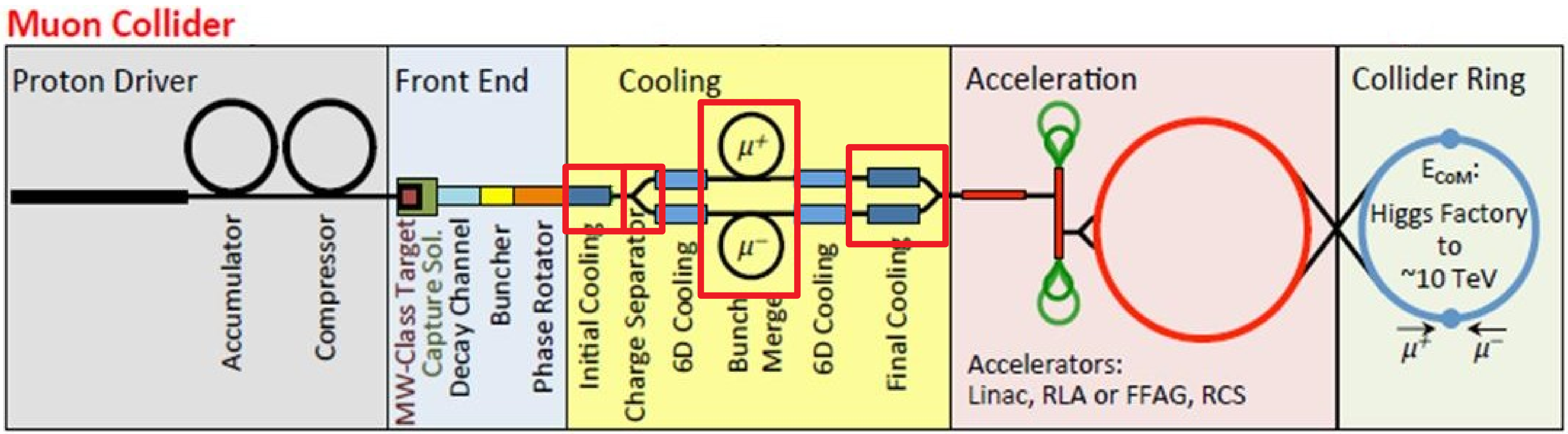
RF – Initial and Final Cooling and Other Things

C. T. Rogers
ISIS
Rutherford Appleton Laboratory

Muon Cooling and Production



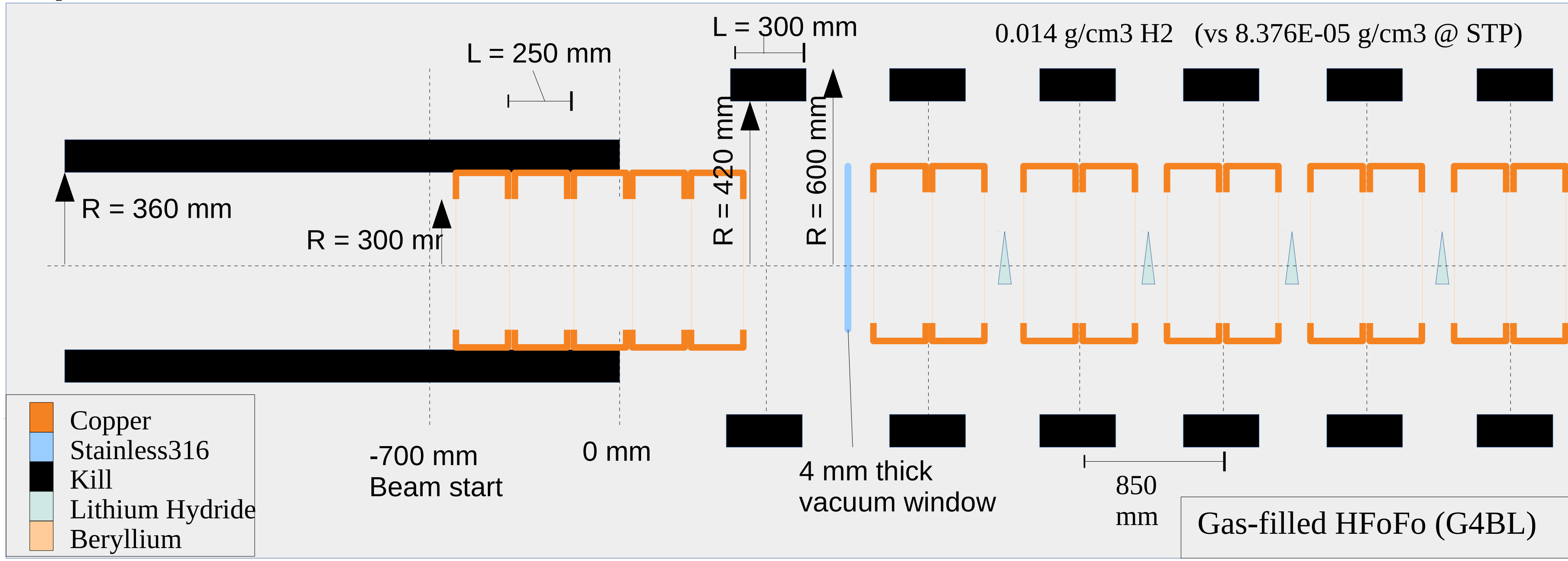
- Initial Cooling ("HFoFo")
- Charge Separation
- Bunch merge
- Final cooling

Muon Cooling and Production

Subsection	Contact	Reference	Lattice Files
Capture			
Particle Selection	Scott Berg	Proc. IPAC2014 TUPME022	With Rogers – not run
Buncher	Dave Neuffer?	https://map-docdb.fnal.gov/cgi-bin/ShowDocument?docid=4355	With Rogers – not run
Phase Rotator	Dave Neuffer?	https://map-docdb.fnal.gov/cgi-bin/ShowDocument?docid=4355	With Rogers – not run
Initial Cooling			
HfoFo – gas filled		https://map-docdb.fnal.gov/cgi-bin/ShowDocument?docid=4377	With Rogers – run
HfoFo – vacuum		https://map-docdb.fnal.gov/cgi-bin/ShowDocument?docid=4377	?
Charge Separation			
Charge Separation	Cary Yoshikawa	https://www.osti.gov/biblio/1113648	?
6D Cooling			
Rectilinear	Diktys Stratakis	https://journals.aps.org/prab/abstract/10.1103/PhysRevSTAB.18.031003	With Rogers – run
Helical snake	Katsuya Yonehara	https://iopscience.iop.org/article/10.1088/1748-0221/13/09/P09003	With Katsuya
Bunch Merge			
Phase Rotator and trombone	Yu Bao	https://journals.aps.org/prab/abstract/10.1103/PhysRevAccelBeams.19.031001	?
6D Cooling			
Rectilinear	Diktys Stratakis	https://journals.aps.org/prab/abstract/10.1103/PhysRevSTAB.18.031003	With Rogers – run
Helical snake	Katsuya Yonehara	https://iopscience.iop.org/article/10.1088/1748-0221/13/09/P09003	With Katsuya
Final Cooling			
Linear Cooling	Hisham Sayed	https://journals.aps.org/prab/abstract/10.1103/PhysRevSTAB.18.091001	?
PIC	James Maloney?	https://arxiv.org/pdf/1401.8256.pdf	?
Potato slicer	Don Summers?	https://map-docdb.fnal.gov/cgi-bin/ShowDocument?docid=4403	

- I am not the expert! But I will do my best...

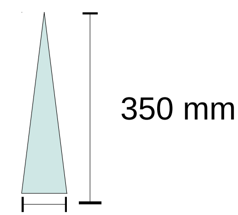
HFoFo Lattice



Wedge absorbers are modelled using a Lithium Hydride trapezium. Cross-section is shown below. Depth (into page) is 700 mm. Different wedges have a different opening angle – range is listed.

RF windows thickness is between 70 and 120 micron.

The current design is gas-filled in order to suppress RF breakdown; but I expect that we will move to vacuum cavities as the design matures. Engineering should proceed assuming vacuum cavities (unless there is good reason not to).



59.3 to 26.766 mm

Note

- HFoFo cools
  - 20 mm → 4 mm transverse
  - 12 mm → 2 mm longitudinal
- Rectilinear “A” (before merge) cools
  - 17 mm → 1.5 mm transverse
  - 46 mm → 2.4 mm longitudinal
- Clear that they are not well integrated

HFoFo Parameters

HfoFo Magnets

Length [mm]	Radial Thickness [mm]	Inner Radius [mm]	Outer Radius [mm]	Current Density [A/mm^2]	Tilt [deg]	Dipole Field [T]	Longitudinal field [T]	Number	Beam sigma(x)
300	180	420	600	94.4 to 85.05	0.14	CHECK	CHECK	186	

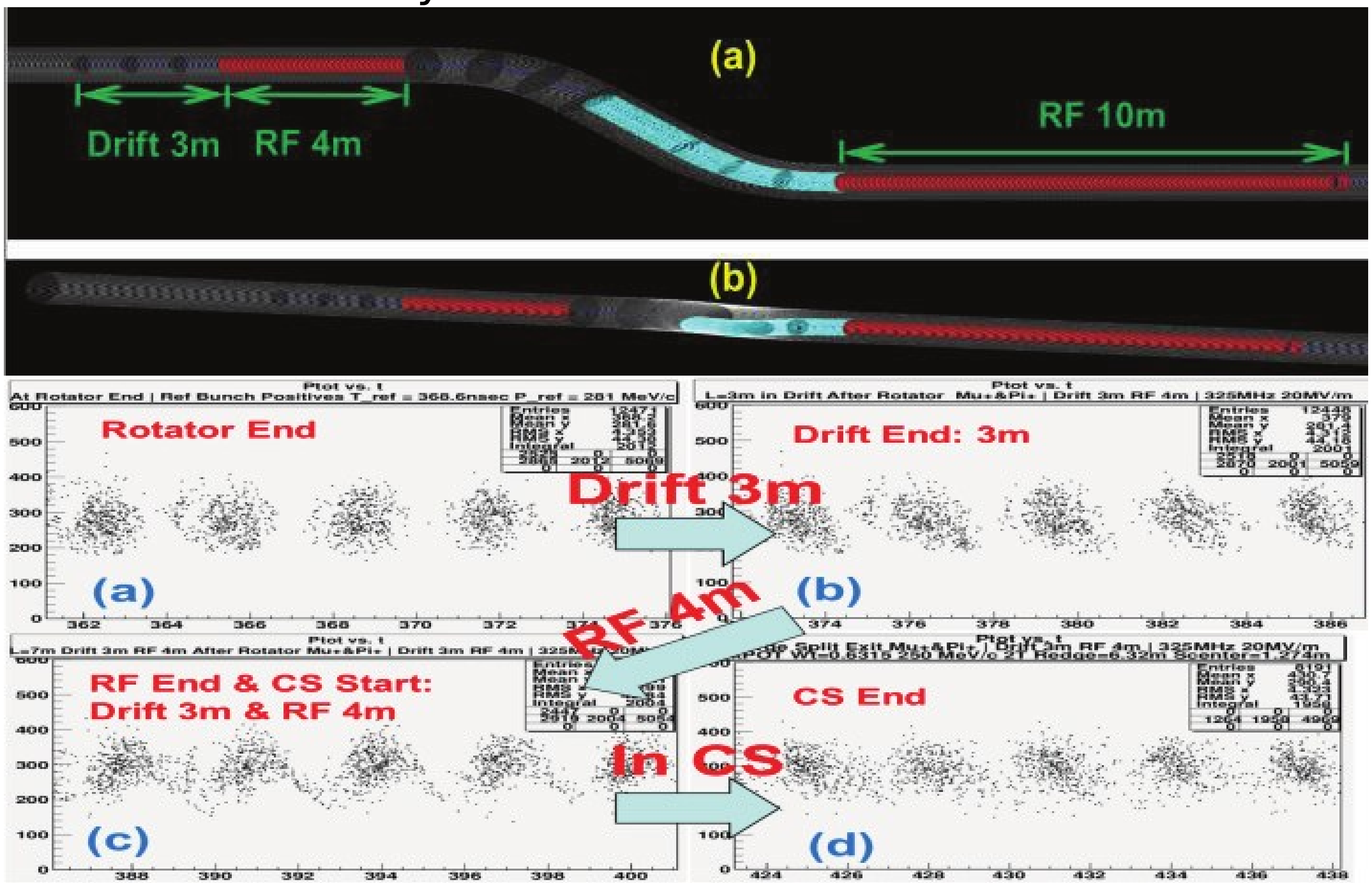
Note that the tilt axis rotates about the z axis by 120 degrees per coil. Adjacent coils have opposite polarity. The total length of a supercell is thus 6 cells.

HfoFo RF

Cells	**F [GHz]**	**V [MV/m]**	**Length [mm]**	**Window thickness [mm]**	**Number**
RFC0	325	20	250	0.12	5
RFC	325	25	250	0.12	114
RFC1	325	25	250	0.1	116
RFC2	325	25	350	0.07	132

Charge separation

- RF required to maintain bunch structure
  - 14 m of RF at 20 MV/m @ 325 MHz
  - No detailed cavity structure studied



Bunch merge

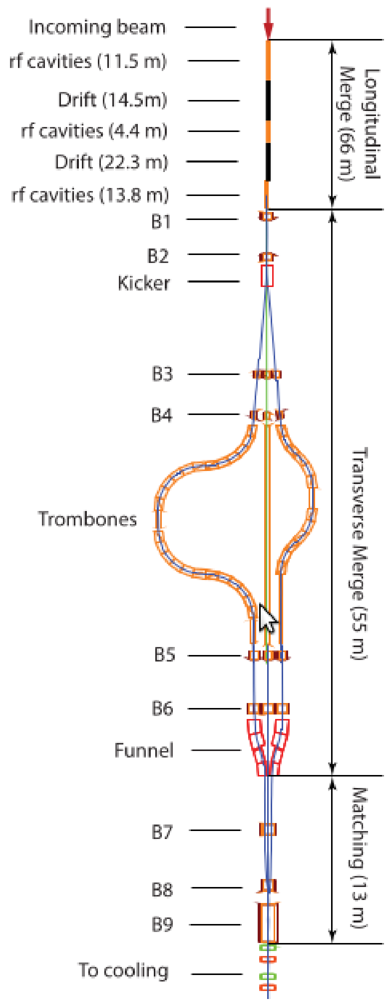
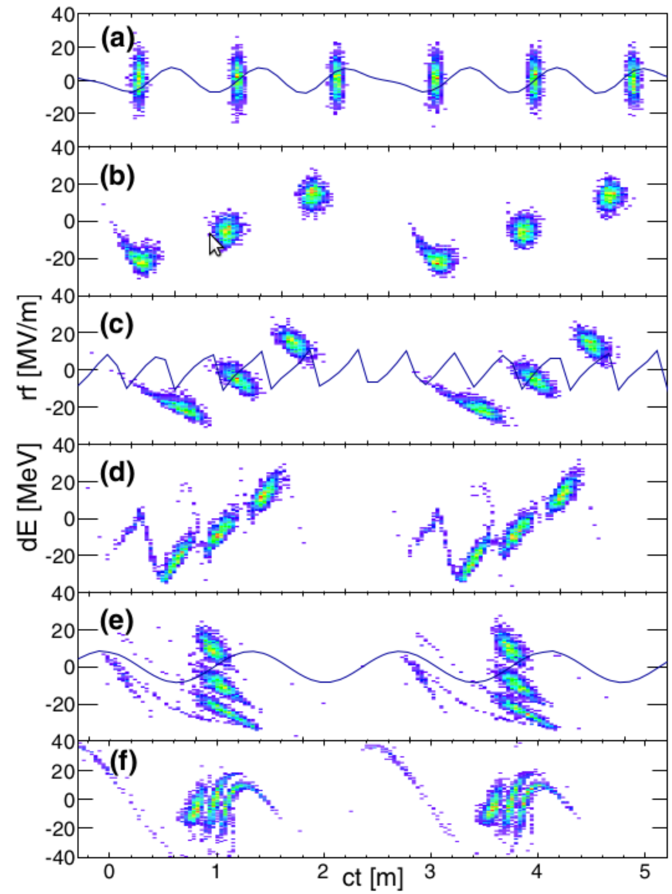


FIG. 3. Merge scheme.

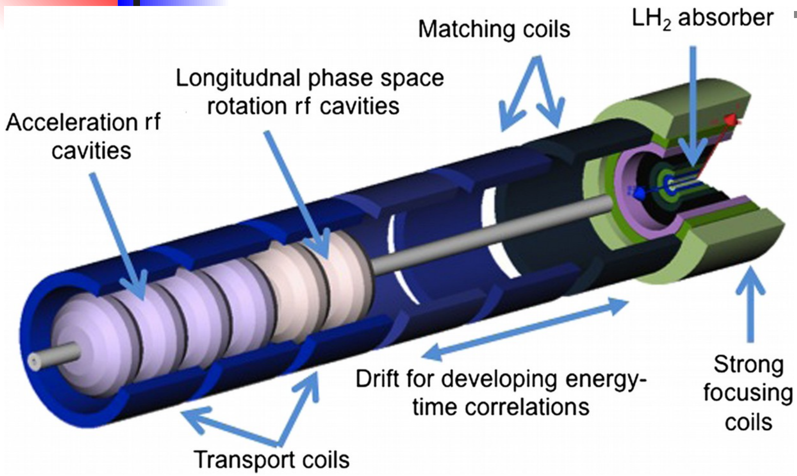
PHYS. REV. ACCEL. BEAMS **19,** 031001 (2016)



Bunch merge

Number of cavities	Length [m]	Frequency [MHz]	Voltage [MV/m]	Stage
10	1.15	Sum of harmonics 108.33-541.67	About 10	a → b
10	?	Sum of harmonics 650 – 1950	About 10	c → d
12	?	216.7 MHz	About 10	e → f
?	3 m total	108	6	Trombones

Final cooling



optimized for each individual stage to reduce the energy spread and achieve the required cooling in the following stage. The first set of rf cavities after the drift is set to have zero phase to rotate the longitudinal phase space of the muon beam. Another set of rf cavities following the phase rotation section is used to accelerate the muon beam to the required energy for the following cooling stage. The accelerating rf cavities frequencies and phases are optimized to match the bunch length at every stage.

Each cooling stage performance was optimized using an

TABLE II. Parameters of the high-field low-energy cooling channel.

Stage [N]	P [MeV/c]	Energy spread σ_E [MeV]	LH$_2$ thickness [cm]	Drift length [m]	rf length [m]	rf frequency [MHz]	Field flip
1	135.0	2.29	65	0.434	2.25	325	Yes
2	130.0	2.48	60	0.459	2.25	250	Yes
3	129.0	2.78	60	0.450	2.5	220	No
4	129.0	3.10	59	0.458	2.5	201	No
5	122.0	3.60	57	1.629	5.0	201	Yes
6	124.0	4.90	53	2.22	4.5	180	No
7	116.0	3.40	42	2.21	3.25	150	No
8	111.0	3.90	40	2.0	3.5	150	No
9	106.0	3.50	40	3.13	5.0	125	Yes
10	98.0	3.07	35	3.13	5.0	120	No
11	89.4	3.11	20	3.12	5.0	110	No
12	87.9	2.76	20	3.1	8.0	100	No
13	85.9	2.67	20	3.0	7.5	100	Yes
14	79.7	3.08	15	2.7	7.0	70	No
15	71.1	4.0	15	2.6	6.0	50	No
16	71.0	3.80	13	2.5	6.0	20	No
17	70.0	3.80	10	...	...	20	...

Final cooling

Momentum [MeV/c]	dE/dx/rho [MeV/ g cm^-2]	rho [g/cm^3]	LH2 Length [cm]	Guess Phase [deg]	RF Length [m]	RF Frequency [MHz]	Transit Time Factor	Energy Loss	RF Gradient [MV/m]	Energy Gain	B Field on Cavity [T]	Peak B Field [T]
135	5.1	7.08E-02	65	30	2.25	325	1	23.47	20.86	23.47	4	27
130	5.4	7.08E-02	60	30	2.25	250	1	22.94	20.39	22.94	4	27
129	5.4	7.08E-02	60	30	2.5	220	1	22.94	18.35	22.94	4	27
129	5.4	7.08E-02	59	30	2.5	201	1	22.56	18.05	22.56	4	27
122	5.6	7.08E-02	57	30	5	201	1	22.60	9.04	22.60	4	27
124	5.6	7.08E-02	53	30	4.5	180	1	21.01	9.34	21.01	4	27
116	5.9	7.08E-02	42	30	3.25	150	1	17.54	10.80	17.54	4	27
111	5.9	7.08E-02	40	30	3.5	150	1	16.71	9.55	16.71	4	27
106	6.2	7.08E-02	40	30	5	125	1	17.56	7.02	17.56	2	30
98	6.5	7.08E-02	35	30	5	120	1	16.11	6.44	16.11	2	30
89.4	7.7	7.08E-02	20	30	5	110	1	10.90	4.36	10.90	2	30
87.9	7.7	7.08E-02	20	30	8	100	1	10.90	2.73	10.90	2	30
85.9	7.7	7.08E-02	20	30	7.5	100	1	10.90	2.91	10.90	1.5	29
79.7	8.6	7.08E-02	15	30	7	70	1	9.13	2.61	9.13	1.5	29
71.1	10	7.08E-02	15	30	6	50	1	10.62	3.54	10.62	1.5	29
71	10	7.08E-02	13	30	6	20	1	9.20	3.07	9.20	1.5	29

Energy loss cut and pasted from PDG tables (approx correct)
RF Gradient is gradient seen by the beam i.e. on axis
RF Phase is a total guess – but typical for cooling lattices
Transit time factor is a total guess – and certainly wrong

Issues

- Peak field is probably not an issue for these sorts of lattices
- Missing details on the final cooling system
  - Low RF frequencies – how were they simulated?
  - What is realistic RF
- Size of 100 MHz RF cavities and integration with magnets
- Superposition of harmonics