Identification of Potential Synergies in the US-UK R&D Program

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Proton Accelerators for Science and Innovation Workshop-Fermilab
January 14, 2012

Introduction

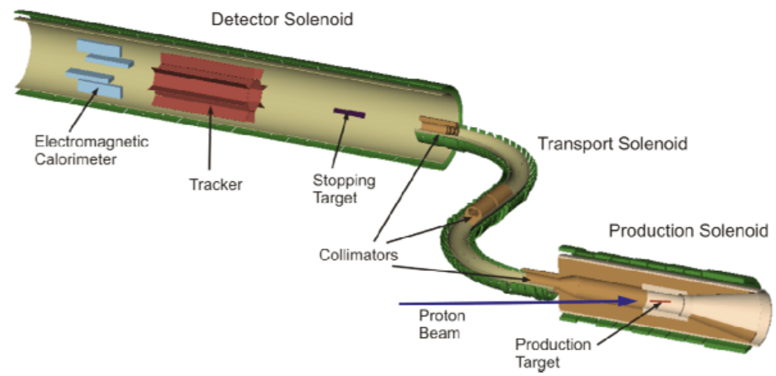
- Both US and UK accelerator physicists are presently engaged in efforts to develop intense muon beams for particle physics experiments
  - examples
    - next-generation mu2e and *g*-2 experiments
    - Neutrino Factory and Muon Collider (NF and MC)
      - these have many common issues and can generally be lumped together

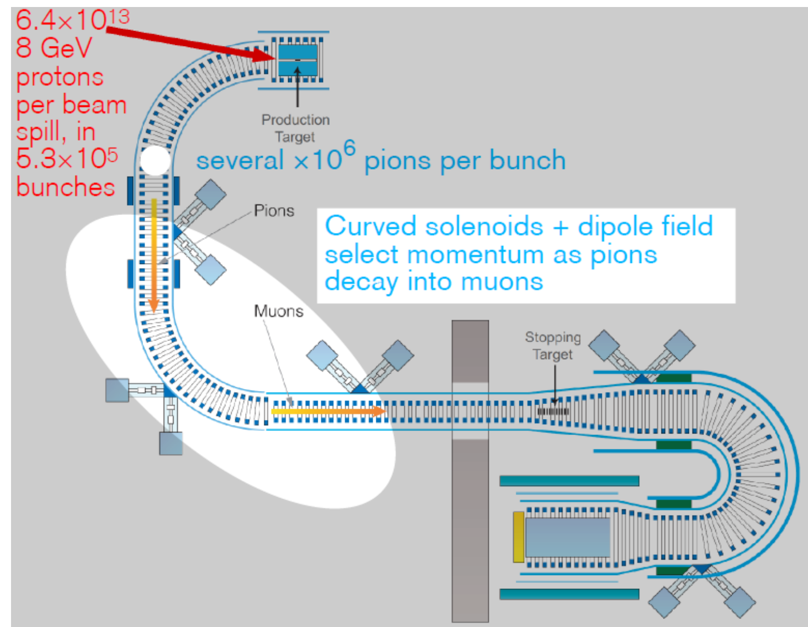
- Both design work (incl. simulations) and component R&D are involved

- In the NF and MC case, there is already close collaboration
  - US: under auspices of Muon Accelerator Program (MAP), led by Fermilab
  - UK: as part of MICE and UKNF activities

LE Muon Technical Challenges

- **Two main experimental goals**
  - **$\mu \rightarrow e$ and $g - 2$**
    - **plans in US (Fermilab) and in Japan**
- **Challenges**
  - **fabrication of long curved solenoids**
  - **control of backgrounds**
  - **suppression of out-of-time particles**
    - **at 10^{-9} or 10^{-10} level**
- **VLENF**
  - **large acceptance ring design**
  - **develop *and test* instrumentation**
  - **detector design optimization**
    - **lower *E* than NF; magnetized**
    - **continue IDS-NF collaboration**



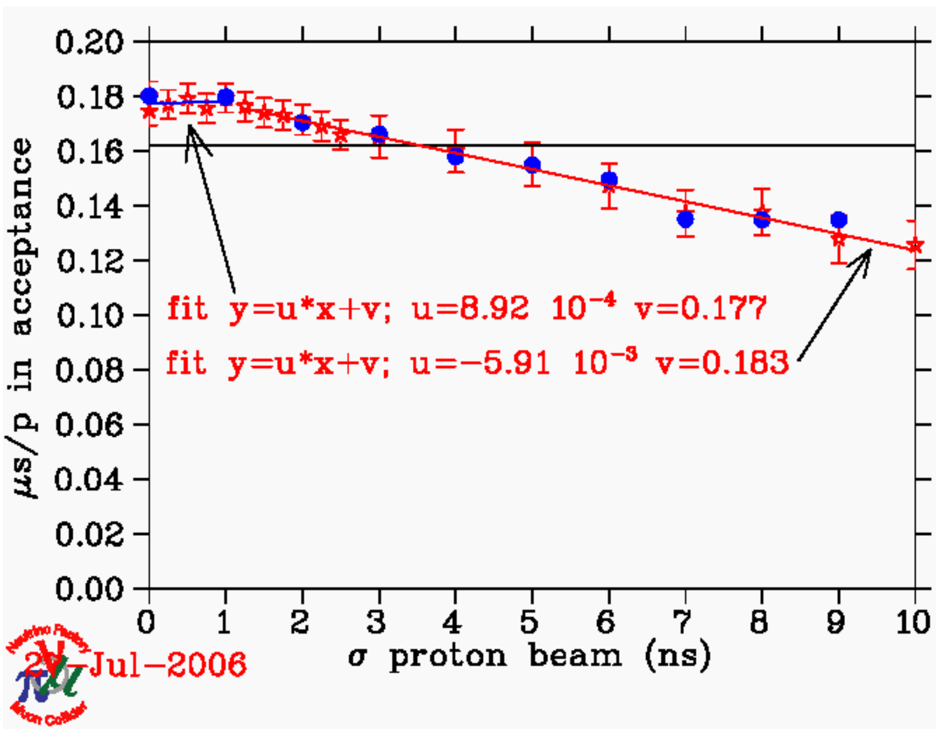


NF Technical Challenges (1)

- **Muons created as tertiary beam ($p \rightarrow \pi \rightarrow \mu$)**
  - **low production rate**
    - **need target that can tolerate multi-MW beam**
  - **large energy spread and transverse phase space**
    - **need emittance cooling**
    - **high-acceptance acceleration system and decay ring**
- **Muons have short lifetime (2.2 μs at rest)**
  - **puts premium on rapid beam manipulations**
    - **high-gradient RF cavities (in magnetic field for cooling)**
    - **presently untested ionization cooling technique**
    - **fast acceleration system**

NF Technical Challenges (2)

- **Proton beam parameters**
  - **desired proton intensity for Neutrino Factory is 4 MW**
    - **e.g., 3.1 x 10^{15} p/s at 8 GeV or 6.2 x 10^{13} p/pulse at 50 Hz**
  - **desired rms bunch length is 1-3 ns to minimize intensity loss**
    - **not easily done at high intensity and moderate energy**

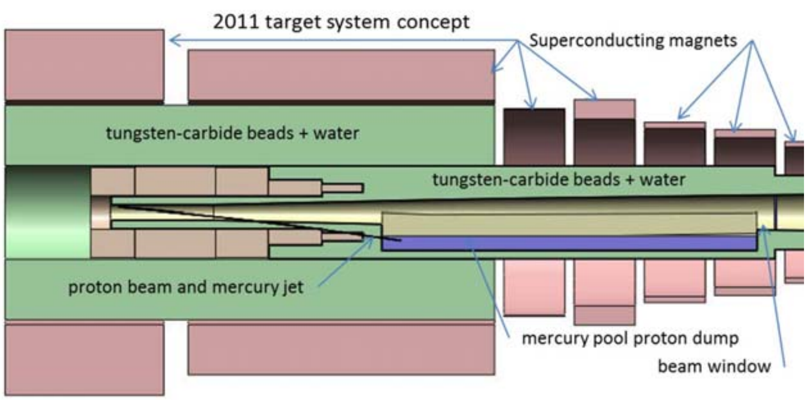


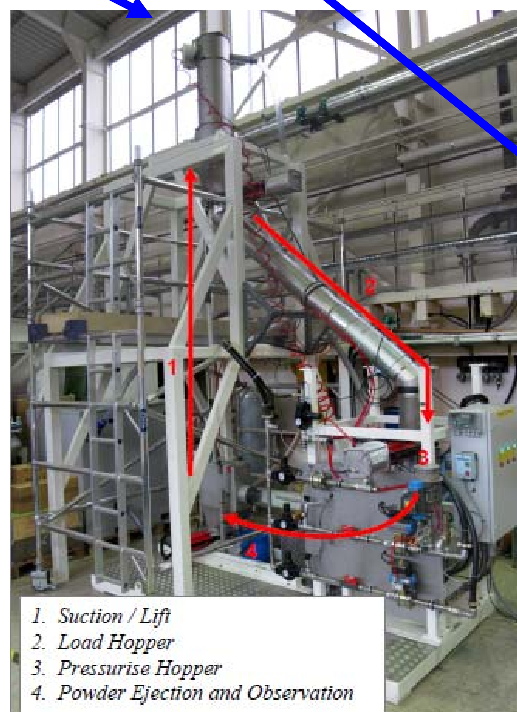
Difficult requirement at low beam energy (5-10 GeV)

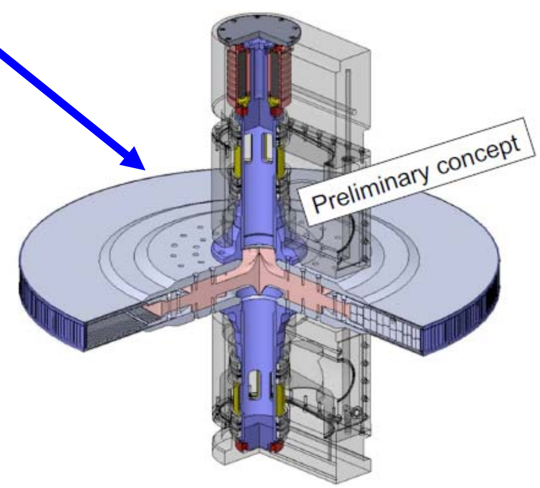
NF Technical Challenges (3)

- **Target**
  - **favored target concept based on Hg jet in 20-T solenoid**
    - **jet velocity of ~20 m/s establishes "new" target each beam pulse**
      - **magnet shielding is daunting, but appears manageable**
  - **alternative approaches (powder or solid targets) also being pursued within EUROnu (both are UK efforts)**
    - **liq. Ga?**

Hg-jet target
(MERIT)

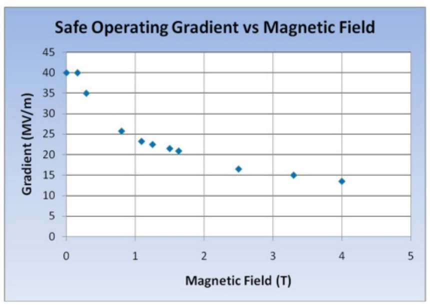


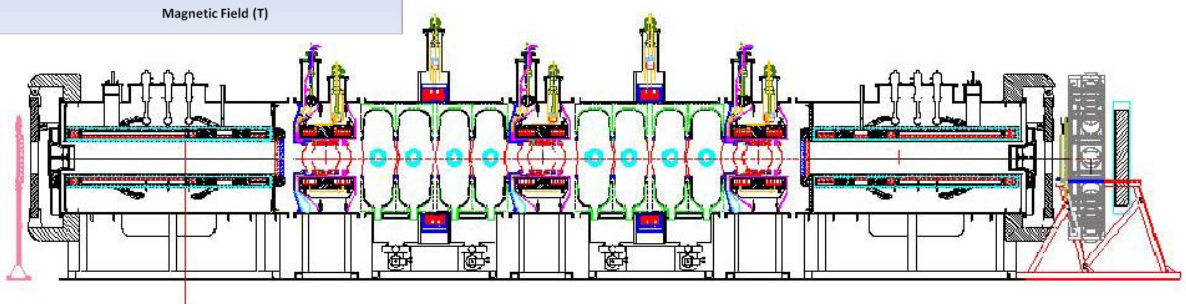


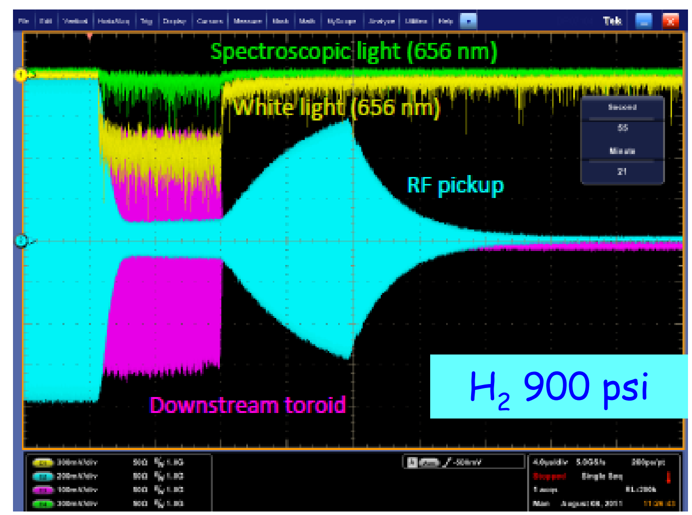


NF Technical Challenges (4)

- **Normal conducting RF in magnetic field**
  - cooling channel requires this
    - 805-MHz experiments indicate substantial degradation of gradient in such conditions
      - initial 201-MHz tests show similar behavior (coupler issue?)
    - gas-filled cavities avoid performance degradation in magnetic field
      - effects of intense ionizing radiation traversing gas now under study
        - first indications: severe beam loading but no sign of breakdown





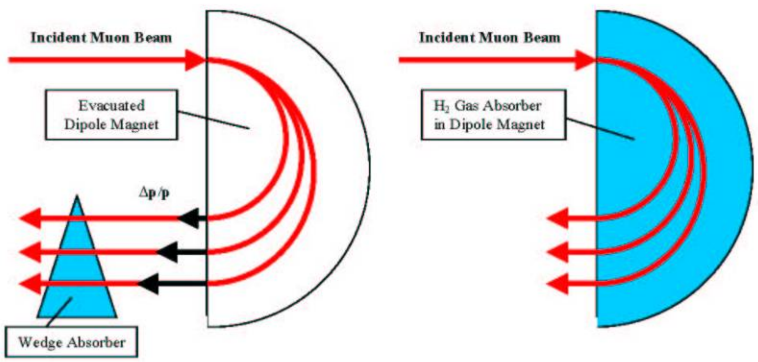


MC Technical Challenges

- In addition to NF challenges, MC has a few of its own
- Longitudinal cooling is required in addition to the transverse cooling used for the NF
  - actual designs for Guggenheim, helical cooling, FOFO snake, etc. must be developed
- Final transverse cooling to very low emittance (~25 μm) required
  - present schemes demand extreme parameters
    - low energy, long bunches, very high solenoidal fields, thin absorbers
      - none of these are easy
- Very rapid acceleration up to energies of a few TeV

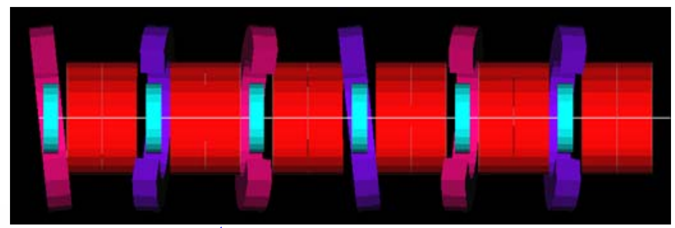
6D Cooling

- **For MC, need 6D cooling (emittance exchange)**
  - **increase energy loss for high-energy compared with low-energy muons**
    - **put wedge-shaped absorber in dispersive region**
    - **use extra path length in continuous absorber**

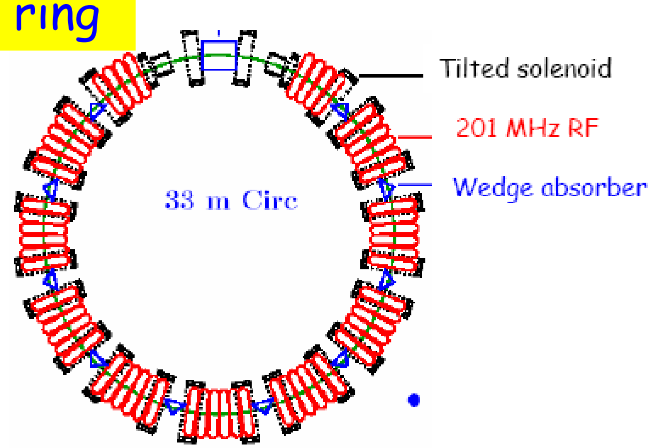


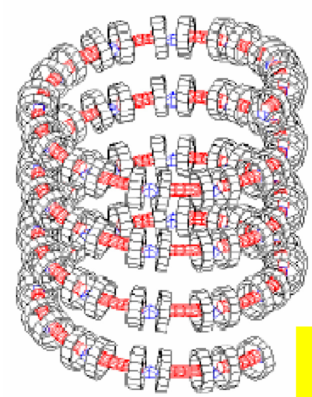
Muons, Inc.

FOFO Snake



Cooling ring





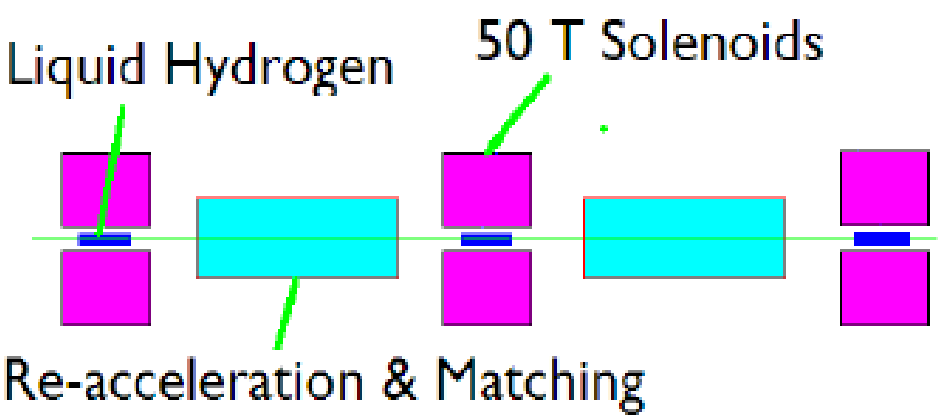
Single pass; avoids injection/extraction issues

"Guggenheim" channel

Final Cooling

- **Final cooling to 25 μm emittance requires strong solenoids**
  - not exactly a catalog item ⇒ R&D effort
  - 40-50 T is not a hard edge, but "more is better"

- **45 T hybrid device exists at NHMFL**
  - very high power device
  - exploring use of HTS for this task
    - most likely technology to work

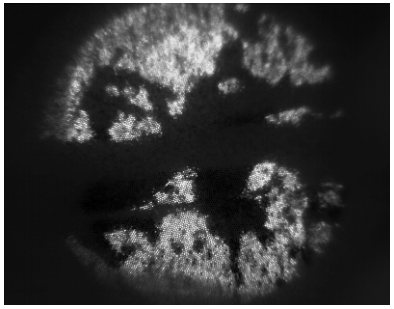


R&D Activities

- To transform challenges to opportunities, worldwide R&D efforts are under way
  - U.S. contributions to these studies via MAP
  - UK contributions via UKNF
  - coordination under IDS-NF auspices
  - main items:
    - target
    - RF (MuCool)
    - cooling (MICE)

Targetry R&D

- Target for 4 MW proton beam is a real challenge
  - MERIT system test (2007) was proof-of-principle test of Hg jet target in 15 T solenoid
    - carried out by collaboration of BNL, CERN, and RAL
    - looked at disruption length, filament velocity, production fall-off due to jet disruption ("pump-probe")
  - concluded that power handling of target is adequate
    - disruption length of 28 cm ⇒ 70 Hz rep. rate at 20 m/s
    - 115 kJ per pulse x 70 Hz gives 8 MW of beam power
      - 4 MW design value should be achievable
    - no damage to containment vessel from 60 m/s filaments

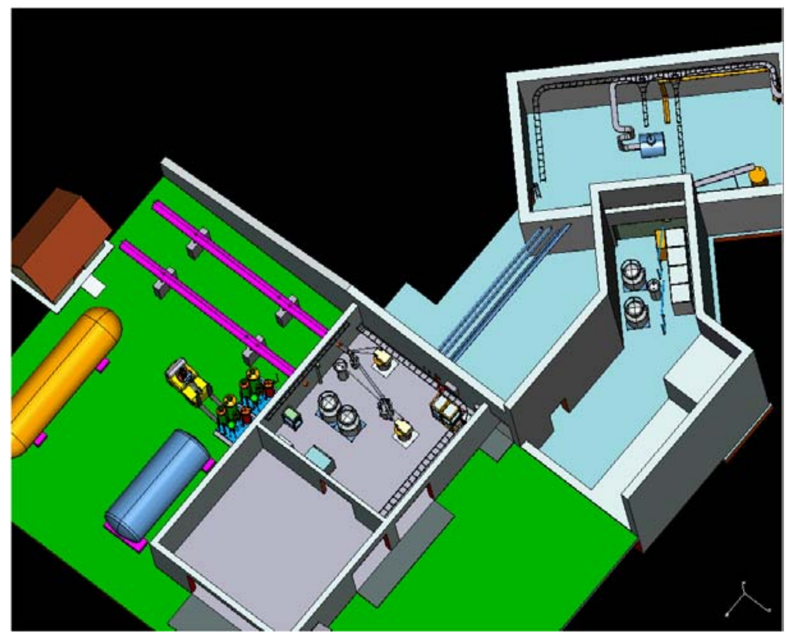


- Issues to pursue (none require beam)
  - splash mitigation in Hg beam dump (from both beam and spent jet)
  - thermal and radiation environment of nearby magnets
  - other liquid metals (Pb-Bi eutectic; Ga)

MERIT serves as a satisfactory proof-of-principle of Hg-jet concept

MuCool R&D

- **MuCool program does R&D on cooling channel components**
  - RF cavities, absorbers
    - focus in recent years has been RF
- **Make use of MuCool Test Area (MTA) at Fermilab**
  - located at end of 400 MeV linac and shielded for beam tests
    - first beam arrived February 28, 2011



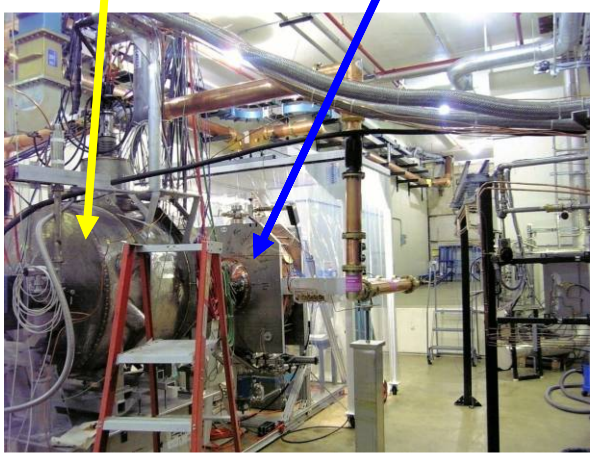
MuCool Results

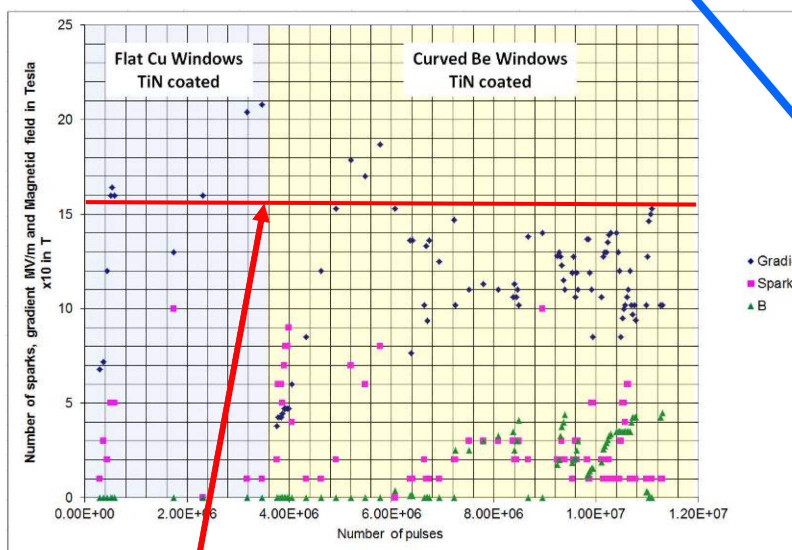
- **201-MHz cavity shows degradation**
  - **reached 21 MV/m without magnetic field**
  - **initial tests in fringe field of 5-T solenoid give reduced gradient**
    - **and lots of scatter**
  - **awaiting coupling coil to achieve realistic field**

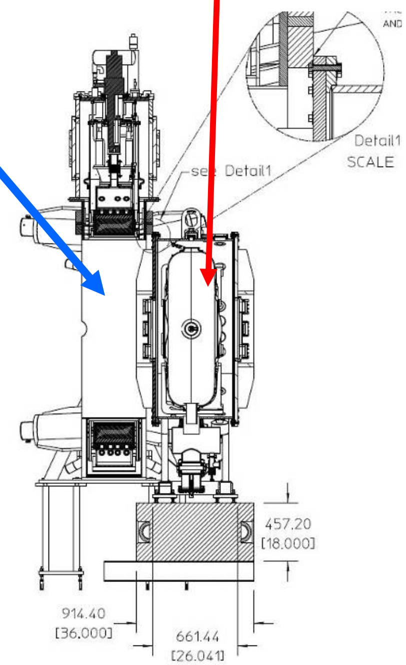
201 MHz cavity

5-T solenoid

201 MHz cavity







Design Gradient

NCRF Strategy

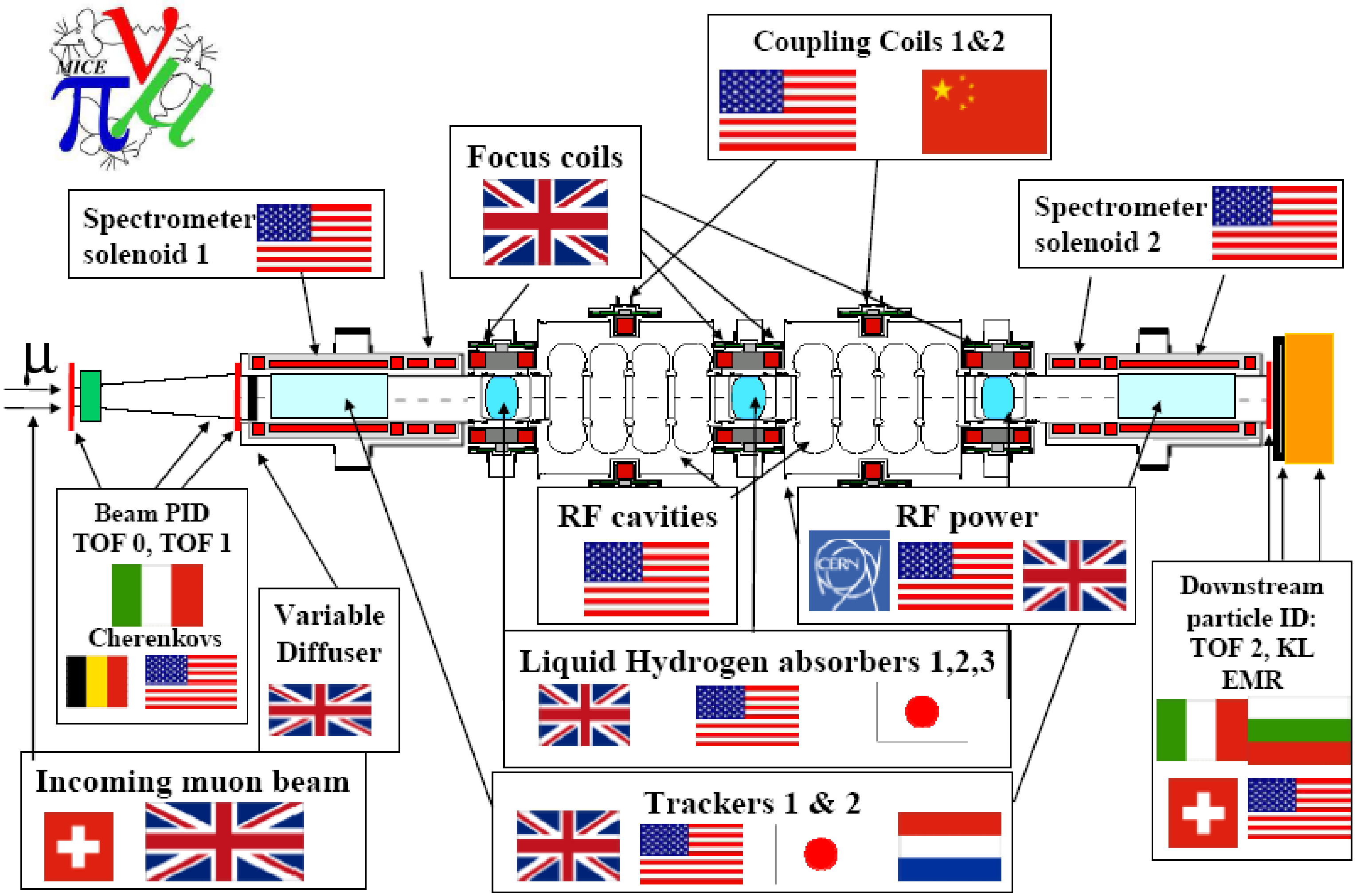
- **Continue assessment of alternative RF technologies**
  - goal: identify ≥1 approach to eliminate (or reduce to acceptable level) gradient degradation in magnetic field
    - vacuum cavities
      - reduce or eliminate surface electric field enhancements
        - SCRF processing techniques (electropolish plus HP water rinse)
        - UK has been involved in this activity
        - ALD techniques (smooth surface with conformal coating at molecular level)
      - materials studies
        - look for materials resistant to damage (Be looks interesting)
    - high-pressure gas-filled RF ("HPRF") cavities
      - use beam tests to see if gas breaks down with intense beam
      - simulations to understand/predict behavior

MICE

- Neutrino Factory (≈10^{21} ν_e aimed at far detector per 10^7-s year) or Muon Collider depends on ionization cooling
  - straightforward physics but not experimentally demonstrated
  - expensive (O(1B$)) facility, so prudence dictates demo of key principle
- Cooling demonstration aims to:
  - design, engineer, and build a section of cooling channel capable of giving the desired performance for a Neutrino Factory
  - place this apparatus in a muon beam and measure its performance in a variety of modes of operation and beam conditions
- Another key aim:
  - show that design tools (simulation codes) agree with experiment
    - gives confidence that we can optimize design of an actual facility
- Getting the components fabricated and operating properly teaches us about both the cost and complexity of a muon cooling channel
  - measuring the "expected" cooling will serve as a proof of principle for the ionization cooling technique

MICE Contributors

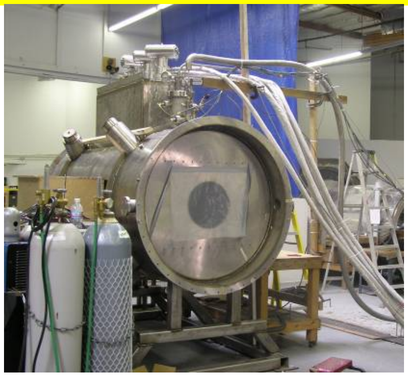
- Many international partners contributing



Cooling Channel Components

- **All cooling channel components are now in production**

Spectrometer Solenoid (Wang NMR)

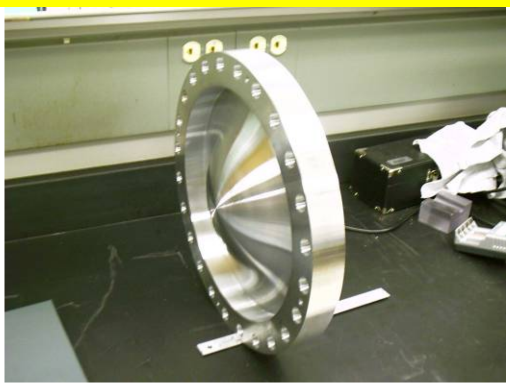


CC completed coil (Qi Huan Co.)

CC winding (Qi Huan Co.)

Absorber (KEK)

Absorber window (U-Miss)



Cavity at LBNL (Applied Fusion)

FC (Tesla Eng., Ltd.)

Synergies-LE Muons

- **Both US and UK teams working on curved solenoid beam lines**
  - sharing design expertise should benefit both
  - modeling and simulations for backgrounds should also be common theme
  - joint development of beam diagnostics
    - beam extinction is a challenge
  - sharing R&D information, e.g., radiation studies

- **PRISM study for FFAG-based $\mu \rightarrow e$**
  - injection/extraction for FFAG is problem of common interest
    - kicker design and *testing*
      - IDS-NF, medical FFAG, VLENF, ADS device…
        - EMMA kickers probably not good "role models"
  - diagnostics that work over wide range of orbit positions
    - IDS-NF, medical FFAG, VLENF, ADS device…

Synergies-NF/MC (1)

- **Proton driver expertise is most valuable UK synergy**
  - ISIS staff well versed in issues of producing and handling intense proton beams
    - linac, chopper already being studied in UK "FETS"
    - plenty of experience measuring and controlling proton beam loss
      - injection, extraction, circulating beam
  - this expertise can also be applied to muon beam losses
    - such work already under way as part of IDS-NF study
      - beam loss in front-end of muon channel is severe
        - needs to be quantified, then mitigated
- **Work on FFAG accelerators likely to play a role in both NF or MC acceleration scheme**
  - EMMA measurements will be important to future design
    - need to make sure that all relevant measurements are completed
      - need transmission; effects of slower resonance crossing
  - injection/extraction kicker concept being developed in UK now for IDS-NF

Synergies-NF/MC (2)

- Target
  - work on alternative solutions (powder, solid) is not being done elsewhere
  - examination of liquid Ga option needs study
    - shortage of experienced engineering help in both US and UK
  - test facility definitely needed
    - observed damage to targets never well-simulated before the fact
- RF materials investigations
  - UK has expertise in processing and materials characterization
    - ALD work in US is under-manned
      - could use help here to evaluate efficacy of this approach
  - mechanism for breakdown still needs study
- SC magnets
  - UK is presently providing engineering support for MICE magnet fabrication
    - expertise in MLI installation from satellite programs is available
      - a real benefit for cryo-cooled magnets
  - high-field solenoids would be a fruitful area for additional collaboration

Synergies-NF/MC (3)

- SCRF
  - cavities needed for all acceleration systems
    - along with robust and efficient power systems
- Simulations
  - detailed simulations needed to finalize NF design
    - even more needed for MC design
      - especially cooling channel (6D, final cooling)
  - UK has complementary expertise in this area
- Diagnostics
  - general need for decay ring, FFAG, RLAs, linac, cooling channel,…
- RCS design and components for collider
  - ISIS expertise could help here
- 6D cooling and final cooling
  - joint effort on design and testing would further MC progress
    - can MICE Hall infrastructure be useful?

Summary

- **Substantial progress being made toward design of accelerator-based muon facilities**

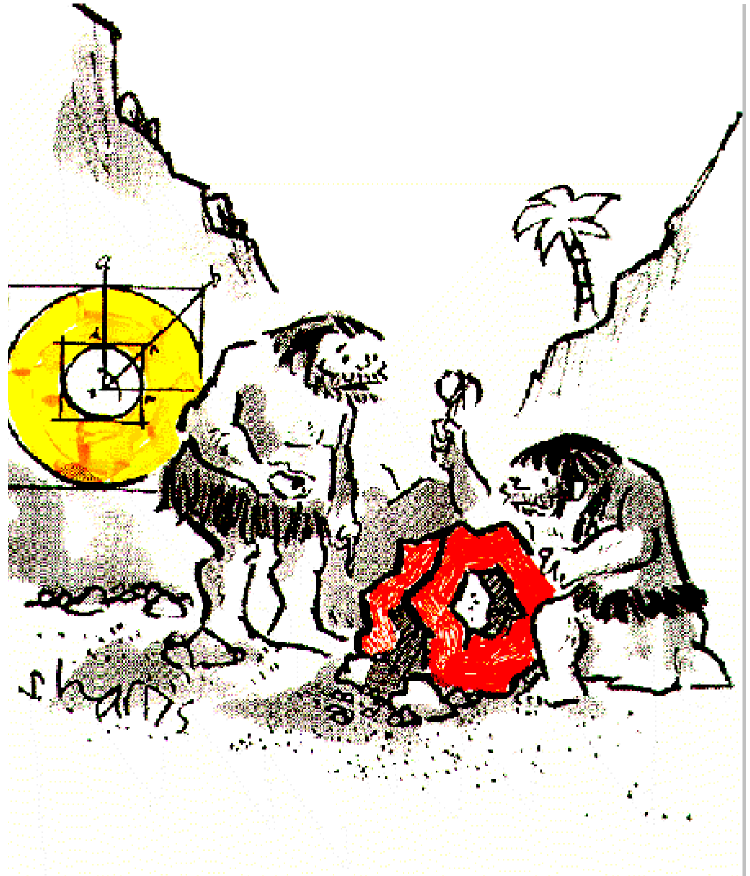
- **Work extends state-of-the-art in accelerator science**
  - **high-power targets, new cooling techniques, ion source development, rapid acceleration techniques,...**

- **Tasks are challenging and would clearly benefit from additional regional collaboration**
  - **MuCool Test Area (US)**
  - **MICE Hall (UK)**

Final Thought

Paper studies alone are *not enough*

We need to build and test things!



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