Accelerator R&D at Fermilab : An Overview

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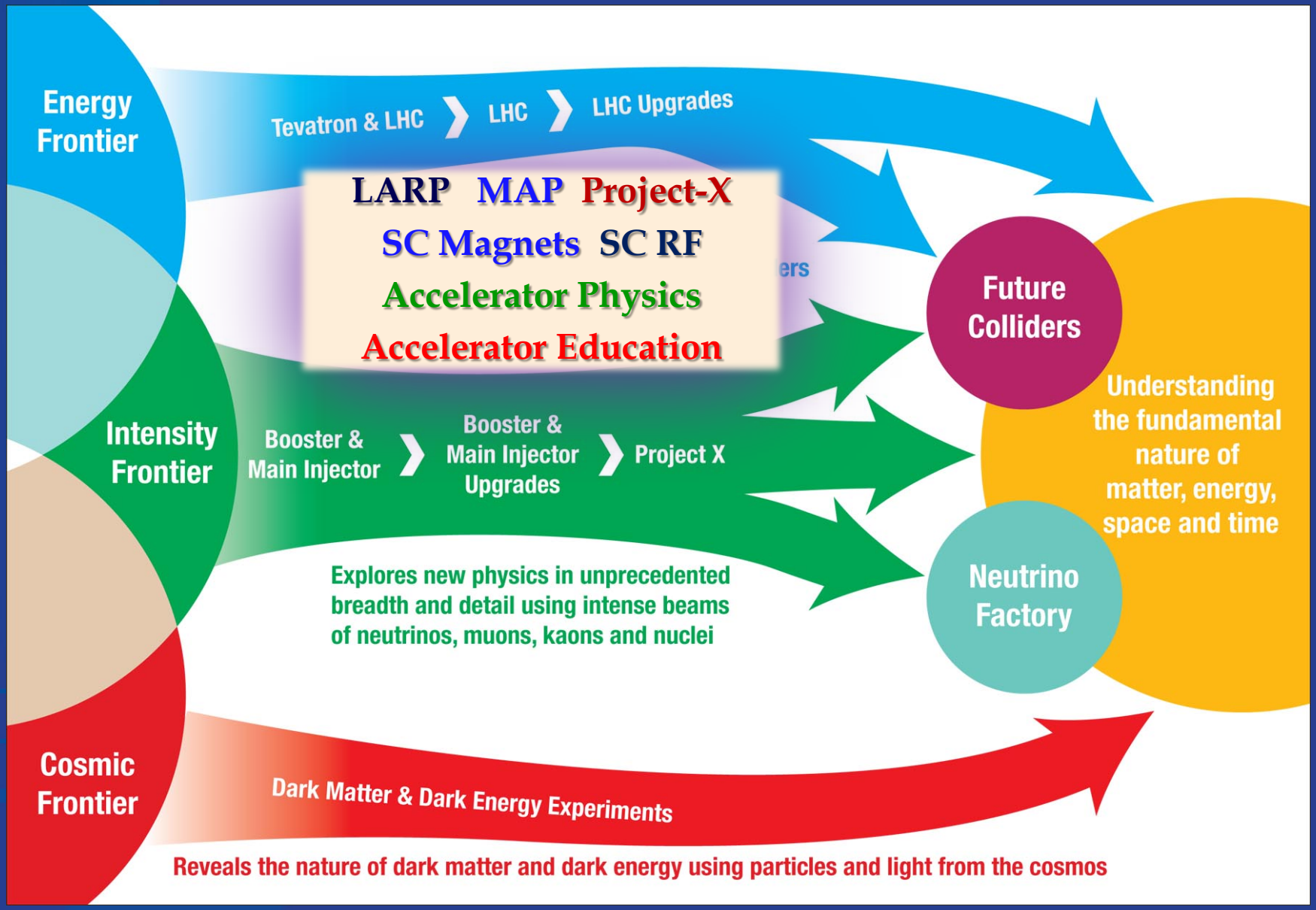
U.S. DEPARTMENT OF ENERGY

Fermilab

Outline

- Accelerator R&D in the Fermilab Context
- Components of the Lab's Acc.R&D Program:
  - "Goal-oriented" (LARP, MAP, Pr X, ILC/SRF)
  - General (SC Mag, SCRF, Acc.Phys, Education)
- Major activities, accomplishments and plans
  - ASTA
- Issues:
  - people, $$, HEP planning → strategy
- Conclusions

US HEP Long-Term Strategy



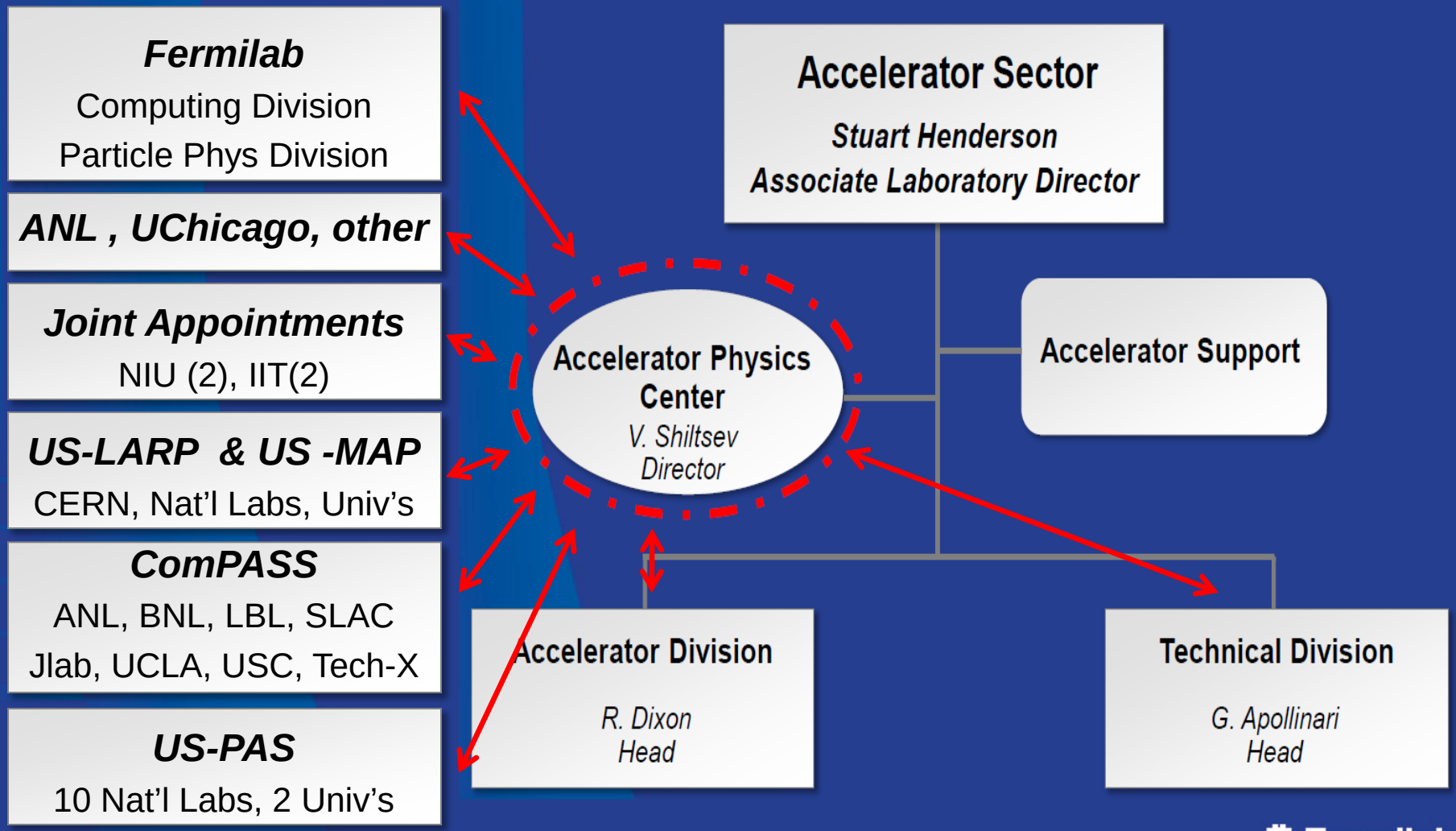
Accel R&D at FNAL: Components

- Two Nat'l Programs (LARP and MAP) and Project –X R&D:
  - Work Lab-wide (AD, APC, TD, SC)
  - Offices in Accelerator Physics Center
- Superconducting RF and High Field magnets
  - Mostly in TD and some in AD
- Accelerator and Beam Physics and Education
  - Very broad… provide support of operations, too
  - Centered and coordinated by APC
- New components: ASTA and IARC

Accelerator and Beam Physics and Education

Activities are conducted within the **Fermilab Accelerator Sector**

Accelerator Physics Center coordinates Accelerator Research activities



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Accelerator Science Activities by Thrust

- **Accelerator and Beam Physics**
  - Experimental Beam Physics studies at existing machines/facilities
  - Accelerator Theory, Simulation and Modeling; Support for the MARS, SYNERGIA, utilized by hundreds of users and dozens of institutions
  - ASTA Science and preparation/exploration of ASTA program
- **Particle Sources, Beam Instrumentation and Controls**
  - A0 program in the past (terminated)
  - HINS program in the past (completed on Jan 6th, 2013)
  - High Brightness Electron Source Lab (HBESL)
  - Photo-injector program at ASTA
- **Novel Accelerator Concepts**
  - Novel halo manipulation methods in proton rings
  - Integrable accelerator optics, space-charge compensation

  (no plasma, etc ="AARD", "Novel Concepts" belong to Accelerator & Beam Physics)
- **Accelerator Training and Education Programs**

Accomplishments:

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

- Carefully planned two 2-weeks 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

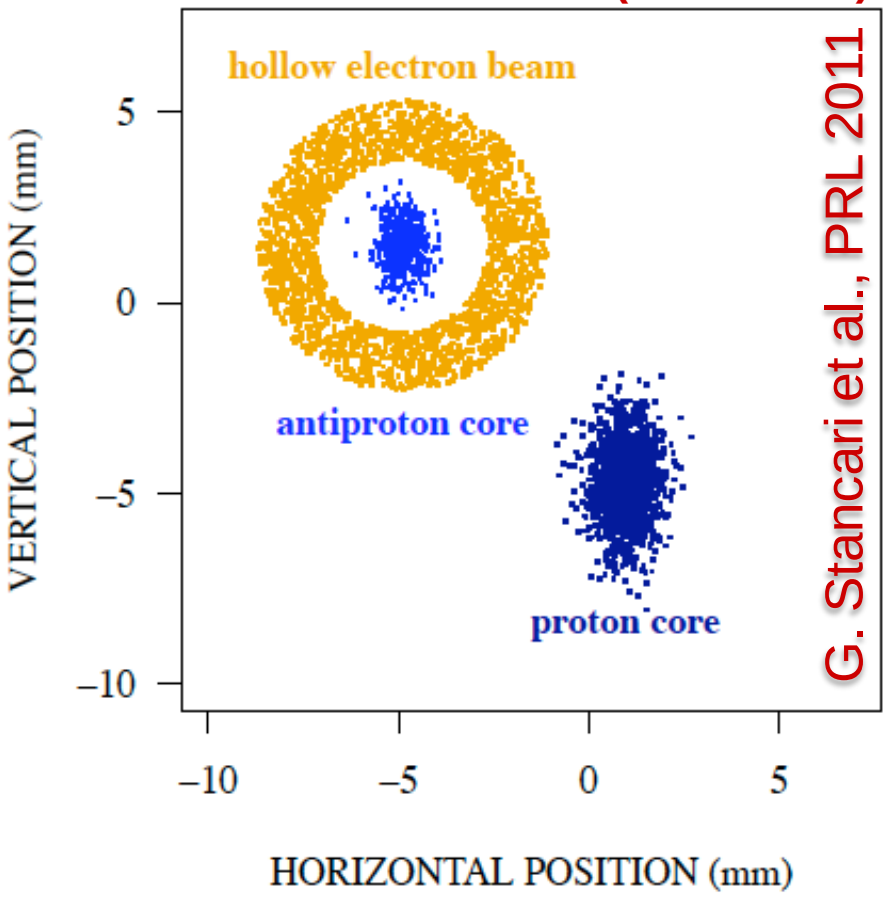
Tube of electron (Tevatron electron Lens)

No E-field inside

Strong E-field ouside drives resonances

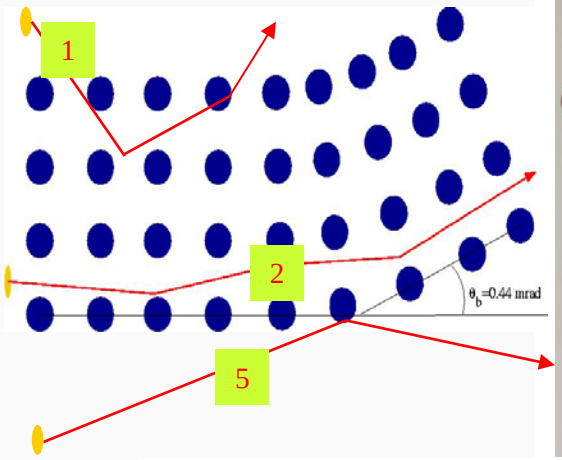
Fast diffusion = “soft collimator” effect

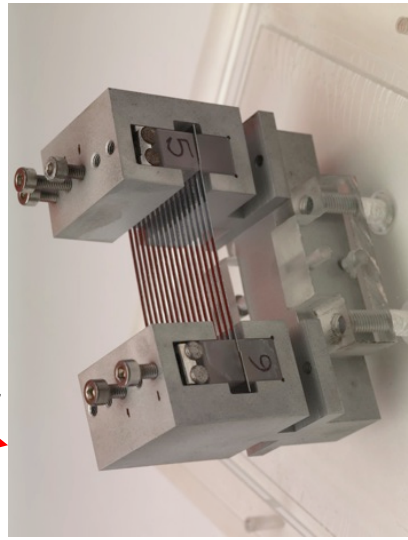
Cleans close to beam as well (no material)

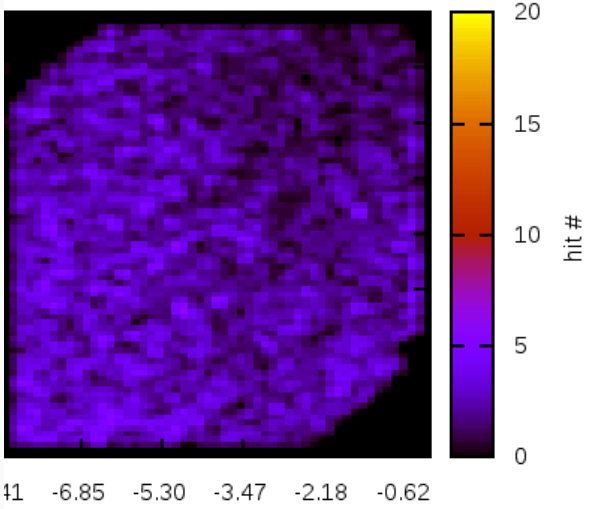


G. Stancari et al., PRL 2011

Bent Crystal Collimation







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

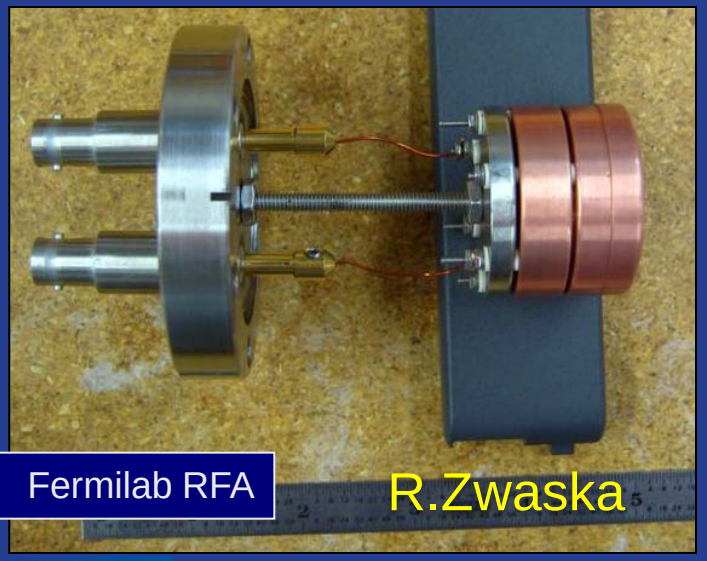
T980 Results D. Still et al. IPAC12

Channeled beam image on pixel detector

Main Injector: *e*- Cloud Experimental Station

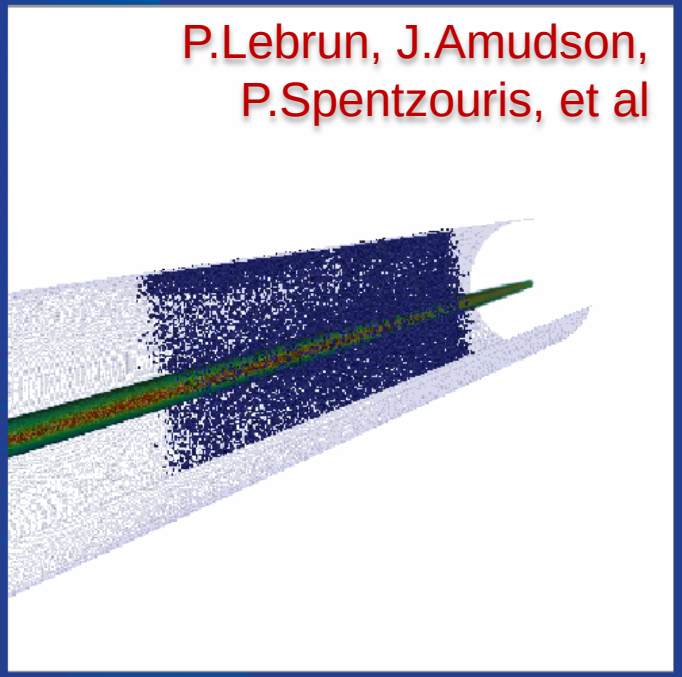
Station in Main Injector since 2009 :

- 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

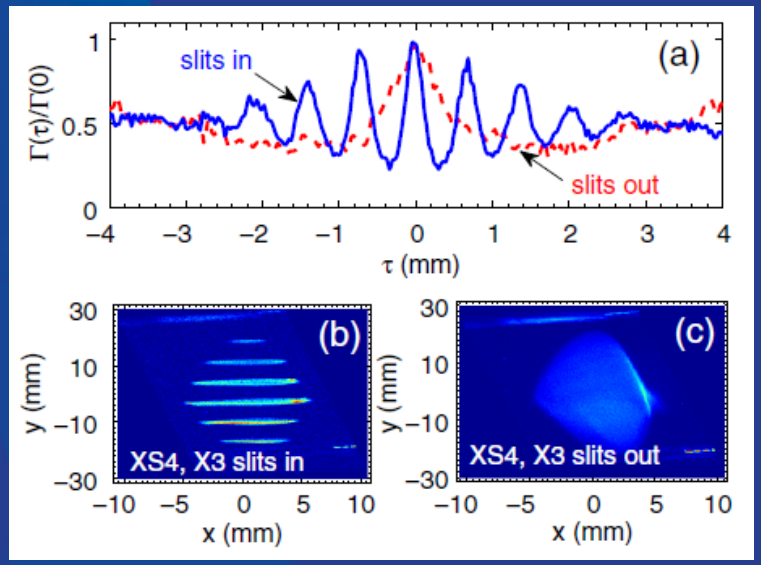
- Utilization of ComPASS tools :
  - *ComPASS VORPAL e-cloud simulation of MI experiments*
- Model microwave experiment (only possible with ComPASS tools), RFA response
- Code comparisons with “standard” tools such as POSINST



A0: transverse-to-longitudinal phase space exchange

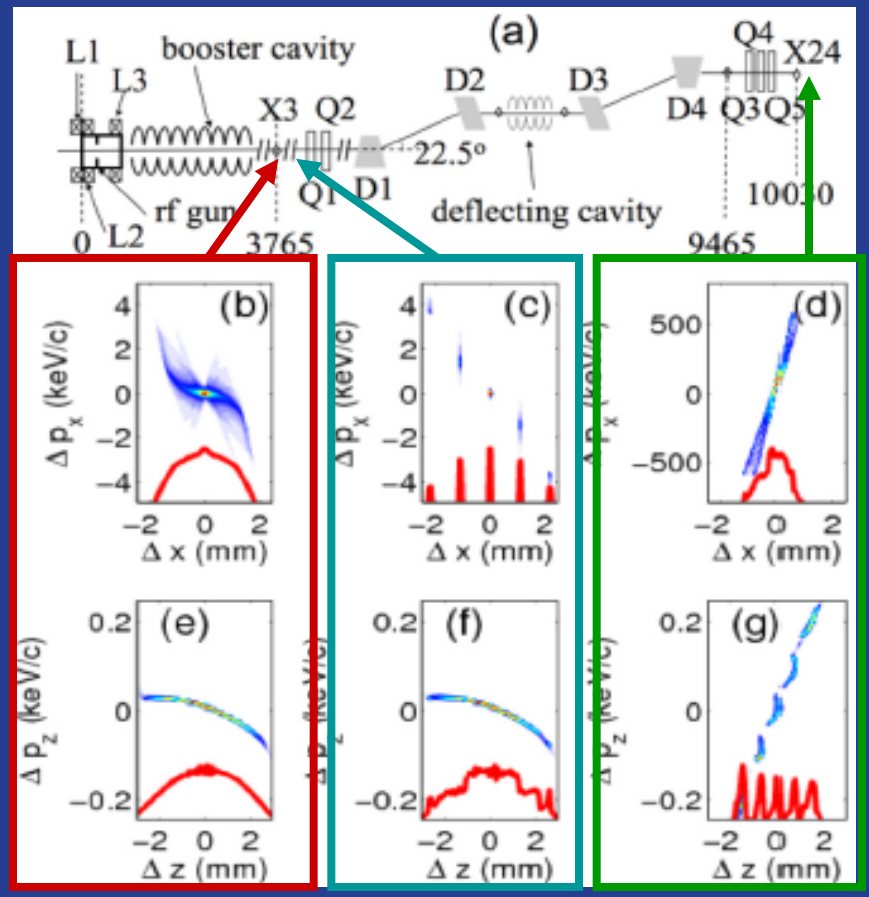
- Demonstrated transverse to longitudinal emittance exchanges

	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



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

- Demonstrated bunch current profile shaping



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

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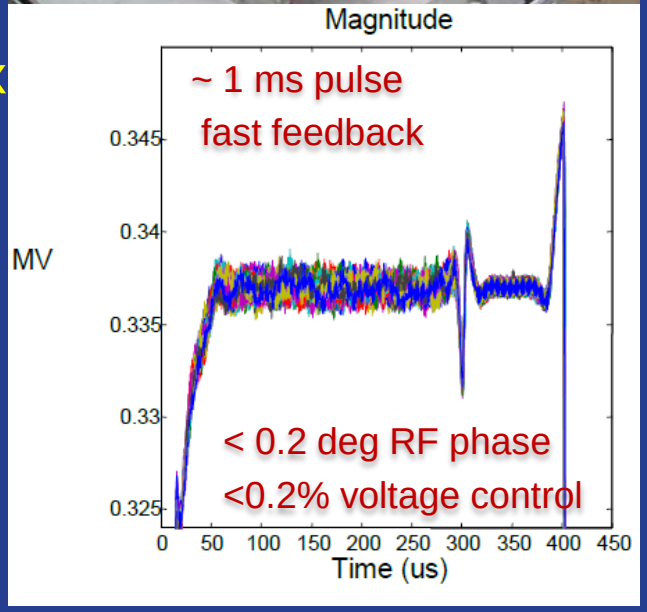
HINS 2.5 MeV Proton RFQ Tests

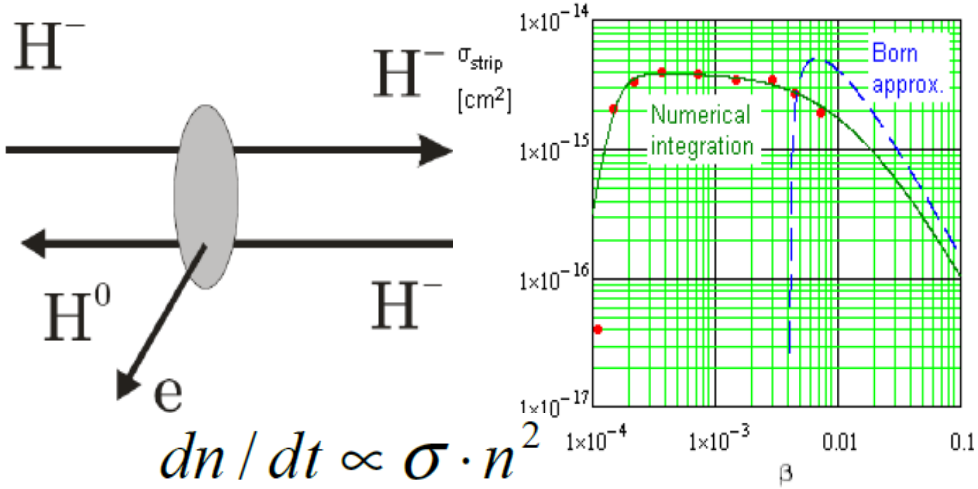
- D.Wildman, J.Steimel, V.Scarpine, M.Chung, et al

- *"High Intensity Neutrino Source"* test-bed at MDB: 2.5 MeV pulsed RFQ H-/p
- Many innovative studies for intensity frontier accelerators:
  - "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*** for acceleration
  - demonstrated the energy stability of the 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)

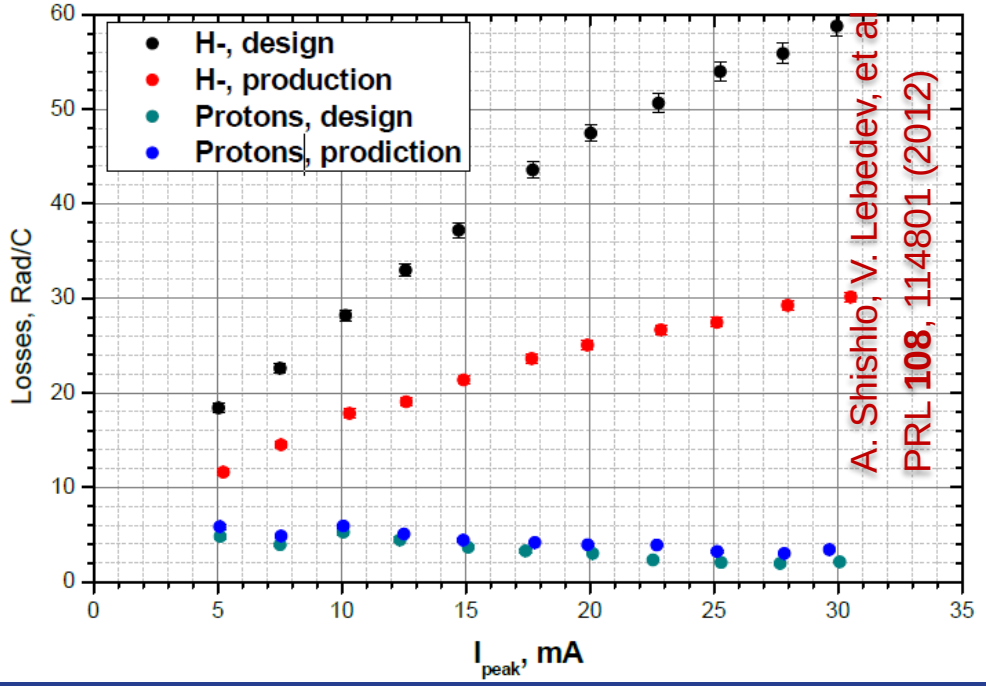


New (Fundamental) Effect: Intrabeam Stripping H-

- It was predicated by V.Lebedev that the reaction $H^- + H^- \rightarrow H^- + H^0 + e$ *(intrabeam stripping)* would lead to losses and can possibly explain higher than expected losses in SC proton linacs
- Theory was developed together with SNS partners
- Experimental beam studies:
  - comparison of beam loss in the superconducting part (SCL) of the SNS for H^- and protons
  - observed significant reduction in the beam loss for protons

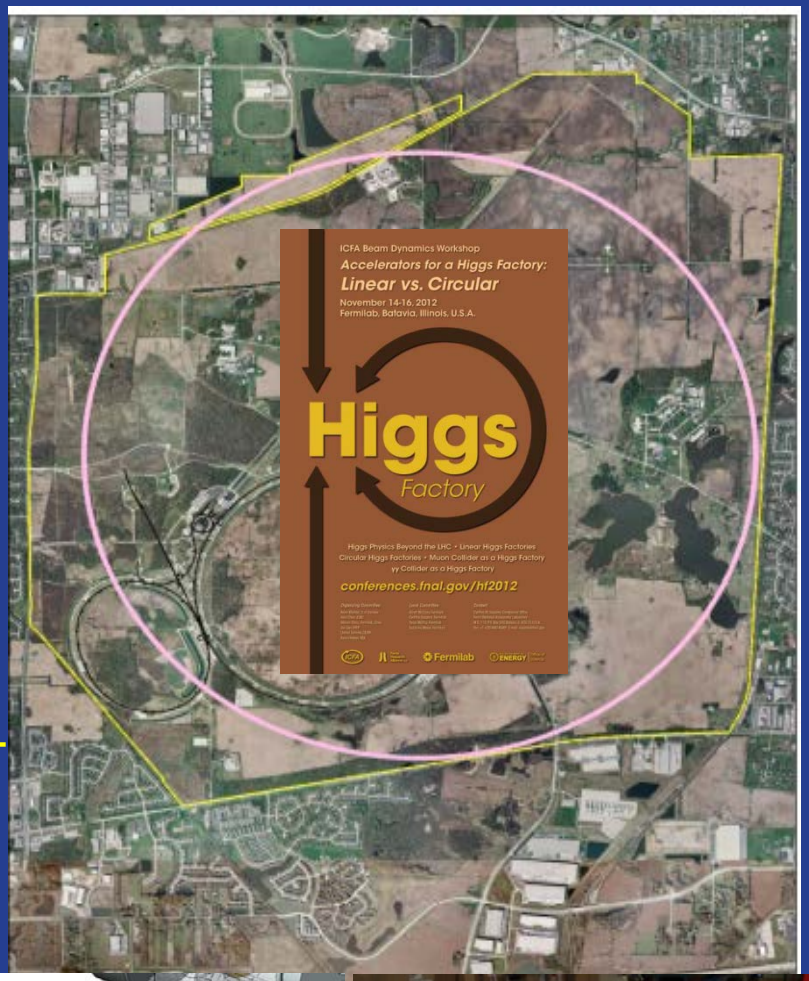


$$dn/dt \propto \sigma \cdot n^2$$

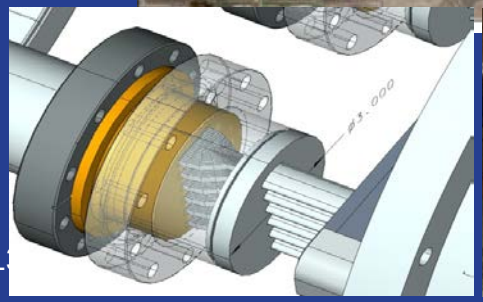


Design and Planning Work: Snowmass

- "Community Summer Study 2013" aka "Snowmass"
- Workshops at Fermilab:
  - Higgs Factory: Linear vs. Circular (Nov 2012)
  - R&D facilities (UoC, Feb 2013)
- Detail design studies:
  - Circular e+e- Higgs Factory "Fermilab site filler" … L=1e34
  - 16 km, 12 GV 100 MW SRF
  - Optics
  - Short lifetime -→ fast injector
    - HTS RCS ?
    - HTS cable loss studies



W.Chou, T.Sen, H.Piekarz

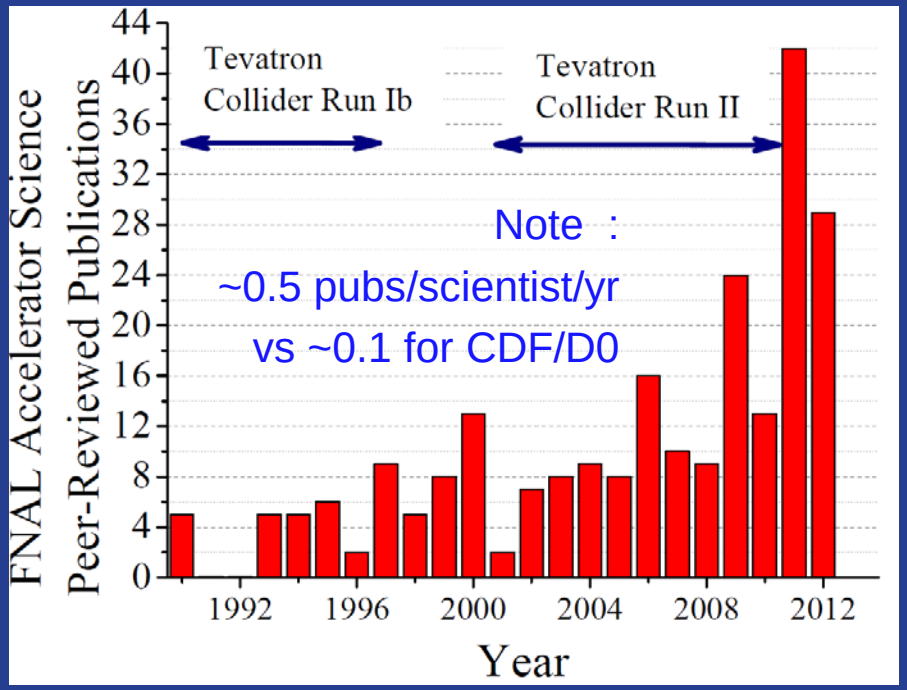


Beam Theory and Simulations

- A number of outstanding advances in beam theory:
  - 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 beam optics that is integrable (i.e. stable)
  - *Outstanding PRSTAB Article for 2010*: V. Danilov, S. Nagaitsev, PRSTAB, 13, 084002 (2010)
- Suite of modeling tools, developed and/or used at Fermilab:
  - MARS 300 users, 40 institutions
  - Synergia 30 8
  - OPTIM 20 5
  - Lifetrac 10 5
  - MADX

Accelerator Science & Tech Publications

- Strong record of peer-reviewed publication: ***130*** papers in ***2009-2013***
  - 2009 24
  - 2010 13
  - 2011 42
  - 2012 29
  - 2013 22 (1/2 year)



- **Very high quality**
  - 1 Nature Physics
  - 2 Annual Rev. Nucl. Part. Phys.
  - 11 Phys Rev Letters
  - 41 Phys Rev Special Topics-AB

(incl. two PRSTAB *Oustanding Articles* of 2010 and 2011)

PhD Degrees on base of research at Fermilab : 9 over 2009-2012

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

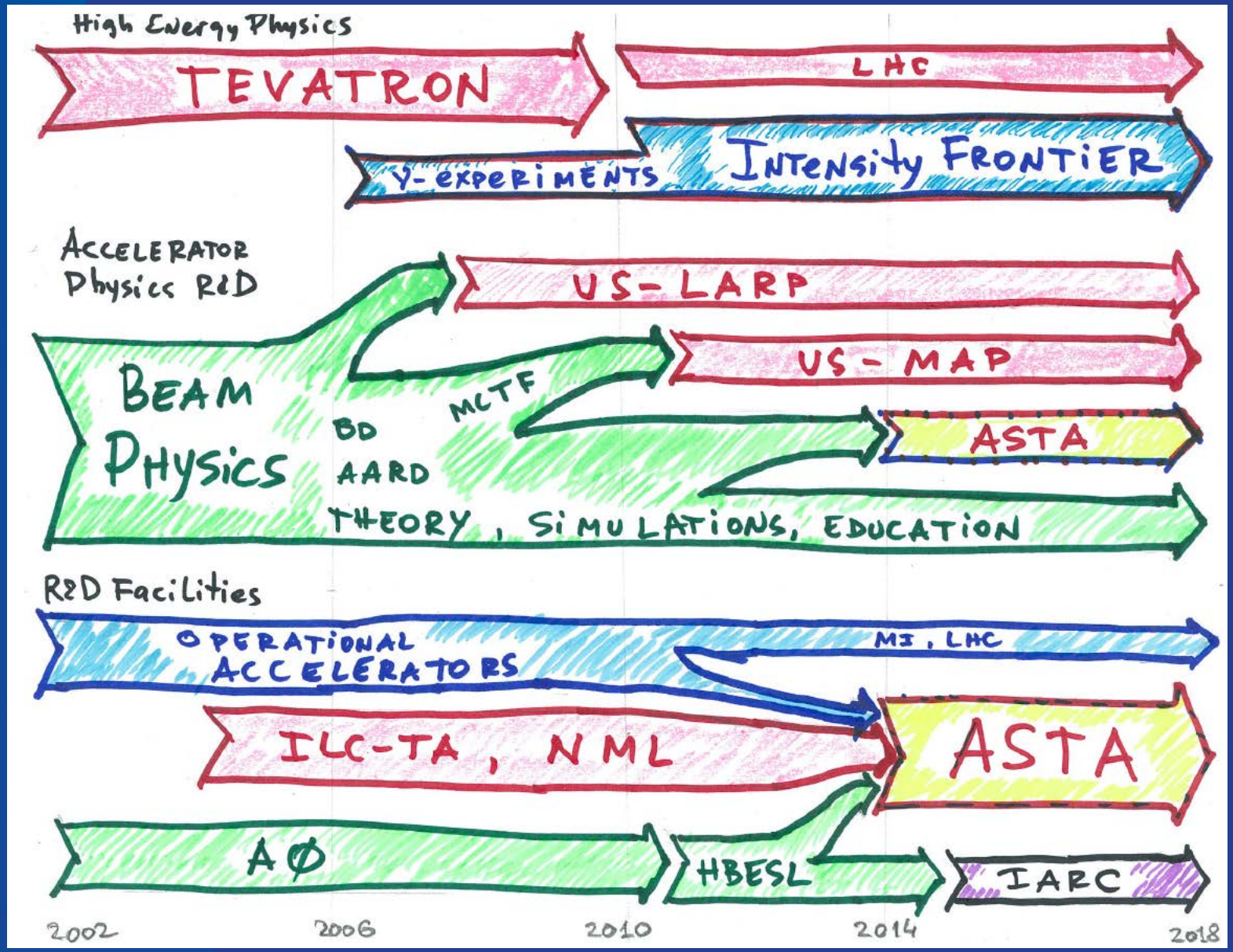
- Currently – *8 students* in *Joint University-Fermilab Accelerator PhD program*
- **4** Joint Faculty Appointments:
  NIU: P.Piot, Y.M.Shin; IIT: Y.Torun, P.Snopok

Education / Undegrad Outreach programs in Accelerator Physics

- US Particle Accelerator School
  - 2 sessions/yr
  - 140-150 students
- Lee Teng Internship (with ANL):
  - Engage highly promising post-junior undergrads to study accelerator S&T
  - 45 participants in 2009-2012
- Int'l Summer Internship :
  - 38 participants in 2009-2012
  - 2 students earned PhD in accelerator physics/technology
  - 11 students are currently enrolled in a MS/PhD programs in accelerators

What's next?

Accelerator R&D in Fermilab's Context



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ASTA Accelerator R&D User's Facility

(Advanced Superconducting Test Accelerator)

- A world-leading facility for Accelerator R&D at Fermilab that
  - Is based on state-of-the-art, modern SC technology
  - Supports an extremely broad accelerator R&D program ranging from HEP to photon sciences to applications
  - Serves critical needs in Intensity Frontier accelerator physics, while helping to fulfill OHEP's Stewardship role
  - Is cost-effective to complete and operate. (There is no competition at this price)
  - serves as a focal point for accelerator science education, not only for Fermilab, but for the nation.

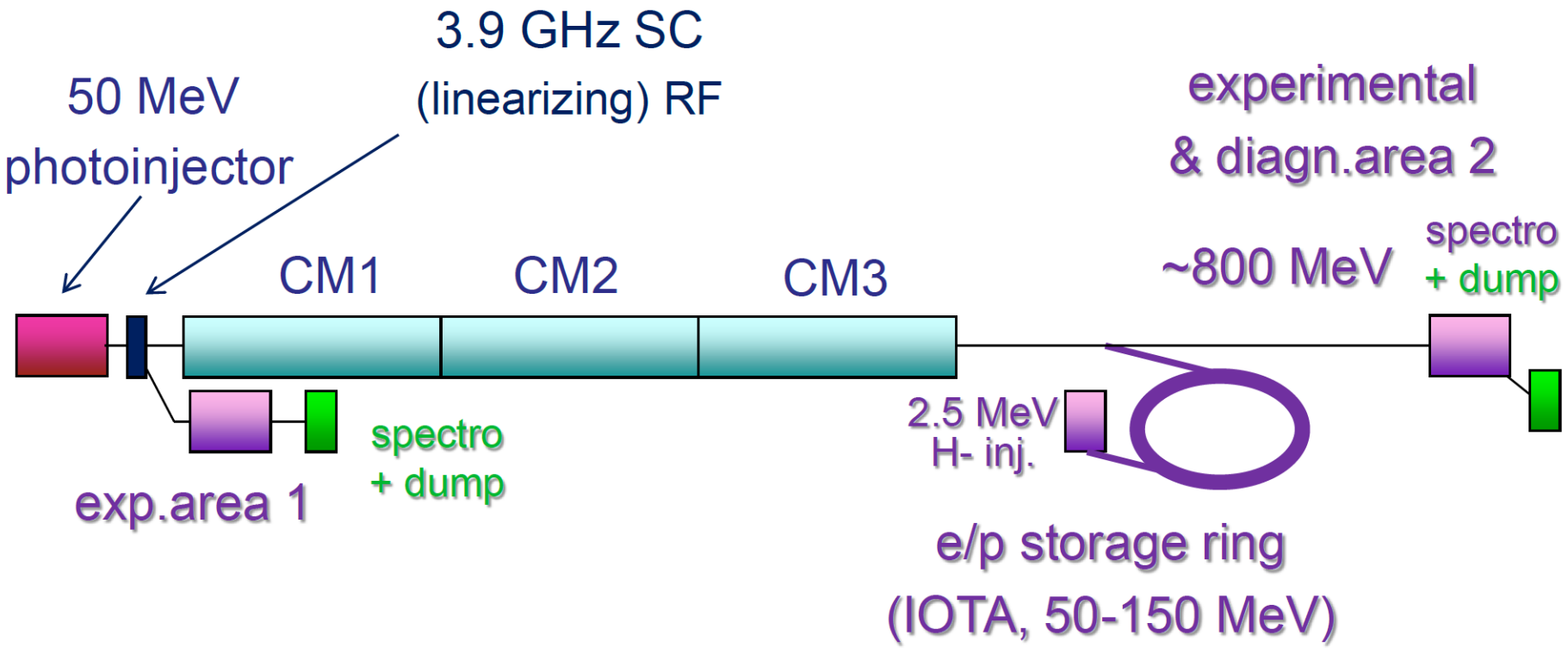
ASTA is a huge opportunity not be missed!

Background and History

- Construction of ASTA and NML began in 2006 as part of the ILC/SRF R&D Program and later American Recovery and Reinvestment Act (ARRA).
- The Facility was motivated by the goal of building, testing and operating a complete ILC RF unit
- To date, an investment of $74M has been made, including $18M of ARRA funding, representing ~80% completion of the facility
- It was recognized early in the planning process that an e- beam meeting the ILC performance parameters was itself a power resource of interest to the wider Advanced Accelerator R&D community.

- ASTA Proposal submitted to DOE on February 26, 2013
- ASTA Proposal reviewed by the DOE OHEP GARD Review panel in March 2013

ASTA (Schematically)



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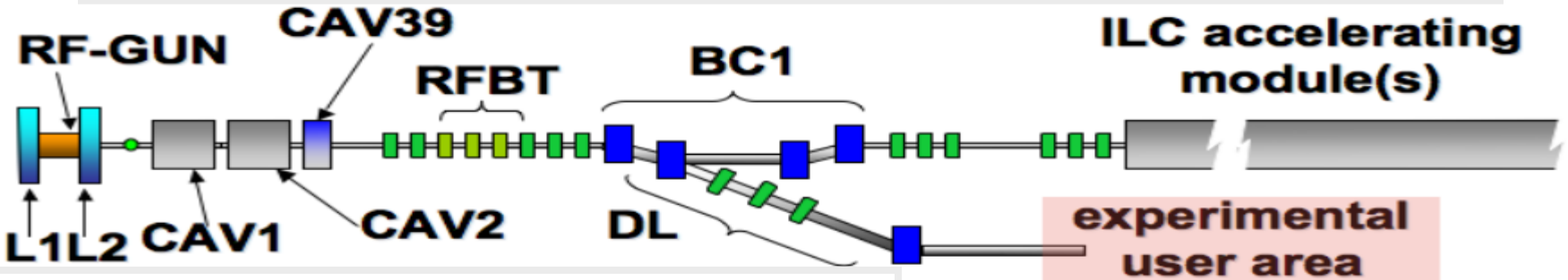
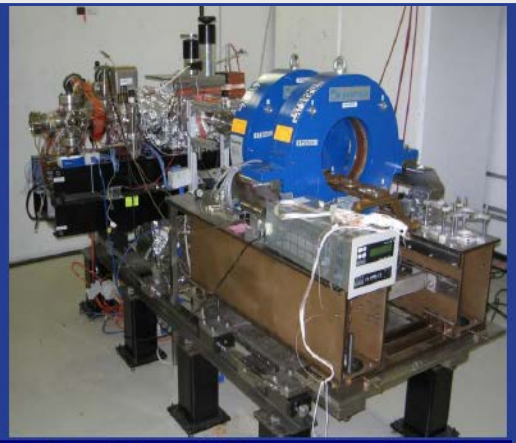
Installing & commissioning injector

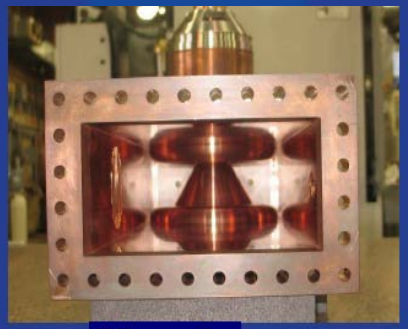


Gun operational, new cavity in CC1

gun cavity



Solenoids and PC transfer chamber



RF coupler

HEQ

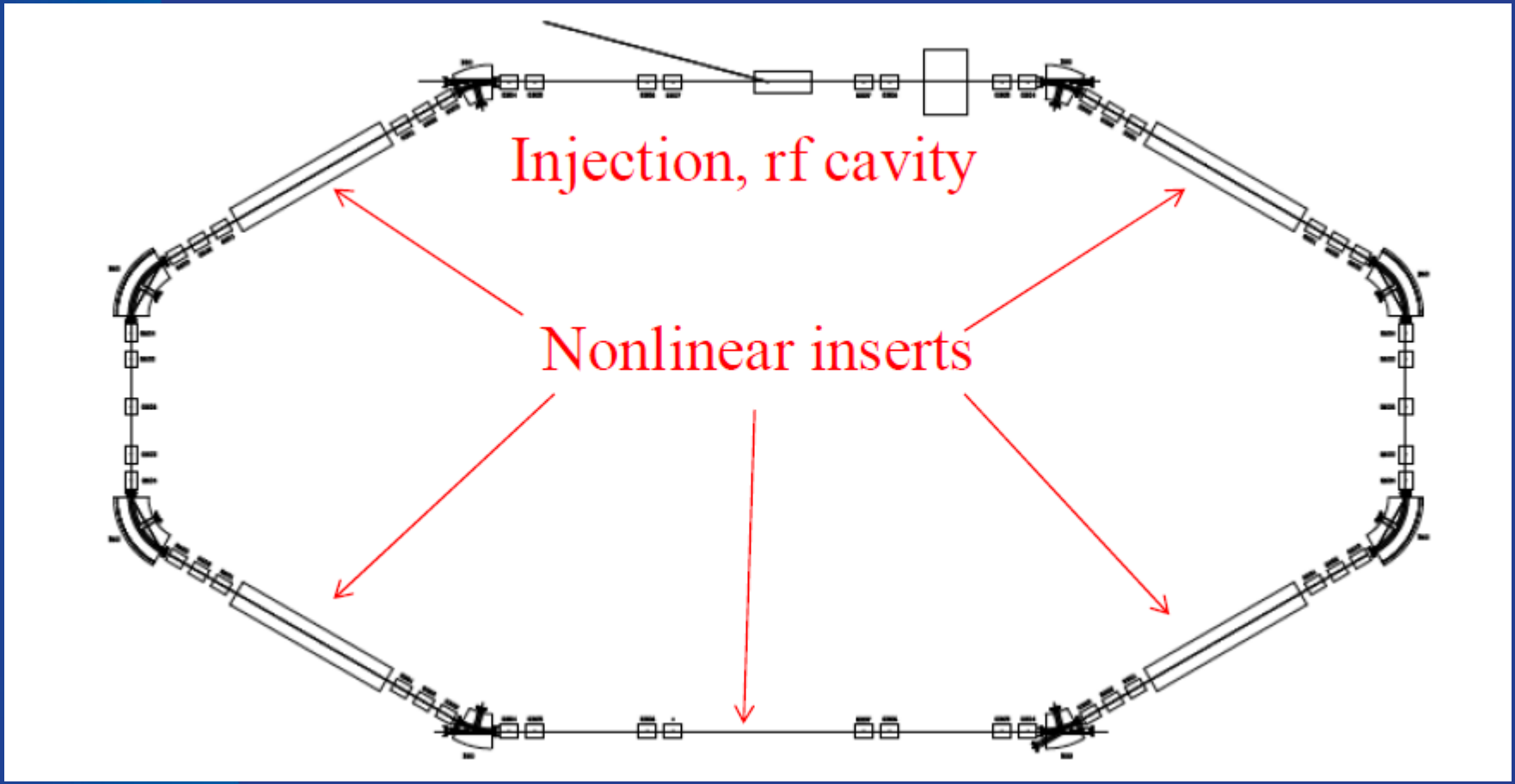
LED

High Energy Beam Dump Core

ASTA Accelerator R&D User's Facility

50 MeV Injector & CM2 in 2013, 300 MeV e- in 2014

Integrable Optics Test Accelerator (IOTA)

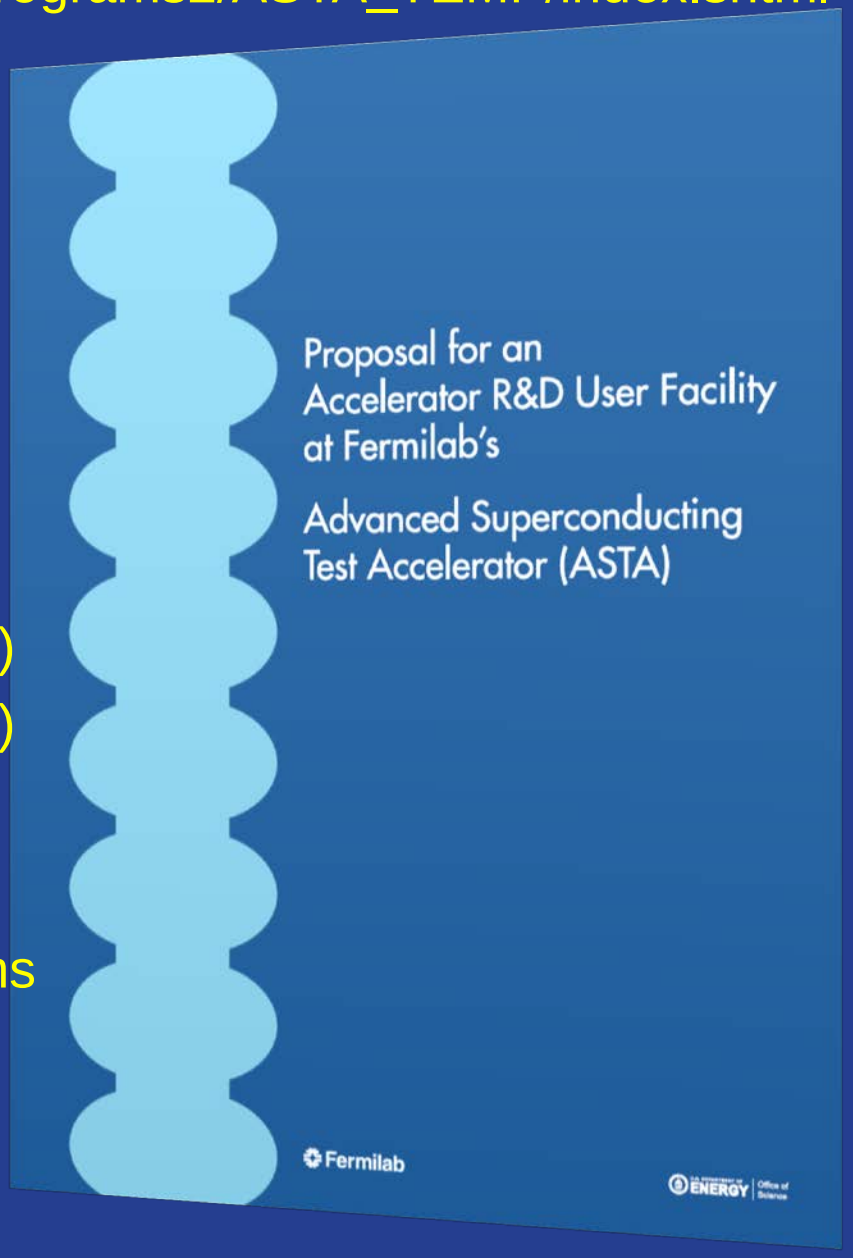


- Main goals for studies with a pencil electron beam:
  - Demonstrate a large tune spread of ~1 (with 4 lenses) without degradation of dynamic aperture (minimum 0.25)
  - Quantify effects of a non-ideal lens and develop a practical lens (m- or e-lens)

ASTA

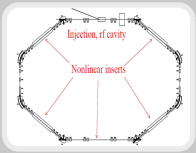
http://apc.fnal.gov/programs2/ASTA_TEMP/index.shtml

- 60 co-authors from 13 institutions
- 24 proposals and growing
  - ~1/2 for HEP (IF, EF, SCRF)
  - ~1/2 – Stewardship and Applications
- At all ASTA experimental areas
  - Exp Area 1 (50 MeV) (10)
  - Exp Area 2 (300-800 MeV) (12)
  - Exp Area 3 (IOTA Ring) (5)
- Broad spectrum of proponents:
  - University groups & National Programs
  - SBIR companies & International
  - Large National Laboratories
  - Detector R&D groups



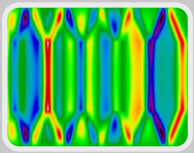
ASTA Science Thrusts

Intensity Frontier of Particle Physics



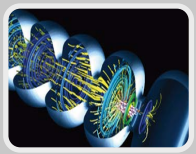
- Nonlinear, integrable optics
- Space-charge compensation

Energy Frontier of Particle Physics



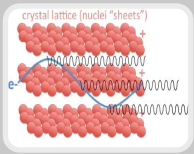
- Optical Stochastic Cooling
- Advanced phase-space manipulation
- Flat beam-driven DWFA in slabs

Superconducting Accelerators for Science



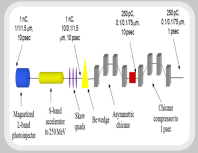
- Beam-based system tests with high-gradient cryomodules
- Long-range wakes
- Ultra-stable operation of SCLs

Novel Radiation Sources



- High-brightness x-ray channeling
- Inverse Compton Gamma Ray source

Stewardship and Applications

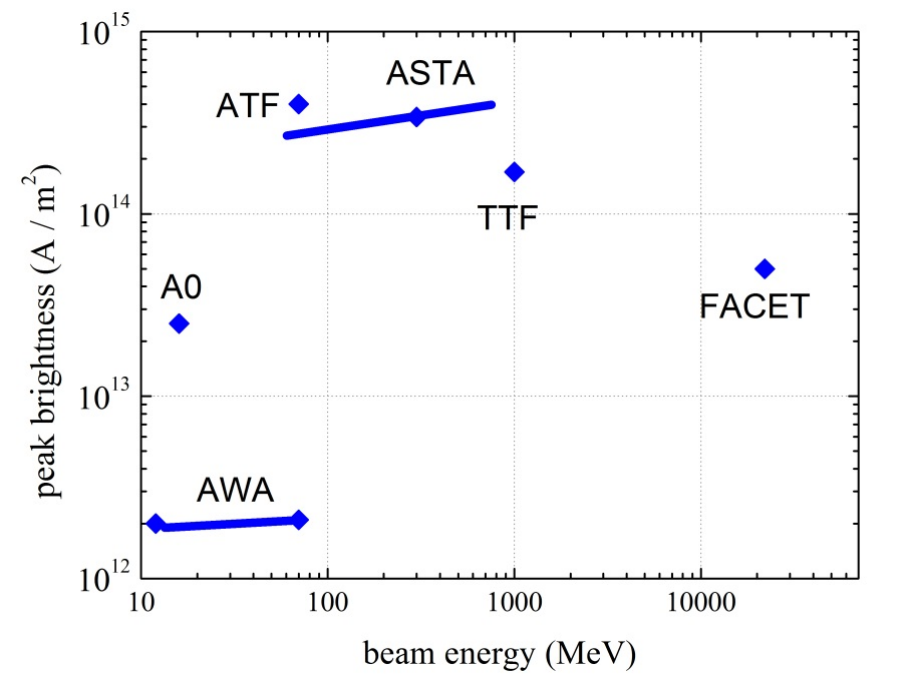


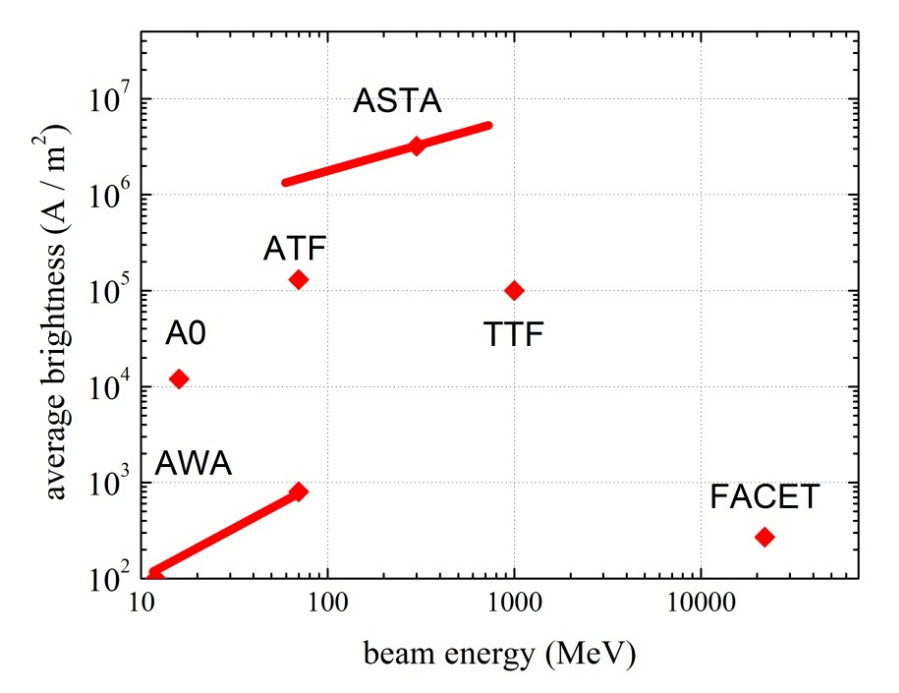
- Generation and Manipulation Ultra-Low Emittance Beams for Future Hard X-ray FELs
- XUV FEL Oscillator

“Why ASTA?” (Uniqueness)

- High repetition-rate:
  - 1 msec long trains of 3000 bunches, with 3 MHz rep rate
- High average power:
  - the highest beam power and highest average brightness
- High energy:
  - ~1 GeV → many experiments (eg photon-science and FEL)
- Extremely stable beams
- Superconducting technology: SRF and beams
- IOTA Storage ring:
  - very flexible storage ring capable of supporting a broad range of ring-based advanced beam dynamics experiments.

Comparison with Other Facilities: Peak and Average Brightness





* see Sec. 5.0 for detail comparison of ASTA to various Accelerator R&D facilities

Strong Institutional Support of ASTA Proposal

Argonne National Laboratory	A.Zholents
Brookhaven National Laboratory	T.Roser
CERN	S.Myers, O.Bruening
Colorado State University	S.Biedron, S.Milton
ComPASS	P.Spentzouris
Illinois Institute of Technology	L.Spentzouris
Indiana University	S.Y.Lee
International Linear Collider (ILC)	L.Evans, M.Harrison
John Adams Institute for Accelerator Science	A.Seryi
Joint Institute for Nuclear Research	I.Meshkov
US LHC Accelerator Physics Program (LARP)	E.Prebys
Lawrence Berkeley National Laboratory	S.Gourlay
US Muon Accelerator Program (MAP)	M.Palmer
Northern Illinois University	D.Hedin, L.Lurio, L.Freeman, P.Vohra
Oak Ridge National Laboratory	J.Galambos
Princeton Plasma Physics Laboratory	R.Davidson, E.Gilson, I.Kaganovich
RadiaBeam Technologies, LLC	S.Boucher
Tech-X Corporation	J.Cary
Thomas Jefferson National Accelerator Facility	A.Hutton
US Particle Accelerator School (USPAS)	W.Barletta

The ASTA Team

ASTA Team:

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ASTA Program Advisory Committee Chair, Gerald Dugan

Mike Church
Commissioning & Operations

J. Leibfritz
Installation & Engineering

Philippe Piot
Physics

Sergei Nagaitsev
IOTA

Peter Garbincius
Program Office

- **Program Advisory Committee:** G. Dugan (chair), M. Blaskiewicz (BNL), J.Byrd (LBNL), R. Palmer(MAP), G. Hoffstaetter (Cornell), A.Zholents (ANL)
- The 1st ASTA User's meeting and first PAC meeting July 23-24, 2013

ASTA is the Key to Laboratory's and HEP long-term future

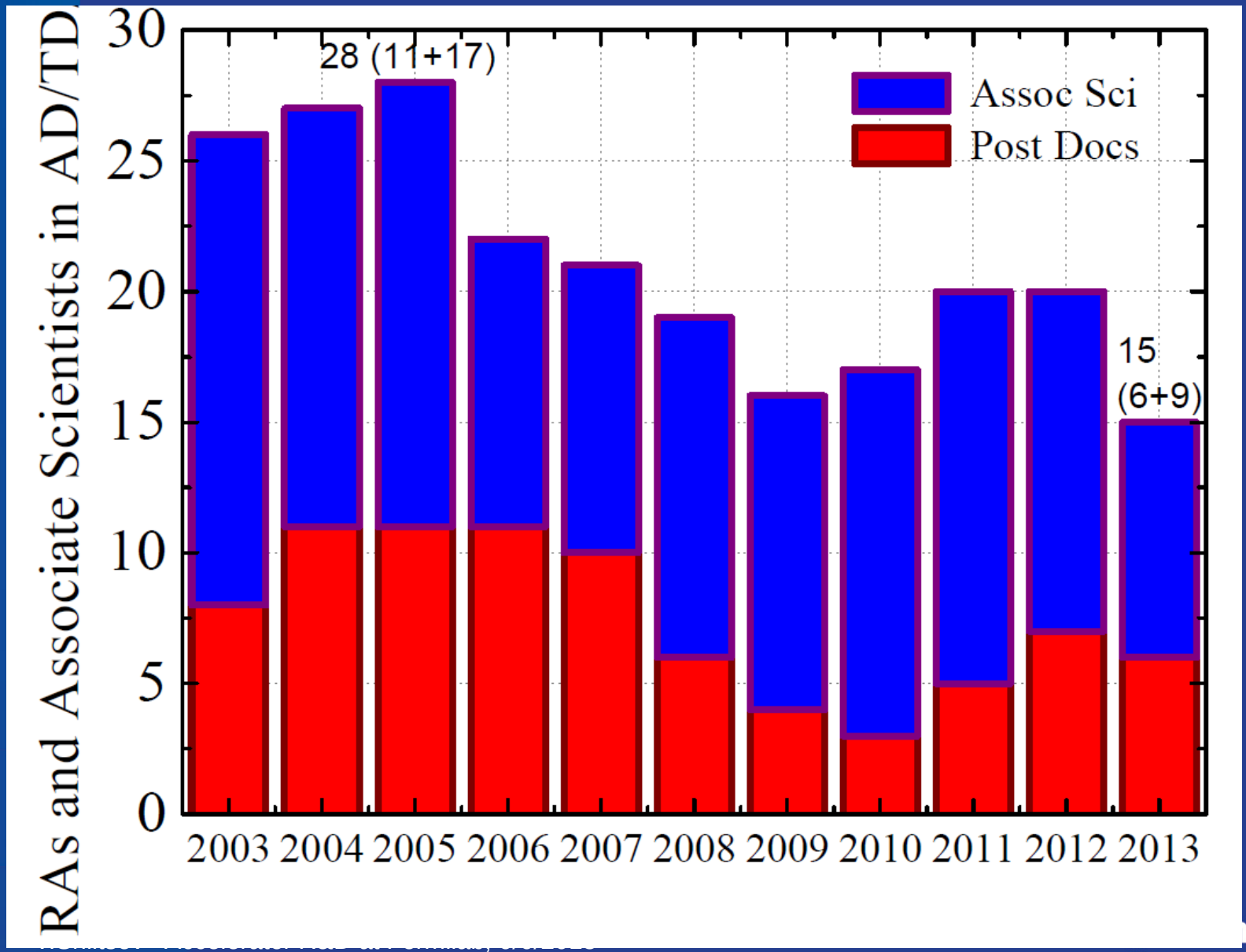
- It is envisioned as the leading and largest National Accelerator R&D program
- ASTA program addresses most relevant accelerator R&D issues of the US high energy physics
- Our near term goal is to engage community around ASTA
- We work hard to secure DOE OHEP support at the requested level
- ASTA is our bet to stop the trends of losses :
  - Accelerator expertise
  - Accelerator talent
  - Funding for the accelerator R&D

Worrysome Sign : Loss of Expertise

- Besides retirement: some 15 leading scientists and engineers in the past 4 years (out of ~110)
- Left the lab for better ~20:
  - D.McGinnis ESS
  - A.Jansson ESS
  - C.Davre ESS
  - M.Wendt CERN
  - J.Kerby ANL
  - Y.E.Sun ANL
  - E.Peoples ANL
  - M.Syphers FRIB
  - J.Crisp FRIB
  - C.Davre ESS
  - R.Moore Boston
  - M.Martens CO
  - K.Ranjan India
  - J.Ozelis industry
  - M.Hu industry
  - etc…

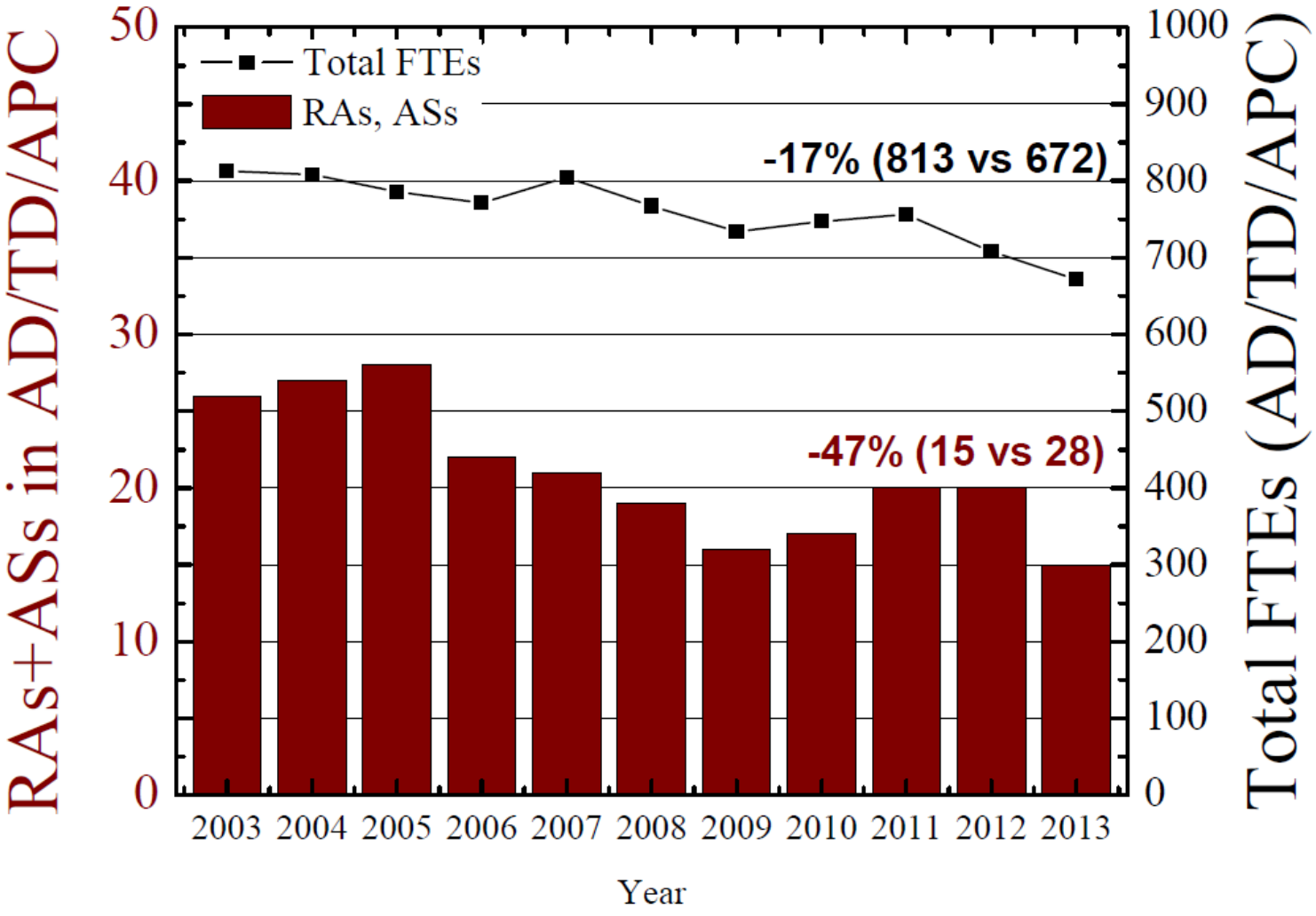
Worrisome Statistics (1)

"Next generation" accelerator scientists in FNAL Accelerator Organization



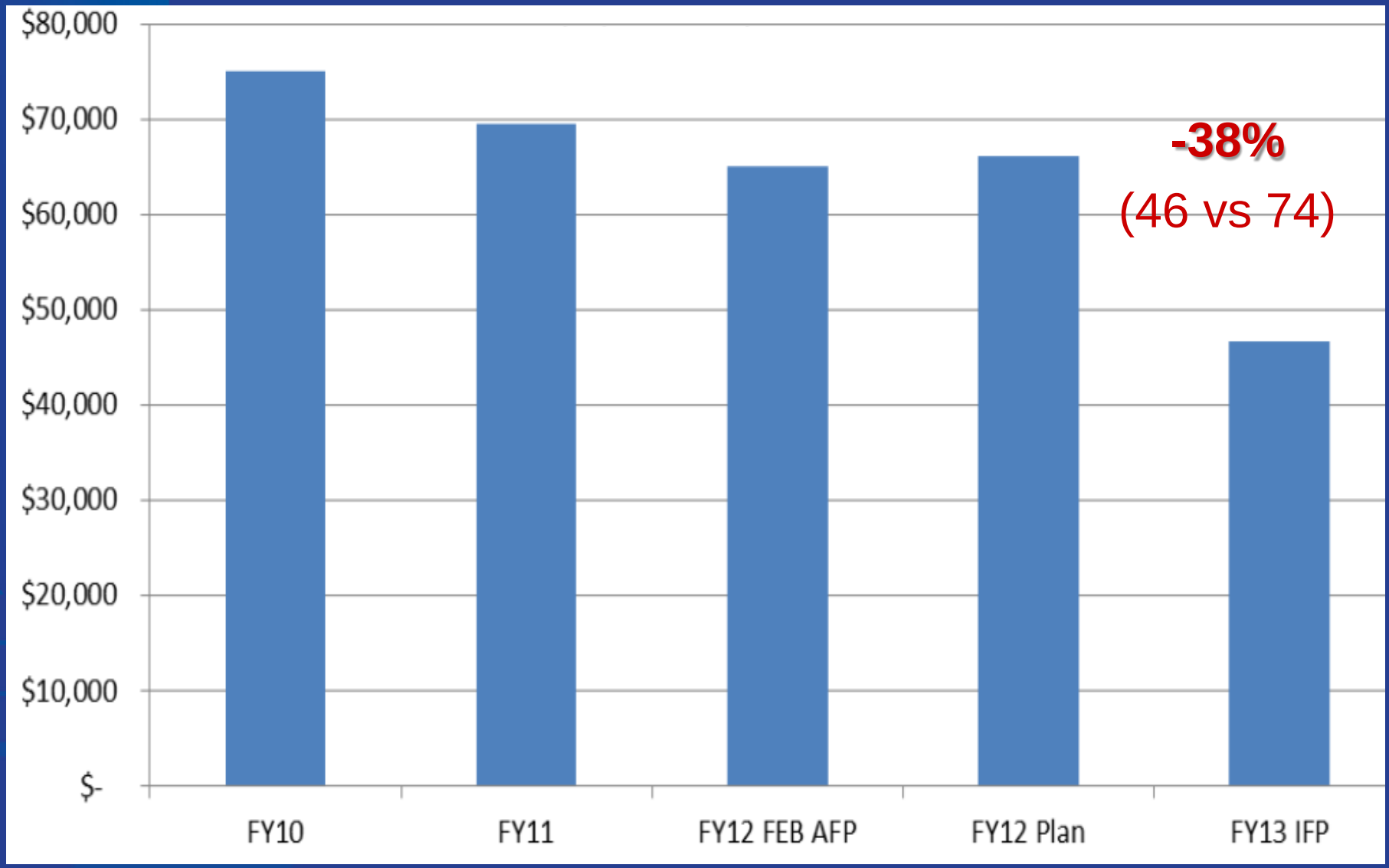
Worrisome Statistics (2)

FNAL Accelerator Organization: RA's and AS's vs Total FTEs



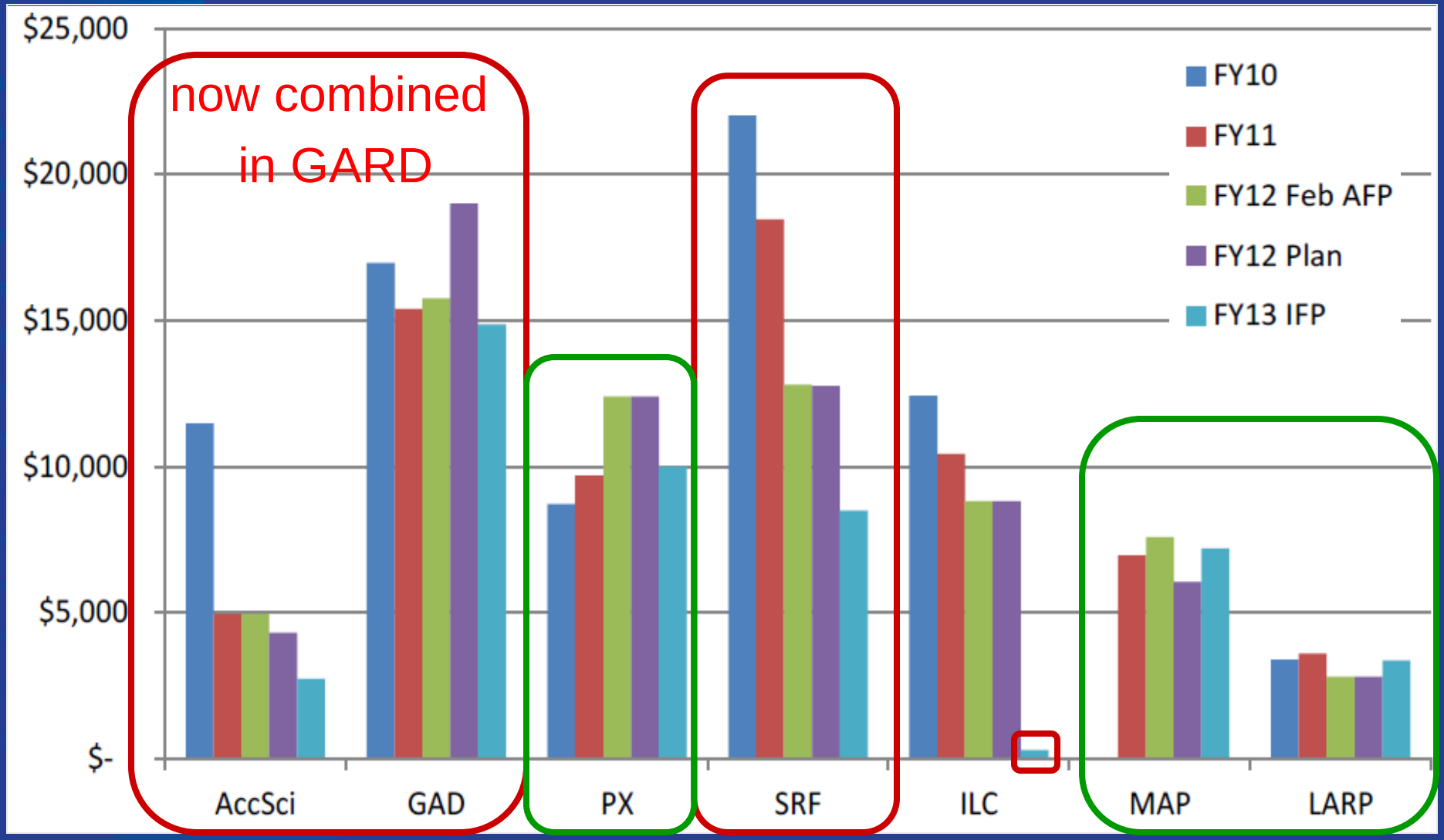
Worrisome Statistics (3)

History of Fermilab's Accelerator R&D portfolio



Worrisome Statistics (4)

Accelerator R&D funding by activity



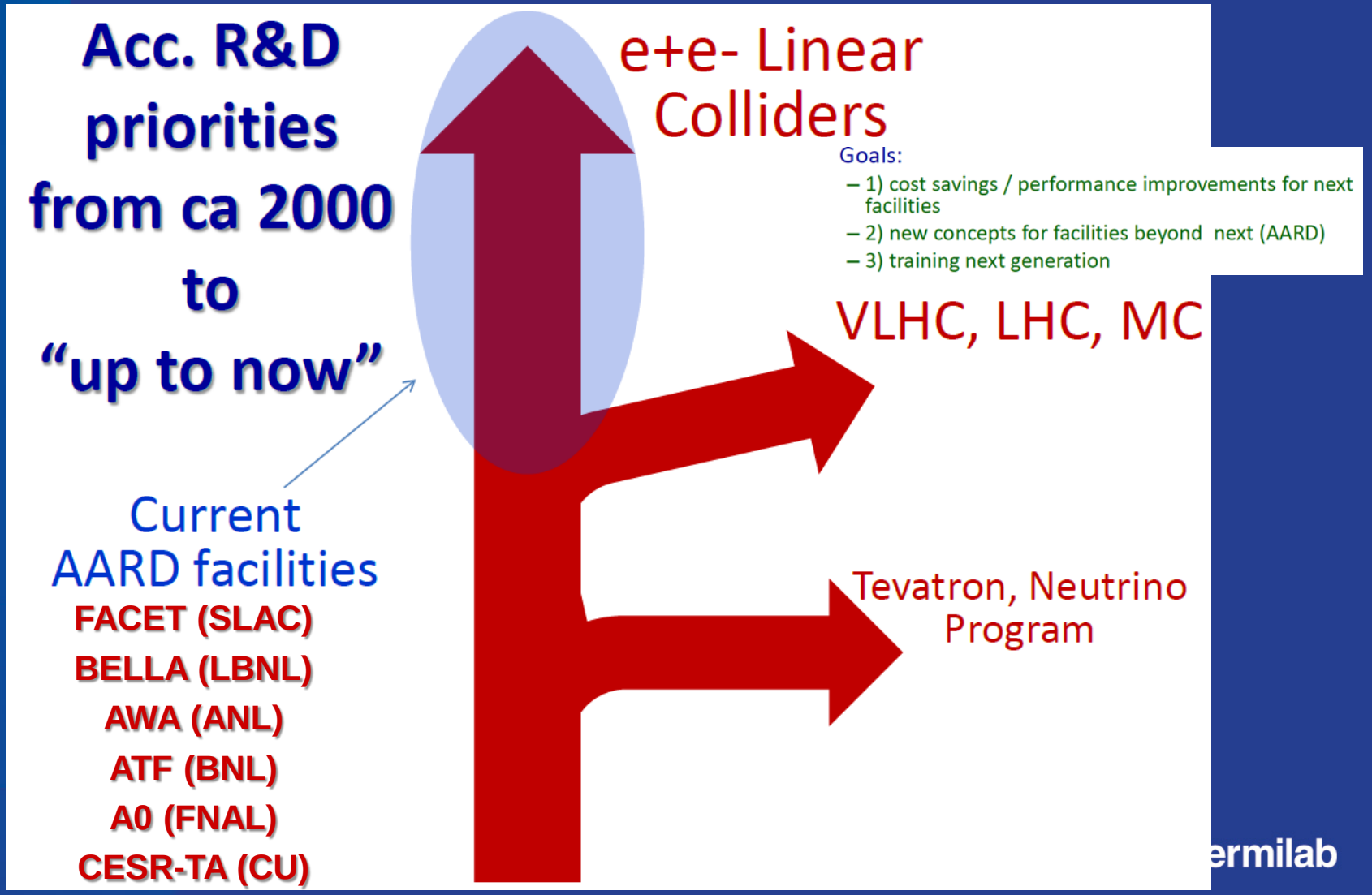
Lessons

I. If situation with Accelerator R&D at Fermilab will go as is goes (-38% in 4 years) – the program will be non-existent in early 2020's

II. Current funding system leaves little room for adjustments, and re-distribution is never zero sum (we lose on every adjustment), so the planning mistakes are very costly:
   - Examples – ILC, Advanced Accel. R&D facilities
   - Better community planning is a must
     - Centrality of Fermilab to be imposed

Accelerator R&D Facilities in the US reflect our thinking ca. 2000

from Snowmass'13 Accelerator R&D Facilities Workshop (U.Chicago, 02/25-26/2013)

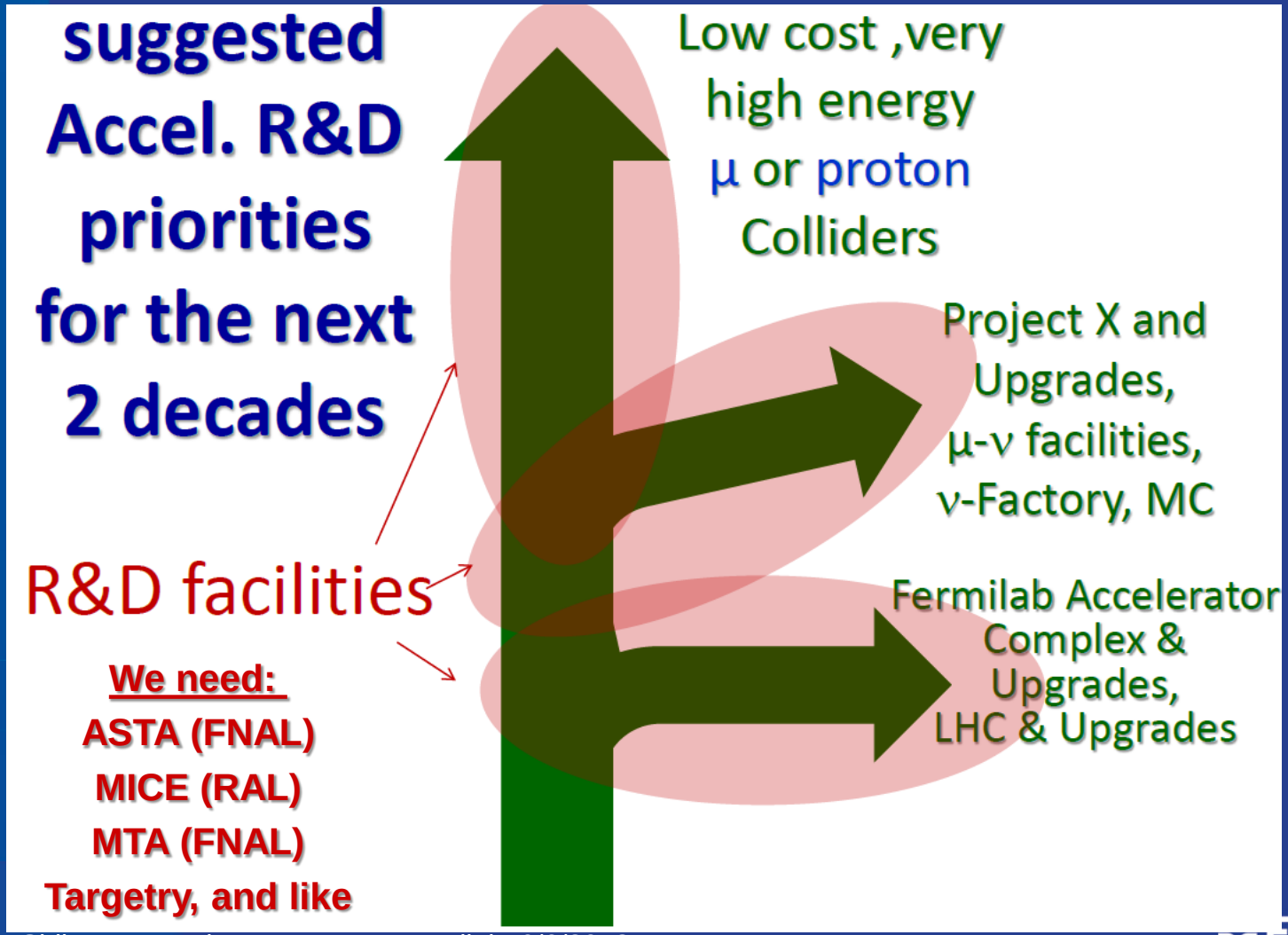


Required Accelerator R&D Facilities

- Should reflect new realities and long-term goals:
  - 1) cost savings / performance improvements for Intensity Frontier facilities (incl SRF and Beam Dynamics studies)
  - 2) cover possible transition from Intensity Frontier to Energy Frontier (current thinking – Muon Collider)
  - 3) electrons are not particles of choice for IF and EF facilities beyond next – muons and protons are
  - 4) AARD should aim at new concepts which offer drastic cost reduction for >10x LHC energy (muons or protons)
- At present, there is a lack of suitable Accelerator R&D facilities to effectively serve these goals

Accelerator R&D Facilities for the Next Two Decades

from Snowmass'13 Accelerator R&D Facilities Workshop (U.Chicago, 02/25-26/2013)



Lessons (cont'd)

III. So far, the most successful form of organization of Accelerator R&D was "National Programs":

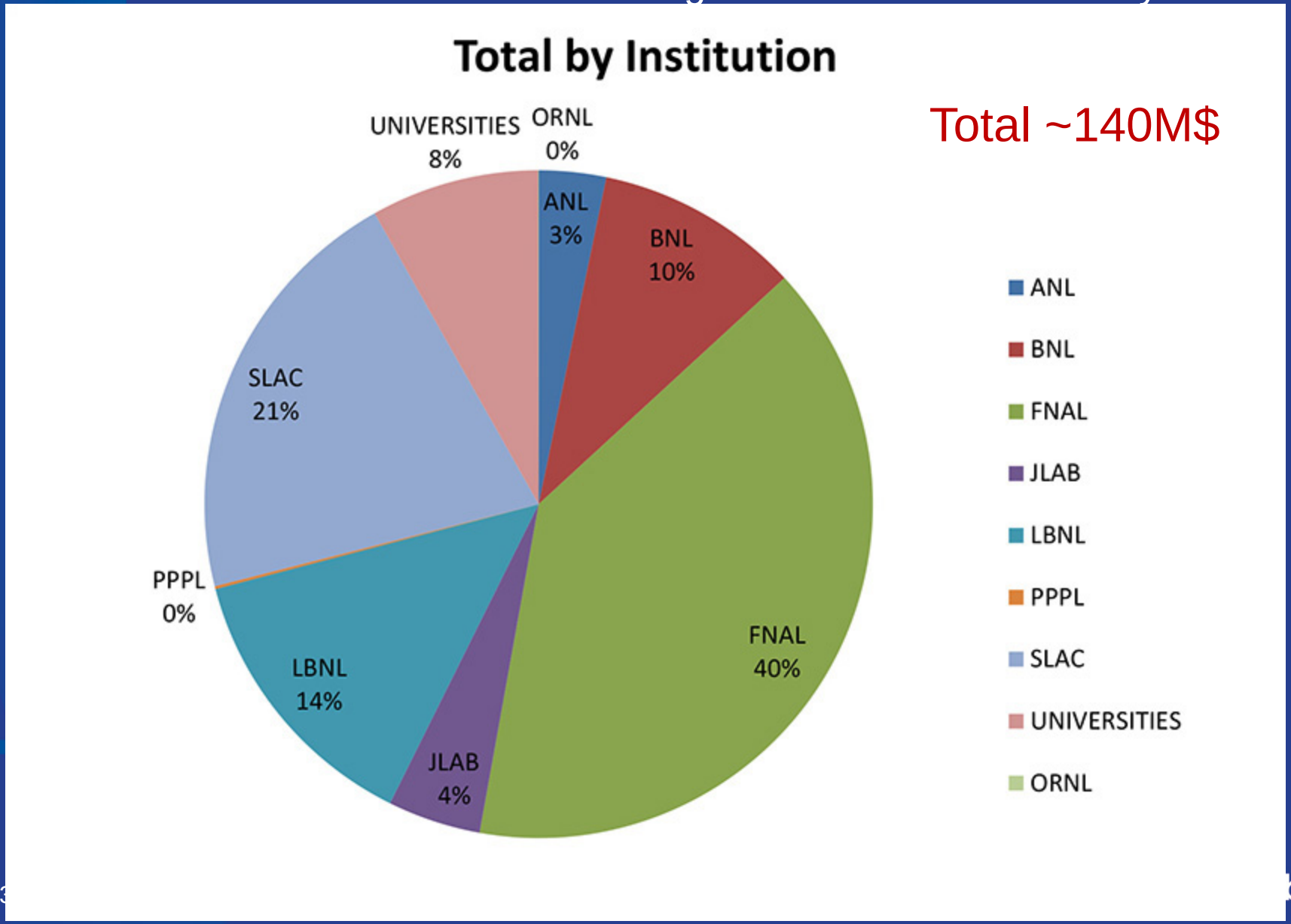
- LARP (since FY2005) - "to help LHC get luminosity sooner and faster"
- MAP (since FY2011) – "to develop the concept… and prove feasibility of a Muon Collider"

- and we plan to promote similarly

- ASTA User's program – "to address the needs of the Intensity Frontier accelerator program…and EF…"
- IARC – "to translate [accelerator S&T] into applications for the nation's health, wealth and security"

Accelerator R&D in the US

OHEP: distribution of 2011 mid- and long-term accelerator R&D by institution



Total ~140M$

Lessons (cont'd)

IV. The format of a "National Program" (eg Accelerator R&D at ASTA) does not assume that all "goes to Fermilab". Instead:

- The broadest possible community
- Fermilab plays key role in establishment and coordination and leads the program

Conclusion

- Fermilab's Accelerator R&D Program is perfectly aligned with the US HEP Strategic Plan, and supports the US's ambitions in the Intensity and Energy Frontiers
- Despite declining budgets, we had tremendous success in the past 4 years:
  - Tevatron and LHC beam studies
  - A0, HINS and HBESL experiments
  - Outburst of landscape-changing concepts supported by theory
  - Expanding support of HEP simulations tools
  - Record 130 peer-review publications, 9 PhDs, awards, etc
- FNAL Accelerator R&D Program plan for the near future :
  - Is of utmost relevance to HEP's mission and goals
  - Has ASTA as key element for Accelerator R&D in US, esp. for *Intensity and Energy Frontiers, SC RF, Applications and Stewardship*