Accelerator Science and Technology

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Strategic Planning Workshop

January 09-10, 2020
AST Goals are diverse, impactful and far reaching

1) Explore scientific limits to accelerating gradients and quality factors for future SRF-based accelerators

2) Establish Fermilab as an essential contributor to future large accelerators

3) Extend the scientific reach of existing accelerator facilities

4) Advance Accelerator and Beam Physics to enable and enhance future accelerators

5) Build capacity of critically needed skills in Accelerator Science and Technology in Fermilab and beyond

Link to 1-pager: https://go.usa.gov/xnCTt
Goal 1: Explore scientific limits to accelerating gradients and quality factors for future SRF-based accelerators
Progress in Superconducting RF

- World leading SRF R&D program at Fermilab
- Program focused on advancing the state of the art in **Q and accelerating gradients** in bulk niobium cavities
  - Pioneered **nitrogen doping** and efficient **magnetic flux expulsion**, now realized in LCLS-2 with hundreds of cavities with **Q > 3e10 at 2K in cryomodule** and advancing further for LCLS-2 HE
  - Achieved record accelerating gradients of **50 MV/m in TESLA shaped cavities**
- Also world leading program in **Nb$_3$Sn**
  - highest accelerating gradient ever achieved for Nb$_3$Sn of **~24 MV/m, with Q > 1e10 at 4.2K**
Highlights of SRF results: high $Q_0$ enabled by N doping now a reality in more than 30 cryomodules for LCLS-II

- Production of >300 nitrogen doped cavities shows that high $Q$ process pioneered by Fermilab is now industrialized successfully: $Q \sim 3 \times 10^{10}$ at mid field, average gradient $\sim 24$ MV/m

- $Q$ at mid field $>$ twice previous state of the art (XFEL)

**European XFEL – $Q_0$ in vertical test at 2.0 K**

**LCLS-II – $Q_0$ in vertical test at 2.0 K**
Highlights of SRF results: very high $E_{\text{acc}}$ up 50 MV/m

- Recent advancements in low temperature bake and electropolishing are producing accelerating voltages never achieved before in tesla shape cavities.
- Cavity sent for verification of performance in all major SRF labs worldwide show tight agreement in performance (even in curious performance bifurcation).
Highlights of SRF results: Progress in Nb₃Sn performance

- Nb₃Sn coated cavities can operate at 4.4 K to reduce cost of cryogenics and enable new compact accelerator applications; in addition, theory predicts potential for $E_{\text{acc}}$ up to 90 MV/m.
- Not yet at ultimate potential, but substantial recent progress, including world record gradient of 24 MV/m at Fermilab.

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**Graph:**
- Q₀ vs. $E_{\text{acc}}$.
- Data points:
  - U. Wuppertal & JLab, 1990
  - Cornell U., 2015
  - Fermilab, 2019

**Images:**
- SEM images of Nb₃Sn film coated on Nb:
  - a) surface
  - b) cross section

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1/9/2020.
Many new advances in SRF technology since ILC TDR

This year with ILC Cost Reduction R&D funds from DOE, anticipate assembly of a cryomodule using cavities with performance > 40 MV/m and higher Q

Goal is to reach higher gradient than has ever been demonstrated in CM test, and higher Q; a key demonstration of the potential for cost reduction for ILC.

Cryomodule “kit” is original contribution from DESY to FNAL SRF ILC program

DESY, SACLAY, TRIUMF, KEK agreed to contribute in addition to the US work FNAL, Jlab, SLAC and Cornell
Goal 2: Establish Fermilab as an essential contributor to future large accelerators
Artificial Pinning Centers (APC) SC wires

• Performance of APC wires is rapidly improving

• Current results:
  – The non-Cu $J_c$ of recent APC wires has achieved the FCC specification.
  – Multifilamentary Ta-doped APC wires showed good drawability: no breakage occurred.
  – Further improvement of non-Cu $J_c$ expected
  – More work needed to operationalize into magnet-grade conductors.
  – Great interest and support by international magnet community – possible solution for FCC conductor
  – Supported by Fermilab LDRD

Xingchen Xu: DOE ECA to develop Nb3Sn conductors for future colliders
Magnet R&D: 15 T dipole (A. Zlobin et al.)

World’s First: 15T demonstrator, paving the way to 16 T dipoles: Magnet Dipole Prototype Cos-Theta type 1 (MDPCT1);

Main Features
1 m long, 60 mm bore diameter Nb₃Sn dipole magnet

Assembly
Fermilab and CERN courier articles, amplified by the web

Achieved 14.13 T a record for an accelerator type dipole
**Summary**

• FY19 was very successful for the SC magnet R&D group at Fermilab
  – APC R&D conductor reached FCC specifications of $J_c=1500$ A/mm$^2$ at 16T and 4.2K
  – The 15 T dipole demonstrator reached 14.1 T - new record for accelerator type dipoles

• We are preparing 15 T dipole for the next test (January/February) and expecting to reach the design field

• MDP is revising the magnet R&D map for the next 3-4 years.

• Fermilab group, an integral part of MDP, we are proposing strong R&D program including, conductor, Nb3Sn and HTS magnets and technological R&D.

• Long-term goals are well defined.
Goal 3: Extend the scientific reach of existing accelerator facilities
PIP-III Definition Committee has been “draft” charged

- OB-00150: Establish the accelerator design principles of the PIP-III complex upgrade toward operation with 2.5 MW proton beams on DUNE target

- “PIP-III: Exploiting PIP-II and delivering Multi-MW on the LBNF Target”

- Definition Committee: ~50/50 internal & external; mix of particle theorists, Acc. physics and technology

- 5 Internal WG to formulate contours of science opportunities and the optimal configuration for the complex

- GOAL: strong plan and white paper by P5/Snowmass ~2021
Booster Collaboration - Next Steps

**June Results:**
- First verification of convective instability.
- Space-charge emittance growth traced to 2Qy resonance.
- Power supply ripple does not threaten Booster operation.

**Future Study Topics:**
S.20.01 Measurement of convective instability at higher intensity with nonzero chromaticity.
S.20.02 Calibration of ionization profile monitors.
S.20.03 Improved modeling of Booster optics.
S.20.04 Correction of the half-integer resonance.

- **Very strong participation from CERN**
- **Build on the success of June studies and improve operational performance**
High Power Targetry R&D Status and Plans

**Multi-MW** Targets & Beam Windows Material R&D Status

- 2017-18: Multi-material RaDIATE Irradiation Run at BLIP, BNL
- 2015-18: Two Thermal Shock Experiments at CERN’s HiRadMat
- 2015-19: Examinations of Spent Targets & Beam Windows
- 2014-19: Grew RaDIATE to 14 institutions & over 70 participants
- 2015-19: Obtained relevant data for currently *in-use* materials:
  - Thermal Shock - up to $2 \times 10^{15}$ p/cm$^2$/pulse, reaching multi-MW Nu target goal
  - Radiation Damage - up to $2 \times 10^{21}$ integrated p/cm$^2$, on the way to multi-MW Nu target goal of $1 \times 10^{23}$ integrated p/cm$^2$

**Future Plans**

- BLIP irradiation run in 2021 for *new* materials
  - Confirm operating parameters for LBNF target materials
  - Explore promising new targetry candidate materials (e.g. high entropy alloys)
- Ion irradiations for radiation damage studies to high-dose
  - Correlate to high-energy proton results and irradiate to $1 \times 10^{23}$ p/cm$^2$
- Develop alternative thermal shock and radiation damage methods
  - Reduce cost and duration of R&D cycles
- Continue to grow and coordinate RaDIATE activities
- Continue opportunities for students (3 students and 2 post-docs supported)

Benefits to multi-MW targets (e.g. LBNF):

- alloy/grade choice
- cooling system design
- tolerable beam intensities
- expected lifetimes

In-beam thermal shock testing of *BLIP irradiated* Be and Ti alloys at CERN
Current Studies Yielding Impactful Results

- Significant hardening at low dose in Be and Ti alloys (beam window materials at NuMI, LBNF, J-PARC)
  - Less hardening at elevated temperatures
- First ever fatigue study on irradiated Ti alloys
  - Indicates about 20% reduction in fatigue strength
- Microstructural examinations underway
- Several publications expected in 2020

Irradiation hardening of S-65F Be
- Reduction of strain to failure
- Increased strength
Additional Resources Needed to Meet HPT Challenges

- **Alternative Thermal Shock and Radiation Damage Methods**
  - Prototype electron beam thermal shock facility at Fermilab (I-ARC)
  - Exploratory study for high dose irradiation facility at Fermilab (PIP-II/III?)

- **High Heat-Flux Cooling R&D**

- **AI for Remote Handling**

- **In-situ Target Health Monitoring/Instrumentation**

- **Novel Target Concepts and Materials**
  - Pebble bed targets
  - High Entropy Alloys
  - Ultra-fine Grain Alloys
  - Variable density targets (utilizing AM capabilities)
  - Nano-structured materials

- **AD developing concept for TSIB**
MARS Development and Project Support

Full MARS15-MADX-PTC Integration: Reliable CPU-efficient modeling on realistic 3D models for design justification and optimization

Recycler and Booster new collimation systems

LBNF

PIP-II
Development and Maintenance of Accelerator Sim. Codes

- **Synergia**: self-consistent 3D particle-in-cell accelerator simulation code C++ code developed at Fermilab (https://synergia.fnal.gov)
  - Specifically to simulate collective effects in accelerators taking advantage of available computing resources (laptops, clusters, supercomputers, GPUs)
  - Space charge, impedance, nonlinear single particle optics
- **Synergia** simulation activities at Fermilab include:
  - Fermilab Booster, space charge, impedance and losses
  - PIP-II injection into the Booster
  - Fermilab Main Injector and Recycler, space charge, impedance, slip stacking, transition crossing, resonance compensation
  - IOTA space charge, electron lens compensation, and more
- **Synergia** is being developed as part of the SciDAC ComPASS4 multi-institution collaboration which Fermilab leads (https://compass.fnal.gov)
Objective added for Controls-Sys. Modernization

- Modernization of accelerator-controls infrastructure is a high priority as we move into the LBNF/DUNE era
- Mission Validation Independent Review (MVIR) in August ‘19 requested creation of a controls modernization project
- PIP-II control sys. based on EPICS
- Common control system for the rest of the complex by start of PIP-II ops; to be established as a separate DOE project
- Planning, hardware and software development already underway

OB-06130: Accelerator Controls System Upgrade (PROPOSED)

- Modernize Fermilab's Accelerator Controls System based on an EPICS architecture
Goal 4: Advance Accelerator and Beam Physics to enable and enhance future accelerators
I. IOTA Ring – priority research focused on high-intensity *proton rings*, driven mostly by Fermilab
   - Nonlinear Integrable Optics
   - Optical Stochastic Cooling
   - Space-charge compensation
   - Suppression of coherent instabilities

II. FAST e- Linac and IOTA – opportunities concurrent with main IOTA program, driven mostly by external partners
   - Radiation generation
   - High average current experiments (ILC-like electron beams)
   - Collaboration with the FACET-II team
   - EIC R&D
   - Quantum science: single and few-electron experiments

Near-term, high-impact science with electrons
High-impact science with protons
2018/19 IOTA/FAST Run-1 – Total Beam Time 1477h

Design intensity

CM2 repair

Holiday break

A. Valishev

8 months
First results from IOTA in nonlinear beam dynamics

1. Henon-Heiles Type System with Octupoles
   (N.Kuklev, U.Chicago)

2. Suppression of Coherent Instability via Landau Damping
   (N.Eddy, V.Lebedev)

3. NIO with 2 Invariants of Motion – Special Magnet
   (S.Szustkowski, NIU)
Preparing for installation of IOTA proton injector

- HINS ion source repurposed as IOTA’s 2.5MeV proton inj.
- Outside NML cave for prep work concurrent with IOTA ops.
- **This year:**
  - design and procure 325-MHz RF system, prepare for commissioning injector
  - Expect installation in cave and operational status
Preparing to install Optical Stochastic Cooling in IOTA

• Initial operations expected in ~April 2020

• Planning a comprehensive OSC program with fundamental beam-physics studies and pathfinding for operational cooling and phase-space-control systems

• Collaboration with Berkeley on single-particle OSC experiments
Goal 5: Build capacity of critically needed skills in Accelerator Science and Technology in Fermilab and beyond
USPAS Winter Session, January 2019
NIU & U Tenn-Battelle Sponsored (Knoxville, TN)

➢ 13 Courses (6 linked to and 4 led by Fermilab instructors)
➢ 32 Instructors/Faculty (12 Instructors + 3 TAs from Fermilab)
➢ 161 Students (11 Employees + 8 University Affiliates from Fermilab)

6th Largest Session Ever

- **Applied Electromagnetism** 27 Students
  Jeremiah Holzbauer, Karie Badgley, Paolo Berrutti

- **Intregrable Dynamics in Accelerators**
  Sergei Nagaitsev, Timofey Zolkin

- **Storage Rings for Precision Physics – g-2** New
  Mike Syphers, Diktys Stratakis

- **Neutrino Beams** New
  Bob Zwaska, Laura Fields

- **High Power Targets for Accelerators** New
  Kavin Ammigan

- **Engineering of Beam Diagnostics** New
  Silvia Zorzetti, Randy Thurman-Keup
12 Courses (1 with Fermilab instructors)
34 Instructors/Faculty (3 instructors + 2 TAs from Fermilab)
177 Students (9 employees + 6 university affiliates from Fermilab)
2nd Largest Session Ever (179 Record from 1997)
7 Fermilab Employees in Indiana Univ./USPAS Masters Program

Fundamentals 43 Students!
Tanaz Mohayai, Elvin Harms, Bob Zwaska
THANK YOU AND CONGRATULATIONS TO EVERYONE IN AST @ FERMILAB
SUPPLEMENTAL
R&D: MDP roadmap

- Following the recommendation of GARD comparative review (2018), DOE organized an international review (Dec. 2019) to discuss the MDP roadmap for the next 4 years
- Fermilab (A.Zlobin) presented 15T magnet results – received with great interest by the international magnet community
- Fermilab group is re-planning the efforts in directions:
  - Push for advances in Nb$_3$Sn conductors and magnet designs that can leverage the enhanced performance
  - Restart HTS magnet technology, with a focus on hybrid magnet tests
  - Advance technology areas on multiple fronts:
    - Magnet training and diagnostic - reducing or eliminating the SC magnet training
    - Instrumentation and quench characterization - better tools to understand magnet quenches
    - Material studies - develop a suite of impregnation materials and techniques tailored to magnet needs
    - Modeling and simulation – utilizing new simulation program
Significant University Involvement in HPT R&D

- High Dose Ion Irradiation of Graphite
  - Abraham Burleigh (PhD student, IIT) under Dr. J. Terry

- Characterization of Graphite by Raman Spectroscopy and Nano-tomography
  - Ming (Eric) Jiang (MSc student, Bristol) under Dr. D. Liu

- Modeling of He bubble Nucleation and Growth in Irradiated Beryllium
  - Jianqi Xi (Post-Doc, UW) under Dr. I. Szlufarska

- Radiation Mapping Drone & Machine Vision for Remote Handling
  - Senior Design Team Projects at UIC under Dr. J. Komperda

- And exploring additional opportunities in 2020