ISS Comparison of Schemes

R. B. Palmer (BNL)
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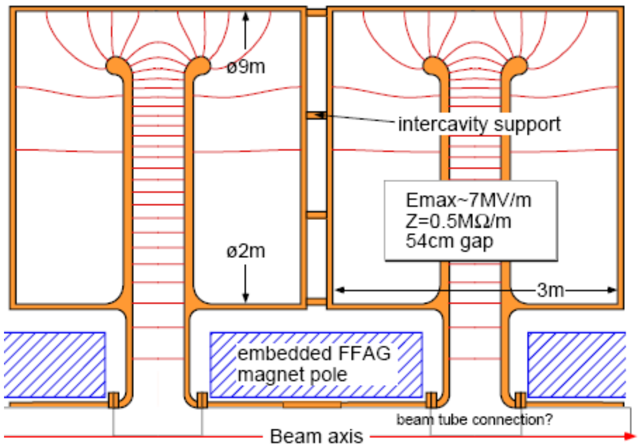
Subjects I will discuss

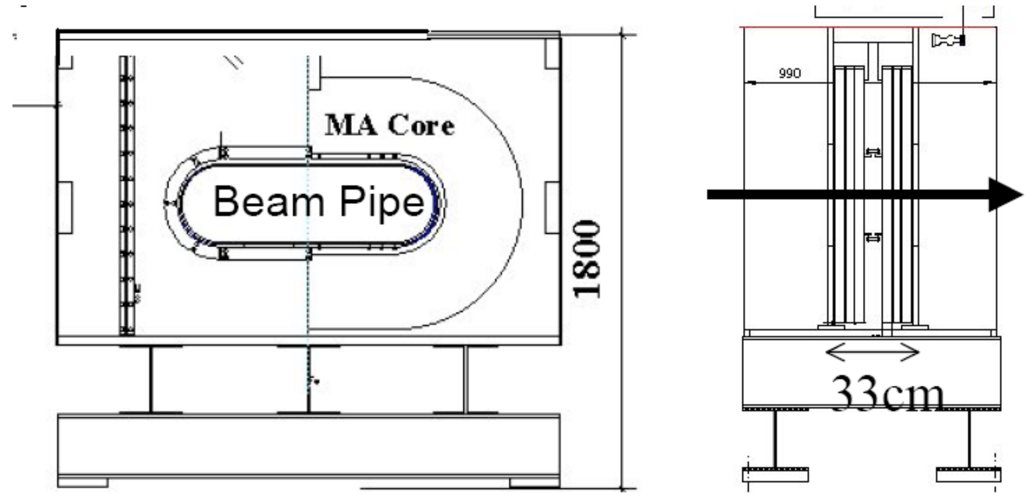
1. RF Systems
2. Pion Production
3. Longitudinal Capture
4. Transverse Capture and Cooling
5. Performance by muons/initial pions
6. Performance by muon decays per year

RF Frequencies and Systems

Japan ≈ 5 MHZ

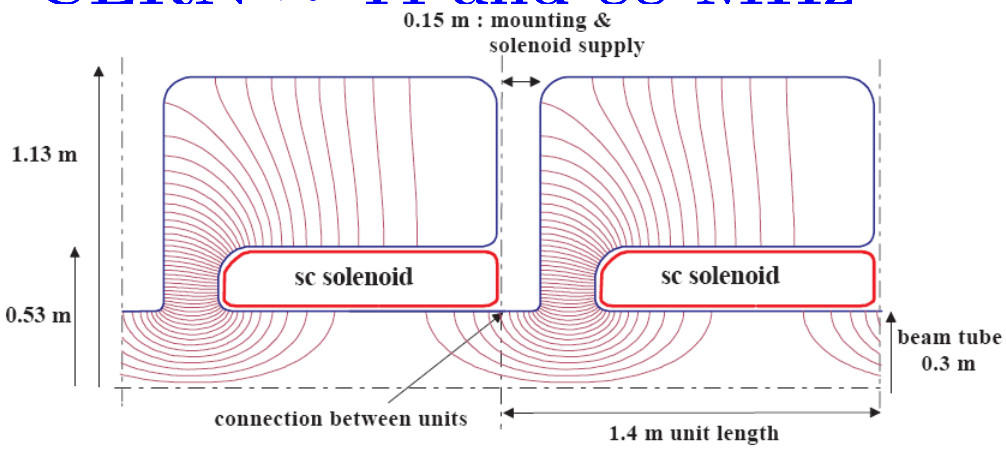


Japan 5 MHz Vacuum RF

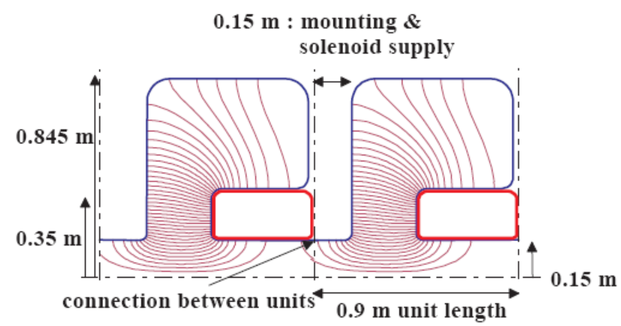


Japan Ferrite Loaded RF (cf PRISM)

CERN ≈ 44 and 88 MHz



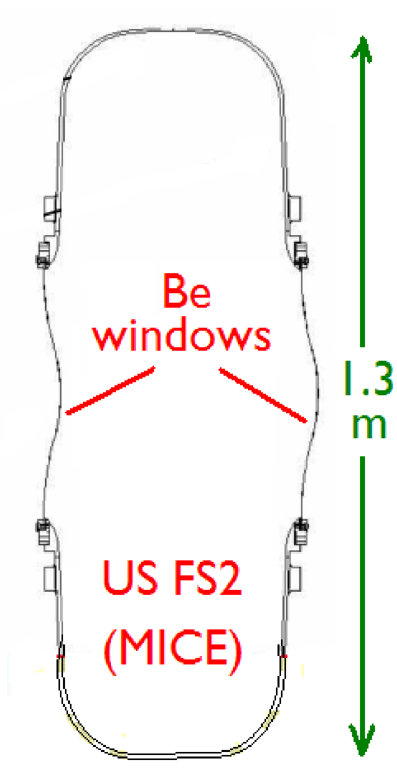
44 MHz

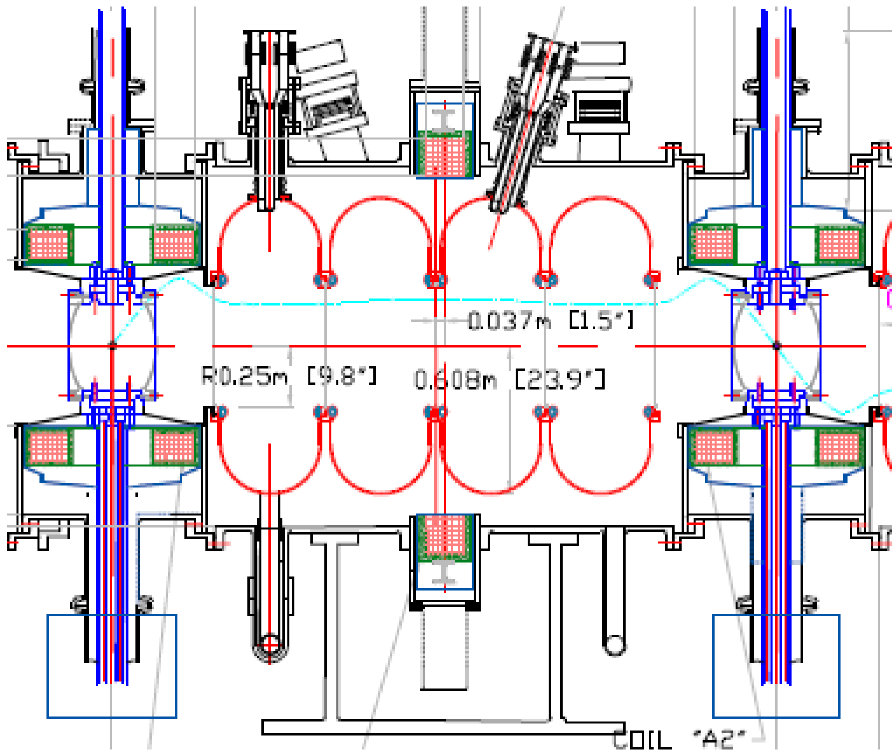


88 MHz

CERN

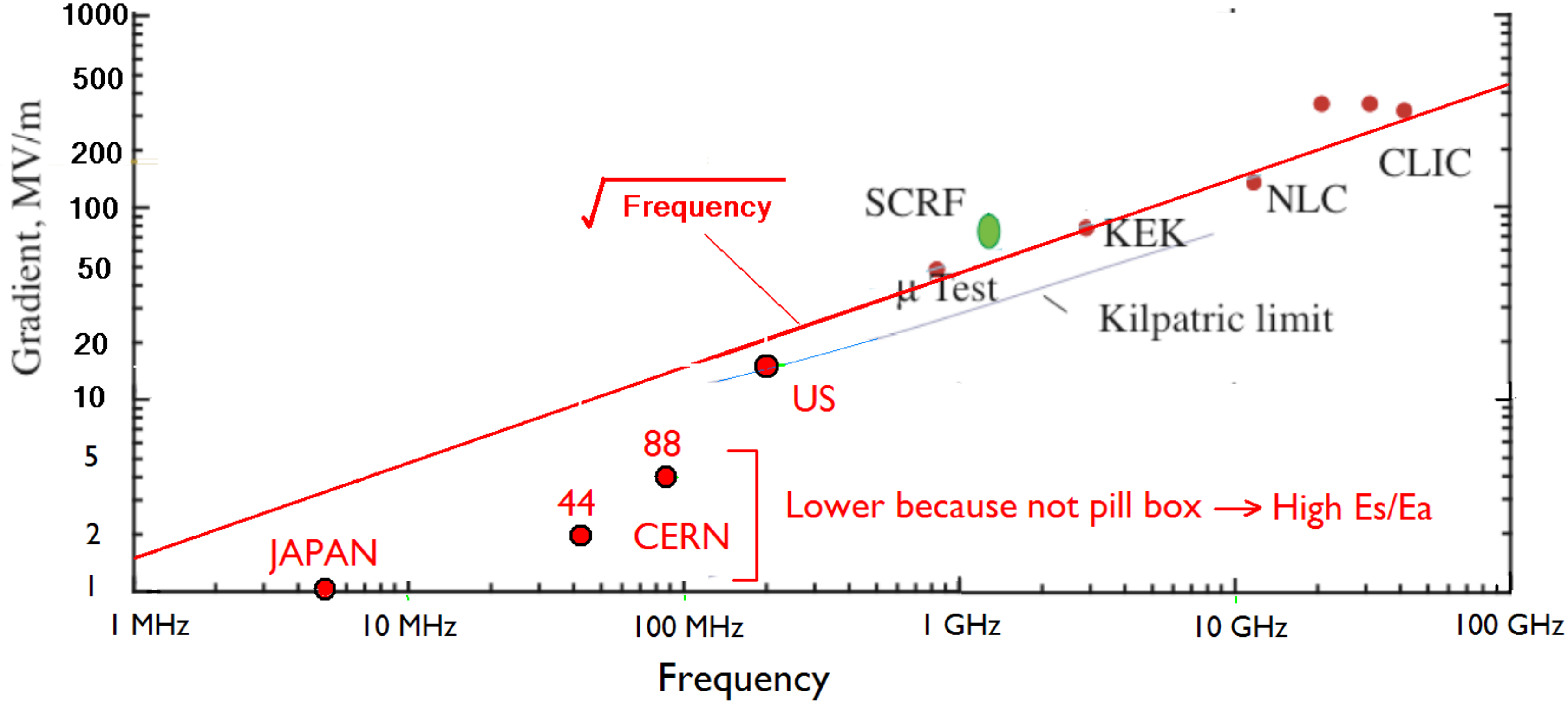
US ≈ 200 MHz





What is best RF frequency ?

• Maximum Accelerating Gradients

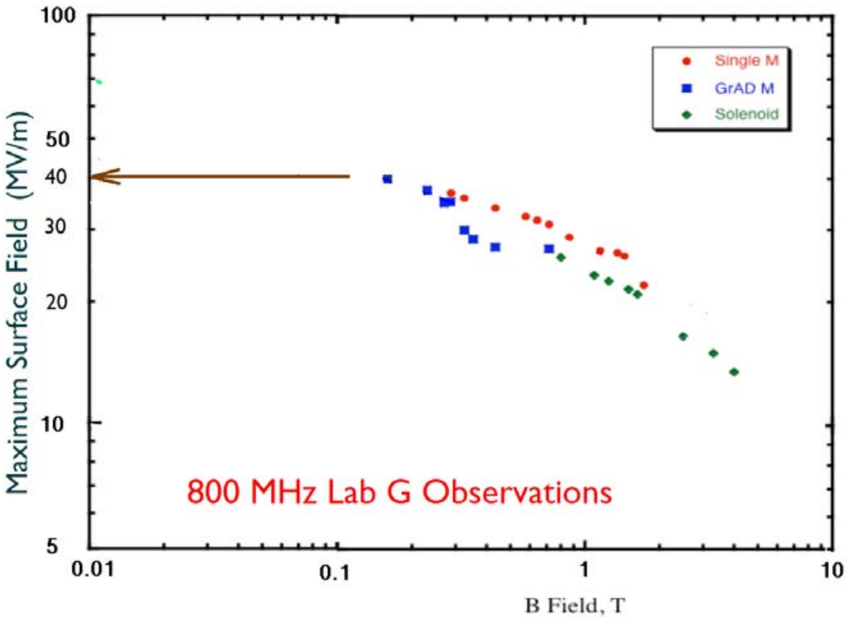


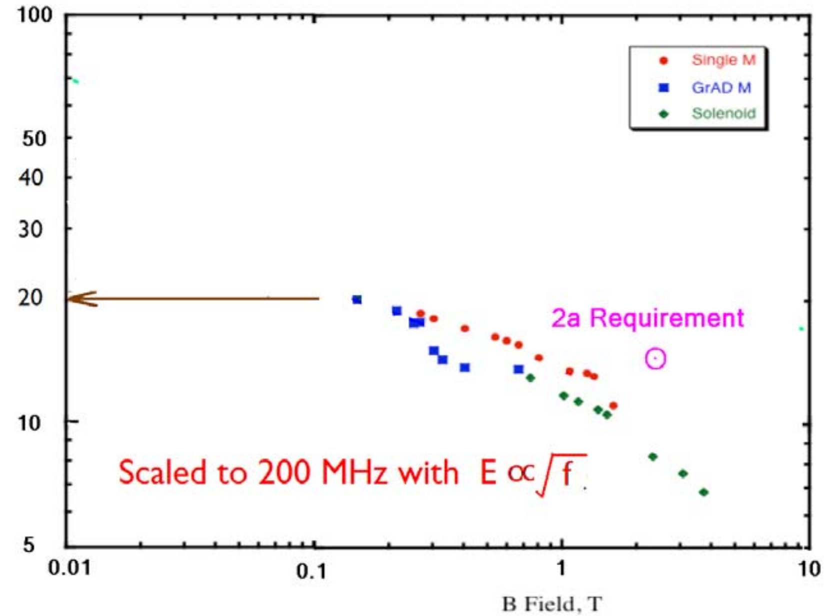
Case	ref	f (MHz)	$<\mathcal{E}>$ (MV/m)	P (MW/m)	P/E (MW/MV)
Japan vac	nufactJ	5	3/3= 1	3/3= 1	1
Japan Ferrite	nufactJ	5	2	3/1.5= 1	1
CERN	nf87	44	1.86/1= 1.86	1.86	0.9
CERN	nf87	88	2.04/.5≈ 4.1	4.1	1
US	FS2	200	16 × 2/3=12	5/.7=7	0.6

Effect of Magnetic Fields

A serious assumption in our Studies

• Maximum Gradient vs, Local Fields





Assuming max gradient $\mathcal{E} \propto \sqrt{\mathrm{f}}$ for all Fields

- S2a (and the CERN) specified Fields will not be attainable
- Would require redesign of lattices
- Not a problem for Japan Scheme
- Importance of Tests at Fermi MTA, and CERN ?

Method to Compare performances

- Study Muons out per Initial Pion
  avoid uncertainties in production
- "Initial Pions" defined to be at $>$ 1m in capture channel
- Assume orthoganality between transverse and longitudinal phase spaces

$$\eta_{\mathrm{front-end}} = \eta_{||} \quad \eta_{\perp}$$

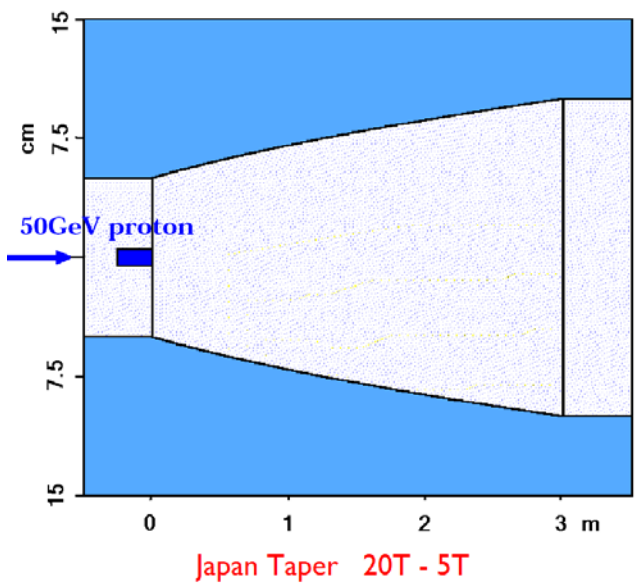
$$\frac{Muons}{Pions} = \eta_{\mathrm{front-end}} \quad \eta_{\mathrm{accel}}$$

- Include decay losses in phase rotation in $\eta_{||}$
- Include decay losses in cooling in $\eta_{\perp}$
- Estimate $\eta_{||}$ from published information
- Estmate $\eta_{\perp}$ without cooling from my simulations
- Estmate $\eta_{\perp}$ with cooling from published $\eta_{\mathrm{front-end}}$ and $\eta_{||}$

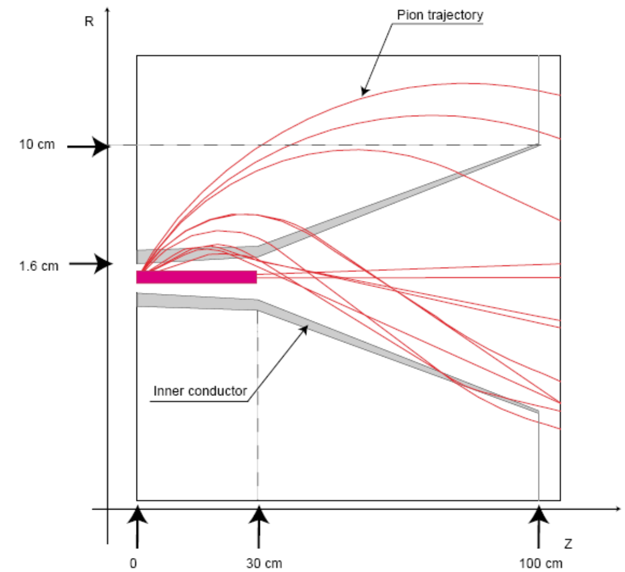
Pion Capture Methods

All use 20 T solenoid except CERN Horn

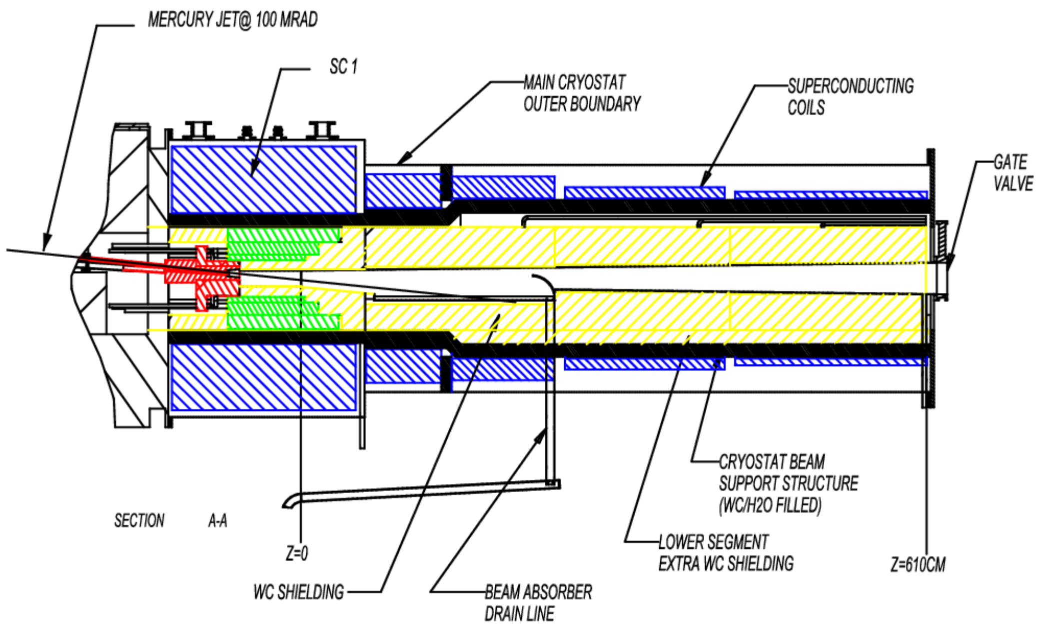
Japan



CERN



US



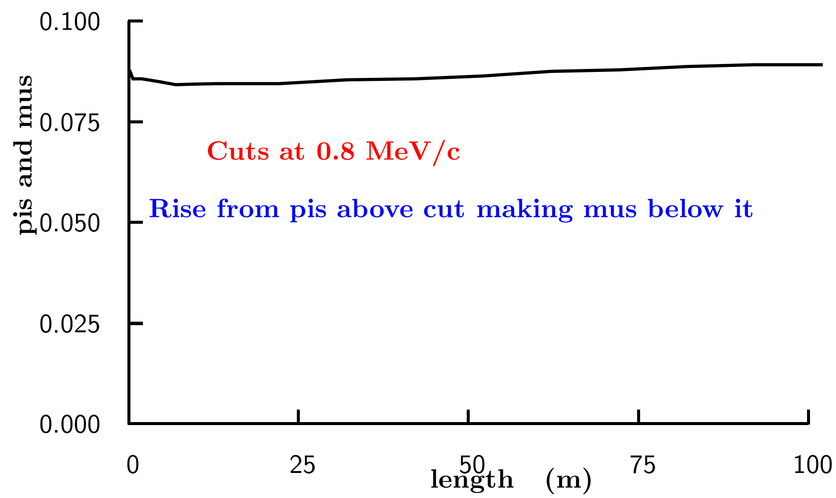
Channel transverse acceptances all very large

Case	mom (MeV/c)	Bz (T)	rad (cm)	Accept (pi mm)
Japan	300	5	16	180
CERN 44/88	286	1.8	30	250
US FS2 decay	220	1.25	30	170
US FS2a decay	220	1.75	30	240
US FS2a cool	220		25	180

Pions initally captured

(number of muons for 1000 proton on the target)

decay	in	180
	out	177
rotation	in	93
	out	93
cooling I	in	32
	out	31
acceleration	in	31
	out	31
cooling II	in	20
	out	15

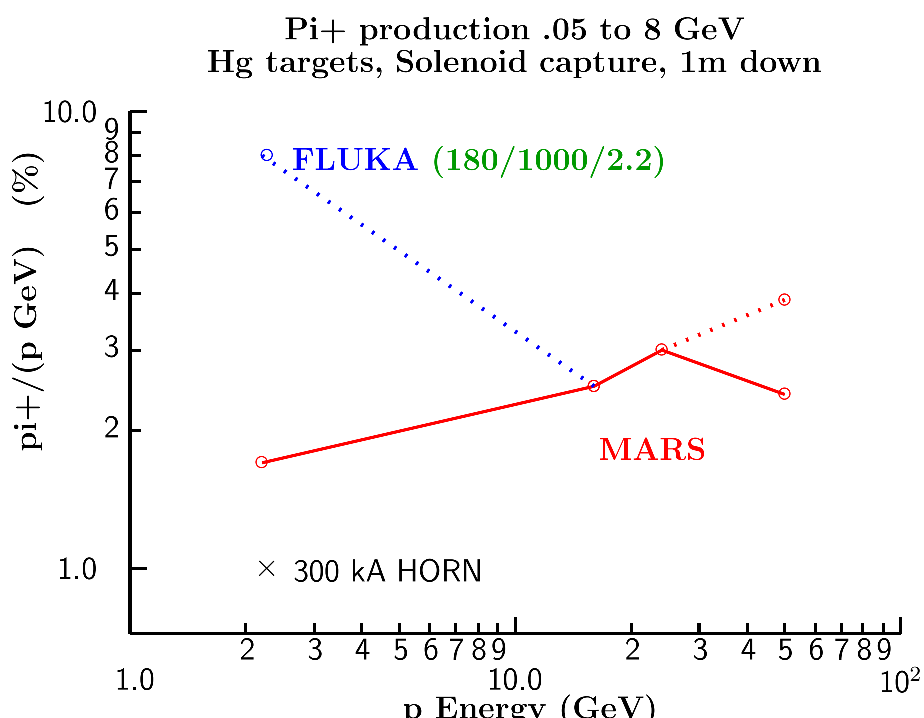


- Both cases: Few lost in tapered channel

Pions Captured   All use Mercury

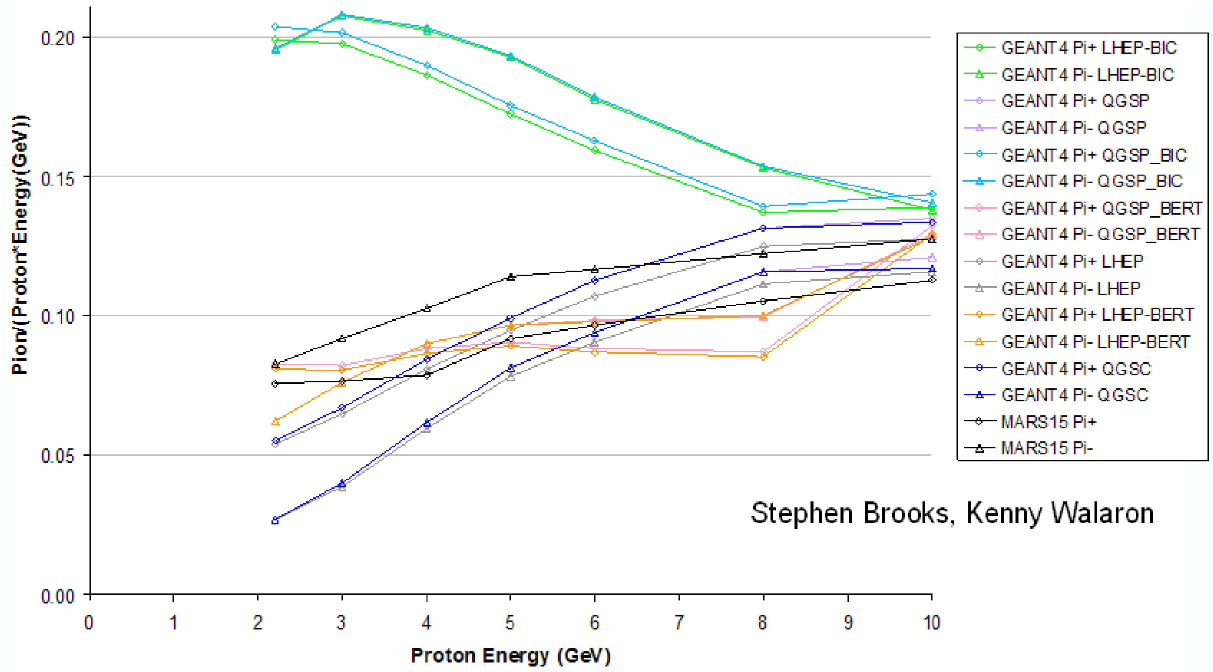
0.05-0.8 GeV/c Production in Proposed Schemes (as reported)

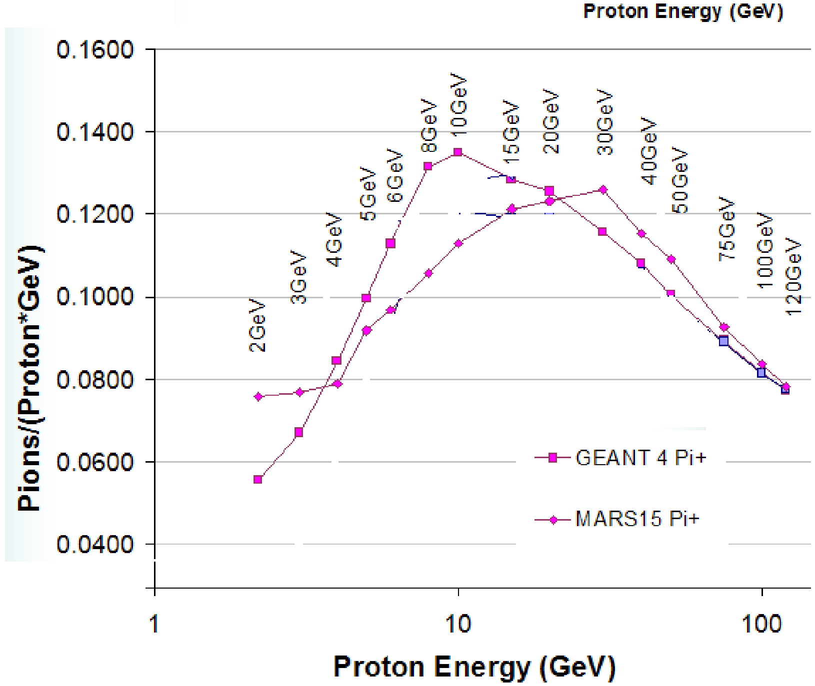
ref	Case	Program	Ep (GeV)	mu/p GeV (%)
NufacJ	Japan text	MARS14	50	1.2/50=2.4
NufacJ	Japan figure	MARS14	50	2/50=4.0
nf20	CERN 44 and 88 MHz	FLUKA	2.2	0.18/2.2=8.2
n42	CERN 300 kA horn	MARS	2.2	1.0
n42	CERN 400 kA horn	MARS	2.2	1.4
n42	CERN Solenoid	MARS	2.2	1.7
n42	CERN Solenoid	MARS	16	2.5
S2a	US Study 2a	MARS	24	0.8/24=3.3



- FLUKA Production at 2.2 GeV Anomalous

Compare with different Production Models





- Significant variations between codes
- Similar anomally at low pi energies with 3 codes

Longitudinal Capture Phase Space

Problem is to match initial muons into RF bucket

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

  σ_t from decay $\approx$ 3 nsec, $\Delta t = 2 \; \sigma_t$ $\quad$ ΔE/E=100%, and $\beta\gamma = 2$:

$$\epsilon_{\|} \;=\; 4(\mathrm{m}) \;=\; 1.3 \; (\mathrm{eV \; sec})$$

- Bucket areas: $A_{\mathrm{bucket}} \;\propto\; \sqrt{\frac{\mathcal{E} \;\; \cos(\phi)}{\mathrm{f}}}$

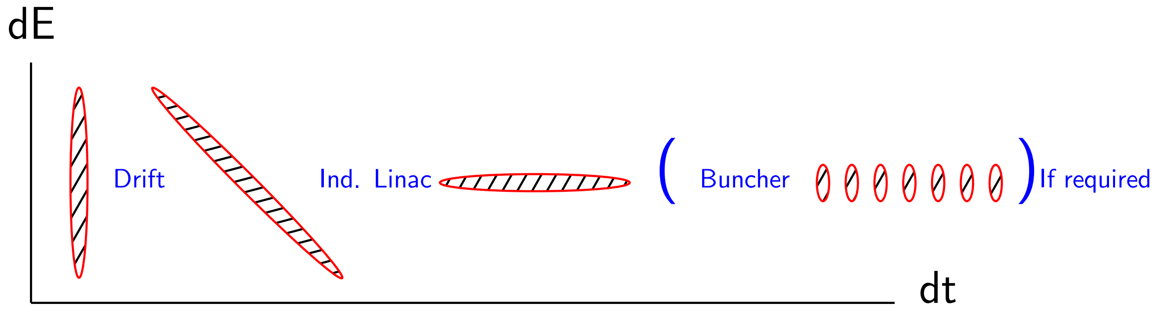
  But if limited by $\Delta = \Delta p/p$, then: $\epsilon_{\mathrm{bucket}} \;\propto \Delta^2 \sqrt{\frac{1}{f \;\mathcal{E} \;\; \cos\phi}}$

Case	f (MHz)	n bunches	$\mathcal{E}$ (MV/m)	$\Delta p/p$	$A_{\|}$ (pi m)	Acc/Init
Japan	5	1	1	50%	13	3.2
CERN 44/88	88	1	4	?	0.3	0.08
US FS2a	200	80	11	22%	0.15×80=12	3.0

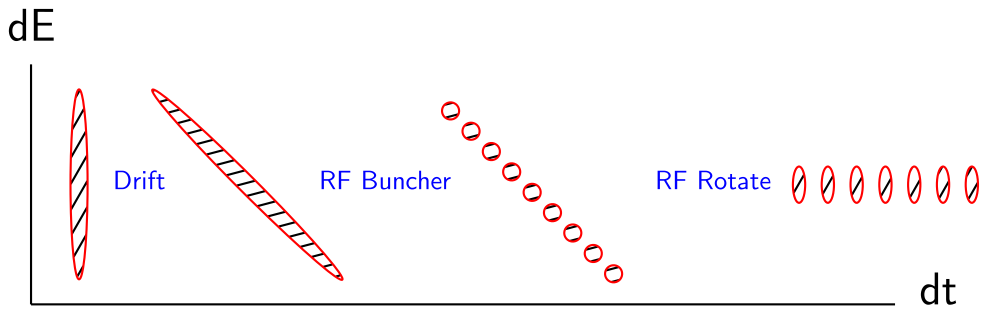
- Japan and US have enough acceptance to capture entire production
- CERN lacks longitudinal acceptance
- To best match into bucket requires "Phase Rotation"

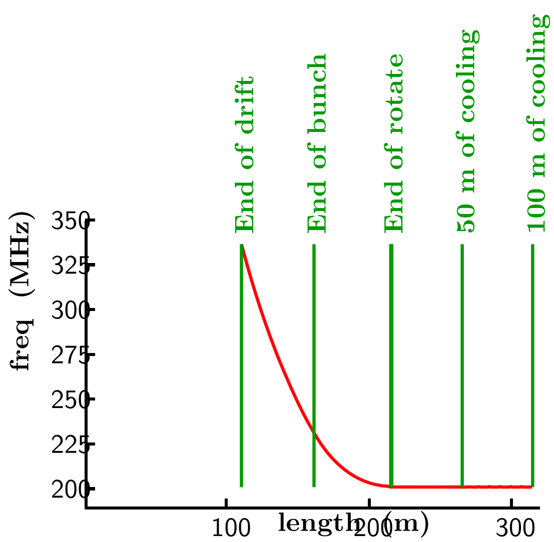
Phase Rotation Schemes

Conventional with LF RF or Induction Linacs



Bunched Beam Rotation with 200 MHz RF (Neuffer)





- RF frequency must vary along bunching channel (high mom. bunches move faster than low)
- Higher freq RF is cheaper than Induction Linacs
- Bunched Beam method captures both signs in interleaved bunches

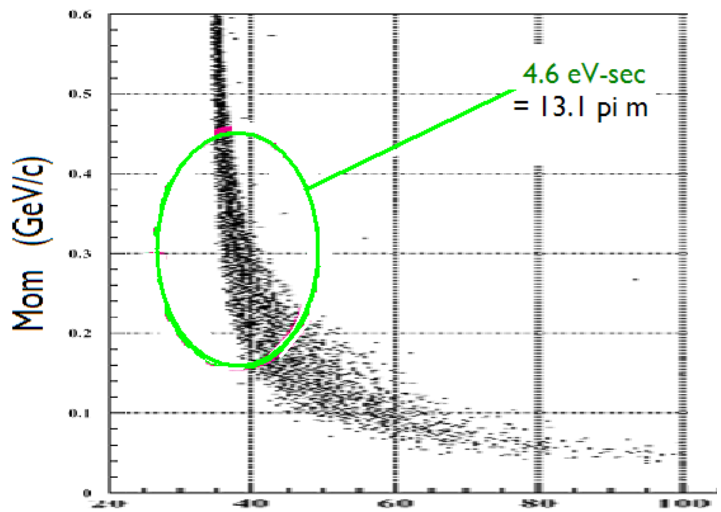
Phase Rotation Parameters

- Japan couples directly into first FFAG's RF bucket
- CERN rotates with 40 MHz RF

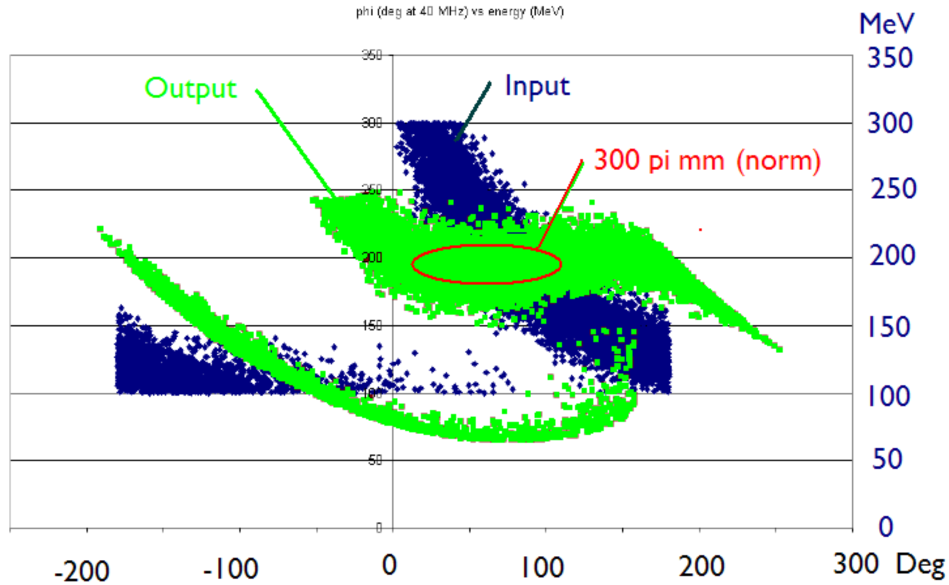
	Decay	Rotation
Length [m]	30	30
Diameter [cm]	60	60
B-field [T]	1.8	1.8
Gradient [MV/m]		2
Kin Energy [MeV]		200

- US Uses Bunched Beam Rotation
  100 m drift, 40 m buncher, 54 m rotator

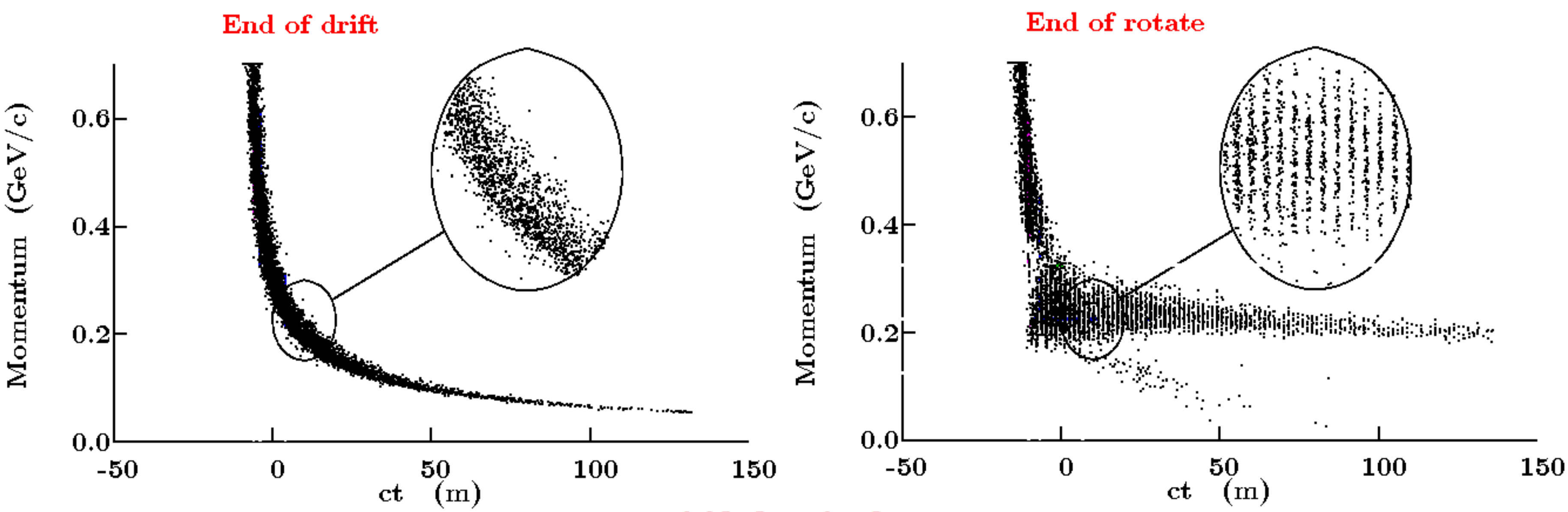
Phase Rotation



Japan: Direct Capture

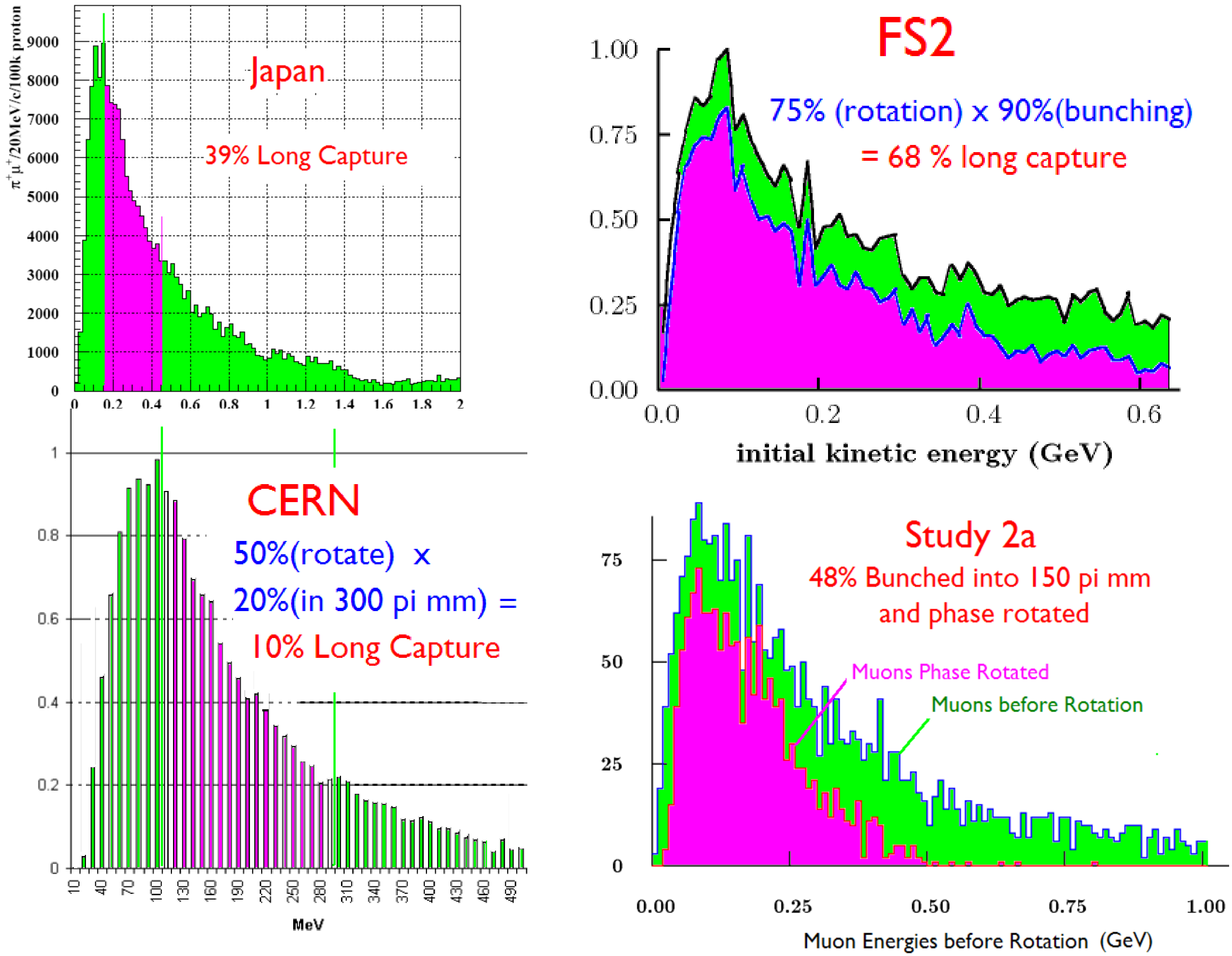


CERN 44/88 MHz



US Study 2a

Longitudinal Capture Efficiency including decays in rotation



Longitudinal Capture Efficiencies η

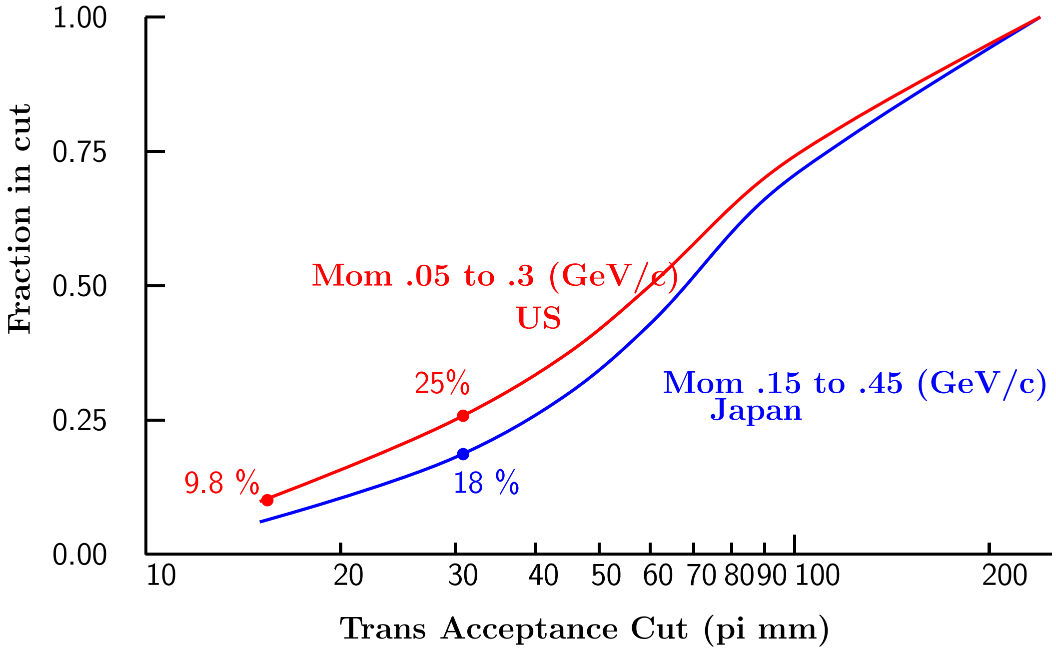
Case	Rotated	% in $A_{\|}$	eta	$A_{\|}/A_{\mathrm{prod}}$
Japan		39%	39%	3.2
CERN	50%	20%	10%	8%
US FS2	75%	90%	68%	3
US Study 2a	48%		48%	3

- Rotation could help Japan scheme
  e.g. in linear channel with large dp/p
- US Schemes are also inefficient
  possibly amplitude-velocity effects
- CERN should rotate to multiple bunches

Transverse Acceptance ($\eta_\perp$) if no cooling

Assume trans momentum distributions same for all p energies (true at high E)

Use 24 GeV MARS with mercury



If no cooling

- 9.8 % for CERN (15 pi mm)
- 18 % for Japan (30 pi mm, .15-.45)
- 25 % for US (300 pi mm, .05-.3)

- Less accepted at higher total momenta
- Average transverse momenta must be rising

Transverse Acceptance ($\eta_\perp$) with Cooling

- Use published $\eta_{\mathrm{front-end}}$ and above $\eta_\perp$

Cooling

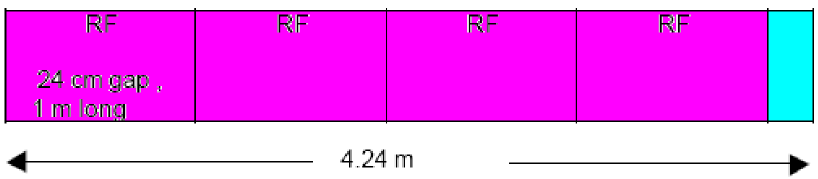
Japan

Cooling with hydrogen gas in first FFAG

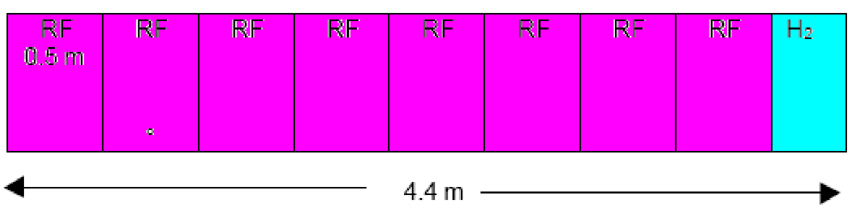
If acceptance of this ring not greater than later rings then there is no gain and lowest mom ring is hardest to get large transverse acceptance

Could lower cost of later rings

CERN



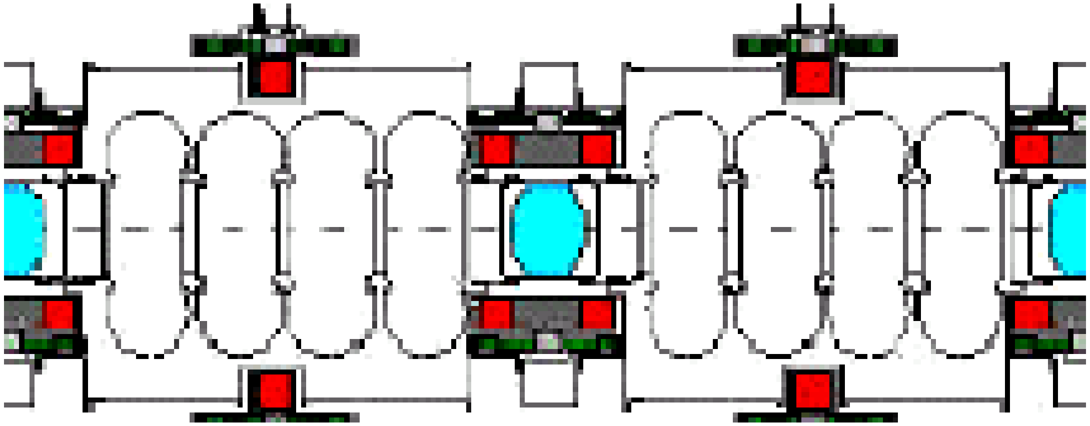
44 MHz



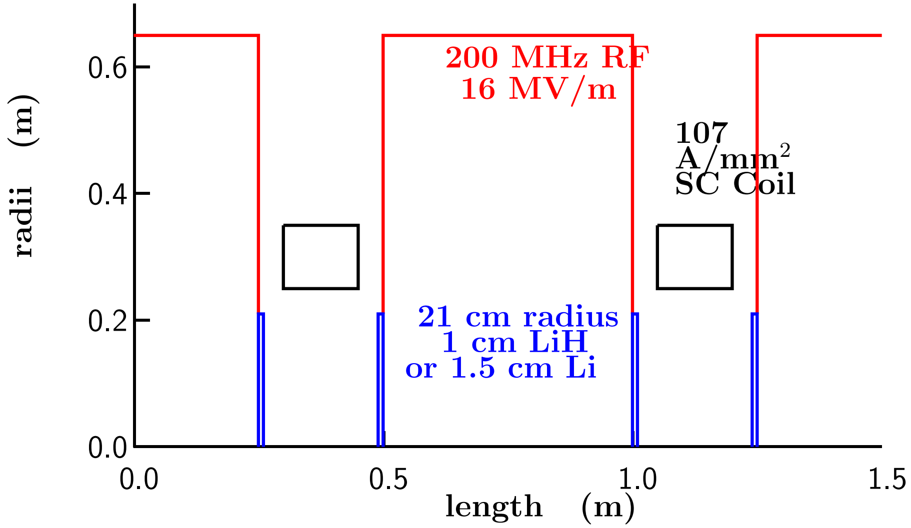
88 MHz

	Cooling I	Accel.	Cooling II
Length [m]	46	32	112
Diameter [cm]	60	60	30
B-field [T]	2.0	2.0	2.6
Frequency [MHz]	40	40	80
Gradient [MV/m]	2	2	4
Kin Energy [MeV]		280	300

US Feasibility Studies



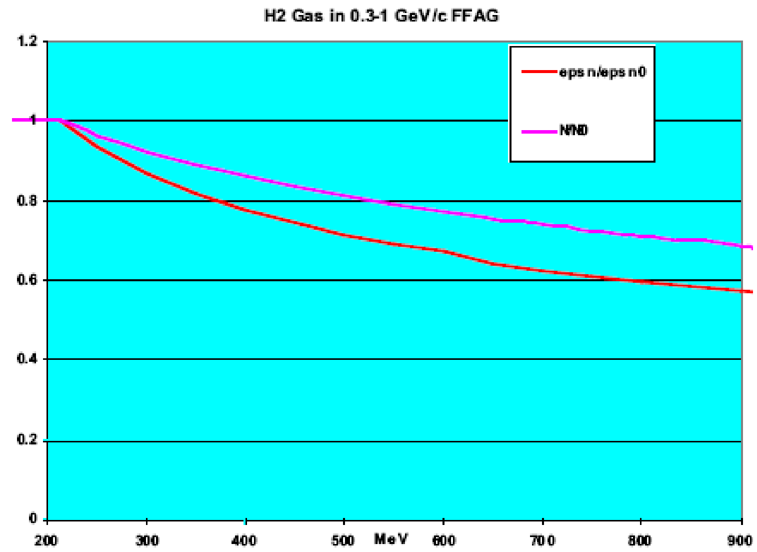
FS2 Cooling



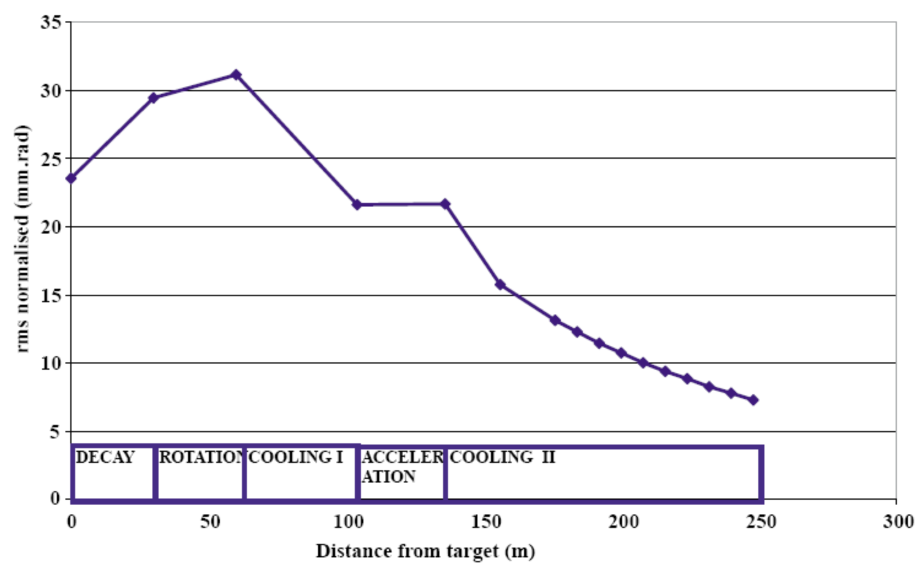
S2a Cooling - same RF

Cooling Performances

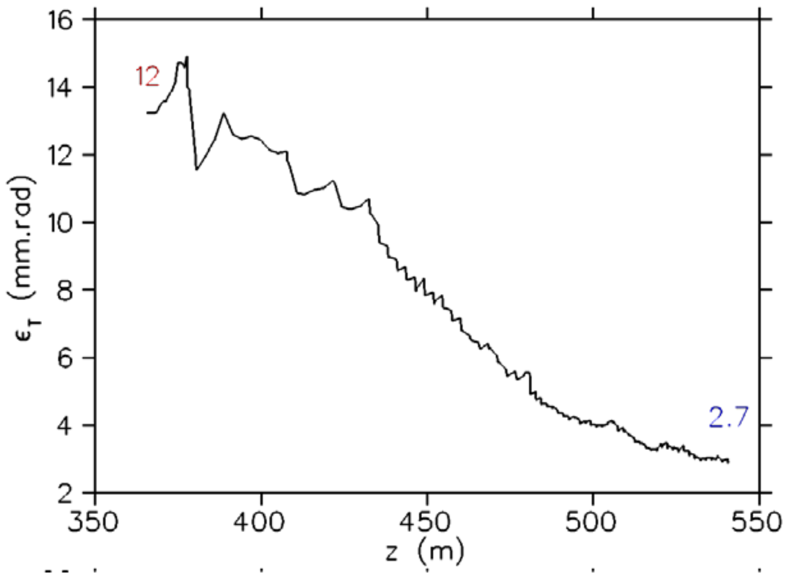
Japan



CERN

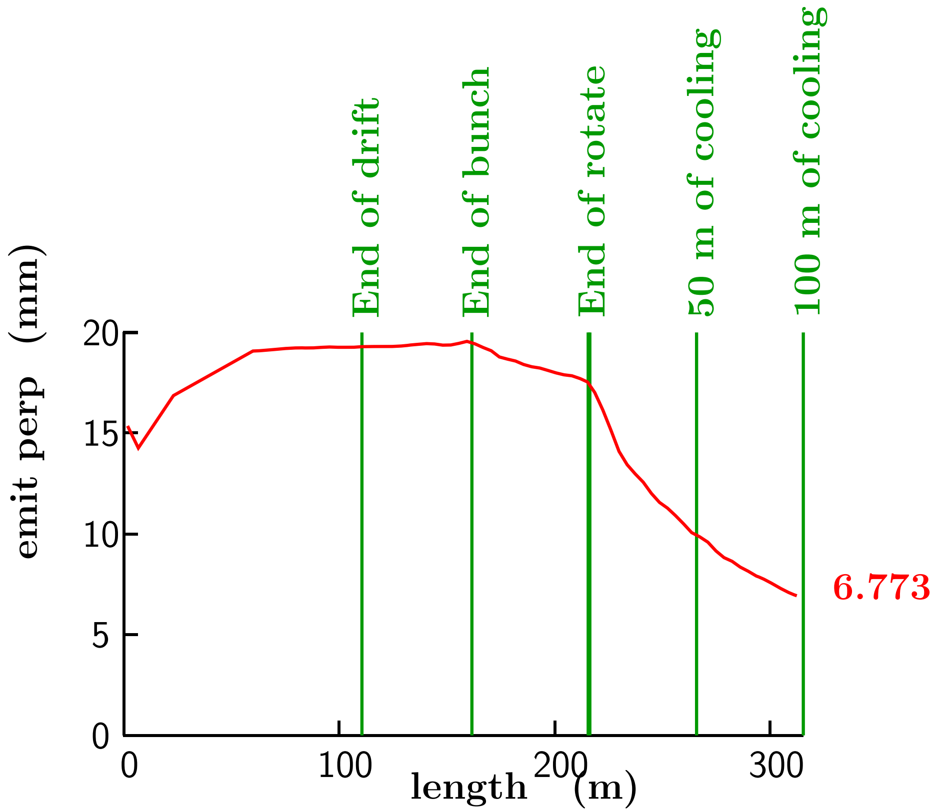


US



12
2.7
ϵ_T (mm.rad)
z (m)
16
14
12
10
8
6
4
2
350
400
450
500
550

FS2



End of drift
End of bunch
End of rotate
50 m of cooling
100 m of cooling
emit perp (mm)
length (m)
6.773
20
15
10
5
0
0
100
200
300

S2a

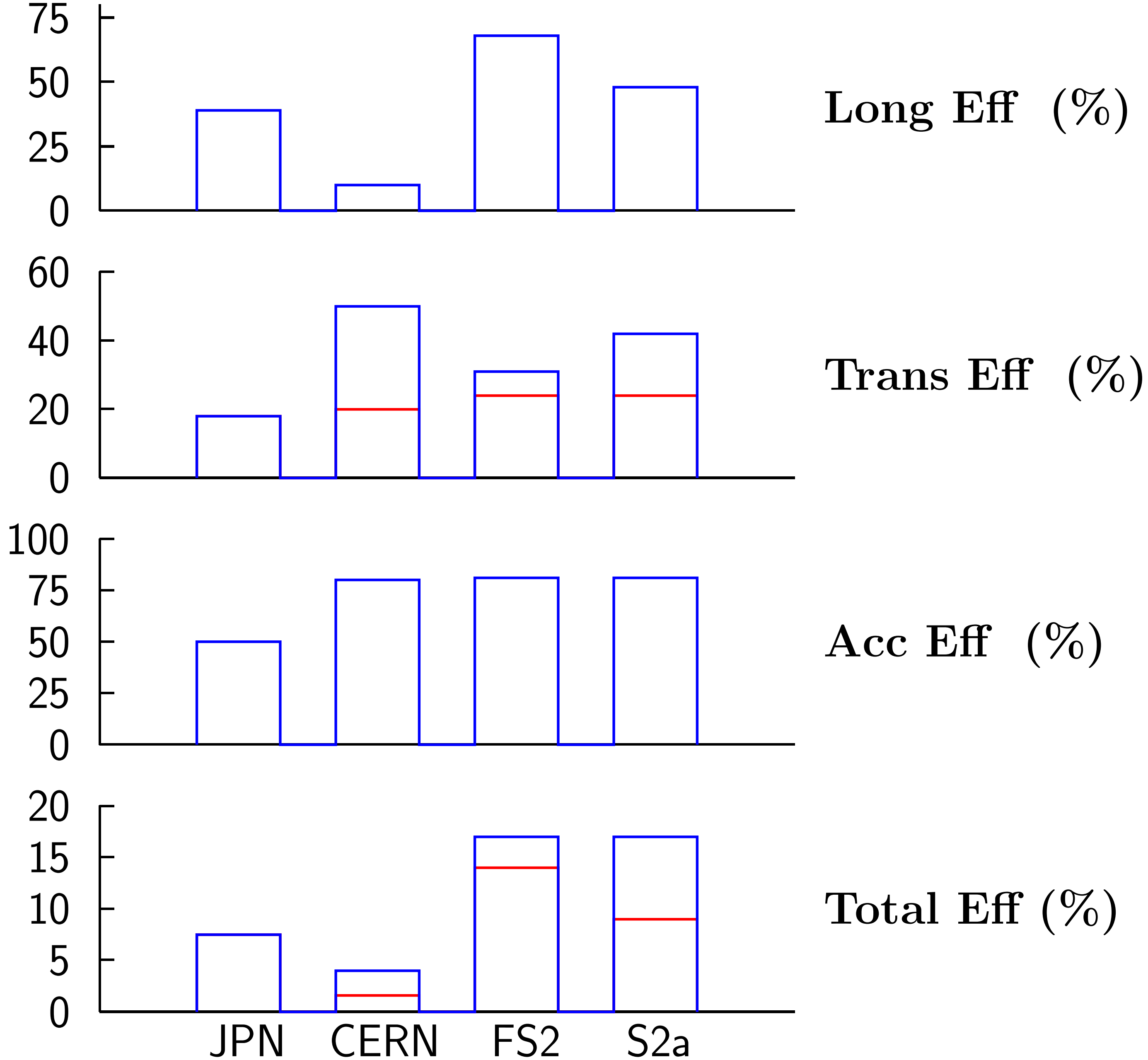
Over All Performance

Due to uncertainty in pion production , look at muons per pion

case	Cool?	Trans Acc pi mm	Long effic.	Trans effic.	Frontend mu/pi	Acc effic.	All mu/pi	Signs
Japan	no	30	.39	(0.18)	0.15[1]	0.5	0.075	1
Cern 44/88	yes	15	(0.10)	(0.5)	0.05[2]	0.8	0.04	1
Cern 44/88	no	15	(0.10)	(0.08)	(0.008)	0.8	(0.0064)	1
Cern 44/88	no	30	(0.10)	(0.20)	(0.02)	0.8	(0.016)	1
US FS2	yes	15	0.68	0.31	0.21	0.81	0.17	1
US FS2	no	15	0.68	0.10	0.07	0.81	0.06	1
US FS2	no	30	0.68	0.24	0.16	0.81	0.14	1
US Study 2a	yes	30	0.48	0.42	0.21	0.81[3]	0.17	2
US Study 2a	no	30	0.48	0.24	0.12	0.81[3]	0.09	2

- Parentheses cover numbers deduced by me

1. 0.3/(50 GeV $\times$ 2.0), 2.0 from sum of pis vs mom plot
2. from nf34, nf20 gives a somewhat higher number
3. Matching loss not included since no such loss in other examples included

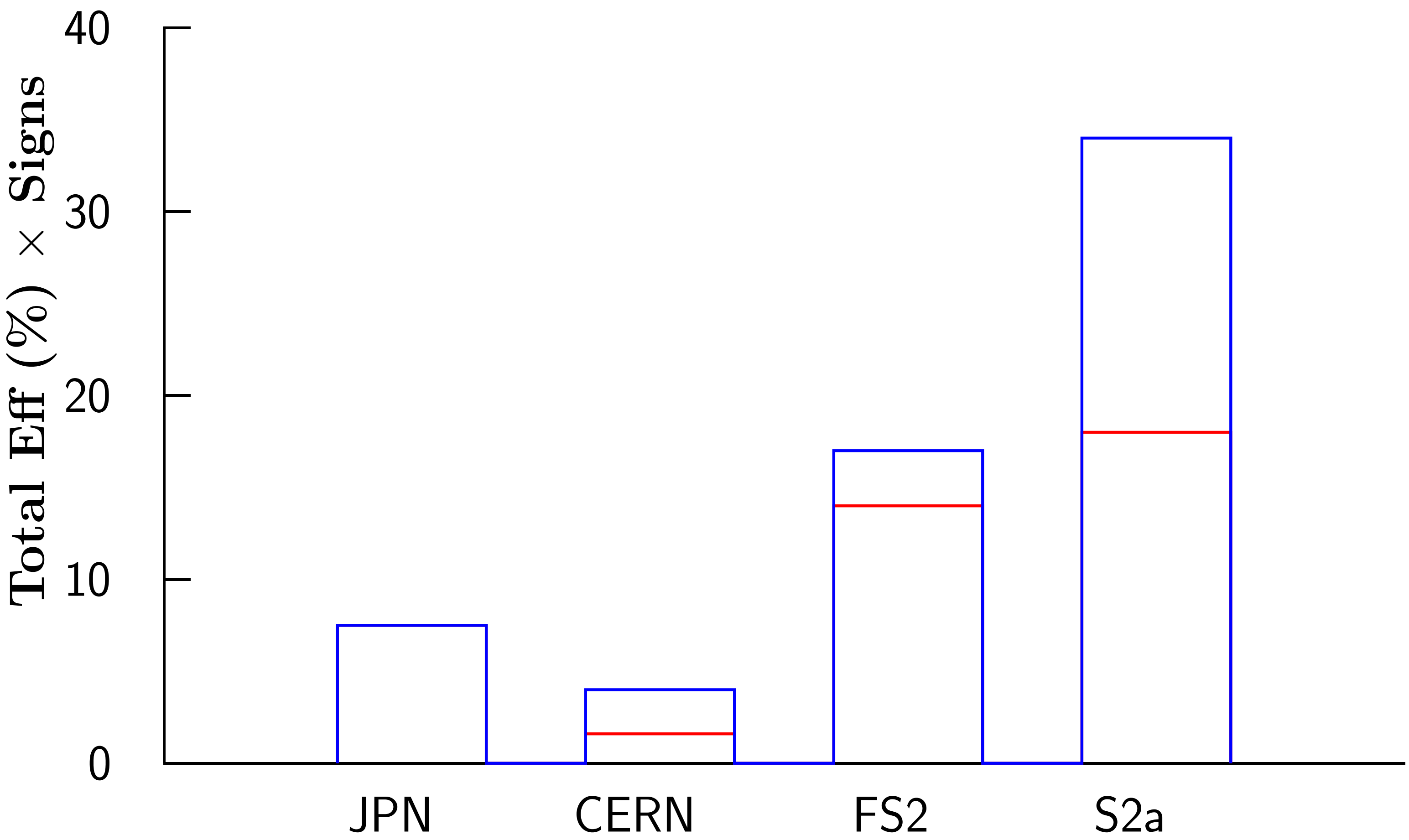


Red is for no cooling into 30 pi mm

Notes

- CERN's gain from cooling (6.25 $\times$) is best
  FS2: 3 $\times$ S2a: 1.7 $\times$)
- Japan's efficiency $\approx$ S2a efficiency without cooling,
  but S2a has 2 signs and cooling giving $\times$ 4.5
- CERN's poor performance mainly due to poor longitudinal efficiency
  as expected from small longitudinal acceptance

Multiply by number of signs



Red is for no cooling into 30 pi mm

Muon decays per year towards detector

- With 4 MW proton power and 300% straight over circumference
- Assume pion per proton = .33 (S2a value taken arbitarily)

case	cooling	trans acc pi mm	signs	mu/pi	mu/year $\times 10^{20}$
Japan	no	30	1	0.075	1.8
Cern 44/88	yes	15	1	0.04	1.0
Cern 44/88	no	15	1	(0.0064)	0.15
Cern 44/88	no	30	1	(0.016)	0.37
US Study 2a	yes	30	2	0.17	8
US Study 2a	no	30	2	0.09	4.2

- Not even the S2a performance quire reaches the 10^{21} goal
- But din'nt CERN (nf20) get $1.6\ 10^{21}$ yet here it geta only $1\ 10^{20}$
  - nf20 assumed a very high pion production
  - nf34, with greater realism ?, got a litttle less
  - this was the numbers into the ring, not decaying towards detector

$$1\ 10^{20} \approx 0.37\ (\text{pi prod}) \times 0.7\ (\text{nf34/nf20}) \times 0.3 \times 1.6\ 10^{21} (\text{nf20})$$

The best features

- In Japan's Scheme
  - The use of very large accelerator/storage ring acceptance
    Allows reasonable performance without cooling
- In CERN's Scheme
  - Using many RF cavites before hydrogen absorbers
    Allows use of fewer, but longer absorbers
    Reduces cost
    Reduces effect of windows
  - Most effective cooling scheme
- In US Scheme
  - Bunched Beam Phase Rotation
    Allows large initial longitudinal acceptance without low frequency
    Captures both signs

Possible improvements

- In Japan's Scheme
  - Add linear Phase rotation before acceleration
    gain of up to a factor of 2
- In CERN's Scheme
  - Use Bunched Beam Phase Rotation
    Gain up to about 5 in longitudinal capture
    and get both signs
    A full order of magnitude improvement ?
- In US Scheme
  - Bunch absorbers a la CERN, use Hydrogen, and add cooling length
    Possible gain approaching 2
    but expensive

Conclusions

- All designs have particular good ideas
- All designs could be improved
- The ISS is going to be very useful