Neutrino Factory Accelerator R&D:

Status and Priorities

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Outline

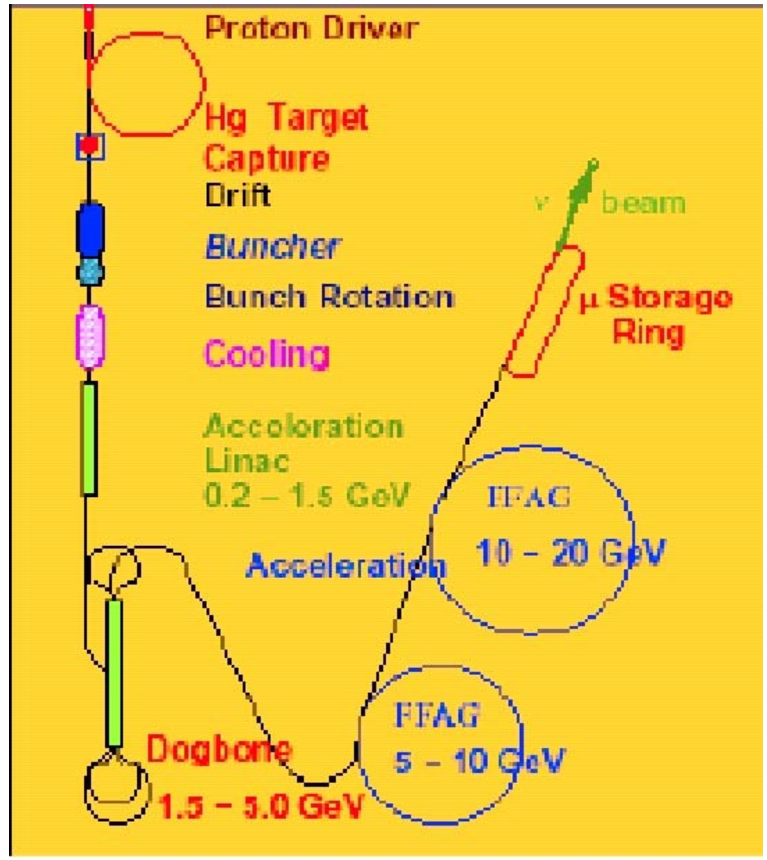
- Introduction
- R&D status
  - simulations
  - component development
  - system tests
- Remaining R&D issues
- Concluding remarks

Introduction

- Construction of a muon-based Neutrino Factory will be a challenging endeavor
  - muons have short lifetime (2.2 μs at rest)
    - all beam manipulations must be done quickly
    - heat load from decay products must be accommodated
  - muons created as a tertiary beam ($p \rightarrow \pi \rightarrow \mu$)
    - large 6D phase space
      - large energy spread, large transverse beam sizes and angles do not lend themselves well to standard accelerator components
    - low intensity ($\Rightarrow$ high-power target)
- These challenges require solutions well beyond those required in "standard" accelerator systems
  - developing and demonstrating suitable solutions requires a substantial R&D effort

Introduction

- Neutrino Factory comprises these sections
  - Proton Driver
    (primary beam on production target)
  - Target and Capture
    (create π's; capture into decay channel)
  - Phase Rotation
    (reduce ΔE of bunch)
  - Cooling
    (reduce transverse emittance of beam)
    ⇒Muon Ionization Cooling Experiment
  - Acceleration
    (130 MeV → 20–50 GeV with RLAs)
  - Storage Ring
    (store muon beam for ≈500 turns; optimize yield with long straight section aimed in desired direction)



Study-IIa Neutrino Factory Layout

- Not an easy project, but no fundamental problems found

Introduction

- To make a Neutrino Factory a worthwhile option for HEP community, we must address these challenges
  - short lifetime puts a premium on very rapid beam conditioning
    - requires high-gradient NCRF cavities for cooling (in B field)
    - requires untested ionization cooling technique
    - requires fast acceleration having large longitudinal and transverse acceptance
  - low production rate requires target that can withstand bombardment by multi-MW proton beam
- R&D effort will enable HEP community to make an informed decision about the desirability of a Neutrino Factory by specifying
  - expected performance
  - technical feasibility/risk
  - approximate cost

Introduction

- R&D mission
  - develop conceptual solutions to produce, condition, accelerate, and store intense muon beams
    - seamlessly integrate these solutions to realize an overall facility concept
    - estimate performance (ν per year)
  - demonstrate technical viability of critical components
    - verify performance of key systems
  - estimate overall cost of Neutrino Factory facility
    - evaluate costs of alternatives sufficiently to identify cost-effective approaches

Introduction

- R&D approaches
  - simulations (€)
    - develop and validate required tools (simulation codes, FEA approaches)
    - carry out design studies for subsystems and overall facility (feasibility studies, international "scoping" study)
  - component development (€€)
    - build and test critical devices in the lab
  - system tests (€€€)
    - validate performance (engineering demonstration) of key systems (target, cooling, ...) to ensure that they behave as predicted
      - we are testing "a" system, not "the" system

Design will continue to evolve, so "calibrating" simulation tools is a main deliverable

Introduction

- Participants
  - program began with individual efforts in different regions
    - has evolved into an international effort
      - NuFact workshops were important mechanism in this evolution!
  - Europe
    - ECFA working groups → BENE
    - CERN Neutrino Factory Working Group → ENG
    - UK Neutrino Factory Collaboration (large overlap of constituency)
  - Japan
    - NuFact-J Working Group
  - US
    - Neutrino Factory and Muon Collider Collaboration

Introduction

- Much of the R&D work to date accomplished by groups in the individual regions
  - there is good sharing of information and success in avoiding unnecessary duplication of effort
- Jointly coordinated programs becoming more common
  - coordination happening at the working level, not dictated "externally" by funding agencies or Lab management
    - such "natural collaboration" is by far the most effective kind
      - driven by science goals, not politics or money
  - examples: MICE, nTOF11, Scoping Study, APS Neutrino Physics Study, FFAG group (EMMA)

Introduction

- In what follows, I will provide an overview of the global Neutrino Factory R&D program
  - this will of necessity be brief, incomplete, and slightly outdated
    - but, I am confident that this week's NuFact meeting has made up for any deficiencies
- I will also share my views on what other work will be needed to arrive at the stage of being ready to produce a CDR and cost estimate for a Neutrino Factory

R&D Status: Simulations

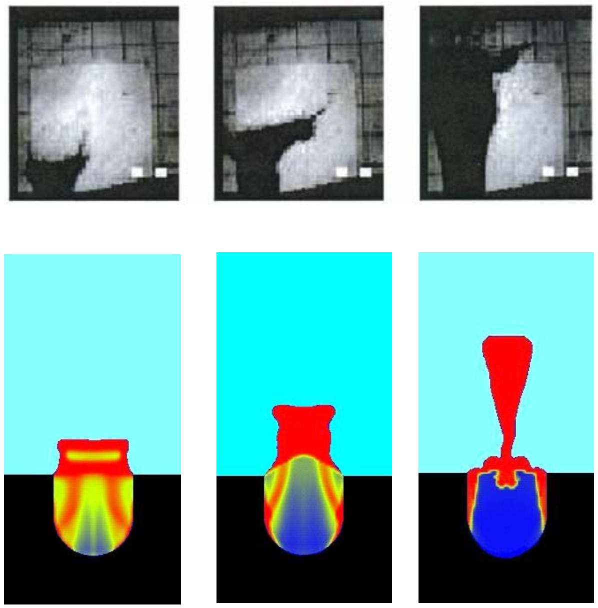
- Simulations
  - four Neutrino Factory feasibility studies have been carried out (2 in US, 1 in Japan, 1 in Europe)
  - US Study 2 updated ("2a") as part of APS Neutrino Physics Study
    - maintained performance compared with Study 2
    - provided possibility for keeping both muon signs simultaneously
    - reduced hardware cost estimate, w/o detector (⇒ on right track!)

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

  - facility design effort will continue with International Scoping Study
    - followed, starting in ≈2007, by "World Design Study" of optimized facility

R&D Status: Simulations

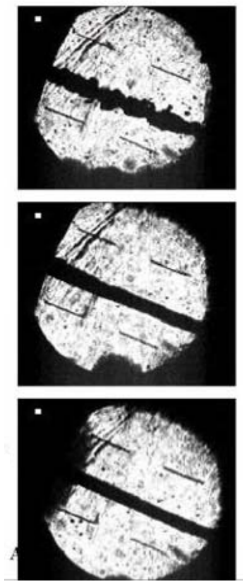
— simulations (Samulyak) of Hg-jet target reaching high levels of sophistication



0 T

10 T

20 T



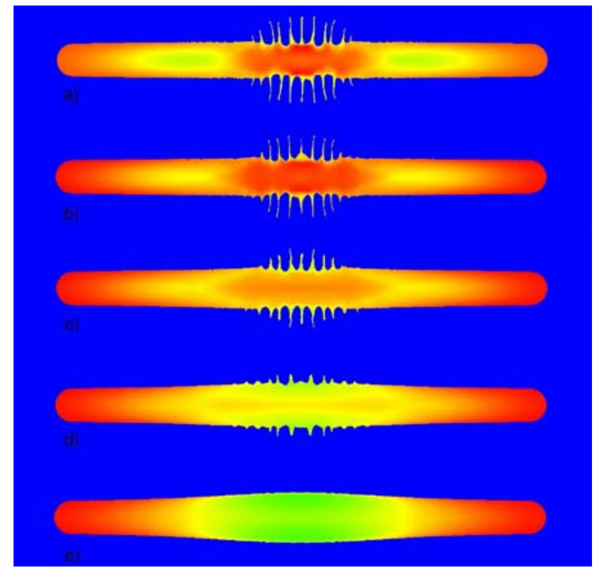
0 T

2 T

4 T

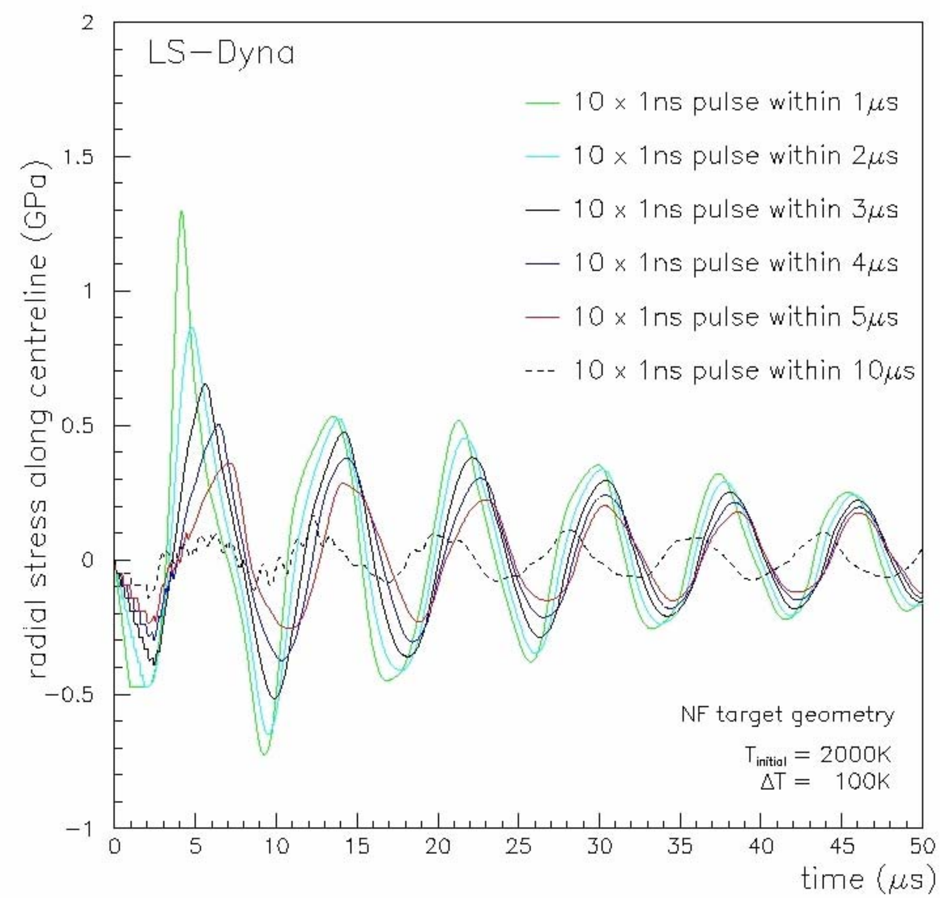
6 T

10 T



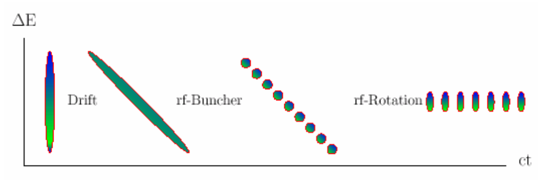
R&D Status: Simulations

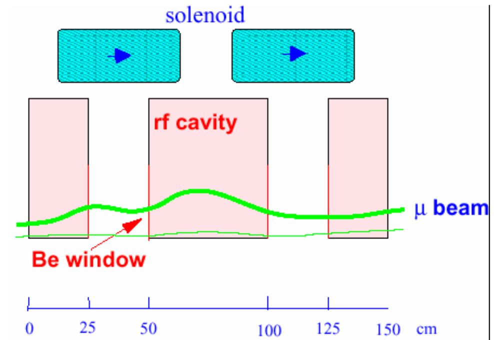
— solid-target (Skoro) simulations looking at time dependence of beam heating



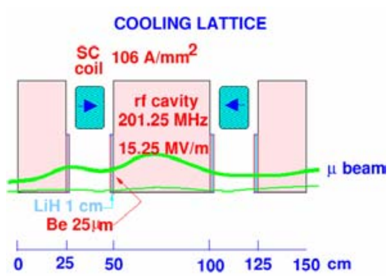
R&D Status: Simulations

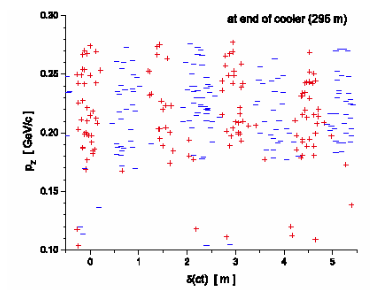
— Study 2a developed RF bunching and phase rotation system



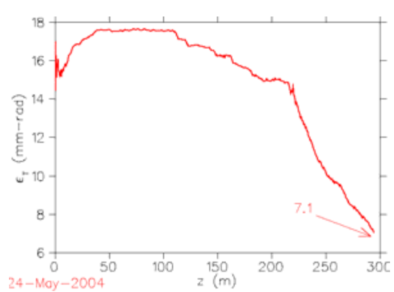


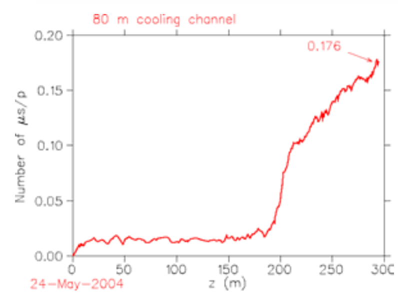
— and simplified cooling channel





Both signs transmitted simultaneously



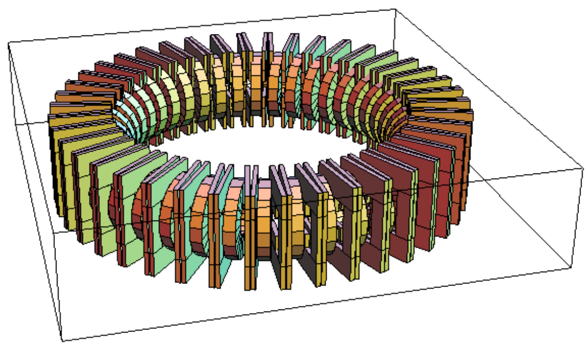


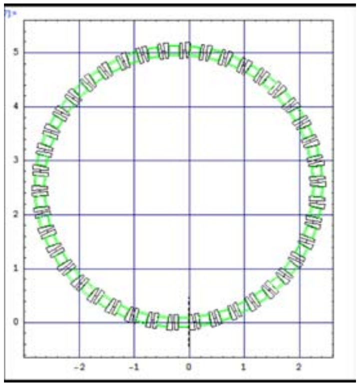
Berkeley Lab

R&D Status: Simulations

Muon Collaboration

- developed non-scaling FFAG acceleration scheme (Europe/US)
  - plans to build and test an electron model are being developed

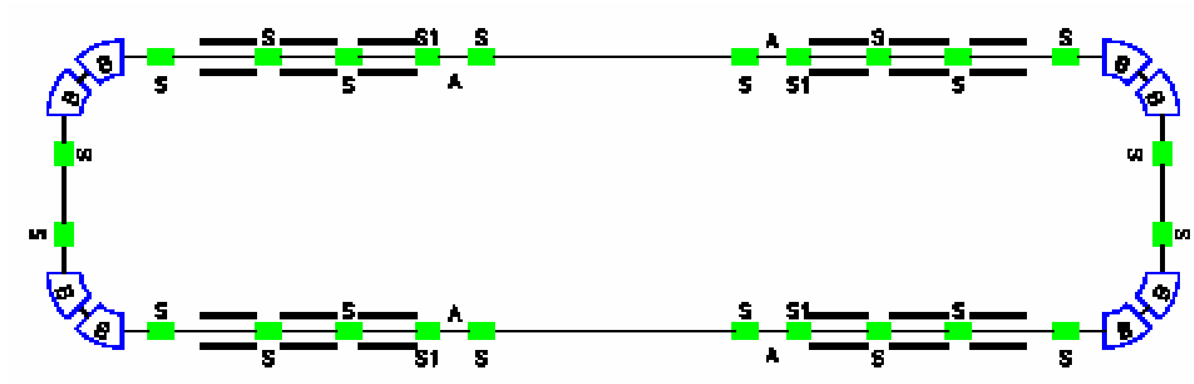




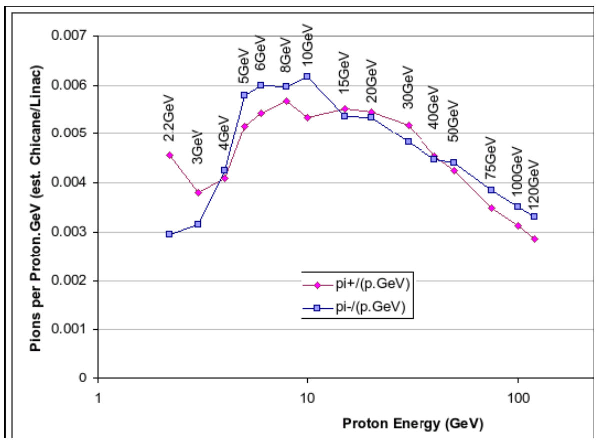
- developed scaling FFAG scheme (Japan)

R&D Status: Simulations

— studying cooling ring designs (US/UK)



— examining optimization of proton driver energy with MARS (UK)



- HARP (CERN) + MIPP (Fermilab) testing these predictions

R&D Status: Component Development

- Component R&D
  - RF cavities are a key technology
    - need 201 MHz NCRF cavities for cooling channel (in 2 T field)
    - use 201 MHz SCRF cavities for acceleration
    - SCRF (700 MHz) planned for proton driver in SPL scenario

201 MHz NCRF

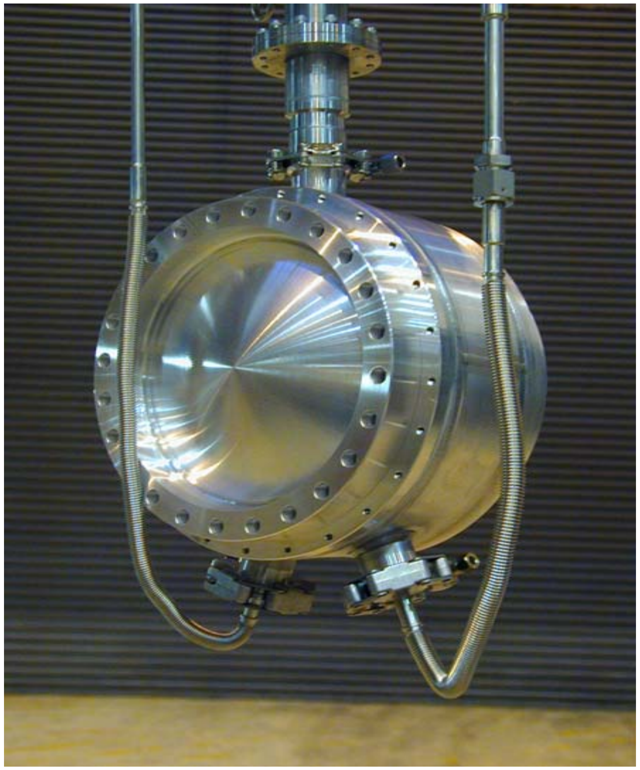
201 MHz SCRF

700 MHz SCRF

R&D Status: Component Development

— LH_2 absorbers are optimal choice for cooling channel

- test program (including safety issues) carried out in Japan + US



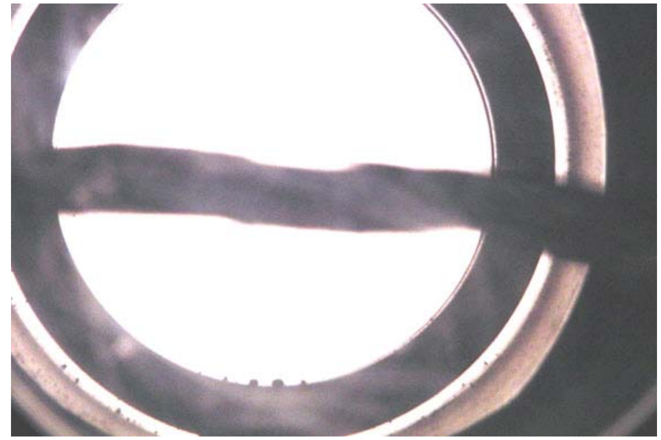
Prototype LH_2 absorber

Test cryostat at MTA

R&D Status: Component Development

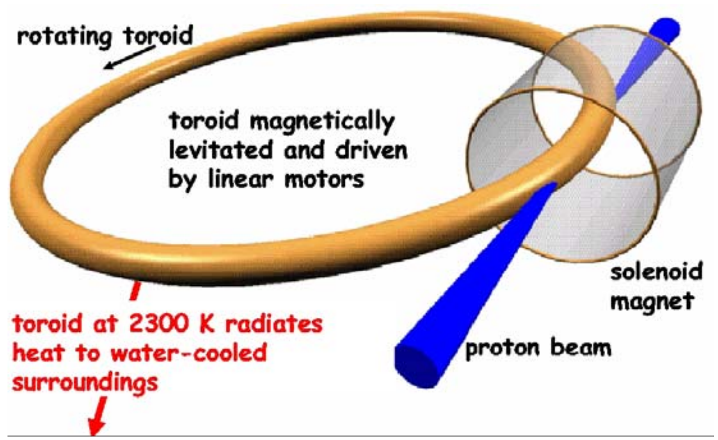
— Hg-jet target development is under way

Test apparatus



Mercury jet…on a good day

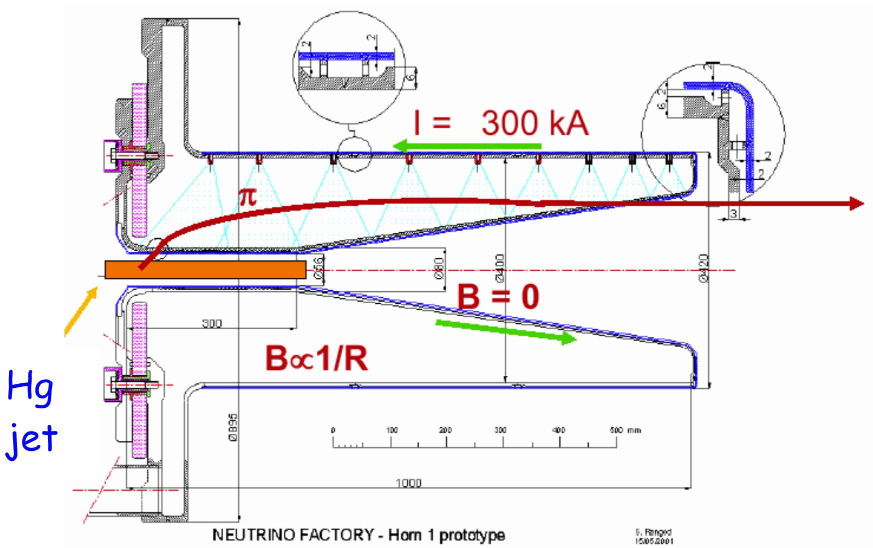
— solid target concepts also being explored

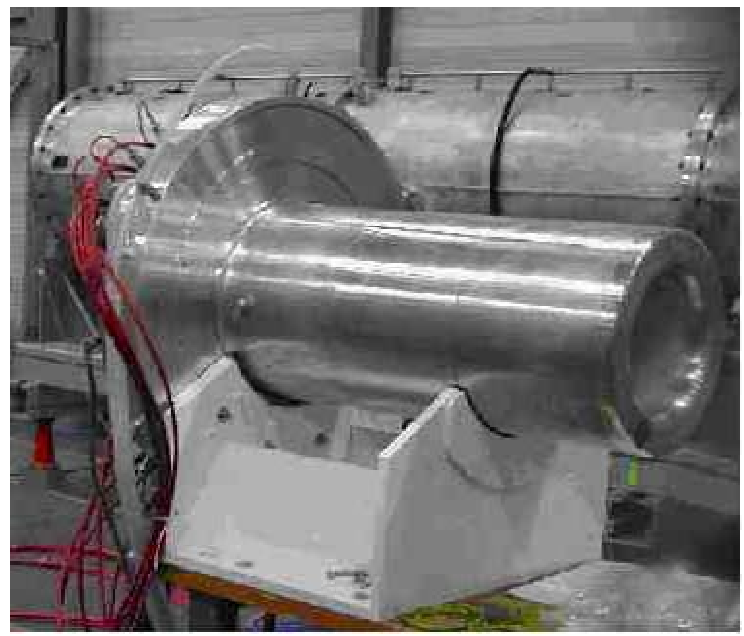


R&D Status: Component Development

— horn development began at CERN, but no longer active

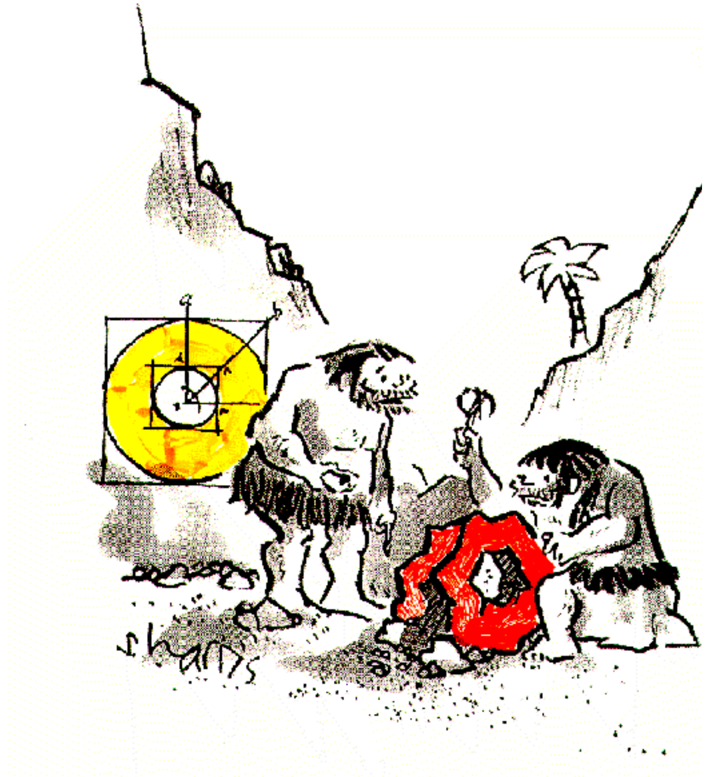
- hope to reinvigorate this work at Orsay (BENE activity)
- simple and relatively inexpensive but focuses only one sign muon at a time
  - issues: lifetime (rad hardness, mechanical strength), reliability





R&D Status: System Tests

- System tests
  - needed to confirm performance of integrated systems
    - demonstrate technology, not just physics



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

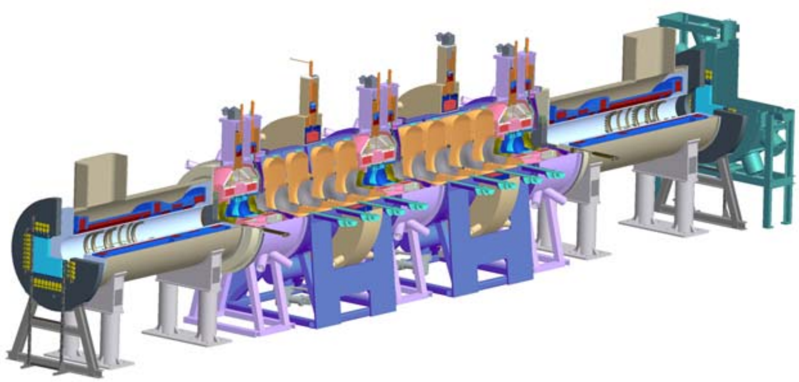
R&D Status: System Tests

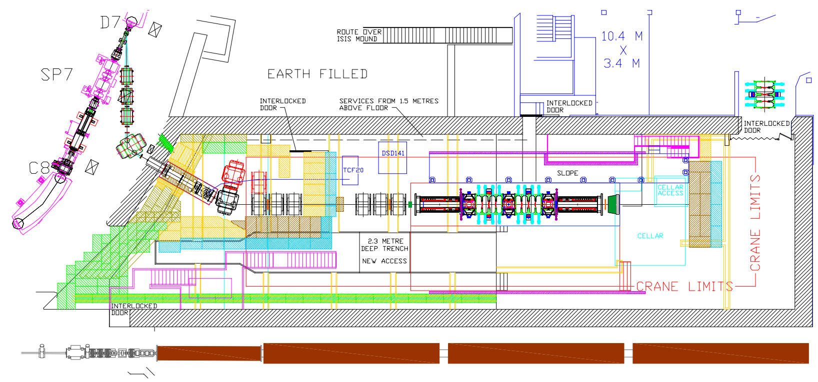
— such experiments are relatively expensive

- be selective: pick cases where it is most necessary
- examples:
  - ionization cooling (MICE)
  - Hg-jet target (nTOF11)
  - scaling FFAG (PRISM) [to be used for science, not just a demo]
  - proton driver front end (e.g., FETS)
  - EMMA [non-scaling FFAG electron model; proposed, not under way]
- carrying out experiments as an international venture has virtue of being an excellent team-building exercise

R&D Status: System Tests (MICE)

- MICE
  - goals
    - *to design, engineer and build a section of cooling channel capable of giving the desired performance for a Neutrino Factory*
    - *to place this apparatus in a muon beam and measure its performance in various modes of operation and beam conditions*





R&D Status: System Tests (MICE)

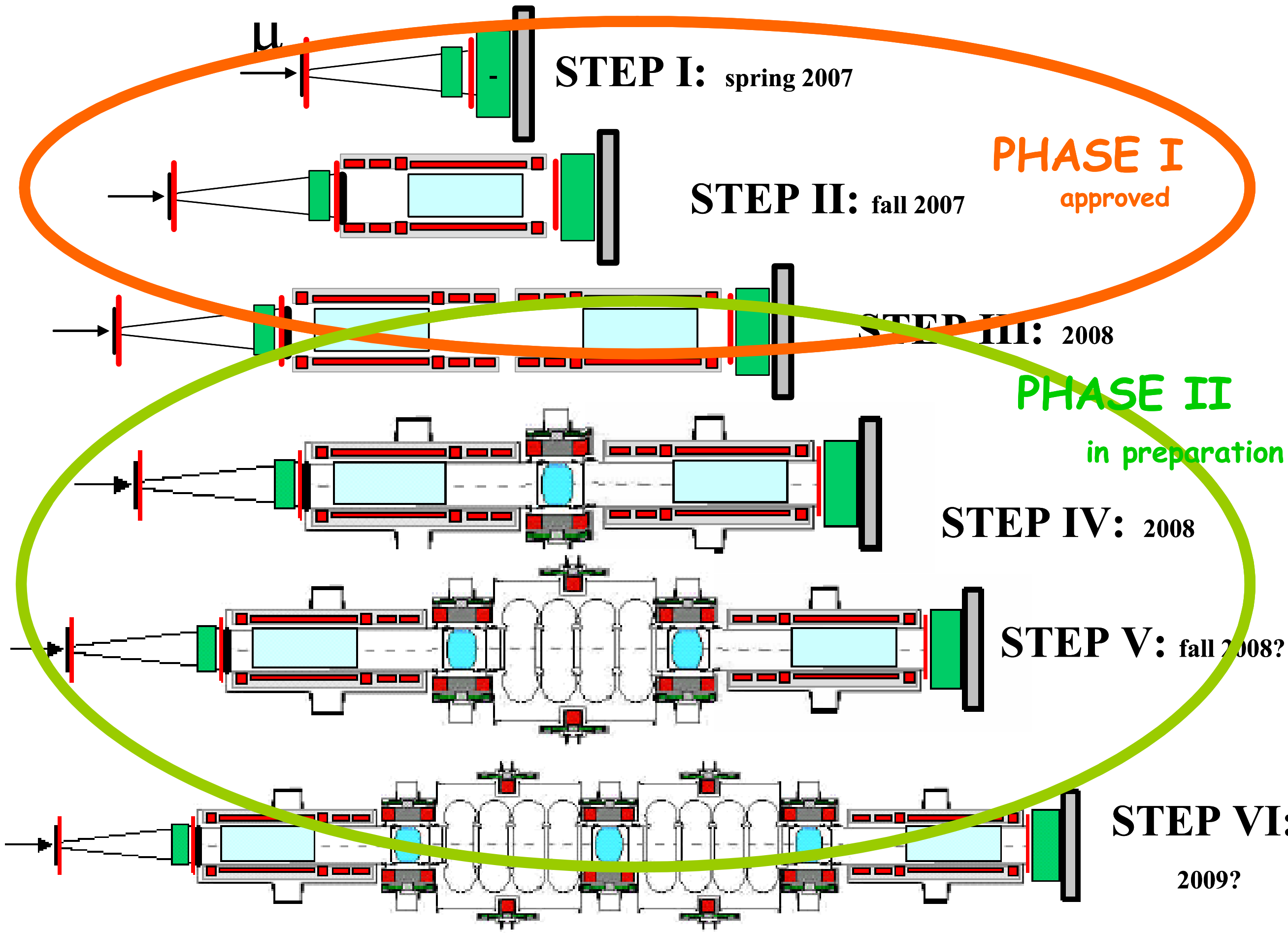
- Main challenges of MICE
  - operating high-gradient RF cavities in solenoidal field and with field terminations (windows or grids)
  - operating LH_2 absorbers with very thin windows and consistent with safety regulations
  - integration of cooling channel components while maintaining operational functionality
- Another challenge
  - for cost reasons, we use only a single cell of a cooling channel

    $\Rightarrow$emittance reduction will be small in absolute terms ($\mathcal{O}$(10%))

    - wish to measure emittance reduction at level of 10^{-3}
- Technical solutions build upon component R&D activities already under way outside of MICE

R&D Status: System Tests (MICE)

– MICE cooling channel will be built up in stages to ensure complete understanding and control of systematic errors



R&D Status: System Tests (MICE)

- MICE status
  - proposal submitted in January, 2003
    - international review held February, 2003 (recommended approval)
    - scientific approval from RAL in October, 2003
  - absorber system concept passed preliminary safety review by international review panel in December, 2003
  - passed Gateway 2-3 review in December 2004
    - Phase I UK funds (£9.7M) now in hand
    - other Phase I contributions (Japan, US, Switzerland) also available now
  - spokesperson: A. Blondel (Geneva)
  - first beam April, 2007

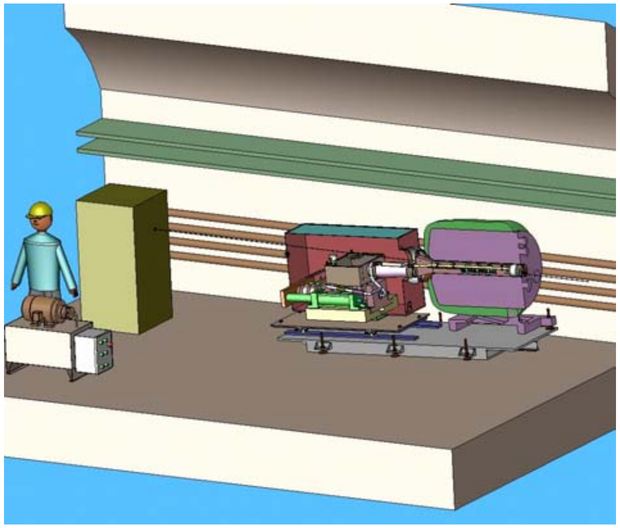
R&D Status: System Tests (nTOF11)

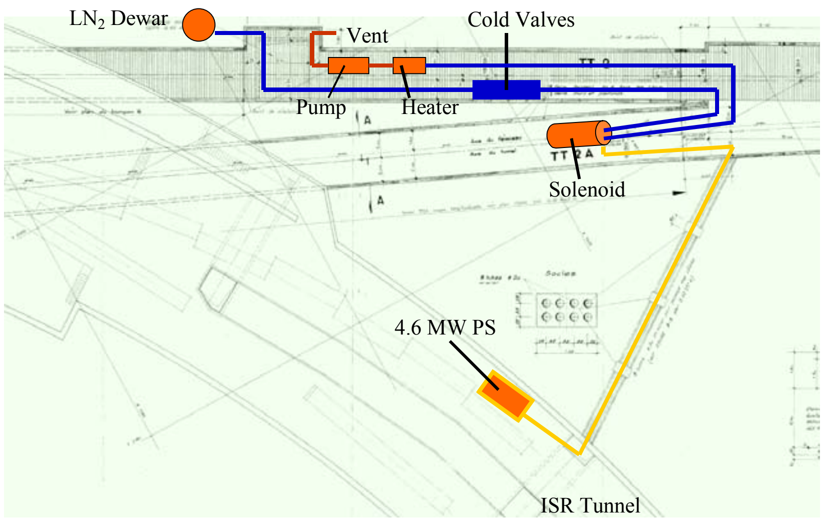
- nTOF11 target experiment
  - studied Hg jet with beam and no magnet (E951 at BNL)
  - studied Hg jet with magnetic field and no beam (CERN/Grenoble)
  - need to put entire system together
    - identified CERN as optimal location for test (BNL facility no longer available)
- experiment proposed by international collaboration (April, 2004)
  - BNL, CERN, KEK, ORNL, Princeton, RAL
  - spokespersons: H. Kirk (BNL), K. McDonald (Princeton)
- approval granted April, 2005
  - first beam April 2007

R&D Status: System Tests (nTOF11)

— **experiment parameters**

Beam energy (GeV)	24
Max. protons per 2 μs spill (Tp)	28
Hg jet diameter (mm)	10
Peak energy deposition (J/g)	180
Jet angle from solenoid axis (mrad)	100
Beam angle from solenoid axis (mrad)	67
Hg jet velocity (m/s)	20

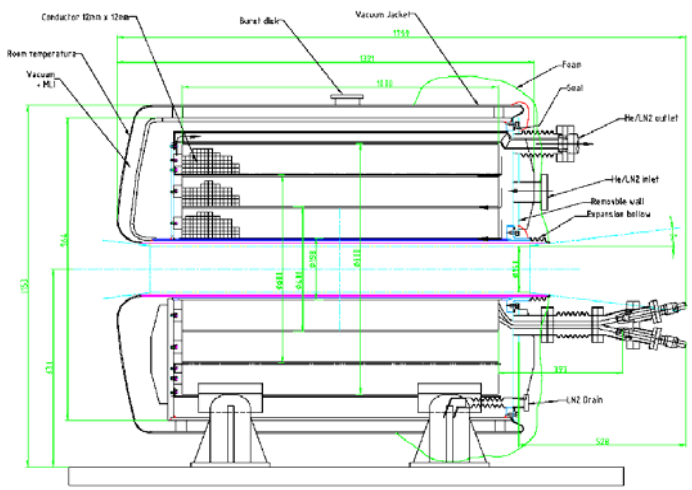




R&D Status: System Tests (nTOF11)

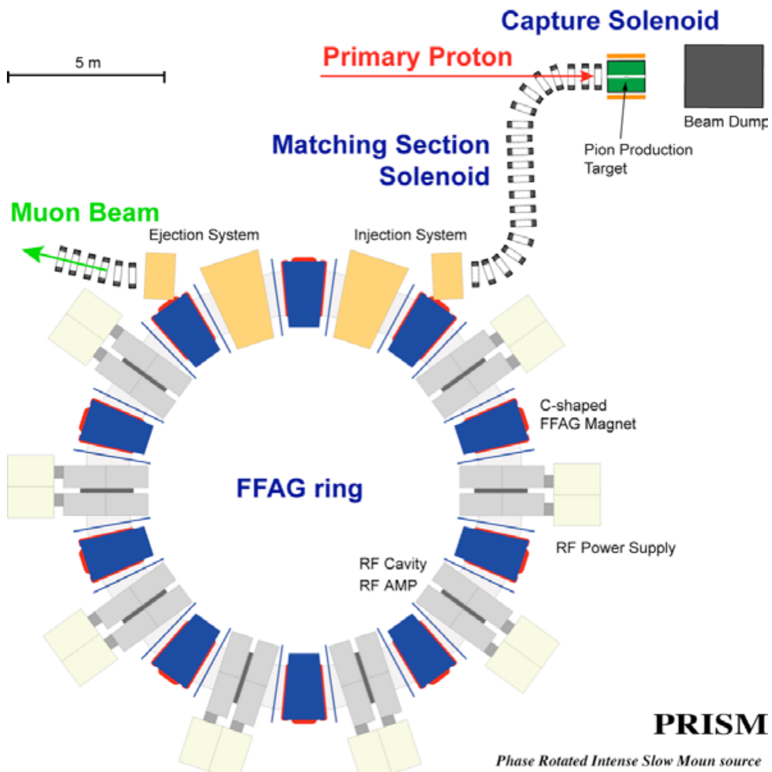
Muon Collaboration

— 15-T magnet fabrication nearly complete



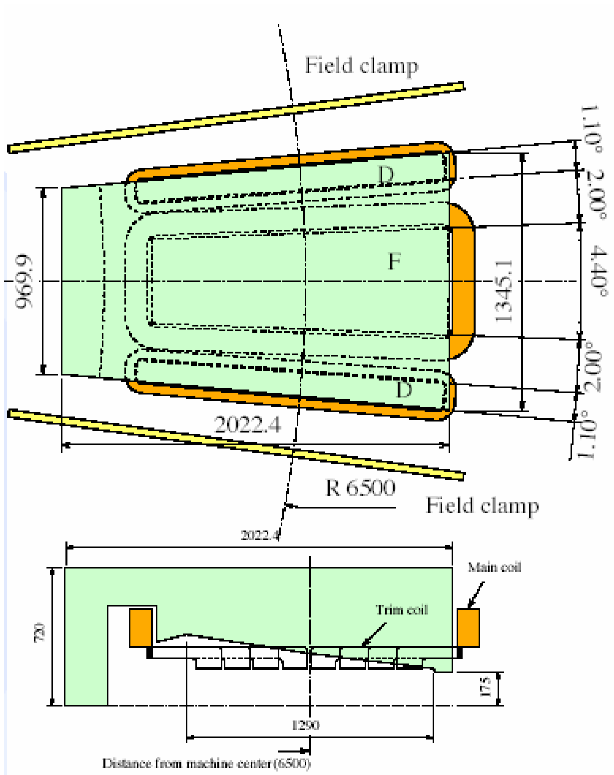
R&D Status: System Tests (PRISM)

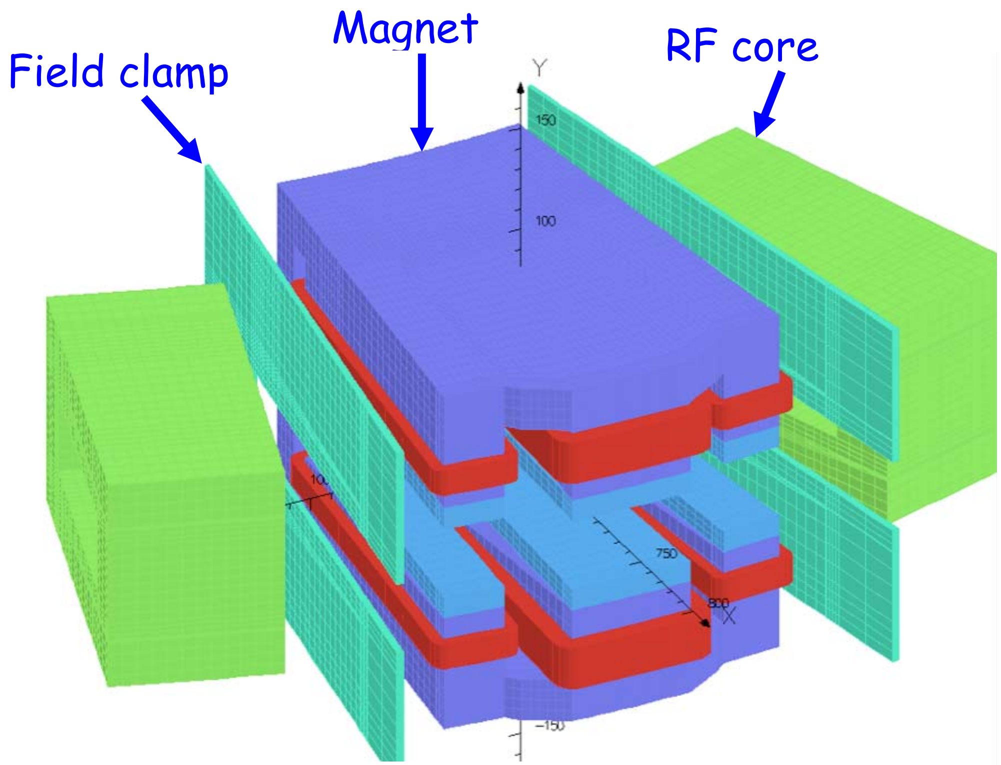
- PRISM (Osaka) will demonstrate scaling FFAG system with muon beam
  - construction completed in 2009
  - first phase (ring itself) funded (complete 2007)



R&D Status: System Tests (PRISM)

- PRISM magnet (DFD triplet) design completed and out for bid
  - C magnet, aperture 100 cm (H) x 30 cm (V)
    - field gradient provided by pole profile, with trim coils for adjustment





3D Tosca model

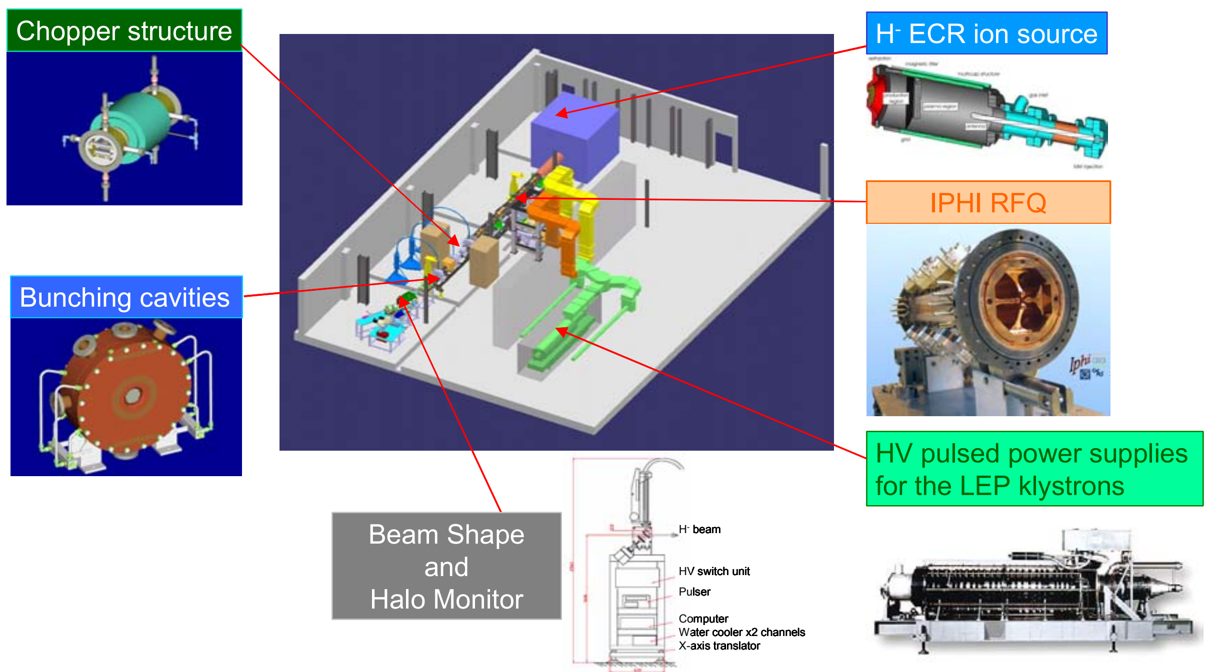
R&D Status: System Tests (PRISM)

- all 40 D coils for PRISM are completed
  - plus 6 of 20 F coils

R&D Status: System Tests (FETS)

— 3 MeV front-end test stand (FETS) being constructed at CERN under CARE auspices

- many interested "customers" (source of neutrons, neutrinos, radioactive ions, driver for nuclear waste transmutation, …)
  - must try to exploit such synergies where possible
- similar proton driver work ongoing at RAL, J-PARC, Fermilab



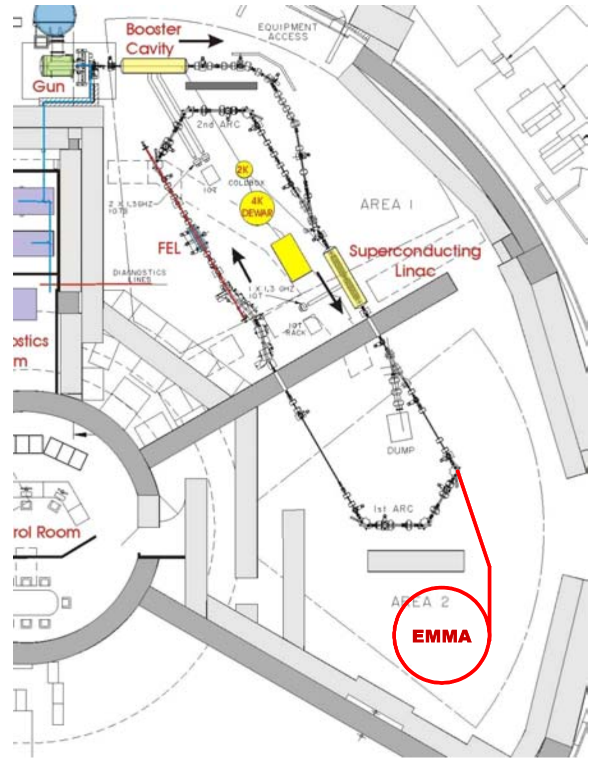
R&D Status: System Tests (FETS)

– EMMA plans are taking shape

- scaled version of muon accelerator (pertinent to proton or heavy ion acceleration also)

Beam	electrons
E (MeV)	10–20
Lattice	42 cells, doublet
Cell length (cm)	37
Circumference (m)	~16
RF distribution	every other cell
f_{RF} (GHz)	1.3[a]
Magnet aperture (cm)	~ 5 x 2.5

[a] TESLA frequency



Remaining R&D Issues

- This section must perforce be rather subjective
  - opinions expressed are my personal views
- In general, I think the right list of topics is being studied
  - little evidence of unnecessary duplication of effort (but need for multiple FETS efforts as R&D has not been well articulated)
  - no evidence of incorrect topics being studied
- Priorities
  - complete current program of component R&D
  - bring system studies to fruition (MICE, nTOF11, PRISM, FETS et al., EMMA)
  - embark on Scoping Study (complete by ≈NuFact06)
    - goal is to narrow the range of options, ideally to a single choice for most items, in preparation for WDS
    - will include both machine and detector in optimization process

Remaining R&D Issues

- In order to optimize the design and narrow the range of options, cost models are required
  - more engineering is needed than has been the case heretofore
    - this may imply additional costs, but it is very important
- There are a few areas that have not received adequate attention
  - design of the muon storage ring and its magnets
  - development of an optimized acceleration scheme
  - evaluation of alternative absorber materials
  - test of solid target *in realistic Neutrino Factory configuration*
- As part of the Scoping Study, a number of decisions must be made
  - ideally, there will be an international consensus on these

Remaining R&D Issues

- Decisions needed
  - solid vs. liquid target
  - optimal proton driver parameters (*E*, pulse structure, rep. rate, beam power)
    - should baseline be 1, 2, 4,... MW?
  - how to migrate from Superbeam driver/target configuration to Neutrino Factory configuration
  - optimal amount of cooling *vs*. acceptance of acceleration system (cost issue)
  - desirability of simultaneous μ^-, μ^+ use
  - desirability of (simultaneous) multiple baselines for storage ring
  - required maximum muon beam energy
  - optimization of neutrino intensity vs. detector size

Concluding Remarks

- Neutrino Factory design progress has been excellent in recent years
  - estimated performance improved and estimated cost decreased
- Thus far, we have worked together well as an international community
  - we must continue this cooperation (including that between accelerator and particle physicists)
    - for technical, financial, and political reasons
- Goal of upcoming Scoping Study is to narrow the options
  - converging on specific choices is always hard
  - I believe our foundations are strong enough to accomplish this as a team
- We do have a common overall goal
  - to get some Lab to identify the Neutrino Factory as its next project

If we are to succeed, this must remain our focus!