Future Accelerator Based Neutrino Beams

Vladimir SHILTSEV (Fermilab)

CERN Council Open Symposium on the Update of European Strategy for Particle Physics
13-16 May 2019 - Granada, Spain
Content:

1. **Super-Beam Facilities and Upgrades** - how to achieve the ultimate energy and performance, R&D required:
   - Fermilab
   - J-PARC

2. **New Proposals** – opportunities and synergies:
   - Protvino/ORKA
   - ESSvSB
   - ENUBET
   - νSTORM
<table>
<thead>
<tr>
<th>Facility/Beamline</th>
<th>Energy (E)</th>
<th>Length (L)</th>
<th>Construction Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>H- RFQ</td>
<td>0.75 MeV</td>
<td>2 m</td>
<td>2013</td>
</tr>
<tr>
<td>Linac</td>
<td>400 MeV</td>
<td>200 m</td>
<td>1970/93</td>
</tr>
<tr>
<td>Booster</td>
<td>8 GeV</td>
<td>500 m</td>
<td>1971</td>
</tr>
<tr>
<td>RR</td>
<td>8 GeV</td>
<td>3.3 km</td>
<td>1999</td>
</tr>
<tr>
<td>MI</td>
<td>120 GeV</td>
<td>3.3 km</td>
<td>1999</td>
</tr>
<tr>
<td>Delivery Ring</td>
<td>3.8-8 GeV</td>
<td>500 m</td>
<td>1985/2014</td>
</tr>
<tr>
<td>Beamlines</td>
<td>3-120 GeV</td>
<td>3.5 km</td>
<td>1970’s-now</td>
</tr>
<tr>
<td>Upgr: PIP-II</td>
<td>800 MeV</td>
<td>240 m</td>
<td>2026</td>
</tr>
<tr>
<td>Upgr: PIP-III</td>
<td>8 GeV</td>
<td>500 m</td>
<td>Ca 2032</td>
</tr>
<tr>
<td>Upgr: beamlines</td>
<td>0.8-8 GeV</td>
<td>500 m</td>
<td>2026</td>
</tr>
</tbody>
</table>
Fermilab Accelerator Complex Users

• **Proton Source (400 MeV Linac and 8 GeV Booster ring):**
  - 8 GeV Booster Neutrino Beam (BNB)
    - ANNIE
    - MicroBooNE
    - MiniBooNE
    - MITPC
    - SciBath
    - **ICARUS**
    - **SBND**
  - Mucool Test Area (MTA, 400 MeV beam test facility)

• **120 GeV Main Injector / 8 GeV Recycler:**
  - NuMI: MINOS+, MINERvA, NOvA
  - **LBNF/DUNE (future)**
  - Fixed Target: SeaQuest, LArIAT, Test Beam Facility
  - Muon: g-2, **Mu2e (future)**

8 GeV proton program expanding
Fermilab Proton Complex Now: \( \sim 0.6 \times 10^{21} \) POTs/Year on \( \nu \) target

**Peak Power (Hour) to NuMI 766.3 kW**

- X-axis: Days since October 1
- Y-axis: Peak Hour (kW)

Legend:
- Fiscal Year 19
- Fiscal Year 18
- Fiscal Year 17
- Fiscal Year 16
- Fiscal Year 15
- Fiscal Year 14
- Fiscal Year 13
- Fiscal Year 12
- Fiscal Year 11
- Fiscal Year 10
- Fiscal Year 09
- Fiscal Year 08
- Fiscal Year 07
- Fiscal Year 06
- Fiscal Year 05
### J-PARC sends neutrinos to Super-K (Hyper K)

#### Materials and Life Science Experimental Facility

<table>
<thead>
<tr>
<th>Facility</th>
<th>Energy (GeV)</th>
<th>Length (m)</th>
<th>Construction Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linac</td>
<td>0.400</td>
<td>330</td>
<td>2008</td>
</tr>
<tr>
<td>RCS</td>
<td>0.03</td>
<td>350</td>
<td>2009</td>
</tr>
<tr>
<td>MR</td>
<td>0.030</td>
<td>1.6</td>
<td>2010</td>
</tr>
<tr>
<td>Beamlines</td>
<td>0.030</td>
<td>200</td>
<td>2009</td>
</tr>
<tr>
<td>Upgr Power</td>
<td></td>
<td></td>
<td>2020-28</td>
</tr>
</tbody>
</table>

#### Nuclear and Particle Experimental Facility

- **3 GeV Synchrotron** (25 Hz, 1 MW)
- **50 GeV Synchrotron** (0.75 MW) now 0.5 MW

**Linac (350m)**

**J-PARC = Japan Proton Accelerator Research Complex**
Fermilab and J-PARC Power Upgrades

Figure of merit for ν research is MW·ktons·yrs

- PIP-II 800 MeV Linac
- PIP-III 8 GeV Linac or RCS
- RF Upgrades Incl. 2\textsuperscript{nd} harm. RF
- Magnet PS Upgrade
- 2.48 s → 1.32 s
40 kt LAr DUNE @ 2.4 MW & 1000 kt water Hyper-K @ 1.3 MW

* complimentary in terms of CPV sensitivity because of different v’s spectrum, different baseline (1300 km vs 295 km) and detector technology
Ways to Increase Beam Power on Target

Particles per pulse

\[ P_{beam} = \frac{N_{pulse}E}{T_{cycle}} \]

Particle energy [eV]

Accelerator cycle period

- **Brute force**:
  - increase the energy \( E \) – magnets, RF
  - decrease the cycle time \( T \) – magnets, RF
  - key challenge: cost (e.g., J-PARC TPC \( \sim \$1.7B \)) and power

- **Increase PPP** (protons per pulse) \( N_p \):
  - key challenges: many beam dynamics issues & cost

- In both cases – need reliable horns and targets:
  - key challenge: lifetime gets worse with power
Fast Cycling Magnets + RF Cavities = 40-50% + 15-25% Cost *

Major power consumers: e.g. FNAL MI:
Magnets 9 MW, RF 2.5 MW, pulsed 1 MW

* incl. magnet PSs and RF sources

Tunable frequency $O(5\%)$

MI 1.7 T, $\sim$3 T/s

MI 52.8 MHz

RF cavity loaded with magnetic alloy cores

JPARC MR 1.1 T, $\sim$1 T/s

JPARC MR 1.7 MHz x harm.
Power Efficiency – Huge Issue

Key R&D:
Efficient magnets:
- NbTi SC 4 T/s for FAIR
- HTS 12 T/s at FNAL
- FFAG accelerators *

Efficient power supplies:
- Energy storage, e.g. capacitive, and recovery

Efficient RF power sources:
- $\eta=55\% \rightarrow \text{over } 80\%$
- klystrons, magnetrons, solid-state, etc

J-PARC: 0.5 MW beams vs ~40 MW site power
Efficiency ~1.3%

- MR Magnets: 10.4 MWh per hour
- MR RF: 3.8 MWh per hour
- RCS Magnets: 9.6 MWh per hour
- RCS RF: 7 MWh per hour
Protons Per Pulse Challenge: to lower beam losses while increasing intensity

Example: Fermilab Complex

$PIP \rightarrow PIP-II \rightarrow PIP-III$

Avg power loss limit (500W):

$\frac{\Delta N}{N_{\max}} < \frac{W}{(N \gamma)}$

But space-charge effects:

$\Delta Q_{sc} \sim \frac{N_{\max}}{\varepsilon \beta \gamma^2}$

Fractional Beam Loss $\Delta N/N$

Booster Batch Intensity (PPP, $10^{12}$)
Intense Beams: Forces and Losses (1)

Electric Force Repels

\[ eE \]

Magnetic Force Attracts

\[ eB(v/c) = eE(v/c)^2 \]

Net Force: Repels

\[ eE - eE(v/c)^2 = eE(1 - \beta^2) = eE/\gamma^2 \]
Defocusing Force is Non-linear

\[ F_{\text{max}} \sim eN/\sigma^2\gamma^2 \]

Space-charge effects (emittance growth, losses):

a) proportional to current \((N)\)

b) scale inversely with beam size \((\sigma)\)

c) scale with time at low energies \((\gamma)\)

Linacs 5-20 MeV/m
Rings 0.002-0.01 MeV/m
Ways to Increase “Protons per Pulse”

- **Increase the injection energy:**
  - Gain about $N_p \sim \beta \gamma^2$, need (often - costly) linacs

- **Flatten the beams (using 2nd harm, RF):**
  - Makes peak SC force smaller, $N_p \sim x2$

- **“Painting” beams at injection:**
  - To linearize SC force across beams $N_p \sim x1.5$

- **Better collimation system beams:**
  - From $\eta \sim 80\%$ to $\sim 95\%$ $N_p \sim x1.5$

- **Make focusing lattice perfectly periodic:**
  - Eg $P=24$ in Fermilab Booster, $P=3$ in JPARC MR $\rightarrow N_p \sim x1.5$

- **Introduce Non-linear Integrable Optics:**
  - Reduces the losses, $N_p \sim x1.5-2$

- **Space-Charge Compensation by electron lenses:**
  - Electrons focus protons $N_p \sim x1.5 - 2$
Option #1: Proton Improvement Plan-II

- **Key elements:**
  - Replace existing 400 MeV linac
  - Higher energy + painting = more beam in Booster
  - Increase Booster rate to 20 Hz
  - "Modest" improvements to Recycler and MI
  - Significant contributions from India

- **Goals:**
  - 1.2 MW @ 120 GeV for LBNF/DUNE
  - Additional power:
    - 82 kW @ 8 GeV
    - Neutrinos (and kaons?)
    - ~100 kW @ 800 MeV
  - Arbitrary bunch structure
  - Muons (\(\mu^2e^*\))

Note that linacs have their limitations, too – eg **H- intrabeam stripping**
IOTA: Integrable Optics Test Accelerator
Space-Charge Compensation R&D

E. Stern et al, THPAF075, IPAC18, Beams Document 6790-v1 FNAL

\[ \text{net force: } e(E - \beta B) = eE/\gamma^2 \]

\[ \text{protons} \]

\[ \text{electrons} \]

adding $1/\gamma^2$ e-

\[ dQ_{\text{sc}} = -0.9 \]

\[ dQ_{\text{sc+el}} = -0.2 \]
Very Important: Targetry, Foils, e-clouds

- Existing $\nu$ targets and horns are good to ~0.8 MW, MW and multi-MW targets are under development
  - Issues depend on pulse structure and include radiation damage and thermal shock waves
  - R&D program to study material properties, new forms (foams, fibers, etc), new target designs (rotating, etc)

- Also under development: injection of high power beams (stripping foils, laser stripping), e-cloud effects, etc

- We learn from lower energy - but record power - machines PSI and SNS (1.4 MW), RAL/ISIS, etc
Proposed Facilities for Neutrino Research
Protvino-to-ORKA: $L=2590\text{ km}$, $E_{\nu} \sim 5 \text{ GeV}$

**U-70 $p^+$ synchrotron:**

70 GeV proton beam

1.5 $10^{13}$ $p^+$ per pulse, $T_{\text{cycle}} = 10\text{ s}$

5μs (fast extraction), $P_{\text{avg}} = 15\text{ kW}$

**Needed upgrades:**

Decay pipe $\sim 180 \text{ m long}$

Power to 90 kW by 2026:

- 5 $10^{13}$ $p^+$ per pulse, $T_{\text{cycle}} = 7 \text{ s}$
- 5 yrs of ORCA data taking

Then to 450 kW by 2035

- (no details yet)
- Super-ORCA

$L=2595 \text{ km}$
ESS Neutrino Super Beams

European Spallation Source:

~600 m SC linac, 1.83 B Euros

2 GeV x 62.5 mA x (\eta=4\%) = 5 MW

2.8 ms pulses

32 MW site power after all the measures

CDR 2021, TDR 2024

Construction start 2026-2029

Linac upgrade 14 Hz → 28 Hz (\eta → 8\%)

Accumulator C~400 m to compress to μs

H- instead of p+, space charge effects

Target station

Cost estimate 1.3 B Euro

- Linac upgrade: 230 MEUR
- Accumulator ring: 150 MEUR
- Target Station: 170 MEUR
- Near and Far Detector: 750 MEUR

~0.3 GeV neutrino beam is directed towards the north in the direction of the Garpenberg mine, 540 km away, which could host the far 1 megaton water Cerenkov detector
ENUBET: SPS-based Short base-line $\nu$’s

- to measure the cross sections as $f(\text{energy})$ with much better precision

**SPS at CERN (max CNGS):**

$E=400$ GeV proton beam

2.25 $10^{13}$ $p^+$ per pulse,

$T_{\text{cycle}}=5.8s$, 10 $\mu s$ (fast extr.)

$\rightarrow$ avg. $P_{\text{beam}} = 510$ kW

8.5 GeV central energy of secondaries (pions, kaons)

0.5-3.5 GeV neutrino’s

~ 40 m
**νSTORM**

**SPS at CERN:**

\[ E = 100 \text{ GeV} \quad P_{\text{beam}} = 156 \text{kW} \]

4 \( 10^{13} \) \( p^+ \) per pulse

\[ T_{\text{cycle}} = 3.6 \text{ s}, \quad 2 \times 10^{-8} \text{ s} \text{ (fast extr.)} \]

\( \mu \pm \) beams 1 GeV/c - 6 GeV/c

momentum spread of 16%

Cost est. 160 MCHF @ CERN

---

**Challenge:**

a) 300 \( \mu \)m rad emittance \( \rightarrow \) 0.5 dia magnets; b) survival \( \sim 60\% \) after 100 turns for \( \delta P/P \sim 10\% \)

Flavour composition and \( \nu \) energy spectrum are precisely known

Near detector \( \sim 50\)m
Far detector \( \sim 2\)km

\( \nu \) flux precision of 1%
Summary:

• Over the past decade we witness impressive progress of high energy high power accelerators for \( \nu \) research:
  • J-PARC achieved \( \sim 500 \text{ kW} \) of 30 GeV beam, Fermilab MI over \( 750 \text{ kW} \) of 120 GeV

• Neutrino physics demands multi-MW facilities:
  • some of them in progress – Fermilab’s PIP-II linac upgrade
  • in general, many challenges faced beyond 1 MW

• Accelerator R&D is required and in many cases started:
  • On cost saving technologies (magnets, RF sources, etc)
  • On control of space-charge effects, instabilities and losses
    • to be tested at operational machines and IOTA ring
  • On MW and multi-MW neutrino targets and horns

• New proposals show promise and should be further studied:
  • Protvino-to-ORKA; ESS\( \nu \)SB; ENUBET; \( \nu \)STORM
Acknowledgements

Yuri Alexahin, Paul Czarapata, Paul Derwent, Jeff Eldred, Steve Holmes, Valeri Lebedev, Sergei Nagaitsev, Bill Pellico, Eric Stern, Cheng-Yan Tan, Alexander Valishev, Bob Zwaska (all – Fermilab), Eric Prebys (UCD), Frank Schmidt (CERN), David Bruhwiler (RadiaSoft)
# PIP-II Performance Goals

<table>
<thead>
<tr>
<th>Performance Parameter</th>
<th>PIP</th>
<th>PIP-II</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Linac Beam Energy</td>
<td>400</td>
<td>800</td>
<td>MeV</td>
</tr>
<tr>
<td>Linac Beam Current</td>
<td>25</td>
<td>2</td>
<td>mA</td>
</tr>
<tr>
<td>Linac Beam Pulse Length</td>
<td>0.03</td>
<td>0.6</td>
<td>msec</td>
</tr>
<tr>
<td>Linac Pulse Repetition Rate</td>
<td>15</td>
<td>20</td>
<td>Hz</td>
</tr>
<tr>
<td>Linac Beam Power to Booster</td>
<td>4</td>
<td>18</td>
<td>kW</td>
</tr>
<tr>
<td><strong>Booster Protons per Pulse</strong></td>
<td>4.3×10^{12}</td>
<td>6.5×10^{12}</td>
<td></td>
</tr>
<tr>
<td>Booster Pulse Repetition Rate</td>
<td>15</td>
<td>20</td>
<td>Hz</td>
</tr>
<tr>
<td>Booster Beam Power @ 8 GeV</td>
<td>80</td>
<td>160</td>
<td>kW</td>
</tr>
<tr>
<td>Beam Power to 8 GeV Program (max; MI @ 120 MeV)</td>
<td>32</td>
<td>80</td>
<td>kW</td>
</tr>
<tr>
<td>Main Injector Protons per Pulse</td>
<td>4.9×10^{13}</td>
<td>7.6×10^{13}</td>
<td></td>
</tr>
<tr>
<td>Main Injector Cycle Time @ 60-120 GeV</td>
<td>1.33*</td>
<td>0.7-1.2</td>
<td>sec</td>
</tr>
<tr>
<td><strong>LBNF Beam Power @ 60-120 GeV</strong></td>
<td>0.7*</td>
<td>1.0-1.2</td>
<td>MW</td>
</tr>
<tr>
<td>LBNF Upgrade Potential @ 60-120 GeV</td>
<td>NA</td>
<td>&gt;2</td>
<td>MW</td>
</tr>
</tbody>
</table>

*NOvA operations at 120 GeV
(How to Get Around) Space Charge Limit

- The maximum useful injected charge into the Booster is limited by the *space charge tune-shift*, which can drive harmonic instabilities.

\[ \Delta \nu \approx \frac{N r_0}{2 \pi \epsilon_N \beta \gamma^2} \frac{FB}{< .3} \]

- Total protons
- Normalized emittance \( \epsilon_N = c \beta \gamma \) = constant
- "Bunch factor" = \( \frac{I_{peak}}{I_{ave}} \)
  (Reduce with higher RF harmonics)
- = 3 for 95% Gaussian emittance
- 1 for 100% uniform (painted) emittance

(if not straightforward solution – double the energy - then)

- **Two novel approaches to increase the SC tune-shift:**
  - "Integrable Non-Linear Optics"
  - Space-Charge Compensation with Electron Lenses
- Possibly augmented with Superperiodic Focusing Lattice and "flat long bunches" (multiple harmonics RF)