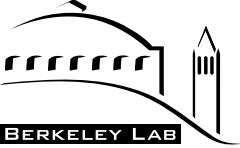


# Neutrino Factory and Beta Beam: *News from APS Neutrino Study*

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BENE Meeting-DESY  
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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 comprises these sections

- Proton Driver

- primary beam on production target

- Target, Capture, and Decay

- create  $\pi$ ; decay into  $\mu$

- Bunching and Phase Rotation

- reduce  $\Delta E$  of bunch

- Cooling

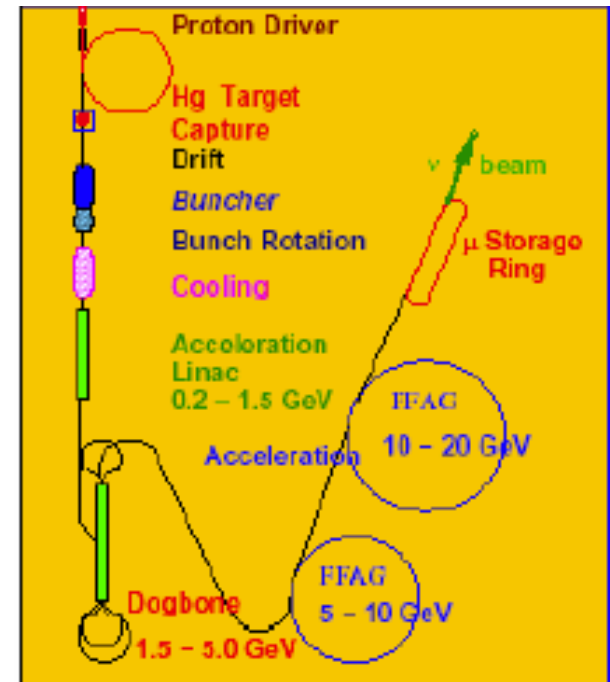
- reduce transverse emittance

- Acceleration

- 130 MeV  $\rightarrow$  20 GeV

- Storage Ring

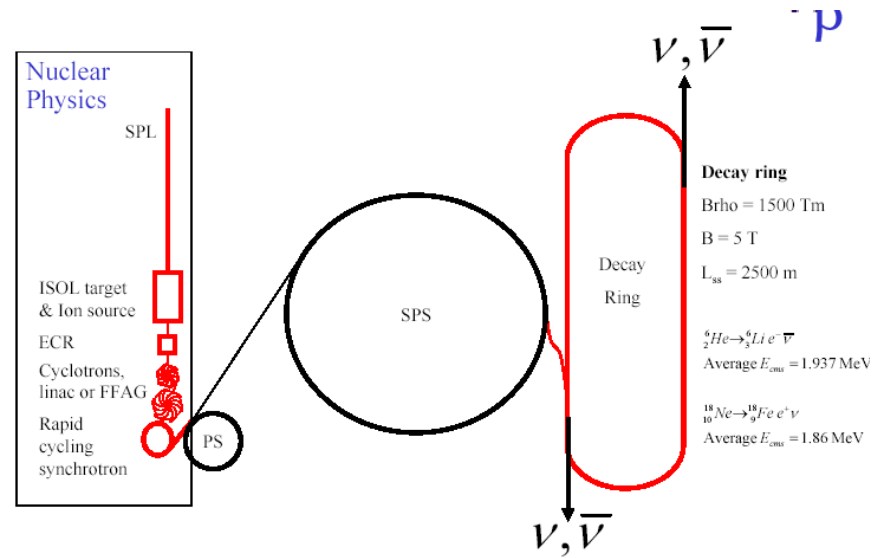
- store for 500 turns; long straight



Very schematic

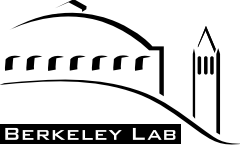
# Beta Beam Ingredients

- 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



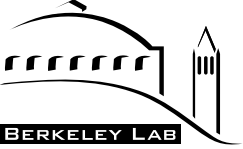
# Comparison of Schemes

- 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
  - $1.2 \times 10^{20}$  vs.  $2.5 \times 10^{19}$   $\nu_e$  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,  $\alpha(\$2B)$
- Increasing proton driver power is cost-effective way to get higher performance *if target does not limit this parameter*

# What Next?

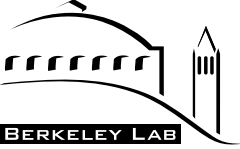
- Already studied portions of NF design space representing
  - low performance, high cost
  - high performance, high cost
- Need to study **high performance, optimized cost**
- Previous work gave good idea where to begin
  - replace induction linacs with RF bunching and phase rotation
  - replace RLA 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  $\mu^-$  and  $\mu^+$  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  ${}^6\text{He}$  for  $\beta^-$  ( $t_{1/2} = 0.8$  s)
  - use  ${}^{18}\text{Ne}$  for  $\beta^+$  ( $t_{1/2} = 1.7$  s)
- Several technical challenges that would benefit from further study
  - production target and ion source to give desired intensity
    - multiple targets needed for  ${}^{18}\text{Ne}$  intensity of  $1.3 \times 10^{13}$
    - 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

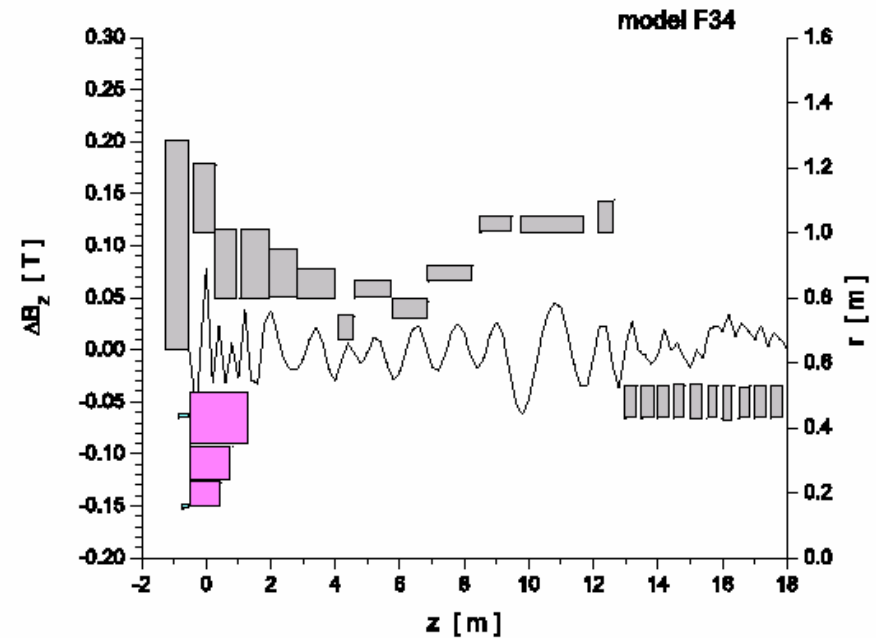
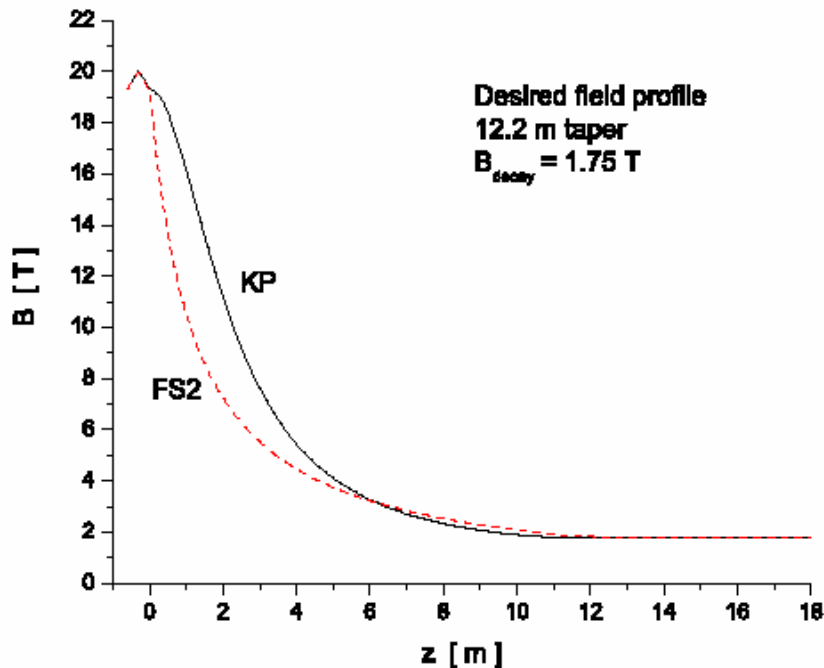
- For NF, examine approaches to reduce facility cost without sacrificing performance
  - carry out end-to-end simulations of entire complex and demonstrate acceptable performance
- For BB, aspire to more modest goals
  - assess status of CERN-based design
  - identify and understand outstanding technical 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

# Neutrino Factory Design Progress

- Took advantage of participation of **MC** experts
  - involved in both of the earlier Feasibility Studies
- Redesigned FS2 Neutrino Factory  $\Rightarrow$  **"FS2 $\alpha$ "**
  - 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

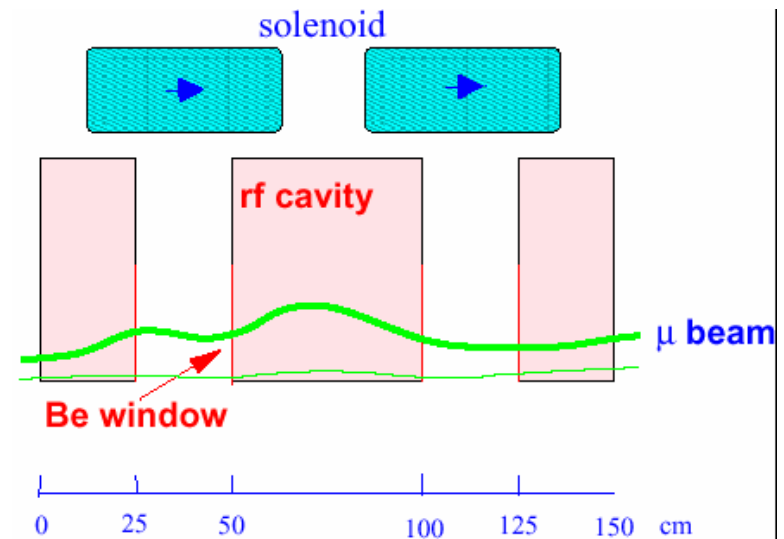
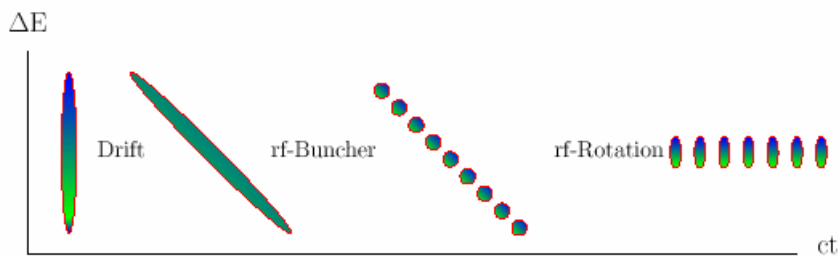
# Capture Section

- 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)



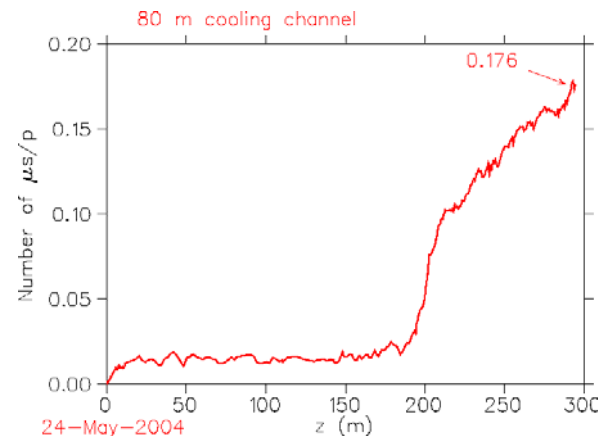
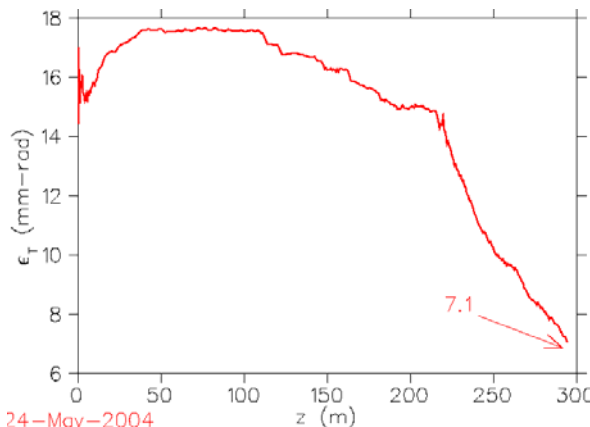
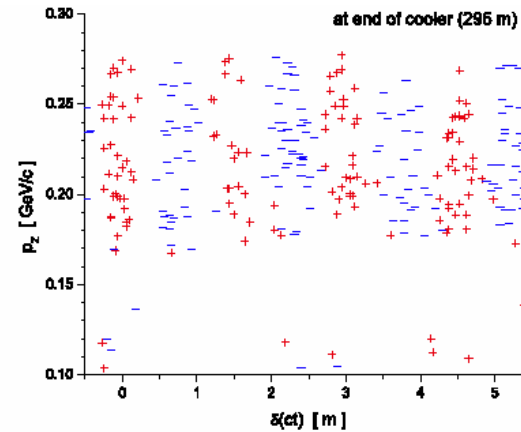
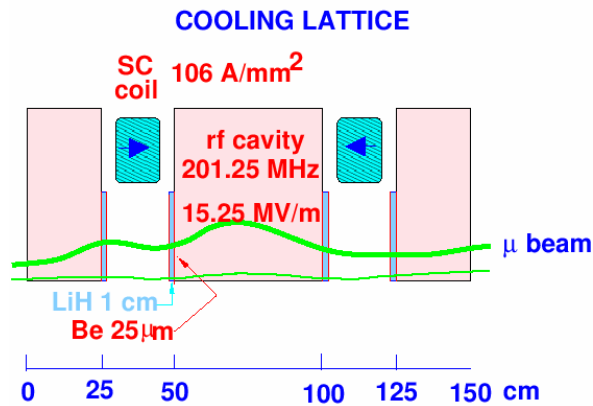
# Buncher and Phase Rotation

- 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  $\mu^+$  and  $\mu^-$



# Cooling

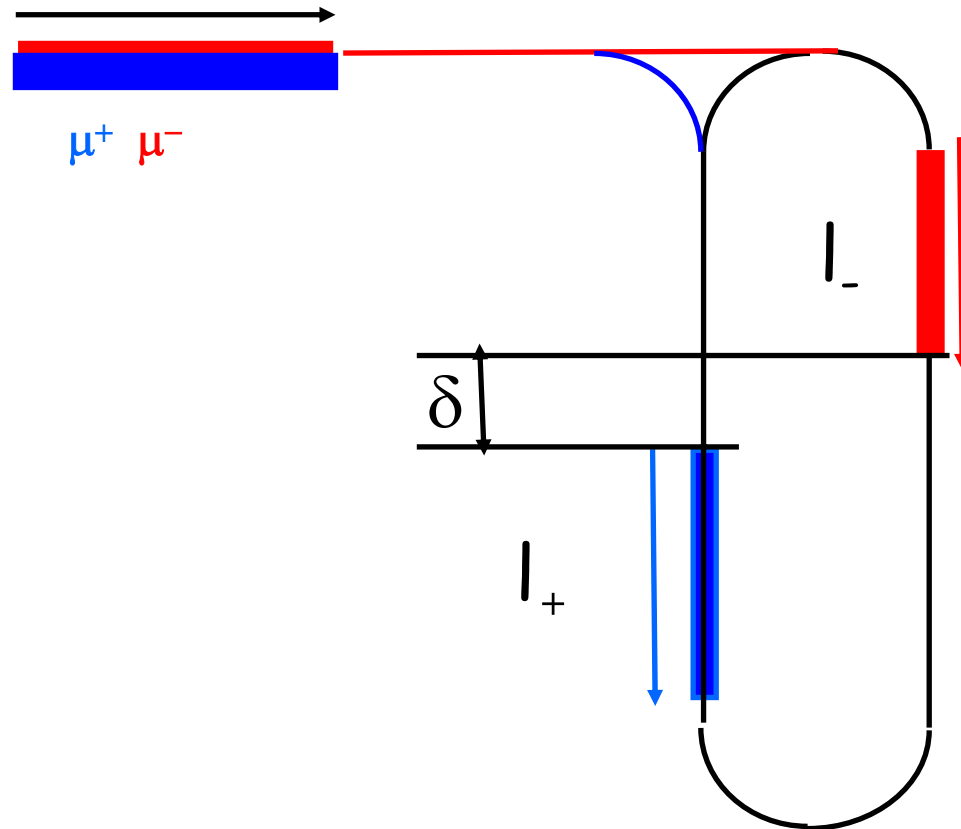
- Cooling channel simplified considerably cf. FS2
  - shorter, fewer magnets, fewer rf cavities, simpler absorbers
    - no LH<sub>2</sub>; replace with LiH
  - performs as effectively as FS2 channel...for both signs



# Using Both Signs

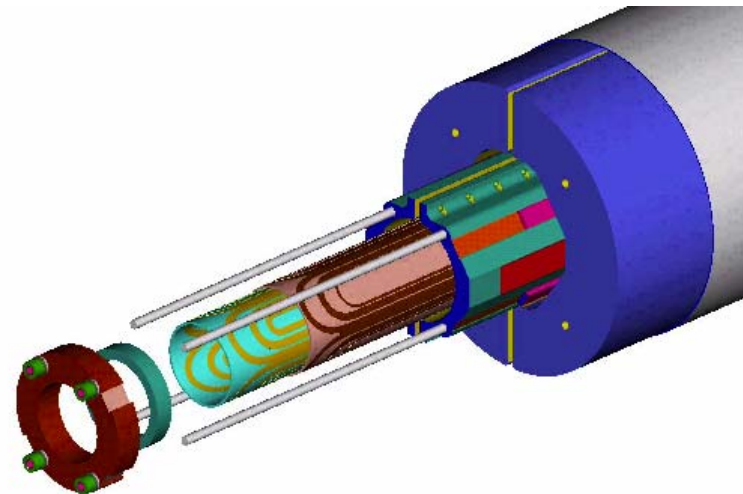
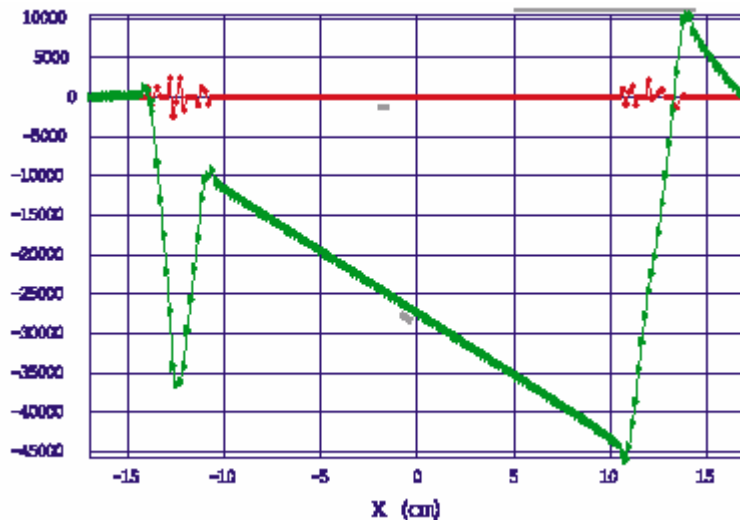
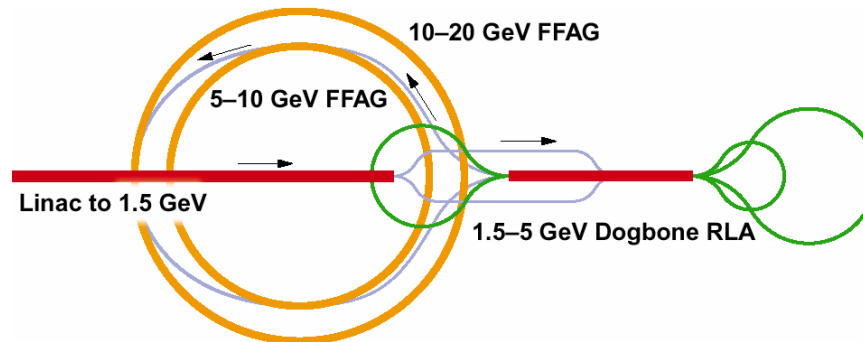
- Two issues (**Blondel**)

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



# Acceleration

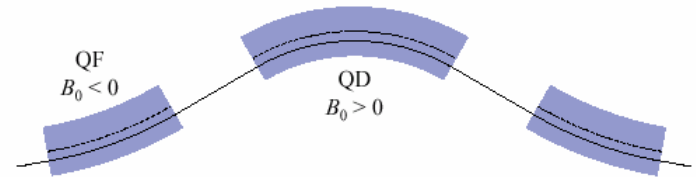
- FFAGs are cost-effective for accelerating muons
  - use eclectic mix of machines to accelerate to 20 GeV
    - linac, dogbone RLA, 2 FFAGs...something for everybody!
  - SC combined-function magnet appears suitable



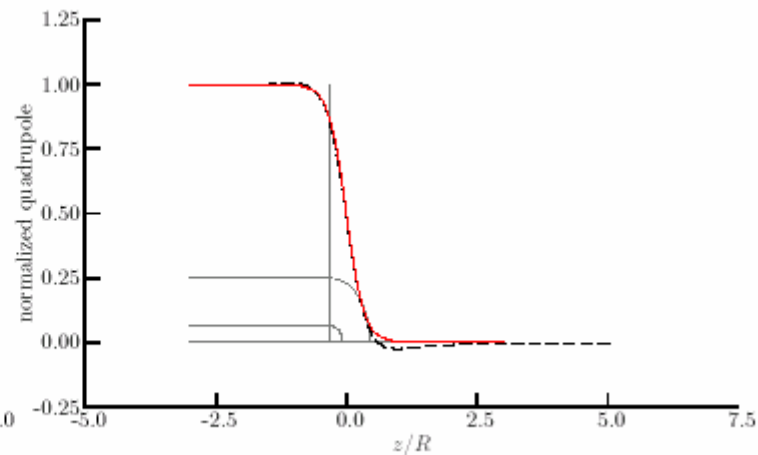
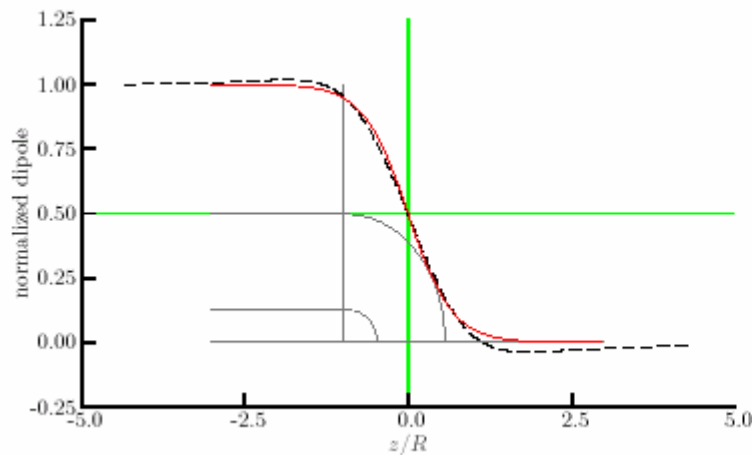
# FFAG Rings

- 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

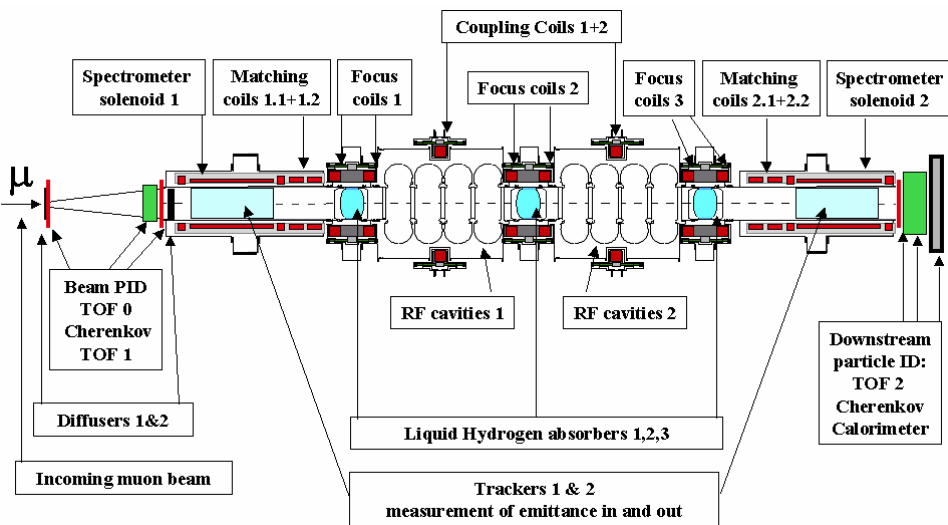
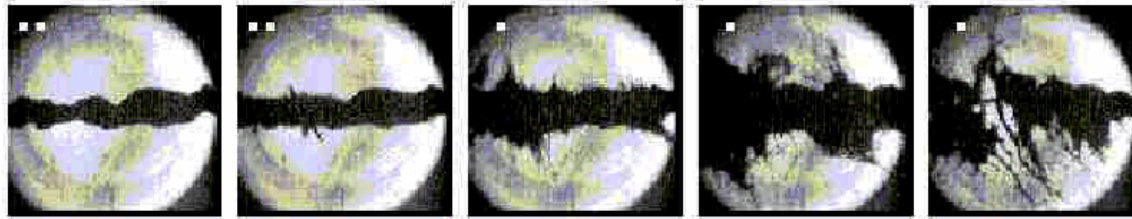
- There are scientific benefits to a higher energy Beta Beam facility than can be provided at CERN
  - $\gamma_{\max}$  for  ${}^6\text{He}$  at SPS  $\approx 150$ ; twice that is preferred
- Looked RHIC and Tevatron; Tevatron is better

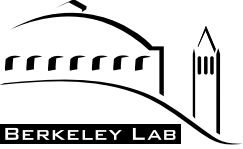
Machine	Proton kinetic energy (GeV)	$\gamma(p)$	$\gamma({}^6\text{He}^{2+})$	$\gamma({}^{18}\text{Ne}^{10+})$
FNAL Booster	8	9.5	3.3	5.4
Main Injector	150	161	64	89
Tevatron	980	1045	349	581
BNL Booster	2	3.1	1.4	1.9
AGS	30	34	11	19
RHIC	250	268	89	149

Machine	Ramp time (s)	${}^6\text{He}^{2+}$ loss (%)	${}^{18}\text{Ne}^{10+}$ 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)

- 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  $^{18}\text{Ne}$  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  $^{18}\text{Ne}$
  - decay losses in acceleration chain and storage ring
  - beam manipulations if both  $^6\text{He}$  and  $^{18}\text{Ne}$  stored simultaneously

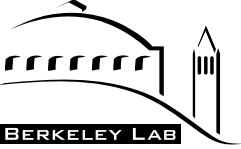
# Cost Savings

- 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)

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

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# The Report



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

## Neutrino Factory and Beta Beam Experiments and Development

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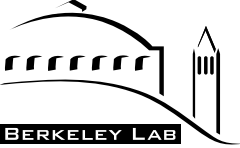
<sup>17</sup>Iowa State University, Ames, IA 50011, USA

(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