Muon Ionization Cooling R&D in the MuCool Program

DPF 2009

Yağmur Torun

Illinois Institute of Technology

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Who ordered that? - I. I. Rabi

- Energy frontier ($\mu^+\mu^-$ collider)
- Neutrino physics (ν factory)
- Muon physics

- Low-energy cooled muon beam: extraordinarily precise LFV experiments (eg. $\mu 2e$)
- Acceleration and storage ring: neutrino mixing with unprecedented precision
- Acceleration to very high energy: energy-frontier collider

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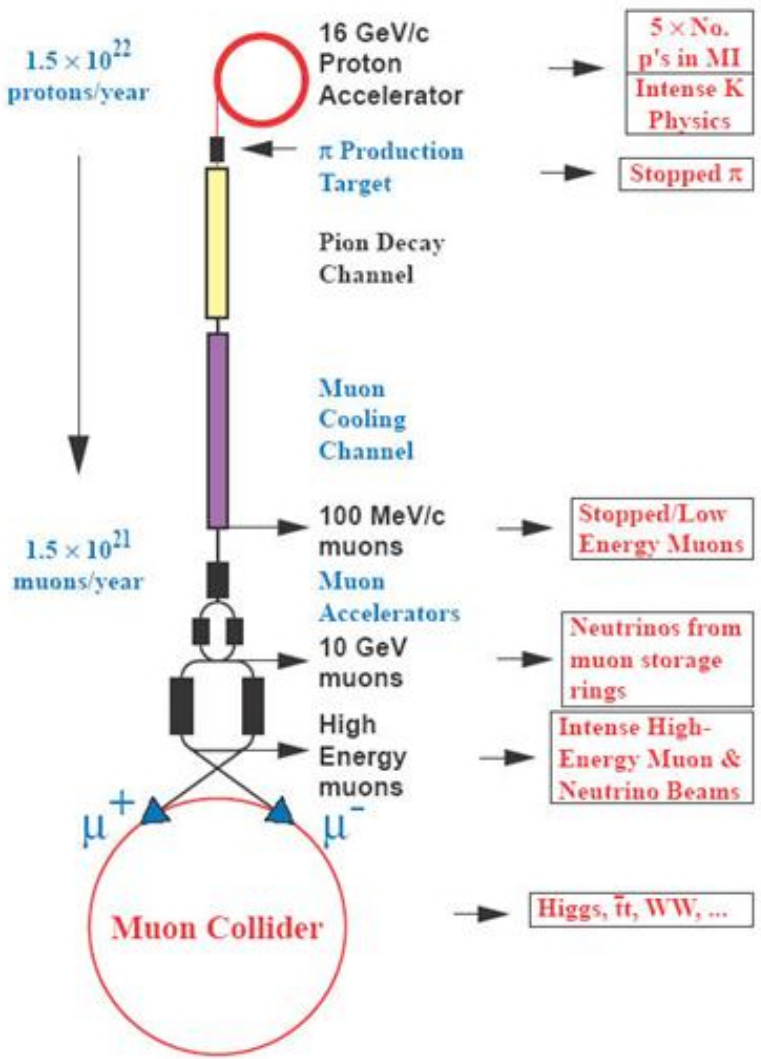

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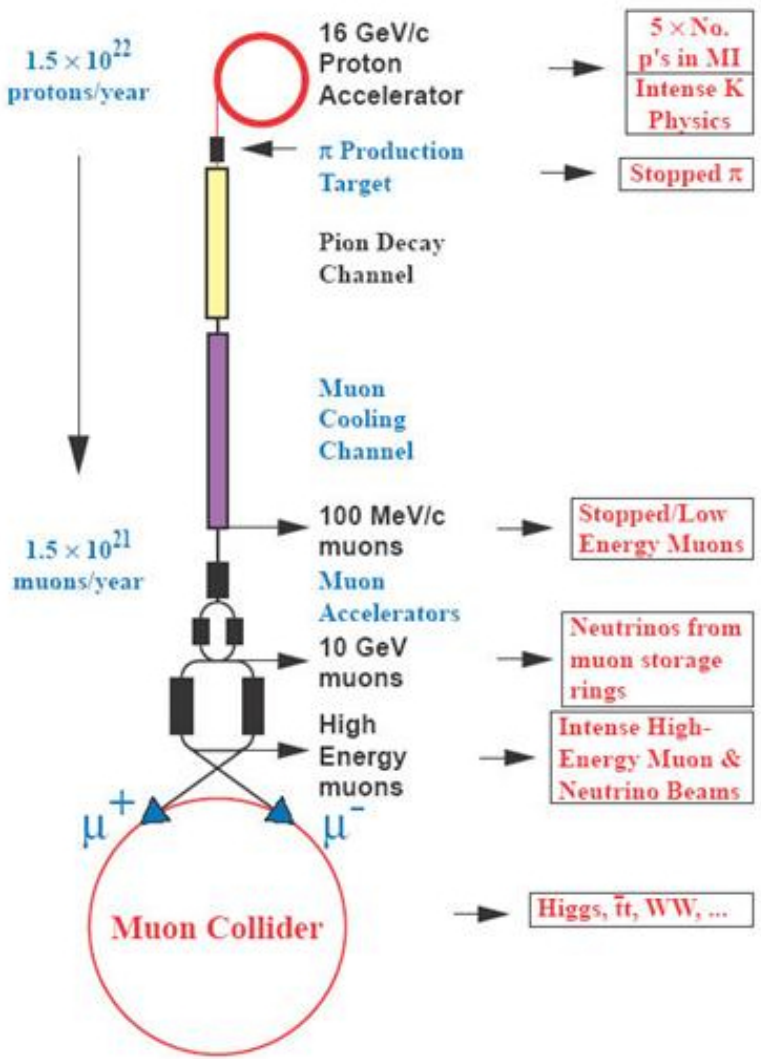

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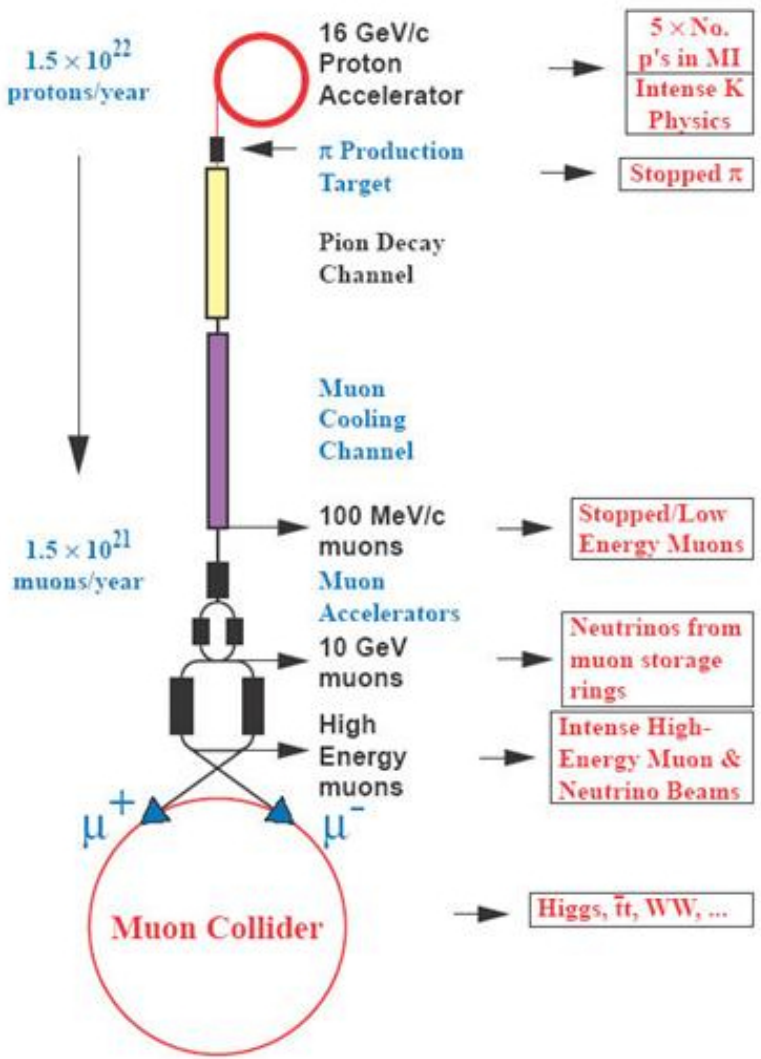

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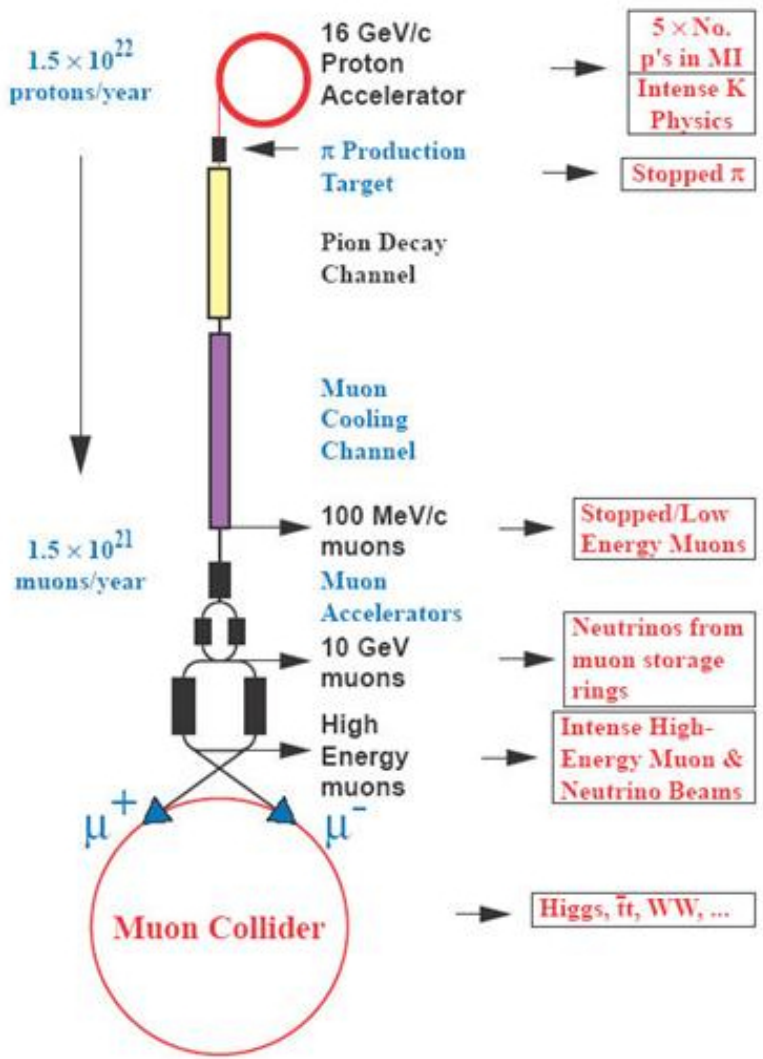

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- large muon mass means
  - negligible synchrotron radiation for high-energy collider (1.5-4TeV)
  - large cross section for some processes ($\sigma \sim m^2$)
  - small beamstrahlung

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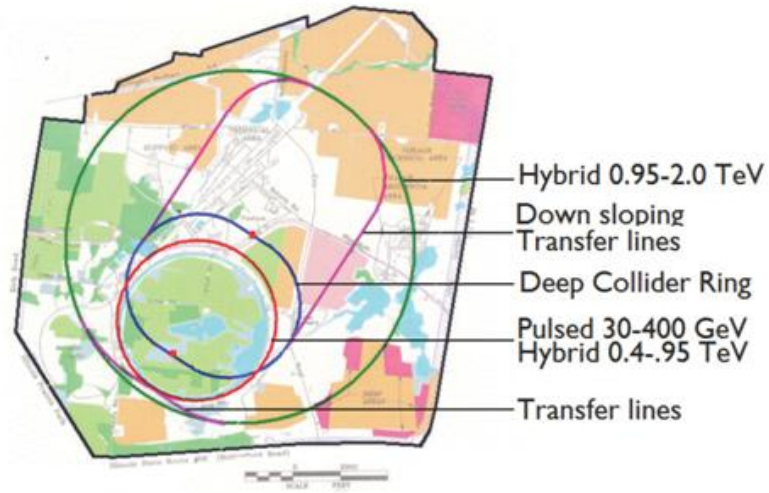

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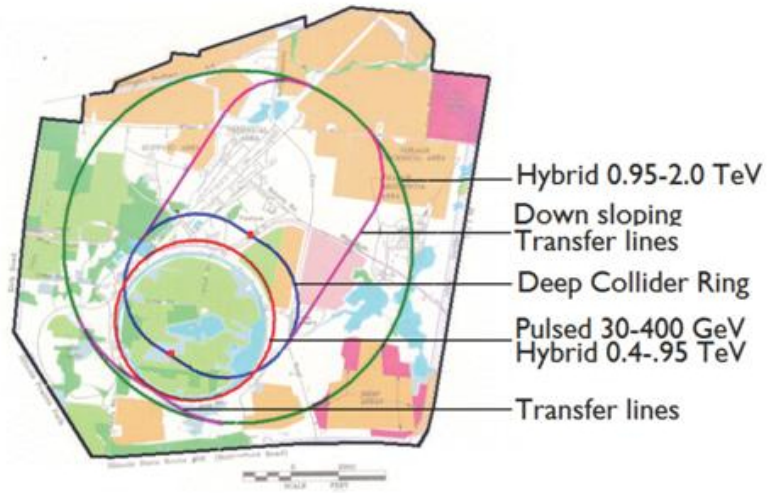

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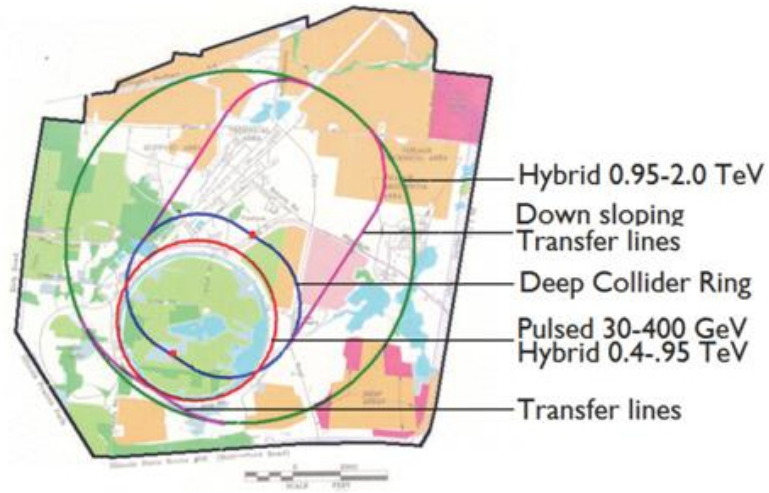

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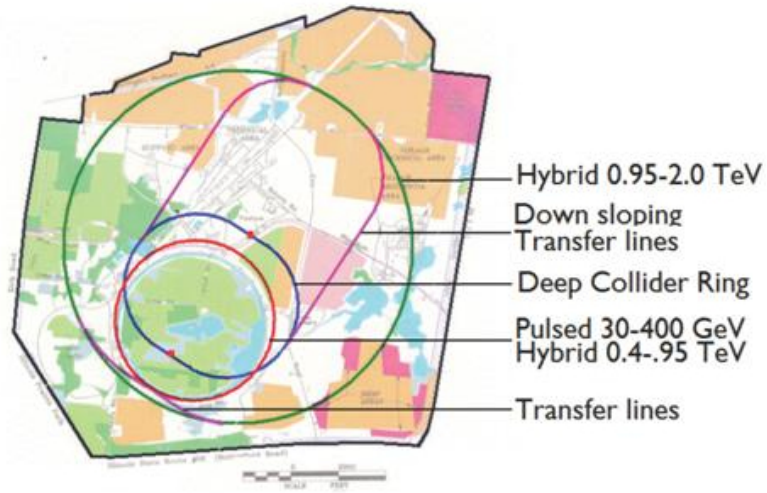

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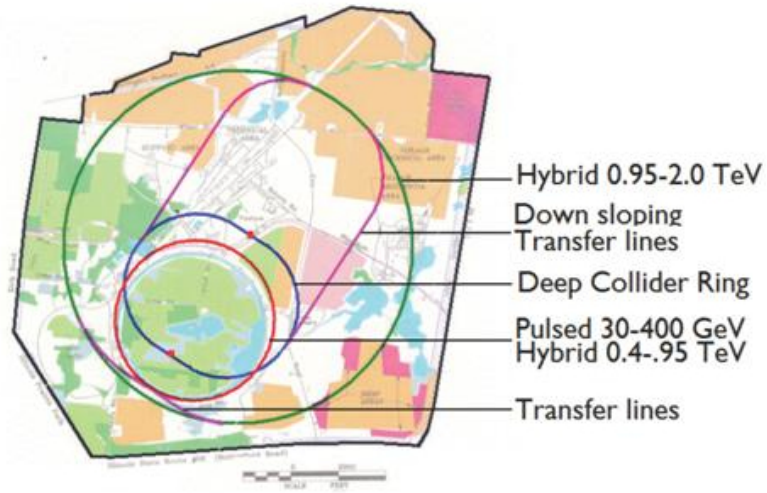

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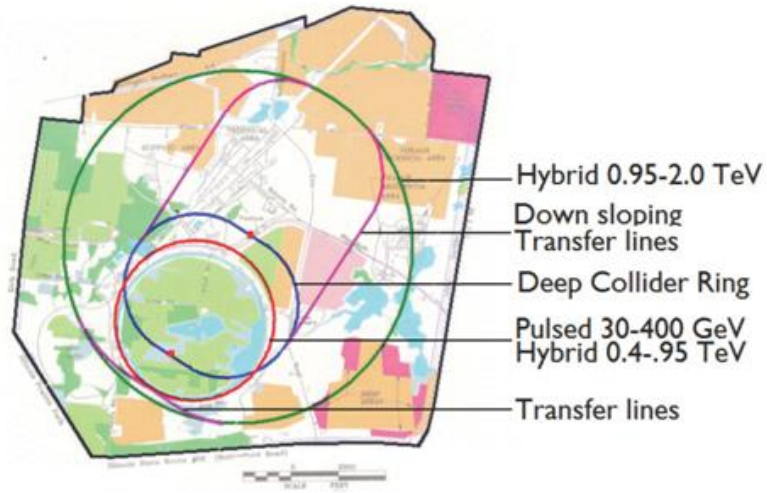


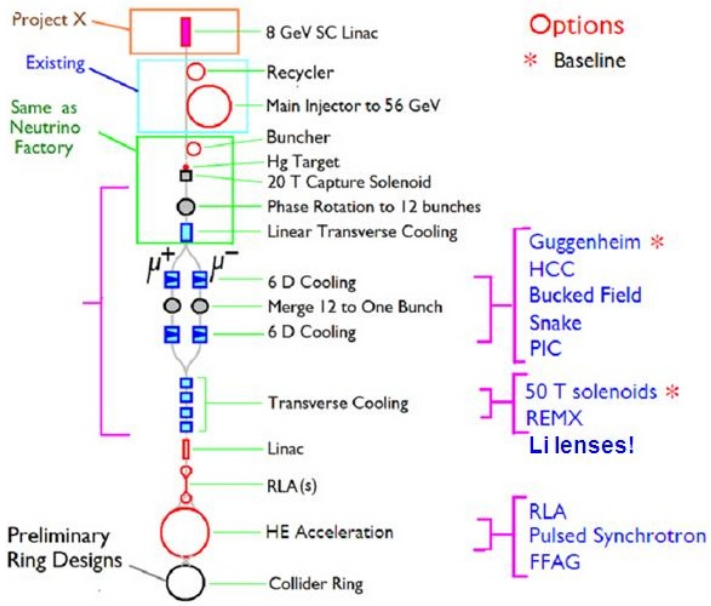
That sounds great! When can you build one of each?

Technical challenges:

- tertiary muon "beam" produced into broad phase space from pion decay

$$p + A \rightarrow X + \pi \rightarrow \nu_\mu + \mu$$

- need high-power p-driver for intensity
- efficient scheme for capturing pions
- and lots of beam cooling to fit muons into accelerator acceptance
- within muon lifetime (2.2μs)
- storage/collider ring magnets and detectors have to cope with muon decay background



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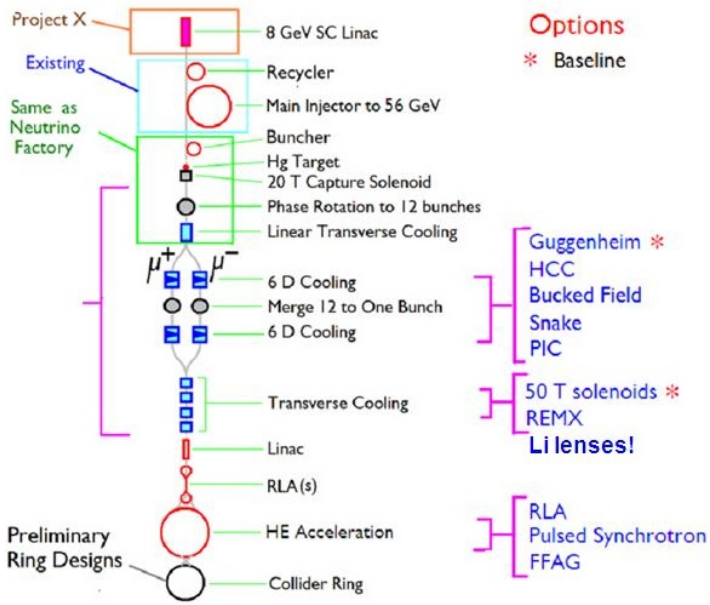

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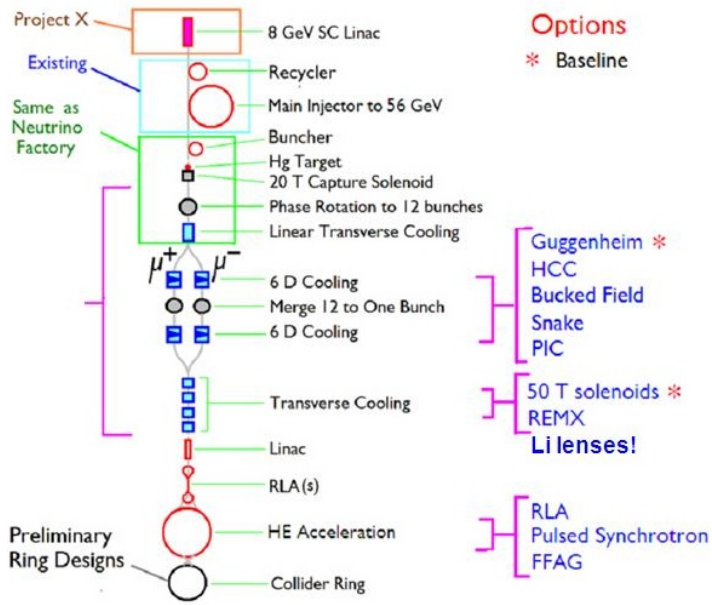

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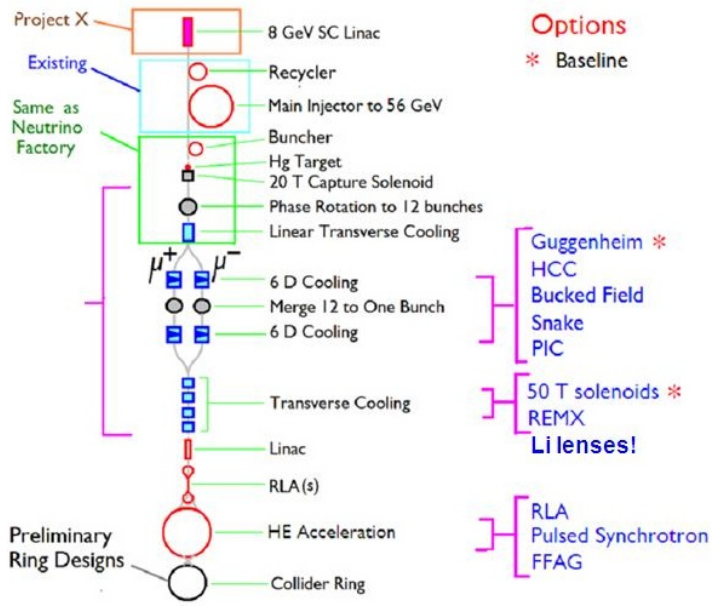

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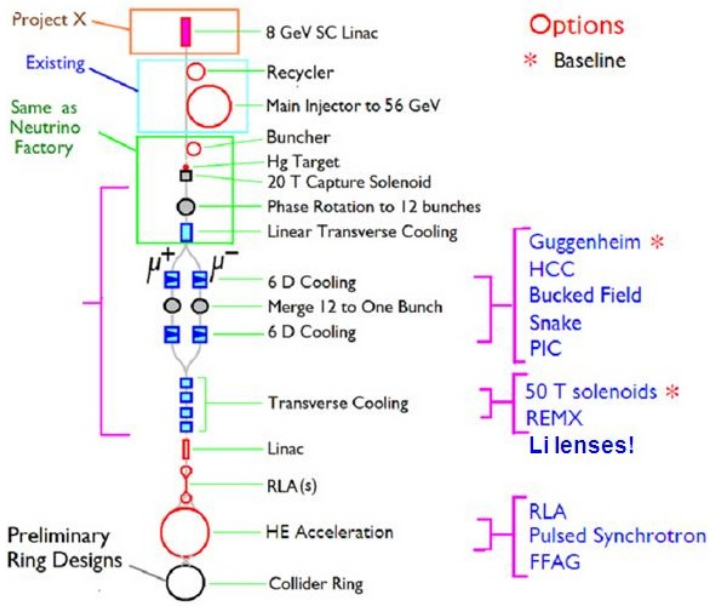

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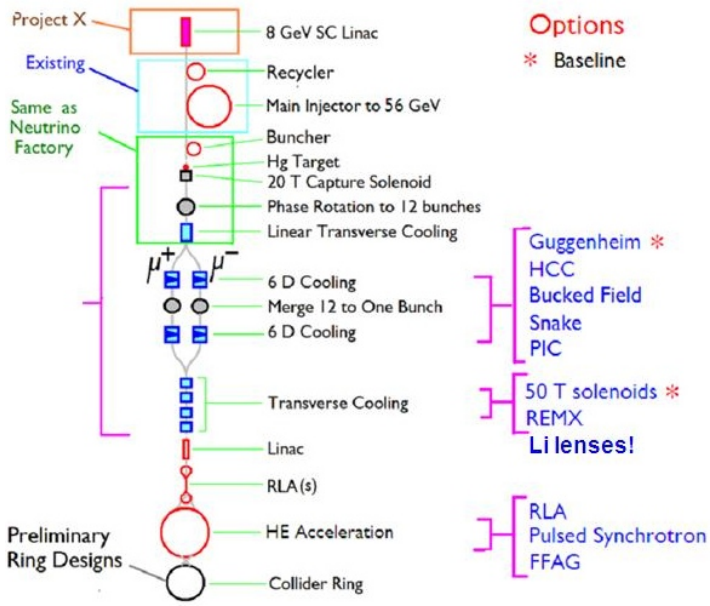

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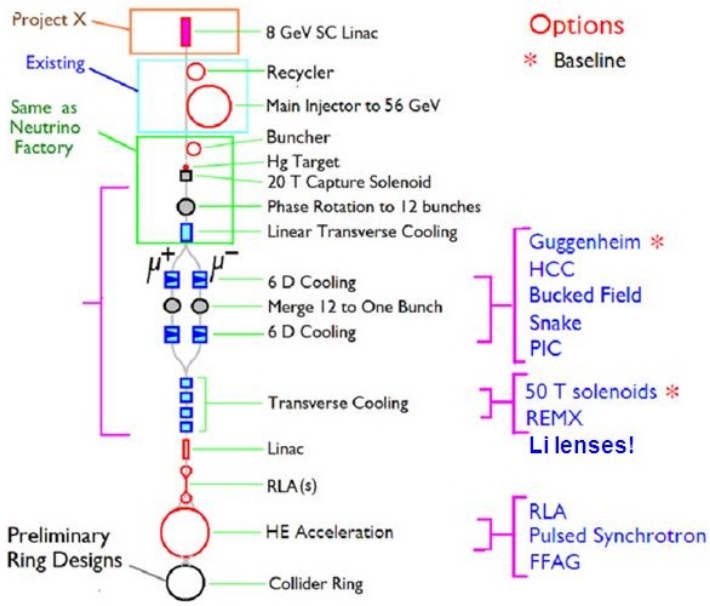

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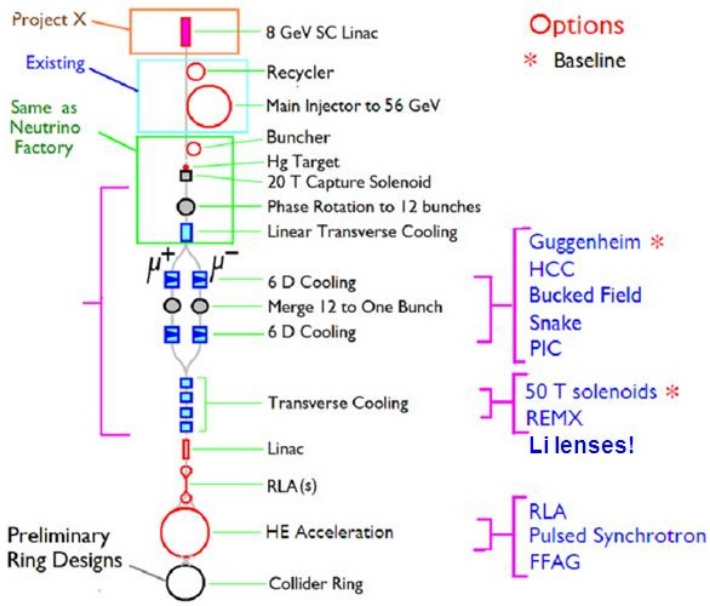

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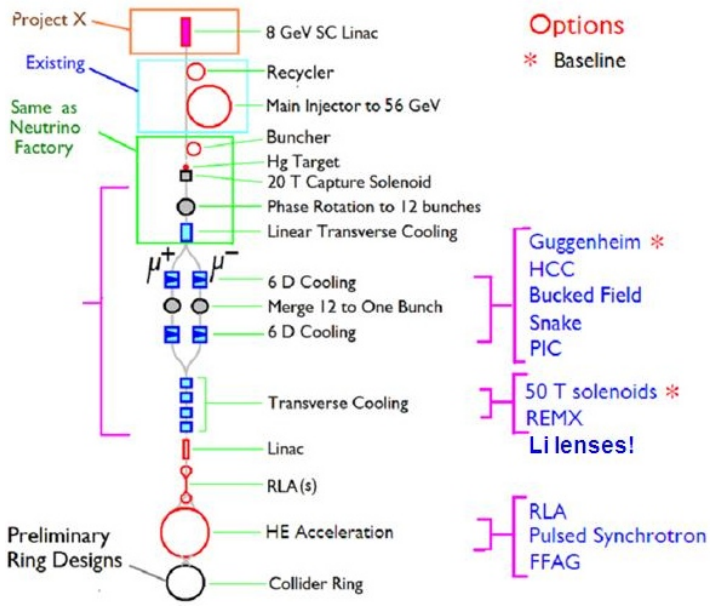

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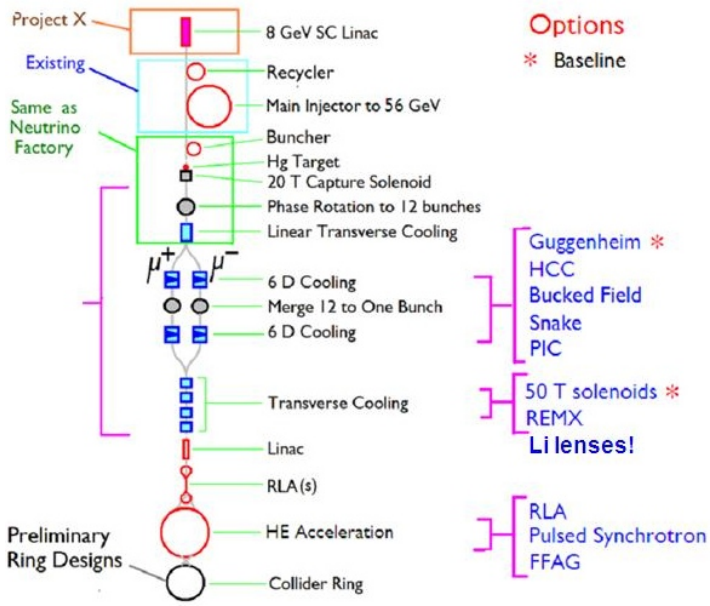

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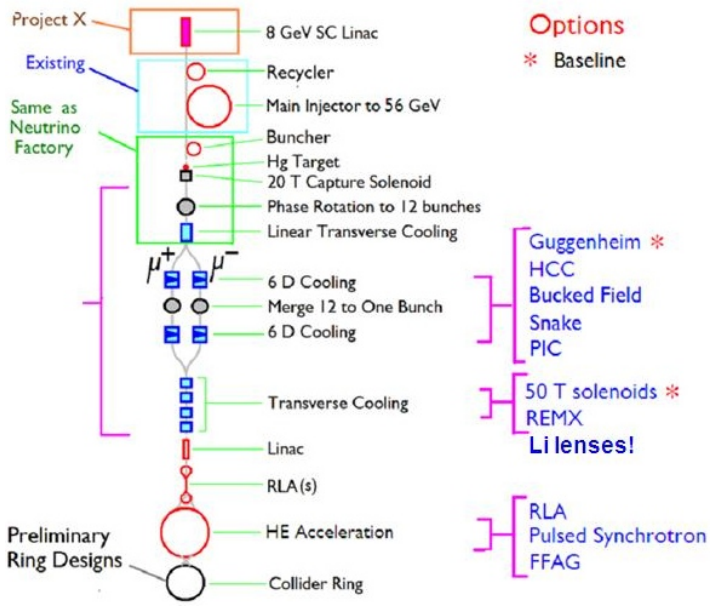

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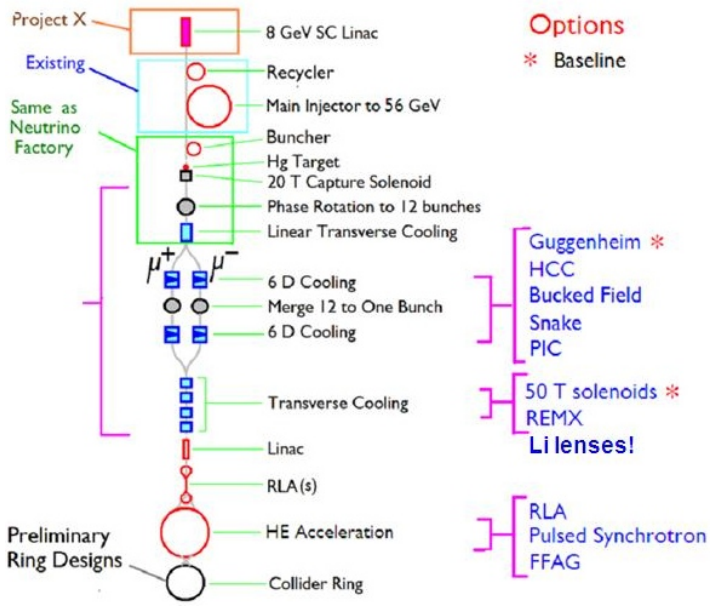

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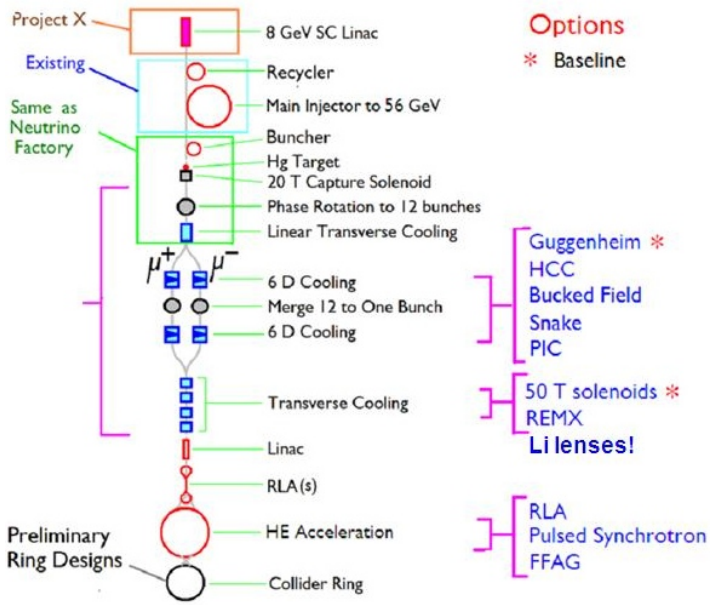

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Ionization Cooling

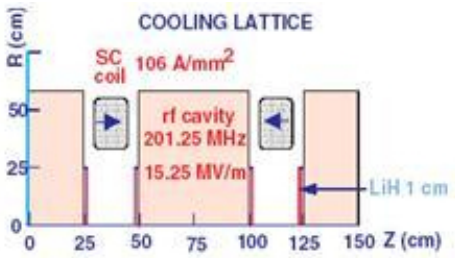
Normalized transverse emittance ε of muon beam in solenoidal channel

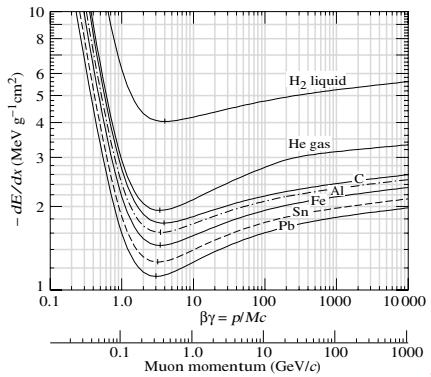
$$\frac{d\varepsilon}{ds} \simeq -\frac{\left\langle \frac{dE}{ds} \right\rangle}{\beta^2 E}(\varepsilon - \varepsilon_0), \quad \varepsilon_0 \simeq \frac{0.875\text{MeV}}{\left\langle \frac{dE}{ds} \right\rangle X_0}\frac{\beta_\perp}{\beta}$$

ε_0: equilibrium emittance (multiple scattering $\sim$ cooling)

Efficient cooling requires:

- Energy absorbers with large dE per radiation length (LH2: 29MeV/m x 8.9m; LiH: 151MeV)
- Strong focusing (large B-field), $\beta_\perp \sim p/B$
- High-gradient rf cavities to replace longitudinal momentum and phase focusing
  performance degraded in B-field (critical R&D)
- tight packing to minimize decay losses
- low muon momentum
- emittance exchange for 6D cooling
  (or twisted field - helical cooling)





Ionization Cooling

- dE/dx in LH2 $\sim$30 MV/m
- Accelerating cavities need to provide lost energy
- Phase focusing requires 2$\times$ gradient
- 4$\times$ space for RF (as LH2) for 15 MV/m gradient
- must work reliably in large (multi-Tesla) magnetic field
- lots of plumbing for vacuum, cryo, rf power and diagnostics
- large beam sizes force low frequency RF (201 MHz)
- thin windows for LH2 containment and RF cavities
- safety issues with absorbers

MuCool Mission

- design, prototype and test components for ionization cooling
  - Energy absorbers
    - Liquid hydrogen
    - Solid LiH
  - RF cavities
    - 201 MHz pillbox (MICE prototype)
    - 805 MHz program for systematic studies
  - Magnets
    - "CatchCo" magnet (similar to focus coil in MICE)
    - Coupling coil under construction
  - Diagnostics
- including associated simulation and theoretical studies
- support system tests
  - MICE
  - Future cooling experiments (MANX, ...)

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  - Future cooling experiments (MANX, ...)

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  - Energy absorbers
    - Liquid hydrogen
    - Solid LiH
  - RF cavities
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    - 805 MHz program for systematic studies
  - Magnets
    - "Lab-G" magnet (similar to focus coil in MICE)
    - Coupling coil under construction
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      – rectangular cavity (magnetic field angle)
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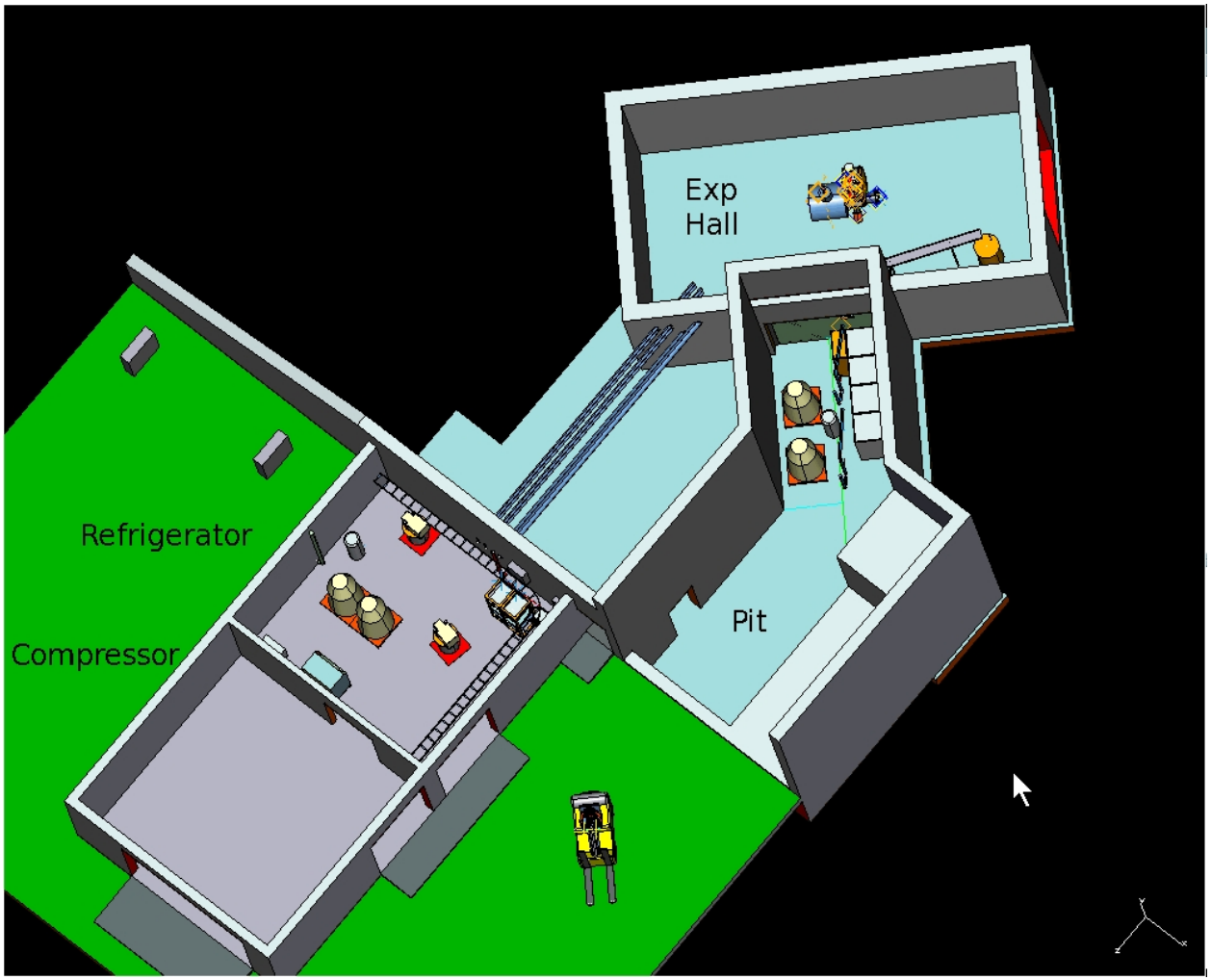
MuCool Test Area (MTA) – http://mice.iit.edu/mta/

Dedicated facility at the end of the Linac built to address MuCool needs



- RF power (13 MW at 805 MHz, 4.5 MW at 201 MHz)
- Superconducting magnet (5 T solenoid)
- Large coupling coil (under construction)
- 805 and 201 MHz pillbox cavities
- Radiation detectors (to be reinstalled)
- Cryo plant (to be commissioned)
- 400 MeV p beamline (commissioned)

MuCool Test Area (MTA)



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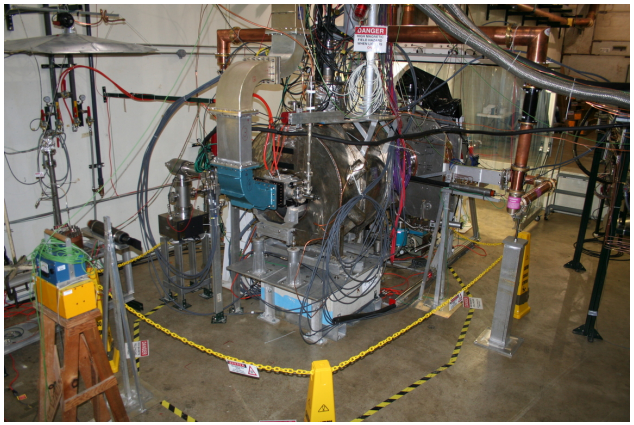
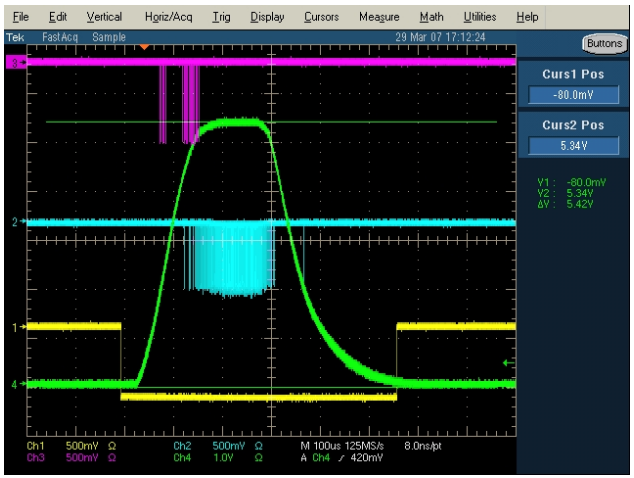
Experimental Hall



Beamline



X-rays at high gradient

Compressor Room

Recent Progress

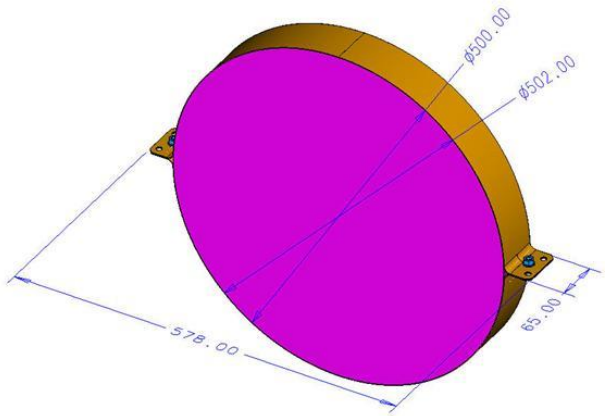
- LiH test discs engineered
- Vacuum RF program (805 and 201 MHz pillbox) continued; new 805 MHz rectangular cavity designed
- Coupling coil being built in China (Harbin IT)
- Working toward new experiment to test high pressure cavity in beam
  - Beamline commissioned to 1st stop
  - MTA reconfiguration work ongoing
- Modeling effort continuing
  - Cavity arcs with/without axial magnetic fields
  - Electron transport in magnetic field

LiH Absorber

- LiH absorbers are now the "baseline" for the initial 4D cooling
  - Replaced LH2
- Material properties of LiH to be confirmed
  - Thermal characteristics
    - Thermal conductivity
    - Stability
  - Radiation Stability
- Program Goal
  - Test Thermal properties of Hot-Isostatic Pressed LiH
    - Claimed to yield material with 98%+ theoretical density
    - Best thermal conductivity

LiH Absorber Disc Fabrication

- Subcontracted for production at Y12
  - Produced by Hot Isostatic Pressing
  - using existing mold design
  - Mechanical properties of final parts will be measured
    - Density, hardness, etc
  - Final Parts to be chemically tested
  - Radiographed to ensure no voids
  - Machined to size
  - Dimensional inspection
  - Coated with vapor barrier
- Production will consist of
  - 30 and 50 cm diameter disks
    (+2" disks for destructive testing)



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  - field emission beamlets focused by magnetic field (enough to drill holes in windows)
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  - establish feasibility of thin windows
  - test buttons with different materials/coatings
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Need to study magnetic field angle dependence

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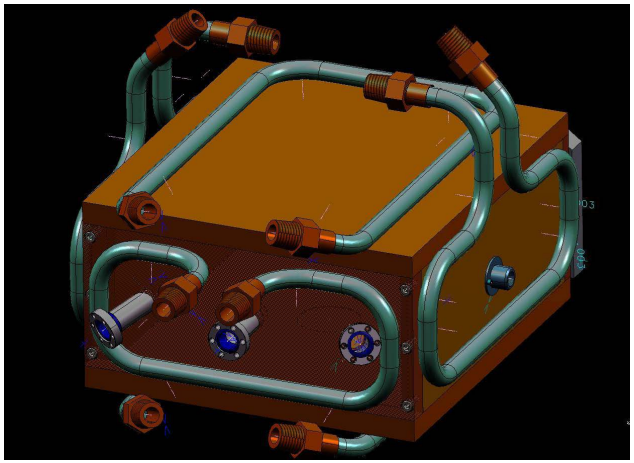

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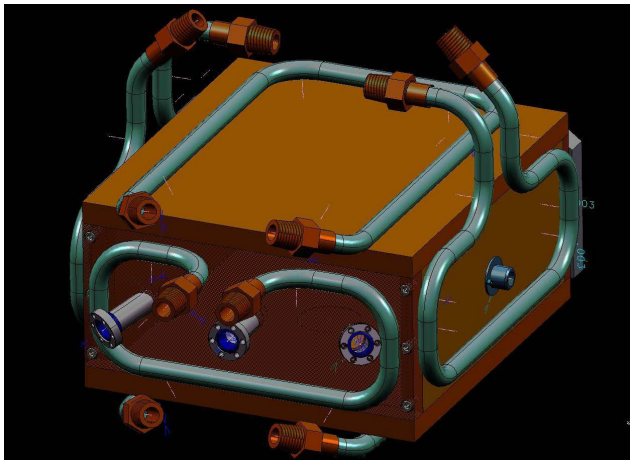

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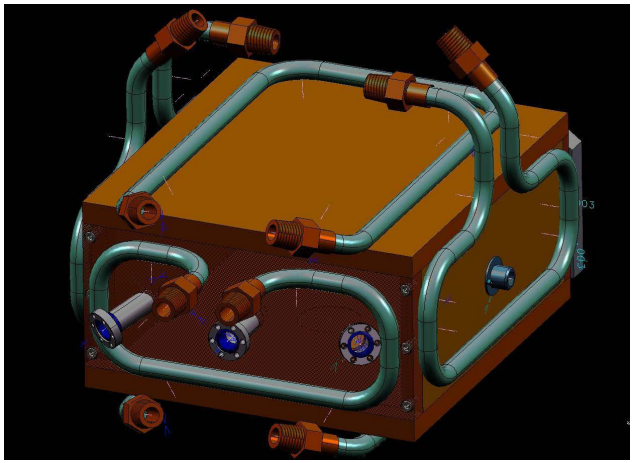

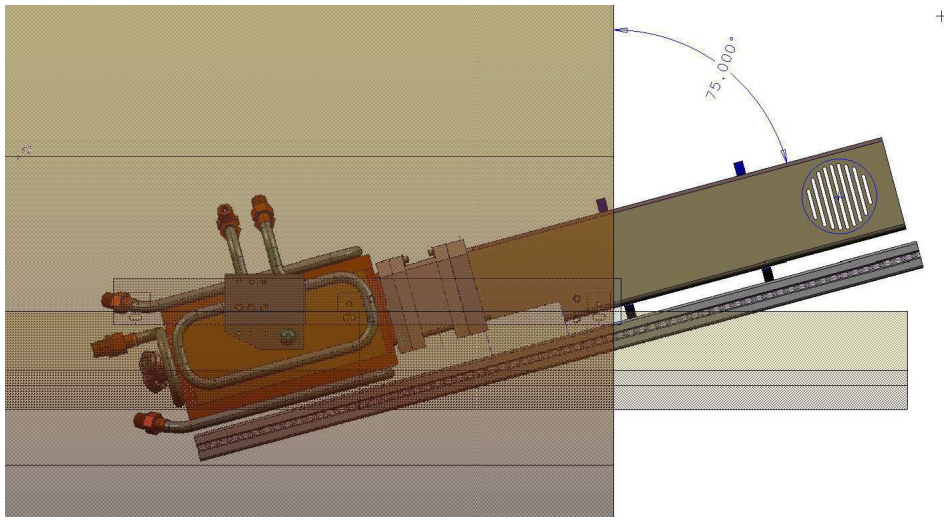

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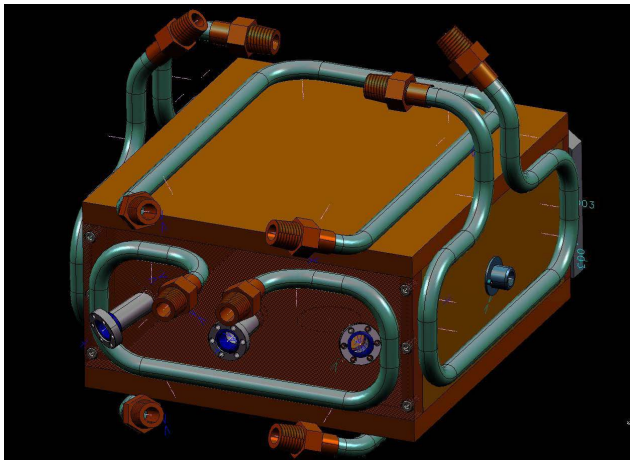

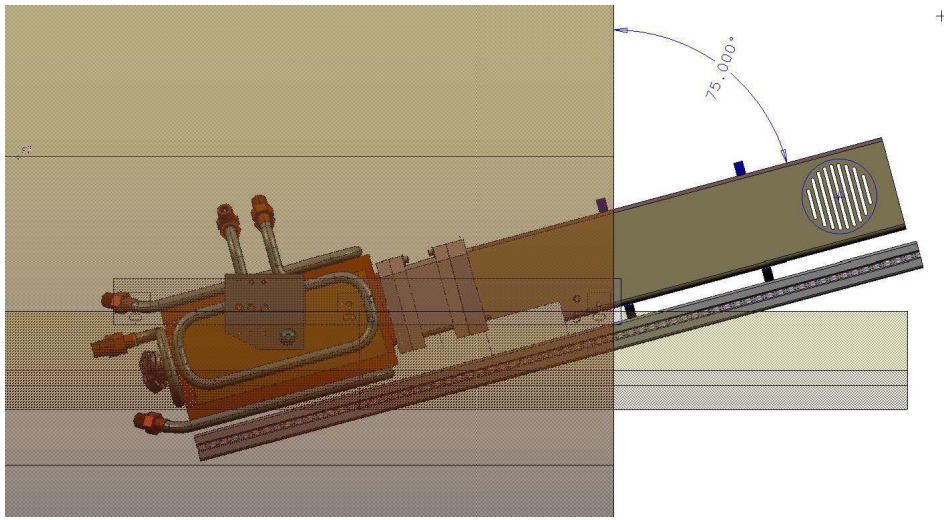

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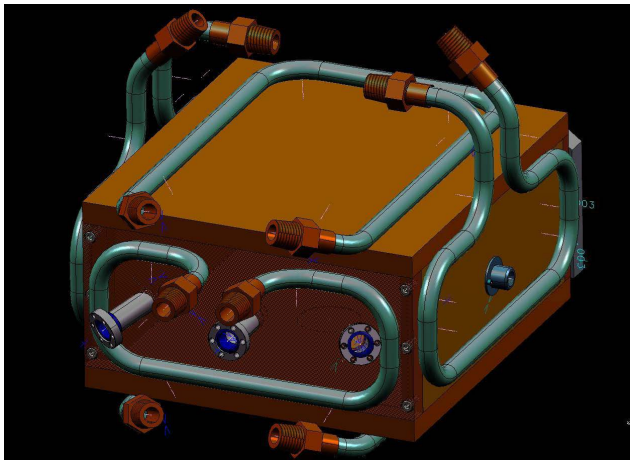

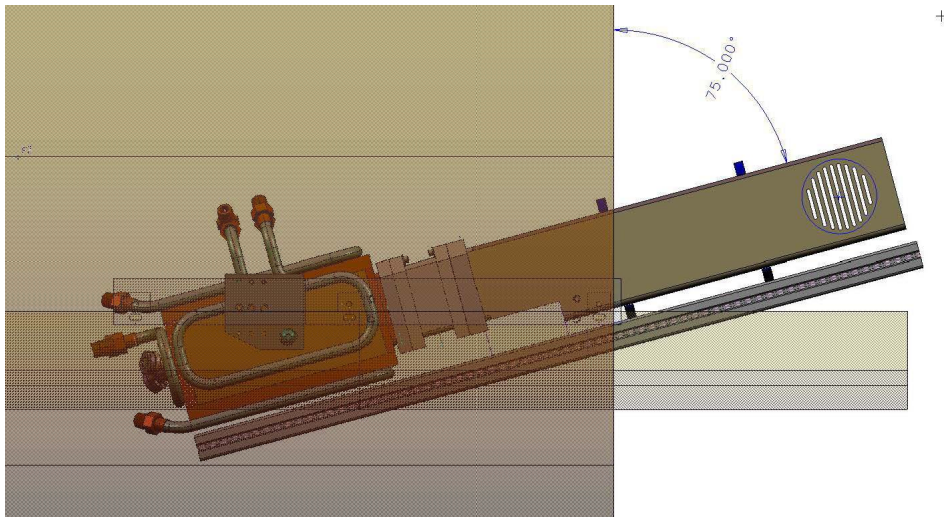

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- Would also like to understand the underlying physics to drive cavity/channel designs
- Several people claim they understand everything

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MTA Reconfiguration

We are in the process of upgrading the facility to support future muon cooling R&D

- Commission cryo infrastructure
  - Valve box in hall
  - Transfer lines to cryo plant in surface building
- Rearrange components in hall for RF tests
  - Stand to raise solenoid to beam height
  - Platform for 201MHz cavity
- Beamline
  - Integrate/commission controls
  - Reroute waveguides in hatch
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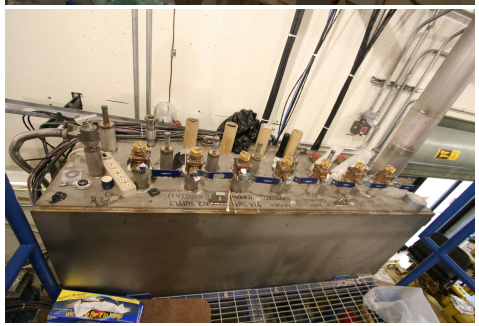
Started Oct 1 – expected completion "mid-2009"

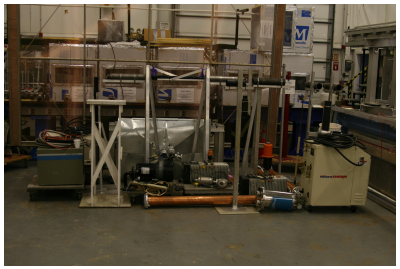
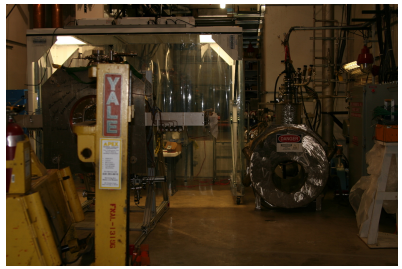
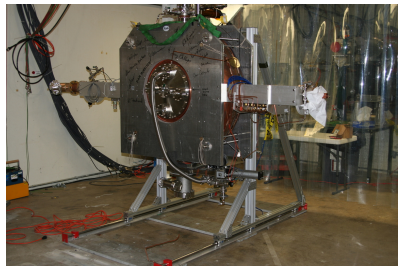
Cryo

- Transfer lines built and installed between hall and refrigerator room (Oct-Feb)
- HVAC unit relocated to accommodate xfer line connection (Oct)
- Valve box installed in hall (Oct), to be connected to magnet
- Plumbing in surface building mostly complete
- Instrumentation, controls, commissioning



Hall reconfiguration

- Detector stands and various small parts removed from hall (Sep)
- Pit shield wall removed, forklift brought in (Oct)
- Solenoid and 201 MHz cavity disconnected/moved (Sep/Oct)

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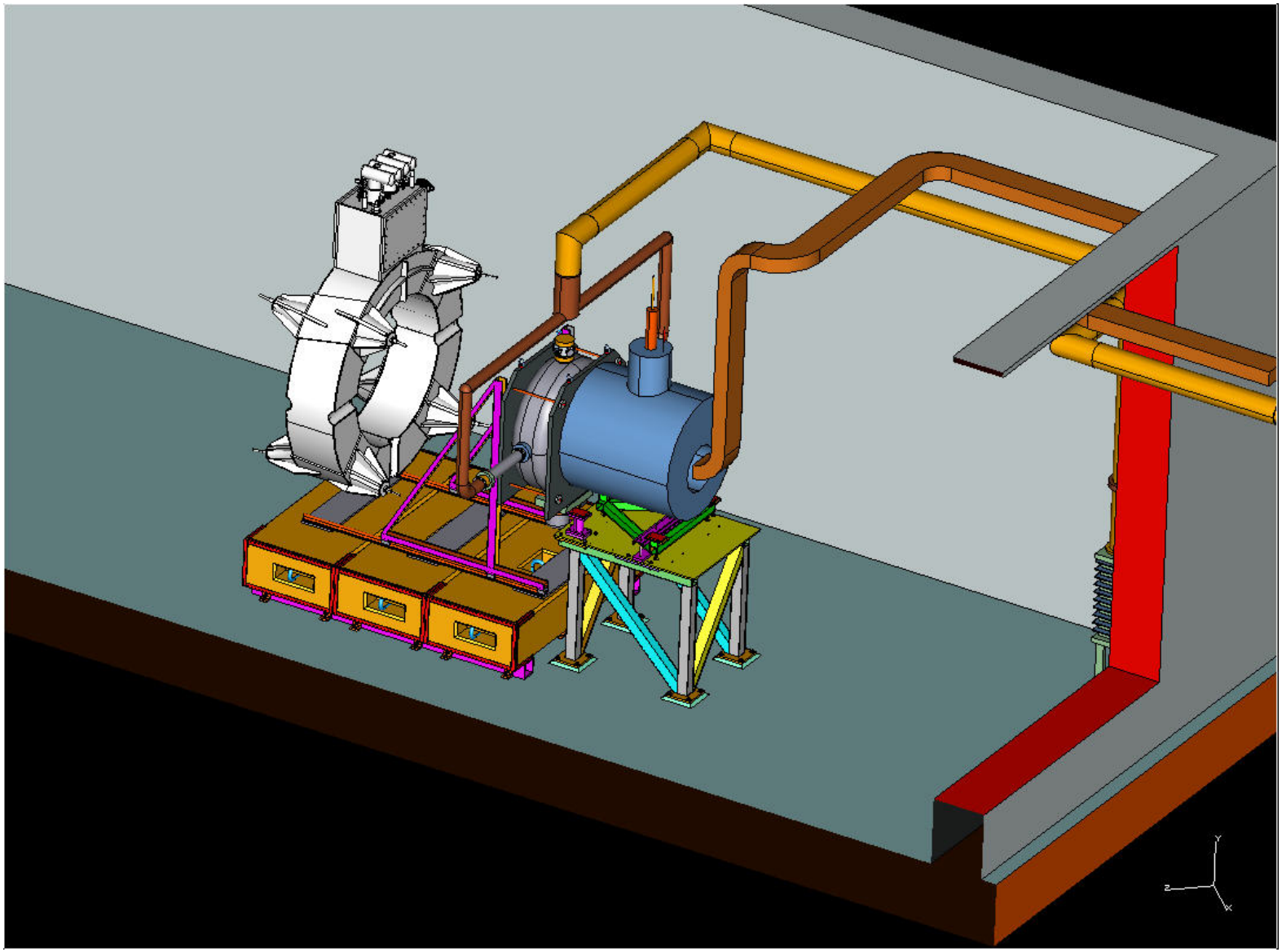
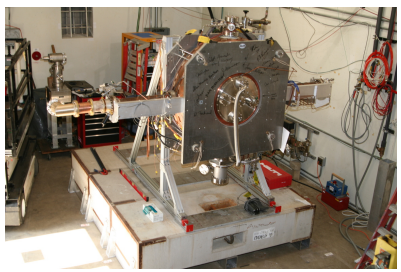
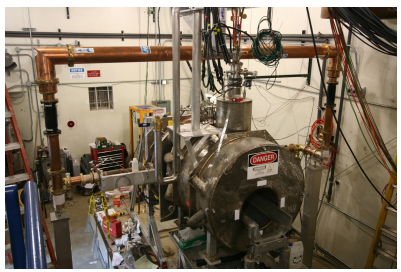


Hall reconfiguration

- 805 and 201 MHz waveguide sections removed (Oct)
- New platform parts fabricated and installed (Oct)
- 201 MHz cavity reinstalled at beam height (Oct)
- Valve box stand fabricated and installed (Oct)
- Magnet stand fabricated (Oct), magnet reinstalled (Jan)
- 201 MHz coax line reconnected to cavity (Jan)
- 805 MHz waveguide installed (Feb)
- Clean room legs extended to new cavity height (Mar)



Hall Reconfiguration

- RF power successfully transmitted through waveguides to 201 MHz cavity and 805 MHz dummy load (Jun 30)
- New cables for future use installed (July)
- Cleanup/wipedown this week
- Still to be installed
  - 805 MHz cavity (Aug?), detectors (Aug)

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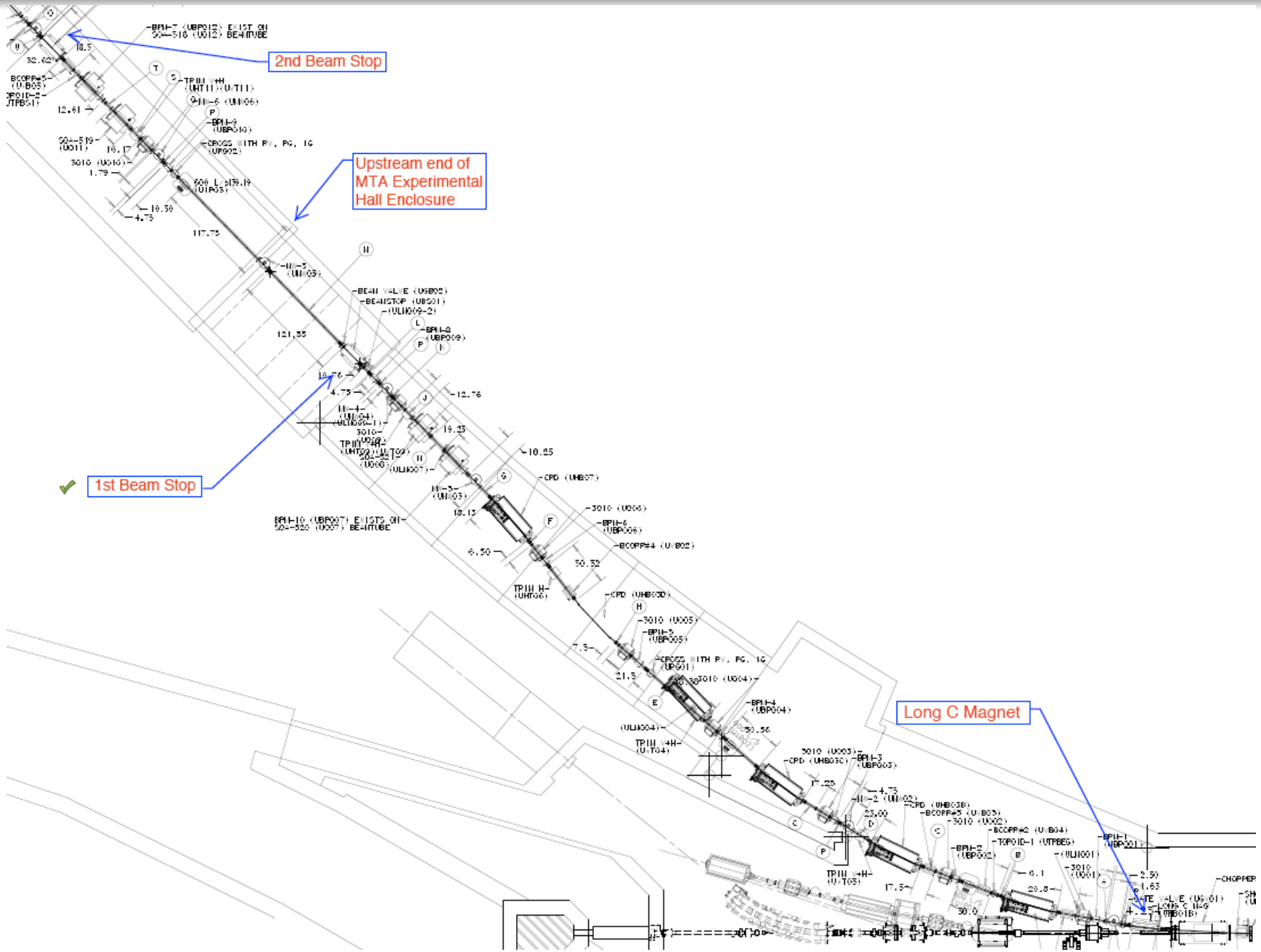
Beamline

- All components installed and aligned
- Integration with Linac control system started some work required to mitigate impact on Linac beam
- Beam successfully transported to first beam stop upstream of MTA (Nov)
- RF waveguide parts installed in hatch (Nov)
- Steel plates cut for new pit shield wall (Nov)
- Pit and hatch shielding designs approved (Mar)
- Beam absorber installed (May)
- Shield walls installed (Jul)
- Rate limiter hardware being built to control pulses/hour
- Beam to hall when all safety approvals in place

Beamline Commissioning



Beamline Commissioning

- 1 hour beam time approved (Nov 21)
  used 47 of our 60 allocated beam pulses, beam on 5th pulse
- After C magnet tuning, beam was fully extinguished in 400-MeV transfer and diagnostic lines and fully extracted into MTA beamline
- MW3 profile (3m upstream of beam stop)

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- Extraction into hall after radiation assessment approval
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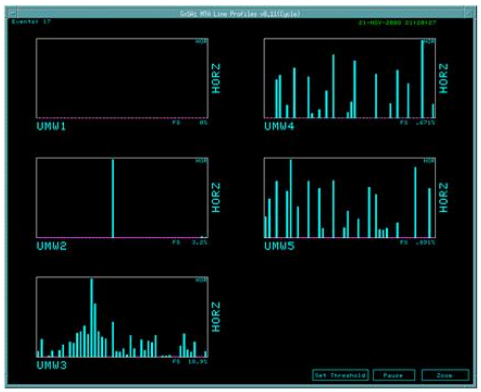

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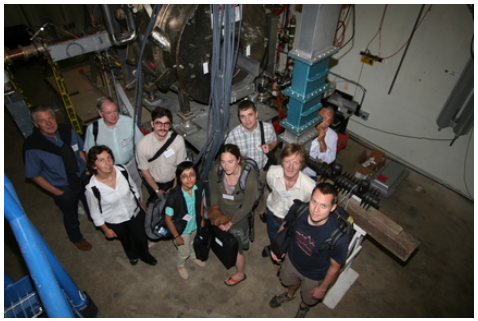
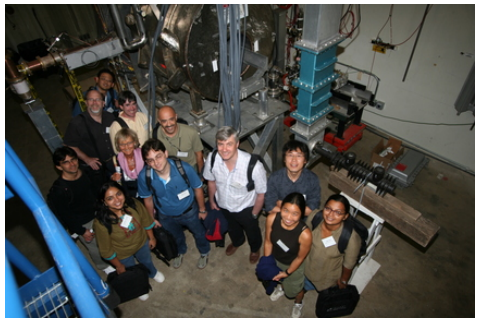
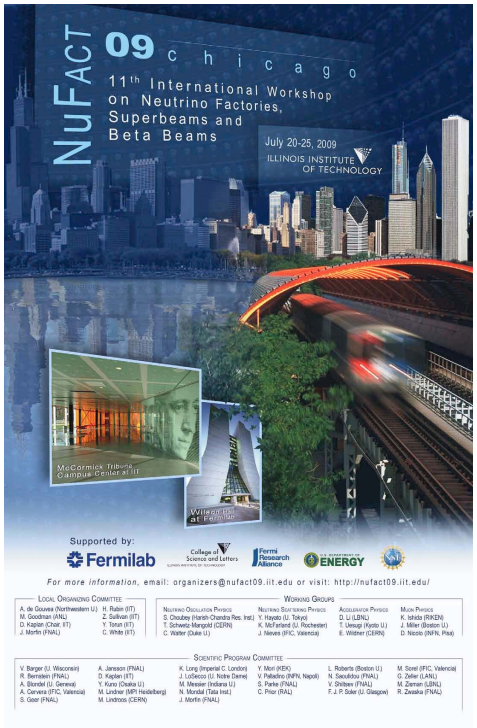
Outlook

- Reconfiguration to be completed soon
- Rich program to resume afterward
  - Beam test of HPRF cavity after beamline commissioning pending rad-safety assessment
  - 201 MHz RF ready to go
    surface inspection before applying rf power
  - 805 MHz cavity to be installed when available
  - Magnet cooldown after cryo plant is commissioned (Sep?)
  - Button tests at 805 MHz using various materials and processing techniques
  - E x B study with new rectangular cavity
  - Installation of coupling coil (Jan?) will require removal of pit shield wall



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