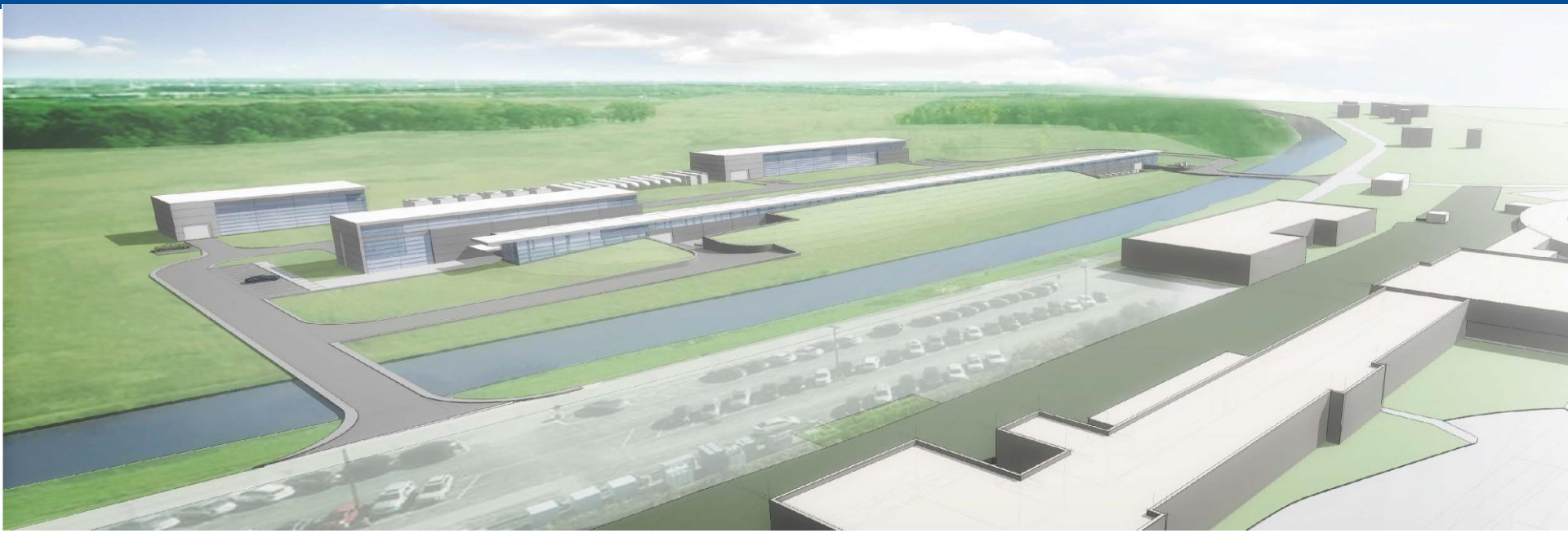


121.3.4 Linac – HWR (Half-Wave Resonator)

SC Acceleration Modules and Cryogenics

Zachary Conway

PIP-II DOE Independent Project Review

12-14 December 2017

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

Outline

- Argonne National Laboratory Organization
- Half-Wave Resonator (HWR) cryomodule requirements.
- HWR cryomodule design overview.
- Scope/deliverables.
- Interface control document for the HWR cryomodule.
- Fabrication and testing status.
- FNAL ESH&Q and Argonne HSE (Health, Safety and Environment)
- Risk assessment.
- Cost.
- Future schedule.
- Summary.

Argonne National Laboratory - Accelerator Development Group:

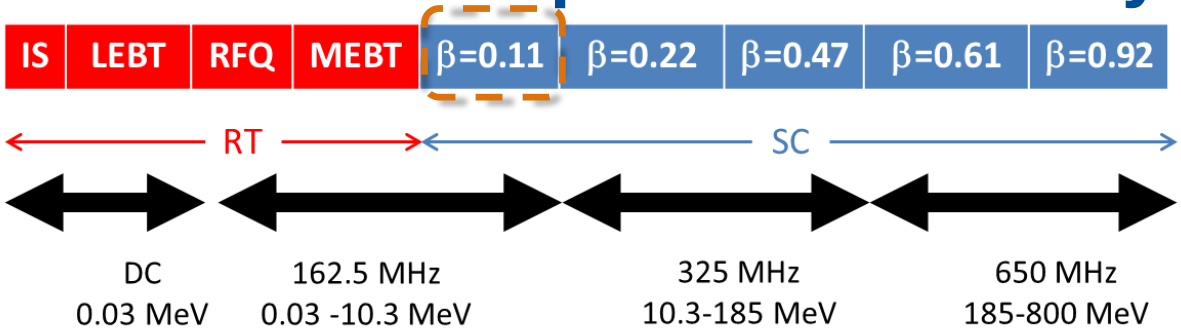
- **Designing, building and commissioning superconducting accelerators since 1977.**
  - **All retired group members still work 1+ days per week.**
- **My relevant experience:**
  - **Superconducting resonators spanning ion/electron velocities from 0.05c to c.**
  - **All superconducting device ancillary hardware.**
  - **6 different types of superconducting resonator cryomodules operating at 2.0 or 4.5 K.**
  - **Superconducting accelerator commissioning.**

Project Organization

- Cryomodule and subcomponents designed by FNAL and ANL.
- ANL is fabricating and assembling the half-wave resonator (HWR) cryomodule.
- At ANL:
  - Group Leader = Mike Kelly.
  - Technical Lead = Zack Conway.
- FNAL:
  - Project Liaison: Andrei Lunin (attends weekly status meetings at ANL and provides interface between FNAL/ANL).
  - Project Engineer: Allan Rowe (L3 & CAM)

WBS 121.3.4 Linac – HWR System Req. TC# ED0001313 Tech. Spec. for HWR Cryomodule

Charge #2



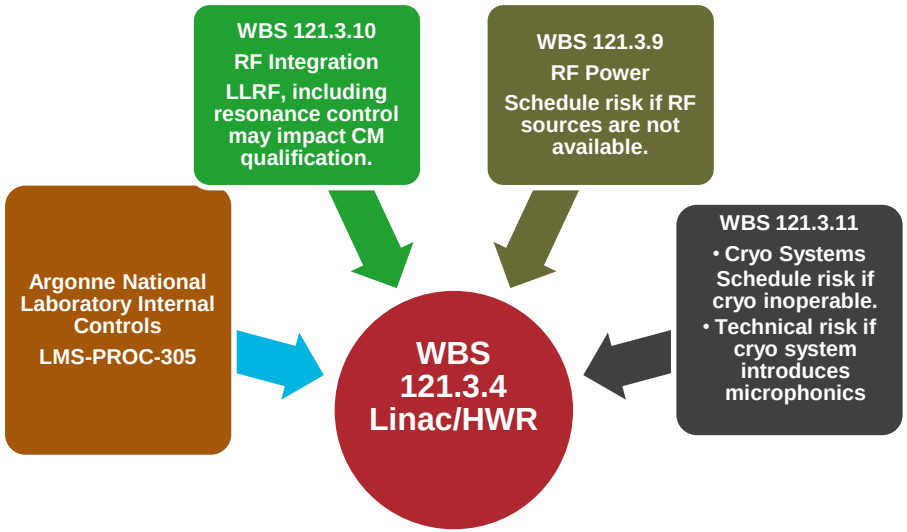
Cryomodule type	Cavities per CM	# CMs	CM length (m)	Q_0 at 2K (10^{10})
HWR	8	1	5.93	0.5
SSR1	8	2	5.2	0.6
SSR2	5	7	6.5	0.8
LB650	3	11	3.9	2.15
HB650	6	4	9.5	3

- **The half-wave resonator (HWR) cryomodule contains 8 β = 0.11 HWRs and 8 solenoids (6 T) with integrated x-y dipole steering coils.**
- **The HWR cryomodule will operate continuous wave with a beam current of 2 – 5 mA to accelerate the beam from 2.1 – 10.3 MeV.**

121.3.4 Interfaces – Technical/Schedule

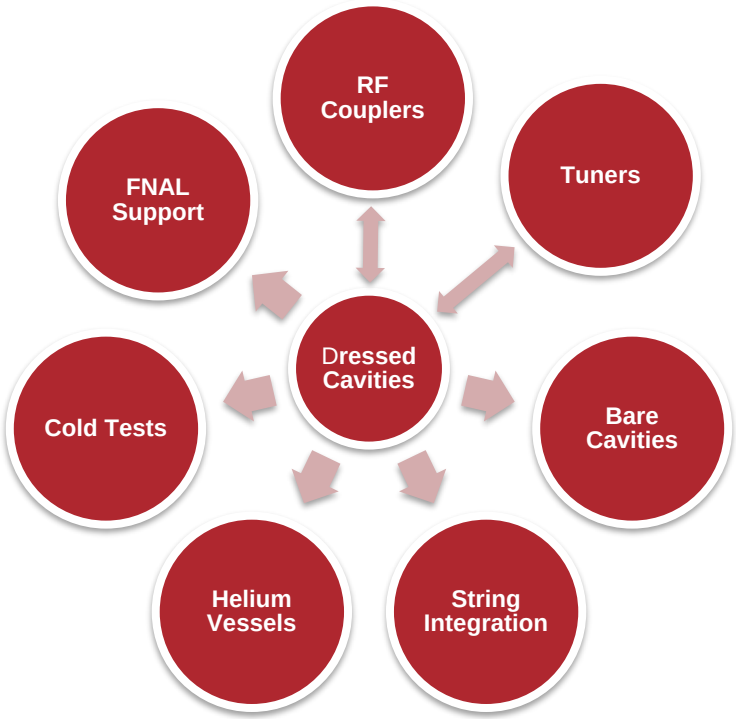
Charge #2

Top 4 system interfaces with 121.3.4:



HWR CM WBSs interface with nearly all systems and support WBSs. The HWR CM has a detailed interface specification which was used to design and build the module.

Argonne HWR Activities:



ANL is providing a fully assembled cryomodule. Dressed cavity interfaces with all critical components in the cryomodule.

Interfaces - Technical/Schedule

Charge #2

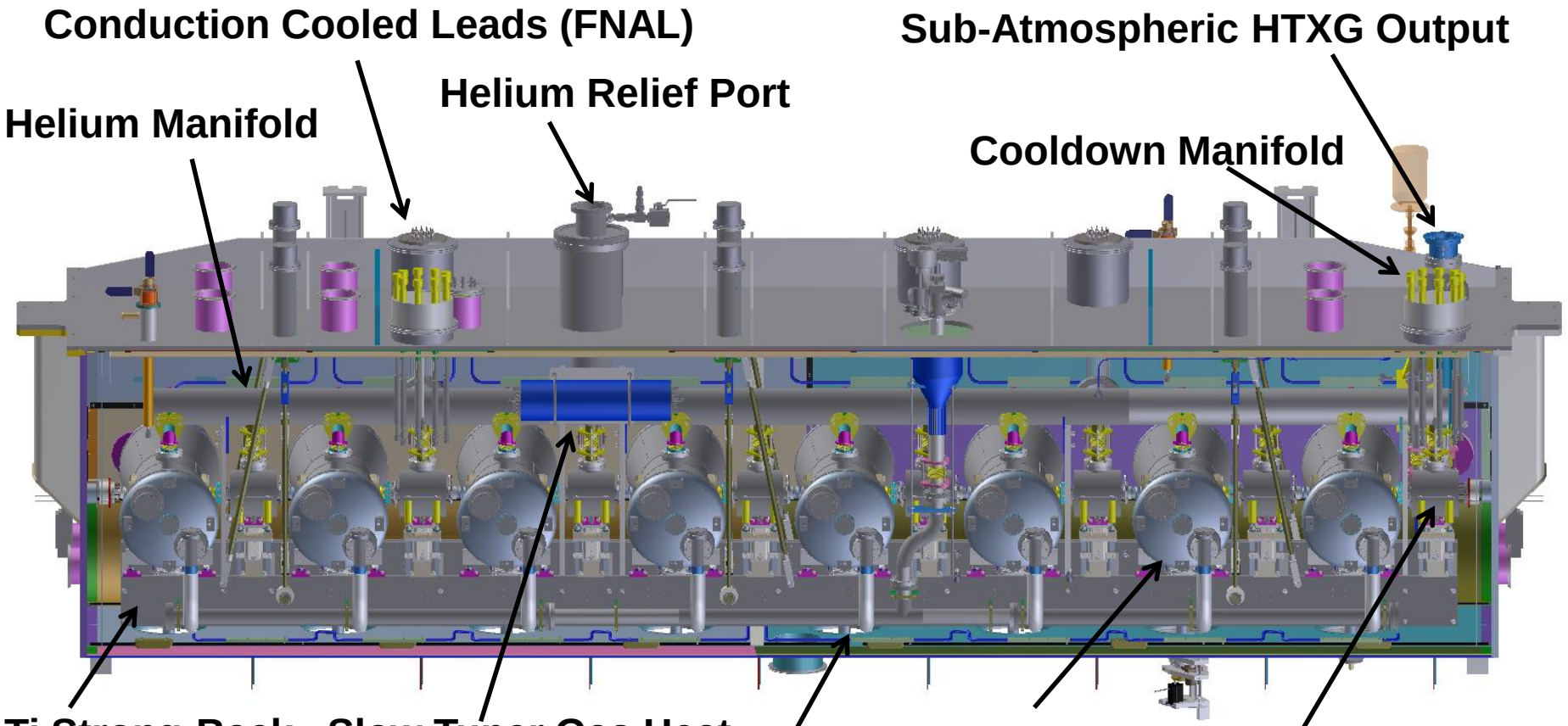
WBS 121.3.4 interface across the PIP-II WBS Matrix

- **The HWR Cryomodule has a controlled document fully elaborating each interface, TC# ED0001313: Technical Specification for the Interfaces, signed 9 April 2014.**

Interfaces for the HWR Cryomodule	
121.3.4 – HWR Cryomodule	121.3.18 – Vacuum
121.3.9 – RF Power	121.3.19 – General Supt. Serv.
121.3.10 – RF Integration	121.3.20 – Safety Systems
121.3.11 – Cryo Systems	121.3.21 – Test Infrastructure
121.3.16 – Beam Instrum.	121.3.22 – Install., Integ., and Comm
121.3.17 – Control Systems	121.5 – Conventional Facilities

- **Interfaces extend from the up- to the down-stream beam line flanges.**
- **Technical specification for the interfaces is supplemented with documented ~weekly integration meetings.**

HWR Cryomodule Design



2.2 m X 2.2 m X 6.2 m

HWR Cryomodule Reviews

Charge #2

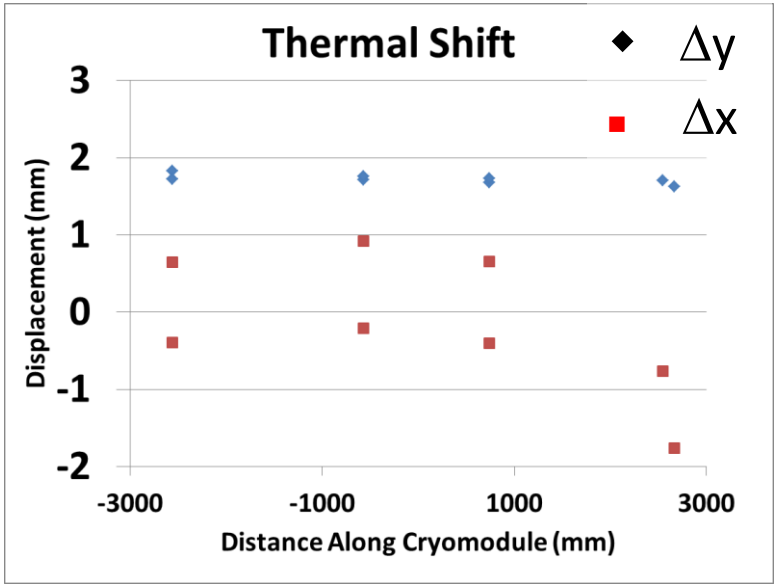
- **Design/safety reviews for the HWRs and cryomodule were held at Argonne (ANL) with FNAL and ANL subject matter experts performing the reviews:**
  - **HWR review 5/17/2012, and**
  - **cryomodule review 5/16/2013.**
- **All design reviews were conducted in compliance with ANL's procedures, LMS-PROC-305.**
- **Procurement readiness reviews were carried out at ANL per ANL controls.**

HWR Cryomodule Mock Assembly

Cryomodule Testing

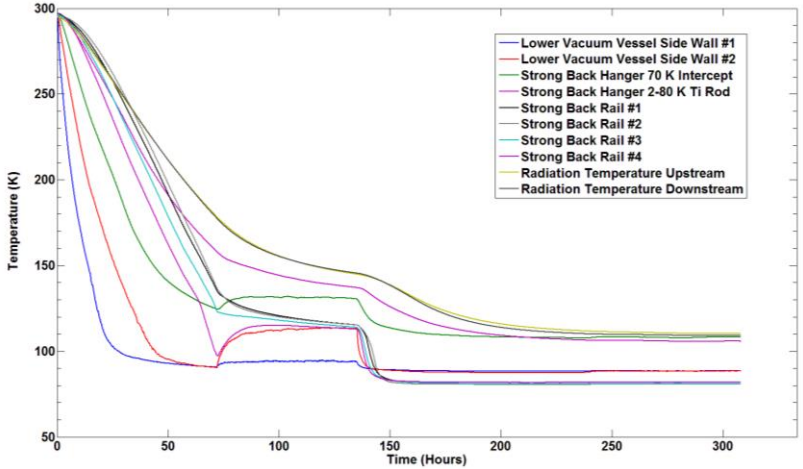
Cryomodule Alignment

Alignment Measurements

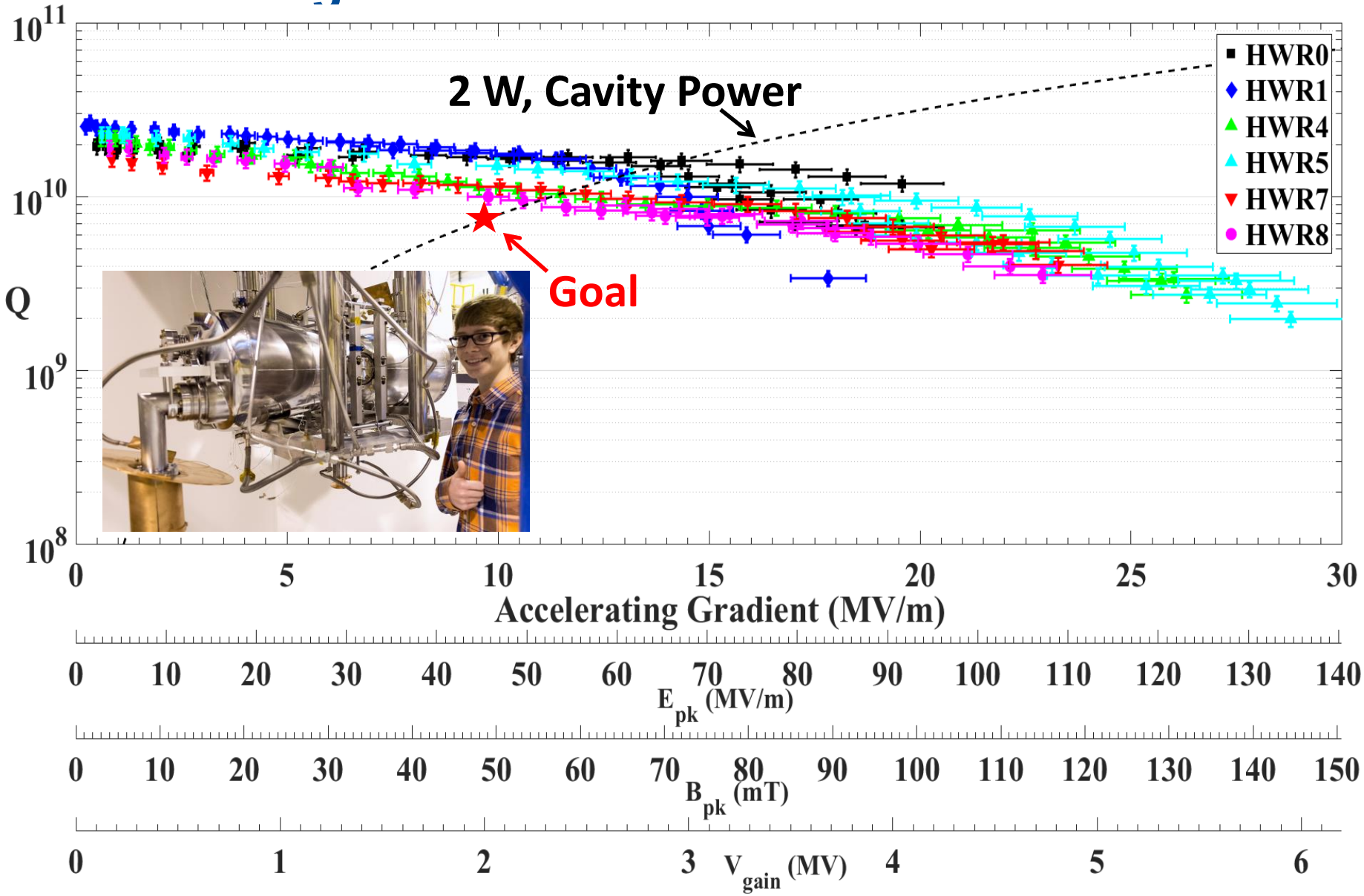


Cryomodule Assembly

Cool Down Data



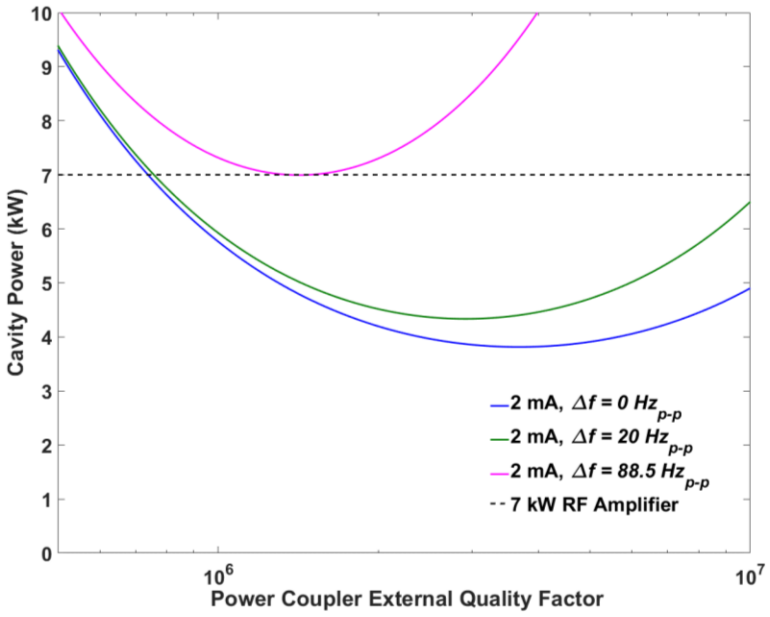
HWR Testing


2 W, Cavity Power
Goal
HWR0
HWR1
HWR4
HWR5
HWR7
HWR8
Q
Accelerating Gradient (MV/m)
E_pk (MV/m)
B_pk (mT)
V_gain (MV)

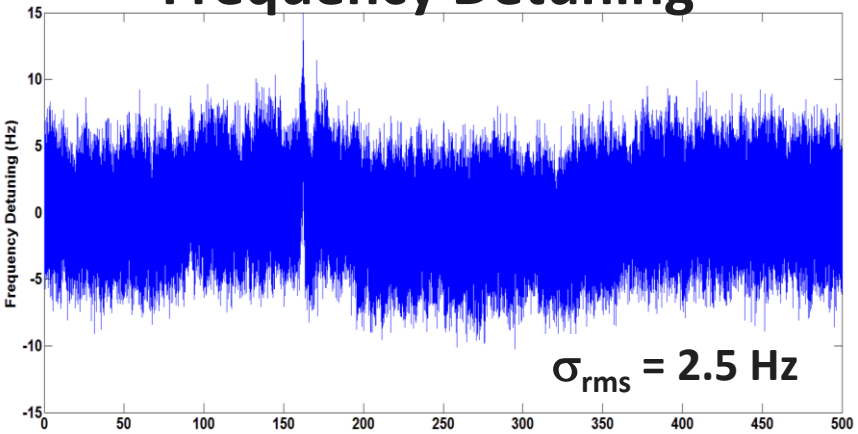
HWR Microphonics and RF Power

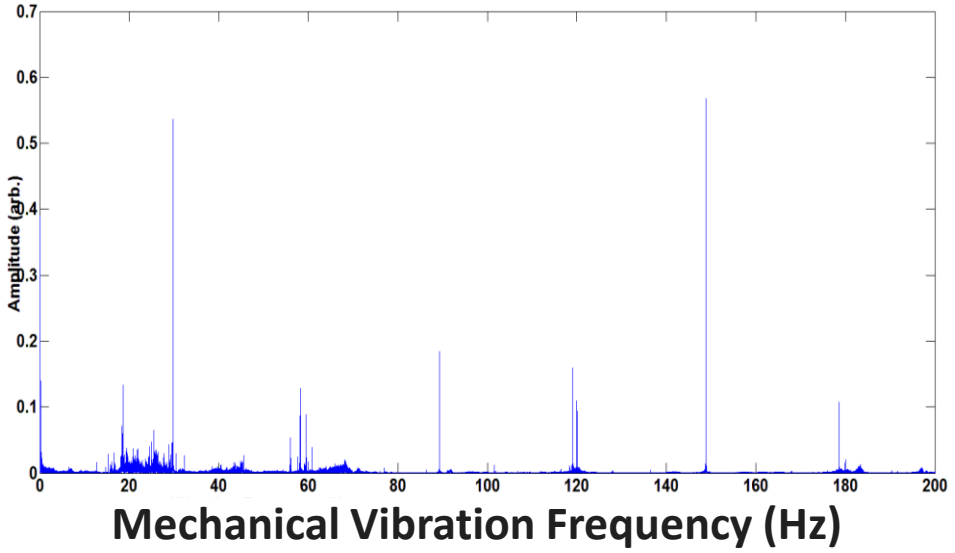
- All HWR tested have a $df/dP \sim 11$ Hz/mbar.
- With a helium pressure stability of 0.1 mbar $\rightarrow \Delta f = 1.1$ Hz.

HWR Cavity Power



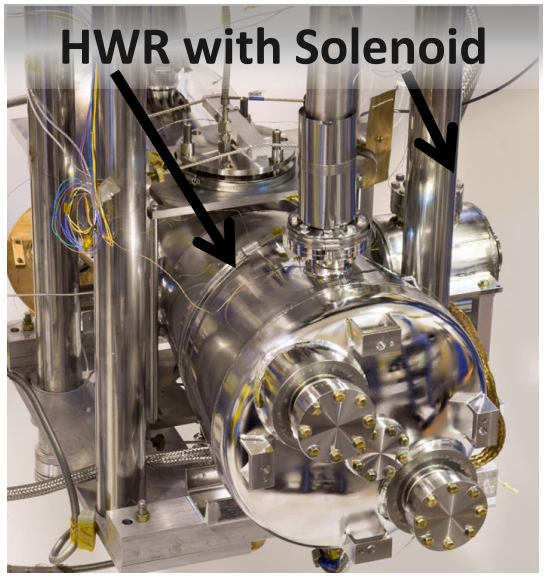
Measured HWR1 Microphonic Frequency Detuning

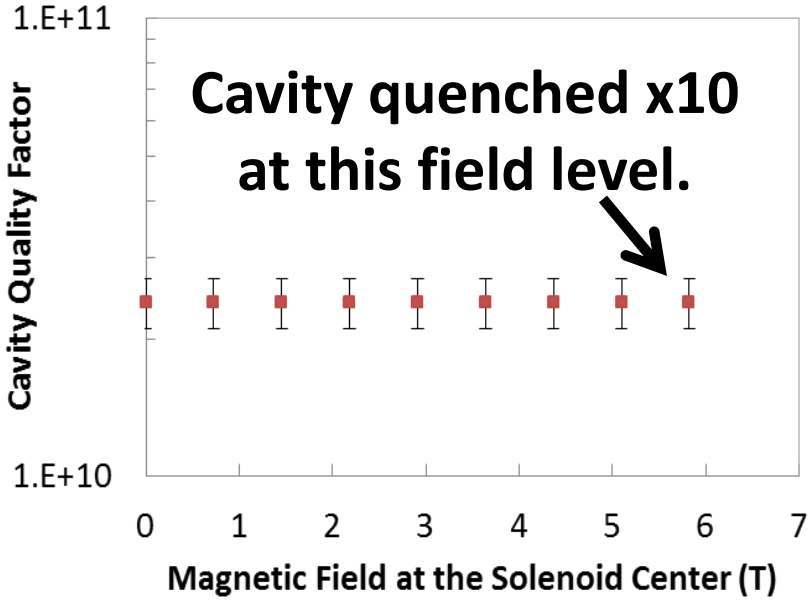




HWR/Solenoid Testing

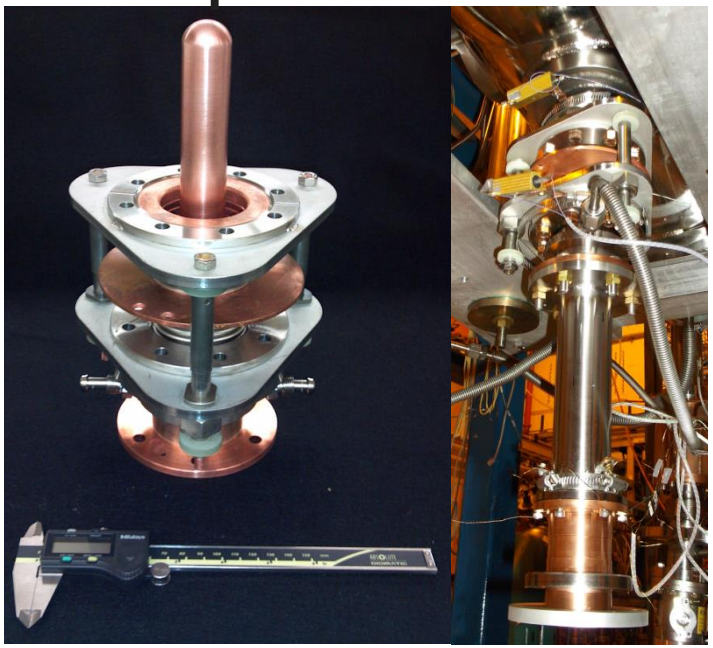
- To decrease the accelerator lattice length we have integrated x-y steering coils into the focusing solenoid package.
- Important design issue:
  - Minimize stray field @ the RF cavity to prevent performance degradation due to trapped magnetic flux.
- Measured RF surface resistance with a sensitivity of ±0.1 nOhm before and after each quench of the cavity.
- The cavity was quenched with the solenoid and the steering coils energized.
- No quantifiable change to the cavity RF surface resistance.





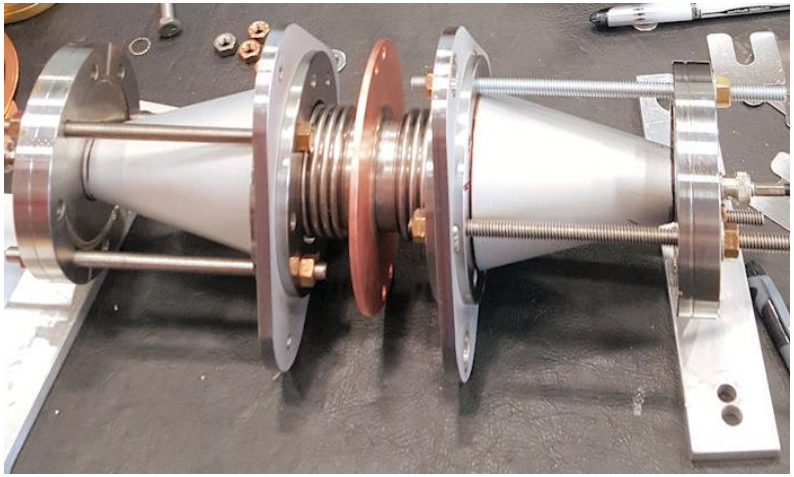
Power Coupler Progress

Coupler Hardware



- Dressed HWR testing starting soon.
- Offline measurements of plated components have been good and are in progress.
  - Q ~ 10000 or > 80% of calculated value for pure copper
- 10 bellows assemblies are being fabricated and plated at AJ Tuck.

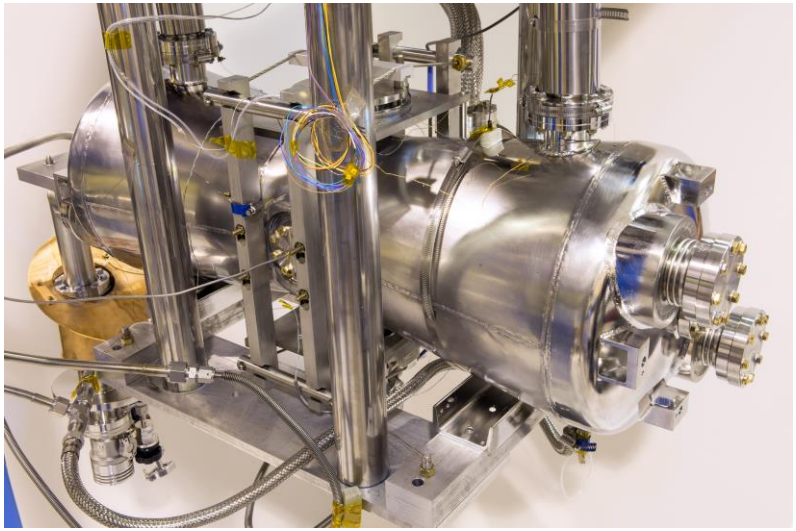
Copper Plating Purity Measurement



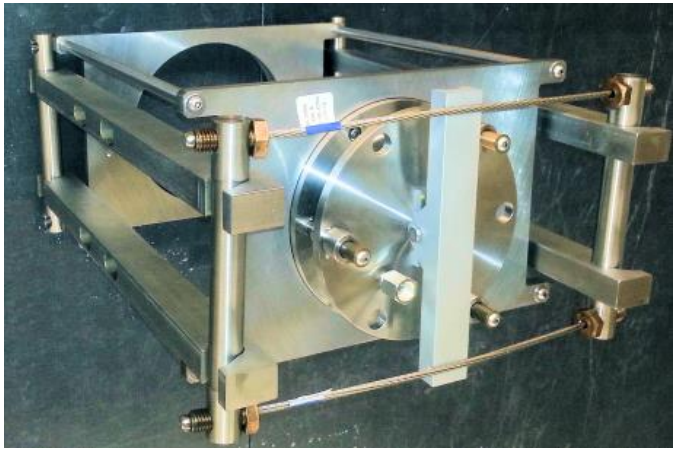
Slow Tuners

- The HWR cryomodule will use pneumatic slow tuners → pneumatic slow tuners have been in operation at Argonne on superconducting cavities since the 1970s.
- Slow tuners are install on all HWRs during offline testing.
  - Slow tuners are actuated through their full range to verify response.
  - 162.5 MHz ± 60 kHz is exceeded for all HWRs.
  - The tuner resolution is < 0.1 Hz, our measurement limit.
- Slow tuners are operating as planned and testing has demonstrated this.

HWR with Slow Tuner



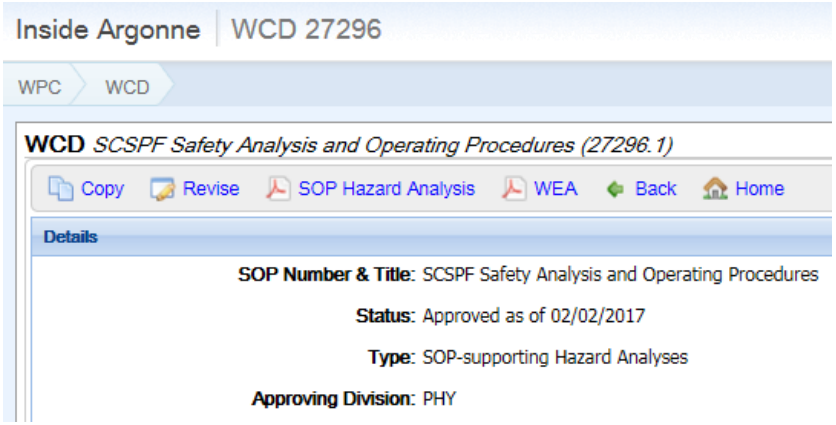
Slow Tuner



ESH&Q

Charge #5

- **Safety is our highest priority.**
- **Work at Argonne is done in compliance with ANL ES&H.**
- **Providing a working piece of hardware goes hand-in-hand with work planning and control at ANL.**
- **FNAL and ANL collaboration on SRF is documented in the FNAL/ANL MOU on SRF Cavity Surface Processing, signed 4/21/2006 with addendum added on 8/15/2014.**
- **Hazards addressed at ANL include:**
  - **Chemical safety,**
  - **Cryogenic safety,**
  - **Pressure systems safety,**
  - **Radiation safety, and**
  - **Cryomodule component testing and assembly work control documents.**



Risk: HWR Cryomodule

- Risk = HWR Cryomodule does not meet technical performance requirements

WBS / Ops Lab Activity	RI-ID	Title	Technical Impact	P * Impact (k$)	P * Impact (months)	Probability
121.03 Linac	RT-121-03-06-001	HWR Cryomodule does not meet technical performance	1 (L) - somewhat substandard	217	2.4	20.00%

- Risk Mitigation:
  - The cryomodule is fully tested in PIP2IT prior to use in PIP-II.
  - All HWRs are tested off-line prior to installation in the cryomodule.
    - Performance testing:
      - all HWRs are tested with a high-external-Q coupler to characterize the RF losses, then
      - all HWRs are tested while fully dressed.
    - Solenoid field operation:
      - Two HWRs have been tested with a cryomodule solenoid. No performance limitations found, see slide 12.
  - All components are tested in a real cryomodule environment prior to installation in the cryomodule.

Cost Summary

Charge #3

Basis of Estimates for COST

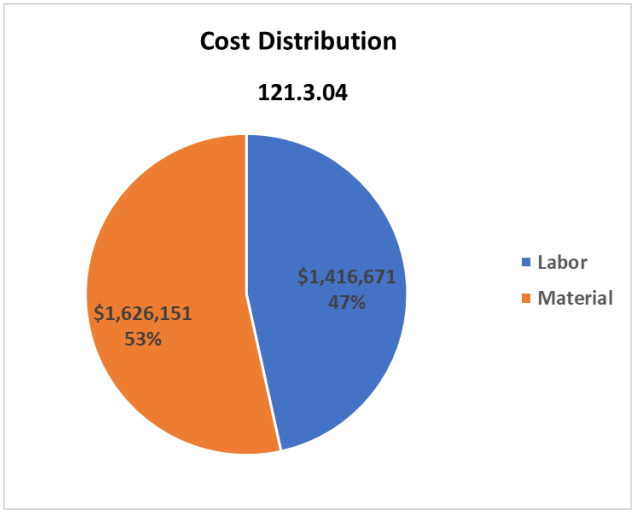
WBS Number	Title	Docdb #
121.3.4.2	BOE Document for 121.3.4.2 HWR PM and Coordination	704
121.3.4.3.1	BOE Document for 121.3.4.3.2 HWR Cryomodule Final Integration	710
121.3.4.3.2	BOE Document for 121.3.4.3.3 HWR Cryomodule: Cryomodule RF Test at PIP2IT	713

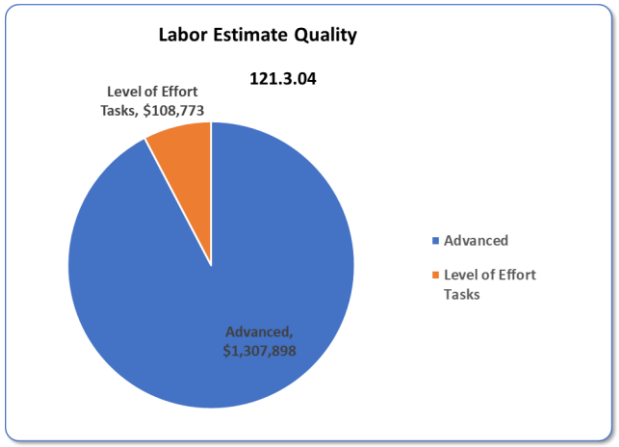
Level 4 WBS - Name	Direct Hrs	Direct M&S	Full Burden+Esc	EUC	% EUC	Total Cost
121.3.04.02 - Linac - HWR - Project Management and Coordination	708	$2,096	$111,380	$11,398	10.2%	$122,781
121.3.04.03 - Linac - HWR - CryoModule (HWR)	8,047	$1,230,876	$2,931,442	$423,936	14.5%	$3,355,383
Grand Total	**8,755**	**$1,232,972**	**$3,042,822**	**$435,334**	**14.3%**	**$3,478,164**

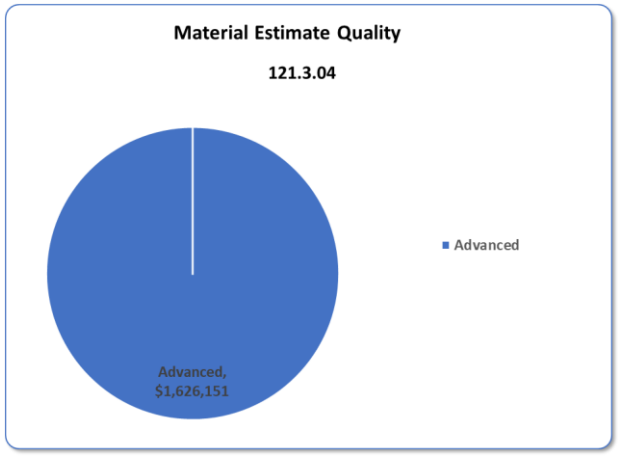
Full Burden + Esc = BOE + Escalation + Overhead

Cost Distribution and Estimate Quality

Charge #3





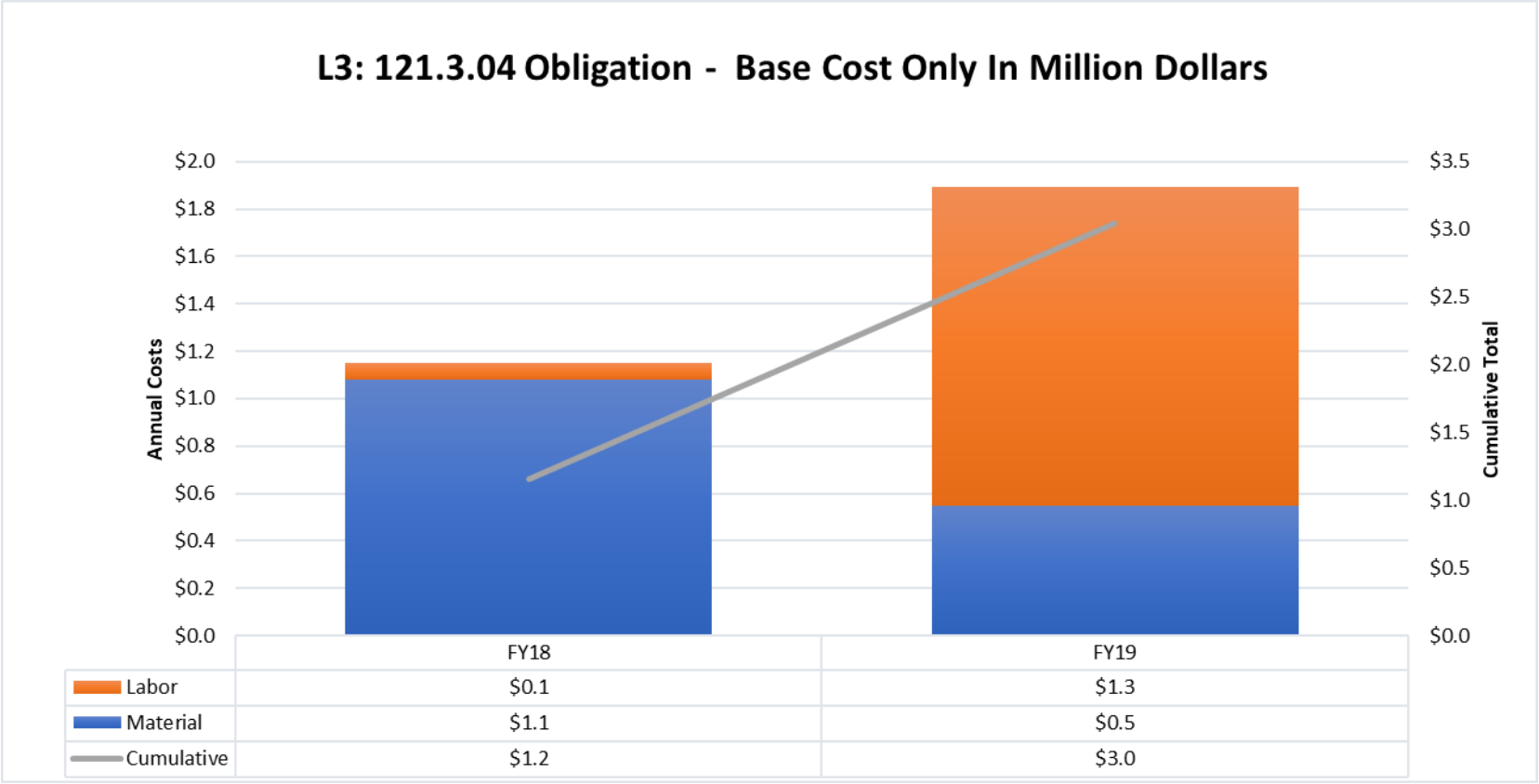


Costs = BOE + Overheads + Escalation

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

Obligation Profile – P6 Base Cost Only

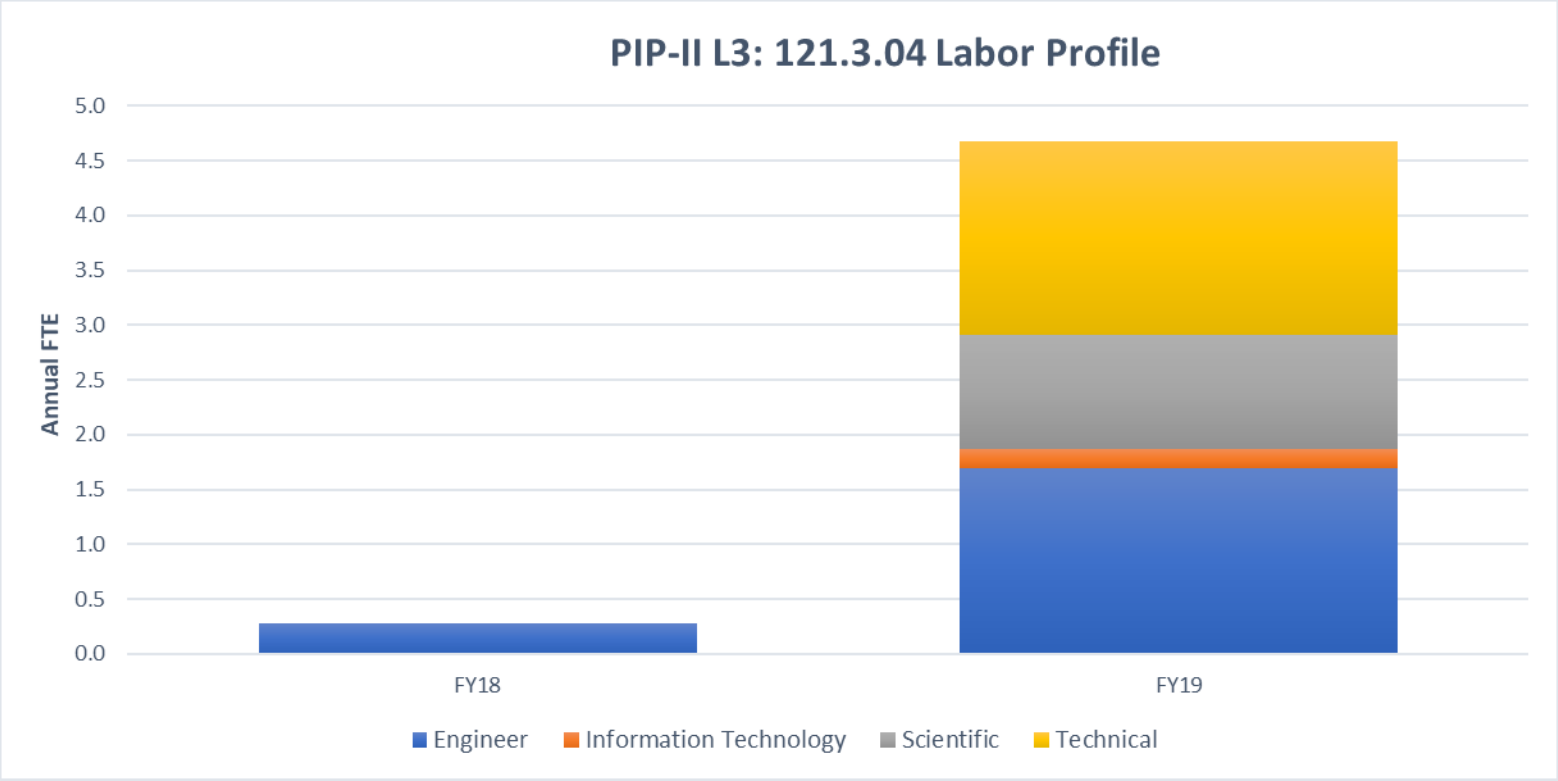
Charge #3



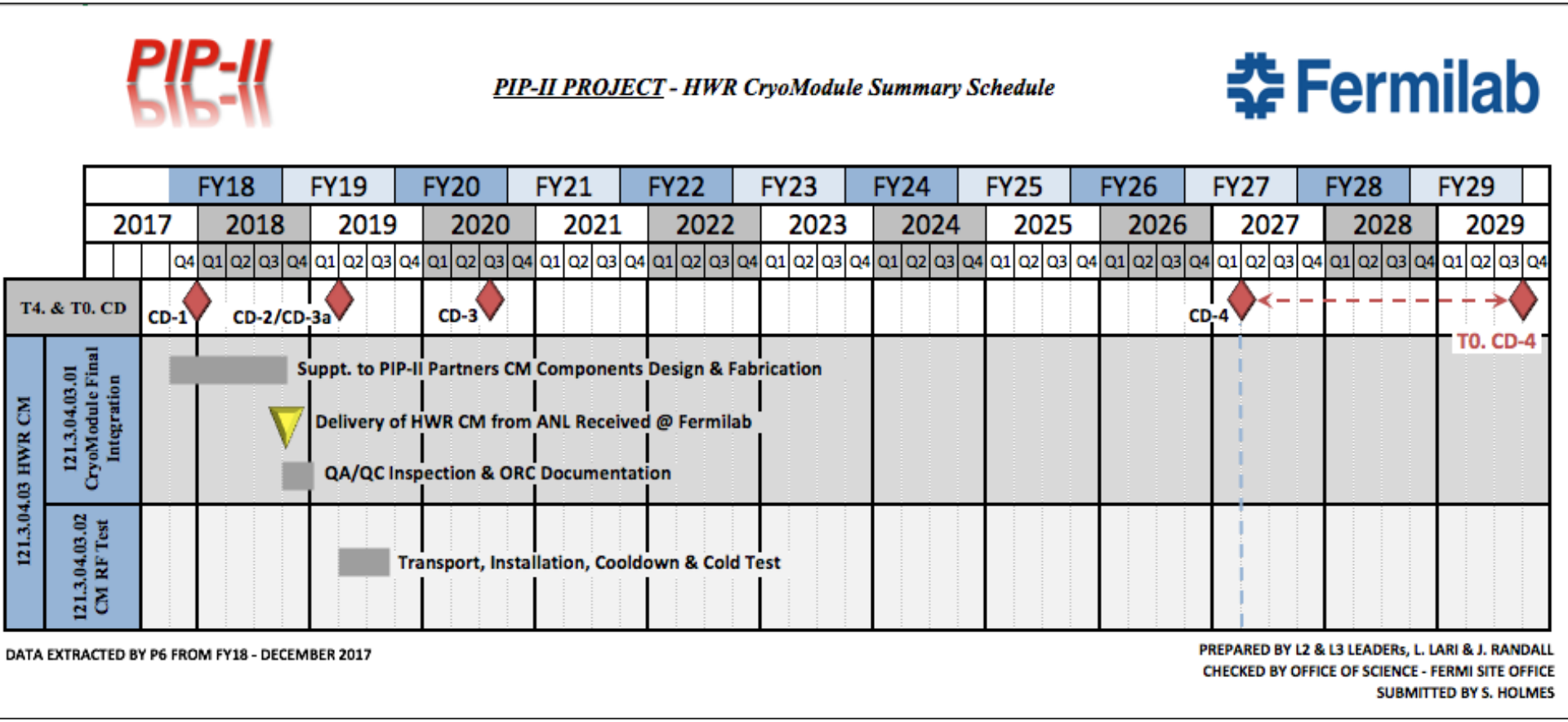
Costs = BOE + Overheads + Escalation

Labor Profile – P6 Hours/FTE

Charge #3



PIP-II HWR Summary Schedule



Summary

- Requirements are defined and traceable.
  - The requirements determined the design.
- Cryomodule and subsystems are almost finished.
  - Then final assembly.
- The cryomodule will be finished and beam tested as part of PIP2IT.
  - Mitigates risk of crymodule performance affecting PIP-II.
- After PIP2IT the HWR cryomodule will be ready for PIP-II.
- We would like to thank FNAL for their help and support.
- Thank you for your attention.