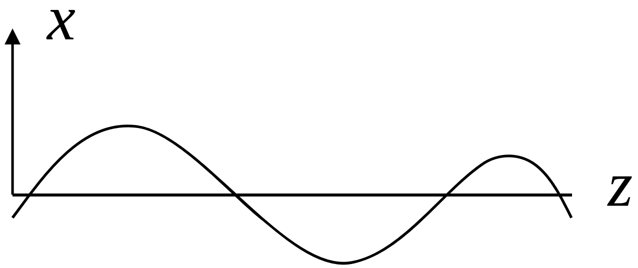
COOLING FOR A NEUTRINO FACTORY

- Stored muon beams ➔ clean ν_μ and ν_e beams
- Physics requirements:
  - ~10^{21} stored muons / year = 10^{14} μ / sec
  - → Detectors of [few x 10kT] x [a few years]
  - – There are tradeoffs
    - Stored muons *versus*
      - – Detector mass
      - – Running time
    - Minimise cost
- Cooling probably necessary for a NF
- Essential for muon collider

SOME DEFINITIONS

Particle makes betatron oscillations around reference trajectory



$$x = \sqrt{A\beta_t}\,\sin(\psi(z) + \psi_0)$$

A = ***Amplitude*** – property of particle
β_t = ***Betatron function*** – property of lattice

Acceptance = largest amplitude particle accepted by a machine

ε = ***Emittance*** = *rms* amplitude of particles in a beam

$\varepsilon_n = \beta\gamma\varepsilon = (p_z/m_0c)\varepsilon$ = ***Normalised Emittance*** [Length]

$(m_0c\varepsilon_n)^2 = \det(\mathbf{V})$ where $\mathbf{V} = (x,p_x)$ covariance matrix

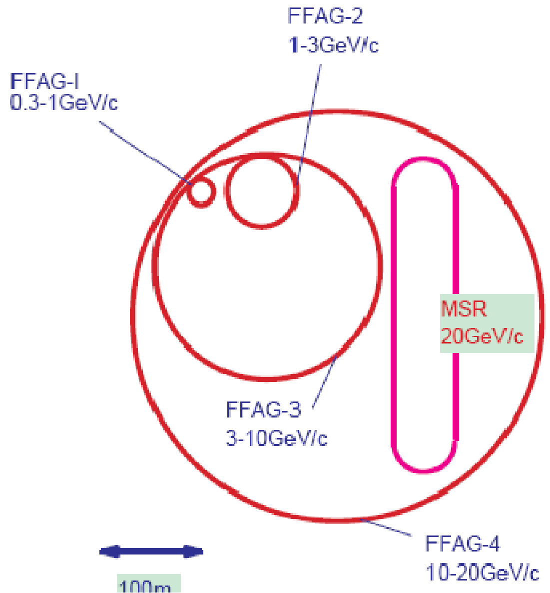
$$= \sigma^2_x\sigma^2_{p_x} - (\sigma^2_{xp_x})^2$$

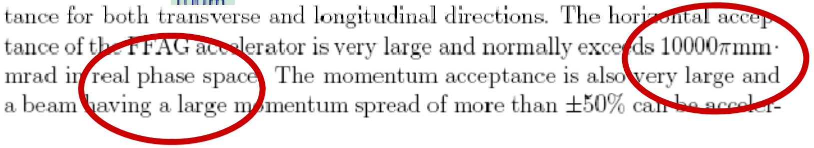
Cooling = reduction of normalised emittance (by reducing p_t)

- Neutrino factory thinking has evolved
- Initially
  - (US, EU) based on muon collider designs
    - Small acceptances
    - Lots of cooling
    - Expensive
  - Or (Japan) *scaling* FFAGs
    - Large acceptance
    - No cooling
- More recently (FS2A, ISS)
  - Possibility of *non-scaling* FFAGs for μ acceleration
    - Large acceptance
    - Modest cooling

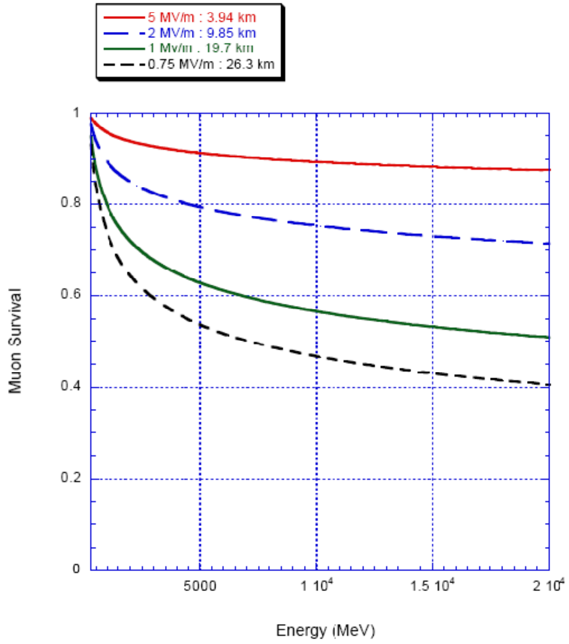
A NEUTRINO FACTORY *WITHOUT* COOLING

FFAG based neutrino facotry in Japan





tance for both transverse and longitudinal directions. The horizontal acceptance of the FFAG accelerator is very large and normally exceeds 10000πmm·mrad in real phase space. The momentum acceptance is also very large and a beam having a large momentum spread of more than ±50% can be acceler-



5 MV/m

1 MV/m

Figure 2.1: Muon survival during acceleration from 300MeV/c to 20GeV/c for various accelerating gradients and fractional distances along the machine

Muon survival versus Energy

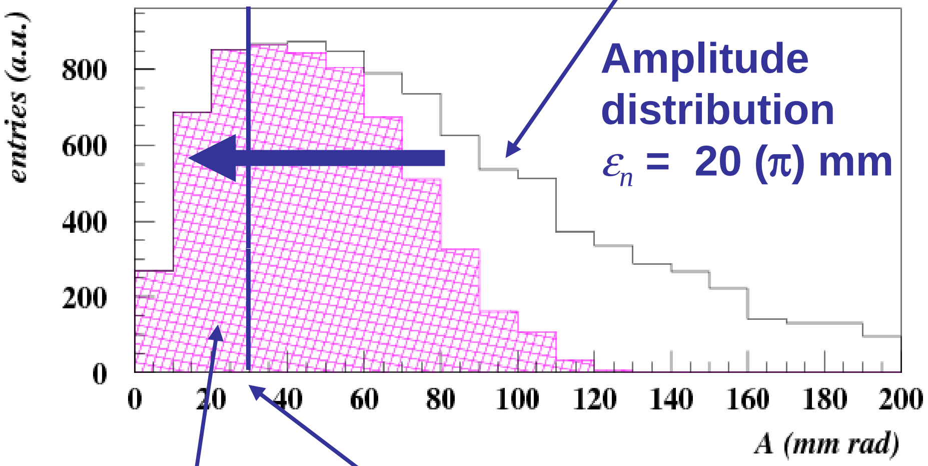
NufactJ at JPARC (2001)

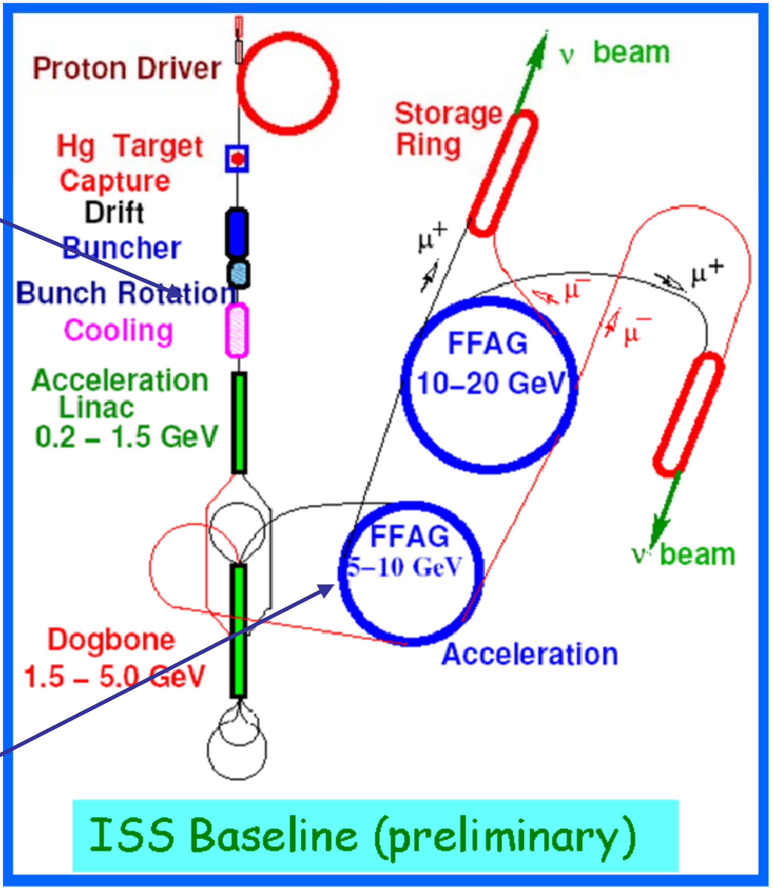
4 cascaded scaling FFAGs

Assumed acceptance of >10(π) mm + acceleration of > 1 MV/m

A NEUTRINO FACTORY *WITH* COOLING

Muon beam has ε_n ~ 20 (π) mm

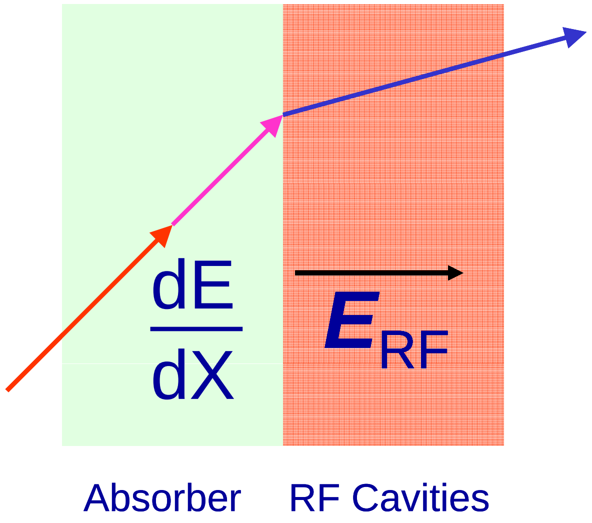


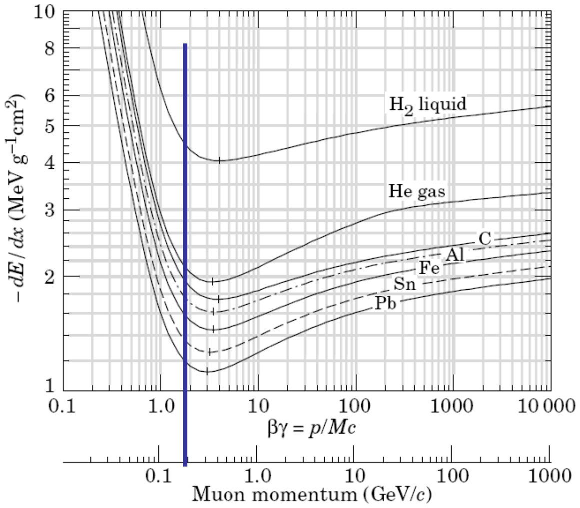


Cool to maximise
μ in acceptance

Acceptance of FFAGs ~30 (π) mm

IONISATION COOLING

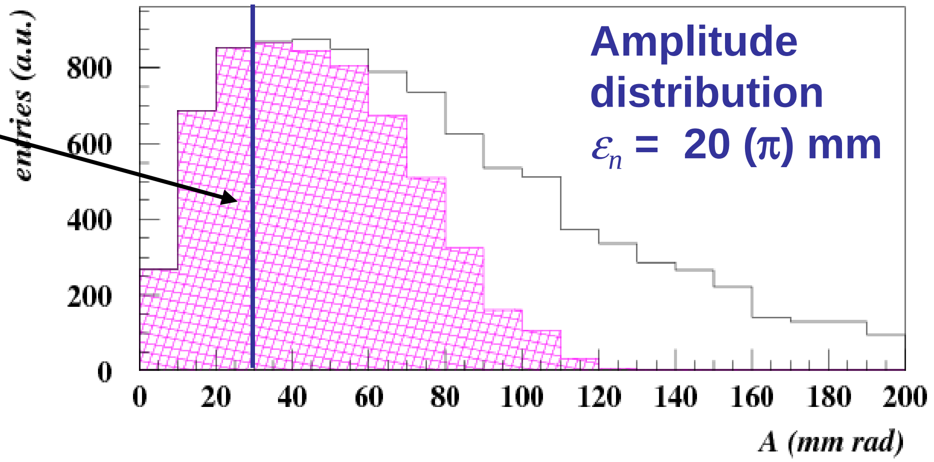




- Pass muons through absorbers ➔ dE/dX reduces p_t and p_l
- RF replaces p_l ➔ beam cooled
- ~ 200 MeV/c is optimum
  - lower momentum ➔ longitudinal emittance growth (+ feedback)
- Transverse emittance decreases exponentially

HOW MUCH COOLING IS NEEDED FOR A NF?

Acceptance = 30mm

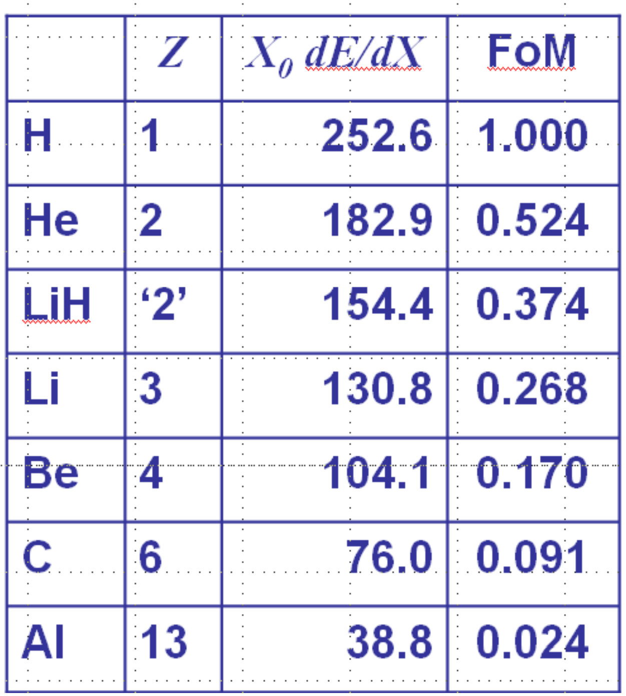


(Coloured histogram is after scraping in one 5.5 MICE/FS2 lattice section)

- Nothing like as demanding as $\mu\mu$ collider
- Depends on final acceptance
- Need enough cooling to get useful gain in number of μ
- Tradeoff against decay losses of ~ 1% / 10m @200 MeV/*c*
- Diminishing returns once most of amplitude distribution inside acceptance
- 2 – 3 emittance reduction if Acc ~ 30mm, more if smaller
  - – Stop and reaccelerate muons ~ once ➔ ε_n ~~ 5 – 7 mm

MATERIALS

$$\frac{d\varepsilon_n}{dz} = \frac{-\varepsilon_n}{\beta^2 E}\left\langle \frac{dE}{dX} \right\rangle + \frac{\beta_t \left(0.014\ \mathrm{GeV}\right)^2}{2\beta^3 E m_\mu X_0}$$



	Z	$X_0\ dE/dX$	FoM
H	1	252.6	1.000
He	2	182.9	0.524
LiH	‘2’	154.4	0.374
Li	3	130.8	0.268
Be	4	104.1	0.170
C	6	76.0	0.091
Al	13	38.8	0.024

dE/dX reduces ε_n

Scattering increases ε_n

➔ low Z absorber material

➔ tight focus (low β_t) ➔ Solenoids

Equilibrium emittance, $\varepsilon^o{}_n$, proportional to $(X_0 <dE/dX>)^{-1}$

Central phase space density proportional to $(\varepsilon^o{}_n)^{-2}$

➔ **Figure of Merit** = $(X_0 <dE/dX>)^2$

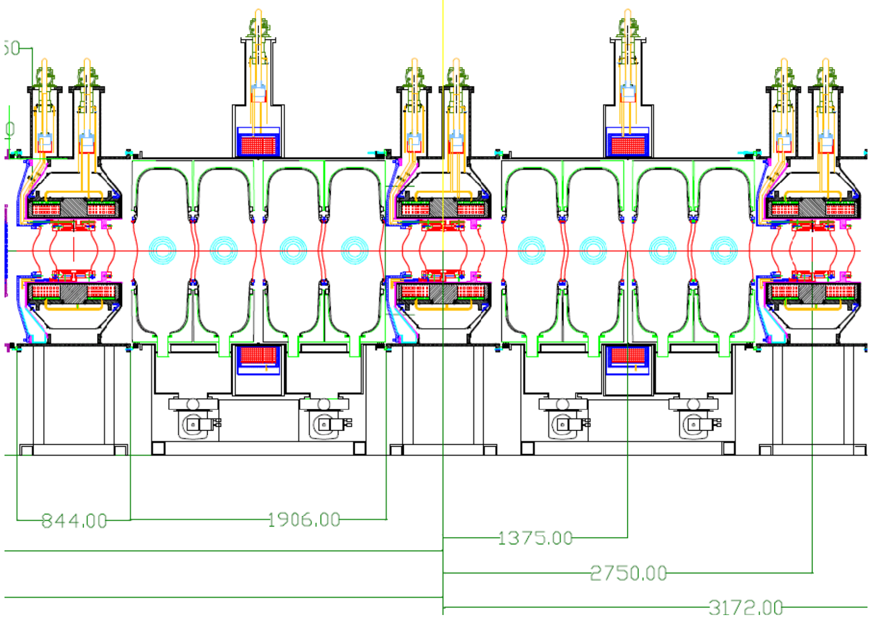
➔ H_2 is best (in theory)

Initial cooling ~independent of material if $\varepsilon_n >> \varepsilon^o{}_n$

FoM possibly more relevant to $\mu\mu$

FS2 COOLING CHANNEL

***Feasibility Study-II of a Muon-Based Neutrino Source*, ed., S. Ozaki, R. Palmer, M. Zisman, and J. Gallardo, BNL-52623 (2001).**



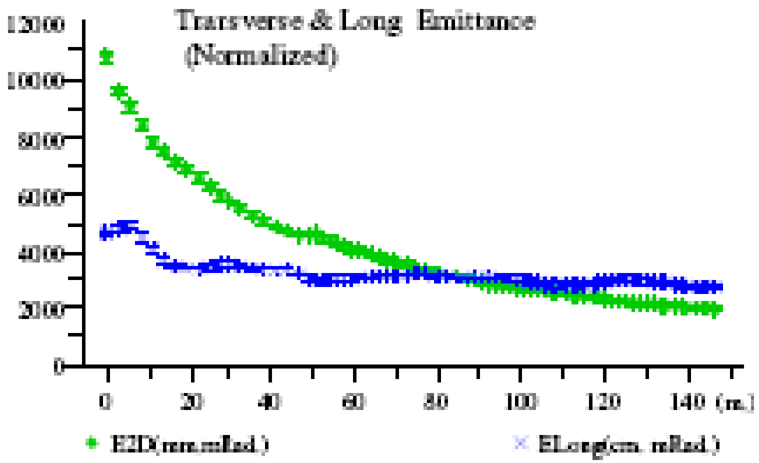
(MICE incarnation)

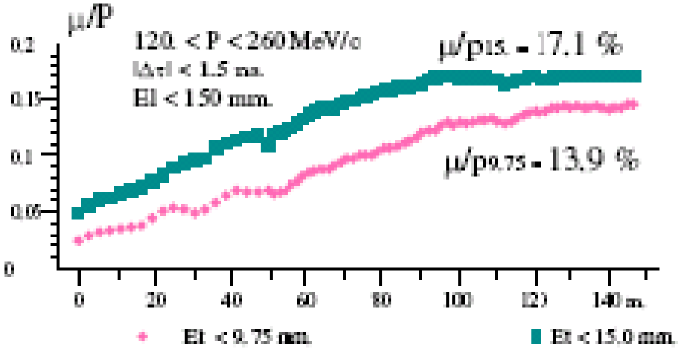
5.5m solenoidal lattice, 200 MHz

~4T peak fields + flips

Tapered β from 42 → 25 cm

LH_2 absorbers, ΔE ~10 MeV





Gain of μ into acceleration

~ 5 for Acc = 9.75mm

~ 3.5 for Acc = 15mm

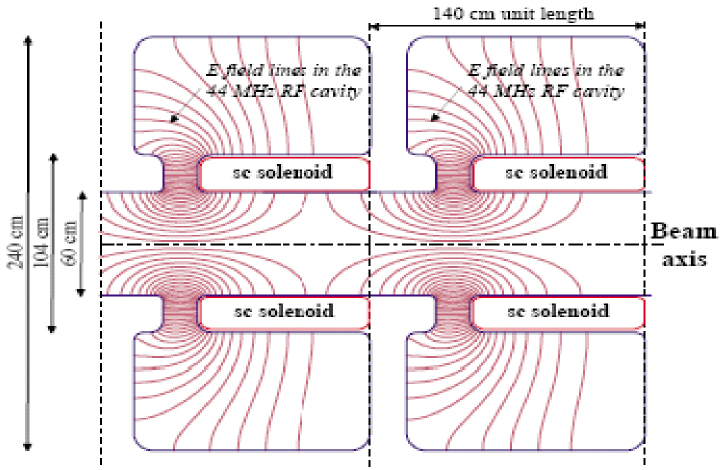
CERN SCHEME A.Blondel *et al.* CERN-2004-002

46m of 44MHz, B = 2.3T
11 x [4 x 1m cavities+24cm LH_2]
ΔE = 5.6MeV/cell

112m of 88MHz, B = 5T
25 x [8 x 0.5m cavities+40cm LH_2]

Absorbers / no absorbers
➔ 10x gain in N_μ
into Acc = 15(π) mm

0.07 mu/pi @2GeV



ng channel modules, with 44 MHz cavities and supercor

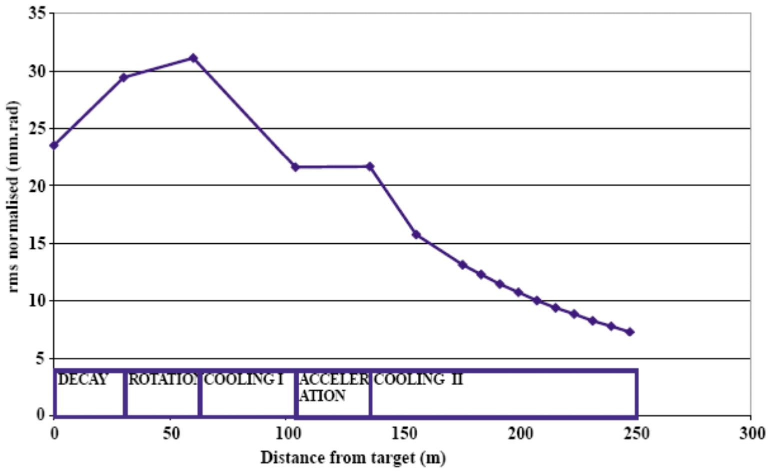
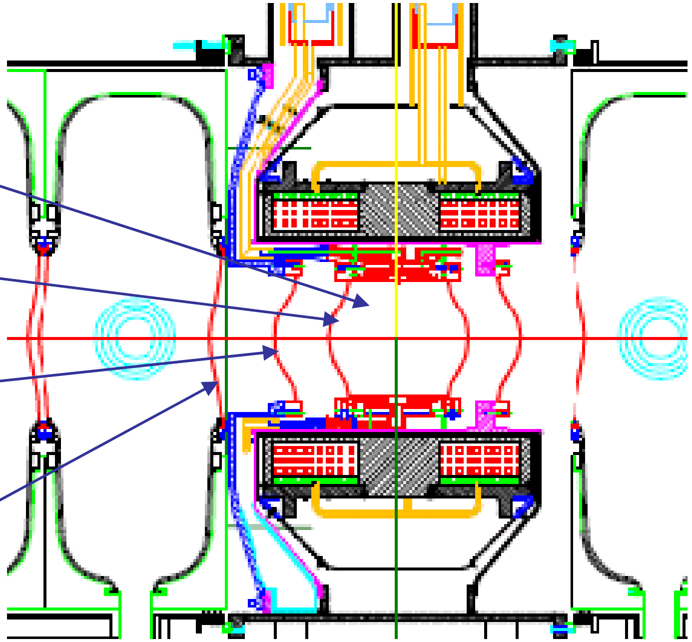


Fig. 6. Evolution of transverse emittance

IS REAL HYDROGEN REALLY SO GOOD?



35cm Hydrogen

Absorber windows 0.16mm

Safety windows 0.16mm

Be cavity windows 0.2mm

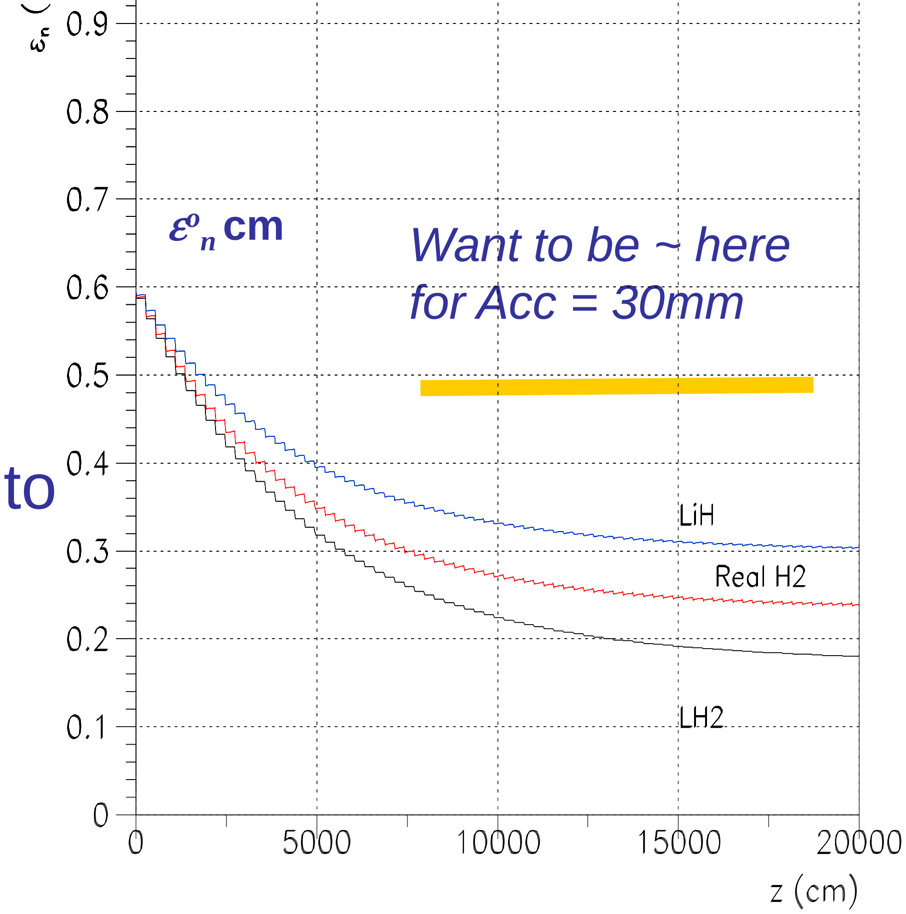
Presence of other material reduces benefit of H_2

Estimate from cooling formula:

Piecewise integration of

$$\frac{d\varepsilon_n}{dz} = \frac{-\varepsilon_n}{\beta^2 E}\left\langle \frac{dE}{dX} \right\rangle + \frac{\beta_t\,(0.014\ \mathrm{GeV})^2}{2\beta^3 E m_\mu X_0}$$

for long FS2-like LH_2 channel to determine effective $\varepsilon^o{}_n$



$\varepsilon^o{}_n$ **cm**

Want to be ~ here for Acc = 30mm

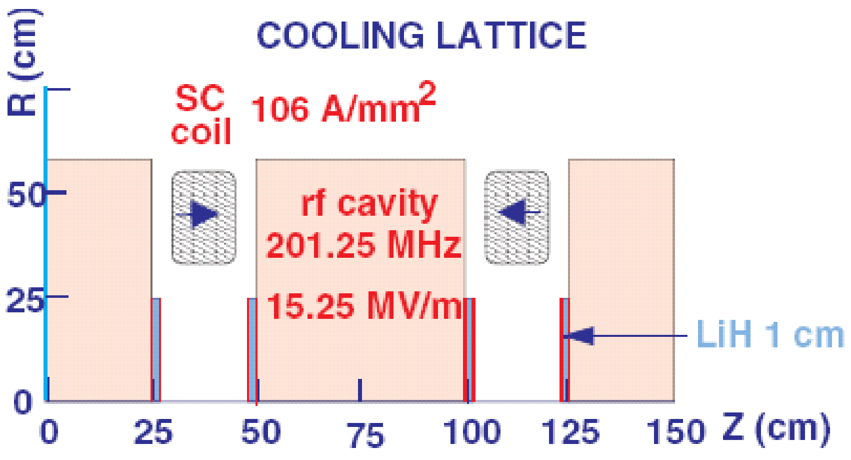
Compare with ideal LH_2 & LiH

LH_2	$\varepsilon^o{}_n$ = 1.76mm
Real LH_2	$\varepsilon^o{}_n$ = 2.36mm
LiH	$\varepsilon^o{}_n$ = 3.01mm

so FoM for LiH *cf* ‘real’ LH_2 ~ 0.6 – not so bad

FS2A/B SCHEME (~ISS)

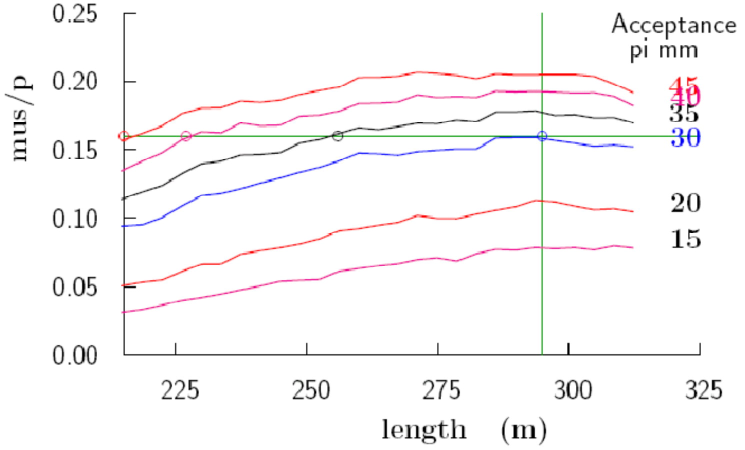
J.S. Berg *et al.* PRST-AB 9, 011001 (2006)

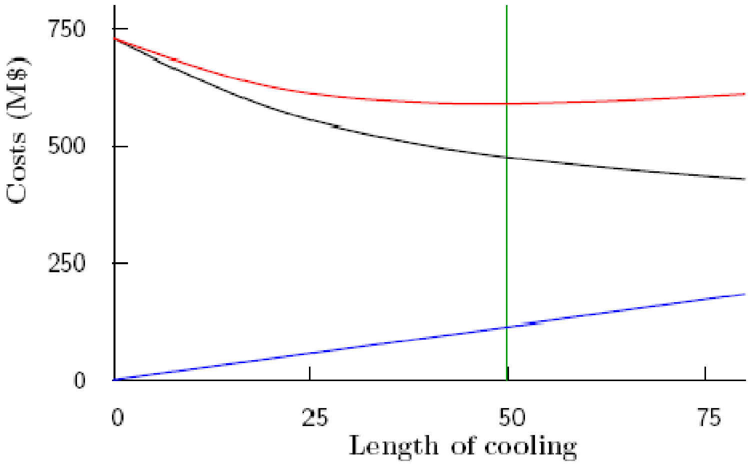


- Assume non-scaling FFAGs for μ acceleration
  - Acceptance 30mm (initially more)
- LiH RF cavity windows as absorbers, ΔE ~3.2MeV
- 2.8T alternating field (β_t ~ 80cm)
- Optimisations, to determine amount of cooling
  - including cost

➔ Same μ / proton yield as FS2; but simpler

OPTIMISATIONS (R. Palmer *et al.*, various talks)





μ / p versus cooling length

Acceptances of 15 – 45mm

Plateaux for ~ 50 – 80m cooling

Total **cost** *versus* cooling

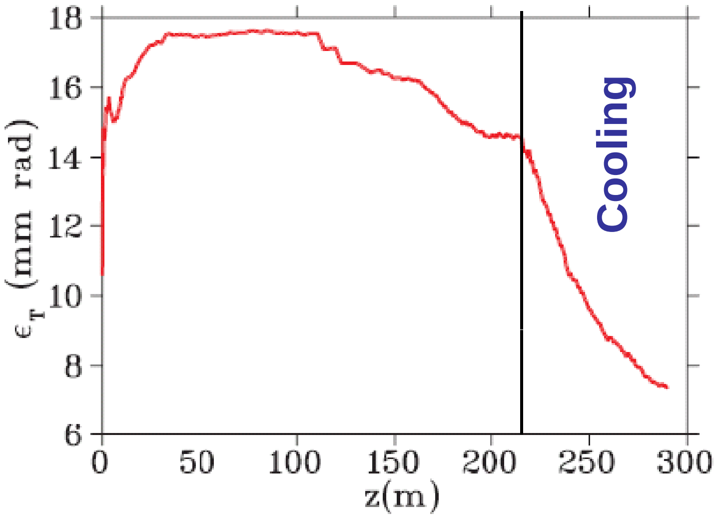
Fix luminosity

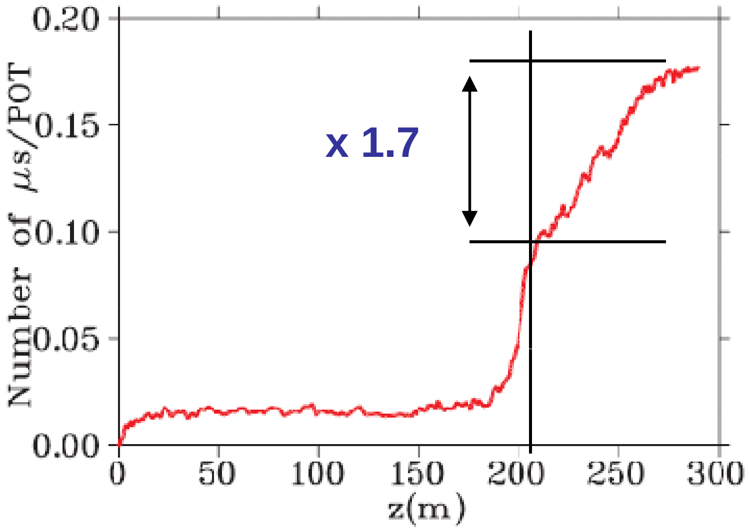
Tradeoff **cooling** ←→ detector **mass**

Shallow minimum in total cost

~50m of cooling with Acc = 30mm

FS2A/B COOLING PERFORMANCE





Cooling is modest – 79m of LiH channel

Transverse emittance reduced by ~ 2 → ~ 7mm

Gain of ~1.7 in μ / p

More cooling doesn’t help

TECHNICAL CHALLENGES

- Many in common with $\mu\mu$ collider
  - Engineering of high field S/C solenoidal channels
    - Large cold – warm forces
      - Especially during quenches (worries some MICE)
  - Removing heat from absorbers
    - 10^{14} μ / sec deposit 16 Watts / MeV of ΔE
      - 160 W in 35cm LH_2 absorbers
      - 60 W in LiH absorbers + ~ 200 W RF heating
    - Re-use of LH_2 absorbers in rings, looks difficult
  - High gradient RF cavities in magnetic fields
    - Remains to be seen ….

RF & MAGNETIC FIELDS

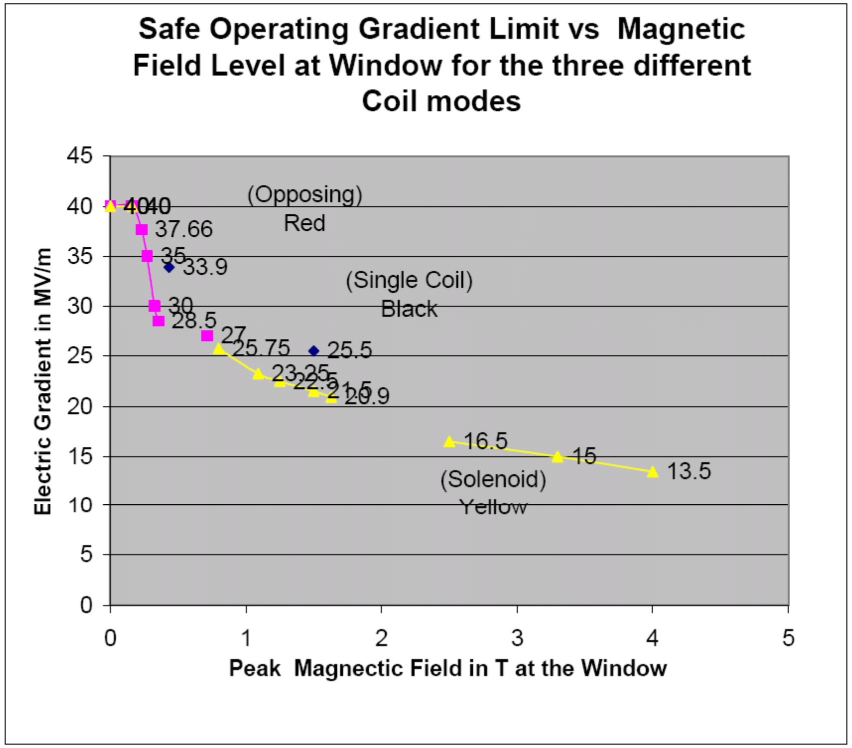
B parallel to **E** reduces maximum safe field in cavity

Expected to be worse at lower frequencies

Not fully understood

Awaits test of 200 MHz cavity with MuCOOL coupling coil

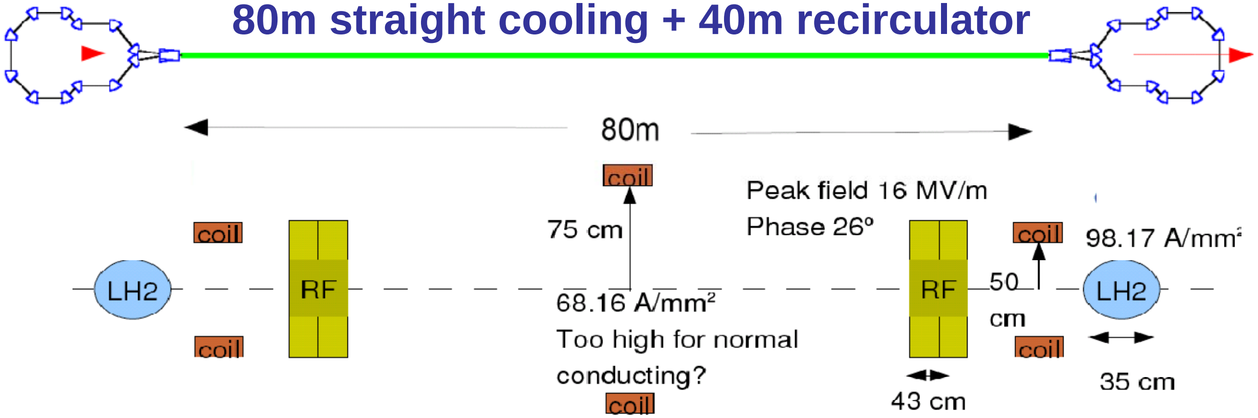
- Solutions
  - – Fill with high pressure H_2
    - H2 is also absorber
      - – but thick windows
  - – Separate RF & **B**



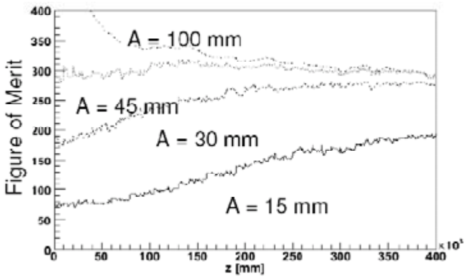
800 MHz cavity in solenoid at Fermilab MTA
(D. Li, MICE CM17, 2007)

C. ROGERS’ SCHEME (NuFACT07)

80m straight cooling + 40m recirculator



- Some separation of **B** and RF
  - (What are fields at cavities?)
- Optimisation for cost
  - re-use absorbers
    - Power?
- Gain of 1.56 in μ/p
  - to be optimised



Length [m]	Figure of Merit
80	1.24
160	1.40
240	1.50
400	1.56

- Figure of Merit = number of μ in 30 mm transverse acceptance and 150 mm longitudinal acceptance
  - FS2A baseline had a figure of merit of 1.7

CONCLUSIONS

- Some modest cooling probably required for NF
  - Depends strongly on properties of μ accelerators
    - Must demonstrate large acceptance of NS FFAGs
    - EMMA in ~ 2 years
- Technical challenges remain
  - Engineering
  - Absorbers
  - RF & magnetic fields
    - MICE & MuCool addressing these
- Still Cooling ← → Exposure tradeoffs

THE END