121.02.04 – 650 MHz CryoModules

SRF and Cryogenics Breakout Session

Saravan K. Chandrasekaran

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)
- Requirements
- Interfaces
- Preliminary Design, Maturity
- Technical Progress to Date
- ESH&Q
- Risks and Mitigations
- Summary

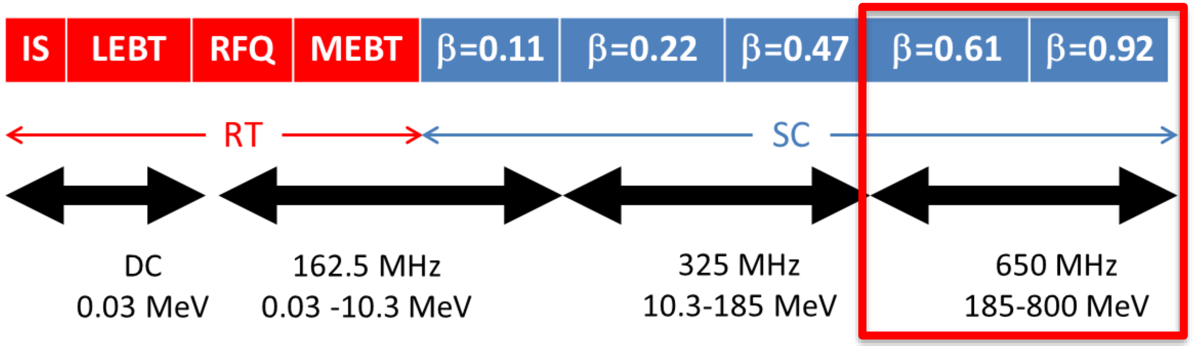
About Me:

- L3 Manager for 650 MHz Cryomodules (CM)
  - Responsible for 650 MHz CM
  - Sub-Project Manager (SPM) for cavities and CM with Partners

- Experiences
  - Subcontracting Officer’s Technical Representative (SOTR) for LCLS-II magnetic shielding
  - Lead for magnetic hygiene & demagnetization for LCLS-II
    - Led efforts across Fermilab, JLab, SLAC
  - Lead engineer for SRF thermal treatment facilities
  - FRIB Research Associate for SRF & magnetic shielding
    - Led magnetic shielding design for FRIB QWR cryomodules
  - Doctorate in Mechanical Engineering on Niobium for SRF

Scope and Deliverables

Charge #2



Cryomodule	Number (Prototype + installed)	Cavity Number	Magnet Number	Testing	Note
LB650	1+11	3	0	Partial Test at Partner lab, Full Test at FNAL	Integrated Design
HB650	1+4	6	0	Test at FNAL	Integrated Design

- CW operation & 2 mA beam current

Scope and Deliverables

Charge #2

- Partnerships:
  - Indian Institutions Fermilab Collaboration (IIFC)
    - Bhabha Atomic Research Center (BARC)
    - Raja Ramanna Centre for Advanced Technology (RRCAT)
    - Variable Energy Cyclotron Center (VECC)
  - France: Commissariat à l'énergie atomique, Saclay (CEA)
  - Italy: Istituto Nazionale di Fisica Nucleare (INFN)
  - UK: Science & Technology Facilities Council, Daresbury (STFC)

Scope and Deliverables

Charge #2

Item	Quantities installed	DOE	Partners R&D & Construction
LB650 proto CM	1		
Cryomodule	1		1
Jacketed Cavities	3	2	4*
Couplers	3		6
Tuners	3		5
LB650 CM1-11	11		
Cryomodule	11		11
Jacketed Cavities	33		43
Couplers	33		40
Tuners	33		38

Item	Quantities installed	DOE	Partners R&D & Construction
HB650 proto CM	1		
Cryomodule	1	1	
Jacketed Cavities	6	7	4
Couplers	6	8	4
Tuners	6	8	4
HB650 CM1-4	4		
Cryomodule	4		4
Jacketed Cavities	24		32 + 6
Couplers	24		42 + 6
Tuners	24		32 + 6

Scope and Deliverables

Charge #2

- Low beta 650 MHz (LB650) – 1 + 11 CM
  - Fermilab scope:
    - Support partner design of cavities, couplers, & cryomodules
    - Fabricate & validate prototype dressed cavities
    - Support partner fabrication & validation of cryomodules & components
    - Testing all cryomodules
  - Partner scope:
    - Design, fabrication, testing of prototype & production CM & components
    - Transportation of CM to Fermilab

Joint design program being established

Scope and Deliverables

Charge #2

- High beta 650 MHz (HB650) – 1 + 4 CM
  - Fermilab scope:
    - Design of cavities, couplers, tuners, cryomodules
    - Fabrication & validation of prototype CM, including components
      - Transportation testing & validation of prototype CM to UK and back
    - Fabrication of a production CM
    - Support partner specific design & fabrication
    - Testing all cryomodules
  - Partner scope:
    - Support Fermilab design
    - Fabrication of prototype components for Partner process validation
    - Fabrication of production cryomodules, including components
    - Design & fabrication of transportation frame & scheme

Joint design program being established

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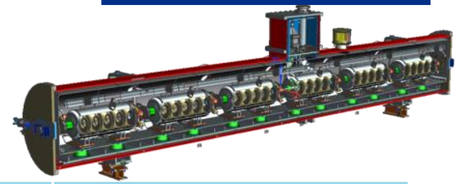
Proton Improvement Plan-II

System Requirements

Charge #2

- 650 MHz Cryomodules

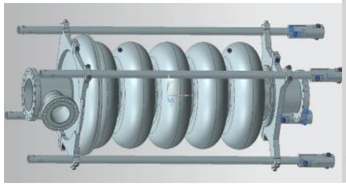


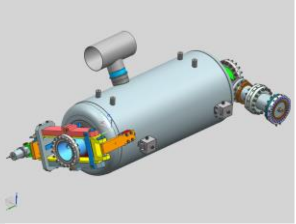
	Units	LB650	HB650
Energy for section	MeV	185 to 500	500 to 800
β_g		0.61	0.92
Cavities per cryomodule		3	6
Cryomodule flange-to-flange length	m	4.32	9.92
2 K heat load	W	< 78	< 175
5 K heat load	W	< 24	< 61
30 – 50 K heat load	W	< 68	< 160
Environmental magnetic field	mG	≤ 5	≤ 5
Transverse cavity alignment error, RMS	mm	0.5	0.5
Angular cavity alignment error, RMS	mrad	1	1

System Requirements

Charge #2

- 650 MHz Cavities, Couplers, & Tuners





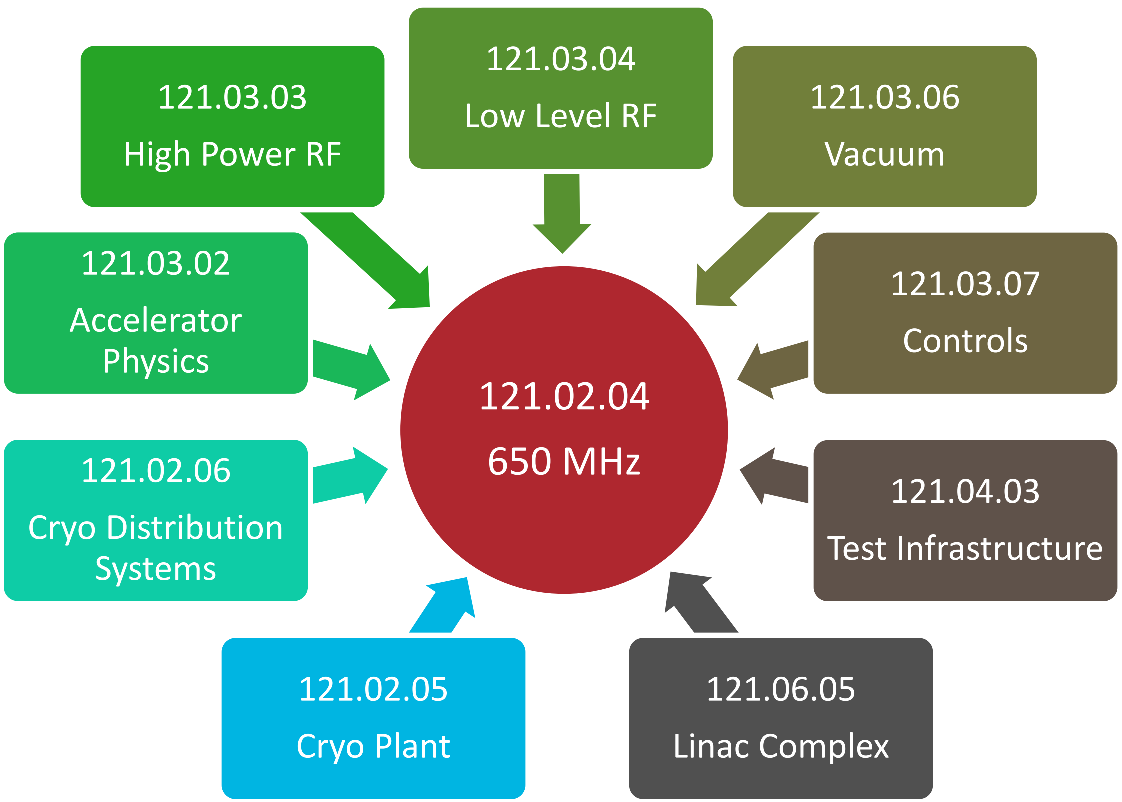
	Units	LB650	HB650
β_g		0.61	0.92
Operating energy gain per cavity	MV	11.9	19.9
Unloaded cavity quality factor		2.15×10^{10}	3×10^{10}
Cavity operating temperature	K	2.0	2.0
2 K heat load per cavity & coupler	W	< 21.1	< 23.9
Cavity longitudinal stiffness	kN/mm	< 5	< 5
Sensitivity to LHe pressure fluctuations	Hz/mbar	< 25	< 25
Lorentz Force Detuning coefficient	$Hz/(MV/m)^2$	< 1.4	< 1.0
Coupler testing power	kW	35	50

Interfaces

Charge #2

- Interfaces well defined
  - Revision controlled in Teamcenter

L2 Sys	L3 WBS	L3 System Name	L3 Sys	ICD TC ID
SRFCryo	121.02.04	650 MHz Cryomodules (650MHz)	650MHz	ED0007567

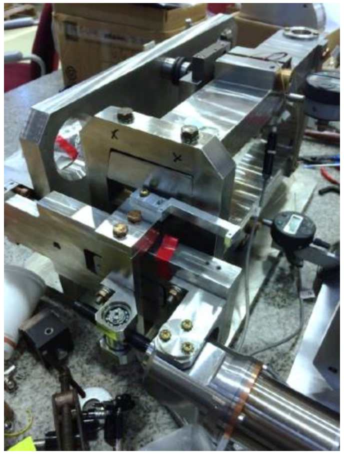


Preliminary Design and Design Maturity

Charge #2

- HB650 Cavities
  - β_g = 0.90 cavity dressing PDR to be held in Dec 2018
    - Gate for dressing these prototype cavities
  - β_g = 0.92 cavity dressing PDR to be held in Dec 2018
    - Gate for Fermilab procurement of bare cavities + Partner dressing of prototype cavities

- Couplers
  - Prototypes procured, and to be tested in early 2019
  - FDR for couplers to be held in 2019
  - LB650 and HB650 to be identical
- Tuners
  - Prototype tuner received and bench tested
  - FDR for tuners to be held in 2019

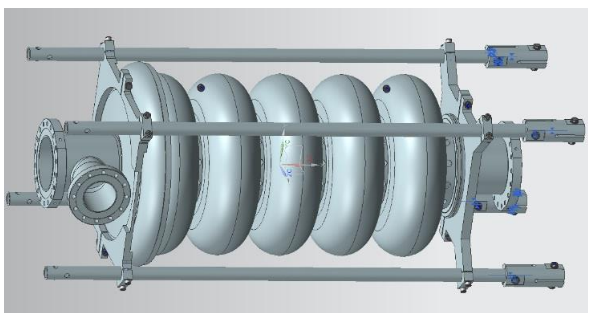


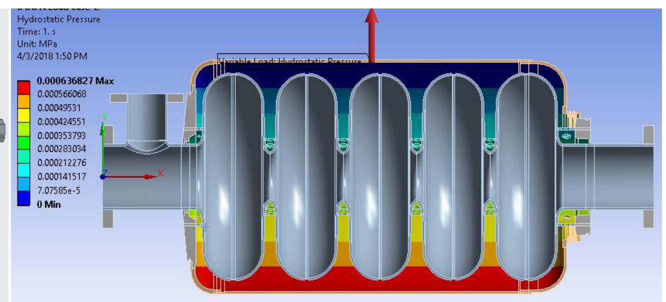
Fermilab PIP-II Proton Improvement Plan-II

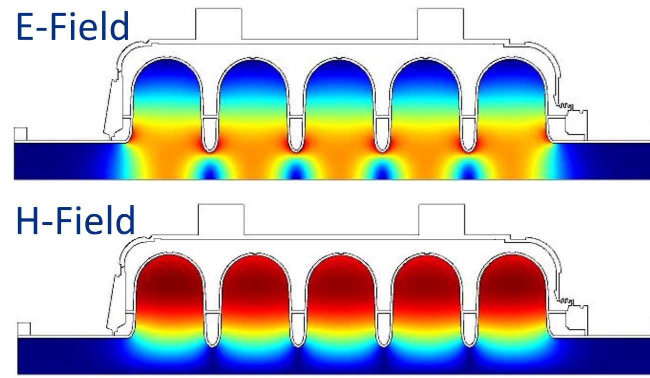
Preliminary Design and Design Maturity

Charge #2

- LB650 5-cell cavities
  - RF design frozen
  - Partner developed mechanical design version 1 being prototyped by the partner with 2 cavity order
    - Fermilab to receive and process cavities in 2019
  - Mechanical design optimization ongoing at second partner lab
    - Prototype cavities to be fabricated by Partner







INFN cavity model

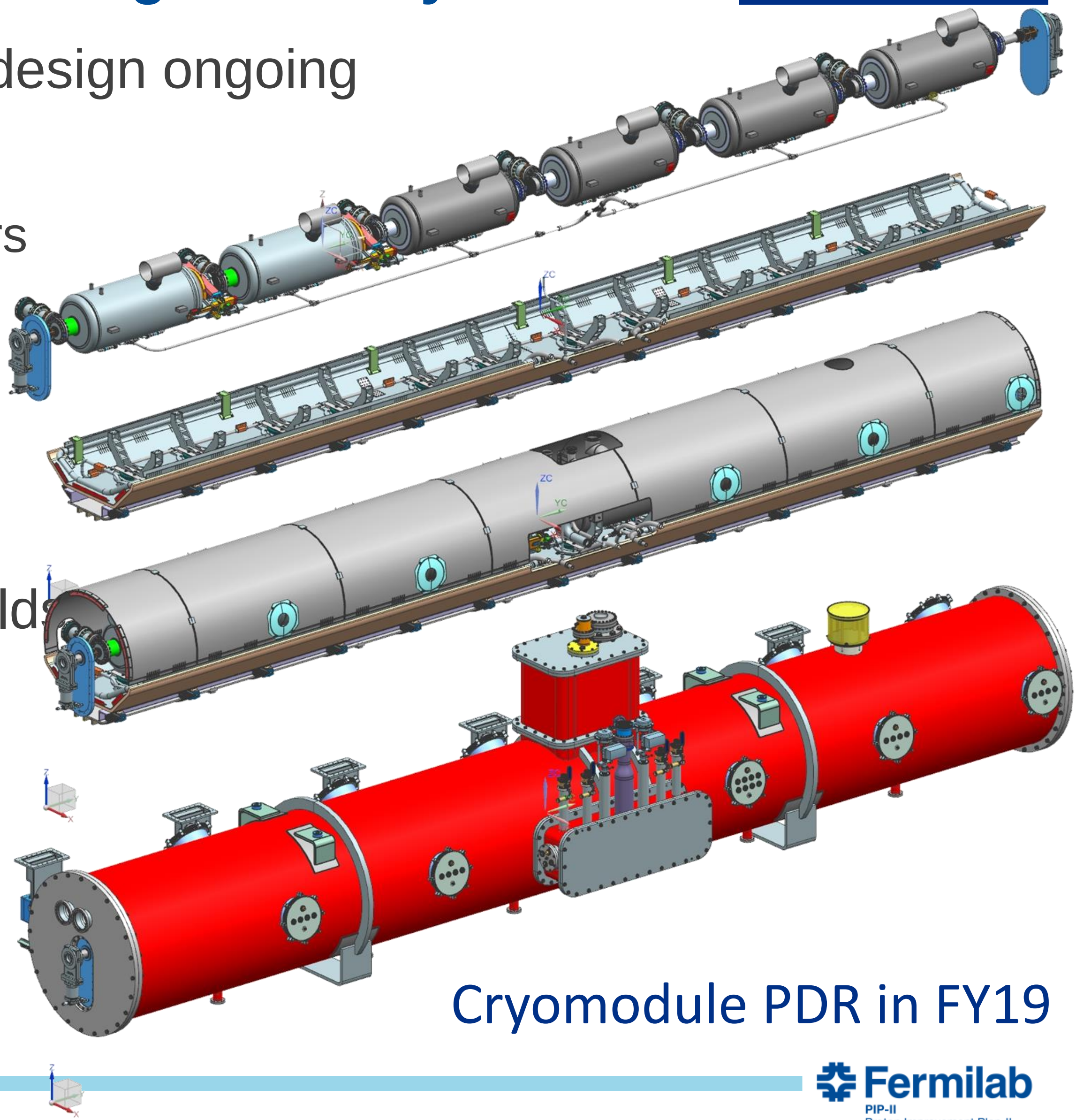
VECC cavity analysis

Fermilab verification

Preliminary Design and Design Maturity

Charge #2

- Cryomodule preliminary design ongoing
- String
  - Cavities, couplers, tuners prototype stage
- Strong back & supports
  - Preliminary design & analysis stage
- Thermal & magnetic shields, piping, vacuum vessel
  - Preliminary design & analysis stage
- Cryomodule
  - Preliminary design & analysis stage

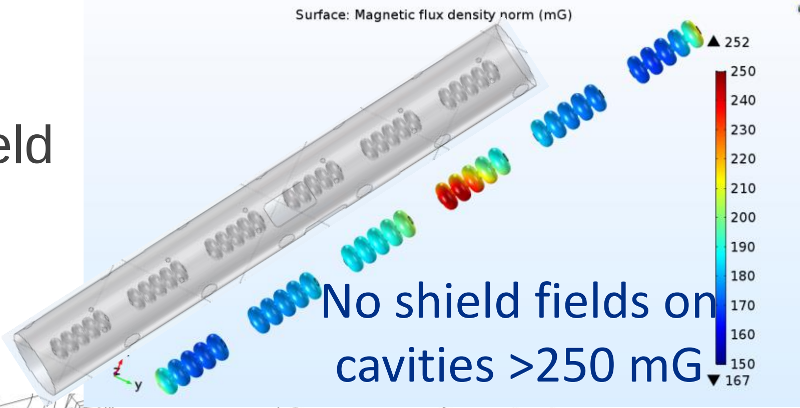


Cryomodule PDR in FY19

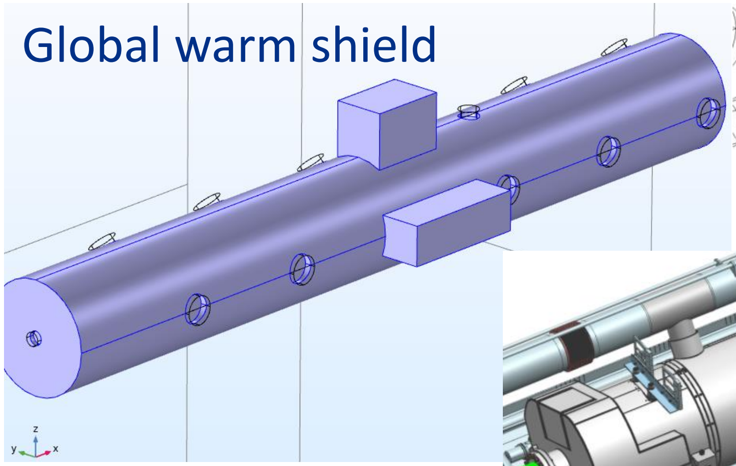
Preliminary Design and Design Maturity

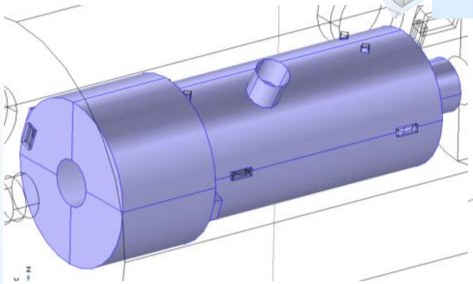
Charge #2

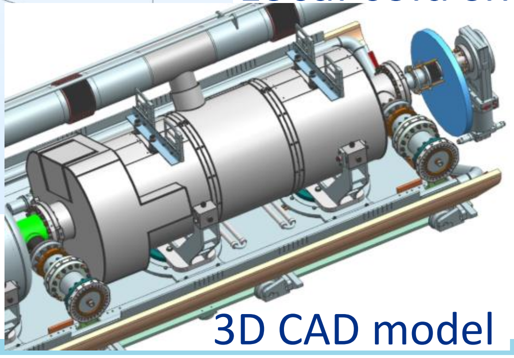
- Environmental average magnetic field specification: ≤5 mG
- Magnetic design completed
  - 1 layer local shield + 1 layer global shield
- Mechanical model design ongoing
- Shield prototype to be procured
- Validation in horizontal test

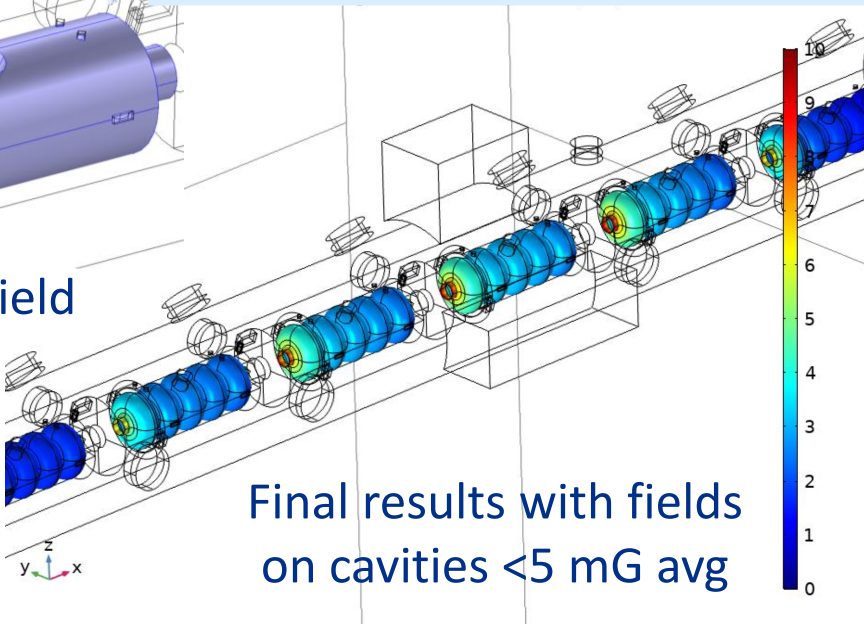


No shield fields on cavities >250 mG


Global warm shield


Local cold shield


3D CAD model

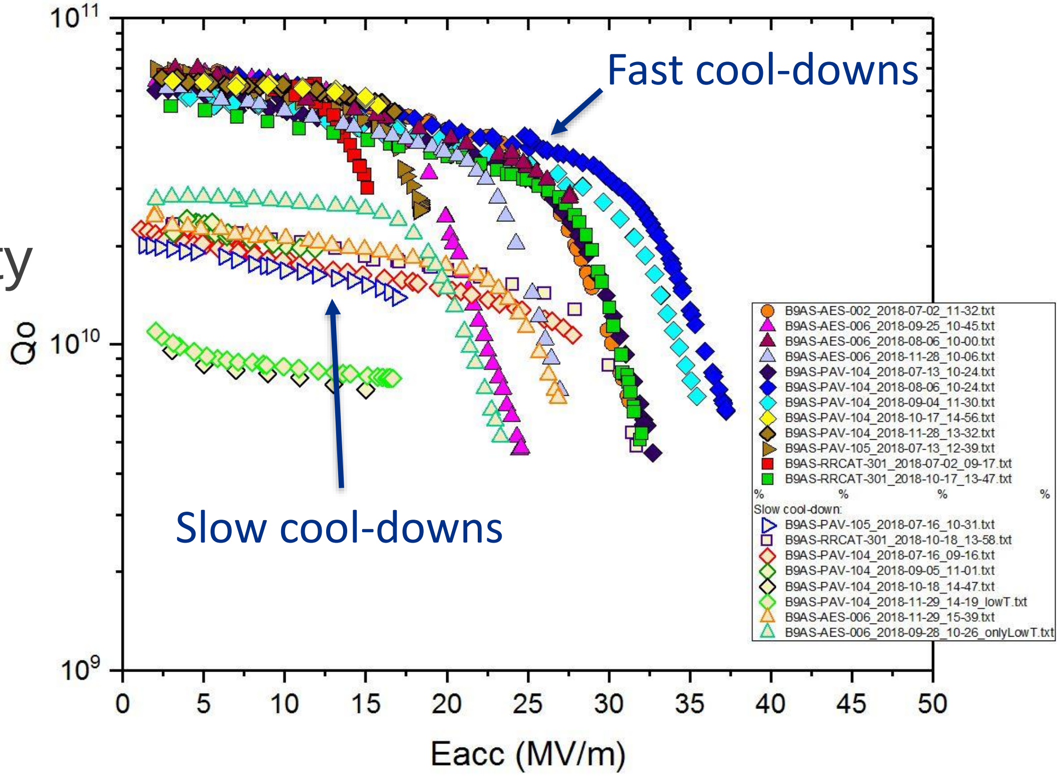


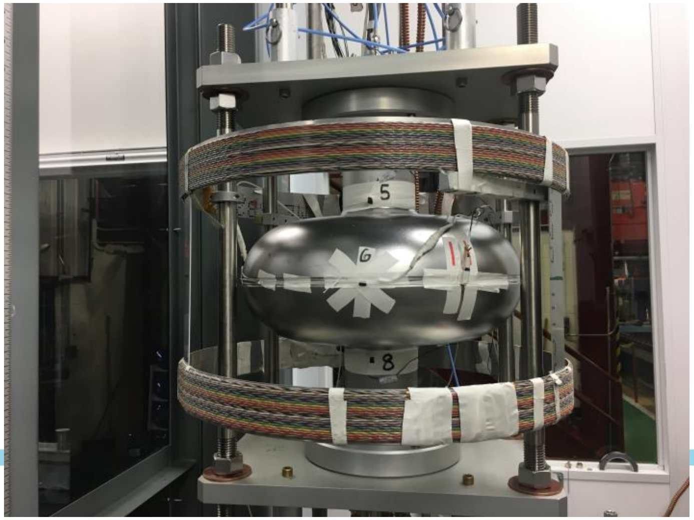
Final results with fields on cavities <5 mG avg

Progress to date – HB650 Cavities

Charge #1

- 1-cell
  - Cavity surface treatment recipe optimization for high-Q
    - Cavities used includes partner cavity
    - Multiple recipes being examined
      - EP + 120 C
      - EP + 75 C + 120 C
      - N doping
  - Magnetic field sensitivity being studied



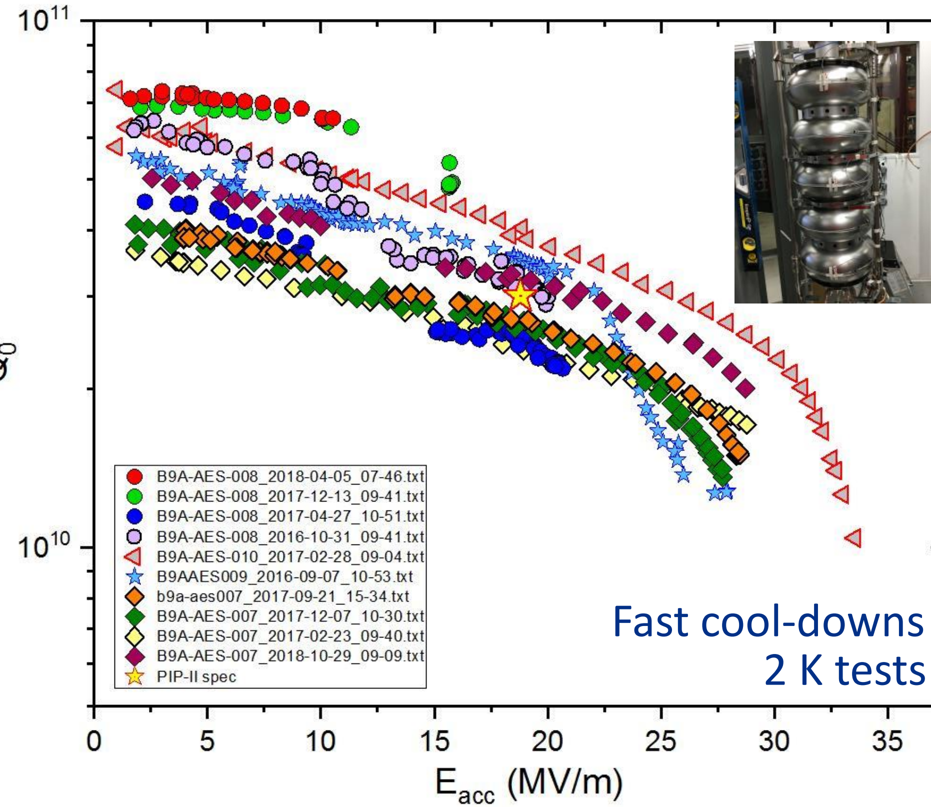


Progress to date – HB650 Cavities

Charge #1

- 5-cells ($\beta_g = 0.90$)
  - Cavity qualification ongoing
    - Driven by 1-cell recipe optimization
  - First cavity to be dressed
    - $Q_0 \approx 4 \times 10^{10}$ at 20 MV/m

Cavity dressing mock-up

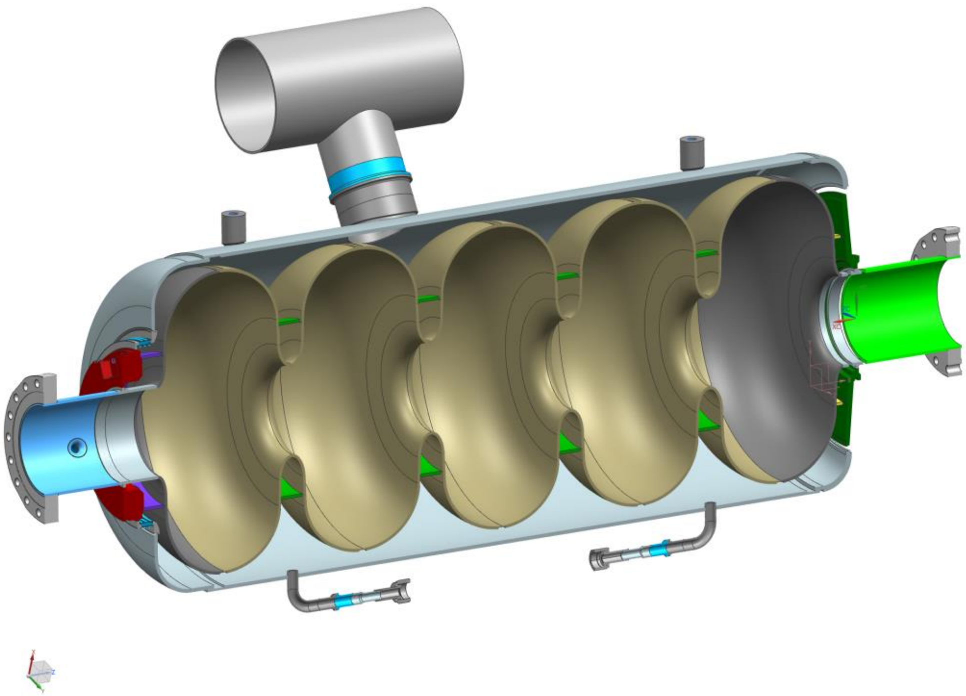


First cavity being prepared for dressing

Charge #1

Progress to date – HB650 Cavities

- 5-cells (β_g = 0.92)
  - Partner fabrication of 4 cavities ongoing
  - Fermilab cavity Nb procurement for 3 cavities ongoing
  - Cavities to be ordered in the near future



Progress to date – LB650 Cavities

Charge #1

- 1-cell
  - Partner procuring 1-cell cavities for:
    - Validation of RF design
    - To optimize surface processing recipe
  - Activity in parallel for 5-cell procurement
    - 1-cell cavities to be delivered before 5-cell cavities

LB650 prototype fabrication in process at vendor

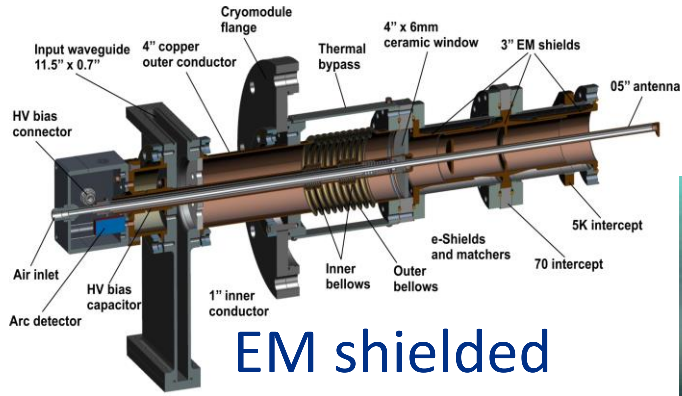
First fabricated 1-cell cavity shown

Progress to date – Couplers

Charge #1

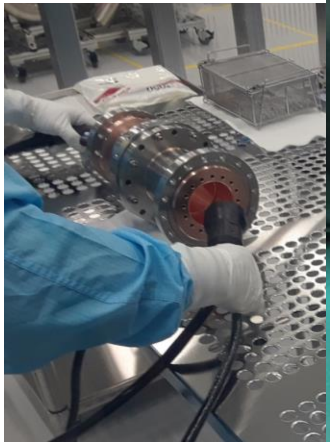
- Prototype couplers procured
  - 2 conventional copper coated + 2 novel EM shielded design
  - No bellows in cold end of coupler (beam vacuum end)

Copper coated



EM shielded

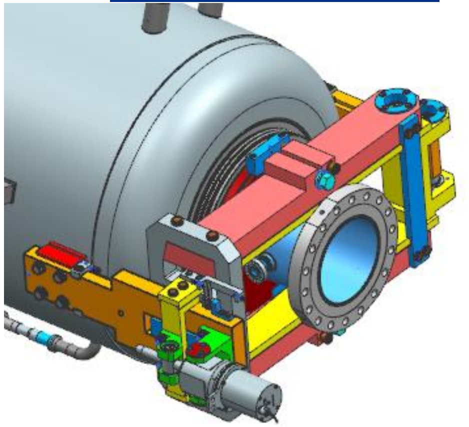
- Particulate testing performed
  - 0 particulates after blowing
- Coupler test/conditioning stand procurement ongoing
- Partner led design optimization to begin

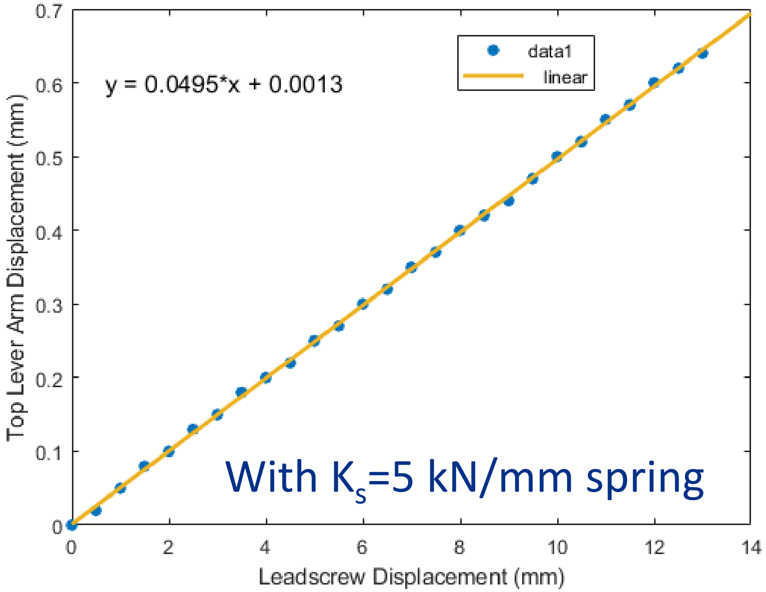


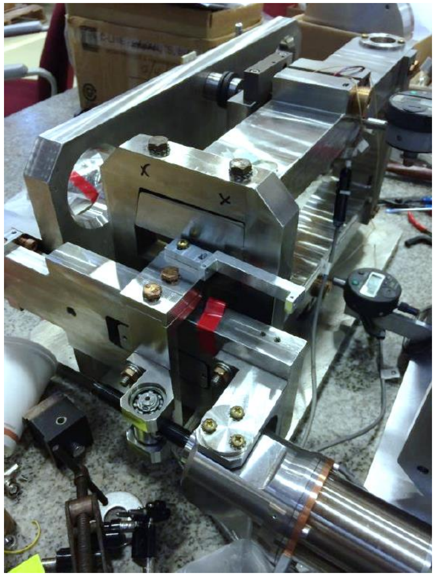
Progress to date – Tuners

Charge #1

- Prototype tuner bench tested & warm validated
  - Tuner machined by Michigan State University
- Range >300 kHz with 1 Hz/step
- Stiffness estimated to be 41 kN/mm
  - Cavity stiffness requirement: 5 kN/mm
- Prototype tuner fabrication by partner begun







$$K_t = K_c \left(\frac{N_D}{N_M - N_D} \right)$$

K_T=5 kN/mm * [18/(20.2-18)]= 41kN/mm

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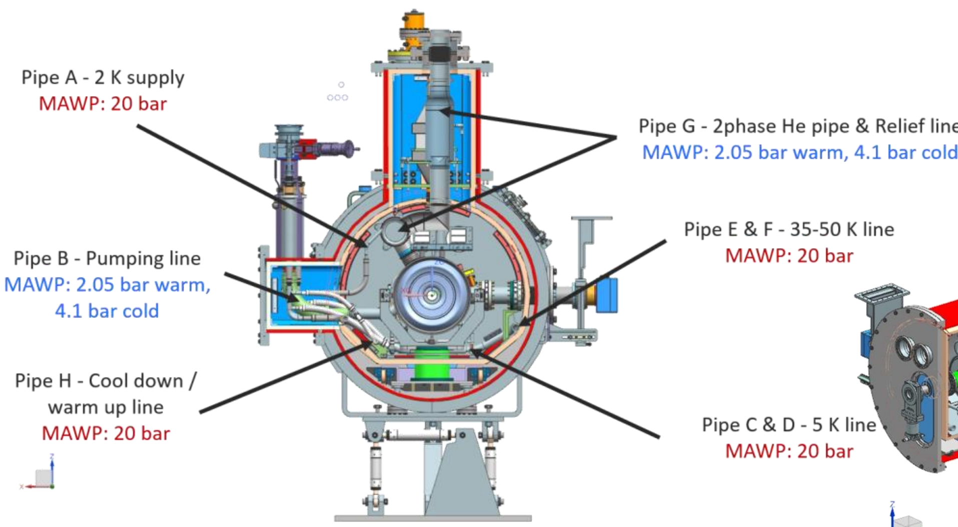
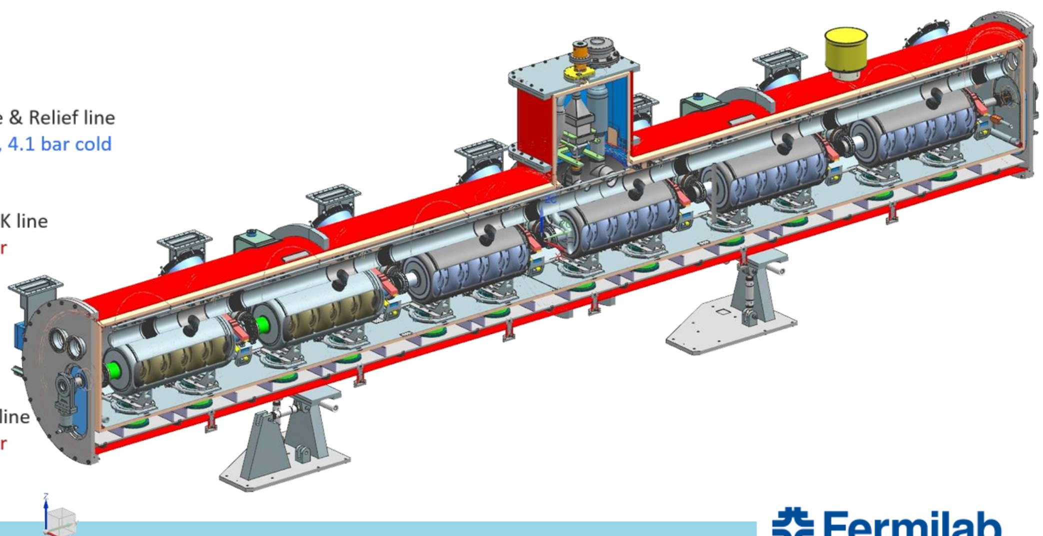
Progress to date – Cryomodule Design

Charge #1

- Integrated engineering design team formed
  - Fermilab is lead for HB650 design, & Partner is lead for LB650
  - Partners participate in sub-system design
  - Similar design approach for HB & LB
    - HB650 cryomodule design to mature first
    - LB650 cryomodule design shall follow
  - Tooling to be designed for cross functionality between HB & LB

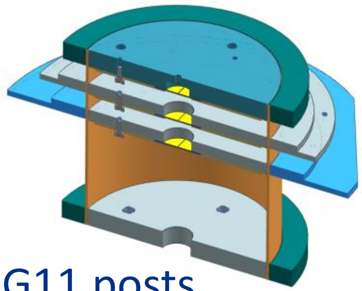


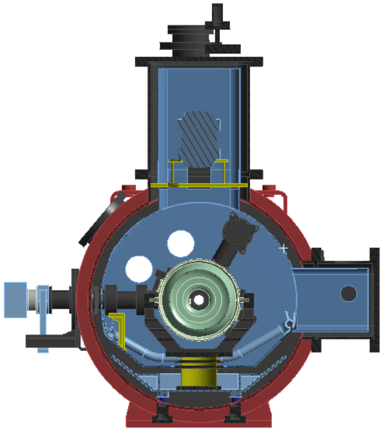


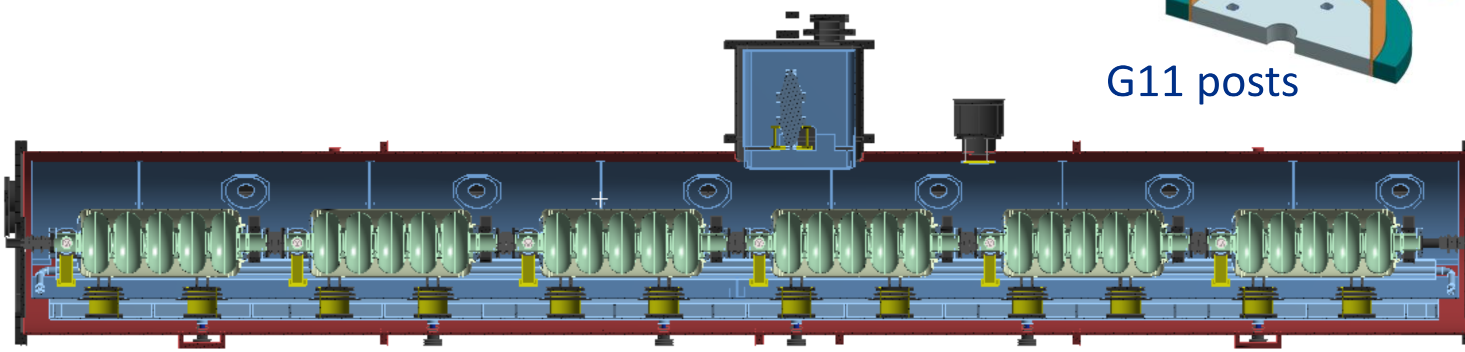
Progress to date – Cryomodule Transport

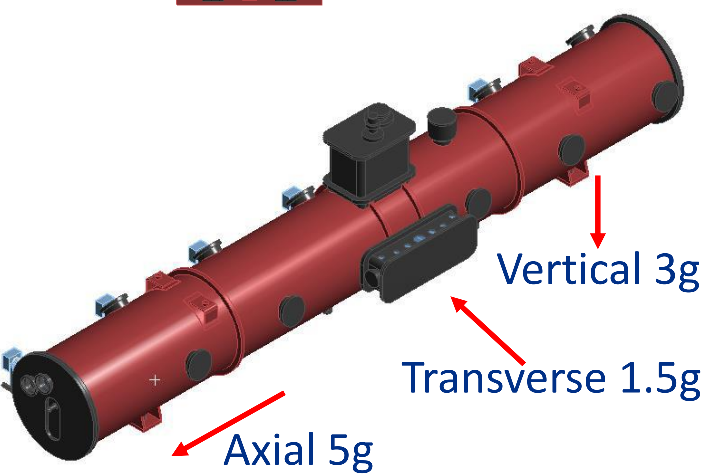
Charge #1

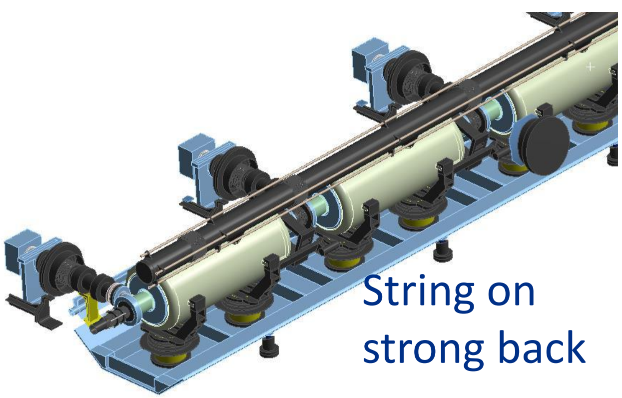
- First iteration of transportation analysis completed
  - Analysis model built to represent whole cryomodule











Progress to date – Cryomodule Transport

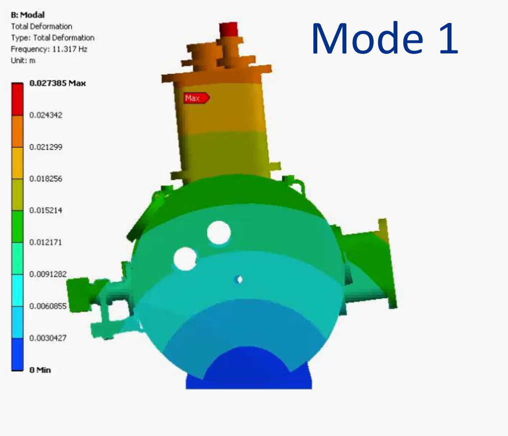
Charge #1

- First iteration of transportation analysis completed
  - Components for improvement identified

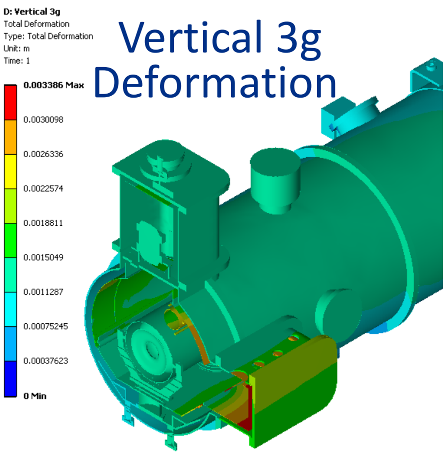
		Max Equivalent Stress			
		Axial 5G, MPa	Transvers 1.5G, Mpa	Vertical 3G, Mpa	Tensile Strength, Mpa
Vessel	ASTM A516 Steel Gr70	144	182	144	260
Thermal Shield	Aluminum 1100	38	30	45	150
2Phase Pipe	316SS	184	108	163	210
Strong Back	Aluminum 6061 T6	27	23	13	255
Support Post	G-11	29	34	12	255 (crosswise) 296(lengthwise) 151(shear strength)
Adjust Support	ASTM A193 B7/ 18-8 SS	140	128	49	210

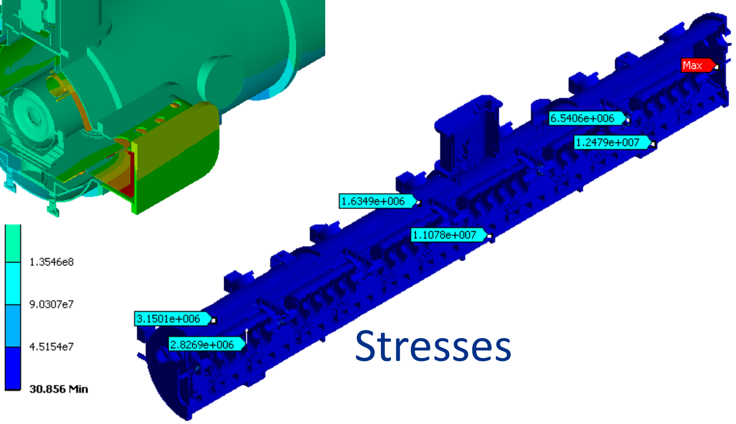
Mode	Frequency [Hz]
1	11.317
2	12.934
3	18.229
4	20.626
5	21.186
6	21.305
7	22.649
8	23.426
9	24.907

Mode 1



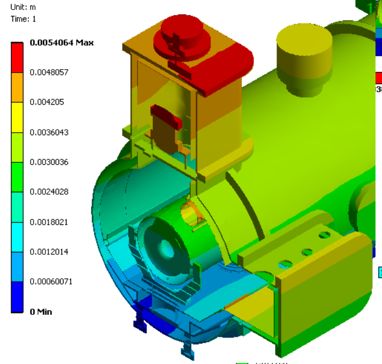
Vertical 3g Deformation



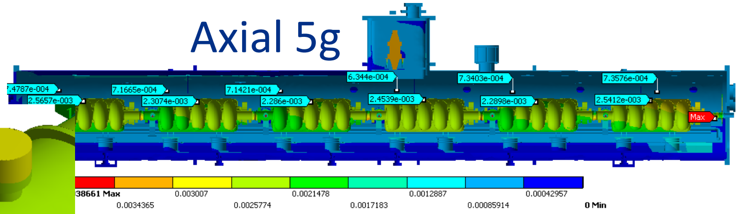


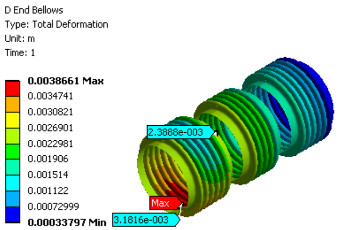
Stresses

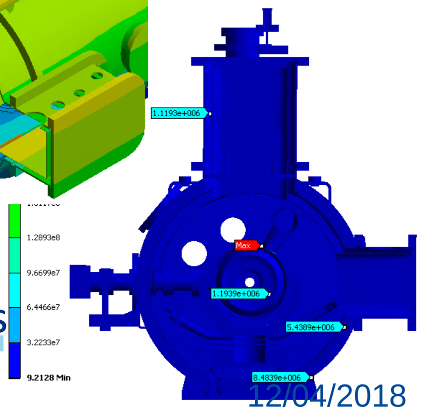
Transverse 1.5g Deformation



Axial 5g







Stresses

ESH

Charge #6

- Safety is the highest priority
- All designs to adhere to Fermilab Environment, Safety and Health Manual (FESHM)
- Cryomodules shall adhere to ASME or PED
- Safety by design is being practiced

Quality Management

Charge #6

- All components and processes covered by QC plans
  - Travelers and operating procedures are being developed
  - Incoming inspections and acceptance testing are planned for all critical components and sub-assemblies
  - Procurement specifications are written for each major component purchase and vendor visits are planned for Fermilab as well as for major Partner procurements
  - Discrepancy Reports and disposition are to be managed in Vector
- Partners shall have same or equivalent QC plans
- Lessons learned from other projects and within PIP-II to be monitored and implemented
  - e.g., Coupler warm ends to be removed for transportation

Risk Management

Charge #2,7

Risk Rank	Risk ID	Title	Impact
High	RT-121-02-001	650 Cryomodule is damaged during transportation	Damaged cryomodules will need to be repaired, jeopardizing testing, linac installation & commissioning
	RT-121-02-003-B	Underestimated resources for design optimization of HB650 CM (1)	A repair strategy will have to be made, and module may have to be disassembled, impacting HB650 production, and LB650 design and production

- Planned mitigation
  - HB650 and LB650 to have prototype cryomodules
    - These modules are to undergo transportation testing, including overseas shipment
  - HB650 prototype cryomodule to begin assembly in 2020, allowing for testing and validating cryomodule

Summary

- Cavity prototypes to be dressed in near future
- Cavity surface preparation recipe optimization is in progress
- Coupler prototypes are fabricated & to be validated
- Tuner prototype was fabricated & validated on bench tests
- Integrated cavity, coupler, tuner, magnetic shield designs are to be validated in horizontal testing
- Cryomodule design is at preliminary stage
  - Integrated engineering design team is being established
  - Transportation analysis is embedded in the design program
- Risks are understood
- ESH and QA plans are being developed

- Thank you for your attention

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

END

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