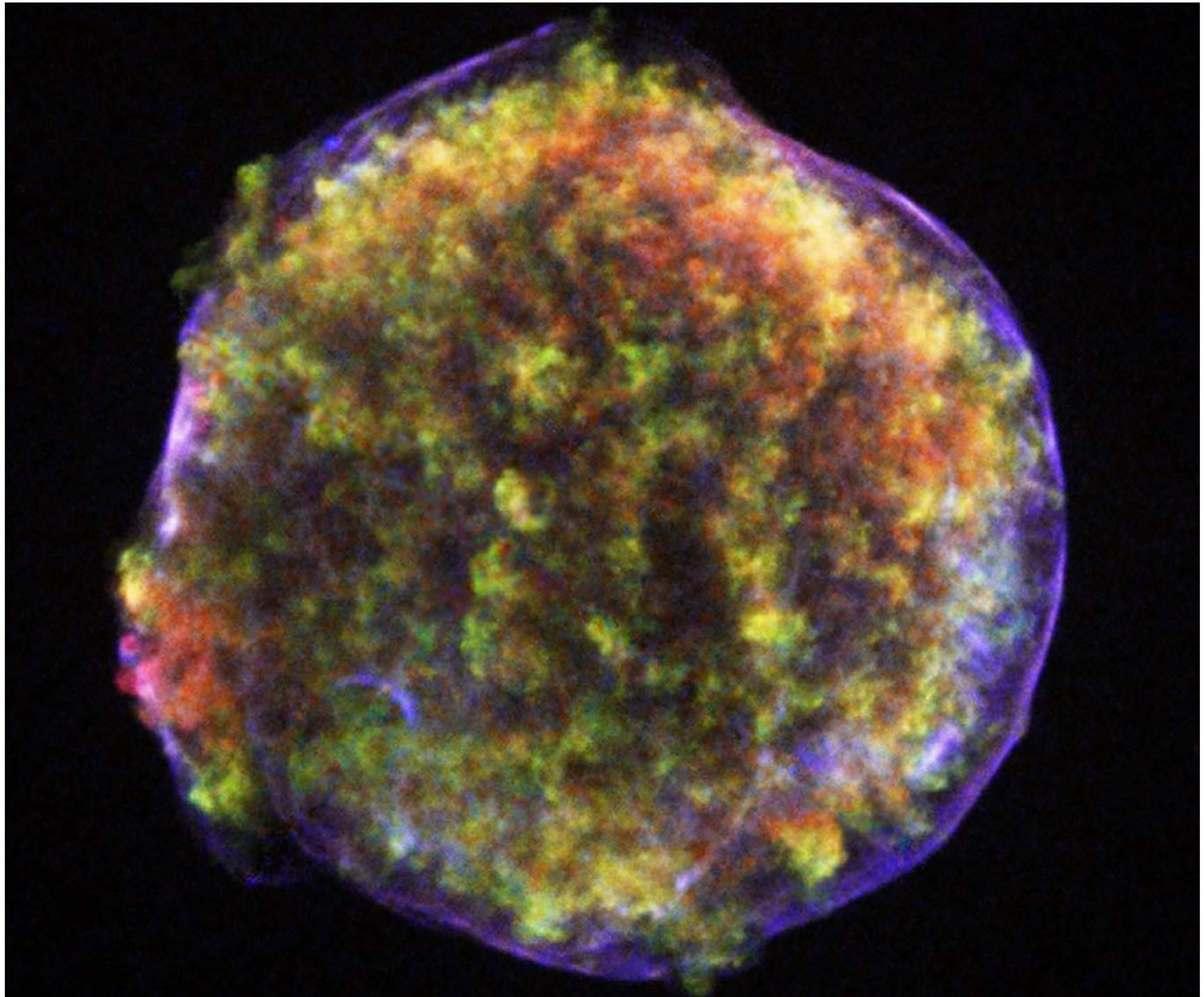


# Man-Made Accelerators (Earth-Based)

Ron Ruth  
SLAC



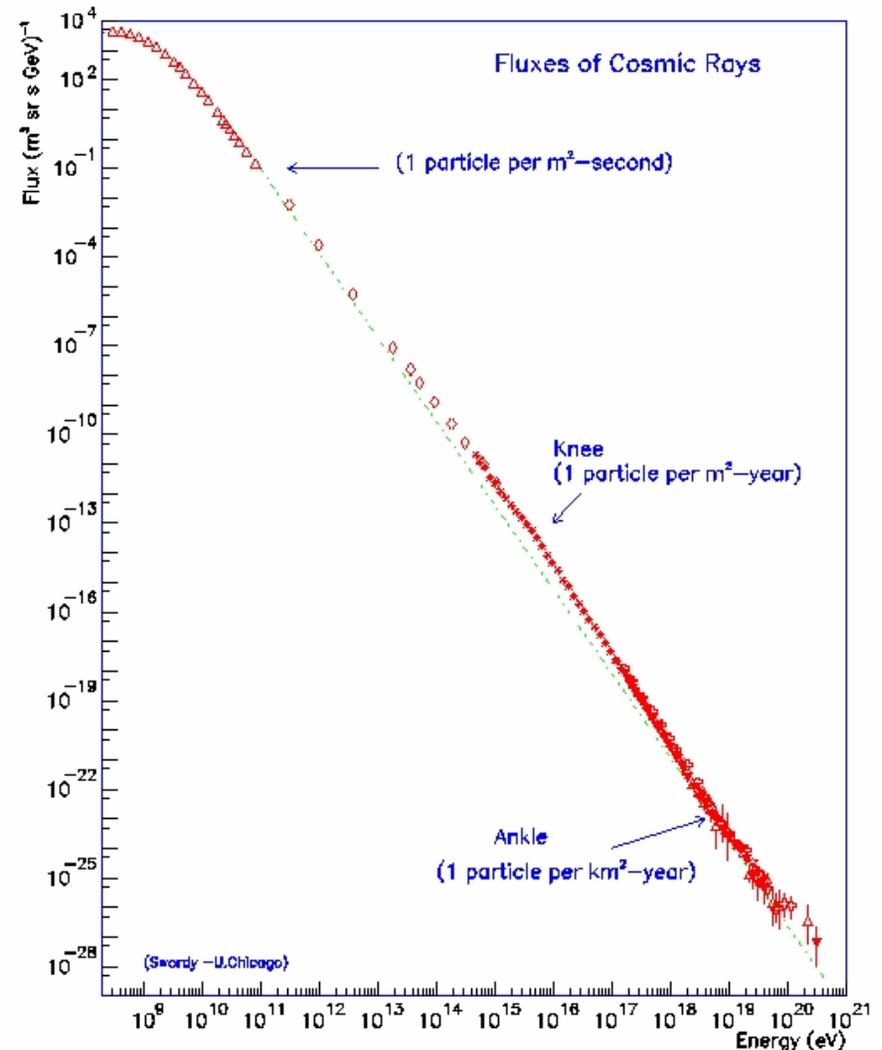


# Outline of Talk

- Introduction
- History of Particle Acceleration
- Basic Principles
  - What are the forces?
  - Acceleration and radiation
  - Synchronism
  - Basic device ideas, linear circular
  - Beams and physics
  - Storage ring colliders
  - Electron Linear Accelerators
  - The next window: linear colliders
- The present generation
  - Storage Ring Factories
  - LHC
  - Linear colliders: ILC
- The next generations
  - Two beam colliders
  - Laser acceleration
  - Plasma acceleration
  - Muon colliders

# Cosmic Ray Spectrum

- OK, OK, so our beam so our energy is a bit lower than yours.
- Only TeV scale now.
- But we have got you with flux, if not energy.
- More on that later.

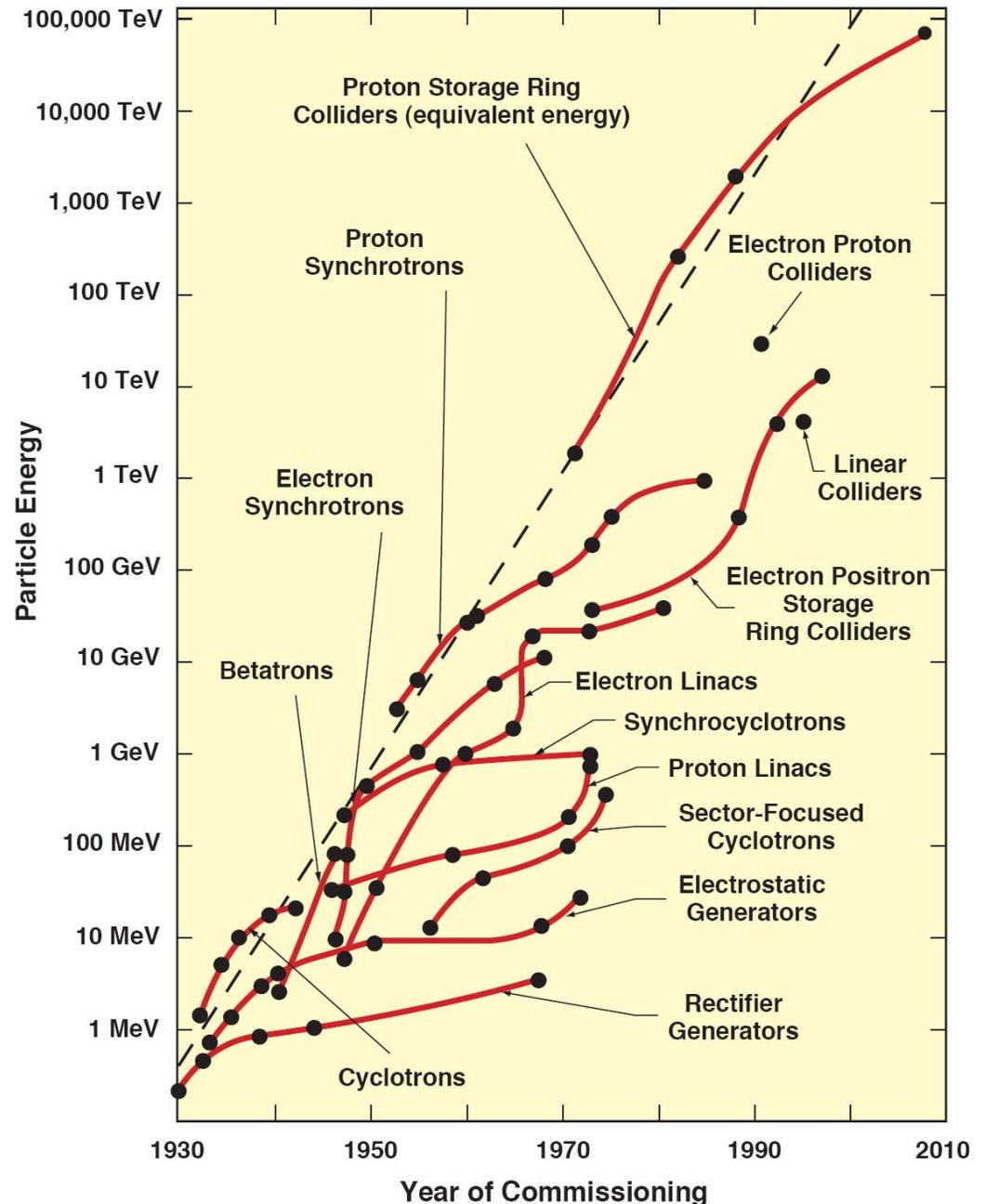


# From 'The Evolution of Particle Accelerators and Colliders' by Wolfgang K. H. Panofsky

“**WHEN J. J. THOMSON** discovered the electron, he did not call the instrument the was using an accelerator, but an accelerator it certainly was. He accelerated particles between two electrodes to which he had applied a difference in electric potential. He manipulated the resulting beam with electric and magnetic fields to determine the charge-to-mass ratio of cathode rays. Thomson achieved his discovery by studying the properties of the beam itself—not its impact on a target or another beam, as we do today. Accelerators have since become indispensable in the quest to understand Nature at smaller and smaller scales. And although they are much bigger and far more complex, they still operate on much the same physical principles as Thomson’s device.” [1897]

# Livingston Chart

- Graph of concepts
- Points are devices
- Energy is plotted in terms of the laboratory energy when colliding with a proton at rest to reach the same center of mass energy.
- **From: The Evolution of Particle Accelerators & Colliders by W. K. H. Panofsky**
- *Lots of people use this picture.*



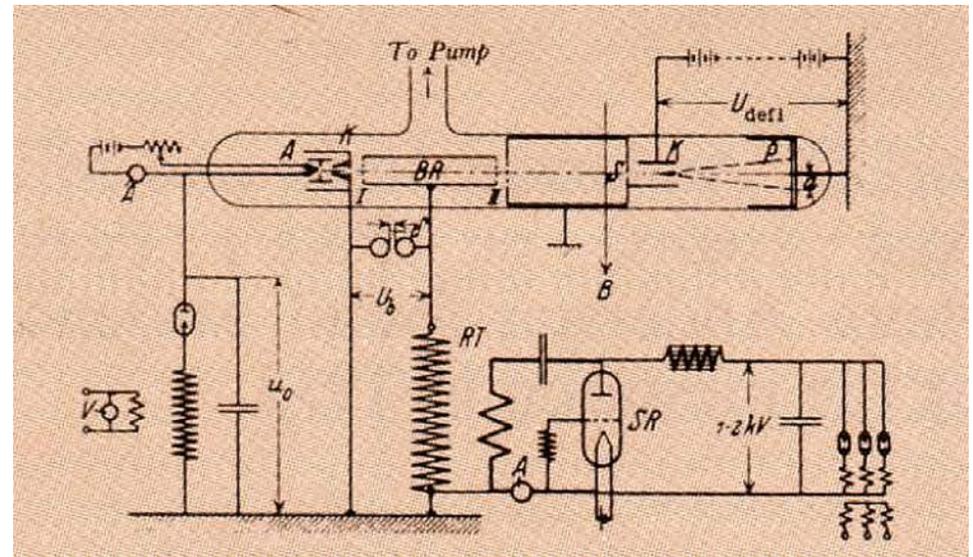
# The birth of an era

- 1919: Ernest Rutherford discovered nuclear disintegration by bombarding nitrogen with alpha particles from natural radioactive substances.
- Later he called for “a copious supply” of particles more energetic than those from natural sources.
- The particle accelerator era was born.



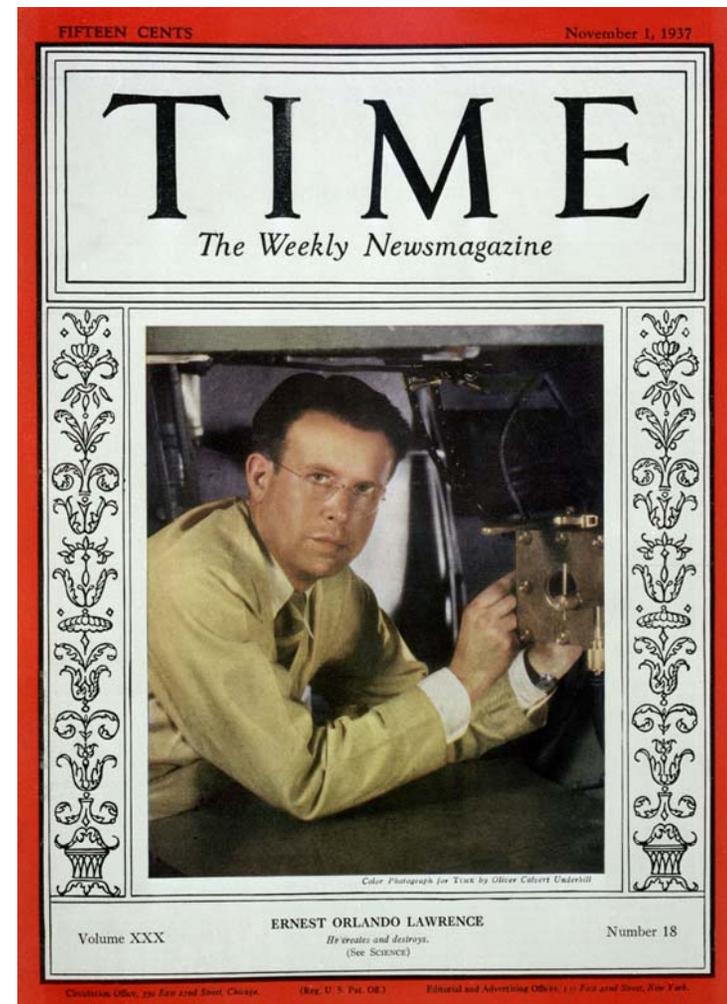
# World's first accelerator

- 1924: Gustav Ising develops the concept of a linear particle accelerator (linac).
- Four years later, Rolf Wideröe builds the world's first linac in an 88-cm long glass tube in Aachen, Germany.



# Cyclotron

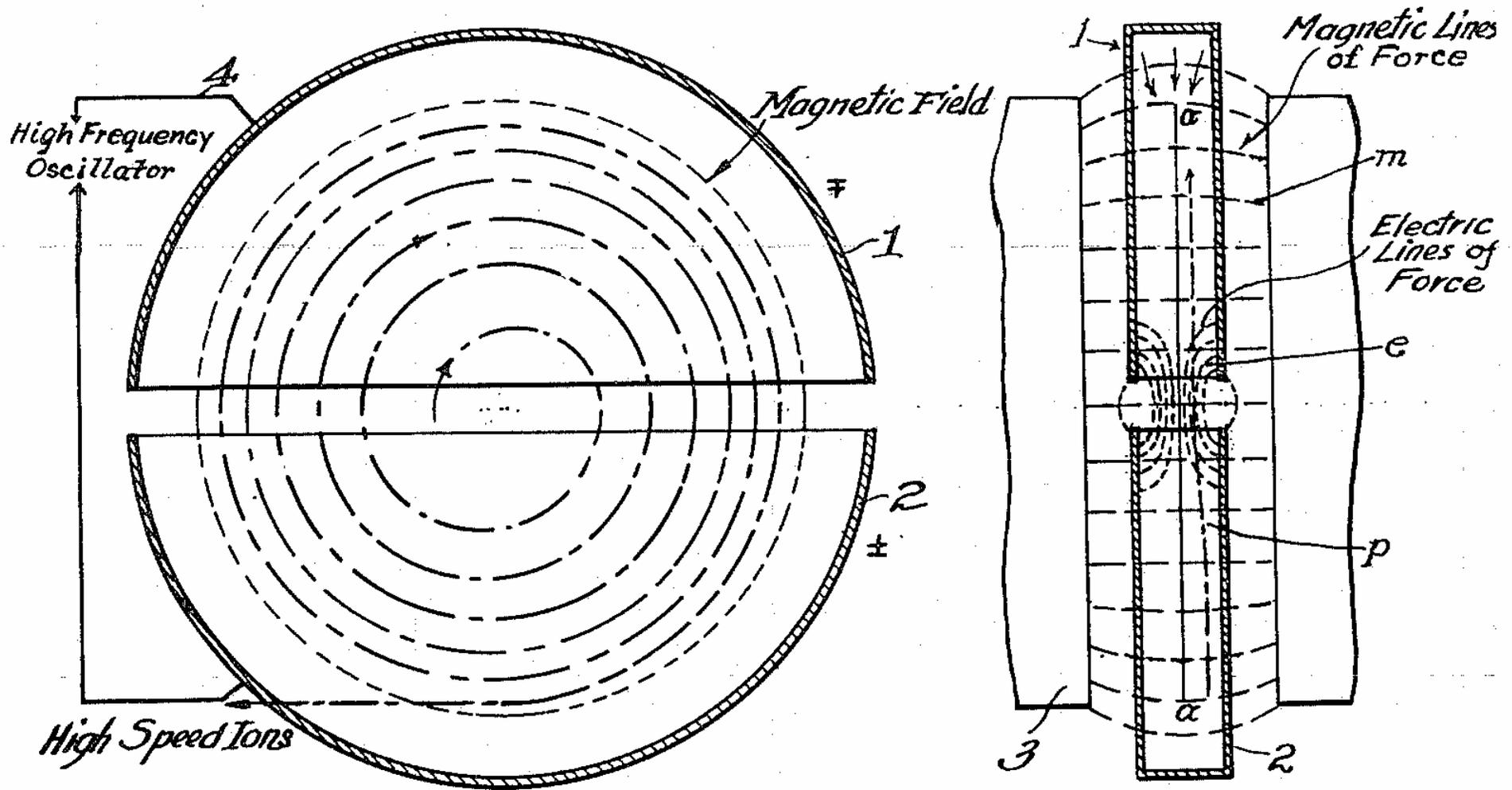
- 1930: Ernest Lawrence invents the cyclotron at the University of California, Berkeley.
- He and his student Stanley Livingston build a cyclotron only 4 inches in diameter.



# Acceleration and Bending

- All accelerators use only the electromagnetic force for bending and acceleration.  $\frac{d\vec{p}}{dt} = e(\vec{E} + \vec{v} \times \vec{B}),$
- Energy change is due only to the electric field on the trajectory parallel to the velocity vector.
- Magnetic fields are used for bending beams.

# Diagram of cyclotron operation from Lawrence's 1934 patent.



# Introduction to Acceleration and Beams

- Two key themes in particle accelerator physics and technology.
- High center-of-mass energy
  - Stimulated and stimulates the invention of new methods of acceleration and new technologies.
  - Stimulated the transition from fixed target devices to colliding beam devices.
- High Event Rate: High Luminosity
  - Stimulates the physics of particle beams.
  - Event Rate = L x (physics cross section)

$$L = \frac{N_1 N_2 f_{rep}}{X \text{ sec Area}}$$

# High Center of Mass Energy

- Straight line acceleration: Linear Acceleration (Linac)
  - High Acceleration Gradient,  $G$  (MV/m)
  - Get it done all at once.
  - Scale set by desired energy and gradient
    - $L \sim E_{cm}/G$
- Circular Acceleration:
  - Accelerate in one or a few locations, but bend the particles back to those locations.
  - Scale set by Momentum and Magnetic Field
    - $L \sim P_{cm}/B$
- $L$  is set by \$, politics, available space, size of earth.
- $E_{cm}$  has always grown based on understanding physics
- $G$ ,  $B$  set by physics, technology and \$

# High Luminosity

- In order to accelerate on the Earth inside an accelerator, we need to form beams of particles.
  - In the old days, this was motivated by keeping the particles inside the accelerator.
  - The event rate for a fixed target does not depend upon the size of the beam, just that it hits the target in roughly the right location.
  - Nowadays this has a big influence on the luminosity.
  - Colliding beams are colliding nonneutral relativistic plasmas.
  - Need to eliminate the empty space.
- Begins with the concept of a design orbit (circ) or trajectory (Linear)
- The beam needs to be near this orbit or trajectory all the time and throughout the length of the device.
  - Thus, the beam size should be small, and the angular divergence (transverse momentum) should also be small.
  - It also matters when the particles arrive at a particular point in space, in many cases the beam is really a bunch with some length.
  - It is also important that the beam be nearly a single energy, so the energy spread should be small.

# High Center of Mass Energy

- High Gradient: for linear accelerators/colliders
  - Need to respect physics limits: breakdown
  - Need to get energy to the beam: Power source
  - Need efficiency
  - Technologies:
    - Klystrons (power sources)
    - High frequency accelerators—High Gradient
    - Superconducting accelerators.
- High Magnetic Field: for circular accelerators/colliders
  - Technology: Superconducting Magnets

# Colliding Beams vs Fixed Target

- For colliding beams of the same energy, the CM is the lab and  $E_{cm} = 2E_{beam}$
- For a fixed target particle mass  $m_t$  illuminated by a highly relativistic beam of energy  $E_b$ .

$$E_{cm} = \sqrt{2E_b m_t c^2}$$

- The switch to colliding beams was necessary to get away from the  $E_b^{1/2}$  dependence.
- This 'free' energy had significant consequences for the required beam quality.

# Particle Beams

- So think of a reference particle defining the reference trajectory or orbit and the reference time (or phase).
- The beam deviates from this particle.
  - $\Delta p_x, \Delta x, \Delta p_y, \Delta y, \Delta E, \Delta t$ , You may think of these as rms values.
  - There is a distribution in this 6 dimensional phase space.
  - Units of the volume = action<sup>3</sup>
  - As the beam is accelerated, the volume is invariant (at best).
- Usually divide momenta and energy to get relative values.
  - During acceleration, the relative volume decreases, angles get smaller and relative energy spread get smaller (ideally).
  - The quantities  $(\Delta p_i \Delta x)/p$  are called the emittances of the beam.
  - The density of the beam in this phase space is called the brightness or brilliance, depending upon who you talk to.
- Bright beams yield high luminosity and event rate.

# Transverse Motion

- A set of particles can be formed into a beam which is in the neighborhood of some design orbit or trajectory by having external fields which confine all particles to that neighborhood.
- For relativistic particles it is useful to use magnetic fields to do the bending.
- First consider a uniform bending field.
- Then integrating the force equation we find

$$\theta = \frac{e}{p_0} \int_{s_1}^{s_2} B dl = \frac{1}{B\rho} \int_{s_1}^{s_2} B dl$$

- The quantity “ $B\rho$ ” is the magnetic rigidity of the beam.
- This is easy to motivate by continuing the integral all the way around a circle.

$$\oint B dl = 2\pi p_0/e = 2\pi B\rho$$

- This is also familiar from the cyclotron frequency of a particle in a uniform magnetic field.

$$\omega_0 = \frac{eB_0}{\gamma m}$$

# Betatron

- 1940: Donald Kerst at the University of Illinois constructs the first betatron, which had been proposed by Joseph Slepian and others in the 1920s.
- The Betatron uses magnetic induction to accelerate the beam.
- A changing magnetic field induces an electric field on the orbit of the particle.



# Synchrotron

- 1943: Marcus Oliphant develops the concept for a new type of accelerator, later named the synchrotron by Edwin McMillan.



# Synchrotron Principles

- Cyclotron: constant magnetic field and a constant-frequency applied electric field (one of these is varied in the synchrocyclotron).
- Synchrotron: both of these fields are varied. By increasing the magnetic field and sometimes the frequency of the applied electric field, as the particles gain energy, their path can be held constant as they are accelerated. Provided that there is synchronism between the particle revolution frequency and the accelerator field, the beam accelerates and the magnetic field is increased. Phase Stability keeps the bunches of particles together.
- In modern synchrotrons using strong focusing, this allows the vacuum chamber to be small and the magnets to be small in volume.
- Can divide the circumference into bending, focusing and some sections for acceleration.

# Phase stability

- 1944: Vladimir Veksler at the Lebedev Institute of Physics and later Edwin McMillan at the University of California, Berkeley, independently discover the principle of phase stability, a cornerstone of modern accelerators.
- The principle is first demonstrated on a modified cyclotron in 1946 at Berkeley.



# RF Systems for Acceleration

- RF structure or cavity.
  - The RF structure or cavity is a resonant cavity which supports the driving RF frequency. In storage rings it is typical to use a standing wave cavity, or several of them coupled together. For a long linac it is common to use traveling wave structures.
  - In the case of proton linacs the design and typically the frequency changes as the beam accelerates, because the velocity of the particle changes which changes the transit time across the cavity and also the time from cavity to cavity.
  - In the case of electron linacs, the initial part of acceleration is a specific design to deal with the lower velocity, while the later acceleration sections are for speed of light particles.

# The Simple Pill Box Accelerator

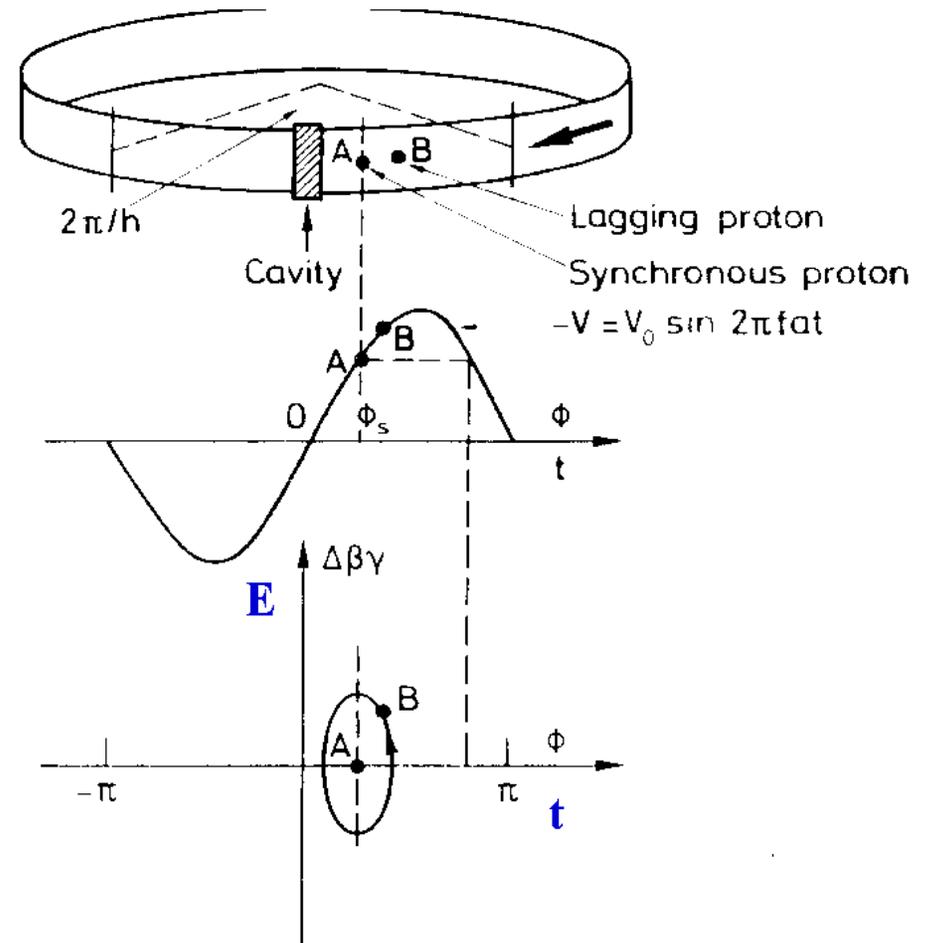
- It is useful to consider a model problem which is a cylinder of finite length with end plates, this is called a pill box.



- The fields supported in this type of cavity can be approximated if the hole is very small by the fields for the cylinder.
- The accelerating field varies sinusoidally.
- The beam must arrive at the cavity synchronized with the field.
- If the particle is close to correct, then Phase Stability will insure that it oscillates about the ideal phase.

## Phase stability

- Phase stability is a key to continuing acceleration.
- If the Magnetic field is increasing slowly, the beam on the average gains energy.
- Those particles with too much energy arrive at a phase to get less.
- Those particles with too little arrive at a phase to get more.



# Transverse Stability

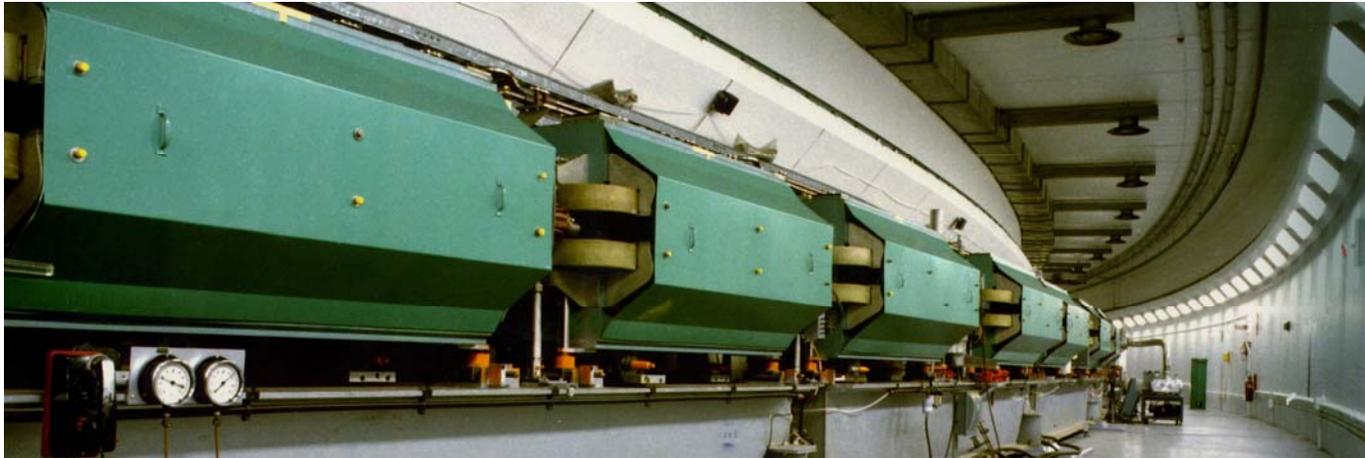
- Beams are confined near the ideal trajectory with quadrupole magnets or by magnetic field tapering in the old days.
- These magnets act just like lenses do to light, but they focus in one direction while defocusing in the other.
- If they are alternated, there is a net focusing.
- This is just the alternating gradient principle for Strong Focusing invented by Courant, Livingston, Snyder and Christofilos

# Strong focusing

- 1952: Ernest Courant, Stanley Livingston and Hartland Snyder at Brookhaven National Laboratory and, independently Nicholas Christofilos earlier in 1950 in Greece discover the principle of strong focusing.
- Strong focusing and phase stability form the foundation of all modern high-energy accelerators.



# The Modern Synchrotron



- 1959: The first two proton synchrotrons using strong focusing – PS at CERN and AGS at BNL – were built.
- An electron synchrotron using strong focusing was built earlier in 1954 at Cornell University.

# The Storage Ring Collider

- The step from the synchrotron to the storage ring was a natural one, but presented lots of challenges.
- If you use the antiparticle colliding with the particle, then you can use the same storage ring for both (magnetic bending)
- You have to make sure they don't collide when you don't want them to, so sometimes electrostatic deflectors have been used to separate beams to keep them from colliding.
- One key item is to decrease the beam size at the interaction point and increase the density there.
- Of course, if you have the same particle type, then you need to have two rings, one for each.

# Collider

- 1961: AdA, the first electron-positron collider, is built at Frascati, Italy.
- It is followed by two electron-electron colliders:
- Princeton-Stanford Collider in the U.S. and
- VEP-1 in Russia.

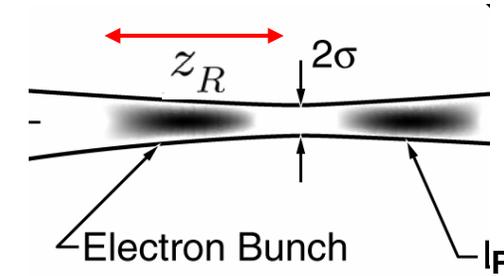


# Focusing to a small spot

- Beams can be focused to a small spot in just the way that light can be.
- In this case, the smaller the beam size, the shorter the depth of focus.
- The small beam size needs larger divergence, and the product of these two is just the 'emittance' discussed earlier.
- This larger divergence needs a large aperture for the preceding lens.
- It works the same for light.
- All you camera buffs out there know all about that.

# Beam-Beam Collision: focusing to a small spot

- Electron beam focusing is analogous to the focusing of a light pulse.
- The depth of focus is referred to as  $\beta^*$  for the electron beam.
- It is called the Raleigh length  $z_R$  for the light pulse.

$$\sigma(z)^2 = \sigma^2 \left( 1 + \frac{z^2}{z_R^2} \right)$$
$$\sigma^2 = z_R (\lambda/4\pi)$$


The diagram illustrates the focusing of two beams. Two dark, elongated regions represent the 'Electron Bunch' and 'Positron bunch'. A red double-headed arrow above the bunches is labeled  $z_R$ , indicating the distance between them. A vertical double-headed arrow between the two bunches is labeled  $2\sigma$ , representing their transverse size. The bunches are shown between two converging lines that represent the focusing of the beams.

# Synchrotron Radiation

- The choice of accelerator type is strongly influenced by particle type.
- The radiation power for circular motion is

$$P = \frac{2r_0}{3mc} \gamma^2 \omega^2 |\vec{p}|^2 = \frac{2r_0}{3mc} \gamma^2 |F_{\perp}|^2 = \frac{\beta^4 c}{2\pi} C_{\gamma} \frac{E^4}{\rho^2}$$

- The constant  $C_{\gamma}$  is frequently used

$$C_{\gamma} = \frac{4\pi}{3} \frac{r_0}{(mc^2)^3} = \begin{cases} 8.846 \times 10^{-5} \text{ m}/(\text{GeV})^3 & \text{for electrons} \\ 4.840 \times 10^{-14} \text{ m}/(\text{GeV})^3 & \text{for muons} \\ 7.783 \times 10^{-18} \text{ m}/(\text{GeV})^3 & \text{for protons.} \end{cases}$$

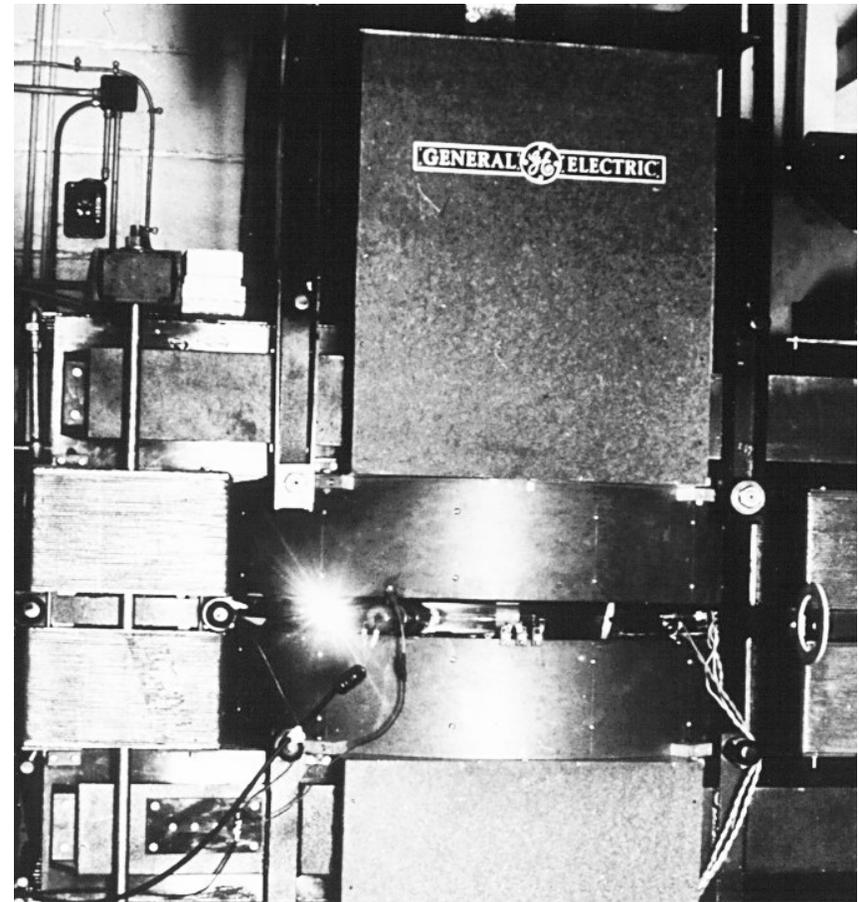
- It is useful to integrate this for the total loss per particle in one turn.

$$U_0 = \oint P dt = C_{\gamma} \beta^3 E_0^4 R \langle 1/\rho^2 \rangle$$

- In practice, using size ( $\rho$ ) to compensate the increasing synchrotron radiation for electrons works only up to a point.
- The power gets too large, but just as important, the energy loss per turn gets too large.
- If you throw all the energy away each turn, might as well use a linac.

# Synchrotron radiation

- 1946: Frank Goward constructs the first electron synchrotron in the U.K.
- This is followed by one built by General Electric in the U.S. where synchrotron radiation is first observed, opening a new era of accelerator-based light sources.



# Intersecting Proton Storage Rings

- 1969: The ISR--  
Intersecting Storage  
Rings, the first large  
proton-proton collider  
began operation at  
CERN.



# Stochastic cooling

- 1968: Simon van der Meer invented stochastic beam cooling, a technique enabling cooling of antiproton beams.
- The proton-antiproton collisions in the SpS in 1981 at CERN lead to the discovery of the Z and W bosons.



# The era of Colliding Beams

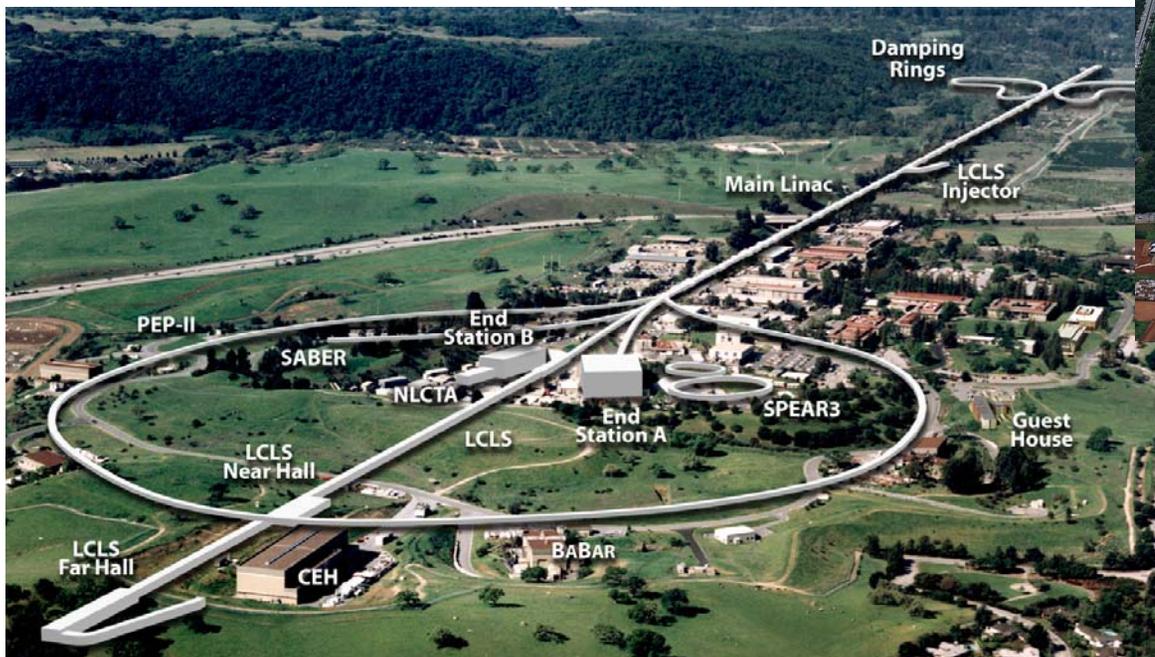
- There has been a rich set of colliding beam storage rings.
- This began with AdA at the lowest energy.
- The energy frontier for electrons ended with LEP around  $E_{cm} = 200$  GeV.
- This was due to synchrotron radiation limitations.
- This motivated Burt Richter to propose the SLC.
- But the electron era has continued on the luminosity frontier.
- The proton colliding beam era is still ongoing.

Table 1: Colliding Beam Machines. [a] DR: Double storage ring. SR: Single storage ring. LC: Linear collider. [b] Princeton-Stanford Colliding Beam Experiment. [c] 200 GeV per charge unit. [d] Planned.

Location	Name (type <sup>[a]</sup> )	Max. $E_{cm}$ (GeV)	Start
Stanford/SLAC, USA	CBX <sup>[b]</sup> ( $e^+e^-$ DR)	1.0	1963
	Spear ( $e^+e^-$ SR)	5.0	1972
	PEP ( $e^+e^-$ SR) [5]	30	1980
	SLC ( $e^+e^-$ LC) [6]	100	1989
	PEP-II ( $e^+e^-$ DR) [7]	10.6	1999 <sup>[d]</sup>
Frascati, Italy	AdA ( $e^+e^-$ SR)	0.5	1962
	Adone ( $e^+e^-$ SR)	3.0	1969
	DAΦNE ( $e^+e^-$ SR)	1.0	1997 <sup>[d]</sup>
Novosibirsk, Siberia	VEP-1 ( $e^+e^-$ DR)	0.26	1963
	VEPP-2/2M ( $e^+e^-$ SR)	1.4	1974
	VEPP-4 ( $e^+e^-$ SR)	14	1979
Cambridge, USA	CEA Bypass ( $e^+e^-$ SR)	6	1971
Orsay, France	ACO ( $e^+e^-$ SR)	1.0	1966
	DCI ( $e^\pm e^\pm$ DR)	3.6	1976
DESY, Germany	Doris ( $e^+e^-$ DR)	6.0	1974
	Petra ( $e^+e^-$ SR)	38	1978
	Hera ( $e^\pm p$ DR) [8]	160	1992
CERN, Europe	ISR ( $pp$ DR) [2]	63	1971
	Sp̄p̄S ( $p\bar{p}$ SR) [9]	630	1981
	LEP ( $e^+e^-$ SR) [10]	190	1989
	LHC ( $pp$ DR) [11]	14,000	2004 <sup>[d]</sup>
Brookhaven, USA	RHIC (heavy ions DR) [12]	200/u <sup>[c]</sup>	1999 <sup>[d]</sup>
	RHIC ( $pp$ DR)	500	
Cornell, USA	CESR ( $e^+e^-$ SR)	12	1979
KEK, Japan	Tristan ( $e^+e^-$ SR) [14]	60	1986
	KEK B ( $e^+e^-$ DR) [13]	10.6	1999 <sup>[d]</sup>
Beijing, China	BEPC ( $e^+e^-$ SR) [15]	3.1	1989
Fermilab, USA	Tevatron ( $p\bar{p}$ SR) [16]	1800	1987

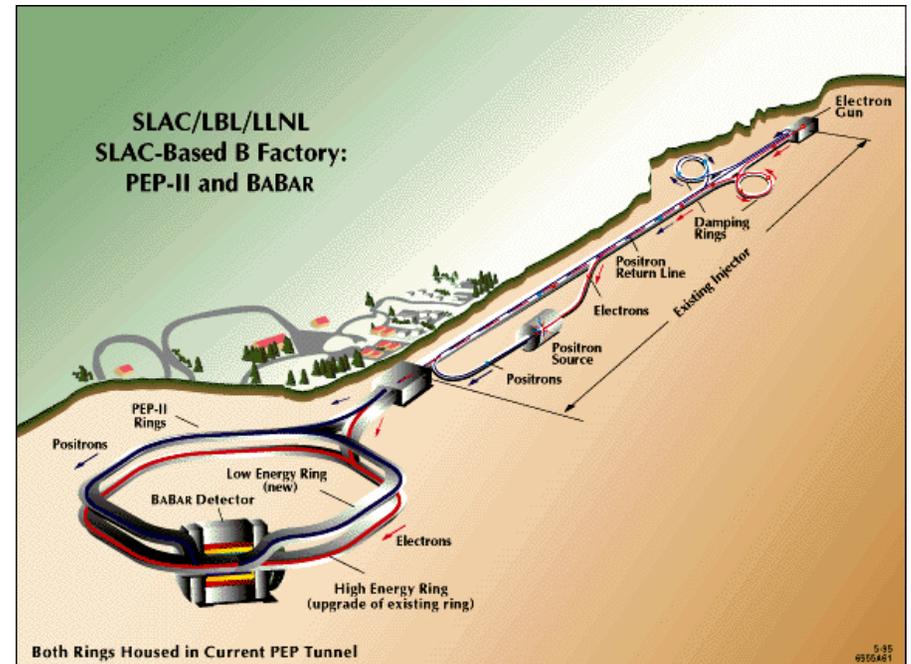
# The Factories: the Luminosity Frontier

- 1998-2008+
- The B factories at SLAC and KEK explore CP violation



# PEP-II B Factory

- The key to the factories:
- High Current: lots of bunches
- Focus Beam to small spots.
- Very smooth chamber
- Sophisticated RF system with feedbacks galore.



# PEP-II Records

Last update:  
April 8, 2008

## Peak Luminosity

**$12.069 \times 10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$**

1722 bunches    2900 mA LER    1875 mA HER

**August 16, 2006**

## Integration records of delivered luminosity

<b>Best shift</b> (8 hrs, 0:00, 08:00, 16:00)	<b>339.0</b> pb <sup>-1</sup>	<b>Aug 16, 2006</b>
<b>Best 3 shifts in a row</b>	<b>910.7</b> pb <sup>-1</sup>	<b>Jul 2-3, 2006</b>
<b>Best day</b>	<b>858.4</b> pb <sup>-1</sup>	<b>Aug 19, 2007</b>
<b>Best 7 days</b> (0:00 to 24:00)	<b>5.411</b> fb <sup>-1</sup>	<b>Aug 14-Aug 20, 2007</b>
<b>Best week</b> (Sun 0:00 to Sat 24:00)	<b>5.137</b> fb <sup>-1</sup>	<b>Aug 12-Aug 18, 2007</b>
<b>Peak HER current</b>	<b>2069</b> mA	<b>Feb 29, 2008</b>
<b>Peak LER current</b>	<b>3213</b> mA	<b>Apr 7, 2008</b>
<b>Best 30 days</b>	<b>19.776</b> fb <sup>-1</sup>	<b>Aug 5 – Sep 3, 2007</b>
<b>Best month</b>	<b>19.732</b> fb <sup>-1</sup>	<b>August 2007</b>
<b>Total delivered</b>	<b>557</b> fb <sup>-1</sup>	

**PEP-II turned off April 7, 2008**

# Superconducting magnet technology



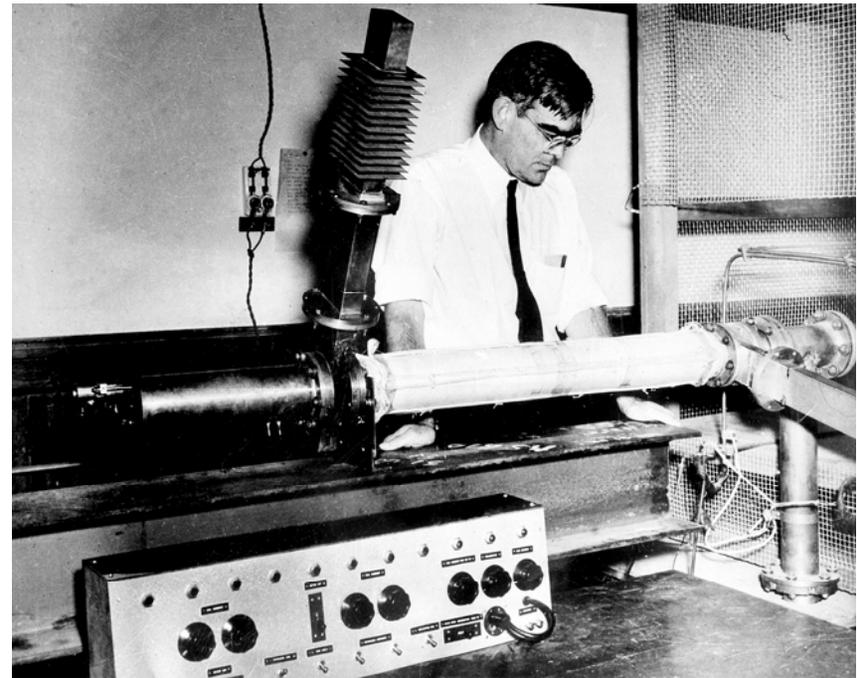
- 1983: The Tevatron, the first large accelerator using superconducting magnet technology, was commissioned at Fermilab.

# Recent News from the Tevatron

- Tevatron Experiments Double-Team Higgs Boson
- Joint CDF, DZero effort lands Fermilab in Higgs territory
- Batavia, Ill.--Scientists from the CDF and DZero collaborations at the U.S. Department of Energy's Fermilab have combined Tevatron data from the two experiments to advance the quest for the long-sought Higgs boson. Their results indicate that Fermilab researchers have for the first time excluded, with 95 percent probability, a mass for the Higgs of 170 GeV. This value lies near the middle of the possible mass range for the particle established by earlier experiments. This result not only restricts the possible masses where the Higgs might lie, but it also demonstrates that the Tevatron experiments are sensitive to potential Higgs signals.
- "These results mean that the Tevatron experiments are very much in the game for finding the Higgs," said Pier Oddone, director of Fermilab.

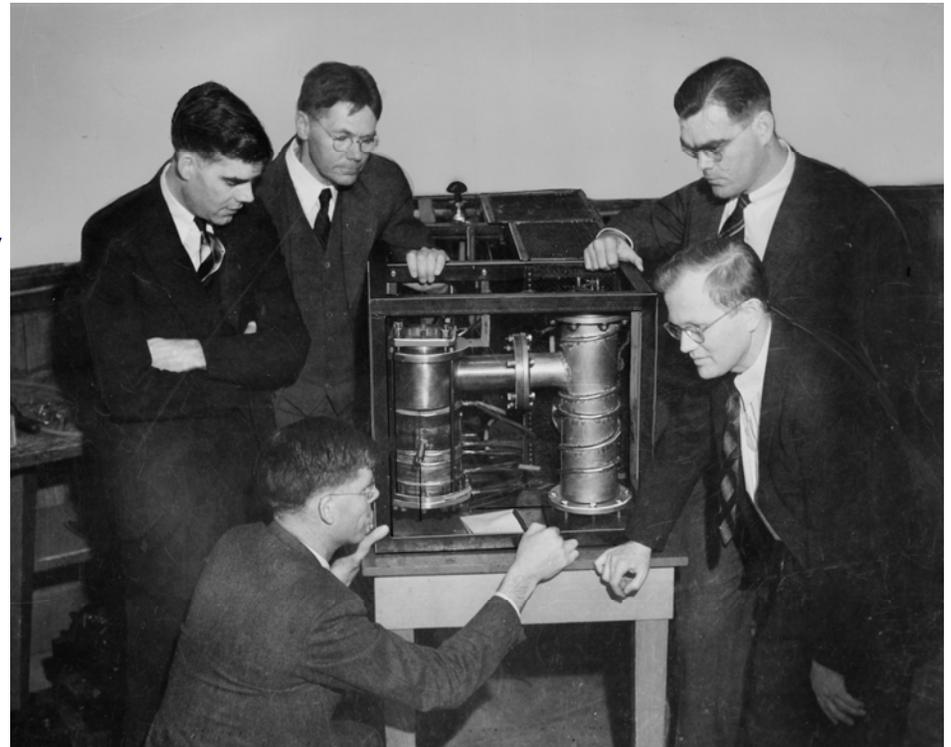
# Electron linac

- 1946: William Walkinshaw and his team at Malvern in the U.K. build the first electron linac powered by a magnetron.
- William Hansen and his team independently build a similar electron linac at Stanford University a few months later. (see image)

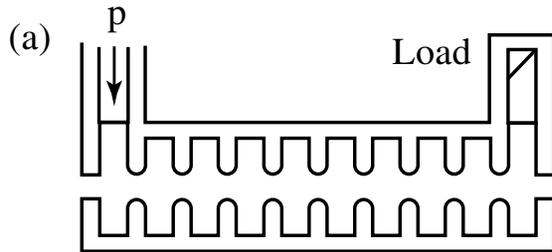


# Klystron

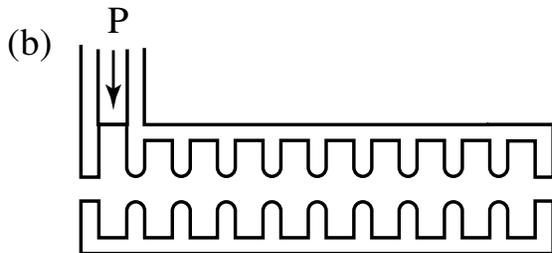
- 1937: Russell and Sigurd Varian and William Hansen invented the klystron, a high-frequency amplifier for generating microwaves, at Stanford University.
- A similar device was proposed by Agnesa Arsenjewa-Heil and Oskar Heil in 1935.



# Linear Accelerator Structure Types



(a) Traveling Wave (TW) Structure



(b) Standing Wave (SW) Structure

3-98  
8334A1

- For an electron Linear Accelerator the speed reaches  $c$  very quickly.
- If a waveguide has periodic interruptions, then phase velocity of the wave can be matched to  $c$ .

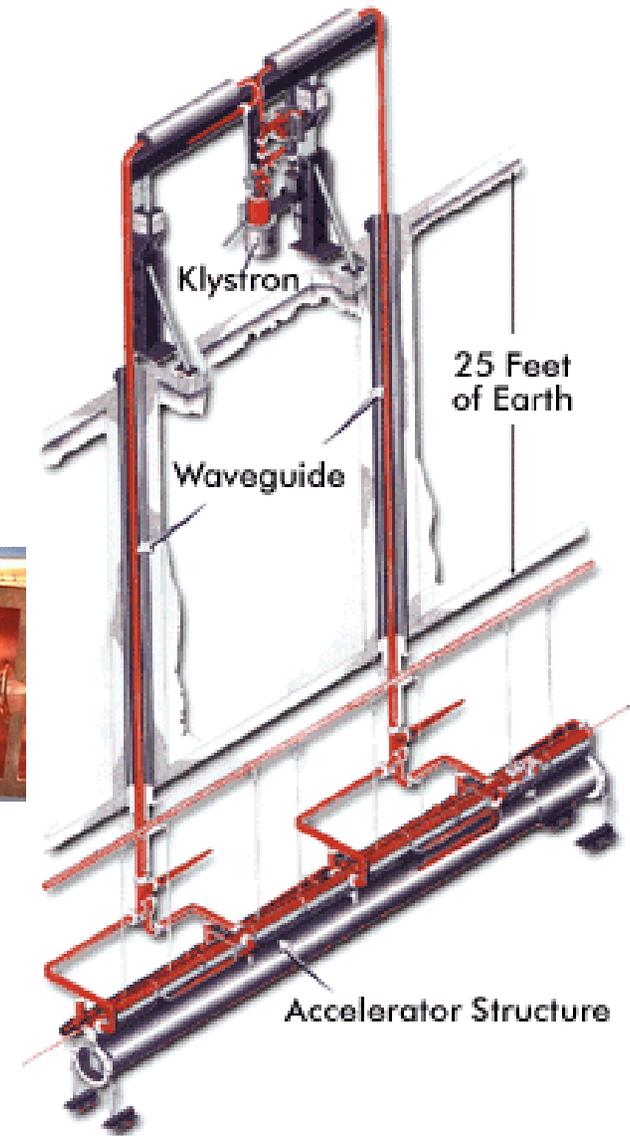
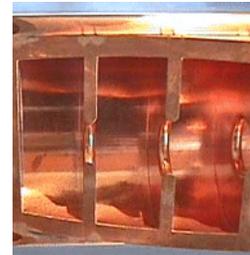
# Stanford Linear Accelerator Center



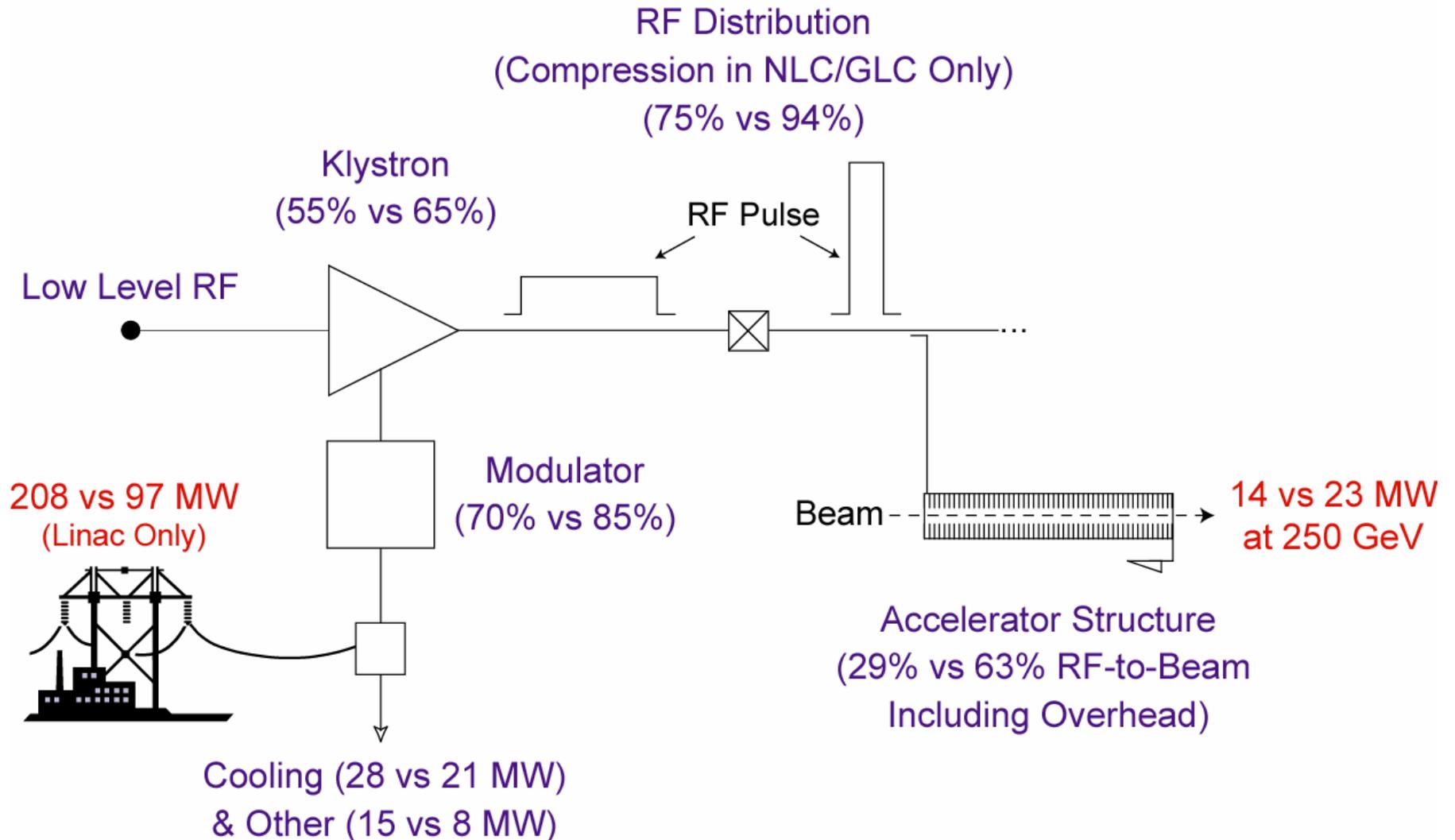
- First large Linear Accelerator complex.
- Following developments at Stanford on Linear Accelerators, Wolfgang Panofsky led the construction of SLAC which began 1962 and was completed in 1966. 20 GeV electron beam in 1967.

# The High Gradient, High Energy Linac

- In a synchrotron the acceleration necessarily occurs near the zero crossing to have enough space for phase stability.
- Once an electron is sufficiently relativistic, might as well keep accelerating with speed of light waves.
- Note that all the acceleration occurs near the crest of the wave because all the particles are frozen in phase due to their speed.
- Need RF power, klystrons, and accelerator structures.

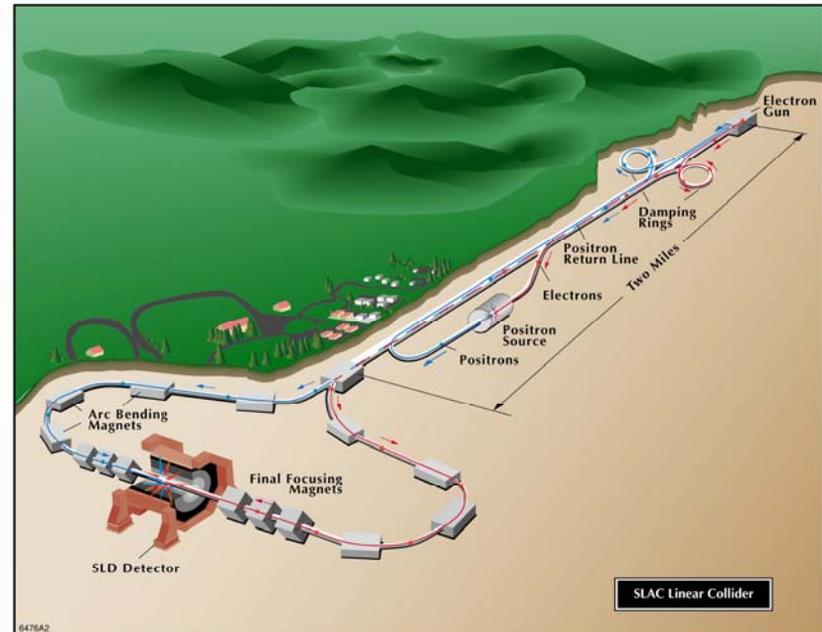


# Overview of a typical RF system for a linear accelerator or collider (ignore the numbers for now)



# Linear Collider

- 1989: SLC, the first linear collider was built at SLAC. The SLC used a folded design proposed by Burt Richter.
- The concept of a linear collider was first proposed by Maury Tigner in 1965.



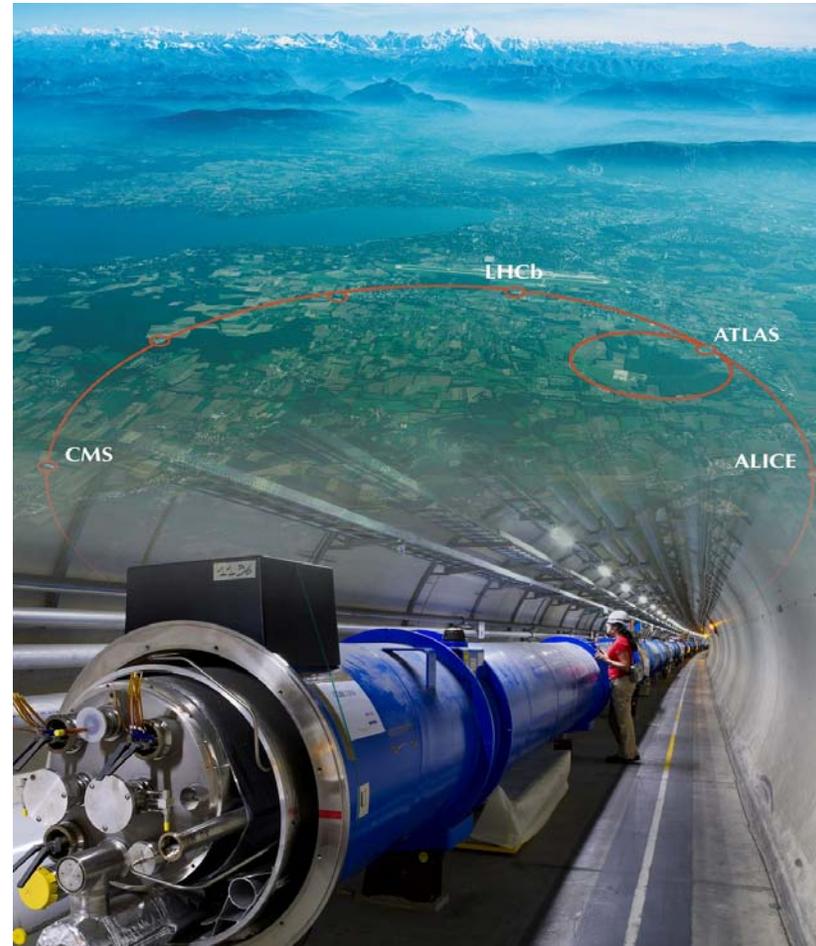
# Rise and fall of SSC

- Construction of the Superconducting Super Collider, a would-be largest accelerator in the world, began in 1989.
- The project was cancelled by the U.S. Congress in 1993.



# World's largest accelerator – LHC

- 2008: The Large Hadron Collider at CERN, with 27 km circumference, will begin operation.

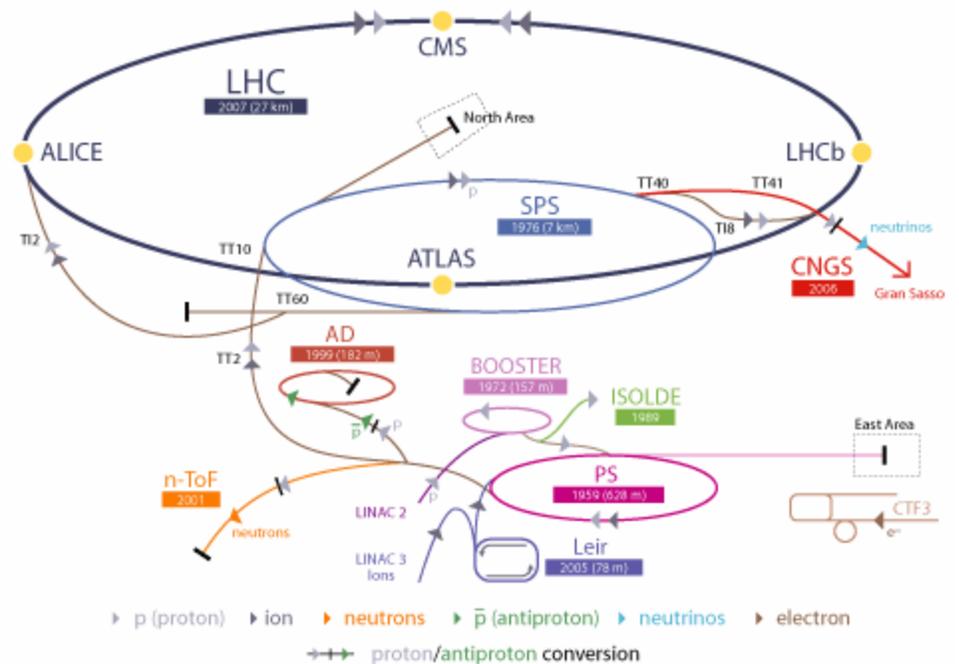


# The Large Hadron Collider



- Protons are obtained by removing electrons from hydrogen atoms.
- They are injected from the linear accelerator (LINAC2) into the PS Booster,
- then the [Proton Synchrotron](#) (PS),
- followed by the [Super Proton Synchrotron](#) (SPS),
- before finally reaching the [Large Hadron Collider](#) (LHC).
- Protons will circulate in the LHC for 20 minutes before reaching the maximum and energy.

CERN Accelerator Complex

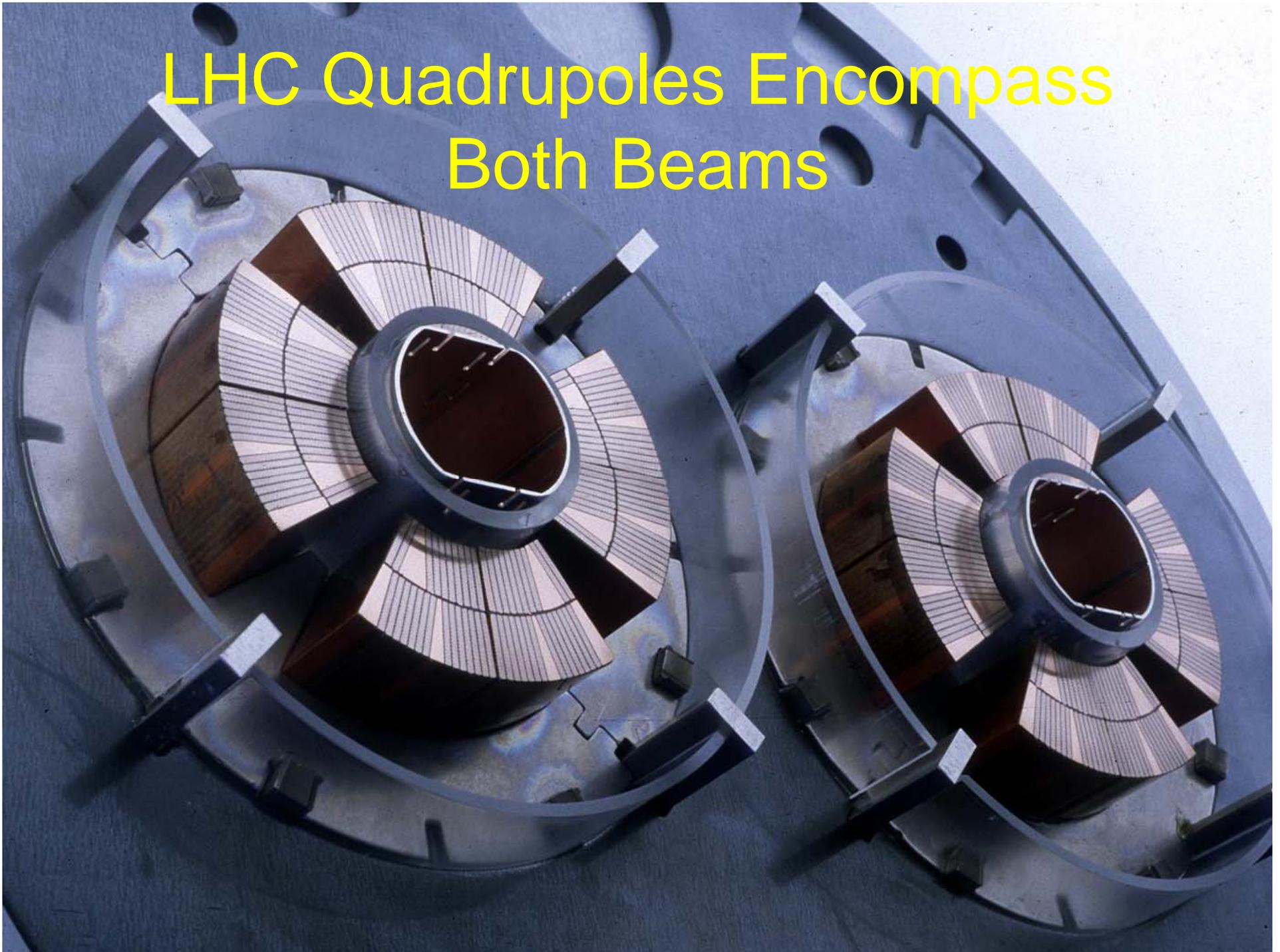


LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron  
 AD Antiproton Decelerator CTF3 Clic Test Facility  
 CNGS Cern Neutrinos to Gran Sasso ISOLDE Isotope Separator OnLine DEvice  
 LEIR Low Energy Ion Ring LINAC LINEAR ACcelerator n-ToF Neutrons Time Of Flight

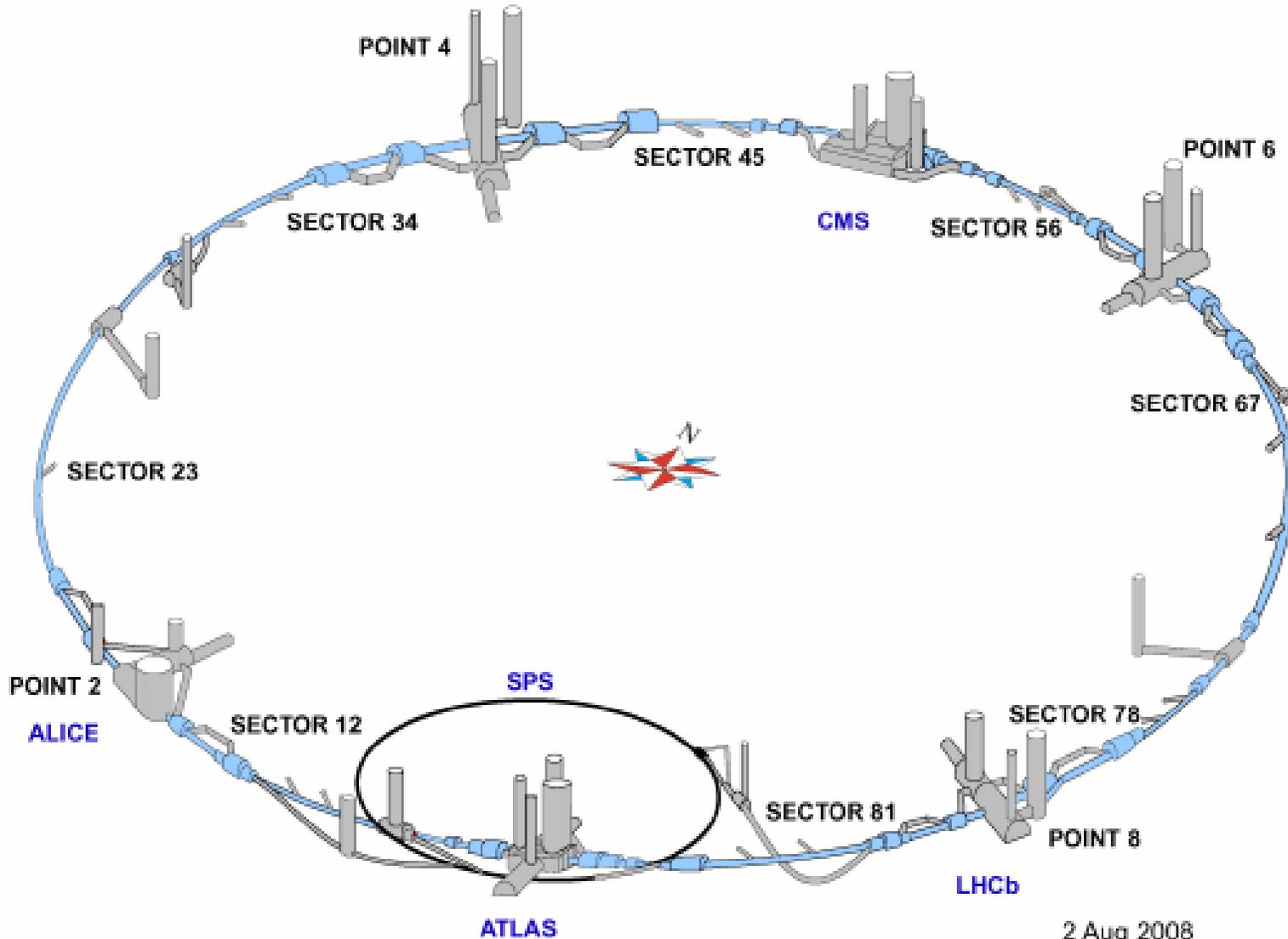
# The LHC Tunnel



# LHC Quadrupoles Encompass Both Beams



# LHC Cool Down Status



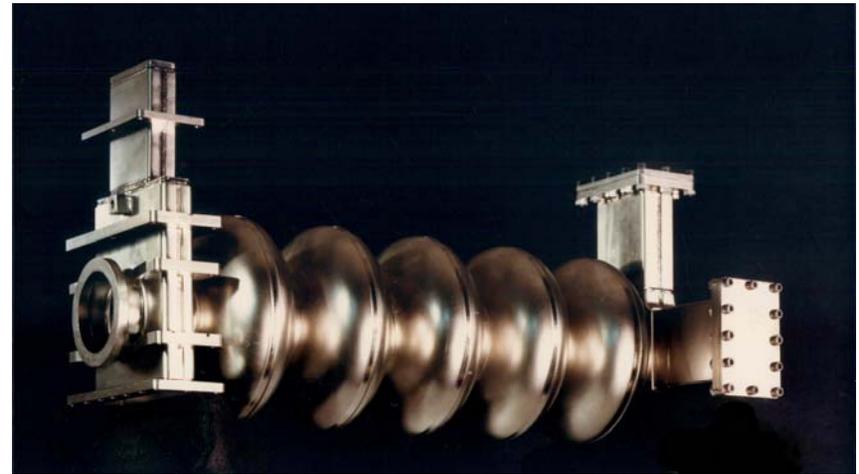
2 Aug 2008

# LHC Schedule

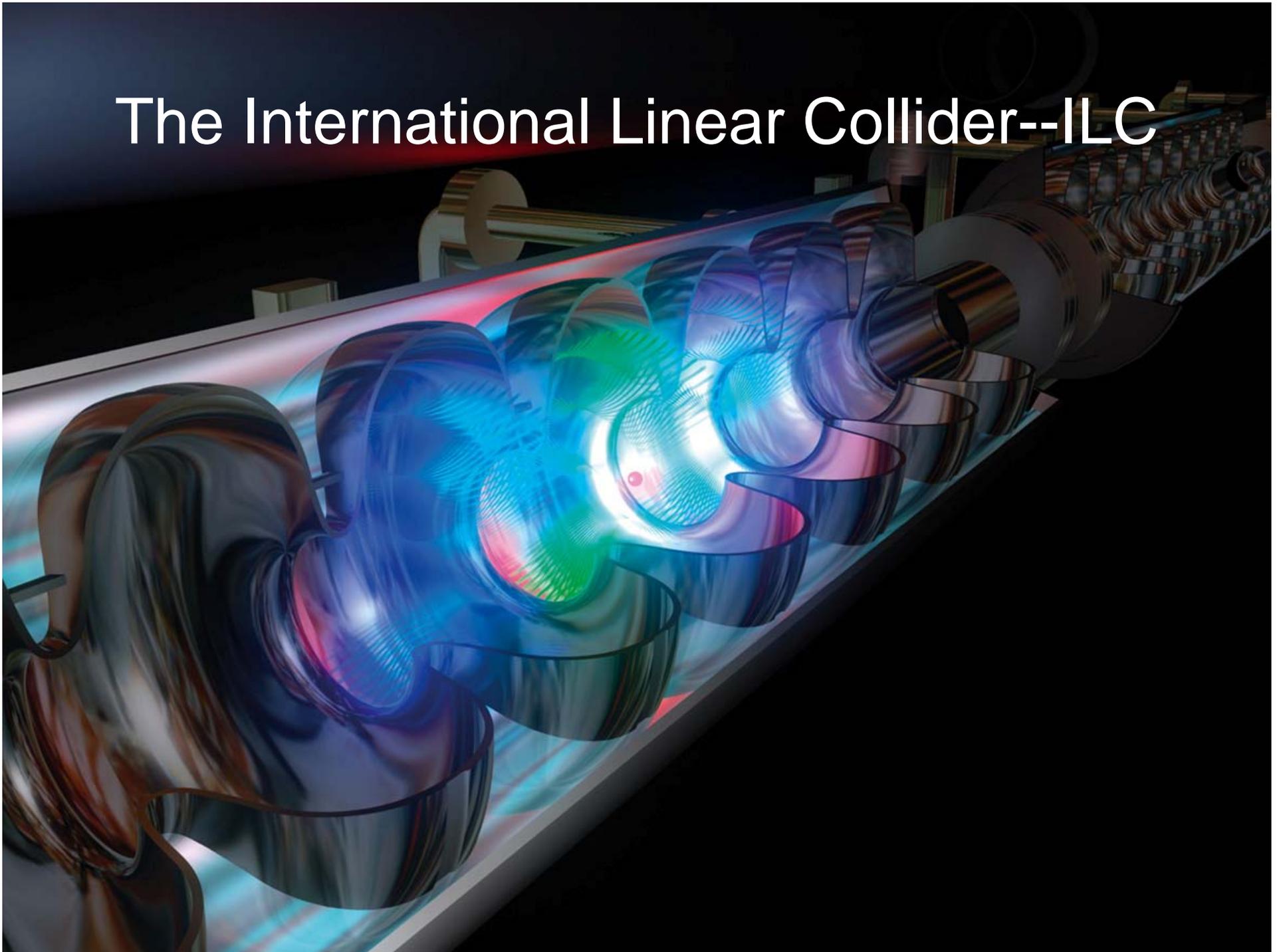
- **End of July:** The LHC is expected to be cooled down. The experiments are requested to have their beam pipes baked out.
- **Early August:** The experimental caverns will be closed after the caverns and tunnel have been patrolled. Safety tests will then be performed. From then on the controlled access system will be fully activated. At this stage an [Injection Test](#) into sector 23 is planned.
- **Early September:** First particles will be injected, and the commissioning with beams will start.
- It is expected that it will take about 2 months to have first collisions at 10 TeV centre of mass energy.
- **Energy of the 2008 run:** Agreed to be 10 TeV. The machine considers this to be a safe setting to optimize up-time of the machine until the winter shut-down (starting likely around end of November). Therefore, simulations can now start for 10 TeV.
- The winter shut-down will then be used to commissioning and train the magnets up to full current, such that the 2009 run will start at the full 14 TeV design energy.
-

# Superconducting RF technology

- 1994: CEBAF, the first large accelerator using superconducting radio frequency technology, was built at the facility later named Jefferson Laboratory.



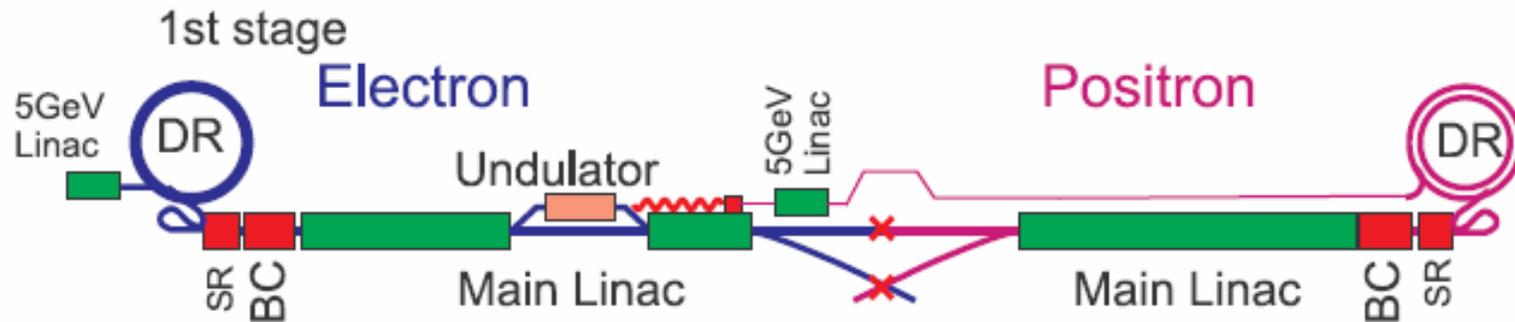
# The International Linear Collider--ILC



# ILC Layout

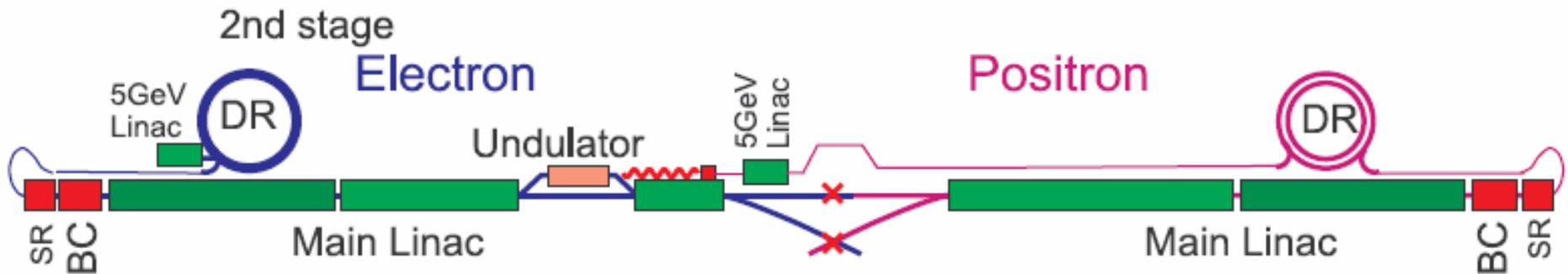
(not to scale)

## Initial



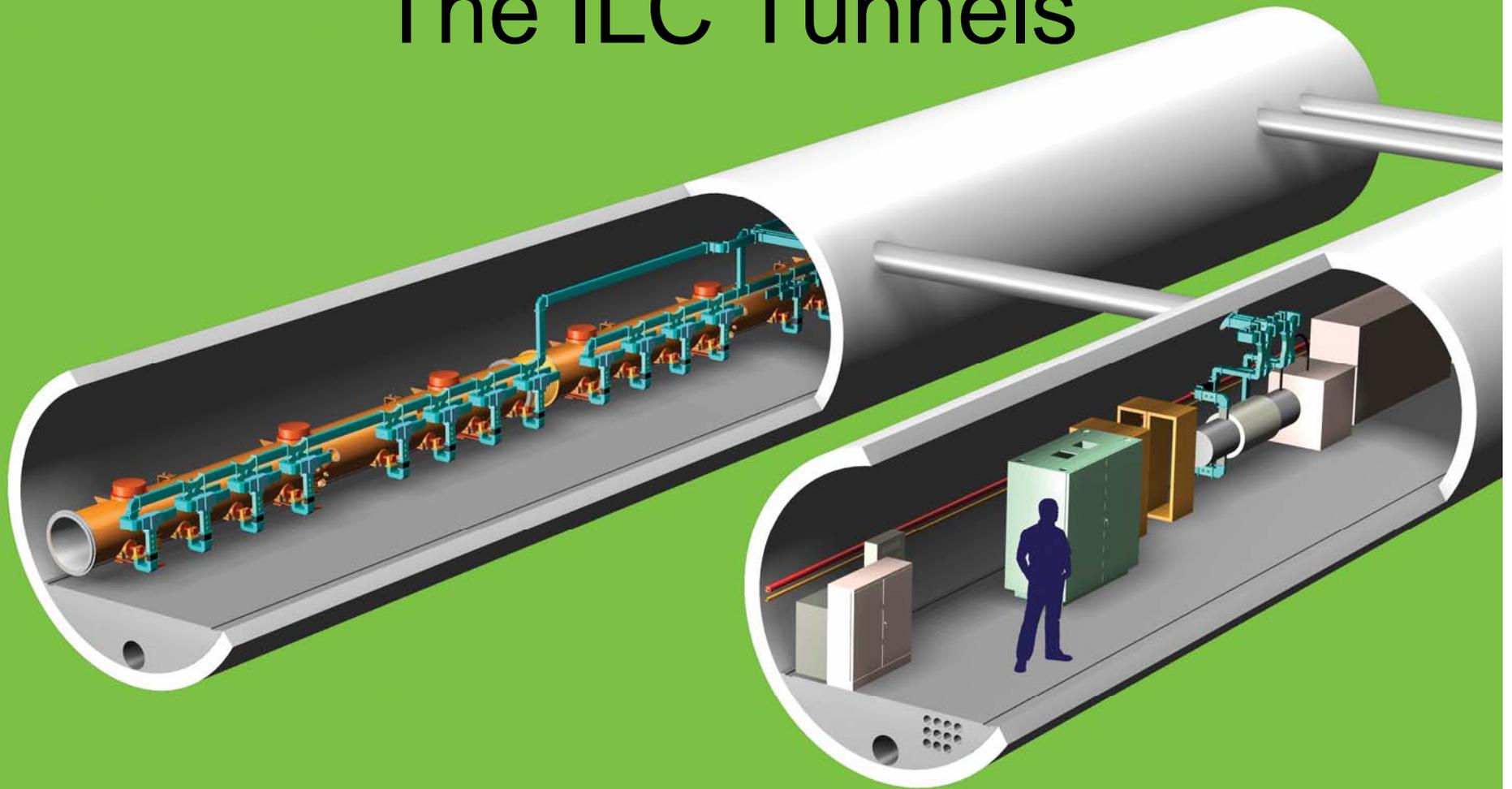
**500 GeV CMS**

## Future Upgrade



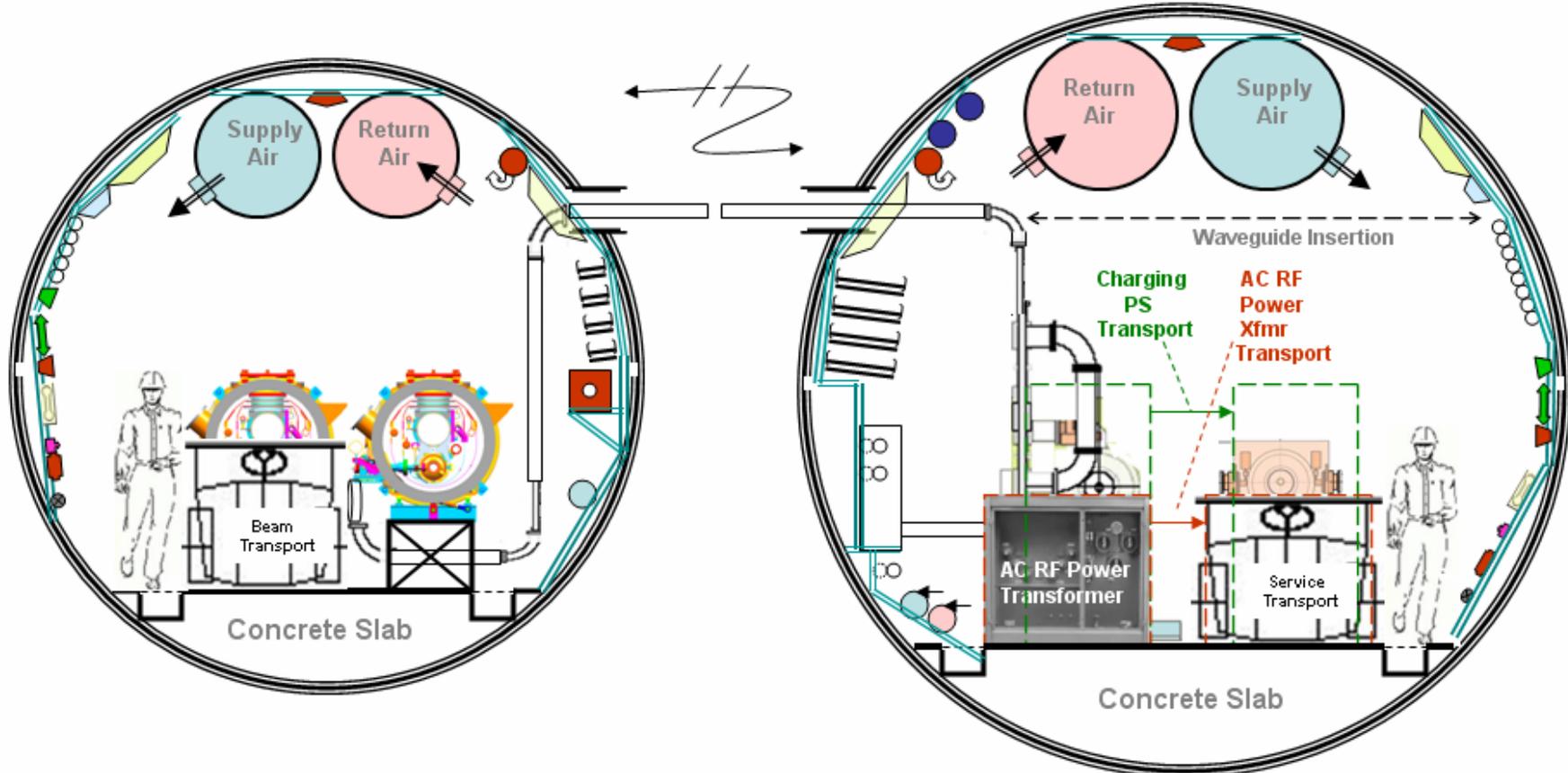
**1000 GeV CMS**

# The ILC Tunnels



# ILC Tunnel Layout

For baseline, developing deep underground (~100 m) layout with 4-5 m diameter tunnels spaced by 5 m.



# Klystrons

Baseline: 10 MW Multi-Beam Klystrons (MBKs) with ~ 65%  
Efficiency: Being Developed by Three Tube Companies in  
Collaboration with DESY



Thales



CPI

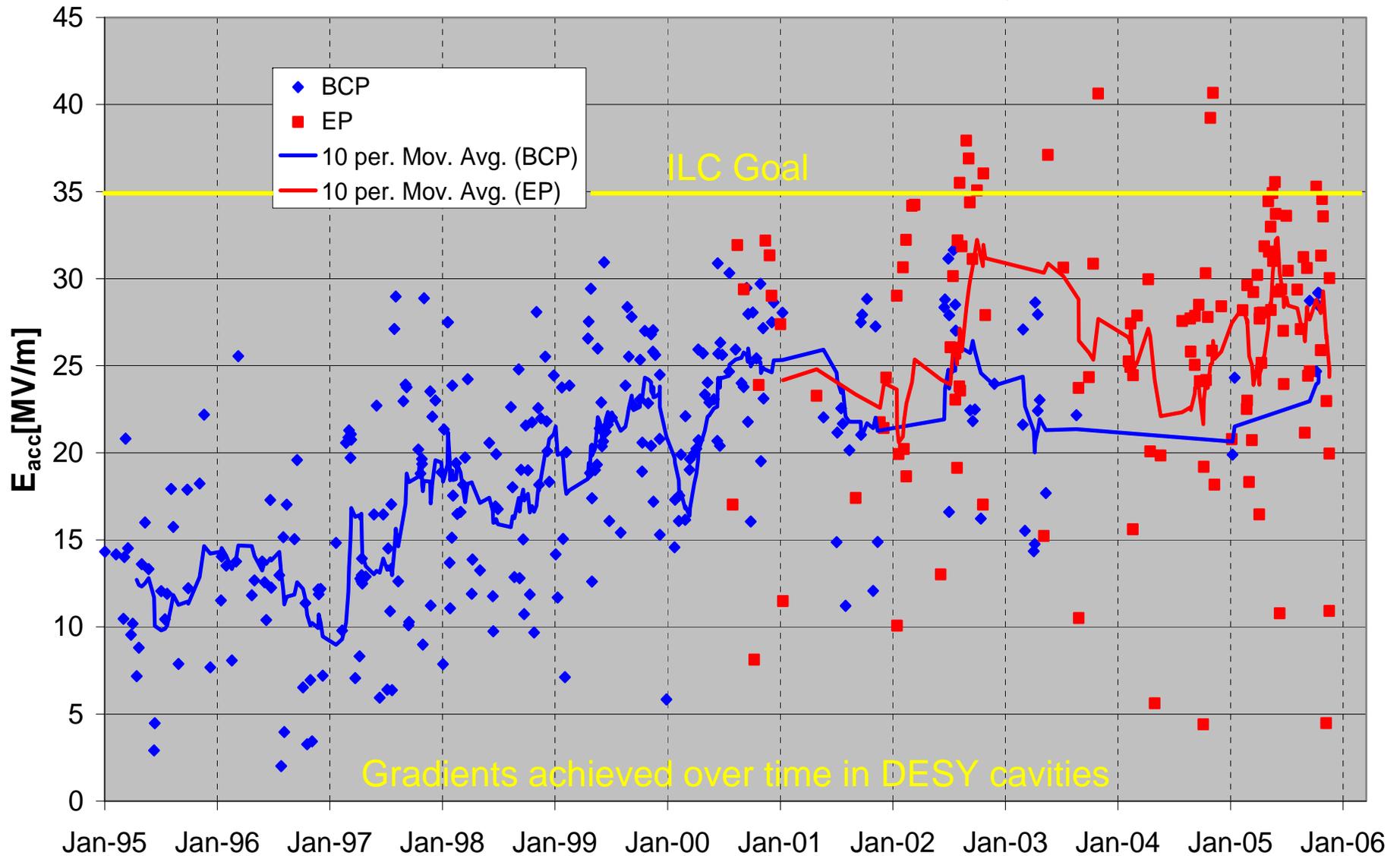


Toshiba

# Super Conducting Cavity



# Main Production Problem Has Been Poor Reproducibility

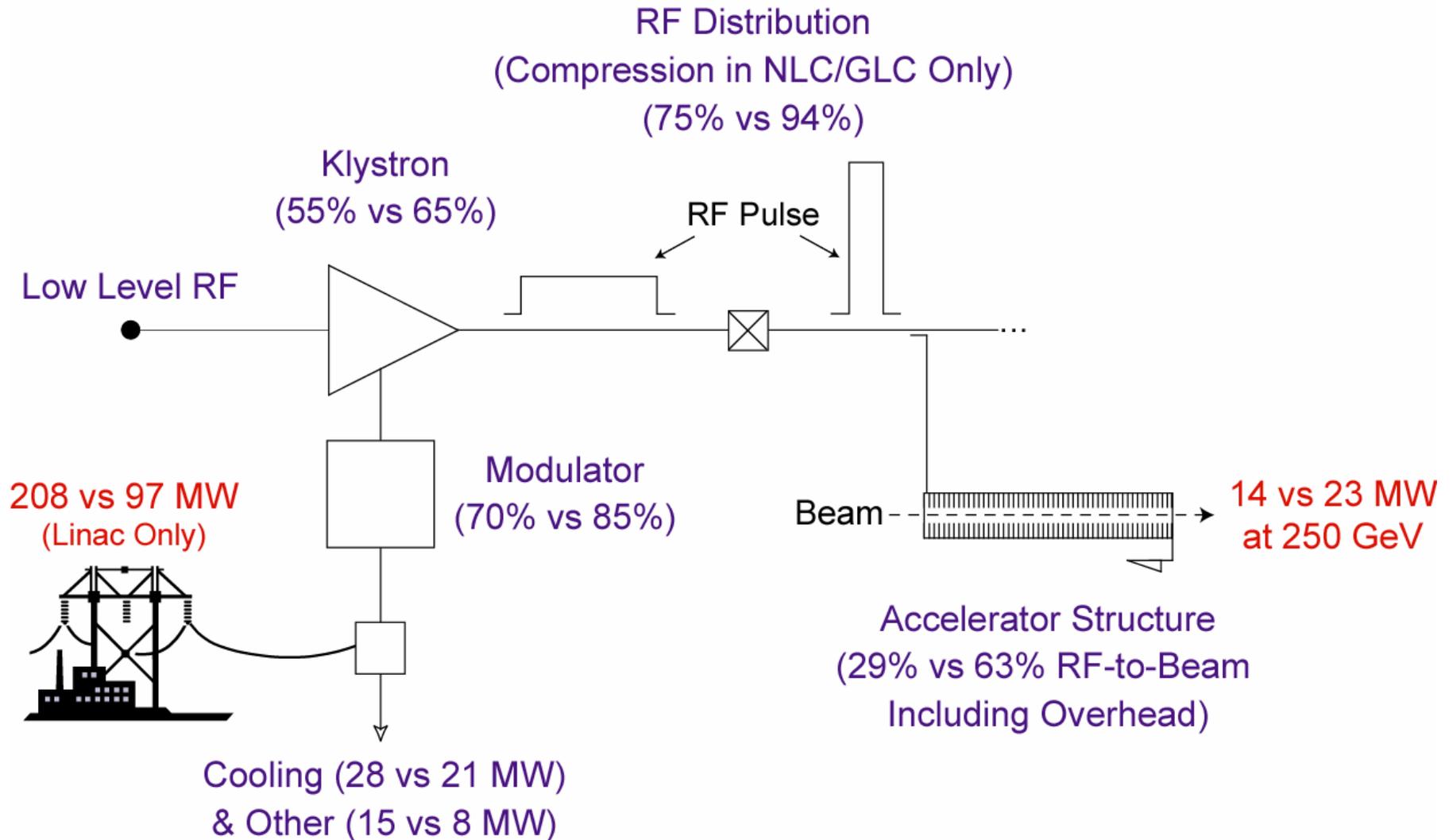


# ILC Design Summary

- Basic linac design complete: converging on details
  - Tradeoffs of operability, availability and cost.
- Major cost and technical risks
  - Producing cryomodules that meet design gradient at a reasonable cost (cost model still in development, XFEL will provide a reference, and will get new industry-based estimates).
  - Producing a robust 10 MW klystron.
- Potential Cost Savings
  - Adopt Marx Modulator
  - Use simpler rf distribution scheme
  - Have one tunnel although ‘the additional cost is marginal when considering the necessary overhead and equipment improvements to comply with reliability and safety issues.’
  - Reduce cavity aperture to 60 mm for 21% reduction in dynamic cryo-loading and 16% reduction in cavity fill time.

# Where Does the Power Go

(NLC/GLC vs TESLA TDR Efficiencies and Average Power)



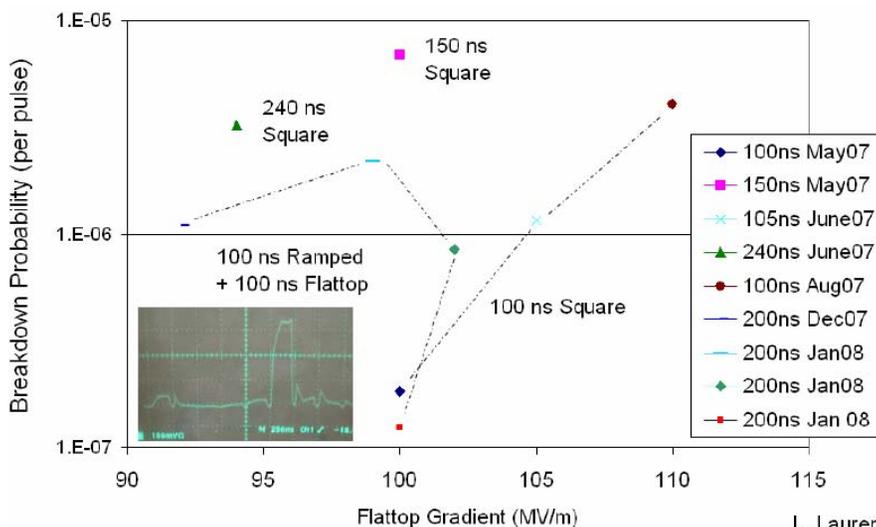
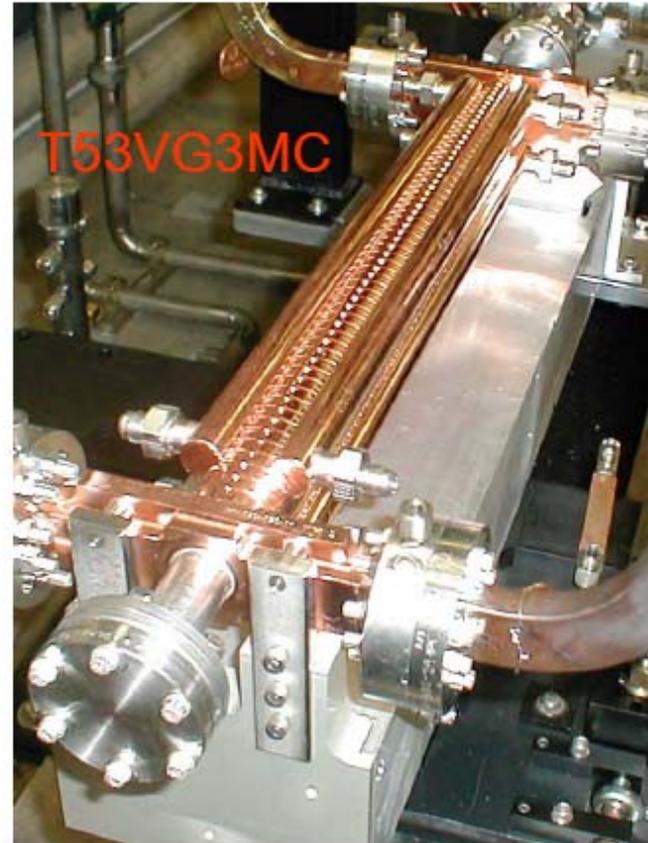
# High Gradient Acceleration

- The state of the art is at 11.4 GHz.
- This is the frequency of the NLC design.
- SLAC has more than 15 years experience with this frequency.
- CLIC has adopted 12 GHz for their two beam collider.
- What is the achievable gradient?
- Tests show that 100 MV/m appears to be achievable with very low breakdown rate.

# Early NLC/GLC Low Vg Test Structure

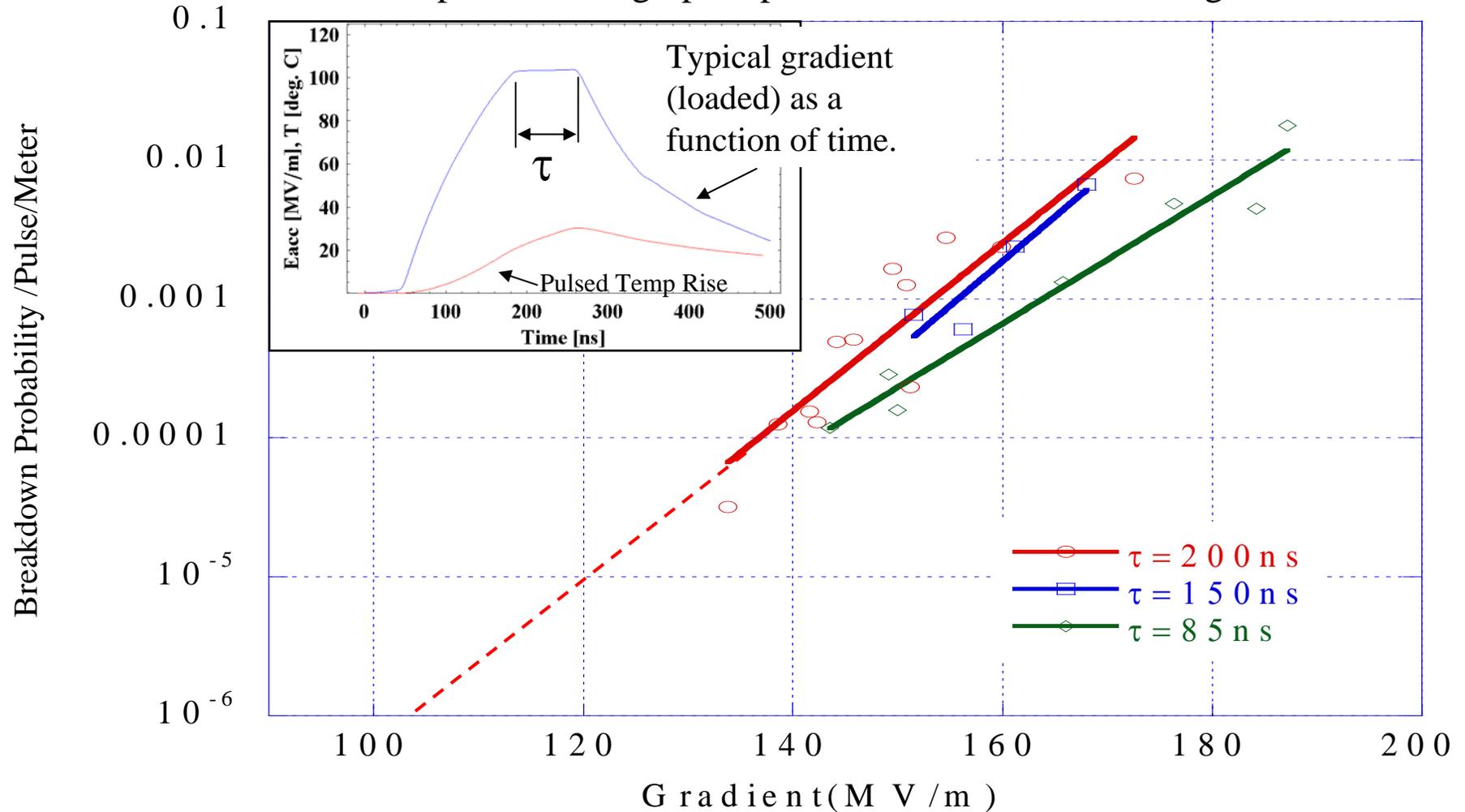
First with Mode Converter input coupler – performed exceptionally well in 2002

- 53 cm long,  $a/\lambda = 13\%$ , initial  $v_g = 3.3\%$ , requires 98 MW for 100 MV/m operation
- In 2002, breakdown rate  $< 5e-7$  at 90 MV/m with 400 ns square pulses
- Reinstalled in 4/07 and have since run 2300 hours with shorter pulses (includes two vents



# Standing-Wave Accelerator Structure Recent Results ( $a/\lambda \sim 0.14$ )

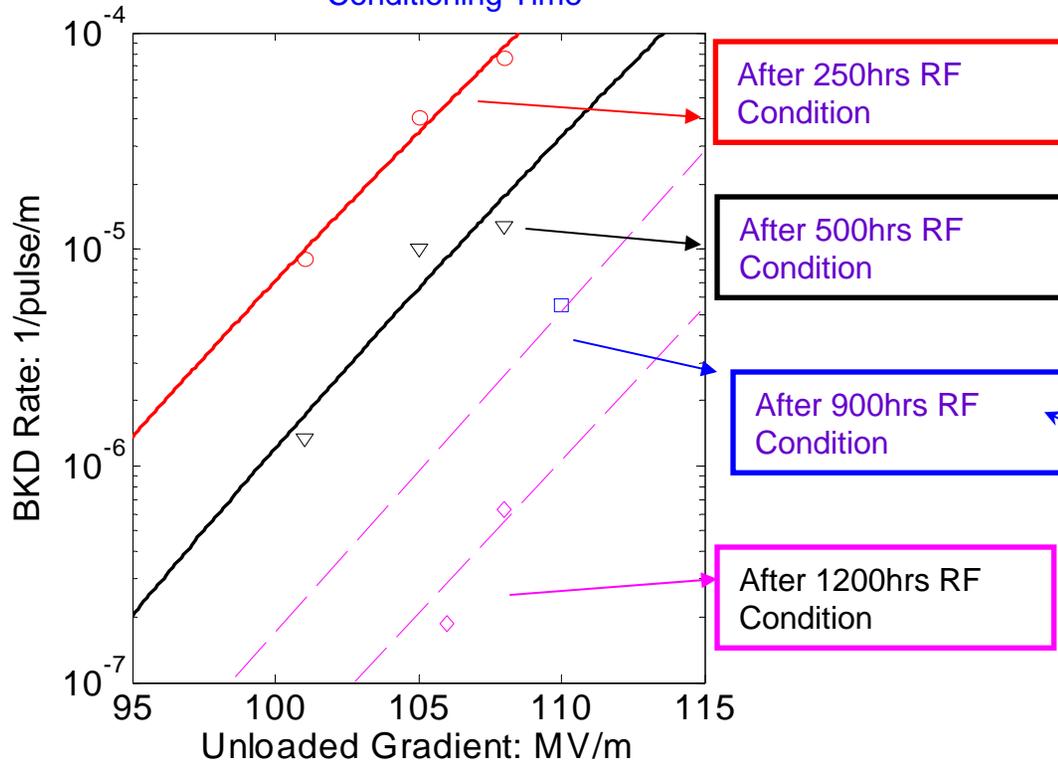
Each point in this graph represents  $\sim 10$  hours or running at 60 Hz



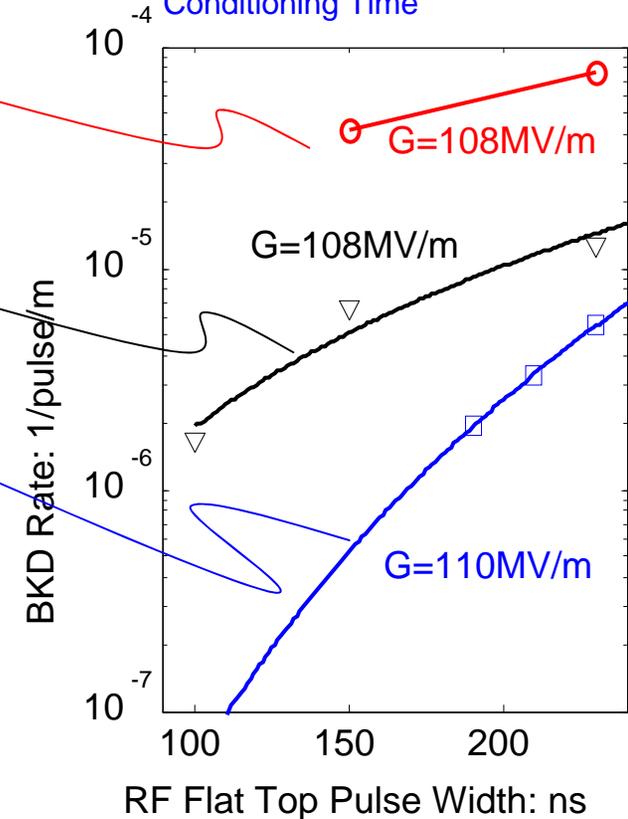
# RF Processing of the T18 Structure



RF BKD Rate Gradient Dependence for 230ns Pulse at Different Conditioning Time



RF BKD Rate Pulse Width Dependence at Different Conditioning Time

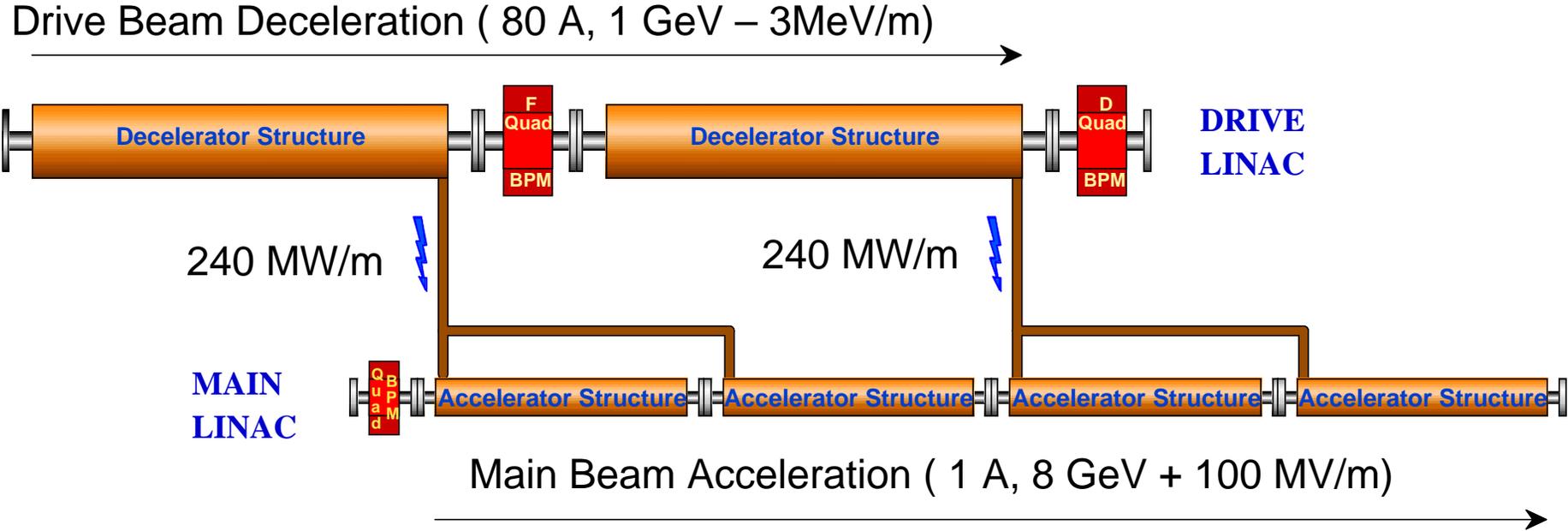


This performance *maybe* good enough for 100MV/m structure for a warm collider, however, it does not yet contain all necessary features such as wake field damping. Future traveling wave structure designs will also have better efficiencies

# Two-Beam Linear Collider (CLIC)

- Two-Beam linear colliders use a high-energy auxiliary drive beam to provide the energy compression prior to RF generation.
  - Use low frequency RF (~ GHz) to efficiently accelerate a high current, long pulse beam. Uses relatively few long-pulse, low-frequency klystrons.
  - Compress the beam pulse by multi turn stacking a delay ring.
  - Distribute the resulting pulses in a beam transport line from the central drive beam accelerator.
  - Decelerate the Drive beam, Accelerate the main beam
  - The overall system acts like a transformer, but with frequency multiplication built in.

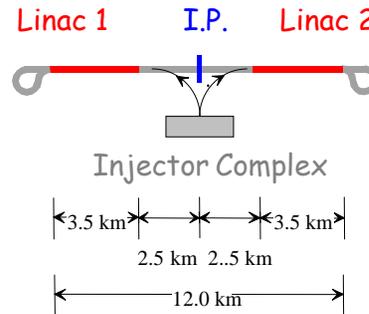
# In the Tunnel Two Beam Looks Relatively Passive **Two-Beam Module Layout**



Two Beam Acceleration (TBA)

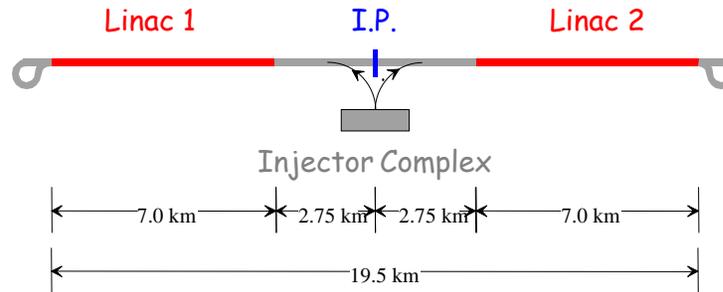
# Drive Beam Generation: Higher energy: ONLY Pulse length of Drive Beam Modulator

0.5 TeV Stage

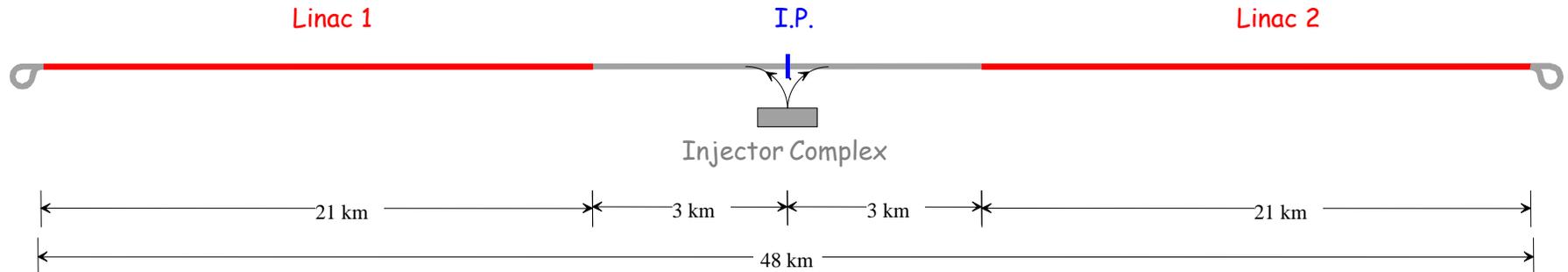


CLIC Layout at various energies

1 TeV Stage



3 TeV Stage



The entire drive beam generation complex remains unchanged for 6x energy

# Necessity for high energy acceleration mechanism

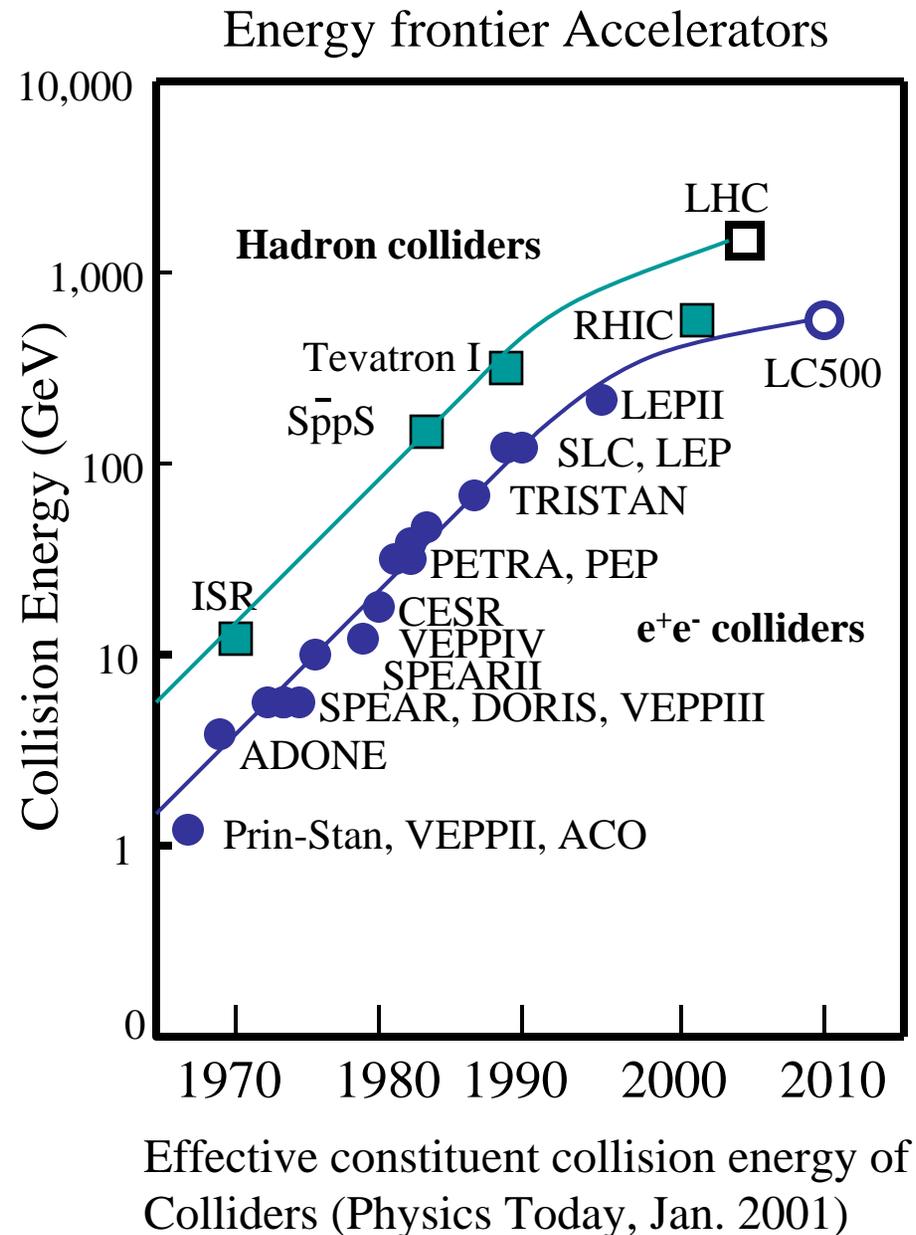
The Laser Acceleration of Particles Workshop, 1982, Los Alamos

“The realization that we seem to be **near the end of the road for conventional accelerators** has generated renewed interest in the possibility of **accelerators with super-high accelerating fields.**”

(AIP Conference Proceedings No. 91, 1982)



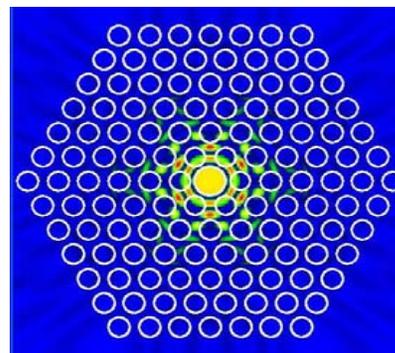
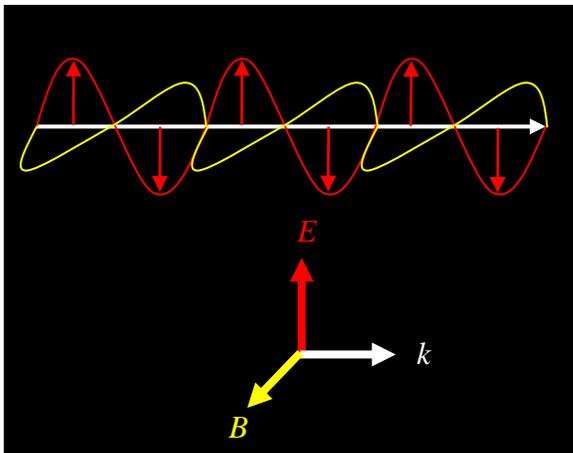
To keep energy frontier trend



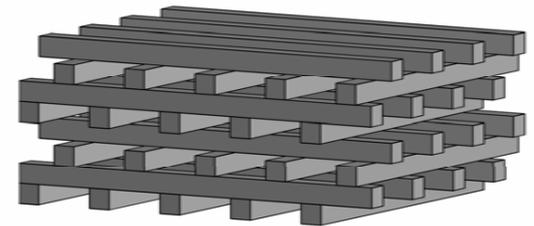
# “Direct” Laser Acceleration (=“no plasma”)

Direct laser acceleration is analogous to microwave-driven particle accelerators, with some differences:

- Lasers produce radiation in very short pulses, allowing **much larger electric fields** without causing breakdown
- Since the wavelength is very short ( $\sim 1$  micron), the particle bunches produced are extremely short ( $\sim 30$  nm  $\Leftrightarrow$  100 attosecond!) leading to **applications in ultrafast science**
- Much of the core technology required (lasers, optics, fibers, and semiconductor “chip” manufacture) is **developed aggressively by industry**
- **The present challenge is that** lasers produce radiation with **transverse electromagnetic** fields; structures must be used that transform and guide the modes to produce a strong longitudinal electric field.



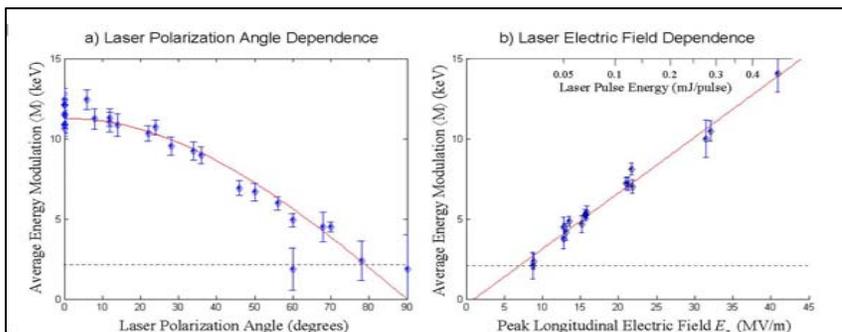
Photonic Crystal Fiber



Photonic Crystal “Woodpile”

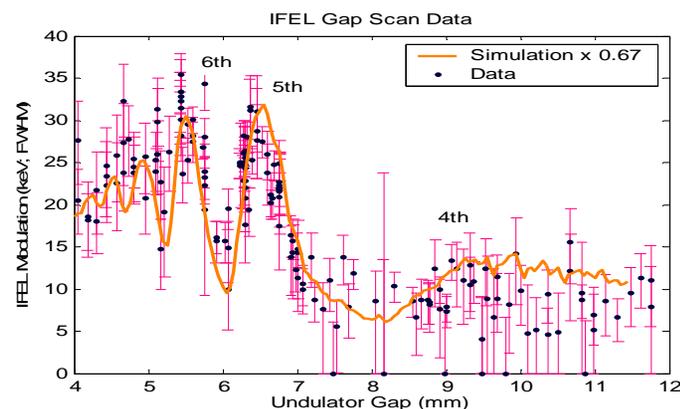
# Experimental Demonstrations of Laser Acceleration

Experiments conducted on Stanford Campus



## Inverse Transition Radiation Acceleration & Experimental Demonstration of the Lawson-Woodward Theorem

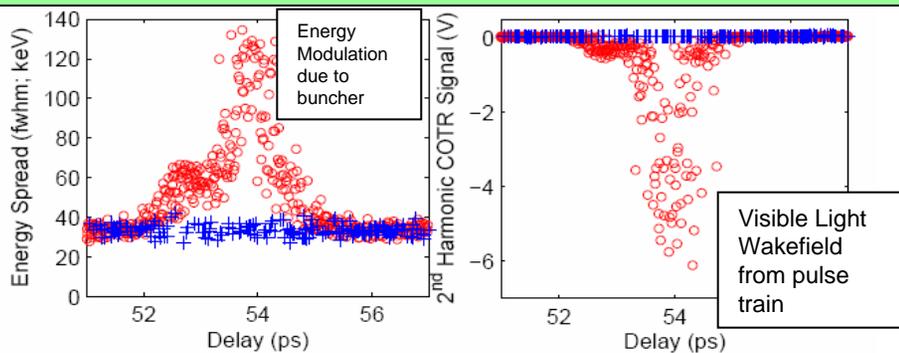
T. Plettner, *et al*, *Phys. Rev. Lett.*, **95**, 134801 (2005).



## Higher-Harmonic Inverse FEL Acceleration

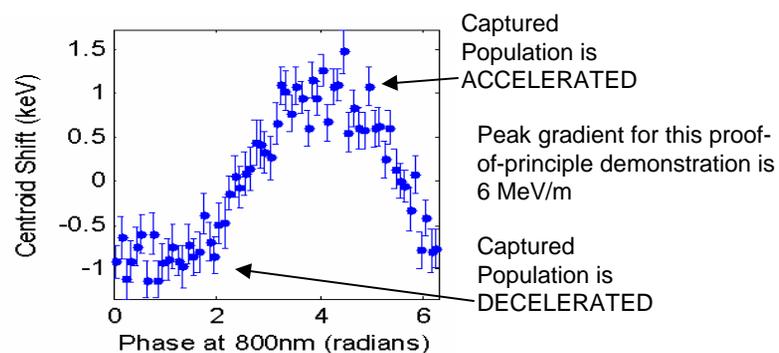
C. M. Sears, *et al*, *Phys. Rev. Lett.*, **95**, 194801 (2005).

Experiments at the recently commissioned E163 Facility at the NLCTA



## Attosecond Pulse Train Production

C. M. Sears, *et al*, *Phys. Rev. ST-AB*, **11**, 061301, (2008).

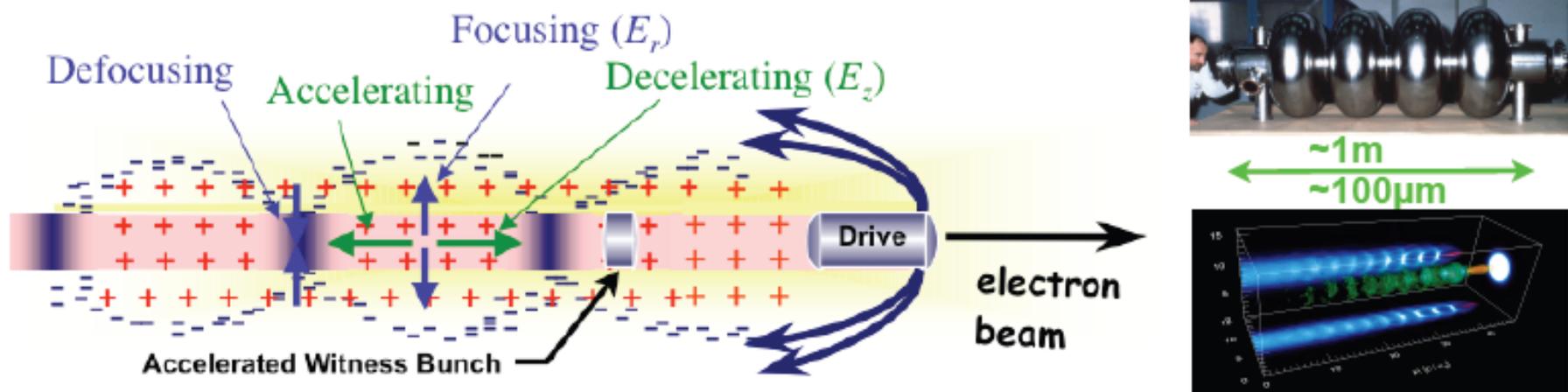


## Particle Acceleration with Visible Light

Electrons were first bunched into sub-femtosecond bunchlets, then captured with attosecond precision and accelerated with light

These experiments demonstrate acceleration of electrons on attosecond timescales and micron dimensions, essential steps along the path towards making direct laser acceleration practical.

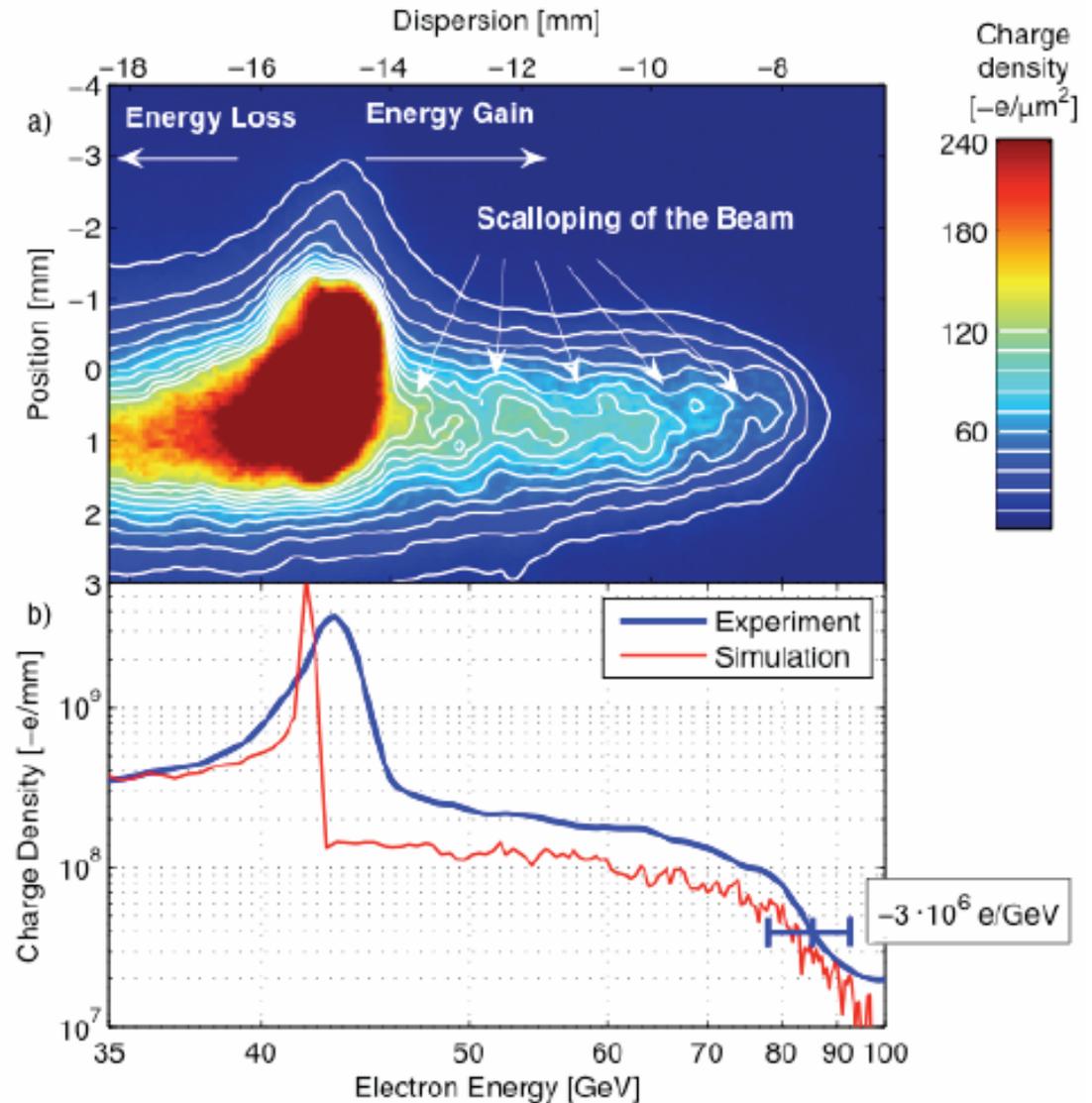
# The Beam Driven Plasma Wakefield Accelerator



- Plasma wave/wake excited by a relativistic particle bunch
- Plasma  $e^-$  expelled by space charge forces  $\Rightarrow$  energy loss + focusing ( $> \text{MT/m}$ )  
(ion channel formation  $r_c \approx (n_b/n_e)^{1/2} \sigma_r$ )
- Plasma  $e^-$  rush back on axis  $\Rightarrow$  energy gain ( $> \text{GeV/m}$ )
- Linear scaling:  $E_{acc} \approx 110 (\text{MeV/m}) \frac{N/2 \times 10^{10}}{(\sigma_z / 0.6 \text{mm})^2} \frac{1}{\sigma_z^2}$   
@  $k_{pe} \sigma_z \approx \sqrt{2}$
- Plasma Wakefield Accelerator (PWFA) = Transformer

# E-167: Energy Doubling with a Plasma Wakefield Accelerator in the FFTB (April 2006)

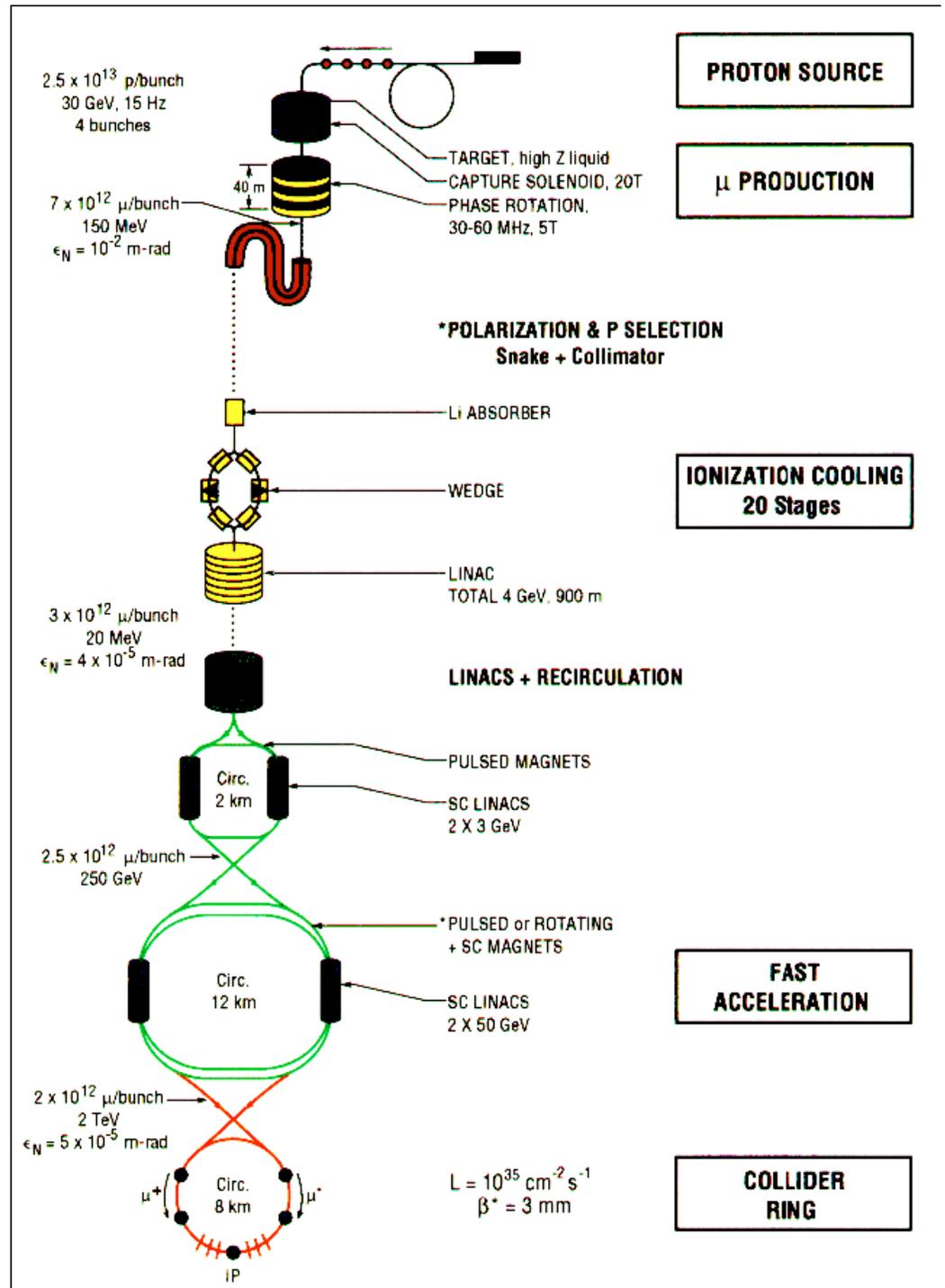
- \* Acceleration gradients of  $\sim 50$  GV/m (3000 x SLAC)
  - Doubled energy of 45 GeV beam in 1 meter plasma
  - Record Energy Gain
  - Highest energy electrons ever produced at SLAC
  - Significant advance in demonstrating the potential of plasma accelerators



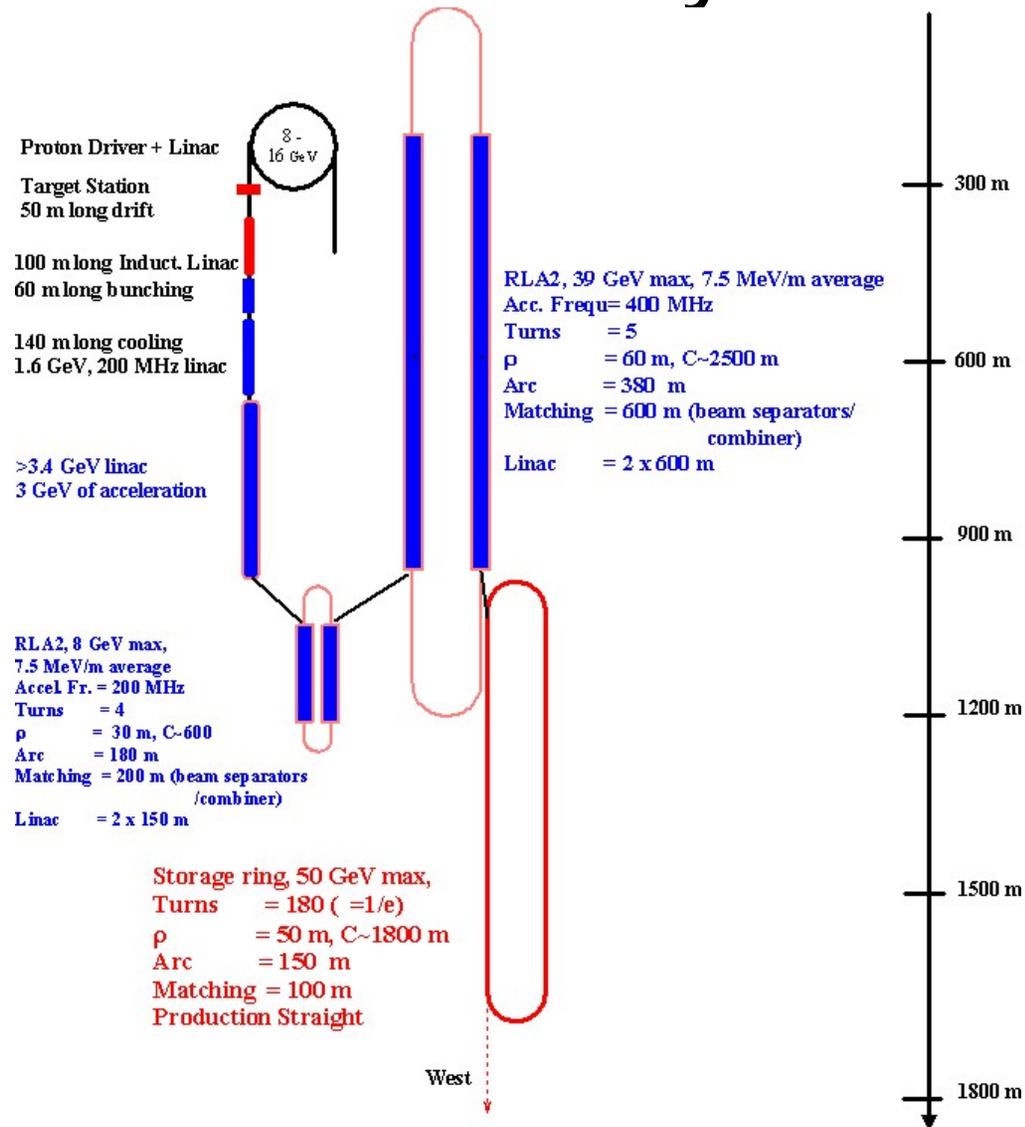
*Nature* 445 741 15-Feb-2007

# Muon Collider

- Concept shown ->
- It runs in pulsed mode like a linear collider.
- But lower synchrotron radiation permits bending during acceleration.
- Also permits many collisions each cycle before the muons decay.
- Problem: generating and cooling the muon beams to get high enough brightness.
- Start out accelerating a football sized object.
- Multiple collisions are required to get the luminosity up to standard, even with the most ambitious estimates of cooling.

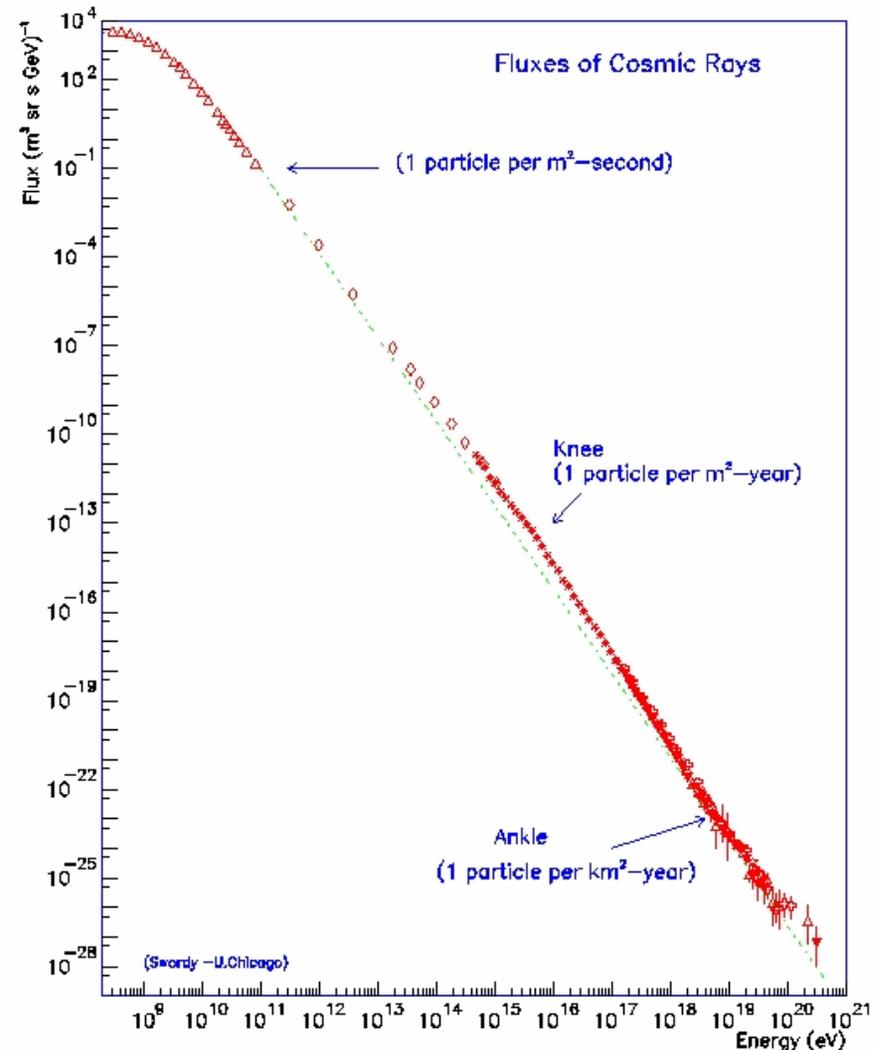


# Neutrino Factory Concept



# Back to the Cosmic Ray Spectrum

- Maybe we should compare the cm energy of one of the highest energy cosmic rays hitting a proton.
- In this case,  $10^{20}$  eV corresponds to  $\sim 500$  TeV in the cm.
- Compare to 14 TeV for LHC.
- Divide by 10 to compare to 3 TeV aspirations for CLIC.
- I guess the Earth based accelerators aren't doing so bad after all.
- And the Earth is in the Cosmos, so they are all 'Cosmic' accelerators in a sense.
- And we are definitely winning in brightness, flux and luminosity...at least in this part of the cosmos.



# Acknowledgements

- History: Alex Chao and Handbook
- Plasma Acceleration: Mark Hogan
- High Gradient Acceleration: Sami Tantawi
- Laser Acceleration: Eric Colby
- ILC info: Chris Adolphsen

# Reference to references

## HANDBOOK OF ACCELERATOR PHYSICS AND ENGINEERING

(3rd Printing)

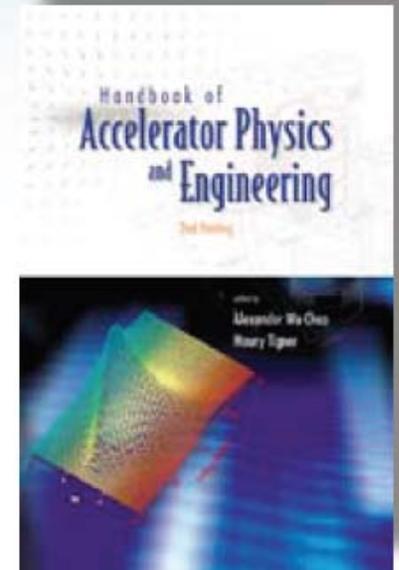
edited by Alexander Wu Chao (Stanford Linear Accelerator Center) &  
Maury Tigner (Cornell University)

Edited by internationally recognized authorities in the field, this expanded edition of the bestselling Handbook first published in 1999 is aimed at the design and operation of modern accelerators including Linacs, Synchrotrons and Storage Rings. It is intended as a vade mecum for professional engineers and physicists engaged in these subjects. With a collection of 2200 equations, 345 illustrations and 185 tables, here one will find, in addition to the common formulae of previous compilations, hard to find, specialized formulae, recipes and material data pooled from the lifetime experience of many of the world's most able practitioners of the art and science of accelerators.

The eight chapters include both theoretical and practical matters as well as an extensive glossary of accelerator types. Chapters on beam dynamics and electromagnetic and nuclear interactions deals with linear and nonlinear single particle and collective effects including spin motion, beam-environment, beam-beam and intrabeam interactions. The impedance concept and calculations are dealt with at length as are the instabilities associated with the various interactions mentioned. A chapter on operational considerations deals with orbit error assessment and correction. Chapters on mechanical and electrical considerations present material data and important aspects of component design including heat transfer and refrigeration. Hardware systems for particle sources, feedback systems, confinement and acceleration (both normal conducting and superconducting) receive detailed treatment in a subsystems chapter, beam measurement techniques and apparatus being treated therein as well. The closing chapter gives data and methods for radiation protection computations as well as much data on radiation damage to various materials and devices.

A detailed index is provided together with reliable references to the literature where the most detailed information available on all subjects treated can be found.

**Readership:** Physicists, engineers and practitioners in accelerator science.



740pp • May 2006

978-981-02-3500-0

981-02-3500-3

US\$99 £62



