Review of Superconducting RF Technology for High-Power Proton Linacs

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Abstract

High-power proton linacs are efficient drivers for spallation neutron sources that have a wide variety of research and transmutation applications. The use of superconducting RF technology for these high-power linacs serves to increase their power efficiency and reduce beam loss. Recognizing these advantages, laboratories worldwide have initiated programs to develop superconducting RF technology for such applications. This paper reviews existing technology development programs and summarizes the status of superconducting RF technology for high-power proton linacs.

1 INTRODUCTION

High-power proton linacs can produce neutrons efficiently through spallation processes. The linac beam parameters are optimized for specific applications and target designs. Nominally, a high-current proton beam of 100 mA with a beam energy of 1 GeV will hit a target of high atomic numbers such as lead and tungsten. More than twenty neutrons per proton can be produced for uses in research and transmutation applications [1]. Research applications mainly involve the use of neutron scattering to investigate material properties [2]. Transmutation applications include the lifetime reduction of nuclear reactor wastes [3] and the production of tritium [4]. Most of these applications require linacs to operate in CW mode, with the pulsed neutron source for research applications as an exception.

Although high-power proton linacs can be built with various technologies, there are two major advantages for building them using superconducting (SC) RF technology [5]. First, SCRF linacs have high power efficiency that is important for linacs having high beam power. They have high power efficiency because the SC cavities have negligible wall loss. Second, SCRF linacs have less beam loss than conventional linacs. Beam loss in proton linacs is caused by the interception of beam halo by the beam pipe. At high current, the level of ionization radiation resulting from beam loss can create significant operation and maintenance difficulties. The large beam aperture typical of SCRF cavities minimizes beam-halo interception and greatly alleviates the beam loss and the resulting ionization radiation.

Recognizing SCRF technology as the most promising choice for high-power linacs, laboratories in many countries have initiated R&D programs to develop SCRF technology specific for high-power proton linacs. The technology development is mainly in the areas of β<1 cavities, high-power couplers, cryomodule integration, and RF control. In this paper, we will briefly review the development programs around the world and the status of the technology development.

2. SCRF TECHNOLOGY DEVELOPMENT PROGRAMS WORLDWIDE

Superconducting RF R&D programs for high-power proton linac are being carried out in many laboratories around the world. This paper will describe the programs in the US, France, Japan, and Italy. We will briefly describe these programs and provide the references so that the readers can find more information. We will also summarize the status of development work in the areas of cavities, couplers, cryomodule integration, and RF control.

2.1 The APT Program in the US [6]

The US program was initiated at Los Alamos National Laboratory (LANL) in 1997. The program has been supported by the Accelerator Production of Tritium (APT) Project, funded by Defense Programs of the US Department of Energy. Other programs that can make use of the developed technology include the Accelerator Transmutation of Waste Project and the Spallation Neutron Source Project in the US.

Figure 1 shows a layout of the APT linac [7]. It has two superconducting linac sections with β=0.64 (211 MeV to 470 MeV) and β=0.82 (470 MeV to 1030 MeV). The goal of the development program is to build a β=0.64 prototype cryomodule and test it. Work includes the design, fabrication, and testing of 5-cell cavities (β=0.64, 700 MHz), and power couplers that transmit up to 250 kW of CW power. The cavities and power couplers will be integrated into a β=0.64 prototype cryomodule and tested at 2 K operating temperature. There will be two 5-cell cavities in the prototype cryomodule. Each cavity will have two power couplers.

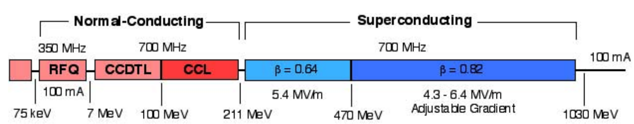

Figure 1. Layout of the APT linac

To date, the program has achieved the following:

- Tests of β=0.48 and 0.64 single-cell cavities showed that required fields (E_{acc}=5 MV/m) can be achieved without multipacting [8];
- A proton irradiation experiment of an operating SC cavity showed no degradation of SC-cavity properties up to 5x10^{15} protons/cm^2 [9];
- Design and fabrication of 5-cell cavities have been completed [10];
- Power couplers have been designed and fabricated; They have been tested at room temperature to above 1 MW of forward power [11];
- Cryomodule design was completed and fabrication has begun[12]; and
- Modification of the LANL SCRF facility was completed for processing and testing 5-cell cavities [13].

Five-cell-cavity and power-coupler tests are scheduled to be completed in the year 2000. A test of the cryogenic design of the power coupler will also be completed in the same year. In 2001, the cryomodule test will take place.

2.2 The ASH Program in France [14]

In France, a 5-year program called ASH (Superconducting Accelerator for Hybrid) will officially start in 2000 for the development of superconducting RF technology for high-power proton linacs. The main support for this program comes from the Hybrid Program initiated in 1998, which aims at evaluating one promising option for dealing with high-level radioactive nuclear wastes by transmutation. It requires a high-power proton accelerator combined with a subcritical fission assembly containing the wastes. Besides nuclear waste management, several other applications are now converging toward pushing ahead this same technology, such as the European Spallation Source [15], the production of neutrino sources, and the acceleration of radioactive beams for nuclear physics.

The deliverable of R&D work for the ASH Program will be a fully evaluated technical proposal with cost for a waste-transmutation accelerator. This proposal will be submitted to the French National Parliament in the year 2005, according to the 1991 French law on nuclear waste. Figure 2 shows the layout of the Demonstrator Accelerator. It contains two SCRF linac sections, β=0.47 between 85 and 185 MeV and β=0.65 between 185 and 450 MeV. The ASH Program will aim at building and testing a fully equipped cryomodule at 700 MHz, including the design and construction of multicell cavities and power couplers. If the cryogenic tests are successful in terms of accelerating field, power handling, and cryogenic losses, the technology will be transferred to industry for production. The project will be supported by a common European effort involving teams from CEA/Saclay, CNRS/Orsay/IPN, CNRS/Orsay/LAL, INFN/Milano, and INFN/Genova. In addition, there is collaboration with the US APT Program (Section 2.1).

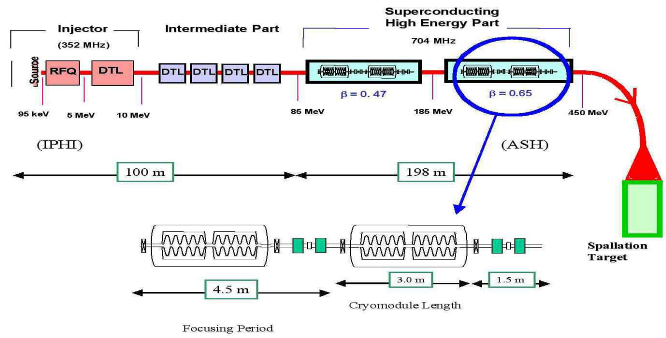

Figure 2. Demonstrator Accelerator of the French Hybrid Project

To date, the program has achieved the following:

- Single-cell 704-MHz cavity tests showed E_{acc} exceeding 26 MV/m without quenching [16];
- Power coupler development is underway, with a full power test planned in the year 2001; and
- A cryostat (named CRYHOLAB) has been designed as a test bed for cavities and power couplers in the horizontal position. It will be operational in 2000 [17].

2.3 JAERI-KEK Joint Program in Japan [18]

The Japan Atomic Energy Research Institute (JAERI) and the High Energy Accelerator Research Organization (KEK) are jointly proposing to construct a high-intensity proton accelerator facility to promote basic science and nuclear technology. This new proposal merges the Neutron Science Project (NSP) at JAERI and the Japan Hadron Facility (JHF) project at KEK. The NSP included the research and development for an accelerator-driven nuclear transmutation system (ADS) as part of the Japanese OMEGA program and the spallation neutron source for the neutron-scattering experiment. The JHF project of KEK was composed of research facilities for particle and nuclear physics, neutrino physics, muon physics, exotic nuclei, and neutron-scattering experiment.

The new joint program, temporarily called the "Joint Project of High Intensity Proton Accelerator," will be constructed at the JAERI Tokai site. The accelerator layout of the Joint Project is shown in Figure 3. The proposal has two phases. Phase I consists of a 400-MeV normal-conducting linac, a 400-to-600-MeV super-conducting linac, a 3-GeV synchrotron with a proton beam of 330 _ A (1 MW), and a 50-GeV synchrotron with proton beam of 15 _ A. Initially, the superconducting 600-MeV linac, probably at 972 MHz, will be used for the ADS experiment. The SC linac will be operated in the pulsed mode at a duty factor of 10%-20 %. After achieving stable pulsed operation, it will be used as the injector to the 3-GeV synchrotron. For Phase II, an upgrade toward 5 MW with a beam energy of a few GeV is proposed. The final upgrade path will be chosen through the operational experience in Phase I. Superconducting-linac development is the key technical development for the upgrade, as well as for the future high intensity of ADS.

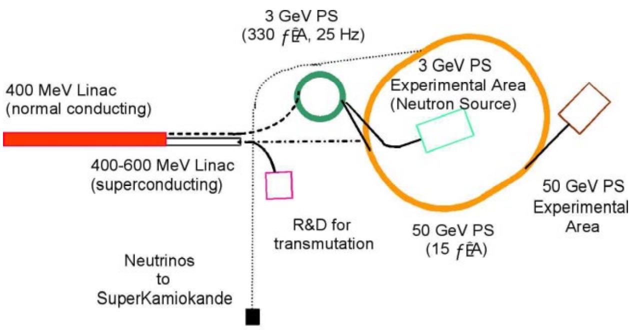

Figure 3. Accelerator complex for the Japan Joint Project (Phase I)

To date, the program has achieved the following:

- Single-cell cavities have been tested at β=0.5 and β=0.886. Maximum surface fields up to 47.3 MV/m at 2 K have been reached [19];
- Fabrication of 5-cell cavities at β=0.5 and β=0.886 was completed, and cavity testing is underway;
- Power couplers in KEK B-factory have transmitted power to beam of 395 kW [20];
- Design of a 600-MHz, β=0.604 cryomodule was completed, and fabrication will be completed in the mid-2000; and
- RF-control simulations showed that the cavity field stability needed for pulsed operation could be achieved with a feedback and feedforward algorithm [21].

2.4 The TRASCO Program in Italy [22]

TRASCO is the Italian acronym for Transmutation (TRASmutazione) of Wastes (SCOrie). It is a two-year program in which INFN, ENEA, and Italian industry will work on the design of an accelerator-driven subcritical fissile system for waste transmutation. The program is in line with the growing European consensus on a long-term reconsideration of the civil use of nuclear power based on a final solution of the waste accumulation problem. The goal of this program is to study the feasibility of a high-power proton linac based on established technologies, and particularly the CERN technology developed for the LEP-II superconducting cavities. This is an extremely attractive approach, because it allows the use of large and expensive facilities existing at CERN and at various European companies for the development of prototypes. Presently, the TRASCO Program in Italy and the ASH Program in France are working closely together to build 704-MHz prototype cavities. The reference linac design contains three sections of superconducting linac with β=0.5, 0.65, and 0.85, covering an energy range of 100-1600 MeV.

To-date, the program has achieved the following:

- The design of the cell shapes for different βs has been completed [23]; and
- A 5-cell β=0.85 cavity was manufactured with a sputtered technique used for LEP-II cavities. This cavity has reached 10 MV/m with a Q_o value of 10^9 [24].

3. STATUS OF TECHNOLOGY

In this section, we describe the requirements of superconducting RF technology for high-power proton linacs and the status of technology development. The areas discussed include the cavity, power coupler, cryomodule, and RF technology.

3.1 Cavities

Unlike electron linacs, where the electrons are at β=1, a proton linac accelerates protons over a range of β that is usually between 0.4 to 1. Because of the high velocity acceptance of the short superconducting cavities, a superconducting linac can efficiently accelerate a proton beam over this wide range of energy by using superconducting cavities with a few β values.

With β<1, the cavities for a proton linac have accelerating cells with reduced lengths as compared to the conventional β=1 cavities. The shorter lengths of these cells have two consequences. First, the ratios of peak surface fields to accelerating fields are higher than β=1 cavities. For example, the E_{peak}/E_{acc} and B_{peak}/E_{acc} are 3.64 and 74.9 Gauss/(MV/m) for the APT β=0.64 cavities, compared to 2 and 42 Gauss/(MV/m) for the TESLA β=1 cavities. The higher ratios make it more difficult to achieve high accelerating fields in β<1 cavities. Second, the reduced cell length, and consequently the smaller sidewall angle, reduces the mechanical strength of the cavities. The concern for mechanical strength can be addressed by installing mechanical reinforcement, using thicker niobium material, and/or optimizing the sidewall angle. Mechanical reinforcement usually introduces complications in fabrication and higher manufacturing costs. It is used only for cavities with very low β. The sidewall angle optimized for high mechanical strength and low surface peak fields, in most cases, are 10º to 15º, as compared to 20º for β=1 cavities.

Because of the power transmission limitation of power couplers, the E_{acc} required in high-power proton linacs is between 5-10 MV/m. This modest value of E_{acc} is comfortably reached using the present standard fabrication and processing techniques for superconducting cavities with high-pressure water rinsing. Heat treatment is needed only at 800° C to minimize the chance of hydrogen effects.

In the APT program, 700-MHz β=0.48 and β=0.64 single-cell cavities have been tested. The cell shape was optimized, keeping the peak surface electric fields below 16 MV/m. Results from vertical cavity tests showed that an E_{acc} of 5 MV/m with a Q_o of $5x10^9$ were achieved (Figure 4). Six 5-cell cavities have been built, and test results of these cavities will be available beginning in the winter of 1999. The single-cell cavities were built with mechanical reinforcement, and the 5-cell cavities were built without reinforcement. In the last two years, the superconducting RF facility in Los Alamos National Laboratory has been modified to process and test 5-cell, 700-MHz cavities.

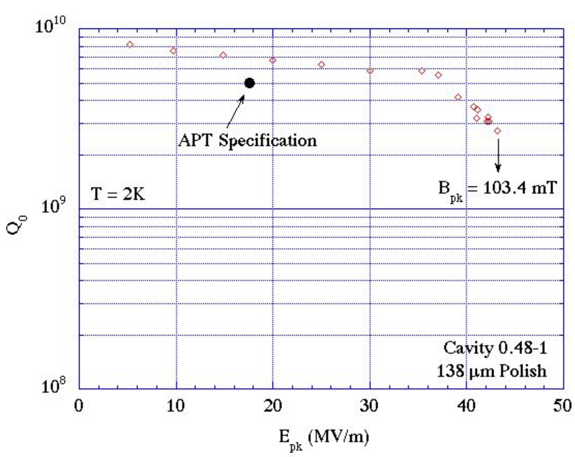

Figure 4. Results of APT single-cell cavity test (β=0.48)

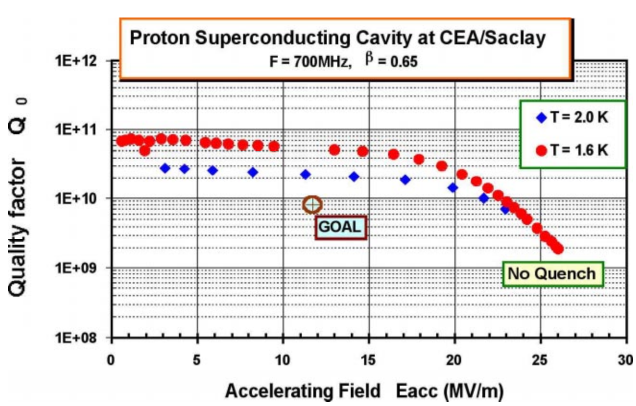

Figure 5. Results of ASH single-cell cavity test (β=0.65)

In the French ASH program, the cell shape was designed using a conservative value of 50 mT for the peak surface magnetic field. Single-cell cavities with β=0.65 were fabricated and tested in a vertical cryostat. Results showed excellent performance, reaching an accelerating field of 26 MV/m without quenching, at a corresponding peak surface magnetic field of 1230 gauss. The test results are shown in Figure 5, where the quality factor Q_o is plotted as a function of the accelerating field. In addition, it has been shown that a heat treatment at 800°C would be required in cavity processing because the Q_o degradation by more than a factor of 30 is observed due to the hydrogen effect. The 5-cell cavity design is now completed. Two 5-cell 700-MHz cavities will be fabricated and tested in the year 2000. As for cavity testing, besides the standard vertical test, a special horizontal cryostat named CRYHOLAB is in fabrication and should be operational for testing 700-MHz multicell cavities in 2000. Dedicated infrastructures, including a cleanroom facility, chemical-polishing facility, and high-pressure-rinsing system, are also being modified to support this program.

In the Japanese Joint Program, two β=0.5 single-cell cavities and one β=0.886 single-cell cavity of 600 MHz have been fabricated. The cell shapes have been designed to keep the peak surface electric field below 20 MV/m. Fabrication processes such as cold rolling, electron beam welding, and surface treatment (barrel polishing, electropolishing heat treatment at 750°C and high-pressure water rinsing at 8 MPa) have been performed based on the KEK experience for the 500-MHz TRISTAN cavity. Vertical tests have been conducted to examine the RF and mechanical properties. Figure 6 shows results of the performance test of β=0.5 cavities. Maximum peak surface fields of 44 MV/m and 47.3 MV/m at 2 K were achieved for β=0.5 and β=0.886, respectively. Two 5-cell cavities with β values of 0.5 and 0.886 were also fabricated. After pretuning and surface treatment, the first vertical test of a 5-cell cavity was performed.

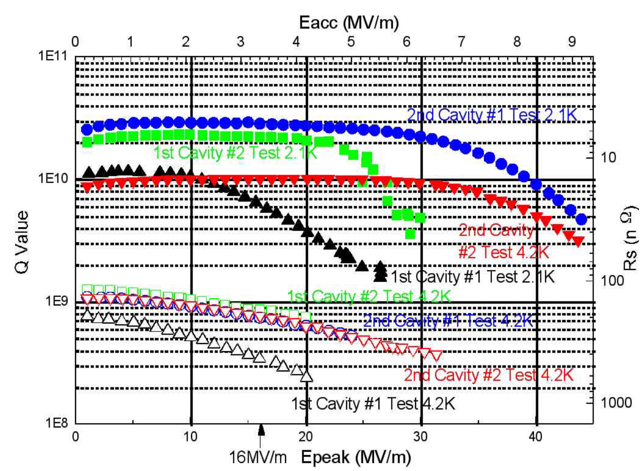

Figure 6. Results of Japanese single-cell cavity test (β=0.5)

In the Italian TRASCO Program, a five-cell β=0.85 704-MHz structure produced using the standard CERN process for making the LEP cavities has been tested. At 4.5 K, the cavity reached the design goal of E_{acc}=5.5 MV/m with a Q_o value of $2.5x10^9$. The ultimate field, which was limited by the available RF power, was 10 MV/m with a Q_o value of 10^9. The Q_o value of the cavity at 1 MV/m was $5.6x10^9$. The same values of quality factors and fields were obtained for a single-cell cavity.

3.2 Power Couplers

The power coupler is the most challenging component in a high-power proton linac because hundreds of kilowatts of CW power must be transmitted to the beam through these couplers. Power couplers have been used at power levels at tens of kW. It is only recently that we have power couplers operating at the levels needed for a high-power proton linac. These high-power couplers include the waveguide couplers at CESR and the coaxial couplers at KEKB, transmitting, respectively, 260 and 390 kW of CW power to the beam. Presently, all coupler designs chosen for high-power proton linacs are of the coaxial type because of compactness and large coupling range.

To design a power coupler for a high-power linac, there are special considerations because of the high power that is transmitted. First, we should push the multipacting threshold beyond the operating power levels. Recent results have shown that the multipacting thresholds in a coaxial line increase with RF frequency to the fourth power [25]. One can, therefore, achieve a higher multipacting threshold by choosing a slightly higher RF frequency. Second, we need to keep the RF losses low in a power coupler by minimizing mismatches and choosing materials and surface-preparation techniques that give high RF surface conductance. We must also closely watch the cooling and heat load of the couplers because the loads are more significant when hundreds of kWs are transmitted. Third, coupling to the cavity field should be high and variable. A high coupling coefficient is required because of the high beam loading. A variable coupling is needed because the cavity external-Q required to accelerate beam at different proton beam energies is different. Fourth, we need a robust design for RF windows operating at the same power levels.

In the US APT Program, the power couplers have been designed for 210 kW transmitted to the beam. Two power couplers are required to supply each cavity with 420 kW of power. The couplers have dual coaxial ceramic (Al_2O_3) warm windows that are manufactured by klystron suppliers. These windows have been tested to 1 MW. The couplers have been tested on a room-temperature test stand to above 1 MW of transmitted power [11,26]. A reflected-power test and a cold test using a LN_2 cold jacket are underway.

In the French ASH Program, power couplers capable of handling more than one hundred kW are needed for the Demonstrator Project. The power requirement will exceed 300-kW CW for the final Hybrid prototype. A new coupler is being designed in collaboration with Los Alamos, aiming at the high level of 300-kW CW, integrating in the design the important requirements of reliability and easy replacement. The present schedule for the coupler development is to perform a first test at an intermediate power of 80 kW in the year 2000 and a full power test in 2001.

In the Japanese Joint Program, the power-coupler design is based on the KEKB design that recently transmitted 390 kW of CW power to the beam.

3.3 Cryomodules

Cryomodules used in SCRF high-power proton linacs do not have special design requirements. They can benefit fully from the existing cryomodule design experience.

Cryomodules designed for high-power proton linacs are usually short, containing only up to four cavities, because magnetic quadrupoles (room-temperature types as preferred in most linac designs) are needed to interlace with the cavities to provide stronger transverse focusing needed for good beam dynamics. Short cryomodules also allows the installation of more frequent beam diagnostics to assure the achievement of good beam matching to linacs. For high-power coupler performance, the assembly of power couplers to cryomodules is usually better performed in a cleanroom.

In the US APT Program, a cryomodule has been designed based on the CERN LEP-II design. The cryomodule is being fabricated and will be tested beginning in the winter 2000.

In the French ASH Program, the cryomodule design work will start next fiscal year. Integration of final cavities and couplers is planned in 2002, and the complete test will be performed in 2003. Industry will be involved at an early stage in order to be ready for fabrication if the hybrid project were to be approved in 2004.

In the Japanese Joint Project, the cryomodule design work for the 600-MHz β=0.604 cavity has been performed to make the complete performance test for fabrication technique and thermal, electrostatic, and mechanical properties. The fabrication of the cryomodule will be completed in the middle of 2000. A new building for a horizontal cavity test is under construction, and infrastructure for the test, including assembly room, RF power source, liquid-helium supply, and x-ray shield is being prepared simultaneously.

3.4 RF Control

Phase and amplitude controls of cavity fields are very important for high-power proton linacs in order to minimize beam-halo formation. The cavity fields have to be stabilized under the influence of microphonics and Lorentz-force detuning (in the case of pulsed operation). RF control is further complicated by the use of one klystron to supply multiple cavities, a scheme to reduce the cost of RF systems. Usually, the klystron is controlled by feedback and feedforward techniques using a signal that represents the sum of the fields of cavities powered by the klystron. The sum of the fields must be controlled to one degree in phase and one percent in amplitude.

In the French ASH Program, work has been done to consider the possibility of using a low-cost RF system that allows the powering of a single cavity with one klystron, and consequently enhancing cavity field control. The cost is minimized by using a common power supply for the klystrons.

The technology for controlling cavity fields under the influence of Lorentz-force detuning and microphonics for pulsed operation has been demonstrated for the electron linac at the TESLA Test Facility linac [27] and will be adapted for use in proton linacs. In the Japan Joint Project, high accuracy in cavity control is required to inject into the 3-GeV synchrotron. An RF-system model is constructed based on the MATLAB/SIMULINK code. The model uses I/Q control model and PID feedback and feedforward controllers. Simulations have been performed using a cavity design at 600 MHz, β=0.604, a 3-mm wall thickness. The optimum PID parameters are calculated for different controller delay times. Simulation results showed that, with influence of the Lorentz detuning, a field stability of less than ±1% and ±1° is achieved with a delay time of 20 μs.

4. SUMMARY

High-power superconducting RF proton linacs are the preferred drivers for future neutron sources for neutron-scattering and transmutation technologies. R&D programs have been established in the US, France, Japan, and Italy to develop technology needed for these linacs. These programs have so far successfully pushed the frontier of the SCRF technology. Single-cell cavity tests with β<1 have shown that the required cavity performance can easily be obtained. Results of multicell cavity tests are beginning to become available. Power couplers have been the most challenging part of the technology for high-power superconducting RF proton linacs. In the last year, we have seen power couplers that can transmit the required hundreds of kW of CW power. In the next two years, we will see the testing of prototype cryomodules, the basic building blocks of superconducting RF linacs, with fully functioning cavities and power couplers.

5. ACHNOWLEDGEMENT

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