Fermilab Accelerator Division in 10 Minutes

Sudeshna Ganguly
On behalf of the Accelerator Division at Fermilab
New Perspective
17 August 2021
Fermilab Accelerator Complex

Fermilab operates the largest US particle accelerator complex, producing the world’s most powerful neutrino beams, along with muon and test beams.

- **Proton Beam**
- **Neutrino Beam**
- **Muon Beam**
Fermilab Accelerator Division: Mission

Delivering beams for research
- NOvA neutrino oscillation experiments (NuMI Beamline)
- Short Baseline neutrino experiments (Booster Neutrino Beamline)
- Mu2e, g-2 experiments (Muon Beamline)

Upgrading accelerator complex/beam line/targets to extend scientific reach
- Proton Improvement Plan-II (PIP-II)

Conducting accelerator physics research
- Optical stochastic cooling at FAST-IOTA
- Research on High Power Target systems
- Robotics for remote handling
- Application of machine learning
Delivering Beams for Research

NuMI Megawatt Upgrade project: maximum beam power to target 1 MW

Summer Shutdown Work

<table>
<thead>
<tr>
<th>Year</th>
<th>Work Items</th>
</tr>
</thead>
</table>
| 2019 | 1. Installation of 1 MW target  
2. Upgrade of radioactive water system of target & horn 1  
3. Upgrade of target, horn cooling system  
4. Installation of target chase supplemental shielding |
| 2020 | 1. Installation of upgraded 1MW horn 1  
2. Replacement of the transverse motion driver of horn  
3. Upgraded HVAC system for horn cooling  
4. Hadron monitor & absorber R & D |
| 2021 | 1. Installation of radiation hardened hadron monitor  
2. Installation of a new gas system for hadron/muon monitors  
3. Installation of temperature sensor on downstream target beam window |

**Set a record!** Main Injector delivered **843 kilowatts of proton beam** on NuMI target system on June 15th!

**Beam power will gradually increase to 1 megawatts** as several upgrades and studies are performed

» Critical requirement is tuning beam spot size on target

» Beam optics will be investigated when beam is available
Delivering Beams for Research

**Mu2e**: search for muons that spontaneously convert to electrons in field of a nucleus ($\mu N \rightarrow eN$)

- Nucleus coherently recoils off outgoing $e^-$!  It does not break up!

### 3rd Order Resonance Extraction
- Quadrupoles drive a $1/3$ integer resonance in horizontal tune
- Sextupoles induce a controlled beam instability
- Septum peels off a micro bunch on each turn
- To control spill rate uniformity during resonant extraction, RF knockout technique used

This beam structure can be realized with delivery ring manipulation for slow (resonant) extraction

**Mu2e production target**

Unique target has been built
- Testing of target at AP0, with Mu2e like beam underway

Courtesy Dave Pushka
Delivering Beams for Research
Muon g-2

Determined $\alpha_\mu$ to an unprecedented 460 ppb precision!

- **Goal of the Accelerator Division is to provide as many muons within magic momentum (~3.1 GeV/c) band**

- Proposal is to reduce the momentum spread in M4/M5
  - Supported by Fermilab’s LDRD program: to design, install and test a wedge in Fermilab’s muon campus, system installed and commissioned
  - **Primary test showed up to a 7% improvement on stored muons**

- Continued work on improving M2/M3 and delivery ring optics to optimize improvement rate of stored muons

Schematic layout of the beam delivery system to Muon g-2

![Diagram](image)

Courtesy Diktys Stratakis
Upgrading Accelerator Complex

**PIP-II/LBNF**

- Powerful proton beams (PIP-II) will enable world’s most intense neutrino beam to LBNF/DUNE, and a broad physics research program

**PIP-II high level performance requirements:**

- **Beam Power**
  - Meeting the needs for the start of DUNE (1.2 MW proton beam)
  - Upgradeable to multi-MW capability (2.4 MW in phase 2)

- **Flexibility**
  - Compatible with CW-operations which greatly increases the linac output
  - Customized beams for specific science needs
  - High-power beam to multiple users simultaneously

- **Reliability**
  - Fully modernizing the front-end of the Fermilab accelerator complex

**Path to 1.2 MW on LBNF Target**

- Increase no. of protons per extracted Booster pulse from $4.3 \times 10^{12}$ to $6.3 \times 10^{12}$
- Reduce Main Injector cycle from 1.33 s to 1.2 s
- Increase Booster rep. rate from 15 Hz to 20 Hz
  - Enable LBNF operations down in energy range 60-120 GeV
  - Support multiuser operations
- New 800 MeV superconducting linac as Booster injector
- Upgrades to Booster, Recycler Ring (RR), and Main Injector (MI)
Accelerator Physics Research

Stochastic Beam Cooling

- **Stochastic Cooling**: measurement and correction of incoherent particle motions via random-sampling process, a powerful technique but limited to GHz BW (highest frequency utilized to date is $8 \text{ GHz}$)
  - Stochastic cooling used for antiprotons in accumulator and recycler rings during Tevatron era
- **Optical Stochastic cooling** extends SC principle to optical bandwidth

Stochastic cooling used for antiprotons in accumulator and recycler rings during Tevatron era

- **Stability required for OSC was demonstrated** in April, 2021
- **OSC energy exchange has character of interference**, observed on 04/20/21

- 10$^3$ – 10$^4$ increase in cooling rate with OSC over SC ($\sim$10s of THz BW vs few GHz)

**OSC apparatus successfully integrated in IOTA**

Courtesy Jonathan Jarvis
Accelerator Physics Research
High Power Targetry

- High-Power Target System is a key element to complete future High Energy Physics (HEP) experiments
- Current target technology tolerates ~ 1MW but future projects aim to deliver up to 2-5 MW
- Thermal Shock and Radiation Damage most cross-cutting challenges facing high power target facilities and can lead to premature failure of the components

Rapid thermal expansion of material surrounded by cooler material creates a sudden localized area of high compressive stress

Thermal Shock Study at HiRadMat Facility at CERN in 2015 & 2018
Currently exploring ideas to perform test at FNAL

[Diagram showing energy deposition in thin graphite disk]

K. Ammigan, MARS simulation

Courtesy Frederique Pellemoine
Accelerator Physics Research
Robotics in Remote Handling

AD scientists and engineers are working hard to introduce robotics in remote handling to minimize radiation exposure

- RVR (Remote Viewing Robot)
- 360 and regular cameras, both with real-time image and video streaming to an iPad or phone
- Future Upgrades: Adding radiation detectors
- Sensors to automate the robot
- Robotic arms
- 5-Axis Robotic Arm
- Designed to mount onto RVR for remote-control camera positioning

AD has committed to placing a req for a Boston Dynamics SPOT robot!

Initial uses: Camera rover with ability to climb stairs (search + secure)

Work underway on Mu2e target remote handling

Work underway on unique and cheap robot for accelerator facility: combine computer vision and ML to identify and locate objects by UIC senior students robotics project

Courtesy Mike Campbell, Yun He, George Lolov, Katsuya Yonehara, Kris Anderson, Noah Curfman
Accelerator Physics Research
Application of Machine Learning

Implementation of AI to improve the accelerator system performance:
- Identifying / predicting incidents
- Detecting anomalies
- Tuning beam parameters
- Optimizing beam quality
- Predicting beam parameters for QA

Example of predicting beam position:
NuMI proton beam on target

Comparing different ML regulation schemes:
Optimized PID regulator vs ML regulator

READS (Real-Time Edge AI for Distributed Systems):
- Improve real-time spill regulation with reinforcement learning algorithms for guided operations optimization
  » Increases Spill Duty Factor of slow spill extraction

Courtesy A. Narayanan & M. Thieme, Published work progress at IPAC’21, paper THPAB243
Thank you from Accelerator Division!