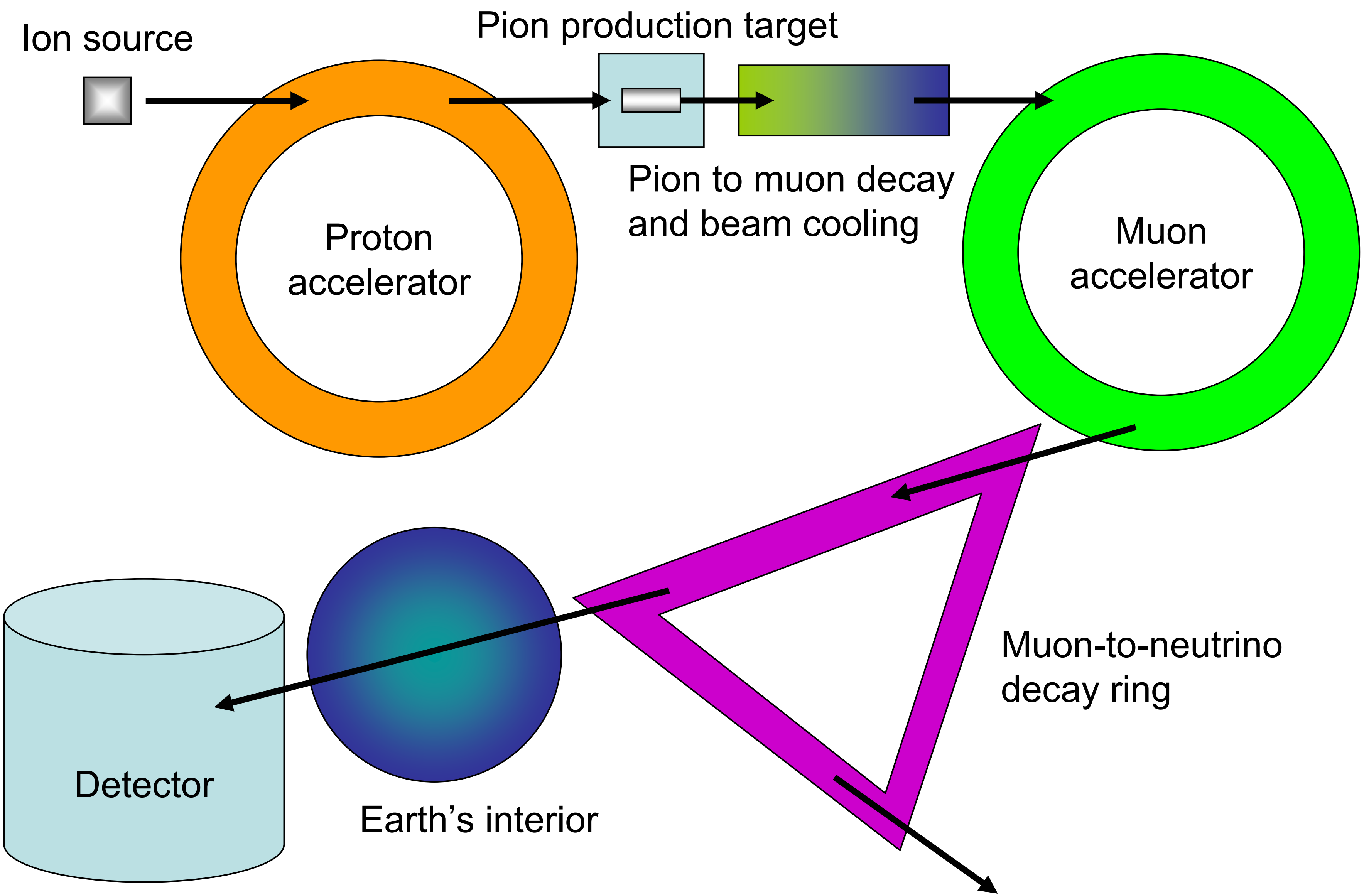
CCLRC

Machine Group Summary

Chris Prior
RAL/ASTeC and University of Oxford

Simplified Neutrino Factory



Previous Studies

- Previous studies in Japan, USA and Europe focused on feasibility and performance
  – cost optimization was secondary, or ignored
- U.S. Study 2a attempted to maintain performance while reducing costs
  – succeeded in keeping both sign muons and substantially lowering hardware cost estimate

	All ($M)	No PD ($M)	No PD & Tgt. ($M)
FS2	1832	1641	1538
FS2a-scaled (%)	67	63	60

Philosophy

- Identify requirements from each area of the facility
- Identify optimum parameters and performance capabilities
- Decide how near we are to achieving the goals
- Identify most promising ideas for further development
- Facility is costly, *O*(€1b), so must be extremely well studied and planned if the project is to succeed.
- **ISS should be based on the need for optimum balance of high performance and cost. Aggregate most promising features of relevant accelerator work carried out worldwide. Also take account of developing detector and physics requirements.**

Accelerator WG Organization

- Accelerator study program managed by “Machine Council”
  - R. Fernow, R. Garoby, Y. Mori, R. Palmer, C. Prior, M. Zisman
- Aided by Task Coordinators
  - Proton Driver: R. Garoby, H. Kirk, Y. Mori, C. Prior
  - Target/Capture: J. Lettry, K. McDonald
  - Phase Rotation/Bunching/Cooling: R. Fernow, K. Yoshimura
  - Acceleration: S. Berg, Y. Mori, C. Prior
  - Storage Ring: C. Johnstone, G. Rees
- Constant liaison between task groups and Machine Council to take into account all requirements and facilitate better collaboration.

Accelerator Study

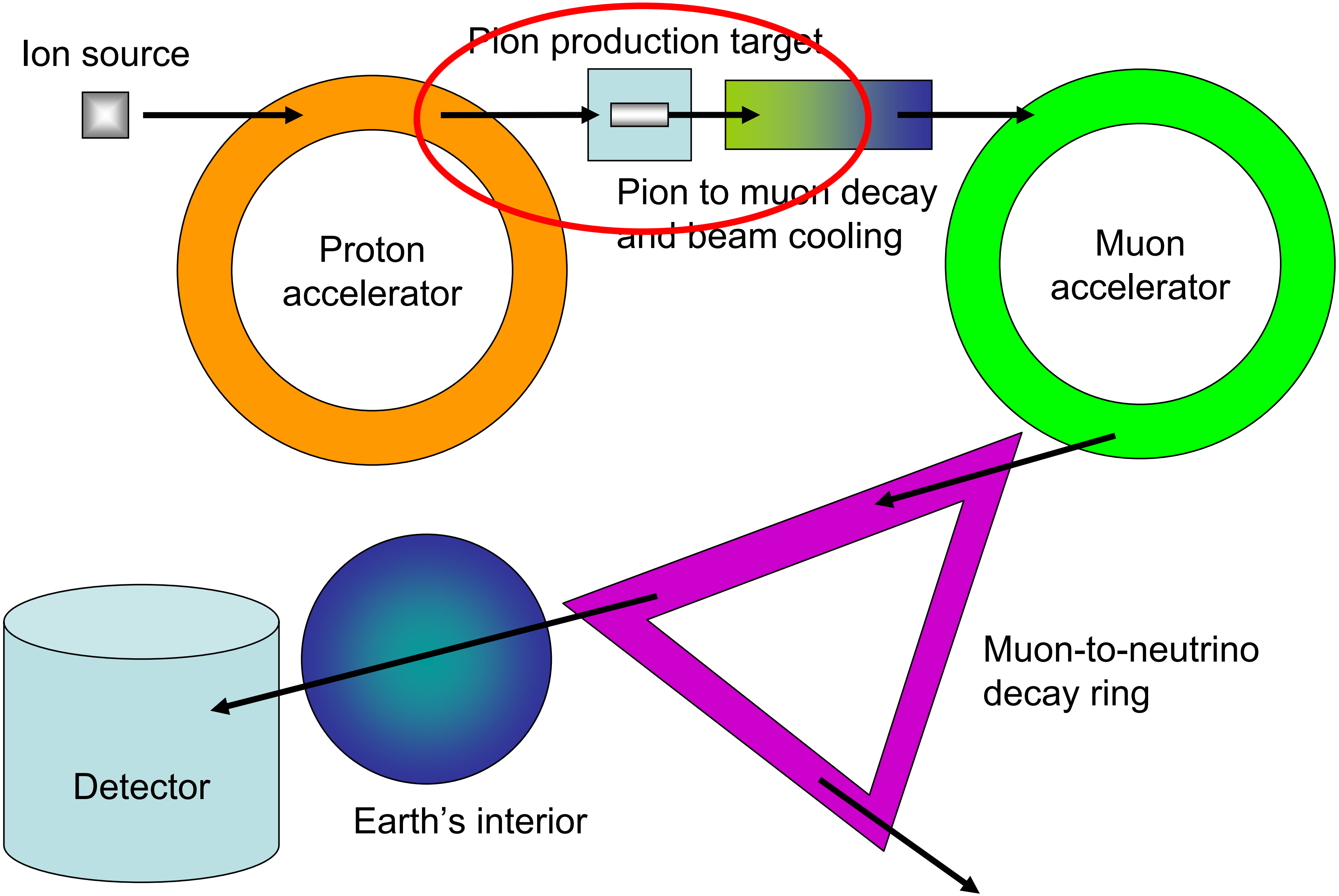
Phase 1 (6 months):

- Study alternative configurations; arrive at baseline specifications for a system to pursue
  - examine both cooling and non-cooling options
- Develop and validate tools for end-to-end simulations of alternative facility concepts
- Making choices requires cost evaluation
  - ISS will require engineers knowledgeable in accelerator and detector design

Phase 2 (6 months):

- Focus on selected options as prelude to subsequent World Design Study
- Develop R&D list as we proceed for a credible, cost-effective design.

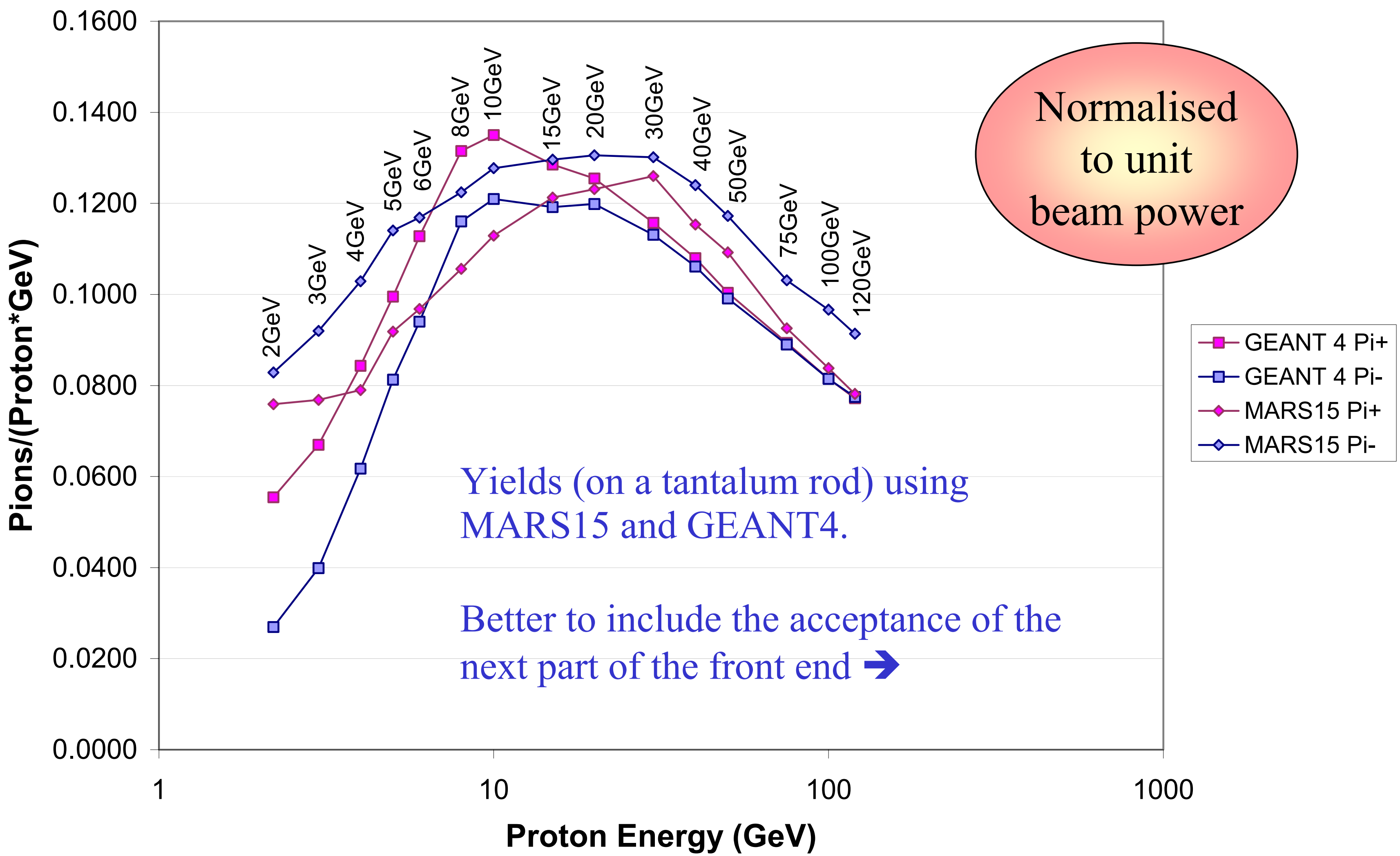
Simplified Neutrino Factory



Driver-Target-Capture

- A target capable of handling 4 MW of proton beam power is arguably the most difficult part of a neutrino facility.
- The proton driver needs to meet target capabilities in terms of pulse structure and frequency.
- Driver/target/capture systems need to be optimised so that the pion/muon distribution from the target gives the maximum number of neutrinos at the detectors (10^{21} per annum required)
- Driver energy and repetition rate are factors here.

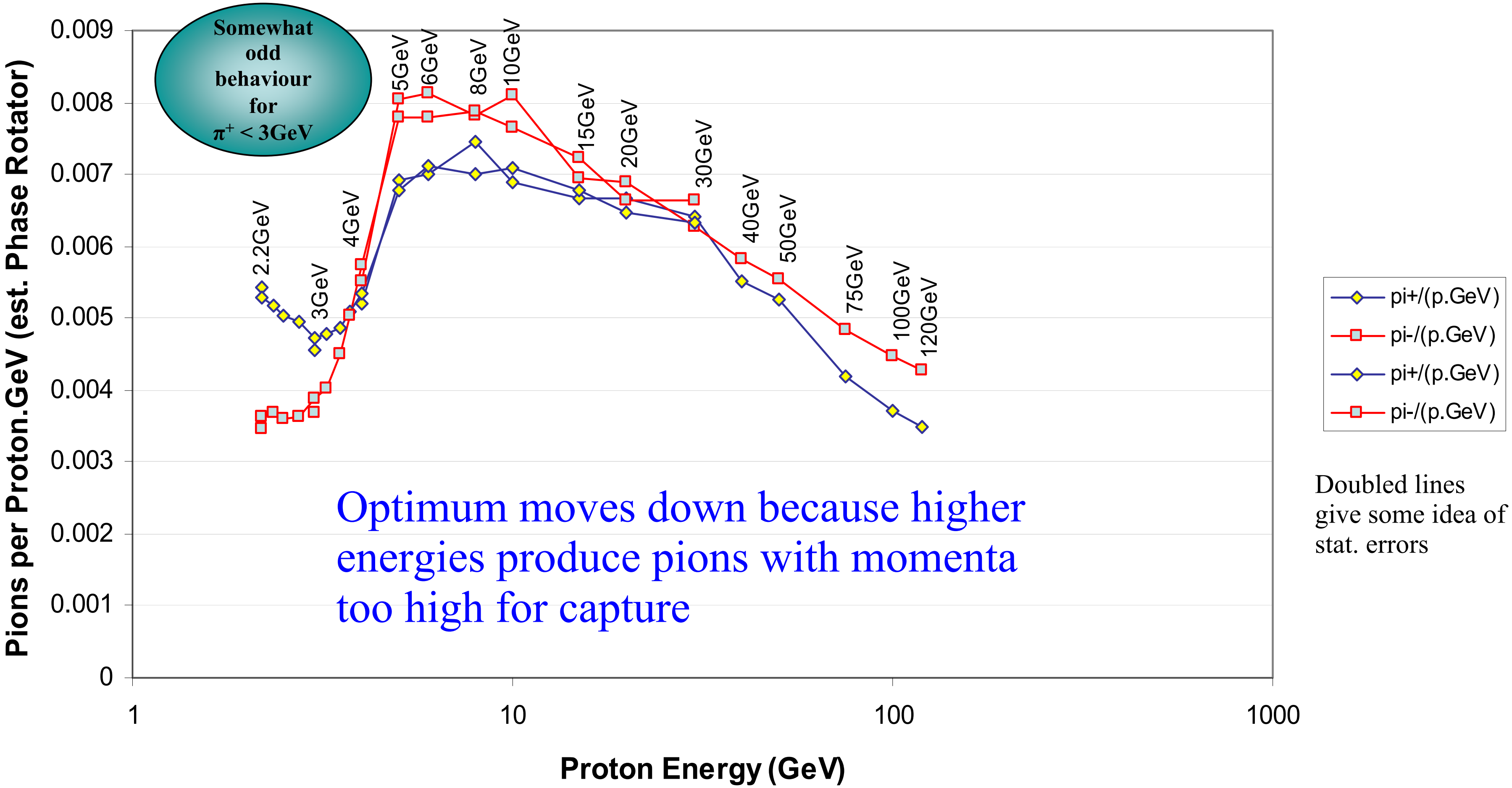
Total Yield of π^+ and π^-



Yields (on a tantalum rod) using MARS15 and GEANT4.

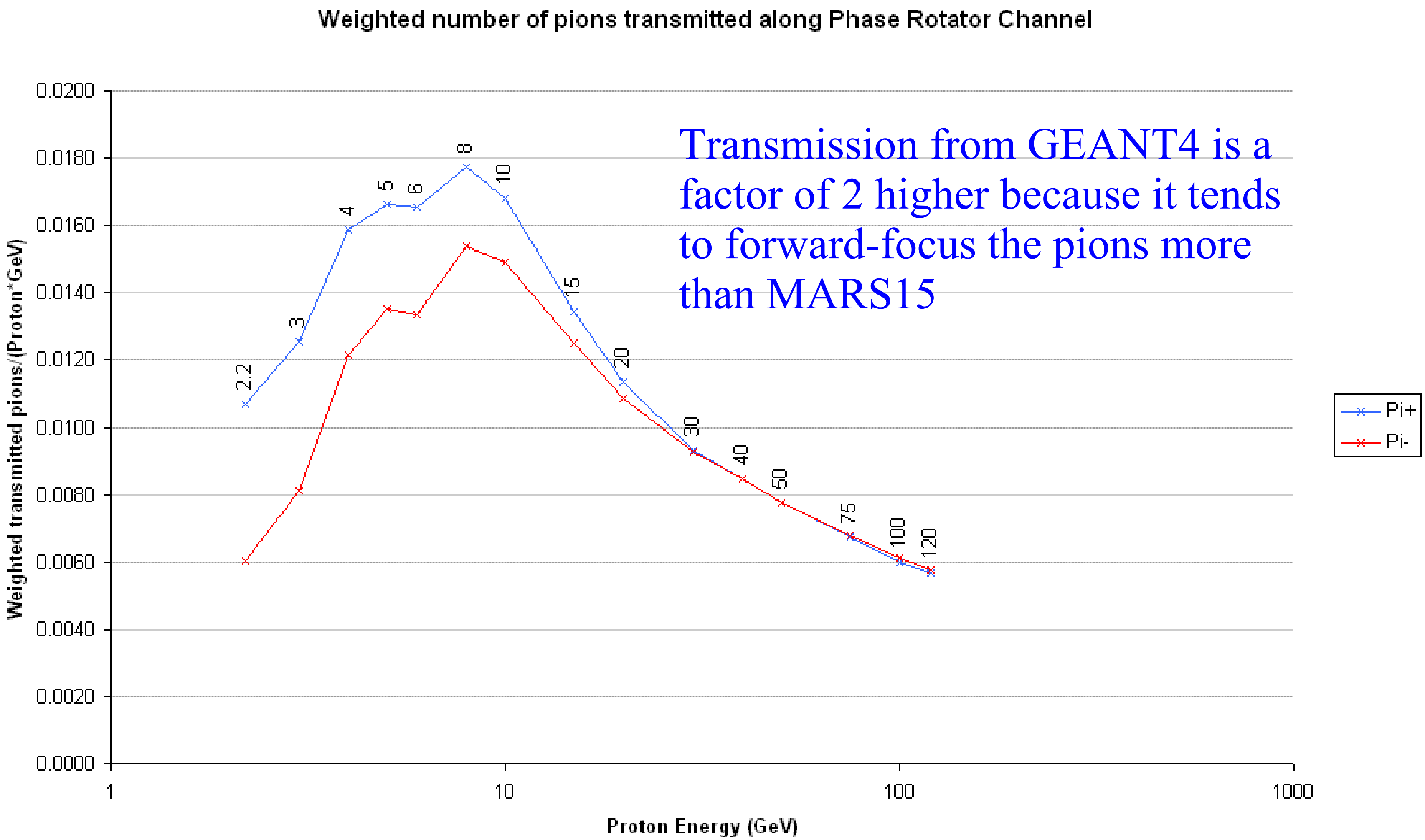
Better to include the acceptance of the next part of the front end ➔

Phase Rotator Transmission (MARS15)



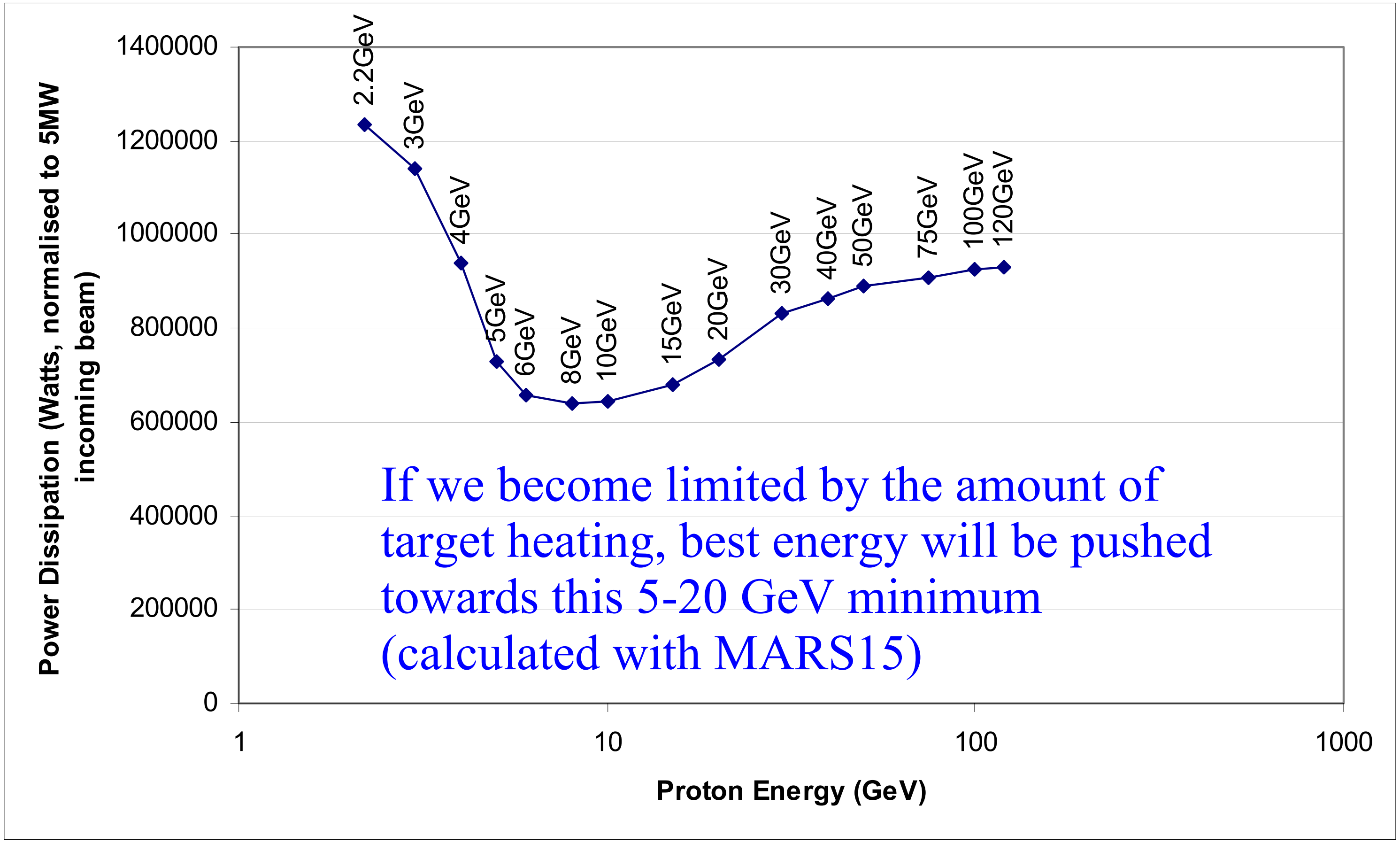
Doubled lines give some idea of stat. errors

Phase Rotator Transmission (GEANT4)



Transmission from GEANT4 is a factor of 2 higher because it tends to forward-focus the pions more than MARS15

Energy (heat) Deposition in Rod



Scaled for 5 MW total beam power; the rest is kinetic energy of secondaries.

Conclusions (Sept'05): Energy choice

- Optimal ranges appear to be:

According to:	For π^+:	For π^-:
MARS15	5-30 GeV	5-10 GeV
GEANT4	4-10 GeV	8-10 GeV

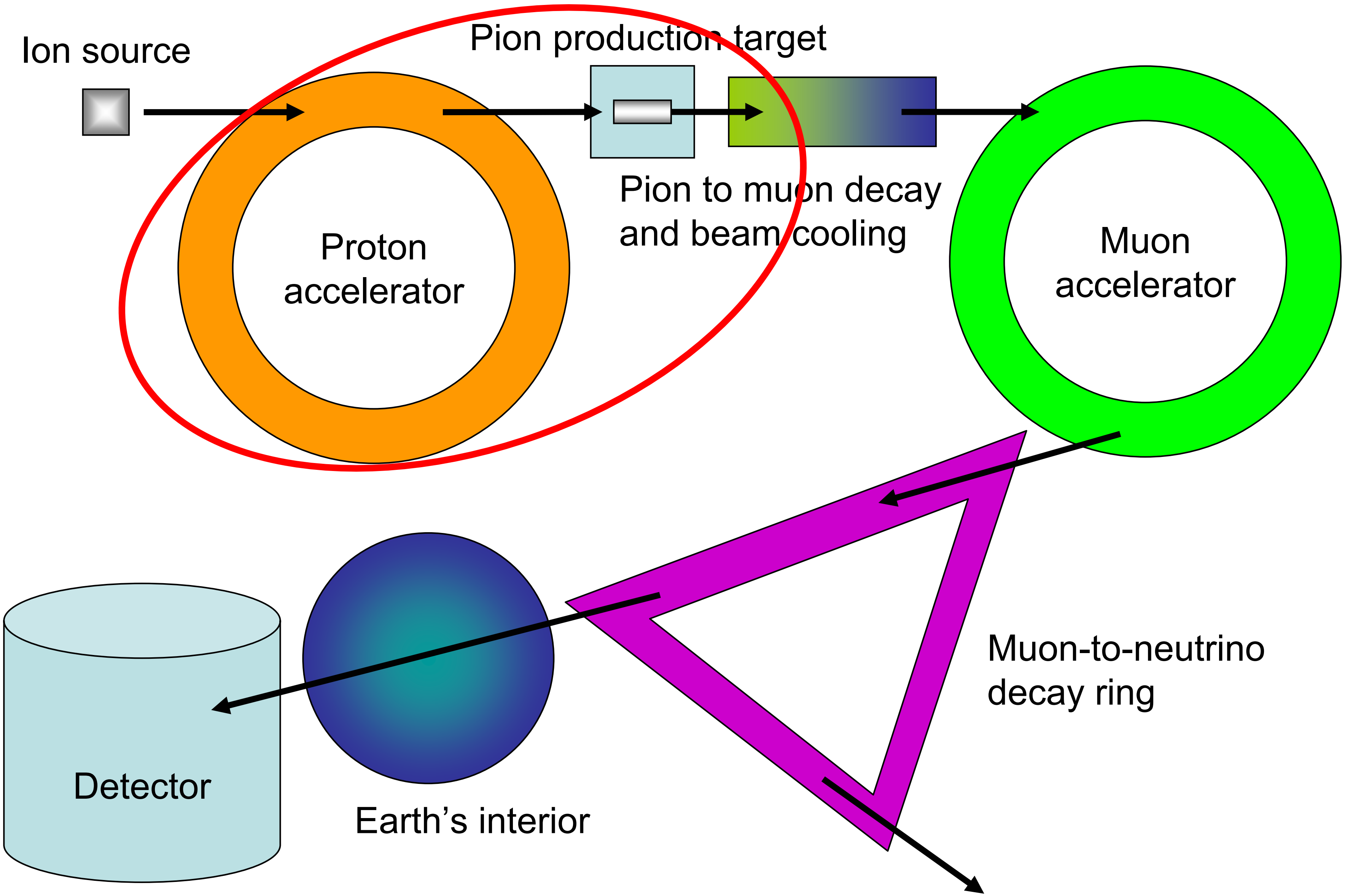
Need to reconcile codes and include HARP data.
Publication promised by the end of 2005.

Structure of Proton Driver Pulse

- Target bombarded at ~50 Hz by a proton beam of ~1 ns long bunches in a pulse of a few μsec duration. Simulations (LS-DYNA/ANSYS) show:
  - A 10-20% effect in radial shock as the different number of bunches in a pulse ranges from 1 to 10.
  - The effect of having longer bunches (2 or 3 ns) is negligible;
  - The effect of different length of a pulse is marked
    - 3μs pulse reduces radial shock, 10-30μs reduces longitudinal shock also.

G. Skoro (Nufact'05)

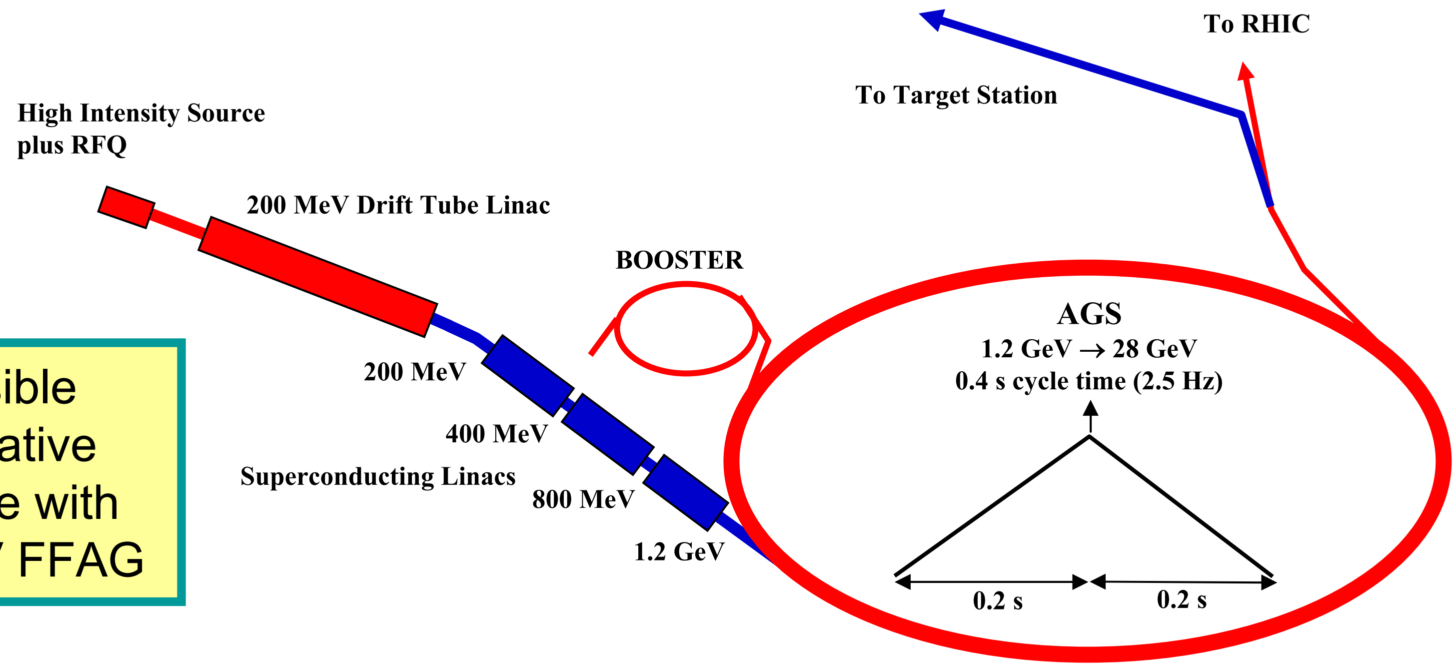
Simplified Neutrino Factory



Proton Driver Phase 1

- Examine candidate machine types for 4 MW operation
  - Linac (SPL and/or Fermilab approach)
  - Synchrotron (J-PARC and/or AGS approach)
  - FFAG (scaling and/or non-scaling)
    - consider
      - beam current limitations (injection, acceleration, activation)
      - bunch length limitations and schemes to provide 1-3-10 ns bunches
      - repetition rate limitations (power, vacuum chamber,…)
      - tolerances (field errors, alignment, RF stability,…)
      - optimization of beam energy
  - Consider which PD type is best suited to neutrino facility requirements (a) ideally, (b) realistically
- Decide on optimum parameter set, consider existing proposals and identify which come closest to, and can be developed into, the ideal.
- Define a figure of merit (muons per MW of proton beam power?)

AGS Upgrade to 1 MW



Possible alternative scheme with 1.5 GeV FFAG

- 1.2 GeV superconducting linac extension for direct injection of $\sim 1 \times 10^{14}$ protons
  - low beam loss at injection; high repetition rate possible
  - further upgrade to 1.5 GeV and 2×10^{14} protons per pulse possible (x 2)
- 2.5 Hz AGS repetition rate
  - triple existing main magnet power supply and magnet current feeds
  - double rf power and accelerating gradient
  - further upgrade to 5 Hz possible (x 2)

AGS 1 MW Upgrade and SC Linac Parameters

Proton Driver Parameters

Item	Value
Total beam power	1 MW
Protons per bunch	0.4×10^{13}
Beam energy	28 GeV
Injection turns	230
Average beam current	38 mA
Repetition rate	2.5 Hz
Cycle time	400 ms
Pulse length	0.72 ms
Number of protons per fill	9.6×10^{13}
Chopping rate	0.75
Number of bunches per fill	24
Linac average/peak current	20/30 mA

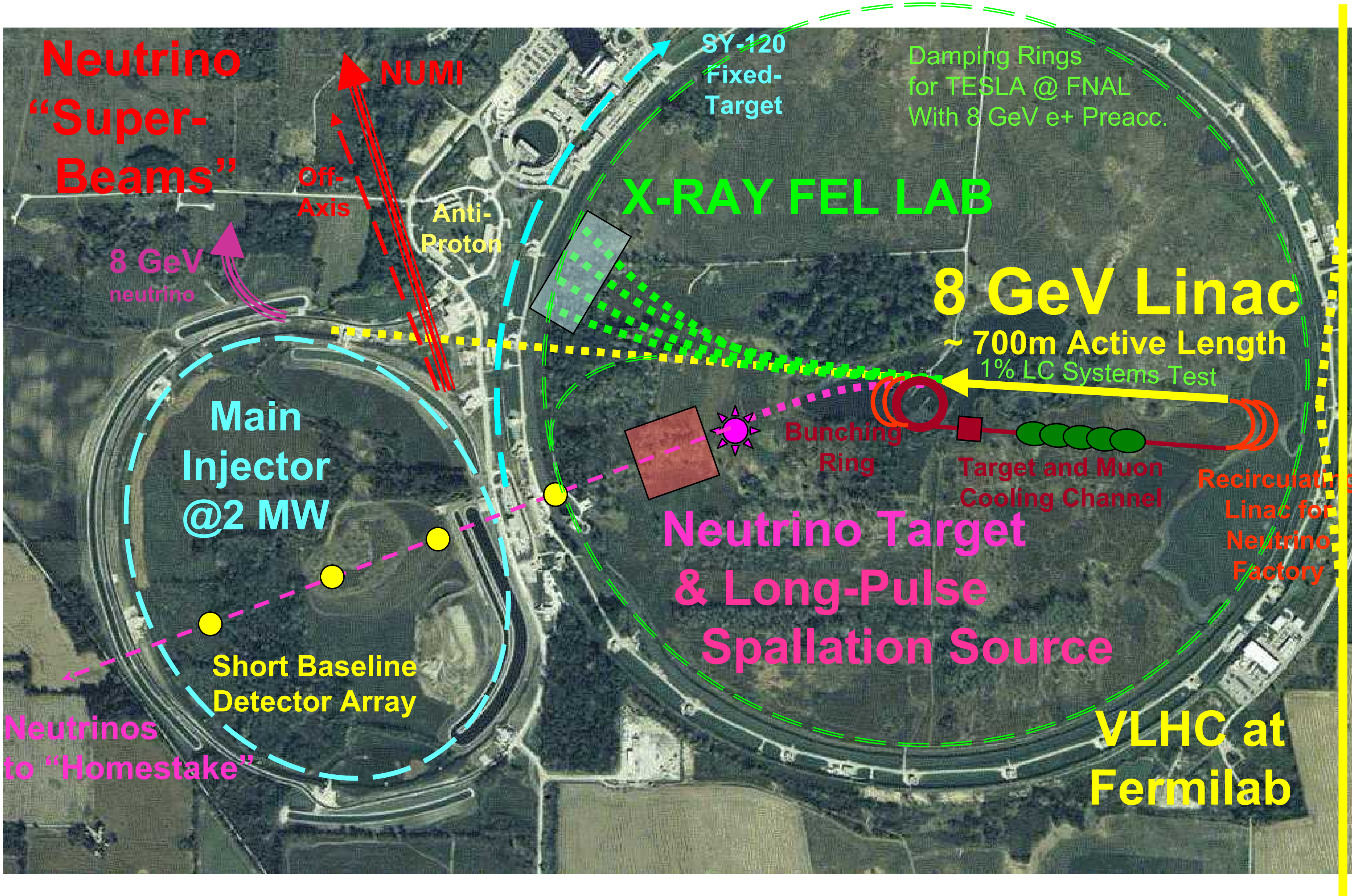
Superconducting Linac Parameters

Linac Section	LE	ME	HE
Av Beam Pwr, kW	7.14	14.0	14.0
Av Beam Curr, mA	35.7	35.7	35.7
K.E. Gain, MeV	200	400	400
Frequency, MHz	805	1610	1610
Total Length, m	37.82	41.40	38.32
Accel Grad, MeV/m	10.8	23.5	23.4
norm rms ε, π mm-mr	2.0	2.0	2.0

Path to 4MW:

- Raise SCL energy to 1.5 GeV, AGS repetition rate to 5Hz with 2×10^{14} ppp.
- Add post AGS accelerator to 40 GeV, raise AGS rep rate to 5 Hz with 1.4×10^{14} ppp.

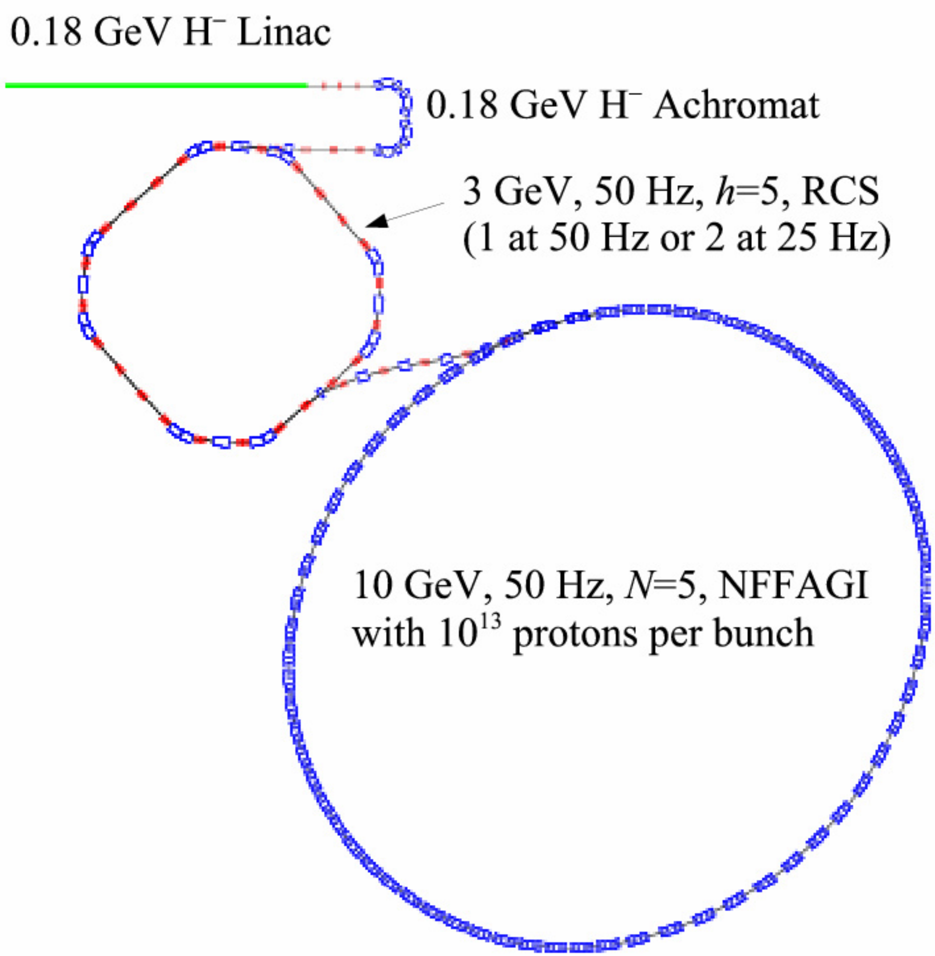
Fermilab 8 GeV SC Linac



Comparison of FNAL PD options

Parameters	Present Proton Source	Proton Driver synchrotron (PD2)	Proton Driver SCRF Linac only (2 MW baseline)	Proton Driver SCRF Linac <u>and</u> MI upgrade ?
Linac (Pulse Freq)	5 Hz	15 Hz	10 Hz	10 Hz
Kinetic energy (MeV)	400	600	8000	8000
Peak current (mA)	40	50	28	28
Pulse length (μs)	25	90	1000	1000
Booster (cycles at 15 Hz)				
Extraction kinetic energy (Gev)	8	8	-	-
Protons per cycle	5×10^{12}	2.5×10^{13}	-	-
Protons per hour	9×10^{16} (5 Hz)	1.4×10^{18}	-	-
8 GeV Beam Power (MW)	0.033 (5 Hz)	0.5	2	1.7
Main Injector				
Extraction Energy for NuMI (Ge	120	120	120	120
Protons per cycle	3×10^{13}	1.5×10^{14}	1.5×10^{14}	1.5×10^{14}
fill time (sec)	0.4 (5/15+0.1)	0.4 (5/15+0.1)	0.1	0.1
ramp time (sec)	1.47	1.13	1.4	0.7
cycle time (sec)	1.87	1.53	1.5	0.8
Protons per hour	5.8×10^{16}	3.5×10^{17}	3.5×10^{17}	6.7×10^{17}
Ave Beam Power (MW)	0.3	1.9	1.9	3.5

Isochronous FFAG 4 MW Proton Driver

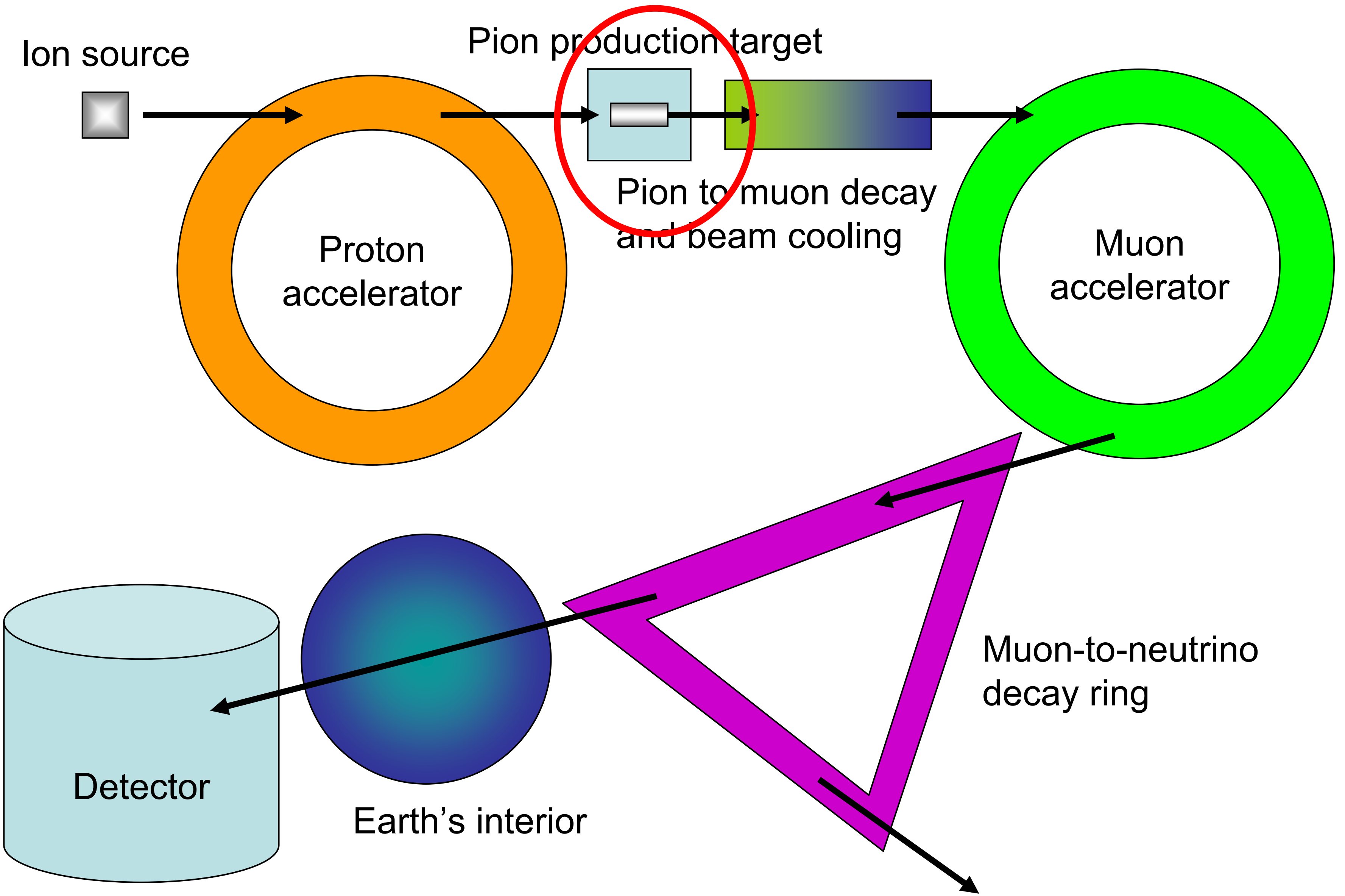


- RAL design
- 5 bunches per pulse
- 50 Hz repetition rate
- 10 GeV
- Isochronous FFAG with insertions

Comparison Table of Proton Drivers

Driver	f (Hz)	T (GeV)	Pulse length (μs)	Bunches per pulse	Bunch length (ns)	Figure of Merit
AGS	5	40	720	24		
FNAL	10	8				
SPL	50	2.2/3.5	3.2	140	1	
J-PARC	0.33	50		9	30	
RAL1	50	8	1.6	4	1	
RAL2	25	15	3.0	6	1	
KEK/ Kyoto	10k	3			10	

Simplified Neutrino Factory



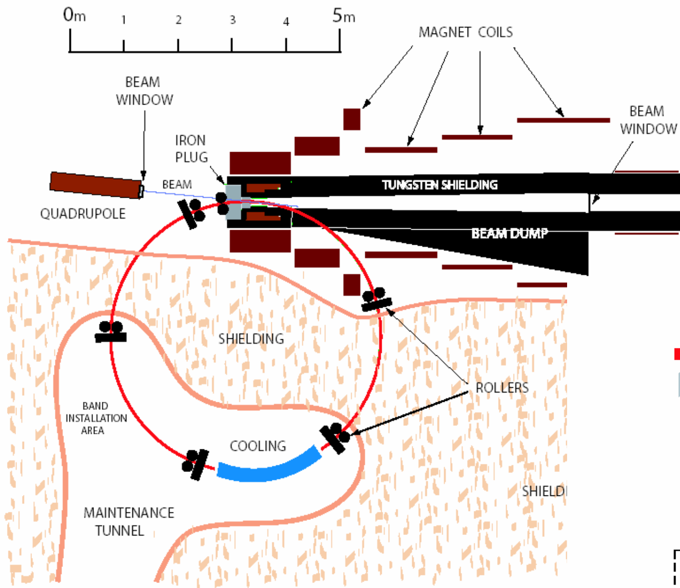
Target

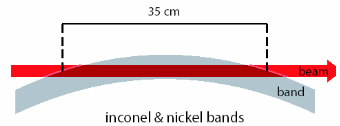
- Optimum target material
  - solid or liquid; low, medium, or high *Z*
  - Alloys, composites, “smart” materials
- Production rates as function of energy for C, Ni, Hg
  - do reality check with HARP data if possible
- Target limitations for 4 MW operation
  - consider bunch intensity, spacing, repetition rate
- Implications of 1 v. 3 ns bunches on delivered beam
  - for various downstream RF systems
- Superbeam v. Neutrino Factory
  - is a single choice of target material adequate for both?

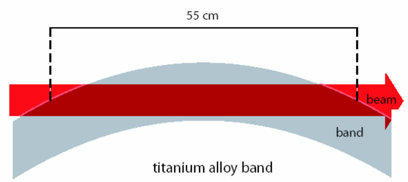
Target Status

- Solid targets
  - Material properties, properties under irradiation, thermal expansion
  - Induced shock
    - CNGS target test at ISOLDE: good agreement between experiment and simulation
  - Thermal stress waves (radial and longitudinal)
- Liquid targets
  - 24 GeV proton beam in liquid mercury (BNL)
- Heat flow
  - He cooling
  - Radiation cooling (levitated ring)
- New material for each proton pulse
  - Chain saw, bullets, molten metal jets

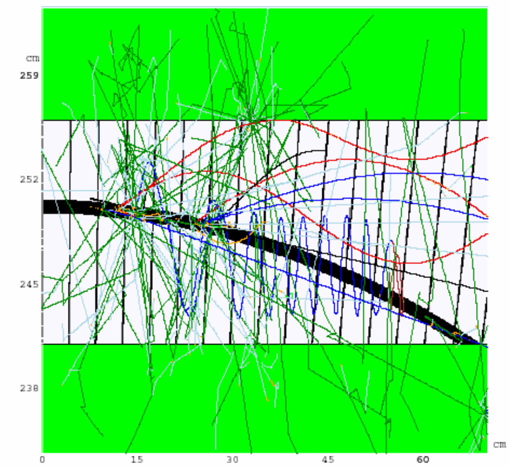
Rotating Band (Muon Collider)



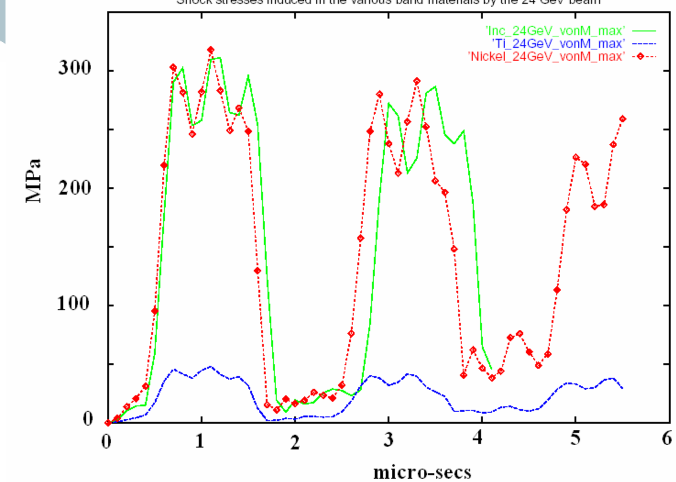




MARS simulation of secondary particle production from 5 interactions of 24 GeV protons in an inconel-718 band target



Shock stresses induced in the various band materials by the 24 GeV beam



MARS & ANSYS predictions for pion yields, energy depositions and induced stress.
Proton bunch charge resulting in 3.2 x 10[13] captured protons.

band material	inconel 718		Ti-alloy		nickel	
proton energy [GeV]	6	24	6	24	6	24
captured π^+ yield/proton	0.102	0.303	0.080	0.249	0.102	0.302
captured π^- yield/proton	0.105	0.273	0.083	0.224	0.105	0.292
$ppp^{3.2}$ $[10^{13}]$	15.5	5.56	19.6	6.78	15.5	5.39
$E^{3.2}_{pulse}$ $[kJ]$	149	214	188	260	149	207
$U^{3.2}_{max}$ [J/g]	32.0	31.7	25.6	21.3	32.5	37.4
$\Delta T^{3.2}_{max}$ [°C]	74	73	49	40	71	81
stress, $VM^{3.2}_{max}$ [MPa]	330	360	72	68	330	340
% of fatigue strength	53-69%	58-75%	10-14%	10-13%	N.A.	N.A.

Target Technologies, Issues and Plans

- Molten metal targets
  - High pressure, high velocity, molten metal fluid dynamics
- Solid targets
  - Effects of impurities on chemical properties
  - High velocity mechanics under vacuum
  - Compaction of beads
- Component reliability or lifetime v. exchange time
  - Horns and 20T solenoids
- Simulation codes
  - Go beyond simple energy deposition: shock transport, 3d models etc
- Drive target scenarios to their limit through simulations – Use experimental data to guide simulations.
- Optical measurement techniques in high radiation environment
- Activation of components, inventory of specific activities v. time
  - Radioactive waste handling, internal transport, intermediate storage, end disposal
- Dedicated experimental area for target tests

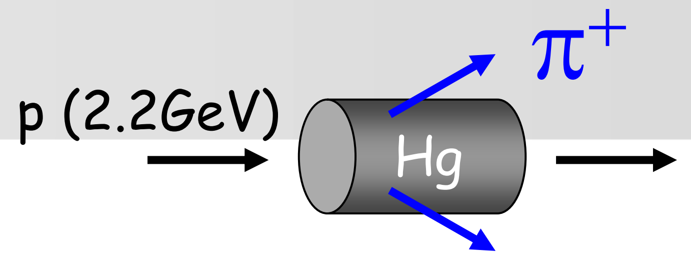
Planned Experimental Target Activities

- MERIT (MERcury Intense Target)
  - PS 24 GeV beam, 2.8 10^{13} protons on 1.2mm × 1.2 mm beam spot
  - Peak energy deposition 180 J/g
  - Beam on target April 2007
- Proton-induced shock on a high temperature Ta cylinder with a VISAR
- Graphite and Carbon-Carbon to be tested to cycles up to 1100 C
  - in vacuum
  - with forced helium
- Thermal diffusivity assessment of irradiated material matrix
- Damage assessment due to defect generation/growth on the irradiated specimens using ultrasonic techniques.
- Material resilience to shock: Use of a high power, focused laser beam
- **Expose/irradiate solid targets to much higher energies. P-bar target area at FNAL is being assessed. This will shed light in the possible difference of induced irradiation damage**

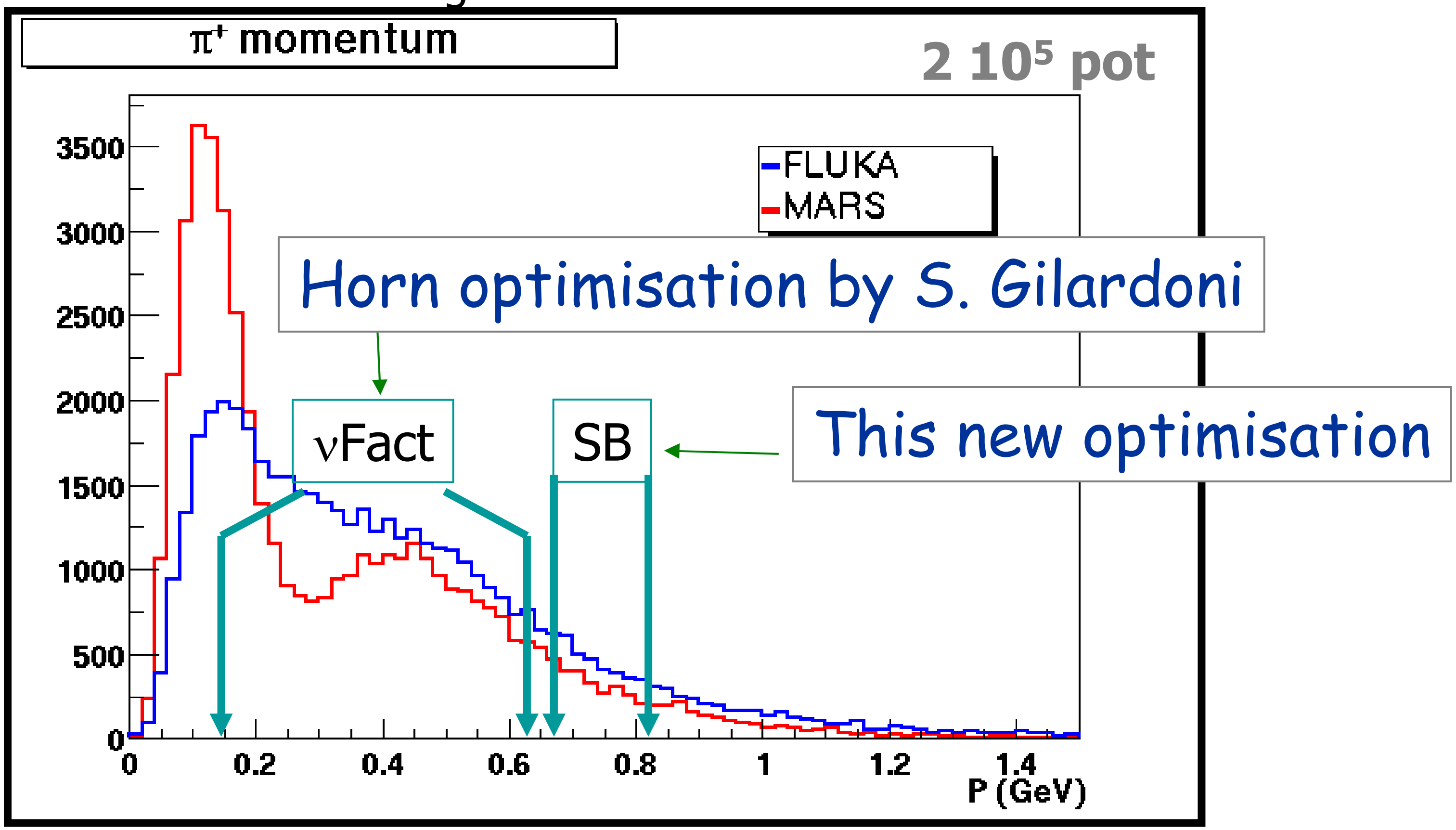
Superbeams

- Superbeam vs. Neutrino Factory comparisons
  - horn vs. solenoid
    - can one solution serve both needs?
- Comparison of Superbeam and Neutrino Factory requirements
  - Horn only for SB; horn or solenoid for NF (~same pion yield)
  - Energy range of pions of interest is wider for NF than SB
  - Horn geometry differs between SB and NF
  - SB optimised for physics → PD energy 3.5 GeV (although peak production is at 5 GeV)
- To what extent can a Superbeam facility be developed into a full Neutrino Factory?
  - Scenarios have different requirements

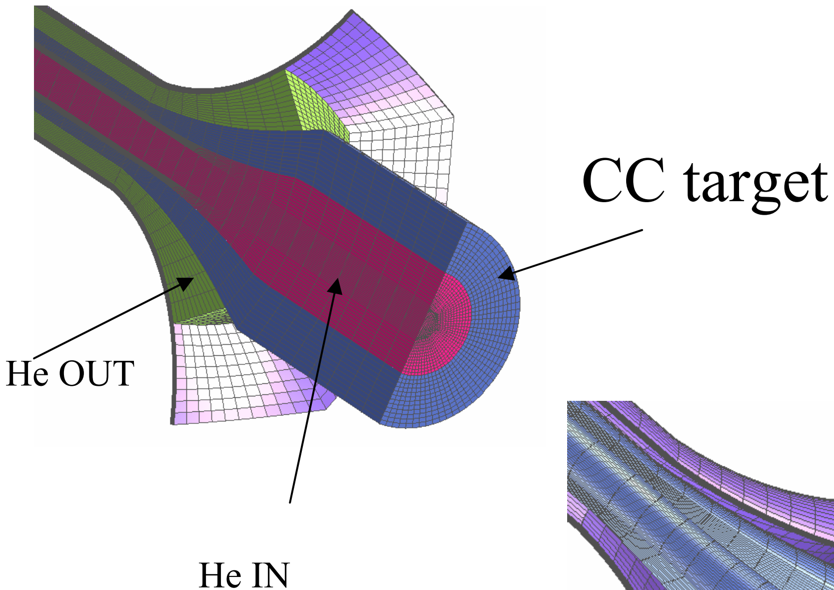
Pion production

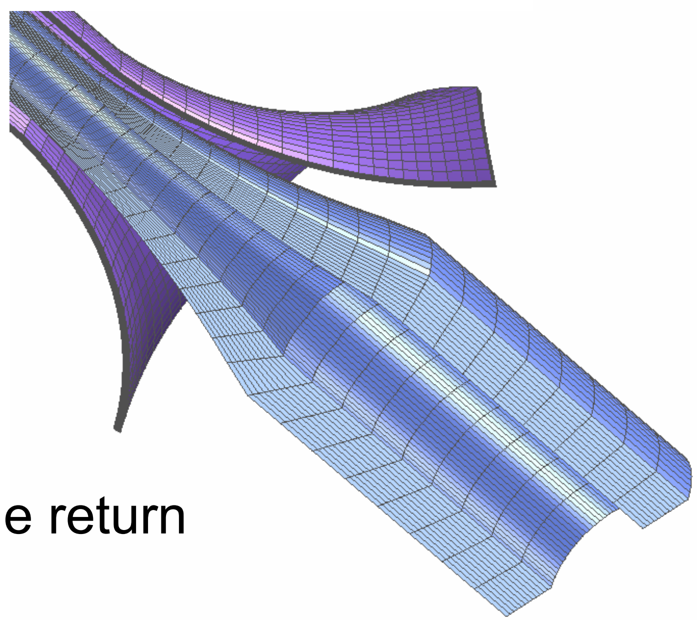


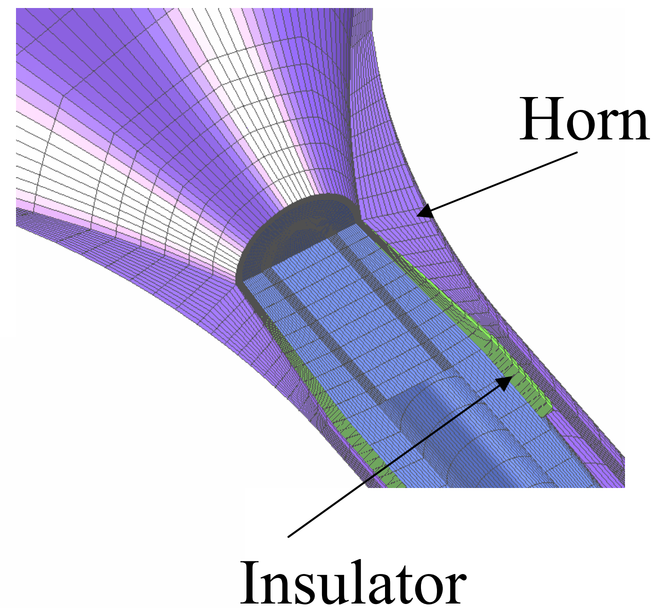
at the exit of the target



BNL Neutrino SuperBeam Target

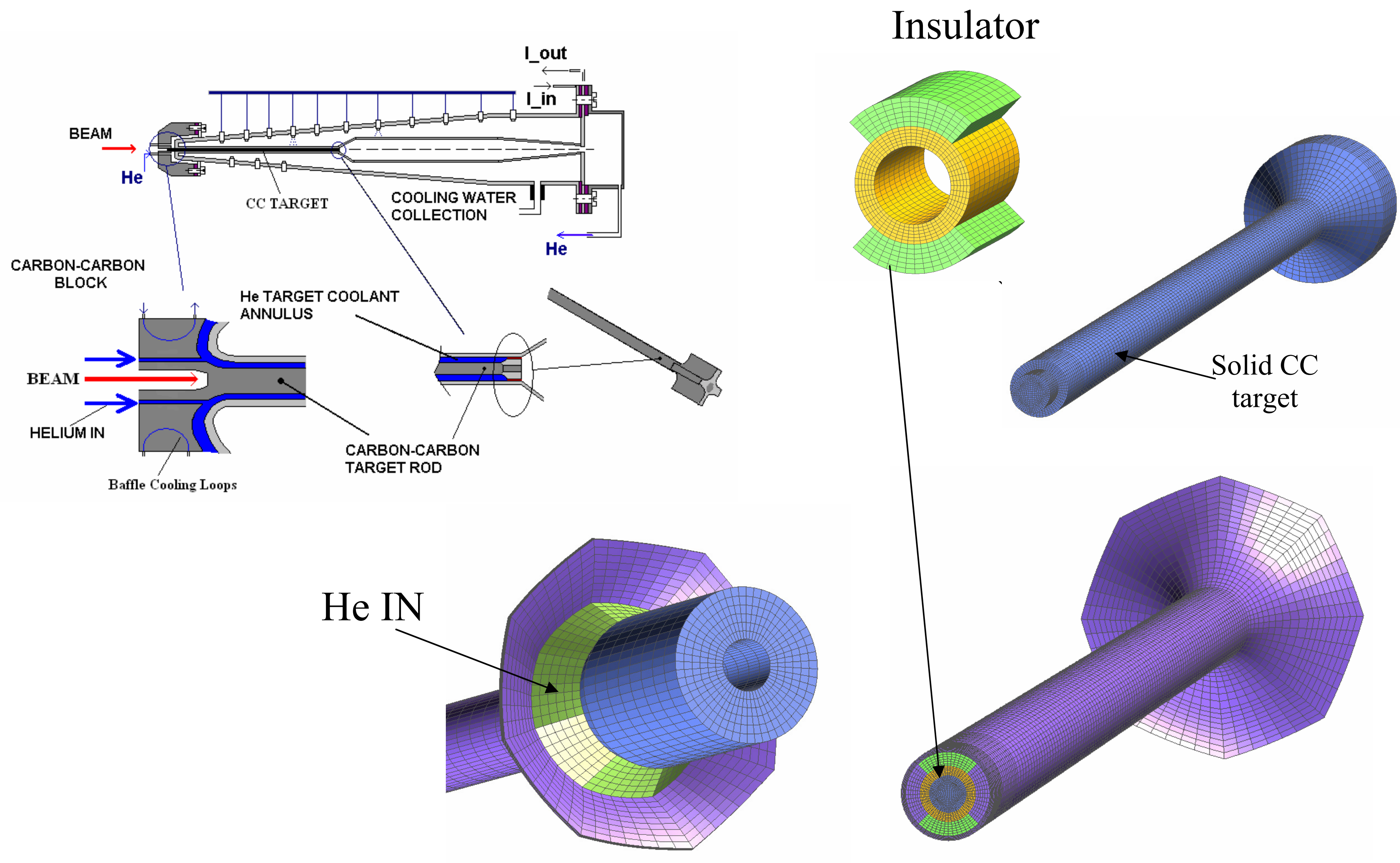




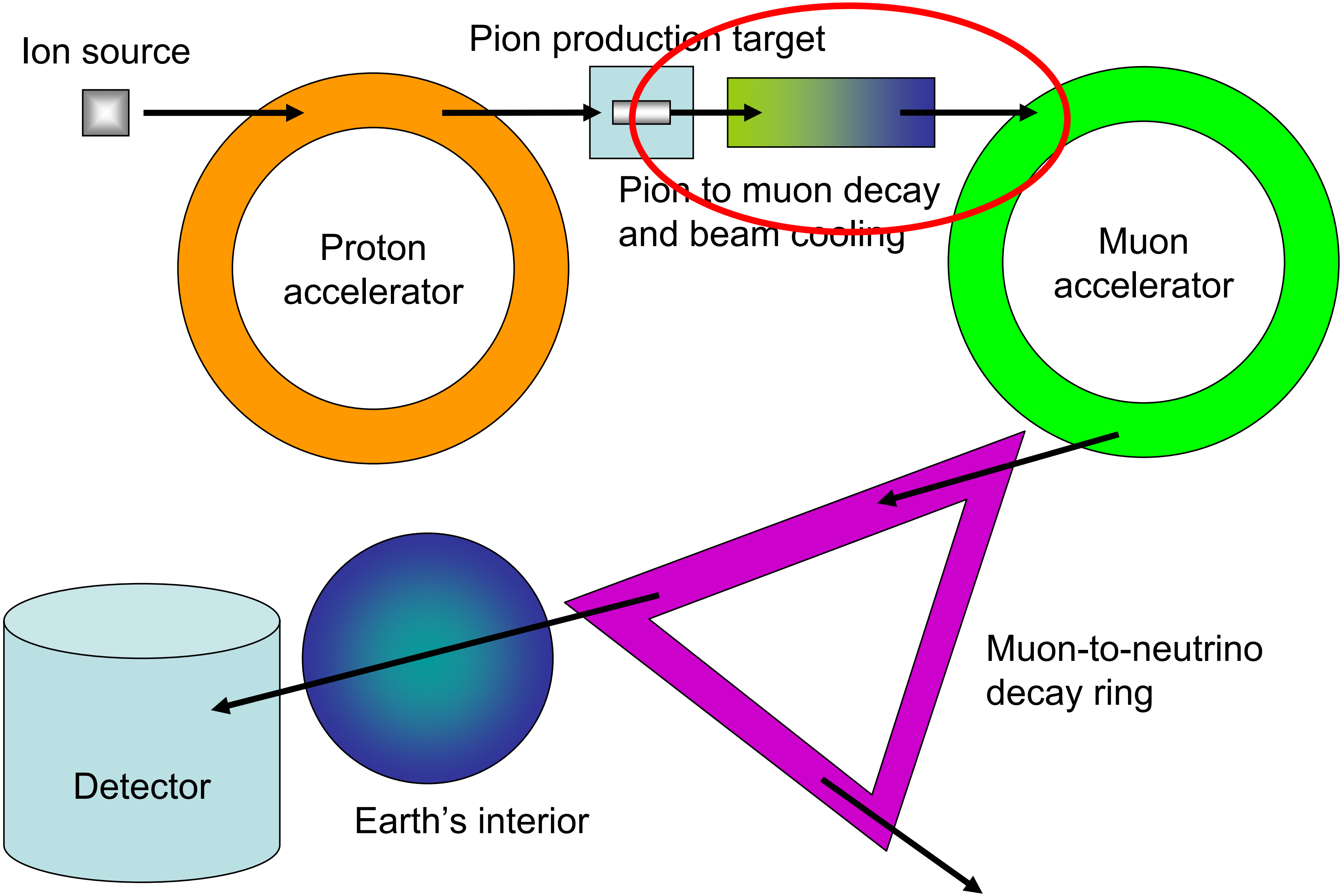


Hollow CC target with He return

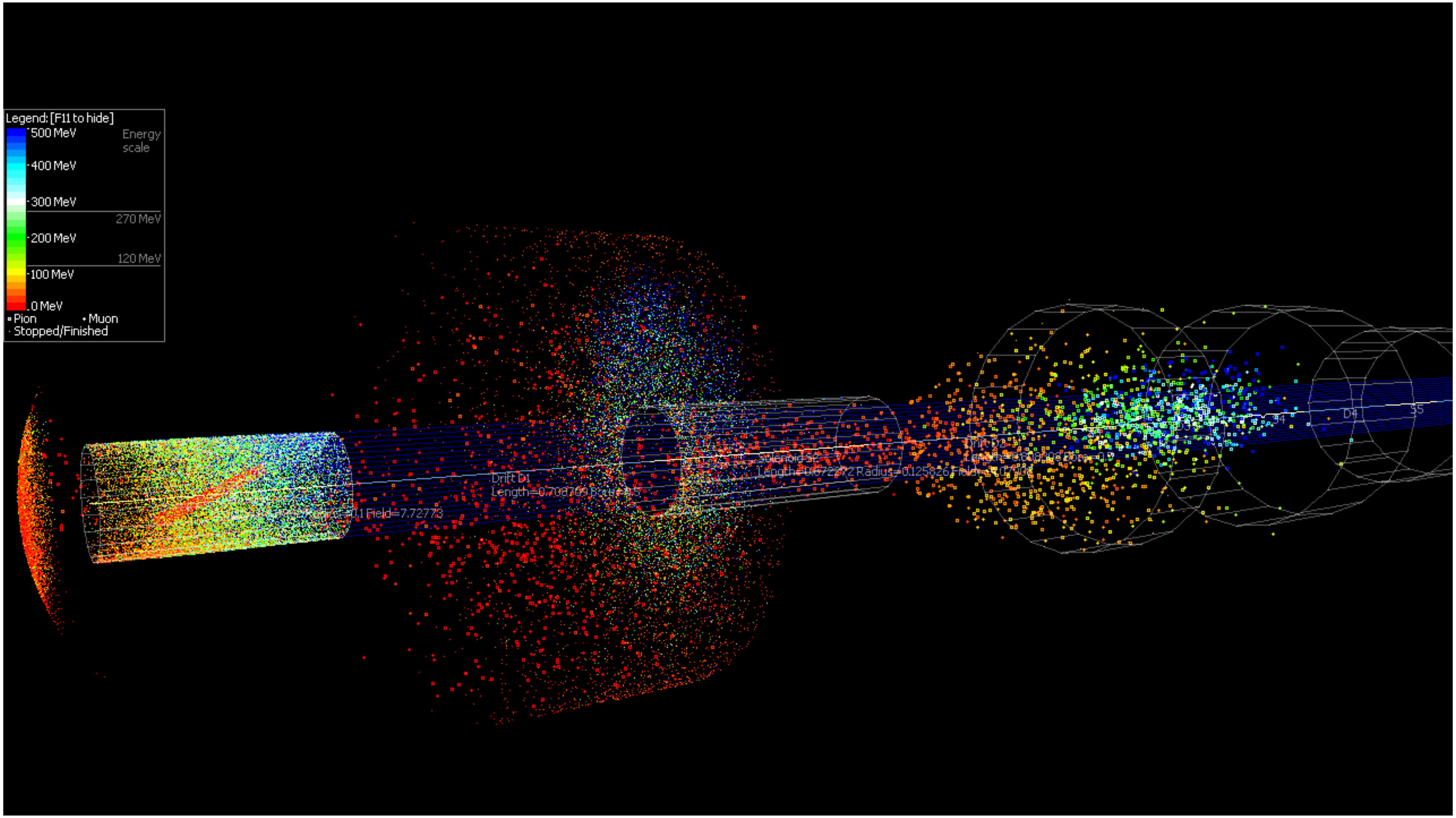
BNL Neutrino SuperBeam Target



Simplified Neutrino Factory



Solenoid Capture Channel



Front-End Tasks (1)

- Compare performance of existing NF schemes, using common proton driver and target configurations:
  - Consider 6 schemes: KEK, CERN with horn, CERN with solenoid, RAL, US Study 2a, US FS2
  - Use 5 beam-target combinations: Carbon with 4 and 40 GeV beams, Ta with10 GeV beam, Hg with 4 and 40 GeV beams.
  - Make ICOOL models of all schemes (with/without cooling)
  - Agree on proper figure of merit (accepted muons per MW or per pion?)
  - Check performance for other muon sign

Conclusions will require cost comparisons, which will come later

Front-End Tasks (2)

- Evaluate implications of reduced RF voltage (in case specifications cannot be met)
  - Consider 75% and 50% of design gradient
  - Re-optimize most promising designs using the smaller gradient
    - e.g. change lattice, amount of absorber, number of cavities
  - Decide what is a “practical” gradient at 5, 40, 88 and 201 MHZ?
- Search for optimised phase rotation/bunching systems
  - RF or FFAG
  - adiabatic or fixed design
  - optimise gradients, number of frequencies, channel length
- Evaluate trade-offs of cooling *v.* acceptance
  - Aim to save money (Palmer/Berg cost scaling rules)

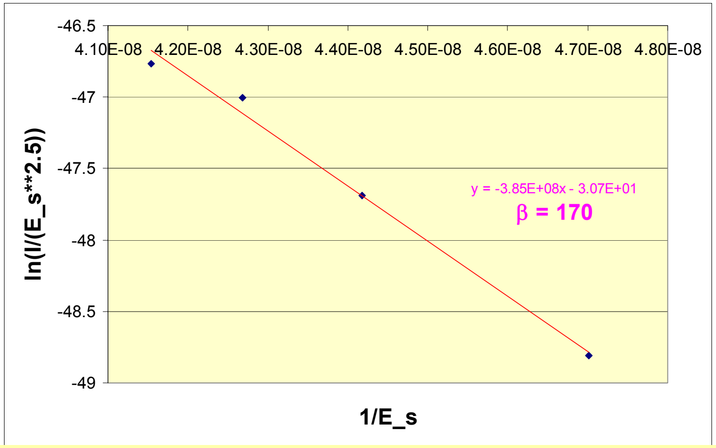
Front-End Tasks (3)

- Evaluate performance and limitations of absorbers & windows
  - Identify practical constraints on absorber & window choices.
  - Consider performance issues and limitations
  - Absorbers: LH_2, LiH, Be.
  - RF windows: Be.
  - Consider implications of keeping both muon signs.
  - Carry out literature review, some engineering analysis.
  - What can be done with additional R&D, more money?
  - Prepare list of issues for each design.
  - Estimate resulting performance limitations.
  - Might require some simulation work.

CERN: 88 MHz Cavity test results

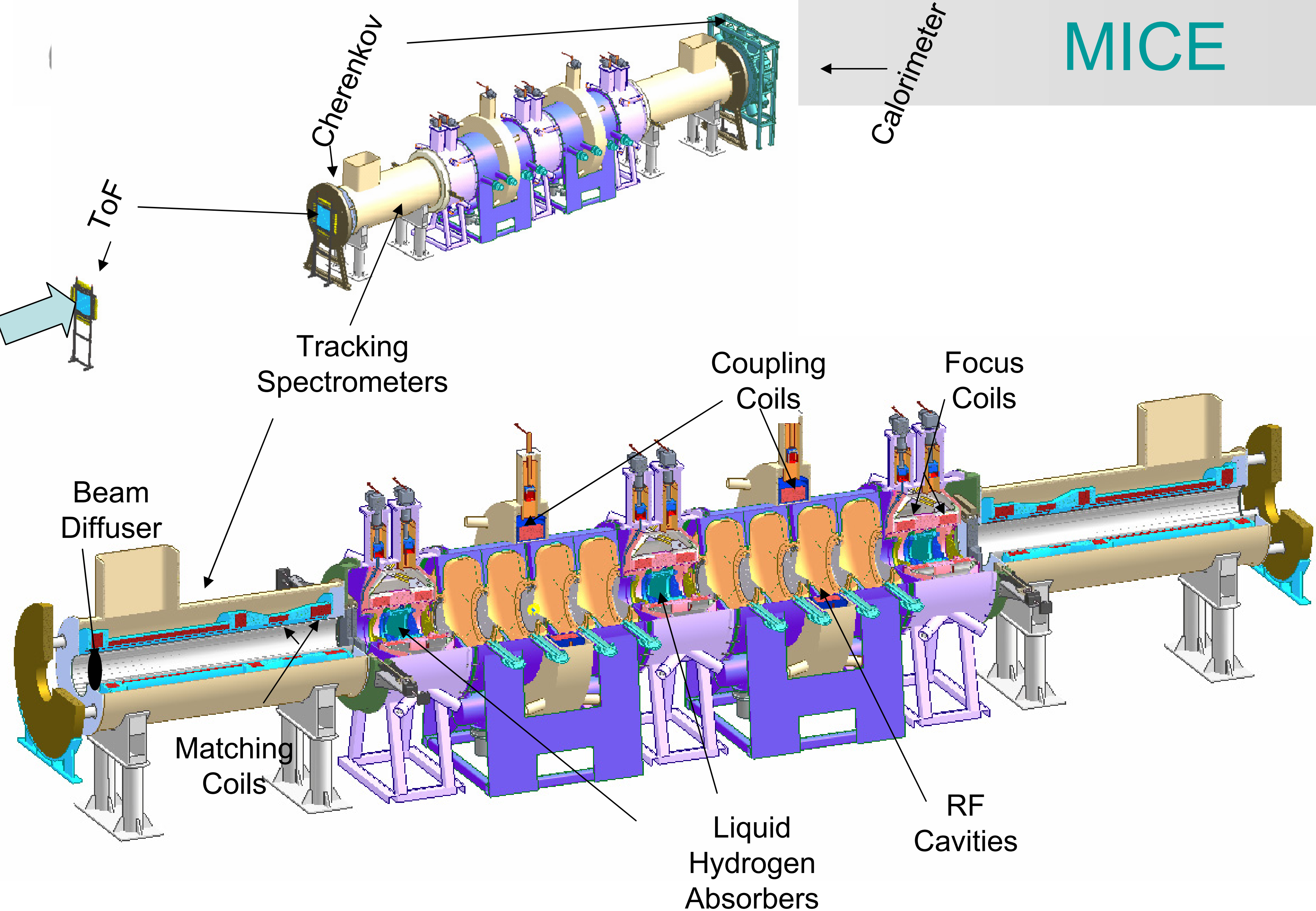
Test of 88 MHz cavity for muon cooling channel
Cavity conditioned at 1 Hz, 170 μs up to:

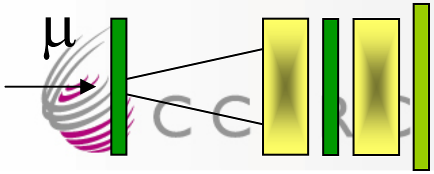
4.1 MV/m overall gradient
14.7 MV/m gap field
25.9 MV/m peak field (=2.4 Kilpatrick)



Fowler-Nordheim plot of field emission current
Enhancement factor β=170

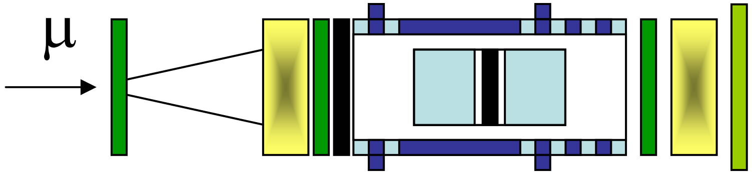
MICE


Cherenkov
Calorimeter
ToF
Tracking Spectrometers
Coupling Coils
Focus Coils
Beam Diffuser
Matching Coils
Liquid Hydrogen Absorbers
RF Cavities



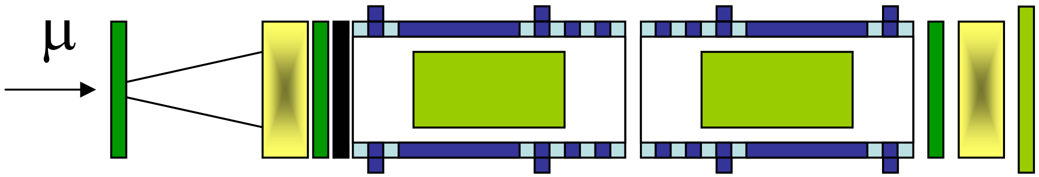
Step I:2007

MICE phase 1



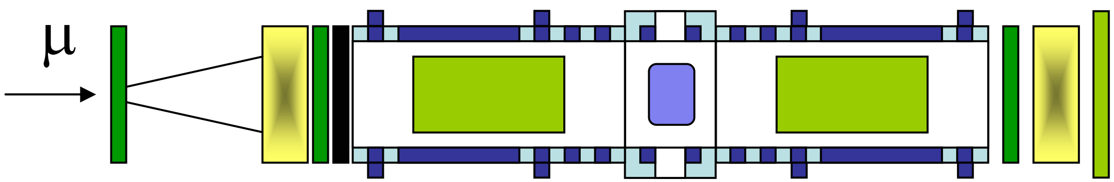
Step II

Constructs: muon beam line on ISIS,
and tracking and particle ID systems to measure cooling channel performance.

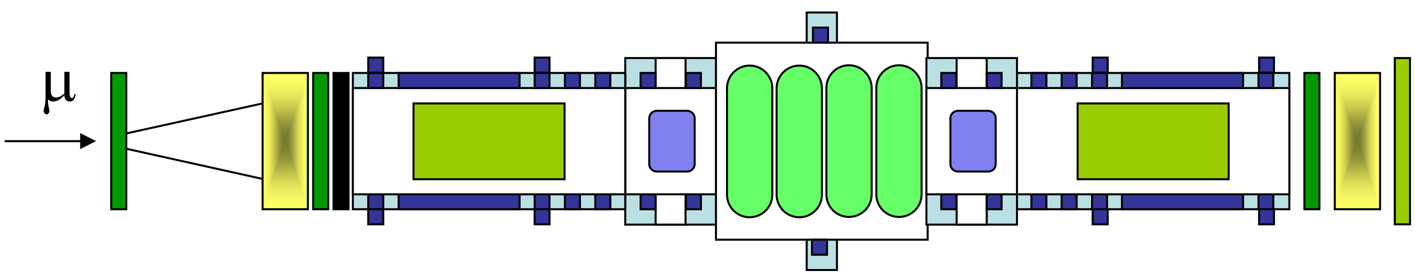


Step III

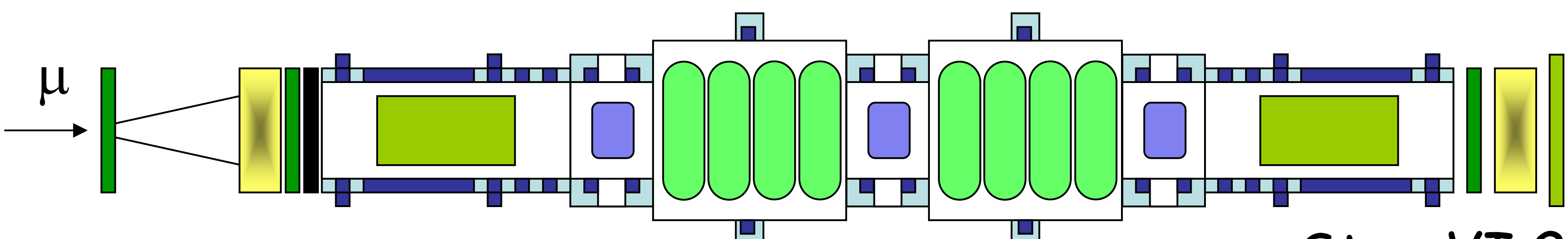
MICE phase 2



Step IV

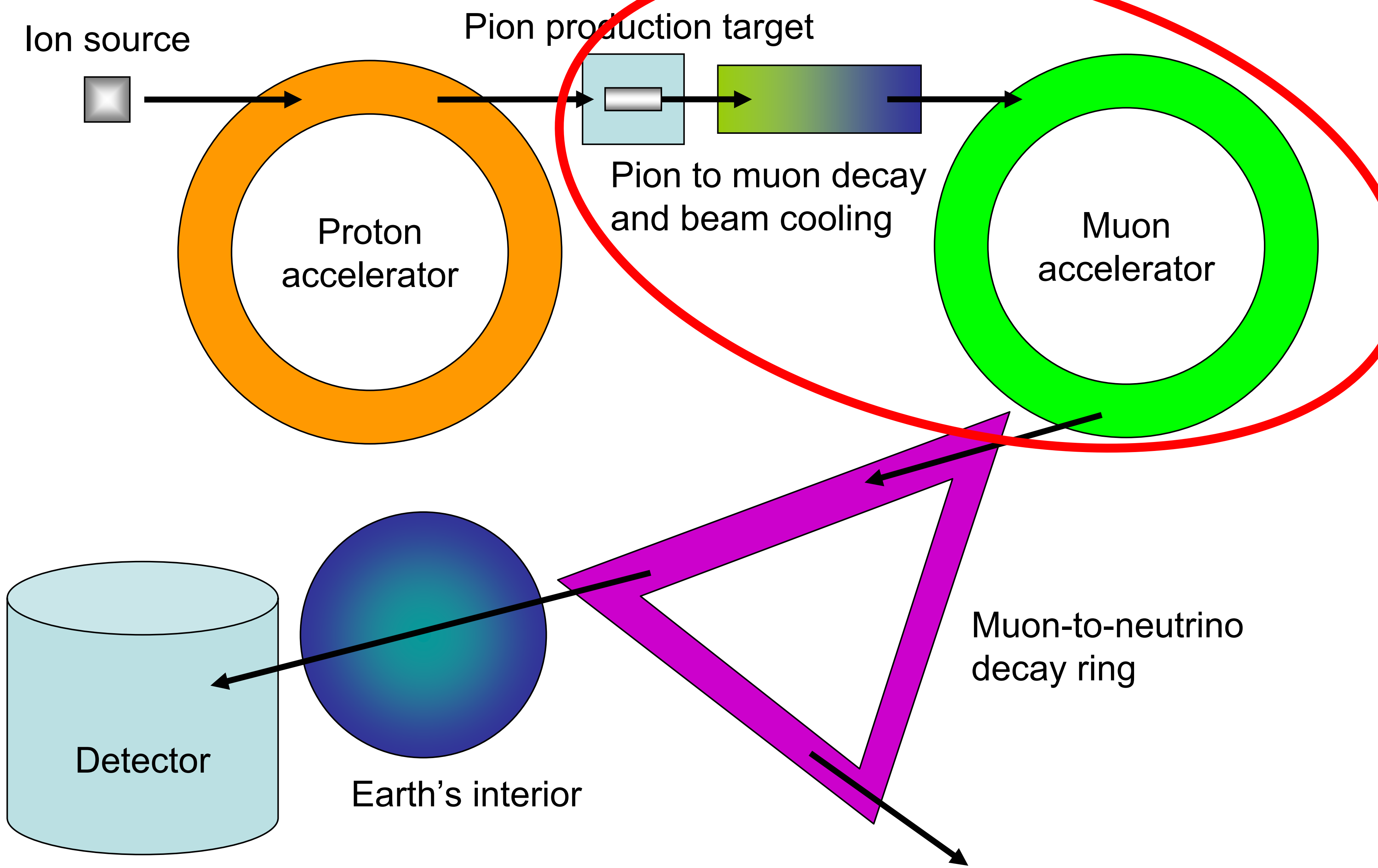


Step V



Step VI 2009?

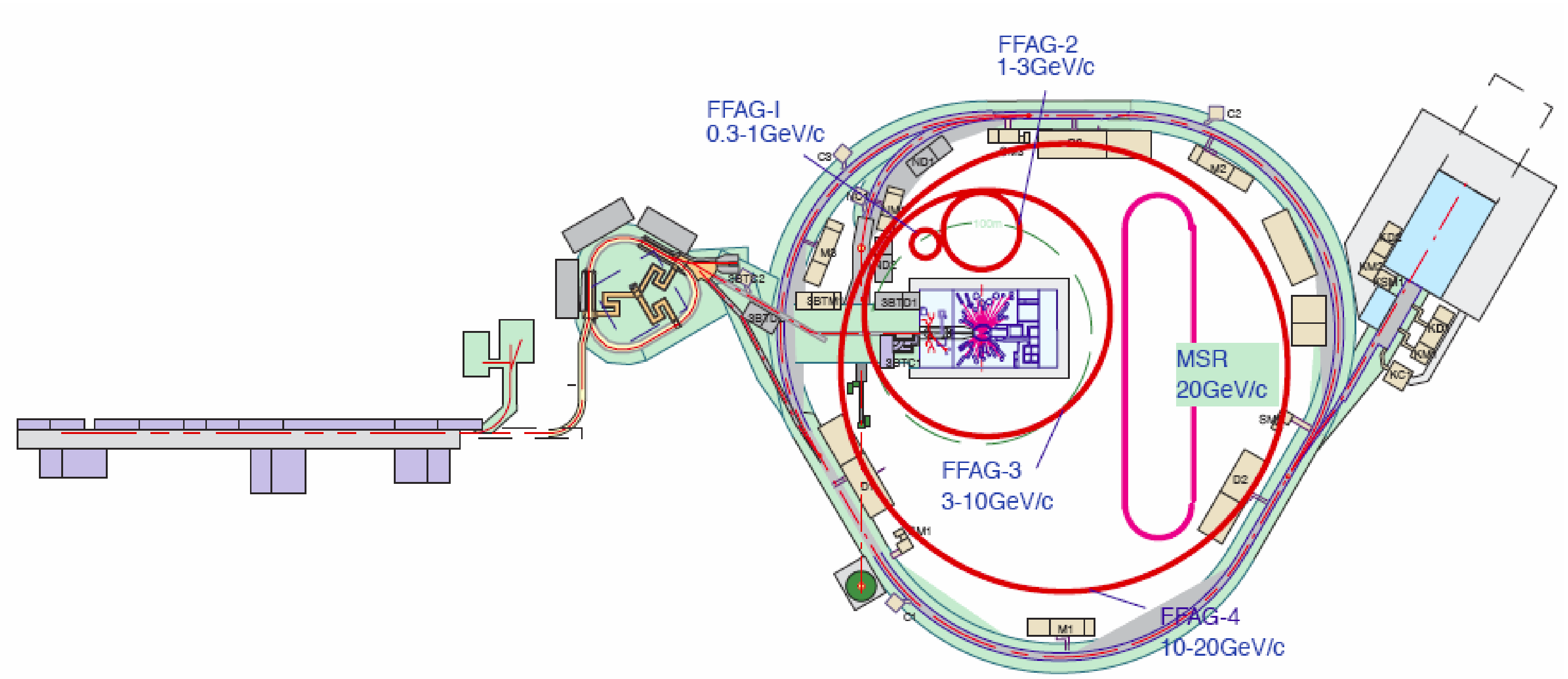
Simplified Neutrino Factory



Acceleration Phase 1

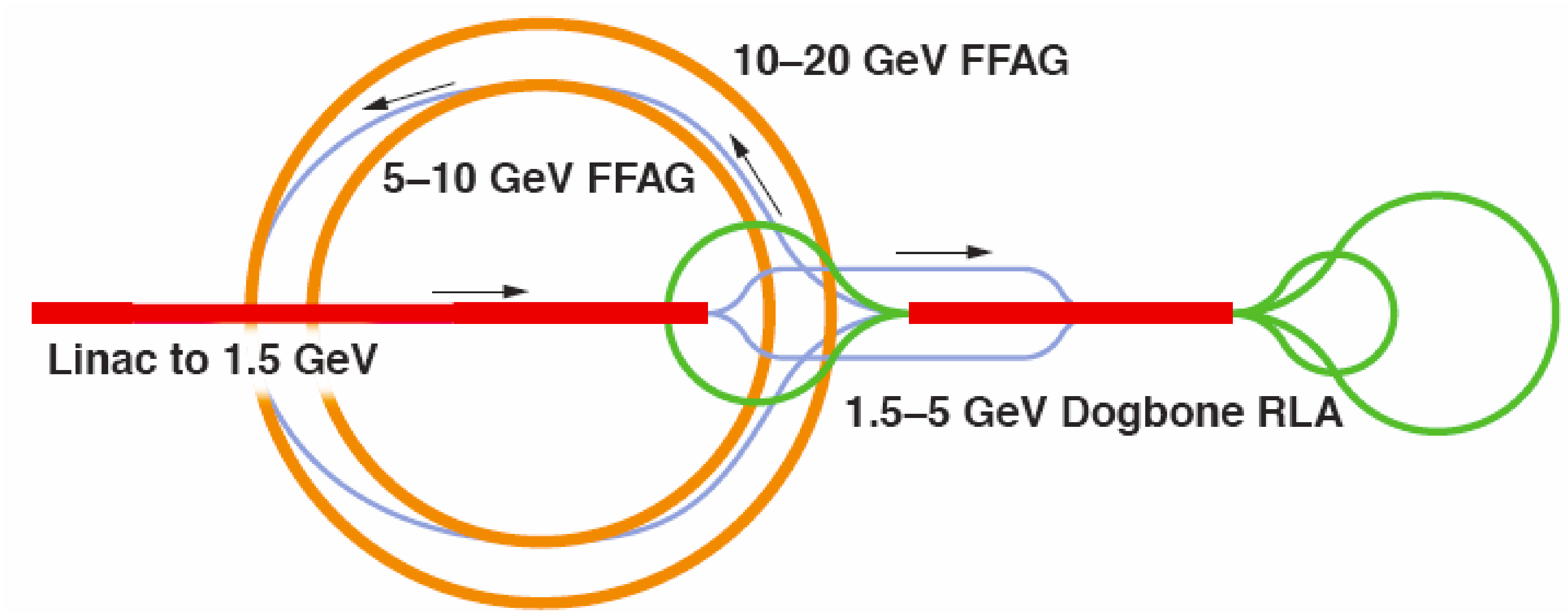
- Compare different schemes
  - RLA, scaling FFAG, non-scaling FFAG, linac
  - consider implications of keeping both sign muons
  - consider not only performance but relative costs
- Prepare scenarios for different values of acceptance
  - transverse and longitudinal
    - small, medium, large (or extra-large?)
  - identify cost implications
- Consider matching between acceleration subsystems
  - are there simplifications in using fewer types of machines?

Acceleration: NuFactJ



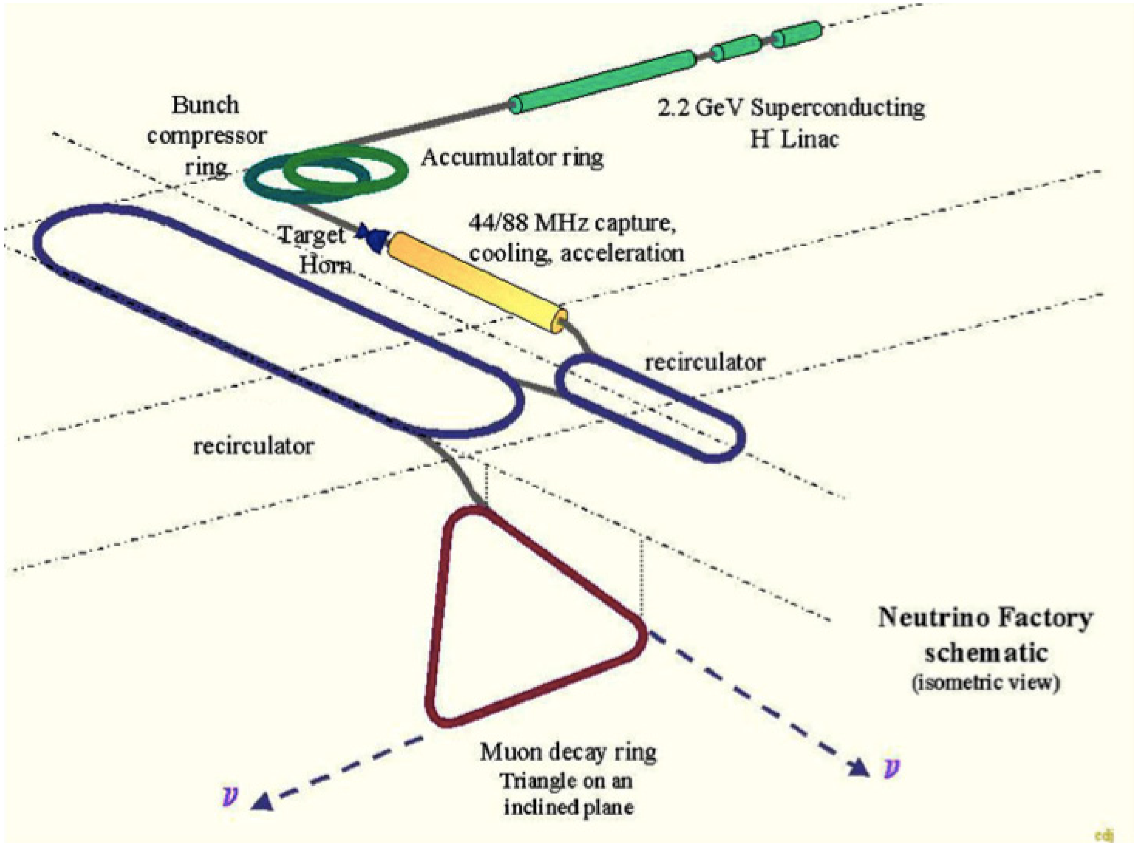
- J-Parc as a proton driver.
- Four scaling FFAG accelerate muons from 0.3 to 20 GeV.
- No bunching, no cooling.
- Single muon bunch throughout the cycle.

Acceleration: US Study IIa



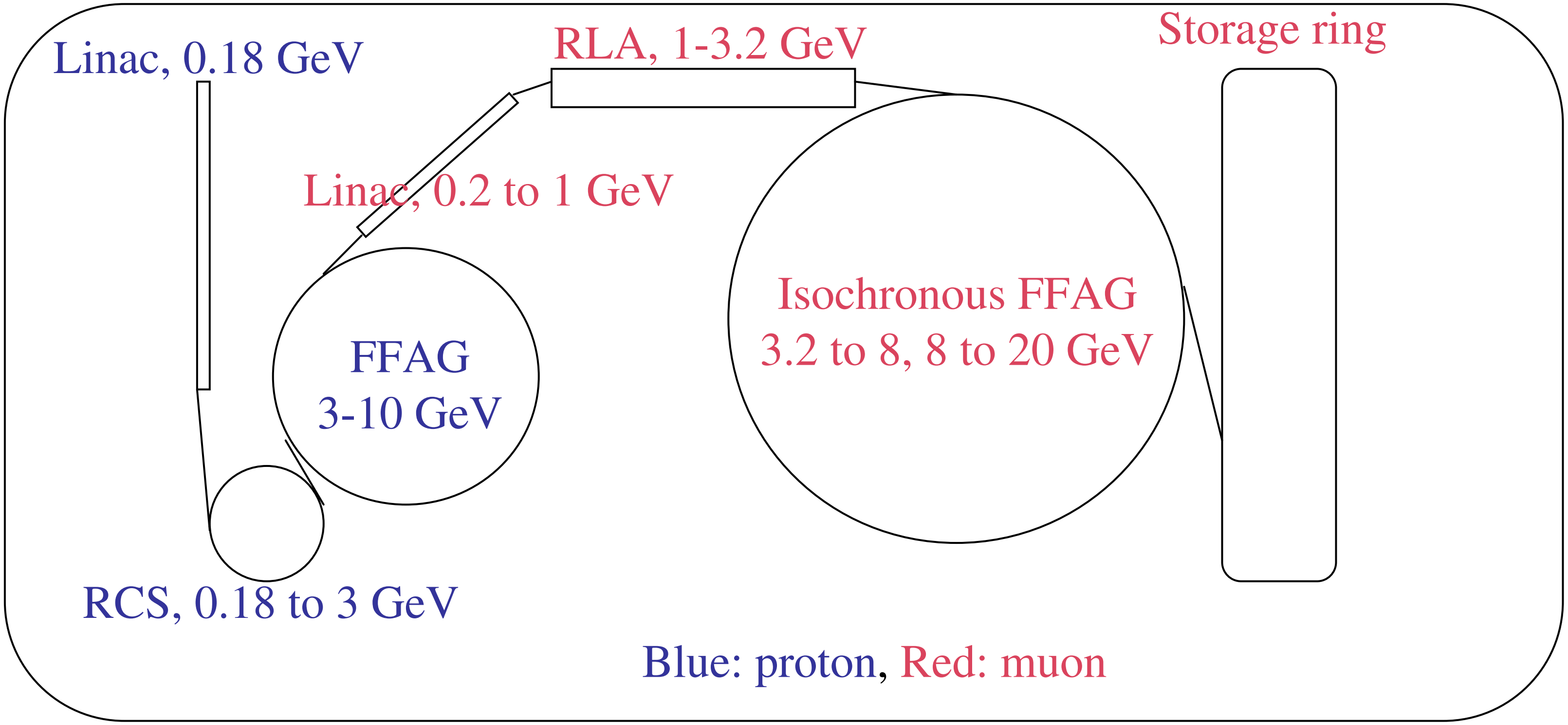
- AGS or Fermilab upgrade as a proton driver.
- Linac and RLA up to 5 GeV.
- Two non-scaling FFAG from 5 to 20 GeV.
- Bunching and cooling to create a multi bunches fit into 200 MHz RF.

Acceleration: CERN NF



- Linac and accumulator+compressor rings as a proton driver.
- Linac and RLA up to the final energy.

Acceleration: UK originated



- Proton driver with FFAG.
- Linac and RLA up to 3.2 GeV.
- Two isochronous FFAG from 3.2 to 20 GeV in the same tunnel.
- RF frequency of IFFAGI can be any, say 200 MHz.

Types of FFAG

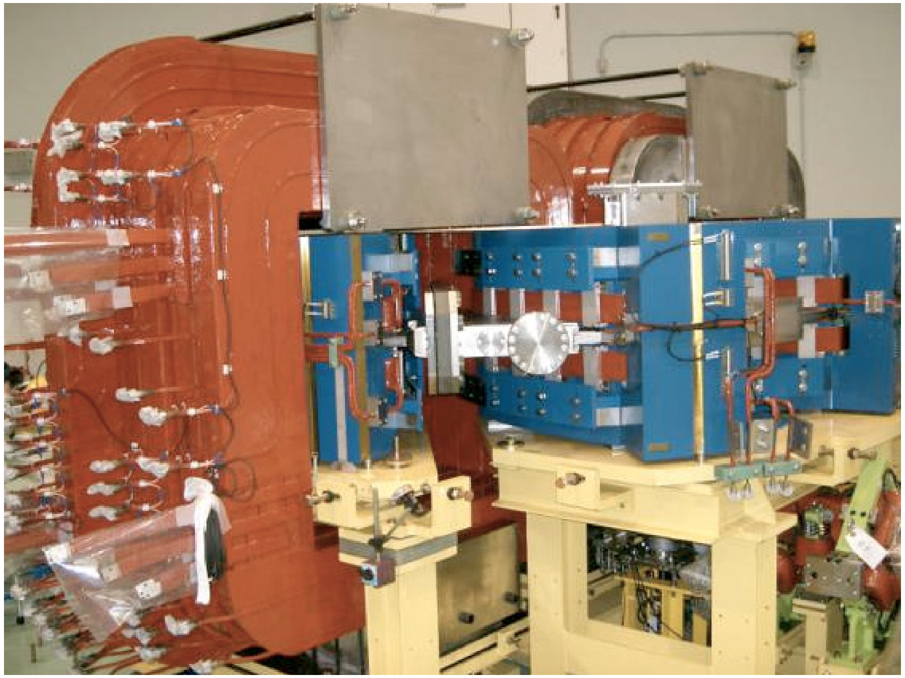
- Scaling:
  - Field ~r^k, large apertures, tune constant, orbit variation up to 0.5m, low frequency RF 5-25 MHz.
- Non-scaling:
  - Linear elements, large apertures, resonance crossing, tiny orbit variation, high frequency RF 200 MHz.
- Isochronous:
  - Nonlinear fields, Q_v constant, Q_h varies, long insertion straights for injection/extraction/collimation, any RF frequency.
- Schönauer:
  - Weakly isochronous, constant tune, RF ~200 MHz.

Issues

- 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

Design progress and R&D: Scaling FFAG

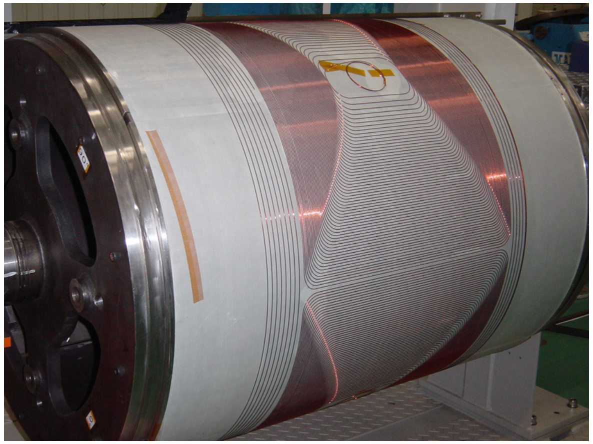
- POP FFAG was commissioned in 2000 and 150 MeV FFAG has been completed.
- Spiral FFAG at Kyoto Univ. accelerates a beam.
  - Crosses integer resonance.
- Resonance crossing study in POP and HIMAC.



CCLRC

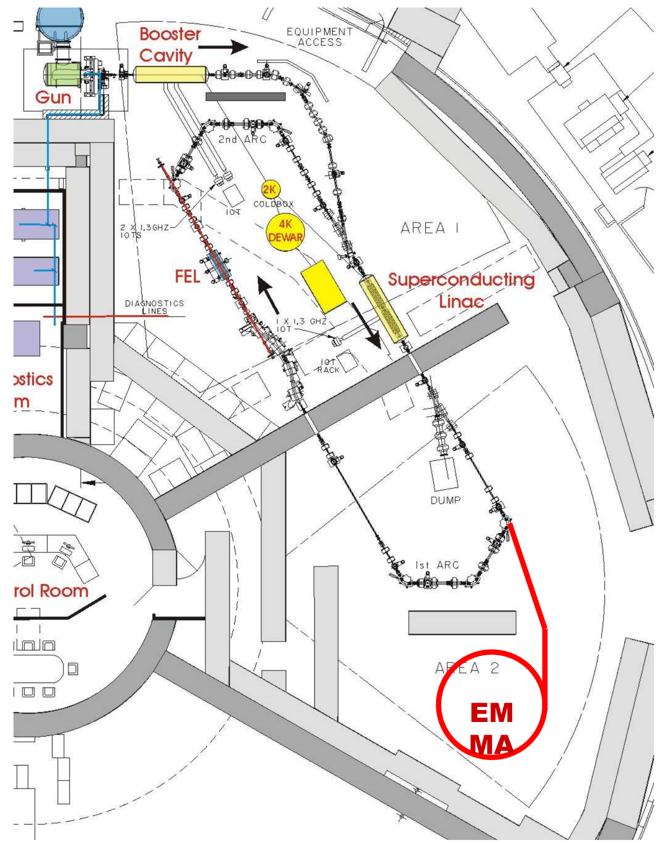
Design Progress and R&D

- Low Frequency RF
  - New version of MA
    - Shunt impedance is 10 times higher.
    - Q value is 30 to 50.
    - Frequency modulation is possible.
- High Frequency RF, 201 MHz cavity
- SC FFAG Magnets
  - Fields for scaling machine
  - Model coil ready, 896 mm x 550 mm, NbTi/Cu, 0.9mm



Design Progress and R&D: Non-Scaling FFAG

- Optimization study by S. Berg.
- Cost model by R. Palmer.
- EMMA (electron test model)
  - Converging on choice of lattice.
  - Hardware design started.
- Proposals to build proton therapy unit based on a non-scaling FFAG with sc technology at IHEP Beijing.

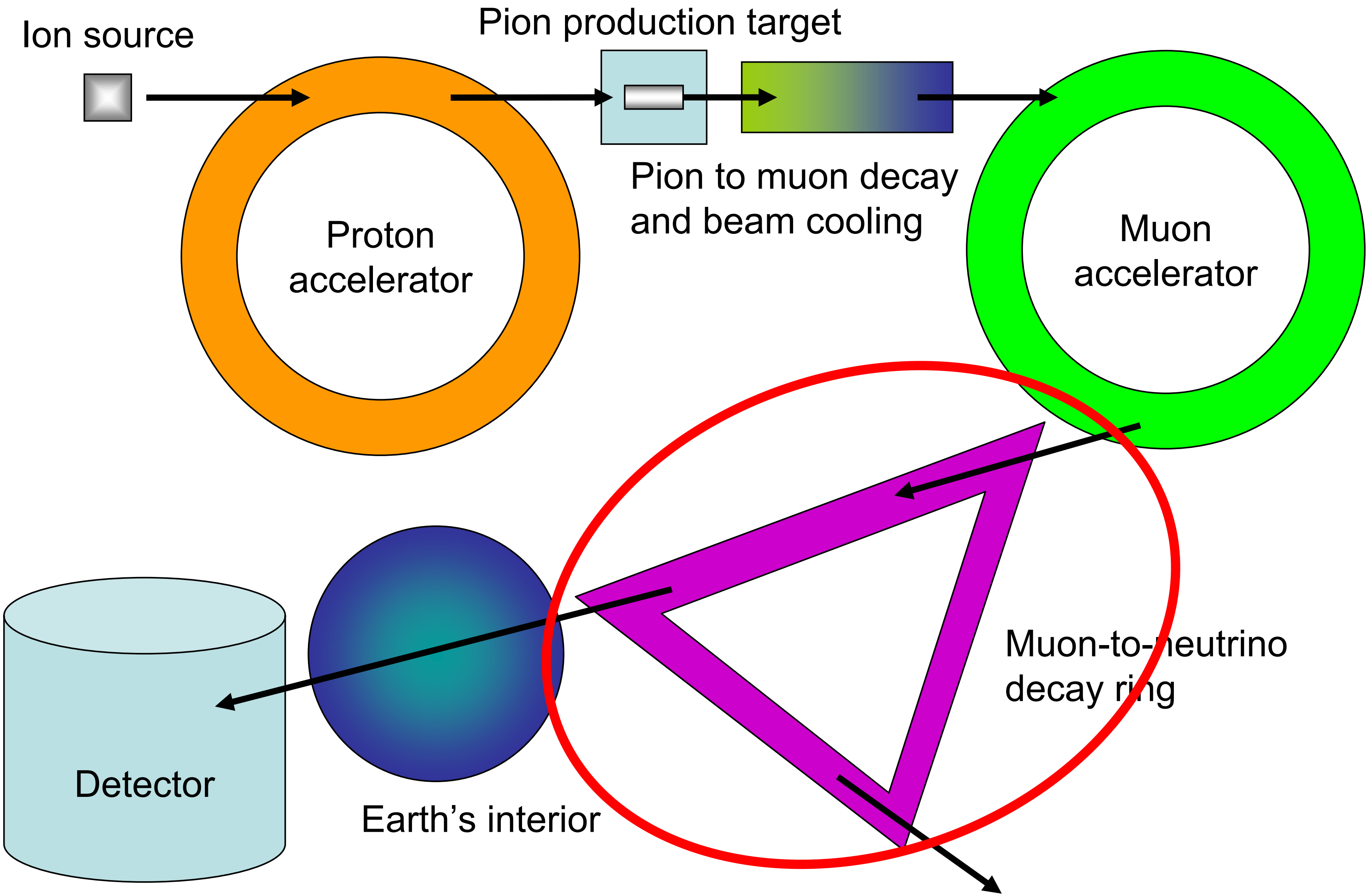


EMMA at Daresbury Laboratory, UK

Acceleration Group Plans

- Assemble parameters; identify what is missing (e.g. transfer lines), fill in the gaps before simulations can start.
- Explore dogbone in further detail.
  - FFAG cannot handle low energy (<2.5 GeV), high frequency.
- Check injection/extraction schemes for FFAGs
- Clearly define RF systems
- Clarify choice of FFAG lattice (doublets/triplets..?)
- Programme of full 6D simulations.

Simplified Neutrino Factory



CCLRC

Effect of Muon Bunch Train on Storage Ring

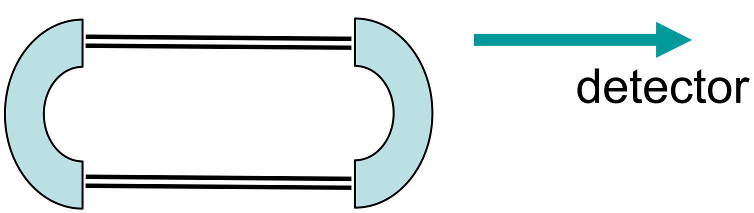
- CERN design:
  - proton and muon bunch number: 140
  - length of muon bunch train $\approx$ 900 m
- US bunch rotation scheme:
  - muon bunch number 90
  - length of n-bunch trains† $\approx$ n x 180 m

A 4 MW driver with 1 ns rms bunches needs $n \geq 4$
So, minimum length for muon storage rings $\approx$ 900 m
(short length of US2a is for a 20 GeV, 1 MW driver)

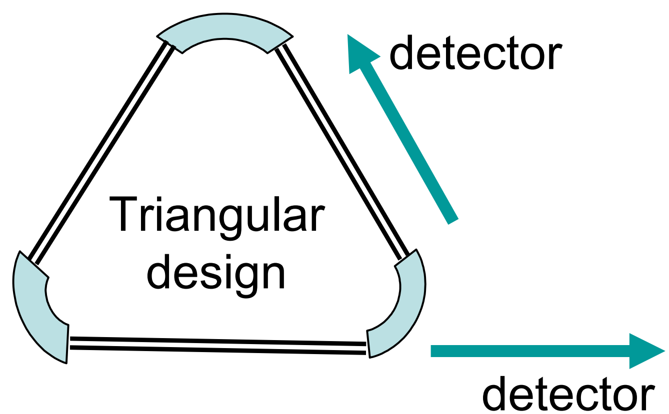
†Here, n is the number of bunches in the proton driver; length for five bunch trains ≈ 900 m

Current Storage Ring Designs

Ring(s)	KE (GeV)	Beam	Detcts	PD Hz,N,MW	Circ (m)	Eff %
US2a	20	μ^+,μ^-	1	3/5/1	358.2	35 (31)
JPARC	20	μ^+/μ^-	1	0.66/8/4	820.0	35
Keil (1T)	50	μ^+/μ^-	2	50/140/4	2074.8	2×28



Racetrack design



Muon Storage Ring Issues (1)

- Energy
  - Design for 20 or for 50 GeV rings, or for 20 GeV upgradeable?
- Design
  - Triangle with 2 detectors, or Racetrack with 1?
  - New idea: Isosceles Triangle design
  - Exercise in 3D geometry.
- Treatment of μ^+ and μ^- beams
  - Merging of μ^+ and μ^- beams in one design or two separate rings
- Muon beam powers 0.5 to 2.5 MW

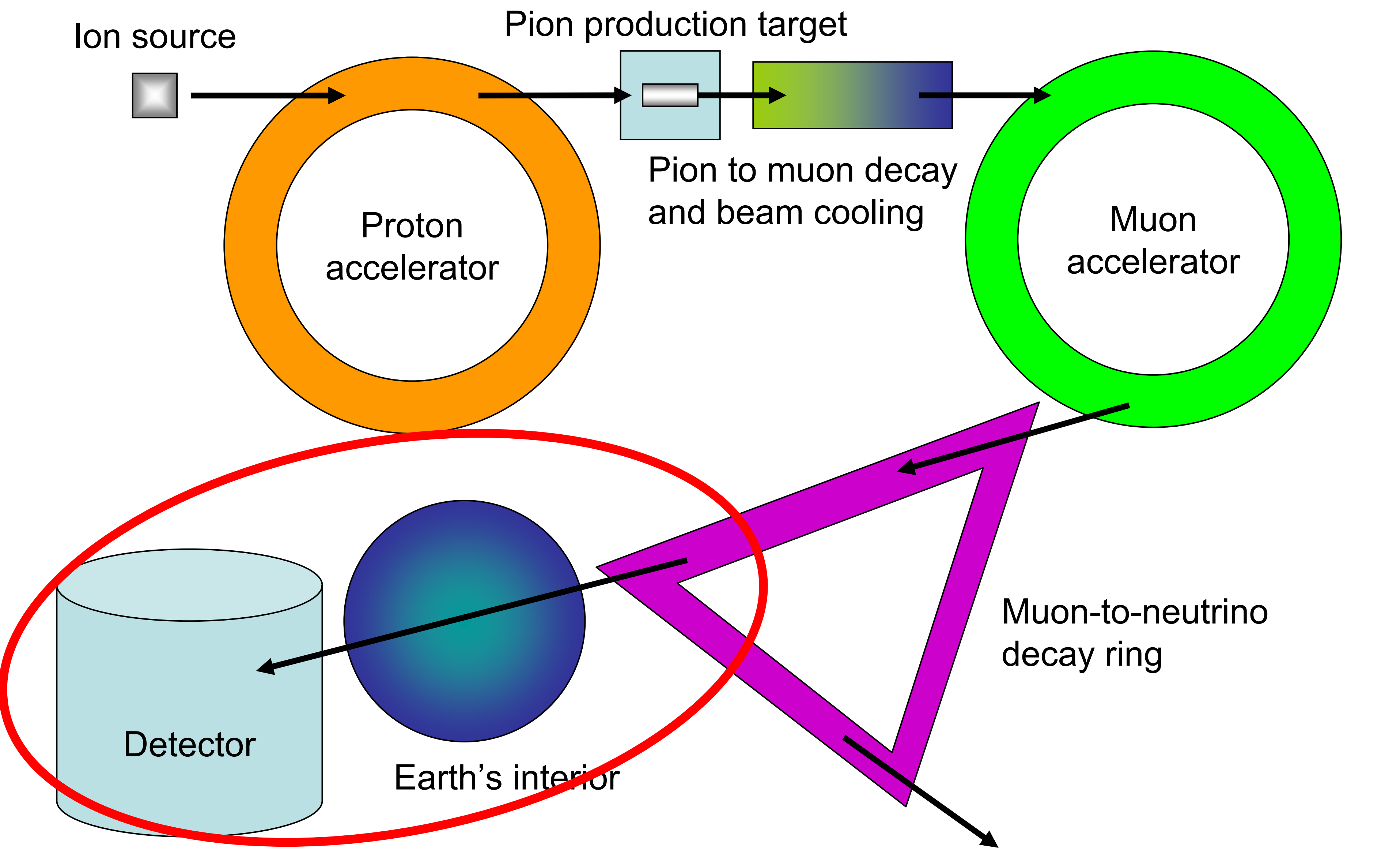
Muon Storage Ring Issues (2)

- Protection from muon beam loss on the walls.
- SC magnet shielding, and the effects of e^+ & e^-.
  - High density material, e.g. tungsten, is proposed.
- Designs for lattice, RF, injection, diagnostics, etc.
- Optimise ring designs.
- Radiation issues at 10^{21} useful neutrinos per year.
- Cost implications of design will be dealt with later.

Storage Ring Provisional Plans

- Liaise with proton driver and muon acceleration groups
- Liaise with detector group on ring orientations
- Liaise with Beta Beams decay ring group
- Explore design of
  - 20 and 20-50 GeV $\mu^{\pm}$ racetrack rings
  - 20 and 20-50 GeV $\mu^{\pm}$ triangular rings
- Study possibility of an isosceles triangle ring
- Study $e^{\pm}$ effects, ring shielding and cooling
- Study injection, loss protection & safety issues
- Study chromaticity correction and RF issues
- Optimise and provide parameters for costing

Simplified Neutrino Factory



Detector

- Not Machine Group responsibility…but
  - need to understand cost trade-offs of higher neutrino intensity v. bigger detector
  - need to understand issues related to simultaneous use of both sign muons

CCLRC

Accelerator Costing

- Time limited but need indications of cost to decide best options
- Simple algorithm developed by Palmer/Berg
  - Green’s formulae for solenoids and dipoles
  - Palmer’s formulae for cavities, dipoles, quadrupoles, combined function magnets
  - Reduction of cost for quantity
- Benchmarked against RHIC and LHC
- Suggests sc magnets in quantity cost same as conventional magnets
- And that US2a is 65% of cost of US2.

Summary

- Challenge is to try to reach consensus on a single optimised Neutrino Factory scheme
- Developing optimal design requires an adequately-funded accelerator R&D program
  - we need to articulate this need and define the ingredients of the program
- Time is tight: a report is due in August 2006.
- More participants are needed.