121.3.5-6 Linac - SSR1, SSR2

SC Acceleration Modules and Cryogenics

Donato Passarelli

PIP-II Independent Project Review

12-14 December 2017

In partnership with:

India/DAE
Italy/INFN
UK/STFC
France/CEA/Irfu, CNRS/IN2P3

Outline

- Overview of SSR1 (WBS 121.3.5) and SSR2 (121.3.6)
- Requirements
- Scope and Deliverables
- Design maturity
- Technical progress to Date
- Interfaces
- Organization
- ESH&Q
- Risk
- Cost
- Schedule
- Summary

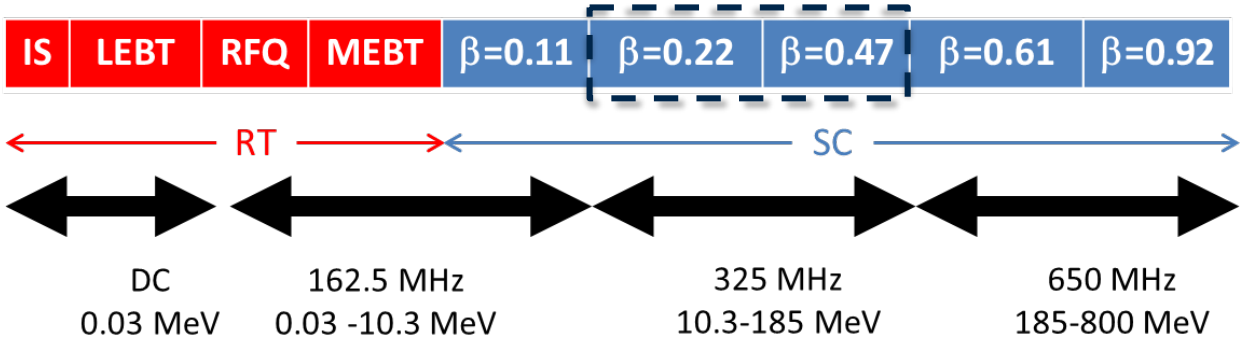
About Me:

- Donato Passarelli, PhD
- L3 Manager for WBS 121.3.5, .6 (SSR1, SSR2)
  - Since 2010 working in Technical Division, SRF Dept.
    - SSR1 cavities, tuners and cryomodule

121.3.5-6 SSR1, SSR2: Overview

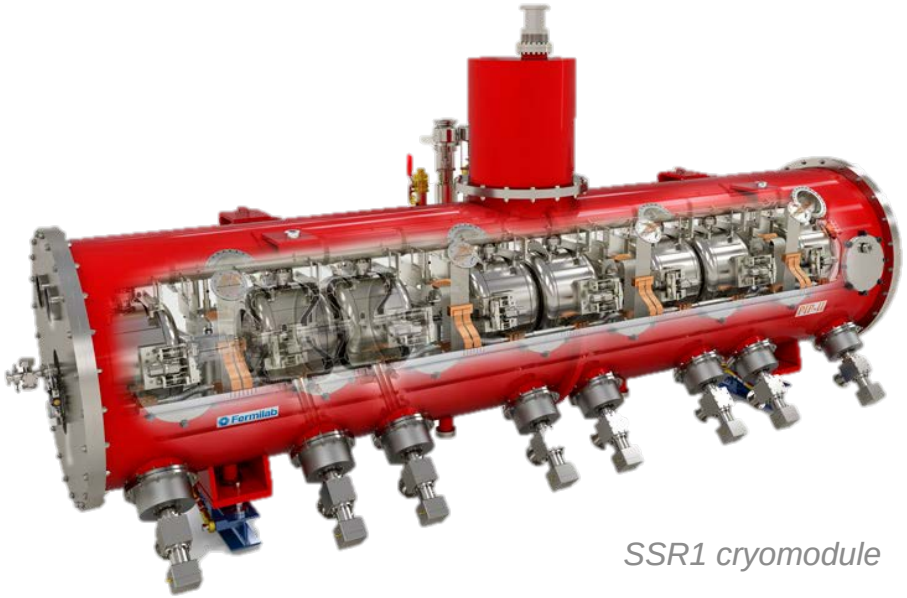
Charge #2

SSR: Single Spoke Resonator



PIP-II Conceptual Design Report: DocDb# 113

	SSR1	SSR2
# CMs	2	7
Cavities per CM	8	5
Solenoids per CM	4	3
CM configuration c: cavities; s: solenoids	4x (csc)	sccscccsc
CM length (m)	5.2	6.5



SSR1 cryomodule

SSR CMs capable of operating in both pulsed and CW modes with a beam current of 2 mA avg.

PIP-II

121.3.5 SSR1: Requirements

Charge #2

Functional Requirement Specification (FRS) are defined and traceable in Teamcenter:

- SSR1 cryomodule: TC# ED0001316
- SSR1 cavities: TC# ED0001317

Cavity operational/test requirements

Parameter	Value
Operating mode	Pulsed with CW capability
Maximum Beam Current	5 mA
Max Leak Rate (room temp)	$< 10^{-10}$ atm-cc/sec
Operating cavity gradient $G_{acc} = V_{opt}/L_{eff}$	10 MV/m
Maximum gradient in VTS	≤ 12 MV/m
Operating temperature	2.0 K
Unloaded quality factor Q_0	$> 6.0 \cdot 10^9$
Dynamic RF power dissipation	< 3 W
Operating LHe Pressure	30±5 mbar
Operating cavity Q-loaded/bandwidth	$3 \cdot 10^6$ / 108 Hz
Sensitivity to LHe pressure fluctuations	< 25 Hz/mbar (dressed cavity)
Lorentz Force Detuning coefficient	< 5 Hz/(MV/m)^2
Longitudinal stiffness	< 5 kN/mm
Operating frequency tuning sensitivity	> 150 kHz/mm
Field Flatness in dressed cavity	> 90%
MAWP	2 bar (RT), 4 bar (2K)
Operating input RF power CW	≤ 15 kW
Operating field probe RF Power CW	100 – 500 mW
Multipacting	none within ±10% of operating gradient

Table of cryomodule requirements

General		
	Beam pipe aperture, mm	30
	Overall length (flange-to-flange), m	≤5.4
	Overall width, m	≤1.6
	Beamline height from the floor, m	1.3
	Cryomodule height (from floor), m	≤2.60
	Ceiling height in the tunnel, m	3.30
	Maximum allowed heat load to 35-50 K, W	255
	Maximum allowed heat load to 5 K, W	80
	Maximum allowed heat load to 2 K, W	50
	Maximum number of lifetime thermal cycles	50
	Intermediate thermal shield temperature, K	35-50
	Thermal intercept temperatures, K	5 and 35-50
	Cryo-system pressure stability at 2 K (RMS), mbar	~0.1
	Environmental contribution to internal field	<15 mG
	Transverse cavity alignment error, mm RMS	<1
	Angular cavity alignment error, mrad RMS	≤5
	Transverse solenoid alignment error, mm RMS	<0.5
	Angular solenoid alignment error, mrad RMS	<0.5
Cavities		
	Cavities per cryomodule	8
	Frequency, MHz	325
	β optimal	0.222
	Operating temperature, K	2
	Operating mode	CW and pulsed
	Operating energy gain at β=0.222, MV/cavity	2.05
	Maximum dynamic cavity heat load to 2 K, W (each, including coupler)	4
	Coupler power rating (TW, full reflection), kW	15

121.3.6 SSR2: Requirements

Charge #2

Functional Requirement Specification (FRS) are defined and traceable in Teamcenter:

- SSR2 cryomodule: TC# ED0001829
- SSR2 cavities: TC# ED0001854

Cavity operational/test requirements

Parameter	Value
Operating mode	Pulsed with CW capability
Maximum Beam Current	5 mA
Max Leak Rate (room temp)	$< 10^{-10}$ atm-cc/sec
Operating cavity gradient $G_{acc} = V_{opt}/L_{eff}$	11.4 MV/m
Maximum gradient in VTS	≤ 13 MV/m
Operating temperature	2.0 K
Unloaded quality factor Q_0	$> 8.0 \cdot 10^9$
Dynamic RF power dissipation	< 11 W
Operating LHe Pressure	30±5 mbar
Operating cavity Q-loaded/bandwidth	$5.1 \cdot 10^6$ / 64 Hz
Sensitivity to LHe pressure fluctuations	< 25 Hz/mbar (dressed cavity)
Lorentz Force Detuning coefficient	< 2.8 Hz/(MV/m)^2
Longitudinal stiffness	< 5 kN/mm
Operating frequency tuning sensitivity	> 150 kHz/mm
Field Flatness in dressed cavity	> 90%
MAWP	2 bar (RT), 4 bar (2K)
Operating input RF power CW	≤ 30 kW
Operating field probe RF Power CW	100 – 500 mW
Multipacting	none within ±10% of operating gradient

Table of cryomodule requirements

General		
	Beam pipe aperture, mm	40
	Overall length (flange-to-flange), m	≤6.5
	Overall width, m	≤1.6
	Beamline height from the floor, m	1.3
	Cryomodule height (from floor), m	≤2.60
	Ceiling height in the tunnel, m	3.30
	Maximum allowed heat load to 35-50 K, W	250
	Maximum allowed heat load to 5 K, W	80
	Maximum allowed heat load to 2 K, W	75
	Maximum number of lifetime thermal cycles	50
	Intermediate thermal shield temperature, K	35-50
	Thermal intercept temperatures, K	5 and 35-50
	Cryo-system pressure stability at 2 K (RMS), mbar	~0.1
	Environmental contribution to internal field	<15 mG
	Transverse cavity alignment error, mm RMS	<1
	Angular cavity alignment error, mrad RMS	≤5
	Transverse solenoid alignment error, mm RMS	<0.5
	Angular solenoid alignment error, mrad RMS	<0.5
	Beam duration for operation in pulsed regime, ms	≤1
	Repetition rate for operation in pulsed regime, Hz	≤20
Cavities		
	Cavities per cryomodule	5
	Frequency, MHz	325
	β optimal	0.475
	Operating temperature, K	2
	Operating mode	CW & pulsed
	Operating energy gain at β=0.475, MV/cavity	5
	Maximum dynamic cavity heat load to 2 K, W (each, including coupler)	12
	Coupler power rating (TW, full reflection), kW	30

121.3.5 SSR1: Scope and Deliverables

Charge #2

- WBS Dictionary: pip2-docdb # 599

121.3.05 Linac - Single Spoke Resonator 1 (SSR1)	This WBS entry covers design, procurement, fabrications and testing of the Single Spoke Resonator type 1 cavities and cryomodules. Final scope will be delivery of 2 tested CMs for installation.

- 121.3.5.2 Project management and coordination
  - BOE document: docdb # 384
- 121.3.5.3 SSR1 1st Prototype Cryomodule
  - BOE document: docdb # 387, 393, 396
- 121.3.5.4 SSR1 2nd Production CryoModule
  - BOE document: docdb # 399, 402, 405

121.3.5 SSR1: Scope and Deliverables

Charge #2

- 121.3.5.2 Project management and coordination
  - Travel costs for management and vendor visits
- 121.3.5.3 SSR1 1st Prototype CM
  - FNAL scope:
    - Qualification of 8 jacketed cavities with coupler and tuner
    - Complete design, procurement, QA/QC and integration of all cryomodule components
    - RF testing and verification of cryomodule performance at PIP2IT
  - DAE (BARC/IUAC) deliverables:
    - Delivery of 2 dressed cavities
  - FNAL deliverables:
    - delivery of tested SSR1 1st CM for installation at PIP-II tunnel
- 121.3.5.4 SSR1 2nd Production CM
  - FNAL scope:
    - Finalization of design and procedures using lessons learned from CM #1
    - Procurement, QA/QC and testing, and integration of the full cryomodule
    - RF testing and verification of cryomodule performance at PIP2IT
  - FNAL deliverables:
    - delivery of tested SSR1 2nd CM for installation at PIP-II tunnel

121.3.6 SSR2: Scope and Deliverables

Charge #2

- WBS Dictionary: pip2-docdb # 599

121.3.06 Linac - Single Spoke Resonator 1 (SSR2)	This WBS entry covers design, procurement, fabrications and testing of the Single Spoke Resonator type 2 cavities and cryomodules. Final scope will be delivery of 7 tested CMs for installation.

- 121.3.6.2 Project management and coordination
  - BOE document: docdb # 423
- 121.3.6.3 SSR2 1st Prototype CryoModule
  - BOE document: docdb # 426, 429, 432
- 121.3.6.4 SSR1 2nd-7th Production CryoModule
  - BOE document: docdb # 438, 441, 444

121.3.6 SSR2: Scope and Deliverables

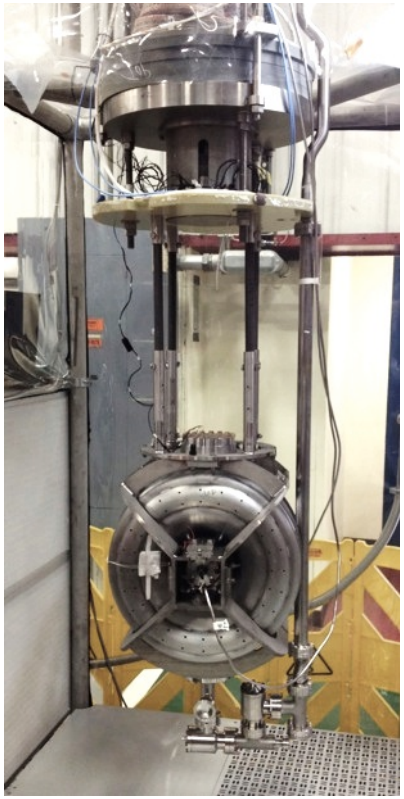
Charge #2

- 121.3.6.2 Project management and coordination
- 121.3.6.3 SSR2 1st Prototype CryoModule
  - FNAL scope:
    - Design, analysis, reviews, procurement, QA/QC, device design verification testing, and integration of 5-cavity cryomodule.
    - Support DAE partners (BARC) in design and fabrication of their deliverables
    - RF testing and verification of cryomodule performance at PIP2IT
  - DAE (BARC) deliverables:
    - Design of bare and jacketed cavities
    - 2 prototype jacketed cavities for qualification at FNAL, 1 tuner, 3 couplers, 3 solenoids and BPMs
  - FNAL deliverables: delivery of qualified SSR2 1st CM for installation at PIP-II tunnel
- 121.3.6.4 SSR2 2nd-7th Production CryoModule
  - FNAL scope:
    - Finalization of design and procedures using lessons learned from CM #1
    - Support DAE partners (BARC) in design and fabrication of their deliverables
    - Procurement, QA/QC and testing, and integration of the full cryomodules
    - RF testing and verification of 2nd-7th cryomodule performance at PIP2IT
  - DAE (BARC) deliverables:
    - 18 jacketed cavities, 19 tuners, 17 couplers, 18 solenoids and BPMs
  - FNAL deliverables: delivery of qualified SSR2 2nd-7th CM for installation at PIP-II tunnel

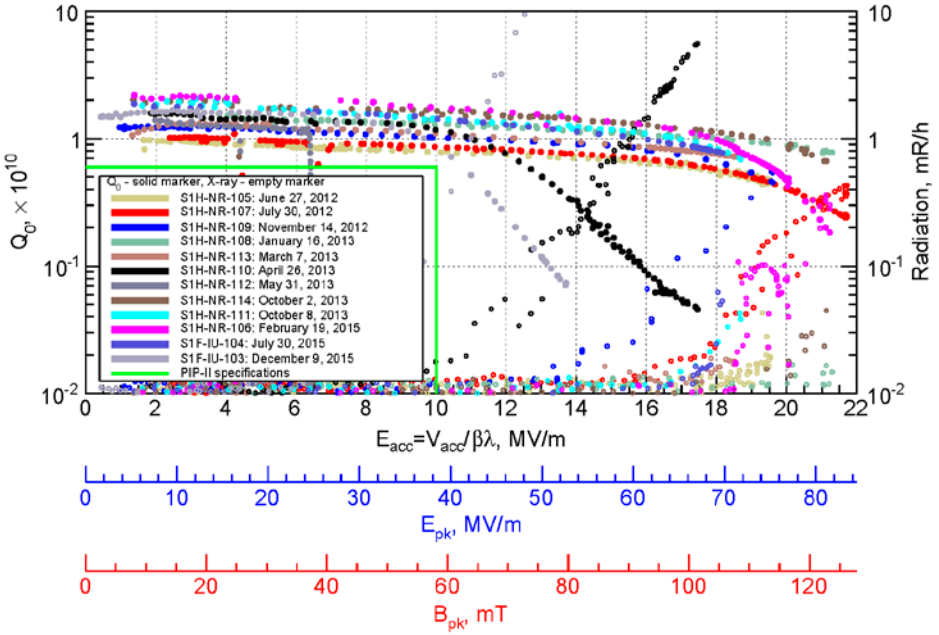
121.3.5 SSR1: Cavities Design Maturity

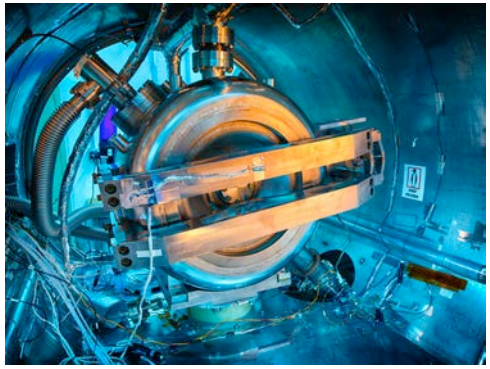
Charge #2

- *SSR1 CM1 is well beyond the conceptual design.*



SRF technology enabled: 12 bare SSR1 cavities (10 FNAL and 2 DAE BARC/IUAC) met PIP-II requirements in VTS.



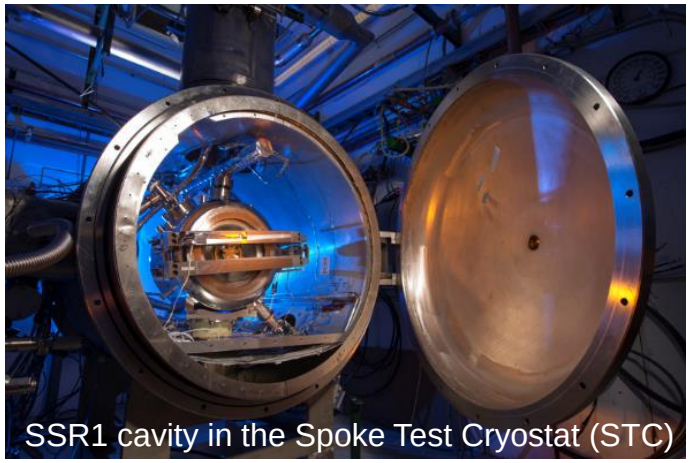


- 10 FNAL cavities were successfully jacketed with stainless steel vessels showing a very low df/dp
- 2 DAE BARC cavities are currently receiving the He- vessel
- Current activities: qualification of jacketed cavities by cold testing at Spoke Test Cryostat (STC) to meet SSR1 cavities FRS (TC# ED0001317)

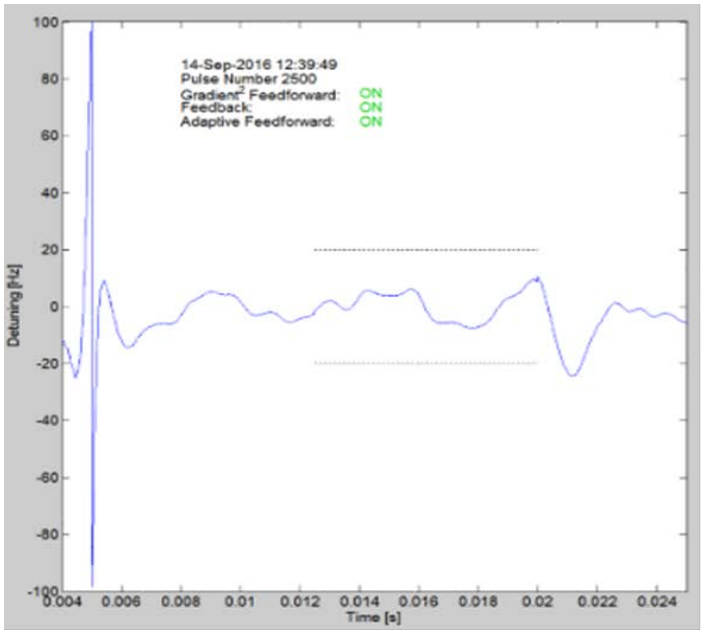
121.3.5 SSR1: Tuner and resonance control

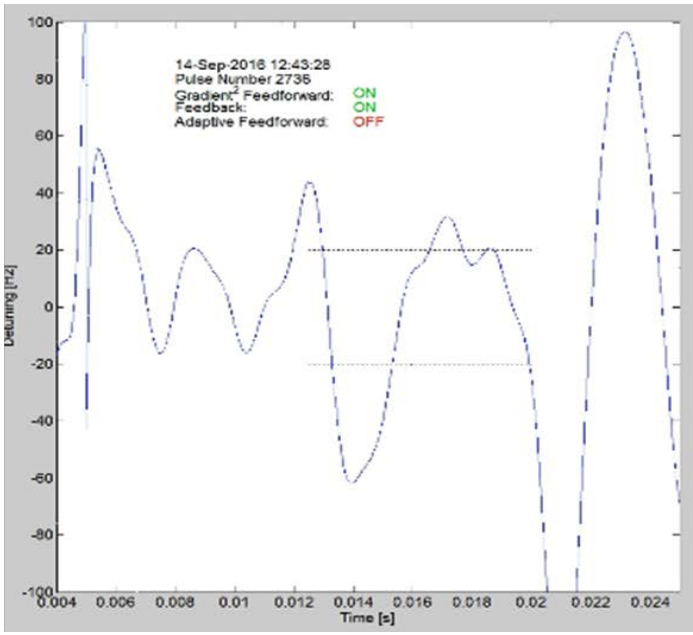
Charge #2

- **Prototype SSR1 tuner**
  - Design completed and one unit was prototyped
  - Successfully tested at 293K and cold temperature
- **Production SSR1 tuner**
  - Design completed
  - 1 out of 10 units was received and currently used for resonance control of SSR1 cavities


SSR1 cavity in the Spoke Test Cryostat (STC)

- **Resonance control studies**
  - Requirements: microphonics <20 Hz
  - Good progress during cold tests at STC and requirements are nearly achieved.



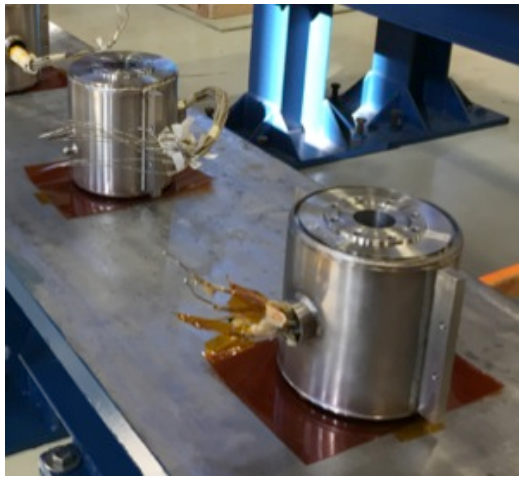


PIP-II

121.3.5 SSR1: Solenoid, BPMs, couplers

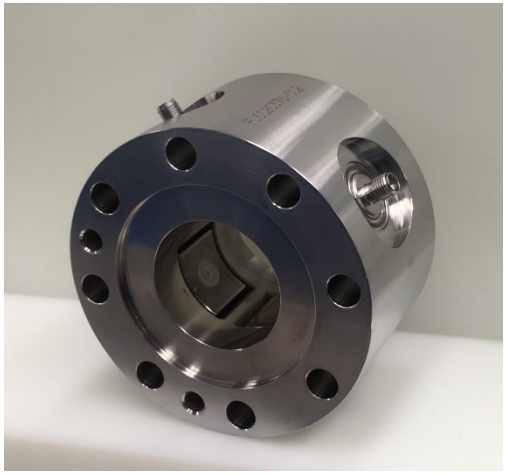
Charge #2

- **Four production solenoids** were successfully designed, procured and qualified.



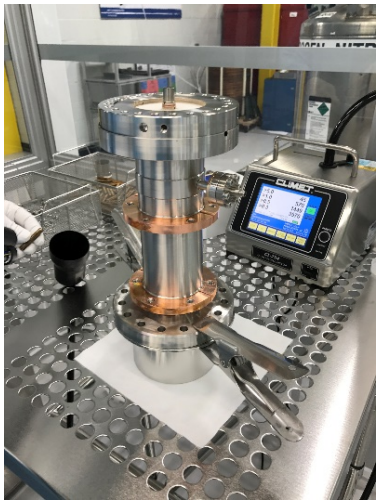
TC# ED0001264

- **Four production BPMs** were successfully designed, procured and qualified.



Joint collaboration ANL &FNAL

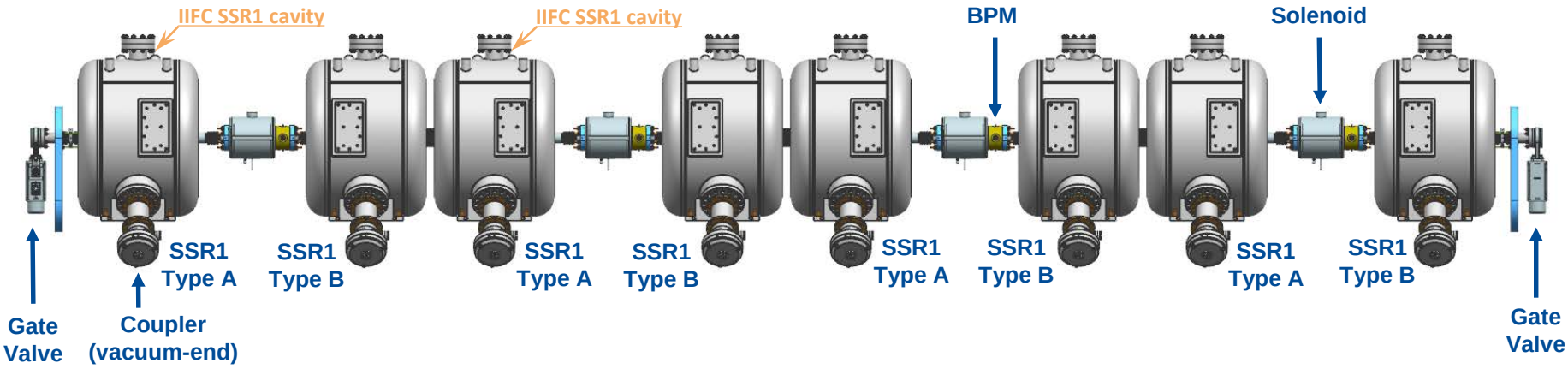
TC# ED0005680



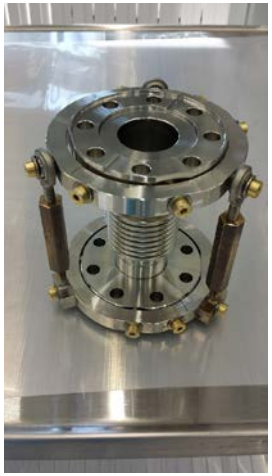
- **Prototype main power couplers**
  - Design, procurement and testing: completed
  - Three prototypes were procured and successfully tested
- **Production main power couplers**
  - Design completed
  - Procurement: in progress
    - The procurement of coupler antennas presented a series of technical issue that led them to be on the SSR1 CM1 critical path.

121.3.5 SSR1: cavity string assembly

Charge #2



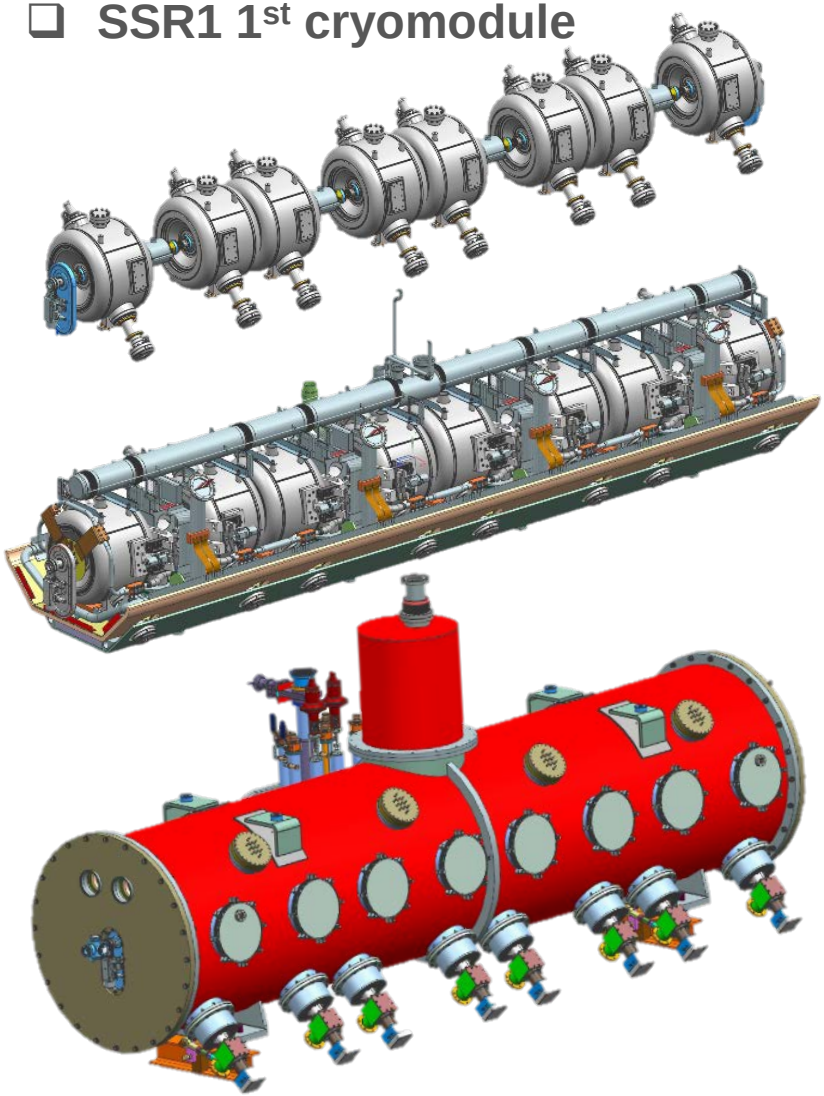
- Free particle assembling procedure for cleanroom activity at Lab 2



121.3.5 SSR1: CM Design Maturity

Charge #2

❑ **SSR1 1st cryomodule**



SSR1 cavity string assembly
- Design: completed
- Procurement: completed
- Assembly starts in March 2018

SSR1 coldmass
- Design: completed
- Assembly starts in July 2018

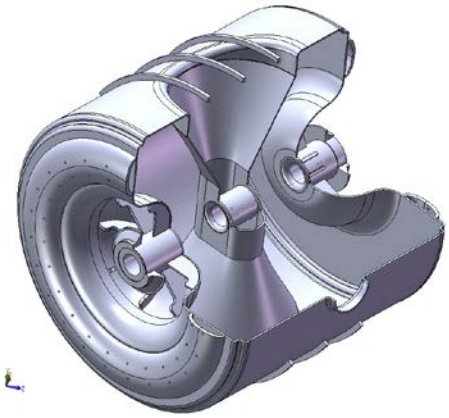
SSR1 final cryomodule
- Design: nearly completed
- Assembly starts in Nov. 2018

❑ **SSR1 2nd cryomodule**

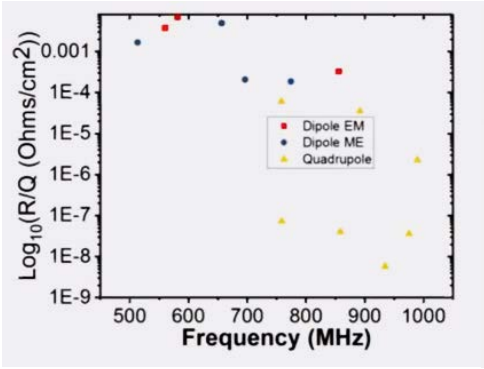
We are collecting lessons learned and list of improvements from the experience in designing and developing the SSR1 1st cryomodule.

121.3.6 SSR2: Design Maturity

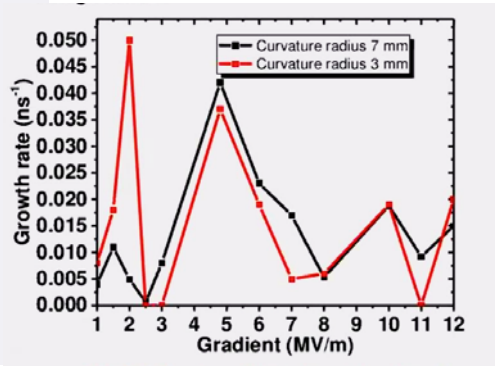
Charge #2



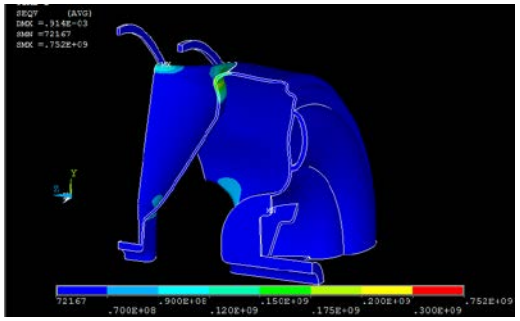
- SSR2 cavities:
  - RF Design Initially developed by Fermilab
  - DAE (BARC) is currently working on mechanical design.
  - Bare Cavity Design Status Review held at BARC Nov 7th 2017
  - PDR at BARC is scheduled for March 2018



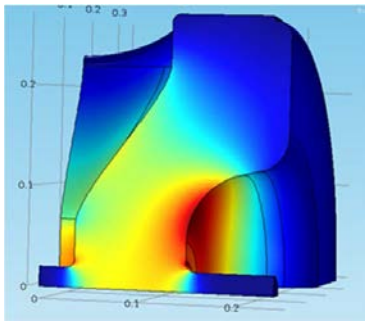
HOM Analysis



Multipacting Analysis



Structural analyses performed by BARC



SSR2 Electric and Magnetic fields

- Design of SSR2 cryomodule and components will be based on SSR1 experience.
- SSR2 Cavity & Cryomodule development is on the critical path for the SRF Linac because it is the least mature of the SRF CMs

121.3.5,6 SSR1, SSR2: Design Review Plan

Charge #2

- Critical component design review cycle

  CDR → FRS/TRS → PDR → FDR →PRR

- Critical Reviews are tracked in P6 as milestones.
- Non-critical components or subsystems are managed within the Division or Department review process as required by the FNAL Engineering Manual.
- Design reviews planned for Partner deliverables as appropriate to ensure technical and ESH&Q requirements are met. Partner milestones identified and implemented in P6.
- SSR1 1st cryomodule (WBS 121.3.5.3)
  - PDR, FDR and PRR of the key-components up to the string assembly were successfully held and documented.

121.3.5,6 SSR1, SSR2: Interfaces

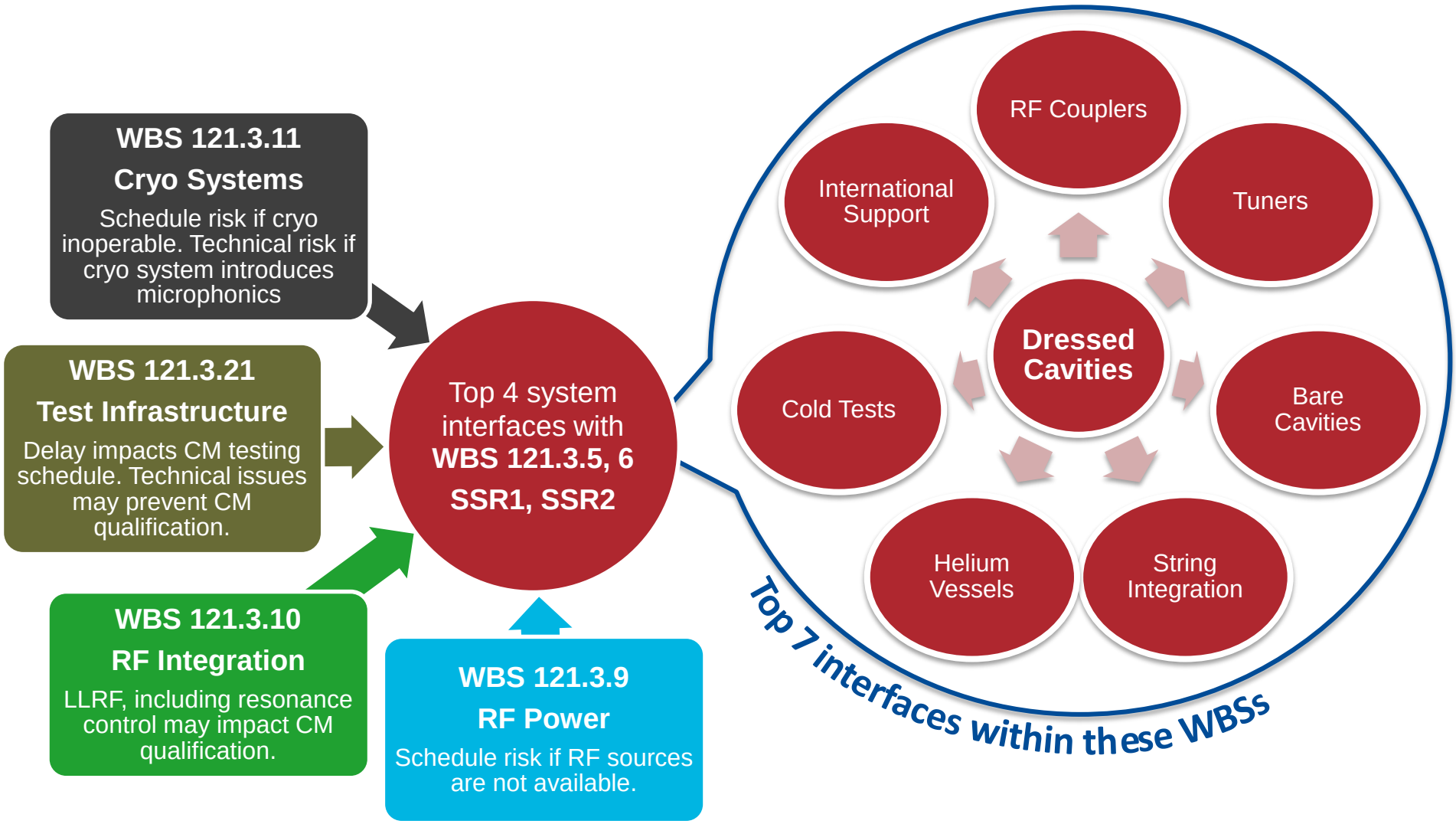
Charge #2

WBS 121.3.5-.6 interface across the PIP-II WBS Matrix

Interfaces to SSR1 (121.3.5) and SSR2 (121.3.6)	
121.3.4 – HWR *(SSR1 only)*	121.3.17 – Control Systems
121.3.5/.6 – SSR1/SSR2	121.3.18 – Vacuum
121.3.7 – LB650 *(SSR2 only)*	121.3.19 – General Supt. Serv.
121.3.9 – RF Power	121.3.20 – Safety Systems
121.3.10 – RF Integration	121.3.21 – Test Infrastructure
121.3.11 – Cryo Systems	121.3.22 – Install., Integ., and Comm
121.3.13 – Magnet PS	121.5 – Conventional Facilities
121.3.16 – Beam Instrum.	

- Technical interfaces are understood and are or will be under revision control and managed through Teamcenter.
  - 121.3.5 SSR1 external interfaces: TC# ED0004129, TC# F10051442
  - 121.3.5 SSR1 internal interfaces: TC# F10002433, TC # F10082628, and SSR1 team meetings (Indico link)

121.3.5,6 Interfaces – Technical/Schedule Impact



121.3.5,6 Interfaces - Partners

Charge #7

- Final Partner deliverables to be formalized in advance of CD-2.
- SPC/SPM and POC direct communication is essential to the success of this collaboration.
- Timely information and material transfer between stakeholders is essential to meet technical and schedule requirements. (By-weekly meeting, TC database)
- 121.3.5 SSR1 partner: DAE-BARC/IUAC
  - fabrication of two dressed cavities
- 121.3.6 SSR2 partner: DAE-BARC
  - Bare and dressed cavities design and production
  - Tuners design and fabrication
  - Solenoids, leads and BPS design and fabrication

121.3.5,6 SSR1, SSR2: Organization

Charge #2, 4, 7

- FNAL L3 Manager Assigned
  - Single L3 for SSR1 (121.3.5) and SSR2 (121.3.6)
  - L4 technical POCs identified within the Technical Division org.
  - Support area staffing and POCs map directly to Technical Division org. chart: VTS testing, Cavity processing and Facilities, QA/QC, etc.
  - Organization is moving with good technical progress.
  - CM design team well-established and experienced.

- Partner organization is established in the DAE.

121.3.5, 6 SSR1, SSR2: ESH&Q

Charge #5

- Project team is committed to construct PIP-II in a safe, environmentally respectful, and cost efficient manner that meets our stakeholder's needs
- All activities will be in full compliance with the PIP-II Integrated Safety Management program defined in DocDB #141 & QA Plan (DocDB #142).
  - Laboratory and DOE standards and practices followed
    - Fermi ES&H Manual
    - Division/Area specific Hazards Analyses and Training
- Specific hazards in PHAR DocDB #140
  - Cryogenics exposure (Cavity/CM Testing)
  - ODH (Cavity/CM Testing)
  - Pressure vessel compliance (Cavity/CM warm&cold ops)
    - All SRF cavities must comply ES&H Manual Chapter 5031.6
    - Cryogenic lines must comply ASME B31.3 for Pressure Piping
  - Chemical/Acids (Cavity processing at ANL, controlled by ANL)
  - Radiation (Cavity/CM testing)
  - Material Handling
- International Risk Mitigation Strategy (DocDB #1201) to be implemented for in-kind contributions.

Risk: SSR Cavity and CM

Charge #3

- SSR1 CM (1) Performance at PIP2IT does not meet technical requirements
- SSR2 CM (1) Performance at PIP2IT does not meet technical requirements
- SSR1 Cryomodule design modifications identified late in design cycle

Title	Technical Impact	P * Impact (k$)	P * Impact (months)	Probability
SSR1 CM (1) Performance at PIP2IT does not meet technical	2 (M) - significantly substandard	433	2.8	40.00%
SSR2 CM (1) Performance at PIP2IT does not meet technical	2 (M) - significantly substandard	333	2.8	40.00%
SSR1 Cryomodule design modifications identified late in design cycle	2 (M) - significantly substandard	217	1.6	20.00%

Risk Mitigation: SSR1 CM (1) Performance at PIP2IT does not meet technical requirements

- SSR1 CM (1) designed to meet/exceed specifications
  - Structural, thermal and multiphysics finite element analyses
  - Dressed cavities with very low df/dp
  - Piping systems and pressure vessels designed to comply the ASME codes
  - Features to mitigate thermal acoustic oscillations and mechanical instabilities
- Pre-qualification of key-components
  - Cold testing fully integrated cavities with coupler and tuner
    - RF and structural/cryogenic performance
    - Resonance control studies
    - Assessment of field emission, multipacting, magnetic field, and other limiting factors
  - Testing solenoids, BPMs
  - QA/QC inspections at each critical step from manufacturing to final installation
- Integration of lessons learned about low beta cavities and cryomodule
  - Processing of cavity surfaces and cleanroom procedures
  - Handling of cavity string assembly, coldmass, cryomodule

121.3.5 SSR1: BOE Summary

Charge #2

WBS Number	Title	Docdb #
121.3.5.2	SSR1 Project Management and Coordination	384
121.3.5.3.1	SSR1 1st CM Cavities	387
121.3.5.3.2 .3 and .4	SSR1 1st CM Integration and Assembly	393
121.3.5.3.5	SSR1 1st CM Test	396
121.3.5.4.1 and .2	SSR1 2nd CM Cavities	399
121.3.5.4.3 .4 and .5	SSR1 2nd CM Integration and Assembly	402
121.3.5.4.6	SSR1 2nd CM Test	405

All relevant BOE Documents (estimate roll-ups, WBS dictionaries, descriptions) exist and have been reviewed and approved.

121.3.6 SSR2: BOE Summary

Charge #2

WBS Number	Title	Docdb #
121.3.6.2	SSR2 PM and Coordination	423
121.3.6.3.1 and .2	SSR2 1st CM Cavities	426
121.3.6.3.3 .4 and .5	SSR2 1st CM Integration and Assembly	429
121.3.6.3.6	SSR2 1st CM Test	432
121.3.6.4.1 and .2	SSR2 2nd-7th CM Cavities	438
121.3.6.4.3 .4 and .5	SSR2 2nd-7th CM Integration and Assembly	441
121.3.6.4.6	SSR2 2nd-7th CM Test	444

All relevant BOE Documents (estimate roll-ups, WBS dictionaries, descriptions) exist and have been reviewed and approved.

121.3.5 SSR1: Cost Summary

Charge #3

Level 4 WBS - Name	Direct Hrs	Direct M&S	Full Burden+Esc	EUC	% EUC	Total Cost
121.3.05.02 - Linac - SSR1 - Project Management and Coordination	6,718	$74,179	$1,230,612	$132,399	10.8%	$1,363,007
121.3.05.03 - Linac - SSR1 - 1st Prototype CryoModule (1stCM)	25,471	$1,318,134	$5,457,926	$1,091,574	20.0%	$6,549,513
121.3.05.04 - Linac - SSR1 - 2nd Production CryoModule (2ndCM)	32,674	$4,160,736	$10,485,618	$2,210,488	21.1%	$12,696,128
Grand Total	**64,863**	**$5,553,049**	**$17,174,156**	**$3,434,461**	**20.0%**	**$20,608,648**

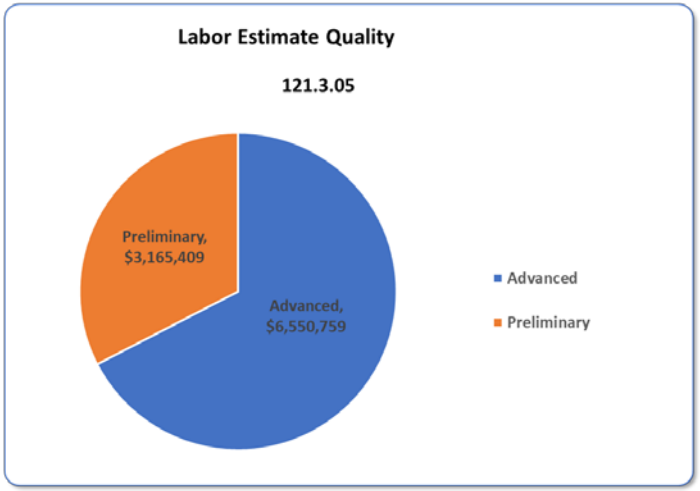
Full Burden + Esc = BOE + Escalation + Overhead

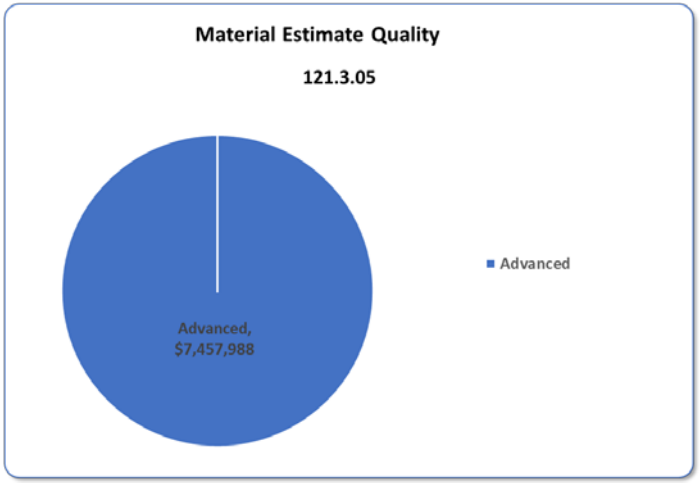
- P6 generated cost table
- Estimates and activities developed down to the L8 for SSR1 CMs.

121.3.5 SSR1: Cost Distribution and Estimate Quality

Charge #3

- "Preliminary estimation": based on similar work (ILC, LCLS-II)
- "Advanced estimation": based on nearly identical work (SSR1)



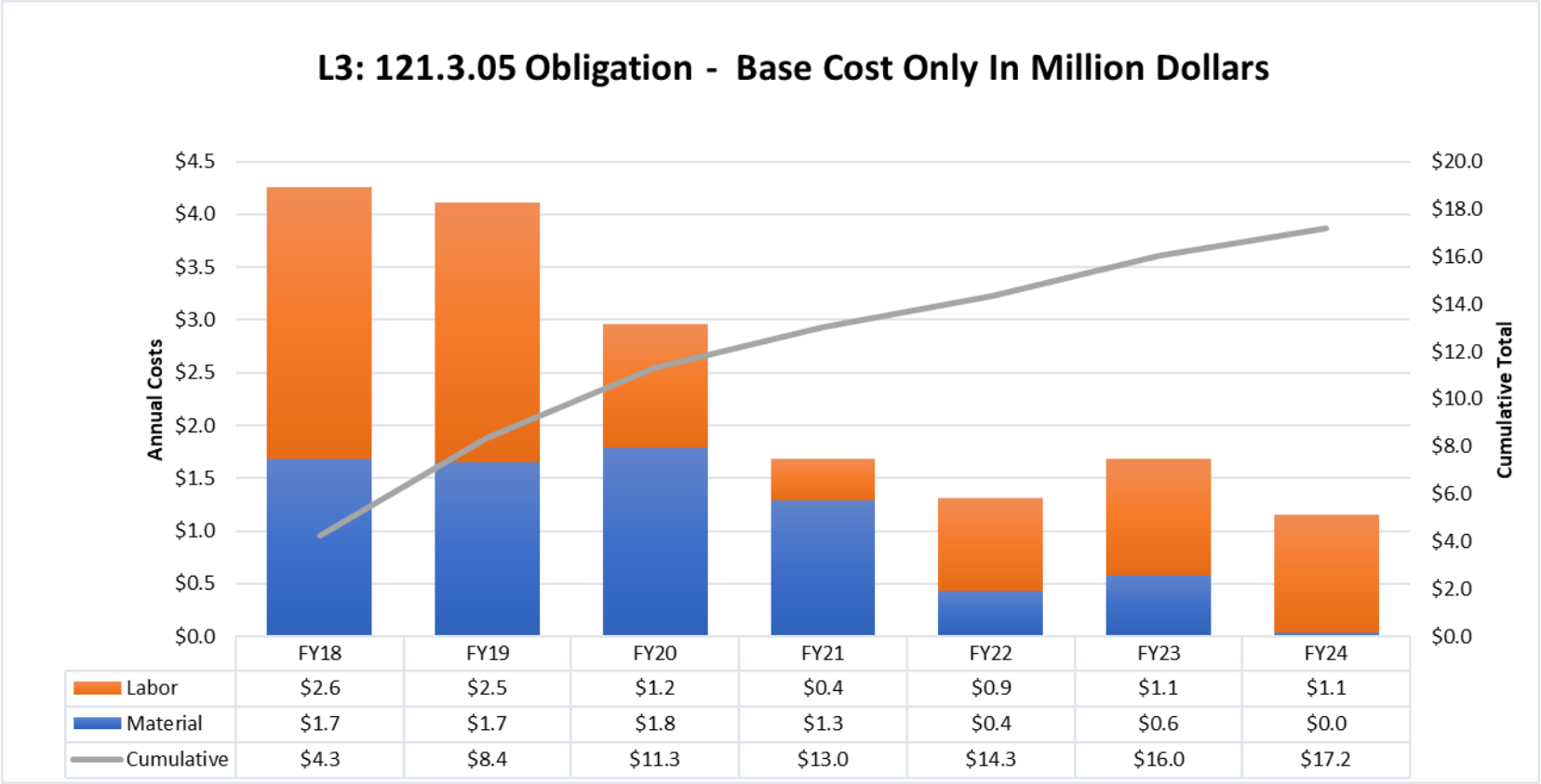


Costs = BOE + Overheads + Escalation

Estimate Quality Categories are per FermilabStandards and descriptions can be found in Docdb item number 345

121.3.5 SSR1: Obligation Profile – P6 Base Cost Only

Charge #3

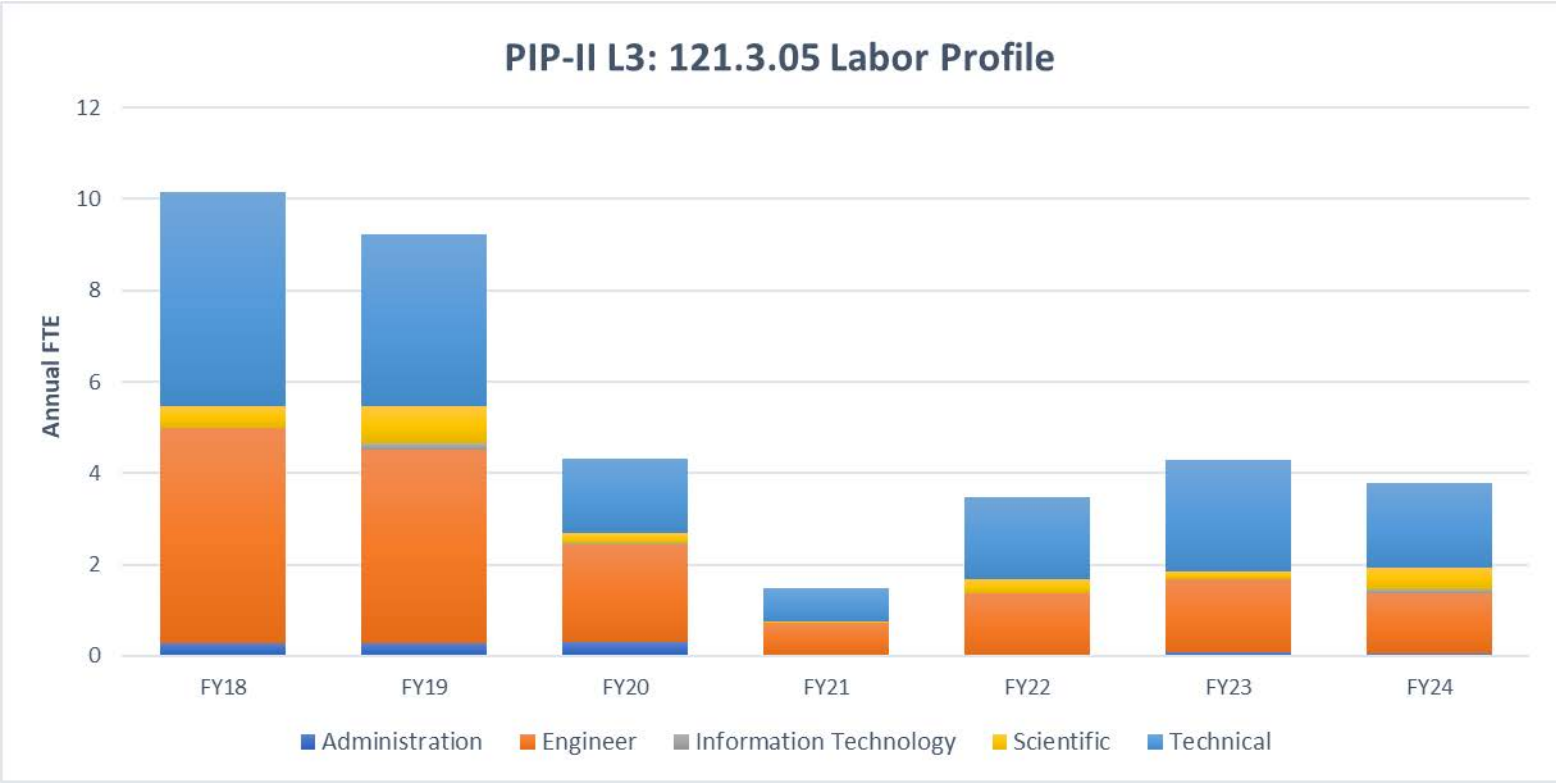


	FY18	FY19	FY20	FY21	FY22	FY23	FY24
Labor	$2.6	$2.5	$1.2	$0.4	$0.9	$1.1	$1.1
Material	$1.7	$1.7	$1.8	$1.3	$0.4	$0.6	$0.0
Cumulative	$4.3	$8.4	$11.3	$13.0	$14.3	$16.0	$17.2

P6 Base Costs = BOE + Overheads + Escalation

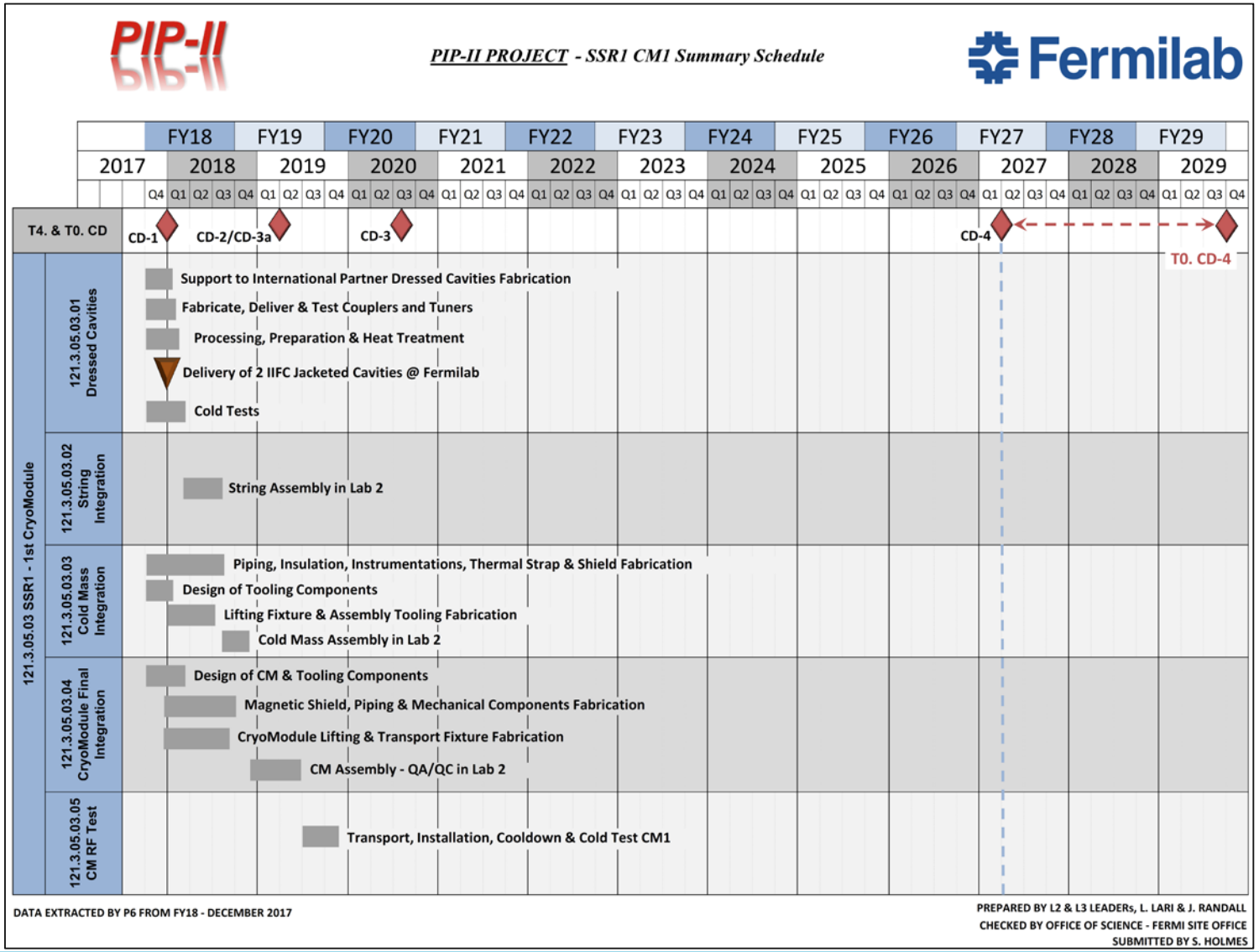
121.3.5 SSR1: Labor Profile – P6 Hours/FTE

Charge #3



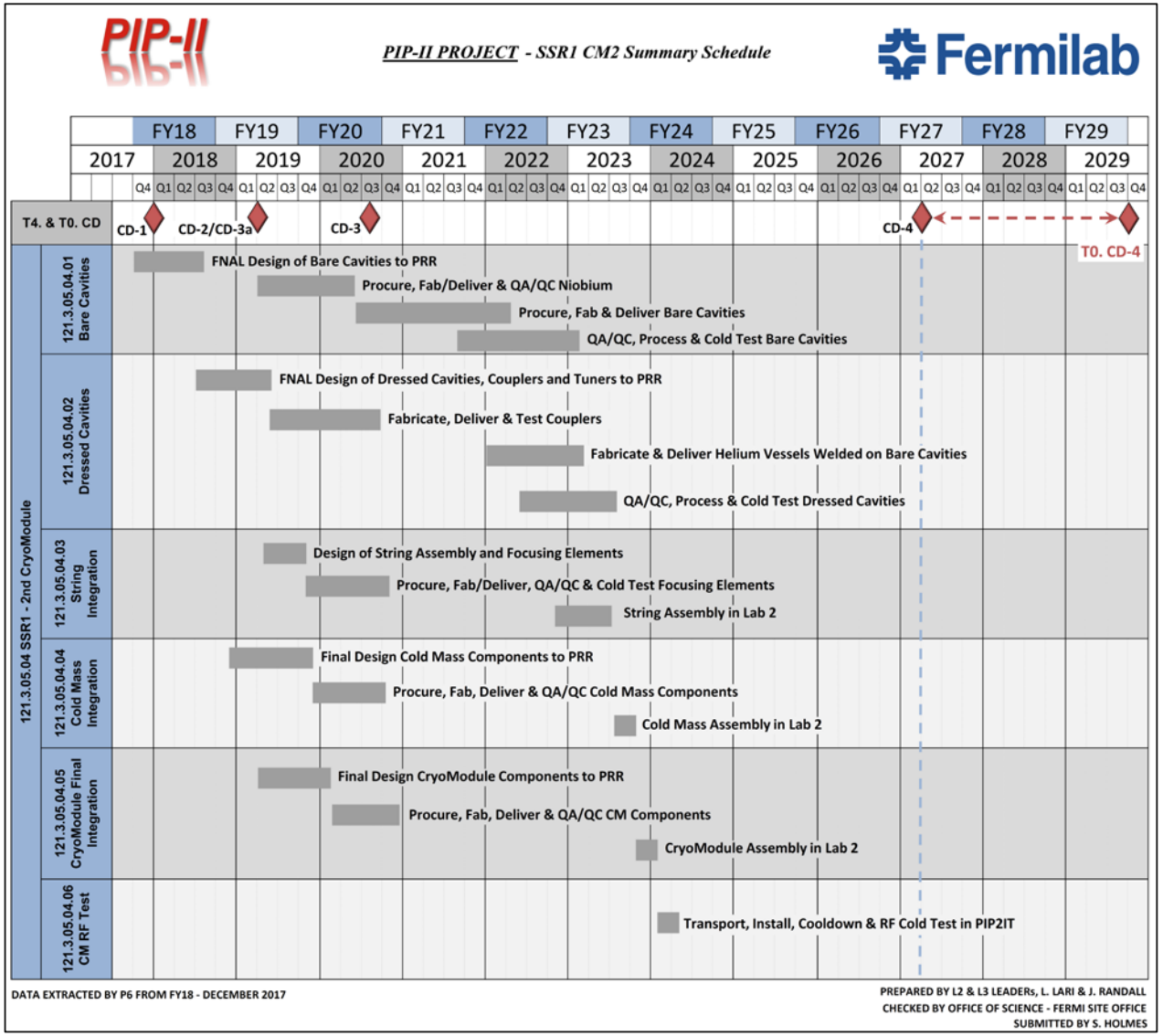
121.3.5.4 SSR1 CM1 Schedule

Charge #3



121.3.5.3 SSR1 CM2 Schedule

Charge #3



121.3.6 SSR2: Cost Summary

Charge #3

Level 4 WBS - Name	Direct Hrs	Direct M&S	Full Burden+Esc	EUC	% EUC	Total Cost
121.3.06.02 - Linac - SSR2 - Project Management and Coordination	9,812	$216,150	$1,771,554	$205,192	11.6%	$1,976,753
121.3.06.03 - Linac - SSR2 - 1st Pre-series Production Cryomodule (1stCM)	57,674	$4,583,124	$15,492,740	$3,823,896	24.7%	$19,316,612
121.3.06.04 - Linac - SSR2 - 2nd to 7th Production Cryomodules (2nd-7thCM)	90,177	$12,723,654	$32,739,029	$7,784,222	23.8%	$40,523,194
Grand Total	**157,663**	**$17,522,928**	**$50,003,323**	**$11,813,310**	**23.6%**	**$61,816,559**

Full Burden + Esc = BOE + Escalation + Overhead

- P6 generated cost table
- Estimates and activities developed down to the L8 for SSR1 CMs.

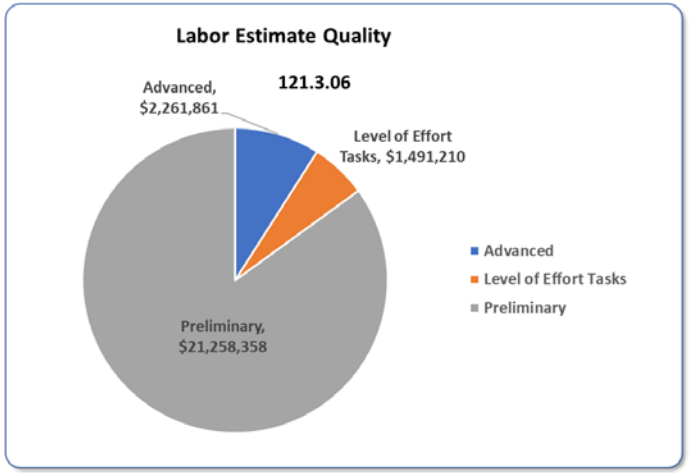
121.3.6 SSR2: Cost Distribution and Estimate Quality

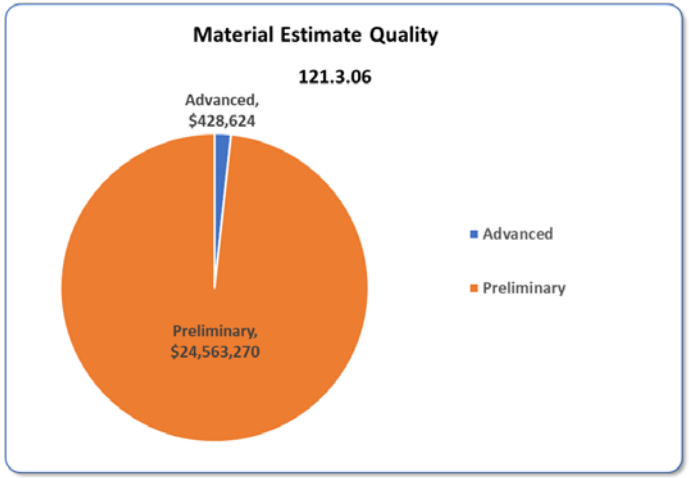
Charge #3

- Estimations for SSR2 CMs are based on experience with SSR1 CM1 (similar work --> preliminary estimations).

Costs = BOE + Overheads + Escalation

Estimate Quality Categories are per FermilabStandards and descriptions can be found in Docdb item number 345

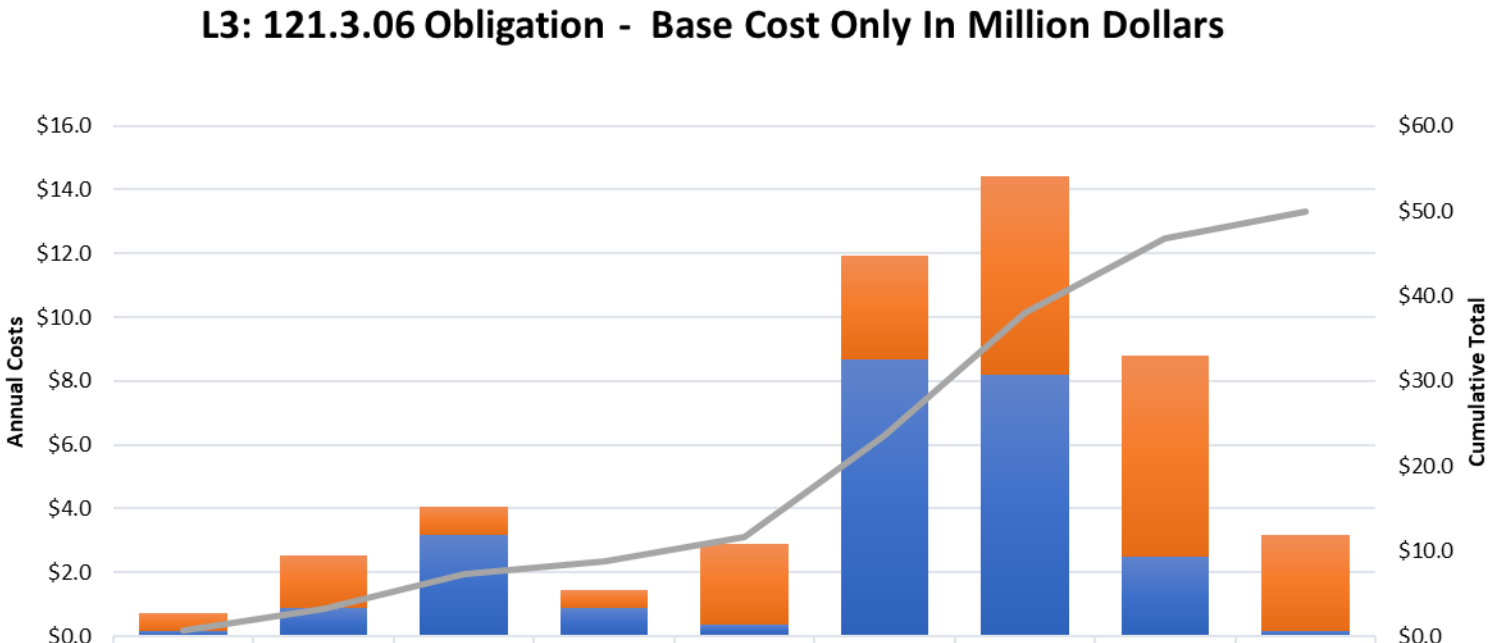




PIP-II

121.3.6 SSR2: Obligation Profile – P6 Base Cost Only

Charge #3



	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26
Labor	$0.6	$1.7	$0.9	$0.6	$2.5	$3.2	$6.2	$6.3	$3.0
Material	$0.2	$0.9	$3.2	$0.9	$0.4	$8.7	$8.2	$2.5	$0.1
Cumulative	$0.7	$3.3	$7.3	$8.8	$11.7	$23.6	$38.0	$46.8	$50.0

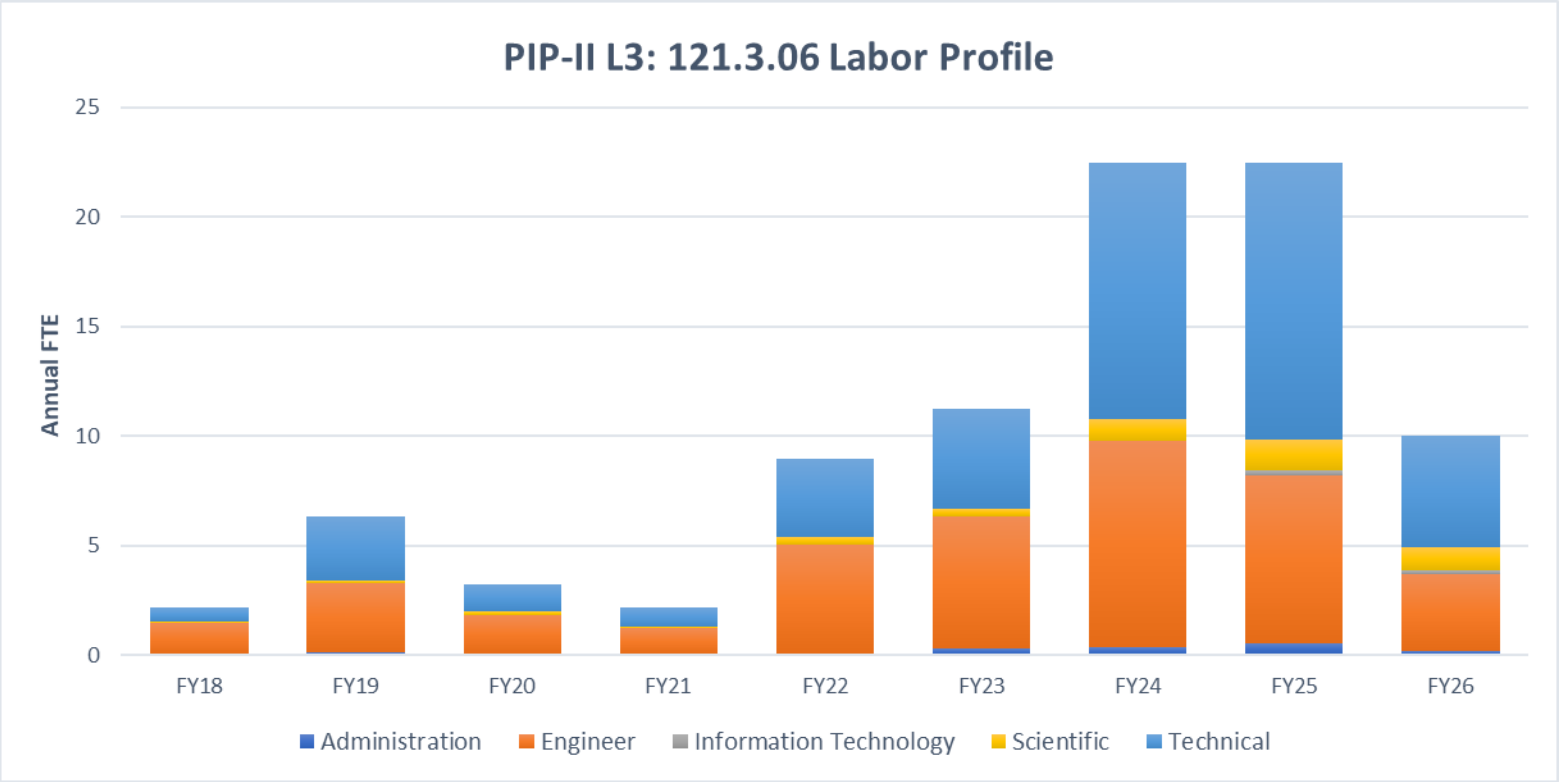
P6 Base Costs = BOE + Overheads + Escalation

The costs build up moving from prototyping to production

PIP-II

121.3.6 SSR2: Labor Profile – P6 Hours/FTE

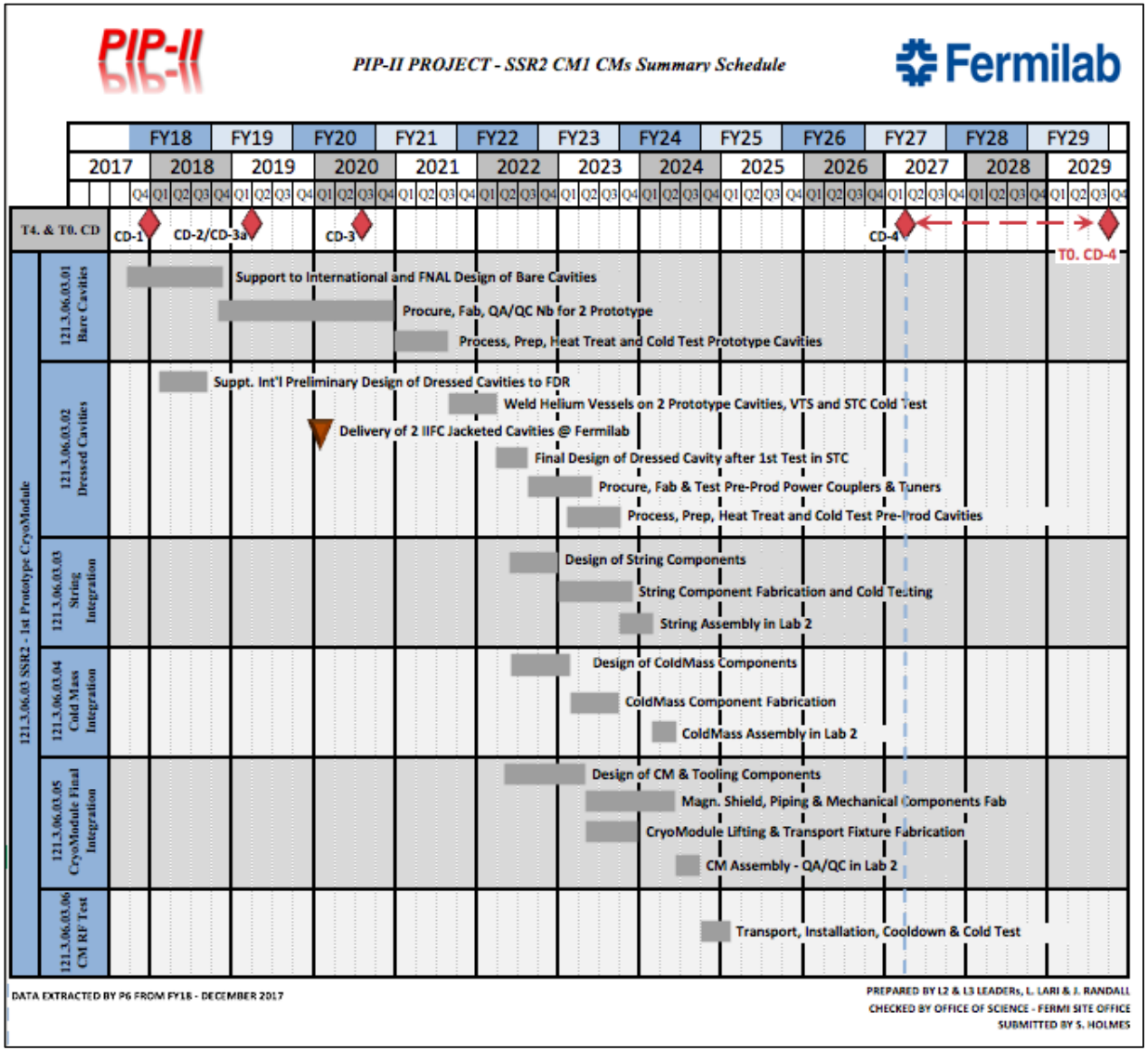
Charge #3



The labor build up moving from prototyping to production

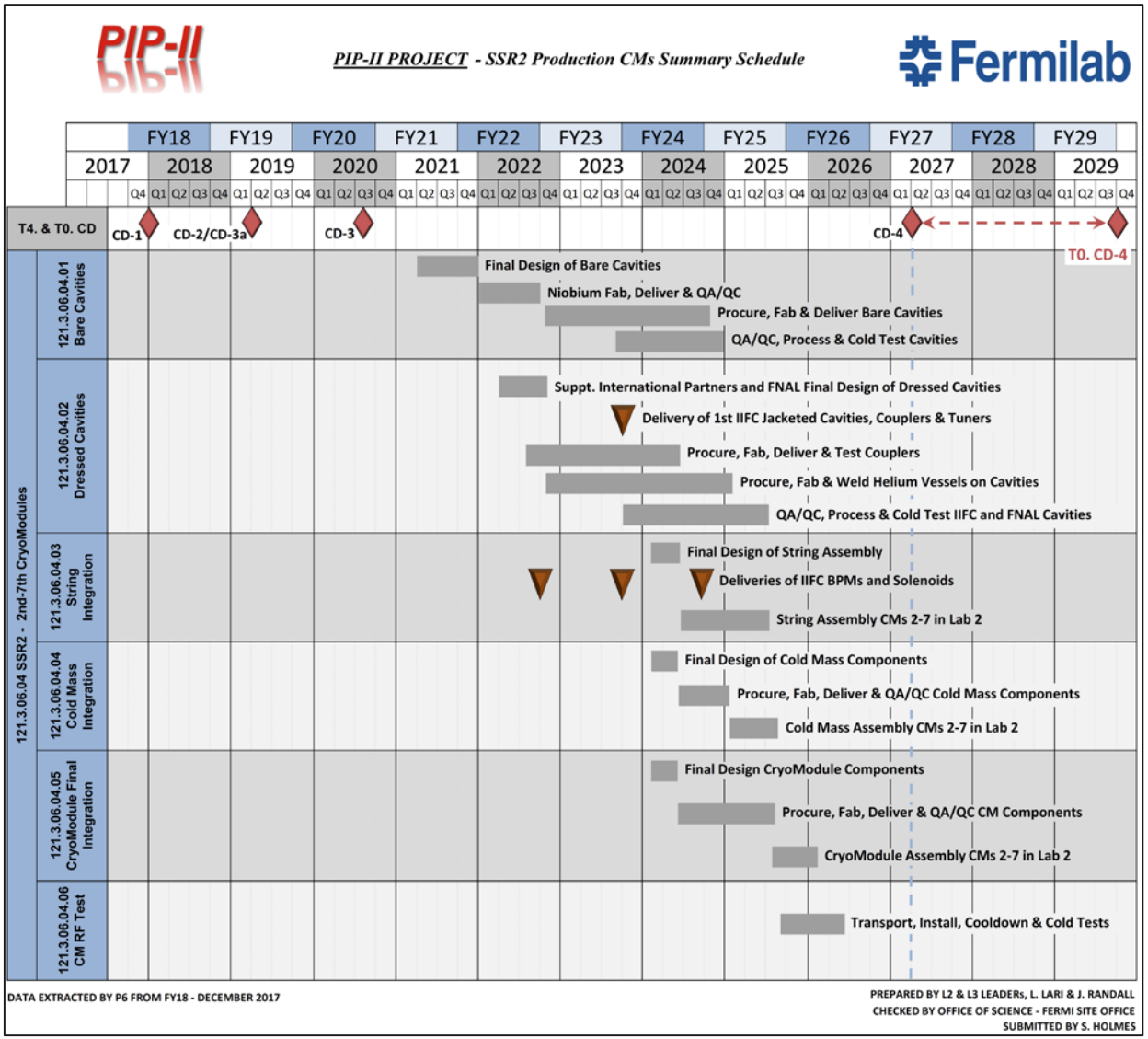
121.3.6.3 SSR2 CM1 Schedule

Charge #3

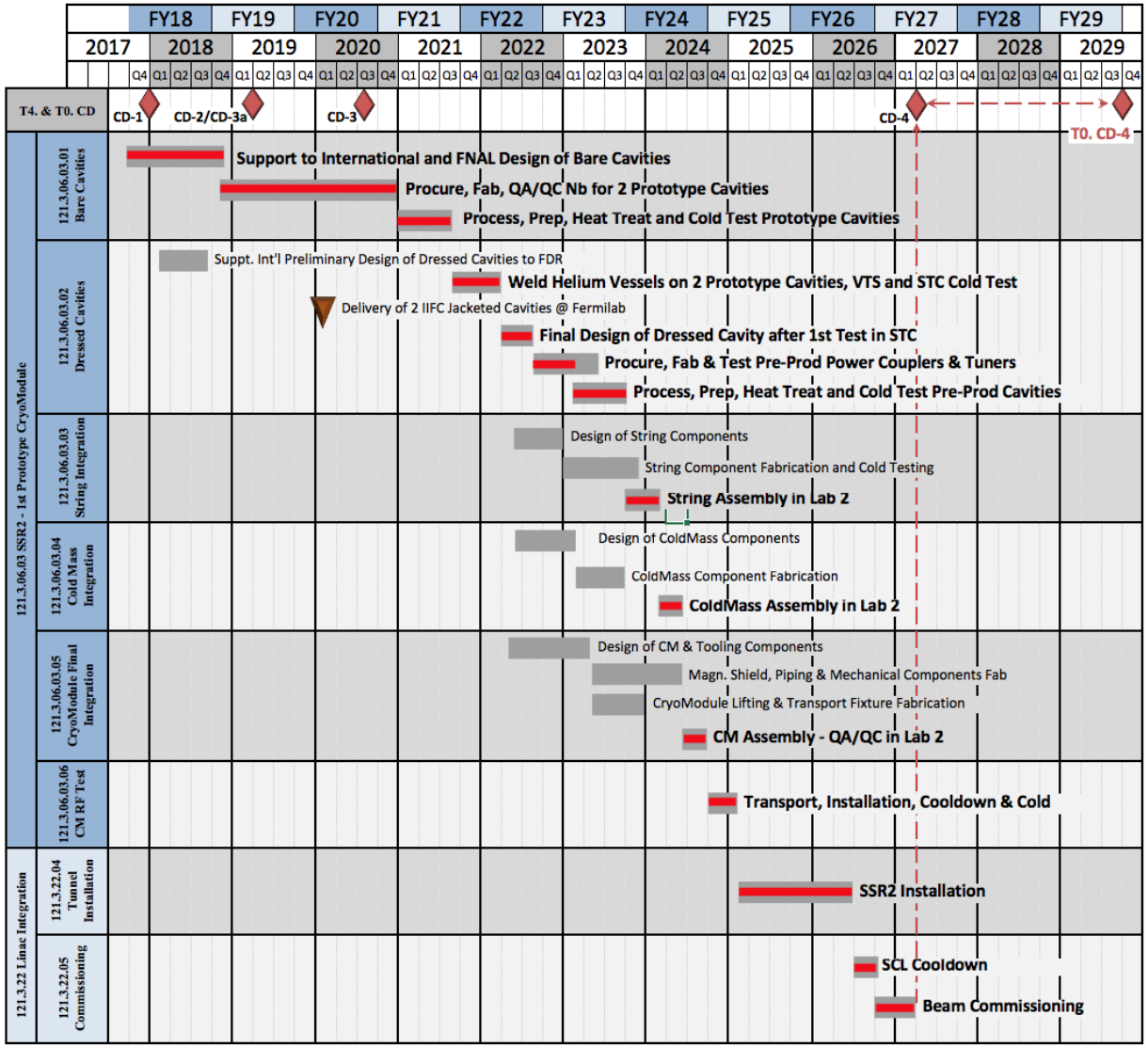


121.3.6.4 SSR2 CM 2-7 Schedule

Charge #3



121.3.6 SSR2 CM1 is on the critical path



Summary

- SSR1 and SSR2 requirements are defined and traceable in Teamcenter.
- Cryomodule sub-system and integrated system designs are sufficiently advanced to proceed to CD-1
  - The status of SSR1 1st CM is advanced.
  - The design and development of SSR CMs and components will be based on the experience and lessons learned with SSR1 1st CM.
- Cost, schedule, and risks are understood.
- ESH&Q plans are established and hazards understood.
- FNAL team and DAE partners are motivated, qualified, and ready to deliver.
- We are ready for CD-1 and look forward to your feedback.
- Thank you for your attention.