Particle Accelerators for High Energy Physics

- Accelerators and HEP
- What's Up Now?
- What's Up Next?

But First ...

- A little about me …

- finley@fnal.gov
- http://tdserver1.fnal.gov/Finley/020712QuarkNet.pdf

Behind the ...

www.VH1.com

SHOW AIRS: SUN 1/27 at 11pm ET

Behind the ...

www.fnal.gov (not likely on www.VH1.com)

Fermilab Accelerators

SHOW AIRS: FRI 7/12 at 930am CT

Your Host: David Finley

finley@fnal.gov

A little about me …
Behind the Scientist

- High School
  - St. Lawrence Seminary
  - Mt. Calvary, Wisconsin
- College: Purdue
  - Physics: BS, MS, PhD
- US Army Officer
  - 72-74 Washington DC
  - Harry Diamond Labs
- Research Associate (PhD)
  - High Energy Physics
  - SUNY Stony Brook NY
- Fermilab (4/1/81 to now)
  - Switchyard Beam Lines
  - Tevatron … Collider
  - Beams Division
  - Future Accelerator R&D
  - 7/12/02 QuarkNet Talk

Accelerators

- Accelerators (Particle Accelerators)
  - today: particle beams for particle physics research
    - mostly use electrons and protons
    - and antiprotons and positrons, and mesons and neutrinos ...
  - not today: materials, medical, military (aka 3M), etc
- Why do this?
- A “few words about” Acceleration

References

- David Griffiths

Introduction to Elementary Particles"
ISBN 0-471-60386-4

- Ernie Malamud
- www-bd.fnal.gov/public/index.html
  malamud@fnal.gov

- David Finley

finley@fnal.gov

- Particle Accelerator

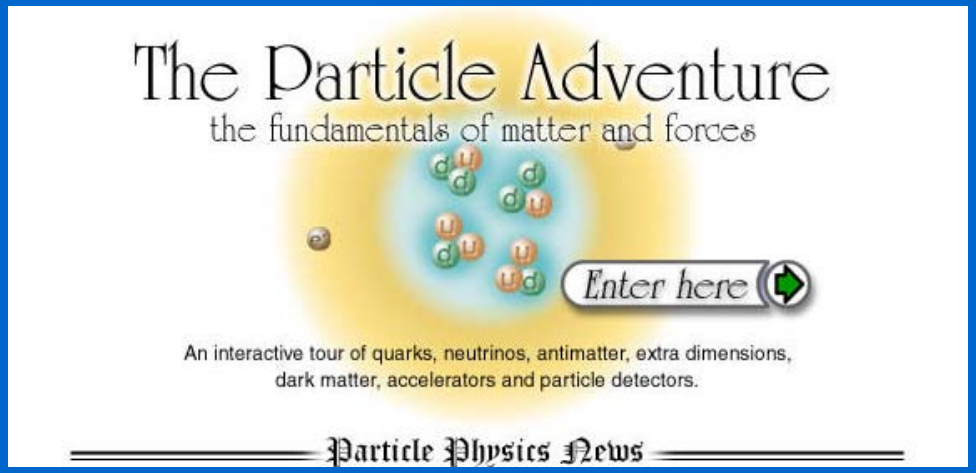
Encyclopedia of Science and Technology
(McGraw-Hill)

- Feynman, Leighton, Sands

"The Feynman Lectures on Physics"
ISBN 0-201-02116-1

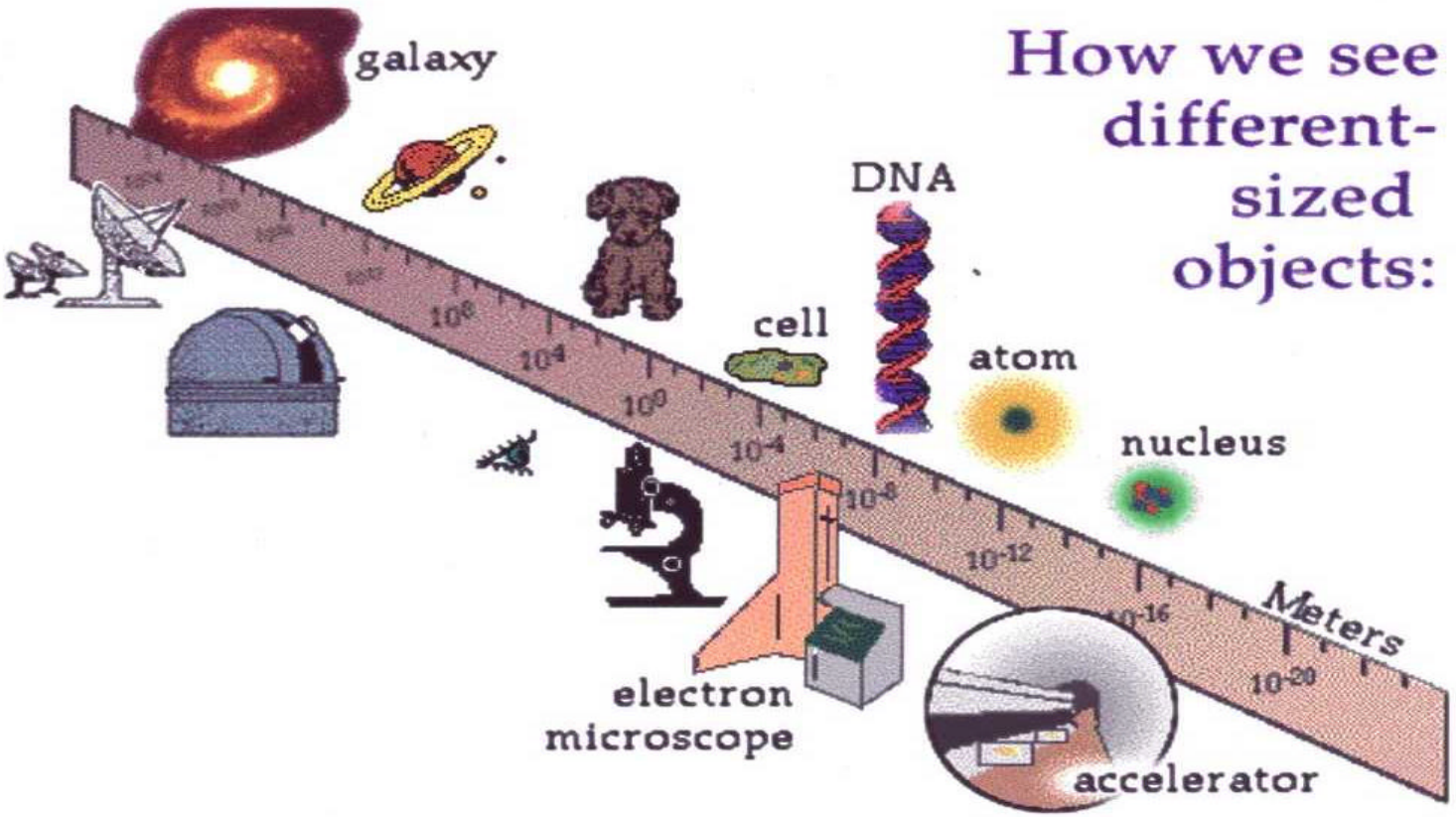
- Lawrence Berkeley National Lab

http://ParticleAdventure.org/



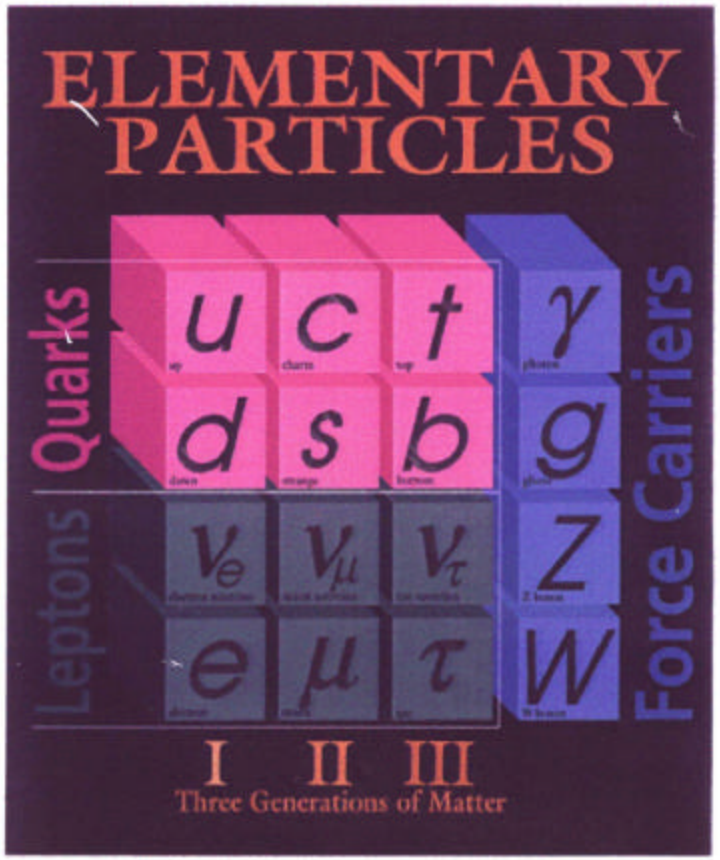
Accelerators - What do we use them for?

- Why do this? This = “particle physics”
  - Q1: What’s it all made of?
  - Q2: How does it all behave?
  - Q3: How do particles come by their mass?
  - Q4: How is it that we see more matter than antimatter?
  - And … Q4++
    - So, how is it all distributed anyway?
    - Etc etc



Courtesy E. Malamud malamud@fnal.gov

Fermilab's Role (so far)



Fermilab has aided in the discovery of the:

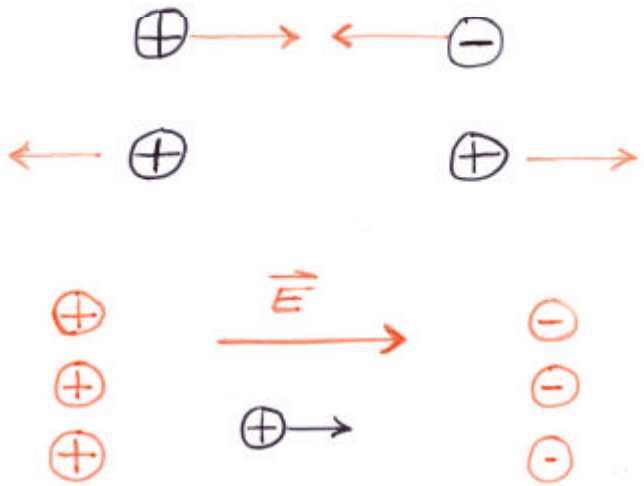
- bottom quark (1977)
- top quark (1995)
- tau neutrino (2000)

Courtesy L. Spentzouris klamp@fnal.gov

Accelerator Basics

- A Little from Maxwell, Newton, Lorentz
  - $\mathbf{F} = e\,\mathbf{E}$ and $\mathbf{F} = q\,(\mathbf{v}/c) \times \mathbf{B}$
  - $\mathbf{F} = d\mathbf{p}/dt$ and $\mathbf{p} = m\,\mathbf{v}$
- A Little Relativity from Einstein
  - $m = m_0 / \sqrt{(1 - \beta^2)}$ with $\beta = v/c$
  - $E = m_0$ + Kinetic Energy and $E = m\,c^2$
- A Little from Murphy (as in Murphy's Law)

Electric Force



Force : $\vec{F}$ = (charge) $\vec{E}$ = e $\vec{E}$

Potential : Volts = - E × (length moved)

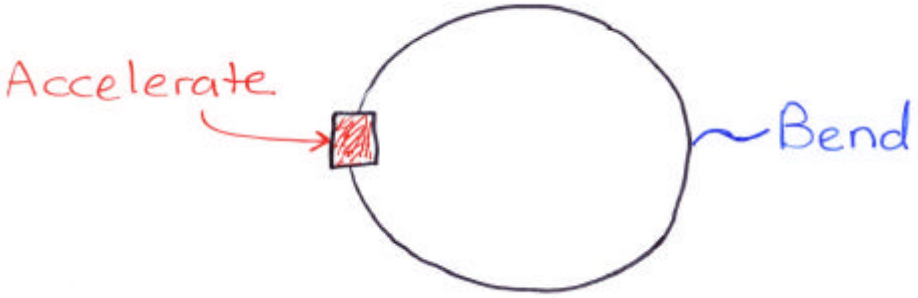
Energy : E = (charge)(volt)

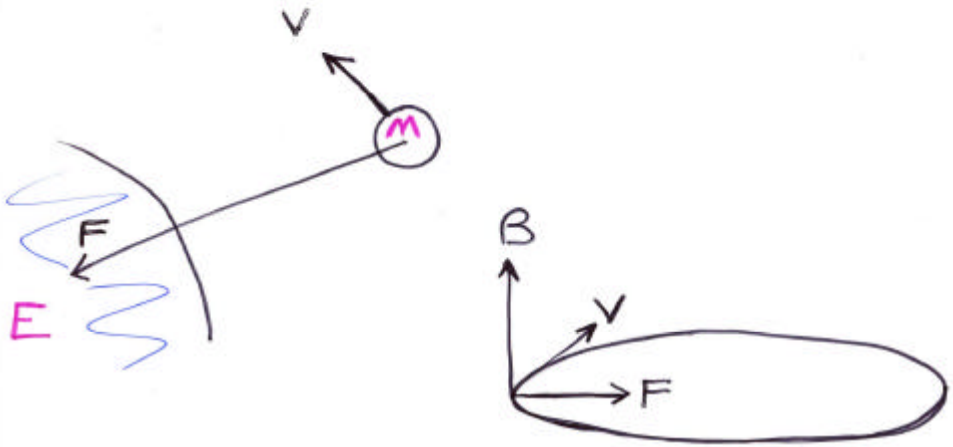
1 eV → Energy gained by e when pulled through 1 Volt

Courtesy L. Spentzouris

klamp@fnal.gov

Magnetic Force





$$F = e(v \times B)$$

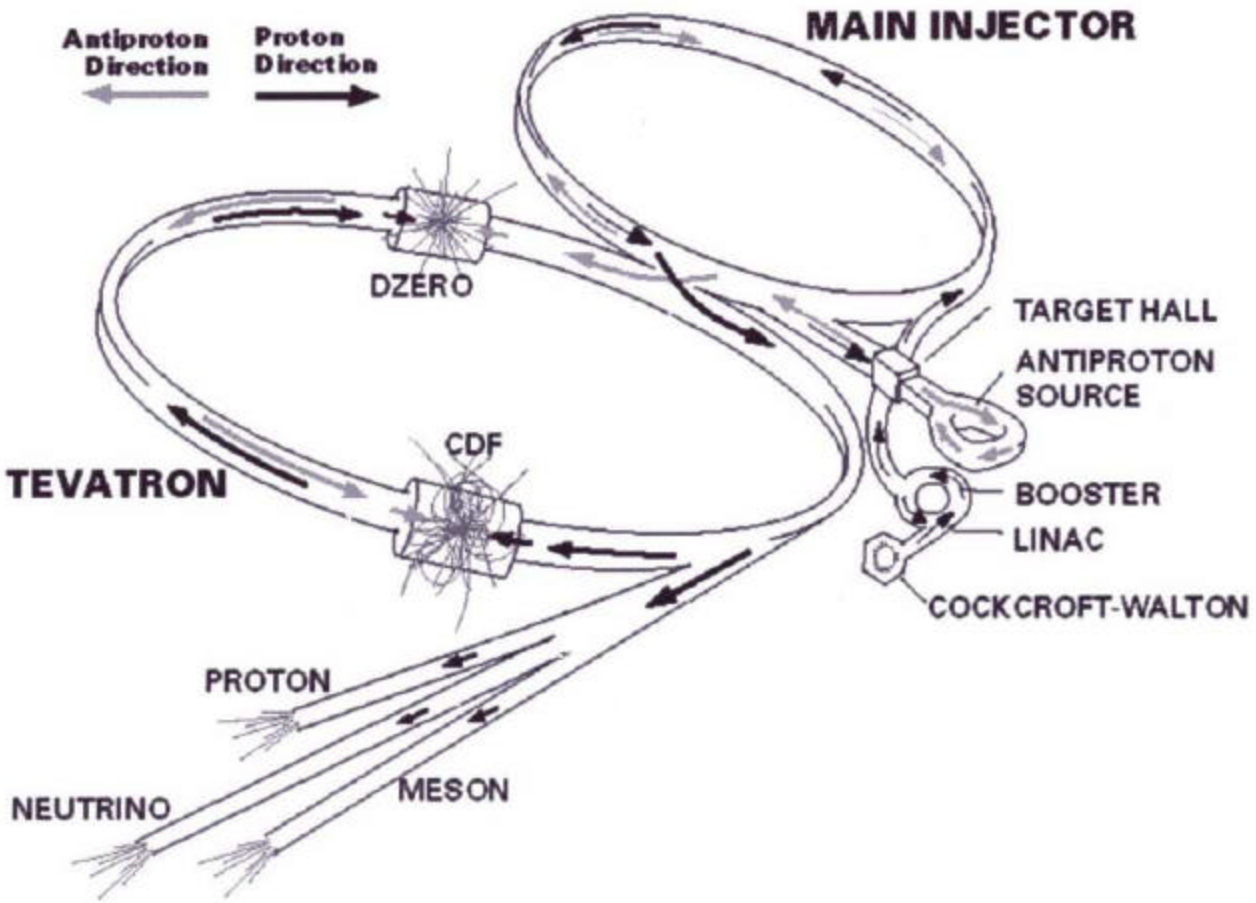
Courtesy L. Spentzouris

klamp@fnal.gov

Particle Accelerators for High Energy Physics

- Accelerators and HEP
- What's Up Now? <<<< We are here
- What's Up Next?

Fermilab's ACCELERATOR Chain



Courtesy E. Malamud malamud@fnal.gov

HiRise and Tevatron

- Insert 93-683-9 “HiRise and Tevatron” and pretend you are on the 15th floor giving a tour and read the following few slides

Overheard on the 15th Floor - 1

- So, if you look over there, you see a big orange building. That's where CDF is located. Collider Detector at Fermilab.
- And on a really clear day you can see the Sears Tower in Chicago over there.
- And directly opposite us over there is a blue building where the D-Zero detector is located.
- The Tevatron accelerator is located about 20 feet under the berm you see.
- We send the proton beam around the 6 kilometers of the Tevatron. It's inside a 7 cm diameter beam pipe with all the air removed. Otherwise the air molecules would eat up all the protons.
- The beam pipe goes though about 1000 superconducting magnets. The magnets have two jobs. Some of them keep the protons focussed so they don't wander off the central path. And the others bend the central path around in a circle so the beam keeps passing through the accelerating stations.

Overheard on the 15th Floor - 2

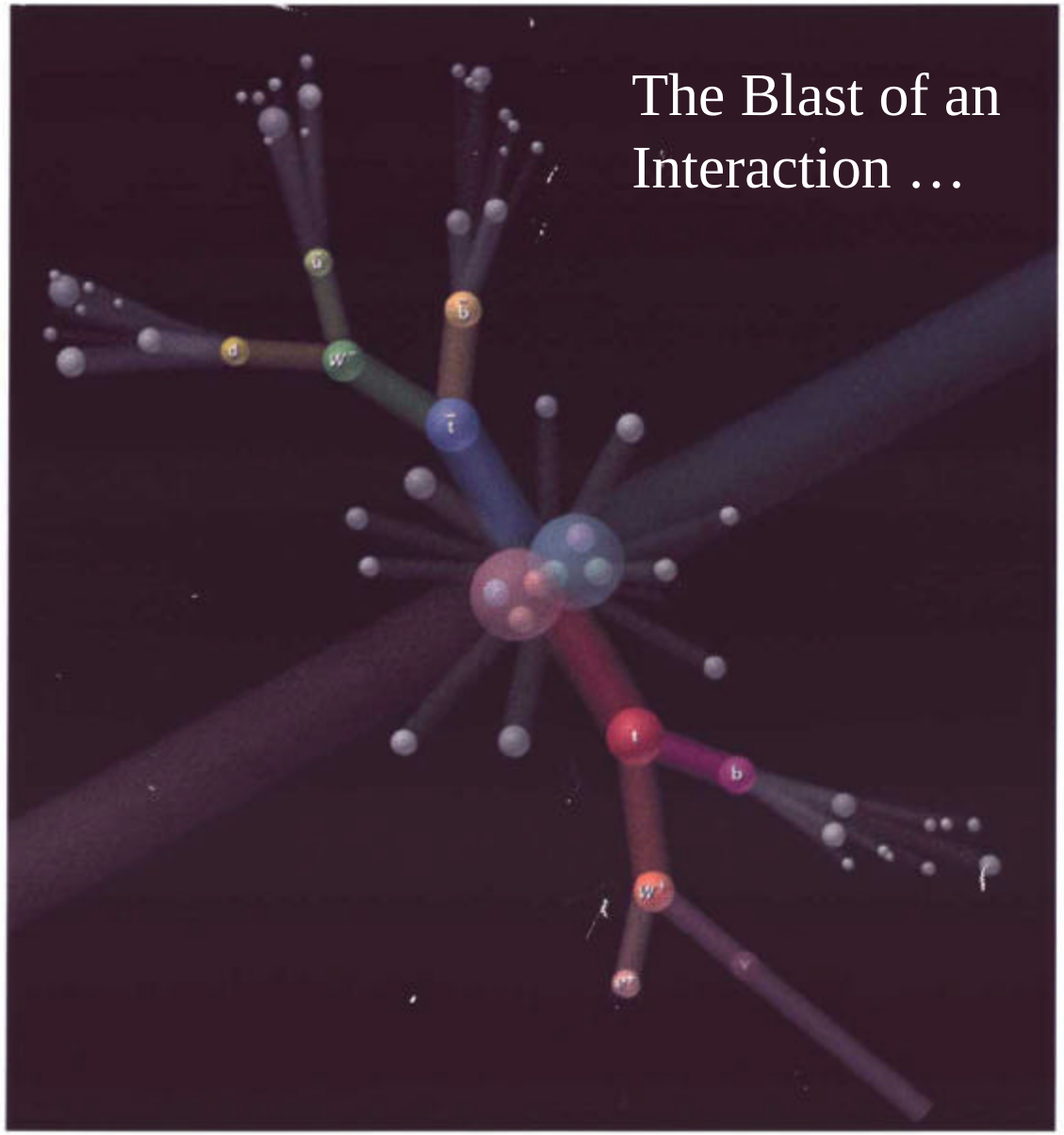
- Over there to the right is where the accelerating stations are located. They provide electric fields which are carefully timed to push the protons along to a higher energy. We use the same technology that radar is based on. For the rf in the Tevatron, the electric field flips its sign about 53 million times a second. So you have to be pretty careful with the timing.
- The beam goes around the 6 kilometers about 50,000 times a second. (47,713 if you are picky about numbers.) Every second!
- With an energy of about one trillion volts, or 1 TeV.
- That's the highest energy particle beam in the world. And will be until about 2006 when CERN starts up the LHC with its 7 TeV proton beams.
- In the Tevatron, a bunch of protons is about 40 microns in diameter at CDF or D-Zero. That's about the diameter of your hair.
- And a meter or so long. Like really long, really thin needles.

Overheard on the 15th Floor - 3

- There are about 100 billion protons in a bunch.
- And we collide it with an antiproton bunch going the opposite direction. About 50,000 times a second.
- An antiproton bunch looks pretty much the same as the proton bunch, but there are fewer antiprotons.
- So we collide these things that are about the size of your hair, and they are going at about the speed of light. You'll have to trust me.
- Antiprotons are antimatter. But, unlike Star Trek, we don't just talk about it, we actually make antimatter and use it. For particle physics research.
- When the bunches pass though one another, a few of the protons and antiprotons interact with one another. These matter / antimatter interactions convert some of the energy to mass.
- Remember $E=mc^2$? That's what really happens. Right over there and there.

Overheard on the 15th Floor - 4

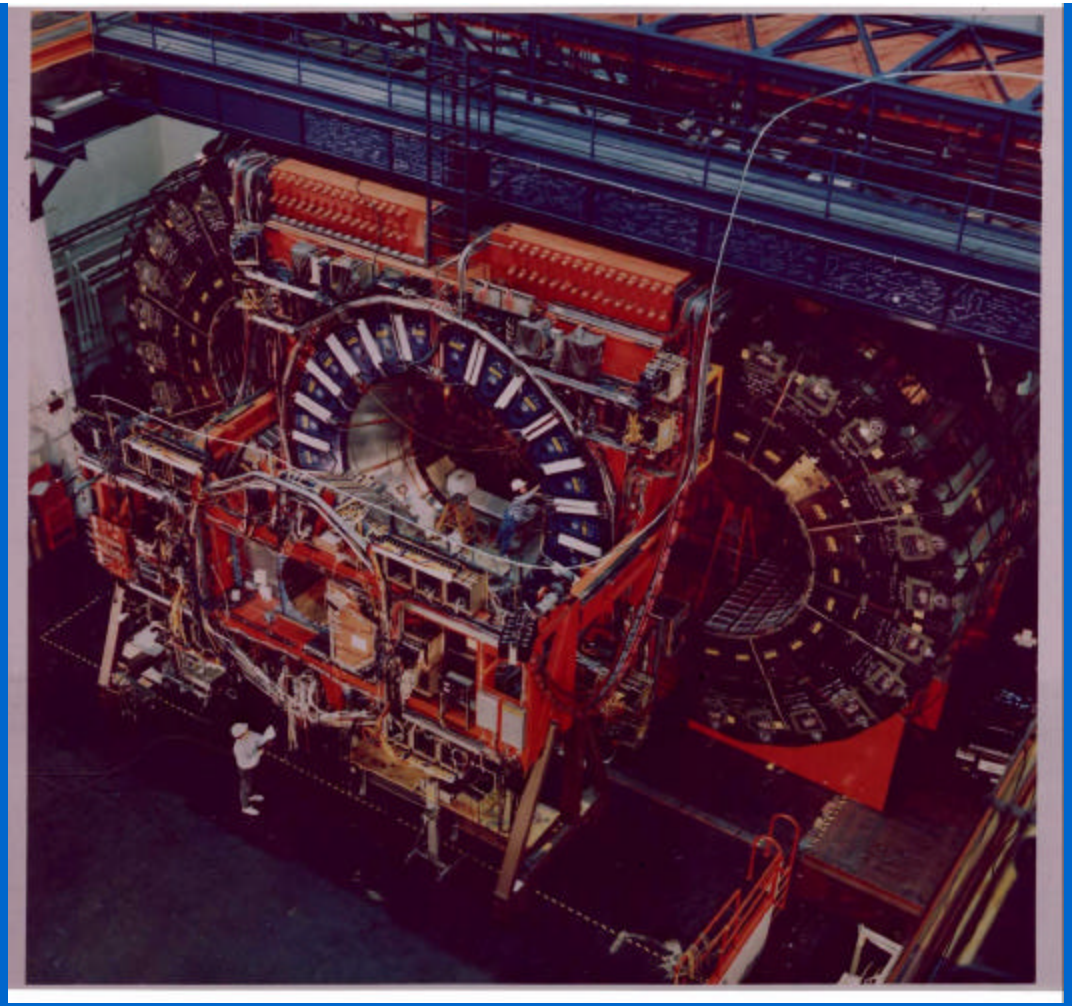
- And sometimes, not very often, an interaction converts the energy to mass in the form of a top quark. And an anti-top quark. Made right here at Fermilab in the Tevatron. And detected right over there in those orange and blue buildings.
- But we really use 36 bunches distributed around the Tevatron. But as we increase the performance of the Tevatron, we will have to start using about 100 bunches in each beam.
- That way we can have more collisions per second, but not many more interactions per bunch crossing. Too many interactions per crossing makes it hard on CDF and D-Zero.
- And it really works.
- And when you get this complex running, you run it 24/7. And pretty much 365. For several years.
- I've been here for about 27 years, and it still amazes me.

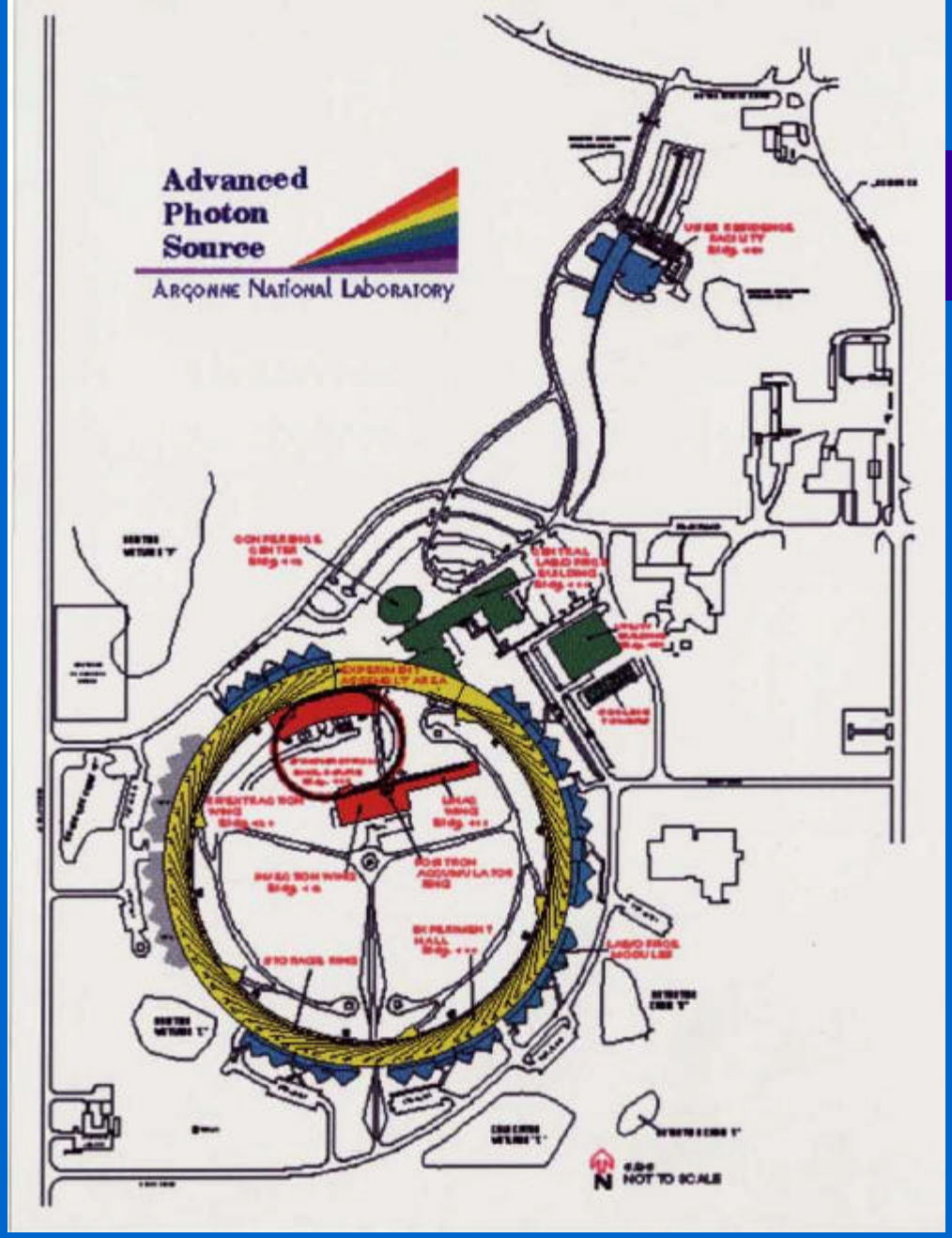


- Protons and antiprotons (really quarks, antiquarks, gluons, sea) come in with kinetic energy …
- $E = mc^2$ … and …
- Lots and lots of new particles come out …
- And the standard model rules! (So far.)

Courtesy E. Malamud malamud@fnal.gov

CDF (Collider Detector at Fermilab)





- The Advanced Photon Source (APS) at Argonne

Right down the road from here..

Bend an electron and you get photons

RHIC

Daily Status Report for June 13

Success!

Last night two experiments (STAR and PHOBOS) measured beam-beam collisions at gamma=30.

We will continue to work on steering at the IP's with colliding beams.

June 13, 2000 PRESS RELEASE

Relativistic Heavy Ion Collider (RHIC) Begins Smashing Atoms

Experiments will yield insights into the structure of matter and how the universe evolved

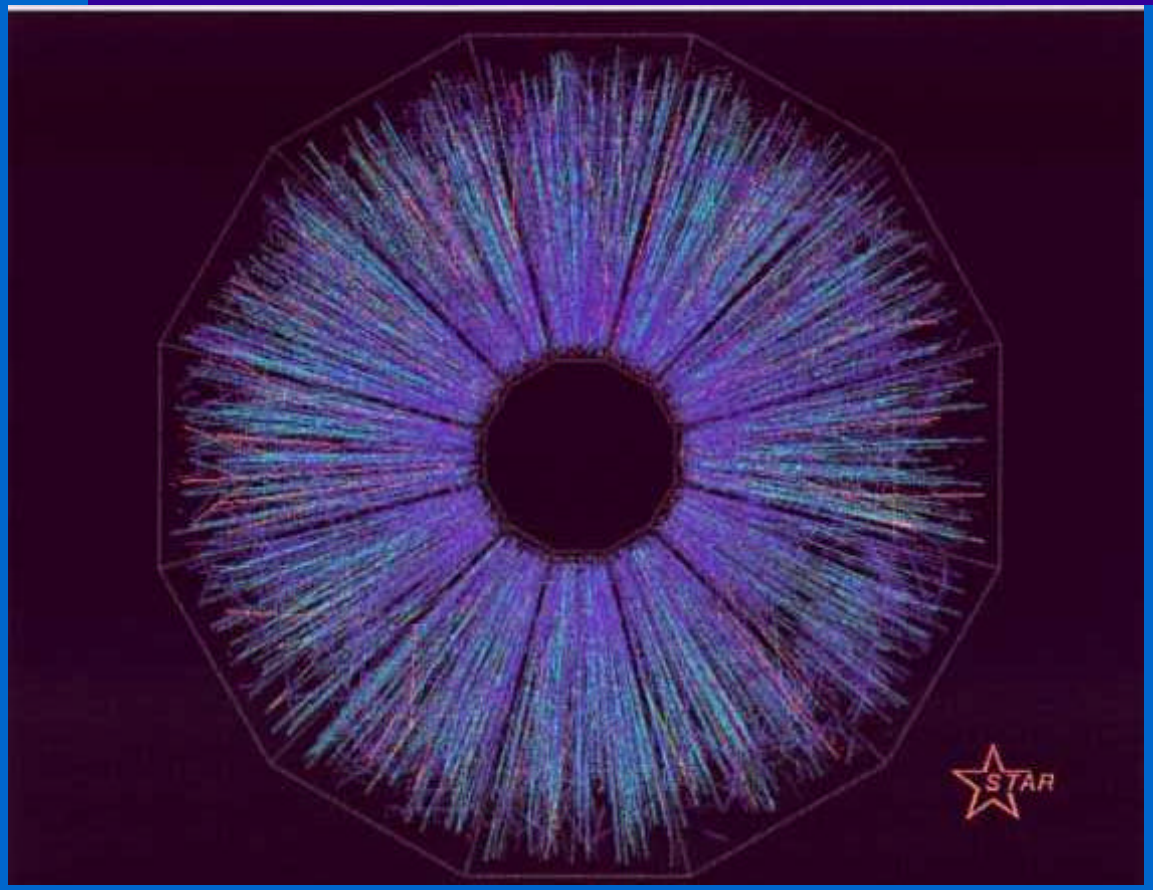
UPTON, NY - Scientists at the U.S. Department of Energy's Brookhaven National Laboratory have begun detecting head-on collisions between gold nuclei in the Relativistic Heavy Ion Collider (RHIC), the world's newest and biggest particle accelerator for studies in nuclear physics. While the beams have been in collision mode since the weekend of June 10, the first spectacular images of particles streaming from a collision point -the definitive evidence the scientists were waiting for - were produced by the STAR detector last night at 9 p.m. High-energy collisions were also seen by the PHOBOS detector early this morning.

Last updated 6/13/00 by Public Affairs

- RHIC is on Long Island in New York.

Ions … nuclei … GOLD no less!

End view of STAR at RHIC



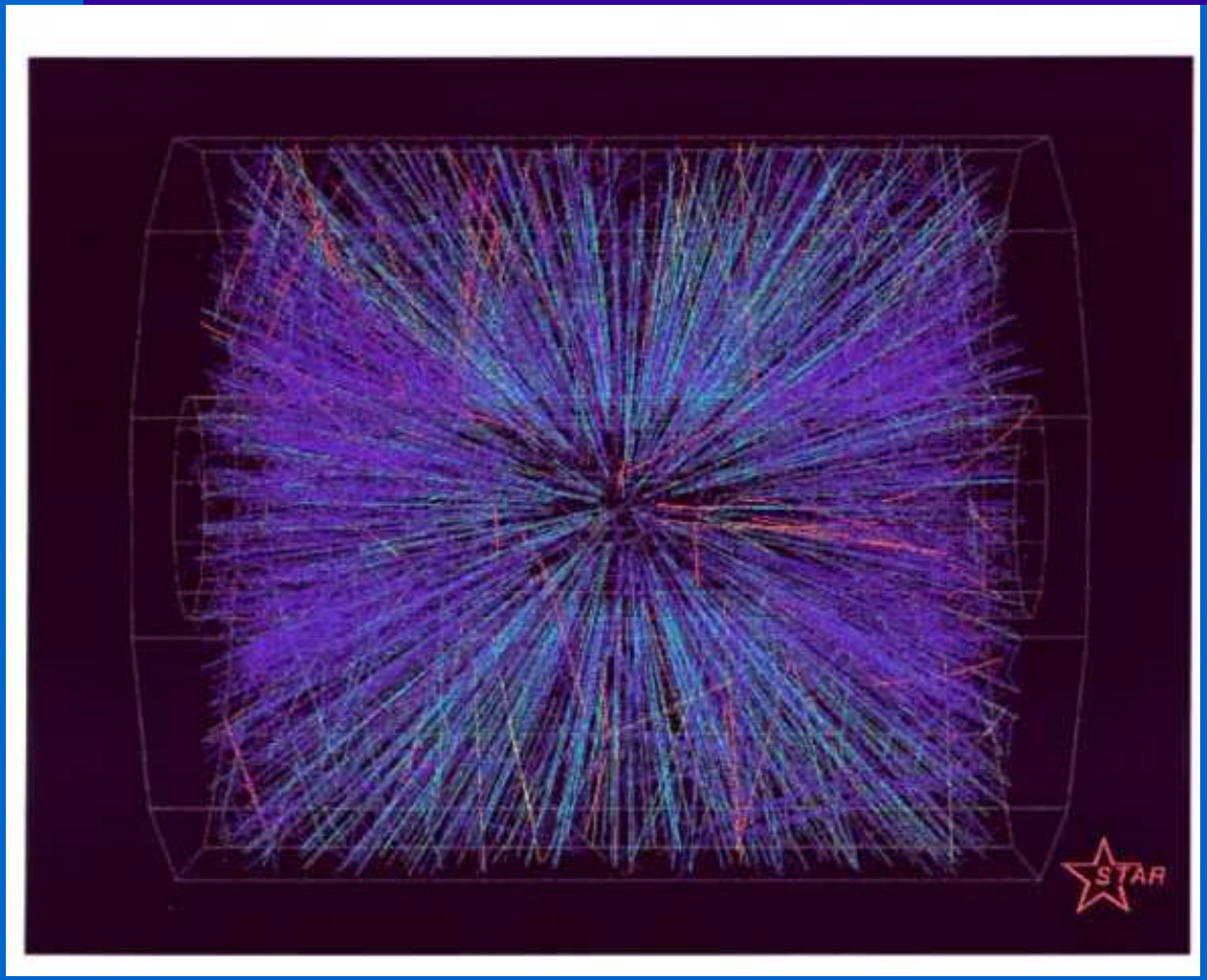
This is the view along the beam line

RHIC collides beams made of gold atoms

The fuzz represents the tracks of the particles created from the kinetic energy of the gold beams

$E = m c^2$ lives!

Side View of STAR at RHIC



Same as previous slide but seen from the side

Try to figure out what's going on here!

The detectors are another real challenge.

CERN

The CERN accelerator is 26 kilometers in circumference

Near Geneva on the Swiss / French Border

LEP (Large Electron Positron collider) turned off in 2000 with a “hint of a Higgs” … no discovery.

The LHC will collide a pair of 7 TeV proton beams starting in about 2006 or so

DESY (Deutches Elektronen-Synchrotron)

The HERA accelerator is about 6.2 km in circumference

Partly under the town of Hamburg, Germany

HERA's superconducting magnets are very similar to those in the Tevatron

HERA collides electron beams with proton beams

SLAC (Stanford Linear Accelerator Center)

The SLAC linac is about 4 km long.

Goes under I-280 outside Palo Alto, California.

50 GeV electrons.

"linear collider" demonstration

B quark factory.

"Partons", Charm quark, Tau lepton

- This is the Tevatron tunnel (pre Main Injector) era)

Particle Accelerators for High Energy Physics

- Accelerators and HEP
- What's Up Now?
- What's Up Next? <<<< We are here

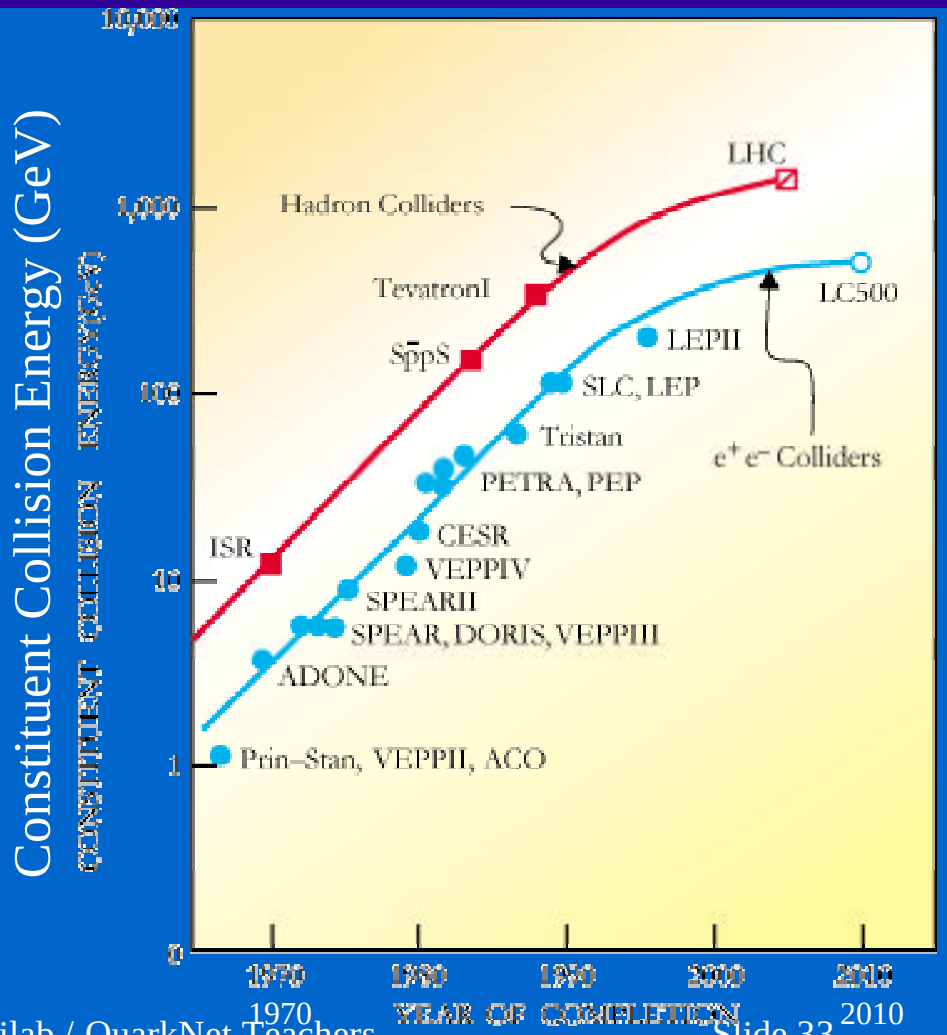
Accelerators - What's Up Next?

- What Up Next?
  - electrons and positrons : e^+e^- Colliding Beams
  - protons and protons : pp Colliding Beams
  - muons and muons : $\mu^+ \mu^-$ Colliding Beams
  - neutrino beam : From decaying muons

- But first, a word about recent times ...

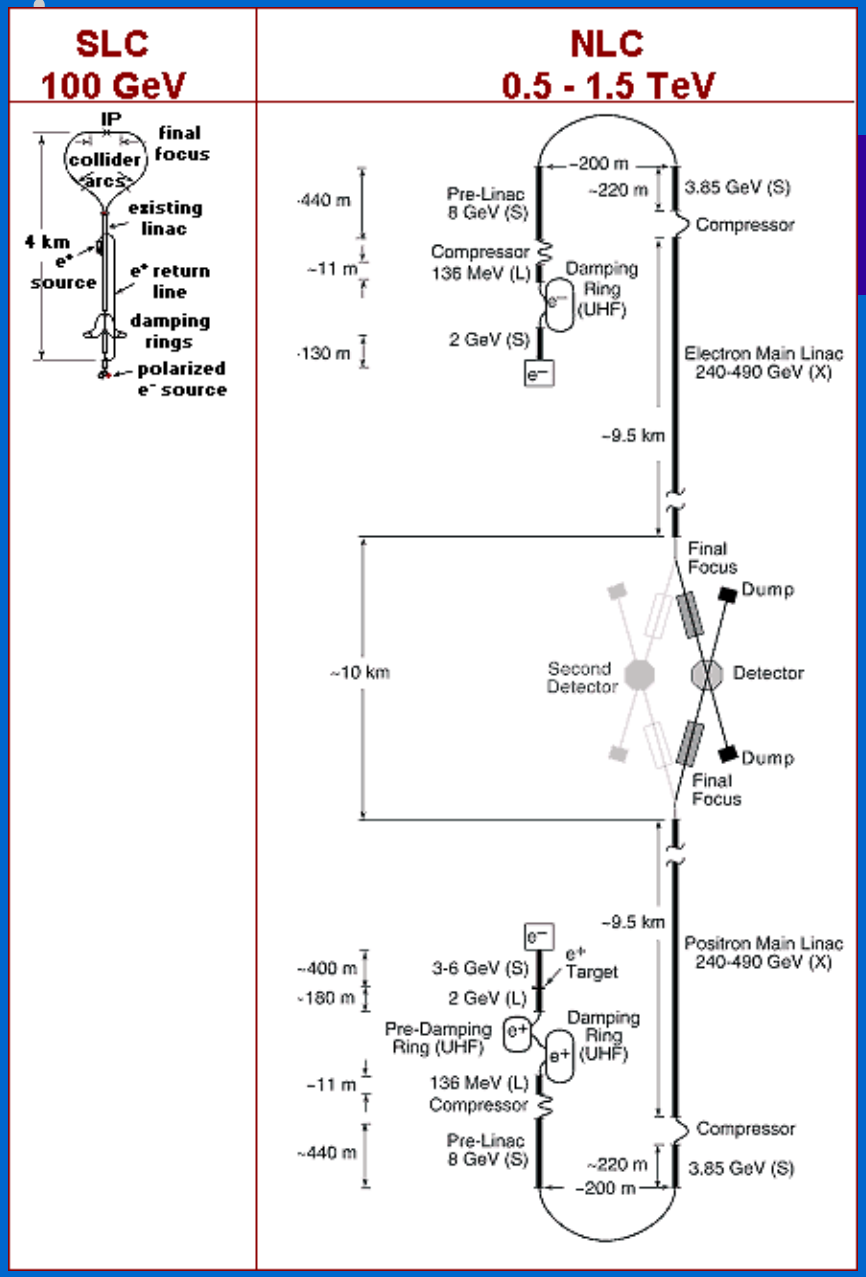
Recent Times ...

- **Physics Today** January 2001
  - Maury Tigner (Cornell University)
- Comparing hadrons and leptons
  - Constituent hadron collision energy is about 1/10 of total hadron beam energies
  - Constituent lepton collision energy is all of total lepton beam energies
- Leveling off? … yes … why?
  - It's a fact of life if you keep using the same concepts and evolve with the same basic technology



e^+e^- Linear Colliders

- The good new is:
  - The electron is a lepton
    - A point (so far as we can see)
    - Simple particles give simpler interactions
  - Precision tool (if you know where to look)
    - Q4: How is it that we see more matter than antimatter?
    - Q2: How does it all behave?
- The bad new is:
  - Not much mass …
    - radiates photons like crazy when you deflect them
    - (This is a good thing at Argonne … but a bad thing for e^+ e^-)



- The NLC is an e+e- Option.

(NLC = Next Linear Collider)

Two straight accelerators about 10 km long each providing 250 GeV beams.

- Several smaller (and rather complicated) accelerators and devices to feed them … 2 GeV, 3-6 GeV, positron target, 3.85 GeV, damping rings, compressors

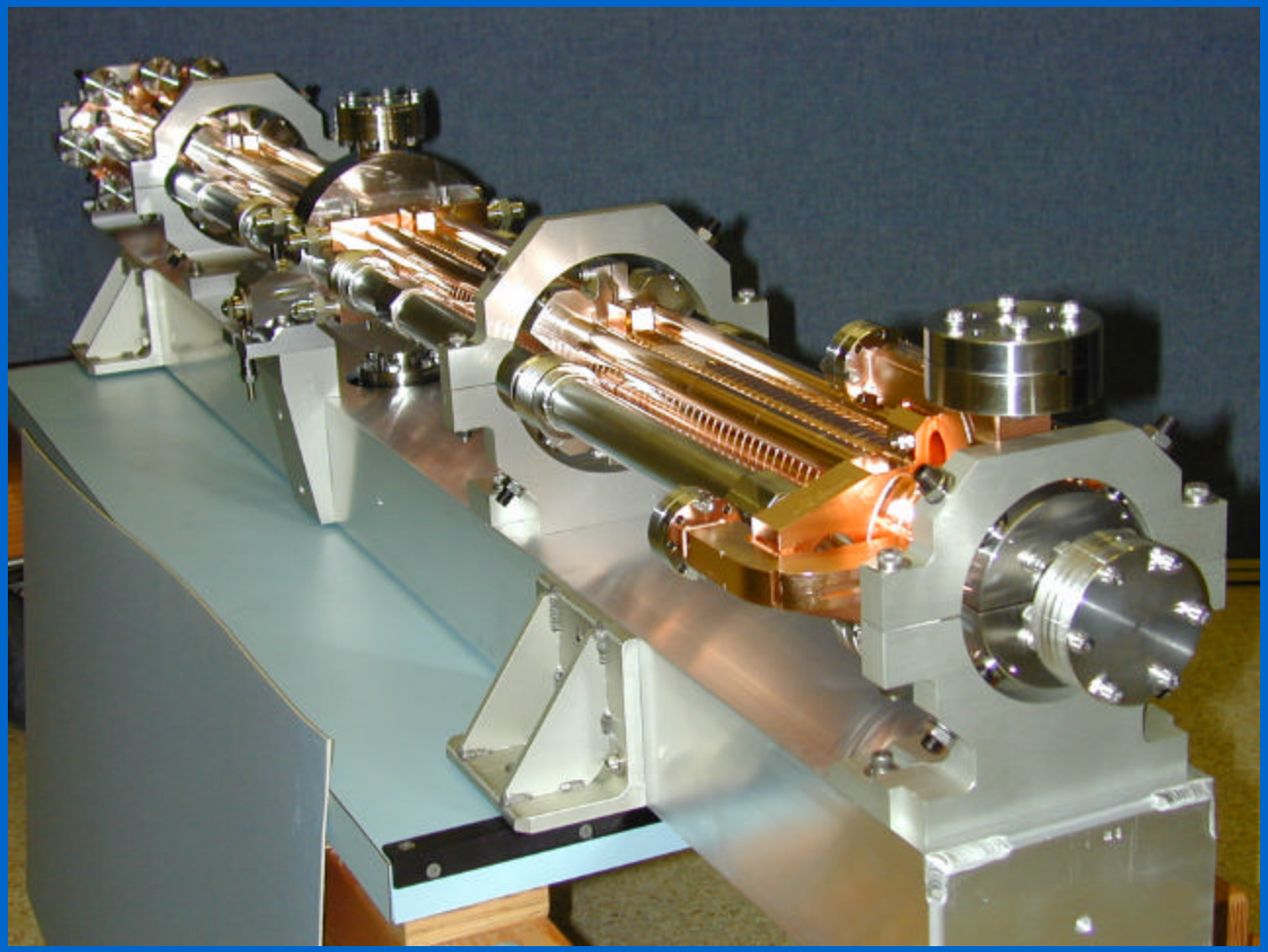
- A pair of final focus lines, a detector, and a beam dump.

- Total Length = about 30 km.

(SLC = SLAC Linear Collider)

(SLAC = Stanford Linear Accelerator Center)

1.8 meter long NLC RF structure

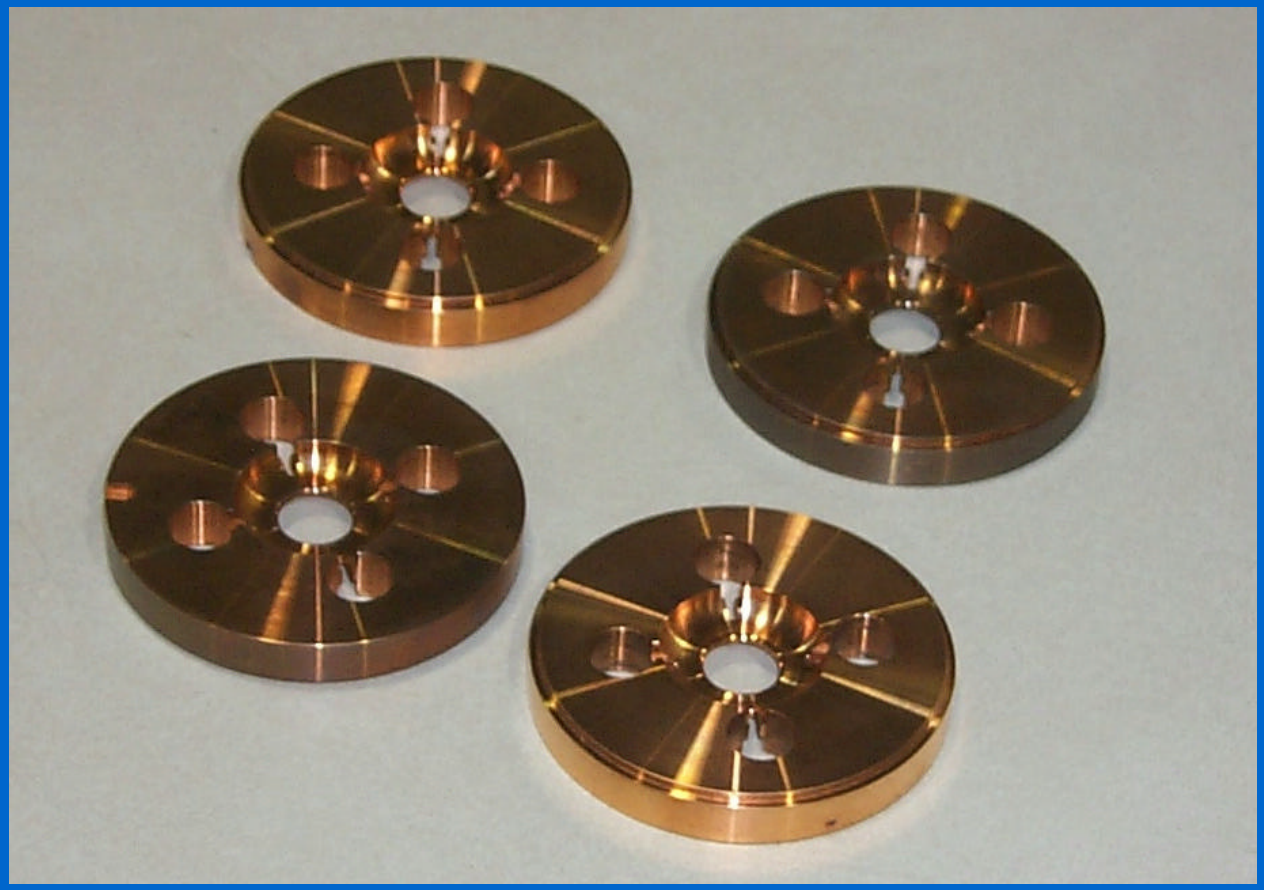


Made by the KEK lab in Japan and tested at the SLAC lab in California

Each structure has 206 disks … see next slide

NLC RF copper disks

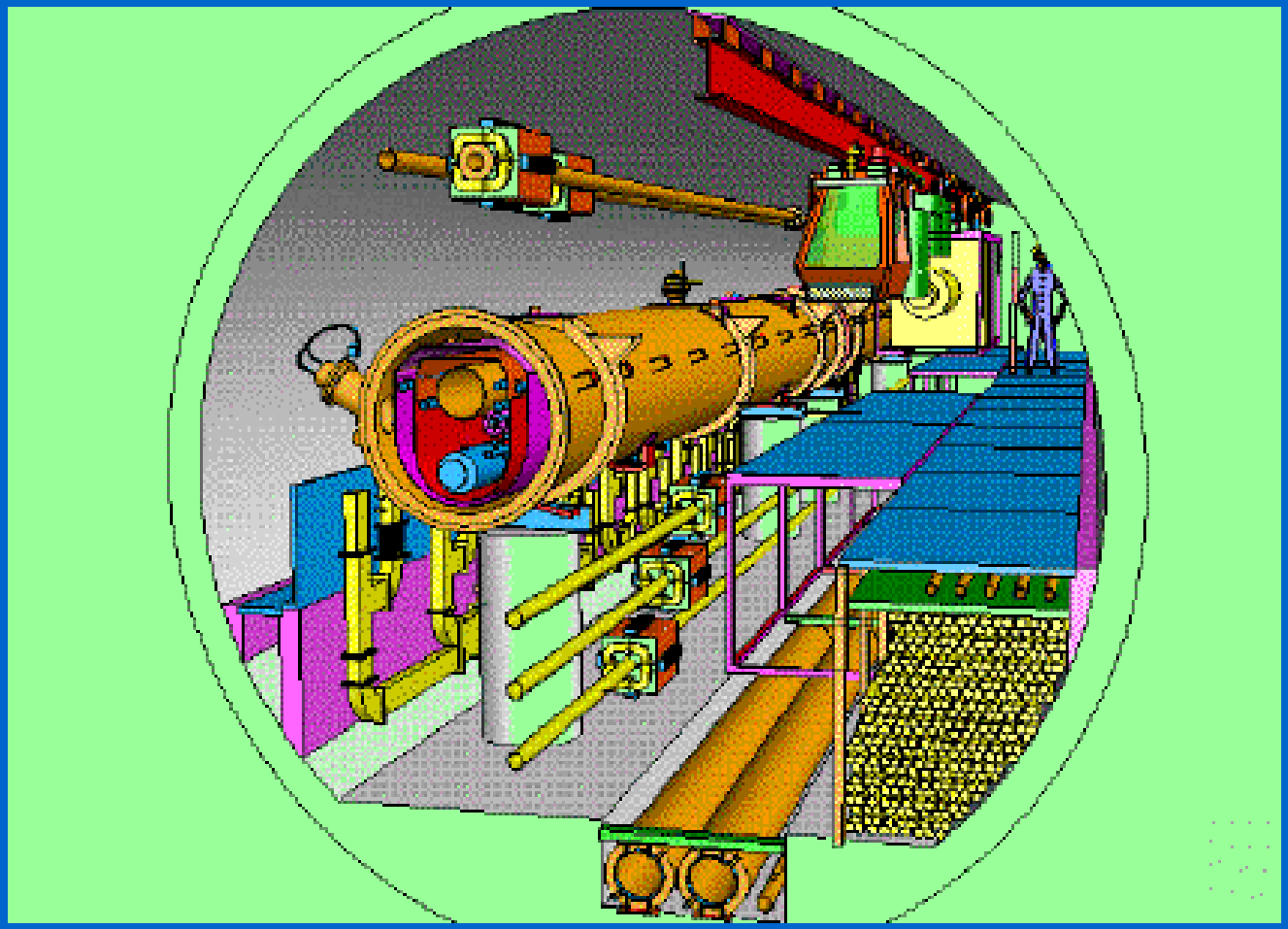
Each disk has a 61 mm outer diameter and 8 mm thickness.



The electron or positron beam goes through the center hole and unwanted energy is taken away in the four side channels.

TESLA at DESY is also an e^+e^- Option

(TESLA = TEv Superconcucting Linear Accelerator)



The DESY lab has proposed an e+e- collider.

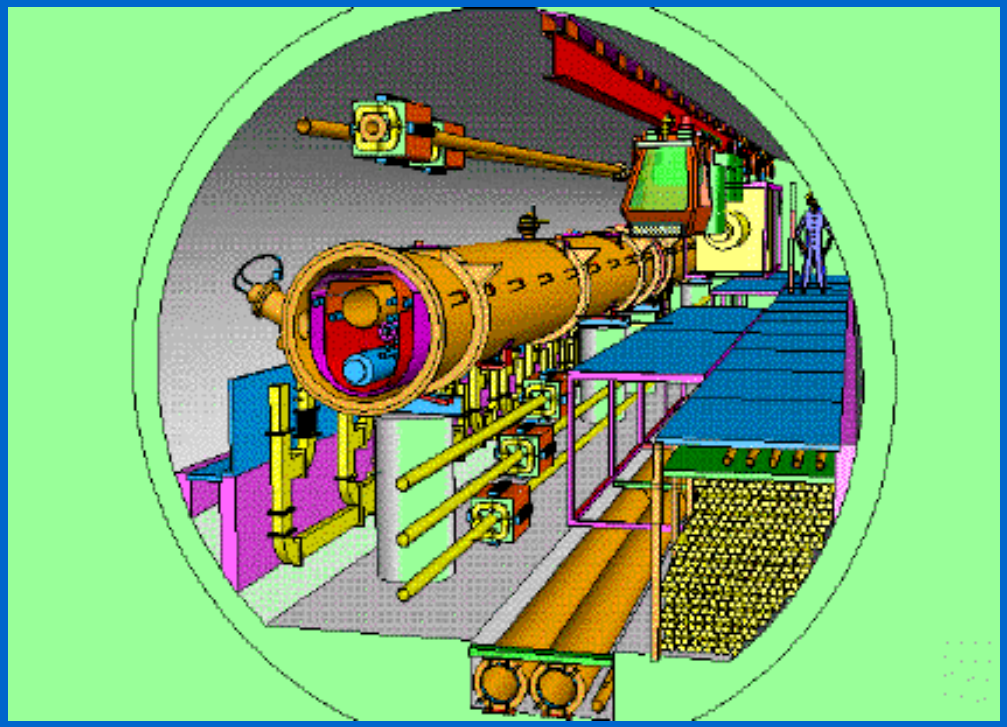
The accelerator is made of superconducting rf cavities.

The tunnel is about 5 meters in diameter.

TESLA & NLC Tunnel Sketches

TESLA Main Linac Beam Enclosure.

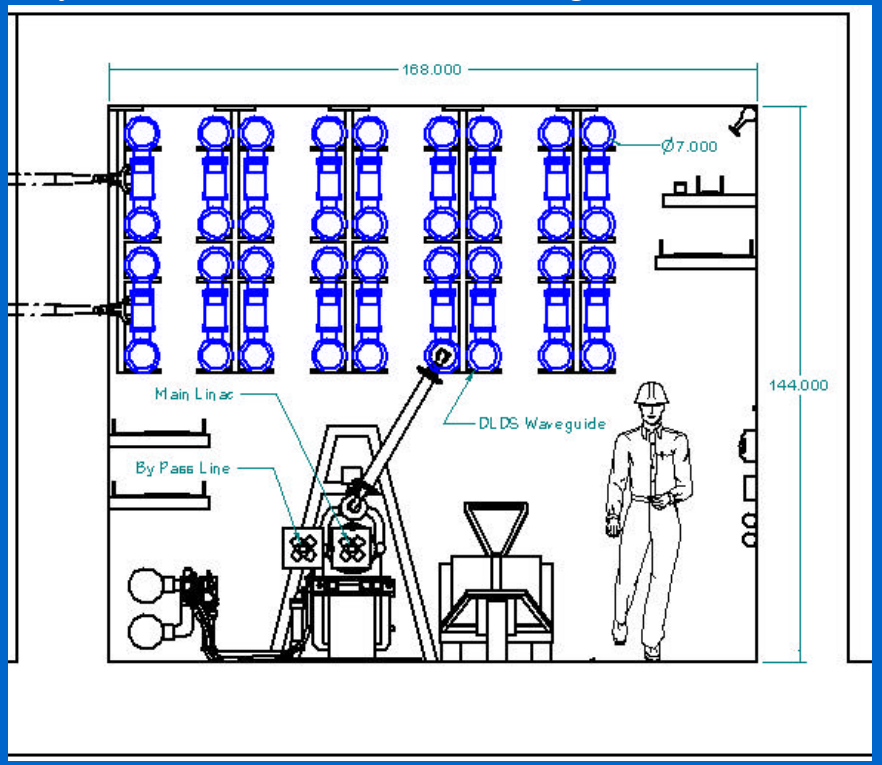
Modulator & refrigerator enclosures / buildings not shown.



Tunnel is 5.2 meter diameter

NLC Main Linac Beam Enclosure.

Klystron & modulator enclosures / buildings not shown.



Tunnel is 12’ high and 14 ft wide (3.66 m x 4.27 m)

Protons on protons

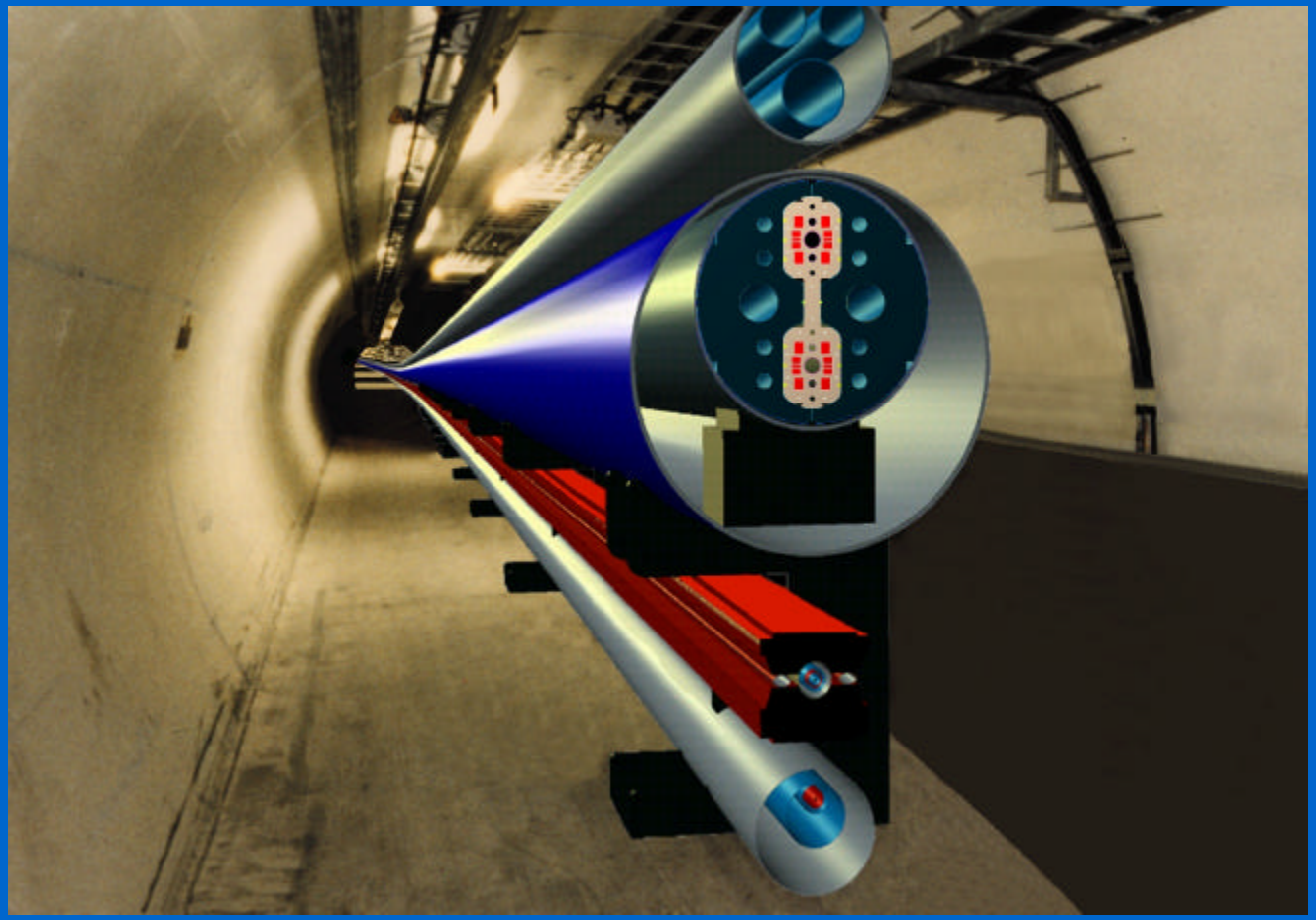
- The good news is:
  - We know how to do this … standard techniques
  - This gives us the energy frontier (about 100 TeV)
  - This is the path to discovery
    - Q1: What's it all made of?
    - Q2: How does it all behave?

- The bad news (if any) is:
  - It gets to be very large …(see later slides)
  - And some* say wait for LHC results at (14 TeV).

* "Some" include Directors of the world's HEP labs.

A Tunnel Vision for the VLHC

Both high and low field options are shown in the LEP tunnel as an example.



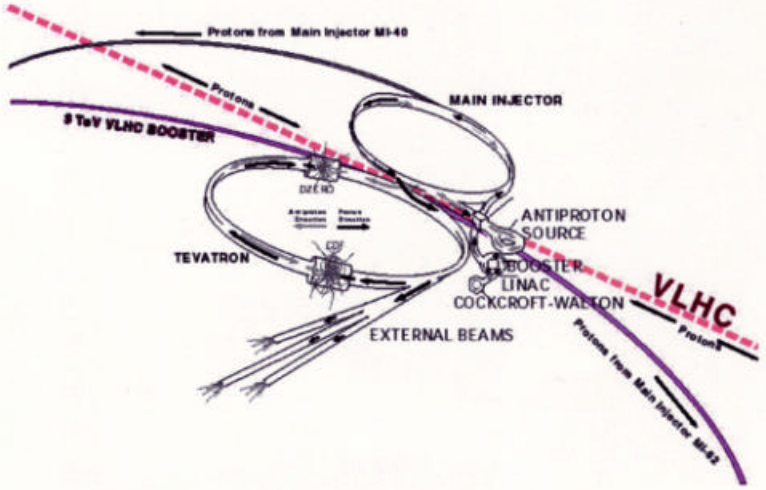
The low field is on the bottom, the high field is on the top.

The tunnel is real and is about 12 feet in diameter.

Comments on a U.S. site at Fermilab:
Geology and Tunneling

The U.S. site of the vlhc is assumed to be Fermilab.

- Existence of the injector chain
- Excellent Geology

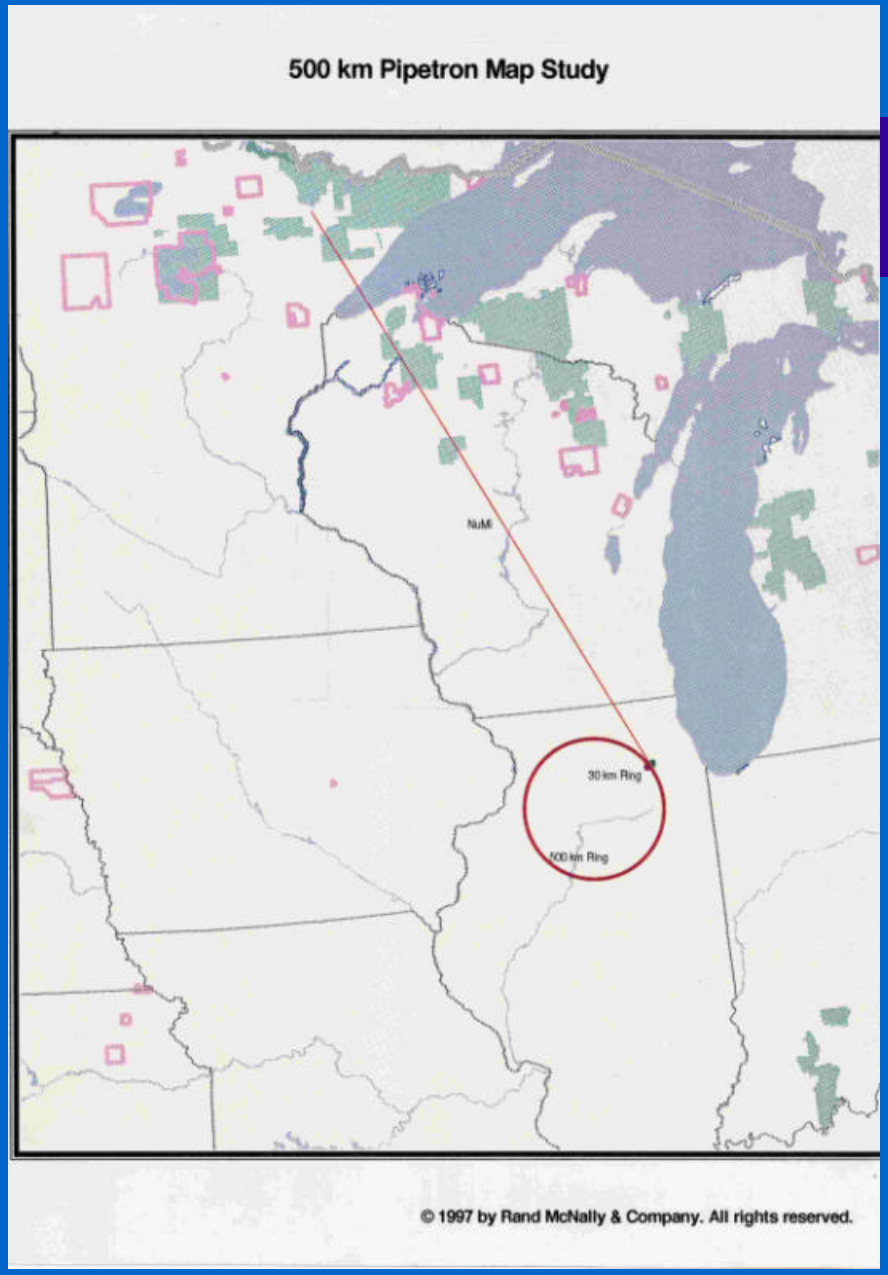


VLHC

Why put the VLHC at Fermilab?

Courtesy E. Malamud

malamud@fnal.gov



VLHC

Recall it is named “very large” for a good reason.

It would not really be “at Fermilab”.

Rather it would be under “Northern Illinois”

But the NuMI neutrino beam already will go from Fermilab to northern Minnesota.

(Yes, under Wisconsin!).

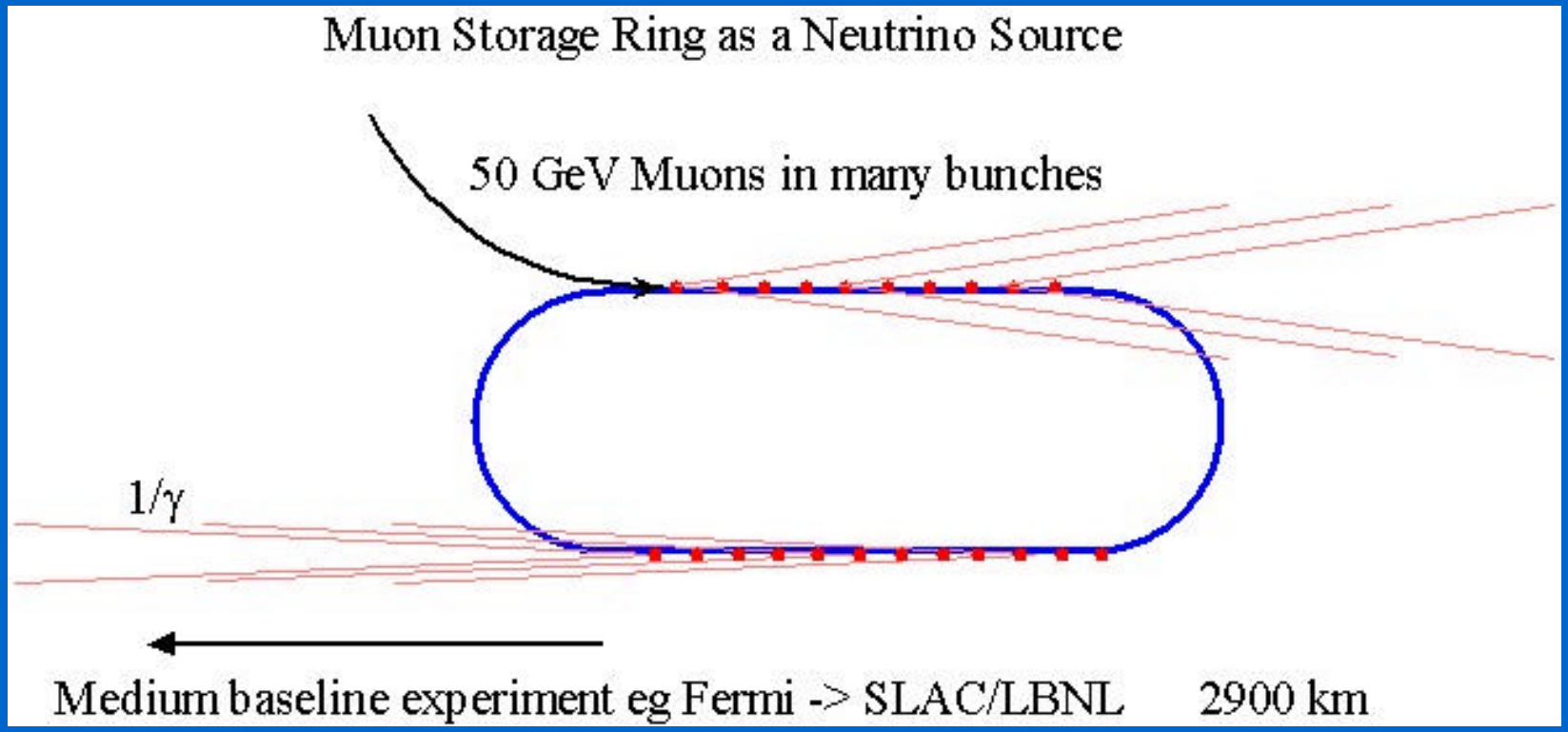
Courtesy E. Malamud
malamud@fnal.gov

Muons on Muons

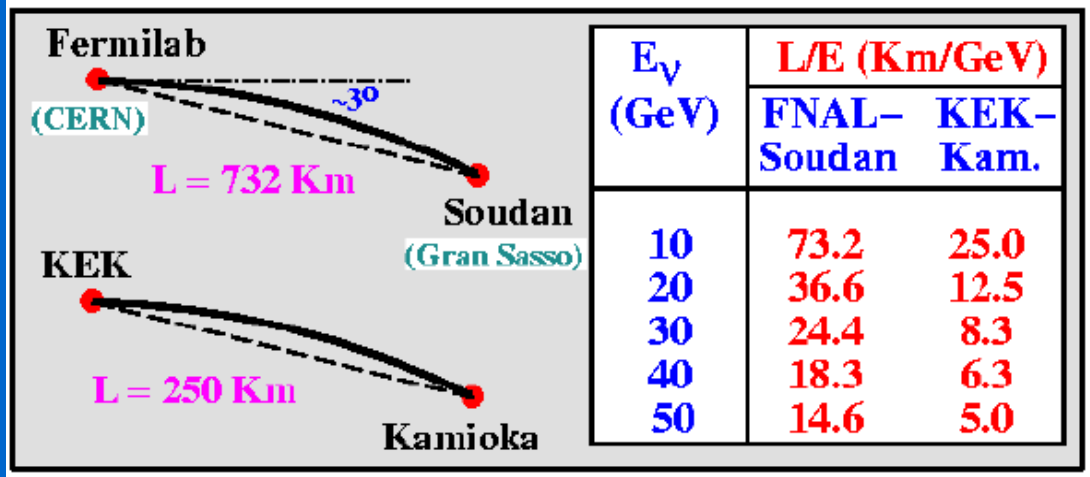
- The good news is:
  - Just another simple lepton … just like the electron
  - But heavier than the electron
    - They don't radiate photons like crazy
    - They interact better (40,000 times better) with Higgs
      - Q3: How do particles come by their mass?
- The bad new is:
  - They only stay around for 0.000 002 seconds (or so)
  - They spit out electrons … which then radiate like crazy
  - And they spit out neutrinos … hmmm …
  - Is this short lifetime so bad?
  - Can it be used to our advantage? >>> See next slides …

Neutrino Factory

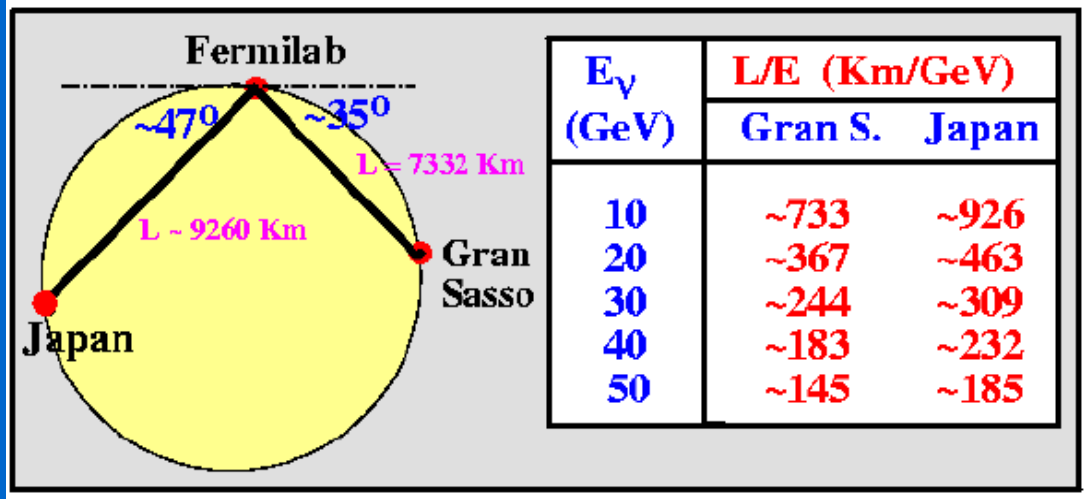
Concept



	L (km)	Dip (Deg.)	Heading (Deg.)
FNAL –> Soudan	732	3	336
FNAL –> Gran Sasso	7332	35	50
FNAL –> Kamioka	9263	47	325



E_ν (GeV)	L/E (Km/GeV) FNAL–Soudan	L/E (Km/GeV) KEK–Kam.
10	73.2	25.0
20	36.6	12.5
30	24.4	8.3
40	18.3	6.3
50	14.6	5.0



E_ν (GeV)	L/E (Km/GeV) Gran S.	L/E (Km/GeV) Japan
10	~733	~926
20	~367	~463
30	~244	~309
40	~183	~232
50	~145	~185

Neutrino Factory

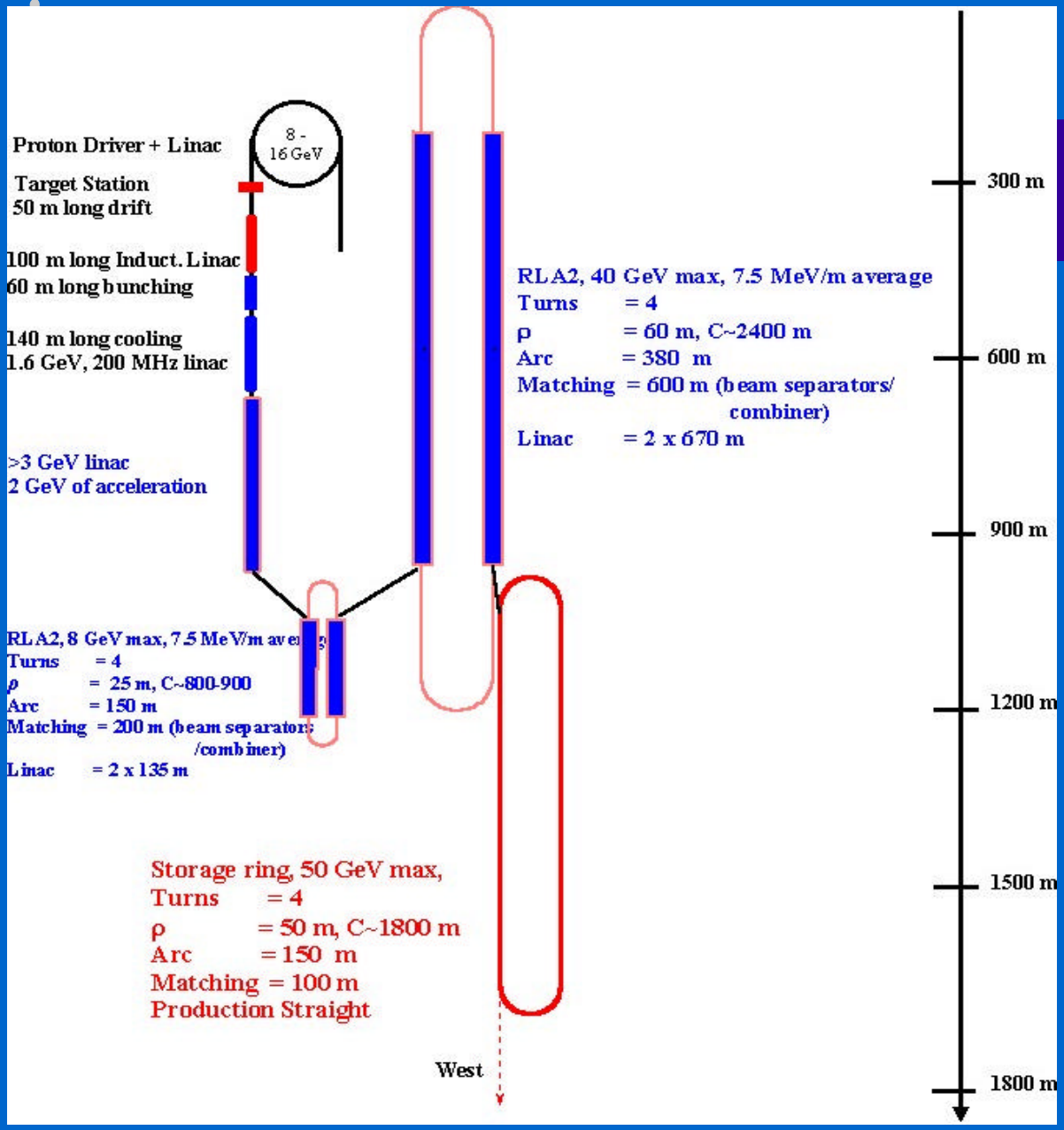
Physics Guidance.

The Distance L between the Neutrino Source and Neutrino Detector is important.

And so is the ratio of L to the Energy E of the neutrino beam.

Courtesy S. Geer

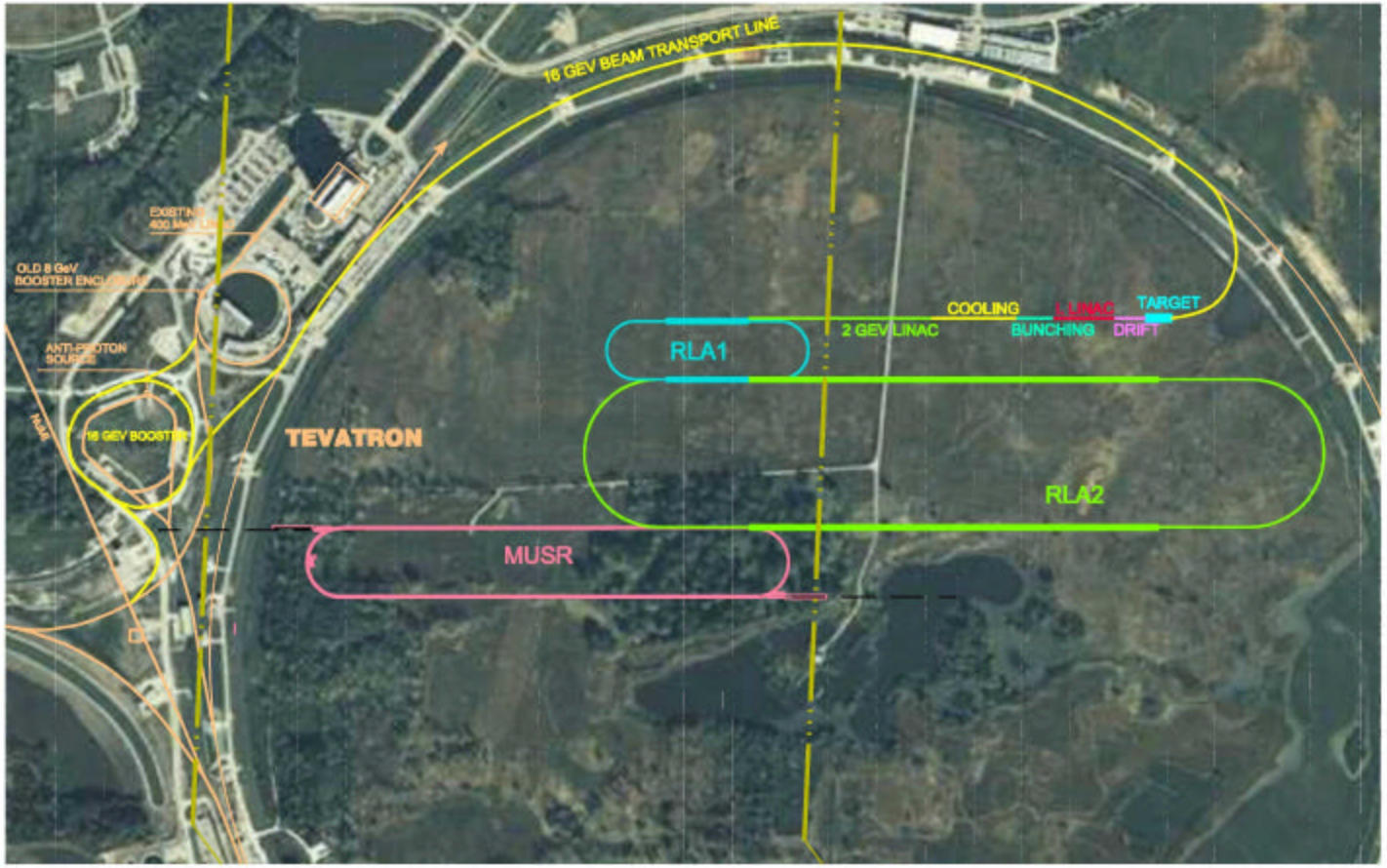
Neutrino Factory



Layout.

It takes a lot of things to feed it, but all together it is not so very large.

A Neutrino Factory at Fermilab



Neutrino Beam

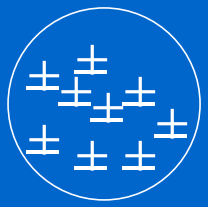
- The good new is:
  - All the muons decay to electrons and neutrinos
  - Never been done … surprises probably in store
    - Q1, Q2, Q3, Q4, Q4++
- The bad news is:
  - Not discovery, not simple … So, maybe not “interesting”?
- Aside: Really global-sized experiments

And Into the Beyond ...

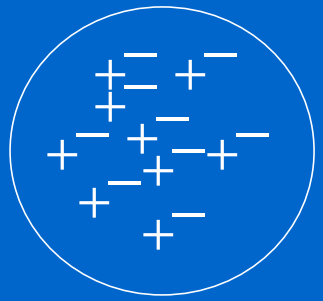
- The good new and the bad new is:
  - Hasn't been done before …
  - For good reasons, usually ...
- One example is Plasma acceleration
  - 100 TeV center of mass … and ...
  - All the equipment fits on the Fermilab site
  - But is costs too much to operate …
  - At least … using today's ideas and technology

Plasma

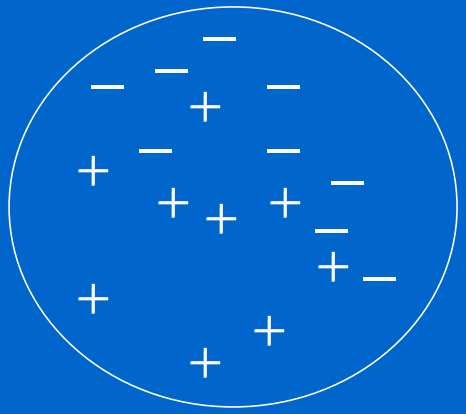
- How is it made?



Start with Atoms

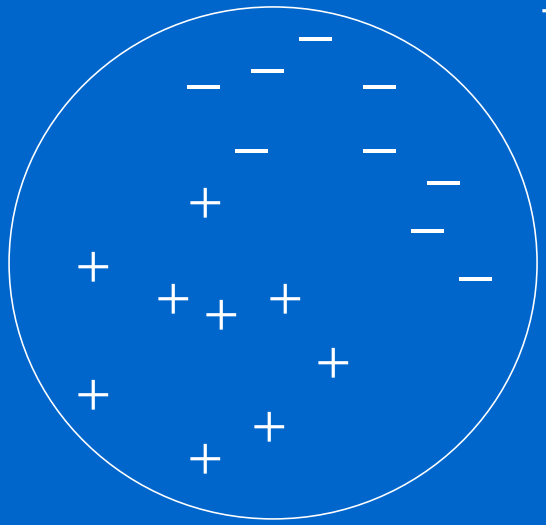


Pull Them …



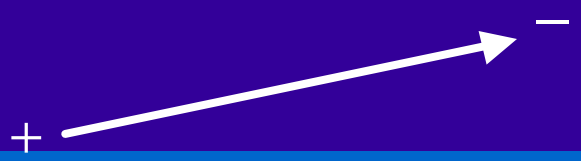
Pull Them …

Ideal (but highly unstable)



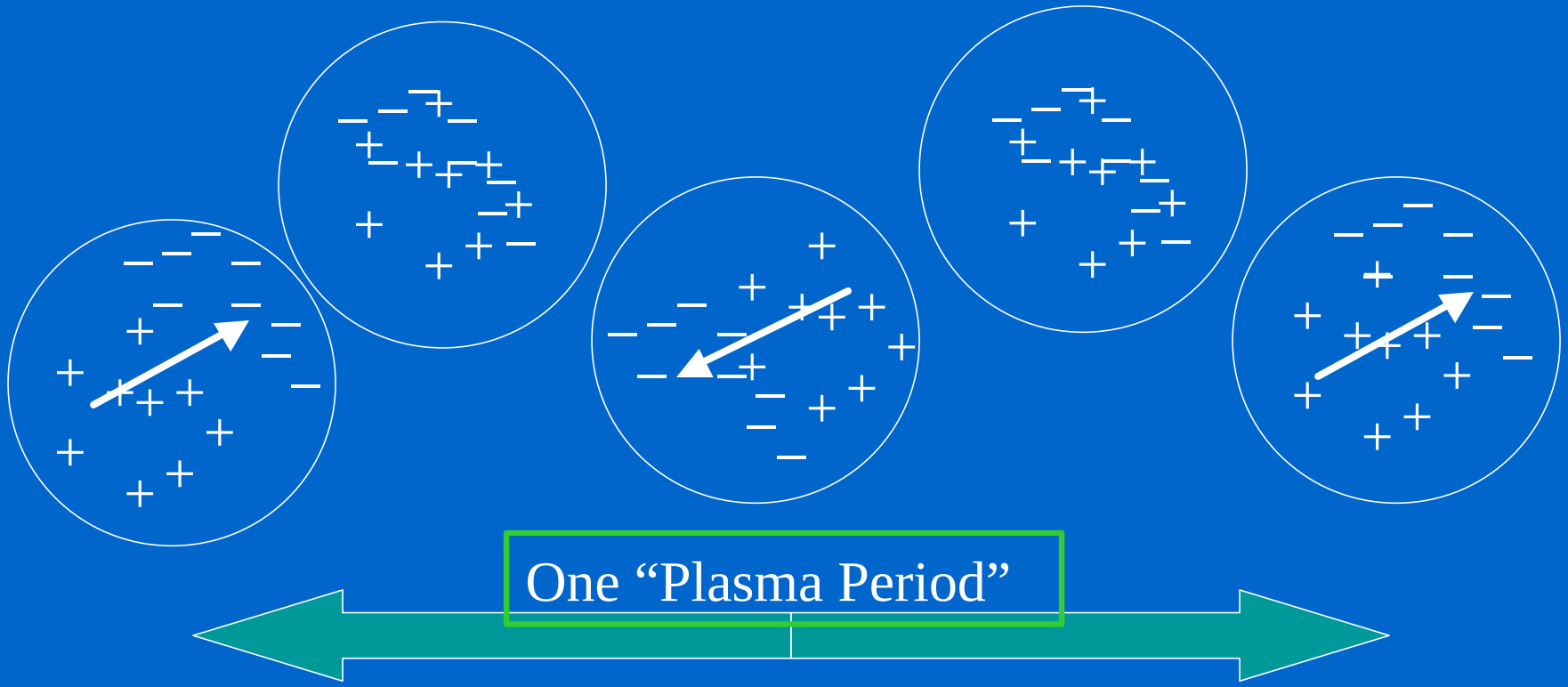
Pull Them Apart!

Plasma

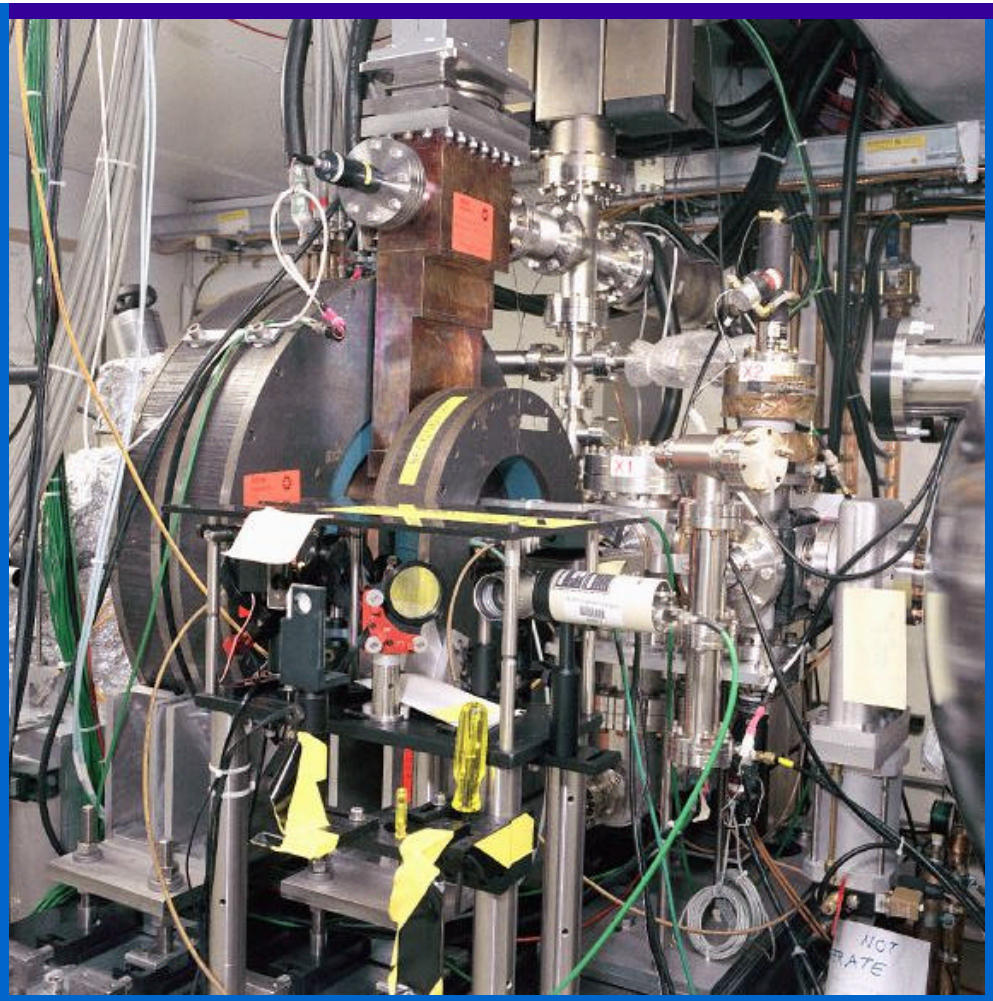


Electric Field

- How does it act?



A0 Photoinjector at Fermilab

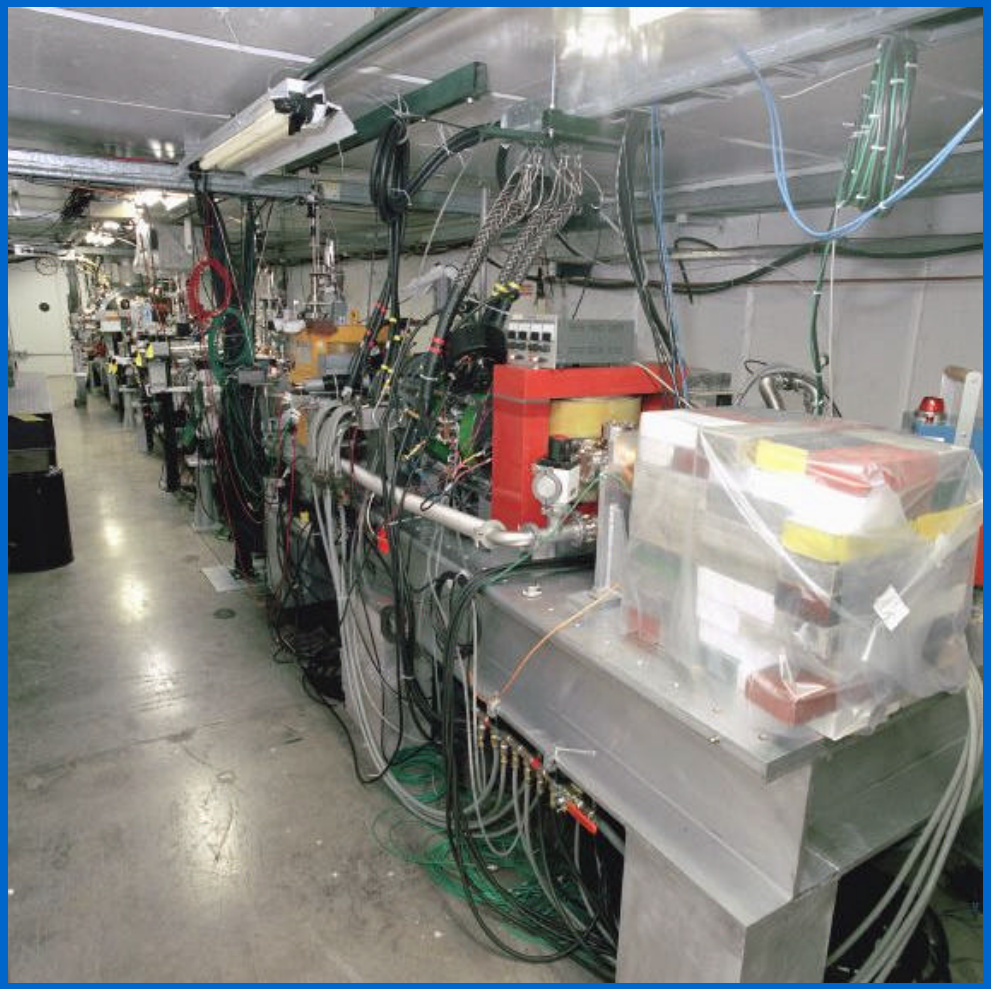


RF Gun and focussing solenoids

NIU (Northern Illinios University) is heavily involved with this project, with Department of Education funds.

http://www-ap.fnal.gov/A0PI/a0pics.html

A0 Photoinjector at Fermilab



Spectrometer magnets, plasma chamber, and beam dump

http://www-ap.fnal.gov/A0PI/a0pics.html

Summary

- This is still fun.
  - Q1: So what IS it all made of? and
  - Q2: How DOES it all behave? etc etc
- There is still lots to do.
  - Decades (in performance and on calendars)
  - The best ideas are yet to come ...

That's It From Me ...

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SHOW AIRS: MON 7/12 at 930am CT

Your Host: David Finley
finley@fnal.gov