Griffin, et al., "Fabrication and Operation of the 4 MV 53 MHz RF System for the Fermilab Antiproton Source Debuncher Ring", IEEE Trans. Nucl. Sci., NS-32, No.5, (1985) 2806-8.