# *The International Scoping Study for a Neutrino Factory*

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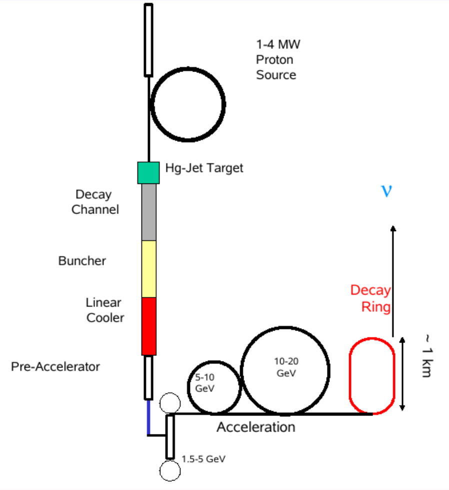
# Outline

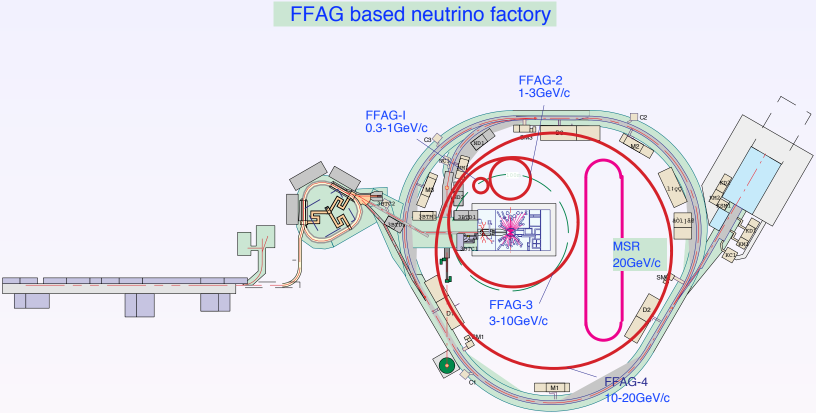
- Neutrino Factory
- The International Scoping Study
- Proton Drivers
- Target
- Muon Front-end
- Muon Acceleration
- Decay Ring
- ISS Decisions

# *Neutrino Factory Overview*

- Proton driver
  - primary beam on production target
- Target, capture, decay
  - create $\pi$, decay into $\mu$
- Bunching, phase rotation
  - reduce $\Delta E$ of bunch
- Cooling
  - reduce transverse emittance
- Acceleration
  - from $\sim$ 130 MeV to 20–50 GeV
- Decay Ring
  - store for $\sim$ 500 turns
  - long $\nu$ production straight



# J-PARC Neutrino Factory Proposal




- Four scaling FFAGs accelerate muons from 0.3 to 20 GeV.
- No cooling.
- Single muon bunch throughout the cycle.

# *Challenges*

- Muons have a short lifetime (2.2 $\mu$s at rest)
  - Puts premium on rapid beam manipulations
    - requires fast acceleration system;
    - requires high gradient NC RF for cooling (in B-field);
    - requires untested ionization cooling technique.
- Muons are created as a tertiary beam ($p \rightarrow \pi \rightarrow \mu$)
  - low production rate

    $\Longrightarrow$ target able to handle multi-MW beam;
  - large muon beam transverse phase space and large energy spread

    $\Longrightarrow$ high acceptance acceleration system and storage ring.
- Neutrinos are themselves a quarternary beam
  - even less intensity and less control;
  - goal is $10^{21}$ decays per year.

# *International Scoping Study*

*Terms of Reference*

The physics case for the facility will be evaluated and options for the accelerator complex and neutrino detection systems will be studied. The principal objective will be to lay the foundations for a full conceptual-design study of the facility. The plan for the scoping study has been prepared in collaboration by the international community: the ECFA/BENE network in Europe, the Japanese NuFact-J collaboration, the US Muon Collider and Neutrino Factory Collaboration and the UK Neutrino Factory collaboration. CCLRC's Rutherford Appleton Laboratory will be the 'host laboratory' for the study.

# *Goals of the Accelerator Study*

- Study alternative configurations; arrive at specifications for a baseline recommendation
- Develop and validate tools for end-to-end simulations of alternative facility concepts
- Focus on selected options as a prelude to subsequent International Design Study (IDS)
  - Note: IDS will have more of an engineering aspect than the ISS
- Carry out a cost evaluation
- R&D list to be developed as study proceeds
  - identify activities that must be accomplished for a credible, cost-effective design
- ISS needs engineering resources knowledgeable in accelerator and detector design

# *ISS Structure*

Three main areas of study: Physics, Detectors, Accelerators
Accelerator Study managed by Machine Council.

- R. Fernow (BNL), R. Garoby (CERN), Y. Mori (KURRI), R. Palmer (BNL), C. Prior (RAL), M. Zisman (LBL, Chairman)

Aided by Task Coordinators

- Proton Driver - R. Garoby, H. Kirk (BNL), Y. Mori, C. Prior
- Target - J. Lettry (CERN), K. McDonald (Princeton)
- Muon Front-end and Cooling - R. Fernow, K. Yoshimura (KEK)
- Muon Acceleration - J.S. Berg (BNL, Y. Mori, C. Prior
- Decay Ring - C. Johnstone (FNAL), G. Rees (RAL)

## *Meetings*

- Main ISS Meetings: CERN (Sep'05), KEK (Jan'06), RAL (Apr'06), NUFACT'06, UCLA (Aug'06)
- Plus several informal workshops/meetings

# Proton Drivers

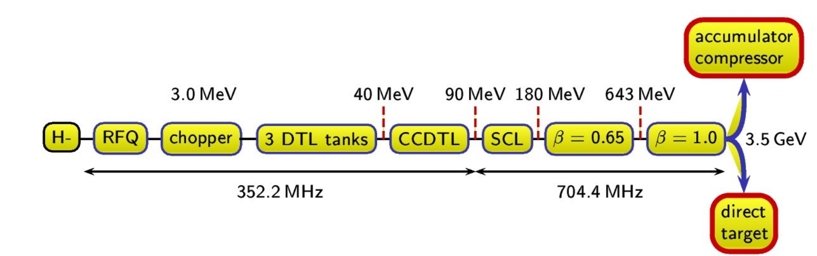
## *NF requirements*

- 4 MW of proton beam power on pion target.
- Delivered in pulses comprising bunches of 1–3 ns duration rms.

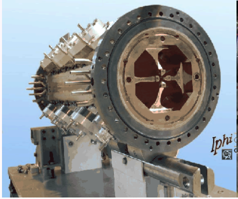
## *Tasks*

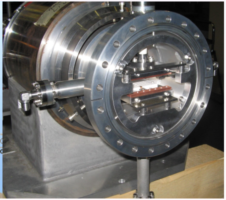
- Consider whether existing machines can be developed to meet NF requirements and analyse new designs.
- Compare merits of different structures – performance and cost.
  - Full energy linac, accumulator and compressor rings.
  - RCS-based drivers.
  - FFAG proton drivers (scaling or non-scaling).
- Decide on optimum repetition rate – relates to target and downstream RF structures.
- Decide on optimum beam energy – depends on target choice.
- Decide on optimum pulse structure – affects whole of remaining structure.
- Weigh up bunch length trade-offs.

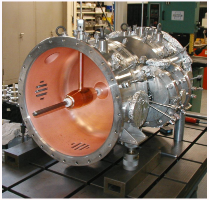
# *Linac-based Proposals – CERN SPL*

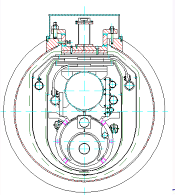



- Phased construction: Linac4 to 160 MeV to feed PS Booster.
- Add 366 m of SC RF to reach 3.5 GeV.
- TESLA/ILC type cryostats, 5-cell SC Nb cavities, cold quadrupoles.
- Layout and beam dynamics (CEA).

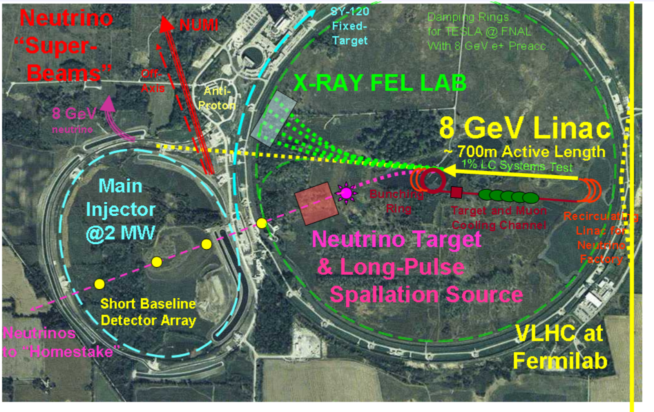






# *Linac-based Proposals – Fermilab 8 GeV Proton Linac*




8 GeV Linac can produce streams of $1.5 \times 10^{14}$ protons at up to 10 Hz

$\Longrightarrow > 10^{22}$

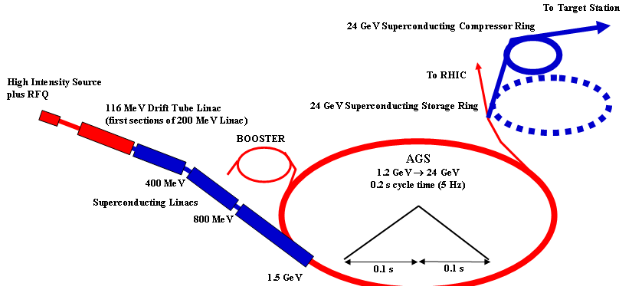
protons/year,

2 MW

- Go to 20 Hz for 4 MW (22.5 MW wall-plug power)
- 4 bunches, 4 ns over 50 ms in accumulator/compressor ring for NF

# Proton Drivers based on Synchrotrons

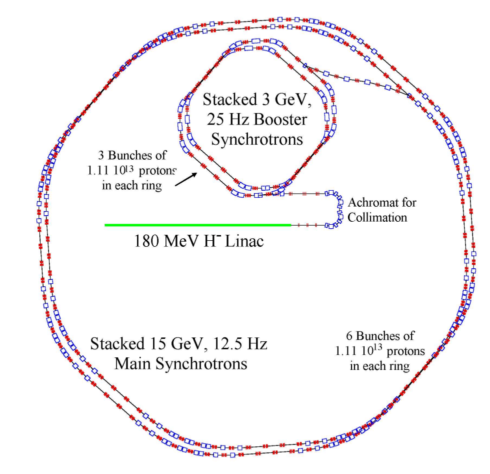
## 4 MW AGS proton driver layout




AGS upgrades to 1 and 4 MW

- J-PARC scheme with 3 and 50 GeV synchrotrons
- RAL models at 5 GeV, 8 GeV, 15 GeV and 30 GeV

# RAL 15 GeV, 25 Hz, 4 MW Driver

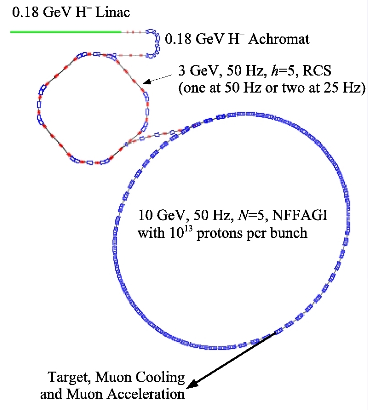



- Main ring of 151 m mean radius to fit CERN's ISR tunnel
- Booster for beam accumulation (phase space painting etc)
- Main RCS for acceleration and bunch compression
- Double rings system
- 6 bunches per pulse, 1 ns rms on target.

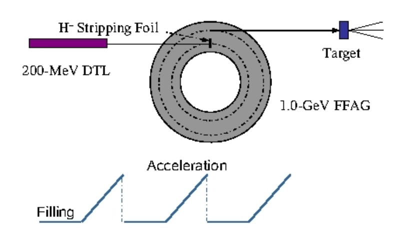
# FFAG-based Proton Drivers

## RAL Model

- 50 Hz, 10 GeV, 4 MW proton driver
- 180 MeV linac
- 3 GeV RCS booster for accumulation
- 3–10 GeV FFAG with insertions




## Ruggiero Model




- 200 MeV – 1 GeV, 10 MW, 1 kHz

# Table of Proton Drivers

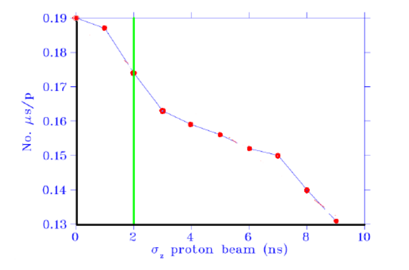
$\tau_p$ = pulse duration, $N_b$ = number of bunches per pulse, $\tau_b$ = final compressed bunch length.

| Driver | Power (MW) | Type | Energy (GeV) | Frequency (Hz) | Protons per pulse ($\times 10^{13}$) | Pulse structure $\tau_p$ ($\mu$s) | $N_b$ | $\tau_b$ (ns) |
|---|---|---|---|---|---|---|---|---|
| BNL-AGS | 1 | Synch | 28 | 2.5 | 9 | 720 | 24 | 3 |
| | 4 | Synch | 28 | 5 | 18 | 720 | 24 | 3 |
| | 4 | Synch | 40 | 5 | 12.5 | 720 | 24 | 3 |
| FNAL | 2 | Synch | 8 | 15 | 10 | 1.6 | 84 | 1 |
| | 2 | Linac | 8 | 10 | 15 | | | |
| FNAL MI | 2 | Synch | 120 | 0.67 | 15 | 10 | 530 | 2 |
| CERN-SPL | 4 | LAR | 2.2 | 50 | 23 | 3.2 | 140 | 1 |
| | 4 | LAR | 3.5 | 50 | 14 | 1.7 | 68 | 1 |
| J-PARC | 0.75 | Synch | 50 | 0.3 | 31 | 4.6 | 8 | 6 |
| RAL | 4 | Synch | 5 | 50 | 10 | 1.4 | 4 | 1 |
| | 4 | Synch | 6–8 | 50 | 8.3 | 1.6 | 6 | 1 |
| | 4 | FFAG | 10 | 50 | 5 | 2.3 | 5 | 1 |
| | 4 | Synch | 15 | 25 | 6.7 | 3.2 | 6 | 1 |
| RAL/CERN | 4 | Synch | 30 | 8.33 | 10 | 3.2 | 8 | 1 |
| KEK/Kyoto | 1 | FFAG | 1 | $10^4$ | 0.06 | 0.4 | 10 | 10 |
| | 1 | FFAG | 3 | $3\ 10^3$ | 0.06 | 0.5 | 10 | 10 |

# *Target/Capture/Decay*

- Optimum target material - solid or liquid; low, medium or high $Z$
    - Targets examined: C, Cu, Hg, Ta, all with $r = 1$ cm
    - Proton beam energies considered: 5, 10 and 24 GeV
    - Proton bunches from 1–3 ns rms

- *Find 1 ns is preferred but 2–3 ns is acceptable;*
- *12% fall-off in performance at 3 ns;*
- *such short bunches hard to achieve at low energy*




- Intensity limitations (from target or beam dump)
- Horn or solenoid capture

# Target Material Comparison

*Hg compared at 10 GeV and 24 GeV*

$$\frac{N^{+}_{10\,\mathrm{GeV}}}{N^{+}_{24\,\mathrm{GeV}}} = 1.07 \qquad \frac{N^{-}_{10\,\mathrm{GeV}}}{N^{-}_{24\,\mathrm{GeV}}} = 1.10$$

*C compared at 5 GeV and 24 GeV*

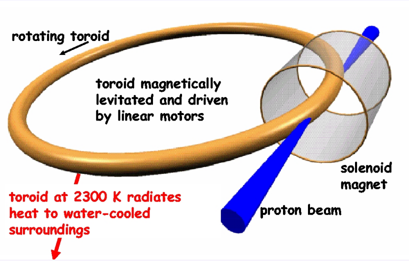
$$\frac{N^{+}_{5\,\mathrm{GeV}}}{N^{+}_{24\,\mathrm{GeV}}} = 1.90 \qquad \frac{N^{-}_{5\,\mathrm{GeV}}}{N^{-}_{24\,\mathrm{GeV}}} = 1.77$$

*Hg at 10 GeV compared with C at 5 GeV*

$$\frac{N^{+}_{\mathrm{Hg},10\,\mathrm{GeV}}}{N^{+}_{\mathrm{C},5\,\mathrm{GeV}}} = 1.18 \qquad \frac{N^{-}_{\mathrm{Hg},10\,\mathrm{GeV}}}{N^{-}_{\mathrm{C},5\,\mathrm{GeV}}} = 1.22$$

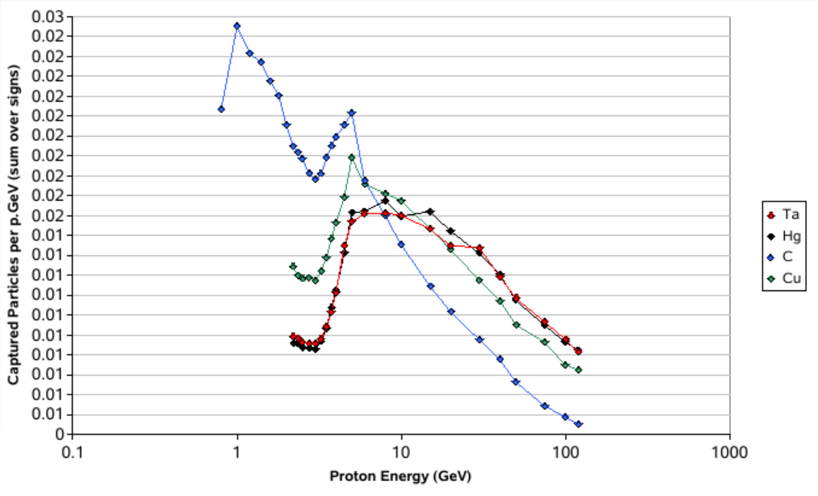
# *Target Choice*

- A solid target design may be possible
- Target changing scheme is difficult



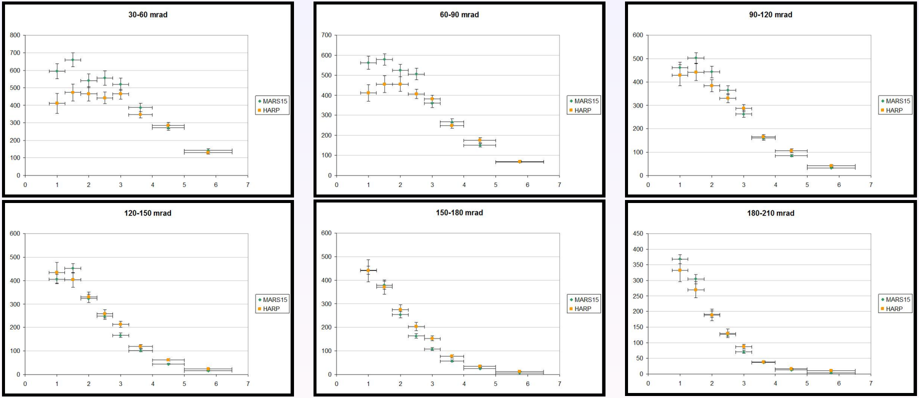

- Liquid mercury jet looks viable – chosen as baseline
- Await exprimental results from MERIT (MERcury Intense Target) experiment at CERN
  - PS 24 GeV beam, $2.8 \times 10^{13}$ protons on $1.2\,\text{mm} \times 1.2\,\text{mm}$ beam spot
  - Peak energy deposition 180 J/g
  - Beam on target April 2007
- A liquid lead alloy with low melting point may be safer option

# *Pion Distribution and Energy Choice*

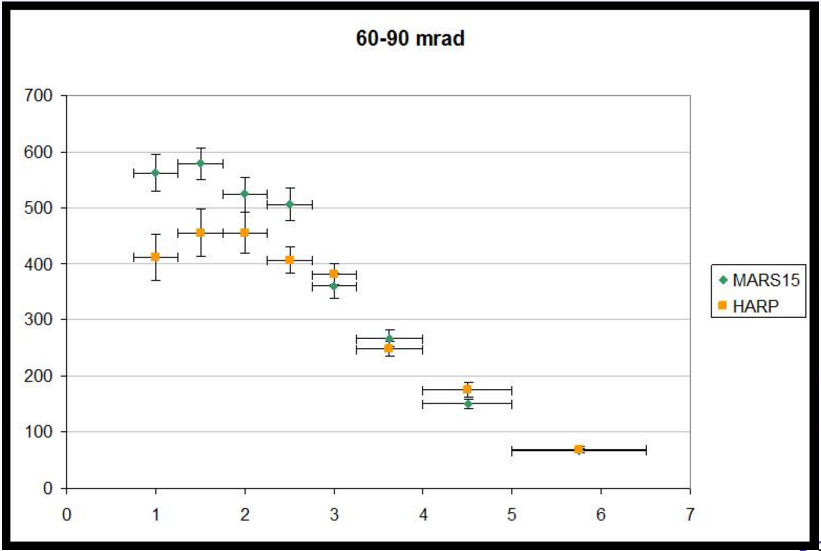



MARS15 output suggests optimum proton beam energy range of 5–15 GeV.

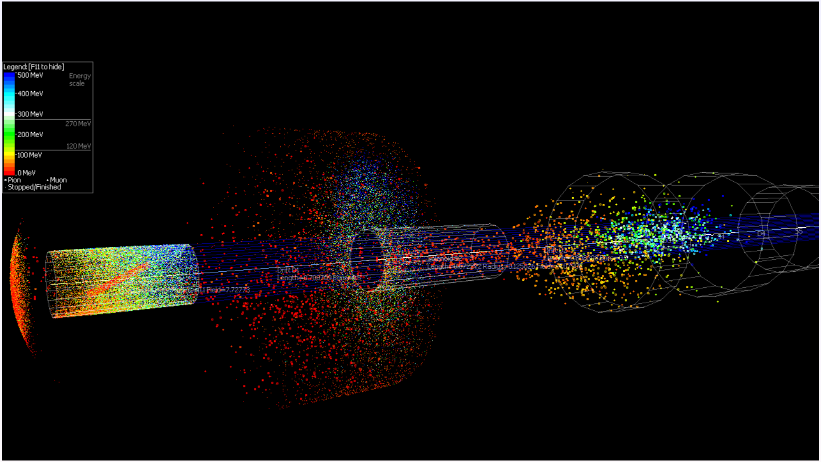
# *Harp Data for Aluminium*



# Harp Data for Aluminium, 2



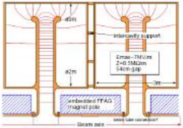
# *Pion Capture/Decay Channel*



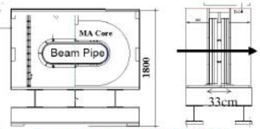

Target is a tilted 20 cm long Ta rod inside a 20 T solenoid
International project to optimize solenoid strengths and positions for maximum transmission.

# *Front-End Schemes*

**5 MHz**
Studied in Japan
0.75-1.0 MV/m ave

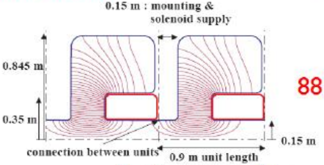


Japan 5 MHz Vacuum RF



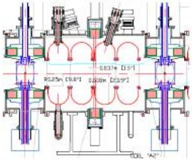

Japan Ferrite Loaded RF (cf PRISM)

**88 MHz**
Studied in CERN
4 MV/m ave
(Also 44 + 88 MHz system with similar performance)




88 MHz

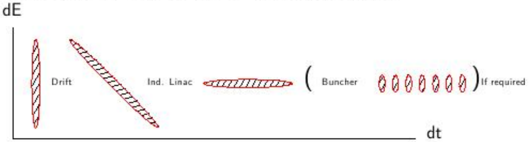
**201 MHz**
Studied in US
10 MV/m ave in cooling

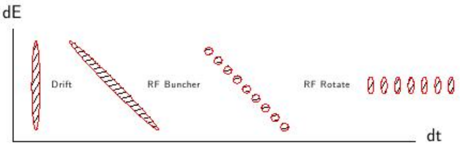
- 5 MHz and 201 MHz systems have enough acceptance to capture entire production
- 88 MHz into one bunch has insufficient longitudinal acceptance
- 88 MHz might be suitable into $\sim$ 25 bunches but not yet investigated

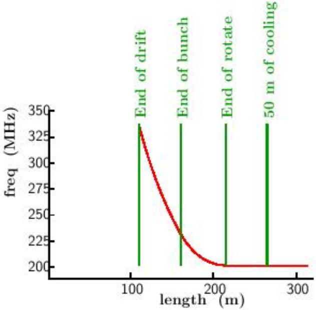
# *US Study 2a: Neuffer Capture Scheme*

Conventional with LF RF or Induction Linacs



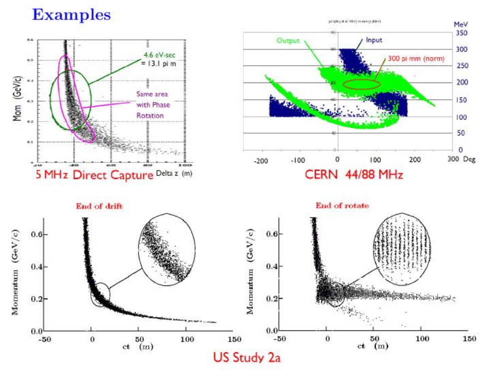

Bunched Beam Rotation with 200 MHz RF (Neuffer)




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

# *Longitudinal Capture Efficiencies*




| | Capture efficiency | signs | efficiency × 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 |

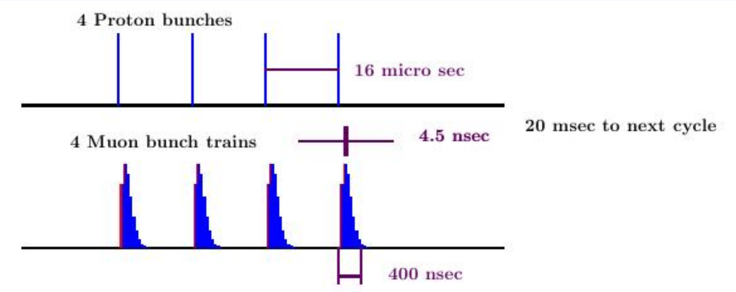
# *Consequences for Proton Driver*

## *Proton Bunch Structure on Target*

- Choose 50 Hz repetition rate
  - Lower rate increases charge per bunch and makes bunch compression harder
  - Higher rate increases RF wall power demand
- Choose trains of $\sim$ 4 bunches
  - Ease bunch compression, fewer acceptable if bunching problem solved
- Spacing between bunches $\geq$ 400 ns to allow use of Neuffer scheme

# Consequences for Proton Driver

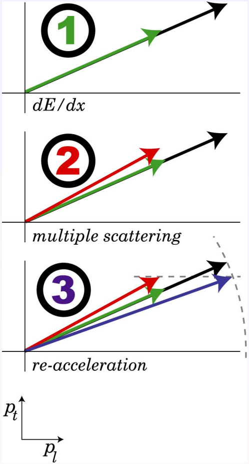
## Spacing between Proton Bunches

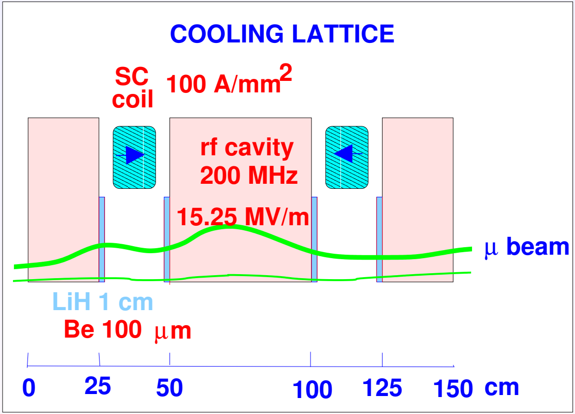



16 $\mu$s between bunches is a good compromise to

- Avoid mercury cavitation and target density loss
- Help top up RF and correct field gradient droop
- Reduce beam loading in downstream FFAG acceleration system

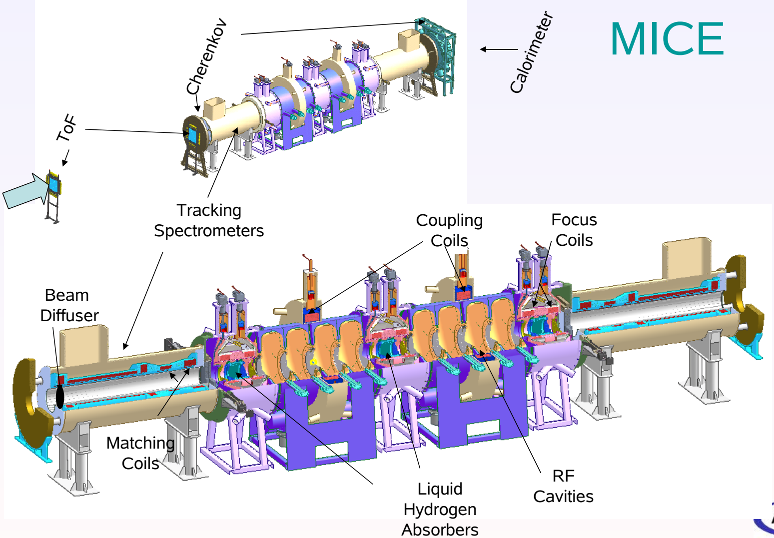
# Ionisation Cooling




1. Liquid hydrogen absorbers remove momentum in all directions
2. Multiple scattering increases transverse emittance
3. RF restores longitudinal momentum, giving overall transverse momentum decrease

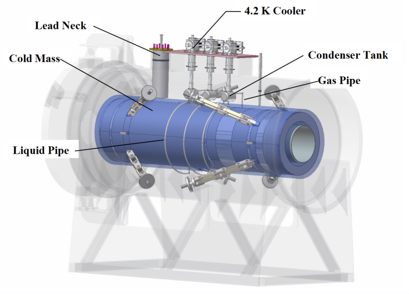
# *Muon Ionization Cooling Experiment*



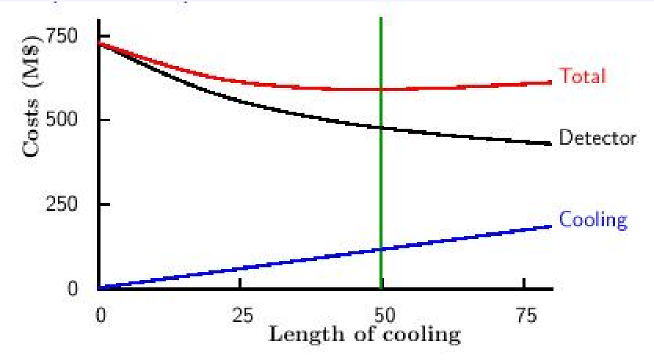

MICE

ASTeC

# *MICE R&D*


4.2 K Cooler
Lead Neck
Cold Mass
Condenser Tank
Gas Pipe
Liquid Pipe

# Cooling v. Detector Size




Assuming two detectors, total cost minimum for 50 m of cooling.

# *Optimising Muon Decays per Year*

| | Rotation | Cooling | Trans. Acc. $\pi$mm.mrad | signs | $\mu/\pi$ | $\mu$ p.a. $\times 10^{21}$ |
|---|---|---|---|---|---|---|
| 5 MHz | none | no | 30 | 1 | 0.08 | 0.19 |
| 44/88 MHz | RF | yes | 15 | 1 | 0.066 | 0.21 |
| 201 MHz US2 | Induction | yes | 15 | 1 | 0.17 | 0.54 |
| 201 MHz US2a | Neuffer | yes | 30 | 2 | 0.17 | 1.07 |

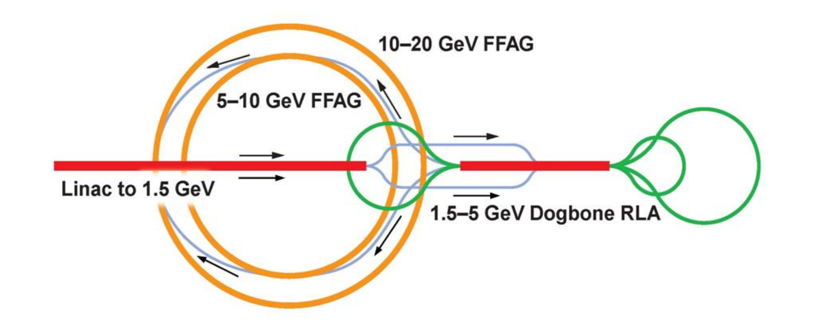
- 201 MHz with Neuffer and two detectors reaches design goal of $10^{21}$ muons per annum
- 88 MHz fails to meet requirements because of small capture phase space and only one muon sign
- 5 MHz fails because of decay loss, no cooling and one muon sign

# *Muon Acceleration*

*Tasks*

- Compare different schemes on an equal footing
  - RLA, scaling FFAG, non-scaling FFAG, isochronous FFAG.
  - implications of keeping both sign muons.
  - need improved tracking codes for non-scaling FFAG designs in this parameter regime.
- Prepare scenarios for different values of acceptance (transverse and longitudinal)
- Consider matching between accelerator subsystems
- Consider both improved performance and relative costs

# *Dogbone RLA*




- Linear pre-acceleration 273 MeV/c to 1.5 GeV
- Symmetric 'Dogbone' RLA, 3 passes, 1.5 GeV to 5 GeV
- Accelerates both $\mu^+$ and $\mu^-$
- FFAG cannot handle low energy ($\lesssim$ 3 GeV), high frequency

# *FFAGs for Muon Acceleration*

*Scaling* Field $\propto r^k$; large apertures; tune constant; orbit variation up to 0.5 m; low frequency RF 5–25 MHz.

*Non-scaling* Linear elements; large apertures; resonance crossing; tiny orbit variation; high frequency RF 200 MHz.

*Isochronous* Nonlinear fields; $Q_v$ constant, $Q_h$ varies; long insertion straights for injection, extraction and collimation; any RF frequency.

*Schönauer* Weakly isochronous; constant tune; RF $\sim$200 MHz.

# *FFAG Neutrino Factory Issues*

*See Shinji Machida's Talk*

- Transverse acceptance
  - Not clear which type of FFAG is most suitable.
- Dynamic aperture
  - Detailed study only for isochronous
- Collimation
  - Constant tune aids capture efficiency
- Choice of acceleration method
  - Isochronous, gutter, RF bucket
- RF frequency choice - addressed above

# *ISS Thoughts*

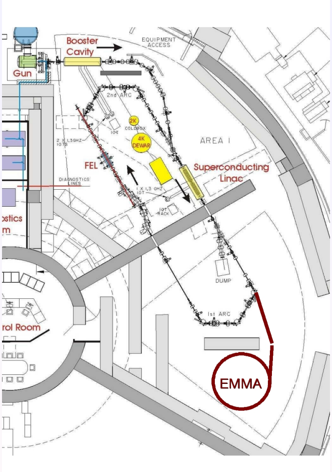
- Scaling FFAG (non-isochronous) requires low frequency RF ($\sim$ 5 MHz)

  $\Longrightarrow$ low gradients

  $\Longrightarrow$ decay losses
- Non-scaling FFAGs (5–10 GeV, 10–20 GeV)
  - amplitude dependent time slip causes energy spread and particle loss
  - costly to correct
- RLA synchrotron motion can cancel amplitude slip effects
- Dogbone RLA may be a (less expensive) solution up to 10 GeV, followed by one or two FFAGs.

# FFAG Design and R&D

- POP and 150 MeV scaling proton FFAGs at KEK
- Spiral FFAG at Kyoto University
- Low frequency RF cavities and high frequency 201 MHz RF cavities studied in Japan
- SC FFAG magnets for scaling machines at KEK
- EMMA (non-scaling electron test model) in UK
- Proposals to build proton therapy unit based on a non-scaling FFAG with sc technology at IHEP Beijing.



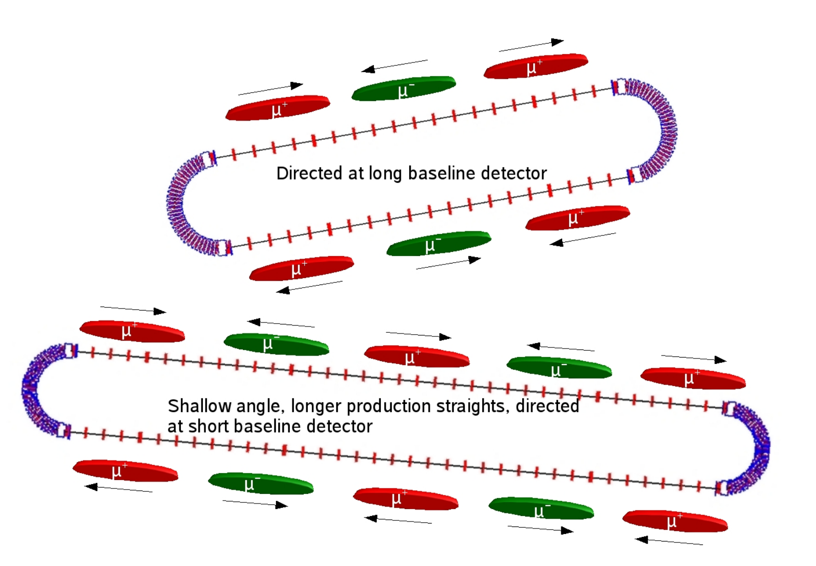

EMMA using ERLP linac at Daresbury Laboratory

# *Decay Rings*

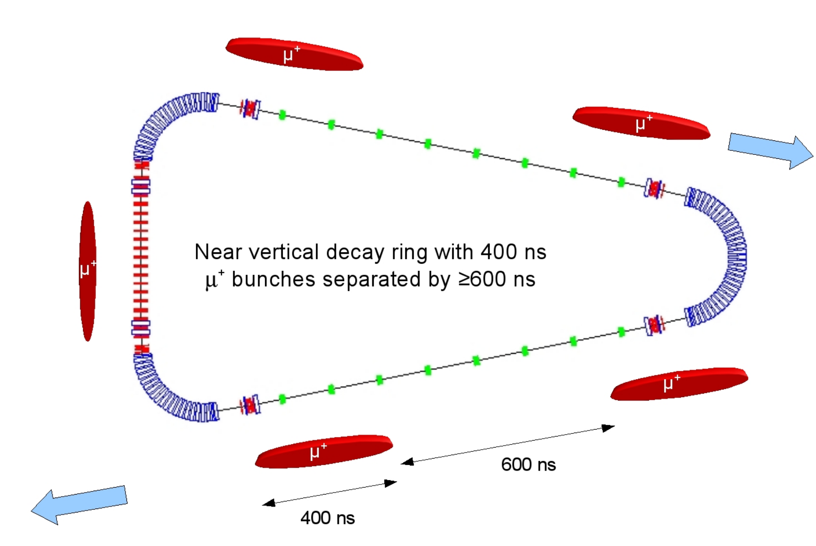
*Issues*

- Consider different ring geometries (racetrack, triangular)
- Design implications of final energy (20 v. 50 GeV)
- Optics requirements v. beam emittance (arcs, injection, decay straights)
- Implications of keeping both sign muons (one or two rings?)
- Can we handle two simultaneous baselines?
- Radiation issues from $10^{21}$ useful neutrinos per year

# Racetrack Option

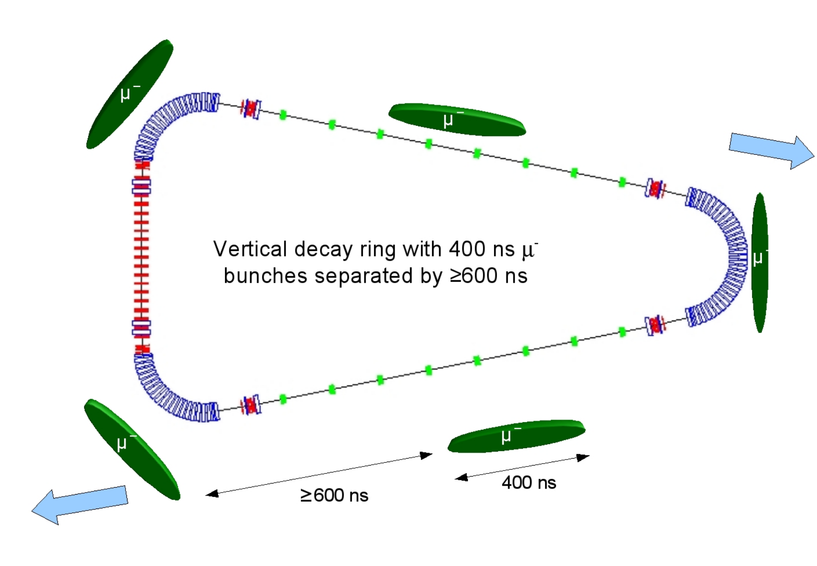


# *Triangular Option*

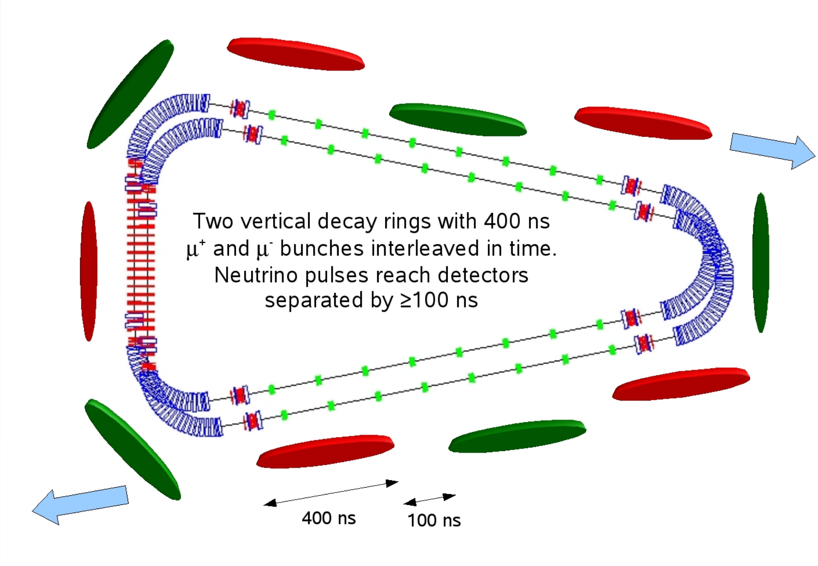



$\sim$ 300 m production straights; two detector sites; efficiency $\sim$ 48%; vary apex angle by inserting extra cells in vertical straight.

# *Triangular Option*



# *Triangular Option*



# *Detector Sites*

- Physics requirements are for two detector sites at medium (2500–3500 km) and long (7000–75000 km) range baselines.
- Racetrack decay ring is more flexible but will point to only one detector.

  $\Longrightarrow$ Two separate rings and tunnels.
  $\Longrightarrow$ Alternate between $\mu^+$ and $\mu^-$ in each ring or devise a counter-rotating scheme with both sign muons in each ring.
- Triangles fit into same tunnel and point to two detectors

  $\Longrightarrow$ Designs for 20 GeV and 50 GeV would fit in same tunnel
  $\Longrightarrow$ Limited choices in detectors and NF sites
  $\Longrightarrow$ One detector site may need to be new

# *NF Sites and Detector Combinations for Triangular Ring*

| NF site | Detector 1 | Distance (km) | Detector 2 | Distance (km) | Apex angle (deg) | Angle to vertical (deg) |
|---|---|---|---|---|---|---|
| BNL | Homestake | 2525 | Arlit | 7369 | 53 | 28 |
| | WIPP Carlsbad | 2883 | Arlit | 7369 | 48 | 0.7 |
| | Homestake | 2525 | Ghana | 7300 | 47 | 7.9 |
| FNAL | Norsaq | 3532 | N. Argentina | 7634 | 77 | 45 |
| JPARC | Daya Bay | 2914 | Oulu | 7073 | 98 | 80 |
| | Daya Bay | 2914 | NW Territories | 7300 | 60 | 35 |
| CERN | Norsaq | 3577 | INO, Pykara | 7158 | 63 | 43 |
| | Baksan | 2911 | Venezuela | 7615 | 50 | 1.2 |
| RAL | Norsaq | 2806 | INO, Pykara | 7630 | 60 | 33.3 |
| | Oulu | 2075 | N. Brazil | 7300 | 46 | 15 |
| | Crete | 2751 | WIPP Carlsbad | 7513 | 49 | 0.9 |

Oulu – Finland; Arlit – Niger; Norsaq – Greenland; WIPP – Waste Inspection Pilot Plant, New Mexico; Daya Bay – S. China; INO – Indian Neutrino Observatory; Baksan – SAGE project, Georgia;

Green indicates a proposed new detector site.

For greatest efficiency, apex angle should be as small as possible and ring almost vertical.

# *Scoping Study Decisions*

- Proton energy: 5–15 GeV
- Proton driver bunch structure: $\sim$ 4 bunches spaced by $\sim$16 $\mu$s
- Proton bunch length: $\sim$2 ns rms
- Repetition rate: $\sim$ 50 Hz
- Target: baseline is liquid mercury
- Pion collection: 20 T solenoid capture system
- RF frequency: 201 MHz
- Phase rotation: baseline is Neuffer bunched beam rotation scheme
- Cooling: baseline is 50 m of ionisation cooling
- Acceleration: No decision yet
- Muon decay ring: choice is site dependent