ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-THOTEV03

PROGRESS OF SUPERCONDUCTING RF ACTIVITIES IN INDIA*

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Abstract

This paper is a summary of the recent progress of SRF activities in India including the institutes viz., RRCAT, BARC, VECC and IUAC. The latest SRF activities for several national accelerator projects and international projects like PIP-II in FNAL are presented. RRCAT in Indore has been pursuing a complete chain of fabrication, RF tests and characterization at various stages including the SCRF infrastructure facilities, processing, HPR, Vertical Test Stand (VTS) and Horizontal Test Stand (HTS). Several cavities have been successfully tested in the vertical test stand, and the Horizontal Test Stand has been commissioned and ready to test the cavities. BARC in Mumbai has developed low beta single spoke cavities for PIP-II R&D in collaboration with IUAC. VECC is pursuing development of single cell and five cell low beta SCRF cavities for PIP-II R&D. IUAC in New Delhi developed SRF cavities using their infrastructure facilities and has supported institutes in India towards 1.3 GHz cavities, single cell LB and HB cavities and development of SSR1 cavities. Status of the SRF cavity development and the latest results of cavity performance qualification are presented in this talk.

INTRODUCTION

India is interested in High Intensity Superconducting Proton Accelerators (HISPA) for building a Facility for Spallation Research, Radio-isotope Production, Radio-active Ion Beam (RIB) facility etc. These demand high intensity proton beams; both pulsed and CW. Participation in International SCRF accelerator projects like PIP-II (Fig. 1) at Fermilab under Indian Institutions Fermilab Collaboration (IIFC), will enable to develop proven HISPA technology and develop essentially all individual components of a HISPA system. Institutes of Department of Atomic Energy are partners to PIP-II development for various subsystems like cryo-plant, Single Spoke Resonators, Low beta 650 MHz cavities and High Beta 650 MHz cavities [1]. RRCAT had developed infrastructure facilities for SCRF cavity development and tests starting from initial development of 1.3 GHz multi-cell SCRF cavities and later for high beta HB 650 MHz cavities under PIP-II R&D program (Fig. 2) [2–4]. BARC is setting up infrastructure facilities for developing Single Spoke Resonators (SSR) development. VECC is pursuing the development of low beta 650 MHz cavities and two single cell LB 650 cavities have been developed jointly with IUAC and tested at Fermilab. IUAC has developed 325 MHz SSR1 cavities. The jacketing of SSR1 cavities was done by BARC and the two cavities were supplied to Fermilab and successfully tested. IUAC has also developed quarter wave resonators for its 15UD Pelletron post SCRF accelerator and successfully accelerated variety of species for nuclear physics research. Apart from the SCRF cavity development, an intense effort has been made to develop 325 MHz, 7 kW solid state amplifiers by BARC as well 650 MHz, 40 kW class solid state amplifier prototypes by RRCAT. Nine 325 MHz, 7 kW amplifiers have been developed and shipped by BARC and installed in the PIP-II IT equipment hall at Fermilab and used for accelerating the beam [5]. One prototype of 40 kW SSPA has been developed and shipped by RRCAT to Fermilab which is made functional and will be coupled to the cavity test system at Fermilab. This paper will give an overview of various infrastructure facilities at the Indian Institutes and the latest results on the cavity and subsystem developments will be presented.

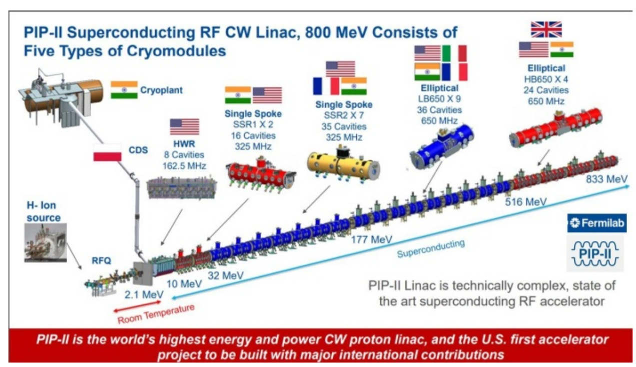

Figure 1: Schematic of PIP-II SCRF CW Linac showing various families of SCRF cavities and contributions from various international partners and India.

SCRF INFRASTRUCTURE AND HB 650 CAVITY DEVELOPMENT AT RRCAT

SCRF cavity development efforts to the R&D phase of PIP-II project under the Indian Institutions Fermilab Collaboration for the PIP-II project at RRCAT include following: (i) $\beta = 0.92$, 650 MHz (HB 650) five-cell bulk niobium SCRF cavities. (ii) Horizontal Test Stand (HTS) cryostats,(iii) 40 kW, 650 MHz solid state RF amplifiers, (iv) processing and HPR of HB 650 SCRF cavities. In addition participation in cryo-module development is also taken up.

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Figure 2: Infrastructure set up at RRCAT for the development of HB 650 beta 0.92 SCRF cavity and tests. From top left to right a) Half-cell forming press, b) RF measurement set up, c) Electron Beam welding machine, d) Electro-polishing set up, e) Cavity tuning machine, f) Vacuum annealing furnace, g) High Pressure Rinsing Lab, h) Clean room assembly lab, i) HB 650 cavity developed at RRCAT, j) Vertical Test Stand with VTS Control Room, k) Helium vessel for HB 650 cavity, l) HB 650 tuner developed at RRCAT, m) Controlled environment dressing furnace, n) Results from the R/Q set up showing field flatness after dressing, o) dressed cavity with tuner assembled on left and first dressed cavity assembled with HTS, p) HTS shielded vault, q) 650 MHz 40 kW Solid state power amplifier coupled to HTS, r) LLRF and RFPI (developed by BARC) for the HTS at RRCAT.

HB 650 SCRF Cavities

In initial tests lessons were learnt to improve from 14 MV/m to 21.4 MV/m, and after re-HPR reached 29 MV/m qualifying at 19 MV/m at the desired Q (Fig. 3). Dressing/jacketing of one cavity was also successful at RRCAT and second one at Fermilab with joint participation (Fig. 4). Vertical Test Stand (VTS) at RRCAT is operational and in regular use. Installation and commissioning of HTS has been done, first with unity coupler, @1.98 K. RRCAT will soon be reaching to a complete cycle of SCRF cavity development after completing HTS test on dressed cavities with high power coupler AES 10 provided by Fermilab.

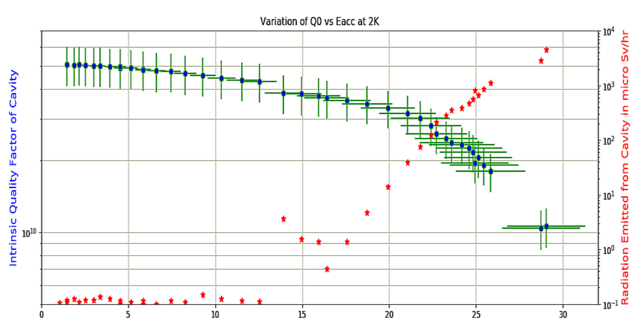

Figure 3: Test results of cavity HB 650 RRCAT 505 showing E_{acc} reaching to 29 MV/m.

Tuner Development for 650 MHz Cavity

RRCAT has developed and fabricated 5 lever tuners out of which two tuners have been shipped to Fermilab (Figs. 5, 6 and 7). One tuner is assembled with 650 MHz 5-cell cavity and tested at 2 K.

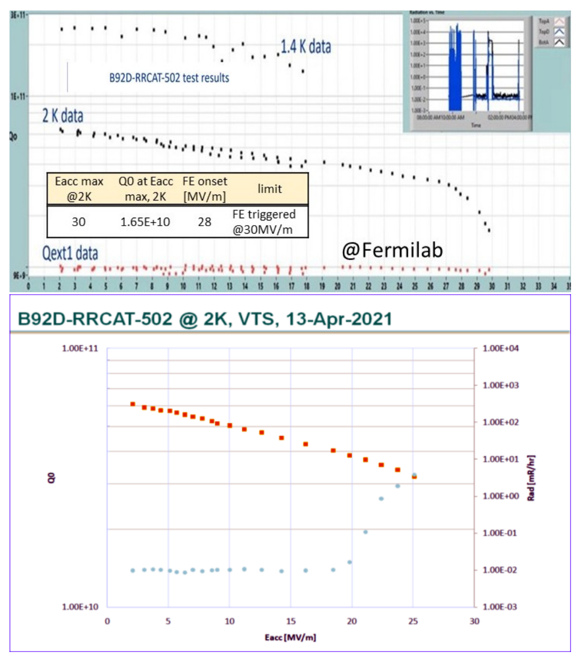

Figure 4: Test results of HB 650 RRCAT 502 cavity at Fermilab reaching to 30 MV/m with FE, upper figure and later with Re-HPR 25.1 MV/m with FE mitigation. Q was measured to be 3.2×10^{10} at max E_{acc} @2 K lower figure.

Vertical Test Stand

RRCAT had developed vertical test stand beginning the testing of 1.3 GHz single cell and multi-cell cavities and also 325 MHz and 650 MHz cavities. The VTS LLRF and control electronics was developed by RRCAT (Fig. 2-j). VTS is operational and is in regular use for testing the 650 MHz five cell cavities as well as single cell cavities for further process

20th Int. Conf. on RF Superconductivity SRF2021, East Lansing, MI, USA JACoW Publishing
ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-THOTEV03

improvements. RRCAT has also set up dedicated cryogenics infrastructure to support the VTS and HTS tests [3,4].

Horizontal Test Stand

RRCAT has developed two HTS cryostats with the help of Indian Industry. One of the cryostat has been installed and integrated with the HTS subsystems and first trial run was done to have cool down to 2 K. RRCAT dressed HB650 cavity 501 has been tested in the HTS for qualification of all subsystems at low RF power using a unity coupler. A dressed cavity with high power coupler received from Fermilab (AES 10) has now been integrated with the HTS at RRCAT and in under progress for HTS tests (Figs. 8 and 9).

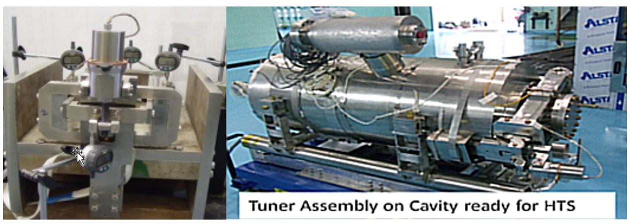

Figure 5: Left Lever tuner developed at RRCAT, Right tuner assembled with the dressed cavity 501.

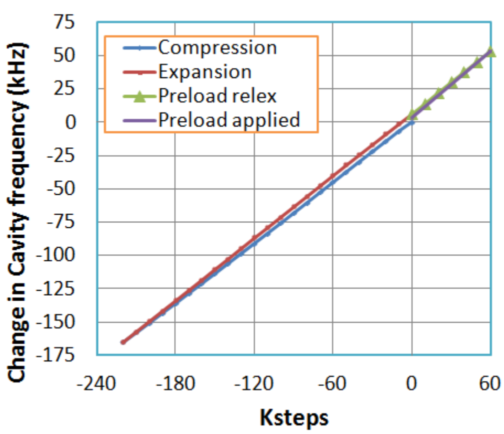

Figure 6: Test results @2 K showing slow tuning range = 215 kHz.

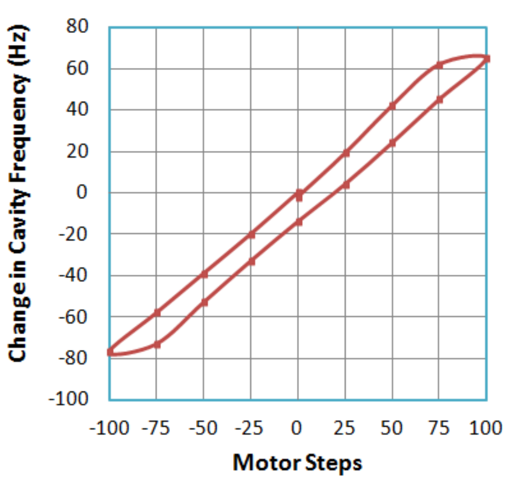

Figure 7: Slow tune resolution of 0.8 Hz/step; Tuner sensitivity = 158 Hz/mm.

Figure 8: Horizontal test stand developed and commissioned at RRCAT. Magnetic shielding has also been developed and installed.

Figure 9: Dressed cavity with high power coupler (AES 10 from Fermilab) installed in the HTS cryostat at RRCAT.

650 MHz Solid State RF Amplifiers for Testing and Powering SCRF Cavities

RRCAT has designed and developed prototypes of 40 kW 650 MHz solid state power amplifiers (Fig 10). The initial series will be used to test the HB 650 cavities in horizontal tests stand at RRCAT [6]. First prototype was tested up to 36 kW output power and the technical requirements have been upgraded to 40 kW 1 dB compression point for further development of next amplifiers.

Figure 10: Upper photos acceptance testing of first 650 MHz SSA prototype at RRCAT. Lower photos the amplifier shipped to Fermilab, assembled and tested for rated power.

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SINGLE SPOKE RESONATOR DEVELOPMENT & INFRASTRUCTURE FACILTIES AT BARC

Bhabha Atomic Research Centre, BARC, Mumbai has done the development of superconducting spoke resonator (SSR) cavities and components of the Cryo-Module Test System (CMTS), under IIFC. BARC successfully carried out Jacketing of two SSR1 cavities (developed by IUAC) and development of SSR1 tuners. Additionally development of a Feed Cap, End Cap and Feed Box for the Cryo-Module Test System (CMTS) was also completed. BARC is now setting up the cavity processing (BCP, HPR) and test stand (VTS, HTS) facilities in collaboration with Fermilab.

325 MHz, SSR 1 SCRF Cavities

Two 325 MHz Niobium Single Spoke Resonator (SSR1) cavities developed at IUAC were successfully jacketed with SS Helium vessel by BARC (Fig. 11). One cavity has been used in the SSR cryomodule at PIP2IT, Fermilab, and has accelerated the beam. This cavity is one of the best performing cavities in the cryomodule (Figs. 12 and 13).

Figure 11: SSR 1 cavities after dressing at BARC.

Figure 12: SSR1 Tuners developed at BARC.

Cryo-Module Test System (CMTS) - Feed & End Cap

BARC has supplied Feedcap, End cap and CMTS feed box for the CMTS Fermilab (Fig. 14).

325 MHz RF Amplifiers for SSR Cavities in PIP2IT

Nine amplifiers developed with Electronics Corporation of India Ltd. (ECIL), were supplied to Fermilab by BARC (Fig. 15). Eight amplifiers have been connected to SSR-1 cavities in PIP2IT, and have contributed to beam acceleration to 17 MeV [7].

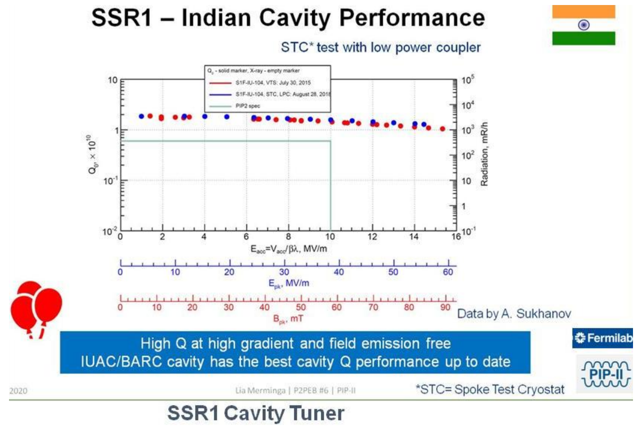

Figure 13: Test results of SSR1 performed at Fermilab.

Figure 14: Feed cap and end cap developed by BARC.

Figure 15: 325 MHz solid state amplifiers for PIP-II IT supplied by BARC.

SSR Cavity Processing and Testing Facilities Coming up at BARC

Following SCRF infrastructure facilities are being set up at BARC in collaboration with RRCAT and Fermilab (Figs. 16 and 17) [8]:

a Buffered Chemical Polishing facility
b High Pressure Rinsing setup
c High temperature furnace.
d Cavity Test facilities being developed at BARC
e Vertical Test Stand (VTS)
f Horizontal Test Stand (HTS)

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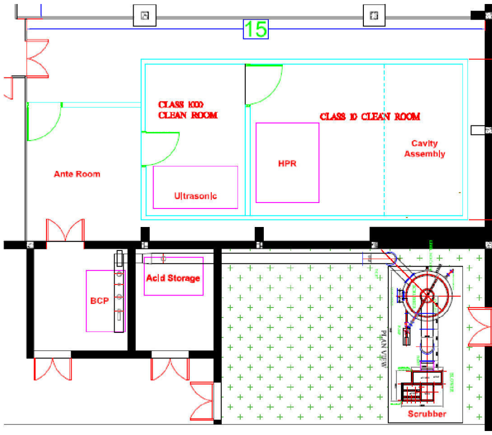

Figure 16: The schematic of SCRF infrastructure facilities being set up at BARC.

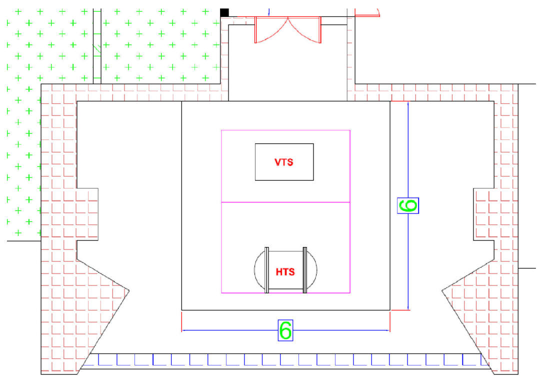

Figure 17: Schematic of Cavity Test facilities VTS/HTS being set up at BARC.

LOW BETA 650 MHz (LB650) SCRF CAVITY DEVELOPMENT AND RELATED INFRASTRUCTURE AT VECC

Figures 18 and 19 show a glimpse of the infrastructure facilities at VECC. Forming and initial machining for the low beta 650 MHz single cell cavity was done by VECC. The electron beam welding was done by IUAC. The testing of the two cavities developed by VECC/IUAC was done at Fermilab VTS after processing and HPR.

Figure 18: LB single-cell development photos from top left: showing forming, machining, RF measurements, EBW, cryo-shock, MSLD and final RF measurements.

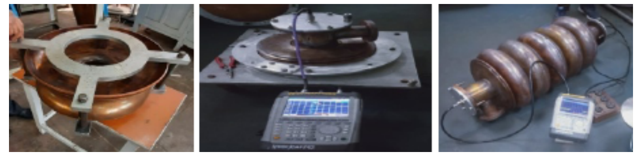

Figure 19: LB 650 multi-cell trials in copper.

The first LB 650 single cell cavity performed well and sustained 74 MV/m Peak Electric Field (E_{pk}) and 137 mT Peak Magnetic Field (B_{pk}), with E_{acc} of 34.5 MV/m @2 K (Fig. 20) [9].

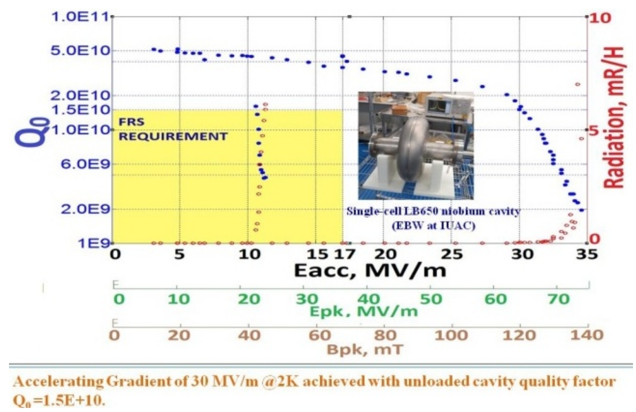

Figure 20: Results of the first LB 650 single cell cavity developed by VECC/IUAC.

The second single cell cavity reached the maximum accelerating gradient of 25 MV/m @2 K with unloaded cavity quality factor $Q_0 = 1.57 \times 10^{10}$ tested at Fermilab VTS (design gradient is 19 MV/m) (Fig. 21).

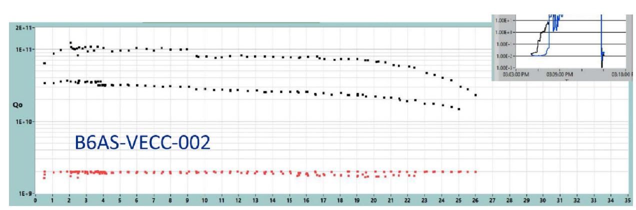

Figure 21: Test results of the second single cell cavity developed by VECC/IUAC.

SRF INFRASTRUCTURE, QUARTER WAVE RESONATORS AND SINGLE SPOKE RESONATOR DEVELOPEMENT AT IUAC

IUAC, New Delhi has created infrastructure facilities for the SRF development starting from the QWR [10].

Inter University Accelerator Centre (IUAC), New Delhi has closely collaborated with RRCAT, BARC and VECC. IUAC developed the 1.3 GHz SCRF cavities initially and later HB650 MHz single-cell cavity in collaboration with RRCAT. The infrastructure at IUAC is shown in Figs. 22, 23 and 24. Two 325 MHz SSR1 niobium cavities were developed by IUAC/BARC under the IIFC collaboration 25. After successful testing at 2 K in the VTS at Fermilab they were dressed at BARC (Fig. 11). Two 650 MHz single-cell

ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-THOTEV03

LB cavities were developed by VECC in collaboration with IUAC.

Superconducting QWR Development at IUAC

IUAC developed QWRs for the post accelerator for 15UD Pelletron accelerator using its infrastructure (Fig. 26) [11].

Table 1 shows the QWR parameters. The 4 K performance of an indigenously built QWR is shown in Fig. 27.

IUAC has also developed a prototype low beta niobium QWR (β = 0.05) operating at 97 MHz for their High Current Injector programme (Fig. 28). The resonator has exceeded the nominal design goal of 6 MV/m accelerating gradient by achieving 10.5 MV/m with 6 W RF input power (Fig. 29) [12].

Figure 22: Infrastructure facilities at IUAC. Photo on left, EBW machine (15 kW), photo on right High vacuum furnace with Nb getter box.

Figure 23: Left Class-100 clean room for HPR set up; right: Electro-polishing set up.

Figure 24: Left Test cryostat, right 1.3 GHz and 650 MHz single cell cavities developed in collaboration with RRCAT.

Figure 25: Left: Niobium SSR1 resonator built by IUAC. The photograph shows the interior of the resonator just before its completion. Right: LB 650 cavity developed by VECC in collaboration with IUAC.

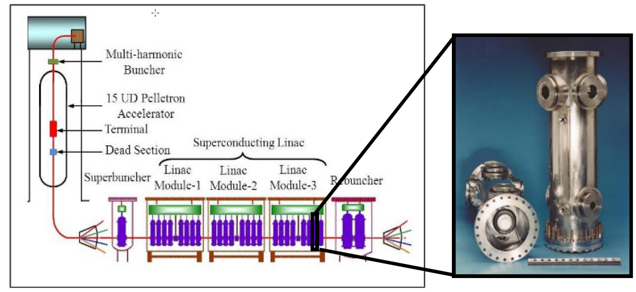

Figure 26: The 15 UD Pelletron Accelerator and Superconducting Linac (using QWR shown on right) at IUAC.

Table 1: QWR Parameters (Referenced to E_{acc} = 1 MV/m)

Resonator Parameter	Value
Resonance Frequency f	97 MHz
Synchronous velocity β_0	0.081
Energy content U_0	110 mJ
Peak Magnetic Field B_{pk}	13.1 ”,
Peak Electric Field E_{pk}	3.9 MV/m
Geometry factor QR_s	15.1

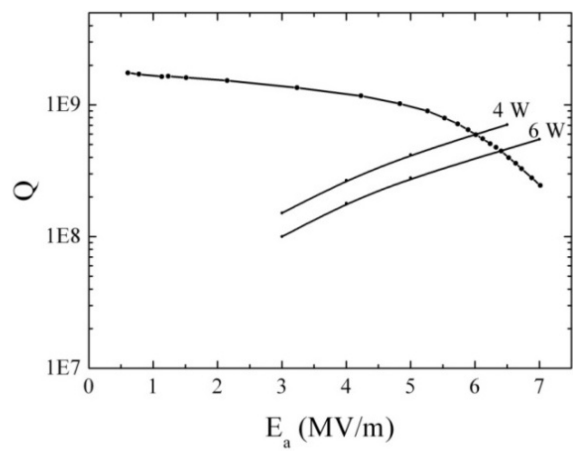

Figure 27: 4 K test result of an indigenously built QWR.

CONCLUSION

- Recent progress in SRF is presented from Indian Institutes: RRCAT, Indore; BARC, Mumbai; VECC, Kolkata and IUAC, New Delhi.
- RRCAT made significant progress in development and testing of HB 650 MHz cavities for PIP-II R & D in collaboration with Fermilab. All the necessary SRF infrastructure along with Vertical Test Stands and Horizontal Test Stands have been created at RRCAT.
- RRCAT has also developed prototype 40 kW, 650 MHz Solid State Amplifiers and using it for its own HTS tests and also delivered one to Fermilab for qualification and tests.
- IUAC/BARC made significant progress in SSR1 cavity development. The first two SSR1 cavities have performed very well.

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- VECC is developing five-cell LB 650 cavities. Progress has been made first by developing single cell LB 650 cavities in collaboration with IUAC.A5-cell niobium LB cavity will be developed soon.
- IUAC has extended its SRF facilities for the development of single-cell HB650, single-cell LB 650 and SSR1 cavity development to RRCAT, VECC and BARC.
- The SRF development in India with International Collaboration is taken up for its own SRF accelerators needs.

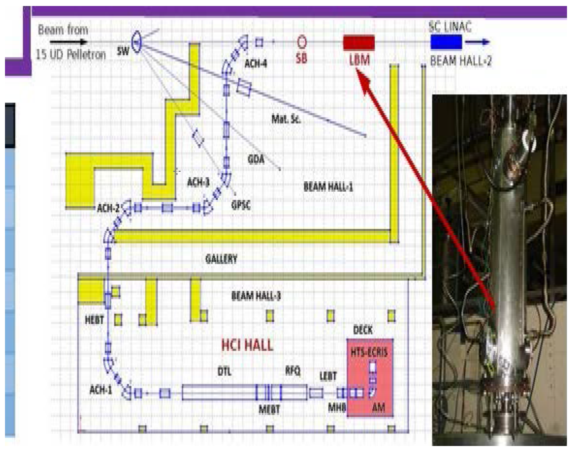

Figure 28: Layout of the under-development high current injector (HCI) at IUAC.

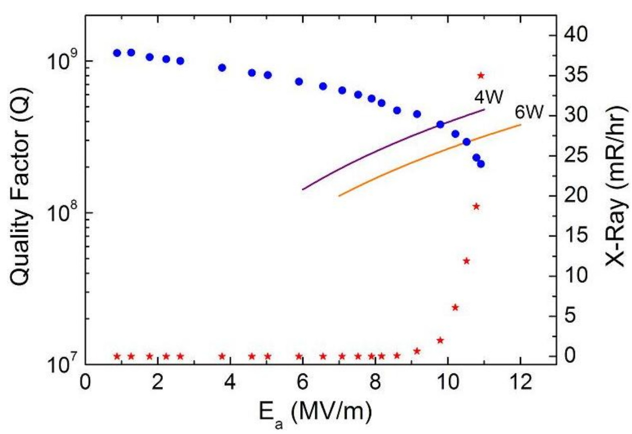

Figure 29: 4 K test result of the low beta QWR.

ACKNOWLEDGEMENTS

We are thankful to Mr. K. N. Vyas, Chairman AEC and Secretary DAE, Dr. A. Mohanty, Director, BARC and Mr. D. Das former Director, RRCAT for their constant encouragement and support for the work. We gratefully acknowledge the support of Fermilab colleagues for their support during the testing and processing of some of the cavities. The present work has been reported on behalf of teams from RRCAT, BARC, VECC and IUAC who have contributed to the development of various technologies and testing. Acknowledgement is also due to the colleagues from RRCAT, BARC and VECC viz., M. Lad, P. Khare, S. Raghavendra, V. Jain, M. Bagre, A. Jain, R. Ghosh (RRCAT), V. Mishra, G. Joshi, M. Pande, R. Kumar, K. Singh, (BARC), S. Seth (VECC).

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