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https://www.aps.org/units/dpb/news/edition4th.cfm

- The American Physical Society (APS) and its
  - ***Division of Physics of Beams*** (DPB)
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Other APS Membership Benefits

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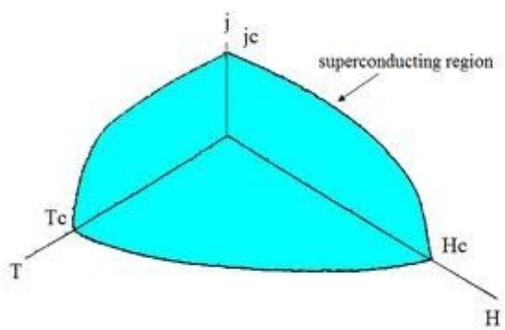
Outlook for the Field

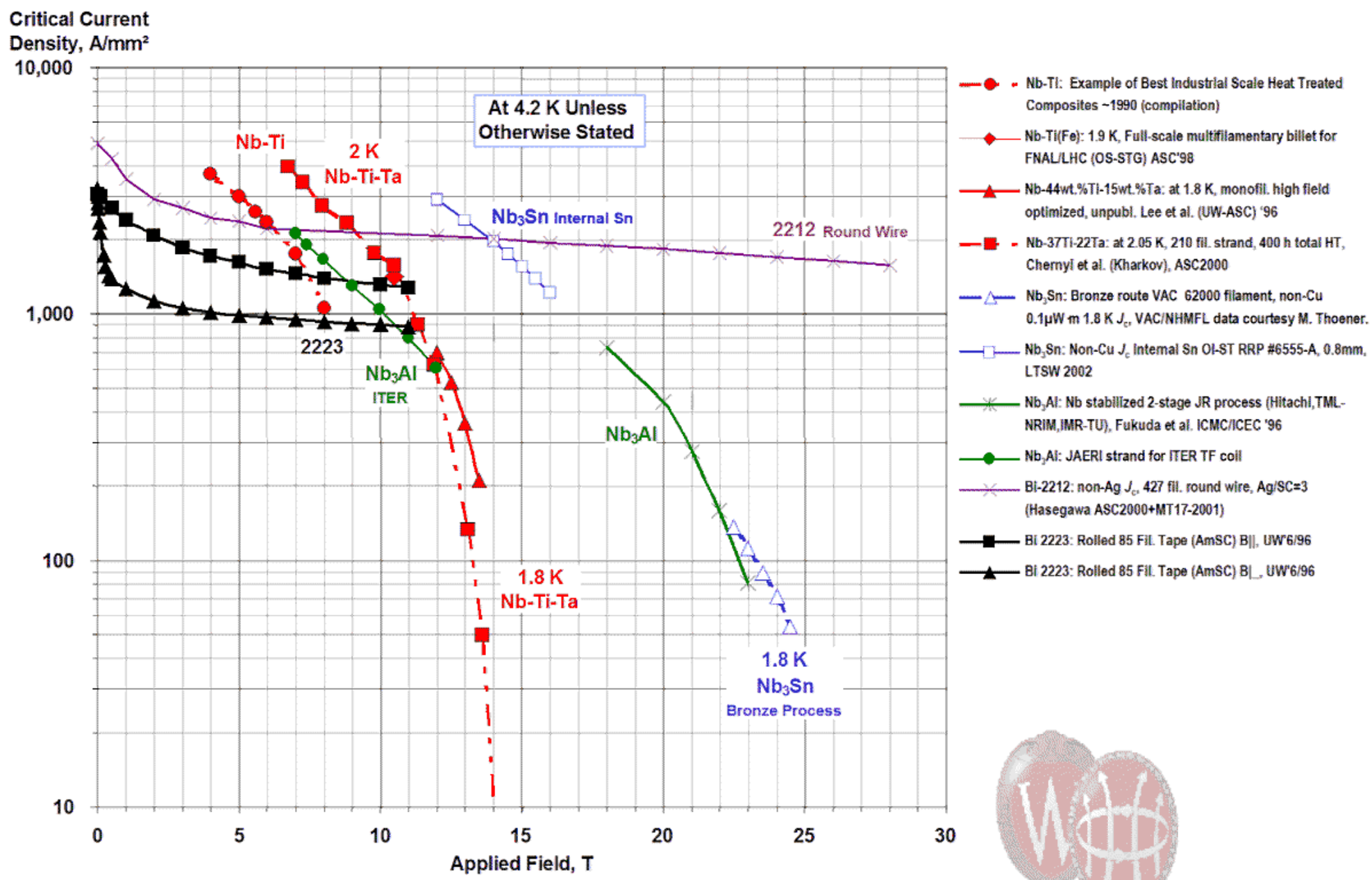
- Accelerator Magnets
- Accelerator Cavities
- Accelerator projects
- Future acceleration techniques
- Future accelerator applications

Advancing Critical Currents in Superconductors

University of Wisconsin-Madison
Applied Superconductivity Center



note: “engineering” current densities will be less than these “critical” current densities

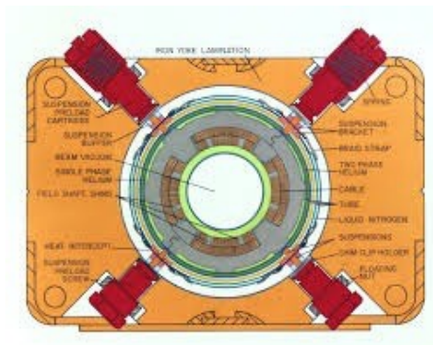


Accelerator Magnets

magnetic pressure:

$$P = \frac{B^2}{2\mu_0}$$

$$\frac{(4\ \mathrm{T})^2}{8\pi 10^{-7}} = 6.4\mathrm{MN/m}^2 = 64\ \mathrm{atm}$$



$$\frac{(8\ \mathrm{T})^2}{8\pi 10^{-7}} = 250\ \mathrm{atm}$$

quench training:

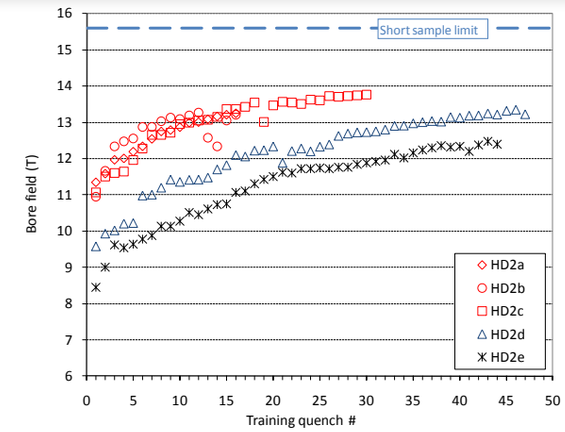


Figure 12: Bore field (T) as a function of training

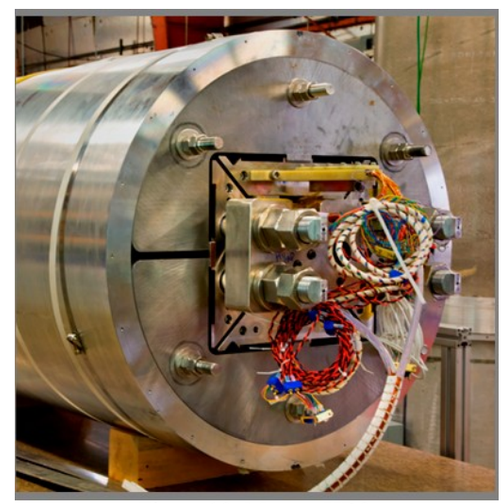


Figure 10: Magnet HD2

$$\frac{(13\ \mathrm{T})^2}{8\pi 10^{-7}} = 670\ \mathrm{atm}$$

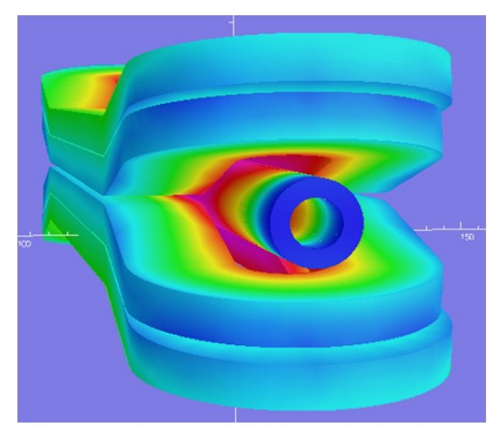


Figure 11: Computed field magnitude of HD2

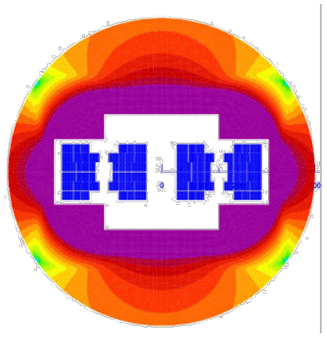
$$\frac{(16\ \mathrm{T})^2}{8\pi 10^{-7}} = 1000\ \mathrm{atm}$$

$$\frac{(20\ \mathrm{T})^2}{8\pi 10^{-7}} = 1600\ \mathrm{atm}$$

Advanced Magnet Design

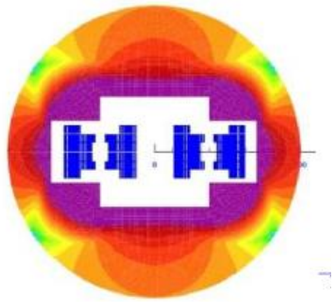
Texas A&M, LBNL, BNL, CERN …

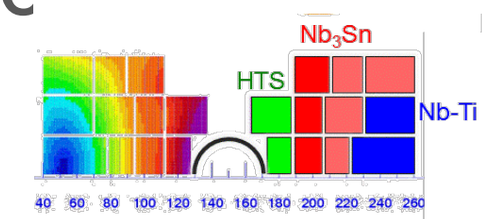
- "stress management"
  - "block" coils
  - end designs are critic



J_{eng} ~ 400 A/mm^2

Nb-Ti up to	8 T
Nb_3Sn up to	13 T
HTS up to	20 T



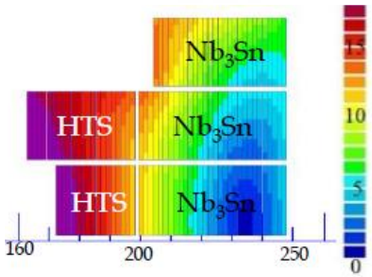


Cost optimized, graded winding

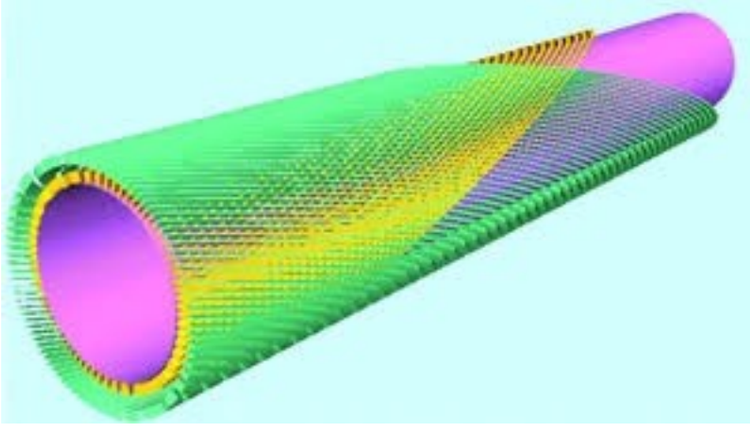
HTS: more than 1500 tons procurement by 2030

↓

Concept and models now



- Canted Cosine Theta Design

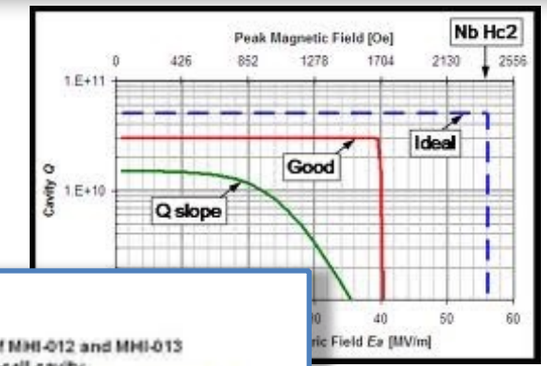


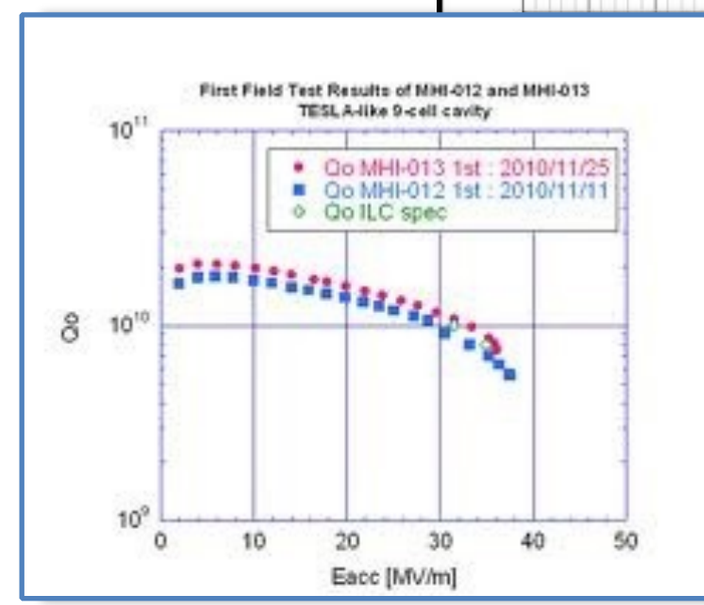
nested arrangement of canted coils can possibly reach fields up to 16-20 T

LBNL

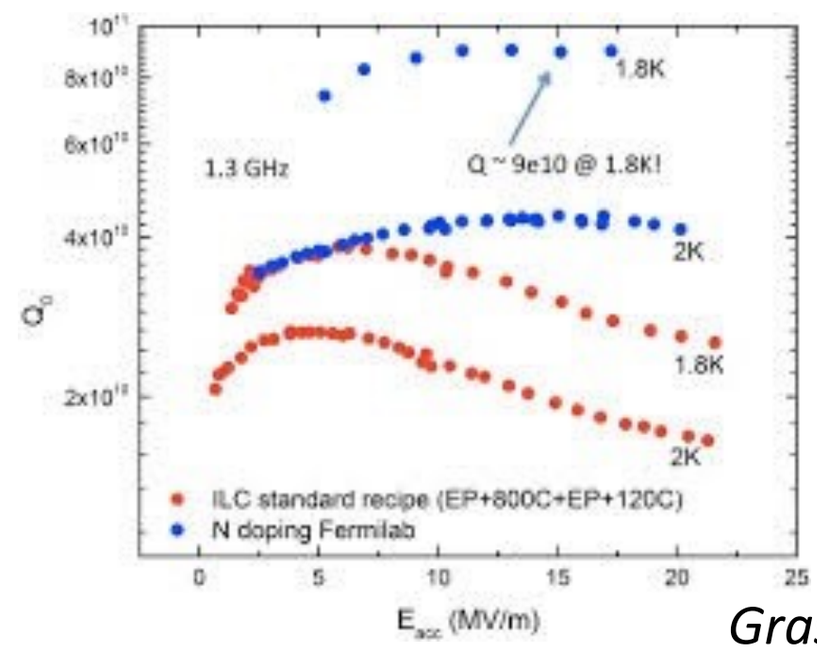
Accelerator Cavities

- SRF (efficient, 30-50 MV/m)
- vs. Cu (100-150 MV/m)





- development of production techniques
  - surface treatments, doping of Nb to reduce Q-slope, etc.



Grassellino, et al.

- Nb-coated materials — lower cost SRF?

Some Projects — Current and Envisioned

- FRIB (MSU) 200 MeV/u, 400 kW Facility for Rare Isotope Beams
- LCLS-II (SLAC) 4 GeV Linac Coherent Light Source upgrade
- FAIR (GSI) 34 GeV/u, 100 kW
- ESS (Lund) 5 MW European Spallation Source (2 GeV p linac)
- PIP-II (FNAL) 800 MeV p, MW-scale linac
- ILC (?? Japan ??) 500 GeV electron-positron collider
- CLIC (?? CERN??) 3 TeV electron-positron collider
- e^- — ion collider (?? BNL? JLab?) 5-20 GeV e- / 50-250 GeV ions
- FCC (?? CERN ??) 100 km Future Circular Collider 100 TeV pp
- China: 50-80 km ring(s), 240 GeV ee collider; 70-100 TeV pp
- DAEdALUS cyclotrons, 800 MeV
- NuSTORM / NuFactory / Muon Collider — neutrino, muon sources
- …

Future Applications of Accelerators

- Energy — ADS
- Homeland Security
- Defense
- New Medical Techniques
- Isotope Production
- New industrial applications?

Some Accelerator Research & Development

- Magnets and Cavities — efforts continue
- Energy Recovery Linacs (ERL) efforts

- Plasma Wake Field
- Photonic Band-Gap

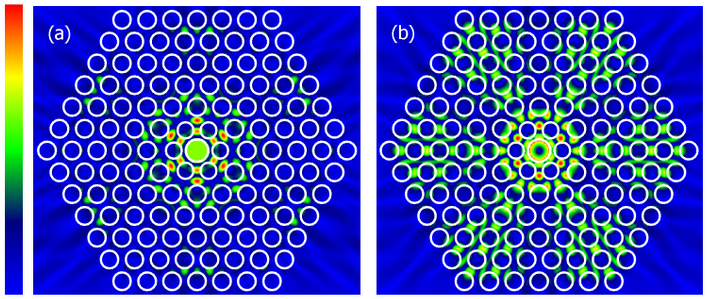


Figure 10: (a) Longitudinal and (b) radial electric field intensities calculated with the multipole method for the TM defect mode of the 9.8-micron fiber.

Noble, et al.

- Laser/Plasma
- Compact cyclotrons (3-D cyclotrons)
- …

Extrapolating to the Future: Livingston Plot

- In 1954, M. Stanley Livingston produced a curve in his book *High Energy Accelerators*, indicating exponential growth in particle beam energies over "past" ~25 years;
  - the 33 "Bev" (GeV) AGS at Brookhaven and 28 GeV PS at CERN were underway, and kept up the trend
- The advent of Strong Focusing (A-G focusing) was key to keeping this trend going...

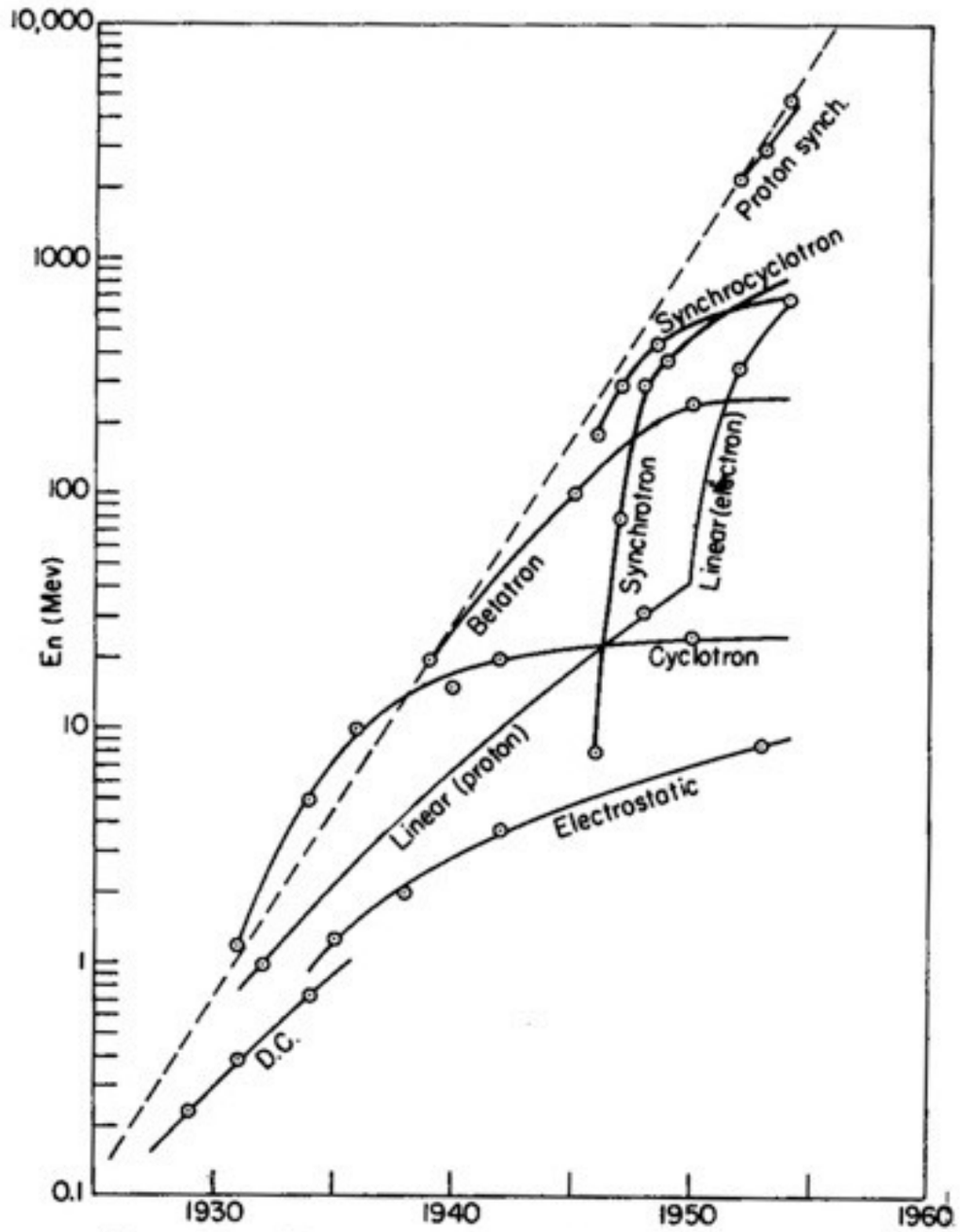
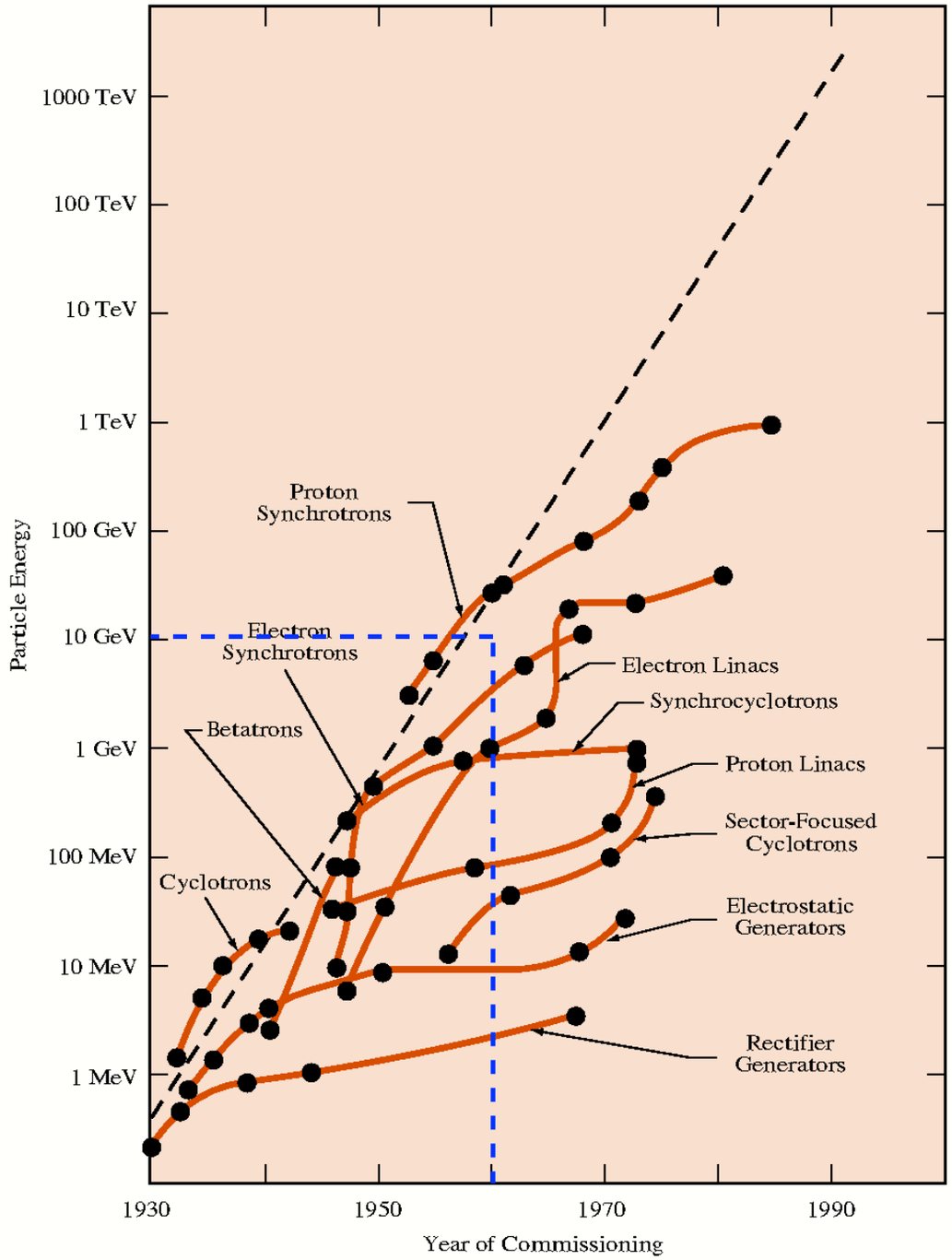


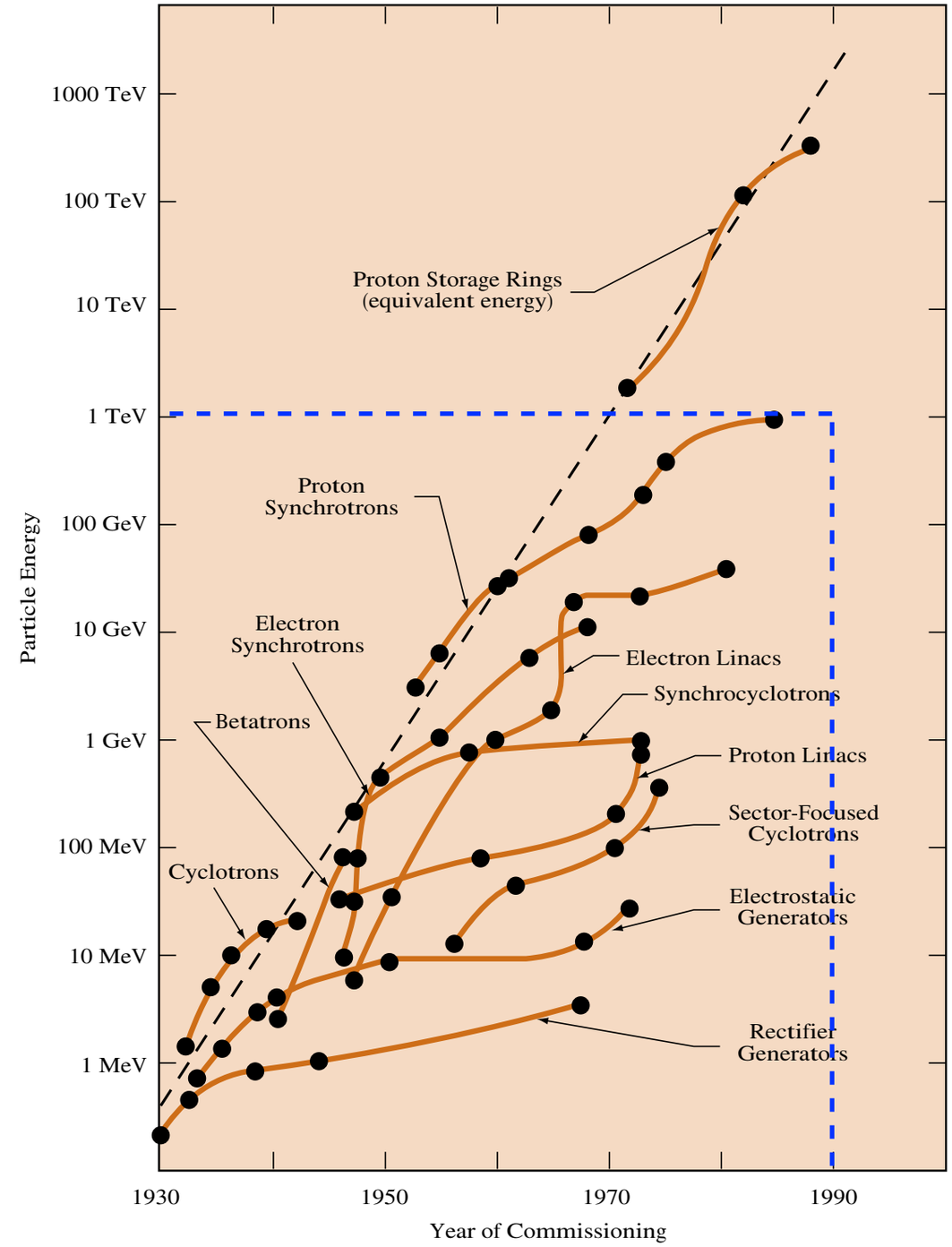
FIG. 7-8. Exponential rise in energy attained with accelerators during the past 25 years.

The Past 40 Years

Livingston Revisited

from W. Panofsky. *Beam Line* (SLAC) 1997





Possible Next Steps for High Energy Particle Accelerators with standard RF technology

*Some ideas, around **18 years ago**...*

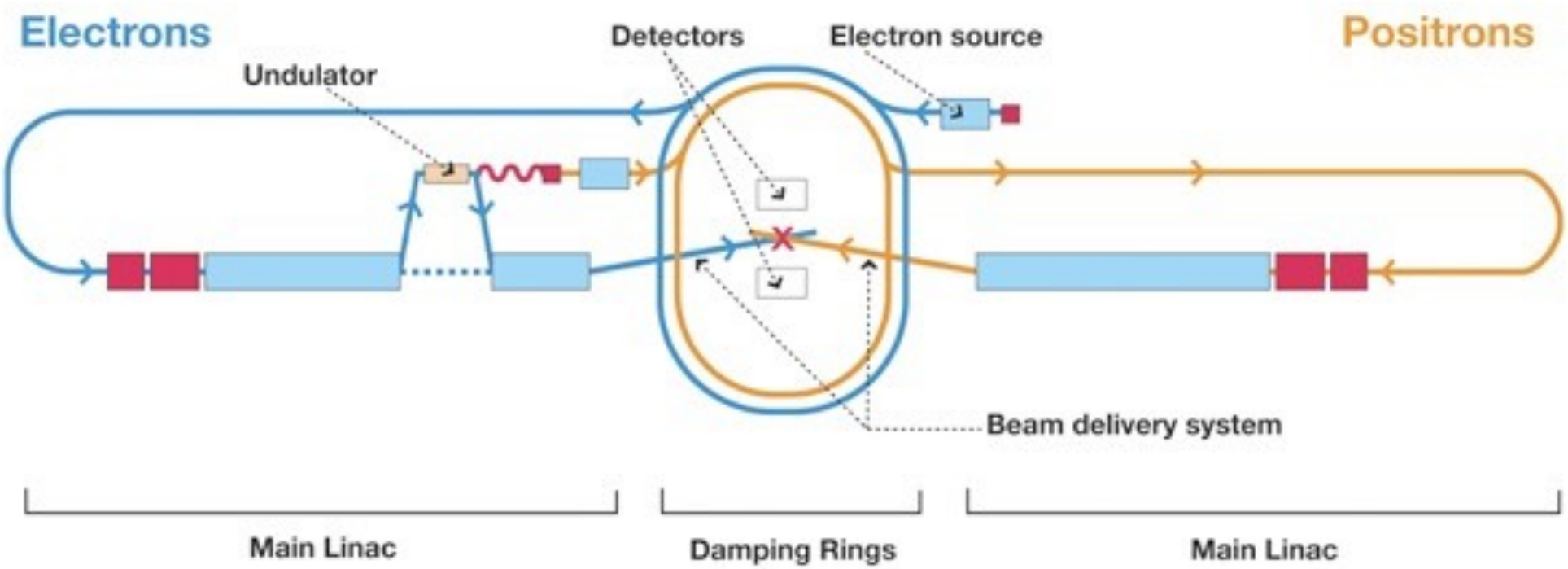
- Very Large Hadron Collider (VLHC) -- 20x20 to 100x100 TeV (pp)
- International Linear Collider -- 0.25 x 0.25 up to 0.5 x 0.5 TeV (e+e-)
- Muon Collider -- generate beams of muons, accelerate (quickly!) to few TeV and collide

- Snowmass 2001 -- VLHC (no) vs. ILC (yes); [μ-μ: too far away...]
  - ILC more “complementary” to LHC; natural next step
  - physics events easier to “disentangle” -- leptons vs. hadrons
  - ILC more affordable (???)

- Look at Linear Collider ...

ILC Conceptual Layout

- Use (part of) Main Linac to accelerate beams for positron production
- Use Damping Rings to generate small beams at low energy (~10 GeV) *via* Synch. Radiation -- makes flat beams, longer bunches than desired
- Beams travel length of tunnel, turn around (bunch compression) and enter Main Linacs
- Exit Main Linacs with E~250 GeV; deliver to Experiments



ILC Conceptual Layout

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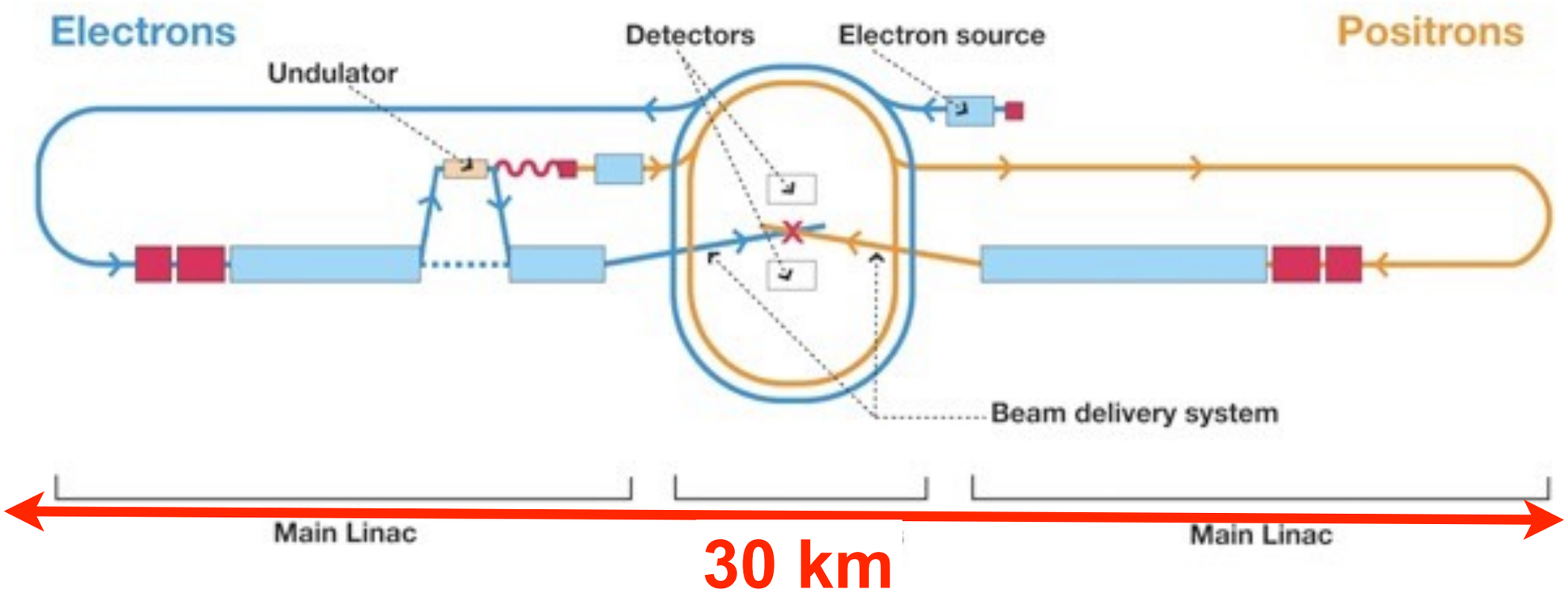


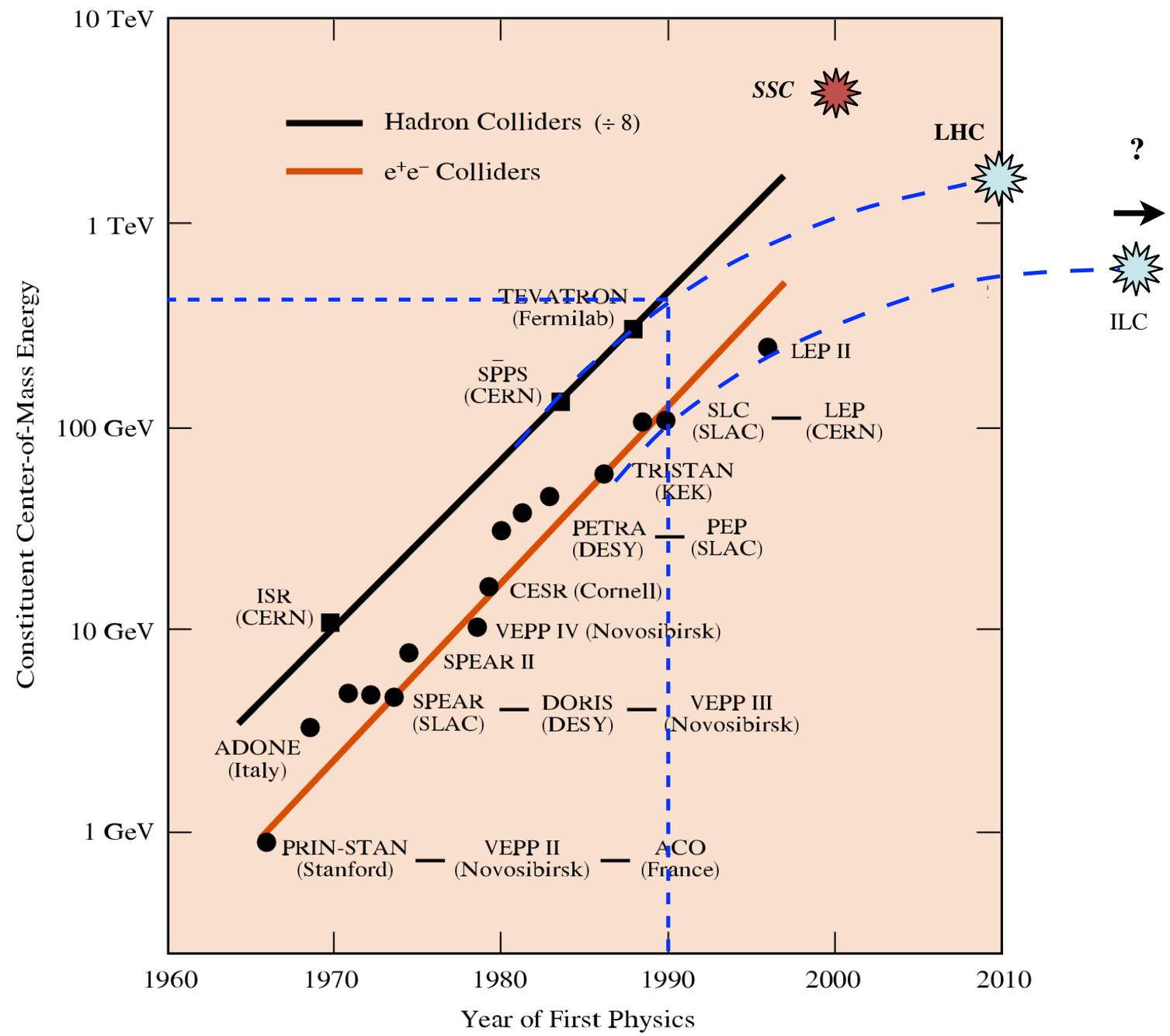
Same limiting factors ...

- superconducting technology -- accel. cavities this time, not magnets
- high accelerating gradient (>35 MeV/m)
- Synchrotron Radiation
  - effects obvious in e+e-; hence, the **L** in **ILC**
  - real estate vs. electric field strength
- stored energy an issue in LHC; *beam power* issue in linac
- energy deposition at Interaction Points; backgrounds
- small apertures --> alignment tolerances (micron scale)
- requires very small beam sizes at collision point -- nm scale
  - damping rings -- S.R. put to good use
  - emittance exchange -- eliminate need for damping rings?

The Livingston Curve Again

adopted from W. Panofsky. *Beam Line* (SLAC) 1997

- In attempt to compare e- & p, switch to C-of-M view of constituents
- seeing a new roll-off happening
- driven by budgets, if constrained to present technology
- thus, need new technologies to make affordable...



Lawrence Berkeley Lab Laser Wakefield Acceleration

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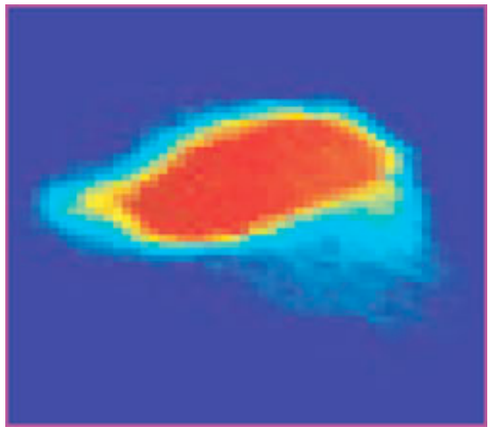
From Zero to a Billion Electron Volts in 3.3 Centimeters
Highest Energies Yet From Laser Wakefield Acceleration

Contact: Paul Preuss, (510) 486-6249, paul_preuss@lbl.gov

BERKELEY, CA — In a precedent-shattering demonstration of the potential of laser-wakefield acceleration, scientists at the Department of Energy's Lawrence Berkeley National Laboratory, working with colleagues at the University of Oxford, have accelerated electron beams to energies exceeding a billion electron volts (1 GeV) in a distance of just 3.3 centimeters. The researchers report their results in the October issue of *Nature Physics*.

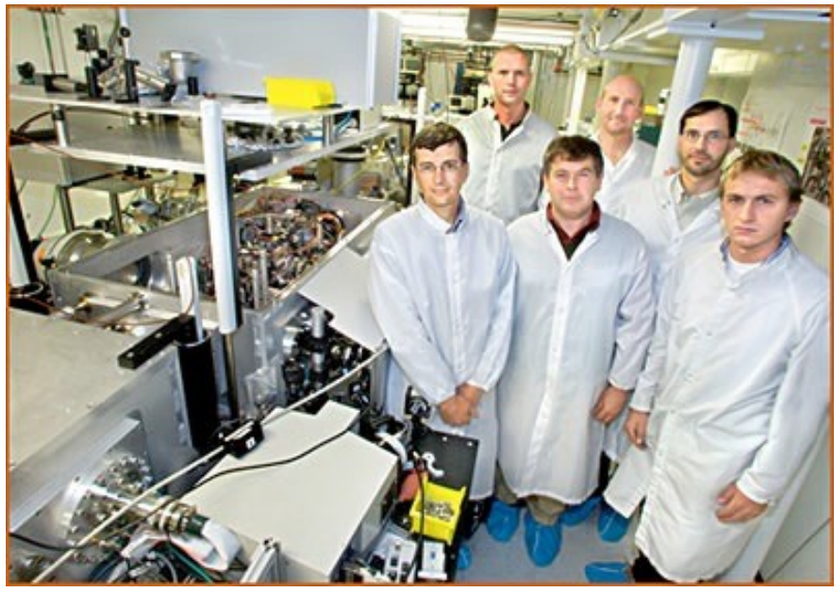


Billion-electron-volt, high-quality electron beams have been produced with laser wakefield acceleration in recent experiments by Berkeley Lab's LOASIS group, in collaboration with scientists from Oxford University.

By comparison, SLAC, the Stanford Linear Accelerator Center, boosts electrons to 50 GeV over a distance of two miles (3.2 kilometers) with radiofrequency cavities whose accelerating electric fields are limited to about 20 million volts per meter.

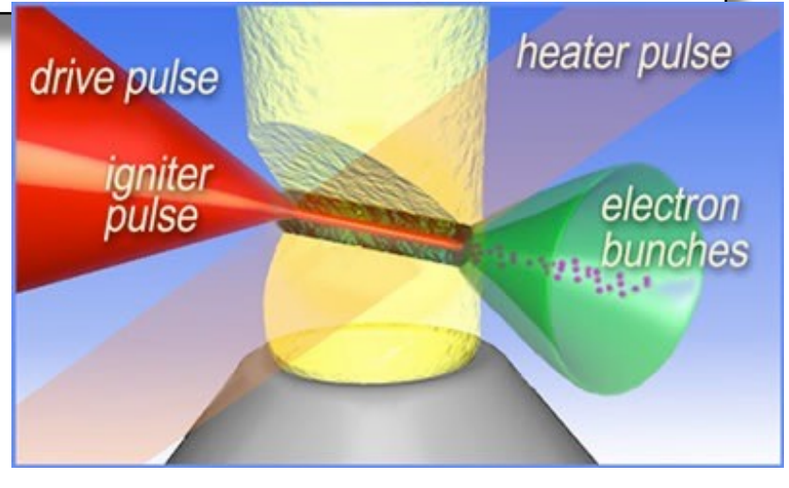
The electric field of a plasma wave driven by a laser pulse can reach 100 *billion* volts per meter, however, which has made it
Oxford
energy

This is
Lab's A
"Billion
accelerators open the way to very compact high-energy experiments and superbright free-electron lasers."



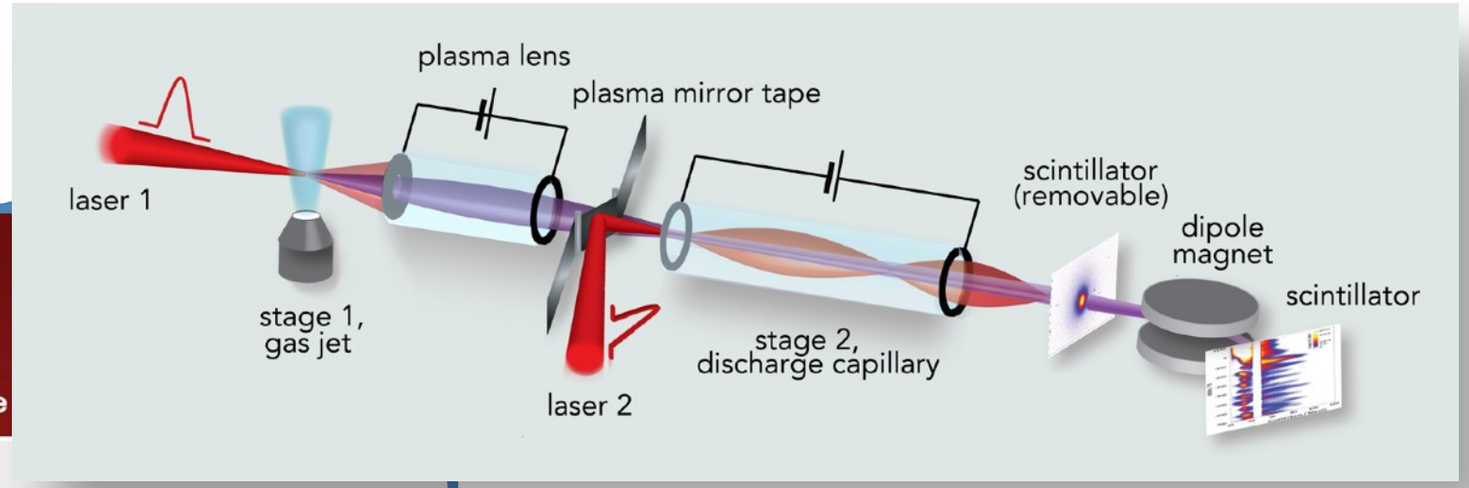
- 30 *G*eV/m, compared to 30 *M*eV/m in present SRF cavity designs
- ... and, *small* momentum spread (2-5%) as well

Also, similar (but different) efforts at U Texas, U Michigan, Stanford/SLAC, elsewhere...



Lawrence Berkeley Lab Laser Wakefield Acceleration

- Staging Demo



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NATURE | LETTER

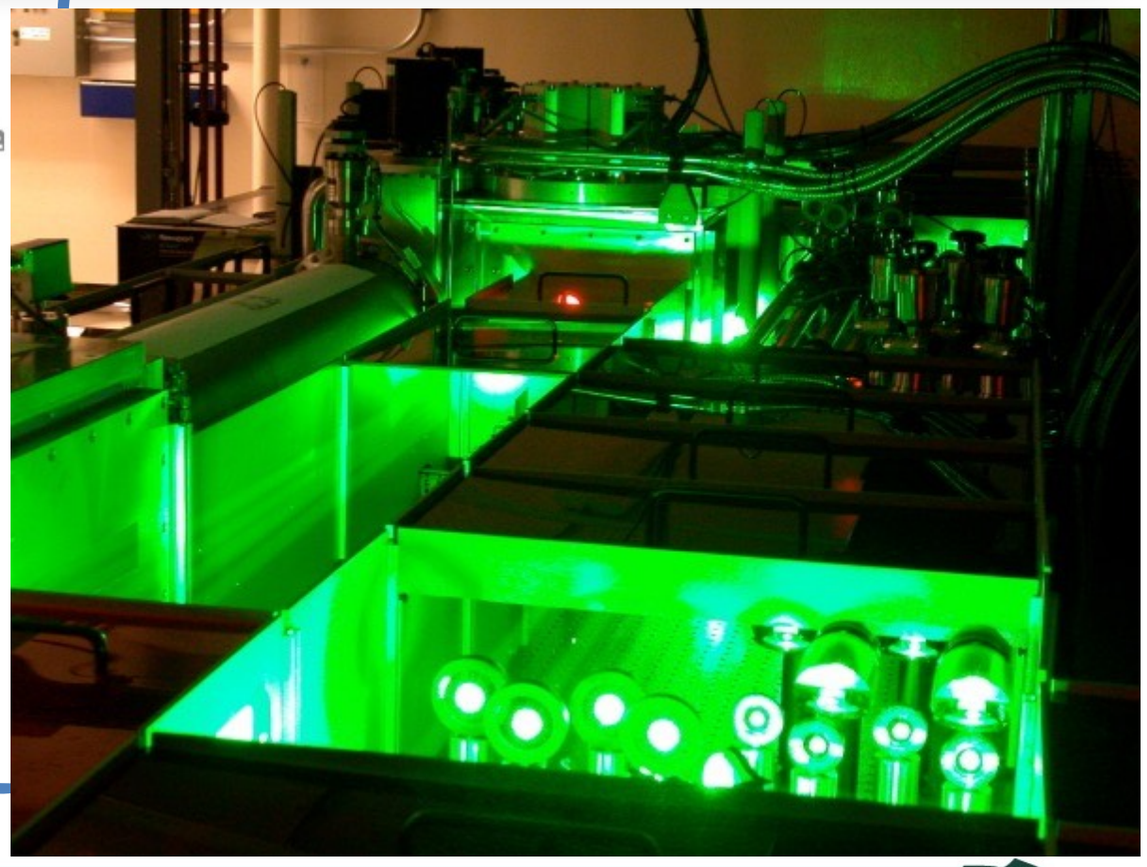
Multistage coupling of independent laser-plasma accelerators

S. Steinke, J. van Tilborg, C. Benedetti, C. G. R. Geddes, C. B. Schroeder, J. Daniels, K. K. Swanson, A. J. Gonsalves, K. Nakamura, N. H. Matlis, B. H. Shaw, E. Esarey & W. P. Leemans

Affiliations | Contributions | Corresponding author

Nature (2016) | doi:10.1038/nature16525

Received 24 September 2015 | Accepted 27 November 2015 | Published online 01 February 2016



In the Meantime, … FCC?

- Coming off of the successful first running of LHC, and the Nobel-Prize-winning Higgs discovery, Europe is engaging the international community in studies of a **Future Circular Collider**
- China is also looking at large rings for its future

Parameters are a 50 TeV x 50 TeV p-p collider, with circumference ~100 km (about same size as the Texas SSC, which was a 20 TeV x 20 TeV collider)

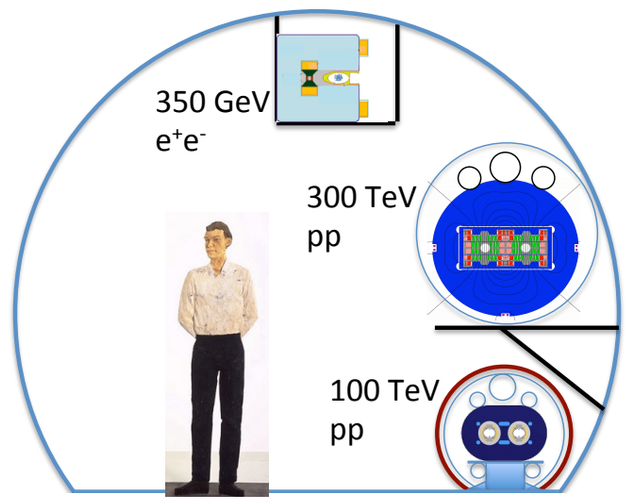
View from France into Switzerland, showing existing LHC complex (orange) and a possible 100 TeV collider ring (yellow)

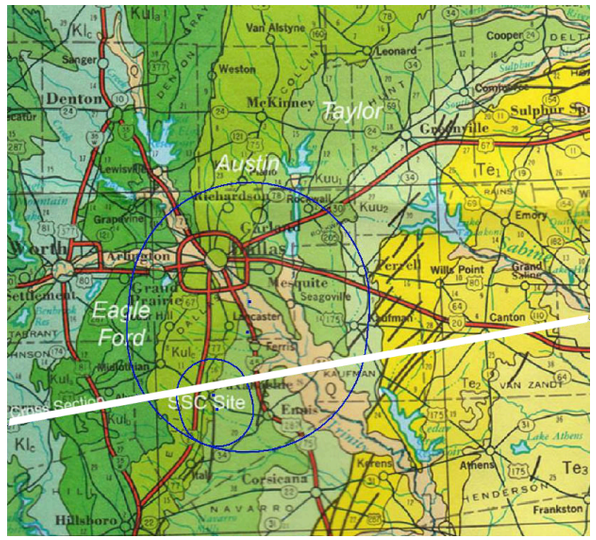
photo courtesy J. Wenninger (CERN)

High- *vs*. Low-Field Magnets

- Possible that it's more economic to build lower field magnets in a larger tunnel
  - compare overall costs of the project
  - upgrade paths

Large-circumference, Low-field Optimization of a Future Circular Collider





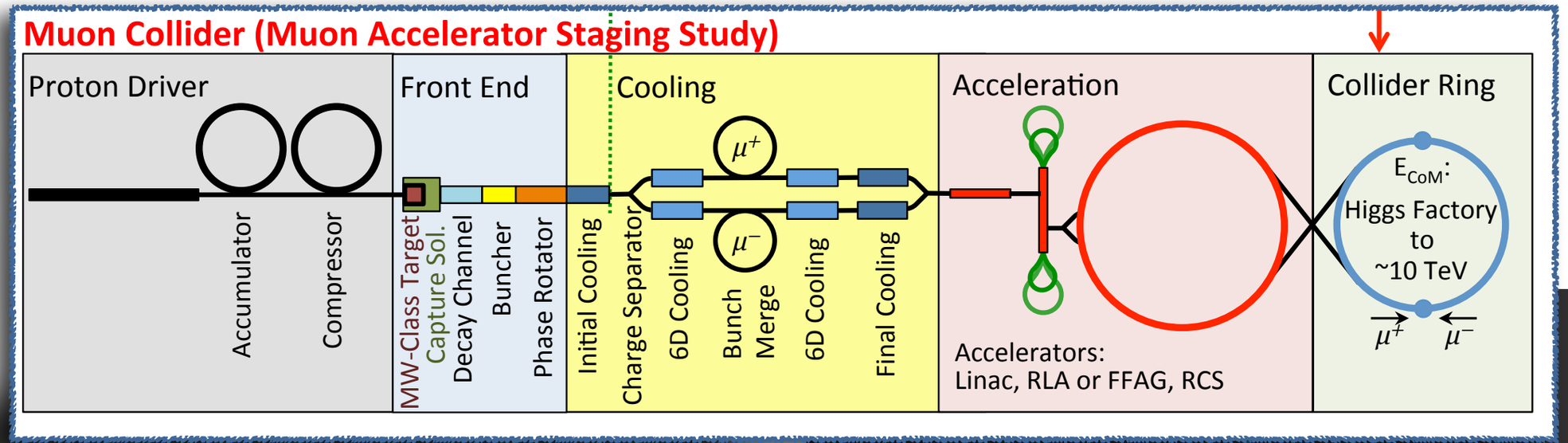
Peter McIntyre, Saeed Assadi, Chase Collins, James Gerity, Joshua Kellams, Tom Mann, Al McInturff, Chris Mathewson, Nate Pogue, Akhdiyor Sattarov, Richard York[1]

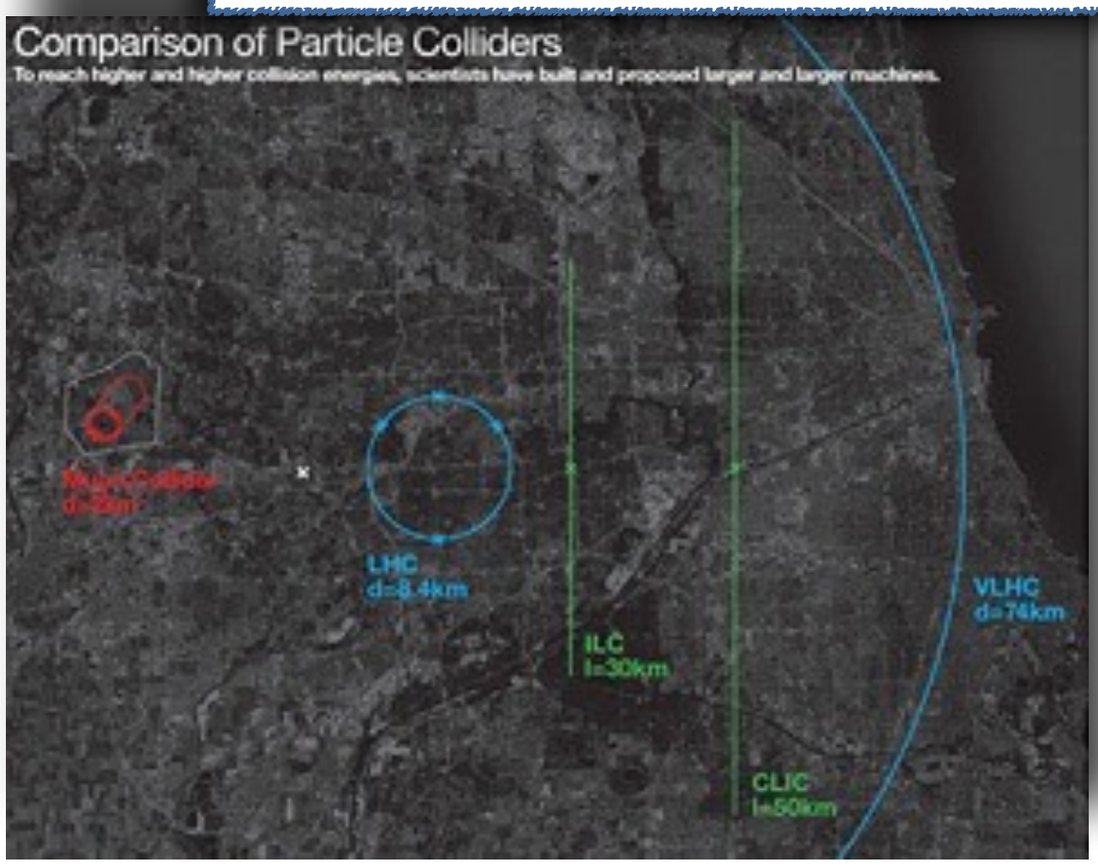
Texas A&M University

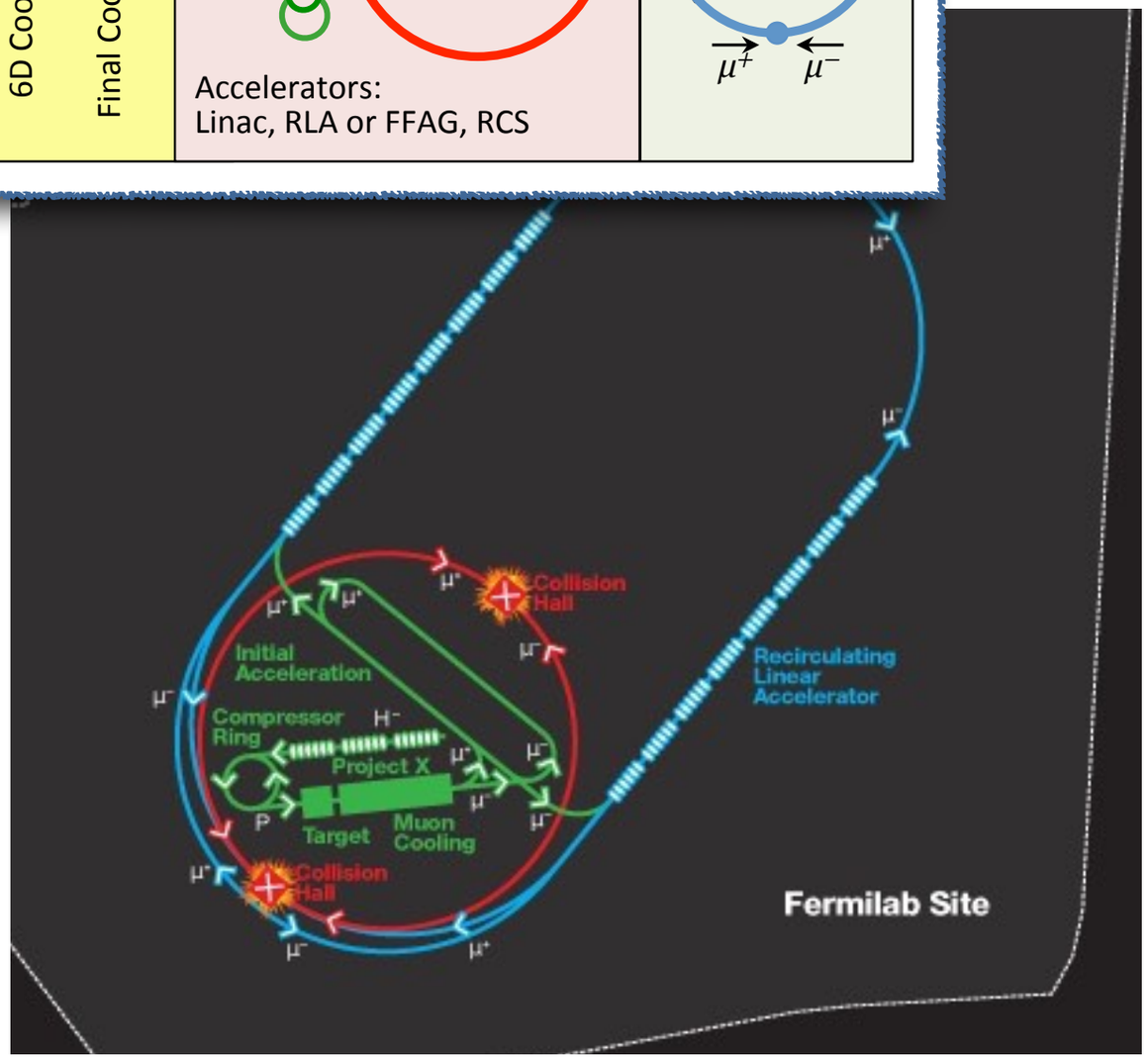
[1] Michigan State Univ.

Can world organizations get behind this concept?

Muon Colliders

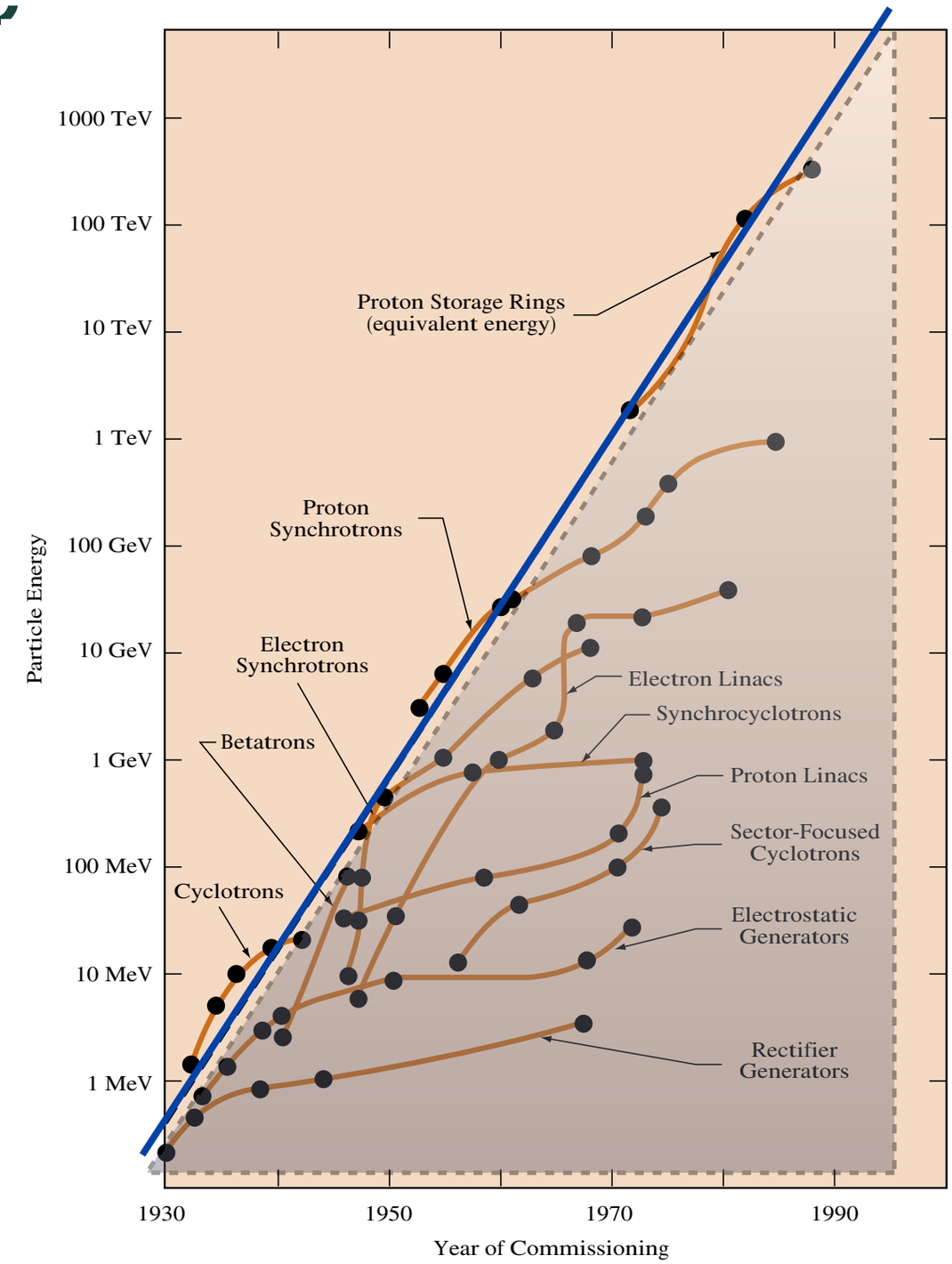






Looking Below the Curve

- Accelerator Facilities, and the need for scientists to develop, build, commission, operate, improve them have seen an enormous growth over the decades
- While peak accelerator energies continue to drive particle physics, much work to do and applications to develop at lower energies
- Many, many facilities and industrial uses are not shown here, but flood the area “below the curve”



Some Present Major Facilities

North America

88" Cycl.	88-Inch Cyclotron, Lawrence Berkeley Laboratory (LBL), Berkeley, CA
ALS	Advanced Light Source, Lawrence Berkeley Laboratory (LBL), Berkeley, CA (ALS Status)
ANL	Argonne National Laboratory, Chicago, IL (Advanced Photon Source APS, Argonne Tandem Linac Accelerator System ATLAS)
BATES	Bates Linear Accelerator Center, Massachusetts Institute of Technology, USA
BNL	Brookhaven National Laboratory, Upton, NY (AGS, ATF, NSLS, RHIC)

Particle Accelerators Around the World

Please note that this list does not include accelerators which are used for medical or industrial purposes only.

Please visit also the WWW Virtual library of Beam Physics and Accelerator Technology, the Division of Physics of Beams of the American Physical Society, and the Los Alamos Accelerator Code Group.

Sorted by Location

http://www-elsa.physik.uni-bonn.de/accelerator_list.html

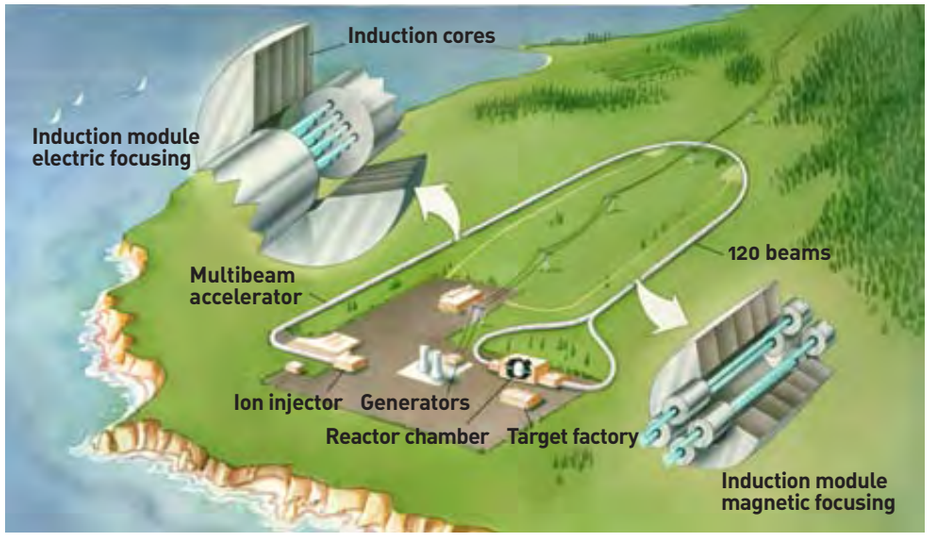
Europe

AGOR	Accelerateur Groningen-ORsay, KVI Groningen, Netherlands
ALBA	Synchrotron Light Facility *(under construction)*, Barcelona, Spain
ANKA	Ångströmquelle Karlsruhe, Karlsruhe, Germany (Forschungsgruppe Synchrotronstrahlung (FGS))
BESSY	Berliner Elektronenspeicherring-Gesellschaft für Synchrotronstrahlung, Germany
CEMHTI	Conditions Extrêmes et Matériaux : Haute Température et Irradiation, Orléans, France
CERN	Centre Europeen de Recherche Nucleaire, Geneva, Suisse (LHC, PS-Division, SL-Division)
CMAM	Centro de Microanálisis de Materiales, Universidad Autonoma de Madrid, Spain
COSY	Cooler Synchrotron, IKP, FZ Jülich, Germany (COSY Status)
CYCLONE	Cyclotron of Louvain la Neuve, Louvain-la-Neuve, Belgium
DELTA	Dortmunder ELekTronenspeicherring-Anlage, Zentrum für Synchrotronstrahlung der Technischen Universität Dortmund, Germany
DESY	Deutsches Elektronen Synchrotron, Hamburg, Germany (XFEL, PETRA III, FLASH, ILC, PITZ)
ELBE	ELectron source with high Brilliance and low Emittance, Forschungszentrum Dresden - Rossendorf e.V. (FZD), Germany
ELETTRA	AREA Science Park, Trieste, Italy
ELSA	Electron Stretcher Accelerator, Bonn University, Germany (ELSA status)
ESRF	European Synchrotron Radiation Facility, Grenoble, France
GANIL	Grand Accélérateur National d'Ions Lourds, Caen, France (GANIL, SPIRAL2)
GSI	Gesellschaft für Schwerionenforschung, Darmstadt, Germany

CAMD	Center for Advanced Microstructures and Devices, Louisiana State University
CENPA	Center for Experimental Nuclear Physics and Astrophysics, University of Washington, USA
CESR	Cornell Electron-positron Storage Ring, Cornell University, Ithaca, NY
CHESS	Cornell High Energy Synchrotron Source, Cornell University, Ithaca, NY
CLS	Canadian Light Source, U of Saskatchewan, Saskatoon, Canada
CNL	Crocker Nuclear Laboratory, University of California Davis, CA
FNAL	Fermi National Accelerator Laboratory , Batavia, IL (Tevatron)
FSU	John D. Fox Superconducting Accelerator Laboratory, Florida State University, USA
IAC	Idaho accelerator center, Pocatello, Idaho
ININ	National Institute for Nuclear Research, Mexico
ISNAP	Institute for Structure and Nuclear Astrophysics, Notre Dame University, USA
IUCF	Indiana University Cyclotron Facility, Bloomington, Indiana
JLab	aka TJNAF, Thomas Jefferson National Accelerator Facility (formerly known as CEBAF), Newport News, VA
LAC	Louisiana Accelerator Center, U of Louisiana at Lafayette, Louisiana
LANL	Los Alamos National Laboratory
MIBL	Michigan Ion Beam Laboratory, University of Michigan
NSCL	National Superconducting Cyclotron Laboratory, Michigan State University
ORNL	Oak Ridge National Laboratory Oak Ridge, Tennessee
OUAL	John E. Edwards Accelerator Laboratory, Ohio University, USA
PBPL	Particle Beam Physics Lab (Neptune-Laboratory, PEGASUS - Photoelectron Generated Amplified Spontaneous Radition Source)
SLAC	Stanford Linear Accelerator Center, (SLC - SLAC Linear electron positron Collider, SSRL - Stanford Synchrotron Radiation Laboratory)
SNS	Spallation Neutron Source, Oak Ridge, Tennessee
SRC	Synchrotron Radiation Center, U of Wisconsin - Madison
SURF III	Synchrotron Ultraviolet Radiation Facility, National Institute of Standards and Technology (NIST), Gaithersburg, Maryland
TAMU	Cyclotron Institute, Texas A&M University, USA
TRIUMF	Canada's National Laboratory for Particle and Nuclear Physics, Vancouver, BC (Canada)
TUNL	Triangle Universities Nuclear Laboratory, USA
UMASS	University of Massachusetts Lowell Radiation Laboratory, USA
UNAM	Universidad Nacional Autónoma de México, Mexico
WMU	Van de Graaff Accelerator at the Physics Department of the Western Michigan

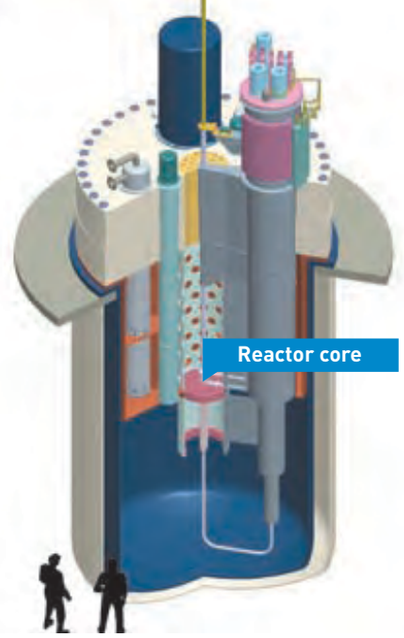
Industry and Others

- Besides basic physics research, accelerator science has reached out into medicine, food industry, national security, materials, ...
  - ~26,000 accelerators worldwide*
  - ~1% are research machines with energies above 1 GeV; of the rest, about 44% are for radiotherapy, 41% for ion implantation, 9% for industrial processing and research, and 4% for biomedical and other low-energy research*
- Many Concepts for the Future



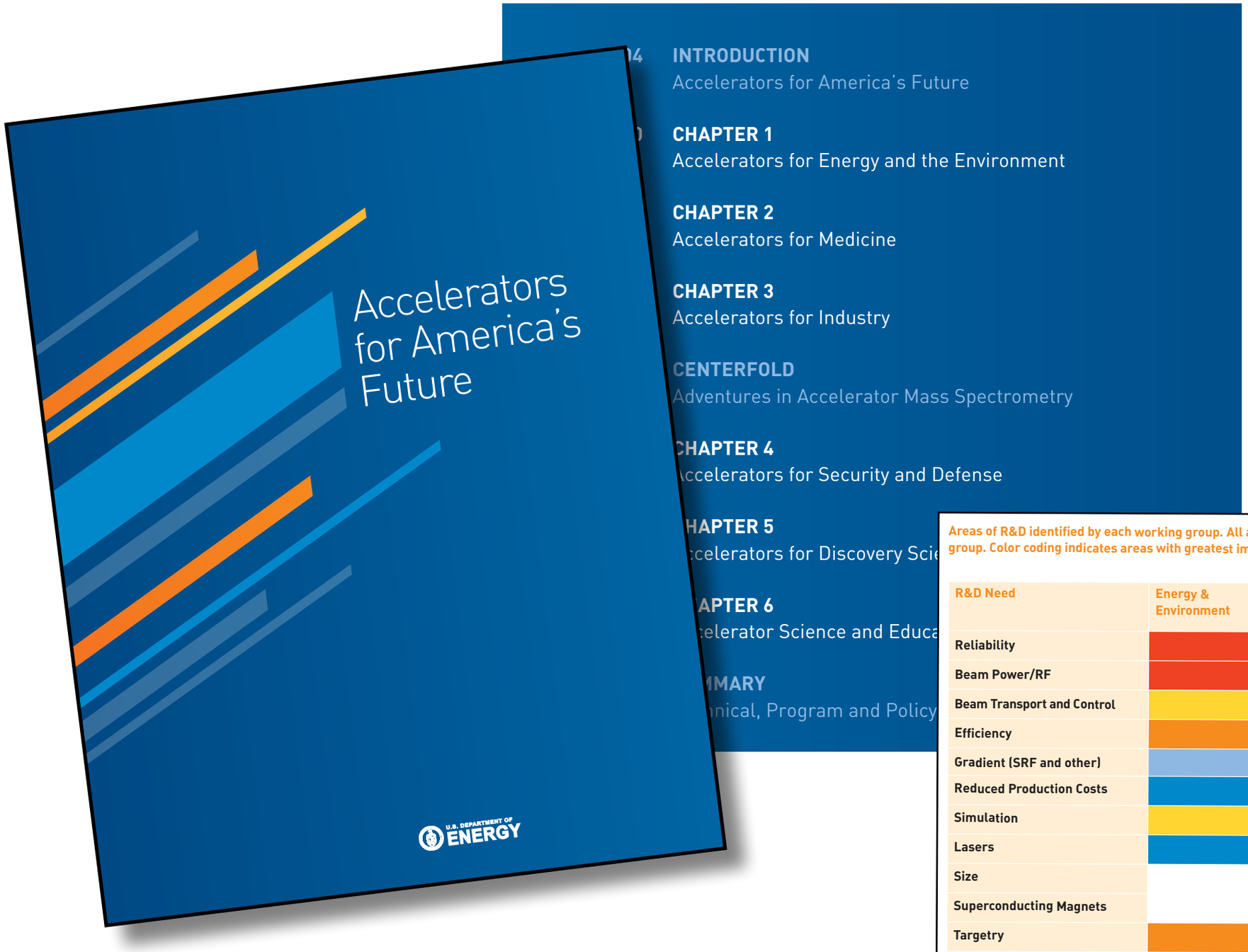
Concept of an inertial-fusion power plant based on a heavy-ion induction linear accelerator
Image courtesy of Lawrence Berkeley National Laboratory

Assembly of a superconducting accelerator section for production of ion beams
Photo courtesy of J. Nolen, Argonne National Laboratory



*Feder, T. (2010). "Accelerator school travels university circuit". *Physics Today* **63** (2): 20. Bibcode 2010PhT....63b..20F. doi:10.1063/1.3326981

Accelerators for America's Future



- Symposium and workshop held in Washington, D.C., October 2009
- 100-page Report available at web site

Areas of R&D identified by each working group. All areas are of importance to each working group. Color coding indicates areas with greatest impact.

R&D Need	Energy & Environment	Medicine	Industry	Security & Defense	Discovery Science
Reliability					
Beam Power/RF					
Beam Transport and Control					
Efficiency					
Gradient (SRF and other)					
Reduced Production Costs					
Simulation					
Lasers					
Size					
Superconducting Magnets					
Targetry					
Particle Sources					

Color code: Increased priority

http://www.acceleratorsamerica.org/

Professional Organizations and Journals

- American Physical Society (APS)
  - Division of Physics of Beams (DPB)
- Institute of Electrical and Electronics Engineers (IEEE)
- Physical Review Accelerators and Beams (PRAB)
  - previously called *PR Special Topics —AB*
  - prominent peer-reviewed journal for the field
- Nuclear Instruments and Methods - A (NIM-A)
  - many peer-reviewed accelerator articles
- Joint Accelerator Conferences Website (JACoW)
  - on-line proceedings of major accelerator conferences

The Future

- If USPAS is a guide, attendance has held steadily at ~300 students per year over the past many years, even while projects such as the SSC were cancelled, or while “ILC’s” were put off into the distant future.
  - again -- the big accelerators are only <1%!!
- Accelerators for America’s Future symposium and workshop indicated major interests from industry, medical field, etc., in addition to pure research
- Major labs are investing (as funding allows...) in future programs
  - LHC upgrades; Fermilab neutrino program + Proton Improvement Plan
  - Light sources and XFEL’s
  - FRIB at MSU
- New generations of High Energy? Much R&D going on in...
  - International Linear Collider (ILC), Compact Linear Collider (CLIC)
  - Future Circular Colliders (FCC)
  - Muon Collider (on hold for now)
  - Plasmas, wake fields

A “Final” word

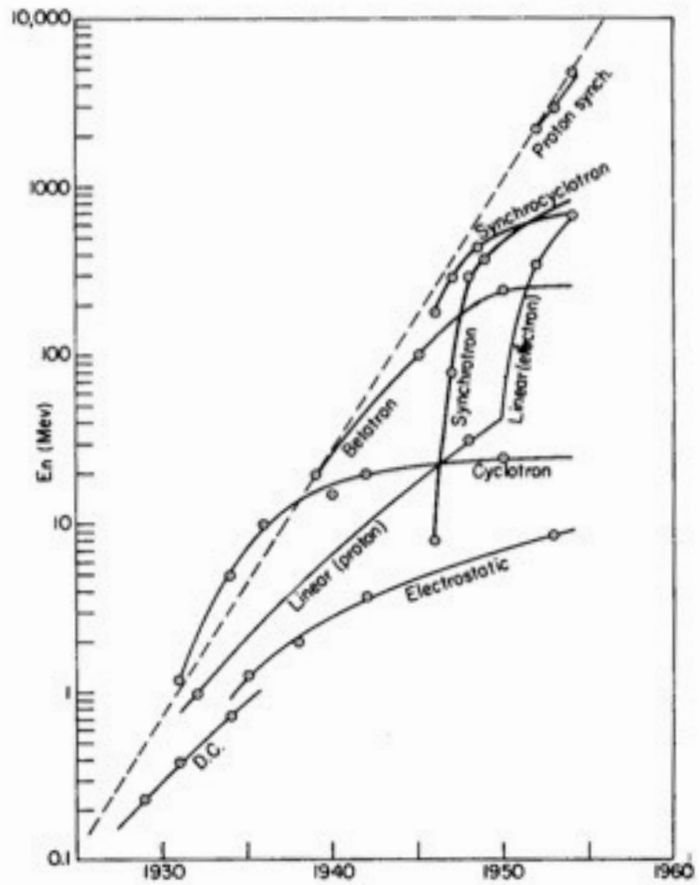


FIG. 7-8. Exponential rise in energy attained with accelerators during the past 25 years.

of the plot is the approximately linear slope of this envelope, which means that energy has in fact increased exponentially with time. The rate of rise is such that the energy has increased by a factor of 10 every six years, from a start at 100 kv in 1929 to 3 billion volts in 1952.

It is interesting to extrapolate this curve into the future, to predict the energy of accelerators after another six years. We have reason to hope that either the Brookhaven or the CERN A-G proton synchrotrons will have reached 25 Bev by that

time. Further extrapolation of this exponentially rising curve would predict truly gigantic accelerators which would exceed any possible budgets, even those of government laboratories. So we will postpone such speculation until the present machines can demonstrate their value to science.

Those of us in the accelerator field are frequently asked, “When will this development of higher-and-higher-energy accelerators stop?” Yet it must be recognized that it is not the urge to higher voltage which inspires this growth, but the pressure of the continuously expanding horizons of science. As long as there are unsolved problems in Nature which might be answered by higher-energy particles, and as long as the scientific urge to know the answers continues, there will be a steady and persistent demand to develop the tools and instruments required.

A “Final” word

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M. Stanley Livingston, 1954

The Team wants to

Thank You!

Thanks for all your hard work during the past two weeks, and good luck on your future endeavors!

(and, on tomorrow's **FINAL EXAM**!)

A *REVIEW* will be held here at **1:00 p.m.** this afternoon.

exam: in this room, tomorrow **9:30 a.m.** sharp!

Mike, Elvin, Karie, Kent, David