Fermilab

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Fermilab Accelerator R&D program and our recommendations to the HEPAP sub-panel

Sergei Nagaitsev
Fermilab
27 August 2014

Fermilab after the Tevatron

- *Fermilab operates the largest HEP accelerator complex in the U.S., 2nd largest in the world (even after termination of the Tevatron)*
- Also part of operations:
  - Proton Improvement Plan (PIP)
  - Muon Campus projects
  - Test facilities (magnets, SRF cavities)
- Projects: Muon g-2, Mu2e, LBNF, MicroBooNE, LCLS-II (at SLAC), PIP-II
- Programs: MAP, LARP, ILC
- Research and Development
- Commercialization of our accelerator technologies.

Accelerators

Fermilab operates a total of 16 km of accelerators and beamlines

- A 400-MeV proton linear accelerator (0.15 km)
- An 8-GeV Booster synchrotron (0.5 km)
- An 8-GeV accumulator ring (3.3 km)
- A 120-GeV synchrotron (3.3 km)
- A Muon Campus Delivery ring (0.5 km)
- Soon: Muon g-2 ring
- Transfer lines and fixed target beam lines (8 km)
- Two high power target stations, several low-power targets

- People: 660 (AD, APC, TD) – ops, projects, programs, R&D, program support, WFO

Fermilab Accelerator Complex

Linac: NTF, MTA

BNB: MicroBooNE

NuMI: MINOS+, MINERvA, NOvA

Fixed Target: SeaQuest, Test Beam Facility, M-Center

Muon: g-2, Mu2e (future)

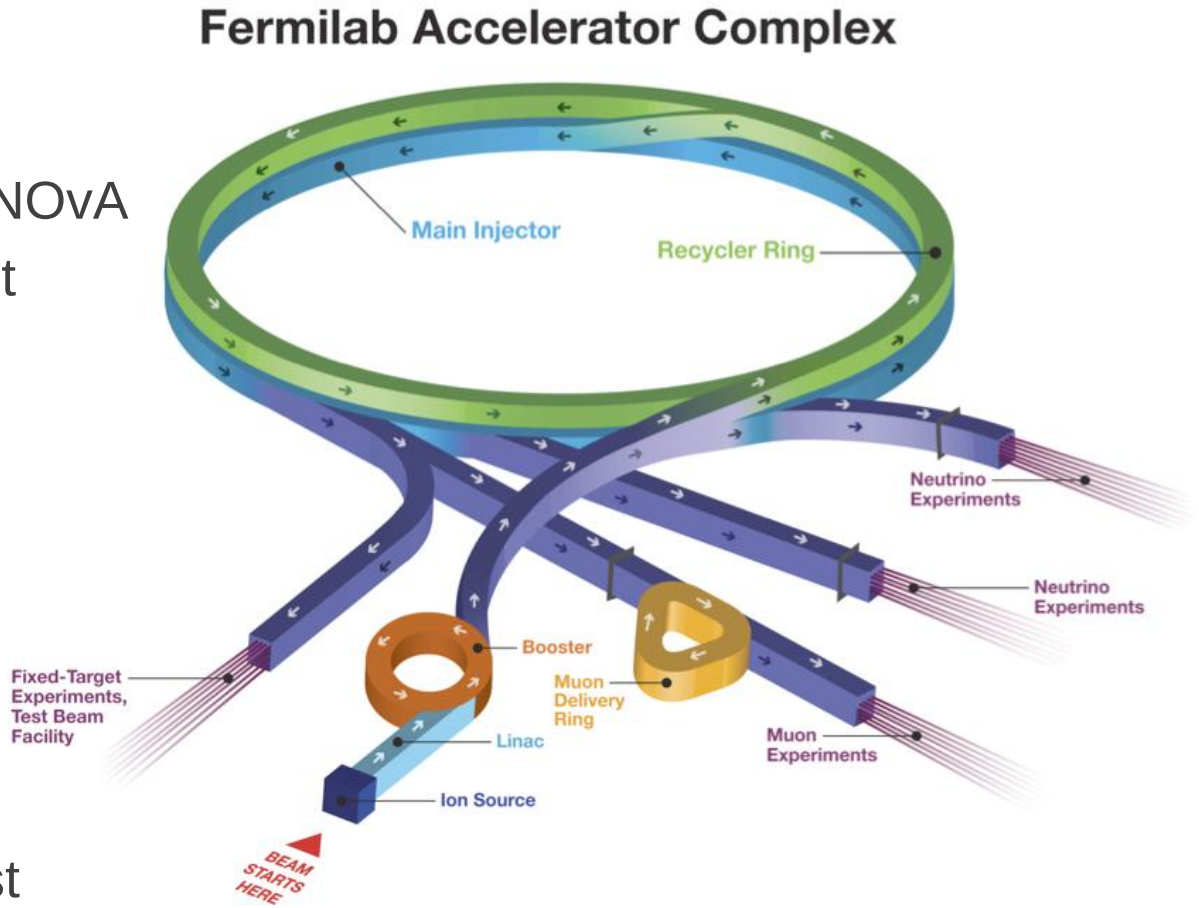
Also, test and R&D facilities:

ASTA /IOTA

PXIE

CMTF

Various cryo and magnet test stands



Accelerator R&D Test Facilities (Ops and Infrastructure)

- Nearly all accelerator projects and programs rely on Test Facility Operations: GARD, PIP-II, LCLS-II, LARP, Muon Campus magnets, Mu2e solenoids.
  - The Common Test Facilities: covers the Operations and Maintenance of the cryogenic and multi-purpose systems (like the CHL).
  - The Magnet Test Facilities: covers the operation and maintenance of all the technical facilities managed by the Fermilab Technical Division, both cold and warm magnets.
  - The SRF Infrastructure and Operations: CMTS construction, operations of VTS, HTS, clean rooms, ASTA, cryomodule assembly areas, etc
  - FY15 guidance: 41 FTEs, $13.2M total
  - FY14: $22.2M , FY13 (actual): $25.6M

HEP General Accelerator R&D Program at Fermilab

- Fermilab is the only single purpose US HEP laboratory:
  - (OHEP 02/22/2013) : "..recognizing the centrality of Fermilab while maintaining a healthy US research ecosystem…"
- Fermilab either leads or has a major stake in everything of critical importance for the field - including accelerator R&D :
  - LARP, ILC, PIP-II, MAP, ***General Accelerator R&D***
  - Fermilab is the US (and world's) leader in accelerator and beam physics in high-power beams;
- Fermilab Accelerator R&D program is embedded in, and leverages resources and infrastructure from operations, projects and programs.
  - GARD is the only source of mid- and long-term accelerator R&D funding;

Highlights of Fermilab's Accelerator R&D Program

2009-2014

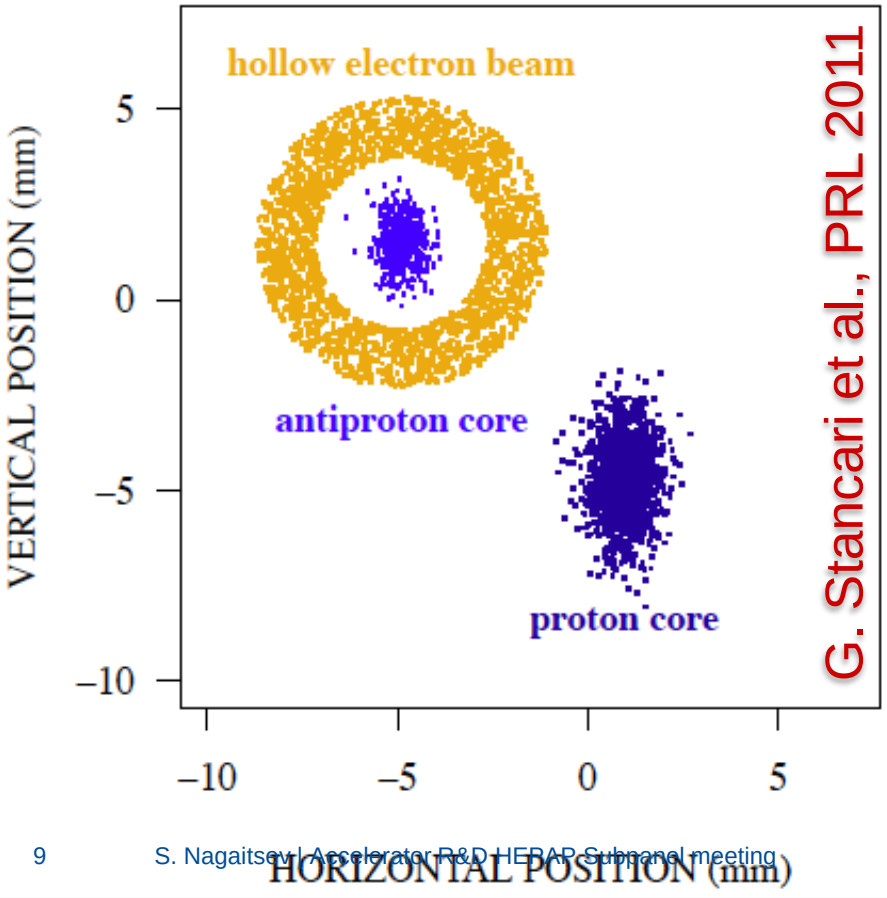
Tevatron End-of-Run Beam Studies Campaign (2011)

- Two 2-week periods of experimental studies
  - for the benefit of accelerator science and future machines
  - collaborated with CERN, BNL and LBNL
- Key experiments:
  - Collimation with bent crystals (T980)
  - Collimation with hollow electron beam lens (HEBC)
  - Studies of beam-beam effects:
    - AC dipole with colliding beams
    - Effect of Beam-Beam interaction on coherent stability
    - Beam-Beam resonances vs. transverse separation
    - Effect of bunch length to β-function ratio (betatron phase averaging)

Novel Halo Collimation Methods

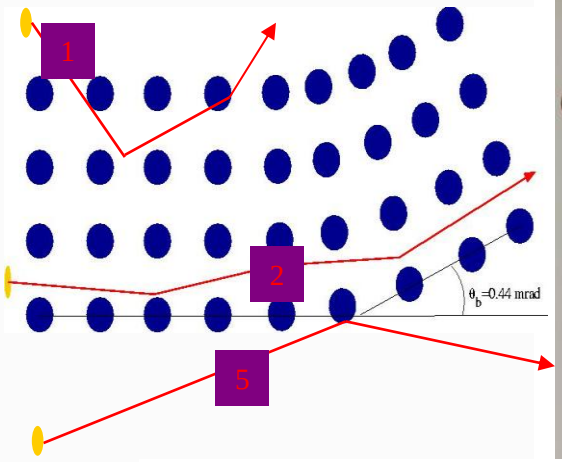
Hollow Electron Beam

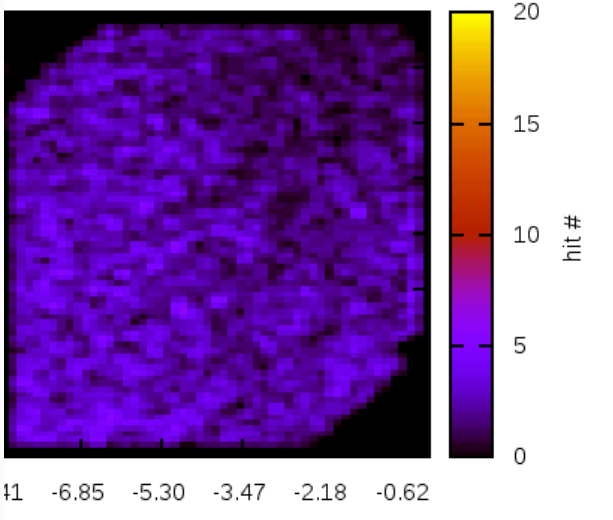
A hollow el beam (Tevatron electron Lens)
No E-field inside
Strong E-field ouside drives resonances
Fast diffusion = "soft collimator" effect
Works near beam as well (no material)



G. Stancari et al., PRL 2011

Bent Crystal Collimation





N.Mokhov, et al JINST 6 T08005 (2011).

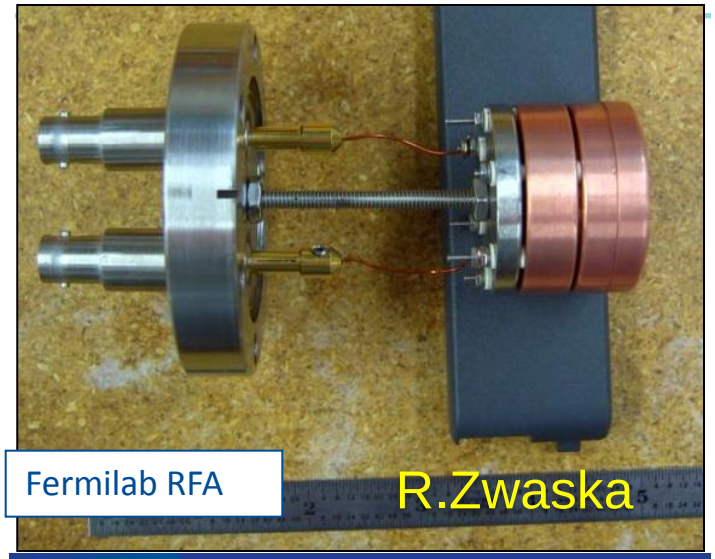
T980 Results D. Still et al. IPAC12

Channeled beam image on pixel detector

Main Injector: *e*- Cloud Experimental Station

Station in Main Injector since 2009 :

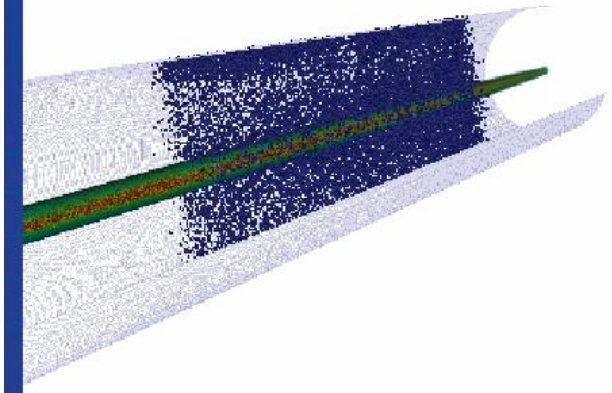
- 2 experimental Chambers (coated and SS)
  - Test various coatings for ECloud suppression
  - Measure spatial extinction of ECloud
- 3 Fermilab and 1 Argonne RFA
  - Retarding Field Analyzers
  - Directly measure electron flux
- 3 microwave antennas and 2 absorbers
  - Measure ECloud density by phase delay of microwaves
- So far, three materials tested:
  - TiN (2009-10) – suppressed vs. Stainless (5-1000x)
  - α-C (2010-12, from CERN) – similar suppression as TiN
  - DLC (2013-, from KEK) – Awaiting the return of beam



Augmented by comprehensive simulations

- Utilization of ComPASS tools :
  - *ComPASS VORPAL e-cloud simulation of MI experiments*
- Model microwave experiment (only possible with ComPASS tools), RFA response
- Code comparisons with “standard” tools such as POSINST

P.Lebrun, J.Amundson, P.Spentzouris, et al

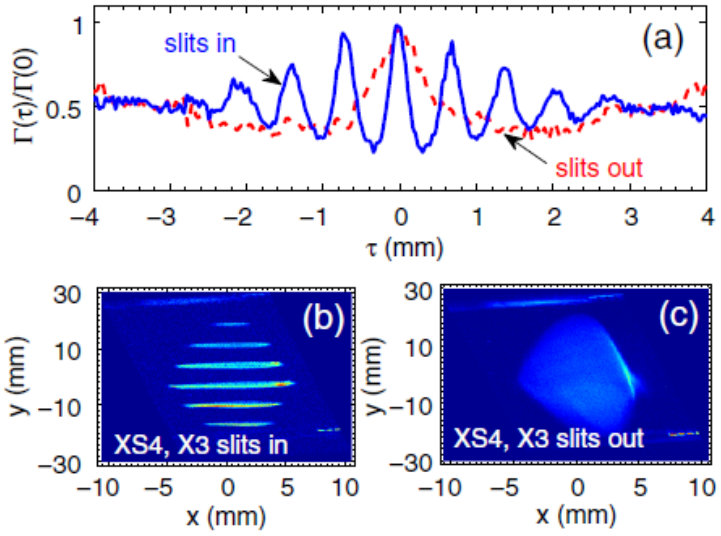


Transverse-to-longitudinal phase space exchange

- Demonstrated transverse to longitudinal emittance exchanges

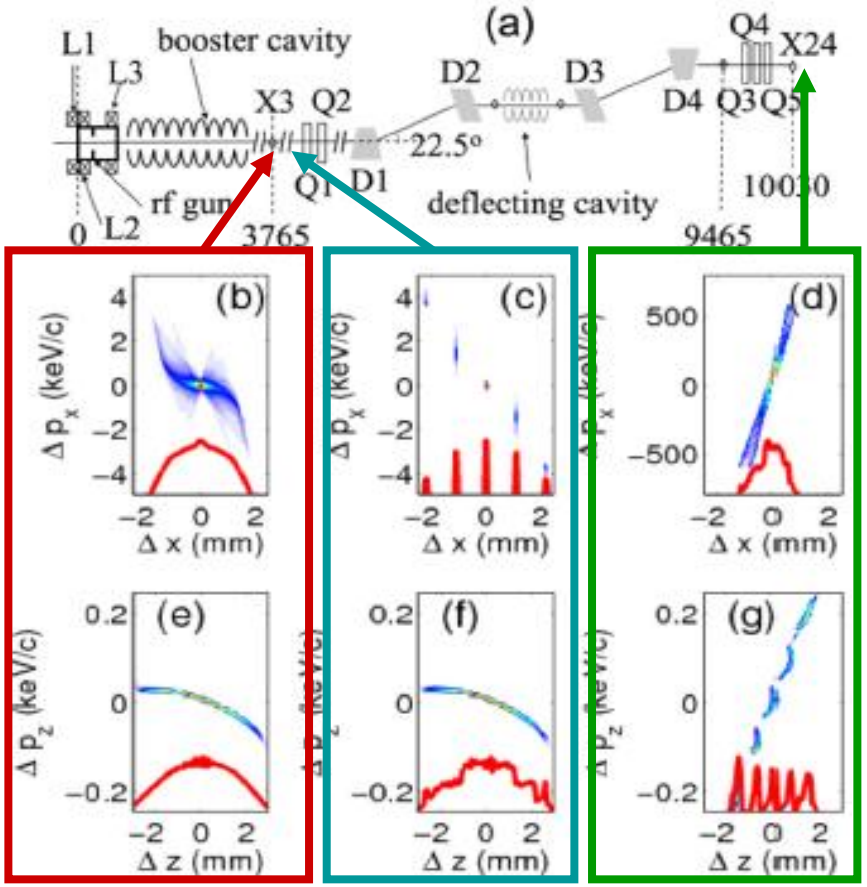
Y.-E. Sun et al., PRL 105, 234801 (2010)
P. Piot et al., PRSTAB 14, 022801 (2011)

	Simulated		Measured	
	In	Out	In	Out
ε_x^n	2.9	13.2	2.9 ± 0.1	11.3 ± 1.1
ε_y^n	2.4	2.4	2.4 ± 0.1	2.9 ± 0.5
ε_z^n	13.1	3.2	13.1 ± 1.3	3.1 ± 0.3



- Demonstrated bunch current profile shaping

J. Ruan et al., PRL 106 244801 (2011)



The Six-Cavity Test

D.Wildman, J.Steinel, V.Scarpine, M.Chung, et al

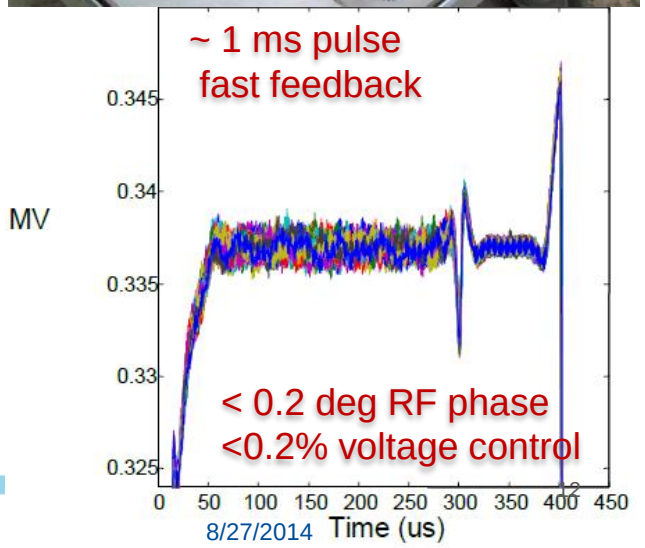
- "Six-Cavity Test' has demonstrated the use of high power ***RF vector modulators*** to control 6 RF cavities + RFQ driven by a ***single high power klystron***
- demonstrated the energy stability with a 7-mA proton beam accelerated through the six cavities from 2.5 MeV to 3.4 MeV.

Diagnostics development and tests:

- together with RAL and Argonne

Finished operation Jan'2013

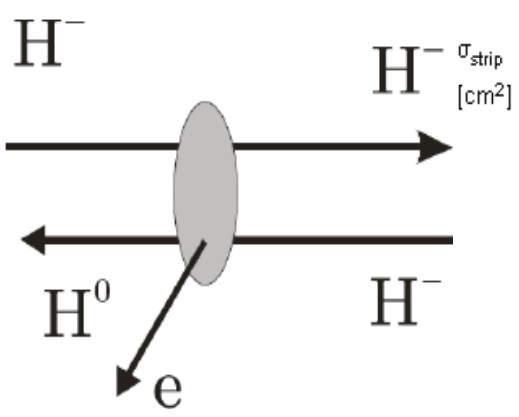
Will move to ASTA (*p*'s for IOTA)

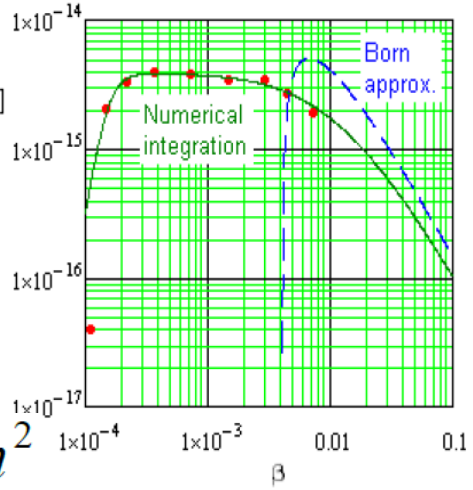


New Effect: Intrabeam Stripping of H- in linacs

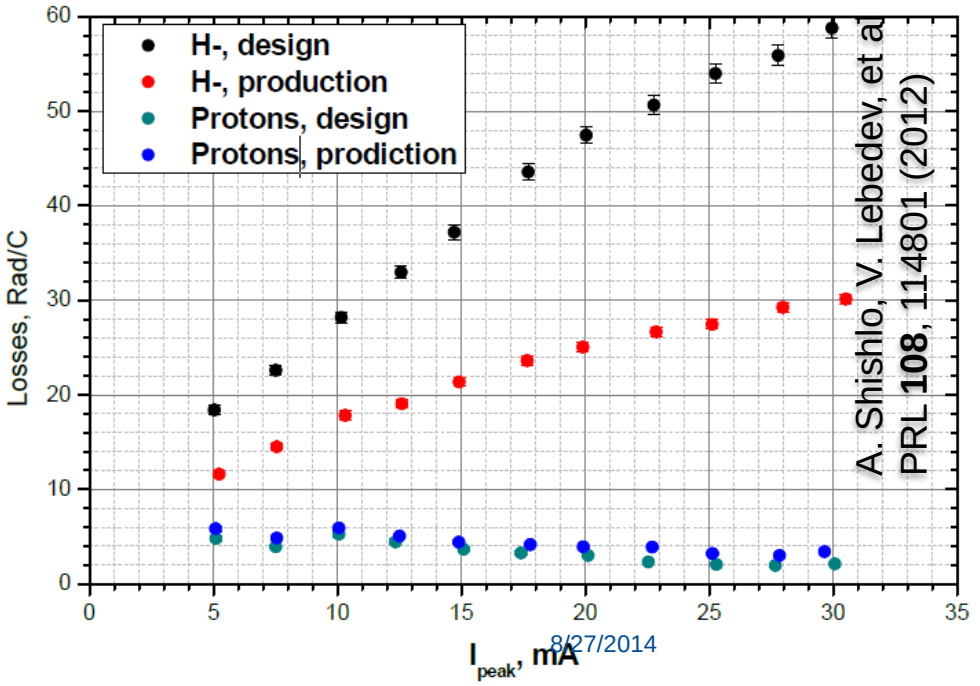
- Predicted by V.Lebedev:

  $H^- + H^- \rightarrow H^- + H^0 + e$ *(intrabeam stripping)* leads to losses and can explain higher than expected losses i in the SNS linac
- Theory was developed together with SNS colleagues
- Experimental beam studies:
  - comparison of beam loss in the superconducting part (SCL) of the SNS for H^- anc protons
  - observed significant reduction in the beam loss for protons



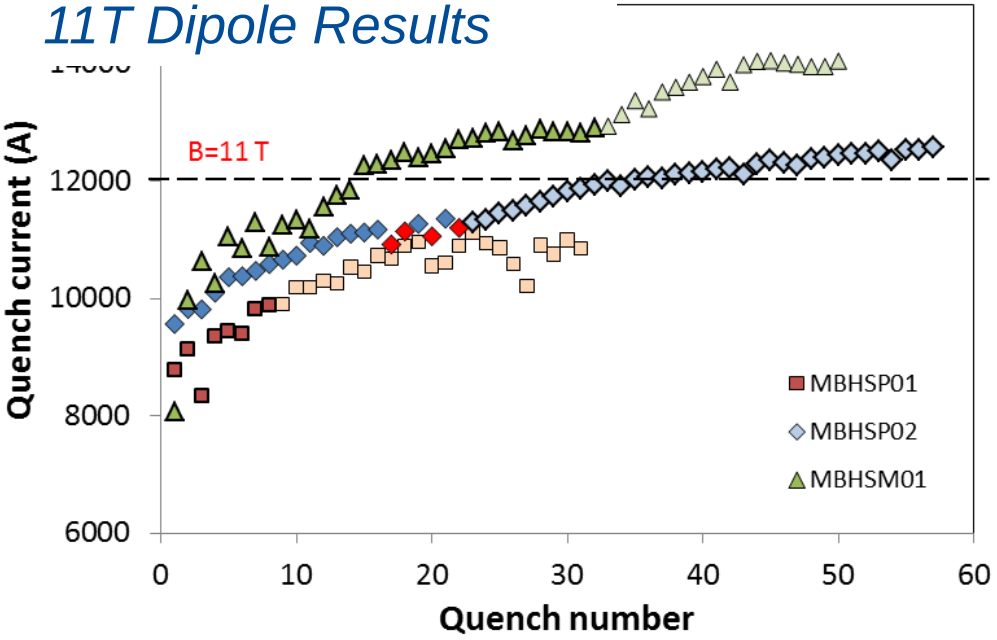


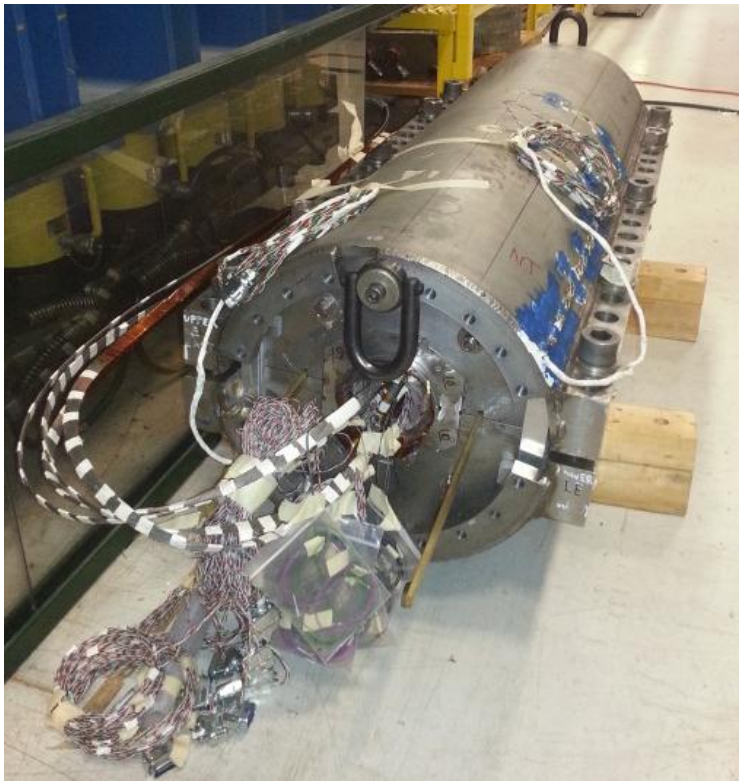
$$dn/dt \propto \sigma \cdot n^2$$



High-Field Magnets

11T Dipole Results

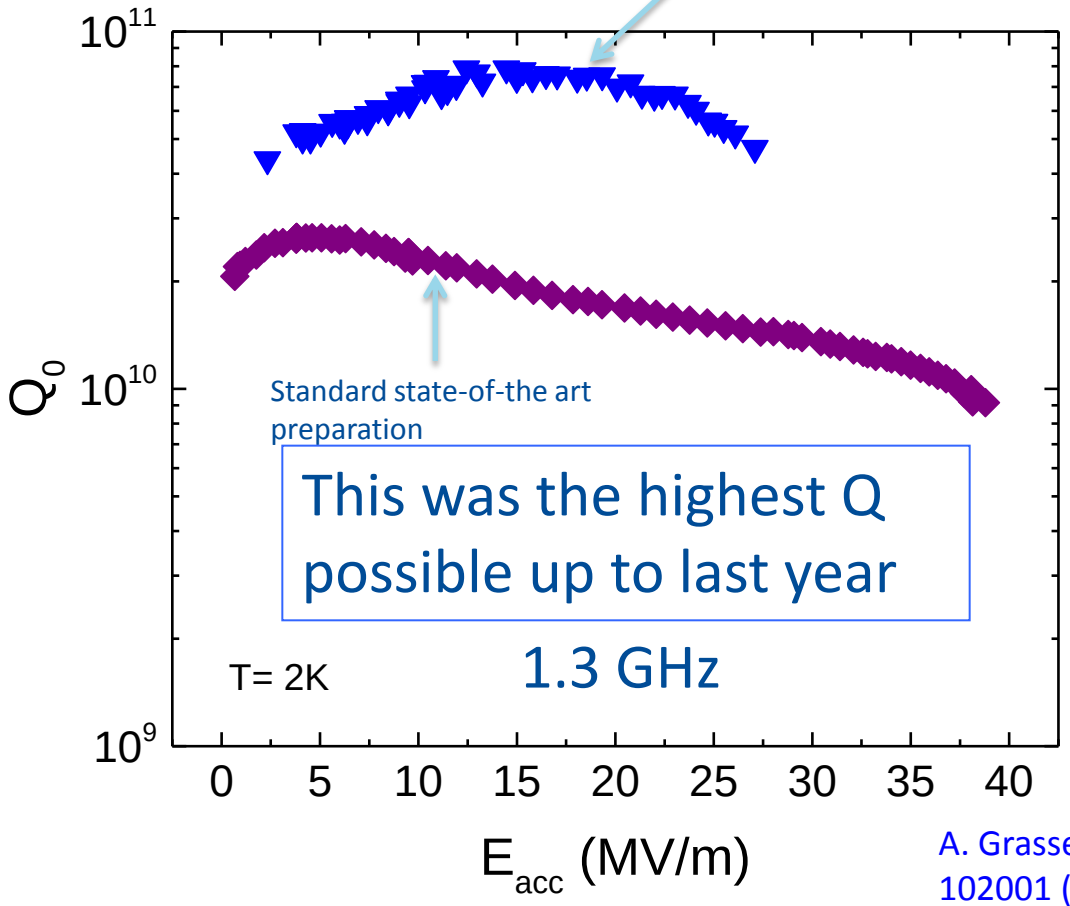




- 11 T Dipole Development in 2010-2014

Nitrogen doping: a breakthrough in BCS resistance (Q)

Record after nitrogen doping – up to 4 times higher Q!



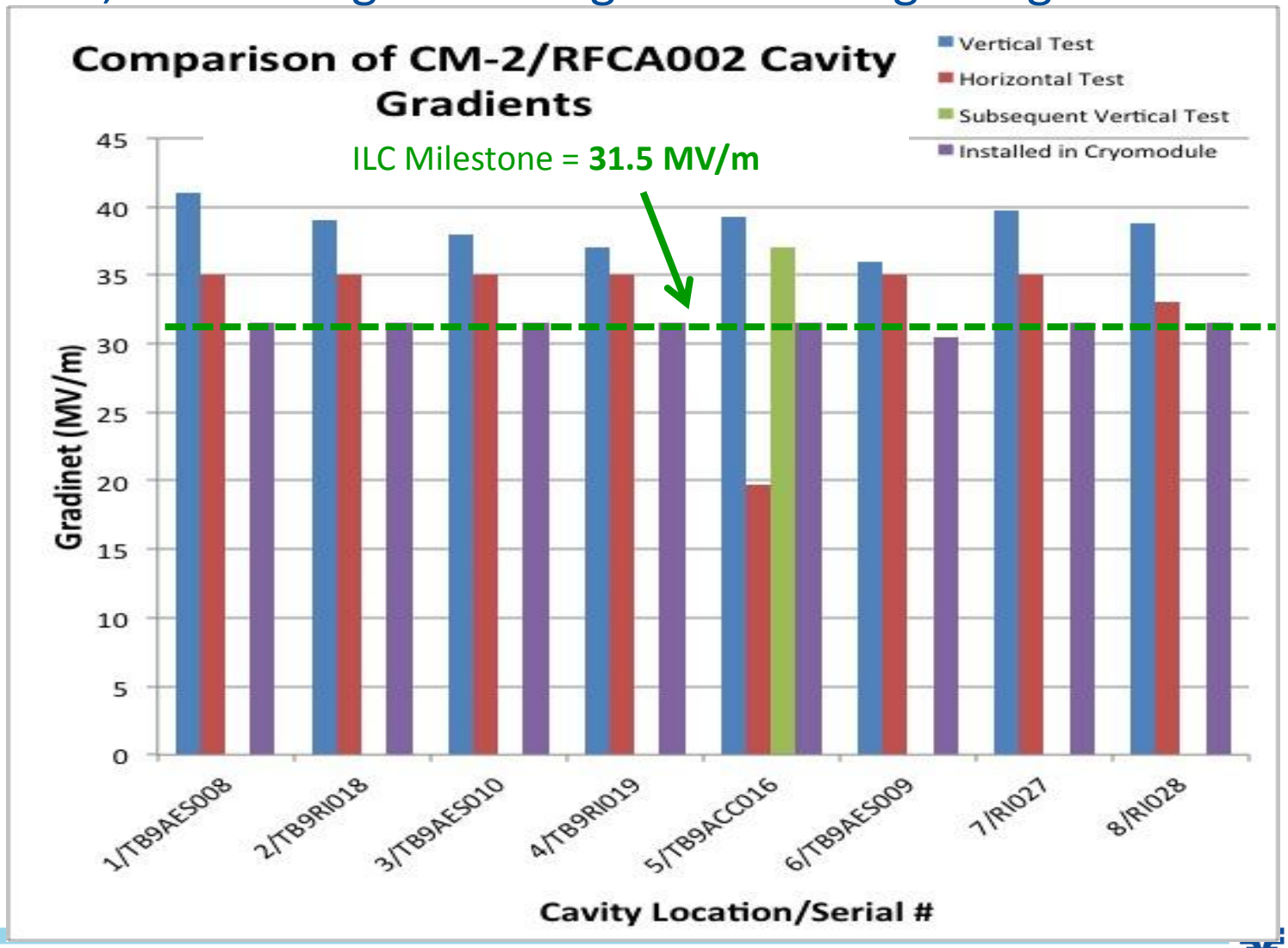
- Injection of small nitrogen partial pressure at the end of 800C degassing, followed by EP-> drastic increase in Q
- Demonstrated on many 1-cell and 9-cell 1.3 GHz cavities

A. Grassellino et al, 2013 Supercond. Sci. Technol. **26** 102001 (Rapid Communication) – selected for highlights of 2013

Fermilab

Fermilab CM2 – Cavities Tested One-by-One => Highest Gradient CM in the World

Now, 7 are being tested together. Still highest gradient.



Fermilab

ASTA : Fermilab's Main Accelerator R&D Beam Facility

Unique R&D facility close to completion:
IOTA ring, high-brightness photo-injector, ILC cryomodule, proton RQF

~90M$ investment by OHEP since 2006

- **Science goal:** Experimentally demonstrate novel techniques of integrable beam optics and space charge compensation, SRF research
- **Technical challenge:** fabrication high-precision nonlinear magnets; injector for delivery of pencil electron beam and high-current low energy proton beam, beam thru SRF CM
- **FY14 highlights:** Half of IOTA ring elements built and received as in-kind; electron injector and SRF cryomodule commissioned

IOTA operations start: 2018 (with protons)

Partnerships

- Nat. labs: 7
- U.S. universities: 6
- International: 4

Beam Theory and Simulations

- A number of outstanding advances in beam theory:
  - A series of works (2009-2012) by Burov, Balbekov,and Lebedev on beam dynamics of longitudinal and transverse instabilities with space-charge
  - Theory of nonlinear but integrable (stable) beam optics
  - *"Outstanding" PRSTAB Article of 2010*: V. Danilov, S. N., PRSTAB, 13, 084002 (2010)
  - *"Outstanding" PRSTAB Article of 2011*: P. Piot, Y.-E Sun, J. G. Power, and M. Rihaoui, PRSTAB 14, 022801 (2011).
  - A suite of modeling tools, developed at Fermilab:
  - MARS 300 users, 40 institutions
  - Synergia 30 8
  - OPTIM 20 5
  - Lifetrac 10 5

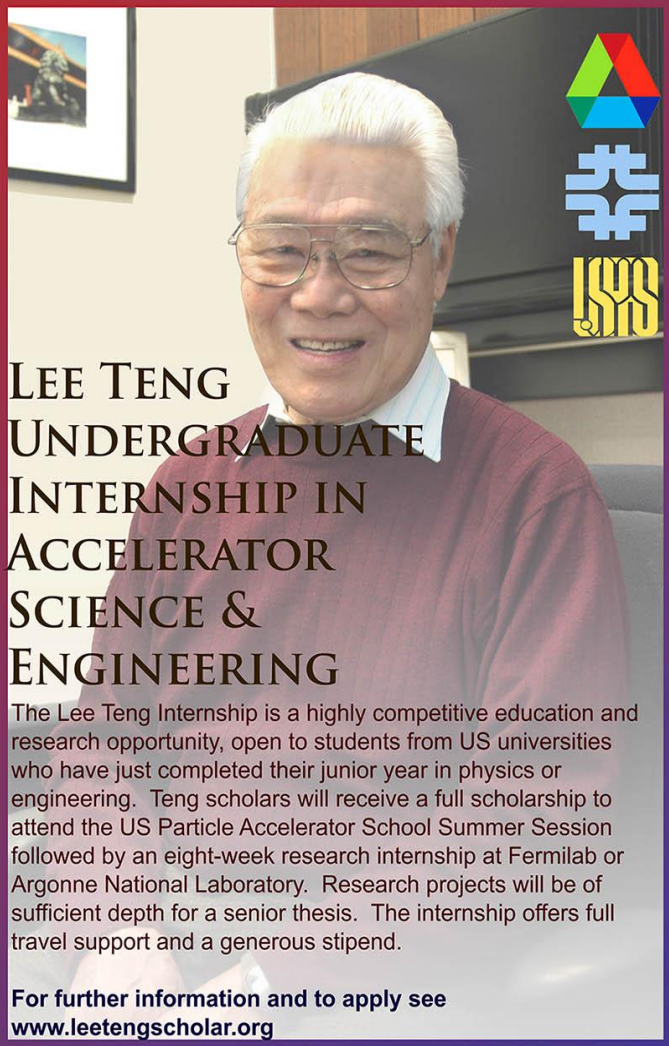
PhD Degrees based on research at Fermilab : 9 over 2009-2014

Denise Ford	2013	Northwestern
Timothy Maxwell	2012	Northern Illinois University
Alexey Petrenko	2012	Budker Institute of Nuclear Physics
Arun Saini	2012	University of Delhi
W.-M. Tam	2010	Indiana University
Dan McCarron	2010	Illinois Institute of Technology
Igor Tropin	2010	Tomsk University
Uros Mavric	2009	University of Ljubljana
Timothy Koeth	2009	Rutgers University

- Currently – *8 students* in *Joint University-Fermilab Accelerator PhD program,* also students supported by NIU, Uchicago, UMD, IIT, CSU
- **4** Joint Faculty Appointments: NIU: P.Piot, Y.M.Shin, S.Chattopadhyay; IIT: P.Snopok

Other Education / Undergrad Outreach programs in Accelerator Physics

- Lee Teng Internship (with ANL):
  - Engage highly promising post-junior undergrads to study accelerator S&T
  - 61 participants in 2009-2014
  - Interns study “Fundamentals” at USPAS, undertake research project at the labs for ~2 mos in the summer
  - Committee chaired by E.Prebys
- Int’l Summer Internship :
  - ~60 participants in 2009-2014
  - 2 students earned PhD in accelerator physics/technology
  - 11 students are currently enrolled in a MS/PhD programs in accelerators



US PAS Office & Fermilab

US-PAS Office (part of APC)

William Barletta (Director)

Susan Winchester

Irina Novitskaya

*Attendance numbers **140-150** per session show that there is a steady interest in accelerator science*

***Lecturers** (2014):*

William Barletta
Don Cossairt
Dan Green
Amber Johnson
Mauricio Lopes
Michael McGee
Eric Prebys
Matt Quinn
Warren Schappert

Total over 2009-2014:

***40 instructors and assistants** from Fermilab*

Also…

- ***Awards:***
  - *IEEE PAST* *2009* *K.Seyia*
  - *APS Thesis* *2010* *R.Miyamoto*
  - *DOE Early Career* *2012* *P.Snopok, T.M.Shen, A.Romanenko*
  - *DOE Early Career* *2013* *A. Grassellino*
- ***Editors and Editorial Boards***
  - W.Chou *ICFA Beam Dynamics Newsletter*
  - L.Cooley *Superconductor Science and Technology*
  - V.Shiltsev *Phys. Rev. ST-AB, JINST*
- ***Referees for Peer-Review Journals***
  - Phys. Rev. Letters, Phys. Rev. ST-AB, JINST, NIM-A, IEEE Trans. Nucl. Sci., Review of Scientific Instruments, European Physical Journal, Physics Procedia, NIM-B, NIM-B Proc, Prog. Nucl.Sci.Tech.
  - *APS Outstanding Referee* - T.Sen 2013
- ***Membership in Program and Organizing Committees of all major accelerator conferences and workshops:***
  - IPACs, NA-PACs, AAC, HB, BIW, LINAC, RESMM, SRF, MT etc.

15 *APS Fellows* are involved in Fermilab's Accelerator R&D

E.Barzi

A.Bross

S.Geer

E. Prebys

H.Edwards

H. Padamsee

S.Holmes

S. Mishra

V.Lebedev

N.Mokhov

S.Nagaitsev

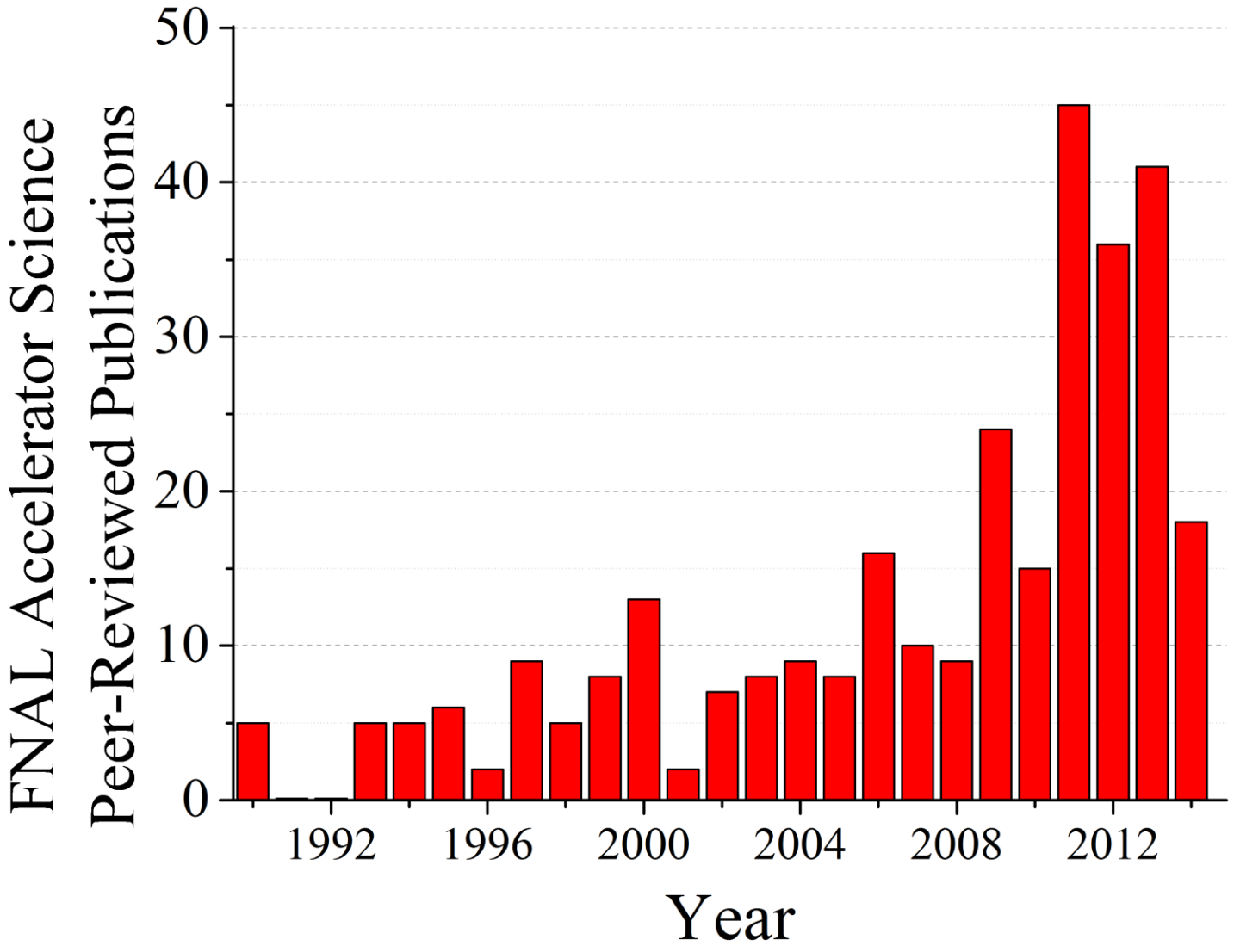
D.Neuffer

V.Shiltsev

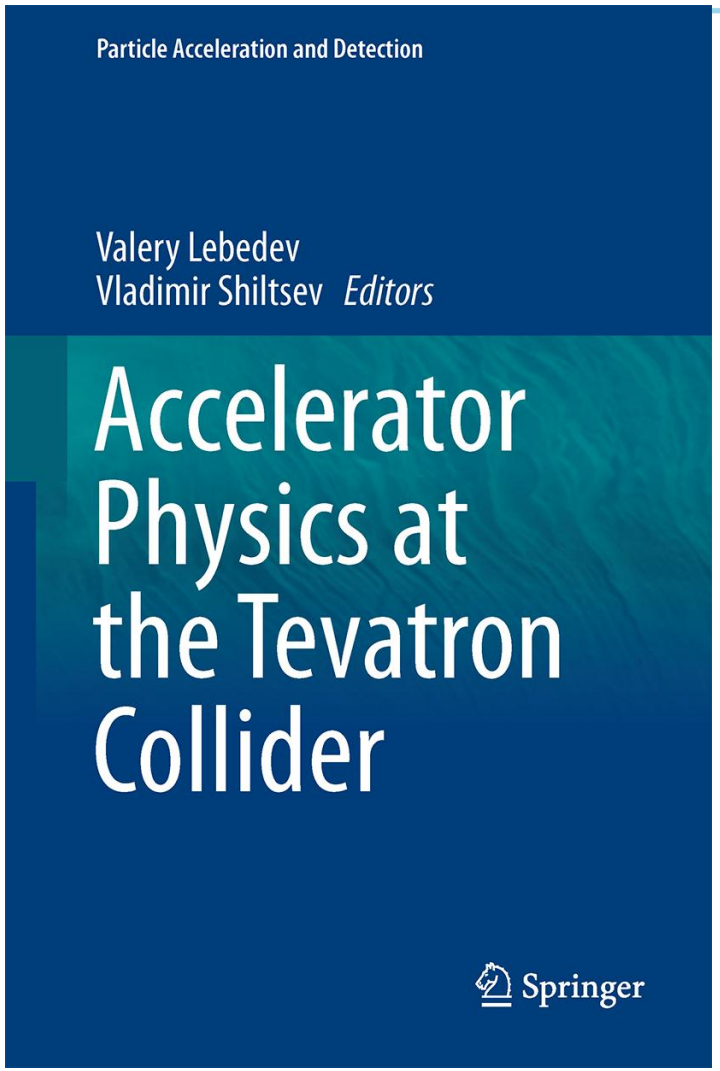
A.Tollestrup

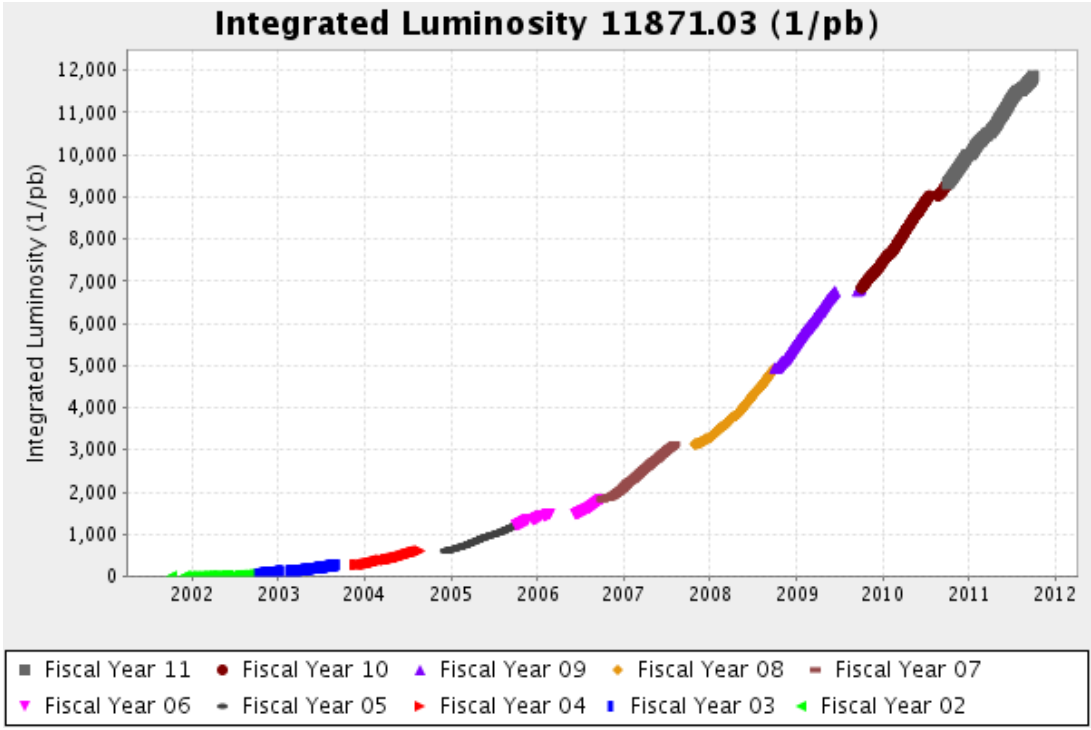
V.Yarba

Peer-reviewed accelerator science publications



Our story about the Tevatron Run II





Available on Amazon.com

Fermilab

Quality and Impact

- Quality and Impact
  - We are carrying out world leading research and development in many areas of central importance to the future of accelerator-based HEP, ranging from
    - SCRF science and technology, to
    - high field magnets for future accelerators, to
    - MW-power beams and targets, to
    - advanced theoretical and experimental beam physics
  - Fermilab GARD focuses on “outcomes and capabilities” to make HEP machines viable and cost-effective.
  - We pay attention to training and university – lab partnerships
  - We have a highly-competent world-renowned team to carry-out research and to support the operations, programs, projects.
- FY15 (plan): $11.5M, FY14: $17.8M, FY13(actual): $23.6M

Present national GARD thrusts

- Advanced Accelerator Concepts
- NC/High-gradient structures and RF sources
- Accelerator, Beam and Computational Physics **V**
- Particle Sources **V**
- Beam Instrumentation and Control **V**
- Superconducting RF **V**
- Superconducting Magnets and Material **V**
- Other (Training) **V**

V – where Fermilab plays substantial role

Advanced Accelerator Concepts

- Fermilab is NOT part of this thrust
- Presently geared toward e+e- colliders
- How can we help?

NC/High-gradient structures and RF sources

- NC/High-Gradient structures:
  - In 2004 we manufactured a record-setting NLC structure.
  - In 2005 we turned our attention to ILC.
  - Now, CLIC (CERN) is the world leader in this area.
  - CERN is planning to commercialize the CLIC technology.
  - This thrust is NOT a priority for the US HEP!
- RF sources – Fermilab would like to be part of this R&D
  - patent pending on a new magnetron-based technology;
  - Focus on cost- effective rf sources for srf linacs

Superconductive RF

- Fermilab is becoming a national leader in the SRF science and technology
  - extensive infrastructure and experienced staff;
  - everything we see in the national program has SRF;

- The P5 report told us:

  "It is appropriate for the PIP-II effort to be supported partially by temporary redirection of GARD funding of SCRF R&D and facilities at Fermilab."

  This has been **already <u>implemented</u>** in the FY15 budget
- However, the SRF research should **<u>be strengthened</u>** instead
  - See talks by Padamsee/Romanenko

National General Accelerator R&D Recommendations

for the Fermilab GARD Priorities Working Group

Fermilab GARD Priorities Working Group

- Sergei Nagaitsev (co-chair), Joe Lykken (co-chair)

Hasan Padamsee	Dmitri Denisov
Steve Holmes	Gina Rameika
Vladimir Shiltsev	Michael Lindgren
Robert Zwaska	Estia Eichten
Alex Romanenko	Pushpa Bhat
Alexander Zlobin	Robert Bernstein
Mark Palmer	Chris Polly
Teng-ming Shen	Pat Hurh
Panagiotis Spentzouris	Robert Roser
Helen Edwards	Byron Lundberg
Swapan Chattopadhyay	Steve Geer
Valeri Lebedev	Greg Bock

Present GARD thrusts are out-of-date

- We examined the present national GARD thrusts and determined that they are NOT aligned with P5 priorities!

Our basis – the P5 Report

- The P5 report presented a vision and a strategy for maintaining our position as a global leader in elementary particle physics in the next decade and beyond;
- It is a well-balanced document and all Fermilab scientists are strongly behind it;
- Our recommendations for GARD priorities are well aligned with the report;
- We recognize that funding is not available to do everything;
- There has to be a balance between domestic and world priorities, between mid- and long-term, between theory, modeling, experiment and training, and between science and technology.

Strategic Considerations (from P5 report)

- "A very high-energy proton-proton collider is the most powerful future tool…"
- Neutrinos: aim at ~600 kTon*MW*yr
- "Power upgrades beyond PIP-II will require R&D for high average power proton linacs and target systems."
- For e+e- colliders: "…Primary goals are improving the accelerating gradient and lowering the power consumption."
- "Support the discipline of accelerator science through advanced accelerator facilities and through funding for university programs."
- "Focus on outcomes and capabilities that will dramatically improve cost effectiveness for mid-term and far-term future."
- "Strengthen University - National lab partnerships."
- Incorporate the balance of mid-term vs far-term R&D as well as impacts.

We recommend the following GARD thrusts

1. High-field magnets and materials
2. Multi-MW beams and targets
3. Cost-Effective SRF Technology
4. Advanced Accelerator Concepts
5. Accelerator Science, Modeling & Design
6. Core Accelerator Competencies

GARD Thrusts: Rationale and Goals

1. High-field magnets and materials
   - Long-term; maintain US leadership in SC magnets; Nb_3Sn, HTS
   - Significant T*m cost reduction, modest support of global design
2. Novel techniques for multi-MW beams and targets

PIP-II Beyond PIP-II (mid-term)

	1st 10 years	2nd 10 years		
To Achieve :	100 kT-MW-year	500 kT-MW-year		
We combine :		Option 1	Option 2	Option 3
Mass	10 kT	50 kT	20 kT	10 kT
Power	1 MW	1 MW	2.5 MW	5 MW

   - Mid-term strategy after PIP-II depends on the technical feasibility of each option and the analysis of costs/kiloton versus costs/MW
   - R&D on effective control of beam losses in proton machines with significantly higher currents (Q_{SC}) and on multi-MW targets

GARD Thrusts: Rationale and Goals (2)

3. Cost-Effective SRF Technology
   - Crucial enabling technology for accelerators
   - Aim at a substantial reduction in construction and operation costs
   - Improve gradients, increase Q-factor, study new materials;
   - Affects both far- and mid-term accelerators

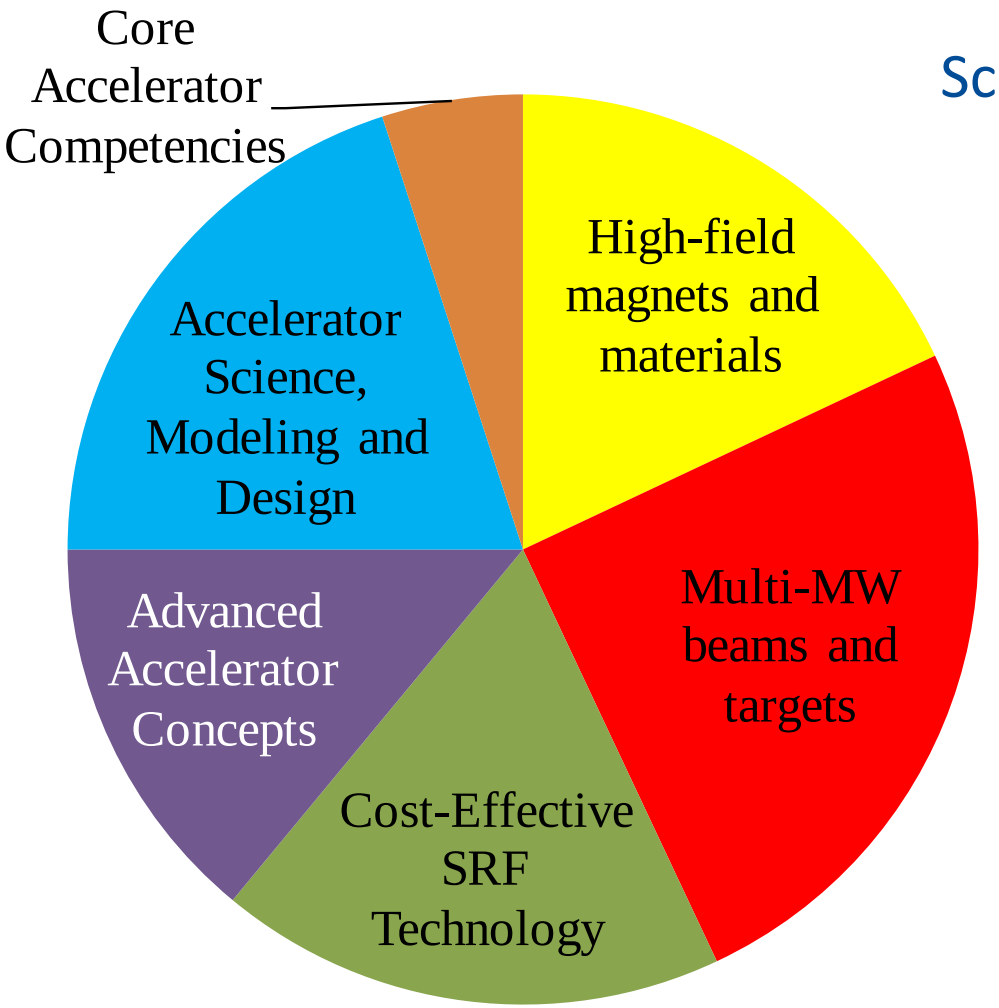
4. Advanced Accelerator Concepts
   - Conceptual and technical feasibility of advanced collider concepts; aim at HEP applications and significant **total** cost reduction
   - Intense secondary beams for next-generation precisions experiments (such as “beyond mu2e”, “beyond g-2” and a NF)
   - Both long- and mid-term

GARD Thrusts: Rationale and Goals (3)

5. Accelerator Science, Modeling and Design
   - Conceptual design and modeling of new machines
   - Cross-cutting accelerator theory and experiments
   - Excellence in high-performance high-fidelity computer modeling
   - Combination of both mid-term and long-term efforts

6. Core Accelerator Competencies
   - Accelerator training and education for HEP and beyond
     - Jointly - Universities and National Labs
   - Novel particle sources; Advanced beam instrumentation
   - NC rf and cost-effective rf sources
   - Both mid-term and long-term efforts

National GARD resource allocations (our recommendation)



Scenario C

- In Scenario C we recommend to:
  - Strengthen the high-field magnet program, maintain US leadership in this area;
  - Strengthen the high-gradient, high-Q SRF research for TeV-scale e+e- colliders and other applications;

Summary

- Fermilab is a world leader in Accelerator Science and Technology
- Fermilab strongly supports the P5 report
  - P5 calls for realignment of the national Accel R&D program;
- We are realigning Fermilab and we recommend how to realign the national program
- We are asking the Accel. R&D sub-panel to recommend for the SRF research to be funded at a healthy level.
- We are asking the Accel. R&D sub-panel to recognize the importance of the “MW beams and targets” thrust in the national R&D program
- We believe that the R&D toward a 100-TeV pp collider has the highest priority (in the long-term) and that the US leadership in this area should be maintained.