RF Power

David Peterson, James Steimel

DOE Independent Project Review of PIP-II

15 November 2016

Outline

- Background
- Construction phase scope of work
- R&D phase goals
- R&D status
- R&D schedule to complete
- R&D milestones and delivery goals
- R&D division of responsibility between Fermilab and DAE
- Summary

RF Power - Managers

David Peterson, PIP-II RF Power, Level 3 Manager – Since Oct 2016

Electrical Engineer – MSEE 1983, University of Illinois, Urbana

- IBM – Electron Beam Lithography
- Fermilab –
  - 1984 Tev I Project -> Antiproton Source
    - Microwave & RF Systems engineer for Stochastic Cooling, RF, beam instrumentation, interlocks, controls integration
    - Loma Linda Medical Accelerator instrumentation
    - Engineering Group Leader
    - PET Helium3 Linac RF and vacuum controls
    - SSR1, Coupler Test and HINS RF & Interlocks at MDB
  - 2011 AD/RF
    - Engineering Group Leader
    - PIP-II RFQ amplifier initial cost estimates
    - MuCool MTA test area cavity conditioning system
    - Pbar Rings conversion to Muon Campus, Muon Campus RF and instrumentation support
    - PIP-II Injector Test RF systems integration and support

Jim Steimel, PIP-II Project Electrical Engineer

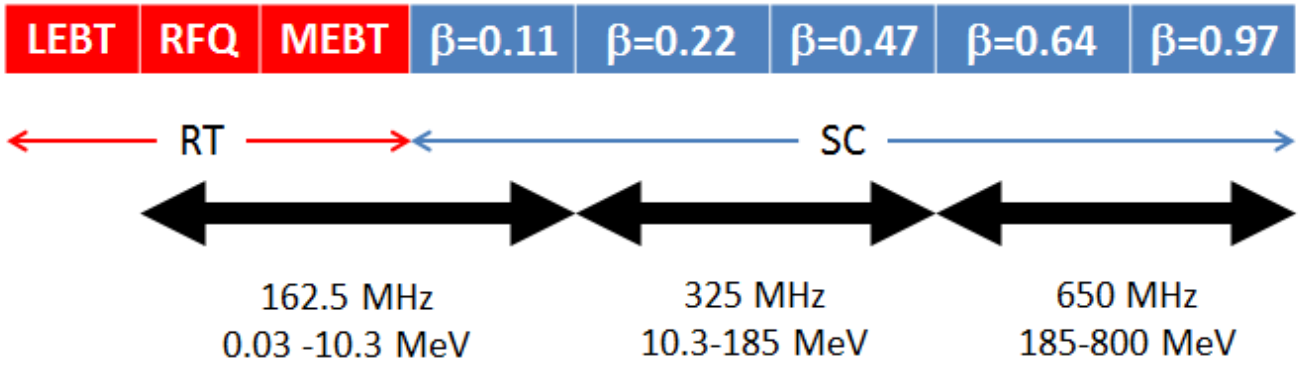
Fermilab Electrical Engineer – MSEE 1991, University of Michigan, Ann Arbor

- 1991 AD/Booster
  - RF Systems engineer for Booster RF systems.
  - Designer of high bandwidth, beam stability control systems for Booster, Main Ring, and Main Injector.
- 1996 AD/Luminosity Upgrades
  - Designer of beam stability control systems for the Tevatron.
  - Coordinate proof-of-principle experiment for slip stacking in Main Ring.
- 1998 AD/Tevatron
  - Instrumentation group leader.
  - Coordinated upgrade of Tevatron BPM processing system.
  - Continued design and maintenance of beam stability control for Tevatron.
  - Designed and implemented beam loading compensation control for Main Injector RF.
- 2009 AD-APC/HINS
  - Deputy department head for construction of a linear accelerator for testing the proof-of-principle of running a linear accelerator from a single RF source.
  - Commissioned 50mA proton ion source, 2.5 MW klystron, 500 kW - 2.5 MeV RFQ, and 6-spoke cavity MEBT beam line.
- 2012 AD/SRF-Proton
  - Chief electrical engineer for PXIE beam line.
  - Managed construction and commissioning of RFQ and cavities for PXIE beam line.
- 2015 AD/PIP-II
  - Chief electrical engineer for PIP-II.
  - IIFC liaison for Level III manager of PIP-II RF Power (Dave Peterson).

Construction Phase - Scope of Work

"**RF Power**" includes

- Amplifiers
- Circulators
- RF Distribution
  - Coax transmission lines and waveguide
  - Connectors, elbows, adapters, etc.
  - Directional Couplers
  - Loads
- Controls & Interlocks (where not otherwise provided)
  - Reflected power and RF leakage detection
  - Interface to Accelerator Control Network



Construction Phase - Amplifiers

Section	Num of ampl	Freq (MHz)	Power (kW)	Duty
RFQ	2	162.5	75	CW
Buncher	3	162.5	3	CW
HWR	1	162.5	3	CW
HWR	7	162.5	7	CW
SSR1	16	325	7	Pulse/CW
SSR2	35	325	20	Pulse/CW
LB650	33	650	40	Pulse/CW
HB650	24	650	70	Pulse/CW

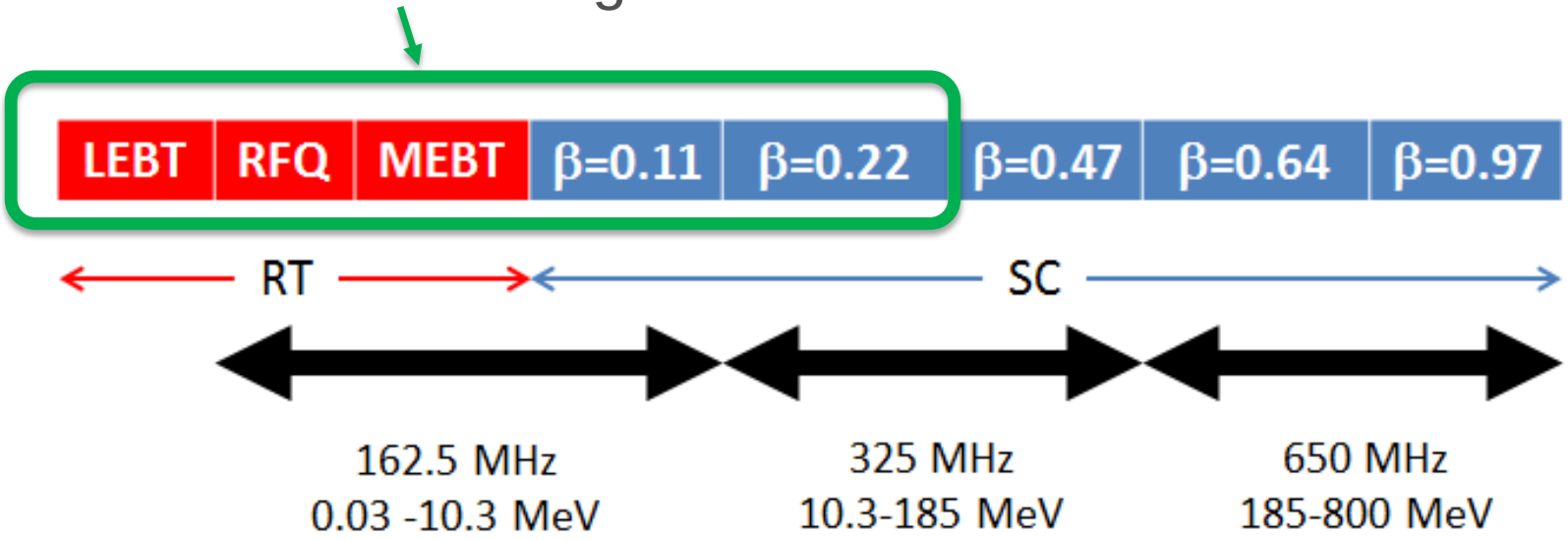
= Room Temperature Cavities

= Superconducting Cavities

V. Lebedev, FNAL, The PIP-II Reference Design Report

R&D Phase - Scope of Work

- Linac RF Power through SSR1



- Additional Test Areas
  - 650 MHz RF Power for STC and Coupler Test Stand using Fermilab owned 30 kW IOT amplifiers
  - 650 MHz RF Power for HTS-2 and CMTS using RRCAT 40 kW Solid State Amplifiers

R&D Phase Goals

- FRONT END 162.5 MHZ RF POWER
  - Installation, Verification and Commissioning of 75 kW amplifiers for RFQ (Done)
  - PLC Interlocks
  - Installation & Verification of 3kW Amplifiers
  - Installation and Commissioning of 3kW Distribution
- SRF CAVITY 162.5 MHZ RF POWER
  - Procurement and Testing of 7kW Amplifiers
  - Procurement, Testing, and Commissioning of 7kW Amplifiers
- STC 650 MHZ POWER
- COUPLER TEST STAND 650 MHZ POWER

R&D Phase Goals cont'd

- 325 MHZ RF POWER AMPLIFIERS from BARC
  - 7 KW Power Amplifier
    - 325 MHz IIFC Liaison
    - Design of 325 MHz, 7 kW RF Power for SSR1 CM
    - First prototype constructed as per BARC design and jointly tested in India
    - Fabrication and testing of 8 Nos. of 7kW, 325 MHz RF System
  - Design and Installation of 325 MHz Distribution

- 650 MHZ RF POWER AMPLIFIERS from RRCAT
  - 40 KW Power Amplifier
    - 650 MHz IIFC Liaison
    - Design of 650 MHz, 40 kW RF Power for HTS-2 & CMTF
    - First prototype constructed & tested as per RRCAT design
    - Fabrication and testing of 2 Nos. of 40kW, 650 MHz RF System
    - Fabrication and testing of 6 Nos. of 40kW, 650 MHz RF System for CMTF
    - Design and Installation of 650 MHz Distribution HTS-2
    - Design and Installation of 650 MHz Distribution CMTS

R&D Status – RFQ Amplifiers

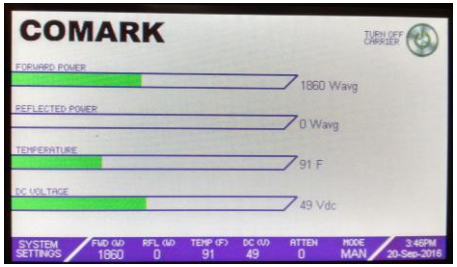
- SigmaPhi 162.5 MHz, 75 kW amplifiers for RFQ are operational.
  - First RF out of amplifier #1 Sept 2014 & #2 Nov 2014
  - First power to RFQ February 15, 2016
  - Over 29.8 million pulses and 368 hours of CW operation
  - Some failures
    - RF “Slices” had some poor solder and water tubing joints
    - 480VAC input terminals insufficiently torqued
    - Some intermittent CAN Bus and Ethernet communications
  - Work continues on the module and slice test stand.

SigmaPhi 162.5 MHz 75 kW Amplifiers

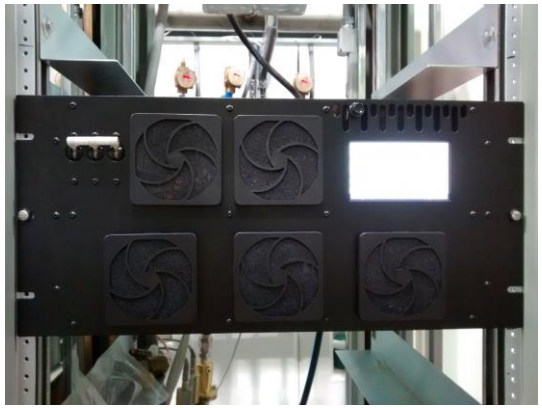
R&D Status - Amplifiers

Comark/Technalogix 162.5 MHz, 3 kW amplifiers

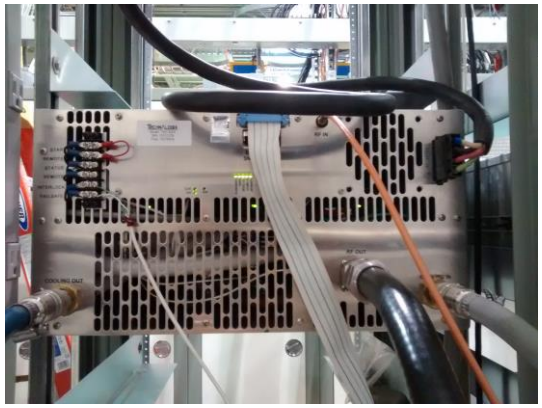
- RF performance meets specifications
  - Gain, Gain and Phase vs Power, 1dB Compression, Spurious and Harmonics, Pulse performance
  - >100 hour continuous duty burn-in at 2 kW
- Two amplifiers at Fermilab
  - Original version powering Buncher 1 Cavity.
  - Newer Version 2 combines RF and Power Supply units
- Control interface issues still being addressed
  - Some spurious trips of Carrier enable
  - Non-functional Carrier status bit



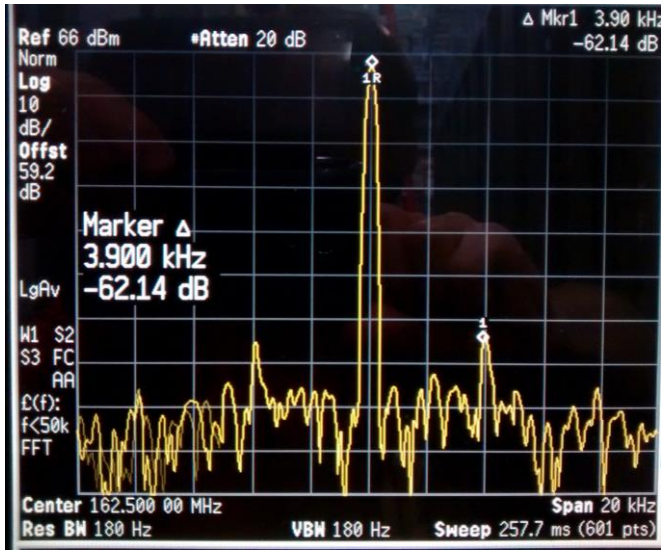
Front Panel Display



Comark/Technalogix
3 kW amplifier



Rear View



Spurious output: +/-3.9 kHz, -62.1 dBc.

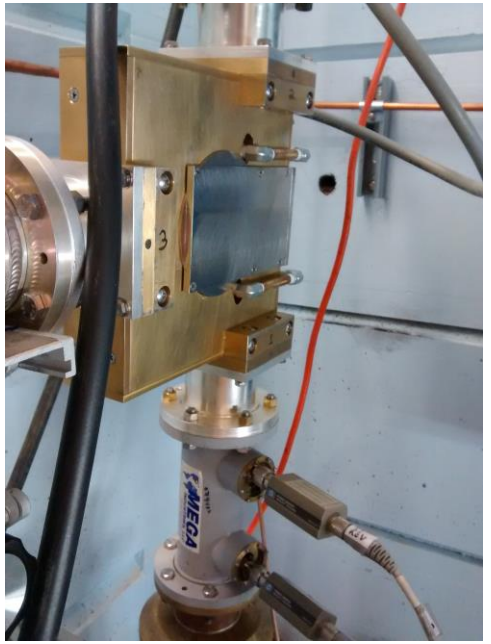
R&D Status - Circulators

- Comark provided UTE Circulator
  - Sufficient for Buncher cavities
  - Does not provide sufficient isolation for HWR operation: ~ 6 dB with short circuit

UTE 3 kW Circulator

UTE Circulator and Buncher 1 Cavity

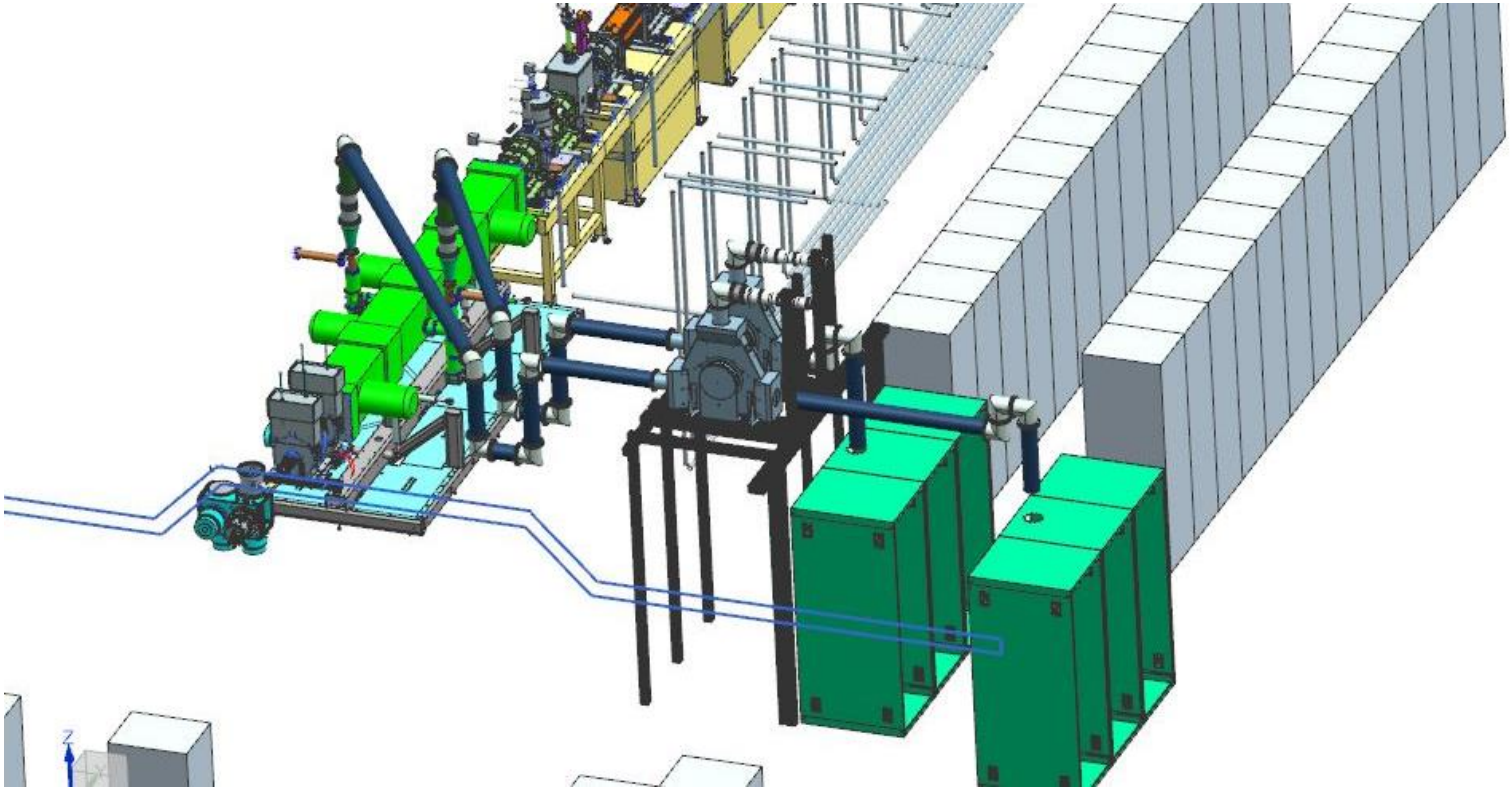
- McManus 162.5 MHz, 7 KW Circulator
  - Passed 3 kW and 7 kW tests
    - 7 kW Insertion loss <0.33 dB
    - Isolation 23.1 dB @ 162.5 MHz, >20 dB across 6 MHz BW
    - Short Circuit return loss 13.7 dB
  - Is a possible alternative for the UTE circulators in the 3 kW systems



McManus 7 kW Circulator Test

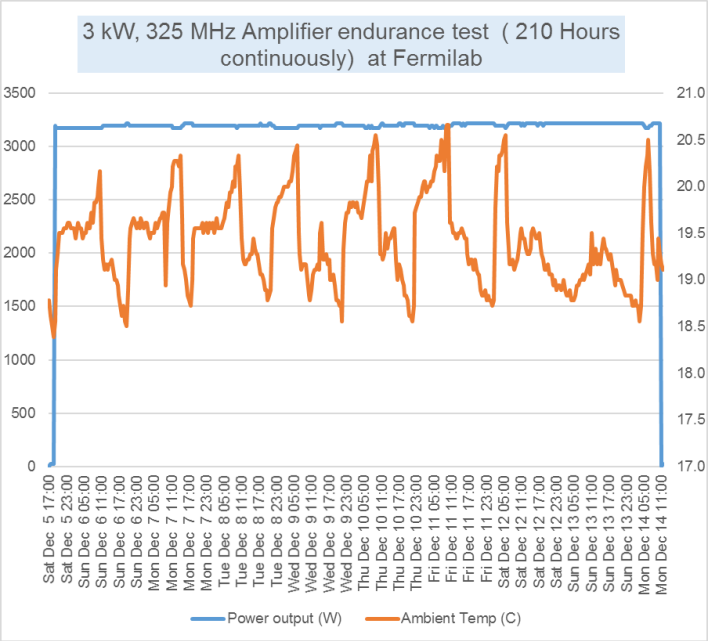
R&D Status – RF Distribution

RF Distribution in place for RFQ and Buncher 1.



R&D Status - 325 MHz RF Power Amplifiers

- A 3 kW Solid State RF Amplifier (SSRA) system was developed based on the old FRS (of Dec. 2010) by DAE and was jointly tested successfully at Fermilab in late 2015.



Plot of 9 days of continuous CW operation

BARC 325 MHz, 3 kW Amplifier at Fermilab

R&D Status - 325 MHz RF Power Amplifiers

- 7kW prototype based on original specifications already tested at BARC.
- New specifications based on experience with 3kW prototype complete.
- 7kW RF Power Amplifier TRS completed and approved June 2, 2016, in Teamcenter ED0004290-Rev A.

325 MHz, 7 kW Solid State Amplifier at BARC

R&D Status - 650 MHz RF Power Amplifiers

- 30 kW prototype based on early specifications constructed and tested.
- Design modifications for 40 kW prototype underway; final specifications nearly complete.
- 40kW, 650 MHz Solid State RF Power Amplifier TRS completed and approved Aug. 2016 in Teamcenter ED0005489-Rev (-).

650 MHz, 30 kW Amplifier at RRCAT

R&D IIFC Schedule to complete

	Q1CY16	Q2CY16	Q3CY16	Q4CY16	Q1CY17	Q2CY17	Q3CY17	Q4CY17	Q1CY18	Q2CY18	Q3CY18	Q4CY18	Q1CY19	Q2CY19	Q3CY19	Q4CY19
325 MHz RF Power																
Technical Requirement Specifications		★														
Design of SSRA				★												
Fabrication of 1st Prototype & Certification							★									
Delivery of 9, 7 kWatt Unit to Fermilab										★						
RF Power system Ready for 1st SSR1 Cryomodule												★				
650 MHz RF Power																
Technical Requirement Specifications			★													
Design of SSRA				★												
Fabrication of 2 units for HTS2 & Certification											★					
RF Power system (SSRA, RFPI and LLRF) Ready for HTS2												★				
Delivery of 7, 40 kWatt Unit to Fermilab														★		
RF Power system (SSRA, RFPI and LLRF) Ready for HB650																★

R&D RF Power Milestones and Delivery Goals

Major Milestone	Qty	Delivery date
Complete commissioning of 162.5 MHz, 75 kW RF Systems (RFQ)	2	Q2-FY16
Complete commissioning of 162.5 MHz, 3 kW RF Systems (MEBT & HWR)	5	Q2-FY17
Delivery of 162.5 MHz, 7 kW RF Amplifiers (HWR)	8	Q4-FY18
Commissioning of 650 MHz, 30 kW RF system for STC	1	Q1-FY18
Fabrication and testing of 650 MHz, 30 kW RF System for coupler testing	1	Q4-FY17

R&D IIFC RF Power Milestones and Delivery Goals

Major Milestone	Qty	Delivery date
Design of 325 MHz, 7 kW RF System	1	Q1-FY17
Design of 650 MHz, 40 kW RF System	1	Q1-FY17
Fabrication and testing of 40kW, 650 MHz RF System for HTS-2, HB650, Horizontal Test	2	Q4-FY18
Fabrication and testing of 7kW, 325 MHz RF System for SSR1 CM at CMTF, Fermilab	8	Q3-FY18
Fabrication and testing of 40kW, 650 MHz RF System for CMTS, HB650 Cryomodule	6	Q3-FY19

R&D Division of Responsibility - Fermilab and DAE

- Fermilab provides 162.5 MHz RF amplifiers, circulators, and RF distribution.
- DAE provides 325 MHz 7 kW and 650 MHz 40 kW Solid State RF amplifiers.
- Fermilab provides 325 MHz and 650 MHz circulators and RF distribution.
- Fermilab provides 650 MHz IOT amplifiers for initial STC and Coupler Test Stand operations.

Summary

- Planning
  - RF Power construction phase will provide amplifiers, circulators, RF distribution, and front end controls & interlocks.
  - The R&D phase includes the RF Power requirements through SSR1 and the 650 MHz RF Power for STC, Coupler Test Stand, HTS-2 and CMTS.
- Status
  - RFQ RF is operational.
  - Buncher Cavity 1 RF is operational.
  - Work continues on interface corrections to 162.5 MHz, 3 kW amplifiers.
  - A 7 kW 162.5 MHz circulator meets all specifications.
  - BARC 325 MHz, 7 kW amplifier undergoing tests.
  - RRCAT 650 MHz, 40 kW amplifier design proceeding.
- Collaboration
  - The IIFC division of responsibility is
    - Fermilab will be providing all 162.5 MHz components.
    - Fermilab will be providing 650 MHz amplifiers, circulators and RF distribution for the STC and Coupler Test Stand.
    - BARC will be providing 325 MHz 7 kW amplifiers for the SSR1 cavities.
    - RRCAT will be providing 650 MHz 40 kW amplifiers for HTS-2 & CMTF.
    - Fermilab will be providing circulators and RF distribution for the DAE amplifiers.
- The R&D schedule shows completion of RF Power in Q4 of CY2019.

Backup