6D Cooling: RF Issues

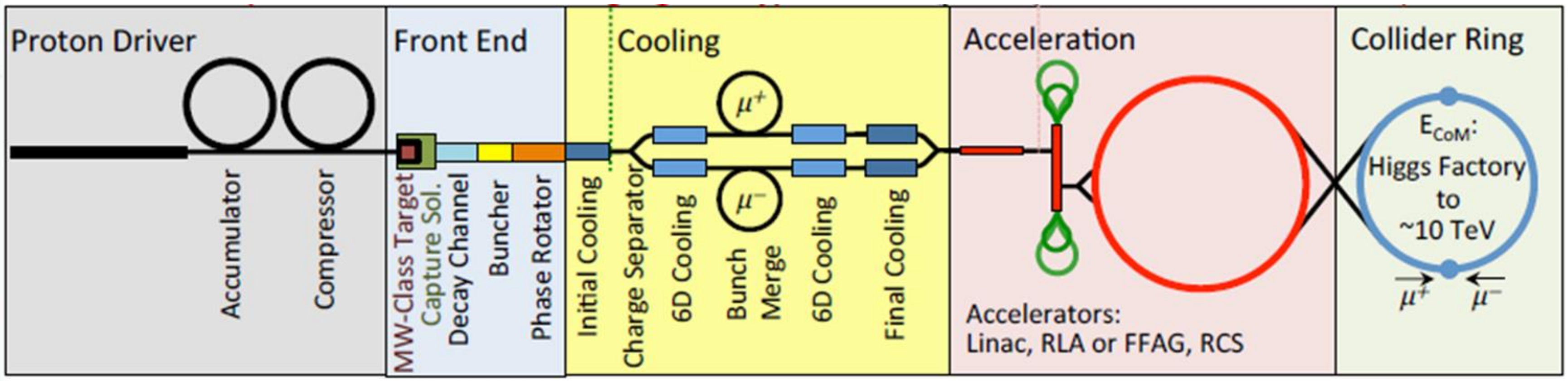
Diktys Stratakis
Fermi National Accelerator Laboratory

1st Muon Community Meeting (online only)
May 20, 2021

Outline

- Rectilinear cooling channel overview
- What we learned about rf cavities from the MAP study:
  - RF breakdown in B-fields
  - Required rf gradients for 6D cooling
  - Optimum rf length and relation to power
  - rf windows design
  - cryostats
  - Required spacing for rf towards implementation
- Remaining questions related to rf and cooling

Muon Collider as viewed by MAP



- The desired 6D emittance for a Muon Collider (MC) is 5-6 orders of magnitude less from the emittance of the muon beam at the production target
- As a result, significant “muon cooling” is required.

History

- MAP considered to alternatives schemes for 6D cooling and formed two independent teams
- Helical cooling channel (HCC) team lead by K. Yonehara
- Vacuum cooling channel (VCC) team lead by D. Stratakis
- The effort had three main phases:
  - 1. Perform a end-to-end simulation study and verify performance goals specified by MAP [Done]
  - 2. Consult with magnet & rf experts, modify design accordingly [Started]
  - 3. Carry out a engineering study of at least one cooling stage [Not started]
- I will share the lessons learned for the VCC team

Vacuum Cooling Channel team

Concept Leaders
R. B. Palmer & D. Stratakis

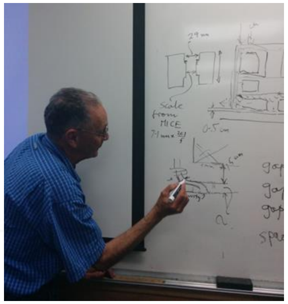
6D Theory & Simulation
- Y. Alexahin[2]
- V. Balbekov[2]
- Y. Bao[4]
- J. S. Berg[1]
- D. Grote[3]
- D. Neuffer[2]
- R. B. Palmer[1]
- T. Roberts[7]
- D. Stratakis[1]
- H. Sayed[1]

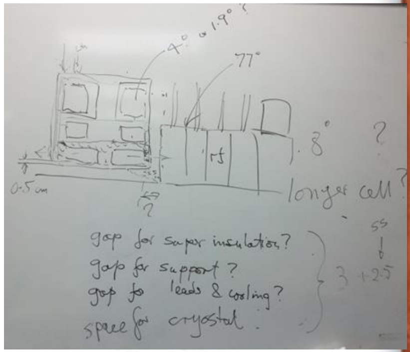
Vacuum RF system
- D. Bowring[2]
- D. Li[5]
- T. Luo[5]
- A. Moretti[2]
- Y. Torun[2]

Magnet system
- I. Novitski[2]
- S. Prestemon[5]
- A. Zlobin[2]
- F. Borgnolutti[5]
- H. Witte[1]

Absorbers
- A. Bross[2]
- K. McDonald[6]
- D. Summers[8]

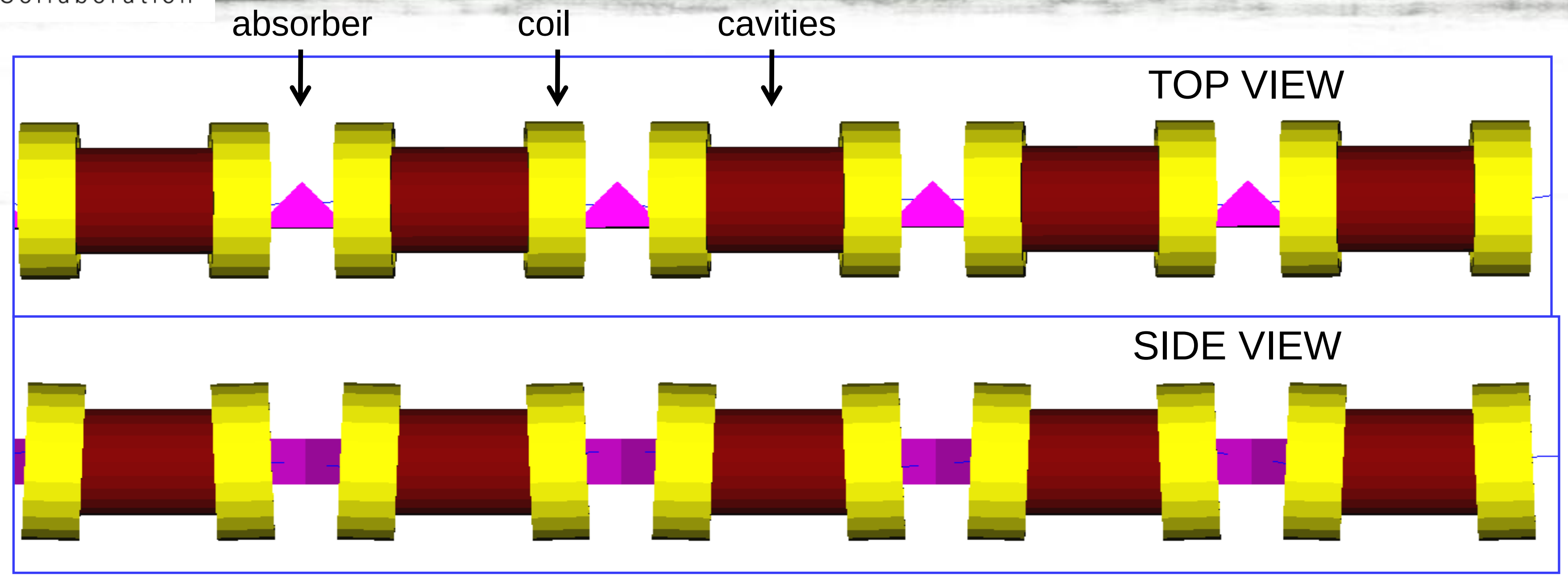
[1]BNL
[2]FNAL
[3]LLNL
[4]UCR
[5]LBNL
[6]Princeton Univ.
[7]Muons,Inc
[8]Univ. Mississippi





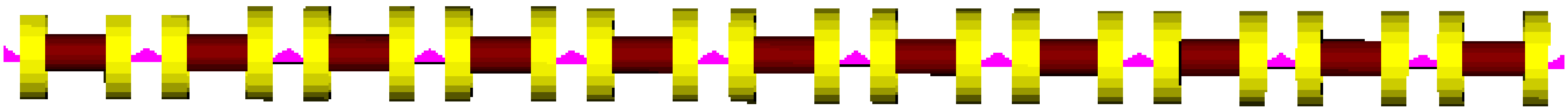
- Between 2013-2015, organized 3 workshops, VCC-dedicated, to discuss progress & exchange ideas with rf & magnet experts

Rectilinear channel concept

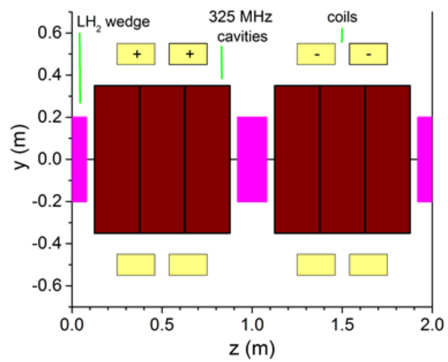


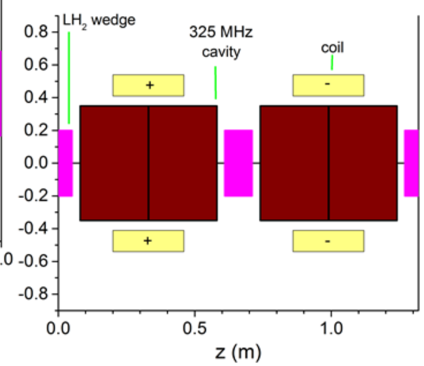
- Straight geometry simplifies construction and relaxes several technological challenges
- Multiple stages with different cell lengths, focusing fields, rf frequencies to ensure fast cooling
- Its performance will be discussed later today

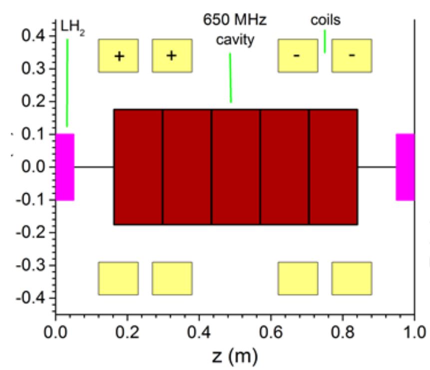
Cooling before merge (4 stages)

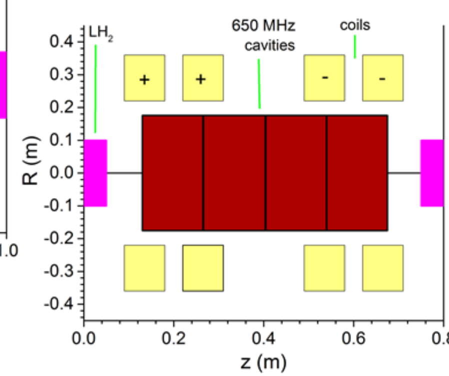


STAGE 1	STAGE 2	STAGE 3	STAGE 4
132 m (66 cells)	171.6 m (130 cells)	107 m (107 cells)	70.4 m (88 cells)









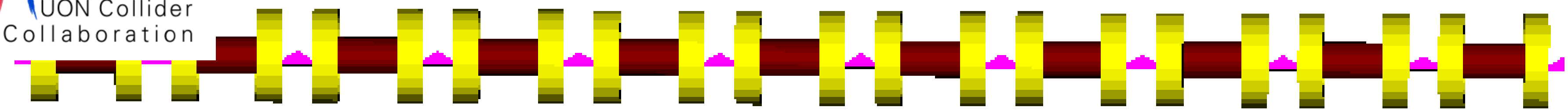
Absorber
TOP VIEW

Parameters before the merge

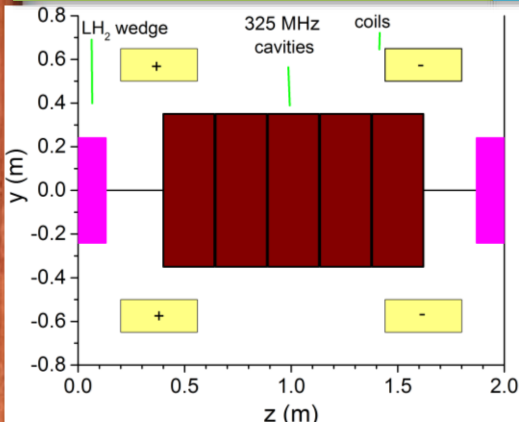
Parameters	Stage 1	Stage 2	Stage 3	Stage 4
Coil tilt (deg.)	3.13	1.80	1.60	0.70
Current density (A/mm^2)	63.25	126.6	165.0	195.0
Max B on coil (T)	4.20	8.47	9.56	11.83
Max B on axis (T)	2.35	3.50	4.82	6.06
Trans. beta (cm)	81.9	54.8	38.3	30.3
Absorber angle (deg.)	40	44	100	110
Absorber type	LH_2	LH_2	LH_2	LH_2
Rf frequency (MHz)	**325**	**325**	650	650
RF gradient (MV/m)	22	22	28	30
Cell length (m)	2.0	1.32	1.0	0.8
Total length (m)	132	171.6	107	70.4

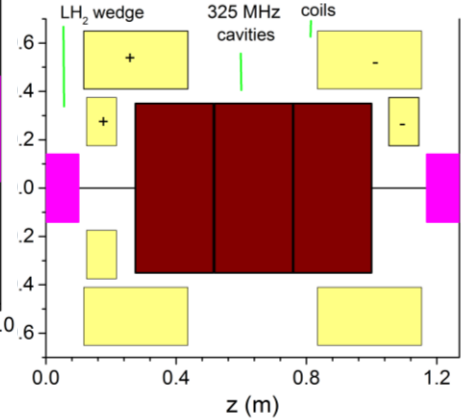
- Lattice parameters have been modified over time

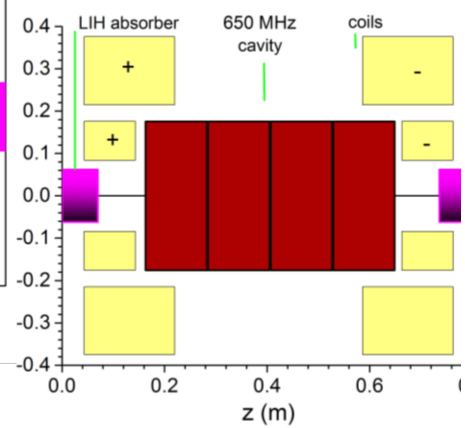
Cooling after merge (8 stages)

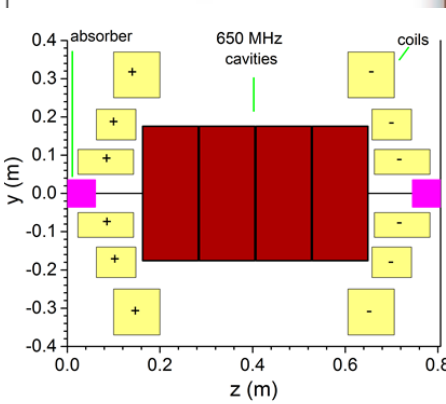


STAGE 2	STAGE 4	STAGE 6	STAGE 8
64 m (32 cells)	62.5 m (50 cells)	62 m (77 cells)	41.1 m (51 cells)









3.7 T (8.4 T) | 6.0 T (9.2 T) | 10.8 T (14.2 T) | 13.6 T (15.0 T)

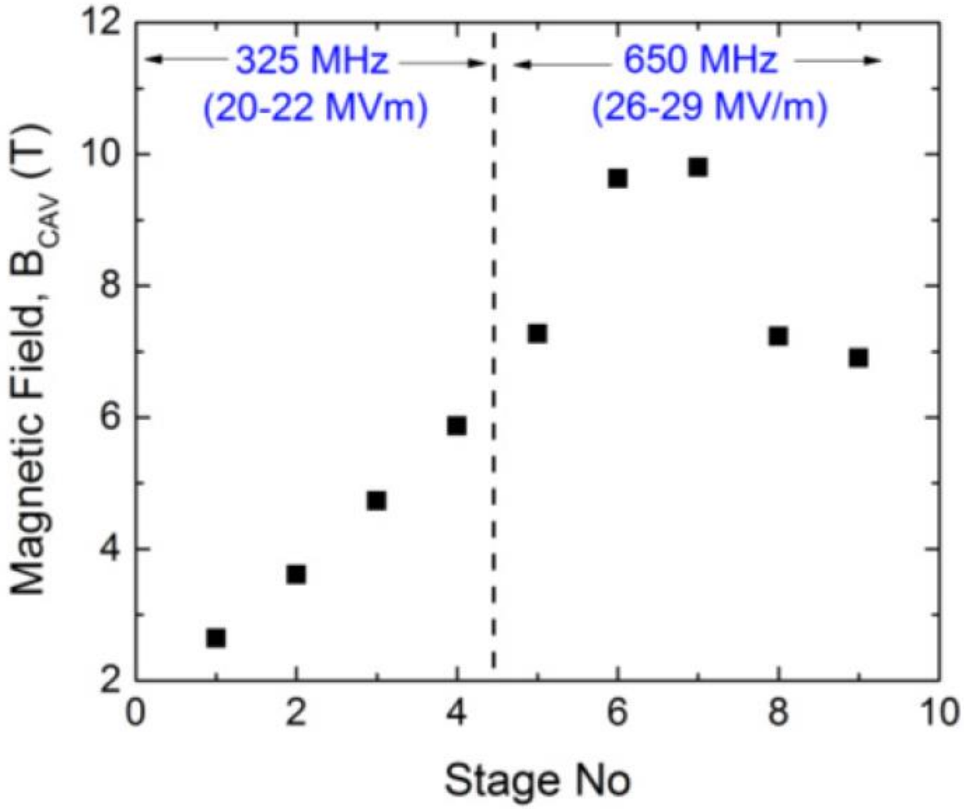
Peak B-field on axis (coil)

Parameters after the merge

Parameters	St. 1	St. 2	St. 3	St. 4	St. 5	St. 6	St. 7	St. 8
Coil tilt (deg.)	0.9	1.3	1.1	1.1	0.66	0.7	0.8	0.8
Cur. Density (A/mm^2)	69.8	90.0	123.0	94.0	168.1	185.0	198.0	198.
Max B on coil (T)	6.8	8.4	12.2	9.2	14.1	14.2	14.20	14.5
Max B on axis (T)	2.6	3.70	4.9	6.0	9.8	10.8	12.50	12.9
Trans. beta (cm)	42.0	27.4	20.2	14.0	8.1	5.9	4.2	3.7
Wedge ang. (deg.)	120	117	113	124	61	90	90	90
Absorber type	LH_2	LH_2	LH_2	LH_2	LiH	LiH	LiH	LiH
Rf freq. (MHz)	325	325	325	325	650	650	650	650
RF grad. (MV/m)	19.0	19.5	21.0	22.0	27.0	28.5	26.0	26.0
Cell length (m)	2.75	2.00	1.50	1.27	0.806	0.806	0.806	0.806
Total length (m)	55.0	64.0	81.0	63.5	73.3	62.0	40.3	41.1

- Lattice parameters have been modified over time

B-Field at cavity edge (approx.)



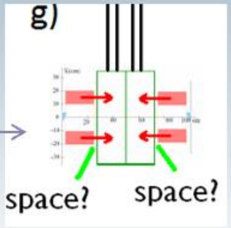
- Approximate numbers. Need to be checked again.

International MUON Collider Collaboration

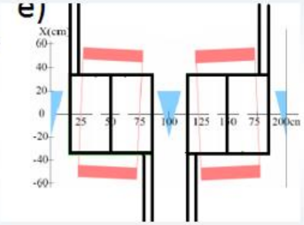
A slide presented back in 2014…

Questions to the RF Group

- Operation of RF at 77 K. Power requirements?
- Space needed between rf & coil?



- Is it ok if waveguide connects to rf not from the center?



- Maximum length of cryostat?
- Missing cell configuration by removing rf is feasible?
- RF length: 24 cm (325 MHz), 12 cm (650 MHz) ok?
- Space between cavities? waveguide thickness?
- Integration of Be windows into cavity (Materion)
  - Two step graded rf windows (Slide 8). Feasible?
  - Stage 1 need a 30 cm radius window. Feasible?
  - Last stage has 4.5 cm. Minimum Be thickness?

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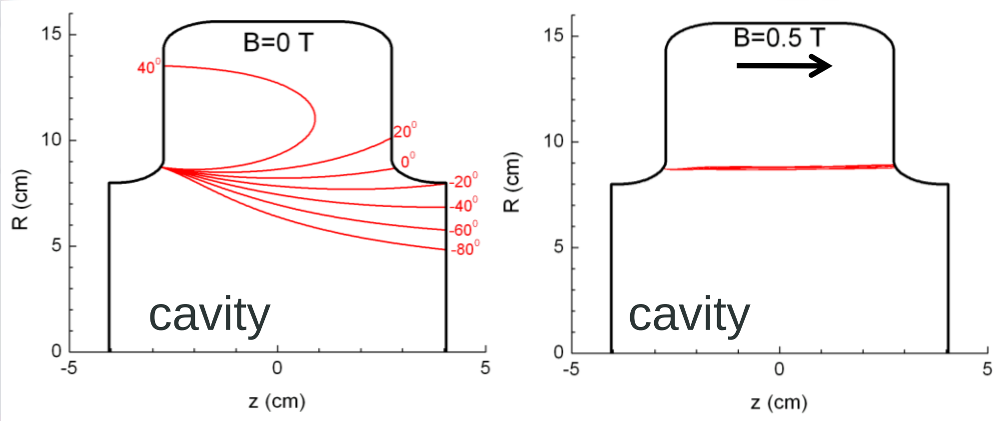
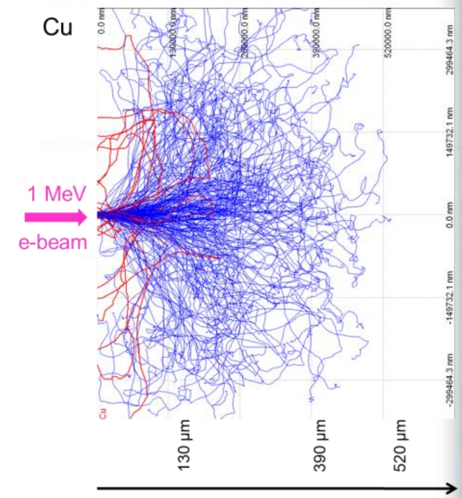
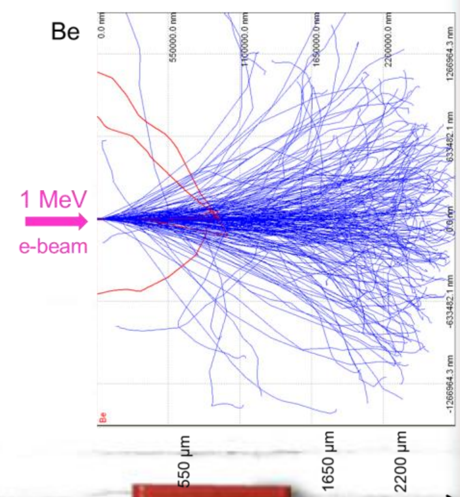
Operation of rf cavities in B-fields



Damage on a 805 MHz rf cavity immersed in a multi-T magnetic field.

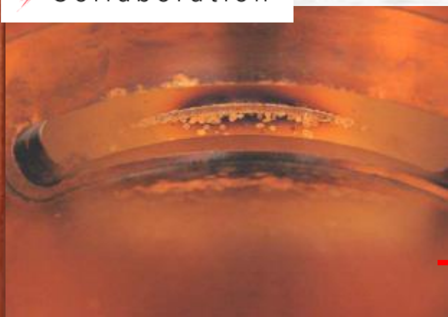


- Electrons impact rf surface and deposit heat in a small volume
- Surface damage via pulsed heating
- Effect is amplified with a B-field: A Cu made cavity may damaged when B> 1T
- Solution: Use dense materials like Be

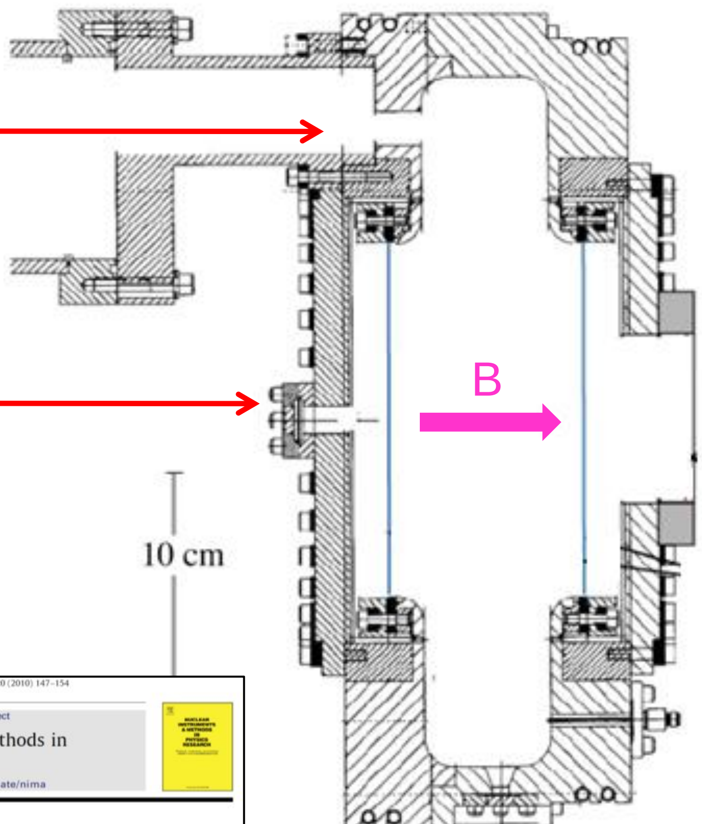


International
UON Collider
Collaboration

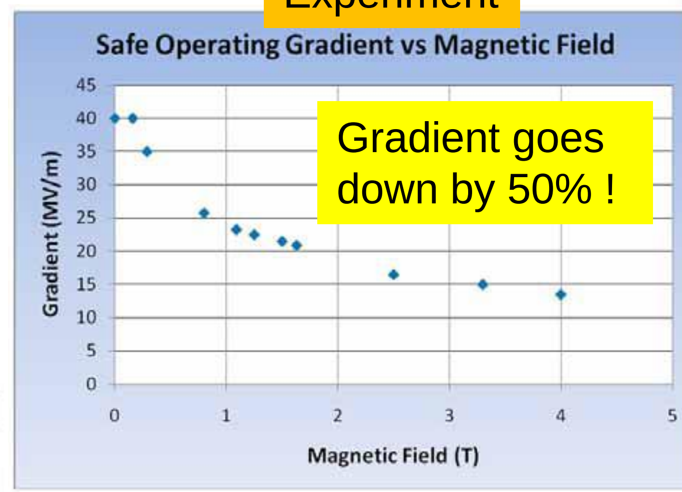
Data vs. model predictions



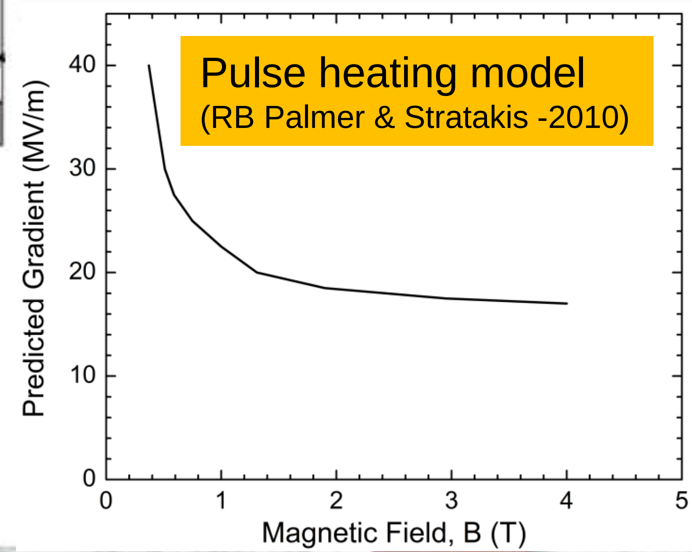
805 MHz
Cu made cavity



Experiment



Gradient goes down by 50% !



Pulse heating model
(RB Palmer & Stratakis -2010)

Nuclear Instruments and Methods in Physics Research A 620 (2010) 147–154
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journal homepage: www.elsevier.com/locate/nima

Effects of external magnetic fields on the operation of high-gradient accelerating structures

Diktys Stratakis*, Juan C. Gallardo, Robert B. Palmer
Department of Physics, Brookhaven National Laboratory, Upton, NY 11973, USA

RF gradients (J. S. Berg)

- Due to this limitation VCC team decided to restrict the rf gradients in our design according to Scott's numbers

Slide from 2013…

Choice of rf gradient

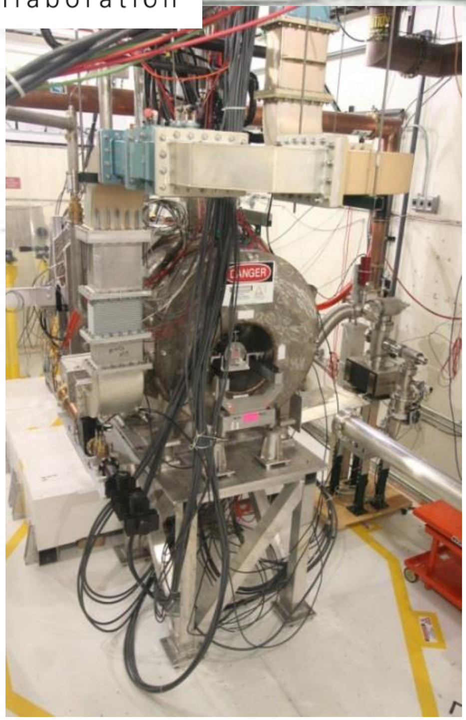
- Need consistent value for comparison
- Cavity lengths also matter
- Propose consistent values
  - consistent with 17 MV/m at 201.25 MHz

Freq. MHz	Length cm	Grad MV/m	ΔE $v = c$ MeV	ΔE 200 MeV/c MeV
325	30	22	5.51	5.23
650	15	31	3.88	3.68
975	10	38	3.17	3.01

8 October 2013 J. S. Berg | Analysis of Cooling Lattices | Vacuum RF (26)

J. S. Berg, Vacuum RF Meeting Talk, Oct. 8, 2013

Modular cavity : A game changer

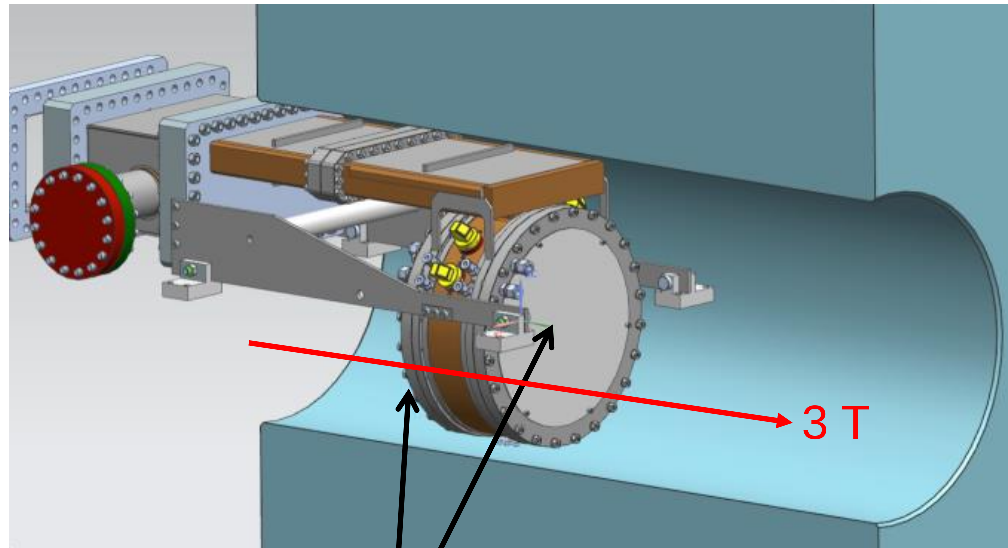


PHYSICAL REVIEW ACCELERATORS AND BEAMS **23,** 072001 (2020)

Operation of normal-conducting rf cavities in multi-Tesla magnetic fields for muon ionization cooling: A feasibility demonstration

D. Bowring,* A. Bross, P. Lane, M. Leonova, A. Moretti, D. Neuffer, R. Pasquinelli, D. Peterson, M. Popovic, D. Stratakis, and K. Yonehara

Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA



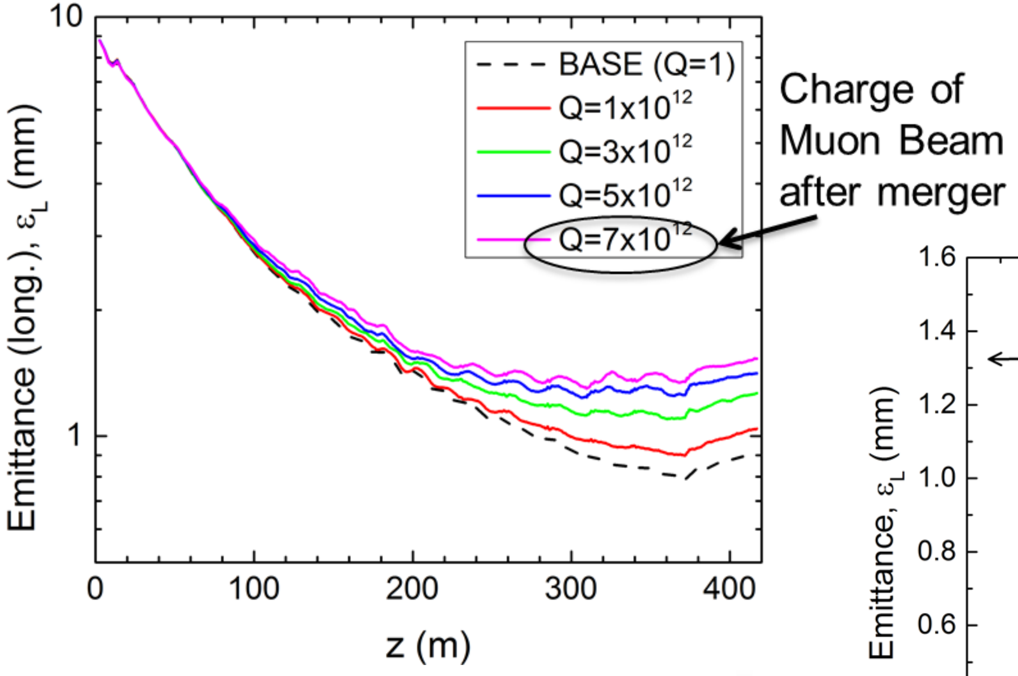
removable plates (Cu, Al, Be)

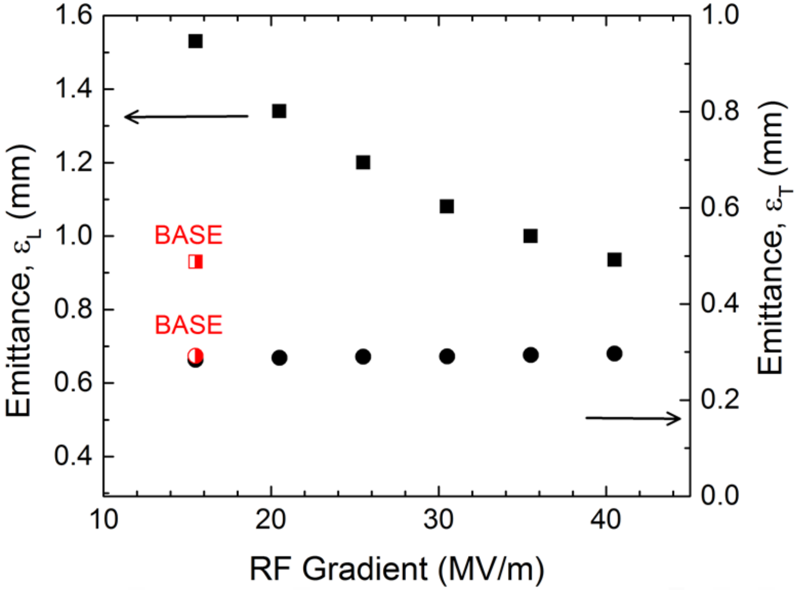
Material	*B*-field (T)	SOG (MV/m)	BDP ($\times 10^{-5}$)
Cu	0	24.4 ± 0.7	1.8 ± 0.4
Cu	3	12.9 ± 0.4	0.8 ± 0.2
Be	0	41.1 ± 2.1	1.1 ± 0.3
Be	3	$> 49.8 \pm 2.5$	0.2 ± 0.07
Be/Cu	0	43.9 ± 0.5	1.18 ± 1.18
Be/Cu	3	10.1 ± 0.1	0.48 ± 0.14

- The above experiment, open a path for using higher rf gradients – never simulated this

RF gradient and space charge

- Simulations have shown that space-charge effects can be compensated by increasing rf gradient

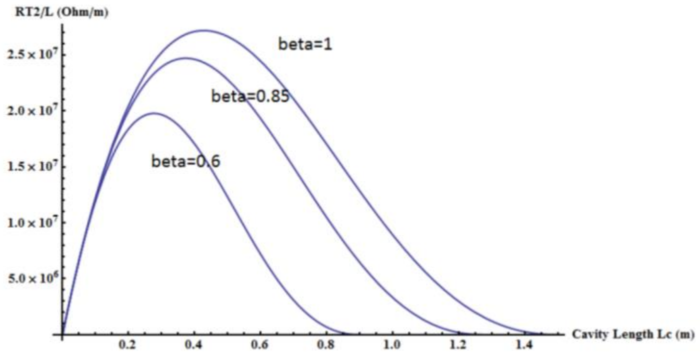


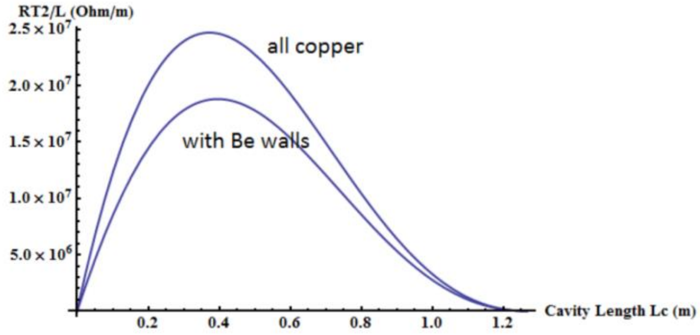


RF length (T. Luo)

f_0=325 MHz, R_c=0.353 m			
β	0.6	0.85	1.0
L_c (m)	0.180	0.245	0.282
RT^2/L_c $(M\Omega/m)$	36.8 / 18.6	48.2 / 23.9	54.3 / 26.7
Power (MW)	4.56 / 8.71	4.77 / 9.22	4.89 / 9.52
f_0=650 MHz, R_c=0.177 m			
β	0.6	0.85	1.0
L_c (m)	0.090	0.122	0.141
RT^2/L_c $(M\Omega/m)$	52.0 / 26.3	68.1 / 33.8	76.8 / 37.7
Power (MW)	1.61 / 3.08	1.69 / 3.26	1.73 / 3.37

$$P = \frac{(E \cdot L_c)^2}{(RT^2/L_c)_{max} \cdot L_c}.$$



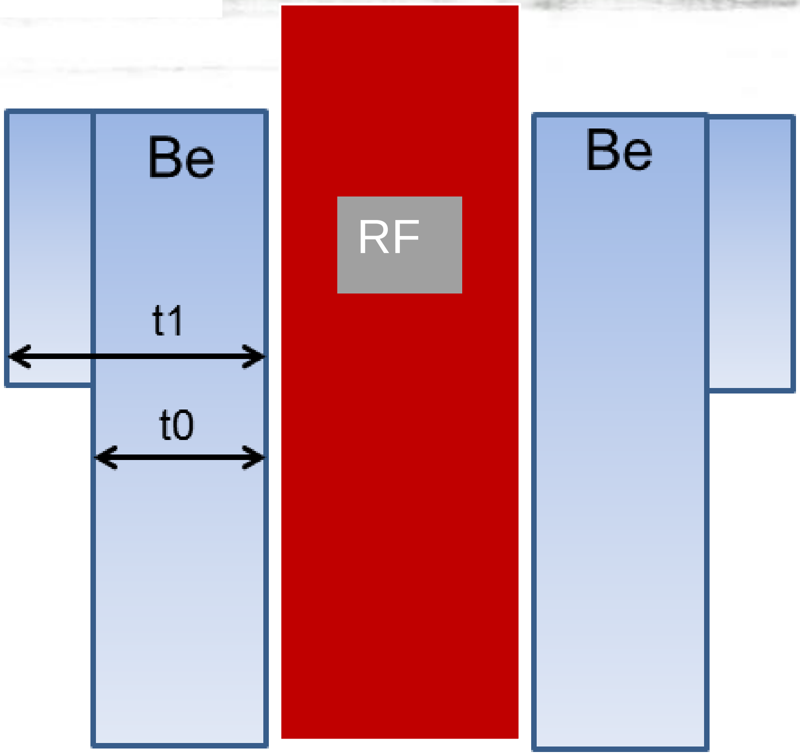


- Performance sensitive to rf length
- The optimum length for a Be made cavity might be different
- This should be taken into account in new designs

RF windows design

- Beryllium windows are used in muon cooling to reduce surface gradients and improve shunt impedances
- These windows are heated by ohmic losses of rf surface currents. With vacuum rf this heat is only removed by radial conduction in the beryllium
- With inadequate cooling the central temperature can induce serious stresses and window bowing
- This sets minimum window thicknesses requirements.

Cooling Channel before the merge

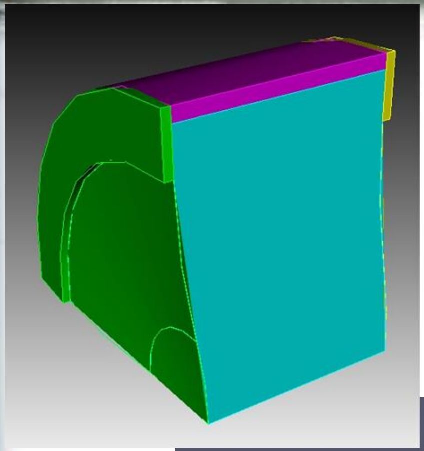


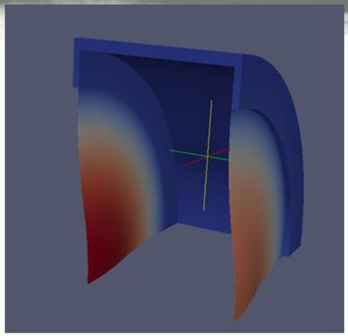
Stage	f (MHz)	rWin (cm)	rStep (cm)	t0 (mm)	t1 (mm)
1	325	30	16	0.3	1.4
2	325	25	15	0.2	0.8
3	650	19	10	0.2	0.6
4	650	13.2	11.4	0.125	0.38

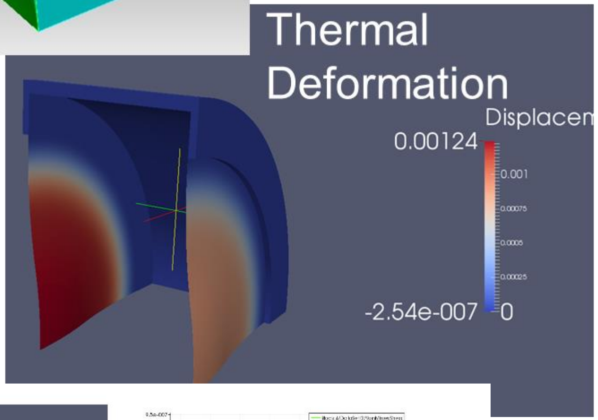
Parameter	Baseline	With Be
Cool rate (trans.)	11.8	10.7
Cool rate (long.)	20.7	18.0
Transmission	49.1%	46.0%

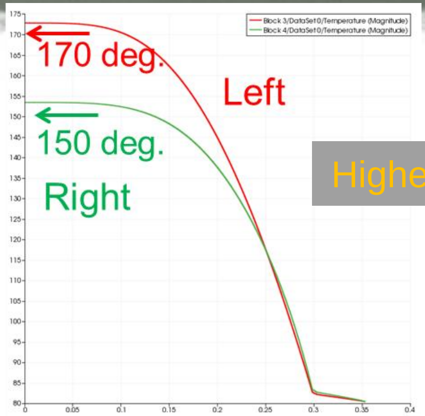
- We considered stepped windows considered

Window thermal & stress analysis (Luo)

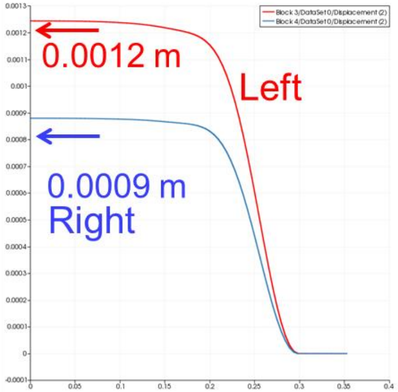




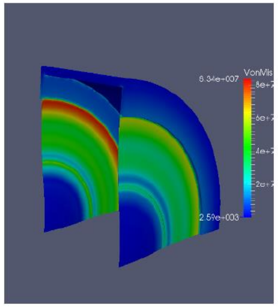


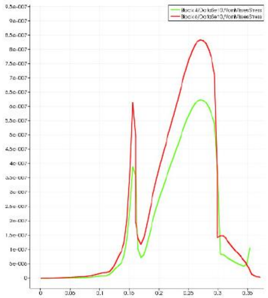


Highest temperature rise ~ 70K



Frequency shift ~10 kHz

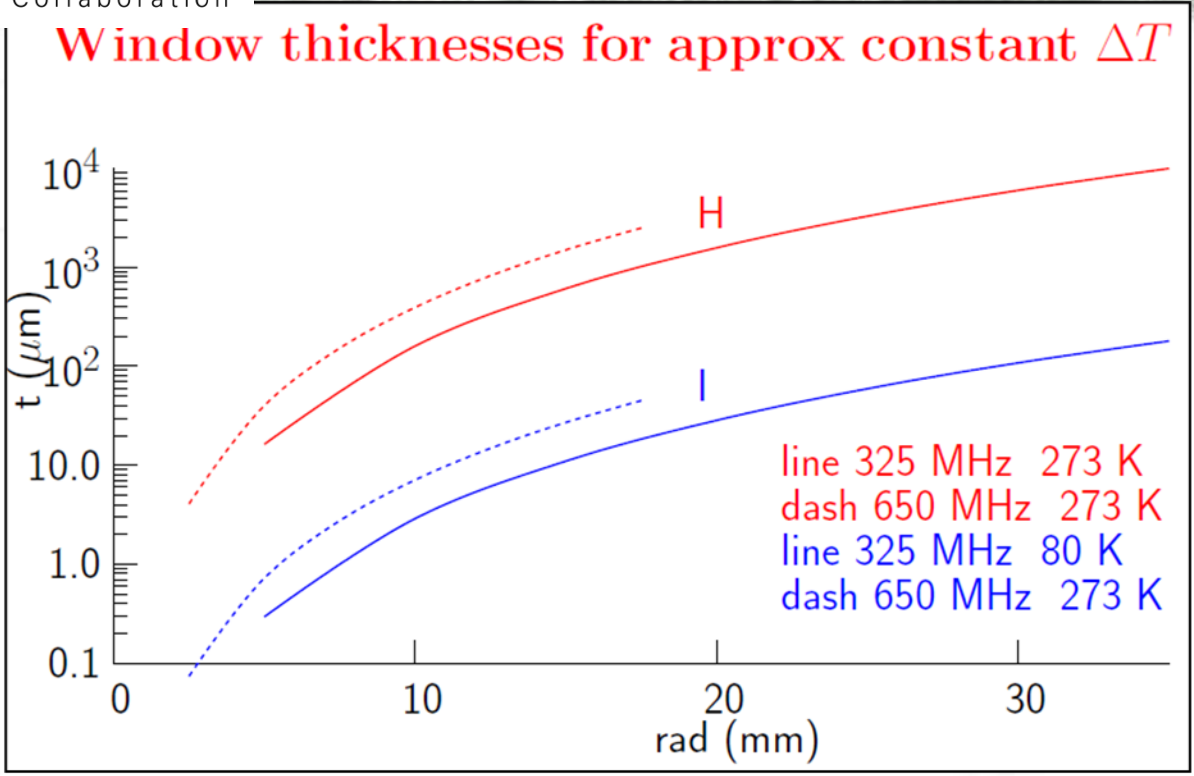




Thermal stress
a quarter
of yield strength

- Only stage A1 studied. Results encouraging but more studies are needed

RF window thickness (Palmer, Fernow)



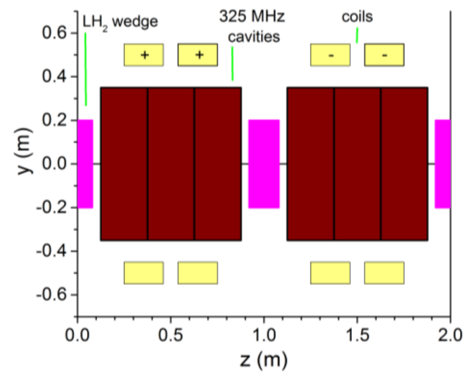
Predictions at 80 deg. for our 6D lattice

stage	freq MHz	pipe cm	window μm
	before	merge	
1	325	35	180
2	325	19	22
3	650	13	10.5
4	650	8.2	5
	after	merge	
1	325	28	90
2	325	24	60
3	325	18	20
4	325	14	10
5	650	9	6
6	650	7.2	2
7	650	4.9	<2
8	650	4.5	<2

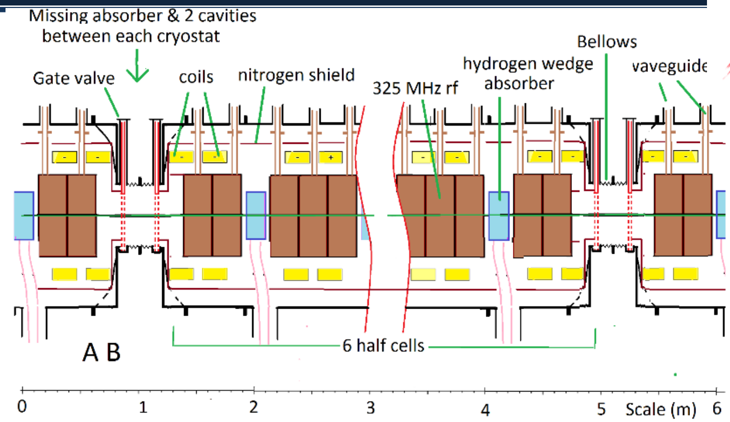
- Windows up to 50 times thinner when operating at 80 degrees.

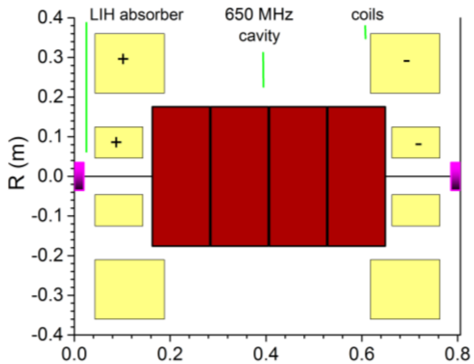
R. C. Fernow, MUC-NOTE-COOL 317 (2005)

Concept for cryostats (Palmer)

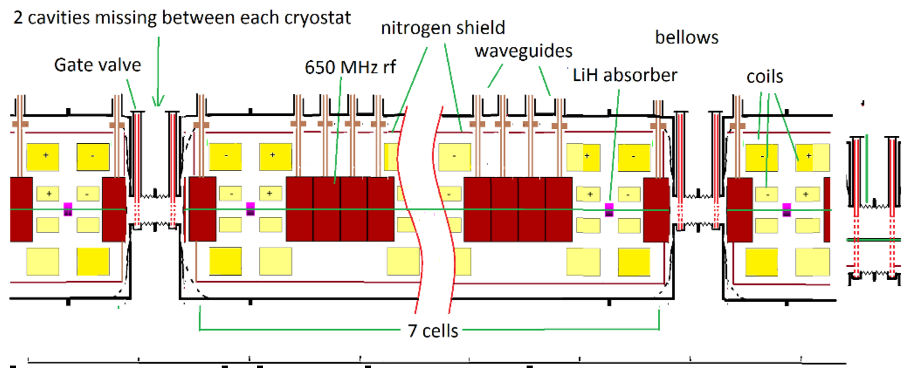


First Stage





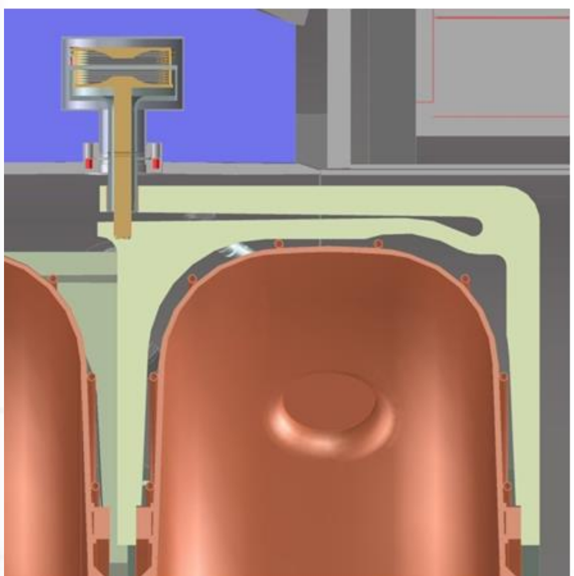
Last Stage

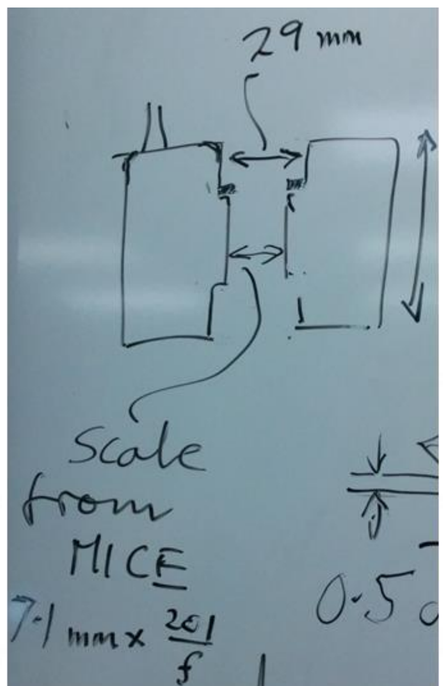


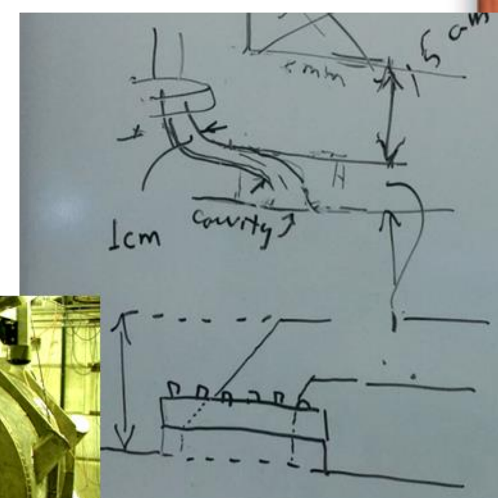
- Approximately 6 cells are housed in shared cryostats
- Space created by omitting absorbers or some rf cavities
- Space generated can be used add diagnostics
- Impact on performance is unknown

What we leaned about spacing

- A separation of 5.0 cm (2.5 cm each) needs to be added between cavities for tuners and flanges
- Cavities can be powered by a curved waveguide-> simplifies the focusing magnet (no need to split the coils).







Further design questions

- What is the optimum length for RF cavities? How does this change for Be based cavities? How much would a cooling channel benefit from using higher gradients?
- What is the safe thickness for Be windows? How thin can we make them realistically? Is a stepped window design realistic?
- How things could change for an operation at 77 K ?
- Sensitivity of cooling performance by adding separations between rf cavities and including realistic Be window thickness's?