121.02.03 SRF - Single Spoke Resonator Cryomodules

SRF and Cryogenics Breakout Session

Donato Passarelli

PIP-II IPR

4-6 December 2018

In partnership with:
India/DAE
Italy/INFN
UK/STFC
France/CEA/Irfu, CNRS/IN2P3

Outline

- Scope/Deliverables
  - Including In-Kind Contributions from partners
- Requirements
- Interfaces
- Preliminary Design, Maturity
- Technical Progress to Date
- ESH&Q
- Risks and Mitigations
- Summary

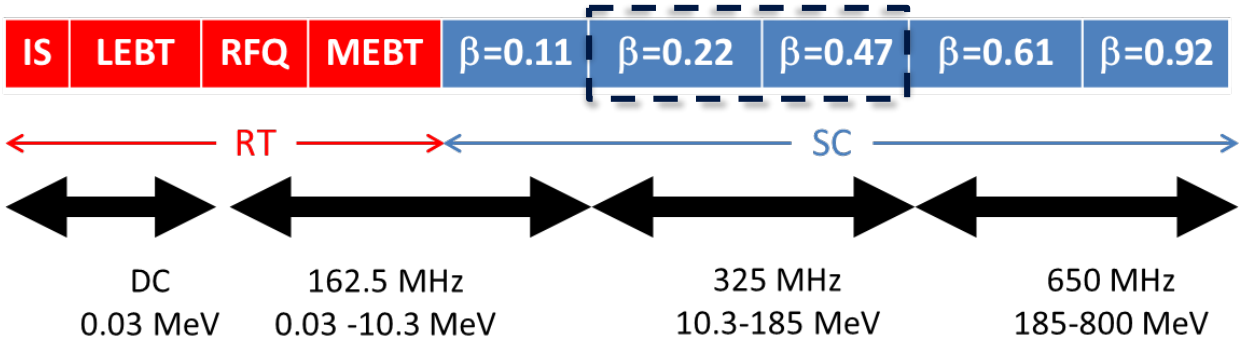
About Me:

- Donato Passarelli
  - L3 Manager for SSR cavities and cryomodules
  - Group Leader, Mechanical Engineering in APS-TD
  - Working in the SRF field (SSR at FNAL) since 2010
  - PhD in Mechanical Engineering on SSR1 cavities and tuner

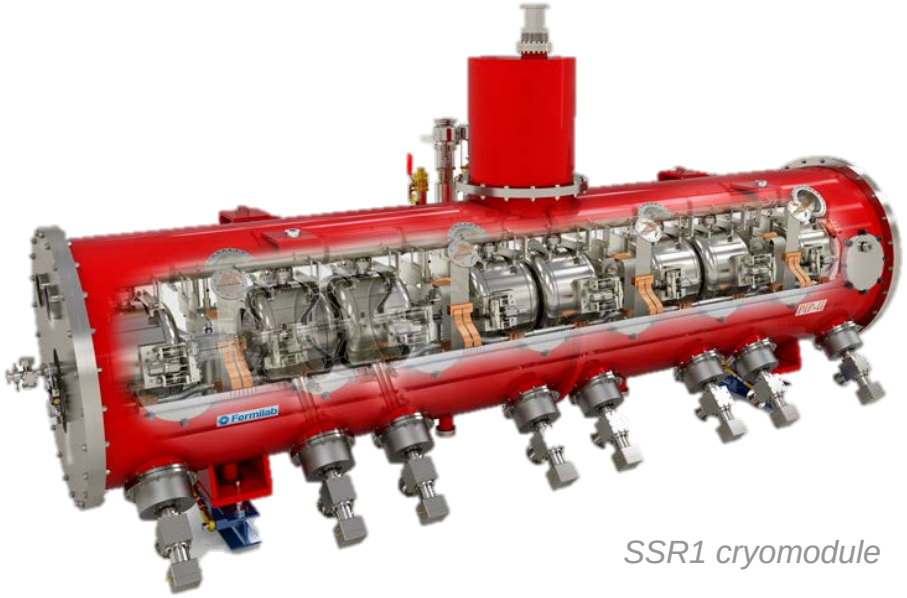
121.02.03 SSR Scope and Deliverables

Charge #2

Design, procurement, fabrications and testing of the Single Spoke Resonator (SSR1, SSR2) cavities and cryomodules



	SSR1	SSR2
# CMs	1+2	1+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

Final scope will be delivery of tested CMs for installation into PIP-II tunnel

121.02.03 SSR Scope and Deliverables

Charge #2

SSR1, SSR2 International Partners:

India

France

121.02.03 SSR Scope and Deliverables

Charge #2

Item	Quantities installed	DOE	Partners R&D & Construction
SSR1 proto CM	1		
Cryomodule	1	1	
Jacketed Cavities	8	8	2
Couplers	8	11	
Tuners	8	10	2
SC Solenoids	4	5	
Cold BPMs	4	5	
SSR1 CM1-2	2		
Cryomodule	2	2	
Jacketed Cavities	16	18	18
Couplers	16	18	
Tuners	16	16	16
SC Solenoids	8		10
Cold BPMs	8	10	

Item	Quantities installed	DOE	Partners R&D & Construction
SSR2 proto CM	1		
Cryomodule	1	1	
Jacketed Cavities	5	2	6
Couplers	5	2	7
Tuners	5	1	6
SC Solenoids	3		4
Cold BPMs	3	4	
SSR2 CM1-7	7		
Cryomodule	7	6	1
Jacketed Cavities	35		40 + 5
Couplers	35		40 + 5
Tuners	35		37 + 5
SC Solenoids	21		23
Cold BPMs	21	23	

CM assembly and final qualification testing at Fermilab

121.02.03.02 SSR1 Scope and Deliverables

Charge #2

- SSR1 Prototype CM
  - FNAL scope:
    - Qualification of 8 jacketed cavities with coupler and tuner
    - Complete procurement, QA/QC and integration of all cryomodule components
    - RF testing and verification of cryomodule performance at PIP2IT
  - Partners deliverables:
    - 2 jacketed cavities, 2 tuners
  - FNAL deliverables:
    - delivery of tested and qualified proto SSR1 CM at PIP2IT
- SSR1 Production CMs (1, 2)
  - FNAL scope:
    - Finalization of design and procedures using lessons learned from proto CM
    - Testing and qualification of 16 fully integrated cavities
    - Procurement, QA/QC, assembly and integration of the full cryomodules
    - RF testing and verification of cryomodule performance at PIP2IT
  - Partners deliverables:
    - 18 Jacketed cavities, 16 tuners, 10 SC solenoids
  - FNAL deliverables:
    - delivery of 2 tested and qualified CMs for installation at PIP-II tunnel

121.02.03.02 SSR2 Scope and Deliverables

Charge #2

- SSR2 Prototype CM
  - FNAL scope:
    - Design/support partners to design cavities and cryomodule components
    - Fabrication of prototype cavities, tuners, couplers
    - Testing and qualification of fully integrated cavities
    - Procurement, QA/QC, assembly and integration of all cryomodule components
    - RF testing and verification of cryomodule performance at PIP2IT
  - Partners deliverables:
    - 6 jacketed cavities, 6 tuners, 7 couplers, 4 SC solenoids
  - FNAL deliverables:
    - tested and qualified proto SSR1 CM at PIP2IT
- SSR2 Production CMs (1…7)
  - FNAL scope:
    - Finalization of design and procedures using lessons learned from proto CM
    - Testing and qualification of fully integrated cavities
    - Procurement (1…6), QA/QC, assembly and integration of the full cryomodules
    - RF testing and verification of cryomodule performance at PIP2IT
  - Partners deliverables:
    - 45 jacketed cavities, 45 couplers, 42 tuners, 23 SC solenoids, all CM components for the 7^{th} CM
  - FNAL deliverables:
    - 7 tested and qualified CMs for installation at PIP-II tunnel

121.02.03 System Requirements

Charge #2

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

- SSR1 cryomodule: TC# ED0001316
- SSR2 cryomodule: TC# ED0001829

Main Cryomodule Parameters	Units	SSR1	SSR2
Energy for section	MeV	10.3 to 35	35 to 185
Cavities (solenoids) per cryomodule		8 (4)	5 (3)
Cryomodule flange-to-flange length	m	≤ 5.4	≤ 6.5
2 K heat load	W	< 50	< 75
5 K heat load	W	< 80	< 80
30 – 50 K heat load	W	< 255	< 250
Environmental magnetic field	mG	≤ 15	≤ 15
Transverse cavity (solenoids) alignment error, RMS	mm	≤ 1 (0.5)	≤ 0.5 (0.5)
Angular cavity (solenoids) alignment error, RMS	mrad	≤ 5 (0.5)	≤ 5 (0.5)

Table of main cryomodules requirements

121.02.03 System Requirements

Charge #2

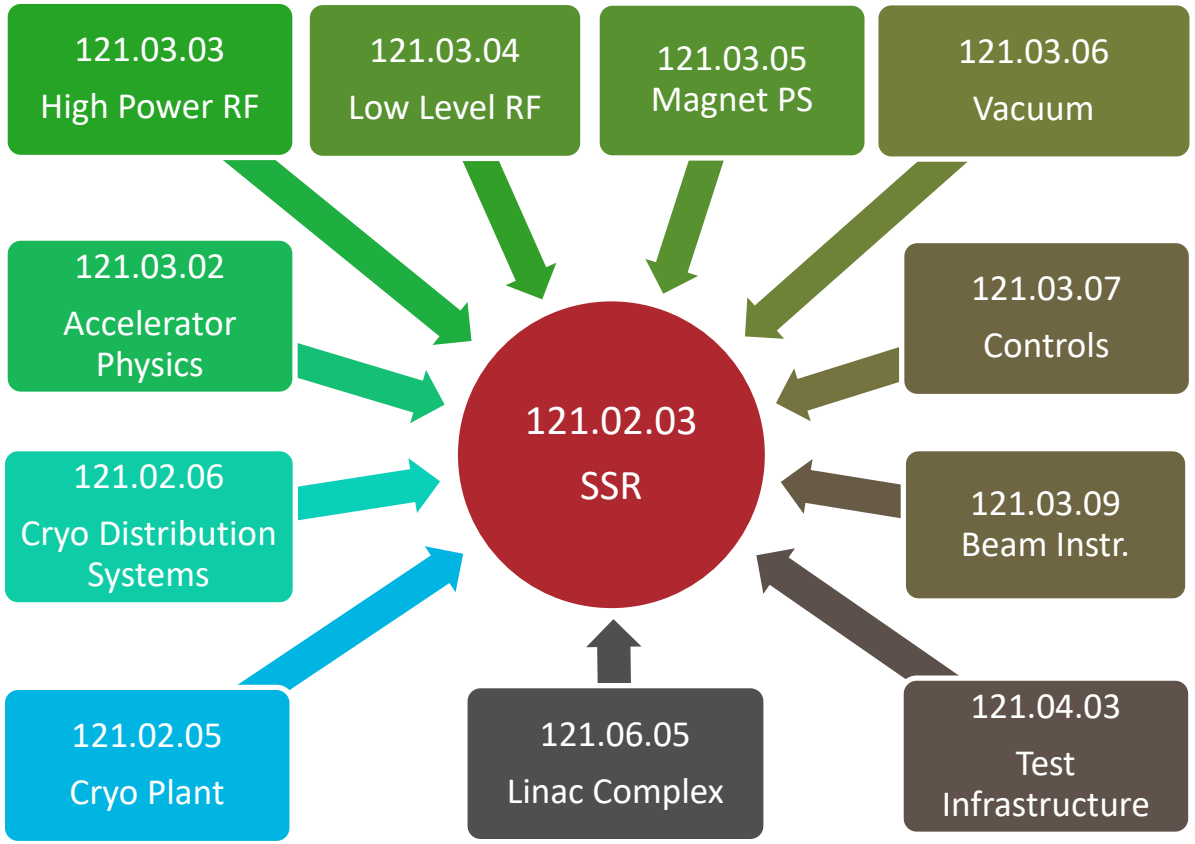
- SSR1 cavities
- SSR2 cavities

Main Cavities Parameters	Units	SSR1	SSR2
Frequency	MHz	325	325
β_g (β_{opt})		0.186 (0.222)	0.398 (0.475)
Aperture diameter (Effective length)	mm	30 (205)	40 (438)
Operating energy gain per cavity	MV	2.05	5
Unloaded cavity quality factor (Q_0) at 2K		0.6×10^{10}	0.8×10^{10}
Cavity operating temperature	K	2.0	2.0
MAWP at room temperature (at 2K)	bar	> 2.05 (4.1)	> 2.05 (4.1)
Sensitivity to LHe pressure fluctuations	Hz/mbar	< 25	< 25
Lorentz Force Detuning coefficient	Hz/(MV/m)^2	< 5	< 2.8
Coupler testing power (in full reflection)	kW	10	20

121.02.03 Interfaces

Charge #2

L2 Sys	L3 WBS	L3 System Name	L3 Sys	ICD TC ID
SRFCryo	121.2.03	Single Spoke Resonator Cryomodule (SSR)	SSR	ED0007565

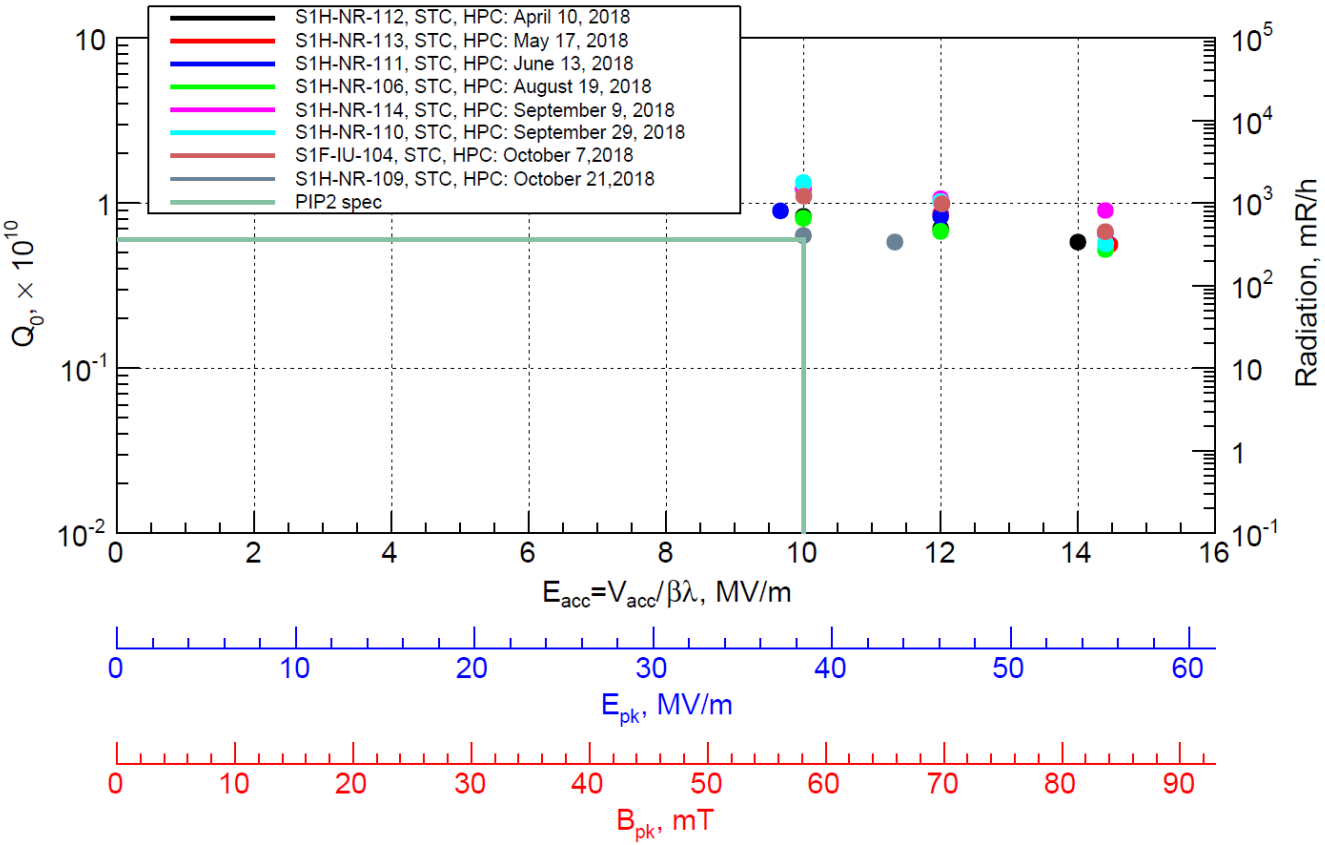


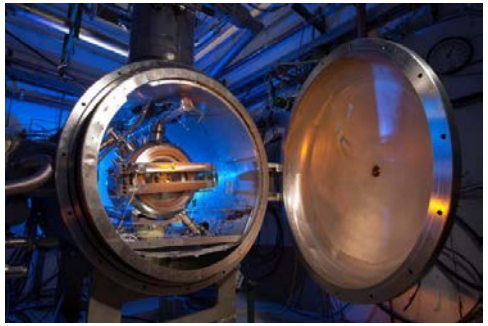
Interfaces are identified and revision controlled documents exist in Teamcenter

SSR1 cavities

Charge #2

- 8 fully integrated cavities were tested and qualified
  - S104, S106, S109, S110, S111, S112, S113, S114
    - S107 is conditionally qualified and it will serve as spare one





SSR1 cavities performance

Charge #2

Cavity ID #	Type	Date of test, *yyyy-mm-dd*	Q0, x10e8 @10 MV/m	Eacc max, MV/m	Rad. onset field, MV/m	Rad, mR/h @10 MV/m	Rad, mR/h @Eacc max
S1F-IU-104	A	2018-10-07	110	14.4	13	0	45
S1H-NR-106	B	2018-08-19	80	14.4	12.7	0	153
S1H-NR-109	A	2018-10-21	64	11.7	9.3	27	170
S1H-NR-110	A	2018-09-29	133	14.4	11	0	666
S1H-NR-111	A	2018-06-13	90	14.4	n/a	0	0
S1H-NR-112	B	2018-04-10	83	14.4	n/a	0	0
S1H-NR-113	B	2018-05-17	122	14.4	n/a	0	0
S1H-NR-114	B	2018-09-09	121	14.4	14.4	0	9

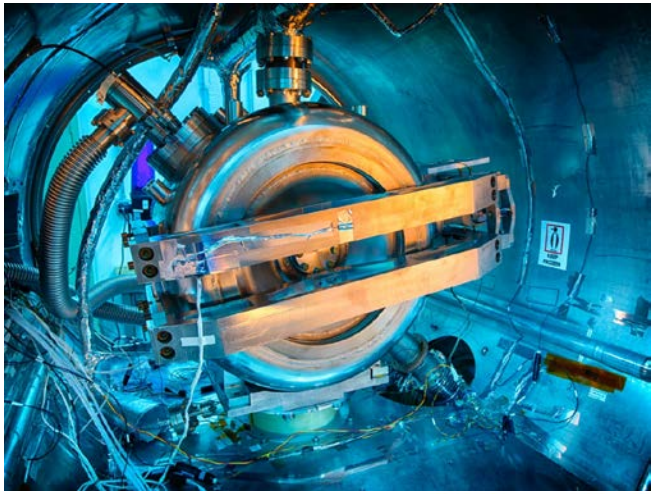
df/dp for all cavities with tuner engaged:

- $4 \leq df/dp \leq 10$ Hz/Torr

LFD coefficient for all cavities with tuner engaged:

- $4 \leq$ LFD coeff. ≤ 7 Hz/(MV·m)^2

All 8 cavities were found within the **frequency target range at 2k**



SSR1 cavities S103 and S104 from partners

Charge #2

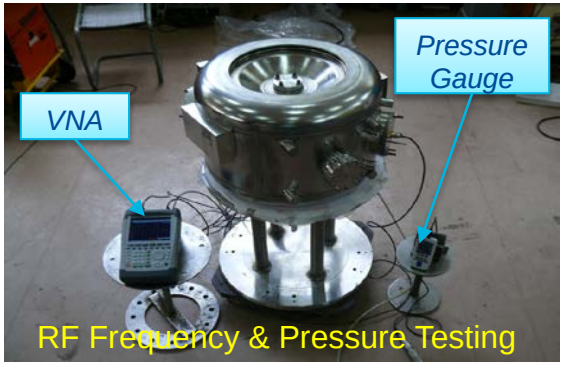

Shell before Weldment


Components


Dome Head


Dry fitting before weldment


Tack Welded



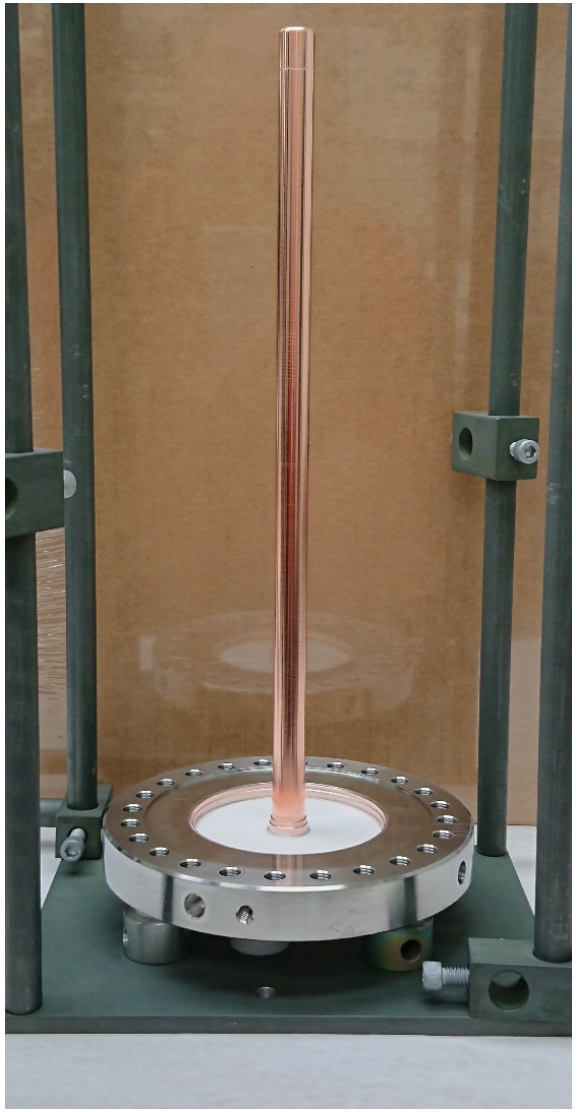
RF Frequency & Pressure Testing


Dressed Cavity

- Components for He Jacketing for two cavities S103 and S104 were manufactured in house at BARC, Mumbai
- He Jacketing followed by RF measurement and Pressure testing were done on the Dressed cavity prior to shipping to FNAL

SSR1 couplers

Charge #2

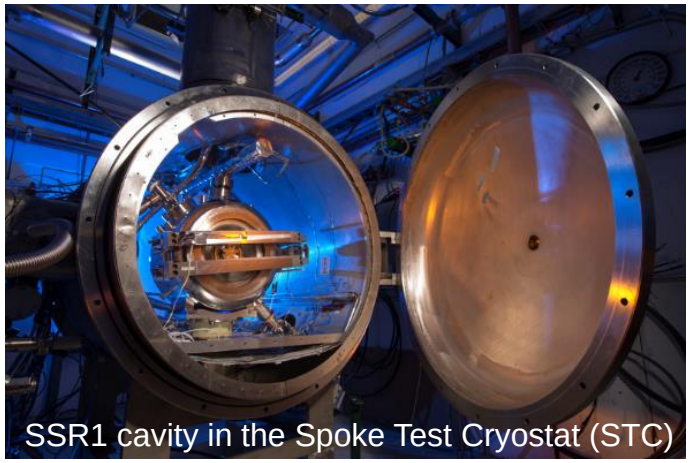


- 8 vacuum end couplers were successfully:
  - QC inspected
  - qualified at room temperature on the RF test stand (10 kW full reflection)
  - cleaned and particle-free installed on cavities
  - qualified during integrated cavity tests in the Spoke Test Cryostat

SSR1 Tuner and resonance control

Charge #2

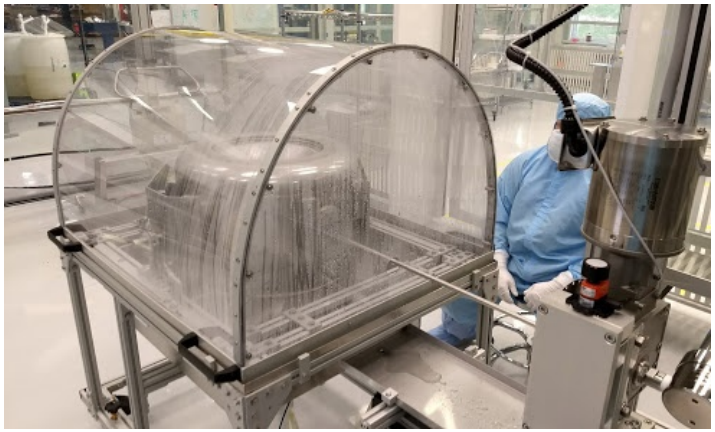
- **Prototype SSR1 tuner**
  - Design completed and one unit was prototyped
  - Successfully tested at 293K and cold temperature
- **Production SSR1 tuner**
  - Design completed
  - 1 out of 10 units was received and used for resonance control of SSR1 cavities
  - Active components for 1st cryomodule (9 electromechanical and 18 piezo actuators) were tested at cold temperature
- **Resonance control studies**
  - Requirements: microphonics <20 Hz
  - Good progress during cold tests at STC. ResControl algorithms, developed for ILC/ProjectX and LCLS II, successfully applied and requirements are nearly achieved.



SSR1 cavity in the Spoke Test Cryostat (STC)

Lab 2 cleanroom

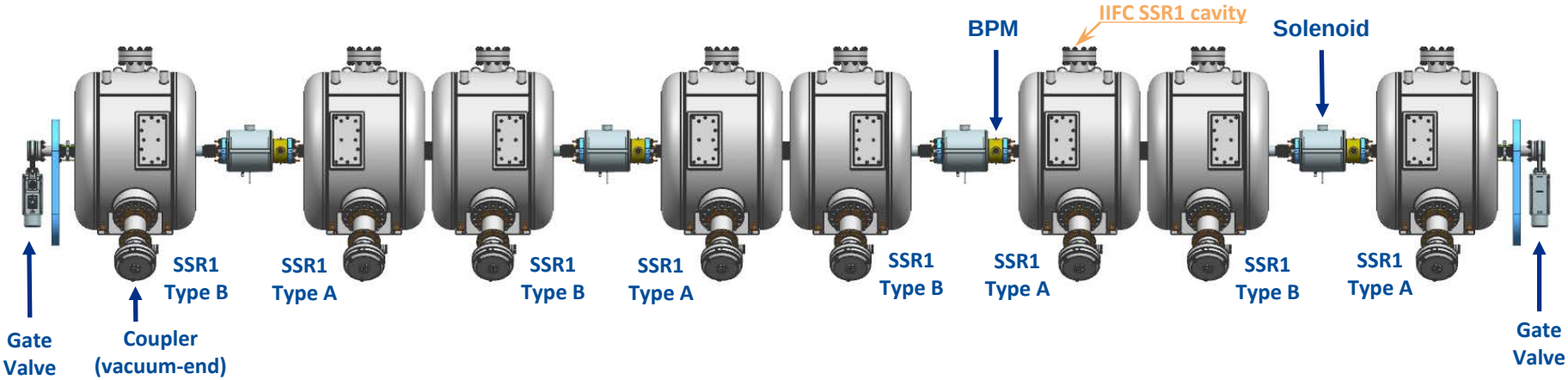
Charge #2



Lab 2 cleanroom is a qualified facility for SRF activities: SSR1 string assembly

SSR1 cavities string assembly

Charge #2

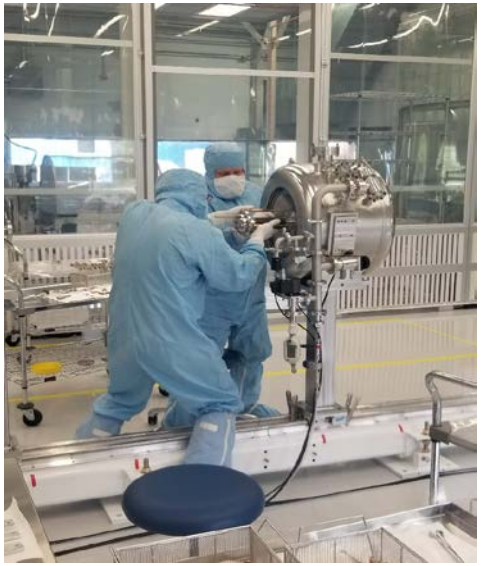


Currently working on the cavity string assembly in the Lab2 cleanroom

- All string assembly components were subject QC inspections
- Particle-free procedures were developed and validated by qualifying cavities
- Alignment is being performed using laser trackers
- Possible design improvements have been identified and collected

SSR1 cavities string assembly: preparation

Charge #2

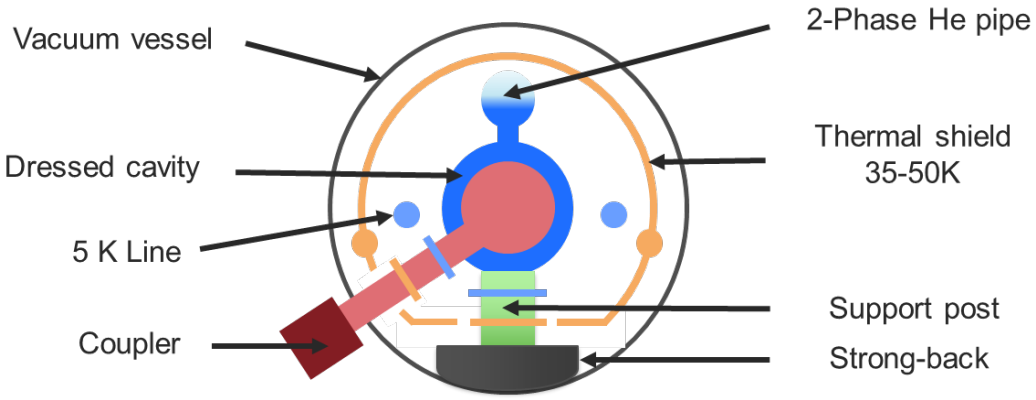



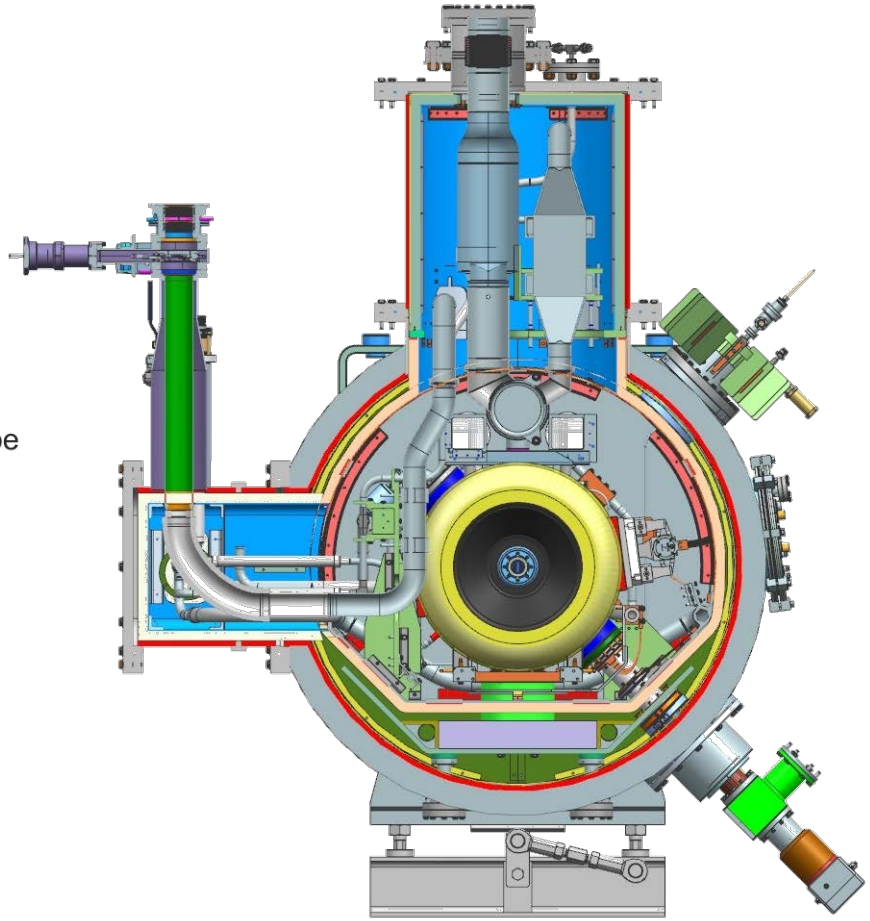


SSR1 Cryomodule

Charge #2

Conceptual layout of PIP-II CMs

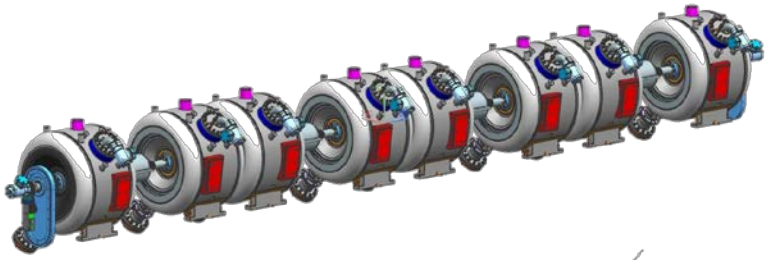


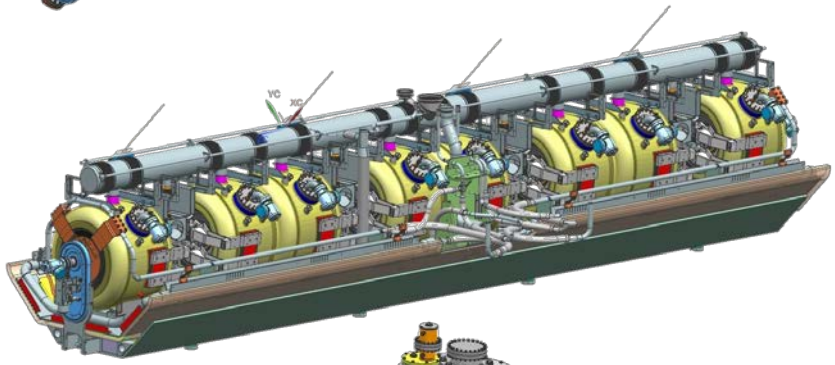


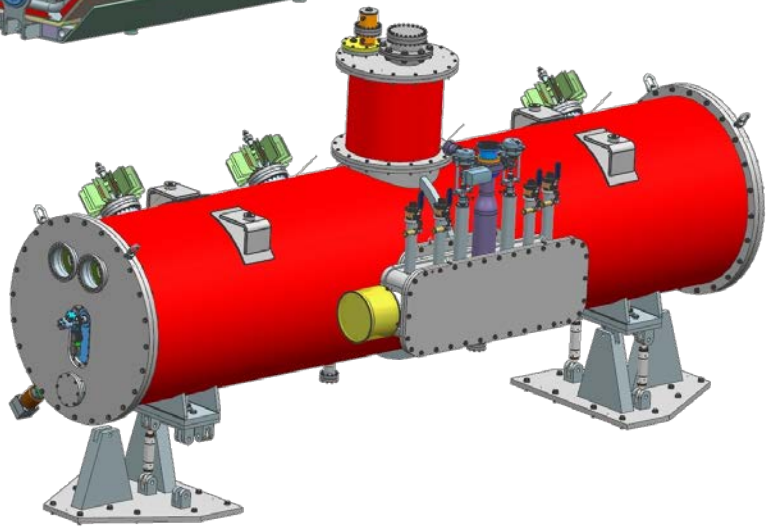
SSR1 CM cross section

SSR1 Cryomodule: design maturity

Charge #2





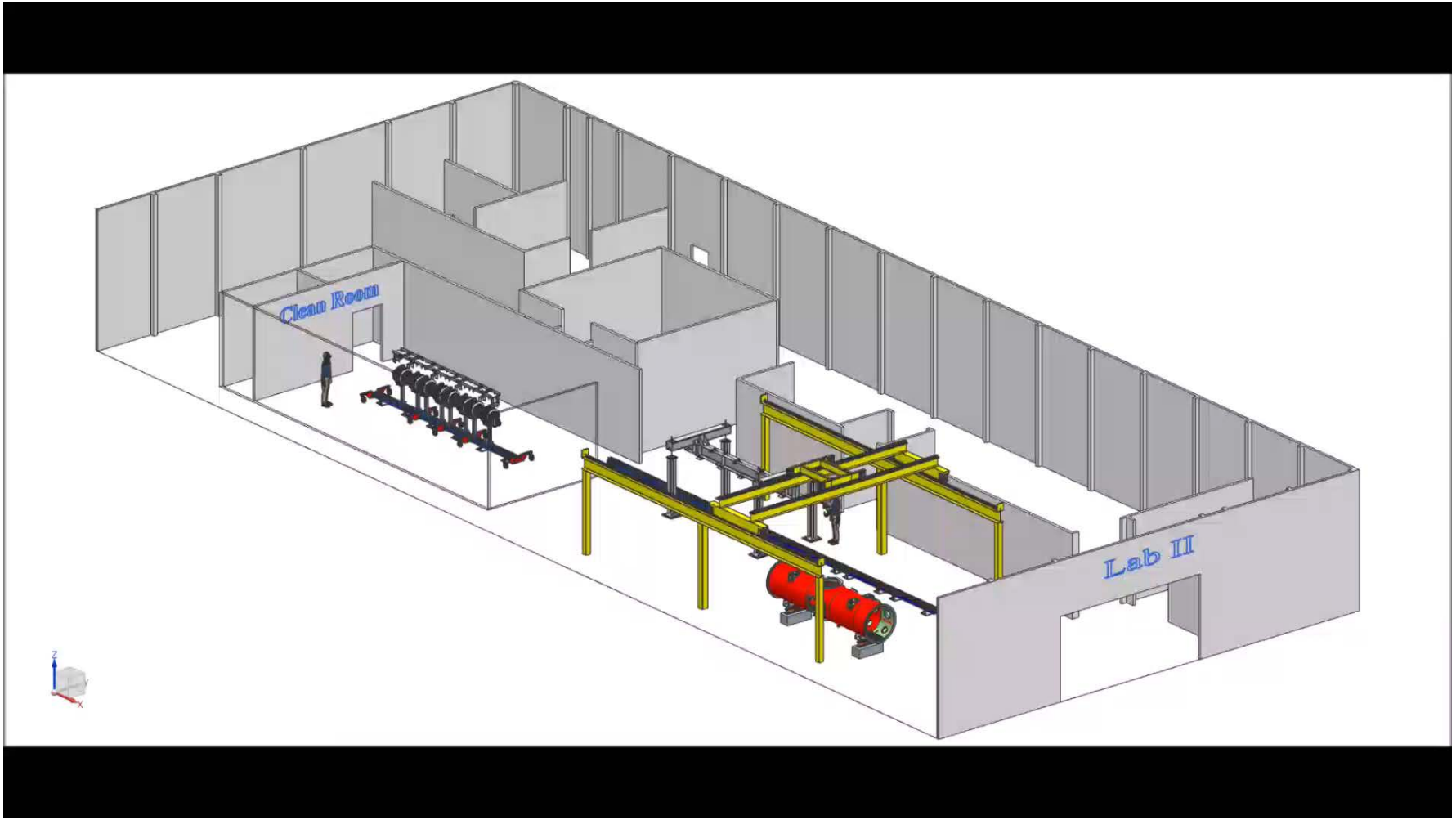


- **SSR1 Cavity String assembly**
  - Design: completed
  - Procurement: completed
  - Assembly is ongoing
    - Completion expected by Dec 21, 2018
- **SSR1 Coldmass**
  - Design: completed
  - Procurement: ongoing
- **SSR1 Top cryomodule assembly**
  - Design: ready for FDR
  - Transportation tooling: in progress
  - Procurement: ongoing
  - Expected CM completion date
    - May 2019
  - Testing at PIP2IT

SSR1 CM assembly sequence

Charge #2

Procedures for the final CM integration are currently being developed



SSR1 CM Documentation

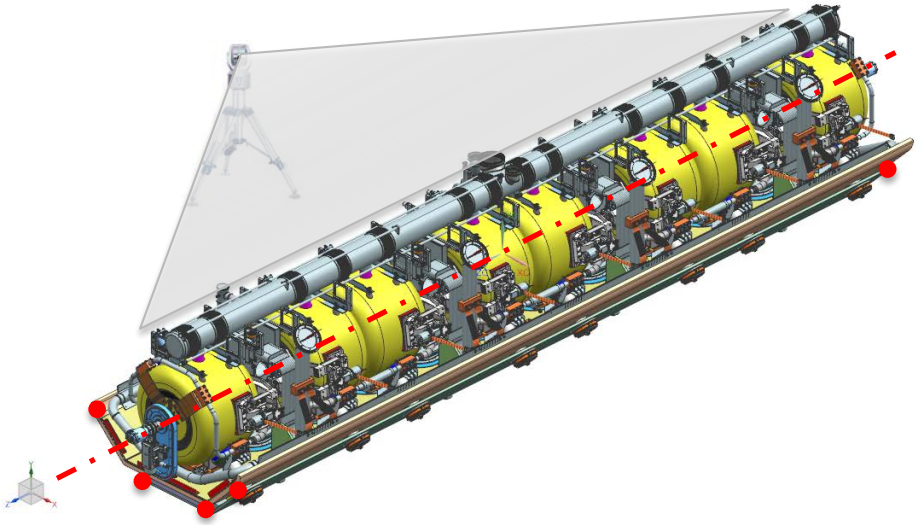
Charge #2

- Documents revision controlled in Teamcenter:
  - FRS, TRS and ICD
  - 2D drawings and 3D models
  - Reports of design reviews
  - P&ID was created and constantly updated
  - Piping engineering note: ready for final review (pre-approval)
  - Vacuum vessel engineering note: pre-approved
  - Procurement specifications

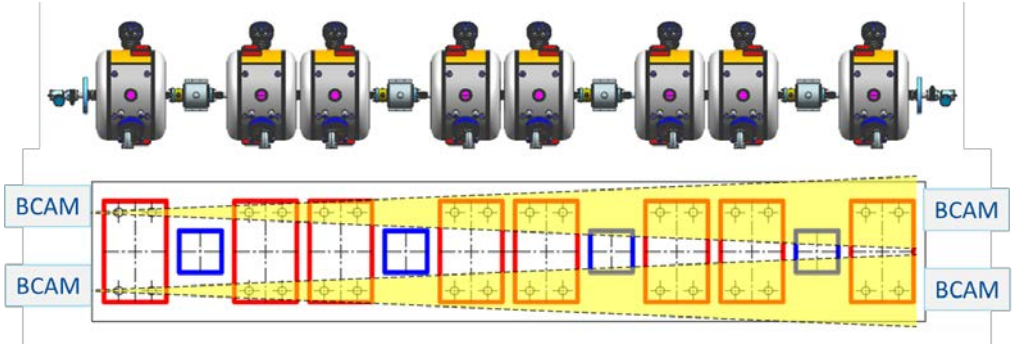
SSR1 cryomodules alignment

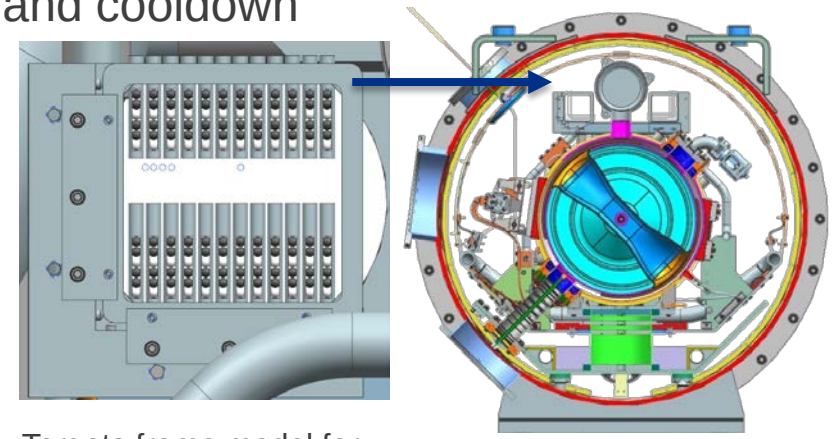
Charge #2

- **Laser trackers** will be used for the **Final alignment of cavities and solenoids** within the PIP-II alignment requirements, taking into account also the shifts due to cooldown.



- **HBCAM (Brandeis CAMera)** will be employed for **monitoring the alignment** of solenoids and cavities during transportation and cooldown



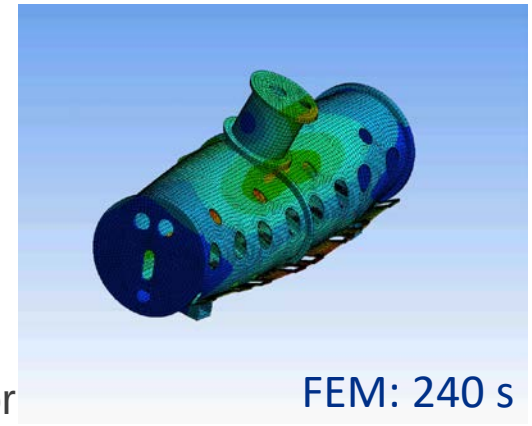


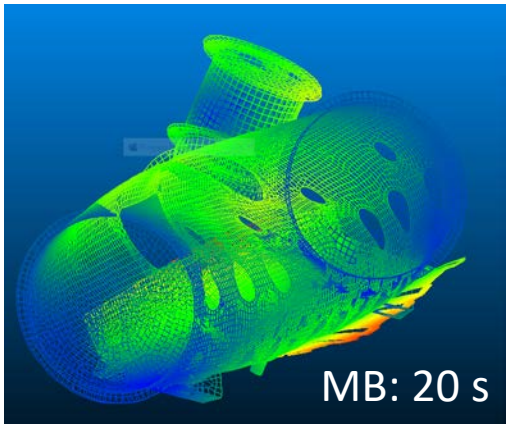
Targets frame model for the PIP-II cryomodule

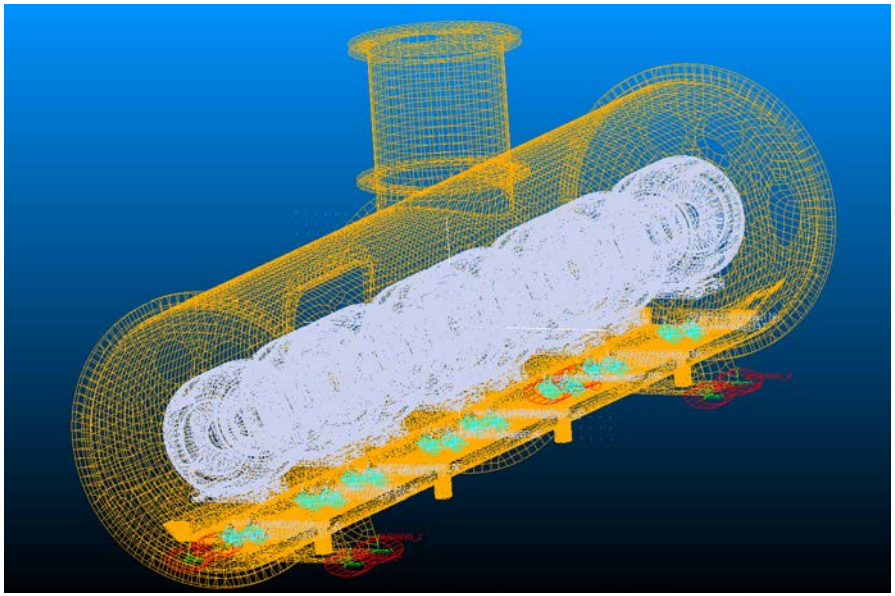
SSR1 CM transportation tooling

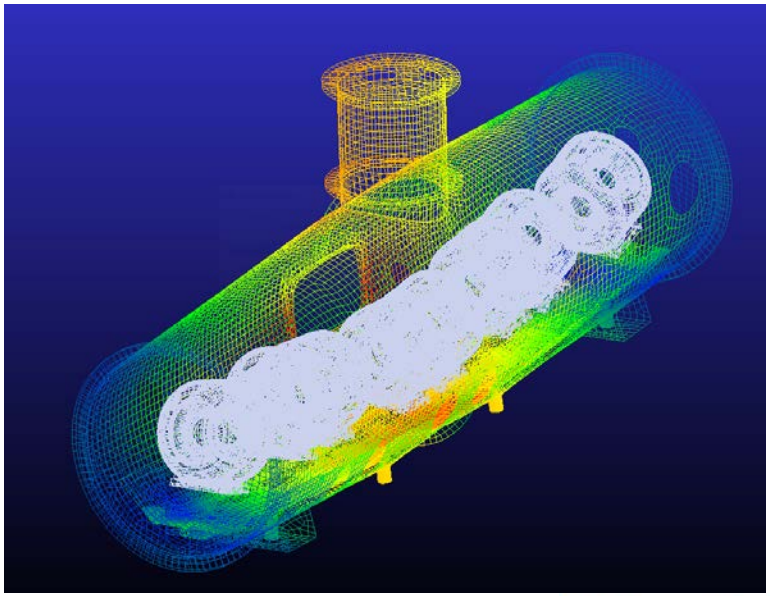
Charge #2

Mixed approach: FEM – MultiBody. Assembly stiffness is computed through FE analysis (small components are simulated as lamped springs/masses) and then imported and combined in multi-body analysis: suspension system optimization, assembly dynamic characterization for transportation tooling desing









SSR2 Preliminary design

Charge #2

- Cavity
  - RF design optimization and structural design is ongoing together with our partners (integrated team)
  - PDR is planned in March 2019
- Coupler
  - RF and structural design is being developed incorporating lessons learned from SSR1 couplers experience
- Tuner
  - An evaluation to adapt SSR1 tuner design is ongoing
- Cryomodule
  - A conceptual model of the cryomodule is needed to check interfaces

ESH

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 Laboratory and DOE standards
  - Fermi ES&H Manual
    - 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
  - Division/Area specific Hazards Analyses and Training
    - Cryogenics exposure (Cavity/CM Testing)
    - ODH (Cavity/CM Testing)
    - Chemical/Acids (Cavity processing at ANL, controlled by ANL)
    - Radiation (Cavity/CM testing)
    - Material Handling

Quality Management

Charge #6

- Quality control
  - Procurement Quality / Supplier Quality are addressed by written procurement specifications and vendor visits
  - Incoming inspections are planned for all components (graded approach)
  - Acceptance testing are planned for critical sub-assemblies and documented in the Fermilab Vector database
    - Operating procedures
    - Travelers
  - Discrepancy reports and dispositions managed in Vector are used to address corrective actions
- QA Expectations for Partners
  - Partners shall have same or equivalent QC plans

Risk Management

Charge #2,7

Risk Rank	Risk ID	Title	Summary
High	RT-121-02-003	Underestimated resources for design optimization of SSR1 CM (1)	If the SSR1 CM (1) does not meet technical performance requirements during PIP2IT testing, then the module must be removed from the PIP2IT beamline and a repair strategy implemented that may include cold-mass disassembly which will jeopardize PIP2IT testing plans, CM assembly of the HB650 CM(1), and delay the final designs of the SSR2 CM.
	RT-121-02-003-C	Underestimated resources for design optimization of SSR2 CM (1)	If the SSR2 CM (1) does not meet technical performance requirements during PIP2IT testing, then the module must be removed from the PIP2IT beamline and a repair strategy implemented that may include cold-mass disassembly which will jeopardize PIP2IT testing plans and delay the final designs of the SSR2 CM.

Risk Register

Summary

- FRS and ICD are defined and traceable in Teamcenter
- Proto SSR1 CM
  - Results of Integrated tests of SSR1 cavity, coupler and tuner in the Spoke Test Cryostat meet/exceed the requirements
  - SSR1 cavity string assembly is currently being assembled in the cleanroom at Lab 2
  - Components and sub-assemblies for the final CM integration are in the procurement phase. Detailed assembly procedures and tooling are being developed.
- Proto SSR2 CM
  - Cavity design is ongoing
  - Lessons learned from SSR1 experience will be applied
- ESH and QA plans are in place
- Risks are understood and tracked in the risk register

Thank you for your attention

We are on track for CD-2/3a and look forward to your feedback

END