



U.S. DEPARTMENT OF  
**ENERGY**

Office of  
Science

---

# **Review of the Muon Accelerator Program at Fermilab**

Closeout Presentation  
August 26, 2010

# 1. Accelerator Systems

---

Tom Markiewicz (SLAC), Steve Peggs (BNL/ESS)

## Findings:

- We were impressed by the high morale of the MAP team, who hosted a smoothly organized meeting that included many carefully prepared and well delivered presentations. Congratulations and thanks to all!
- Q: “... determine if [this proposal] is suitable for funding.”
- A: Yes, because of the importance of the  $\mu$ -collider to the HEP community.



U.S. DEPARTMENT OF  
**ENERGY**

Office of  
Science

# 1. Accelerator Systems - Findings

---

- “Milestones & deliverables” Tables 3, 9, 11 & 13 (proposal pages 8, 29, 34 & 44) are intended to be used to track the progress of the R&D
  - Table 3: Design & Simulation
  - Table 9: Neutrino Factory RDR task
  - Table 11: Technology Development
  - Table 13: System Test
- The proposal describes a plan spanning a 6 year “Phase 1” period.
- If Phase 1 is successful it may be followed by a “Phase 2” that would include a number of technology demonstrators.



# 1. Accelerator Systems - Findings

---

- The MICE experiment has experienced significant delays, perhaps with more to come.
- The MAP collaboration stated at the review that:
  - “We are fully committed to the success of MICE.”
  - “MAP is committed to ensuring that the US contributions [eg magnets] work as specified. Overall responsibility for the success must rest with the MICE collaboration, of which MAP is only one part.”
- “We believe the [MICE] **Spectrometer Solenoids (SS)** are close to working.”
  - SS were designed and are being built by a vendor local to LBNL (Wang).
  - A review of design modifications for the SSs will occur in Oct 2010.
  - SS magnet 1 will be re-assembled no earlier than Jan 2011.
  - SS magnet 2 around April 2011.



# 1. Accelerator Systems - Findings

---

- “Less is known about the [MICE] **Coupling Coils (CC)** since the first one is in fabrication. ... The main risk is that the cryocoolers will be insufficient.”
  - CC magnets and cryomodules are being designed and built in collaboration with ICST in Harbin.
  - The 1<sup>st</sup> CC cold mass is scheduled to be tested in Dec 2010.
  - CC magnets 1, 2, 3 scheduled to be completed by Q3 11, Q1 12, Q2 12.
  - CC magnets 2 & 3 are then shipped to RAL.
- “Our first fallback position is to increase the number of cryocoolers ... .”
- “Our 2<sup>nd</sup> fallback position is to buy & install a dedicated helium refrigerator in MICE.”



# 1. Accelerator Systems

---

## Comments

- We agree that the significance of a potential Muon Collider as a U.S. HE frontier machine merits its funding increase request.
- The value of a Neutrino Factory as the first stage of a Muon Collider is under-emphasized in the proposal
  - A Muon Collider strategy that is based on a staged approach – concentrating current resources on technology demonstrations needed to convince the community that a Neutrino Factory is feasible – should be considered



# 1. Accelerator Systems - Comments

---

- The charge to the review states:
  - “The [P5] panel also recommends R&D for alternative accelerator technologies, to **permit an informed choice** when the lepton collider energy is established.”
- And asks (in part):
  - “Does the proposal devote appropriate effort to **demonstrating** that **the most critical technical issues** to building a muon collider or neutrino factory can be solved?”
- The items in red appear to form the basis for a MAP **Mission Statement**.
- We believe that such a **Mission Statement** should emphasize technology demonstrations over developing detailed design reports.

# 1. Accelerator Systems - Comments

---

- MICE is a high profile international activity that is crucial for the advancement of NF and MC plans.
- Successes with MICE in the middle of MAP Phase 1 would greatly boost the knowledge, morale and prestige of the collaboration.
- MAP should have no higher priority than to honor its commitment “to ensuring that the US contributions [MICE magnets] work as specified”, ...
- ... **and** to work with the rest of the MICE collaboration to ensure the overall success of the experiment.



# 1. Accelerator Systems - Comments

---

Answering the charge questions:

- *Q1: “Does the proposal devote appropriate effort to demonstrating that the most critical technical issues to building a MC or NF can be solved?”*
  - The proposal describes a thoughtful and detailed plan that evolved from previous activities under NFMCC & MCTF
  - The proposal matches the resources that could be made available, in the context of an international program.
  - The committee believes that the proposed activities are spread too thinly over too many topics. We suggest:
    - **raising** the priority of performing and planning for technology demonstrations that would “permit an informed choice”, and
    - **lowering** the priority of detailed design tasks



# 1. Accelerator Systems - Comments

---

- *Q2: “Are there clear milestones that can be used to track progress of the R&D?”*
  - There are “milestones and deliverables” in 4 tables in the proposal, but they are not clearly linked to each other, nor to decision trees.
  - Successful technical demonstration of 4D ionization cooling in MICE is nowhere included as a milestone or deliverable.
  - More clarity is required, with linkages between tasks.
  - We recommend constructing a tentative list of potential demonstrators that could be considered for implementation in MAP Phase 2, if Phase 1 is successful.

# 1. Accelerator Systems

---

## Recommendations

1. Prepare a brief and direct MAP Mission Statement, by October 1, 2010.
2. Prepare a list and a schedule of technical down-selections that will be made by the end of Phase 1, for presentation at the next review.



## 2. RF Systems (1/7)

---

Subcommittee members: Erk Jensen and Chris Adolphsen

### FINDINGS

- RF is of central importance for the NF and in particular the MC; highest gradients are required, primarily to minimize the muon decay losses.
- Many RF systems are required, ranging from 4 MHz to 1.3 GHz.  
(transparency below for an initial – very incomplete – try of an overview).
- Highest possible gradients in the presence of strong axial magnetic fields are necessary. While the R&D aimed at demonstrating a viable approach is multipronged, it is fraught with many uncertainties:
  - The past 805 MHz results are suspect due to what appears to be coupler pulse-heating related damage – fortunately, the cavity has been refurbished and will be tested again soon.
  - A 805 MHz cavity with an all Be interior is planned but the effects of Be on breakdown are not known - nose tests will be done first.



## 2. RF Systems (2/7)

	GeV	$f$ [MHz]		$\mu\text{pp}$	total MV	RF power peak/avg
P Driver (PX)	8	1300		2E14 ppp	800	
Buncher	.2	234 ... 320	NCRF			24 MW / 230 kW
Rotator	.2	202 ... 230	NCRF			140 MW / 1.3 MW
Cooler	.2	201	NCRF	3.5E13	150	400 MW / 4 MW
6D cooling	.2	201, 402, 805	NCRF			
final cooling	.2	4 ... 300	NCRF		1200?	
Linac	.9	201	SRF		700	
RLA	3.6	201	SRF		600	
RLA	12.6	201	SRF		2000	
FFAG/RLA	25	201	SRF		1000	
RCS1	400	805 ? 1300 ?	SRF		16000	~/14 MW
RCS2	750	805 ? 1300 ?	SRF		15000	
Collider Ring	750	805 ? 1300 ?	?	2E12	16	

Please fill in the blanks!



## 2. RF Systems (3/7)

---

### Findings (continued):

- A 805 MHz cavity made with an ALD coating will be evaluated but breakdown will remove the coating – SC cavity ALD results are probably not relevant – nose tests will be done first.
- The existing 201 MHz cavity will not be immersed in a full solenoidal field until at least 2012. Cavities for MICE will be tested later.
- The magnetic insulated cavity approach is only being evaluated indirectly with a waveguide cavity – also the effect of the lower shunt impedance and smaller packing fraction for such a cavity has not yet been evaluated.
- Early open cavity results were promising but the required power is higher and it appears the window damage is higher.
- Pressurized gas filled cavities may give distinct advantages for the performance of ionization cooling.
  - The existing high pressure cavity will be tested with beam to study RF loading effects of ionization electrons. The practicality of having a large high pressure H<sub>2</sub> chamber with multiple RF feeds has not been evaluated.



## 2. RF Systems (4/7)

---

### Findings (continued):

- There has not been a systematic study of the impact on machine performance of operating at a lower-than-design gradient for the various cavity systems.
- There has not been any serious study of the cost tradeoffs of the various approaches to high gradient.
- The group plans to down select a cavity approach in 2012 before the MICE cavity operation – need this decision to help choose a 6D cooling approach.
- RF systems for muon acceleration are more conventional, but the large voltages RCS's lead to unconventionally large synchrotron tunes ( $\nu = 1 \dots 2!$ )



## 2. RF Systems (5/7)

---

### Comments:

- The cavity findings have been based on very limited statistics – there are many ways of degrading cavity performance so one should be wary of generalizing the results from any one test. More and better data are required to understand the dependence of  $E_{max}$  on  $B$ . Too few relevant test data do not allow conclusion or down selection.
- Relevant R&D on high gradients and the physics of breakdown has been done by the NC Linear Collider community (CLIC & US HG coll.) – there is a reservoir of knowledge in these areas in other R&D programs and collaboration/co-ordination is strongly encouraged to assure that unnecessary R&D effort would not be doubled (ALD, different materials, surface preparation methods, tricks of the trade ...).
- The RF systems of the MC cooling channels are in a very early stage; some initial technical design/costing is necessary to imagine possible implementations at least conceptually.



## 2. RF Systems (6/7)

---

### Comments (cont'd.):

- Serious concern for absorber filled cavities: the full impact of “beam loading” by ionization needs continued study.
- The down-selections of the RF systems cannot be done independently of the other efforts.
- Having Be windows between the cavities will suppress the continued acceleration of dark current, but may generate a large, low energy, electron current due to the cascading of showering electrons.
- Be has its issues; due to its toxicity, its handling and manufacturing, but maybe also cavity failure modes, raise safety concerns.



## 2. RF Systems (7/7)

---

### Recommendations:

1. Continue R&D on RF systems.
2. Take advantage of ongoing effort on world-wide high gradient R&D
3. By 30-Nov-10, prepare a revised R&D plan that addresses the issues mentioned in the comments and consider the following suggestions:
  - Focus on key issues: 1) High gradient in the presence of  $B$ , 2) absorber filled cavities and their issues (pressure, “beam loading”), 3) large synchrotron tune RCS.
  - To allow prioritization of the test program for the next few years, rough cost studies of the various scenarios are encouraged. They will also help the down selection.
  - The testing program should be intensified: do more tests of the existing 201 MHz cavity and build more of the 805 MHz cavities to improve statistics
  - Delay down-selection: The present plan calls for an RF system down-selection by 2012, which seems too early; we recommend to postpone this, tied to milestones rather than calendar dates.



### 3. Beam Physics and Simulation

---

John Cary (Colorado), Yunhai Cai (SLAC)

#### Findings:

- A preliminary design with a luminosity of  $10^{34} \text{ cm}^{-2}\text{s}^{-1}$  at 1.5 TeV center mass energy was presented along with a comprehensive list of tasks for each subsystem of the Muon collider.
  - Successful experiment of MERIT for demonstrating the feasibility of Hg-jet target
  - 4D ionization demonstration experiment: MICE well underway
- Much progresses had been made over the past decades in understanding beam physics in the process of ionization cooling. In particular, two different codes have been developed for the simulation. In general, they agree well with each other. They have become an essential tool for design of Muon collider.
- Many new ideas and innovations
  - Three schemes of 6D cooling channel

### 3. Beam Physics and Simulation

---

#### Comments:

- It may be difficult to complete the many tasks presented during the next five years, perhaps impossible if one task is to provide a design of a Muon collider.
- While much good simulation has been done, there is also a need for global optimizations, which require simple analytic models. We did not see a clear picture of major tradeoff in the entire preliminary design.
- We saw little *verification*\* and no *validation*\* of the simulation codes against experiments. More validation would alleviate concern that the codes might be missing some physics. This is especially critical for 4D ionization cooling, which is key for success of Muon collider.
- It appears that there could be plasma effects arising through the beam matter interactions. We did not see estimates of the plasma effects (wake fields, inductive current ionization, ...)

\***Verification** is ensuring that the code is solving the equations correctly.

\***Validation** is ensuring that the right equations are being solved.

### 3. Beam Physics and Simulation

---

#### Comments (continued):

- Acceleration:
  - 25 GeV to 750 GeV in a fast ramping synchrotron with a unit of synchrotron tune enters a new operation region where strong coupling between betatron and synchrotron can occur. Need to have simulations of a strawman lattice.
- Design of collider ring: Solid design of optics and initial simulation of background
  - High single charge ( $10^{12}$ ) with very small momentum compaction ( $10^{-5}$ ) might lead to microwave generation, e.g., by coherent synchrotron radiation
  - High single charge with very small synchrotron tune might lead to head-tail instability.
  - IR design for 3.0 TeV energy could be very difficult because of the large aperture required to avoid radiation damage.
  - Beam-beam parameter of 0.09 without any radiation damping may not be as easy as described in the proposal.
- Target:
  - Lifetime of the superconducting solenoid may be limited due to the severe radiation environment.

## 3. Beam Physics and Simulation

---

### 3.3 Recommendation: Provide a revised R&D Program that

- Better streamlines and prioritizes the tasks according to overall goals, in particular,
  - Focusing on the new issues in Muon system, ionization cooling, huge beam loss, radiation damage, plasma creation, magnetic loss of accelerating gradient, and other intense beam effects...
  - Not trying to design a Muon collider.
- Validates simulation codes using experimental results from MICE as earlier as possible, so that they can be confidently used in the design process
- Estimates intense beam, plasma, other collective effects, and if they are possibly important, establishes a simulation program for helping to understand them.
- Includes hosting a workshop to engage the accelerator community to solve these tough problems.

## 4. Magnet Systems

---

Subcommittee members: Peter McIntyre (TAMU) and Al Zeller (MSU)

### Findings:

- The significance of successfully completing and operating MICE cannot be overstated
  - The team recognizes this and states that it will have very high priority
  - A back up plan of a new liquid helium plant is proposed, assuming that all of the problems are cooling related
- Very-high-field superconducting magnets are required through the entire sequence of muon source and cooling systems: 20 T large-bore focusing solenoid on target; tens of meters of >20 T large-bore solenoids in whichever of the 6D cooling scenarios is selected; 30-50 T small-bore solenoids for final transverse cooling. These magnets pose one of the greatest technology challenges in the muon collider design.

## 4. Magnet Systems Findings -2

---

- YBCO tape has now been developed to reproducible performance in pre-reacted tape, high engineering current density, and excellent strain tolerance. Piece length is only ~50 m piece length, and with the de-funding of its development for AC power it cannot be assumed that piece-length will improve in the foreseeable future.
- Bi-2212 round wire is commercially available in km piece-length. Coil technology for Bi-2212 is being developed by NHMFL, VHFSCMC, and others. Issues remain for core leakage and cation diffusion during heat treatment, temperature control during heat treatment of large coils, and strain sensitivity.
- Recent tests of model windings and development of large coils for 30 T NMR are driving steady improvement in wire performance and coil technology. There is reason to expect ongoing improvement in Bi-2212 because manufacturing is not capital intensive.
- The high-field magnet R&D proposed within MAP has three components: conductor R&D, coil technology development, and demonstration of an insert winding with self-field of 20 T in 8 T background field by FY13.

## 4. Magnet Systems Comments

---

### Comments:

- Much development remains to be done before the coil technology for MAP requirements is demonstrated, and the development within MAP is unlikely within the proposed resource levels.
- The presently funded efforts of NHMFL and VHFSMC are directly relevant to MAP requirements and it is reasonable to hope that they will bring the necessary core technology to readiness during the 6-year period of MAP.
- There are two main issues that are distinct in the high-field magnets for MAP compared with those being developed by NMHFL, and should be central to MAP R&D.:
  - The large-bore magnets have very high stored energy. This will require high-current cable conductor rather than wire or tape if the magnets are to operate safely.
  - Most of the high-field magnets for cooling require that the high-field inserts extend to the ends of the magnet (very different from NMR solenoids). This means that end forces and turning fields will dominate the conductor requirements, particularly for YBCO.



## 4. Magnet Systems Comments - 2

---

- The sheer number of technical challenges resulted in a shotgun approach in the proposed program, where all problems are examined a little. While there is a general priority list, it still appears too large for available resources.
- Viewed within the spectrum of challenging issues facing MAP and the scale of parallel efforts at NHMFL and FHFSMC, it is not clear that the Demonstration Magnet milestone is a wise near-term investment of MAP's resources.
- The list of intermediate milestones does not address the unique engineering needs for the MAP magnets, as highlighted above.
- The technology needed for the Nb<sub>3</sub>Sn arc magnets will benefit from the LARP program, and MAP wisely relies upon that development for hardware activity
- Given resource limitations, care should be taken to limit insert winding development to specific issues that are needed to inform the selection of cooling options. The program to develop 4-coil HCC segments is a good example. There, however, the proposed scope for the first 3 years is ambitious and resource-intensive. Attention should focus from the outset on the most challenging element – the HTS segment.



## 4. Magnet Systems Recommendations

---

### Recommendations:

1. Delivery of the magnet systems for MICE is a near-term and overdue commitment. Articulate to DOE management a detailed plan to deliver on this commitment by September 30, 2010.
2. Prioritize hardware activities on high-field solenoids to demonstrate that the most critical technical issues can be solved. Rely upon the large-scope efforts at NHMFL and VHFSCMC for development of core technology. Focus MAP R&D upon those elements of the technology that are particular to MAP.
3. Establish intermediate technical milestones that accomplish the most important or significant tasks pertinent to strategic down-selects.



# Milestones and technical issues for the next five years

---

- Complete MICE experiment, verify 4D ionization cooling scheme and validate simulation codes (FY2013)
- Achieve adequate gradient (16 MV/m) in presence of high magnetic field (6 T) (FY2014)
- Design and propose a realistic and cost effective experiment for a 6D-cooling experiment to demonstration of feasibility for a Muon Collider at  $10^{34}\text{cm}^{-2}\text{s}^{-1}$  at 1.5 TeV center of mass energy (FY2015)
- Understand major risks and cost drivers in Neutrino Factory and Muon Collider (FY2011 - FY2015)
- Show validated simulation capability for single particle, intense beam, (cavity breakdown), and interactions with matter (FY2011 - FY2015). This task requires continuous integration with experiments.

## *Provide input to*

- Development of a compelling and comparative (to LHC upgrades) physics case with an adequate support of machine-detector interface (FY2011 – FY2015)

## *Prepare for*

- Complete the 6D cooling experiment (FY2018)
- Complete a conceptual design report of a Muon collider [FY2020 (LHCU, CLIC)]

# 5. Management and Organization

---

John Womersley (STFC)

## Findings

- The former MCTF and NFMCC organizations have been combined to create an interim MAP organization which is in place and functioning.
- A clear reporting line to the Fermilab director and to DOE is in place.
- A permanent MAP program director has yet to be appointed.
- Interim Management has successfully developed the project plan that we have reviewed.
- The team presented a process for making technology down-selects in a structured way.
- MAP is very dependent on small fractions of effort:  
214 participants in MAP, but only 31 FTE, from 14 institutions

# 5. Management and Organization

---

## Comments (1/4):

- The MAP management structure has strong roots in its preceding national and Fermilab programs and structures (NFMCC & MCTF).
- The organization is very much a superposition of the previous organizations; there is not much evidence yet of re-organisation or that the sum-is-greater-than-the-parts from combining NFMCC and MCTF. A further evolution of the management structure would better serve a national program, supporting the potential construction of a US NF or MC at Fermilab.
- The MAP organization combines the attributes of a scientific collaboration (like the IB described by Don Hartill) and a project. This means the management has lots of boards and committees whose distinct roles aren't immediately apparent and which potentially waste time and effort.
  - *There are also parallel overlapping structures for the MICE experiment and the NF-IDS.*

# 5. Management and Organization

---

## Comments (2/4):

- Internal management structure should reflect the program deliverables and milestones.
- The ability of management to focus effort on the highest priorities is a key attribute of a successful project. Is this true of MAP?
- The MAP program manager should evolve the project team away from the consensual, collaboration-style mode in which they have been working towards more of a project focused approach, while maintaining the innovative spirit of the participants.
- International inputs and advice have in the past come through international members on MUTAC. The MAP PM should take steps to improve the international connections of/into the program as it becomes more project-like.

# 5. Management and Organization

---

## Comments (3/4):

- Is the team sufficiently strong to deliver what it has proposed to do?
  - *Effort is not very focused.*
  - *The program is spreading itself very thin - lots of activities have their own advocates and sometimes even their own independent funding (SBIR, NSF grants...).*
  - *There is a need for more people working on MAP at the 100% level.*
  - *Being able to call on national lab effort is essential, but does mean that the program can be at the mercy of internal lab priorities.*



# 5. Management and Organization

---

## Comments (4/4):

- Even though MAP is an R&D project and includes a lot of simulation work, full use should be made of project management and project control tools. Appropriate milestones and contingency are necessary.
  - *What we were shown at this review did not seem very detailed in this regard.*
- The MAP Program Director should ensure the program plan focuses effort on highest priorities including the current MICE magnet problems.
- The MAP Program Director should ensure that technology down-selects are made as soon as possible, to allow resources to be focused.

# 5. Management and Organization

---

## Recommendations:

1. The Fermilab Director should appoint and fully empower a MAP Program Director who is able to move resources as needed within the program and who can concentrate effort on the highest priorities.
2. MCOG should ensure that MAP is adequately resourced with staff of the appropriate skills to deliver, and that MAP receives sufficient priority within the various national laboratories.
3. The MAP Program Director should take steps to streamline and reduce the various advisory and oversight bodies inherited from NFMCC and MCTF, and to ensure that the appropriate international connections are in place.
4. A revised R&D plan addressing the issues described earlier must be submitted by November 30, 2010.