ISS COOLING

R. B. Palmer (BNL)
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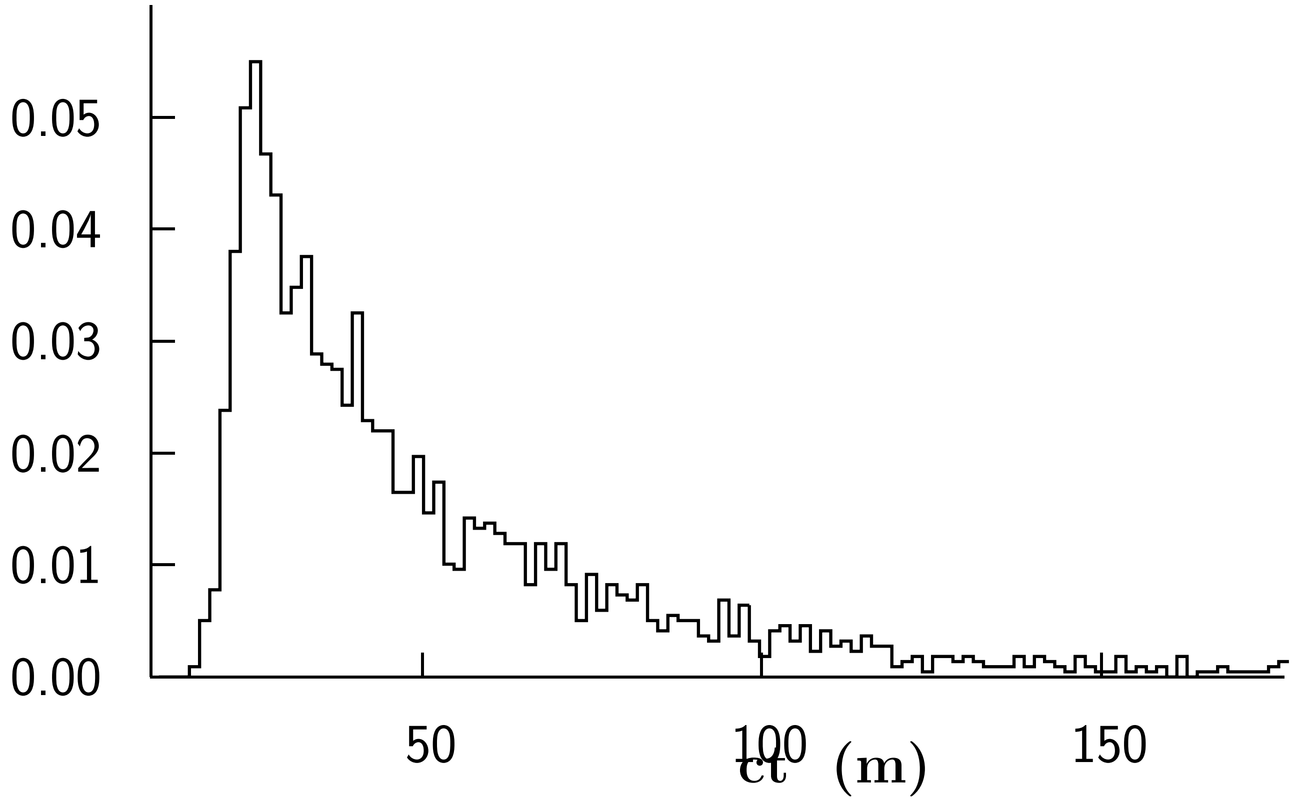
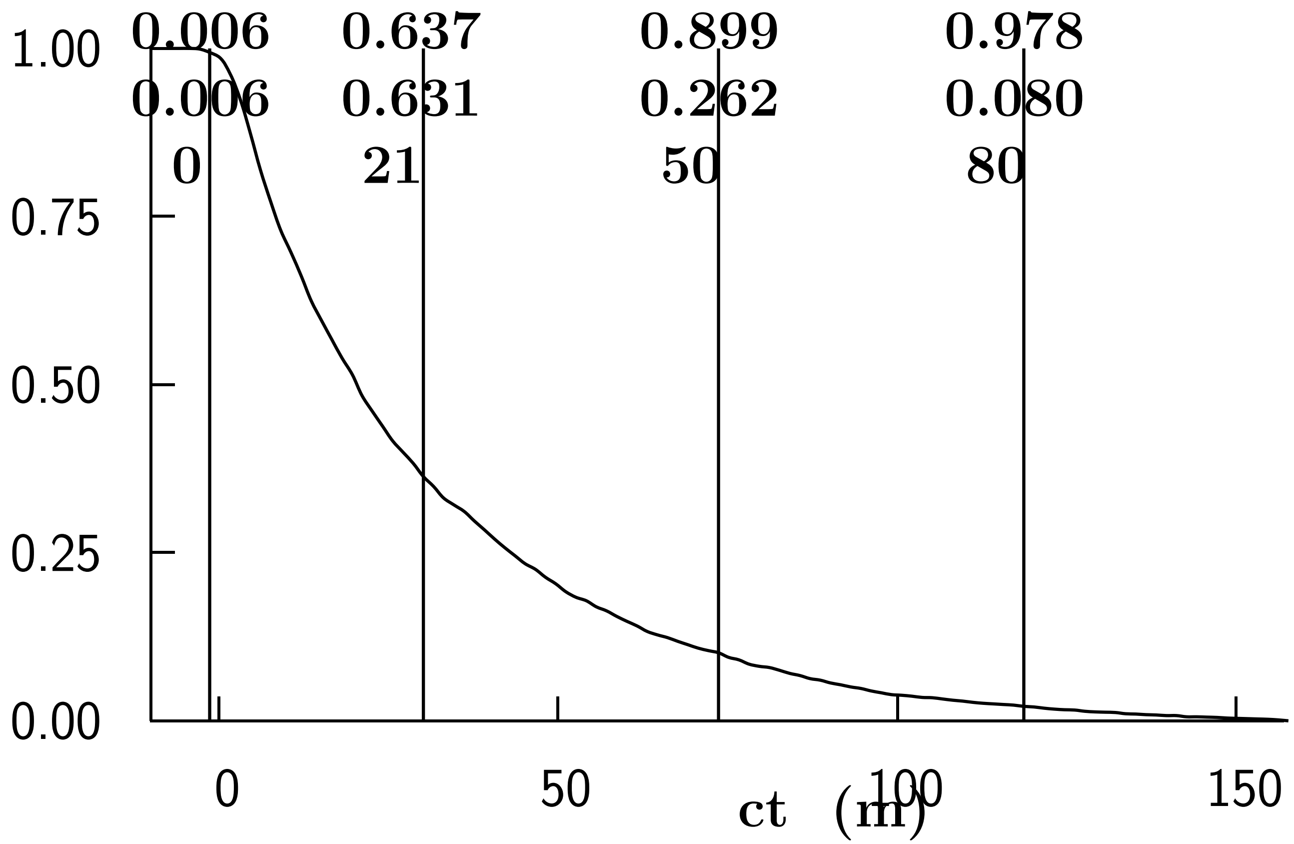
253 237.4 50 m cooling




0.006
0.006
0
0.637
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21
0.899
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50
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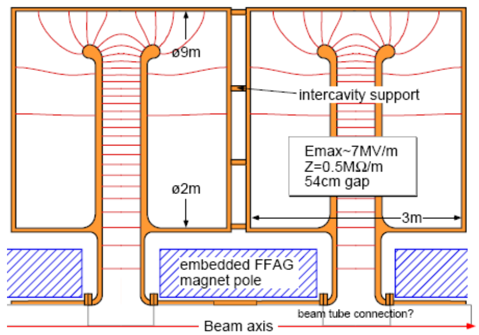
1.00
0.75
0.50
0.25
0.00
0
50
100
150
ct (m)

5) RF Frequency: 5, 88, 201 MHz

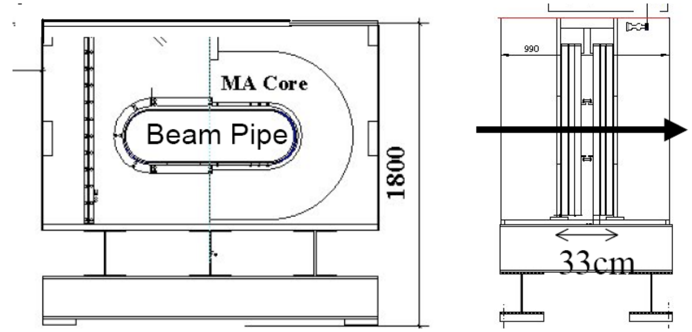
5 MHz

Studied in Japan

0.75-1.0 MV/m ave



Japan 5 MHz Vacuum RF



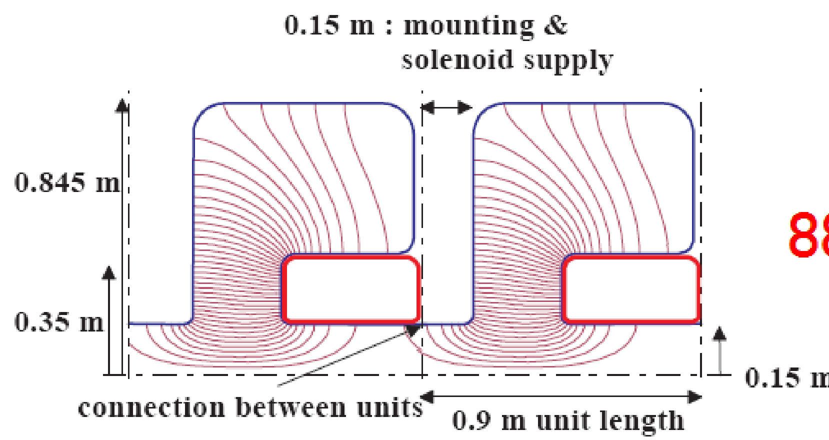
Japan Ferrite Loaded RF (cf PRISM)

88 MHz

Studied in CERN

4 MV/m ave

(Also 44 + 88 MHz system with similar performance)

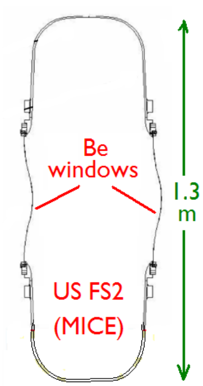


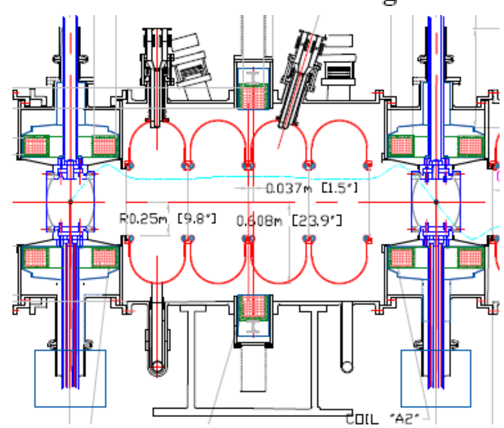
88 MHz

201 MHz

Studied in US

10 MV/m ave in cooling





5.1) Compare Longitudinal Phase Space

Problem is to match initial muon longitudinal phase space into RF bucket(s)

- Initial Longitudinal Acceptance $A_{||}$ of all muons: $$A_{||} = \beta\gamma \frac{\Delta_E}{E} c\Delta_t$$

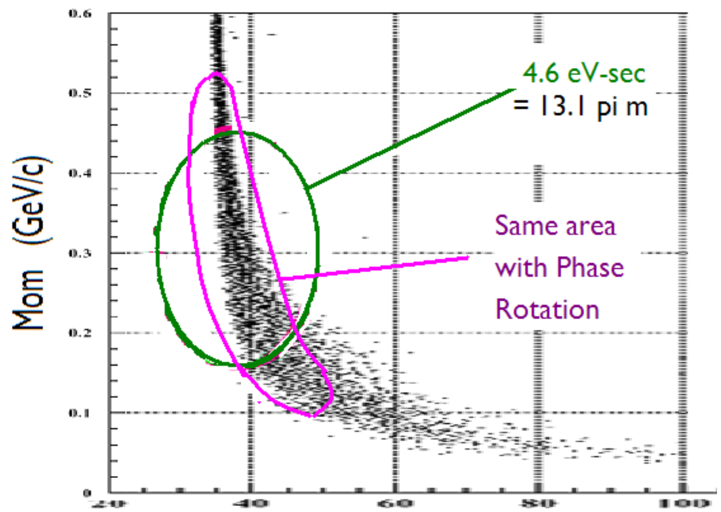
$$\boxed{A_{||} = 2 \times 100\% \times 2 \times 3(ns) = 4 \ (\pi \text{ m})}$$ (1.3 eV sec)

- Bucket areas A_{bucket}: $$A_{\text{bucket}} \propto \left(\frac{\Delta p}{p}\right)^2 \sqrt{\frac{1}{f \ \mathcal{E} \ \cos\phi}}$$

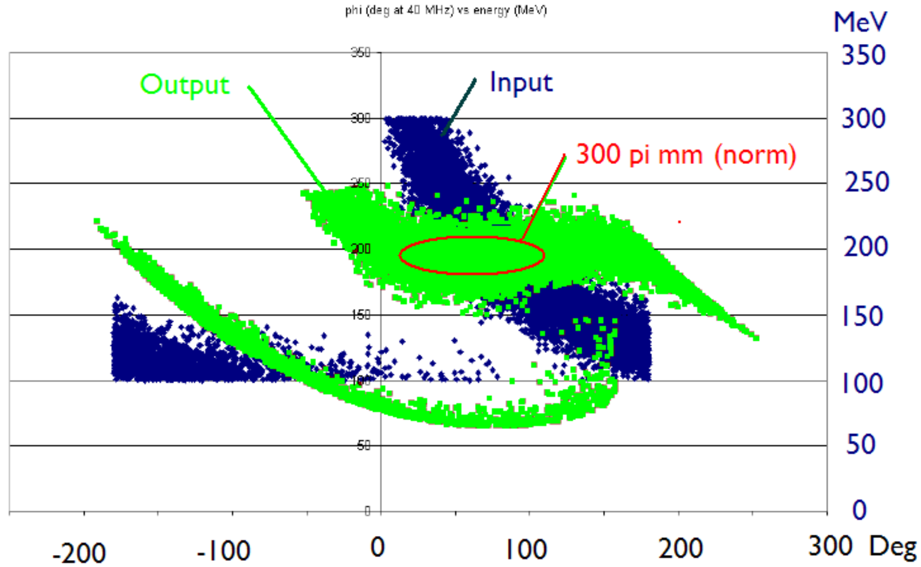
f (MHz)	Neuffer	n bunches	$A_{\parallel}$ (pi m)	$A_{bucket}/A_{\parallel}$	
5	No	1	13	3.2	very good
88	No	1	0.3	0.08	bad
88	Yes	25	0.3× 25=7.5	1.8	good
201	Yes	50	0.15×50=7.5	1.8	good

- 5 MHz and 201 MHz have enough acceptance to capture entire production
- 88 MHz into one bunch lacks longitudinal acceptance
- 88 MHz into 25 bunches probably ok, but not tried yet

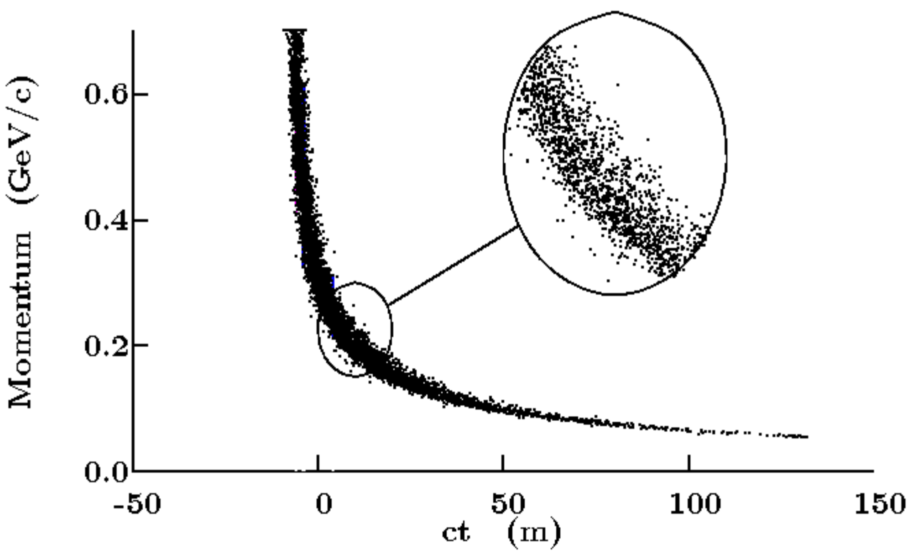
5.2) Matching into RF: "Phase Rotation"

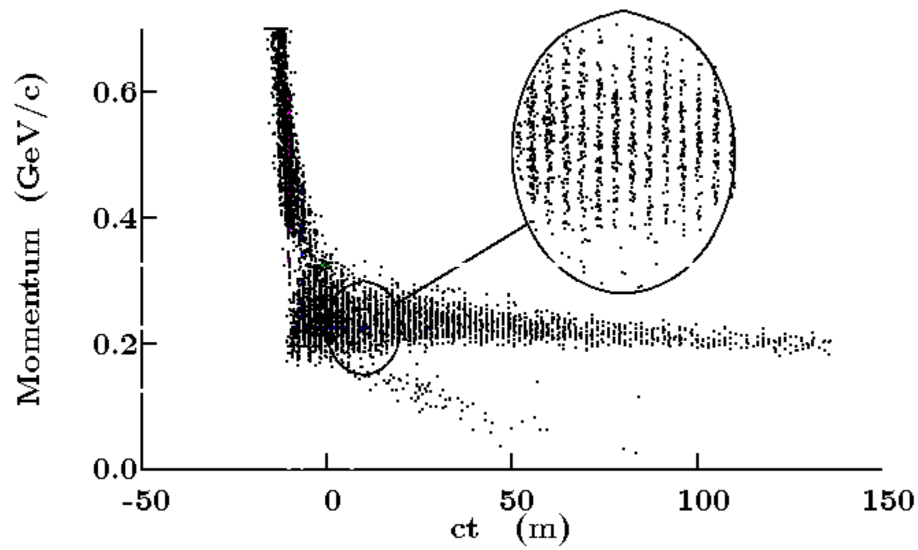


5 MHz Direct Capture



CERN 44/88 MHz





US Study 2a

Estimated Longitudinal Capture Efficiencies

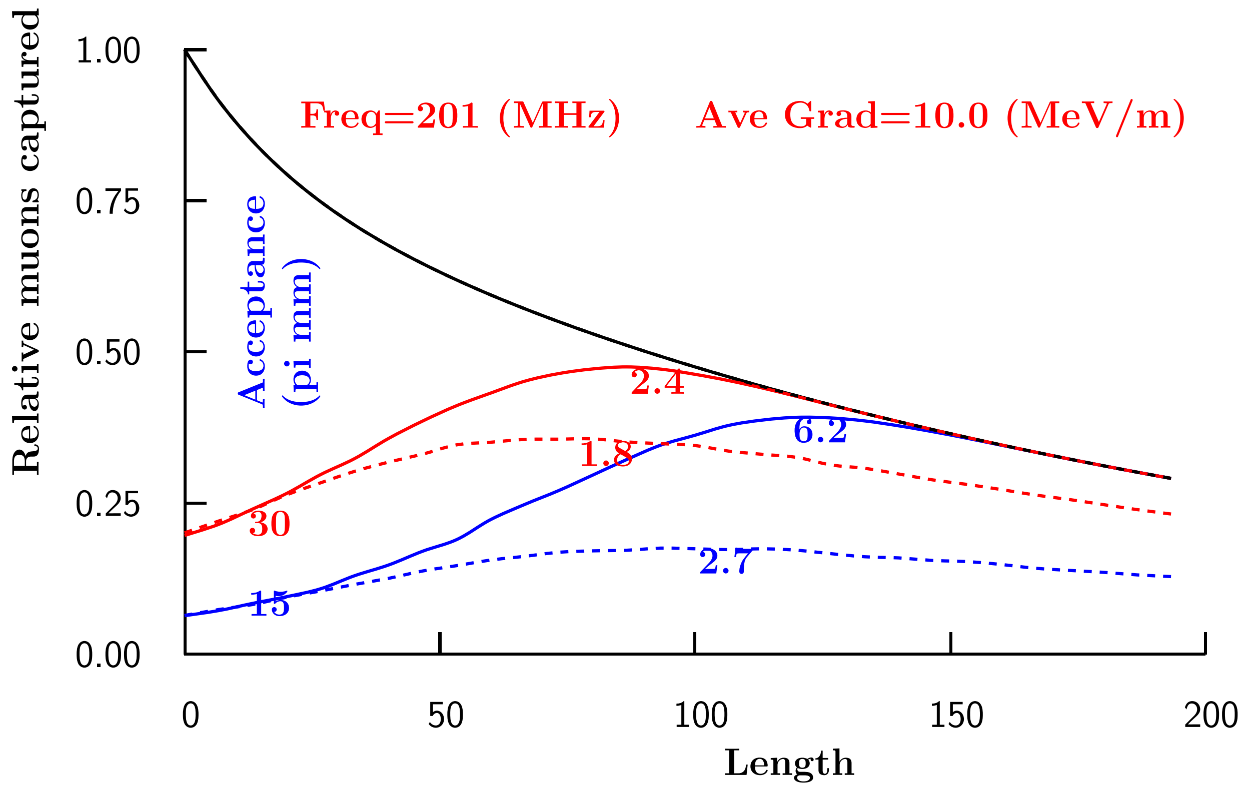
Case	Capture efficiency $\eta_{\parallel}$	signs	$\eta_{\parallel} \times$ signs	
5 MHz	39%	1	39%	ok
5 MHz + Phase Rotation	≈60%)	1	60%	good
88 MHz	(15%)	1	15%	poor
88 MHz + Neuffer	(48%)	2	96%	very good
201 MHz Induction linacs	56%	1	56%	good
201 MHz + Neuffer	48%	2	96%	very good

- 88 MHz + Neuffer
  or 201 MHz + Neuffer   are Favored
  Note: proton bunches must be $\geq$ 80 m apart

- 88 MHz without Neuffer is 15% as efficient
  due to small $A_{\text{bucket}}/A_{\text{Production}}$ and single sign
- 5 MHz and 201 MHz without Neuffer are 60% as efficient
  due to single sign

5.3) Cooling

- Analytic calculations of muon gain vs cooling length
- 200 MeV/c nominal momentum
- Solid line: Tapered cooling with ϵ(min)=ϵ/3
- Dashed line: Un-tapered cooling with ϵ(min)=6 pi mm



factor 1.8 max for non-tapered agrees with full simulation's 1.7

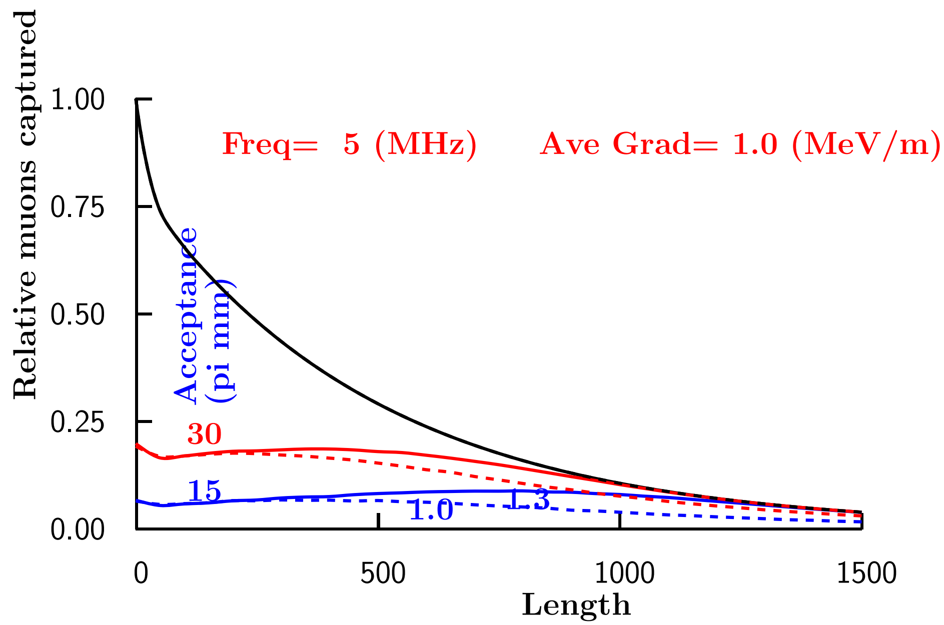
For other frequencies

taper	no	yes	no	yes
Acceptance (pi mm)	30	30	15	15
201 MHz	1.8	2.4	2.7	6.2
88 MHz	1.5	1.9	2.1	4.7
5 MHz	-	-	-	1.3

- 201 MHz Favored
  If 30 pi mm ok non-tapered channel ok
  If 15 pi mm required then tapered channel needed

- 88 MHz slightly less good

- 5 MHz gives negligible gain
  and is very long
  If 30 pi mm acceptable without cooling?
  if 15 pi mm very low performance



5.4) Acceleration

For constant accelerating gradient $\mathcal{E}$: $\eta_{accel} = \left(\frac{n_2}{n_1}\right) = \left(\frac{E_1}{E_2}\right)^{\frac{m_\mu}{c\tau_\mu \mathcal{E}}}$

	E_1 GeV	E_2 GeV	$\mathcal{E}$ MeV/m	η_{accel}
5 MHz	0.21	20	1/.75	0.5/ 0.36
88+176 MHz	0.20	20	1.8	0.65
201 MHz	0.13	20	4.0	0.81

- 5 MHz had earlier give $\mathcal{E} = 1$ (MeV/c), but have recently lowered it to 0.75 MV/m
  The figures for 44/88 and 201 MHz are "effective", the real values are not constant
- Cavity gradients in 44/88 MHz Scheme are 4 and 10 MeV/m at 88 and 176 MHz
- Cavity gradient in the 201 MHz schemes is 17 MV/m superconducting

- 201 MHz Favored

- 88 MHz is 80% as good
- 5 MHz is 44-62 % as good

5.5) Useful Muon decays per year (from Studies)

- With 4 MW proton power
- Use published muopns per initial pion
  because published results used differing production models
- Captured pions per proton GeV = .039 (S2a value) *1.1 (for 8/10 GeV)
- 48% straights over circumference for triangle storage rings
- 10^7 seconds per year
- Include 20% loss for matching, injection, etc
- Compare with Lyon NuFact goal of 10^{21} Useful decays per year

case	cooling	trans acc pi mm	signs	mu/pi	mu/year $\times 10^{21}$
5 MHz	no	30	1	0.08	.19
44/88 MHz	yes	15	1	0.066	.21
201 MHz FS2	yes	15	1	0.17	.54
201 MHz S2a	yes	30	2	0.17	1.07

- Only 201 MHz S2a with 2 detectors reaches the 10^{21} goal

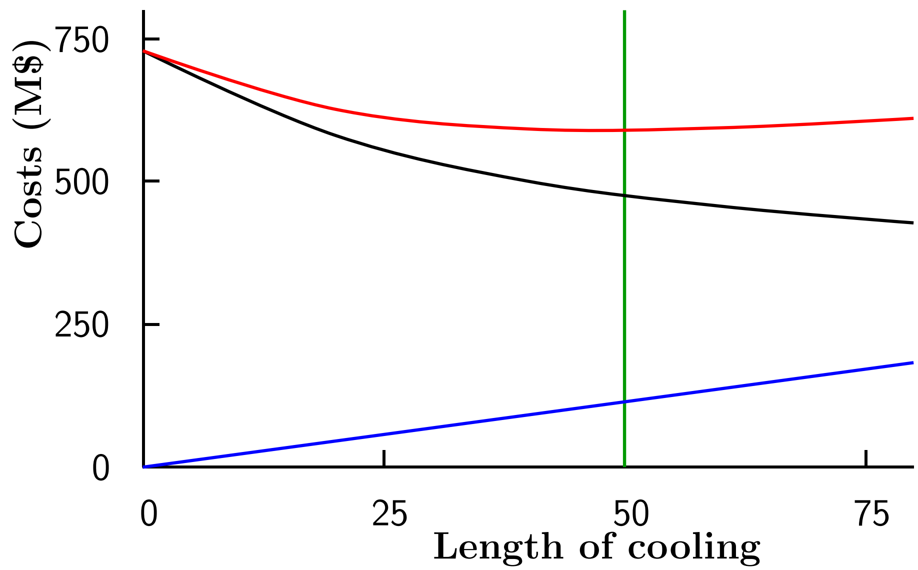
5.6) RF Frequency Conclusion

Freq. MHz	Capture effic. %	Un-tapered cooling factor	Tapered Cooling factor	Accel un-decayed %	muons/year $\times 10^{21}$ Studies	
Acc. Acceptance		30	15		(15/30)	(pi mm)
5 + no rotation	39	1.0	1.0	36-50	.19 (30)	poor
5 + Rotation	60	1.0	1.0	36-50		poor
88 + RF	15	1.5	4.7	65	0.21 (15)	poor
88 + Neuffer	96	1.5	4.7	65		2nd best
201 + Induction	56	1.8	6.2	80	0.54 (15)	3rd best
201 + Neuffer	96	1.8	6.2	81	1.07	best

- 201 MHz is Favored (1.3 for 30 pi mm)
- 88 MHz + Neuffer Phase Rotation is second (0.9 for 30 pi mm) but not yet demonstrated
- 5 MHz with Rotaion (0.3 for 30 pi mm) is next but bad if acceptance 15 pi mm
- 88 MHz without Neuffer Rotation is worst option (0.15 for 30 pi mm)
- 401 MHz should be studied but may have loading and aperture problems

6) Optimization of Cooling vs Detector Size

- Assume base detector costs (two detectors) is 500 unloaded M$
- Scale detector sizes (and costs) for same number of events with different cooling lengths

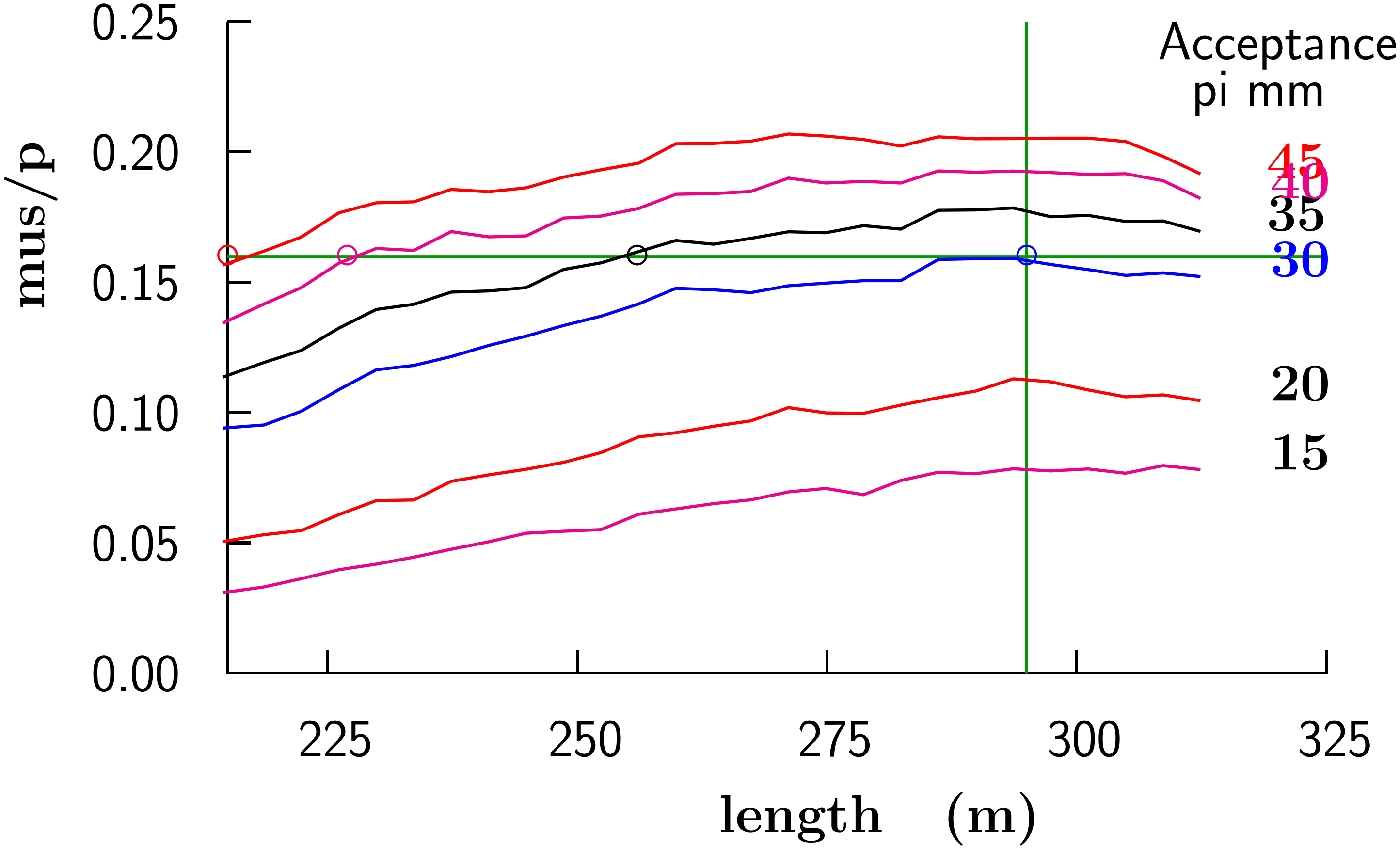


- Minimum total cost minimum at 50 m (vs. 80 m)
- Saving for Factory of 70 M$
- Saving for Factory and Detector 17 M$
- Saving at minimum relative to no cooling and larger detectors: 136 M$

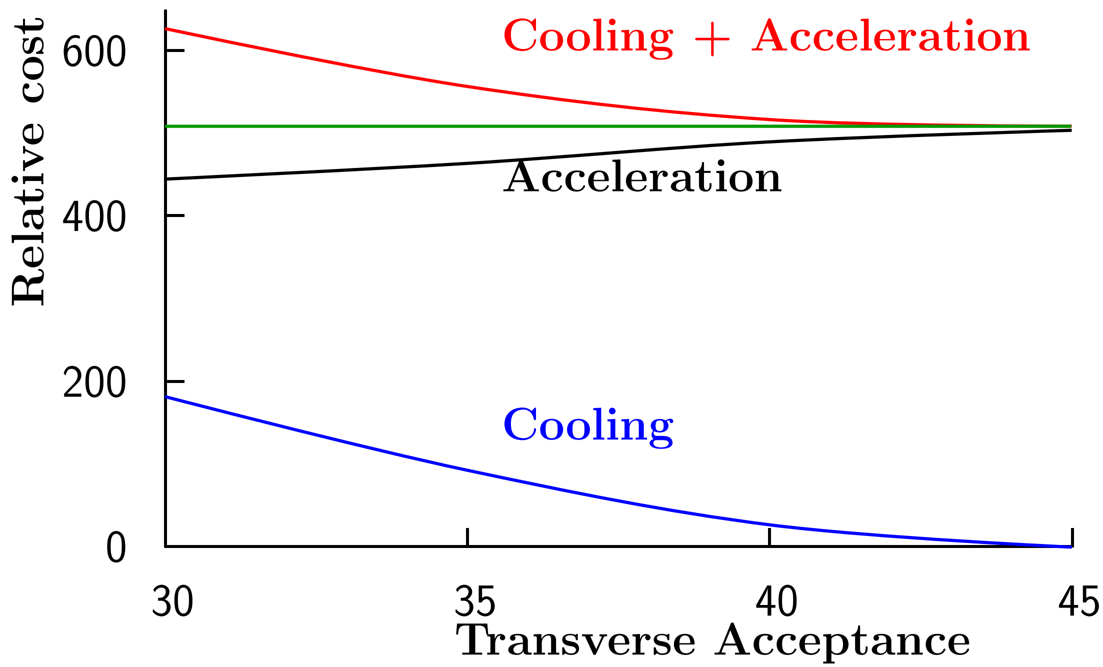
- Favor Moderate Cooling

Appendix: Cooling vs Accelerator Acceptance

- Using US Study 2a (APS Neutrino Matrix) as example
- Use ICOOL for performance simulation
- Determine how much cooling needed to get same performance with larger apertures



- Use J.S.Berg estimates of FFAG cost vs aperture
- Assume other acceleration and collider ring costs vary in the same proportion
- Plot cost of cooling plus acceleration vs acceleration acceptance

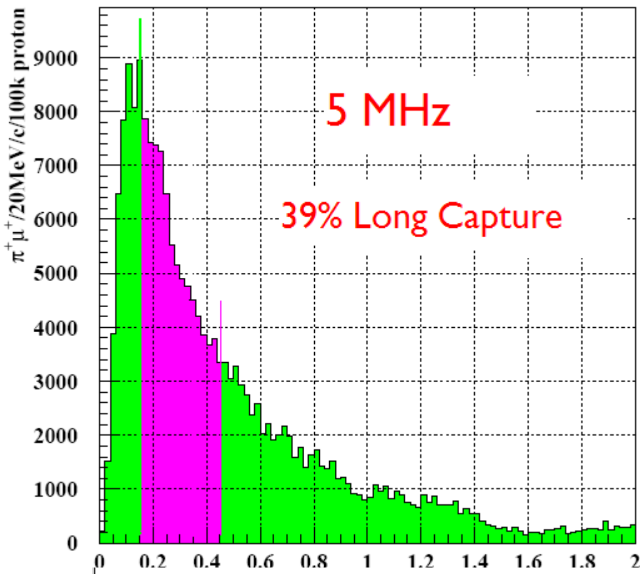


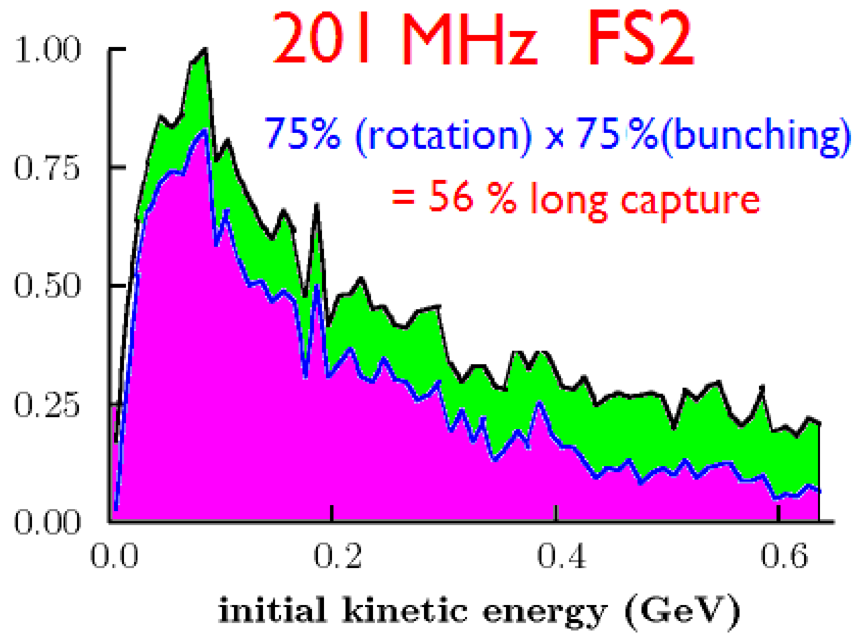
- Suggests minimum cost with 45 pi mm acceptance and NO cooling
- But a 45 pi mm acceptance FFAG has time of flight problems
- And cost of lower energy acceleration probably rise faster with acceptance than FFAG
- This conclusion is probably moot

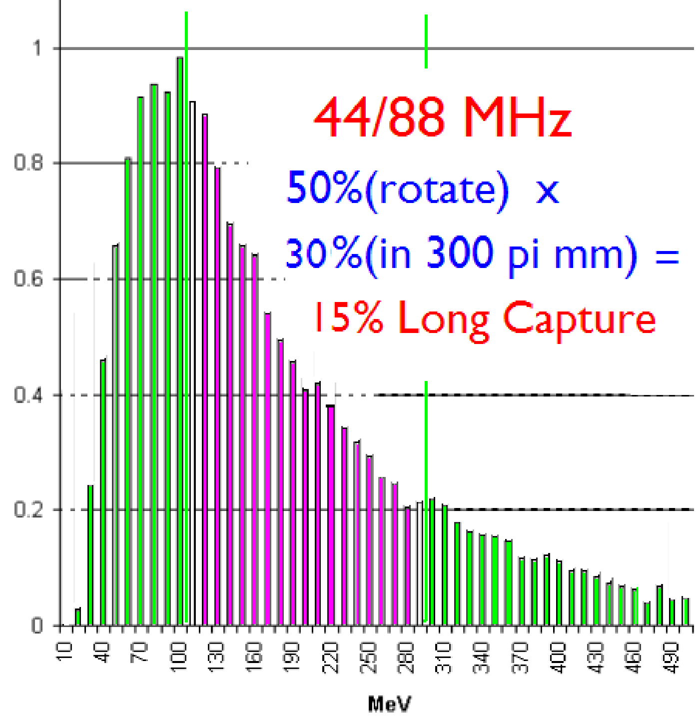
Some Advantages of using No Cooling

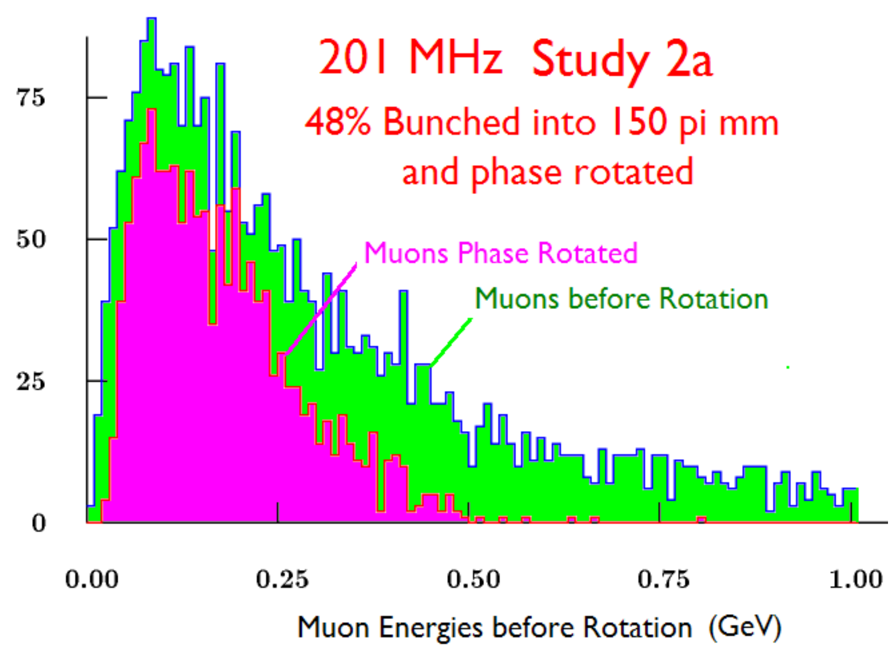
- No field "flips" needed
- Less dependence on use of RF in magnetic fields
  - Relatively easy to design with fields less than 0.5 T
- Reduced Requirement on capture acceptance
  - Smaller aperture phase rotation RF
  - Could reconsider 400 MHz rf
  - Smaller or lower field focusing in drift
  - Lower Capture Field

Appendix: Longitudinal Capture Efficiency









5.5) Overall Performance **Parentheses on estimated values**

- Study Muons out per Captured Pion (at 1m in capture channel) NOT mu/proton
  Independent of p energy
  Independent of production model

case	Cool?	$A_\perp$ pi mm	$\eta_{\|\|}$	$\eta_\perp$	$\eta_{\rm front}$	$\eta_{\rm accel}$ %	$n_{\rm signs}$	$\eta_{\rm all}$ %
5 MHz	no	30	.39	(0.18)	16 (7)	0.36	1	6[1] (2.5)
44/88 MHz	yes	15	(0.15)	[0.67][2]	10	0.66	1	6.6[3]
44/88 MHz	no	30	(0.15)	(0.24)	(3.6)	0.66	1	(2.4)
201 MHz FS2	yes	15	0.56	0.38	21	0.81	1	17
201 MHz FS2	no	30	0.56	0.24	13	0.81	1	11
201 MHz S2a	yes	30	0.48	0.42	20	0.81[4]	2	33
201 MHz S2a	no	30	0.48	0.24	12	0.81[4]	2	19

- 5 MHz's efficiency without cooling equals 44/88's with cooling, showing the advantage of 5 MHz larger acceptance
- We believe 5 MHz's efficiency could be raised by adding phase rotation and cooling, but is unlikely to match 201 MHz S2a because of greater decay losses in acceleration, and apparent inability to capture both signs
- 44/88 MHz's performance has the best cooling performance ($\eta_\perp$), but this is offset by its poor longitudinal acceptance ($\eta_\parallel$)
- 201 MHz S2a's strength comes from the combination of good longitudinal acceptance ($\eta_\parallel$) and the capture of both signs

Notes for previous table

1. This value is obtained from quoted 0.3 captured muons per proton, 3.5% MARS captured pions per proton GeV, and 0.5 acceleration decay loss. The discrepancy with my estimate is not understood.
2. This is derived from our estimate of $\eta_{\|}$ and the CERN given η_{front} and seems unrealistic
3. From table in CERN note #20
4. Matching loss not included since no such loss in other examples included