Joint Project Document for the Research and Development Phase of the Indian Institutions and Fermilab Collaboration Under the framework of Project Annex-I to the Implementing Agreement between DAE, India and DOE, USA

1. Prologue

An Implementing Agreement between the Department of Atomic Energy (DAE) of the Republic of India and the Department of Energy (DOE) of the United States of America, referred to as the "Parties", for Cooperation in the area of Accelerator and Particle Detector Research and Development for Discovery Science was signed on July 19, 2011. In terms of Article 3 of this Implementing Agreement, a Project Annex – I has been signed between DAE and DOE in the area of accelerator and particle detector research and development for discovery science for high intensity proton accelerators. The objective of this Project Annex – I is to establish the framework for specific collaboration, including research, design, development and construction of High Intensity Superconducting Radio Frequency Linear Proton Accelerators (HISPA) in the Parties' respective countries. As per section F of Project Annex – I ("Contribution from the Parties"), the Parties intend to make in-kind contributions to each other's accelerator programs. The HISPA design, technology, and supporting infrastructure knowledge transfers from DOE to the DAE are the planned in-kind contribution from the United States. The engineering resources, design, manufacturing, and supply of HISPA accelerator hardware from the DAE to DOE, amounting to a maximum total of $200 million (direct cost in U.S. accounting in terms of 2012 US Dollars), are the planned in-kind contribution from India over the years 2013-2022. This Joint Project Document describes the activities to be pursued by the "Parties" during the Research and Development phase of the Indian Institutions and Fermilab Collaboration (IIFC) under the framework of Project Annex – I to the Implementing Agreement between DAE, India and DOE, USA.

2. Introduction

The HISPA programs at the Indian DAE laboratories: Bhabha Atomic Research Centre (BARC) and Raja Ramanna Centre for Advanced Technology (RRCAT), India and the U.S. DOE's Fermi National Accelerator Laboratory (FNAL or referred to as Fermilab) are being jointly developed under the IIFC. Two more Indian Institutions VECC (Variable Energy Cyclotron Centre) and IUAC (Inter University Accelerator Centre) are also participating in IIFC. The IIFC is developing a common Superconducting Radio-Frequency (SRF) accelerator technology design for both Indian and Fermilab programs and is currently carrying out R&D activities, with the goal of joint preparation towards the construction of an accelerator for the respective domestic programs.

Fermilab has proposed the construction of a HISPA (aka PIP-II). The PIP-II (Proton Improvement Plan – II) is part of the laboratory's long-term strategy to transform its accelerator complex to support a world-leading program in neutrino and rare decay physics (Ref. 1). Fermilab plans to build an SRF linac for the upgrade of its accelerator complex. In the 1st phase a 0.8 GeV SRF linac is proposed, enabling 1.2 MW beam power from the Fermilab Accelerator Complex for the Deep Underground Neutrino Experiment (DUNE). In subsequent phases the Fermilab accelerator complex could be upgraded to inject 8 GeV beam directly into the Fermilab Main Injector providing 2.4 MW beam to DUNE. The Indian Spallation Neutron Source (ISNS) being developed at Raja Ramanna Centre for Advanced Technology (RRCAT) will use similar HISPA technology to accelerate proton beams to energy of 1.0-2.0 GeV with beam power of up to 1 MW. The Bhabha Atomic Research Centre (BARC) will use HISPA technology to build a 1 GeV continuous-wave (CW) linac for its "Physics and Advanced Technologies for High Intensity Proton Accelerator (PATHIPA)" program.

This document outlines strategy and deliverables for the research and development phase for HISPA. The goal of the R&D phase is to reduce technical, cost, and schedule risks to a level that will allow initiation of the construction phase with high confidence of success.

DAE will develop additional components, if required, for Indian accelerators.

3. Goals

The high level goals of the joint R&D under the Indian Institutions and Fermilab Collaboration are:

a) Development and High Power Testing of SSR1 (Single Spoke Resonator 1), SSR2 (Single Spoke Resonator 2), LB650 (Low Beta 650 MHz) and HB650 (High Beta 650 MHz) cavities.
b) Development and testing of one SSR1 Cryomodule and testing it with beam at PXIE (PIP-II Injector Experiment), Fermilab;
c) Development and testing of one HB650 MHz Cryomodule and testing it in the Cryomodule Test Facility at Fermilab;
d) Development of associated components such as RF couplers, tuners, magnets, solid-state power amplifiers and cavity test facilities like HTS, etc.

At the end of this R&D program (2018) the IIFC would have completed many of the critical R&D and should be in position to take up the construction of projects for its respective domestic programs.

4. Accelerator Design and Development

The IIFC is jointly working on the design of high-intensity proton accelerators to be built in both countries. Fermilab is working towards finalizing the PIP-II accelerator design. Indian DAE laboratories (BARC and RRCAT) would build accelerators (ISNS and PATHIPA) using the similar components, but it is understood that the goals of the three accelerators are different. During the R&D phase the collaboration will jointly work on all aspects of the accelerator design and integration, and on development of selected components.

Fermilab will share the details of the existing PIP-II accelerator design, non-commercial software and analysis tools with DAE laboratories. The members of the IIFC will work jointly to develop these designs further for the specific use of the various accelerator projects.

Fermilab will invite DAE physicists and engineers to participate in installation, commissioning and beam studies for the front-end systems test in PXIE at Fermilab.

Fabrication of components will be started only after design drawings and technical specifications are finalized. Any change in design after starting/completion of fabrication will be accounted in costing of the component.

5. Warm Front End (0-2 MeV)

Fermilab has invited collaborating DAE laboratories to participate in the development and testing of the one-of-a-kind HISPA front end that includes the H- ion source, a warm Radio Frequency Quadrupole (RFQ), and Medium Energy Beam Transport line (MEBT). Fermilab is currently developing the warm front end as part of PXIE in collaboration with other US and Indian institutions.

DAE laboratories have developed prototype warm dipole and quadrupole magnets for the MEBT line. These prototypes have been tested at Fermilab. Fermilab has accepted and approved the design, and fabrication of the remaining magnets has been authorized with the following schedule.

Milestones	Major Milestones	Quantity	Delivery date
1	Electromagnetic Dipole	2	Done
	Electromagnetic Quadrupole	3	Done
	Electromagnetic Quadrupole Type “F”	4	30 Jun 2016
	Electromagnetic Quadrupole Type “D”	8	30 Jun 2016
	Magnet Assembly frame type ‘T’	4	30 Jun 2016
2	Electromagnetic Dipole	4	30 Nov 2015
	Electromagnetic Quadrupole Type “F”	3	30Aug 2016
	Electromagnetic Quadrupole Type “D”	6	30Aug 2016
	Magnet Assembly frame type ‘T’	3	30Aug 2016
3	Electromagnetic Dipole	3	31 March 2016
	Electromagnetic Quadrupole Type “F”	4	31 Oct 2016
	Magnet Assembly frame type ‘D’	2	31 Oct 2016
4	Electromagnetic Dipole	6	30 June 2016
	Electromagnetic Quadrupole Type “F”	7	30Dec 2016
	Electromagnetic Quadrupole Type “D”	2	30Dec 2016
	Magnet Assembly frame type ‘T’	1	30Dec 2016
	Magnet Assembly frame type ‘D’	1	30Dec 2016

6. Superconducting Radio-Frequency Cavities and Cryomodules

The development of superconducting RF cavities will involve characterization of the Nb material; fabrication of cavities, including electron-beam welding; cavity treatment procedures such as barrel polishing, buffer chemical polishing (BCP) and electro-polishing (EP); low RF power tests of cavities in a vertical test stand (VTS); and attachment of helium vessels, tuners and couplers followed by full RF power tests in a horizontal test stand (HTS). This work will proceed in an iterative manner, with physics and mechanical design and development proceeding in tandem with structure development.

Cavities and focusing elements are grouped within cryomodules. The five CW cryomodule types planned for the Fermilab and the DAE laboratories’ continuous-wave linacs are summarized in Table 1. Each cryomodule will be configured as a standalone unit, i.e. the vacuum vessel ends will be closed and cryogenic connections will be made at each module. Connections for cryogens and cryogenic control valves will be located in a mid-span vacuum vessel extension. The module-to-module connections will incorporate beam instrumentations and focusing and correction magnets. There will be minimal beam instrumentations internal to the cryomodule assembly.

Section	β_G	Freq (MHz)	Typeof cavity	Energy range (MeV)***
HWR	0.11*	162.5	Half wave resonator	2.1-10
SSR1	0.22*	325	Single-spoke resonator	10-35
SSR2	0.47*	325	Single-spoke resonator	35-185
LB650	0.61**	650	Elliptic 5-cell	185 - 500
HB650	0.92**	650	Elliptic 5-cell	500 - 800#

*$\beta_G = 2d/\lambda$, where d is the distance from the center of the first gap of a half-wave or a single-spoke cavity to the center of its second gap, and $\lambda$is the RF wavelength;
**$\beta_G = 2d/\lambda$, where d is the length of the regular cells of a multi-cell elliptical cavity, and $\lambda$is the RF wavelength;
***break points are given for the current beam dynamics version [1],
#Note: PIP-II linac extends to 800 MeV.

Table 1. Present configuration of the HISPA Cavity types and high-level parameters.

In the 162.5 and 325 MHz sections of the linac, focusing is provided by superconducting solenoids. In the 650 MHz sections a standard focusing and defocusing quadrupole doublet lattice is used. Normal-conducting doublets are located between cryomodules for both low-beta (LB650) and high-beta (HB650) cryomodules. Additionally, at least in the current design, superconducting doublets are located in the center of low-beta cryomodules. The current arrangement of focusing periods by cryomodule type is shown in Table 2. The IIFC would jointly develop the design of cavities and cryomodules that could be used for the respective linacs. The prototype HWR and SSR1 cryomodules currently under construction will be deployed in PXIE.

The IIFC has agreed to jointly research, design and develop all the cavities, cryomodules and associated subsystems (helium vessels, slow and fast mechanical tuners, power couplers, solenoids, quadrupoles, dipoles magnets and instrumentation).

Fermilab would collaborate with Indian Institutions in developing and sharing the complete technical project specifications, technical designs and project execution plans, as well as quality control (QC) and quality acceptance (QA) documents for each of these elements. These accelerator and component designs are one of the deliverables from the US DOE laboratory Fermilab to the Indian DAE laboratories.

Section	Freq. (MHz)	Energy (MeV)	Cav/mag/CM	Gradient (MV/m)	Q_0@2K (10^{10})	CM Configuration	CM length (m)
HWR (β_G=0.11)	162.5	2.1-10	8 /8*/1	8.2	0.5	8 x (sc)	5.8
SSR1 (β_G=0.22)	325	10-35	16 /8*/ 2	12	0.8	4 x (csc)	5.2
SSR2 (β_G=0.47)	325	35-185	35 /21*/ 7	11.4	1.0	sccsccsc	6.5
LB650 (β_G=0.61)	650	185-500	33 /22**/ 11	16.6	1.5	fdcccfd	7.1
HB650 (β_G=0.92)	650	500-1000	42 / 16**/ 7	17	2.0	fdccccccfd	9.5

*Superconducting solenoids, **Warm doublets external to cryomodules

Table 2. Present configuration of the number of cavities and cryomodules in the 800 MeV PIP-IIlinac. In CM (Cryomodule) configuration s is solenoid, c is cavity, f is focusing magnet and d is defocusing magnet.

DAE laboratories working toward dressed cavity fabrication would a) procure raw niobium, b) fabricate cavities, c) chemically surface treat the cavities utilizing a jointly agreed upon processing and treating procedure, d) perform low-power performance tests in the vertical test stand at 2 K, and install the jointly developed e) helium vessels, f) slow and fast mechanical tuners to the cavities, g) power couplers and h) perform full power tests at 2 degrees Kelvin.

DAE laboratories would fabricate cryomodule parts and the cavity support system. This element includes cryomodule vacuum vessels, magnetic and thermal shields, interconnecting piping, insulation, cavity and magnet supports and adjusting mechanisms, heat exchangers, cavity vacuum systems and connections to the pressure relief and cryogenic systems. All of these research, design and development including prototype testing are expected to be finalized by December 2018 at the conclusion of the current Research and Development phase.

6.1 325 MHz Dressed SSR1

Acceleration from 10.3 to 35 MeV utilizes superconducting SSR1cavities. The SSR1 cryomodule design contains eight cavities and four solenoid magnets. The overall cryomodule length is approximately 5.2 m.

Inter-University Accelerator Centre (IUAC) has finished the fabrication of 2 SSR1 cavities using the design and Niobium provided by Fermilab. IUAC working with a local institute has developed all the necessary tooling for the fabrication of SSR1 cavities. IUAC has followed a fabrication procedure in which all the Nb pieces are electro-polished before e-beam welding. Both the cavities have been sent to Fermilab for processing and vertical testing. DAE laboratories will fabricate Helium Vessel and Tuners using the design and drawings provided by Fermilab and send them to Fermilab, for dressing and high power testing. These two cavities will be dressed at Fermilab using the above Helium vessels and Tuners provided by DAE laboratories.

Milestone	Major Milestone	Quantity	Delivery date	Remarks
1	Fabrication of SSR1 Cavities	2	31 Mar 2015	Done
	Delivery of SSR1 cavities	2	30 April 2015	Done
	Processing and Vertical Testing of SSR1 Cavities by Fermilab/ANL	2	31 Aug 2015	
2	Fabrication of Helium Vessel	2	31 Dec 2016	# 1
	Fabrication of Tuner	2	31 Jul 2016	# 2

1 Design and fabrication drawings to be provided by Fermilab by 31 Dec 2015.

2 Design to be provided by Fermilab.

6.2 325 MHz Dressed SSR2

Acceleration from 35 to 185 MeV utilizes superconducting SSR2 cavities. The quadrupole fields from these cavities are compensated by focusing magnets and corrector coils that have independent leads. The SSR2 cryomodule comprises five dressed cavities and three solenoids. The overall cryomodule length is about 6.5 m.

DAE laboratories have initiated the design of SSR2 cavities using the Functional Requirements Specification (FRS) provided by Fermilab. Following a joint review of the design, DAE laboratories will fabricate 2 SSR2 cavities. The first two cavities will be sent to Fermilab for processing and vertical testing. Fermilab will procure and make payments towards cost of all the niobium and materials required for the fabrication of the first two SSR2 cavities and provide the same to DAE laboratories.

Milestone	Major Milestone	Quantity	Delivery date	Remarks
1	Development of SSR2 Design, and review		30June 2016	# 3
2	Fermilab will supply Nb, SS and Ti for SSR2	2	31 Dec 2015	
3	Fabrication of SSR2 Cavities	2	31 Dec 2017	
4	Processing and Vertical Testing of SSR2 cavities at Fermilab	2	30 June 2018	

3 Subject to inputs from Fermilab by 30 September 2015.

6.3 650 MHz Dressed Cavity and Cryomodule

Two different types of 650 MHz cavities and cryomodules are being developed for the superconducting linac. Acceleration from 185 to 500 MeV utilizes superconducting 650 MHz, beta = 0.61 cavities with cell dimensions shortened for low-beta operation. The LB650 Cryomodule design contains three cavities. The overall cryomodule length will be approximately3.5 m.

Acceleration from 500 to 800 MeV utilizes superconducting 650 MHz, beta = 0.92 cavities. The HB650 Cryomodule design contains six cavities with no magnets, focusing and corrector magnets being at room temperature between cryomodules. Cryomodule length will be approximately9.5 m.

650 MHz Dressed LB650 MHz cavity: DAE laboratories have developed complete design of a LB650 MHz cavity and is proceeding to fabricate a 1-cell cavity. The 1-cell LB650 cavity will be processed and vertical tested at Fermilab. DAE laboratories will proceed to complete the design of 5-cell LB650. After a joint review of the design DAE laboratories will fabricate a total of two LB650 cavities.

DAE laboratories and Fermilab will work together in finalizing the design of the End Group, its interface to Helium Vessel, Helium Vessel with magnetic shield, Mechanical Slow and Fast Tuners.

The above two 5-cell cavities will be processed, vertical tested and then dressed with Helium vessel, End Group, Slow and Fast Tuners and Power Couplers. These sub-components are described in subsequent sub-section and these sub-components will be made available to the concerned DAE laboratories for dressing. The dressed LB650 cavities will be High Power tested at Fermilab.

Milestone	Major Milestone	Quantity	Delivery date
1	Fabricate 1-cell LB650 Cavity	1	30 September 2015
	Process and test 1-cell LB650 Cavity at Fermilab		30 Nov 2015
2	Finalize the design of 5-Cell LB650 Cavity		31 Dec 2015
3	Design review of 5-cell LB650 Cavity		31 Jan 2016
4	Fabrication of 1^{st}5-cell LB650 Cavity	1	31 Dec 2016
	Processing and Vertical testing of 5-cell Cavity		30 Jun 2017
	Dressing LB650 Cavity		31 Dec 2017
	Testing of 1^{st}5-Cell Dressed LB650 at Fermilab		31 Mar 2018
5	Fabrication of 2^{nd}5-cell LB650 Cavity	1	30 Sept 2017
	Processing and Vertical testing of 5-cell Cavity		31 Mar 2018
	Dressing LB650 Cavity		30 Sept 2018
	Testing of 2^{nd}5-Cell Dressed LB650 at Fermilab		31 Dec 2018

650 MHz Dressed HB650 MHz cavity: Fermilab has finalized the base design of 5-cell HB650 MHz cavity and has shared that design with DAE laboratories. DAE laboratories have fabricated two 1-cell cavities based on this cavity shape. One 1-cell cavity has been processed and tested at Fermilab. It has reached the PIP-II design gradient of ~20 MV/m. DAE laboratories have also fabricated a 2^{nd} 1-cell cavity that is under processing and testing at DAE laboratories.

Based on the design provided by Fermilab, DAE laboratories will fabricate one 5-cell HB650 Cavity with end groups. Subsequent to a successful test of this first 5-cell dressed cavity, DAE laboratories will fabricate three more similar cavities. Thus a total of four 5-cell dressed HB650 cavities will be developed.

DAE laboratories and Fermilab will work together in finalizing the design of the End Group, its interface to Helium Vessel, Helium Vessel with magnetic shield, Mechanical Slow and Fast Tuners.

DAE laboratories are establishing an extensive SRF infrastructure. It is expected that most of the cavities produced by DAE laboratories will be processed, vertically low power tested, Dressed and Horizontally high power tested at DAE laboratories. The cavities will be built-to-print on best effort basis.

Milestone	Major Milestone	Qty	Delivery date	Remarks
1	Fabricate 5-cell HB650 Cavity	1	30 Sept 2016	# 4
	Process and test 5-cell HB650 Cavity at DAE laboratories		31 March 2017	
	Dressing of 5-cell HB650		31 Oct 2017	
	Testing of 5-cell dressed HB650 at DAE laboratories/Fermilab		31 March 2018	# 5
2	Fabrication, Processing, Vertical Testing, dressing and high power testing of 5-cell HB650at DAE laboratories	1	30 Sept 2018	
3	Fabrication, Processing, Vertical Testing, dressing and high power testing of 5-cell HB650 at DAE laboratories	2	31 Dec 2018	

4 Subject to supply of design and drawings by Fermilab to DAE laboratories by 31 December 2015.

5 Subject to operationalization of integrated HTS-2 at DAE laboratories by 30 September 2017.

6.4 Helium Vessel and Cavity End Group

DAE laboratories and Fermilab will work jointly to evolve specification, and to carry out design, prototype and eventual fabrication and testing of Helium Vessel for various (SSR1, SSR2, LB650 and HB650) cavities. The Helium vessel design will also include its interface to the Cavity, in the case of LB650 and HB650 cavity end groups.

Milestone	Major Milestone	Quantity	Delivery date	Remarks
1	Design of SSR1 Helium Vessel		Done	# 6
	Design of SSR2 Helium Vessel		30 June 2016	
	Design of LB650 Helium Vessel		31 December 2015	
	Design of HB650 Helium Vessel		31 December 2015	
2	Design of 5-cell LB650 End Group		31 December 2015	# 6
	Design of 5-cell HB650 End Group		31 December 2015	

3	Fabrication of SSR1 Helium Vessel	2	31 March 2017	# 7
	Fabricate SSR2 Helium Vessel	2	31 March 2018	
	Fabrication of 5-cell LB650 Helium Vessel and its interface to the end group at DAE laboratories	2	30 Sept 2017	
	Fabrication of 5-cell HB650 Helium Vessel and its interface to the end group at DAE laboratories	4	30 April 2017	

6 Milestones at 1 and 2 are deliverables from Fermilab.

7 Subject to supply of design inputs from Fermilab by 31 December 2015.

6.5 Slow and Fast Tuner

Each cavity utilizes a mechanical (slow) and piezo (fast) tuner to keep the cavity frequency in tune with the respective radio-frequency source and to compensate for Lorentz-Force Detuning and microphonics. The system includes both the mechanical parts and a cryogenic motor.

DAE laboratories and Fermilab will work jointly to evolve specification, and to carry out design, prototype and eventual fabrication and testing of Slow and Fast Tuner for various (SSR1, SSR2, LB650 and HB650) cavities. The Tuner design will also include its interface to the Cavity. In the case of LB650 and HB650 cavity, the tuners are expected to be installed at non-coupler end groups.

Milestone	Major Milestone	Quantity	Delivery date	Remarks
1	Design of SSR1 Slow and Fast Tuner		Done	# 8
	Design of SSR2 Slow and Fast Tuner		30 June 2016	
	Design of LB650 Slow and Fast Tuner		31 March 2016	
	Design of HB650 Slow and Fast Tuner		31 March 2016	
2	Design of 5-cell LB650 Tuner interface		31 March 2016	# 8
	Design of 5-cell HB650 Tuner interface		31 March 2016	

3	Fabricate SSR2 Tuner	2	30 June 2018	# 9
	Fabrication of 5-cell LB650 Tuner, motor, readout and its interface to the end group at DAE laboratories	2	30 Sept 2017	
	Fabrication of 5-cell HB650 Tuner, motor, readout and its interface to the end group at DAE laboratories	4	30 Sept 2017	

8 Milestones at 1 and 2 are deliverables from Fermilab.

9 Subject to supply of design inputs from Fermilab by 31 March 2016.

6.6 Power Couplers

The power coupler is used to couple the RF power source at room temperature to a superconducting cavity at 2 K. The power coupler functional and technical specifications and technical design would be jointly developed.

DAE laboratories and Fermilab will work jointly to evolve specification, and to carry out design, prototype and eventual fabrication, conditioning and testing of couplers for 325 MHz Single Spoke Resonator cavities and 650 MHz elliptical cavities, and their instrumentation. The collaboration will leak check, and will perform RF and mechanical measurements and conditioning as well as full-power testing of these couplers.

The 325 MHz couplers will be operated at a maximum power of 20 kW (SSR2 requirement) but should be tested at 40 kW. Similarly the 650 MHz couplers will be operated at a maximum power of 70 kW (HB650 requirement) but should be tested at 120 kW. The testing of both types of power couples will be carried out at Fermilab.

Milestone	Major Milestone	Quantity	Delivery date
1	Design of 325 MHz Power Coupler		Done
	Design of 650 MHz Power Coupler		31 May 2016
2	Fabrication of 325 MHz Power Coupler	3	31 Dec 2016
	Fabrication of 650 MHz Power Coupler	6	30 Jul 2017

6.7 Magnets (Superconducting Solenoid and Warm)

The superconducting linac design utilizes eight different types of magnets matched to the momentum of the particles in that section of the linac. DAE laboratories and Fermilab will work jointly in evolving specification of these magnets. DAE laboratories will design, prototype and eventually fabricate and test the various (SSR1, SSR2, LB650 and HB650) magnets. The Spoke Resonator Cryomodules will utilize Superconducting Solenoid Magnet. The design and a prototype of a SSR1 solenoid magnet exist at Fermilab. DAE laboratories will design and develop the superconducting solenoid magnet along with its correctors and shielding coils for the SSR2 cavities. There will be no magnets within the LB650 and HB650 cryomodules; warm correction dipoles and quadrupole magnets will be located outside these cryomodules. DAE laboratories are also working on warm magnets for the MEBT of PIP-II/PXIE.

Milestone	Major Milestone	Quantity	Delivery date
1	Design of 325 MHz (SSR2) CM Solenoid Magnets		30 Jun 2016
	Design of 650 MHz CM Warm Magnets		31 July 2016
2	Fabrication and testing of 325 MHz CM Solenoid Magnet	4	31 Dec 2017
	Fabrication and testing of 650 MHz Warm Magnet	2	31 Dec 2017

6.8 Superconducting Cryomodule Design

The superconducting linac design utilizes four different types of cryomodule one each for SSR1, SSR2, LB650 and HB650 cavities.

The SSR1 Cryomodule has been designed by Fermilab with engineering help from DAE laboratories. DAE laboratories will design the SSR2 cryomodule, which will be derived from SSR1 CM design.

Fermilab and DAE laboratories have been working jointly on the design of 650 MHz cryomodule. The proposed new concept of the elliptical cavities cryomodule is similar to the SSR1 cryomodule. Details of this design needs to be developed.

Cryomodule hardware is not a deliverable for DAE laboratories during the R&D Phase.

Milestone	Major Milestone	Quantity	Delivery Date	Remarks
1	Design of 325 MHz SSR1 Cryomodule		Done	
2	Design of 325 MHz SSR2 Cryomodule by DAE laboratories and Fermilab		31 Jan 2018	# 10
3	Technical requirement specification (TRS) by Fermilab		31 Oct 2015	
4	Design of 650 MHz LB/HB Cryomodule DAE laboratories and Fermilab		28 Feb 2017	

10 Subject to supply of SSR1 Cryomodule design by Fermilab by 30 September 2015.

7. Radio-Frequency (RF) Power Systems

7.1 RF Power

The PIP-II linac will have one RF amplifier per cavity. The radio-frequency quadrupole (RFQ), buncher, half-wave resonator (HWR), single-spoke resonator (SSR1 & SSR2) and low-beta and high-beta elliptical (LB650 & HB650) RF systems will utilize continuous wave (CW) amplifiers. However, in PIP-II all amplifiers downstream of the HWR will be operated initially in pulsed mode. There are three frequencies of operation, 162.5 MHz (HWR), 325 MHz (SSR1 & SSR2) and 650 MHz (LB650 & HB650). The power levels for 325 MHz Solid State RF Amplifier are 7 kW (SSR1) and 20 kW (SSR2). Only 7 kW units are deliverable during the R&D phase. The power level for 650 MHz Solid State RF Amplifiers are 40 kW (LB650) and70 kW (HB650). Only 40 kW units are deliverable during the R&D phase.

Two cryomodules at 325 MHz will be populated with eight SSR1s powered by 7 kW solid-state amplifiers. 20kW solid-state amplifiers will power seven SSR2 cryomodules with five cavities each. 11 LB650s cryomodules with 3 cavities each will be powered by a 40kW amplifier. 4 HB650 cryomodule with 6 cavities each will be powered by a 70kW amplifier.

The low-level RF (LLRF) system will provide a drive signal to each RF power amplifier. The amplifier(s) will provide sample signals of the pre-driver and final outputs. All amplifiers will be self-contained units complete with integral power supplies, protection circuits and control interfaces. Each RF system consists of a Solid State Amplifier, a circulator and load to isolate the cavity from the power amplifier. This level of protection is essential in SRF systems due to full power reflection from the cavity in the absence of beam. Circulators and RF loads are not part of the deliverables in the R&D phase.

All of the RF amplifiers will be water cooled to ensure reliable operation and to minimize the heat load to the building HVAC (Heating, Ventilation and Air Conditioning) system. Cavity and drive sample signals will be provided to the LLRF for vector regulation and frequency control of the cavities. The collaboration would jointly develop the design specifications for the solid state RF amplifiers, including the LLRF and RF protection systems.

DAE laboratories would lead the technical design effort for high-level RF amplifiers based on Functional Requirements and Interface Specifications provided by Fermilab, and would make the complete design of the system available to Fermilab for post-project fabrication and maintenance. Fermilab will provide the technical design of the LLRF and RF protection system and will work with DAE laboratories to upgrade the system to current firmware.

During the R&D Phase, DAE laboratories will develop a 325 MHz RF System that will be used in commissioning of the SSR1 Cryomodule at PXIE, 650 MHz RF System that will be used in commissioning of HTS-2 at Fermilab and for testing of IIFC built HB650 CM at Fermilab CMTS. One more 650 MHz RF System will be developed for HTS-2 at DAE laboratories. It is also expected that DAE laboratories staff together with Fermilab staff will participate in this integration activities.

Fermilab's schedule for testing of the SSR1 CM at PXIE would require eight 325 MHz 7 kW RF power sources by end of Sept 2017.

Milestone	Major Milestone	Quantity	Delivery date
1	Design of 325 MHz 7 kW RF System		Done
	Design of 325 MHz 10 kW RF System		Done
	Design of 650 MHz 30 kW RF System		Done
	Design of 650 MHz 40 kW RF System		31 Dec 2015
2	Fabrication and testing of 2 nos. of 40 kW, 650 MHz RF System for HTS-2 for Fermilab and 2 nos. for HTS-2 for DAE laboratories.	4	30 June 2017
	Fabrication and testing of 8, 7kW, 325 MHz RF System for SSR1 CM at PXIE, Fermilab	8	31 Oct 2017
	Fabrication of 6, 40 kW 650 MHz RF System for CMTF being fabricated by DAE laboratories for Fermilab	6	31 Jan 2018

7.2 RF Interlocks

The scope of RF interlocks is system protection. The systems may include solid state amplifiers, a modulator, isolators, circulators, couplers, coupler windows and RF cavities. The role of the RF interlocks is to allow the system to operate within nominal parameters and inhibit system operation outside these parameters.

The RF protection system will be used at CMTF, HTS-2, and all Cryomodules. One RF protection system design can be used in all three types of systems with minor modifications or deletion of monitored signals.

The RF protection system can be used in pulsed mode and/or CW mode. Its primary function is to inhibit the fast GaAs RF switches through which LLRF power is delivered to the solid state amplifiers connected to couplers through waveguides. The signal controlling the fast RF switch is generated by the RF interlock system by monitoring flow of RF power at the outputs of the power amplifiers as well as input to all couplers. The RF interlock system must be capable of opening the RF switch within 500 nanoseconds from the time any of the reflected power levels exceed a pre-determined level.

Also contributing to controlling the RF switch are signals from photo-multiplier tubes and field emission probes. The response time to the presence of signals in these devices can fall within the 500 nanosecond window.

Signals derived from temperature monitors at the couplers and vacuum of the cryomodule also are responsible for opening the RF switch, inhibiting the LLRF signal path. These types of signals are slower in changing but once reaching a pre-determined level the system should respond in the prescribed time frame by opening the RF switch.

The RF interlocks digitizes all analog signals during the time the RF power is delivered to the cryomodule. It also must inhibit the RF amplifiers when PMT trips, Field emission trips, or reflected power trips occur immediately after recovering from previous trips.

Fermilab has provided the complete design of the current system in operation at Fermilab.DAE laboratories and Fermilab have jointly developed the architecture of a new system. Design, development and testing of this system will be done by DAE laboratories.

Milestone	Major Milestones	Quantity	Delivery date
1	Design of RF Protection Interlock System		Done
2	Prototype testing of the RF Protection System at DAE laboratories	1	30 Sept 2015
	Testing of the RF Protection System at CMTS, build by DAE laboratories and installed at Fermilab	1	31 Dec 2015
3	Development of RF Protection System for the DAE laboratories and Fermilab Horizontal Test Stands.	2	31 Oct 2016
4	Development of RF Protection System for the SSR1 Cryomodule being developed by Fermilab	1	31 Dec 2017
	Development of RF Protection System for CMTF being built by DAE laboratories for Fermilab	1	31 July 2018

7.3 Low-Level Radio Frequency (LLRF) Control System

The LLRF is the most crucial element for the successful and efficient operation of any accelerator. The low-level RF cavity control systems will be grouped by pairs of cryomodules, allowing a maximum of 16 cavities to be controlled from two relay racks of a LLRF unit.

Fermilab would provide the complete design of the current LLRF system in operation at Fermilab, including the software and its interface to the accelerator controls. DAE laboratories and Fermilab would jointly develop the new system.

Milestone	Major Milestone	Quantity	Delivery date	Remarks
1	Initial Design Specification of LLRF System		30 Sept 2015	
2	Prototype of the LLRF System for Horizontal Test Stand being developed by DAE laboratories for Fermilab	1	30 Sept 2016	# 11
3	Development of Prototype LLRF System for the Horizontal Test Stand being developed by DAE laboratories for DAE laboratories and Fermilab.	2	31 Oct 2016	
4	Development of a new LLRF System for the SSR1 Cryomodule being developed by Fermilab	1	31 Dec 2017	
	Development of a new LLRF System for the CMTF being developed by DAE laboratories for Fermilab	1	31 July 2018	

11 Subject to design input from Fermilab by 31 Dec 2015.

8. Development of the Fermilab and DAE Laboratories Infrastructure

Fermilab is already working with DAE laboratories to develop infrastructure at collaborating laboratories. Following test facilities will be developed jointly.

8.1 Horizontal Test Stand

The Horizontal Test Stand (HTS-2) is used to test dressed elliptical cavities before it would be installed in a Cryomodule string. Fermilab and DAE laboratories have jointly developed and reviewed the design of HTS-2 cryostat. DAE laboratories and Fermilab will jointly develop control system for HTS-2. Two cryostats for HTS-2 will be fabricated and integrated at DAE laboratories jointly by Fermilab and DAE laboratories. After integration, the first one will be delivered to Fermilab and the second will be used by DAE laboratories. Fermilab will supply all the necessary software and hardware required for integration and operationalization of both HTS-2 for Fermilab and DAE laboratories.

Milestone	Major Milestone	Quantity	Delivery date
1	Design of HTS-2 Cryostat		Done
	Review of HTS-2 Cryostat Design		Done
	Procurement Review of HTS-2 Cryostat Design		Done
2	Fermilab to supply necessary software and hardware required for integration of HTS-2	2 sets	31 Dec 2015
3	Fabrication of HTS-2 Cryostats, one for Fermilab and one for DAE laboratories	2	31 Dec 2016
4	Development of controls for HTS-2	2 sets	31 Dec 2016
5	Integration of first HTS-2 Cryostat at DAE laboratories and delivery to Fermilab	1	31 July 2017
6	Integration of HTS-2 cryostat for DAE laboratories	1	30Sept 2017

8.2 Cryomodule Test Stand

The Cryomodule Test Stand (CMTS) is used to test a completed cryomodule before it would be installed in an accelerator. Fermilab has proposed to build three CMTS for the PIP-II construction. Fermilab has designs for most of the subcomponents needed for the fabrication of a CMTS, but an integrated design needs to be developed. Fermilab has shared subcomponent designs with DAE laboratories for the CMTS design. DAE laboratories working with Fermilab cryogenic department has developed a new design for the 1.3 GHz CMTS(Feed Cap, End Cap, Feed Box, Cryogenic distribution etc.) for installation and commissioning at Fermilab.

Based on the experience gained during the design, fabrication and commissioning of the CMTS, the DAE laboratories team will jointly work with Fermilab in developing specification and design of a 650 MHz cavity Cryomodule Test Facility (CMTF). The CMTF will consist of a 650 MHz Cryomodule Test Stand, Six 40 kW 650 MHz Solid State RF Amplifiers, Circulator, RF Protection, Low Level RF and Control Application.

The integrated CMTF will be tested at DAE laboratories and delivered to Fermilab for installation and commissioning. DAE laboratories may build additional CMTF for the Indian accelerators.

Milestone	Major Milestone	Quantity	Delivery date	Remarks
1	1.3 GHz CMTS Feed Cap	1	Done	
	1.3 GHz CMTS End Cap	1	Done	
2	1.3 GHz CMTS Feed Box	1	31 Mar 2016	
	1.3 GHz CMTS Cryo-distribution	1	31 Mar 2016	
3	Development of CMTF design Document for 650 MHz Cryomodule		31 Dec 2016	# 12
4	Review of CMTF Design		31 Mar 2017	
5	Fabrication of CMTF Cryostat	1	31 Mar 2018	
6	Development of CMTF Controls	1	31 Mar 2018	
7	Integration of CMTF Systems without cryostat	1	31 July 2018	
8	Delivery of Integrated CMTF System to Fermilab	1	31 Dec 2018	

#12 : Subject to supply of FRS and TRS by Fermilab for 650 MHz CMTF by 31 Oct 2015.

9. PXIE Accelerator Installation, Integration and Commissioning

Scientific and engineering staff of the collaborating DAE laboratories will participate in the installation, integration and commissioning and testing of the Fermilab front end systems of PXIE. Fermilab will provide local support for the visiting DAE laboratories staff. The information generated during these phases will be available to DAE laboratories for use at a later date.

10. Deliverables from Fermilab

The HISPA design, technology and supporting infrastructure knowledge related to the activities described in this document and some hardware and software as indicated at specific places in the document will be deliverables from Fermilab to DAE laboratories during the R&D phase.

11. Schedule

The IIFC has jointly developed a schedule for the research, design, prototyping and construction of the components during the R&D phase as described in this document. It is understood that we are in the early stage of the design process. The collaboration expects to finalize most of the R&D by end of CY 2018.

Fermilab working with DAE laboratories will prepare a table of information detailing the components (hardware as well as software), along with their specifications and quantities, required for various sub-systems covered in this document, and give it to DAE laboratories by

30 September 2015. Fermilab will also provide FRS (Functional Requirements Specification), TRS (Technical Requirements Specification) and design and drawings of various sub-systems. The schedules given in this document are subject to timely receipt of all relevant inputs from Fermilab.

Technical Coordinators will identify Sub-Project Coordinators for every component/system. The Sub-Project Coordinators in each side will interact directly with their counterparts. However, clearances for every milestone will be given by the Technical Coordinator in each side.

It is understood that this is an R&D project and all the technical progress may not happen as planned. The schedule would be adjusted as we progress through this joint project and the progress made during the R&D phase. The progress will be jointly reviewed by IIFC Management on a quarterly basis and schedule could be adjusted by the signatories in March of every year.

12. Reference

1. PIP-II, RDR, version 1.00, 3/02/2015, http://pip2-docdb.fnal.gov/cgi-bin/RetrieveFile?docid=1&filename=PIP-II_RDR_v0.0.pdf&version=1

13. Approvals

This Joint Project Document for the R&D phase of IIFC under the framework of Project Annex – I to the Implementing Agreement between DAE, India and DOE, U.S.A is signed below. Subsequent to signing this document, the work described in this document will be managed by the Directors of BARC and Fermilab.

FOR THE DEPARTMENT OF ATOMIC ENERGY OF THE REPUBLIC OF INDIA

Sekhar Basu

Sekhar Basu, Date: August 28, 2015
Director, BARC
(Principal Coordinator)

FOR THE DEPARTMENT OF ENERGY OF THE UNITED STATES OF AMERICA

James Siegrist

Jim Siegrist, Date: August 28, 2015
Associate Director, HEP, US-DOE
(Principal Coordinator)