Neutrino Factory and Muon Collider Collaboration

R&D Program: Progress and Plans

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Outline

- Introduction
- Collaboration R&D goals
- R&D progress
- R&D plans
- R&D budget
- R&D schedule
- Summary

Introduction

- **Since last year, *MC* effort has focused primarily on Neutrino Factory R&D topics**
  - **Muon Collider issues have not been (and should not be) forgotten**
    - **emittance exchange workshop scheduled at BNL in September**
- **Change in emphasis did have one R&D implication**
  - **initial MUCOOL development based on 805-MHz components (RF cavity, power supply, solenoid)**
    - **work continued to learn about high-gradient performance in the presence of solenoid field**
  - **now need components sized for initial cooling channel parameters**
    - **201 MHz RF cavity, power source, large-bore solenoid**
  - **R&D on these items is getting under way**

Introduction

- **Fermilab Feasibility Study taught us much about Neutrino Factory design**
  - **technical feasibility was established**
  - **a scientifically-productive staged approach to the facility is possible**
  - **a carbon target is viable for an entry level facility**
  - **front-end (capture, phase rotation, bunching, cooling) must be treated in integrated fashion**
    - **beam simulation work in Study-II is focusing on this**
  - **some components do not easily "scale" to 201-MHz dimensions**
    - **conventional wisdom says that solenoids are easy**
      - **solenoids with 1.5 m bore diameter and high field (≈3.5 T) are not**
  - **"cost drivers" were identified**
    - **R&D to produce cost-effective designs now included in the program**

Introduction

- ***MC*** **has grown to 139 members from 30 institutions (+39 in past 6 months)**
  - **new NSF-sponsored University groups strengthening us further**
    - **both intellectually and financially**
- **We have the scientific personnel to carry out required R&D program in a timely way**
- **Committed to encouraging international cooperation and coordination for Neutrino Factory and Muon Collider R&D**
  - **expect to strengthen R&D ties between the various groups and avoid unnecessary duplication of effort**
    - **this is being encouraged from elsewhere also (Maiani letter)**

Introduction

- **Participating institutions**

Beam Simulations
- ANL
- BNL
- CERN
- Fermilab
- LBNL
- Michigan State U.
- Princeton U.
- U. Chicago
- UC-Berkeley
- UCLA

MUCOOL
- ANL
- BNL
- Columbia U.
- Fermilab
- Illinois Institute of Technology
- Indiana U.
- LBNL
- National High Magnetic Field Lab
- Northern Illinois U.
- Northwestern U.
- U. Mississippi
- UCLA

Targetry
- ANL
- BNL
- CERN
- Fermilab
- LBNL
- Michigan State U.
- National High Magnetic Field Lab
- ORNL
- Princeton U.

Acceleration/Storage Ring
- BNL
- Cornell U.
- Fermilab
- Jlab
- Michigan State U.
- UCLA

Proton Driver
- BNL
- Fermilab

Phase Rotation
- BNL
- Fermilab
- LBNL

Introduction

- ***MC*** **recently reorganized to improve R&D planning and monitoring**
  - **added the role of Project Manager (PM)**
  - **PM has "line responsibility" for managing *MC* R&D program**
    - ***MC*** **member, appointed by—and reporting to—MCOG (with DOE-HEP concurrence)**
- **"Project" Office is being set up at LBNL**

Collaboration R&D Goals

- Define where we want to be 5 years from now in all R&D areas, then work backward to see what's needed to get there (funding and effort)
- At the end of 5 years (science/technology-driven schedule)
  - all optics designs completed and self-consistent
  - validation experiments completed or well along
  - know what we want to build
  - know how to build "hard parts" (prototypes completed or designed)
  - ready to design and cost most components ($\Rightarrow$ ready to begin CDR)
- Aim for "ZDR-level" understanding of a Neutrino Factory in $\approx$3 years
- Aim to begin CDR after 5 years of R&D work (complete in $\approx$2 years)
  - implies "prying loose" significant engineering support early
- This aggressive schedule requires an augmented funding level

R&D Progress

- **R&D activities fall into four main categories**
  - **beam simulations/theory (Organizer: Jonathan Wurtele, UCB/LBNL)**
  - **targetry experiment (E951 at BNL) to demonstrate technical feasibility of key concepts (Organizer: Kirk McDonald, Princeton U.)**
  - **MUCOOL to demonstrate feasibility of required components and study cooling effects (Organizer: Steve Geer, Fermilab)**
  - **component development, e.g.,**
    - **201-MHz SCRF cavities for acceleration section (Cornell)**
    - **induction linac with internal SC solenoid for phase rotation (LBNL)**
    - **20 T SC solenoid system (NHMFL)**
    - **muon beam diagnostics (UCLA, U-Mississippi, Northwestern)**
    - **low-frequency, high-gradient proton driver cavity (Fermilab, BNL)**
- **Significant effort also invested in Feasibility Study activities, drawing other groups into the R&D program (FNAL → BNL)**

R&D Progress

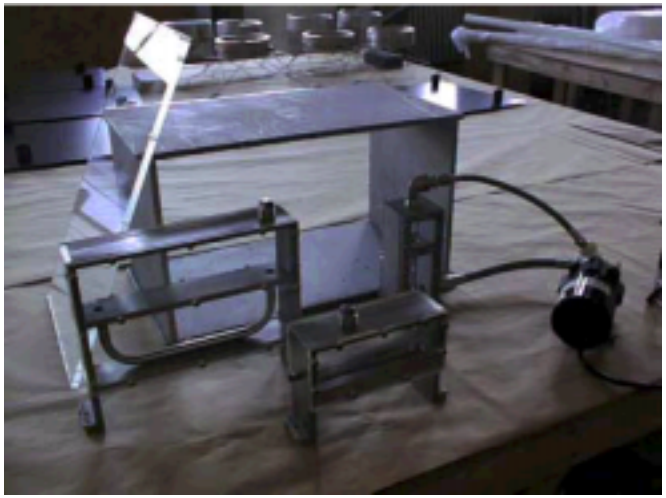
- **Targetry goals**
  - **demonstrate performance of MW-level target in high-field solenoid**
    - **requires supporting target simulation effort**
  - **measure pion and neutron yields to benchmark code**
  - **demonstrate lifetime of target (Hg jet and solid)**
- **Progress**
  - **A3 beam line at BNL nearly completed**
    - **initial target beam tests begin next year**
  - **initial Hg-jet target apparatus built**
    - **test in high magnetic field at NHMFL**
  - **simulations to assess mechanical behavior of target under way**
  - **engineering of components for experiment [20-T pulsed solenoid, 70 MHz high-gradient RF cavity] has begun**

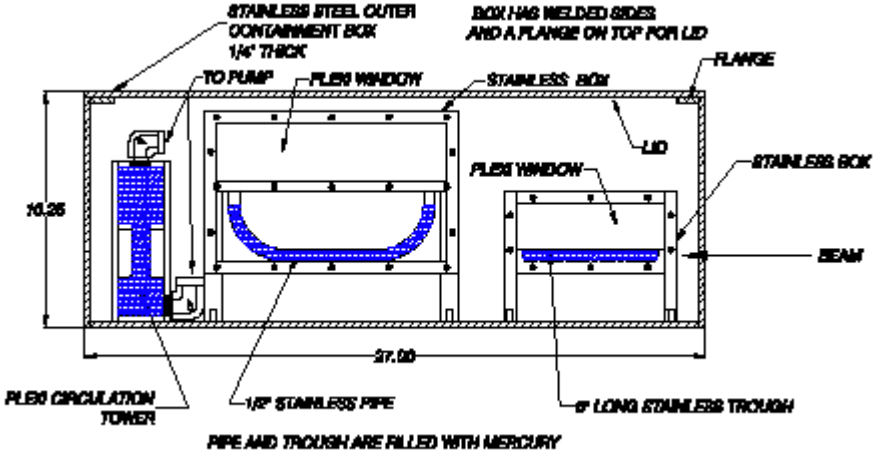
R&D Progress

- **A3 beamline at BNL**

R&D Progress

- **Prototype Hg target test apparatus**

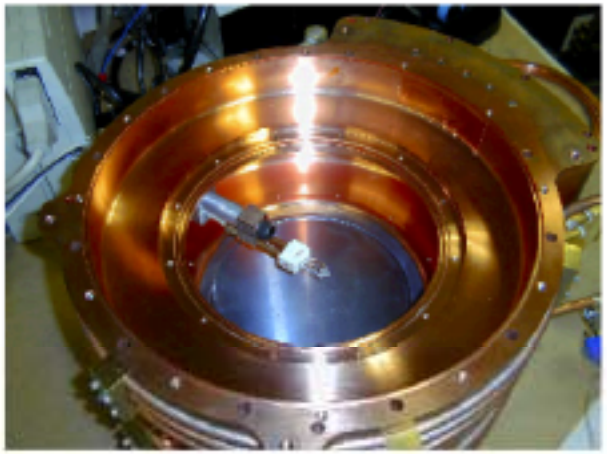


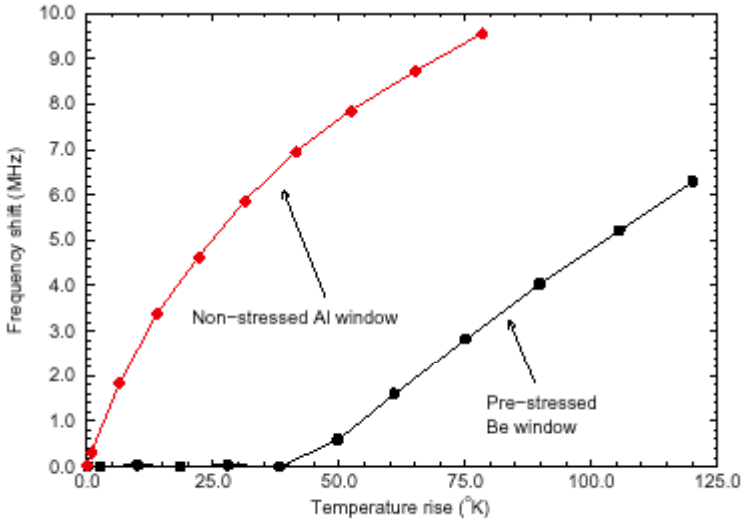


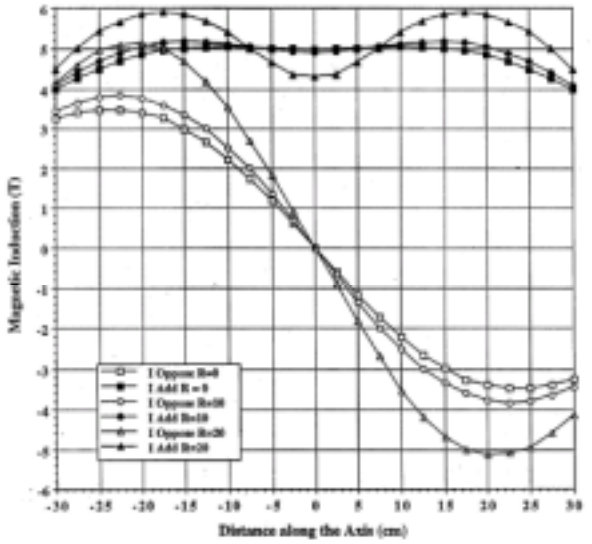
R&D Progress

- **MUCOOL goals**
  - **build component prototypes and bench test complete cooling cell**
  - **test cooling channel components (including diagnostics) in a muon beam…somewhere**
- **Progress**
  - **805 MHz components**
    - **high-power open cell cavity fab nearly complete (high-gradient performance) [A. Moretti]**
    - **high-power Be-window pillbox cavity fab under way (multipactor; Be performance) [J. Corlett]**
    - **initial Be window deformation tests completed with encouraging results[D. Li]**
    - **solenoid for testing cavities completed and meets design specs [M. A. Green]**

R&D Progress



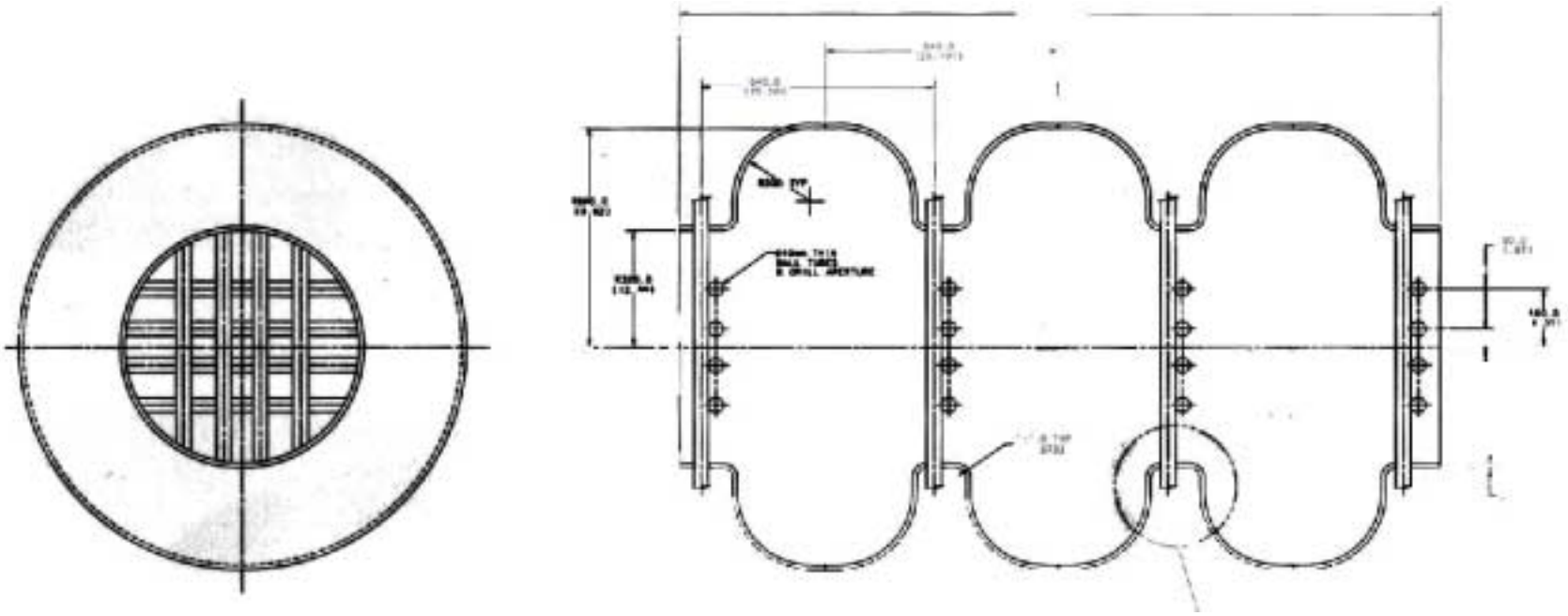

Frequency shift (MHz)
Temperature rise (°K)
Non−stressed Al window
Pre−stressed
Be window
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0.0
25.0
50.0
75.0
100.0
125.0


Magnetic Induction (T)
Distance along the Axis (cm)

R&D Progress

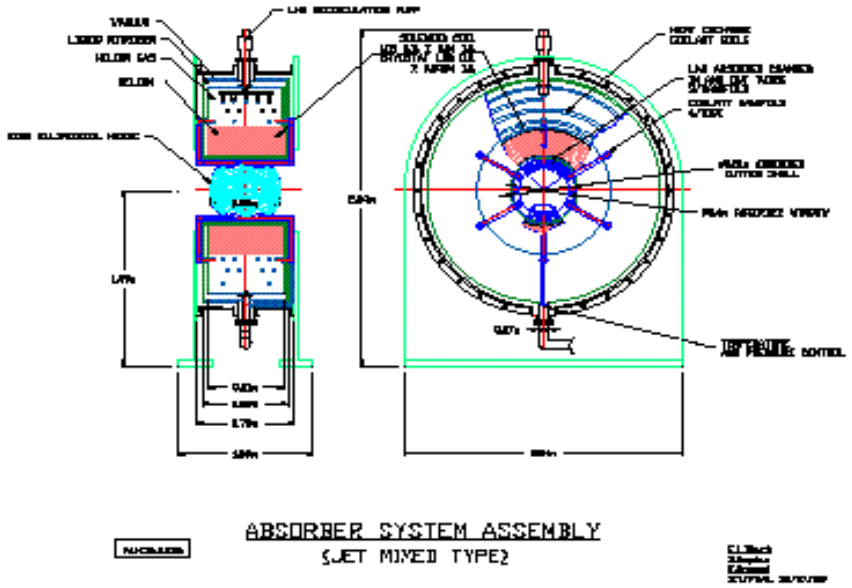
— 201 MHz components

- design of high-power cavity suitable for cooling channel has begun [T. Jurgens]
  - Be windows and gridded cell being studied

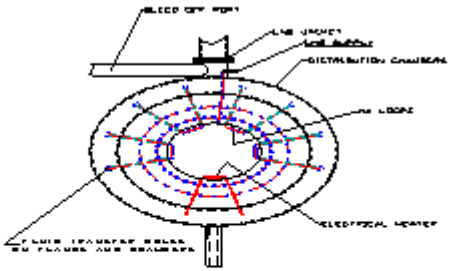


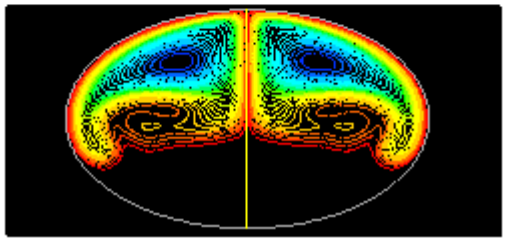
R&D Progress

- fabrication of prototype LH_2 absorber about to begin [D. Kaplan, M. Cummings]
  - design based on sophisticated thermal modeling



Internal heat exchange:



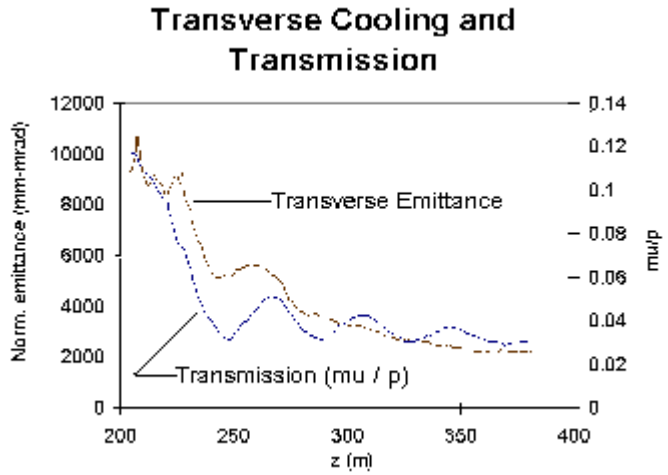


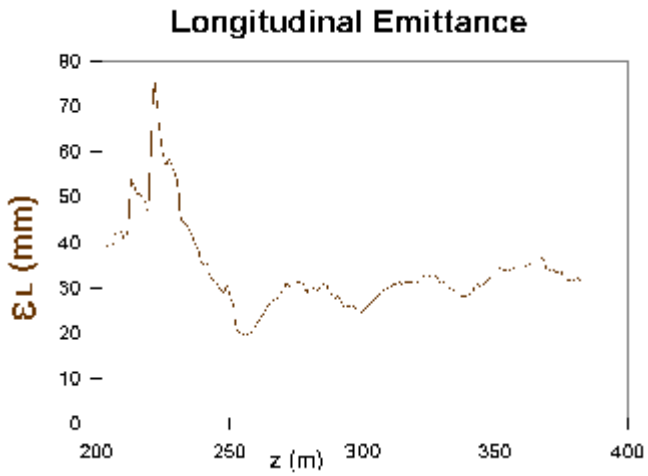
R&D Progress

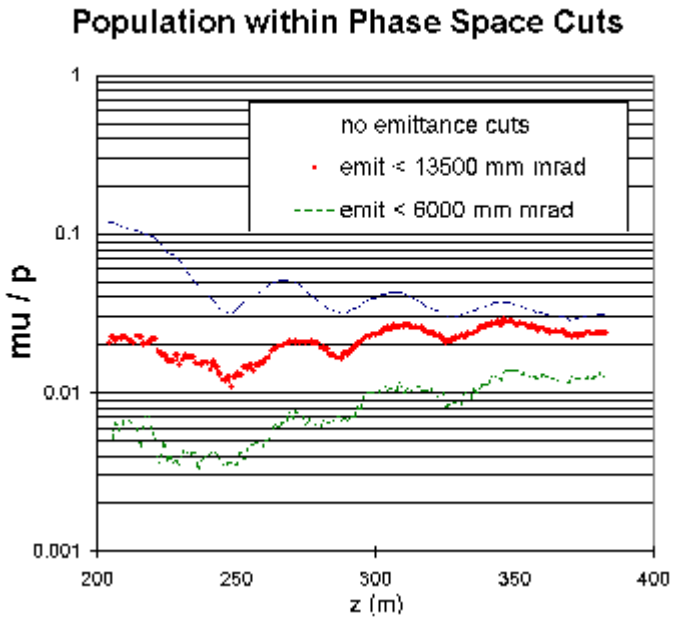
- **Beam simulation goals**
  - **complete end-to-end simulations, including effects of errors**
    - **Target/Capture, Front End, Acceleration, Storage Ring**
  - **develop concept for emittance exchange (longitudinal → transverse)**
  - **develop analytical tools for understanding front-end performance**
  - **support MUCOOL demonstration design**
- **Progress**
  - **completed integrated front-end solution [C. Kim *et al.*]**
    - **still to be optimized in terms of performance**
  - **analytical tools developed [G. Penn; K.J. Kim]**
  - **emittance exchange workshop to be held at BNL in September [R. Fernow, G. Hanson]**
  - **acceleration scheme based on RLAs developed [V. Lebedev]**

R&D Progress

— simulation beginning from induction linac (175 MHz RF) (C. Kim)







Lattice Properties:

Peak Field on Axis	3.4 T
Peak Field at Coils	12 T
Current Density	132 A/mm2
LH length	12.6 cm --> 13.2 cm
LH radius	15 cm --> 10 cm
Al wall thickness	400 μ --> 200 μ
Be window thickness	125 μ
Be window radius	19 cm
RF	175 MHz, 14 MV/m

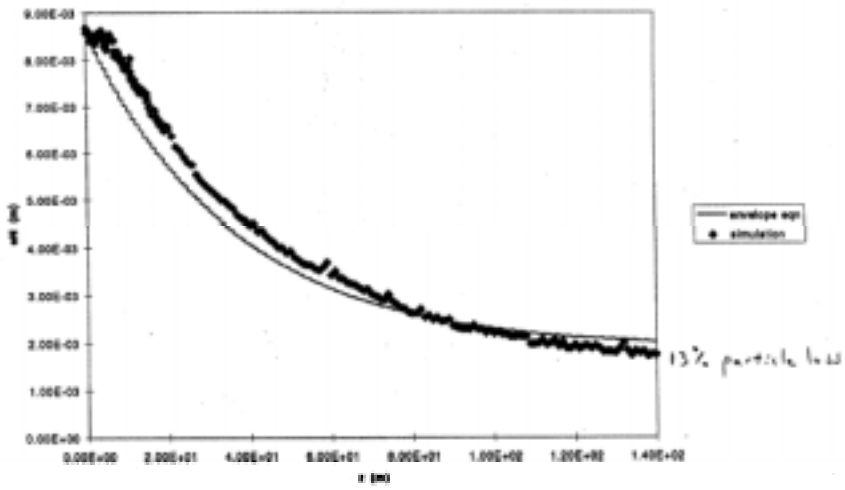
total transmission, 0.03 mu/p at 2100 mm mrad

within 6000 mm mrad cut, 0.014 mu/p

momentum cut, 0.15 < Pz < 0.25 GeV/c

R&D Progress

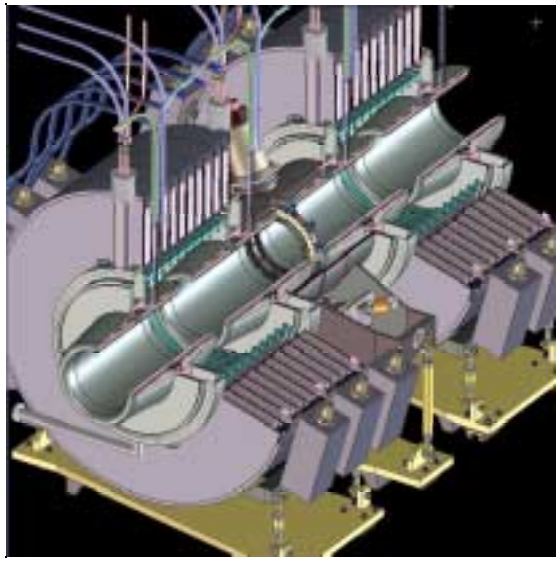
— **comparison of simulation (points) with much faster analytical calculation shows good agreement (G. Penn)**

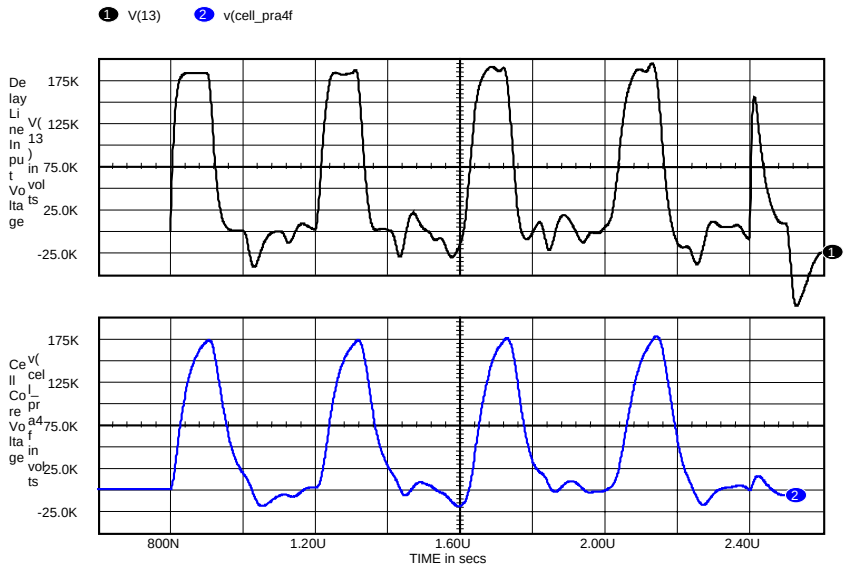


R&D Progress

- **Component development goals**
  - **demonstrate high-gradient 201-MHz SCRF cavity (acceleration)**
  - **demonstrate induction linac cell with internal SC solenoid (phase rotation)**
    - **demonstrate realistic pulser system to drive it**
  - **demonstrate high-gradient, low frequency RF cavity for proton driver**
  - **identify and demonstrate other critical technologies**
- **Progress**
  - **design of 201-MHz SCRF cavity under way at Cornell (supported by NSF)**
  - **developing test cavity and inductive inserts for proton driver**
  - **initial concept developed for induction linac with internal solenoid focusing**

R&D Progress




1 V(13)
2 v(cell_pra4f
Delay Line Input Voltage
V(13) in volts
175K
125K
75.0K
25.0K
-25.0K
Cell Core Voltage
v(cell_pra4f in volts
175K
125K
75.0K
25.0K
-25.0K
800N
1.20U
1.60U
2.00U
2.40U
TIME in secs

R&D Plans

- **Beam simulations**
  - **need better optimized upstream beamline to improve cooling channel performance**
    - **error sensitivity of cooling channel must be understood**
      - **solenoid strength and multipole errors; RF cavity *V*, ϕ, and HOMs; absorber variations; energy straggling, multiple scattering tails,…**
    - **only from these studies can we define**
      - **component specifications to compare with what we build**
      - **diagnostics that can measure what we need to control**
      - **the need for, and plans for, experimental tests of key issues**

R&D Plans

- **Targetry**
  - **E951 program is proceeding on schedule**
    - **first beam tests at BNL A3 line next year (Princeton, BNL)**
    - **neutron yield and pion yield measurements will be carried out subsequently (MSU *et al.*; Princeton, BNL)**
  - **develop target solenoid for E951 tests (NHMFL)**
    - **evaluate rad-hard materials and robust coil designs (MSU)**
  - **augment solid-target effort (FNAL, ORNL)**
    - **consider also "facility" issues (shielding, remote handling, radioactive storage)**

R&D Plans

- **MUCOOL**
  - **carry out high-power tests on 805-MHz cavities (FNAL, LBNL)**
    - **see what limits gradient; study multipactor and Be window behavior**
  - **build prototype LH_2 absorber and test with beam (IIT *et al.*, FNAL)**
  - **shift focus to 201-MHz development (FNAL, LBNL)**
    - **cavity design is under way (delivery and testing will take 3 years)**
    - **Be window design for large aperture cavity must be developed**
  - **design and fabricate solenoid to test cavity**
    - **Feasibility Study showed that this magnet is not easy**
      - **explore idea of initial testing with scale-model magnets**
        - **like NASA ("faster, cheaper, almost as good")**
  - **definition of demonstration awaits guidance from simulation effort**

R&D Plans

- **Component development**
  - **SCRF cavity program getting under way at Cornell (NSF supported)**
    - **upgrade processing facilities; set up 201-MHz power source**
    - **explore cost-effective fabrication techniques**
    - **develop method to provide adequate mechanical stiffness**
    - **demonstrate high-power pulsed operation at design gradient**
  - **induction linac prototype development**
    - **verify gradient performance, pulser design, internal SC solenoid**
  - **engineering design of 201-MHz power source, e.g., multibeam klystron**
  - **begin consideration of "operational" diagnostics (ANL, U-Miss, UCLA, Princeton, Northwestern)**
    - **what is needed to transport beam, characterize beam, maintain beam properties during storage**

R&D Plans

- **Proton driver (FNAL, BNL)**
  - **develop and test high-gradient pulsed RF cavity**
  - **demonstrate intense, short proton bunches (≈1 ns)**
- **Feasibility study**
  - **BNL and *MC* jointly carrying out study of "high-end" Neutrino Factory design**
    - **estimate performance and identify R&D needs and cost drivers, building upon previous Fermilab study**

R&D Budget

- **Funding has been increasing**
  - **direct *MC* funds "leveraged"**
    - **sponsoring Labs cover physics staff costs**

Year	DOE ($M)	NSF ($M)	TOTAL ($M)
FY99	2.2	––	2.2
FY00	4.7	1.2	5.9

  - **additional funds contributed by Fermilab and BNL in support of feasibility study activities**
- **We hope for more support in FY01**

R&D Budget

- **Summary of FY99 spending**
  - **— note mix of institutions participating**
  - **— note base program contribution of "matching funds"**

Institution	Collaboration		Base Program	Overall
	Committed ($K)	Uncommitted ($K)	Committed ($K)	Committed ($K)
ANL	150		100	250
BNL	462.1	102.9	1264	1726.1
FNAL [1]	834		965	1799
LBNL [2]	274.2	115.3	123.3	397.5
Princeton U.	90	40	135	225
UC-Berkeley	50		125	175
UCLA	60		47.9	107.9
Mississippi	50		83	133
TOTALS	**1970.3**	**258.2**	**2843.2**	**4813.5**

NOTES:

[1] *Includes $124K carryover from FY98.*

[2] *Includes $54.5K carryover from FY98 and $50K uncommitted transferred from BNL.*

R&D Budget

- **Representative details**

Institution: Argonne National Laboratory

Task	Muon Collaboration Funds			Laboratory Funds		
	Effort ($K)	M&S ($K)	Sum ($K)	Effort ($K)	M&S ($K)	Sum ($K)
Targetry Studies						
Liquid Target Studies	$ 65.000	$ 5.000	$ 70.000			
Cooling Studies						
Lithium Lens				$10.000		$10.000
Cavity X-rays					$10.000	$10.000
Physics Salaries						
Cooling (Bent Solenoid, Cav. X-rays)	$ 75.000		$ 75.000	$75.000		$75.000
Administration and Travel		$ 5.000	$ 5.000		$5.000	$5.000
SUBTOTALS	**$ 140.000**	**$ 10.000**		**$85.000**	**$15.000**	
TOTALS			**$ 150.000**			**$100.000**

R&D Budget

- **Representative accomplishments**

Argonne National Laboratory
(Accomplishments–FY1999)

- Developed theory of bent solenoid channel and identified specific aberrations and emittance growth mechanisms
- Explored methods of producing small emittance from low momentum muons in a lithium lens, with the aim of defining an optimum lens configuration
- Began measurements of the x-ray spectrum from an RF cavity to assess its effect on the diagnostics envisioned for the proposed FNAL muon cooling experiment
- Developed code for liquid metal magneto-hydrodynamics that is being used to predict heating, pressure, and mechanical deformation of a liquid-metal jet injected into a 20-T solenoid and heated by an intense proton beam
- Quantified slow (Joule) and fast (beam) pressure pulses in a liquid-lithium cell and carried out preliminary analysis of thermal, pressure, and mechanical response

R&D Budget

- **FY00 funding distribution (only DOE funds)**

Institution	MUCOOL Expt. & Generic Studies	TARGETRY Expt.	SALARY	RESERVE	TOTAL ($K)
BNL		1818			1818
FNAL	1229		90		1319
LBNL	438	75		15	528
ANL	25	80	200		305
IIT	157				157
Mississippi	68				68
Princeton	80	100	60		240
UCB			120		120
UCLA	50		80		130
TOTAL ($K)	**2047**	**2073**	**550**	**15**	**4685**

— **NSF has recently provided $1.2M for muon-related R&D**

R&D Budget

- **FY00 year-to-date summary (through April '00)**

Institution	Collaboration		Base Program	Overall
	Year To Date ($K)	Uncommitted ($K)	Year To Date ($K)	Year To Date ($K)
ANL	230	75	0	230
BNL	1028	790	1549	2577
FNAL [1]	1162	157	1257	2419
LBNL	211	317	126	337
Princeton U. [2]	174	106	200	374
UC-Berkeley	75	45	24	99
UCLA	63	67	16	79
Mississippi	50	18	83	133
Cornell + NSF Contracts	0	1194	0	0
TOTALS [3]	**2993**	**1575**	**3255**	**6248**
		2768		

NOTES:

[1] *Includes $157K IIT subcontract.*

[2] *Includes $40K carryover from FY99.*

[3] *Additional NSF funding highlighted.*

R&D Budget

- **Budgets based on technology-limited schedule prepared (FY01–FY05)**
  - **FY01 (*MC* + base) is reasonably well defined; out-years less so**

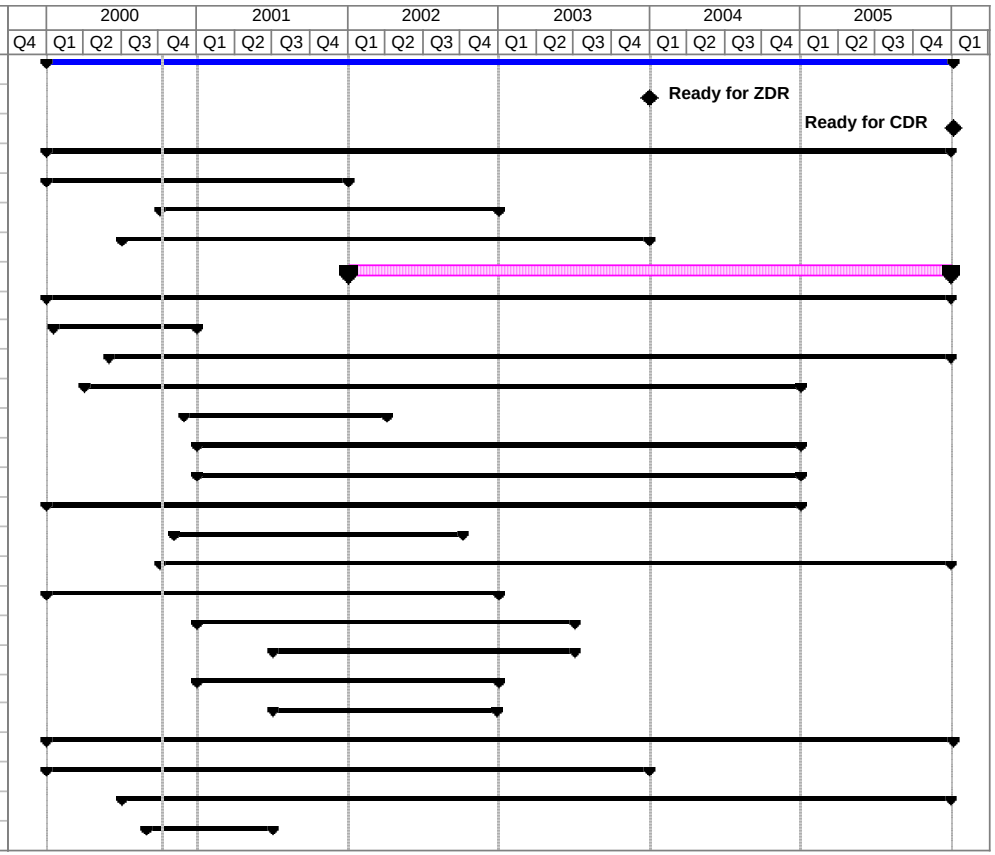
R&D area	FY01 ($M)	FY02 ($M)	FY03 ($M)	FY04 ($M)	FY05 ($M)	Sum ($M)	Prior ($M)	Overall ($M)
MUCOOL	4.9	3.8	4.3	23.3	17.5	53.7	7.3	61.0
Targetry	5.7	5.2	4.4	3.7	2.1	21.1	4.1	25.2
Proton Driver	0.1	0.1	0.1	0.1	0.1	0.5	0.6	1.1
Beam Simulations	2.3	2.0	2.0	2.0	2.0	10.3	4.0	14.3
Acceleration/Storage Ring	0.9	0.6	0.6	0.6	0.6	3.1	0.5	3.6
Components	1.9	4.0	7.0	2.3	1.0	16.2	0.1	16.3
ZDR Preparation				10.0	10.0	20.0	---	20.0
TOTAL	16	16	18	42	33	125	17	142

  - **reaching the ZDR stage will require about $66M ($50M in future funds)**
- **At present funding levels, shortfall next year would be about $5M**
  - **hope for NSF increase to get closer to what's needed, but this leaves no flexibility for alternatives (e.g., band targets) or collider work**

R&D Schedule

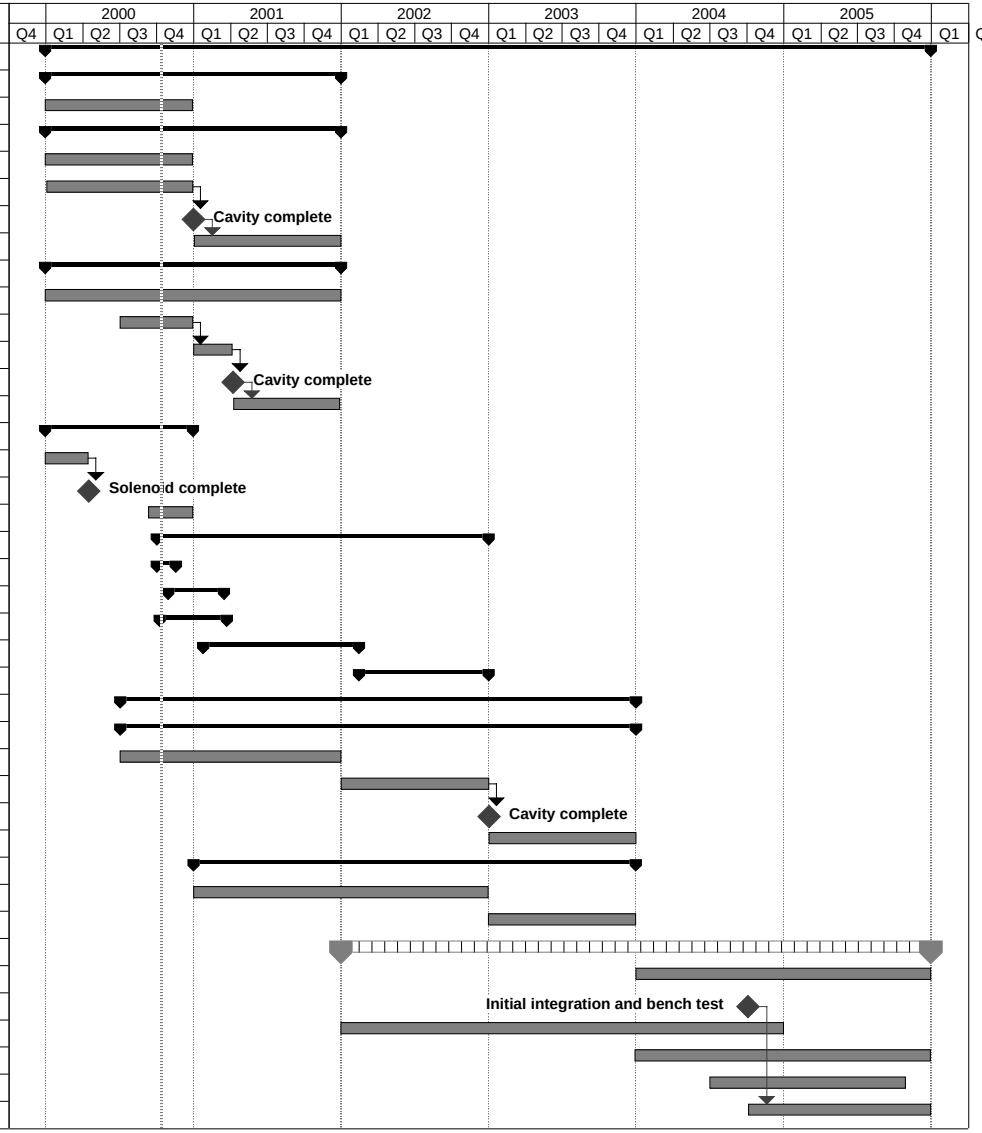
- **Preliminary R&D schedule based on technology-limited plan developed**
  - **— not resource loaded yet, nor fully linked (plan and schedule will be iterated this summer)**

ID	Task Name
1	**Neutrino Factory R&D**
2	Ready for ZDR
3	Ready for CDR
4	**MUCOOL**
5	**805 MHz RF**
22	**Liquid hydrogen absorber**
64	**201 MHz RF**
73	**Cooling demonstration**
80	**Targetry**
81	**AGS extraction prep**
84	**Liquid metal jet**
106	**AGS extraction upgrade**
111	**Pulsed solenoid**
123	**Hybrid magnet development**
125	**Solid target studies**
129	**RF systems**
157	**Cavity solenoid**
169	**Capture experiment**
185	**Simulation and validation**
198	**Proton Driver**
199	**High-gradient RF**
202	**Inductive inserts**
205	**Short bunch tests**
207	**Beam simulations**
215	**Acceleration and storage ring**
219	**Components**
237	**Feasibility study II**



R&D Schedule

ID	Task Name
4	**MUCOOL**
5	**805 MHz RF**
6	Lab G preparation
7	**Open cell cavity fab**
8	Design
9	Fabricate
10	Cavity complete
11	Test
12	**Be window cavity**
13	Be window testing
14	Pillbox cavity design
15	Pillbox cavity fab
16	Cavity complete
17	Test
18	**805 MHz test solenoid**
19	Design and fab
20	Solenoid complete
21	Make operational in Lab G
22	**Liquid hydrogen absorber**
23	**Materials tests**
28	**Al widow destruction test**
36	**Fluid flow study**
44	**Absorber Cryogenic test**
61	**Beam tests**
64	**201 MHz RF**
65	**RF cavity**
66	Design
67	Fab
68	Cavity complete
69	Test
70	**201 MHz test solenoid**
71	Design and fab
72	Test
73	**Cooling demonstration**
74	Fab channel components
75	Initial integration and bench test
76	Detector development
77	Detector fab
78	Install components
79	Beam tests



R&D Schedule

- **Focus here on three-year period (FY2001, FY2002, FY2003)**
  - **program components include**
    - **beam simulations**
    - **targetry**
    - **MUCOOL**
    - **proton driver**
    - **components**
    - **feasibility studies**

R&D Schedule

- **FY01 highlights**
  - **complete front-end simulations, including error sensitivity studies and multiple scattering and straggling issues**
  - **commission A3 beamline and carry out initial beam test of target (~6 weeks parasitic operation)**
  - **begin design of radiatively cooled solid target**
  - **complete target-solenoid design**
  - **high-power tests of 805-MHz open-cell and Be-window pillbox cavities**
  - **complete design of prototype LH_2 absorber**
  - **continue Be window development**
  - **fabricate 201-MHz SCRF cavity**
  - **conceptual design of induction linac with internal solenoid and pulser**
  - **complete feasibility study of high-end facility and prepare report on facility design and physics reach for Snowmass '01**

R&D Schedule

- **FY02 highlights**
  - **complete acceleration and storage ring simulation studies including errors and fringe fields**
  - **begin yield measurements to benchmark MARS (π, n)**
  - **construct prototype carbon target**
  - **test 70 MHz RF cavity in high-radiation environment**
  - **begin fabrication of high-power 201-MHz NCRF cavity and its test solenoid**
  - **complete LH_2 absorber tests with beam**
  - **test 201-MHz SCRF cavity (CW and pulsed)**
  - **design prototype high-power 201-MHz RF source**
  - **begin fabrication of induction linac module and pulser**

R&D Schedule

- **FY03 highlights**
  - **integrate simulations end-to-end (target to storage ring) with realistic errors and component specifications**
  - **test target with solenoid and RF cavity at 10^{14} ppp (~6 weeks parasitic beam)**
  - **complete pion yield tests (~6 weeks parasitic beam)**
  - **begin high-power tests of 201-MHz NCRF components**
  - **complete and test induction linac module**
  - **begin beam tests of diagnostics**

Summary

- *MC* R&D program is vigorous and healthy
  - clear directions to proceed on all fronts
- Long-range planning to direct R&D program has been initiated
- *MC* membership and funding both growing at healthy rate
  - grass-roots effort of both high-energy and accelerator physicists
  - we have the manpower to carry out our program
- Involvement of NSF institutions (Universities ⇒ students) strengthens effort
  - involvement of international institutions and groups is also growing
- We must continue these positive trends
- HEPAP endorsement of *MC* R&D plan is critical to increasing financial support from Labs (base program) and funding agencies (DOE, NSF)
- At Snowmass '01 we will give detailed information to permit community to consider and evaluate the physics potential of a Neutrino Factory