A New 2 K Superconducting Half-Wave Cavity Cryomodule for PIP-II

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On Behalf of the ANL Physics Division Linac Development Group
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- FNAL Cryogenics Group & Tech Division.

- Many Vendors:
  - Meyer Tool and Manufacturing, IL.
  - Advanced Energy Systems, NY.
  - Adron EDM, WI.
  - Ti Fab, PA.
  - Numerical Precision, IL.
  - M-1 Tool Works, IL.
Introduction

- We are building a cryogenic accelerator system which will contain accelerator cavities and magnets operating at 2 K.

- Will be the first operational 2 K cryomodule for superconducting accelerator cavities with low-beta (beta = v/c < 0.5) structures.
  - Using many techniques developed by velocity-of-light (or close to) accelerators; e.g., elliptical cell cavities.
  - Others are in development too; e.g., IFMIF, MSU-FRIB.

- Design goals for the:
  - Operate at 2 K instead of 4 K.
  - Further reduce static cryogenic loads relative to previous low-velocity cavity cryomodules.
  - Comply with DOE, ANL and FNAL safety guidelines for cryogenic, vacuum and pressure vessels.
  - Enable faster more-accurate alignment.
Half-Wave Resonator Cryomodule

- Conduction Cooled Leads (FNAL)
- Helium Manifold
- Helium Relief Port
- Sub-Atmospheric HTXG Assembly
- Cooldown Manifolds
- Ti Strong-Back
- Vacuum Manifold
- Half-Wave Resonator
- SC Solenoid

Not Labeled/Hard to See:
1) Couplers.
2) BPMs.
3) 70K HTXG.
4) Beam-line gate valves.

2.2 m X 2.2 m X 6.2 m
2 K Low-Beta Cavity Cryomodules

- Low-beta = low-frequency and losses scale as $f^2$. Low-beta cavities have traditionally operated at 4.2 K to save on refrigeration.
- Why operate at 2 K now?
  - The rest of the system is 2 K = Simplified Cryogenic Distribution.
  - The performance improvement justifies the extra cryogenic cost.

Cryogenic Performance of 2 Half-Wave Resonators

- 4.2 K Performance: ~8 W Heating
- 2 K Performance: ~0.8 W Heating
Cryomodule 2 K Design Thermal Loads

- **Solenoid Conduction Cooled Leads, 25 W**
- **Cavities 1 & 2 1 W Dynamic Load**
- **Cavities 3 – 8 Dynamic Load 8 W**
- **Power Couplers 3 W Dynamic Load**
- **Helium Distribution System, 5 W**
- **Radiation, 3 W**
- **Instrumentation, 2 W**
- **Gate Valves, ½ W**
- **Misc. Connections, ½ W**
- **Slow Tuners, ½ W**
- **Cooldown Lines, ½ W**
- **Beam Line Vacuum System, ½ W**
- **Power Coupler Static Load, ½ W**

Calculated 2 K Cryogenic Load 50 W
Alignment - 1: Thermal Contraction & Kinematics

- Need to align solenoids to ±250 μm_{rms} and ±0.1° in pitch, yaw and roll relative to the beam axis.
- Transverse shift ~ negligible.
  - We have changed from a Kelvin to a Maxwell planar kinematic coupling.
    - Maxwell geometry can be designed to be thermally invariant.
    - Kelvin geometry shifts toward fixed point.
- Vertical Shift = 650 μm up.
  - Hanger Contraction = +1,640 μm up.
  - Alignment System contraction = -990 μm up.
  - Possible to zero.

Cold-Mass Hangers

- Hangers have to:
  - Support the 4 ton cold-mass.
  - Allow for adjustment and alignment of the cold-mass.
  - Thermally isolate the ~2 K cold-mass from room temperature.

- We take advantage of:
  - Low thermal conductivity materials.
  - Relatively high thermal contact resistance for grease- and lubrication-free connections.
Alignment - 2: Ti Strong-Back

- When lid is on the box the loaded strong-back rails are flat and parallel within 0.005”.
- Lifting may perturb the alignment.
- Reduced lifting disturbance via design.

Lifting Analysis Design Evolution

- Model of Lid/Strong-Back being Lifted
- Lifting Points

- Stringer
  - Original
  - Rev. 1
  - Rev. 2
Design: Cavities and Cryomodules

- Design must protect against:
  - Plastic Collapse.
  - Local Failure.
  - Buckling.
  - Failure with Cyclic Loading.

- Design must also:
  - Maintain alignment.
  - Not break penetrations.

- Not discussing solenoids. They receive an ASME U-stamp.

20°C Material Properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Young’s Modulus (ksi)</th>
<th>Poisson’s Ratio</th>
<th>Density (lbs/in³)</th>
<th>Maximum Allowable Stress (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>304 Stainless Steel</td>
<td>29,000</td>
<td>0.270</td>
<td>0.286</td>
<td>20.0</td>
</tr>
<tr>
<td>Niobium</td>
<td>15,200</td>
<td>0.396</td>
<td>0.310</td>
<td>5.5</td>
</tr>
</tbody>
</table>
Vessel Design: Cryomodule

- Vacuum Vessel @ 14.7 psiv.
- Used ASME BPVC code to demonstrate protect against:
  - Plastic Collapse (Limit-Load).
  - Local Failure.
  - Buckling.
  - Ratcheting and Cyclic Loading.
- Very safe vacuum vessel.

- Magnetic shielding lines the inner surface of the vacuum vessel.
- 70 K thermal shield inboard of magnetic shield.
  - 32 layers MLI outside.
  - 16 layers MLI inside.
Vessel Design: Cavities

- Design Loads:
  - 2 bar @ R.T.
  - 4 bar @ 2 K.
- Used the rules in the ASME BPVC. No code stamp.
- Used material properties for Nb in compliance with FNAL safety guidelines.

Finished Cavity

Niobium Cavity

Before Gusseting and Ti Plate Reinforcing.

“Doughnut”
Summary

- At ANL we are developing a 2K superconducting accelerator cavity cryomodule.
- Cryomodule assembly is starting now.
- Hope to test the system without cavities or solenoids late this year.

Delivery of Cryomodule @ ANL

Primary Stresses
14.7 psiv, Red > 20 ksi

Secondary Stresses w/ 14.7 psiv
Red > 30 ksi