An Upgrade Path toward Multi-MW Beam Power at Fermilab

Jeffrey Eldred
NuFACT 2021
September 6th 2021
Fermilab Upcoming Upgrades Now 750kW
Fermilab Upcoming Upgrades PIP-II 1.2MW

1.2 MW LBNF Neutrinos to DUNE

PIP-II SRF Linac 0.8 GeV
DUNE long-baseline neutrino program calls for 2.4 MW
DUNE Physics, with 2.4 MW at 6 years

### Physics Milestone

<table>
<thead>
<tr>
<th>Milestone Description</th>
<th>Exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td>5σ Mass Ordering</td>
<td>1</td>
</tr>
<tr>
<td>($\delta_{CP} = -\pi/2$)</td>
<td></td>
</tr>
<tr>
<td>5σ Mass Ordering</td>
<td>2</td>
</tr>
<tr>
<td>(100% of $\delta_{CP}$ values)</td>
<td></td>
</tr>
<tr>
<td>3σ CP Violation</td>
<td>3</td>
</tr>
<tr>
<td>($\delta_{CP} = -\pi/2$)</td>
<td></td>
</tr>
<tr>
<td>3σ CP Violation</td>
<td>5</td>
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<tr>
<td>(50% of $\delta_{CP}$ values)</td>
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<tr>
<td>5σ CP Violation</td>
<td>7</td>
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<tr>
<td>($\delta_{CP} = -\pi/2$)</td>
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<tr>
<td>5σ CP Violation</td>
<td>10</td>
</tr>
<tr>
<td>(50% of $\delta_{CP}$ values)</td>
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<tr>
<td>3σ CP Violation</td>
<td>13</td>
</tr>
<tr>
<td>(75% of $\delta_{CP}$ values)</td>
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<tr>
<td>$\delta_{CP}$ Resolution of 10 degrees</td>
<td>8</td>
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<tr>
<td>($\delta_{CP} = 0$)</td>
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<tr>
<td>$\delta_{CP}$ Resolution of 20 degrees</td>
<td>12</td>
</tr>
<tr>
<td>($\delta_{CP} = -\pi/2$)</td>
<td></td>
</tr>
<tr>
<td>$\sin^2 2\theta_{13}$ Resolution of 0.004</td>
<td>15</td>
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</table>

DUNE TDR, 2018
Fermilab Upcoming Upgrades Future 2.4MW

Fermilab Accelerator Complex

2.4 MW LBNF Neutrinos to DUNE

Recycler?

Replace Booster

PIP-II SRF Linac 1-3 GeV

Fixed-Target Experiments, Test Beam Facility

Low-Energy Neutrino Experiments

High-Energy Neutrino Experiments

Muons Delivery Ring

Muon Experiments

Jeffrey Eldred | An Upgrade Path toward Multi-MW Beam Power at Fermilab

9/8/2021
2.4 MW Upgrade: Build RCS and/or Linac to 8 GeV

How we get to 2.4 MW will set the stage for the future of Fermilab!
8 GeV Linac Option

Main Injector (MI)

Optional Storage Ring

Recycler?

8 GeV Linac

PIP-II Linac

8 GeV Linac Option
Rapid-Cycling Synchotron (RCS) Option

Optional 1-3 GeV Linac Upgrade

Main Injector (MI)

Optional Storage Ring

RCS

PIP-II Linac

Optional Storage Ring
In 2008, **Project X**: 8 GeV SRF Linac, directly into Main Injector.

In 2010, **Project X ICD-2**: 2 GeV Linac, New 2-8 GeV RCS.

In 2018, **S. Nagaitsev and V. Lebedev**: updated version of ICD-2.

In 2019, **J. Eldred, V. Lebedev, A. Valishev**: parametric study of RCS design.

The RCS path to multi-MW are well-considered, design requirements are needed.

In 2020, **Committee for Fermilab Booster Upgrade** an integrated design effort:
- Science Working Group (R. Harnik & about 25-75 people)
- Accelerator Working Group (M. Syphers & about 25 people)

We have been asked to develop a scenario to present to the Fermilab directorate and to present on Fermilab’s behalf for Snowmass.

However, this design team does not represent any decision at higher levels.

**2 GeV Linac + RCS Scenario:**
- Accelerator Working Group paper - recent ArXiv paper.
- Science Working Group paper - mostly complete, still open.
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<th>Dark Sectors</th>
<th>ν Physics</th>
<th>CLFV</th>
<th>Precision tests</th>
<th>R&amp;D</th>
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<td>Stopped Pion Source</td>
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<td>High Energy Proton Fixed Target</td>
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<td>Electron missing momentum</td>
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<td>N-Nbar oscillations</td>
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<td>Muon Collider R&amp;D and Neutrino Factories</td>
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<td>Tau Neutrinos</td>
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<td>Proton Storage Ring: EDM and Axion Searches</td>
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<td>Test-beam Facility</td>
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<tr>
<td>Muon Beam Dump</td>
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Proposed Experiments

2 GeV CW-capable beam, 2mA
- mu2e-II type charged-lepton flavor violation experiment
- Low energy muon experiments (muonium, muon decay)
- REDTOP run-II/run-III program (rare-decays)
- neutron-antineutron oscillation experiments

2 GeV pulsed beam from Storage Ring, ~1 MW
- stopped pion source experiments
- dark matter search at GeV-scale
- PRISM charged-lepton flavor violation experiments

8 GeV RCS program, ~1 MW
- kaon decay-at-rest program
- dark matter search from intermediate energy protons
- proton irradiation facility
- any successors to short-baseline neutrino program
- NuSTORM and muon-collider R&D
- muon beam dump, missing muon momentum

120 GeV Slow-Extraction program, 8e12 over six second, once per min.
- dark matter spectrometer experiment
- muon missing-momentum experiment
- test beam program
I) Assume PIP-II proceeds according to current plans.

II) Scenario should enable the Main Injector to achieve the 2.4 MW at 120 GeV for DUNE/LBNF in the near term.
   - and for a 60 GeV MI cycle, at least 2 MW.

III) Scenario should allow a robust experimental program and enable future high-power upgrades.

IV) Identify topics which may require R&D.
Linac + RCS Scenario

At 2 GeV injection energy, space-charge is manageable for ~37e12 RCS, - For 20 Hz rep. rate, the beam can be stacked directly into Main Injector. - If we stack directly into MI, there will be extra cycles for 8 GeV program. - **Sidebar:** Whether it would be possible/preferable to get to 2.4 MW with a Recycler-like 8-GeV storage ring is hotly debated.

At 2 mA linac injection current, long injection time becomes an issue for high-intensity, fast-ramping RCS.

**Solution 1:** Retrofit PIP-II linac for 5-10 mA pulses, 0.6-1.2 ms injection. - This strategy has strong precedents at other facilities (SNS, J-PARC) - If that retrofit were to take place earlier, would benefit PIP-II Booster.

**Solution 2:** Create 2 GeV storage ring for injection, transfer to RCS. - Allows dedicated injection optics and longer accumulation time. - With a subsequent laser stripping update, allows additional opportunity for MW-class pulsed 2 GeV proton program (capability overlaps with SNS).

Path to 4 MW Main Injector, by upgrade MI ramp rate & second target hall
### High-Level Parameters of Possible Upgrade Scheme

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PIP-II</th>
<th>RCS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linac Energy</td>
<td>0.8 GeV</td>
<td>2 GeV</td>
</tr>
<tr>
<td>Linac Current</td>
<td>2 mA</td>
<td>2 mA</td>
</tr>
<tr>
<td>RCS Energy</td>
<td>8 GeV</td>
<td>8 GeV</td>
</tr>
<tr>
<td>RCS Intensity</td>
<td>6.5 e12</td>
<td>37 e12</td>
</tr>
<tr>
<td>RCS Rep. Rate</td>
<td>20 Hz</td>
<td>20 Hz</td>
</tr>
<tr>
<td>Number of Batches</td>
<td>12</td>
<td>5</td>
</tr>
<tr>
<td>Available RCS Power</td>
<td>0.08 MW</td>
<td>0.8 MW</td>
</tr>
<tr>
<td>Main Injector Intensity</td>
<td>80 e12</td>
<td>185 e12</td>
</tr>
<tr>
<td>Main Injector Cycle Time</td>
<td>1.2 s</td>
<td>1.4 s</td>
</tr>
<tr>
<td>Main Injector Power (120 GeV)</td>
<td>1.2 MW</td>
<td>2.4 MW</td>
</tr>
<tr>
<td>Ultimate Main Injector Power</td>
<td>1.2 MW</td>
<td>4.0 MW</td>
</tr>
</tbody>
</table>
Differs from ICD-2 scenario by:
- higher RCS intensity & Main Injector power
  - an updated 2.4 MW scenario is in the works.
- RCS does not use Recycler Ring for stacking.
- higher rep. rate and RCS power.
Facility Capabilities (2mA CW + 2 GeV SR scenario)

2 GeV CW-capable beam, 2mA
- upgradeable to 4 MW shared with any pulsed 2 GeV program.

2 GeV pulsed beam from Storage Ring, ~1 MW
- requires laser stripping and 2 GeV Storage Ring.
- 37 e12 at 60-120 Hz.
- investigating ~400ns pulse compression.

8 GeV RCS program, 0.8 MW
- 37e12 every 20 Hz.
- 0.8 MW concurrent with 120 GeV program.
- upgradeable to ~2 MW with RCS ramp-rate and optics improvement.

120 GeV DUNE/LBNF program, 2.4 MW
- upgradeable to 4 MW with Main Injector ramp-rate.

120 GeV Slow-Extraction program, 8e12 over six second, once per min
- loss-limited, may be upgradeable.
Proposed Experiments

2 GeV CW-capable beam, 2mA
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120 GeV Slow-Extraction program, 8e12 over six second, once per min.
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- muon missing-momentum experiment
- test beam program
RCS Design Parameters
The RCS would operate at 20 Hz and accelerate from 2 to 8 GeV. A second ring operating at 2 GeV is proposed to be located above the RCS and used to accumulate charge from the upgraded linac.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RCS Circumference</td>
<td>570 m</td>
</tr>
<tr>
<td>RCS Rep. Rate</td>
<td>20 Hz</td>
</tr>
<tr>
<td>RCS Energy</td>
<td>8 GeV</td>
</tr>
<tr>
<td>RCS Intensity</td>
<td>37 e12</td>
</tr>
<tr>
<td>Number of Batches</td>
<td>5</td>
</tr>
<tr>
<td>Average Current</td>
<td>3 A</td>
</tr>
<tr>
<td>Available RCS Beam Power</td>
<td>0.8 MW</td>
</tr>
<tr>
<td>Min/Max Dipole</td>
<td>0.31-1 T</td>
</tr>
<tr>
<td>Min/Max Quadrupole Field</td>
<td>4.2-14 T/m</td>
</tr>
<tr>
<td>RF Freq. Range</td>
<td>50.3-52.8 MHz</td>
</tr>
<tr>
<td>Total RF Voltage</td>
<td>1.25 MV</td>
</tr>
<tr>
<td>No. cavities (60 kV)</td>
<td>21</td>
</tr>
<tr>
<td>Available RCS Beam Power</td>
<td>1.2 MW</td>
</tr>
<tr>
<td>Min/Max Quadrupole Field</td>
<td>1.9 MV</td>
</tr>
<tr>
<td>RF Freq. Range</td>
<td>32</td>
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</tbody>
</table>
Preliminary RCS Lattice Configurations

2 GeV Injection Ring, one of four periods

2 - 8 GeV RCS Ring, one of eight periods

2 GeV Ring Optimized for Injection

8 GeV Ring Optimized for Acceleration
H- Foil Stripping Injection
17 m straight.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>SR Circumference</td>
<td>570 m</td>
</tr>
<tr>
<td>SR Energy</td>
<td>2 GeV</td>
</tr>
<tr>
<td>Superperiodicity</td>
<td>4</td>
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<tr>
<td>Injection Insertion Length</td>
<td>12 m</td>
</tr>
<tr>
<td>Dipoles per Superperiod</td>
<td>12</td>
</tr>
<tr>
<td>Dipole Strength</td>
<td>&lt;0.4 T</td>
</tr>
</tbody>
</table>
Anti-Correlated Painted Injection

Injection painting scheme chosen to:
1) Minimize foil hits from the circulating beam.
2) Optimize stability of the beam distribution.
**Scenario 1:** Retrofit PIP-II linac to 5mA pulsed.

**Scenario 2:** Use six 120 Hz painting cycles to accumulate beam in storage ring every 20 Hz.
Summary

We have a self-consistent design for to 2.4 MW DUNE:
- 2 GeV upgrade of PIP-II + new 570m 8 GeV RCS.
- Upgrade is compatible with a wide range of proposed experiments.
- Accelerator design details are in paper and backup slides.

This specific scenario is unique for:
- does not require slip-stacking or Recycler.
- synergy with a 2 GeV accumulator ring.
- provides path to 4 MW upgrade of DUNE/LBNF.

The scenario also has options for being staged or scaled down.
- which beamlines should we plan to support?

Next Steps

Feedback on physics prioritization and experiment siting from Snowmass.

Further and more in-depth design is possible after CD-0.
Backup
Linac can be commissioned concurrent with PIP-II operations, RCS can be commissioned at partial linac energy, etc.

**At ~1.2 GeV,** the PIP-II Booster **1.2 MW** benchmark is crossed.  
**At ~1.6 GeV,** we have **1.8 MW** without Main Injector RF upgrade.  
  - If we can still use Recycler, RCS rep. rate only needs 10 Hz.
PIP-II Linac Upgrade to 2 GeV

<table>
<thead>
<tr>
<th>Linac Parameters</th>
<th>PIP-II Multi-users</th>
<th>with 2 GeV Upgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy</td>
<td>0.8</td>
<td>2.0</td>
</tr>
<tr>
<td>Ave. Beam Current</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Bunch Length</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Min. Bunch Spacing</td>
<td>6.2</td>
<td>6.2</td>
</tr>
<tr>
<td>Max. H- per bunch</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Beam Power</td>
<td>1.6</td>
<td>4</td>
</tr>
</tbody>
</table>

800 MeV – 1 GeV Beam

Future Upgrades
- RCS
  - LBNF Upgrade to 2.4 MW
  - 2 GeV storage ring
  - High power, low duty factor

E. Pozdeyev, 2020
Main Injector Operations

Keep 8 GeV injection into MI, re-using portions of Recycler as injection line
Removing slip stacking operation (Recycler) creates lower momentum spread in MI; helps to alleviate issues at crossing of transition energy

“Transition”: energy where revolution frequency is independent of momentum

Special optics manipulation at the transition energy (left; part of PIP-II) and smaller momentum spread provide adequate phase space through transition:

transition energy in
Main Injector ($\gamma = 21.5$)
Main Injector RF System

MI RF system would be upgraded with new modern RF cavity system

– increases RF power to meet final intensity requirements
– also enables increased ramp rate to achieve higher overall beam power above 2.4 MW

<table>
<thead>
<tr>
<th>RF System Specifications</th>
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<tbody>
<tr>
<td><strong>Frequency</strong></td>
<td>52.617 — 53.104 MHz</td>
</tr>
<tr>
<td><strong>Max. Acceleration Rate</strong></td>
<td>240 GeV/s</td>
</tr>
<tr>
<td><strong>Acceleration Voltage</strong></td>
<td>2.7 MV</td>
</tr>
<tr>
<td><strong>Peak Beam Power</strong></td>
<td>7.1 MW</td>
</tr>
<tr>
<td><strong>Average Beam Power</strong></td>
<td>3.6 MW</td>
</tr>
<tr>
<td><strong>Peak Voltage</strong></td>
<td>4.8 MV</td>
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<tr>
<td><strong>Average Beam Current</strong></td>
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<tr>
<td><strong>Fundamental RF Current</strong></td>
<td>4.6-5.2 A</td>
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<tr>
<td><strong>No. RF Stations required</strong></td>
<td>31</td>
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</tbody>
</table>
Possible MI Upgrade for Higher Power Beyond 2.4 MW

Upgrade magnet power supply system to support higher ramp rate — reduce cycle time from ~1.5 s to about 0.9 s — factor of ~ 5/3

240 GeV/s → 600 GeV/s

I. Kourbanis
Some R&D Areas

High-Power Targets:
- neutrino target for DUNE/LBNF, designs for other experiments.

H- Stripping Laser Technology:
- anticipating progress at SNS, J-PARC, FNAL.

Conventional RF design:
- large frequency sweep, significant beam-loading, high-gradient

IOTA Technology:
- innovations in electron lens and nonlinear optics.

Ceramic beampipes:
- reliability and cost for ceramics, metallization, brazed-flanges.
Space-charge Tune-spread Losses:

If we go to higher than PIP-II intensity, but without a momentum separation between the beams, we will cross the same res. lines.

How well can we compensate the resonances lines?
Recycler Intensity Challenges

Tight Aperture Losses:
Aperture limits RCS normalized emittance

Electron Cloud Instability:

S. Antipov et al. PRSTAB 2017
Slip-stacking Accumulation

1: An off-momentum batch is injected ...

2: Slipping motion causes batches to gradually overlap ...

3: Subsequent batch injections are made ...

4: Beams are accelerated as one after accumulation is complete.

RF frequency separation:
\[ \Delta f = h_{RCS} f_{RCS} \]
\[ \Delta f = \left( h_{Booster} \frac{C_{RCS}}{C_{Booster}} \right) f_{RCS} \]

Momentum separation:
\[ \Delta \delta = \frac{\Delta f}{f_{rev} h \eta} \]
2.4 MW with Slip-stacking

**Conventional Stacking:**

**Slip-stacking:**