Neutrino Factory and Beta Beam:
News from APS Neutrino Study

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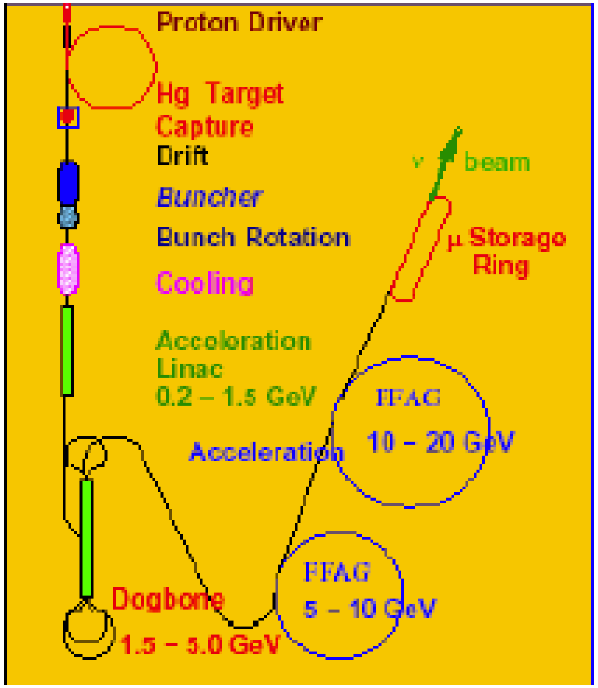
Introduction

- Active Neutrino Factory design and R&D groups already exist
  - Neutrino Factory and Muon Collider Collaboration (U.S.)
  - European Neutrino Group (EU)
  - Japanese Neutrino Group (Japan)
- Beta beam effort mainly in Europe
- APS Study WG initial goals
  - NF: build on existing work and document for broader neutrino-science community
  - BB: understand existing work, evaluate required R&D program, and consider possible U.S. implementation

Neutrino Factory Ingredients

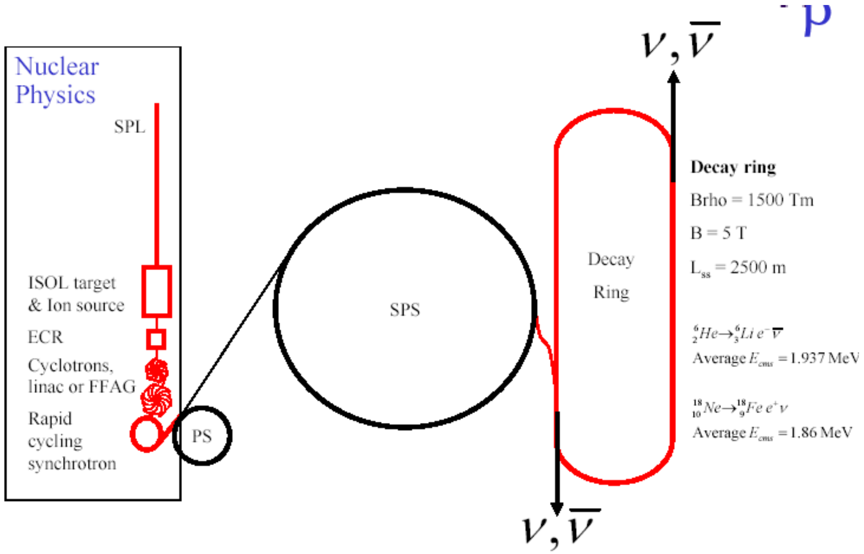
- Neutrino Factory comprises these sections
  - Proton Driver
    - primary beam on production target
  - Target, Capture, and Decay
    - create π; decay into μ
  - Bunching and Phase Rotation
    - reduce ΔE of bunch
  - Cooling
    - reduce transverse emittance
  - Acceleration
    - 130 MeV $\rightarrow$ 20 GeV
  - Storage Ring
    - store for 500 turns; long straight



Very schematic

Beta Beam Ingredients

- **Beta Beam facility comprises these sections**
  - **Proton Driver**
    - SPL (2.2 GeV; 4 MW)
  - **ISOL Target**
    - spallation neutrons or direct protons
  - **Ion Source**
    - pulsed ECR
  - **Acceleration**
    - linac, cyclotron, FFAG
    - PS, SPS
  - **Decay Ring**
    - SPS size; 2500 m straight



Comparison of Schemes

- Most design aspects common to both NF and BB
- NF requires one more step than BB facility
  - cooling of muon beam
- NF likewise requires one step less
  - ionization and bunching of beta-unstable isotopes
- Both NF and BB place a premium on rapid acceleration
  - BB less so than NF

Neutrino Factory Study I

- Study I (1999—2000) instigated by Fermilab

- Focus on feasibility
  - first attempt to specify NF from end to end
  - approach: base design on (reasonably) well-understood technologies
  - no attempt to optimize either cost or overall performance

- Proper approach at the time, as feasibility was most at issue

- Led to predictable result: feasibility established, performance poor, costs relatively high

Neutrino Factory Study II

- Study II (2000—2001) collaboration of MC, BNL
- Goal: maintain convincing feasibility, improve performance substantially
  - optimizing cost again given lower priority
- Result: performance 5x Study I
  - 1.2×10^{20} vs. 2.5×10^{19} ν_e per year (10^7 s) per MW
- Cost about 75% of Study I
  - due to choice of 20 GeV rather than 50 GeV

Lessons Learned

- Necessary to optimize "front end" (decay, bunching, phase rotation, cooling)
- Simulate entire concept before starting detailed engineering (develop self-consistent solution)
- Work as partners with engineers to converge on buildable design
- Facility is costly, $\mathcal{O}$($2B)
- Increasing proton driver power is cost-effective way to get higher performance *if target does not limit this parameter*

What Next?

- Already studied portions of NF design space representing
  - low performance, high cost
  - high performance, high cost
- Need to study high performance, optimized cost
- Previous work gave good idea where to begin
  - replace induction linacs with RF bunching and phase rotation
  - replace RLA with FFAG ring or very rapidly cycling synchrotron
  - examine trade-offs between amount of cooling and downstream acceptance
    - also between beam intensity and detector size

Why These Choices?

- Areas selected could markedly reduce facility cost
  - RF bunching and phase rotation section shorter than induction linac version, and uses less expensive components
    - original version took 25% of total cost
    - new scheme keeps both μ^- and μ^+ simultaneously
  - RLAs were major cost (23%) of Study II design
    - large aperture FFAG magnets accommodate energy swing without need for separate arcs
      - avoids large-aperture splitter-recombiner magnets
  - increased acceptance downstream should allow reduction in cooling requirements (20% of facility cost)
- Note that replacement systems are not free!

Beta Beam Issues

- Beta beam facility based on production, acceleration and storage of light, beta-unstable isotopes
  - use ^{6}He for β^- ($t_{1/2}$ = 0.8 s)
  - use ^{18}Ne for β^+ ($t_{1/2}$ = 1.7 s)
- Several technical challenges that would benefit from further study
  - production target and ion source to give desired intensity
    - multiple targets needed for ^{18}Ne intensity of 1.3×10^{13}
    - pulsed ECR source needed to give bunches of fully stripped ions
  - space-charge blowup and radiation losses in accelerator chain
  - stacking multiple turns in decay ring
- Generalize scenario beyond CERN site-specific version

Working Group Specific Goals

- For NF, examine approaches to reduce facility cost without sacrificing performance
  - carry out end-to-end simulations of entire complex and demonstrate acceptable performance
- For BB, aspire to more modest goals
  - assess status of CERN-based design
  - identify and understand outstanding technical issues and time scale for dealing with them
  - consider implications of U.S. site
- In practice, we came closer to NF goals than BB goals

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Muon Collaboration

Neutrino Factory Design Progress

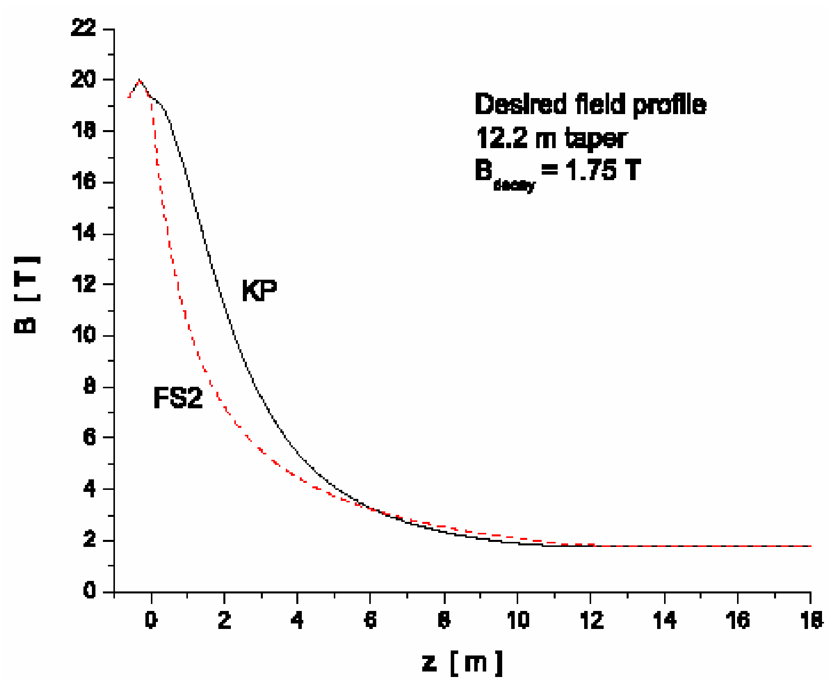
- Took advantage of participation of MC experts
  - involved in both of the earlier Feasibility Studies

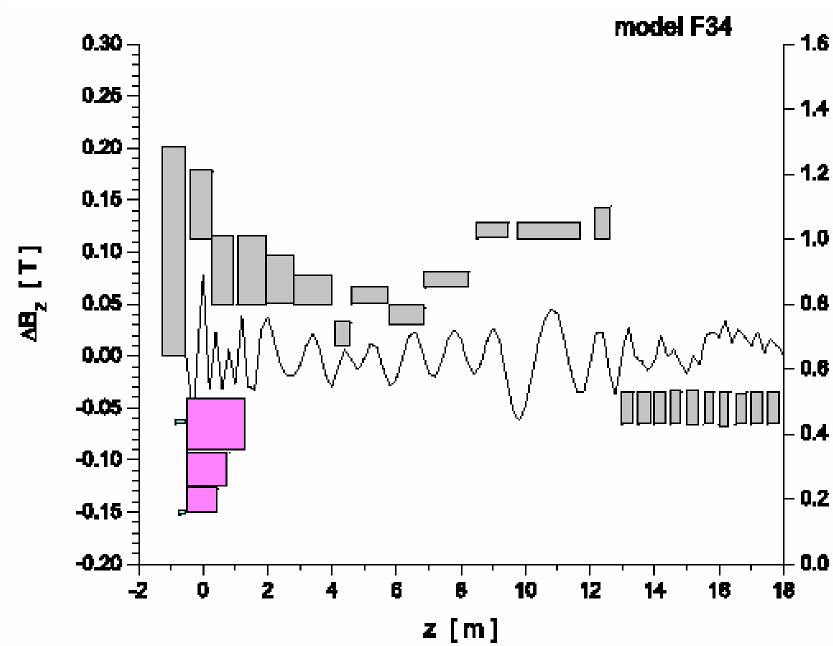
- Redesigned FS2 Neutrino Factory ⇒ "FS2a"
  - Capture, Bunching and Phase Rotation, Cooling Acceleration
    - "that's where the money is"
      - about 3/4 of NF cost is here
    - goal: develop cost-effective design based on new ideas
      - get a rough idea of cost savings wrt FS2

  - no work on Target or Storage Ring…yet

Capture Section

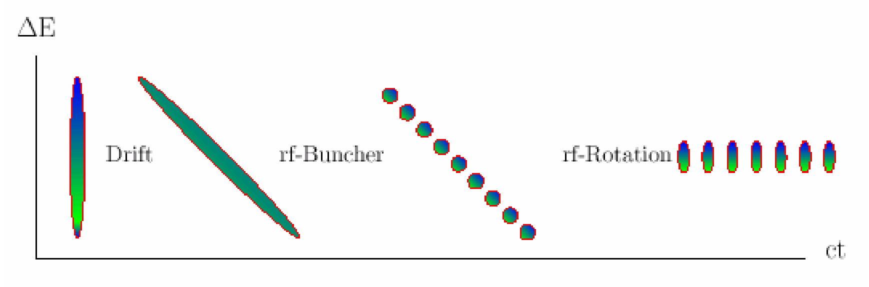
- **Reoptimized capture section magnetic profile**
  - **not much different, but gained 10% more intensity**
  - **magnetic field tapers from 20 T to 1.75 T (1.25 T in FS2)**

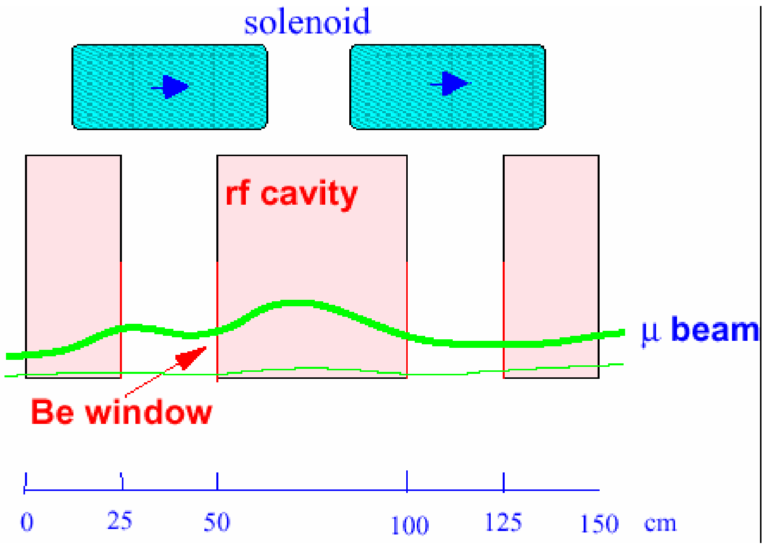




Buncher and Phase Rotation

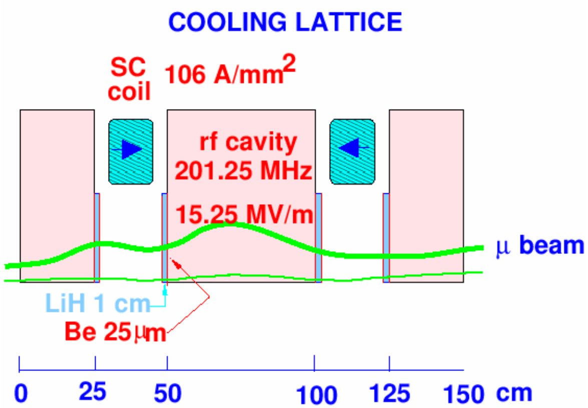
- FS2: induction linacs to phase rotate, rf to bunch
  - worked well, but relatively expensive
    - keeps only one sign muon
- FS2a: rf to bunch, then rf to phase rotate
  - performance less good, but less expensive
    - keeps both μ^+ and μ^-

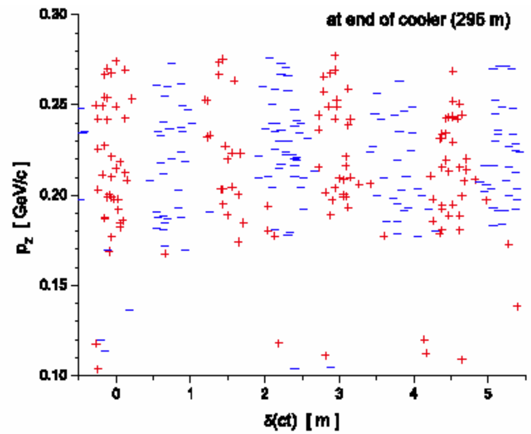


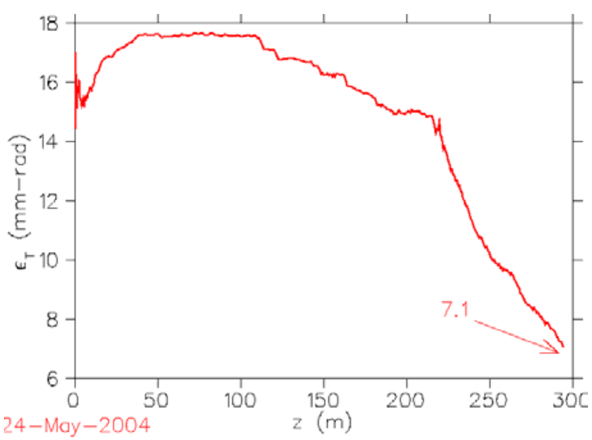


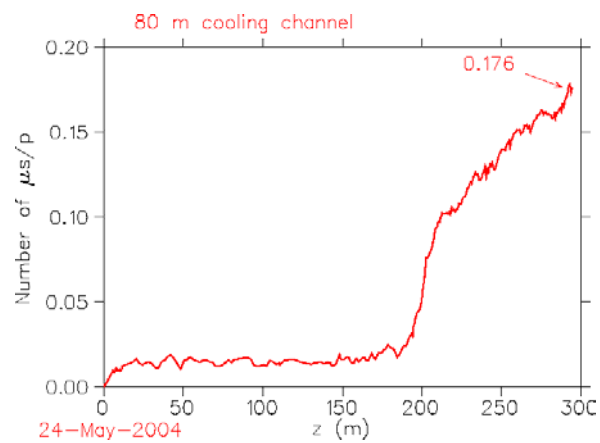
Cooling

- **Cooling channel simplified considerably cf. FS2**
  - shorter, fewer magnets, fewer rf cavities, simpler absorbers
    - no LH_2; replace with LiH
  - performs as effectively as FS2 channel…for both signs



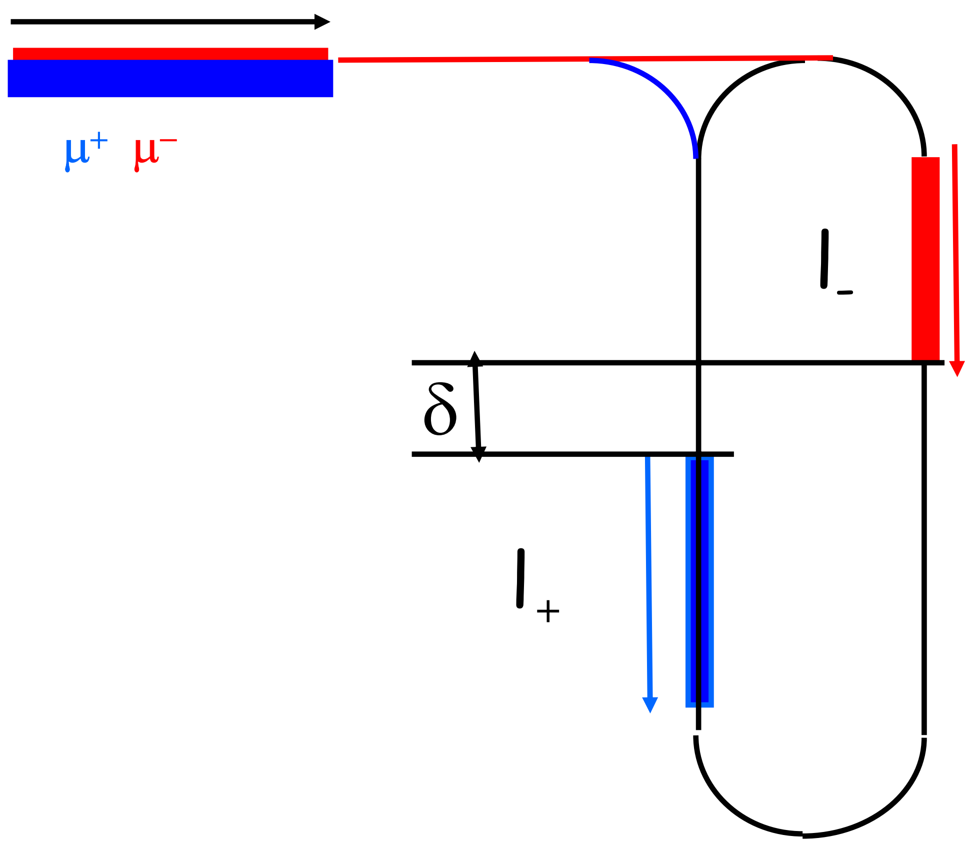






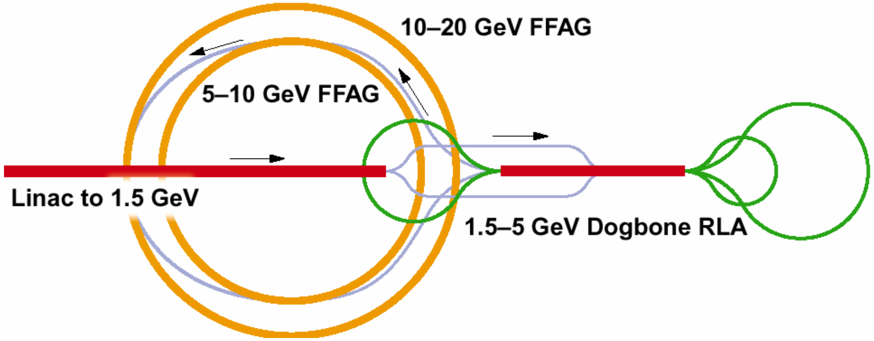
Using Both Signs

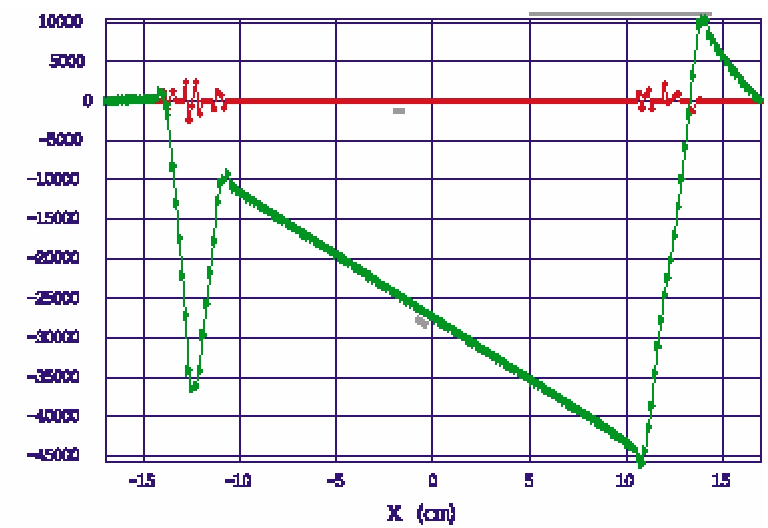
- Two issues (Blondel)
  - timing to distinguish μ^- and μ^+ ($\delta \geq 100$ ns)
  - possible need for two near detectors (or use stacked rings if that is cheaper)

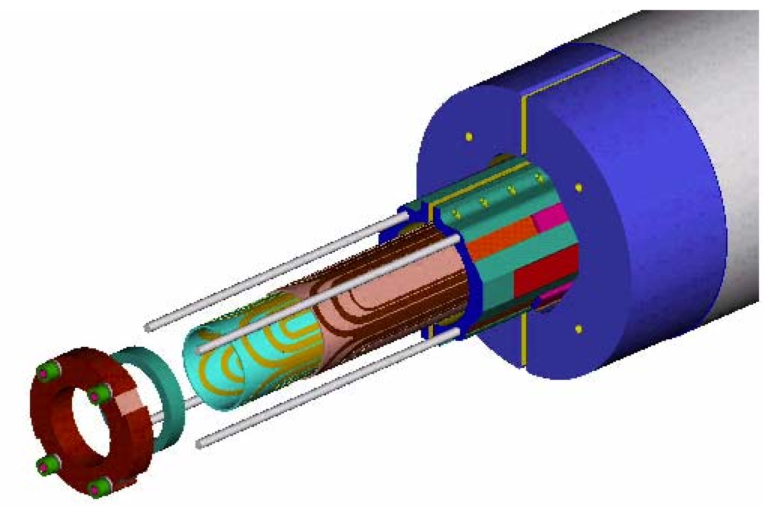


Acceleration

- FFAGs are cost-effective for accelerating muons
  - use eclectic mix of machines to accelerate to 20 GeV
    - linac, dogbone RLA, 2 FFAGs…something for everybody!
  - SC combined-function magnet appears suitable

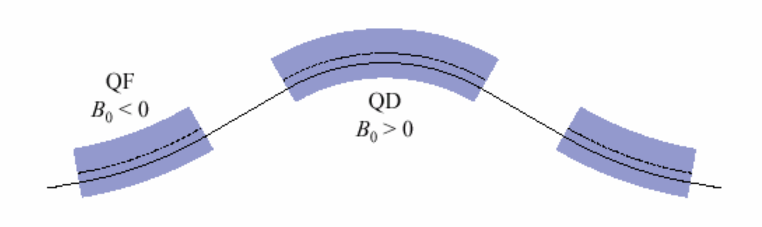




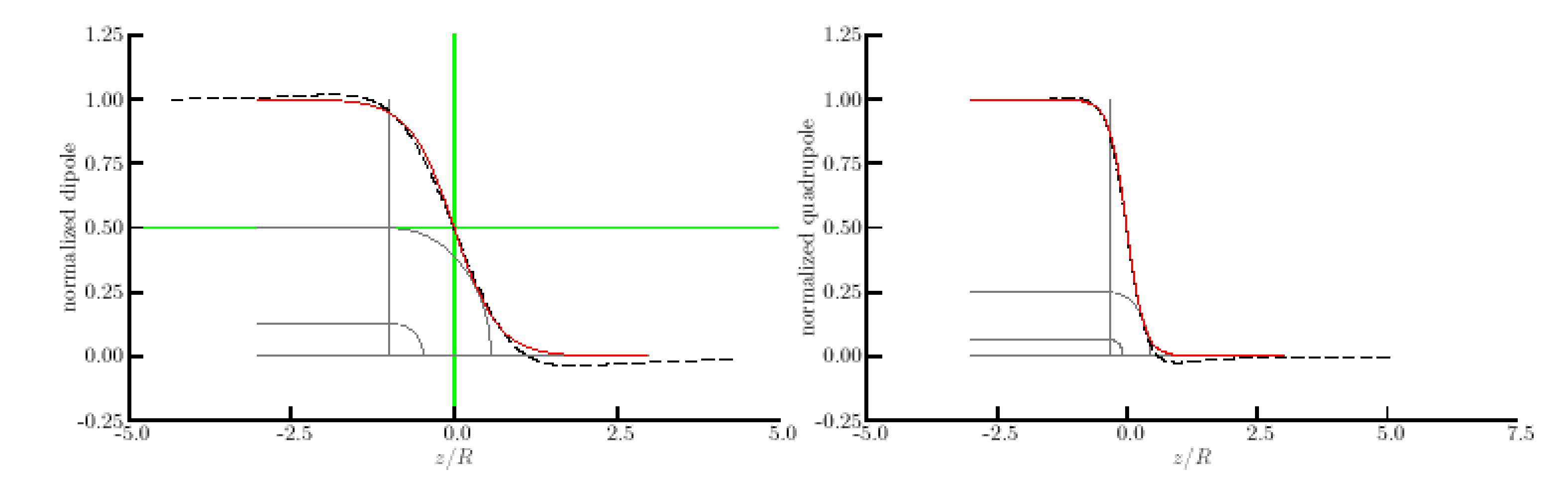


FFAG Rings

- FFAG scheme being developed by Berg, Johnstone, Trbojevic, Palmer, Keil, Sessler, Koscielniak,…
  - use combined-function magnets in doublet or triplet arrangement



  - track with realistic end fields (okay!) (dashed, TOSCA, solid, ICOOL)



Beta Beams in the Colonies

- There are scientific benefits to a higher energy Beta Beam facility than can be provided at CERN
  - γ_{max} for ^{6}He at SPS ≈ 150; twice that is preferred

- Looked RHIC and Tevatron; Tevatron is better

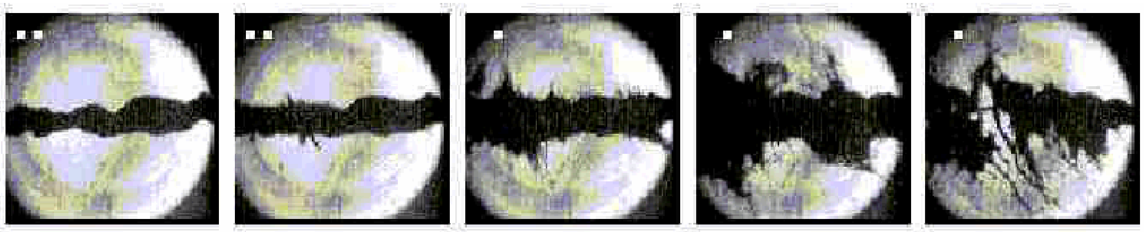
Machine	Proton kinetic energy (GeV)	$\gamma(p)$	$\gamma(^6He^{2+})$	$\gamma(^{18}Ne^{10+})$
FNAL Booster	8	9.5	3.3	5.4
Main Injector	150	161	64	89
Tevatron	980	1045	349	581
BNL Booster	2	3.1	1.4	1.9
AGS	30	34	11	19
RHIC	250	268	89	149

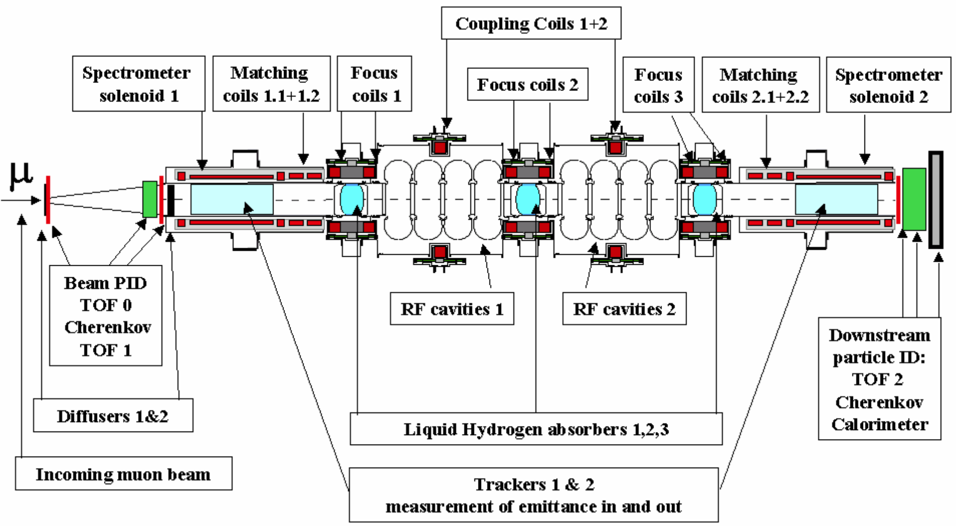
Machine	Ramp time (s)	$^6He^{2+}$ loss (%)	$^{18}Ne^{10+}$) loss (%)
FNAL Booster	0.03	2	1
Main Injector	0.7	2	1
Tevatron	17	10	3
BNL Booster	0.1	14	5
AGS	0.5	9	3
RHIC	100 (40)	91 (62)	50 (24)

Neutrino Factory R&D

- Ongoing program in US carried out by MC
  - major programs in cooling, targetry, acceleration
    - MUCOOL: testing LH2 absorbers, high-gradient ncrf
      - high gradient does not coexist graciously with B_{sol}
    - Targetry: testing solid and Hg jet in proton beam
    - Acceleration: developing high-gradient scrf, studying FFAGs
  - new initiatives are planned and ready to launch
    - MICE: demonstrate ionization cooling with realistic hardware (have scientific approval from RAL)
    - Targetry: test Hg jet with 15-T solenoid at CERN
    - Acceleration: build electron model of non-scaling FFAG

Neutrino Factory R&D - II





Beta Beam R&D Issues

- No work ongoing in US except what was done for this Study
- Issues (our view)
  - target to produce ^{18}Ne must tolerate intense beam
  - collection efficiency from target to remote ion source
  - ion source capability to provide required charge state and bunching; multiple targets proposed for ^{18}Ne
  - decay losses in acceleration chain and storage ring
  - beam manipulations if both ^{6}He and ^{18}Ne stored simultaneously

Cost Savings

- **Not practical to do a bottom-up costing of our new design so we scaled from FS2**
  - we have done well with the major cost items, but savings on the lesser items are not yet exploited
  - these are hardware-only costs (no ED&I, burden, escalation, contingency)

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

The Report

BNL-72369-2004, FNAL-TM-2259, LBNL-55478

Neutrino Factory and Beta Beam Experiments and Development

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(Dated: July 30, 2004)

http://www.cap.bnl.gov/mumu/study2a/REPORT/NF-BB-WG.pdf

WG Recommended That

- ongoing Neutrino Factory R&D in the US be given continued encouragement and financial support
  - HEPAP suggested $8M per year; much less being provided
- US funding agencies find a way to support MICE, in collaboration with EU and Japanese partners
  - experiment has scientific approval to run at RAL
- support be found to ensure that the international Targetry R&D experiment proceeds as planned
  - proposal submitted to CERN, awaiting response
- a World Design Study, aimed at solidly establishing the cost of a cost-effective Neutrino Factory, be supported at the same level as FS1 and FS2
  - planning for this is already under way
- progress on Beta Beam development be monitored, and that US colleagues cooperate fully with EU counterparts in assessing how US facilities might play a role in such a program
  - no significant US R&D effort due to limited resources

Status of Study

- Completed in late June, 2004
- Since then, we have worked to produce final summary report
  - report contains overview of physics opportunities, overall recommendations, and summaries of WG recommendations
    - overall recommendations are consistent with WG recommendations...*but not identical*
      - many more people to satisfy in main report!
- Writing subcommittee chaired by Hamish Robertson
  - went through text line by line…and sometimes word by word
  - how many physicists does it take to write a Neutrino study report?
- Report presented to DOE/NSF October 25

Summary

- APS Neutrino Study has outlined breadth and scientific importance of neutrino science program
- Importance of adequately-funded accelerator R&D program is indicated
  - importance of staying abreast of European BB effort likewise mentioned
- One issue: U.S. community is not yet unequivocally convinced NF or BB facility is needed
  - facilities still viewed by many as a back-up option to Superbeams
- We need to make the scientific case stronger
  - cost matters, and efforts to reduce price tag will help