Ernest Orlando Lawrence
Berkeley National Laboratory

Neutrino Factory
Muon Collider

201-MHz RF Studies and Plans

Derun Li

Center for Beam Physics
Lawrence Berkeley National Laboratory

MUTAC Review at LBNL
April 8-10, 2008

Ernest Orlando Lawrence
Berkeley National Laboratory

Outline

- Introduction
  - brief review
- Progress on 201-MHz test program
  - RF tests with curved thin Be windows
    - Curved Be windows installed
    - Cavity retuned to 200-MHz
    - Tested up to 19 MV/m
  - RF tests with stray magnetic fields of Lab-G magnet
    - Move the cavity next to Lab-G magnet
    - New transmission line
    - New Vacuum pump
    - Preliminary test results
  - Simulation study of RF cavity in strong magnetic field
- Plans
  - More 201-MHz test with SC coupling coil (M. Green's talk)
  - Beam test at MTA (A. Boss's talk)
  - 201-MHz cavities for MICE
    - Review and plans
- Summary

Primary Goals

- Development of normal conducting 201-MHz cavity that can operate at a gradient of ~ 16 MV/m in a few Tesla magnetic fields environment
  - Prototype: exploring engineering solutions (challenges)
  - RF conditioning and operation without and with *B* fields
- Last MUTAC review
  - The 201-MHz cavity reached 16 MV/m without external magnetic field
  - The cavity kept at 16 MV/m with ~ a few hundred Gauss stray magnetic fields from Lab-G magnet
- We understand: operating a NC RF cavity (with thin and curved Be windows) at ~ 16 MV/m in strong *B* field could be very challenging, but to be confirmed experimentally
  - Test with stronger magnetic fields: move the cavity as close as possible to Lab-G magnet
  - SC coupling coil for MUCOOL: being fabricated at ICST, Harbin

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201-MHz Prototype Cavity

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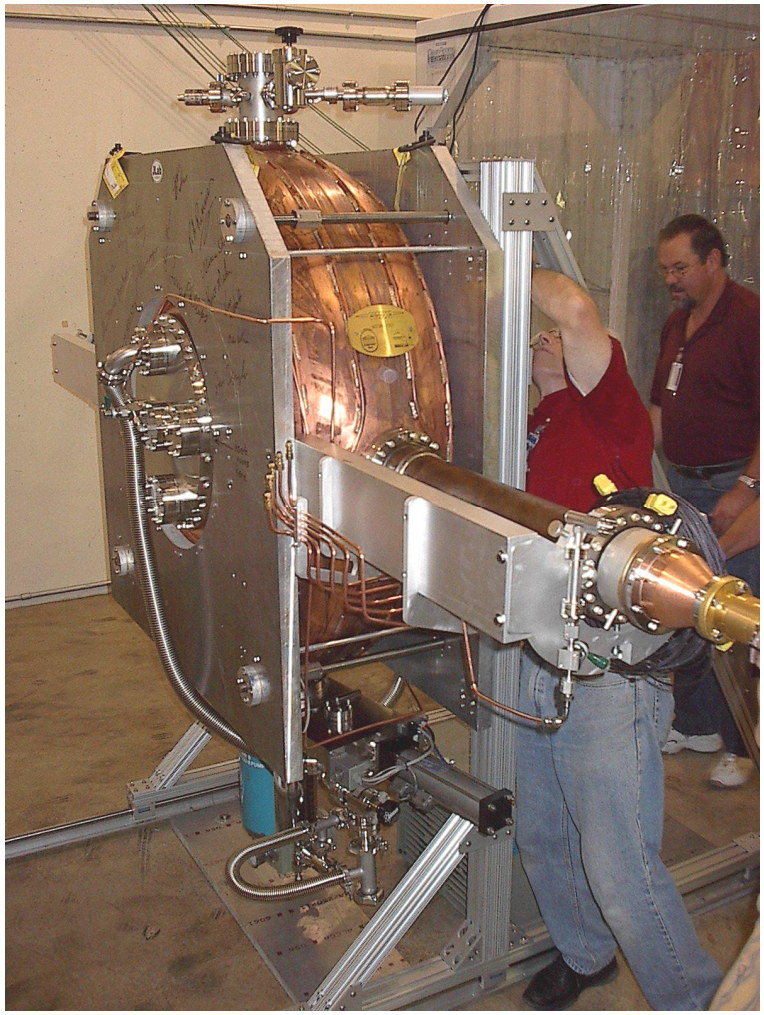
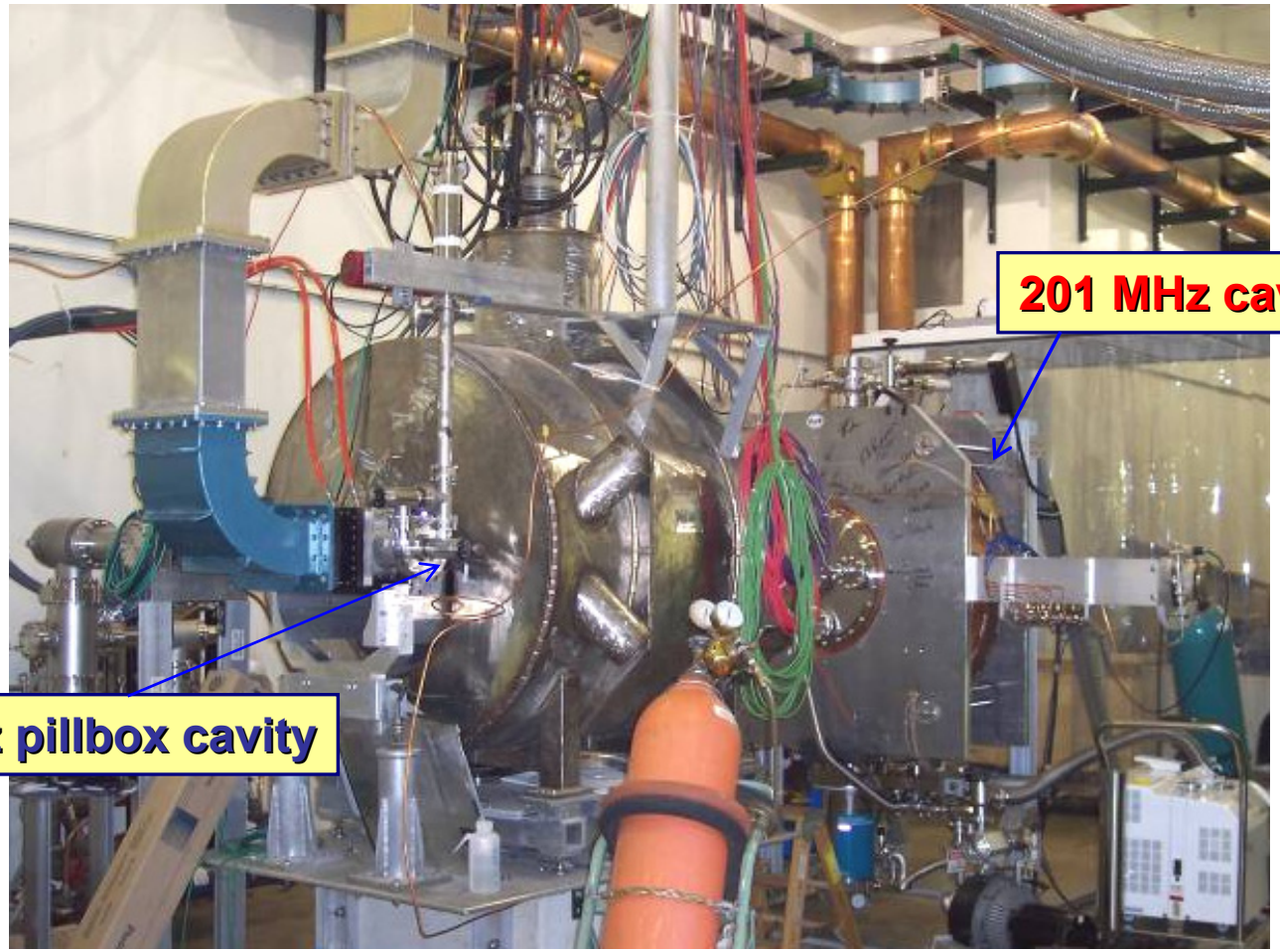
- **The cavity design parameters**
  - Frequency: 201.25 MHz
  - $\beta = 0.87$
  - Shunt impedance (VT^2/P): ~ 22 MΩ/m
  - Quality factor (Q_0): ~ 53,500
  - Be window radius and thickness: 21-cm and 0.38-mm
- **Nominal parameters for cooling channels in a muon collider or a neutrino factory**
  - ~ 16 MV/m peak accelerating field
  - Peak input RF power ~ 4.6 MW per cavity (85% of Q_0, 3τ filling time)
  - Average power dissipation per cavity ~ 8.4 kW
  - Average power dissipation per Be window ~ 100 watts



The 201-MHz cavity at MTA

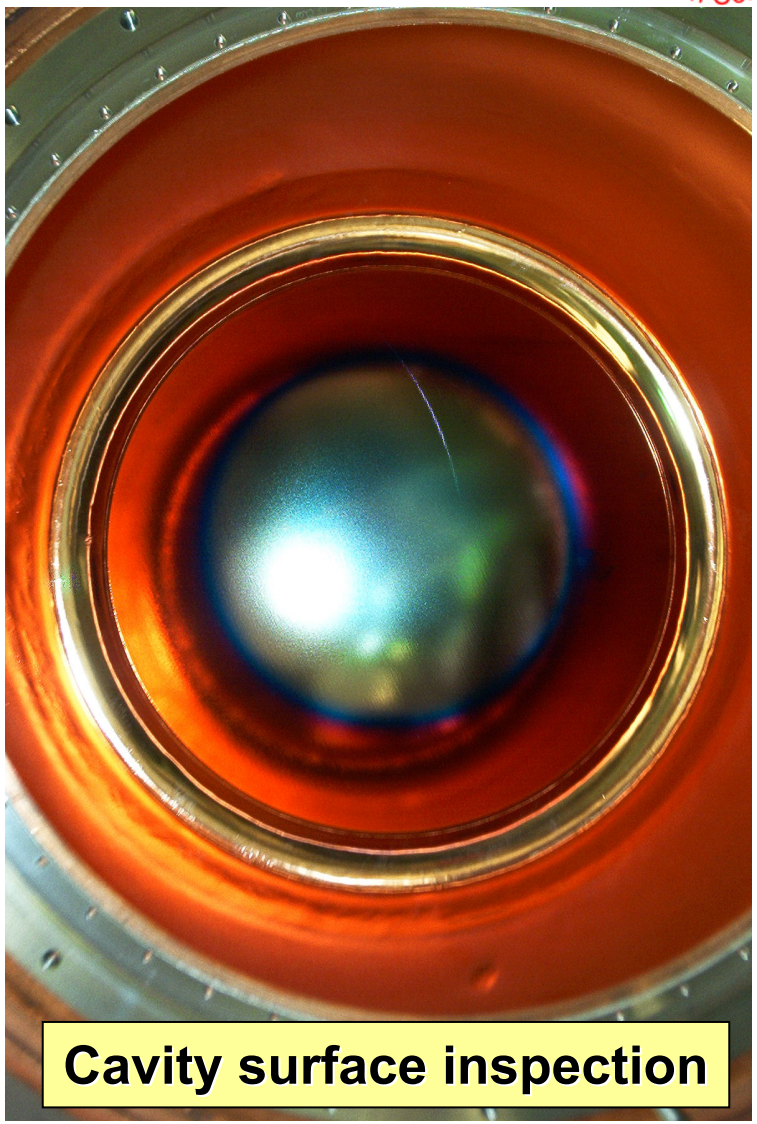
Test Setup at MTA

The 805-MHz and 201-MHz cavities at MTA, FNAL for RF breakdown studies with external magnetic fields.



Installation of Curved Be Windows

Be window installation



Cavity surface inspection

RF Tests of Be Windows

- The cavity reached to ~ 19 MV/m quickly
  - Cavity frequency had to be retuned
  - Cavity frequency was stable during the operation, however, we did observe frequency shift due to RF heating on the windows
    - Frequency shift of ~ 125 kHz (from 0 to ~ 19 MV/m, 150-micro-second pulse, 10-Hz repetition rate) in ~ 10 minutes, well within the tuning range (~ 110 kHz/mm, ± 4-mm range)
- With low external magnetic field
  - Cavity can be operated at ~ 19 MV/m with a few hundred Gauss stray field from Lab-G magnet
- Tests with stronger external magnetic fields
  - SC coupling coil for MuCool

New Vacuum Pumping System

Getter pumping system:

→ 1500 l/s Getter pump

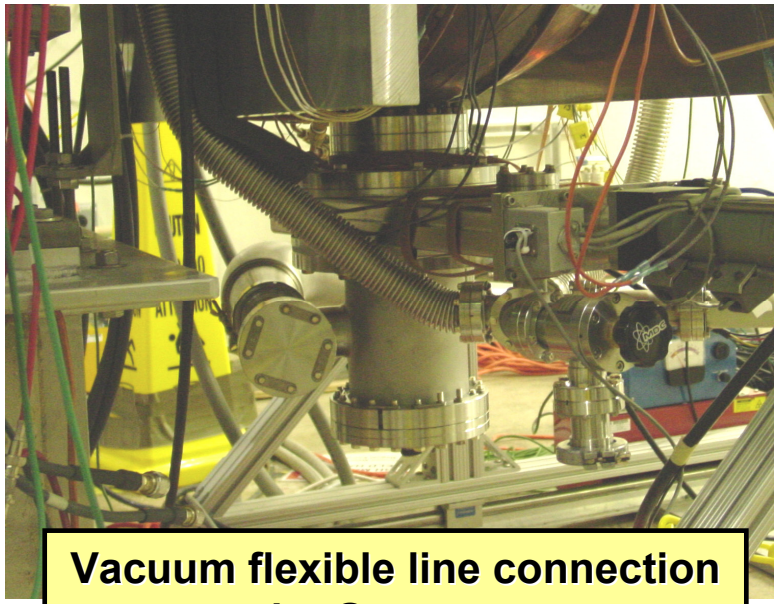
→ Backed by a 20 l/s Ion pump

→ Rough down by a with a Turbo-pump and dry pump

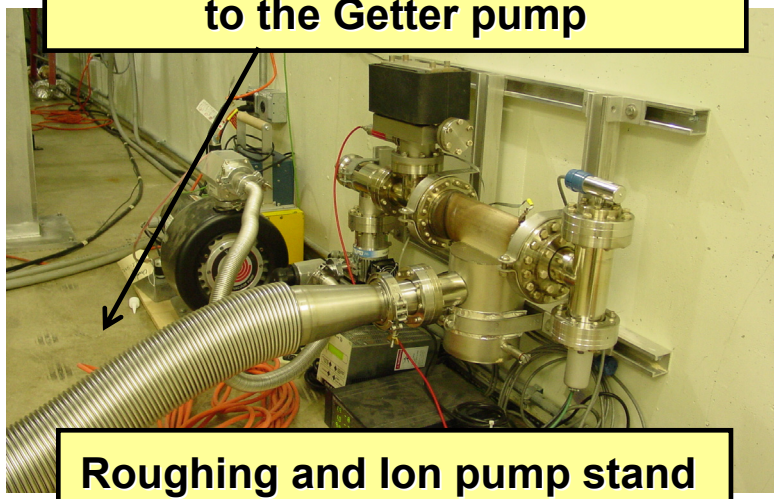
→ Vacuum valves & Ion gages

→ System has been running over a month without needing a re-charge

→ Has achieved base vacuum level of 2.5×10^{-8} Torr



Vacuum flexible line connection to the Getter pump



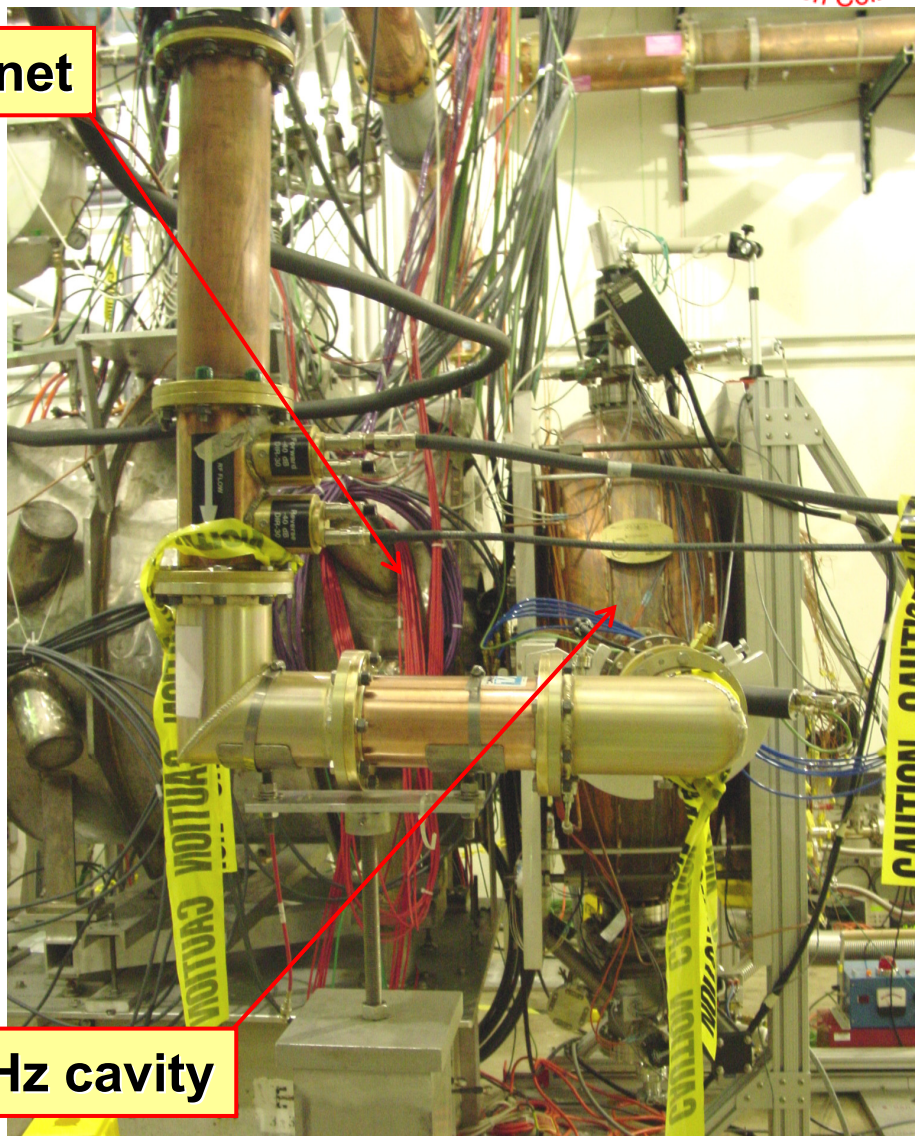
Roughing and Ion pump stand

Tests with Magnetic Fields

The 100-cm long coaxial section was replaced by 20-cm one

Separation of the nearest curved Be window from the face of Lab-G magnet is 10-cm (before was 110-cm)

Maximum magnetic field near the Be window ~ 1.5 Tesla (5 Tesla in magnet)



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Preliminary Test at B=0

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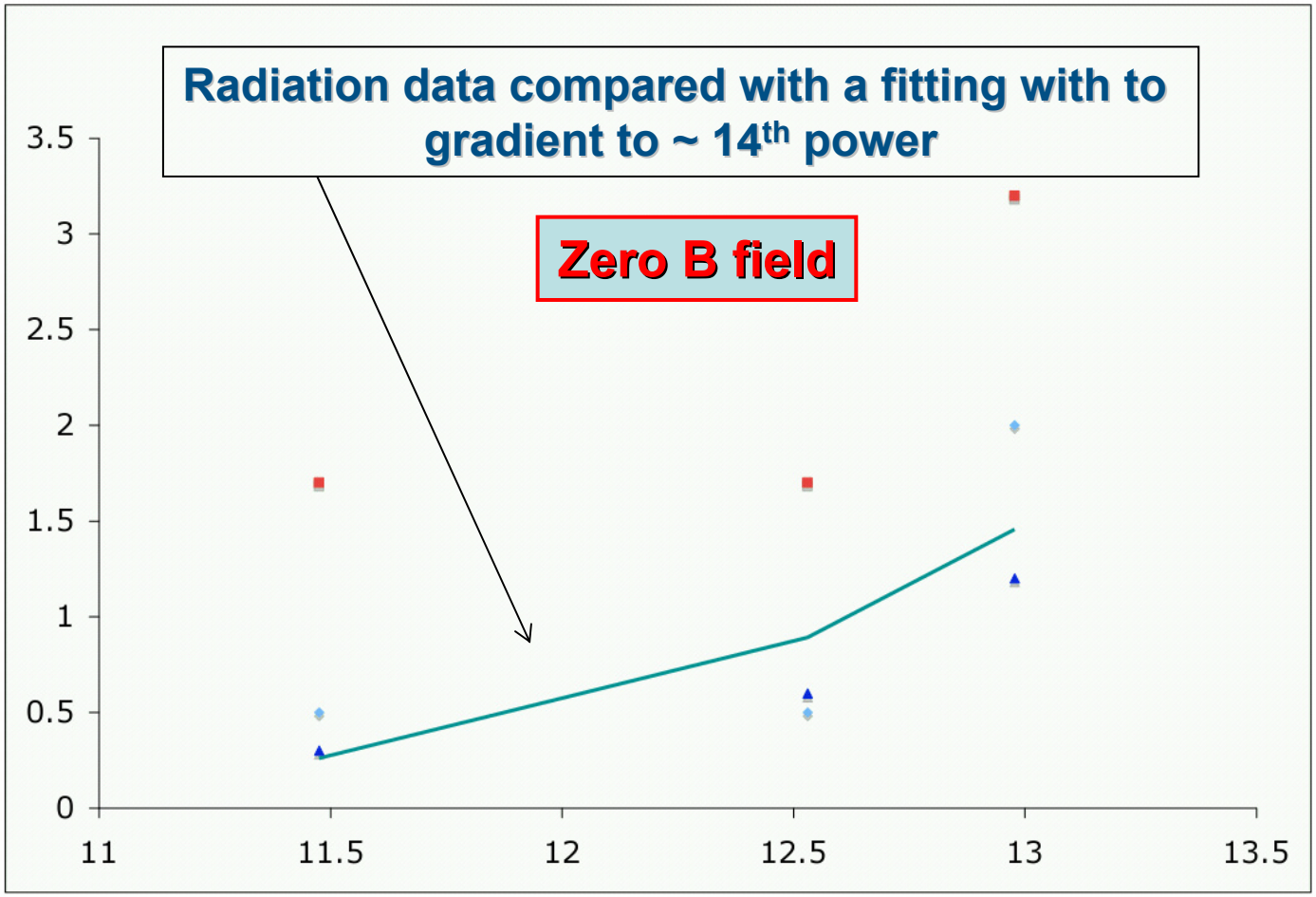

Represent Chipmonk #1, #2 and #3, respectively

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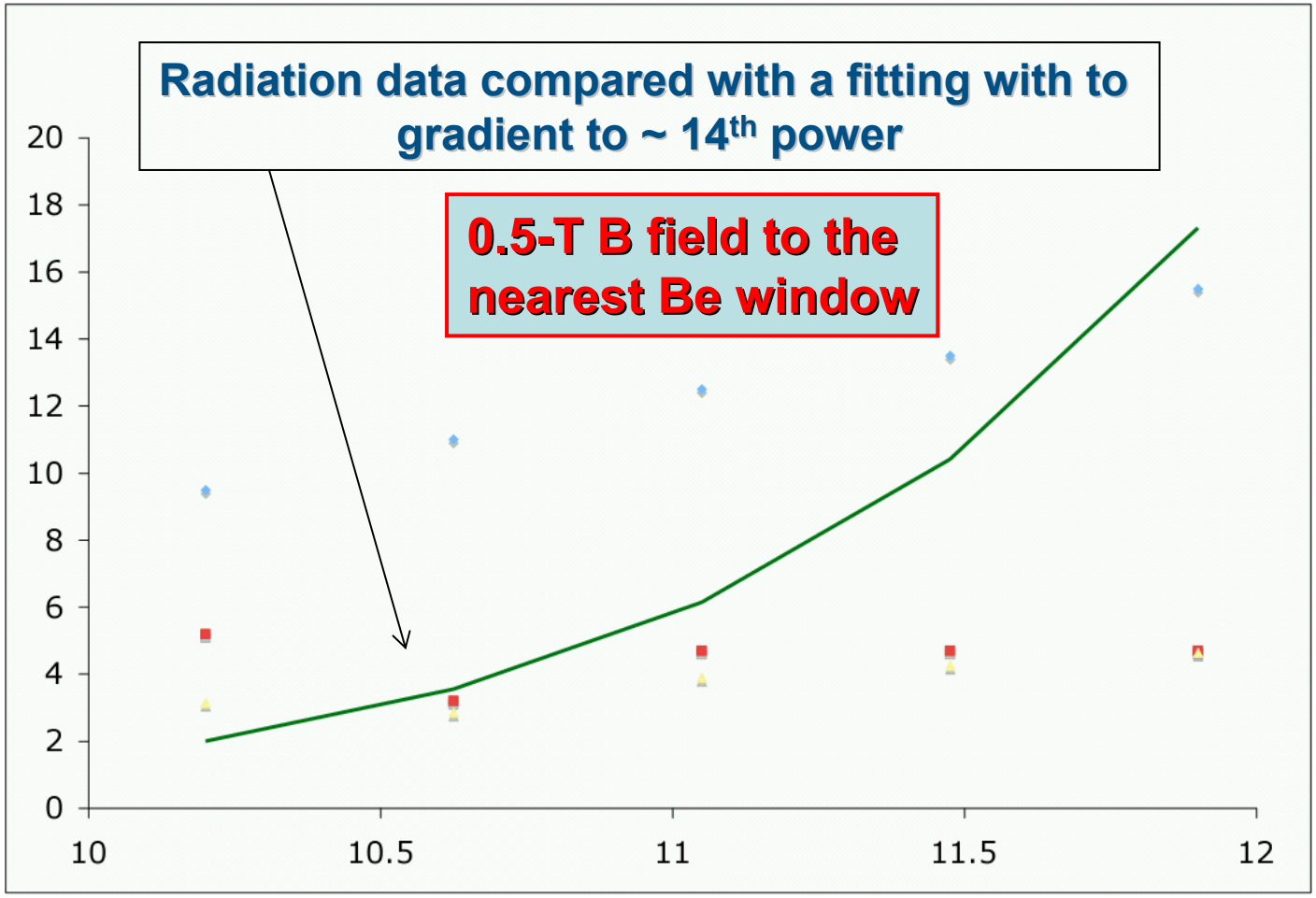
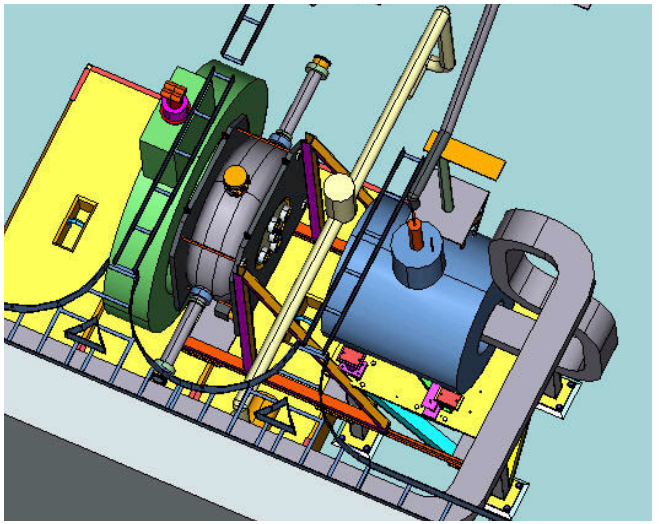
Radiation at 0.5-T Field



Represent Chipmonk #1, #2 and #3, respectively

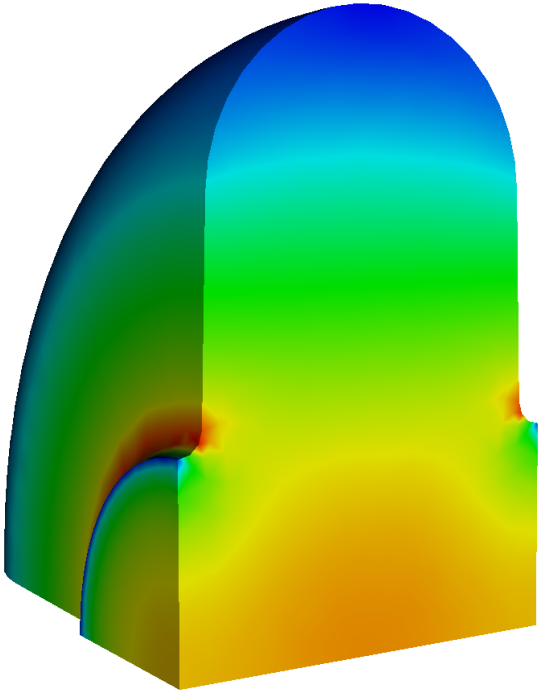
Preliminary Test Results

- Multi-pactoring was observed at the entire magnetic field range up to 3.75-T (~ 1.1-T at nearest Be window)
- A strong correlationship exists between cavity vacuum and radiation levels
- We have achieved ~ 14 MV/m at 2.5-T (~ 0.75-T to the nearest curved thin Be window)
- The test results are very encouraging, data analysis is being conducted
- We may need to commission (condition) the 201-MHz cavity longer to reduce the multi-pactoring before we can properly measure and study the magnetic field effects in the stray field
- Numerical studies with external magnetic fields and SC coupling coil

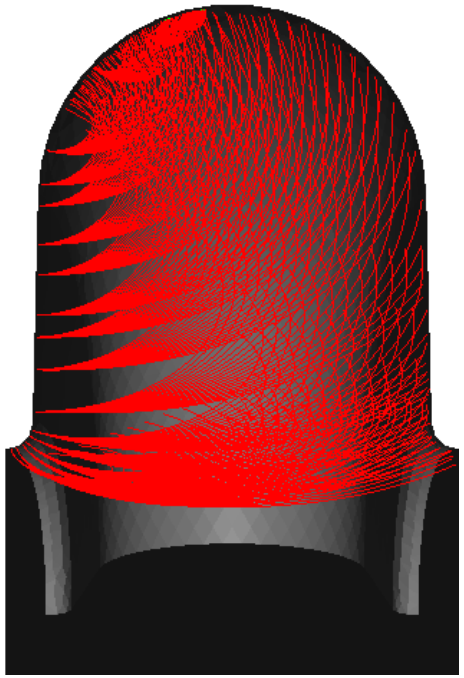


Numerical Study with B Field

- **Preliminary studies, in collaboration with Dr. Zenghai Li at SLAC using Omega-3P and Track-3P codes**
  - **Cavity with flat windows: 5 MV/m on axis; 2-T uniform external magnetic field; scan of a few points from one cavity side**



E field contour



Trajectories without external B field

Trajectories with external B = 2-T field

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201-MHz Cavity for MICE

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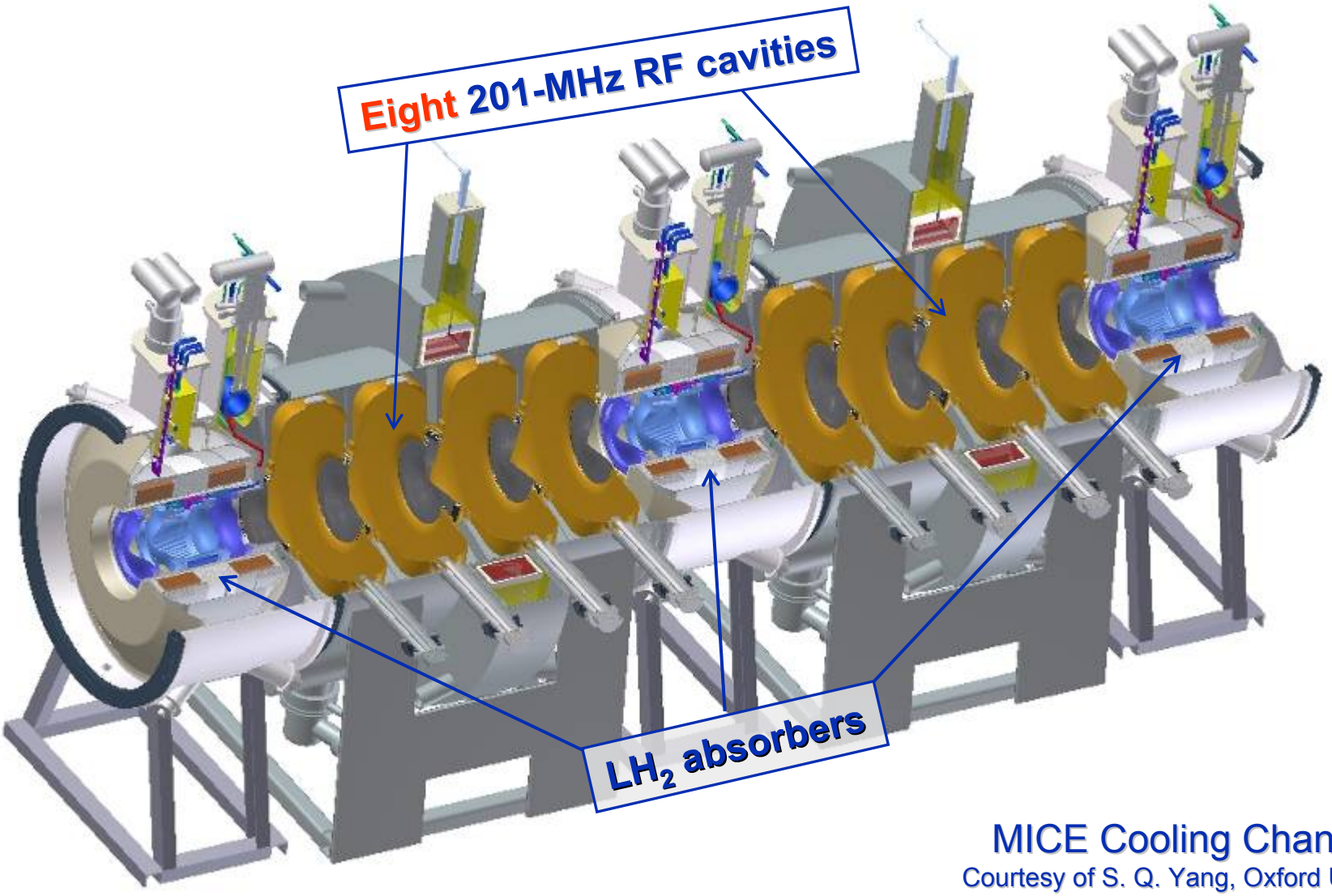
- Eight 201-MHz cavities + with materials for two more spare cavities
- Baseline design: 201-MHz for MUCOOL, but
  - Cavity body profile needs to be modified
    - Resonant frequency
    - Better estimation of spring back after spinning
  - Port extruding
    - Port interface is different from the MUCOOL cavity
  - RF coupler and ceramic window
    - The same window as for the MUCOOL cavity: Toshiba ceramic windows for SNS
  - Curved Beryllium windows
    - Improved design to better control silver alloy flow during the brazing
  - Tuners and interface with RFCC module
  - Post-processing: water cooling pipes, cleaning (EP & water rinsing), low power measurement, tuning, assembly and shipping

MICE Cooling Channel



MICE Cooling Channel
Courtesy of S. Q. Yang, Oxford Univ.

Cavity Design Parameters

- **The cavity design parameters**
  - Frequency: 201.25 MHz
  - $\beta = 0.87$
  - Shunt impedance (VT^2/P): ~ 22 MΩ/m
  - Quality factor (Q_0): ~ 53,500
  - Be window radius and thickness: 21-cm and 0.38-mm
- **Nominal parameters for cooling channels in a muon collider or a neutrino factory and MICE**
  - ~ 16 MV/m (~ 8 MV/m) peak accelerating field
  - Peak input RF power ~ 4.6 MW (~ 1 MW) per cavity (85% of Q_0, 3τ filling)
  - Average power dissipation per cavity ~ 8.4 kW (~ 1 kW at 1 Hz repetition rate and 1 ms pulse length)
  - Average power dissipation per Be window

    ~ 100 watts (~ 12 watts)

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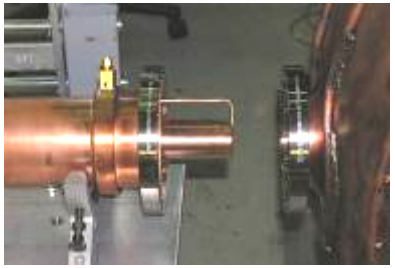
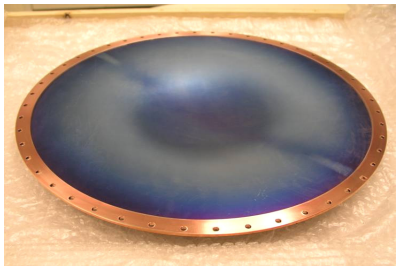
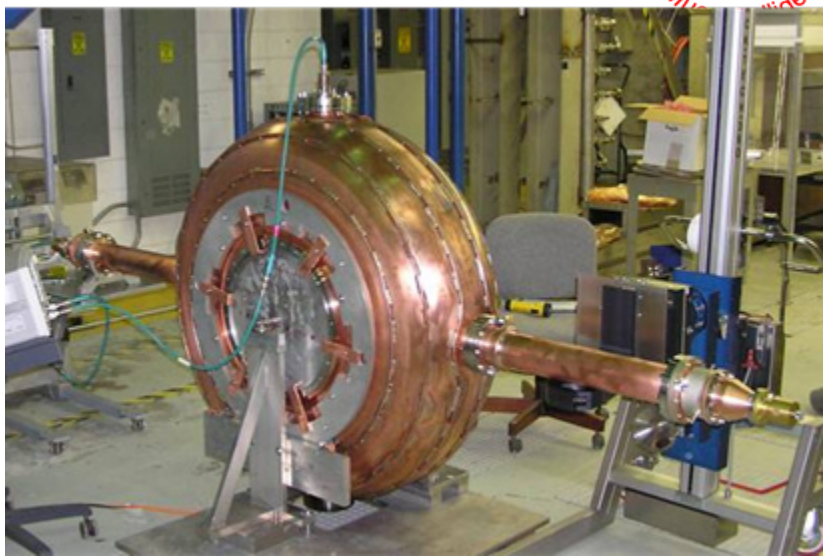
MUCOOL Cavity Review







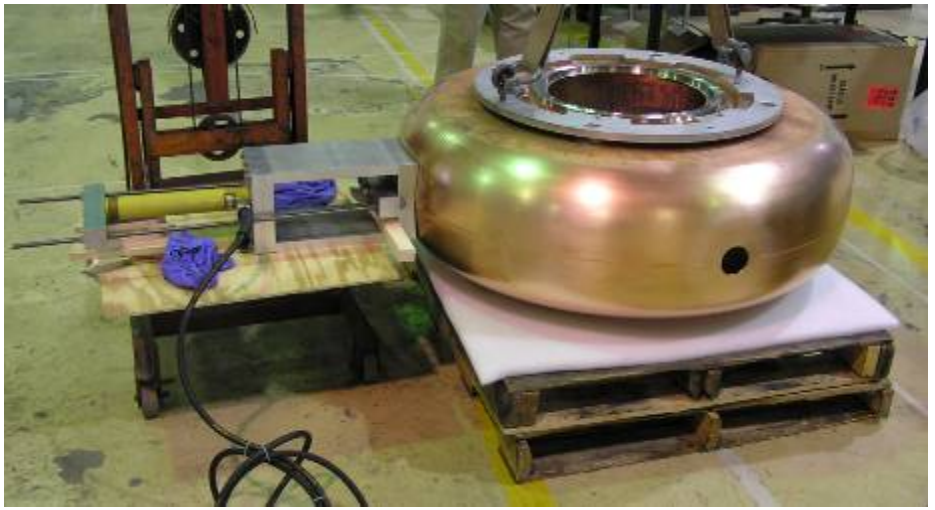
- Design and engineering at LBNL
- Half shells spun at Acme in Minnesota
- Parts made in Univ. of Mississippi and LBNL
- E-beam welding & port-pulling, cleaning and EP at J-Lab, NASA
- Coupler tests at SNS, Oak Ridge National Lab
- Final assembly and high power tests at MTA, FNAL (March-2006) and reached 16-MV/m without external magnetic field

Cavity Body

- The frequency for MuCool cavity is slightly lower than 200-MHz, but within the bandwidth of RF source
  - Mechanical (fixed) tuners available and tested in air
- MICE cavities
  - Target frequency is 201.250-MHz
  - One RF source (tube) powers more than one cavity
  - Each cavity will be made (spinning) to frequency very close to 201-MHz
    - Modifying the existing mold used for MUCOOL cavity
    - A new mold (could be new materials)
  - 3D simulations to predict the frequency shifts by ports, curved Be windows and thermal contraction (LN operation)
  - Conceptual tuner designs (fine tuning)

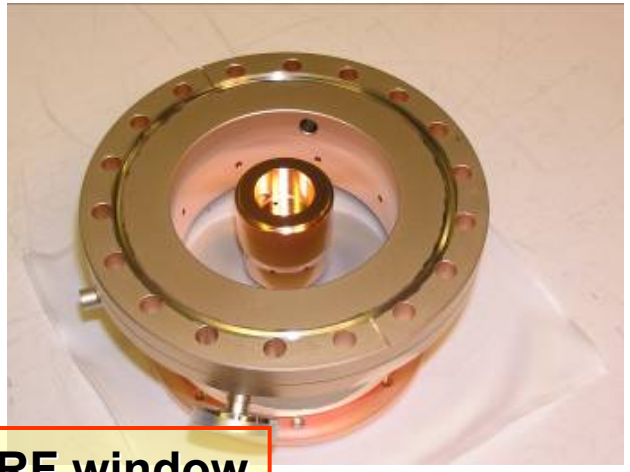
Ports Extruding and Coupler

Local annealing of ports



Cavity ports being extruded (pulled)

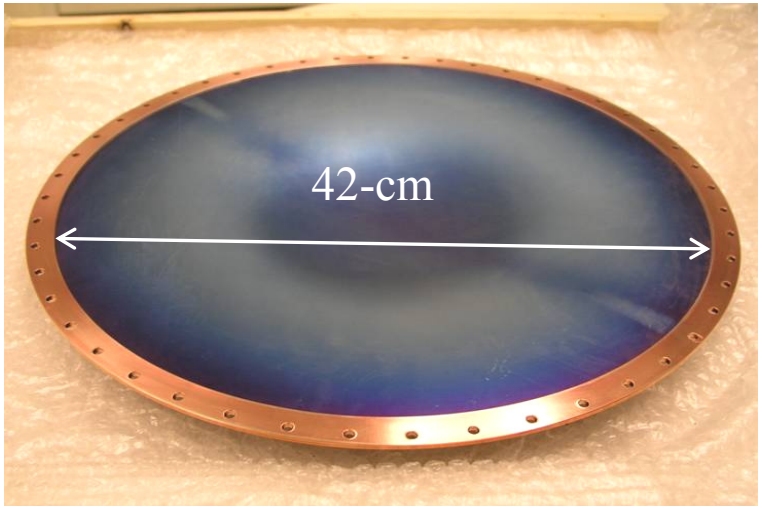
Extruded port

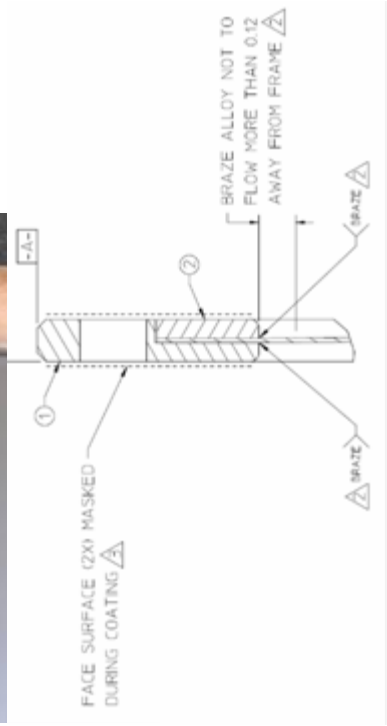


Power coupler and RF window

Curved Be Windows

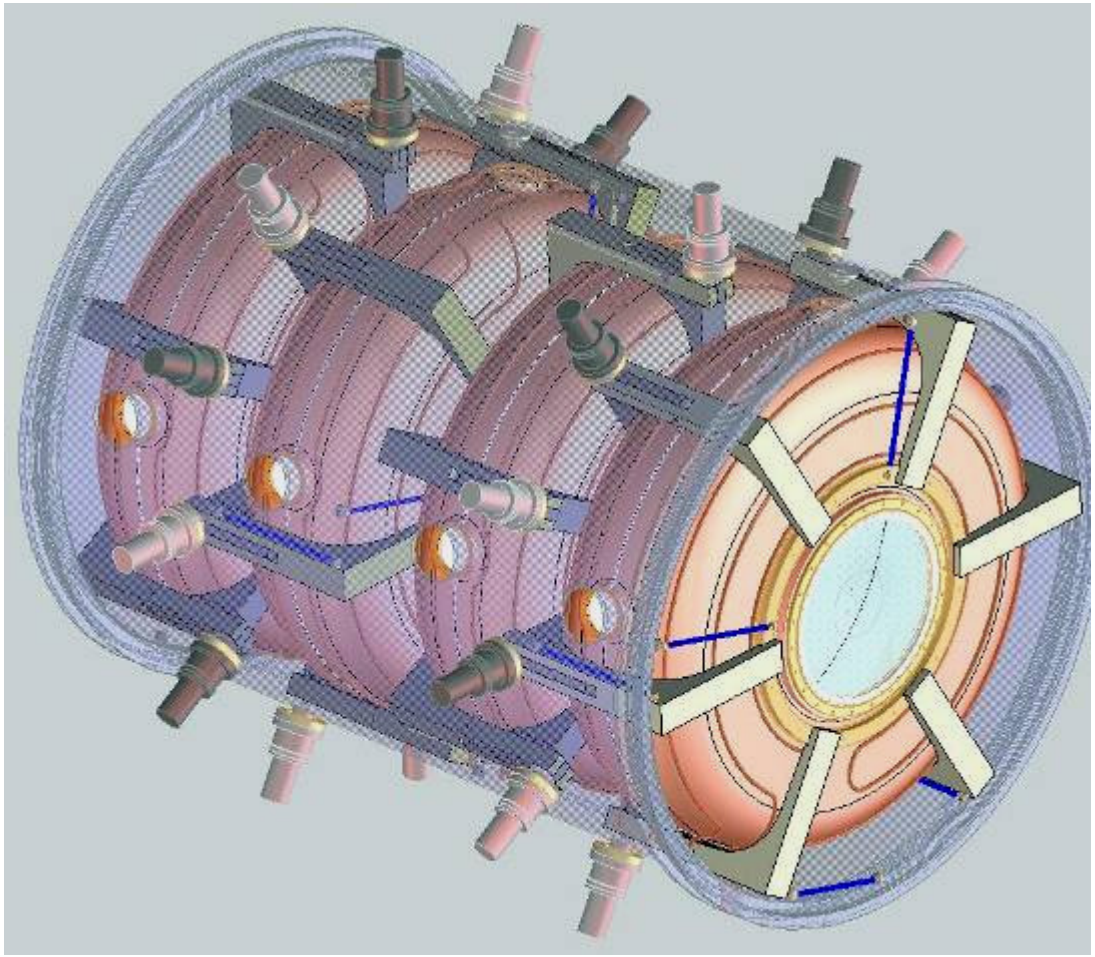
- **We have made two windows so far**
  - 21-cm and 0.38-mm thick
  - ***Good*** braze (between annular frames and foil)
  - Achieved ~ 95 % of the designed profile
  - Thin Ti-N coatings
- **The windows have been tested**





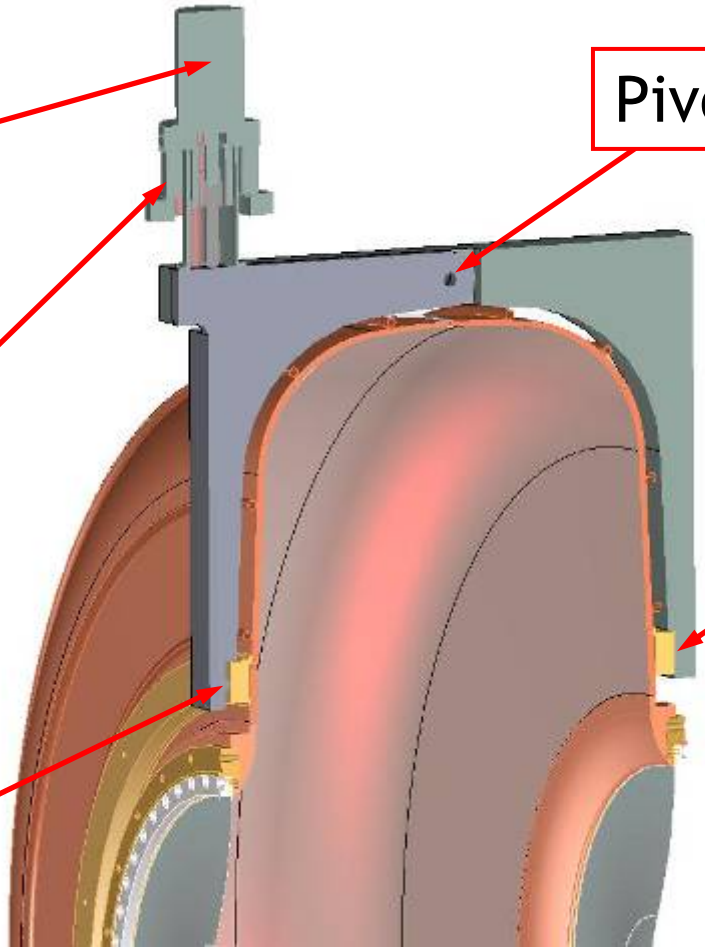
Tuners for MICE Cavities

Four 201-MHz cavities in each RFCC module; one tuner assembly (six sets of tuners) on each cavity.



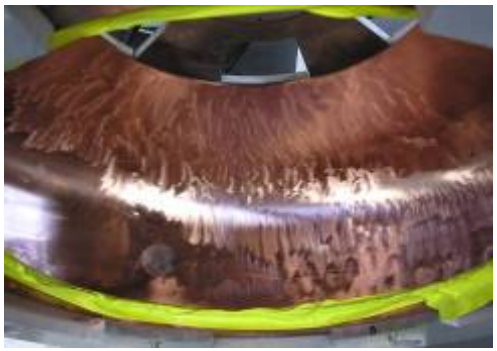
- Clocking of tuner position between adjacent cavities avoids interference
- Actuators offset from cavity center plane due to width of coupling coil
- Soft connection only (bellows) between tuner/actuators and vacuum vessel shell

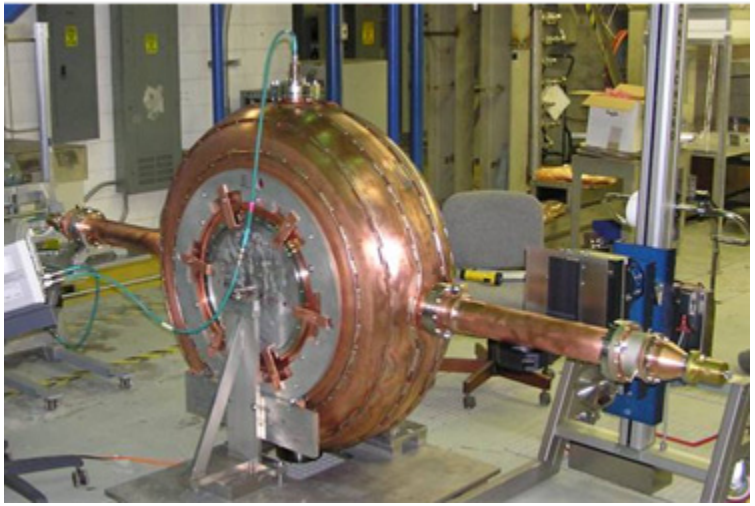
Tuner Concept for MICE Cavity (Sectional View)

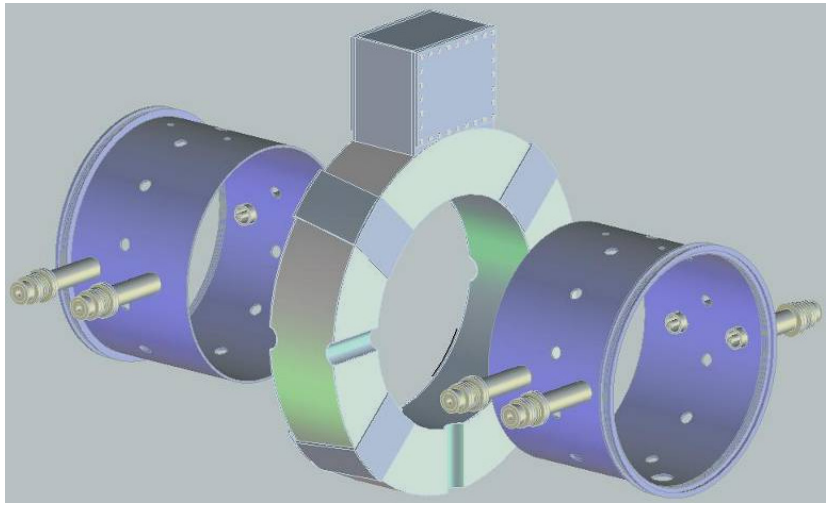


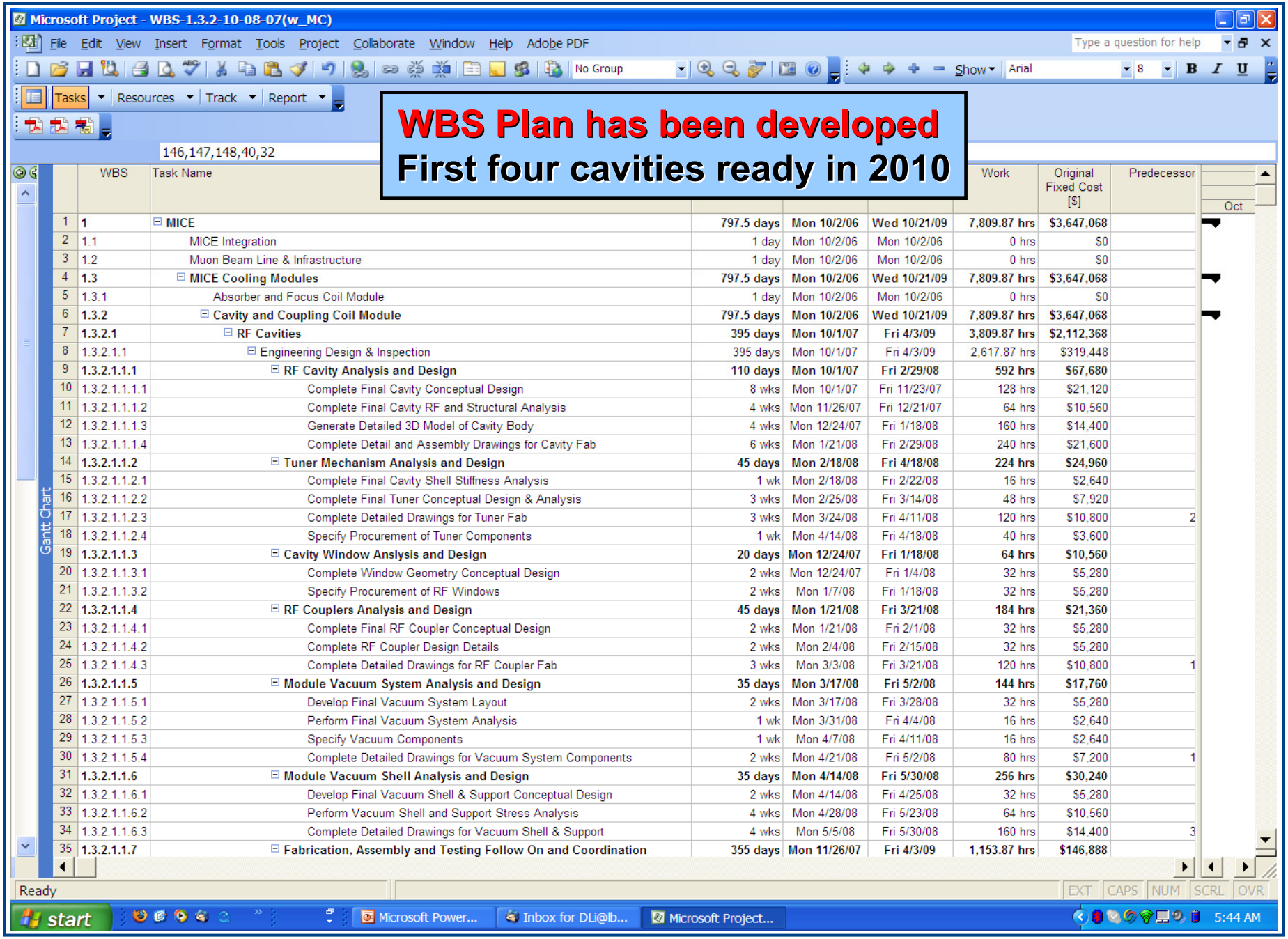
Post-Processing

- Cavity cleaning, assembly and integration
- Low power measurements and shipping









	WBS	Task Name	Duration	Start	Finish	Work	Original Fixed Cost [$]	Predecessor
1	**1**	**MICE**	**797.5 days**	**Mon 10/2/06**	**Wed 10/21/09**	**7,809.87 hrs**	**$3,647,068**	
2	1.1	MICE Integration	1 day	Mon 10/2/06	Mon 10/2/06	0 hrs	$0	
3	1.2	Muon Beam Line & Infrastructure	1 day	Mon 10/2/06	Mon 10/2/06	0 hrs	$0	
4	**1.3**	**MICE Cooling Modules**	**797.5 days**	**Mon 10/2/06**	**Wed 10/21/09**	**7,809.87 hrs**	**$3,647,068**	
5	1.3.1	Absorber and Focus Coil Module	1 day	Mon 10/2/06	Mon 10/2/06	0 hrs	$0	
6	**1.3.2**	**Cavity and Coupling Coil Module**	**797.5 days**	**Mon 10/2/06**	**Wed 10/21/09**	**7,809.87 hrs**	**$3,647,068**	
7	**1.3.2.1**	**RF Cavities**	**395 days**	**Mon 10/1/07**	**Fri 4/3/09**	**3,809.87 hrs**	**$2,112,368**	
8	1.3.2.1.1	Engineering Design & Inspection	395 days	Mon 10/1/07	Fri 4/3/09	2,617.87 hrs	$319,448	
9	**1.3.2.1.1.1**	**RF Cavity Analysis and Design**	**110 days**	**Mon 10/1/07**	**Fri 2/29/08**	**592 hrs**	**$67,680**	
10	1.3.2.1.1.1.1	Complete Final Cavity Conceptual Design	8 wks	Mon 10/1/07	Fri 11/23/07	128 hrs	$21,120	
11	1.3.2.1.1.1.2	Complete Final Cavity RF and Structural Analysis	4 wks	Mon 11/26/07	Fri 12/21/07	64 hrs	$10,560	
12	1.3.2.1.1.1.3	Generate Detailed 3D Model of Cavity Body	4 wks	Mon 12/24/07	Fri 1/18/08	160 hrs	$14,400	
13	1.3.2.1.1.1.4	Complete Detail and Assembly Drawings for Cavity Fab	6 wks	Mon 1/21/08	Fri 2/29/08	240 hrs	$21,600	
14	**1.3.2.1.1.2**	**Tuner Mechanism Analysis and Design**	**45 days**	**Mon 2/18/08**	**Fri 4/18/08**	**224 hrs**	**$24,960**	
15	1.3.2.1.1.2.1	Complete Final Cavity Shell Stiffness Analysis	1 wk	Mon 2/18/08	Fri 2/22/08	16 hrs	$2,640	
16	1.3.2.1.1.2.2	Complete Final Tuner Conceptual Design & Analysis	3 wks	Mon 2/25/08	Fri 3/14/08	48 hrs	$7,920	
17	1.3.2.1.1.2.3	Complete Detailed Drawings for Tuner Fab	3 wks	Mon 3/24/08	Fri 4/11/08	120 hrs	$10,800	2
18	1.3.2.1.1.2.4	Specify Procurement of Tuner Components	1 wk	Mon 4/14/08	Fri 4/18/08	40 hrs	$3,600	
19	**1.3.2.1.1.3**	**Cavity Window Anslysis and Design**	**20 days**	**Mon 12/24/07**	**Fri 1/18/08**	**64 hrs**	**$10,560**	
20	1.3.2.1.1.3.1	Complete Window Geometry Conceptual Design	2 wks	Mon 12/24/07	Fri 1/4/08	32 hrs	$5,280	
21	1.3.2.1.1.3.2	Specify Procurement of RF Windows	2 wks	Mon 1/7/08	Fri 1/18/08	32 hrs	$5,280	
22	**1.3.2.1.1.4**	**RF Couplers Analysis and Design**	**45 days**	**Mon 1/21/08**	**Fri 3/21/08**	**184 hrs**	**$21,360**	
23	1.3.2.1.1.4.1	Complete Final RF Coupler Conceptual Design	2 wks	Mon 1/21/08	Fri 2/1/08	32 hrs	$5,280	
24	1.3.2.1.1.4.2	Complete RF Coupler Design Details	2 wks	Mon 2/4/08	Fri 2/15/08	32 hrs	$5,280	
25	1.3.2.1.1.4.3	Complete Detailed Drawings for RF Coupler Fab	3 wks	Mon 3/3/08	Fri 3/21/08	120 hrs	$10,800	1
26	**1.3.2.1.1.5**	**Module Vacuum System Analysis and Design**	**35 days**	**Mon 3/17/08**	**Fri 5/2/08**	**144 hrs**	**$17,760**	
27	1.3.2.1.1.5.1	Develop Final Vacuum System Layout	2 wks	Mon 3/17/08	Fri 3/28/08	32 hrs	$5,280	
28	1.3.2.1.1.5.2	Perform Final Vacuum System Analysis	1 wk	Mon 3/31/08	Fri 4/4/08	16 hrs	$2,640	
29	1.3.2.1.1.5.3	Specify Vacuum Components	1 wk	Mon 4/7/08	Fri 4/11/08	16 hrs	$2,640	
30	1.3.2.1.1.5.4	Complete Detailed Drawings for Vacuum System Components	2 wks	Mon 4/21/08	Fri 5/2/08	80 hrs	$7,200	1
31	**1.3.2.1.1.6**	**Module Vacuum Shell Analysis and Design**	**35 days**	**Mon 4/14/08**	**Fri 5/30/08**	**256 hrs**	**$30,240**	
32	1.3.2.1.1.6.1	Develop Final Vacuum Shell & Support Conceptual Design	2 wks	Mon 4/14/08	Fri 4/25/08	32 hrs	$5,280	
33	1.3.2.1.1.6.2	Perform Vacuum Shell and Support Stress Analysis	4 wks	Mon 4/28/08	Fri 5/23/08	64 hrs	$10,560	
34	1.3.2.1.1.6.3	Complete Detailed Drawings for Vacuum Shell & Support	4 wks	Mon 5/5/08	Fri 5/30/08	160 hrs	$14,400	3
35	**1.3.2.1.1.7**	**Fabrication, Assembly and Testing Follow On and Coordination**	**355 days**	**Mon 11/26/07**	**Fri 4/3/09**	**1,153.87 hrs**	**$146,888**	

Summary

- Curved Be windows were installed and tested
  - Reached ~ 19 MV/m with stray magnetic fields of a few hundred Gauss
  - Reached to ~ 14 MV/m with ~ 0.75-T (@ nearest Be window) magnetic field by moving next to Lab-G magnet
  - Preliminary results are encouraging
- Numerical studies of the cavity in magnetic fields started in collaboration with SLAC
- Plans for building eight 201-MHz cavities for MICE are developed
  - Four cavities will be delivered by 2010
- Need MuCool coupling coil to provide the needed strong magnetic field for further studies