Recommendations from The International Scoping Study for a Neutrino Factory

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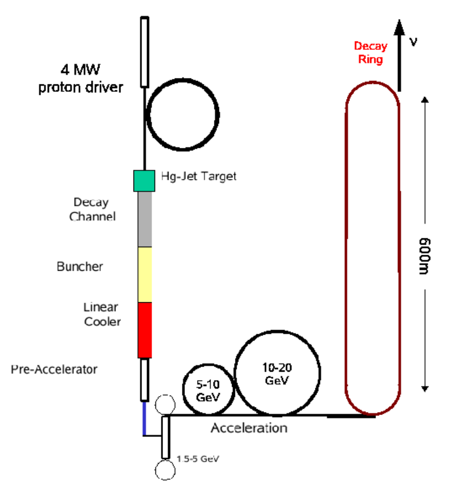
Neutrino Factory Overview

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



Outline

Neutrino Factory

The International Scoping Study

Proton Drivers

Target

Muon Front-end

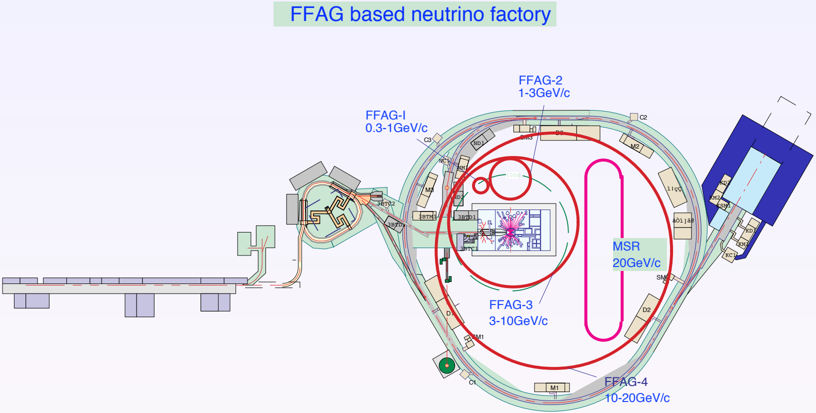
Muon Acceleration

Decay Ring

ISS Decisions

R&D Identified by ISS

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 μs 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 ($p \to \pi \to \mu$)
  - low production rate

    $\Longrightarrow$ target able to handle multi-MW proton 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

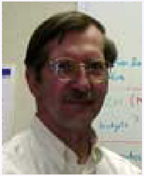
Terms of Reference

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.

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)

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)
- Carry out a cost evaluation
- R&D list to be developed as study proceeds

Requirements from the Facility

- Muon energies of 20 GeV, system upgradable to 50 GeV
- 10^{21} muon decays per year
- Pulses of ν and $\bar{\nu}$ separated by $\sim$100 ns at detectors roughly 3000 km and 7500 km away.

Proton Drivers

NF requirements

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

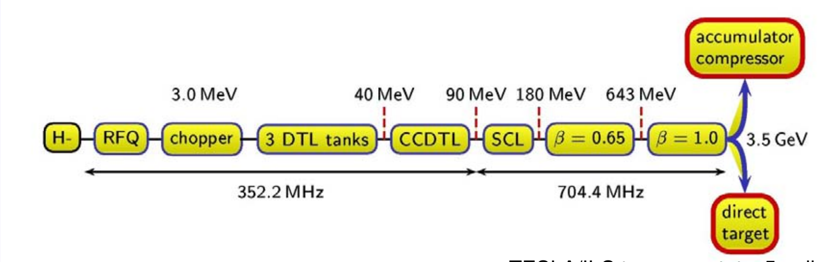
Tasks

- 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.

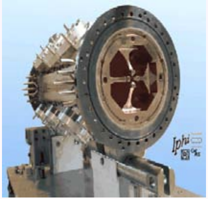
Factors Affecting Proton Driver Design Specifications

- Required production of 10^{21} neutrinos per year
- Muon yield as a function of proton energy and target material
- Heating and stress levels of target material
- Muon capture as function of proton bunch extent
- Proton pulse structure and time duration on target
- Peak beam loading levels in the $\mu^{\pm}$ accelerators
- Bunch train stacking in the μ^{+} and μ^{-} decay rings

Linac-based Proposals – CERN SPL



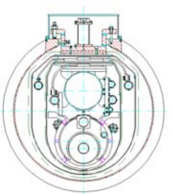
- Phased construction: Linac4 to 160 MeV to feed PS Booster.
- Add 366 m of SC RF to reach 3.5 GeV.
- TESLA/ILC type cryostats, 5-cell SC Nb cavities, cold quadrupoles.
- Layout and beam dynamics (CEA).



IPHI RFQ

Chopper

CCDTL - BINP



High β Cavity

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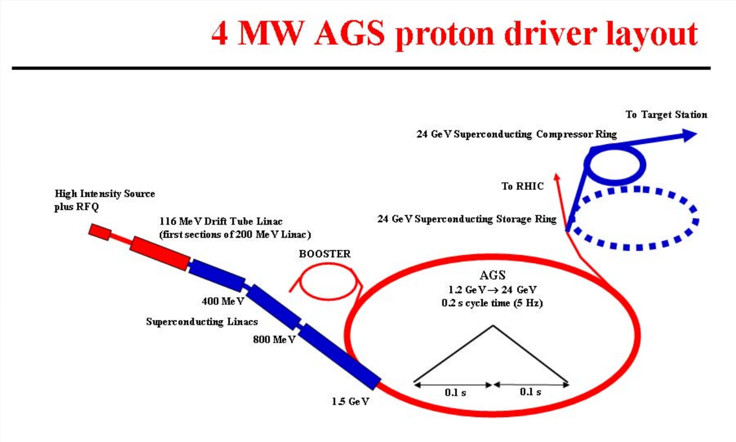
Proton Drivers based on Synchrotrons

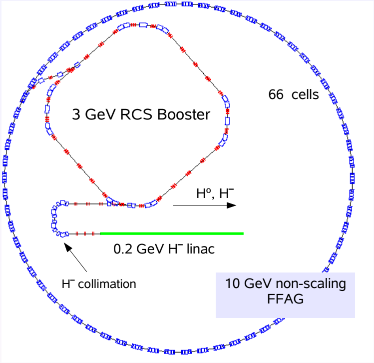


- AGS upgraded to 1 or 4 MW
- J-PARC scheme with 3 and 50 GeV synchrotrons
- RAL models at 5 GeV, 8 GeV, 15 GeV and 30 GeV

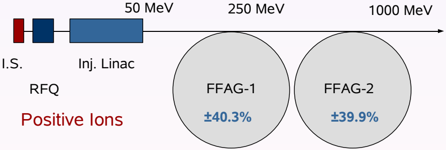
FFAG-based Proton Drivers

RAL Model

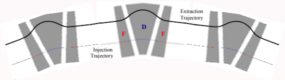
- 50 Hz, 10 GeV, 4 MW proton driver
- 200 MeV linac
- 3 GeV RCS booster for accumulation
- 3–10 GeV non-scaling FFAG
- 3 or 5 proton bunches



Ruggiero Model



10 mA



1 kHz, 10 kHz or CW modes
1 GeV, 10 MW

Table of Proton Drivers

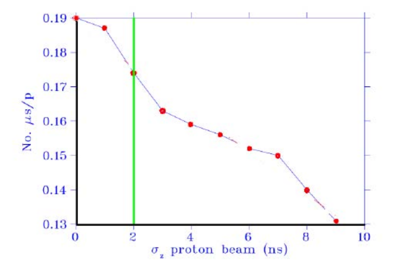
τ_p = pulse duration, N_b = number of bunches per pulse, τ_b = final compressed bunch length.

Driver	Power (MW)	Type	Energy (GeV)	Frequency (Hz)	Protons per pulse ($\times 10^{13}$)	Pulse structure τ_p (μs)	N_b	τ_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

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

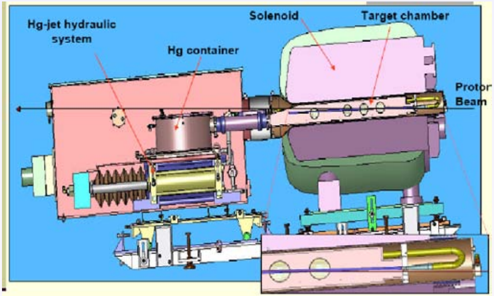
Hg at 10 GeV compared with C at 5 GeV

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

Target Choice

1. Liquid Targets

- Liquid mercury jet looks viable – chosen as baseline
- MERIT (MERcury Intense Target) experiment at CERN



- CERN PS 24 GeV beam, 2.8×10^{13} protons on $1.2\,\text{mm} \times 1.2\,\text{mm}$ beam spot
- Peak energy deposition 180 J/g

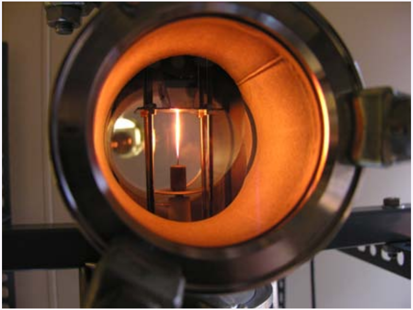
A liquid target performs best with a short proton pulse length $\lesssim 40\ \mu$s.

A liquid lead alloy with low melting point may be a safer option than mercury

Target Choice

2. Solid Targets

- A rotating band target may be possible, but target changing scheme is difficult.
- Tungsten target shock experiments at RAL suggest good lifetimes



A solid target operates best with a longer pulse, $\lesssim 70\,\mu$s because of its ability to relax during deposition.

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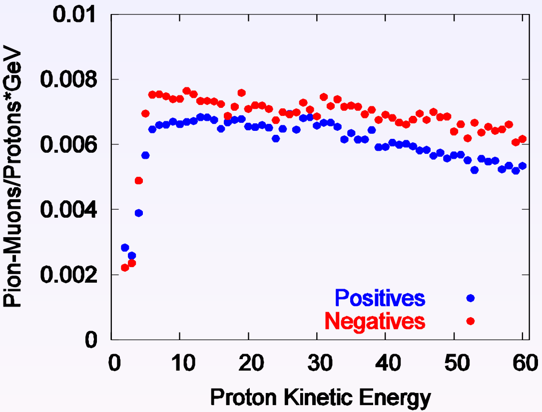
Pion Distribution and Energy Choice



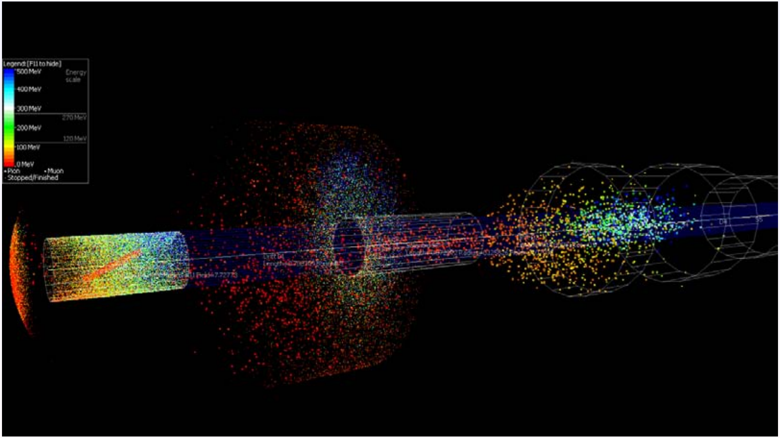
MARS output suggests optimum proton beam energy range of 5–15 GeV.

Benefits of higher energy (easier bunch compression, better performance) are outweighed by additional cost

Muon Front-End

Pion Capture Scheme

Solenoids with fields starting at 20 T and decreasing to 1.75 T



Target is a tilted 20 cm long Ta rod inside a 20 T solenoid

Muon Front-End

Front-end comprises:

- Pion capture channel; pions decay to muons
- Muon phase rotation section to reduce energy spead and increse bunch length
- Ionisation cooling channel to reduce transverse emittance

ISS Comparative Study

Aim: identify front-end channel likely to produce greatest number of neutrino events, assuming the same pion production from a 10 GeV proton beam.

- Japanese NUFACT-J, frequency 5 MHz; no cooling, large aperture scaling FFAGs
- CERN linear cooling channel, frequency 88 MHz
- US Study IIa, linear cooling channel, frequency 201 MHz

The only scheme to meet design goal of 10^{21} muon decays per year is US Study IIa.

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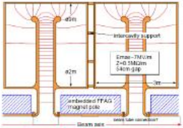
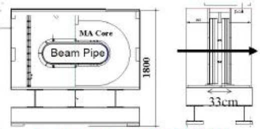
Front-End Schemes

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

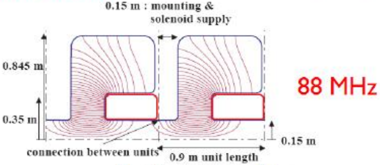


Japan 5 MHz Vacuum RF

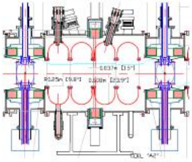


Japan Ferrite Loaded RF (cf PRISM)

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

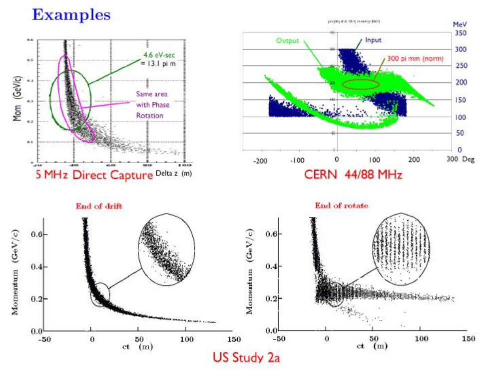


201 MHz
Studied in US
10 MV/m ave in cooling

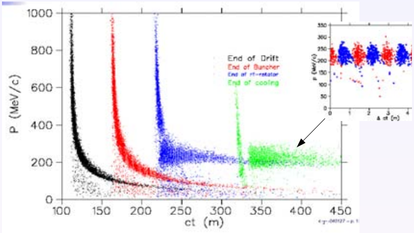


- 5 MHz and 201 MHz systems have enough acceptance to capture entire production
- 88 MHz into one bunch has insufficient longitudinal acceptance
- 88 MHz might be suitable into ∼ 25 bunches but not yet investigated

Longitudinal Capture Efficiencies



Neuffer Bunching Scheme



	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

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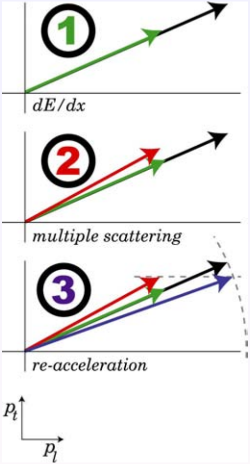
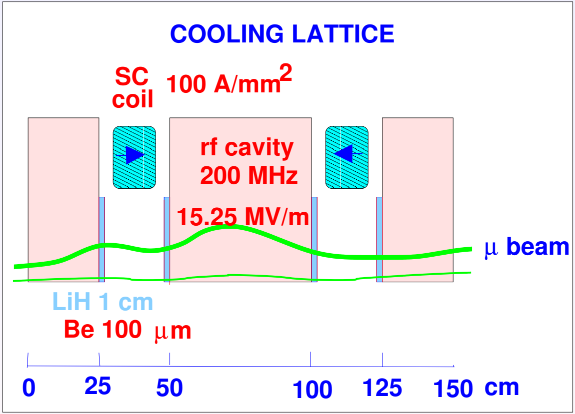
Optimising Muon Decays per Year

	Rotation	Cooling	Trans. Acc. πmm.rad	signs	μ p.a. $\times 10^{21}$
5 MHz	no	no	30	1	0.11
5 MHz	yes	yes	30	2	0.34
44/88 MHz	RF	yes	15	1	0.16
44/88 MHz	Neuffer	yes	15	2	1.0
201 MHz US2	Induction	yes	15	1	0.45
201 MHz US2	Induction	no	30	1	0.35
201 MHz US2a	Neuffer	yes	30	2	1.06
201 MHz US2a	Neuffer	no	30	2	0.61

- 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

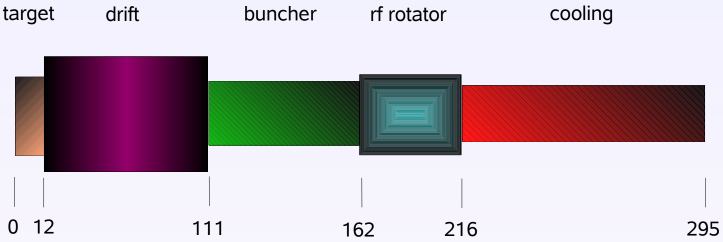
Ionisation Cooling





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

ISS Recommended Front-end



- Target followed by 12 m long capture channel, solenoids 20 T→1.75 T
- Drift section, 100 m, pions decay to muons
- 50 m long adiabatic buncher - modest RF gradients, frequencies changing along the line
- Rotator section, 50 m, higher RF gradients, decreasing frequencies. Beam rotates to reduce energy spread to $\sim$10% emerging beam in trains of 80 interleaved $\mu^{\pm}$ bunches.
- 80 m cooling channel: solenoid focusing, 201 MHz RF cavities, LiH absorbers; transverse emittance reduced $\epsilon_{n,rms}$: $17 \rightarrow 7\pi$ mm.rad (at central momentum p_0=220 MeV/c).

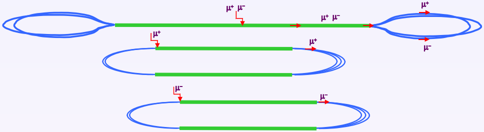
Muon Acceleration

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

Accelerator Choice

Racetrack v. Dogbone



Recirculate to save on expensive RF, but energy separation at switchyard limits number of passes through linac.
Dogbone is preferred to racetrack

FFAGs

Choice between:

- scaling - large apertures, constant tune, low frequency RF ($\Longrightarrow$ low gradients, decay loss)
- non-scaling - linear elements, large apertures, resonance crossing, high frequency RF
- isochronous - nonlinear fields, Q_v constant, Q_h varies; any frequency RF

Machida THYAB01

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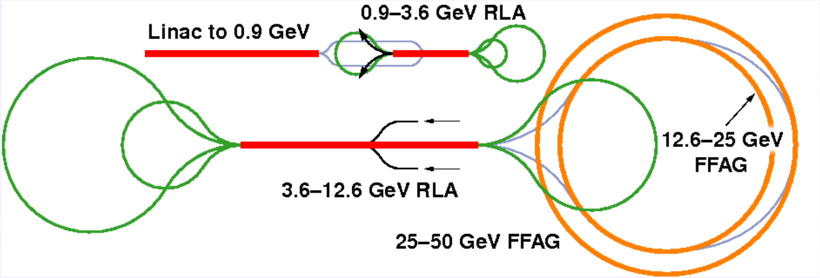
ISS Recommended Scheme for Muon Acceleration



- Linear pre-acceleration 138 MeV to 0.9 GeV
- Symmetric Dogbone RLA, $3\frac{1}{2}$ passes, 0.9 GeV to 3.6 GeV
- Second dogbone RLA, $3\frac{1}{2}$ passes, 3.6 GeV to 12.6 GeV
- Non-scaling FFAG to accelerate to 25 GeV
- A second non-scaling FFAG can be added if 50 GeV is required
- Note: accelerates both μ^+ and μ^-

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Muon Decay Rings

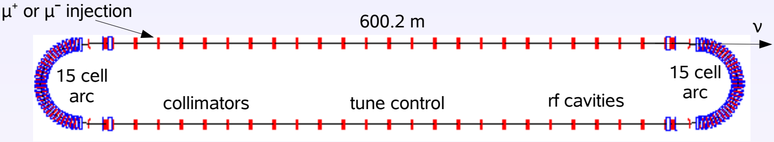
Issues addressed by ISS

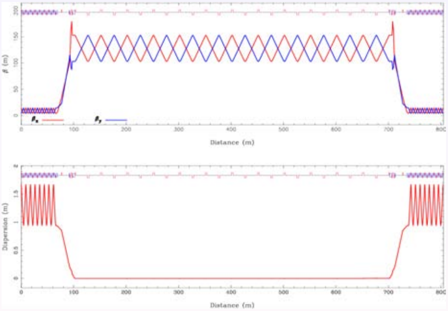
- Comparison of different ring geometries (racetrack, triangular, bowtie)
- Design implications of final energy (20 v. 50 GeV)
- Optics requirements v. beam emittance (arcs, injection, decay straights)
- Implications of keeping both sign muons (one or two rings?)
- How to handle two simultaneous baselines.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

ISS team developed new rings for each geometry

- Designed for 20 GeV upgradable to 50 GeV
- Same circumference 1608.8 m, fitting bunch structure based on proton
- Planned baselines to detectors of $\sim$3000 km and $\sim$7500 km

Racetrack Design

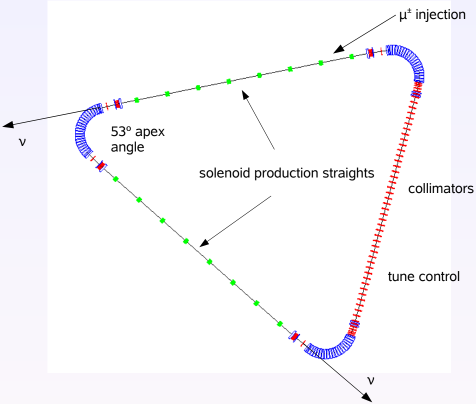


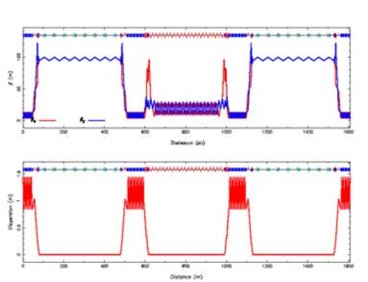


- 600 m straight section; efficiency 37%
- Quadrupole focusing in production straights, $\beta \sim 153$ m.
- Design shown has muons of one sign only; adapted, could do $\mu^{\pm}$ counter-rotating
- Separate tunnels for each ring, pointing at detectors, max depth 435 m
- Flexible - any detector site can be chosen

Racetrack is provisionally chosen as ISS recommendation

Isosceles Triangular Design for Muon Decay Ring



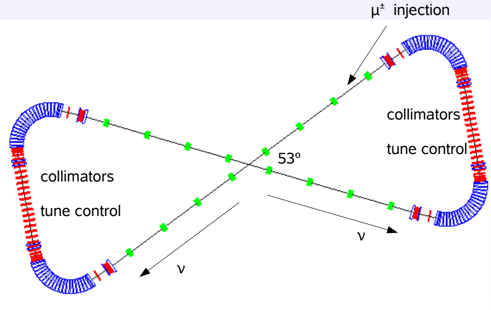


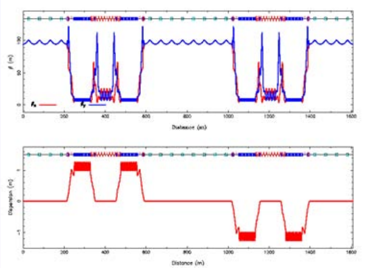
- Two production straights each 400 m; efficiency 2×24%
- Solenoid focusing in production straights, $\beta \sim 94$ m.
- Each ring serves both detectors, max depth 384 m

- Two rings in a single tunnel, one for μ^+, one for μ^-, bunch trains interleaved in time to give required $\gtrsim$100 ns between $\nu, \bar{\nu}$, at detectors

Less flexibility but more efficient; could be good choice depending on chosen sites

Bow-tie Design for Muon Decay Ring





- Similar to isosceles model, two rings in same tunnel
- Two production straights each 400 m; efficiency 2×24%
- Solenoid focusing in production straights, $\beta \sim 94$ m.
- Each ring serves both detectors, max depth $\lesssim 200$ m

- But preserves polarization, which could intefere with accuracy of beam instrumentation

  $\longrightarrow$ could be overcome by changing optics to lie on a polarization resonance.

NF Sites and Detector Combinations for Triangular Rings

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;

RED 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: $\sim$ 3–5 bunches spaced by $\sim$17 μs
- 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: nominally racetrack, but choice is site dependent

R&D Identified by ISS

1. Proton driver

- Complete the front-end test stand at RAL to demonstrate clean fast beam chopping, essential for low loss ring injection
- Build and test an electron model of a non-scaling proton FFAG
- Develop FFAG tracking codes with space charge to explore halo formation, beam loss and collimation issues.
- Develop high gradient, low frequency RF cavities; study beam loading issues
- Accumulator and compressor ring design for linac-based options; vacuum studies, instabilities and halo formation.

R&D Identified by ISS

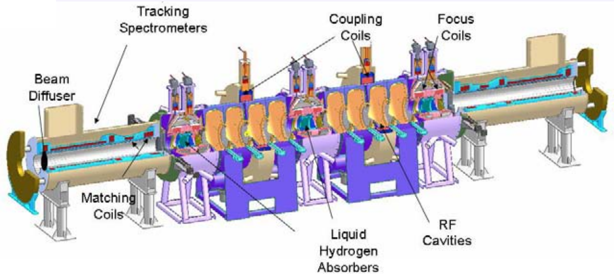
2. Target

- Progress MERIT experiment; explore high Z-targets (e.g. Pb-Bi eutectic)
- Develop solid targets capable of handling at least 1 MW
  - shock tests and irradiation studies
  - design beam dumps
  - determine acceptable single bunch and bunch train spacings

R&D Identified by ISS

3. Muon Front-End

- Complete MICE experiment to demonstrate ionisation cooling



- Develop high gradient cavities that operate in strong solenoid magnetic fields
- Study H_2-gas-filled cavities

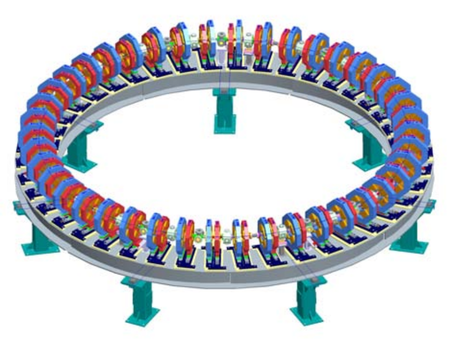
- Carry out absorber termal tests with LiH sandwiched in beryllium
- Study other cooling channels (Guggenheim, dogbone) and options for 6D cooling.
- Optimise system by balancing cooling channel performance against acceptance of accelerating system.

R&D Identified by ISS

4. Acceleration

Edgecock THOBAB01

- Construction and development of EMMA
  - Electron test model of a non-scaling FFAG
  - Uses Daresbury Lab ERLP linac as injector
- Study use of high frequency cavities in scaling FFAGs



- Demonstrate operation of SC RF cavities in close proximity to high-field magnets and that requisite gradients can be achieved (Cornell)
- Examine further the harmonic number jump proposals (BNL); possible hardware test.
- Develop new non-linear modelling codes

R&D Identified by ISS

5. Decay Rings

- Designs of novel combined function superconducting magnets
  $\longrightarrow$ substantial heat load from muon beam
- Tracking studies with errors (ZGOUBI); code development needed
- Polarization studies to determine feasibility of bow-tie geometry