Accelerator Frontier

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Many thanks to my colleagues.

- Anna Grassellino
- Vladimir Shiltsev
- Chandra Bhat

- ... for providing slides for this presentation
What is Fermilab known for?
(if you were to ask an accelerator scientist or engineer...)

S. Nagaitsev | Accelerator Physics

10/31/17
Technology: 4.5T SC Magnets
This is not the Tevatron! - remnants of the Main Ring (first separated-function synchrotron ever built)

C=6.28 km, ~800 SC magnets @ 4.2 K,

This is the Tevatron!
For their contributions to the design, construction and initial operation of the TEVATRON particle accelerator. The scientific instrument was designed to explore the fundamental properties of matter. The innovative design and successful operation of the TEVATRON has been crucial to the design of the Superconducting Super Collider, the planned next generation particle accelerator.
State of the Art SC Magnets: 3 Decades

4.5 T

Tevatron, 6 m, 76 mm 774 dipoles

4.5 K He, NbTi + warm iron small He-plant

HERA, 9 m, 75 mm 416 dipoles

NbTi cable cold iron Al collar

5.3 T

RHIC, 9 m, 80 mm 264 dipoles

NbTi cable simple & cheap

3.5 T

LHC, 15 m, 56 mm 1276 dipoles

8.3 T

NbTi cable 2K He two bores
Accomplishment: IEEE Milestone Award

• IEEE Board of Directors has approved a Milestone Award for the superconducting magnet system of the Tevatron
  – “The IEEE Milestones program honors significant technical achievements in all areas associated with IEEE…Milestones recognize the technological innovation and excellence for the benefit of humanity found in unique products, services, seminal papers and patents.”
• Ceremony at Fermilab planned for November 2017

Superconducting Magnet System for the Fermilab Tevatron Accelerator/Collider, 1983-1985
The first large-scale use of superconducting magnets enabled the construction of the Tevatron. By 1985, the Tevatron achieved energy above 1 Tera electron-volt (TeV) in proton-antiproton collisions, making it the most powerful particle collider in the world until 2009. The Tevatron construction established the superconducting wire manufacturing infrastructure that made applications such as Magnetic Resonance Imaging (MRI) viable.
Fermilab Invention: RF Barrier Bucket

Broad band ~1kV RF, ferrite loaded

J. Griffin, FNAL 1983
Technology: Pbar Momentum Mining in the RR for Collider Runs

Ch1=Barrier Waveform, Ch2= Stored Antiproton Beam

Development would have been impossible without very sophisticated digital LLRF controls (B. Chase)
The Fermilab Electron Cooling System

Design parameters of the RR ECool

- Energy: 4.3 MeV
- Beam current (DC): 0.5 Amps
- Angular spread: 0.2 mrad
- Effective energy spread: 300 eV

- **Electron beam power:**
  - $4 \text{ MeV} \times 0.5 \text{ A} = 2 \text{ MW DC}$
    - Energy recovery scheme
    - Very low beam losses are required

- **Beam quality:**
  - Transverse electron beam temperature (in the rest frame) should be comparable to the cathode temperature $\sim 1400\text{K}$

- **Development:** 1996-2004
The Recycler (top) and the Main Injector (bottom) rings installed in a common tunnel, 3.3 km long.

Both rings are now used to deliver 700-kW beams for neutrino experiments.
Recycler Permanent Magnets 1.5 T: ~2 km long

Sr-Fe + iron poles
B\textsubscript{max}=1.45T
combined function
T-compensation
dB/B\sim0.01\%
For the detailed, theoretical description of intrabeam scattering, which has empowered major discoveries in a broad range of disciplines by a wide variety of accelerators, including hadron colliders, damping rings/linear colliders, and low emittance synchrotron light sources.
INTRABEAM STRIPPING IN H⁻ LINACS*

V. Lebedev#, N. Solyak, J.-F. Ostiguy, Fermilab, Batavia, IL 60510, U.S.A.
A. Alexandrov, A. Shishlo, ORNL, Oak Ridge, TN 37831, U.S.A.

\[ \frac{dN}{dt} = N^2 \int_{-\infty}^{\infty} \left| u \right| \sigma_H \left( \left| u \right| \right) e^{-\frac{u_x^2}{4\sigma_{x\alpha}^2} - \frac{u_y^2}{4\sigma_{y\gamma}^2} - \frac{u_z^2}{4\sigma_{z\gamma}^2}} du^3. \] (3)
First Observation of Intrabeam Stripping of Negative Hydrogen in a Superconducting Linear Accelerator

A. Shishlo, J. Galambos, A. Aleksandrov, V. Lebedev, and M. Plum

1Spallation Neutron Source Project, Oak Ridge National Laboratory, Oak Ridge, P.O. Box 2008, Tennessee 37831, USA
2Fermilab, P.O. Box 500, Batavia, Illinois 60510, USA
(Received 10 November 2011; published 12 March 2012)

We report on an experiment in which a negative hydrogen ion beam in the Spallation Neutron Source (SNS) linear accelerator was replaced with a beam of protons with similar size and dynamics. Fractional beam loss in the superconducting part of the SNS accelerator was measured to be at least $2 \times 10^{-5}$ for the $\text{H}^-$ beam, and it was an order of magnitude lower for the protons. Also beam loss has a stronger dependence on intensity with $\text{H}^-$ than with proton beams. These measurements verify a recent theoretical

![Graph](image)

FIG. 4 (color online). The normalized BLM signals vs peak current for $\text{H}^-$ (a) and protons (b).
Fermilab SRF science and technology

- R&D program is world leader in SRF science; pursuing fundamental understanding and “materials science” of SRF surfaces
- Pioneered the most important latest advances in SRF such as N doping, N infusion, Magnetic Flux expulsion/retention
- Great partnerships with other lab and university groups around the world
  - Partner lab in the LCLS-II project at SLAC
Great Accelerators near UChicago
Advanced Photon Source @ ANL

$C = 1100 \text{ m, } e^- E = 7 \text{ GeV}$

Serves a community of $>5,000$ unique users per year

World’s brightest storage ring light source, photon energy $> 4 \text{ keV}$

Upgrade in progress (exp. compl. by 2024)
APS Upgrade: 2-3 orders in Brightness

Particle Beam Profiles

APS Now

APS MBA

1 mm

Max. Brightness (standard units)

Photon Energy (keV)

MBA/SCU

Present
APS will maintain US leadership in Photon Science

**FOCUSED BEAMS**

Five synchrotron facilities are developing special magnets so that they can become ultimate storage rings.

- **APS (UPGRADE)**
  - Location: Argonne, Illinois
  - Circumference: 1,104 metres
  - Completed: 2016

- **ESRF (UPGRADE)**
  - Location: Grenoble, France
  - Circumference: 844 m
  - Completed: 2015

- **MAX IV**
  - Location: Lund, Sweden
  - Circumference: 528 m
  - Completed: 2019

- **SIRIUS**
  - Location: Campinas, Brazil
  - Circumference: 518 m
  - Completed: 2016

- **SPRING-8 (UPGRADE)**
  - Location: Harima, Japan
  - Circumference: 1,436 m
  - Planned: 2019

APS, Advanced Photon Source; ESRF, European Synchrotron Radiation Facility.
Fermilab Complex: 16 km of accelerators and beamlines, two high power targets, several low power target stations...

1.98 TeV com $p$-$p\bar{p}$, 6.3 km

120 GeV proton, 3.3 km
Fermilab accelerators

Delivering 8 GeV and 120 GeV protons for neutrino experiments
Muon beams to the g-2 experiment
Fermilab Accelerators Now: Fixed Targets/∼2300 Users

- **Proton Source (400 MeV Linac and 8 GeV Booster ring):**
  - **8 GeV** Booster *Neutrino* Beam (BNB)
    - ANNIE
    - MicroBooNE
    - MiniBooNE
    - MITPC
    - SciBath
  - **ICARUS (future)**
  - **SBND (future)**
  - 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 Neutrino experiments
<table>
<thead>
<tr>
<th>Accelerators for Neutrino Research</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>300+ kW</strong> JPARC (Japan)</td>
</tr>
<tr>
<td><strong>400+ kW</strong> CNGS (CERN)</td>
</tr>
<tr>
<td><strong>700 kW</strong> Fermilab's Main Injector (2017)</td>
</tr>
</tbody>
</table>

**EVOLUTION OF INTENSITY FRONTIER ACCELERATORS**

<table>
<thead>
<tr>
<th><strong>900 kW</strong> Proton Improvement Plan (2020)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1.2+ MW</strong> Proton Improvement Plan-II (ca 2025)</td>
</tr>
<tr>
<td><strong>2.5 MW</strong> Proton Improvement Plan-II (ca 2025)</td>
</tr>
<tr>
<td><strong>Plan for multi-MW Upgrade (under study)</strong></td>
</tr>
<tr>
<td><strong>5 MW?</strong> Proton Improvement Plan-II (ca 2025)</td>
</tr>
</tbody>
</table>
**Proton Improvement Plan II (PIP-II)**

**Key elements:**
- Replace existing 400 MeV linac with an 800 MeV linac capable of CW operation.
  - Higher energy + painting = more beam in Booster
- Increase Booster rate to 20 Hz
- “Modest” improvements to Recycler and MI
- Significant international contributions

**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 (mu2e*)

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**Old 400 MeV linac**

**Proposed 800 MeV PIP-II linac**

**Fermilab**

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Will There Be Energy Frontier Colliders After the LHC?

( Yes or No ) = ( Physics × Feasibility )

- **PHYSICS** case of post-LHC high energy physics machine depends on the LHC discoveries:
  - it might call for a collider (if signals are clear)
  - otherwise, search for signs of new physics in the neutrino/rare decays (*Intensity Frontier*) or astrophysics

- **FEASIBILITY** of an accelerator is actually complex:
  - Feasibility of **ENERGY**
    - Is it possible to reach the $E$ of interest / what’s needed ?
  - Feasibility of **PERFORMANCE**
    - Will we get enough physics out there / luminosity ?
  - Feasibility of **COST**
    - Is it affordable to build and operate ?

- **What can we learn/take from the past/present?**
It’s easier to collide $e^+ / e^-$, because synchrotron radiation naturally “cools” the beam to smaller size.

- **VEP-1 (Встречные Электронные Пучки)** at Novosibirsk, USSR
  - 130 MeV $e^-$ x 130 MeV $e^-$
  - 1963: Construction Finished
  - May 19, 1964: Luminosity Detected

- **ADA (Anello Di Accumulazione)** at INFN, Frascati, Italy
  - 250 MeV $e^+ x 250$ MeV $e^-$
  - 1961: Construction Finished
  - ~ May-June 1964: Luminosity Detected
Colliders: 29 Built... 7 in Operation

One under construction: NICA (JINR, Dubna)
Colliders: Glorious Past

\[ E \sim \exp\left(\frac{t}{5 \text{yrs}}\right) \]

- **pp, ep**
- **e+e-**

Year:
- 1960
- 1970
- 1980
- 1990
- 2000
- 2010

Energy (GeV):
- 10^{-1}
- 10^0
- 10^1
- 10^2
- 10^3
- 10^4

- **ISR**
- **PEP**
- **TRISTAN**
- **LHC**
- **RHIC**
- **HERA**

Inset:
- **CBX**
- **AdA**
- **VEP**

10/31/17
Will There Be an Energy Frontier Collider After the LHC?

"Any headline that ends in a question mark can be answered by the word NO."

Betteridge's law of headlines
Ian Betteridge, a British technology journalist

Hinchliffe's rule, attributed with unknown veracity to Ian Hinchliffe, is this: “If the title of a scholarly article is a yes-no question, the answer is 'no'. “ It can be seen as the academic analog of Betteridge's law of headlines (Betteridge, 2009).
Four “Feasible” Technologies

Normal Conducting Magnets

(CЛИС)

Normal Conducting RF

SC magnets

SC RF

… in addition to “traditional” technologies of tunneling, electric power and site infrastructures, etc …
Possible Future Lepton Colliders

- **CepC/FCC-ee** 250 GeV cm
  C=52/100 km  **SCRF NC Mag**

- **ILC** 30 km long, 250 + 250 GeV $e^+e^-$ - **SCRF**

- **CLIC** $e^+e^-$ 50 km
  1.5 + 1.5 TeV
  - **NC RF**
  - **Two beam acceleration**

- **Muon Collider**
  ~15km $\mu-\mu+$ 3+3 TeV
  **NC RF+SC Magn+Muon produc’n; cooling; accel’n**

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Possible Future Hadron Colliders

- **HE-LHC** same tunnel, 25-30 TeV cm pp 16T SC magnets

- **SSC** 87km
  40cme=20+20TeV
  - 6.6T SC Magnets

- **FCC/SppC**
  80-100/54 km
  100/70 TeV cme
  - 16-20T SC Magn

- **VLHC**
  233 km
  175 TeV cme
  - 9.8T SC Magnets
Option 1: re-use LHC, inj, infrastr.
Option 2: Develop Technology to Lower the Cost

100 TeV $pp$: Qualitative Cost Dependencies

- **base cost parameters set**
- tunnel 5 times cheaper
- magnets 5 times cheaper

**Total Project Cost (arb units)**

**Dipole field $B$ (arb units)**

* for illustration purposes only
On SC Magnet Technology

Driven by SC cable technology
- **NbTi** – upto 10 T
- **Nb$_3$Sn** – upto 16 T
- **HTS** – 20+T

Cost of SC conductor
- **NbTi** – $$
- **Nb$_3$Sn** – $$ x 5
- **HTS** – $$ x 25
High Temperature Superconductors (HTS)

REBa2Cu3O7-x (REBCO, RE = rare earth) coated conductors

Achieved **25 T = 21T LTS +4T HTS** insert

Geneva, 2016

**27 T = 18T LTS +9T HTS** insert

NHMFL (Tallahassie)

YBCO coil test (2015)
R&D On Cost-Effective SRF Structures

New materials (Nb3Sn) – higher gradients
New techniques (Nb on Cu) – lower cost
Surface treatment (N2 doping) – higher Q0 and lower operation cost
Historical prices of Niobium (per ton)
Option 3: “Move to China!”

Average hourly compensation costs of manufacturing employees, selected economies and regions, 2002-2009

<table>
<thead>
<tr>
<th>SSRF</th>
<th>Spring-8</th>
<th>Diamond</th>
<th>NSLSII</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>Japan</td>
<td>UK</td>
<td>USA</td>
</tr>
<tr>
<td>432 m</td>
<td>1436 m</td>
<td>562 m</td>
<td>792 m</td>
</tr>
<tr>
<td>3.5 GeV</td>
<td>8 GeV</td>
<td>3 GeV</td>
<td>3 GeV</td>
</tr>
<tr>
<td>1.2B RMB</td>
<td>11 BY</td>
<td>383 M £</td>
<td>912 M$</td>
</tr>
</tbody>
</table>

Account inflation, convert to USD and scale to \(\sqrt{1\text{ km}}\):

- 350 M$
- 772 M$
- 1040 M$
- 1024 M$
“Move to China!" - Caveats

![Graph showing China average yearly wages from 2006 to 2016.](image)

SOURCE: WWW.TRADINGECONOMICS.COM | MOHRSS, CHINA
A “Dream” Collider

• Far Future “Energy Frontier” assumes
  ❖ 300-1000 TeV (20-100 × LHC)
  ❖ “decent luminosity” (TBD)

• What we know:
  1. For the same reason there is no circular e⁺e⁻ collider above Higgs-F there will be no circular pp colliders beyond 100 TeV → LINEAR
  2. Electrons radiate 100% beam-strahlung (<3 TeV) and in focusing channel (<10 TeV) → μ+μ⁻ or pp
• **Summary**

  - **Accelerators progressed immensely**
    - Now integral part of manufacturing, security, and R&D
  
  - **Post-LHC colliders are possible but**:
    - Dependent on the LHC results *(motivation)*
    - if based on current technologies *(SRF, SCMag, etc)* only HE-LHC is cost feasible (<LHC), some are close *(CepC/FCCee, ILC, Muon Coll, VLHC-I)*, others need significant R&D *(FCC)*…or move to China (?)
    - Or must be based on an entirely new technology
  
  - New ideas are needed! *(UChicago-Fermilab-Argonne)*
• The group of accelerator science and beam physics at the University of Chicago exploits novel concepts in accelerator science and technology, studies limitations affecting the acceleration, control, intensity and quality of particle beams at a fundamental level, and develops new approaches to overcome these limitations.

• Specialty:
  – SRF science and technology
  – Nonlinear beam dynamics
  – Physics of bright X-ray production
U.Chicago Accelerator Science Group

- Faculty:
  - Kwang-Je Kim Argonne/U.Chicago (Physics)
  - Young-Kee Kim U.Chicago (Physics)
  - Sergei Nagaitsev Fermilab / U.Chicago (Physics)
  - Steven J. Sibener U.Chicago (Chemistry)
  - Amie Wilkinson U.Chicago (Mathematics)

- Postdoc: Stas Baturin

- Current Grad Students: Ihar Lobach, Matt Gordon, Bipul Pandey, Lipi Gupta, Alexey Kochemirovskiy, Jeffrey Sayler, Darren Veit

- 6 former grad students

- http://beamscience.uchicago.edu/
• CBB's overarching research goal is to increase the intensity ("brightness") of beams of charged particles by a factor of 100 while decreasing the cost of key accelerator technologies. CBB will promote significant advances in scientific disciplines ranging from physics to chemistry to biology by enhancing the capabilities of the accelerators essential to research in these fields.
Unique Accel. R&D Facility: IOTA at Fermilab

Electrons and protons
Ring and linacs
SRF and nonlinear magnets

MANY Opportunities for research:
- Nonlinear beam dynamics
- Space-charge compensation with electron lenses and electron columns
- Optical stochastic cooling
- Laser plasma wakefield injector
- Acceleration in carbon nanotubes and crystals, etc etc
Connection to UChicago

IOTA

Fermilab Map

Wilson St.

Site 37

Site 39

Meson Area

Proton Area

Wilson Hall & Ramsey Auditorium

Public Areas

not to scale

areas of the map are clickable

download a PDF of this map (for printing)

view legend

view instructions for using this map

C-Zero

Tevatron

D-Zero

Kautz Rd.

Substation

Fermilab Village

Fermilab Computing Center

Main Entrance

Bike Path

NuMI/Minos

MiniBoone

Antiproton Source

Main Injector

Wilson Hall & Ramsey Auditorium

Public Welcome

CDF

Wilson St.
record gradient 31.5 MV/m achieved

1.3 GHz SRF Cryomodule

Proton injector

JOTA Ring

Electron Photoinjector

150 MeV electron beam
Oct 19, 2017
The Lee Teng Internship is an exciting education and research opportunity, open to select students from U.S. universities who have just completed their junior year* in physics, engineering, or computer science.

For further information and to apply, see www.illinoisacceleratorinstitute.org

*Outstanding sophomores may also be considered.

http://www.illinoisacceleratorinstitute.org/