International Scoping Study Accelerator Working Group: Summary and Plans

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Introduction

- Meeting marks culmination of next step in ongoing development of a Neutrino Factory facility concept
  - completed a one-year exploration of an optimized Neutrino Factory design
    - carried out by international team with participants from all regions
      - Europe, Japan, U.S.
  - goal: study alternative configurations to arrive at baseline specifications for a system to pursue further

- Work carried out at four ISS Plenary Meetings
  - CERN (September 2005); KEK (January 2006); RAL (April 2006); UC-Irvine (August 2006)
  - and four Accelerator Group Workshops
    - BNL (December 2005); KEK (January 2006); RAL (April 2006); UC-Irvine (August 2006)

- Communications via NF-SB-ISS-ACCELERATOR e-mail list

History (1)

- There have been 4½ previous NF "feasibility" studies
  - 1 in Japan
  - 1 in Europe
  - 2½ in the U.S.
    - studies I, II, IIa

A Feasibility Study of
A Neutrino Factory in Japan

Version 1.0

NufactJ Working Group

May 24, 2001

The Study of a European Neutrino Factory Complex, P. Gruber *et al.*, CERN/PS/2002-080 (PP), CERN-NUFACT 122, December, 2002; http://slap.web.cern.ch/slap/NuFact/NuFact/nf122.pdf

March, 31st 2000

A Feasibility Study of a

Neutrino Source

Based on a Muon Storage Ring

edited by:

Norbert Holtkamp
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FEASIBILITY STUDY-II OF
A MUON-BASED NEUTRINO SOURCE

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June 14, 2001

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Neutrino Factory and Beta Beam Experiments and Development

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References

- NuFact-J Study (2001)
  - http://www-prism.kek.jp/nufactj/nufactj.pdf
- Study I (1999-2000) instigated by Fermilab
- Study II (2000-2001) collaboration of NFMCC, BNL
  - http://www.cap.bnl.gov/mumu/studyii/final_draft/The-Report.pdf
- European Study (2002) instigated by CERN
  - http://slap.web.cern.ch/slap/NuFact/NuFact/nf122.pdf
- Study IIa (2004) APS Multidivisional Neutrino Study
  - http://www.aps.org/neutrino/loader.cfm?url=/commonspot/security/getfile.cfm&PageID=58766

History (2)

- **Most studies focused on feasibility and performance**
  - cost optimization was secondary, or ignored
- **U.S. Study IIa attempted to maintain performance while reducing costs**
  - succeeded in keeping both sign muons and substantially lowering hardware cost estimate
    - simplified phase rotation
    - simplified cooling channel
    - improved acceleration scheme

NOTE: Hardware costs only. No ED&I, no escalation, no contingency.

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

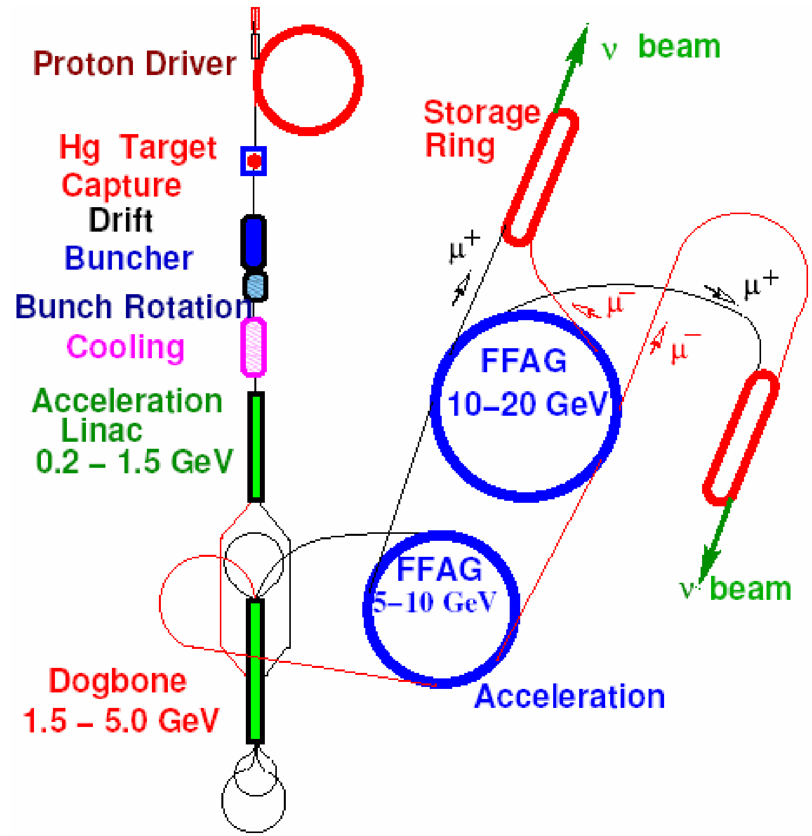
Why Another Study?

- Many different approaches have been considered
  - we wished to compare them to assess which features are optimal
    - in terms of performance
    - (ultimately) in terms of cost
  - we must include the detector in such optimizations
    - and the latest understanding of the (evolving) physics requirements
      - beam energy, baseline(s)
- To select best approaches, must study and understand what the different regions have done
  - partly a team-building exercise
    - number of Neutrino Factory facilities likely to be built worldwide ≤ 1
      - voluntarily working together toward a single design increases odds of *some* facility being built
- Prepares the way for IDS (and hopefully WDS in 2009)

Neutrino Factory Ingredients

- **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**
  - *130 MeV → 20–40 GeV*
- **Decay Ring**
  - *store for ~500 turns; long straight section*

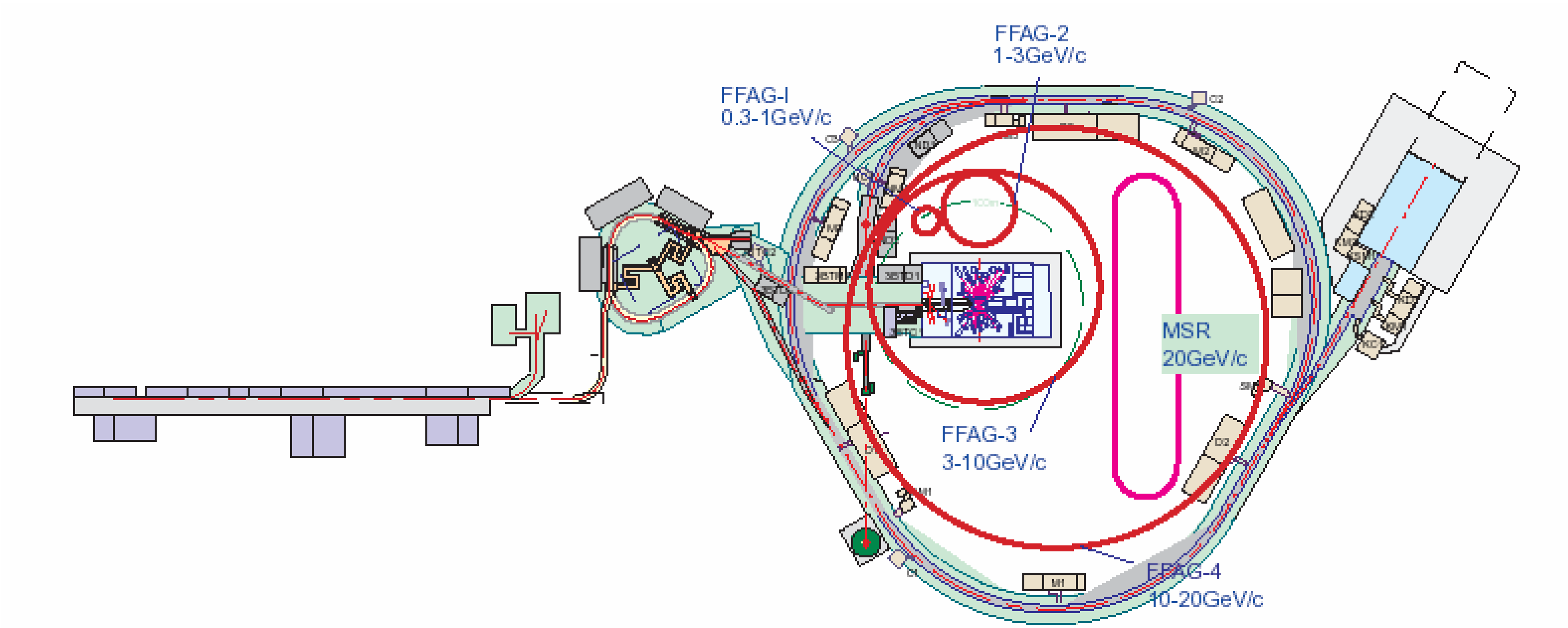
"Front End"



ISS Baseline (preliminary)

FFAG-Based Neutrino Factory

- **Alternative design concept based solely on scaling FFAG rings has been studied**
  - the approach was evaluated and compared with other designs as part of our task
    - implications of keeping both sign muons need evaluation
    - as does performance of high-gradient, low-frequency RF system



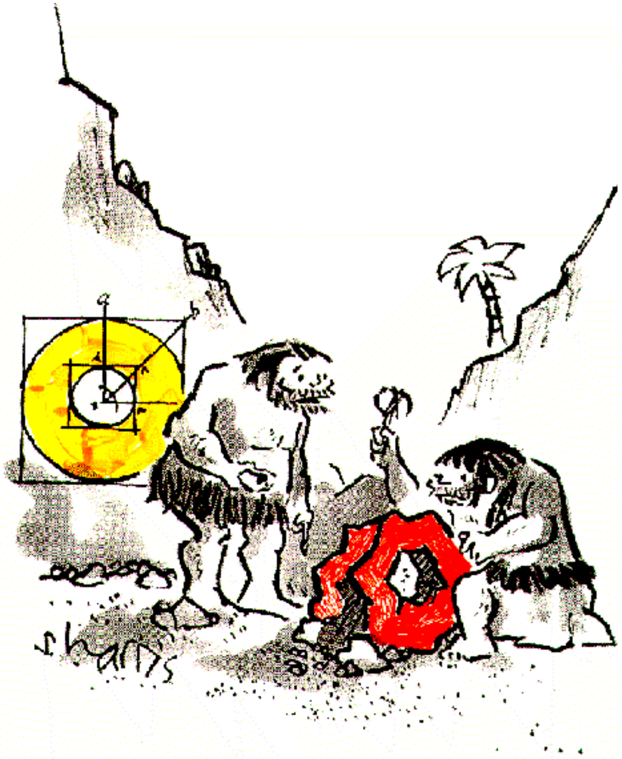
NF Design: Driving Issues

- Constructing a muon-based NF is challenging
  - muons have short lifetime (2.2 μs at rest)
    - puts premium on rapid beam manipulations
      - requires high-gradient NCRF for cooling (in B field)
      - requires presently untested ionization cooling technique
      - requires fast, large acceptance acceleration system
  - muons are created as a tertiary beam ($p \rightarrow \pi \rightarrow \mu$)
    - low production rate ⇒
      - target that can handle multi-MW proton beam
    - large muon beam transverse phase space and large energy spread ⇒
      - high acceptance acceleration system and storage ring
  - neutrinos themselves are a quaternary beam
    - even less intensity and "a mind of their own"

Challenges

- **Challenges go well beyond those of standard beams**
  - **developing solutions requires substantial R&D effort**
    - **R&D should aim to specify:**
      - **expected performance, technical feasibility/risk, cost (matters!)**

We must do experiments and build components. Paper studies are not enough!



"I guess there'll always be a gap between science and technology."

Accelerator WG Organization

- Accelerator Working Group program managed by "Accelerator Council"
  - R. Fernow, R. Garoby, Y. Mori, R. Palmer, C. Prior, M. Zisman
  - met mainly by phone conference
- Aided by Task Coordinators
  - Proton Driver: R. Garoby, H. Kirk, Y. Mori, C. Prior
  - Target/Capture: J. Lettry, K. McDonald
  - Front End: R. Fernow
  - Acceleration: S. Berg, Y. Mori, C. Prior
  - Decay Ring: C. Johnstone, G. Rees

Accelerator Study

- Study alternative configurations; arrive at baseline specifications for a system to pursue
  - examine both cooling and no-cooling options

- Develop and validate tools for end-to-end simulations of alternative facility concepts
  - correlations in beam and details of distributions have significant effect on transmission at interfaces (muons have "memory")
  - simulation effort ties all aspects together

- Develop R&D list as we proceed
  - identify activities that must be accomplished to develop confidence in the community that we have arrived at a design that is:
    - credible
    - cost-effective
  - until construction starts, R&D is what keeps the effort alive

Accelerator Study Approach

- To ensure common understanding of, and buy-in for, the results
  - trade-off studies must include designs from all regions
    - also scientists from all regions (but uncorrelated)

- Examine possibilities to choose the best ones
  - not easily done if each group "defends its own choices"

- Study leadership fostered this "regional mixing"
  - this will equally be true in the IDS phase

Proton Driver Questions

- Optimum beam energy √
  - depends on choice of target
    - consider C, Ta, Hg
- Optimum repetition rate √
  - depends on target and downstream RF systems
  - find that 50 Hz is reasonable compromise for cases studied
- Bunch length trade-offs √
  - need (and approaches) for bunch compression
  - performance implications for downstream systems
- Hardware options (in progress)
  - FFAG, linac, synchrotron
    - compare performance

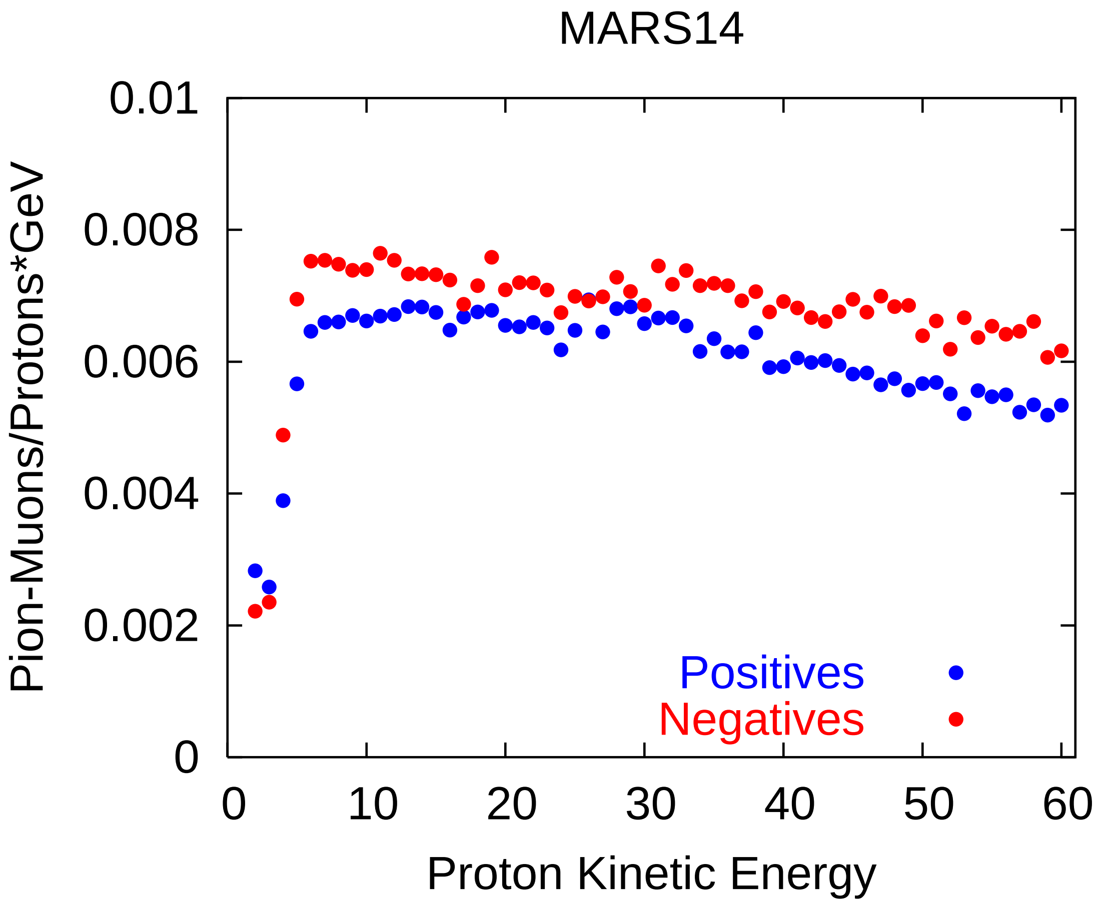
Proton Driver

- Examined candidate machine types for 4 MW operation
  - FFAG (scaling and/or non-scaling)
  - Linac (SPL and/or Fermilab approach)
  - Synchrotron (J-PARC and/or AGS approach)

    - consider
      - beam current limitations (injection, acceleration, activation)
      - bunch length limitations and schemes to provide 1-3 ns bunches
      - repetition rate limitations (power, vacuum chamber,…)
      - tolerances (field errors, alignment, RF stability,…)
      - optimization of beam energy

Optimum Energy

- **Optimum energy for high-*Z* targets is broad, but drops at low-energy**



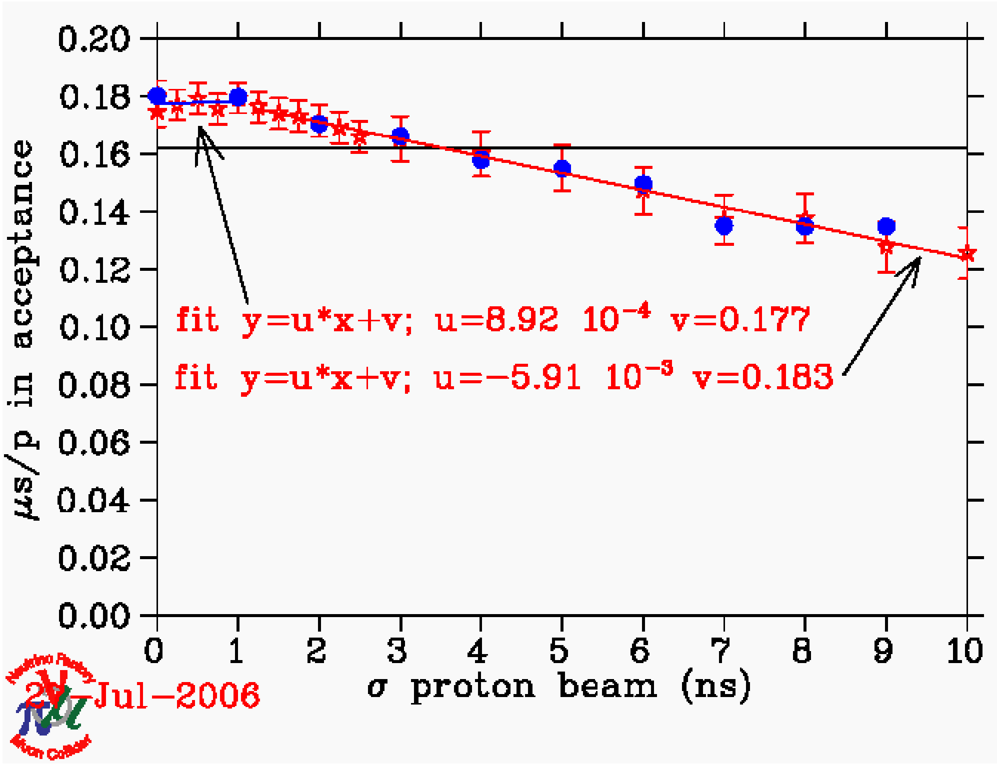
μ^-: 6 – 11 GeV

μ^+: 9 – 19 GeV

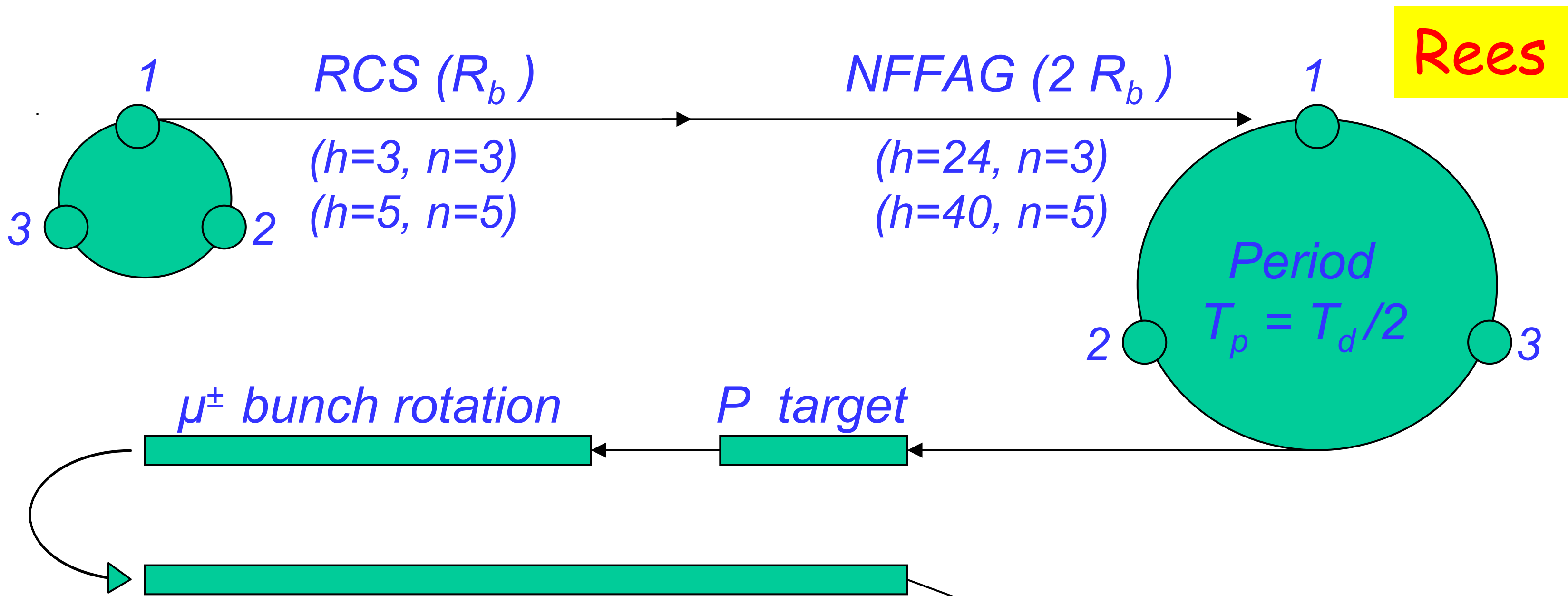
We adopted 10 $\pm$ 5 GeV as representative range

Bunch Length Dependence

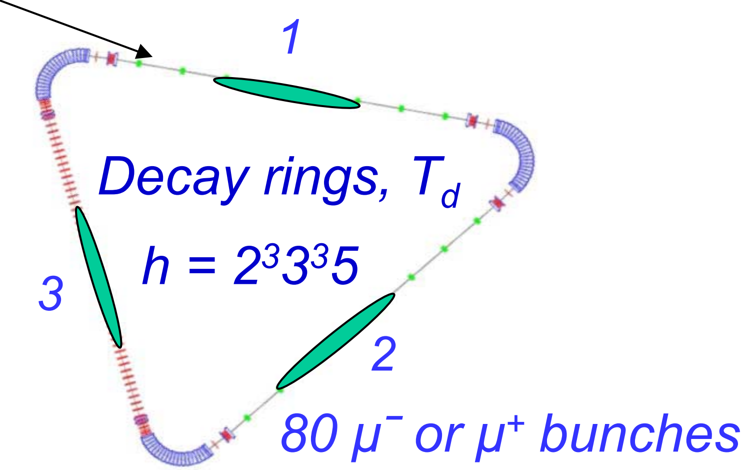
- Investigated by Gallardo *et al.* using Study 2a channel
  - decrease starts from zero bunch length
    - 1 ns is preferred, but 2-3 ns is acceptable
      - such short bunches harder to achieve at low beam energy
  - stronger sensitivity to bunch length than seen in Study 2
    - not yet understood in detail (different phase rotation and bunching)



Bunch Train Patterns



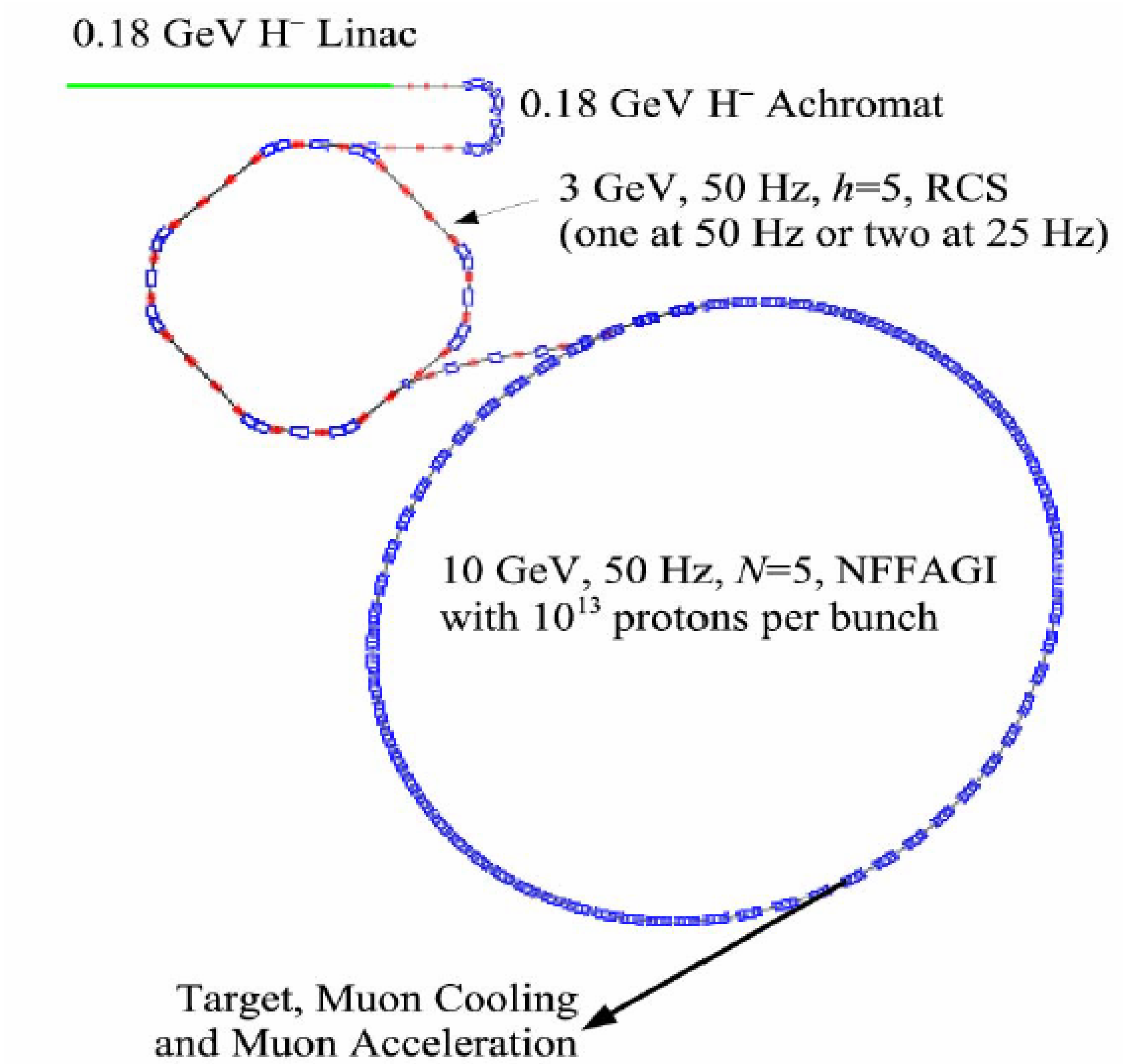
Accel. of trains of 80 μ± bunches



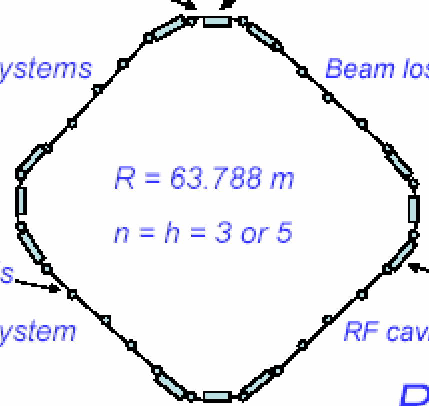
NFFAG ejection delays:
$(p + m/n)\ T_d$ for m = 1 to n (=3,5)

Pulse < 50 μs for liquid target
Pulse > 60 μs for solid targets

FFAG Proton Driver



Layout of 3 GeV, RCS Booster

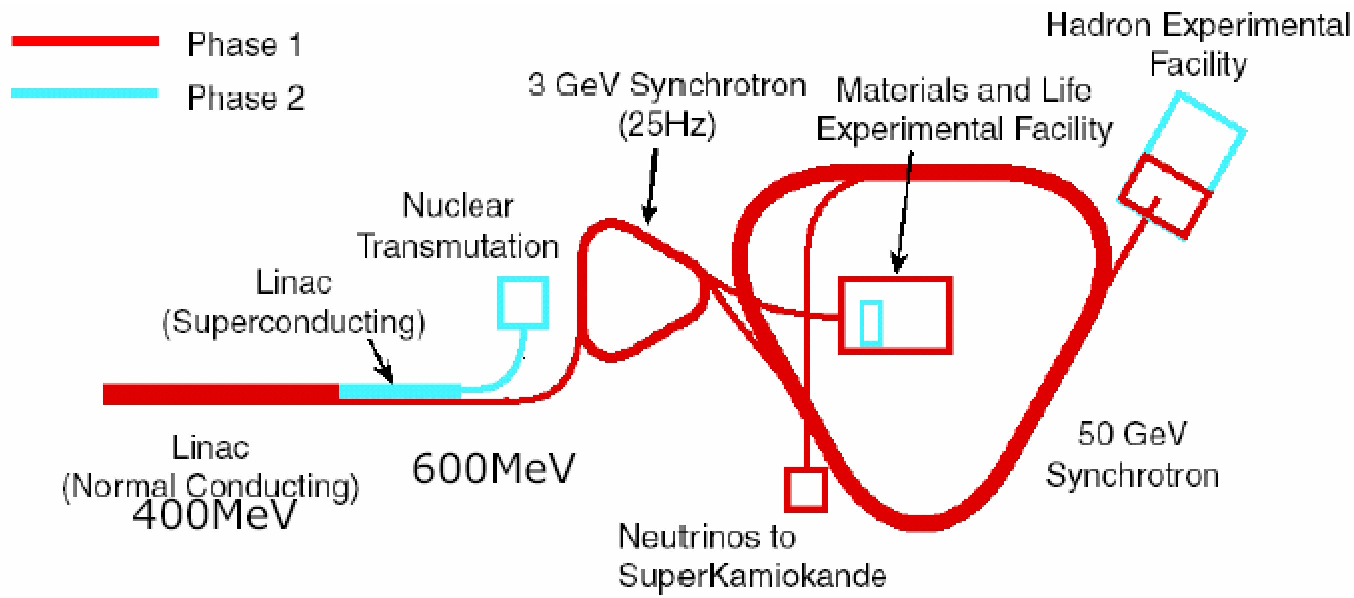


Parameters for 50 Hz, 0.2 to 3 GeV Booster

- *Number of superperiods* — *4*
- *Number of cells/superperiod* — *4(straights) + 3(bends)*
- *Lengths of the cells* — *4(14.0995) + 3(14.6) m*
- *Free length of long straights* — *16 x 10.6 m*
- *Mean ring radius* — *63.788 m*
- *Betatron tunes* (Q_v, Q_h) — *6.38, 6.30*
- *Transition gamma* — *6.57*
- *Main dipole fields* — *0.185 to 1.0996 T*
- *Secondary dipole fields* — *0.0551 to 0.327 T*
- *Triplet length/quad gradient* — *3.5 m/1.0 to 5.9 T* m^{-1}

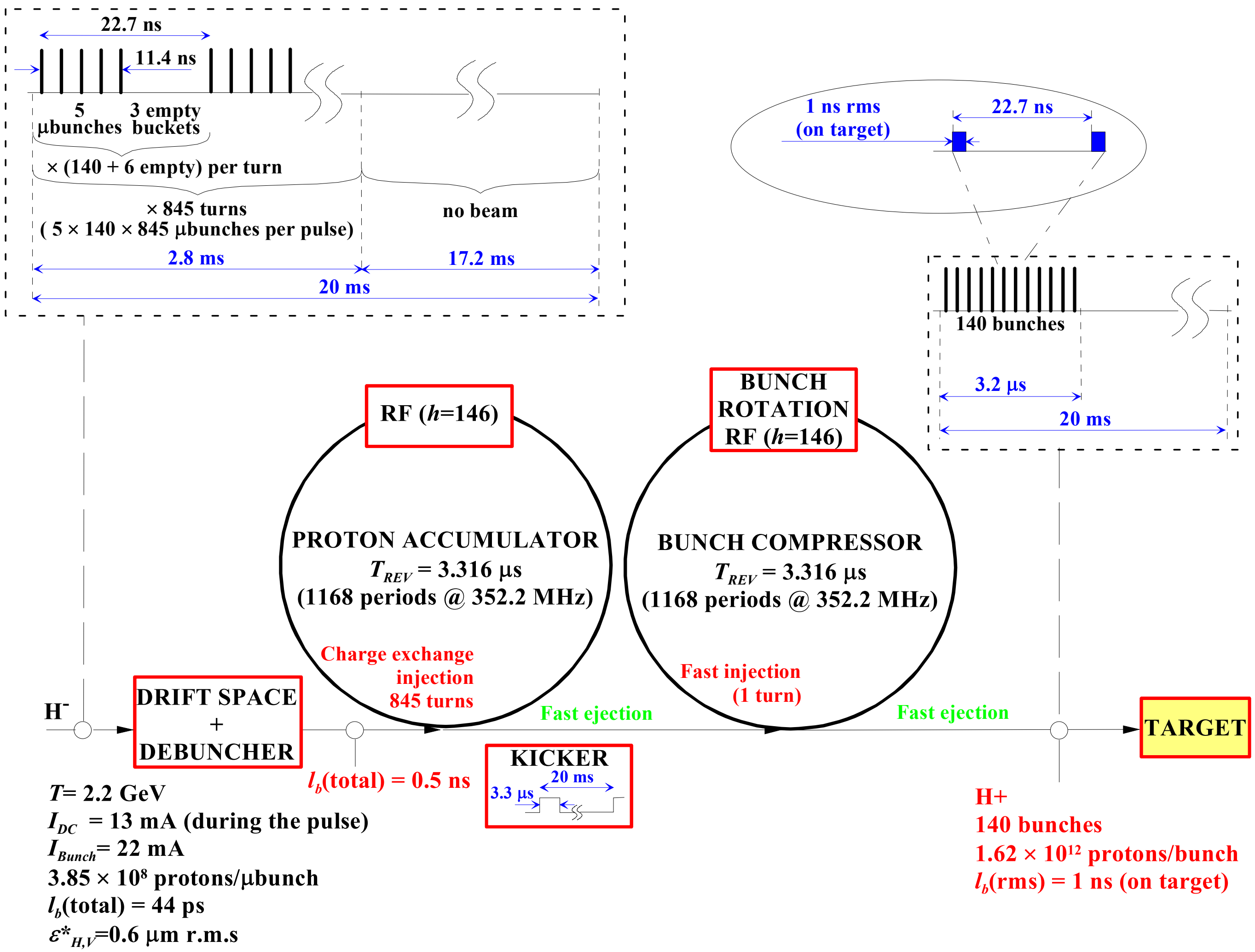
J-PARC Scheme

- Comprises linac, 3 GeV RCS and 50 GeV synchrotron
  - under construction now!



SPL Scheme

- **This scheme does not presently provide the bunch train parameters specified in baseline**



Target/Capture/Decay

- **Optimum target material**
  - study production rates as *f(E)* for C, Hg, Ta √
    - still need reality check with HARP data eventually
- **Target limitations for 4 MW operation**
  - consider bunch intensity, spacing, repetition rate √
  - limits could come from target...or from beam dump
- **Superbeam vs. Neutrino Factory trade-offs**
  - horn vs. solenoid capture √
    - can one solution serve both needs?
  - is a single choice of target material adequate for both? √

Target Material Comparisons (1)

- Studied by Fernow, Gallardo, Brooks, Kirk
  - targets examined: C; Hg; Ta
    - target tilted with respect to solenoid axis
    - re-interactions included
  - accelerator normalized acceptance
    - transverse: 30 mm
    - longitudinal: 150 mm
    - momentum range: 100–300 MeV/c
  - compared: C (5, 24 GeV); Hg (10, 24 GeV)
    - Hg (24 GeV) is nominal Study 2/2a "benchmark" case

Target Material Comparisons (2)

Results from H. Kirk

Compare Meson production for Hg at 24 GeV and 10 GeV

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

Compare Meson production for C at 24 GeV and 5 GeV

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

Compare Meson production for Hg at 10 GeV and C at 5 GeV

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

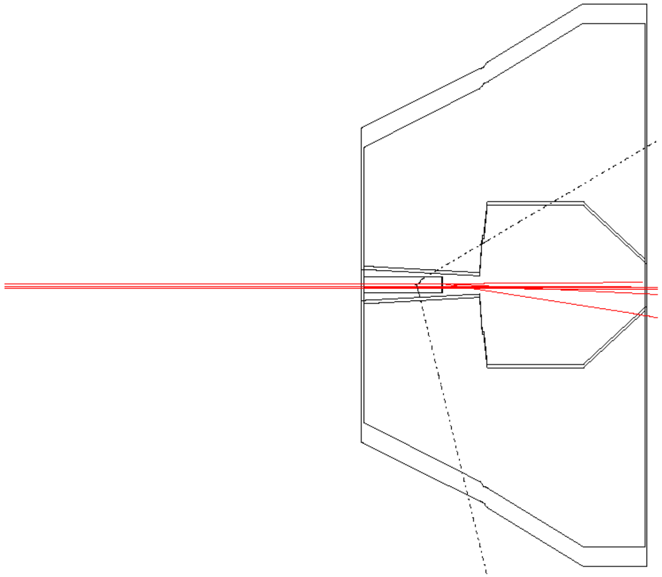
Target Material Comparisons (3)

- Results
  - Hg at 10 GeV looks best thus far
- Power handling capabilities of solid target materials is still an issue
  - C at 4 MW still looks hard
    - would require frequent target changes
- Can required short bunches be produced at E ~ 5 GeV?
  - important for Neutrino Factory but not for Superbeam
- Results all based on MARS predictions
  - need experimental data to validate

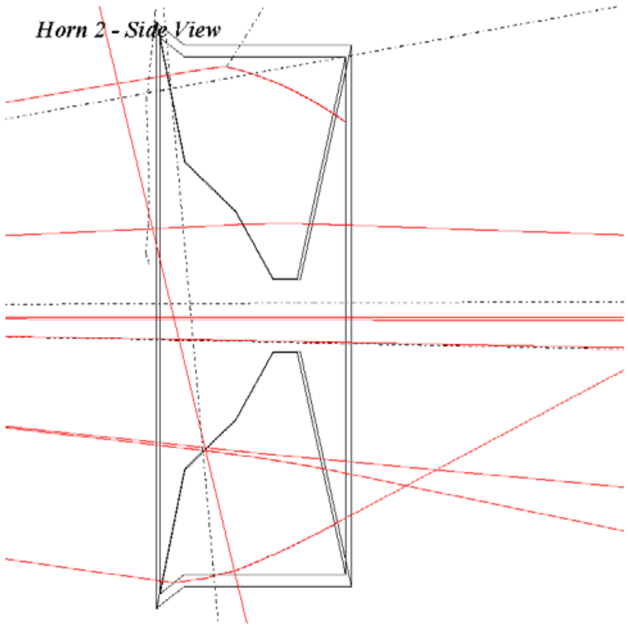
Solenoid vs. Horns (1)

- Looked at spectra produced with dual horn system compared with solenoid capture (not Neutrino Factory version)
  - still questions about normalizations to be resolved

J. Heim, M. Bishai, B. Viren BNL



Horn 1: Length =2.2 m

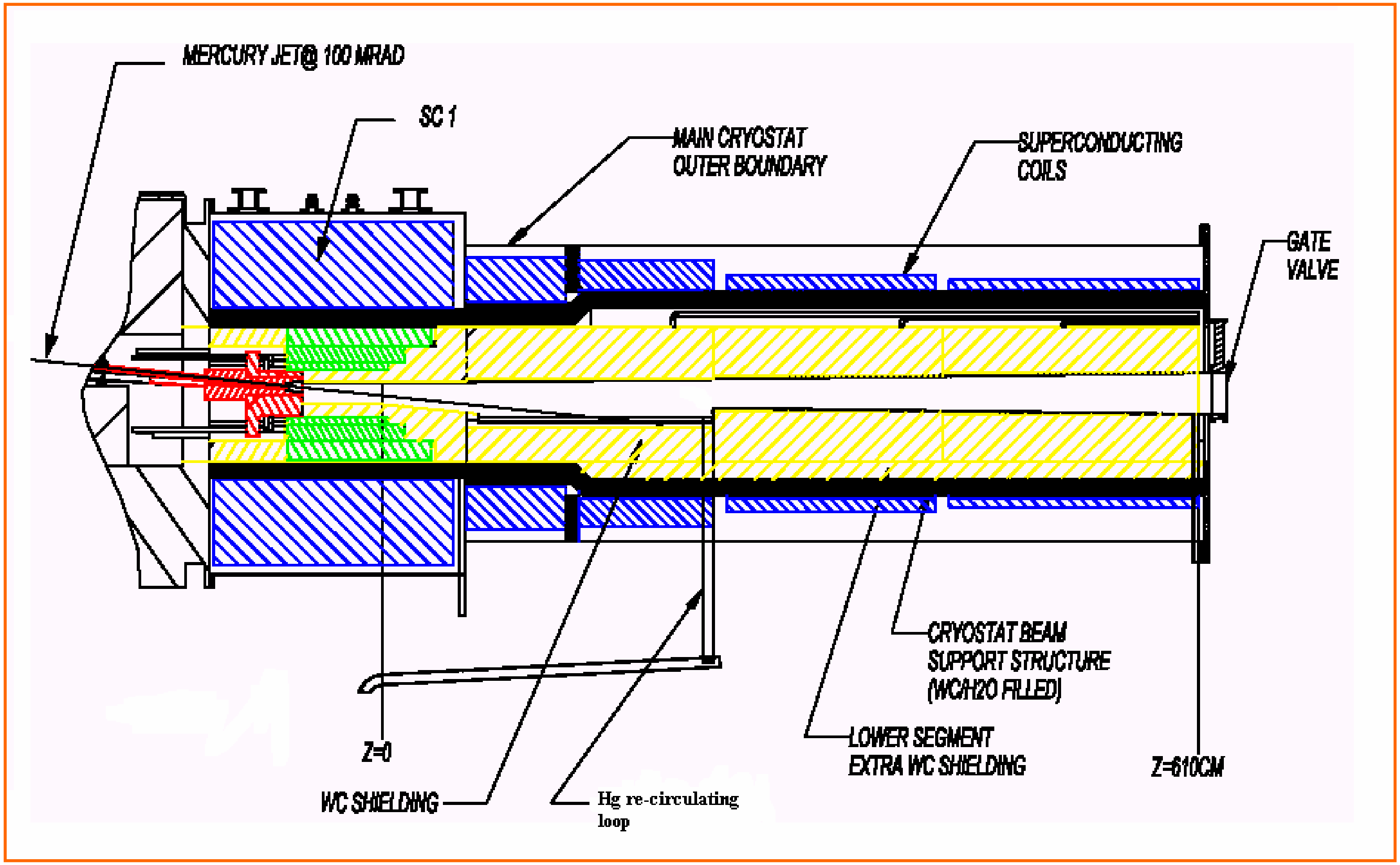


Horn 2: Length =1.6 m

ΔL Horn 2-Horn 1 =10 m

Solenoid vs. Horns (2)

- Neutrino Factory solenoid capture system



Tapers from 20 T, 15 cm to 1.75 T, 60 cm over 20 m

Front End

- Compare performance of existing schemes (KEK, CERN, U.S.-FS 2b)
  - use common proton driver and target configuration(s) √
  - consider possibility of both signs simultaneously √
  - final conclusions require cost comparisons, which will come later
- Evaluate implications of reduced V_{RF} for each scheme
  - take V_{max} = 0.75 V_{des} and 0.5 V_{des}
    - re-optimize system based on new V_{max}, changing lattice, absorber, no. of cavities, etc. √
- Evaluated trade-offs between cooling and downstream acceptance √
- Look at polarization issues √

Cooling Channel Comparisons (1)

- **Palmer has looked at all current designs**
  - FS2, FS2a, CERN, KEK channels
- **Performance of FS2a channel is best**
  - includes benefits of both sign muons

Overall Performance Parentheses on estimated values

case	Cool?	$A_\perp$ pi mm	$\eta_{\|\|}$	$\eta_\perp$	η_{front}	η_{accel} %	η_{signs}	η_{all} %
5 MHz	no	30	.39	(0.18)	16 (7)	0.36	1	6^1 (2.5)
44/88 MHz	yes	15	(0.15)	$[0.67]^2$	10	0.66	1	6.6^3
44/88 MHz	no	30	(0.15)	(0.24)	(3.6)	0.66	1	(2.4)
201 MHz FS2	yes	15	0.56	0.38	21	0.81	1	17
201 MHz FS2	no	30	0.56	0.24	13	0.81	1	11
201 MHz S2a	yes	30	0.48	0.42	20	0.81^4	2	33
201 MHz S2a	no	30	0.48	0.24	12	0.81^4	2	19

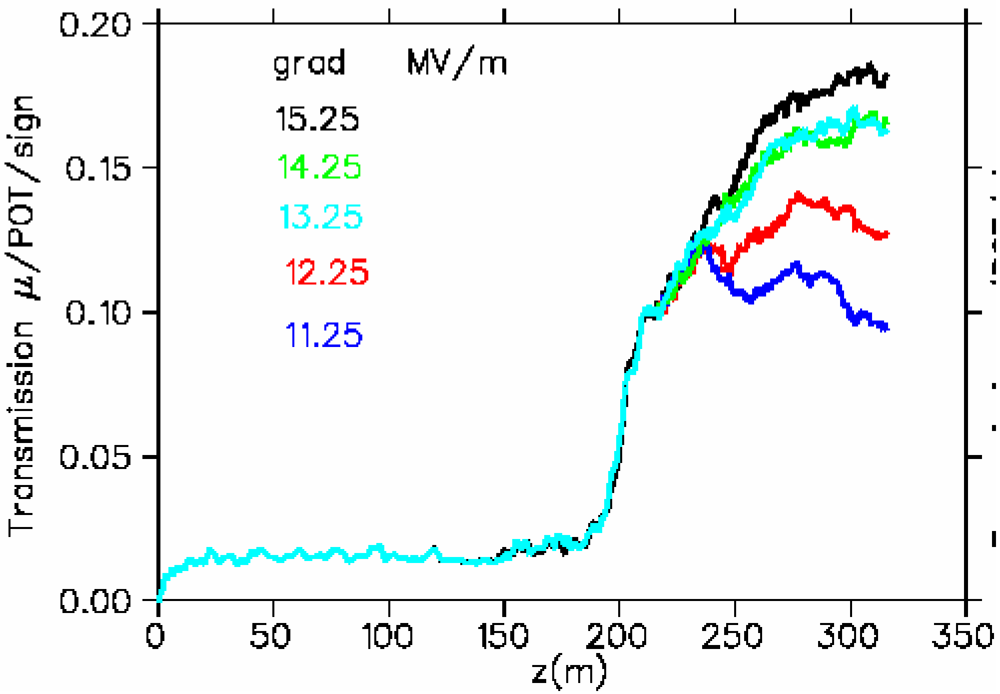
Cooling Channel Comparisons (2)

- **Intensity predictions**
  - only FS2a (with both signs) meets initial NuFact99 goal of 10^{21} useful decays per year

case	cooling	trans acc pi mm	signs	mu/pi	mu/year $\times 10^{21}$
5 MHz	no	30	1	0.08	.22
44/88 MHz	yes	15	1	0.066	.24
201 MHz FS2	yes	15	1	0.17	.62
201 MHz S2a	yes	30	2	0.17	1.22
201 MHz S2a	no	30	2	0.09	.72

Effect of Reduced RF Gradient

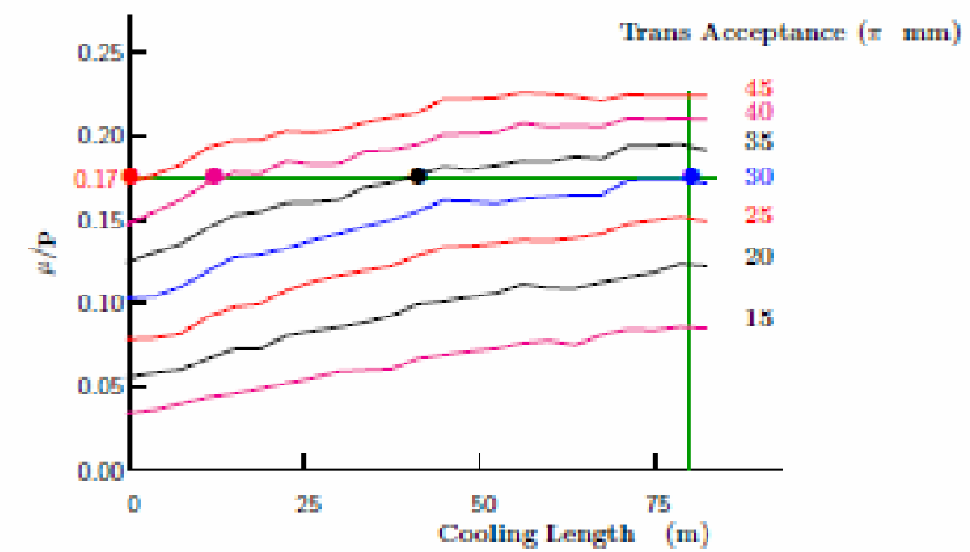
- **Explored effects of reduced RF gradient on throughput (Gallardo)**
  - **operating at reduced gradient lowers transmission without compensation**
    - **adjusting absorber thickness and RF phase would recover some of this**



Cooling vs. Acceptance

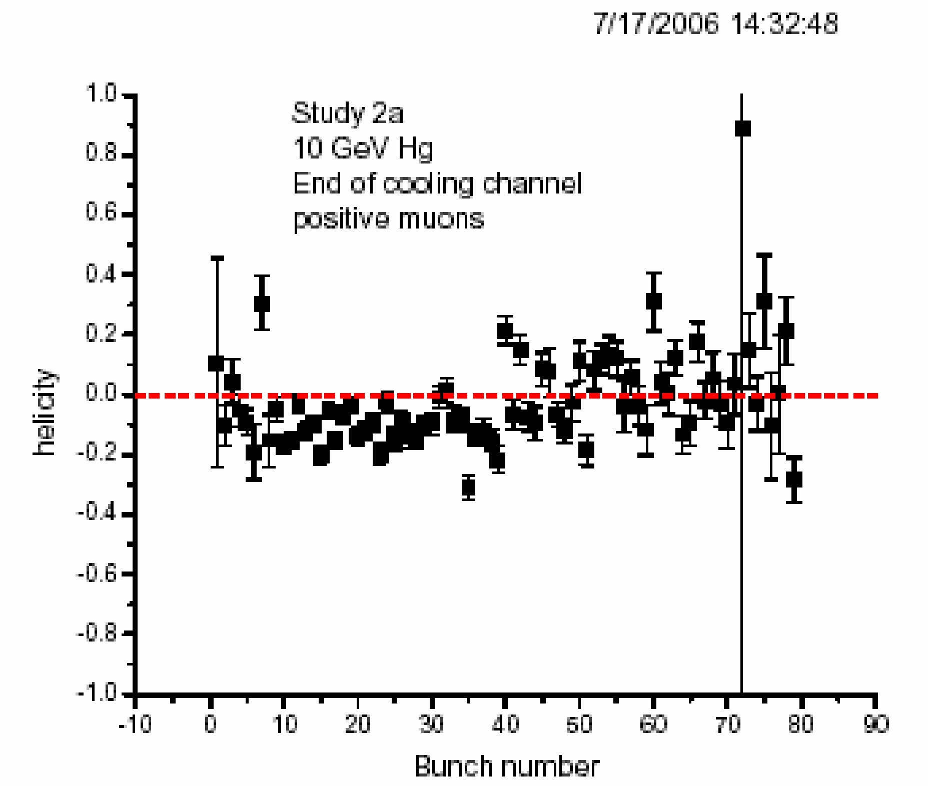
- **Evaluated trade-offs between cooling efficacy and downstream acceptance (Palmer)**
  - *increasing from 30 to 35 π mm-rad halves the required length of cooling channel*
    - at 45 π mm-rad, no cooling needed

- **Not presently clear that A > 30 π mm-rad is practical**
  - *even 30 π mm-rad is not easy!*



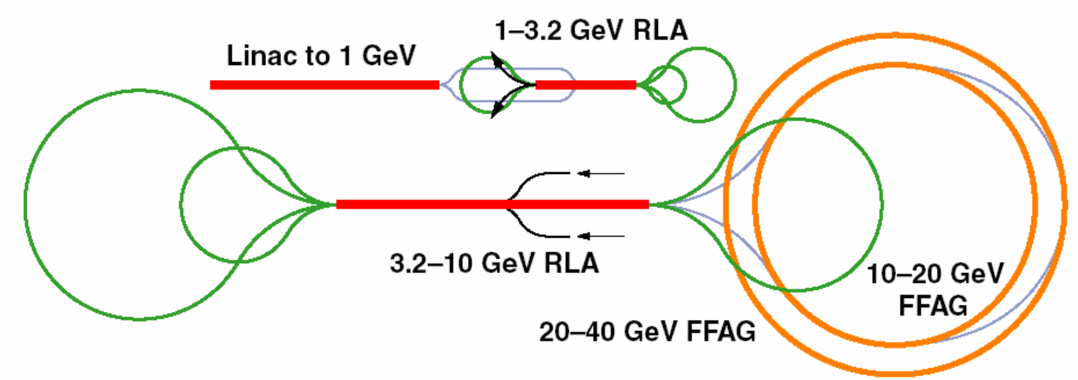
Muon Helicity

- **Average muon helicity is small**
  - **average polarization about 8%**
- **Correlation with position in bunch train is weak**



Acceleration

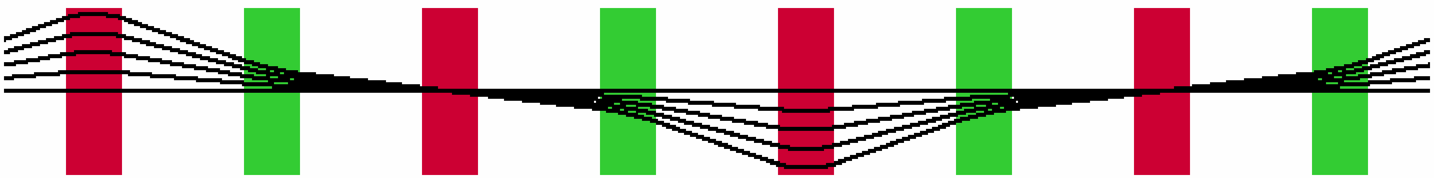
- Compare different schemes *on an even footing*
  - RLA, scaling FFAG, non-scaling FFAG
    - consider implications of keeping both sign muons
    - consider not only performance but relative costs
  - bring scaling FFAG design to same level as non-scaling design
- Look at implications of increasing acceptance
  - transverse and longitudinal
    - some acceptance issues have arisen in non-scaling case (Machida)
      - leading to exploration of a revised acceleration scenario



Non-scaling FFAGs (1)

- In attempting to increase the acceptance, discovered a dynamics problem due to the fact that the revolution time depends on transverse amplitude (Machida, Berg)
  - larger amplitudes and bigger angles give longer path length
    - different flight times for different amplitudes lead to acceleration problems in FFAG
      - large-amplitude particles slip out of phase with RF and are no longer accelerated

- Possible fixes are under study



Non-scaling FFAGs (2)

- Present conclusions
  - 30 π mm-rad probably possible, but is already a stretch
  - cascading FFAG rings is harder than anticipated
    - two in series probably possible, but three in series looks iffy
- We are revisiting acceleration system design in consideration of this issue

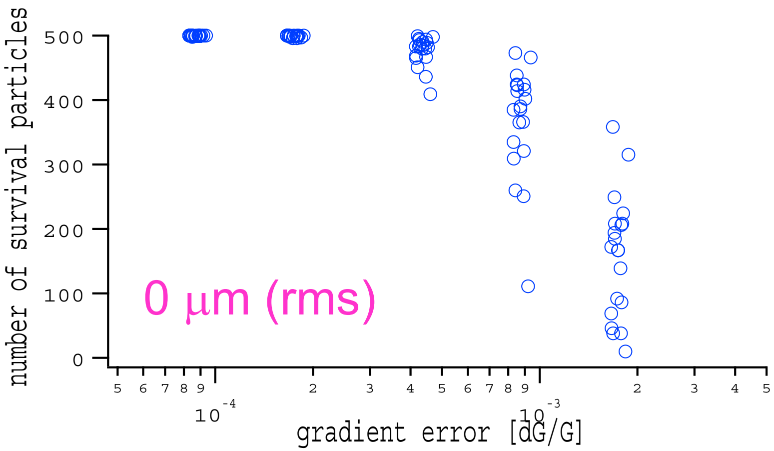
Non-scaling FFAGs (3)

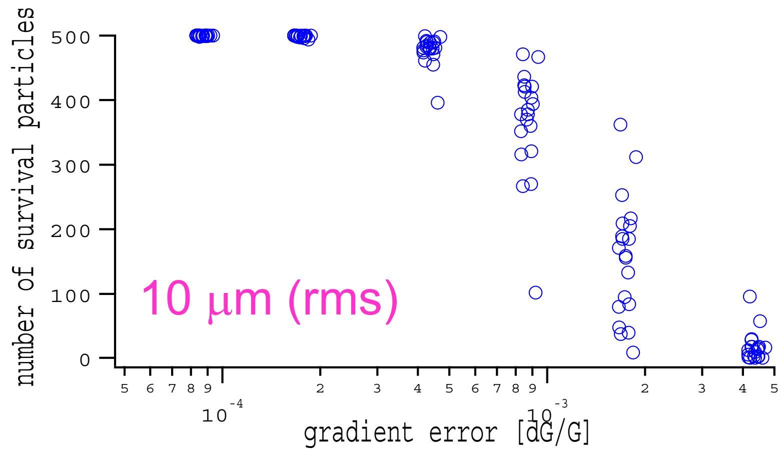
- **Tracking with errors has begun**
  - H, V misalignment of quadrupoles
  - gradient errors
  - use Gaussian errors with 2σ cutoff

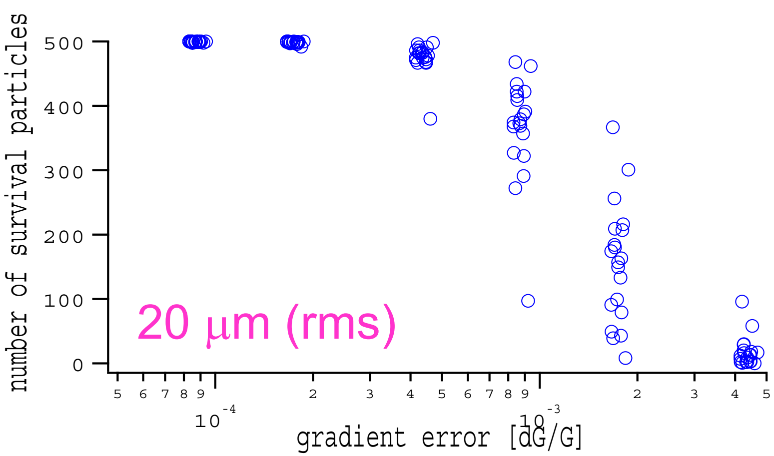
- **Assumptions**
  - constant *E* gain per turn (avoids TOF vs. amplitude effects)
  - 30 π mm-rad emittance
  - nominal initial longitudinal emittance
  - tunes well away from half-integer to avoid large beta beating
  - particle amplitudes beyond 45 π mm-rad are taken as lost

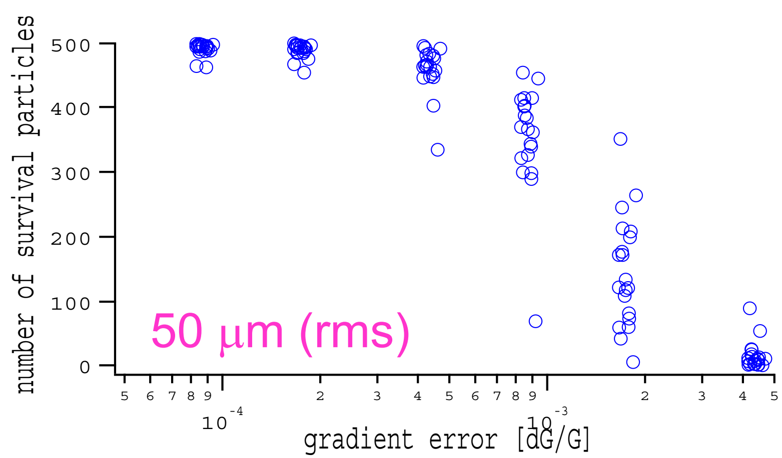
Non-scaling FFAGs (4)

- **Tracking with errors has begun**
  - **rms alignment errors in the range of 20–50 μm are okay**
  - **rms gradient errors of 2–5 × 10^{-4} are okay**
    - **both are tight**







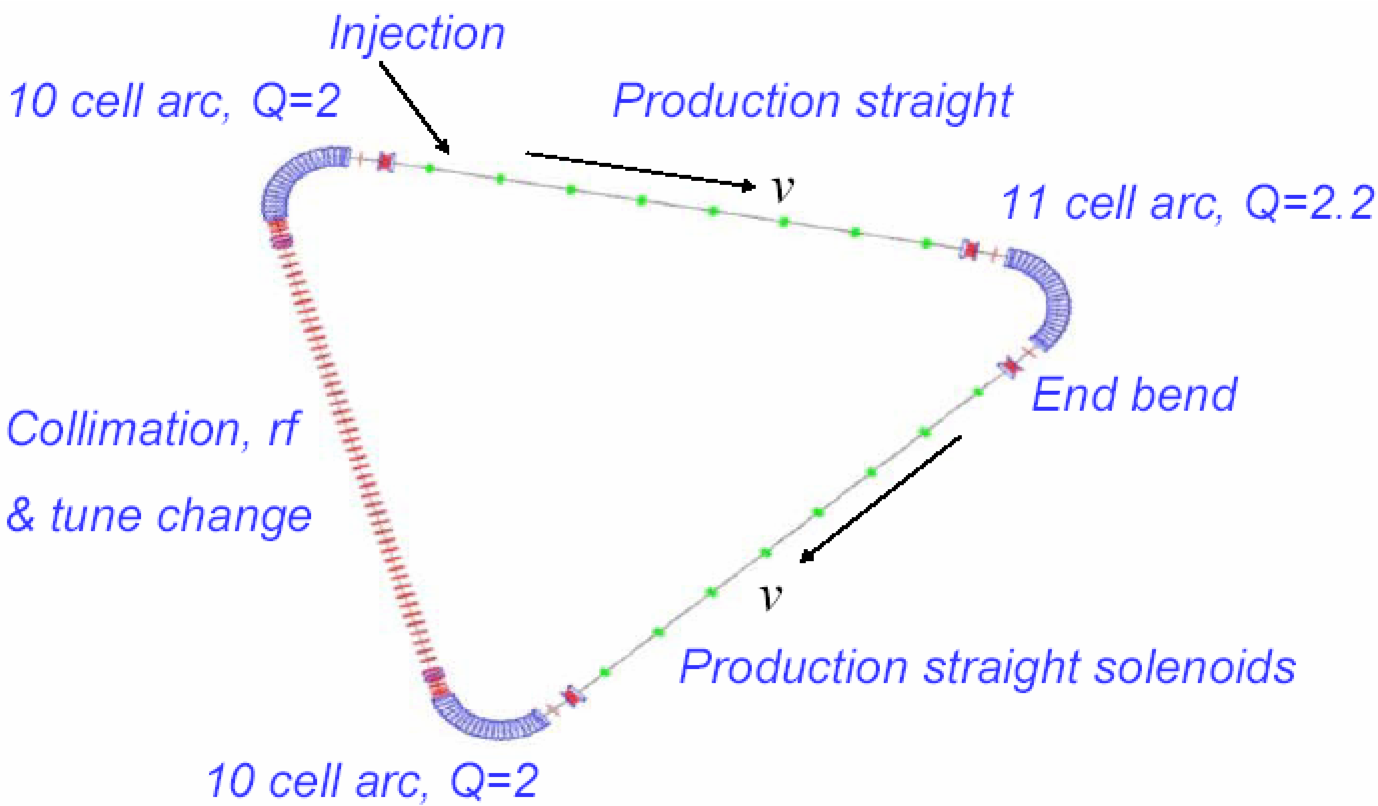


Decay Ring

- Design implications of final energy (20 vs. 40 GeV) √
- Optics requirements vs. beam emittance √
  - arcs, injection and decay straight sections
- Implications of keeping both sign muons √
  - need both injection and decay optics in same straight section
- Implications of two simultaneous baselines √
- Both triangle and racetrack rings have been examined
  - recently started to re-examine "bow-tie" configuration

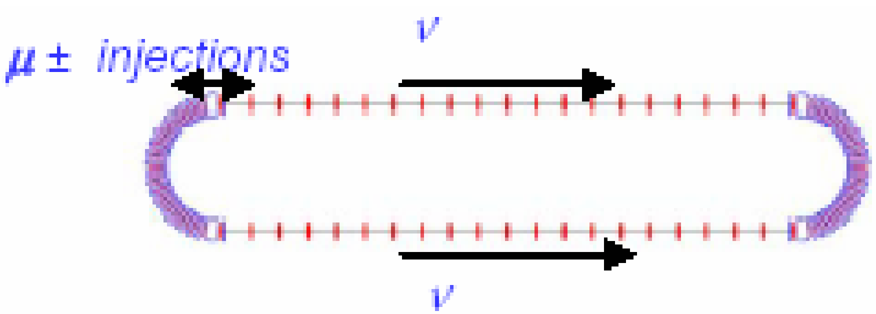
Decay Ring Geometry (1)

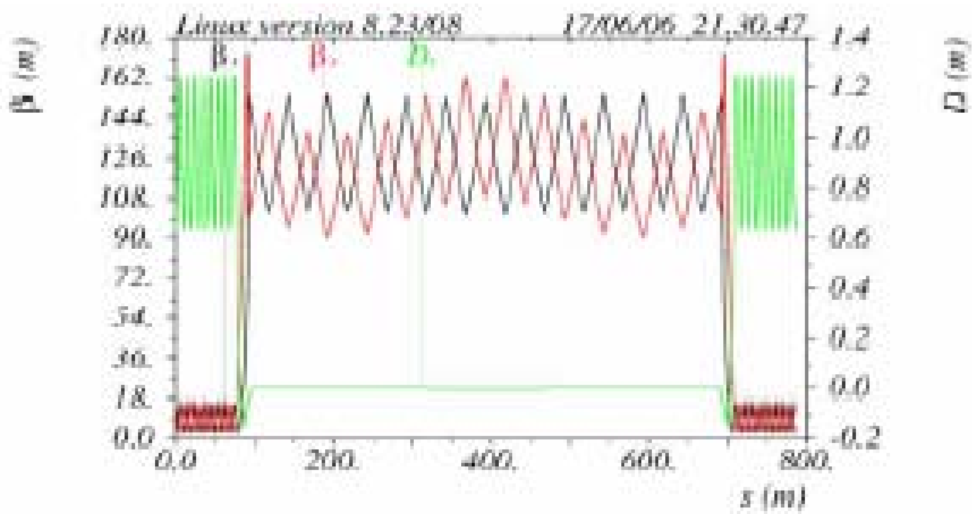
- **Triangle rings would be stacked side by side in tunnel**
  - **one ring stores μ^+ and one ring stores μ^-**
  - **permits illuminating two detectors with (interleaved) neutrinos and antineutrinos simultaneously**



Decay Ring Geometry (2)

- Racetrack rings have two long straight sections that can be aimed at a single detector site
  - store both μ^+ and μ^- in one ring
  - second ring, with both particles, would be used for another detector site
- More flexibility than triangle case, but probably more expensive
  - can stage the rings if one detector is ready first
  - can point to two sites without constraints





Decay Ring Geometry (3)

- **Comparison at similar circumference indicates that, for two suitable detector sites, a triangle ring is more efficient than a racetrack ring**
  - for a single site, racetrack is better

Table 3: Production Straight

Prod Straight	Triangle (for 52.8° apex ∠)	racetrack
Cell Length	49.8	50.0 m
β_{max}	94.3 m	153 m
rms divergence	$0.1/\gamma$	$0.1/\gamma \rightarrow 0.2/\gamma$
Components	SC solenoids	NC quadrupoles
Bore	36.6 cm	46.6 cm
Strength	4.3 → 6.4 T	0.9 →2.2 kG
Length	4.8	1.5 m

Table 4: Design comparison for equal circumferences

General	Triangle (for 52.8° apex ∠)	racetrack
Circumference	1609	1609
Prod straight	2 x 398.5	614 m
Efficiency/ring	2 x 24.8%	38.2%
Depth	>400m	>400m

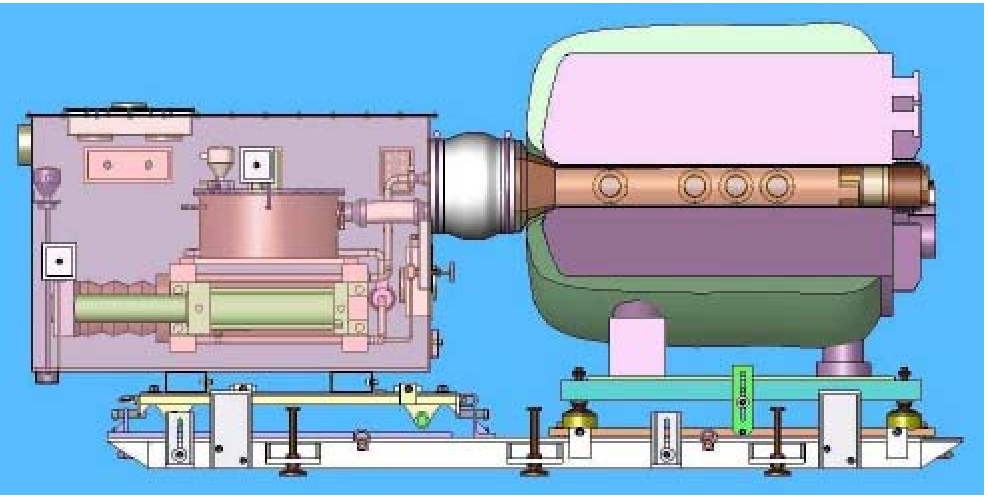
Depth may be an issue for some sites, especially for racetrack with long baseline

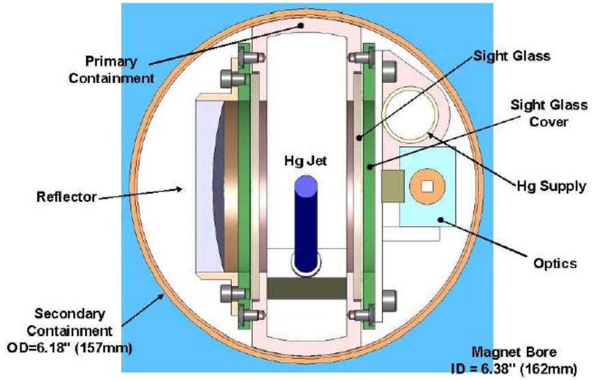
R&D Program

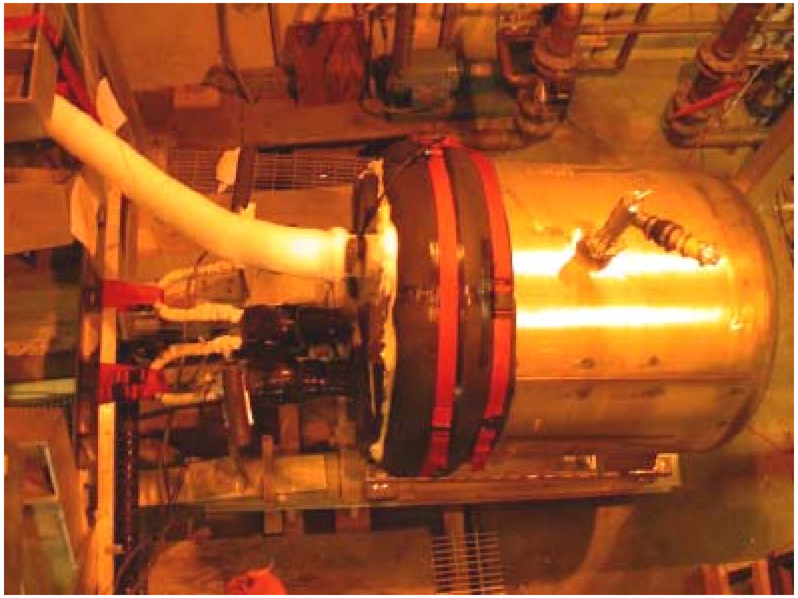
- Two international experiments in progress
  - MERIT and MICE
- Neutrino Factory R&D programs under way in
  - Europe under the auspices of BENE and UKNF
  - Japan, supported by university, and some U.S.-Japan, funds
    - substantial scaling-FFAG results have come from this source
  - U.S. under the auspices of the NFMCC (DOE + NSF supported)
- Proposals in preparation for new international efforts
  - EMMA (UK), electron model to study non-scaling FFAG performance
    - several U.S. firms getting SBIR grants similar FFAG studies
  - high-power target test facility (CERN), to provide dedicated test-bed for next generation of high-power targets
- R&D list prepared during ISS effort **to be in our report**

MERIT

- **MERIT experiment will test Hg jet in 15-T solenoid**
  - 24 GeV proton beam from CERN PS
    - scheduled Spring 2007



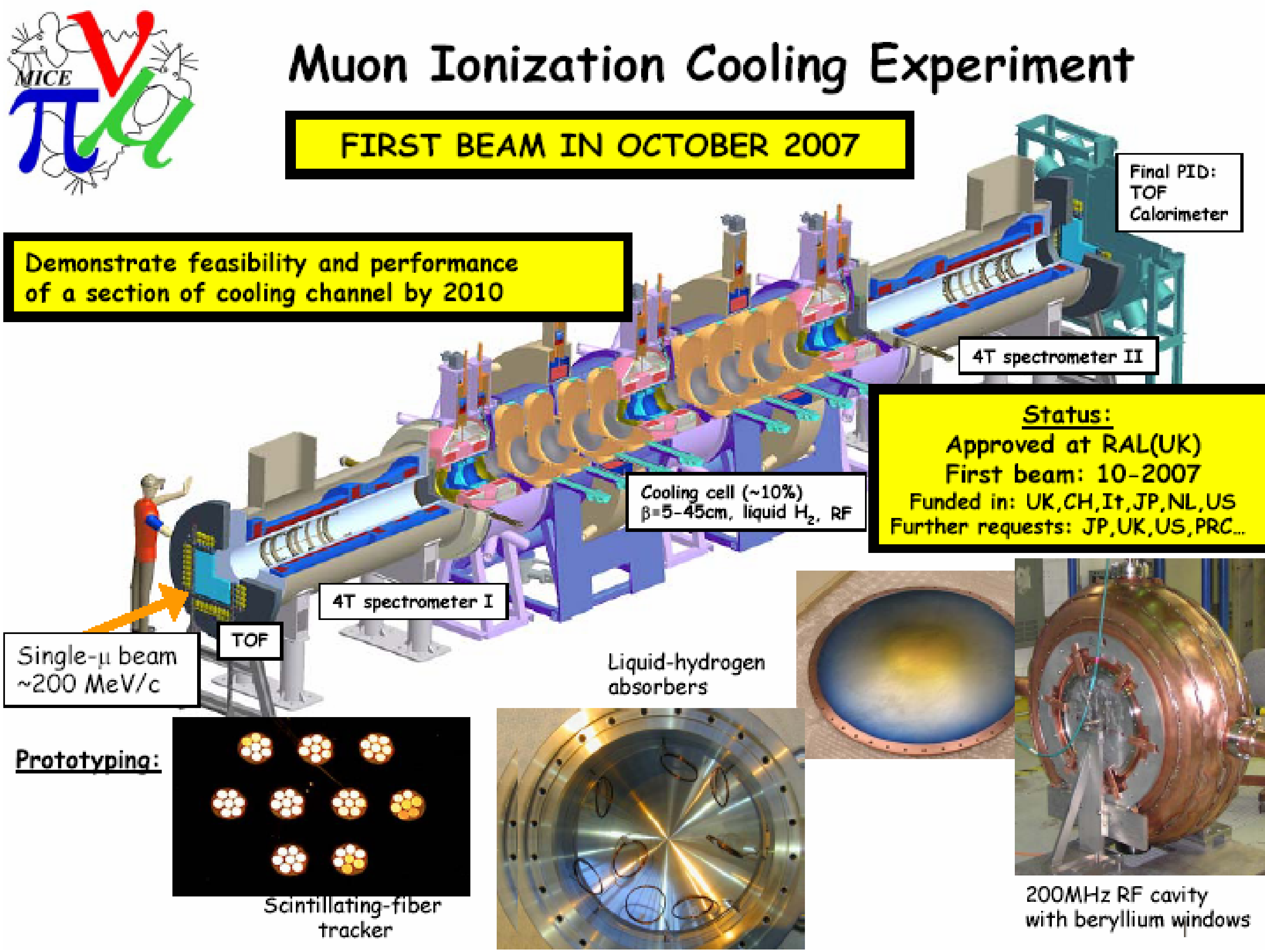




15-T solenoid during tests at MIT

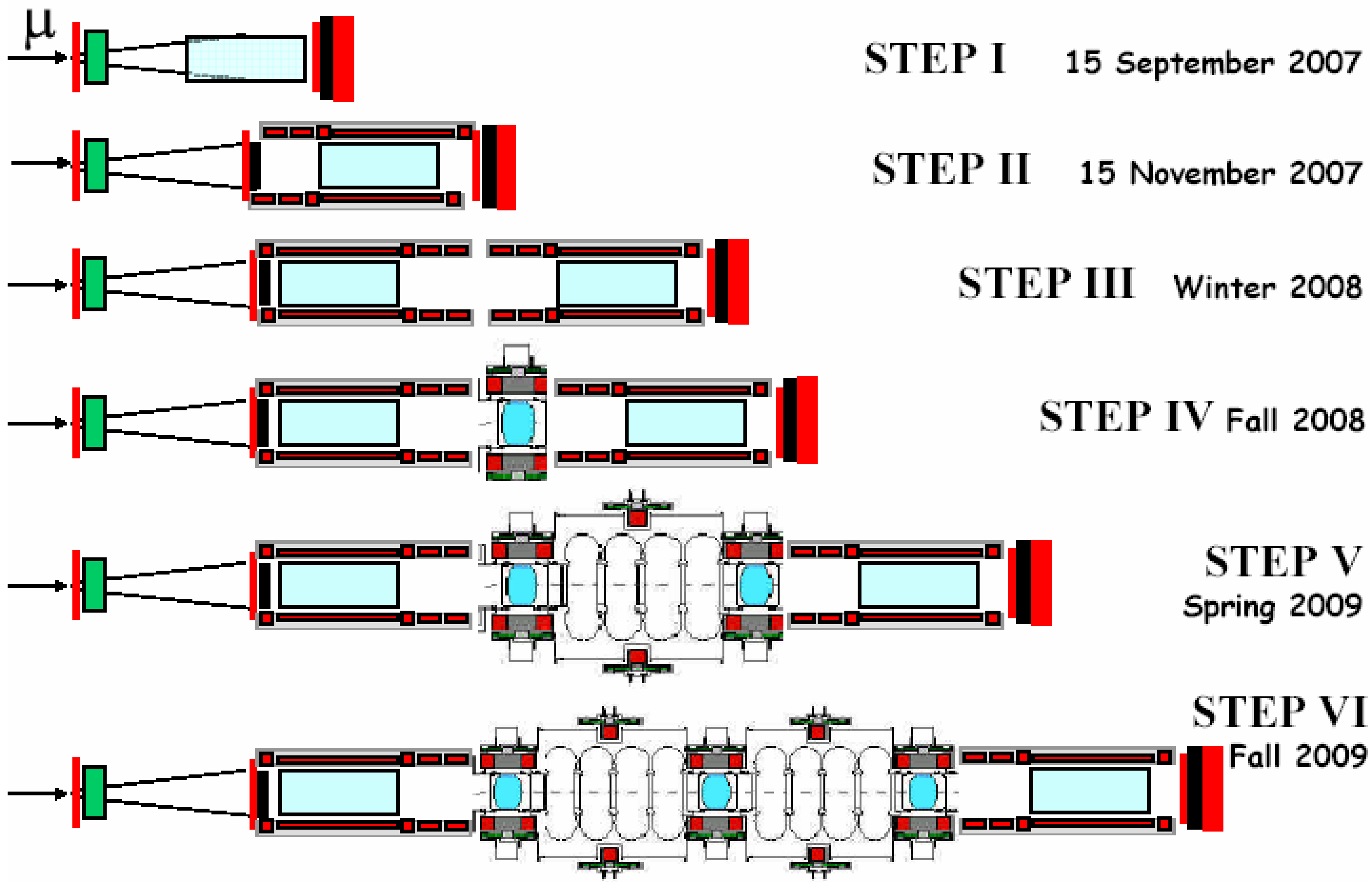
Hg delivery and containment system under construction at ORNL. Integration tests scheduled this Fall at MIT.

MICE (1)

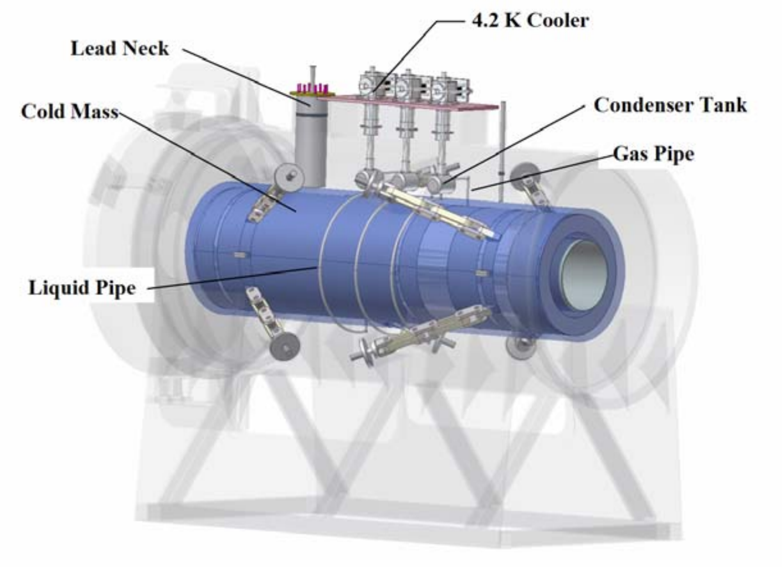

Muon Ionization Cooling Experiment
MICE
FIRST BEAM IN OCTOBER 2007
Demonstrate feasibility and performance of a section of cooling channel by 2010
Final PID:
TOF
Calorimeter
4T spectrometer II
Status:
Approved at RAL(UK)
First beam: 10-2007
Funded in: UK,CH,It,JP,NL,US
Further requests: JP,UK,US,PRC...
Cooling cell (~10%)
β=5-45cm, liquid H2, RF
4T spectrometer I
TOF
Single-μ beam
~200 MeV/c
Prototyping:
Scintillating-fiber tracker
Liquid-hydrogen absorbers
200MHz RF cavity with beryllium windows

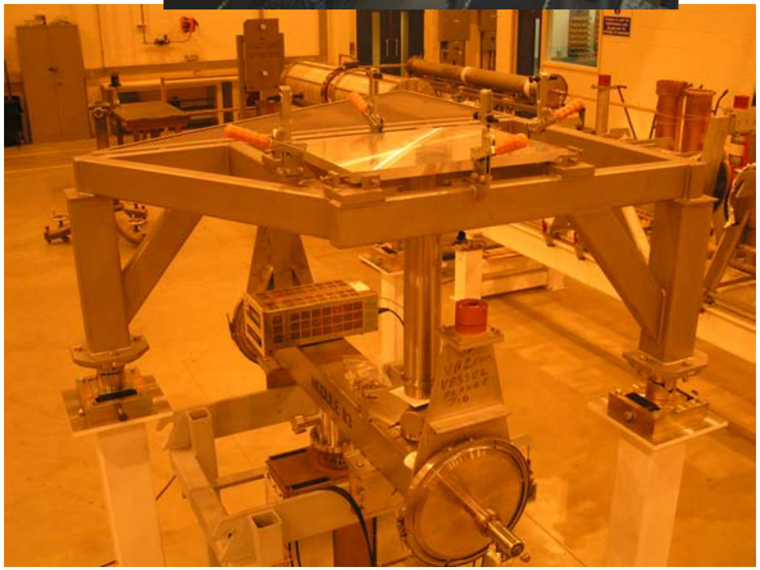
MICE (2)

- MICE channel at RAL will be built in steps to ensure complete understanding and control of systematic errors



MICE (3)


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



Decisions on Baseline (1)

- **Proton Driver**
  - specify parameters, not design
    - implicitly assumes liquid-metal target

Parameter	Value
Energy (GeV)	10 ± 5
Beam power (MW)	4
Repetition rate (Hz)	≈50
No. of bunch trains	3,5[a)]
Bunch length, rms (ns)	2 ± 1
Beam duration[b)] (μs)	≈40

[a)]Values ranging from 1–5 possibly acceptable.
[b)]Maximum spill duration for liquid-metal target.

Decisions on Baseline (2)

- Target
  - assume Hg target; look at Pb-Bi also
- Front End
  - bunching and phase rotation
    - use U.S. Study IIa configuration
  - cooling
    - include in baseline
  - keep both signs of muons
    - "waste not, want not"
- Acceleration
  - used mixed system
    - linac, dog-bone RLA(s), FFAGs
      - transition energies between subsystems still being debated

Decisions on Baseline (3)

- Decay Ring
  - adopt racetrack
    - keep alive triangle as alternative
      - depends on choice of source and baselines
    - energy 20 to 40 GeV
      - 50 GeV okay for ring, but implies more acceleration than presently planned

Accelerator Study Next Phase

- Focus on selected option(s)
  - as part of upcoming International Design Study
    - IDS will eventually have more of an engineering aspect than the ISS
- Making final choices requires ("top-down") cost evaluation
  - requires engineering resources knowledgeable in accelerator and detector design
- Internationally organize R&D efforts in support of facility design

Summary

- Making progress toward consensus on a single optimized Neutrino Factory scheme
  - comparison of competing schemes is complete
  - report to be completed by end of 2006
- Must continue to articulate need for an adequately-funded accelerator R&D program
  - and define its ingredients
  - being encouraged to do this in an international framework
- It has been a privilege to work on the ISS with such a talented and dedicated group
  - my thanks to:
    - Program Committee (Dornan, Blondel, Nagashima)
    - Accelerator Council and task leaders (slide 11)
    - all members of Accelerator Group (see NF-SB-ISS-ACCELERATOR list)