Front End – RF requirements

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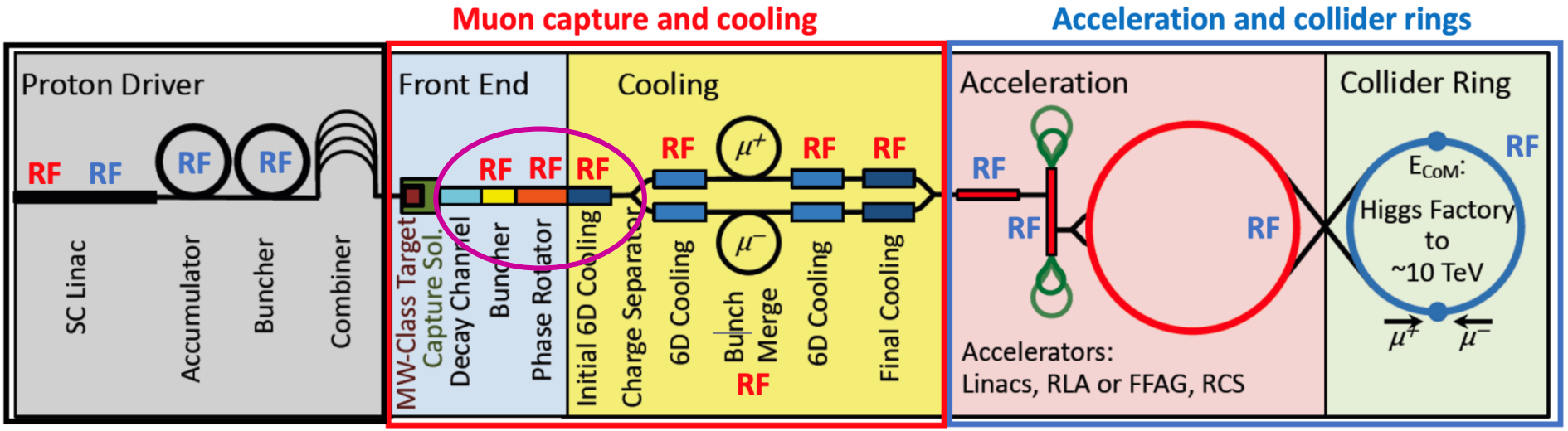
Maybe 2021

Outline

- **Front End for Muon Collider/ Neutrino Factory**
  - Baseline for MAP
    - 8 GeV proton beam on Hg target
    - Drift, bunch, ϕ-E rotate, cool
  - 325 MHz
    - With Chicane/Absorber
  - Helical Snake 6-D Cooler
- **Variations**
  - Transverse cooling only
    - FOFO
  - 200 MHz Front End
    - IDS Neutrino factory
  - Buncher/ Rotator/Cooler with H2 gas
    - If needed to prevent breakdown
  - Optimization s ???


Muon capture and cooling
Acceleration and collider rings
Proton Driver
RF
RF
RF
RF
SC Linac
Accumulator
Buncher
Combiner
Front End
Cooling
RF
RF
RF
RF
μ^+
RF
RF
μ^-
MW-Class Target
Capture Sol.
Decay Channel
Buncher
Phase Rotator
Initial 6D Cooling
Charge Separator
6D Cooling
Bunch Merge
RF
6D Cooling
Final Cooling
Acceleration
Collider Ring
RF
RF
RF
RF
E_{CoM}:
Higgs Factory
to
~10 TeV
μ^+
μ^-
Accelerators:
Linacs, RLA or FFAG, RCS

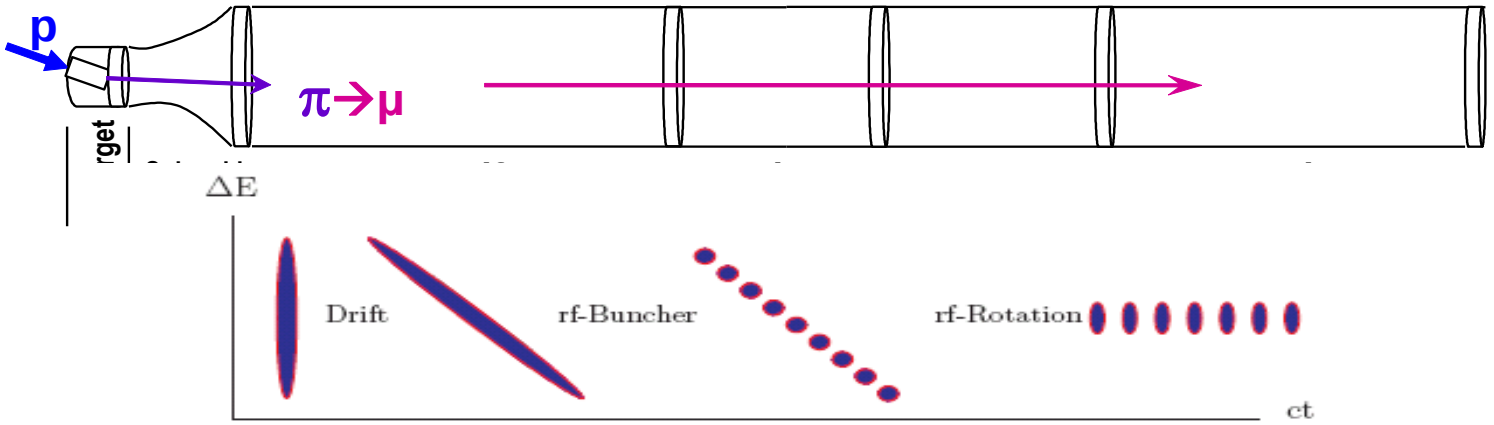
Introduction and Overview

- Summary of RF systems

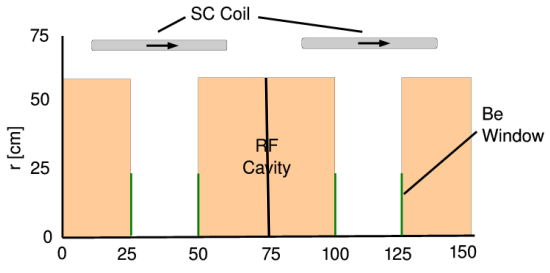
Courtesy of J.P. Delahaye et al.

System			Driver			Front-End	Cooling			Acceleration			Collider	Total
Sub-system			Driver Linac H- (SPL like)		Accum &Comp		Initial	6D (2 lines)	Final (2 lines)	Injector Linac	RLA	RCS	Ring	
Reference expert			F.Gerigk		?	D.Neuffer	C.Rogers	D.Stratakis	C.Rogers	A.Gogagz		S.Berg	E.Gianfelice	
			NC	SC										
	Energy	GeV/c	0.16	5	5	0.255	0.255	0.255	0.255	1.25	62.5	1500	1500	
Beam (system exit)	# bunches (μ+ or μ-)	#	40 mA		1	12	12	1	1	1	1	1	1	
	Charge/bunch	E12			500	3.60	2.57	7.27	4.43	3.59	3.05	2.22	2.20	
	Rep Freq	Hz	5	5	5	5	5	5	5	5	5	5	5	
	Norm Transv Emitt	rad-m				1.5E-02	3.0E-03	8.3E-05	2.5E-05	2.5E-05	2.5E-05	2.5E-05	2.5E-05	
	Norm Long Emitt	rad-m				4.5E-02	1.5E-02	1.9E-03	1.1E-02	1.1E-02	1.1E-02	1.1E-02	1.1E-02	
	Pulse/Bunch length	m	2.2 ms		0.6 (2ns)	1.1E+01	1.1E+01	9.2E-02	9.2E-02	4.6E-02	2.3E-02	2.3E-02	5.0E-03	
	Power (μ+ and μ-)	W	6.40E+04	2.2E+06	2.0E+06	1.8E+04	1.3E+04	3.0E+03	1.8E+03	7.3E+03	3.1E+05	5.4E+06	5.3E+06	
RF cavities	Technology		Linac4HP	SC		0	NC	Vacuum	NC	SRF	SRF	SRF	SRF	
	Number of cavities	#	23	244		120	367	7182	32	52	360	2694	?	11074
	RF length	m	46	237		30	105	1274	151	82	1364	2802	?	6091
	Frf	MHz	352	704	4 ?	326to493	325	325-650	20-325	325	650-1300	1300	800	4 to 1300
	Grf	MV/m	1-3.7	19 - 25		20	20 to 25	19-28.5	7.2-25.5	20	25 to 38	35	?	7 to 35
	Magnetic Field	T	0	0		2	3T	1.7-9.6	1.5-4	0	0	0	0	0 to 9.6
	Installed RF field	MV	169	5700		434	2618	30447	1836	1640	50844	98062	250	1.92E+05
	Energy gain	MeV	160	4840		0	0	0	0	1250	62500	1437000	0	1.51E+06
	Recirculations	#	1	1		1	1	1	1	1	4.5 to 5	13 to 23	1000	1 to 1000
	RF Power	MW	25	282		?	?	?	?	52	360	48	?	?
RF power sources	Technology		klystron	klystron						Klytron-IOT				
	Cavities/Power Source	#	23	244		4				1 to 2	1 to 2			
	RF Pulse (beam) duration	ms	2.42	2.42		4.08E-04	5.04E-04	4.08E-03	5.64E-04	6.36E-04	3.72E-02	1.28E+00	8.70E-01	
	Prf/Power Source	MW	11.7	2.47						1	1			
	Total Power Sources	#	17	244		30				52	341			?
	Installed RF Power	MW	34	352		164				52	341			?
	Total RF Energy	MJ	2.99E-01	3.00E+00		3.35E-01	1.55E-01	4.26E-01	1.56E-02	8.63E-03	3.66E-01	6.13E+00	0.00E+00	10.74

325MHz System for Collider”

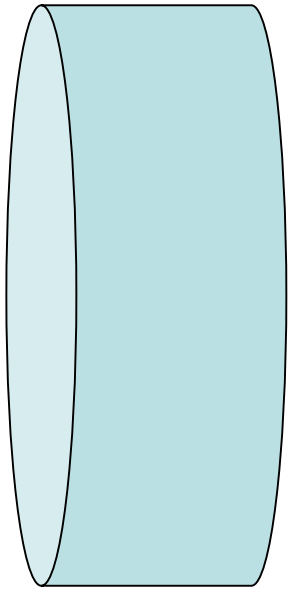


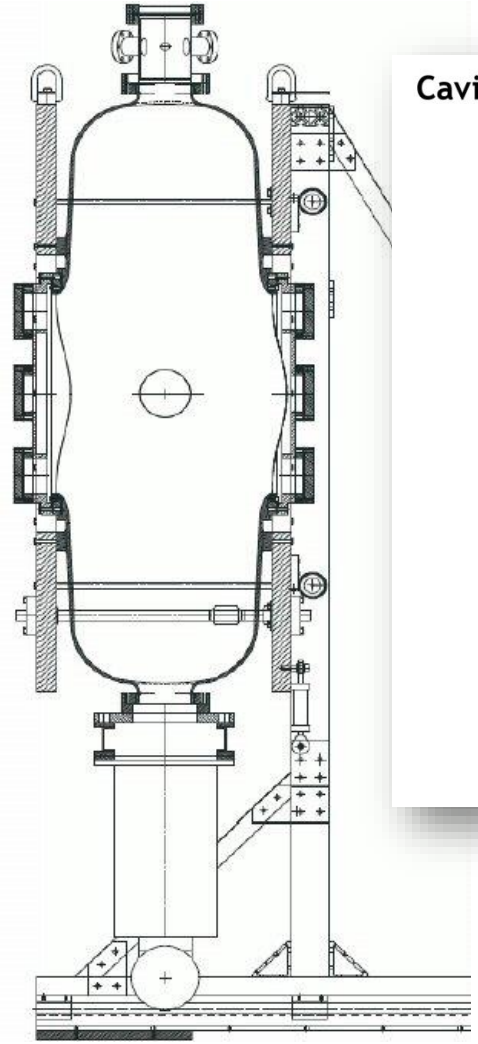
- **Drift**
  - 20T→ 2T
- **Buncher**
  - P_o=250MeV/c
  - P_N=154 MeV/c;
  - V_{rf} : 0→ 15 MV/m
  - f_{RF} : 493→ 365MHz

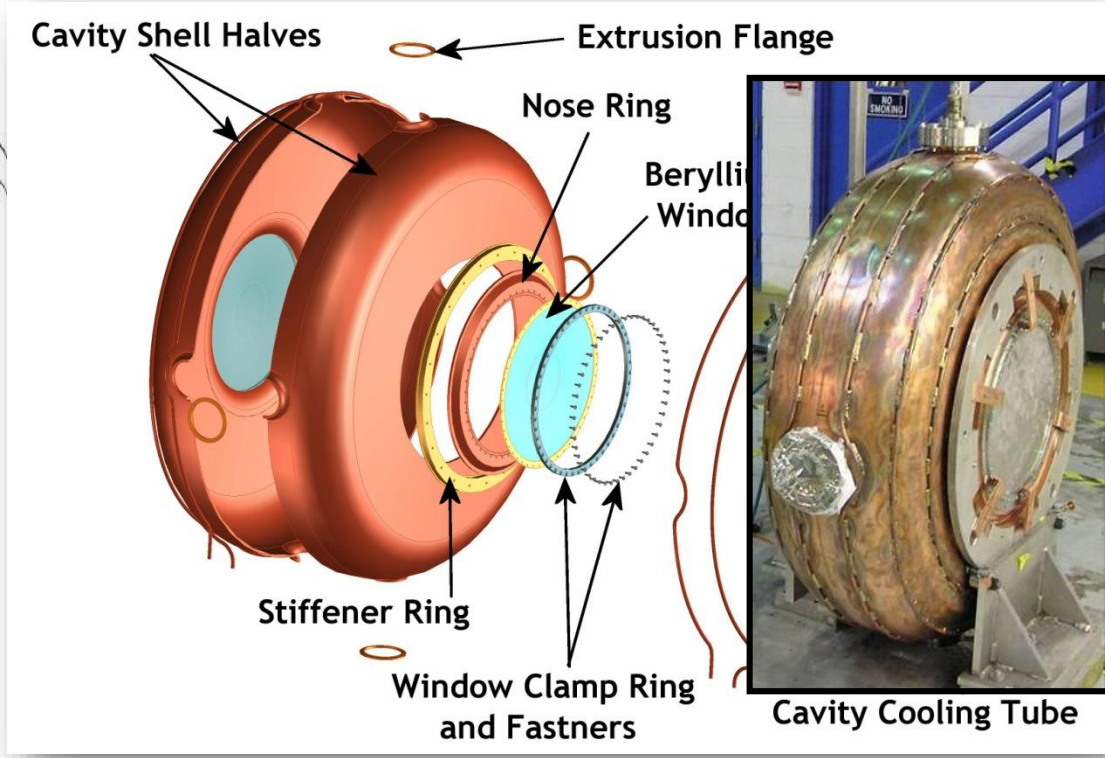


- **Rotator**
  - V_{rf} : 20MV/m
  - f_{RF} : 364→ 326MHz
  - P_0, P_N→245 MeV/c
- **Cooler**
  - 245 MeV/c
  - 325 MHz
  - 25 MV/m
  - 2 1.5 cm LiH absorbers /0.75m

Rf cavity







Concept **design** **construction** **operation**

MAP rf properties (~ Pillbox; ~325 MHz)

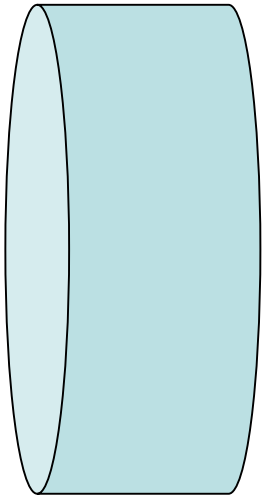
- **Assume pillbox, Cu walls**
  - Compare with MICE rf
- **Q = ~40200**
  - a=0.353m, L=0.25, f=325MHz
  - T_t=0.884, R_s=0.00467
- **P_0 = 3.7 MW at 25MV/m**
  - U_0 = 23.43J, **T_{fill} = 63.7μs**

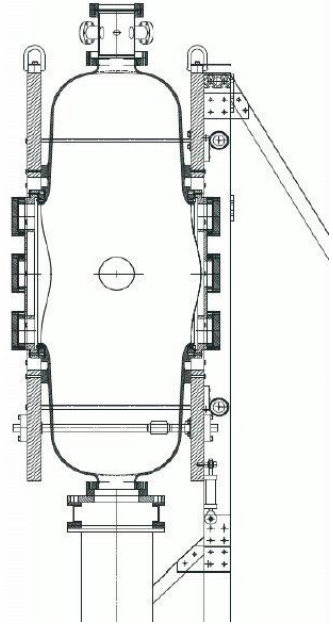
$$Q_0 = \frac{2.405\, Z_0}{2(\pi\, f_{rf}\, \rho\mu_0)^{\frac{1}{2}}\left(1+\frac{a}{L}\right)}$$

ρ_{Cu} =1.68*10^{-8} ohm-m

$$R_s = \sqrt{\rho_{Cu}\pi\,\mu_0\, f_0}$$

$$U_0 = \pi\varepsilon_0 L\, a^2\, 0.52^2\, \frac{E_0^2}{2}$$





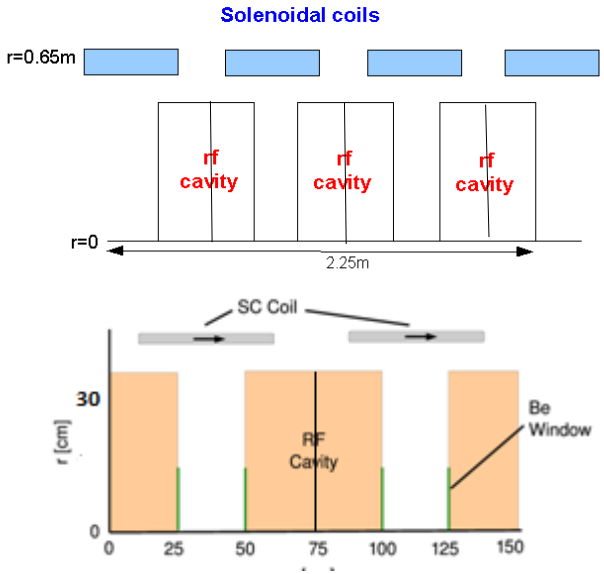
$$P_0 = \frac{\pi R_s\, 0.519^2\, E_0^2\, a(L+a)}{Z_0^2}$$

$$T_{fill} = Q_0\, \frac{\ln(2.0)}{\pi\, f_{rf}}$$

$$T_t = \frac{\sin\left(\frac{\pi\, f_{rf}\, L}{c}\right)}{\frac{\pi\, f_{rf}\, L}{c}}$$

Rf Buncher/Rotator requirements

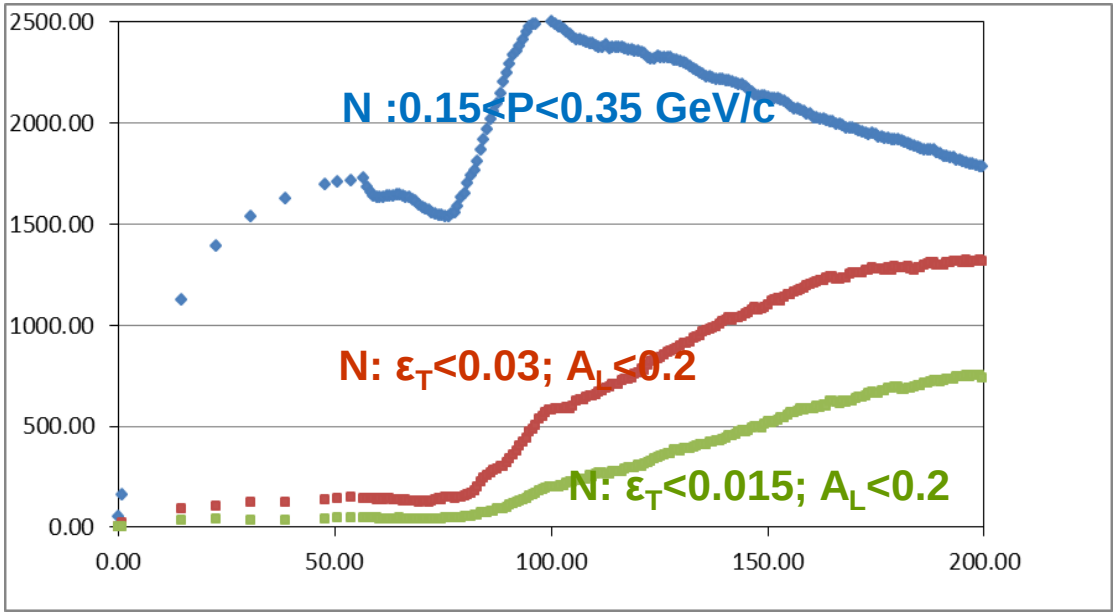
- **Buncher -21m**
  - **37** cavities (**14** frequencies)
  - **13** power supplies **(~1—3MW)**
- **RF Rotator -24m**
  - **64** cavities (**16** frequencies)
  - 20 MV/m, 0.25m
  - **~2 MW** (peak power) per cavity
- **Cooling System – 325 MHz**
  - 200 0.25m cavities (75m cooler), **25MV/m**
  - **~4MW** /cavity



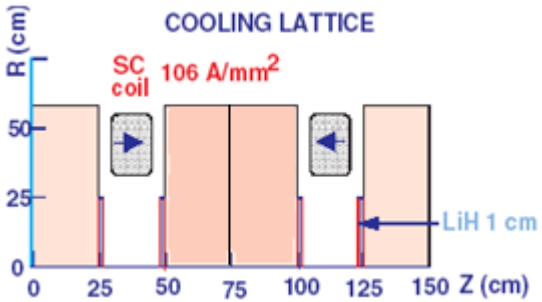
Front End section	Length	#rf cavities	frequencies	# of freq.	rf gradient	rf peak power requirements
Buncher	21m	42	484 to 365	14	0 to 16	0—1.34 MW/cavity
Rotator	24m	56	364to 326	16	20	~2.4 MW/cavity
Cooler	75m	200	325	1	25 MV/m	~3.7MW/cavity
Total df+bxr+rttr	~134m	93		30	~500MV	140MW
6-D cooler	126m	360	325 MHz	1	25 MV/m	~3.7 MW

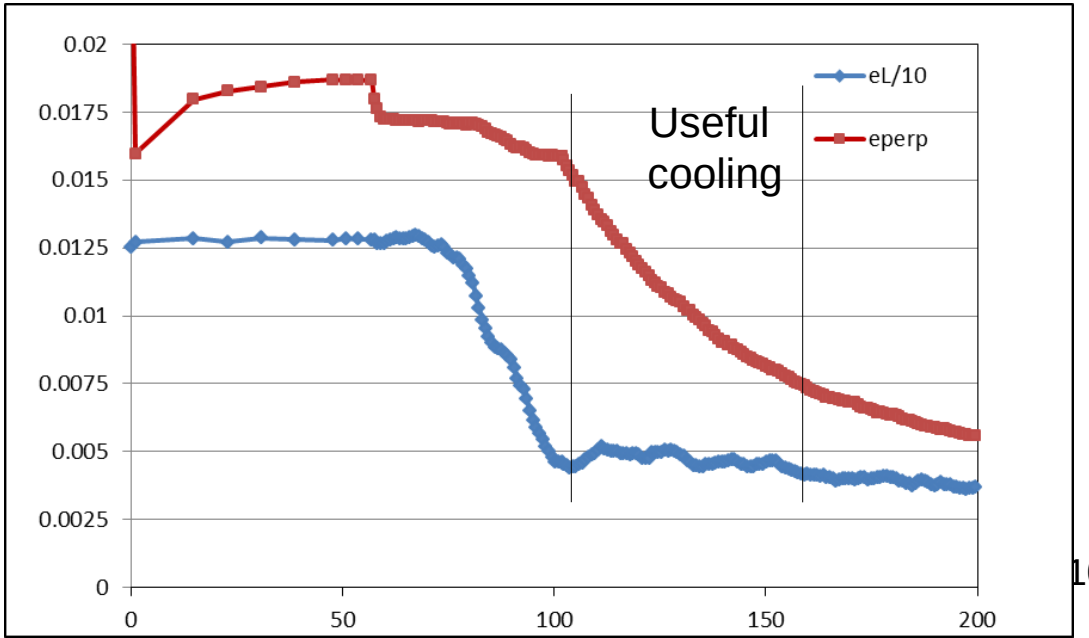
Simulation Results

- **Simulation obtains**
  - ~0.12 μ/p within acceptances
  - ~2014 MARS
  - 8 GeV proton source



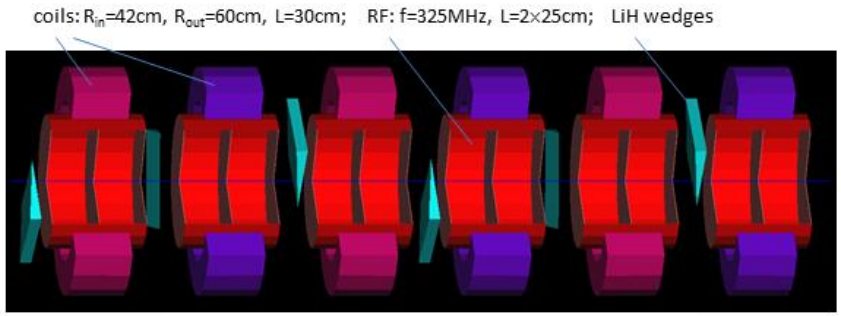
- **FOFO cooling**
  - Cools transversely
  - By factor of 3
    - ~10× in 6-D phase space





RF for 6-D Alexahin cooler

- **Helical FOFO snake**
  - Alternating tilted solenoids
- **126 m long**
  - 2 cavities every 0.7m
  - 160 0.25m cavities 25 MV/m
- **Cools longitudinally and transversely**
  - $\varepsilon_L \times 1/3$, $\varepsilon_1 \times 1/6$, $\varepsilon_2 \times 1/5$
  - ~1/100 × (6-D cooling)
- **Cools both μ^+ and μ^-**



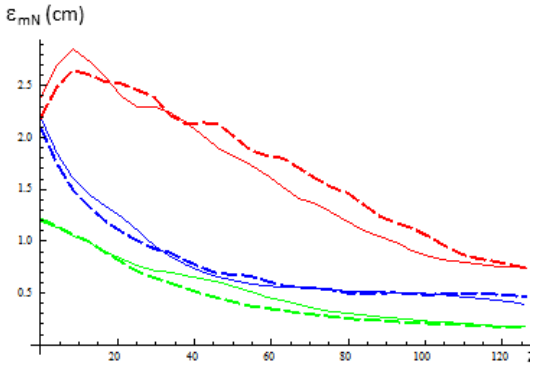


Table of rf cavities, power

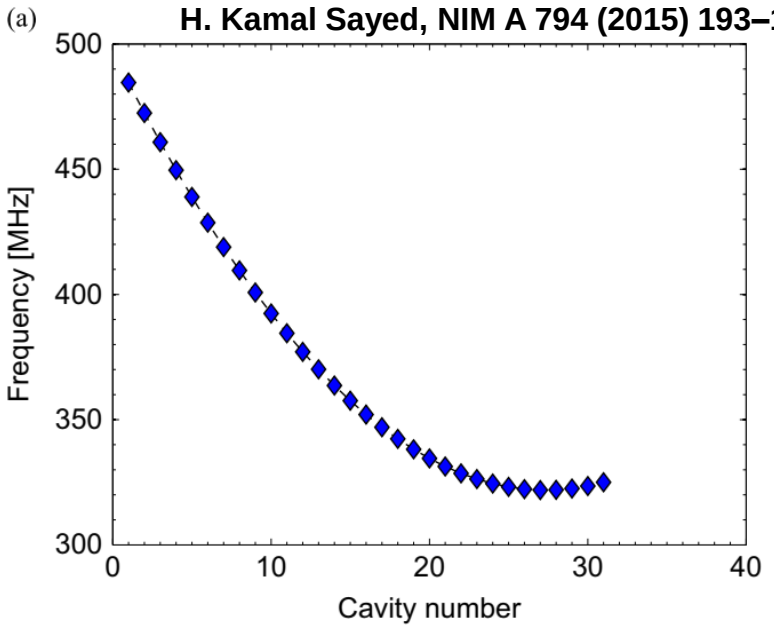
Buncher frequency (MHz)	Buncher gradient (MV/m)	RF Power /cavity (MW) (4 cavities)
493.71	0.30	0.001
482.21	1.24	0.007
470.27	1.95	0.015
458.40	3.38	0.053
448.07	4.45	0.086
437.73	5.52	0.13
427.86	6.60	0.19
418.43	7.67	0.27
409.41	8.74	0.35
400.76	9.81	0.46
392.48	10.88	0.58
384.53	11.95	0.71
376.89	13.02	0.86
369.55	14.30	1.0

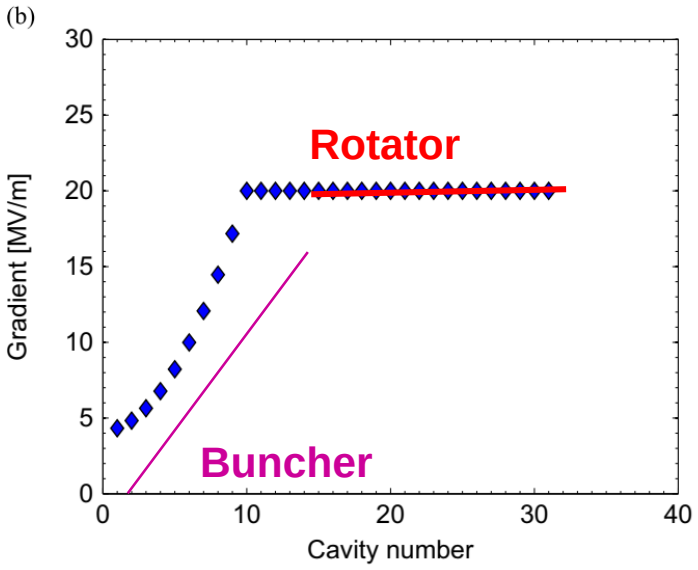
Rotator frequency (MHz)	Rotator gradient (MV/m)	RF Power /cavity (MW) (4 cavities)
363.86	20	2.06
357.57	20	2.1
352.20	20	2.14
347.59	20	2.19
343.65	20	2.23
340.27	20	2.26
337.39	20	2.28
334.95	20	2.30
332.88	20	2.31
331.16	20	2.32
329.75	20	2.33
328.62	20	2.34
327.73	20	2.35
327.08	20	2.36
326.65	20	2.37
326.41	20	2.37

First few buncher cavities are very low gradient;
should be removed, grouped or increased in strength

Optimization (H. Kamal Sayed)

- **Buncher +Rotator-31 cavity sets**
  - Changed frequency, rf gradient
- **Optimized using NERSC supercomputer using evolutionary optimization algorithm, 100's of simulations**
  - Increase E_{rf} in Buncher
    - By ~4 MV/m
  - Rf reaches 325 MHz faster …
    - Could use shorter system ?
    - Could start further downstream



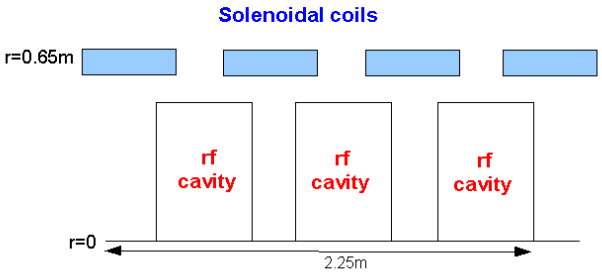


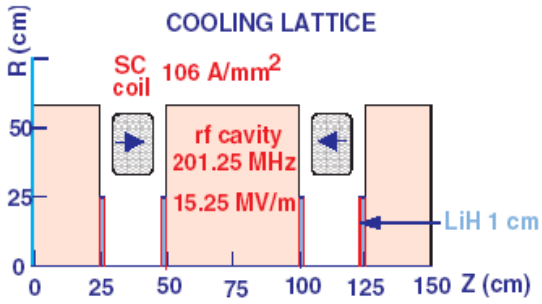
Variations tried, or to try

- **Gas-filled or Vacuum-filled rf**
  - Gas-filled to prevent breakdown, but experiment shows
  - Both can be done
- **201.25 MHz front end**
  - Lower frequency → shorter bunch train
    - 21 → 12 bunches –easier to combine
    - ~1/2 number of cavities; larger apertures
  - Lower gradient for same performance (similar power)
- **Include some cooling in buncher/rotator or before HFOFO**
  - Combine cooling approaches.
- **Chicane after target to reduce downstream losses**
  - in Baseline design
- **Change magnetic fields**
  - 2T → 3T focusing increases mu's by ~15%

IDS RF requirements (200 MHz system)

- **Buncher**
  - **37** cavities (**13** frequencies)
  - **13** power supplies **(~1—3MW)**
- **RF Rotator**
  - **56** cavities (**15** frequencies)
  - 12 MV/m, 0.5m
  - **~2.5MW** (peak power) per cavity
- **Cooling System – 201.25 MHz**
  - 100 0.5m cavities (75m cooler), **15MV/m**
  - **~4MW** /cavity





Front End section	Length	#rf cavities	frequencies	# of freq.	rf gradient	rf peak power requirements
Buncher	33m	37	319.6 to 233.6	13	4 to 7.5	~1 to 3.5 MW/freq.
Rotator	42m	56	230.2 to 202.3	15	12	~2.5MW/cavity
Cooler	75m	100	201.25MHz	1	15 MV/m	~4MW/cavity
Total drift)	~240m	193		29	~1000MV	~550MW


Thank you
for your attention