Muon Collaboration

BERKELEY LAB

Normal Conducting RF Issues and Design

John Corlett, Bob Rimmer

Accelerator and Fusion Research Division

LBNL

Muon Collaboration

NCRF R&D - Staff from multiple institutions

Berkeley

John Corlett

Bob Rimmer

Neal Hartman

Derun Li

Bob MacGill

Fermilab

Norbert Holtkamp

Tom Jurgens

Al Moretti

Zubao Qian

Vincent Wu

BNL

Jim Rose

Harold Kirk

Haipeng Wang

J. Scott Berg

Mississippi

Don Summer

Mike Booke

Princeton

Kirk Macdonald

IIT

Ed Black

Normal conducting RF systems - Feasibility study II parameters

- 201.25 MHz and 402.5 MHz
- High accelerating field (6 - 17.6 MVm^{-1})
- Large beam pipe apertures (30 - 50 cm diameter)
- Strong magnetic field (≈ 5 T)
  - Minimize power requirements
  - Maximize shunt impedance

R&D program in place to develop novel accelerating structures with large shunt impedance

closed-cells

windows or grids of tubes

Many issues to be addressed:

frequency stability, breakdown, secondary emission yield, multipacting, heating, dark current, high-power amplifiers...

Normal conducting RF systems - Feasibility study II parameters

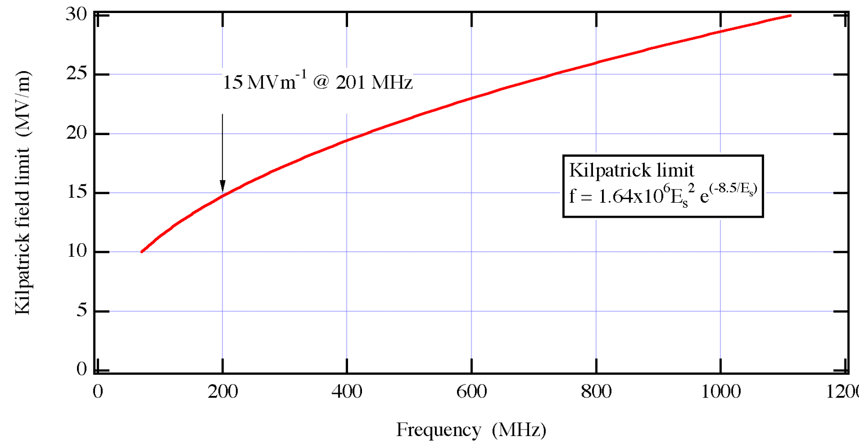
- Optimize cell lengths for maximum efficiency given lattice constraints
  - Maximum multi-cell pillbox shunt impedance at 105° per cell
    - 23.5 $M\Omega m^{-1}$
  - Maximum single-cell pillbox shunt impedance at 160° per cell
    - 20 $M\Omega m^{-1}$

	Frequency	Cell length	# cells per RF section	Gradient	Windows at ends of RF structures		Windows between cells		# sections	Total # RF cells	Shunt impedance	RF input power per cell	Total RF power per cell type	Windows at ends of RF structures		Windows between cells	
					Thickness	Radius	Thickness	Radius						RF power	Temp.	RF power	Temp.
	GHz	cm		MV/m	µm	cm	µm	cm			MΩ/m	MW	MW	W	°C	W	°C
Buncher section																	
	402.5	18.6	1	6.4	100	20			2	2	30.1	0.2	0.4	17	34		
	402.5	18.6	1	6	100	20	?	?	4	4	30.1	0.17	0.68	15	30	?	?
	201.25	37.3	4	6.4	125	21	250	25	1	4	23.4	0.5	2	16	26	32	26
	201.25	37.3	4	6	125	21	250	25	2	8	23.4	0.43	3.44	14	22	28	22
	201.25	37.3	4	8	125	21	250	25	2	8	23.4	0.77	6.16	25	40	50	40
Cooling section																	
[1,1; 1,2; 1,3]	201.25	46.6	4	16.29	125	21	250	25	6	24	22.6	3.5	84	118	189	448	359
[2,1]	201.25	55.9	2	17.6	75	18	125	21	14	28	20.3	4.4	123.2	85	227	304	487
[2,2]	201.25	55.9	2	17.6	75	18	75	18	10	20	20.3	4.4	88	85	227	170	453
[2,3a]	201.25	55.9	2	17.6	75	15	75	18	16	32	20.3	4.4	140.8	43	115	170	453
[2,3b]	201.25	55.9	2	17.6	50	15	50	15	16	32	20.3	4.4	140.8	43	172	85	340

Normal conducting RF systems - Feasibility study II parameters

Muon Collaboration

- Gradient is high
  - Up to 17.6 MVm^{-1}
    - Peak surface fields in pillbox ≈ accelerating field
      - ≈ Kilpatrick level



	Frequency	Cell length	# cells per RF section	Gradient	Windows at ends of RF structures		Windows between cells		# sections	Total # RF cells	Shunt impedance	RF input power per cell	Total RF power per cell type	Windows at ends of RF structures		Windows between cells	
					Thickness	Radius	Thickness	Radius						RF power	Temp.	RF power	Temp.
	GHz	cm		MV/m	μm	cm	μm	cm			MΩ/m	MW	MW	W	°C	W	°C
Buncher section																	
	402.5	18.6	1	6.4	100	20			2	2	30.1	0.2	0.4	17	34		
	402.5	18.6	1	6	100	20	?	?	4	4	30.1	0.17	0.68	15	30	?	?
	201.25	37.3	4	6.4	125	21	250	25	1	4	23.4	0.5	2	16	26	32	26
	201.25	37.3	4	6	125	21	250	25	2	8	23.4	0.43	3.44	14	22	28	22
	201.25	37.3	4	8	125	21	250	25	2	8	23.4	0.77	6.16	25	40	50	40
Cooling section																	
[1,1; 1,2; 1,3]	201.25	46.6	4	16.29	125	21	250	25	6	24	22.6	3.5	84	118	189	448	359
[2,1]	201.25	55.9	2	17.6	75	18	125	21	14	28	20.3	4.4	123.2	85	227	304	487
[2,2]	201.25	55.9	2	17.6	75	18	75	18	10	20	20.3	4.4	88	85	227	170	453
[2,3a]	201.25	55.9	2	17.6	75	15	75	18	16	32	20.3	4.4	140.8	43	115	170	453
[2,3b]	201.25	55.9	2	17.6	50	15	50	15	16	32	20.3	4.4	140.8	43	172	85	340

Muon Collaboration

Normal conducting RF systems - Feasibility study II parameters

- Power requirement large
  - 750 MW total ncrf
    - 7 MW buncher
    - 745 MW cooling
  - Large facilities required for power systems
    - Housing klystrons and modulators
      - *Develop high-peak-power tubes*

	Frequency	Cell length	# cells per RF section	Gradient	Windows at ends of RF structures		Windows between cells		# sections	Total # RF cells	Shunt impedance	RF input power per cell	Total RF power per cell type	Windows at ends of RF structures		Windows between cells	
					Thickness	Radius	Thickness	Radius						RF power	Temp.	RF power	Temp.
	GHz	cm		MV/m	µm	cm	µm	cm			MΩ/m	MW	MW	W	°C	W	°C
Buncher section																	
	402.5	18.6	1	6.4	100	20			2	2	30.1	0.2	0.4	17	34		
	402.5	18.6	1	6	100	20	?	?	4	4	30.1	0.17	0.68	15	30	?	?
	201.25	37.3	4	6.4	125	21	250	25	1	4	23.4	0.5	2	16	26	32	26
	201.25	37.3	4	6	125	21	250	25	2	8	23.4	0.43	3.44	14	22	28	22
	201.25	37.3	4	8	125	21	250	25	2	8	23.4	0.77	6.16	25	40	50	40
Cooling section																	
[1,1; 1,2; 1,3]	201.25	46.6	4	16.29	125	21	250	25	6	24	22.6	3.5	84	118	189	448	359
[2,1]	201.25	55.9	2	17.6	75	18	125	21	14	28	20.3	4.4	123.2	85	227	304	487
[2,2]	201.25	55.9	2	17.6	75	18	75	18	10	20	20.3	4.4	88	85	227	170	453
[2,3a]	201.25	55.9	2	17.6	75	15	75	18	16	32	20.3	4.4	140.8	43	115	170	453
[2,3b]	201.25	55.9	2	17.6	50	15	50	15	16	32	20.3	4.4	140.8	43	172	85	340

Normal conducting RF systems - Feasibility study II parameters

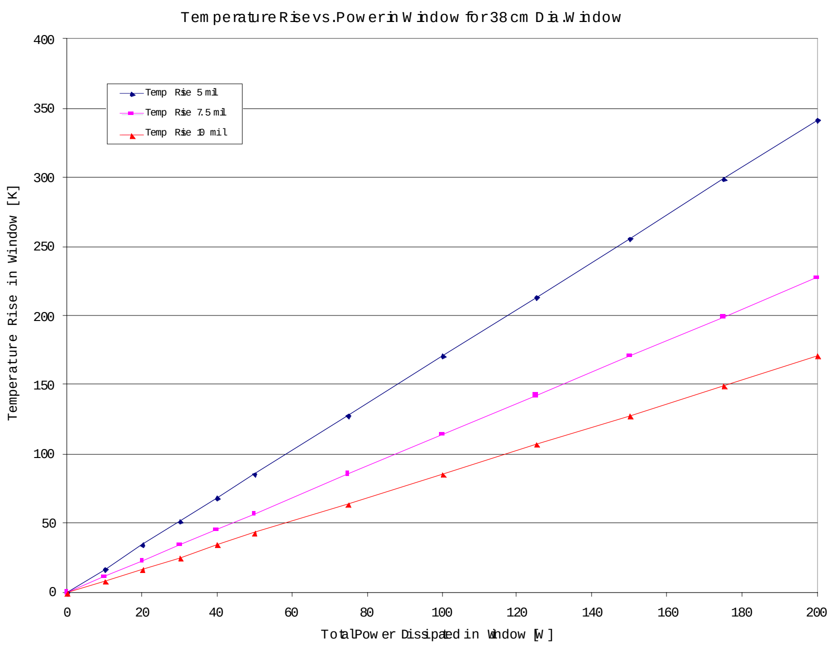
Muon Collaboration

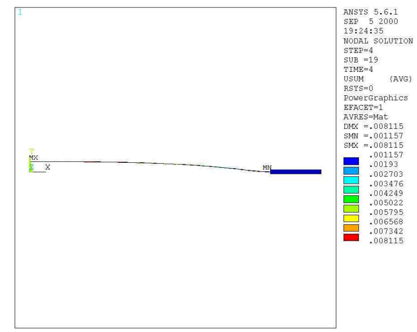
- **Simple Be windows will distort at the required cavity parameters**
  - **Up to 450 W dissipated in one window**
    - **19cm, 125 µm foils may dissipate up to 20 W without distortion**
      - **Total 1.5 kW dissipated in cooling section windows**
  - **Large diameter foils**
    - **Expensive** **($15k - $17k per 19 cm radius foil)**
    - **Availability of large diameter foils is a concern** **(may need to join smaller foils)**
  - **Thin foils**
    - **Develop sandwich structures with cooling gas flowing between Be foils**

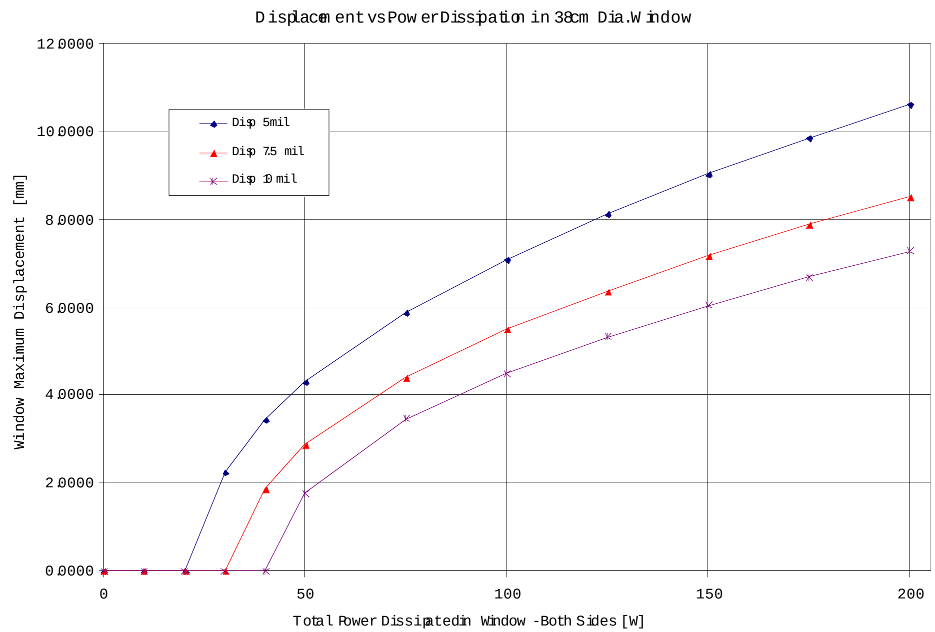
	Frequency	Cell length	# cells per RF section	Gradient	Windows at ends of RF structures		Windows between cells		# sections	Total # RF cells	Shunt impedance	RF input power per cell	Total RF power per cell type	Windows at ends of RF structures		Windows between cells	
	GHz	cm		MV/m	Thickness µm	Radius cm	Thickness µm	Radius cm			MΩ/m	MW	MW	RF power W	Temp. °C	RF power W	Temp. °C
Buncher section																	
	402.5	18.6	1	6.4	100	20			2	2	30.1	0.2	0.4	17	34		
	402.5	18.6	1	6	100	20	?	?	4	4	30.1	0.17	0.68	15	30	?	?
	201.25	37.3	4	6.4	125	21	250	25	1	4	23.4	0.5	2	16	26	32	26
	201.25	37.3	4	6	125	21	250	25	2	8	23.4	0.43	3.44	14	22	28	22
	201.25	37.3	4	8	125	21	250	25	2	8	23.4	0.77	6.16	25	40	50	40
Cooling section																	
[1,1; 1,2; 1,3]	201.25	46.6	4	16.29	125	21	250	25	6	24	22.6	3.5	84	118	189	448	359
[2,1]	201.25	55.9	2	17.6	75	18	125	21	14	28	20.3	4.4	123.2	85	227	304	487
[2,2]	201.25	55.9	2	17.6	75	18	75	18	10	20	20.3	4.4	88	85	227	170	453
[2,3a]	201.25	55.9	2	17.6	75	15	75	18	16	32	20.3	4.4	140.8	43	115	170	453
[2,3b]	201.25	55.9	2	17.6	50	15	50	15	16	32	20.3	4.4	140.8	43	172	85	340

Muon Collaboration

ANSYS model of 19 cm radius Be foil windows in 15 MVm^{-1} pillbox





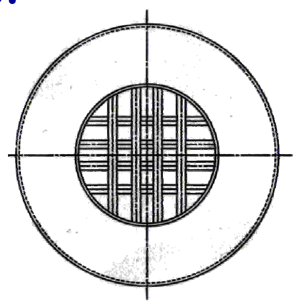


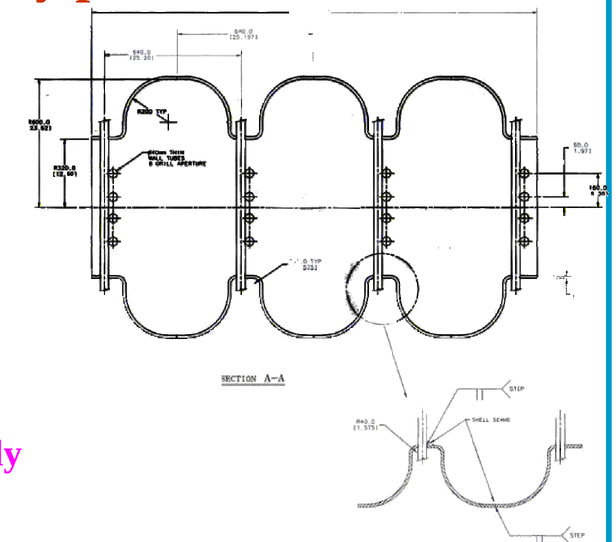
19 cm radius, 125 μm thick foil may dissipate up to ~ 20 W before distorting

Muon Collaboration

Normal conducting RF systems - Feasibility study II parameters

- **Simple Be windows will distort at the required cavity parameters**
  - **Develop thin-walled crossed-tube designs?**
    - **Difficult to fabricate in Be**
    - **Large surface fields and currents**
    - **Cool with gas flow through tubes**
    - **Resistant to deformation**
      - **4x4 grid of 4 cm diameter Al tubes**
        - » **5x scattering of 125 µm Be foil**
        - » **Introduces few MeV momentum deviation radially**
      - **Investigate other grid arrangements and materials**





	Frequency	Cell length	# cells per RF section	Gradient	Windows at ends of RF structures		Windows between cells		# sections	Total # RF cells	Shunt impedance	RF input power per cell	Total RF power per cell type	Windows at ends of RF structures		Windows between cells	
	GHz	cm		MV/m	Thickness µm	Radius cm	Thickness µm	Radius cm			MΩ/m	MW	MW	RF power W	Temp. °C	RF power W	Temp. °C
Buncher section																	
	402.5	18.6	1	6.4	100	20			2	2	30.1	0.2	0.4	17	34		
	402.5	18.6	1	6	100	20	?	?	4	4	30.1	0.17	0.68	15	30	?	?
	201.25	37.3	4	6.4	125	21	250	25	1	4	23.4	0.5	2	16	26	32	26
	201.25	37.3	4	6	125	21	250	25	2	8	23.4	0.43	3.44	14	22	28	22
	201.25	37.3	4	8	125	21	250	25	2	8	23.4	0.77	6.16	25	40	50	40
Cooling section																	
[1,1; 1,2; 1,3]	201.25	46.6	4	16.29	125	21	250	25	6	24	22.6	3.5	84	118	189	448	359
[2,1]	201.25	55.9	2	17.6	75	18	125	21	14	28	20.3	4.4	123.2	85	227	304	487
[2,2]	201.25	55.9	2	17.6	75	18	75	18	10	20	20.3	4.4	88	85	227	170	453
[2,3a]	201.25	55.9	2	17.6	75	15	75	18	16	32	20.3	4.4	140.8	43	115	170	453
[2,3b]	201.25	55.9	2	17.6	50	15	50	15	16	32	20.3	4.4	140.8	43	172	85	340

Muon Collaboration

Normal conducting RF systems - Feasibility study II parameters

- **Simple Be windows will distort at the required cavity parameters**
  - **Develop open-cell structures?**
    - **Peak surface fields are large**
      - **Peak surface fields in open-cell structures ≈ *N* Kilpatrick**
    - **RF power requirements increased**
      - **May be feasible option in some cases**

	Frequency GHz	Cell length cm	# cells per RF section	Gradient MV/m	Windows at ends of RF structures: Thickness µm	Windows at ends of RF structures: Radius cm	Windows between cells: Thickness µm	Windows between cells: Radius cm	# sections	Total # RF cells	Shunt impedance MΩ/m	RF input power per cell MW	Total RF power per cell type MW	Windows at ends of RF structures: RF power W	Windows at ends of RF structures: Temp. °C	Windows between cells: RF power W	Windows between cells: Temp. °C
Buncher section																	
	402.5	18.6	1	6.4	100	20			2	2	30.1	0.2	0.4	17	34		
	402.5	18.6	1	6	100	20	?	?	4	4	30.1	0.17	0.68	15	30	?	?
	201.25	37.3	4	6.4	125	21	250	25	1	4	23.4	0.5	2	16	26	32	26
	201.25	37.3	4	6	125	21	250	25	2	8	23.4	0.43	3.44	14	22	28	22
	201.25	37.3	4	8	125	21	250	25	2	8	23.4	0.77	6.16	25	40	50	40
Cooling section																	
[1,1; 1,2; 1,3]	201.25	46.6	4	16.29	125	21	250	25	6	24	22.6	3.5	84	118	189	448	359
[2,1]	201.25	55.9	2	17.6	75	18	125	21	14	28	20.3	4.4	123.2	85	227	304	487
[2,2]	201.25	55.9	2	17.6	75	18	75	18	10	20	20.3	4.4	88	85	227	170	453
[2,3a]	201.25	55.9	2	17.6	75	15	75	18	16	32	20.3	4.4	140.8	43	115	170	453
[2,3b]	201.25	55.9	2	17.6	50	15	50	15	16	32	20.3	4.4	140.8	43	172	85	340

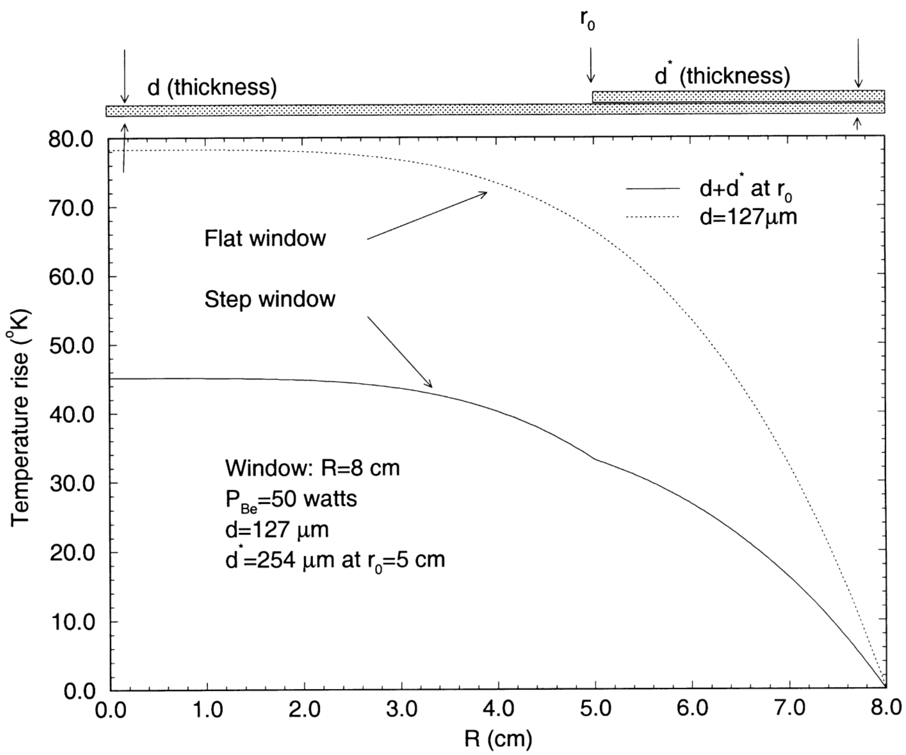
MUCOOL RF R&D is addressing some key issues

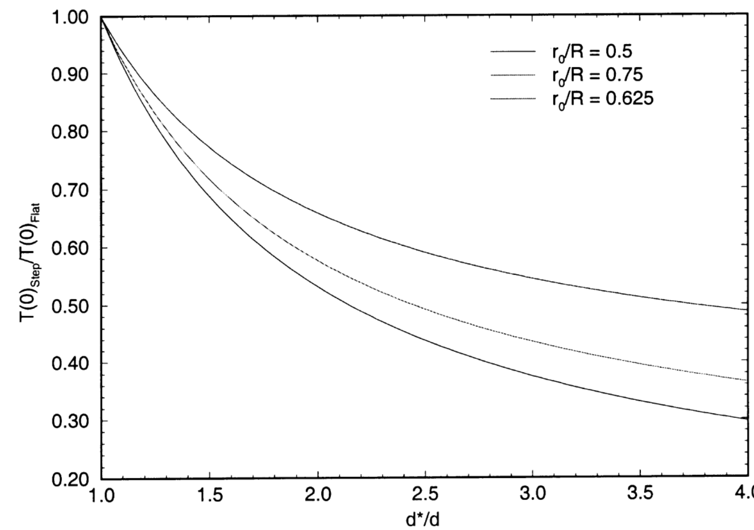
- 805 MHz
  - *Collider* parameters
  - "End" of cooling section
- Hardware
  - π/2 interleaved cavity
    - Be windows
    - Low-power test cavity
      - LN_2 temperature
    - High-power test cavity
  - π-mode open cell cavity
    - Cold-test cavity
    - High-power test cavity
  - Superconducting solenoid
  - Lab G development

- 201.25 MHz RF cavity
  - *Neutrino factory* parameters
  - "Beginning" of cooling section
- Paper studies
  - Interleaved cell cavity
    - Be windows
    - Thin-walled tubes
  - Integration into cooling channel

Increased Be Window Thickness

Muon Collaboration

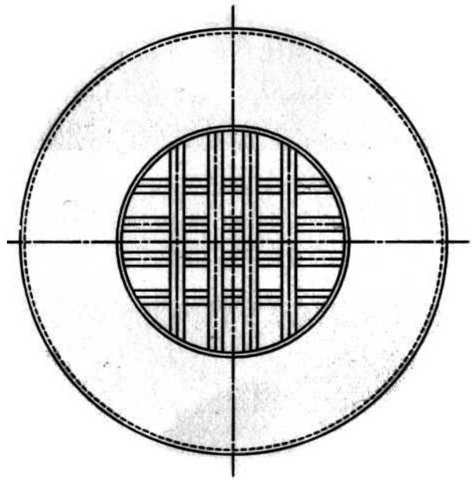


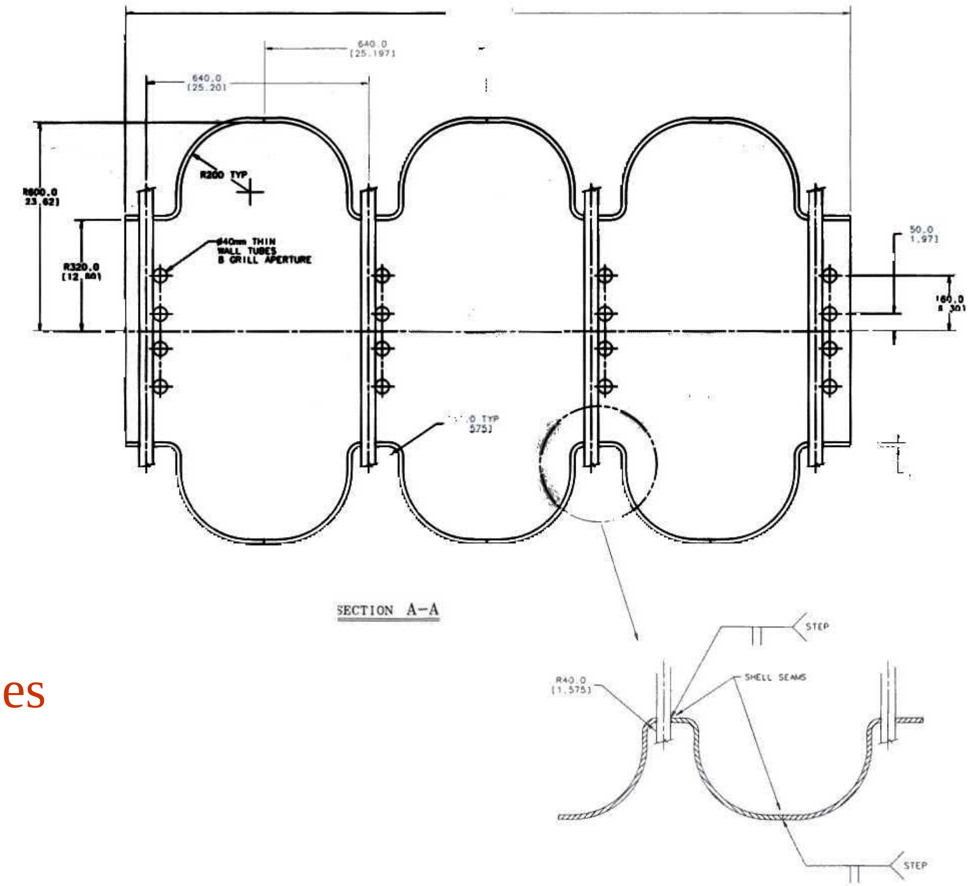


- Thicker window at large radius
  - Increase thermal conduction
    - Cooler window
      - Reduce window expansion

Muon Collaboration

201 MHz Gridded (Crossed-tube) Cavity





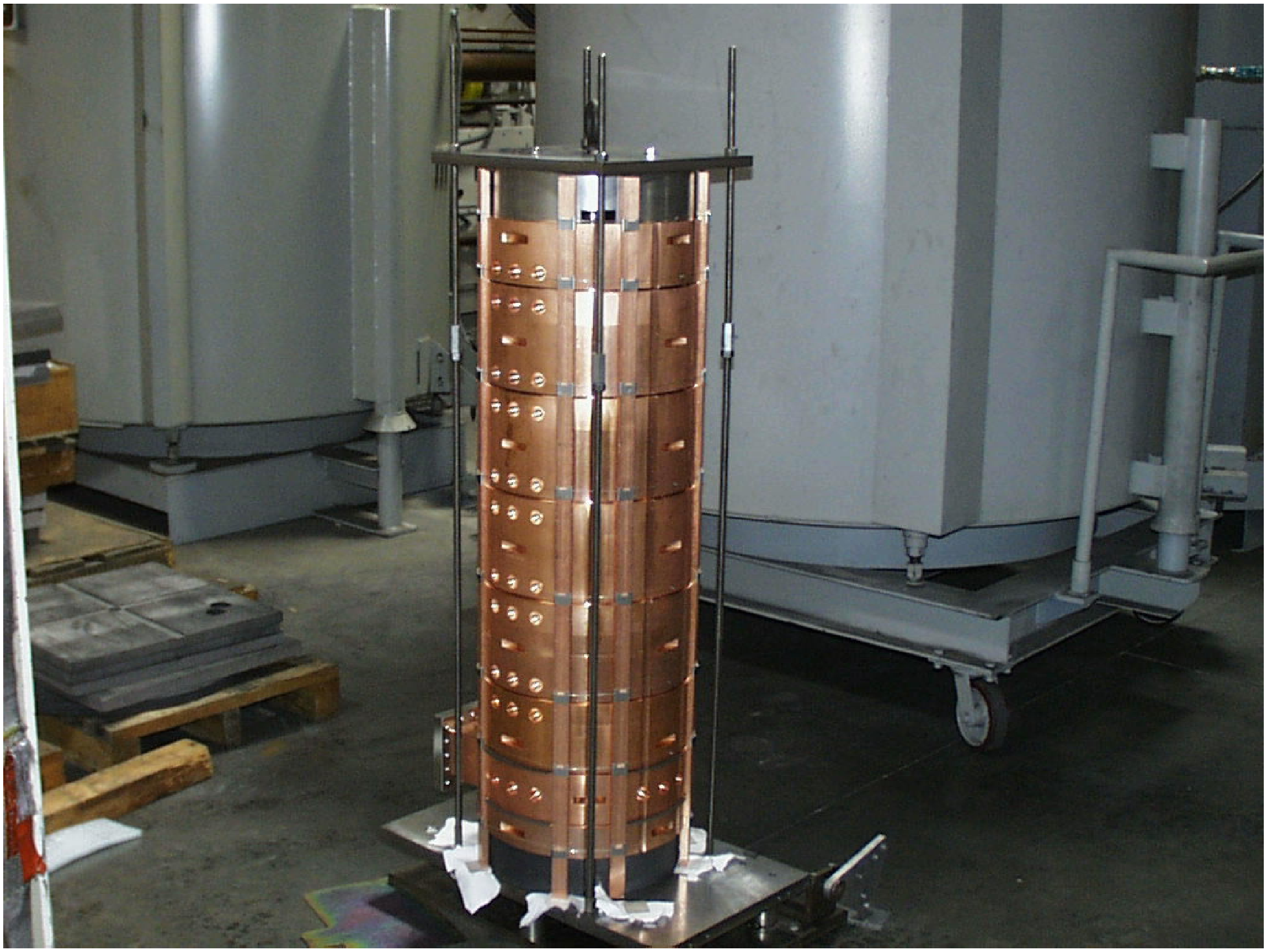
- Large apertures accommodated
- Air cooling inside 4 cm diameter tubes
- Coupling between cavities ~ 0.1%
- Cavities independently excited
- Tube walls can be thin < 0.1 mm
- Spun construction - 1.27cm (0.5 in) wall thickness
- Tunable by wall displacement

Pillbox vs open cell

Muon Collaboration

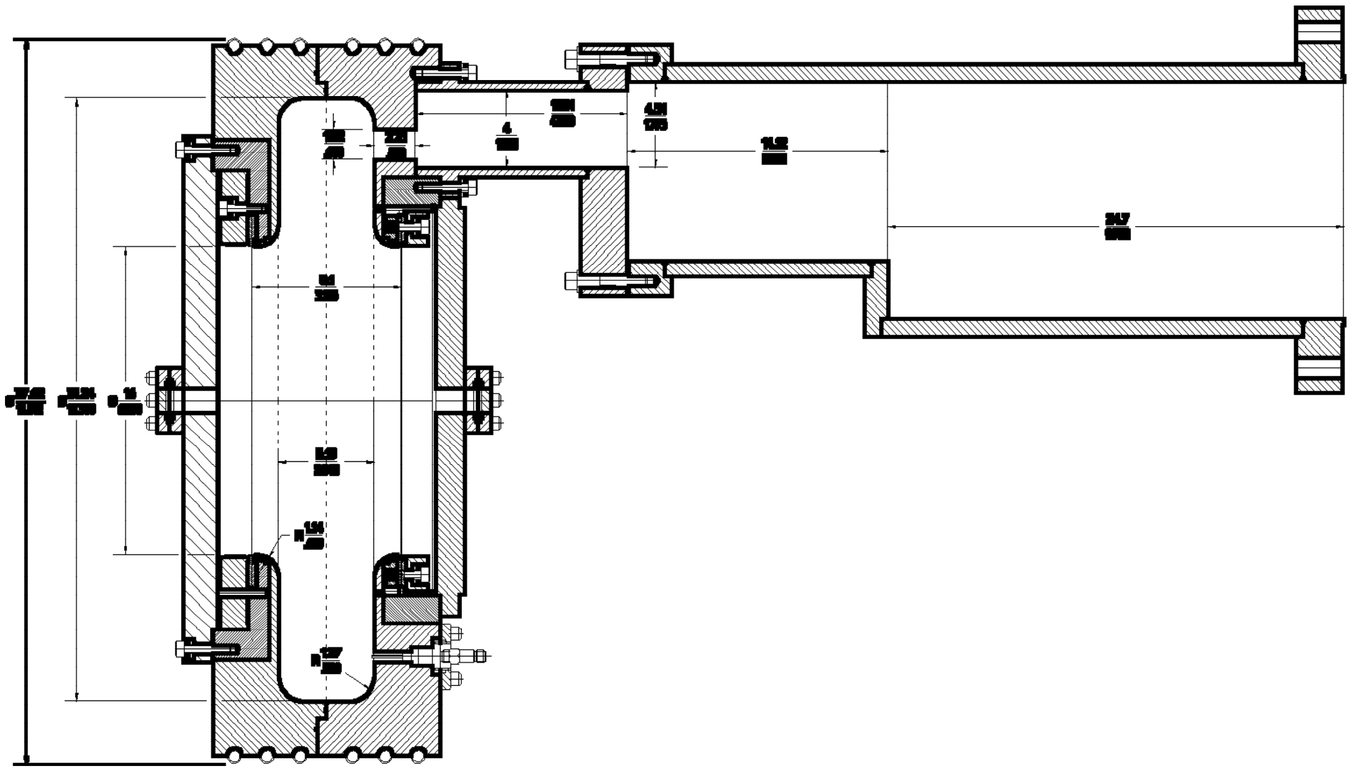
- Pillbox has ends of cavity electromagneticaly “closed”
  - Thin foil windows
  - Thin walled tubes
- “Stackable” cavities
- High shunt impedance
  - Efficient
- Accelerating field = surface field (approximately)
  - Less risk of surface breakdown
- Foil or tubes scatter the beam
- RF heating of foil or tubes
  - Engineering challenges

- Open cell structures avoid thin-walled ends
- One cell per cooling section
- No scattering of beam
- Engineering relatively simple
- Lower shunt impedance
  - More power
    - Challenge in providing RF power
- Surface fields higher than accelerating field
  - Breakdown may be a problem



805 MHz open cell cavity ready for brazing

805 MHz open cell cavity after brazing



805 MHz closed cell cavity

NCRF issues

Open Cell:

- Peak and average power $$$$!
- (note MAFIA numbers must be scaled ~80%)
- New power sources?
- Surface field enhancement
- Beam iris size (follow beam size?)
- Solenoid field / multipactor
- Cooling to N_2 temperature
- Windows, couplers etc.

Closed cell, foils:

- Power (~factor of 2 less?)
- Field enhancement / breakdown damage
- Scattering
- Losses on foils
- Cooling of foils
- Distortion of foils
- Tuning
- Costs / availability of large foils
- SEC of Be and BeO, TiN Coating?
- Graded thickness foils

Closed cell, bars

- Field enhancement / uniformity
- Losses on tubes / Cooling of tubes
- Scattering
- Manufacturing
- Isolation between cells