FERMILAB ACCELERATOR R&D PROGRAM TOWARDS INTENSITY FRONTIER ACCELERATORS : STATUS AND PROGRESS*

V. Shiltsev#, Fermilab, Batavia, IL 60510, USA

Abstract

The 2014 P5 report indicated the accelerator-based neutrino and rare decay physics research as a centrepiece of the US domestic HEP program at Fermilab. Operation, upgrade and development of the accelerators for the near-term and longer-term particle physics program at the Intensity Frontier face formidable challenges. Here we discuss key elements of the accelerator physics and technology R&D program toward future multi-MW proton accelerators and present its status and progress.

INTENSITY FRONTIER ACCELERATORS

The 2014 Particle Physics Project Prioritization Panel (P5) report [1] identified the top priority of the domestic intensity frontier high-energy physics for the next 20-30 years to be a high energy neutrino program to determine the mass hierarchy and measure CP violation, based on the Fermilab accelerator complex which needs to be upgraded for increased proton intensity. To this end, a new beam line - the Long Baseline Neutrino Facility (LBNF) – and new experiment - the Deep Underground Neutrino Experiment (DUNE), located in the Sanford Underground Research Facility (SURF) - are being planned [2].

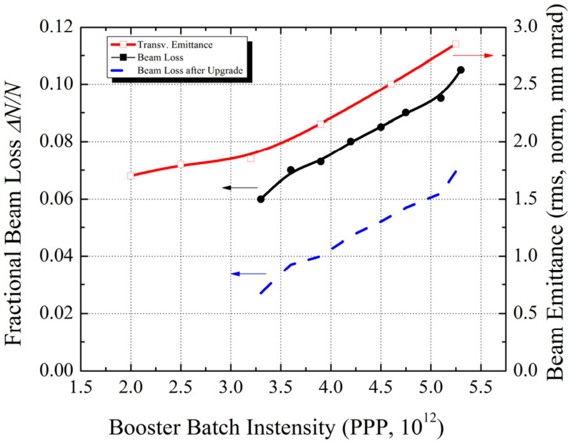

Figure 1: Fermilab Booster performance vs intensity: beam emittance (red line, right axis) and fractional beam loss now (black, left axis) and after anticipated upgrades (blue). Courtesy W.Pellico.

The P5 physics goals require about 900 kt·MW·years of the total exposure (product of the neutrino detector mass, average proton beam power on the neutrino target and data taking period) and that can be achieved assuming a 40 kton Liquid Argon detector and accelerator operation with the eventual multi MW beam power. At present, after commissioning of the 6+6 batch slip-stacking in the Recycler and reduction the Main Injector cycle time to 1.33s from 2.2s during the MINOS/Collider Run II era. Due to these improvements, in 2016 the Main Injector achieved world-record 615 kW average proton beam power over one hour to the NuMI beam line. On that way, the operations team increased number of batches slip-stacked in Recycler in steps (just 6 batches in late 2014, then 2+6, 4+6 and, finally, 6+6 batches in mid-2016). At each step, the increase intensity was followed by tuning for efficiency and minimization of losses. Finally, the peak power of 700 kW for one minute was demonstrated in June 2016 [3]. Sustainable routine operation at that level is expected in 2017 after an upgrade of the Recycler beam collimation system which is going to take place during the Summer 2016 shutdown.

ONGOING STUDIES AND PIP-II

There are a number of ongoing experimental beam studies, theoretical investigations, modelling and simulation efforts dedicated to understanding beam dynamics issues with high intensity beams in the existing accelerators. Those include studies of the space-charge effects in the Booster [4] – see Fig.1, theory and experiments on the coherent beam stability in the Booster, Recycler and Main Injector [5-9], electron-cloud studies which include *in situ* SEY measurements, micro-wave measurements in the Main Injector and development of the most effective vacuum pipe coating and scrubbing methods [10]; evaluation need of a transition crossing optimization in the Booster and Main Injector; investigations of beam losses and efficiency of collimation systems employed in all accelerators [11, 12].

We advance our simulation and modelling capabilities for high-intensity beams by development of a flexible beam dynamics framework on base of SYNERGIA [13] with fully 3D PIC capabilities which include space-charge and impedance, both single and multi-bunch effects, single-particle physics with full dynamics and which could run on desktops, clusters and supercomputers. Continuous development of the MARS-based energy deposition modelling tools [14] includes updates related to recent developments in nuclear interaction models; implementation of polarized particle transport and interaction, developments of radiation damage models and transfer matrix algorithms in accelerator material-free regions; and further enhancement of the geometry modules.

Numerous beam studies and upgrades are taking place in the Booster as part of the *Proton Improvement Plan (PIP)* [15]. They include studies of advanced injection schemes, efficient cogging, collimation efficiency, laser

---

*Fermi Research Alliance, LLC operates Fermilab under contract No. DE-AC02-07CH11359 with the U.S. Department of Energy
#shiltsev@fnal.gov

Copyright © 2016 CC-BY-3.0 and by the respective authors

notching in the linac [16] and are expected to result in substantial reduction of beam losses during the Booster acceleration cycle (see dashed line in Fig.1).

Construction of a new SRF 800 MeV H-/proton linac as part of the *Proton Improvement Plan-II (PIP-II)* project [17] is expected to address the near-term challenges. PIP-II will increase the Booster per pulse intensity by 50% and allow delivery 1.2 MW of the 120 GeV beam power from the Fermilab's Main Injector, with power approaching 1 MW at energies as low as 60 GeV [18], at the start of DUNE/LBNF operations ca 2024. Experimental R&D to minimize the performance risk of the PIP-II accelerator is underway at the PIP-II Injector Test facility [19].

Extensive accelerator R&D program towards multi-MW beams has been started at Fermilab [20, 21] and it has three components: demonstration of novel techniques for high-current beam accelerators at IOTA, cost-effective SC RF and high-power targetry (HPT).

HIGH INTENSITY BEAMS R&D AT IOTA

Progress of the Intensity Frontier accelerator based HEP is hindered by fundamental beam physics phenomena such as space-charge effects, beam halo formation, particle losses, transverse and longitudinal instabilities, beam loading, inefficiencies of beam injection and extraction, etc. The Integrable Optics Test Accelerator (IOTA) [22] ring at Fermilab's Acelerator Science and Tecnology (FAST) facility [23] – see Fig. 2. is being built as a unique test-bed for transformational R&D towards the next generation high-intensity proton facilities, paving the way to cost-effective multi-MW Fermilab accelerator complex beam power upgrade beyond PIP-II The experimental accelerator R&D at the 40 m circumference IOTA ring with high brightness 70 MeV/c protons and 150 MeV/c electrons, augmented with corresponding modeling and design efforts has been started at Fermilab in collaboration more than two dozen partners, including 8 universities, 3 SBIR industrial SBIR companies, 5 National Labs, 4 international partners [24].

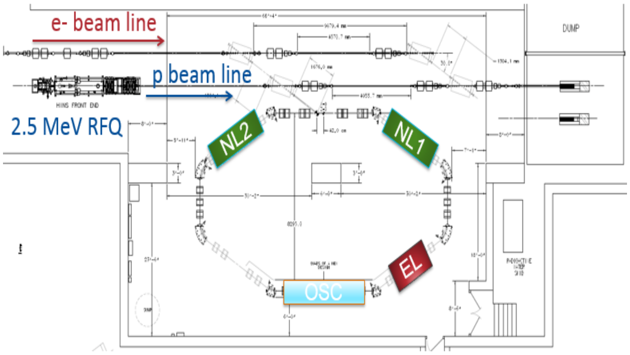

Figure 2: Layout of the IOTA ring and its two injectors.

The goal of the IOTA research program is to carry out experimental studies of transformative techniques to control proton beam instabilities and losses, such as *integrable optics* [25] with non-linear magnets and with electron lenses [26], and *space-charge compensation* with electron lenses [27] and electron columns [28] at beam intensities and brightness 3-4 times the current operational limits, i.e., at the space-charge parameter ΔQ_{SC} approaching or even exceeding 1. Several experiments are planned at IOTA: i) **Test of Integrable Optics (IO) with Electrons** – see e.g., [29-31] with a goal to create IO accelerator lattice with several additional integrals of motion (angular momentum and McMillan-type integrals, quadratic in momentum); ii) **IO with Non-linear Magnets, Test with Protons** [32] will demonstrate nonlinear integrable optics with protons with a large betatron frequency spread $\Delta Q_{SC}>1$ and stable particle motion in a realistic accelerator design; iii) **IO with e-lens(es), Tests with Protons** [33] to demonstrate IO with non-Laplacian electron lenses with the electron charge distribution as $n(r)=1/(1+r^2)^2$ to obtain a large betatron frequency spread $\Delta Q_{SC}>1$ and stable particle motion in a realistic accelerator design; iv) **Space-Charge Compensation (SCC) with e-lens(es), Test with Protons** [34] has the main goal of demonstrating SCC with Gaussian ELs with protons with a large betatron frequency spread $\Delta Q>0.5$ and stable particle motion in a realistic accelerator design. Similar *SCC tests* are envisioned *with electron columns* [35].

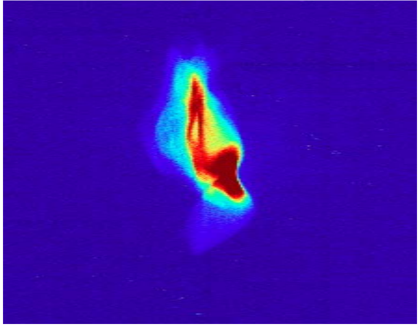

Figure 3: The first IOTA 52.5 MeV electron injector beam profile, as observed on May 15, 2016.

In 2016, the IOTA team has commissioned 50 MeV SRF electron pre-injector [36] – see Fig.3. A number of experimental beam studies had been carried out over a short operation period that followed the commissioning [37-40]. Operation of the IOTA ring with 150 MeV electrons in planned for 2017, after completing of installation of a high energy beamline from the 250 MeV SRF CM to the ring and the high energy high power beam absorber. In parallel, 70 MeV/c proton RFQ injector (2.5 MeV kinetic energy) is being assembled and will be commissioned in a separate MDB building and moved to the FAST facility in 2018. Commissioning of the proton injector and first operation of the IOTA ring with protons is planned for 2019-2020.

COST-EFFICIENT SC RF

Superconducting RF is the state-of-the-art technology with an unmatched capability to provide up to 100% beam duty factor and large apertures to preserve the beam quality. In the past, the SRF R&D program has been focused on improving the accelerating gradients in

Copyright © 2016 CC-BY-3.0 and by the respective authors

"traditional" Nb structures, extending from 3 MV/m to some 35 MV/m. The demands of the Intensity Frontier accelerators shift of focus towards decreasing the costs of SRF construction and operation through: a) nitrogen doping for ultra-high Q cavities, which opens up more than a factor of two in the quality factors (Q) of bulk niobium cavities and, therefore, potential for savings in cryogenics capital and operational costs [41]; b) development Nb_3Sn cavities for 4.2K operation, following the proof-of-principle demo that Nb3Sn cavities could provide the same quality factors at >4.2K as bulk niobium cavities do at 2K [42]; c) using Nb/Cu composite material and monolithic techniques of cavity manufacturing; these avenues promise a factor of >2 reduction in cavity material and manufacturing costs with performance comparable to bulk Nb cavities. It was recently shown that 1.3 GHz Nb-Cu composite based spun cavities can sustain high accelerating gradients. Fermilab, in collaboration with Cornell University, will use the existing Nb-Cu sheets to spin the cavities at INFN(Italy) or US industry (e.g. AES) to complete the 650 MHz cavities with flanges as the first step followed by scaling to 325 MHz if successful. Recent breakthrough in Nb film deposition technology allows films of unprecedented quality with the residual resistivity ratio (RRR) approaching or exceeding 200-300, which is currently the standard for bulk SRF cavities. The RF properties of these films will be tested, and after confirmation of low surface resistance of the samples, a prototype 650 MHz Nb/Cu cavity will be built and studied.

HIGH POWER TARGETRY R&D

There is a need in enhanced modelling of beam energy deposition, secondary particle production and collection, radiation damage (DPA), transmutation products (gas production), and residual dose. Also required are advanced simulations of target material (non-linear) response using FEA codes including fracture and/or phase change; exploration/determination radiation damage effects in candidate target and collimator materials at accelerator target facility operating parameters (e.g., via the RaDIATE Collaboration: Radiation Damage In Accelerator Target Environments).Verification and benchmarking of the above mentioned simulation tools and material properties is needed through dedicated testing at beam facilities and autopsy of existing materials.

Mega-watt class target facilities present many technical challenges, including: radiation damage, rapid heat removal, high thermal shock response, highly non-linear thermo-mechanical simulation, radiation protection, and remote handling [43]. The major goal of the envisioned R&D program for the next decade is to enable well-justified design simulations of high intensity beam/matter interactions using realistic, irradiated material properties for the purposes of designing and predicting lifetimes of multi-MW neutrino and muon target components and systems. This requires: a) irradiated material properties to be measured/evaluated for relevant targetry materials over a range of temperatures (300 – 1300 K), radiation damage (0.1 – 20 DPA (Displacements Per Atom)) and relevant helium production rates (500 – 5000 atomic parts per million/DPA); b) thermal shock response to be evaluated for relevant targetry materials over a range of strain rates (100 – 10000 s^{-1}); c) development and validation of simulation techniques to model material response to beam over the time of exposure (accounting for accumulation of radiation damage and high spatial gradients); d) development of enabling technologies in target materials, manufacturing techniques, cooling technologies, instrumentation, radiation protection, and related systems to meet the targetry challenges of multi-MW and/or high intensity (> 500 MW/m^3 peak energy deposition) requirements of future target facilities.

Radiation damage studies include investigations of materials of high interest (currently graphite, beryllium, tungsten and titanium alloys) under the RaDIATE R&D program [44]. The most major of these activities involve Post-Irradiation Examination (PIE) of previously irradiated materials recovered from spent target components (e.g. NuMI proton beam window), low-energy ion and high energy proton irradiations at available beam facilities (e.g. Brookhaven Linac Isotope Producer [45]), and experiments designed to help correlate low energy ion irradiations to high energy proton irradiations.

Thermal shock response studies include in-beam thermal shock experiments of various grades of commercially pure beryllium at the HiRadMat Facility [46] at CERN (e.g. HRMT-24, "BeGrid" [47]) and high strain rate testing of candidate materials to develop strength and damage models.

REFERENCES

[1] *Building for Discovery* (P5 Report, May 2014); see at `http://science.energy.gov/hep/hepap/reports/`

[2] LBNF and DUNE CDR, arXiv:1601.05471.

[3] M. Convery, *et al.*, presented at NAPAC2016, Chicago, IL, USA, October 2016, paper MOA4IO02, this conference.

[4] N. Eddy, *et al.*, presented at NAPAC2016, Chicago, IL, USA, October 2016, paper TUPOA17, this conference.

[5] A. Valishev and V. Lebedev, presented at NAPAC2016, Chicago, IL, USA, October 2016, paper WEA4CO04, this conference.

[6] A. Macridin, *et al.*, presented at NAPAC2016, Chicago, IL, USA, October 2016, paper WEA4CO03, this conference.

[7] A. Burov, *et al.*, presented at NAPAC2016, Chicago, IL, USA, October 2016, paper WEACO03, this conference.

Copyright © 2016 CC-BY-3.0 and by the respective authors

[8] E. Gianfelice-Wendt, *et al.,* presented at NAPAC2016, Chicago, IL, USA, October 2016, paper WEPOA17, this conference.

[9] R. Ainsworth, *et al.,* presented at NAPAC2016, Chicago, IL, USA, October 2016, paper WEPOA14, this conference.

[10] Y. Je, *et al.,* presented at NAPAC2016, Chicago, IL, USA, October 2016, paper TUPOB63, this conference.

[11] R. Ainsworth, *et al.,* presented at NAPAC2016, Chicago, IL, USA, October 2016, paper WEPOA16, this conference.

[12] V. Kapin, *et al.,* presented at NAPAC2016, Chicago, IL, USA, October 2016, paper WEPOA18, this conference.

[13] J. Amundson, *et al.,* presented at NAPAC2016, Chicago, IL, USA, October 2016, paper THPOA18, this conference.

[14] V. Pronskykh, *et al.,* presented at NAPAC2016, Chicago, IL, USA, October 2016, paper THPOA32, this conference.

[15] W. Pellico, *et al.,* in *Proc. IPAC14,* Dresden, Germany, p. 3409, 2014.

[16] K. Seiya, *et al.,* in *Proc. IPAC15,* Richmond, VA, USA, p. 4024, 2015.

[17] *The PIP-II Reference Design Report*, 2015, `https://indico.fnal.gov/getFile.py/access?resId=0&materialId=2&confId=9939`

[18] I. Kourbanis, *et al.,* presented at NAPAC2016, Chicago, IL, USA, October 2016, paper THA3IO01, this conference.

[19] C. Baffes, *et al.,* presented at NAPAC2016, Chicago, IL, USA, October 2016, paper WEPOA15, this conference.

[20] V. Shiltsev, *et al.,* in *Proc. IPAC15*, Richmond, VA, USA, p. 4019, 2015; arxiv: 1511.01920.

[21] V. Shiltsev, FNAL-Conf-16-32, 2016.

[22] A. Valishev, *et al., Proc. NA-PAC11*, p. 1606, 201.1.

[23] P. Garbincius, et al., Fermilab-TM-2568, 2013.
http://fast.fnal.gov/.

[25] V. Danilov and S. Nagaitsev, *PRSTAB,* vol.13, 084002, 2010.

[26] V. Shiltsev, *Electron Lenses for Super-Colliders*, New York: Springer, 2016.

[27] A. Burov, G.W. Foster, and V. Shiltsev, Fermilab TM-2125, 2000.

[28] V. Shiltsev, in *Proc. IEEE PAC'07*, p. 1159, 2007.

[29] N. Cook, *et al.,* presented at NAPAC2016, Chicago, IL, USA, October 2016, paper WEPOA31, this conference.

[30] T. Zolkin, *et al.,* presented at NAPAC2016, Chicago, IL, USA, October 2016, paper WEA1CO06, this conference.

[31] D. Bruhweiler, *et al.,* presented at NAPAC2016, Chicago, IL, USA, October 2016, paper WEA2IO02, this conference.

[32] C. Hall, *et al.,* presented at NAPAC2016, Chicago, IL, USA, October 2016, paper WEA4C02, this conference.

[33] G. Stancari, et.al, in *Proc. IPAC15*, Richmond, VA, USA, p. 46, 2015.

[34] A. Romanov, *et al.,* presented at NAPAC2016, Chicago, IL, USA, October 2016, paper THPOA23, this conference.

[35] C.S. Park, *et al.,* presented at NAPAC2016, Chicago, IL, USA, October 2016, paper THA3CO04, this conference.

[36] D. Edstrom, et al, presented at NAPAC2016, Chicago, IL, USA, October 2016, paper TUPAO19, this conference.

[37] A. Romanov, *et al.,* presented at NAPAC2016, Chicago, IL, USA, October 2016, paper THPOA22, this conference.

[38] P. Hall, *et al.,* presented at NAPAC2016, Chicago, IL, USA, October 2016, paper TUPOA23, this conference.

[39] J. Hyun, *et al.,* presented at NAPAC2016, Chicago, IL, USA, October 2016, paper TUPOA73, this conference.

[40] Y.M. Shin, *et al.,* presented at NAPAC2016, Chicago, IL, USA, October 2016, paper TUPOB18, this conference.

[41] A. Grassellino, *et al., Supercond. Sci. Technol.,* vol.26, 102001 (Rapid Communication), 2013.

[42] S. Posen, *et al., Applied Physics Letters,* vol.106, 082601 , 2015.

[43] P. Hurh, *et al.,* in *Proc. IPAC13*, Shanghai, China, p. 3484, 2013.

[44] http://radiate.fnal.gov/.

[45] N. Simos, *et al.,* arxiv:1202.3799.

[46] A. Fabich *et al., Proc. IPAC13*, Shanghai, China, p. 3415, 2013.

[47] K. Ammigan et al., *Proc. IPAC15*, Richmond, VA, USA, p. 3289, 2015.

Copyright © 2016 CC-BY-3.0 and by the respective authors