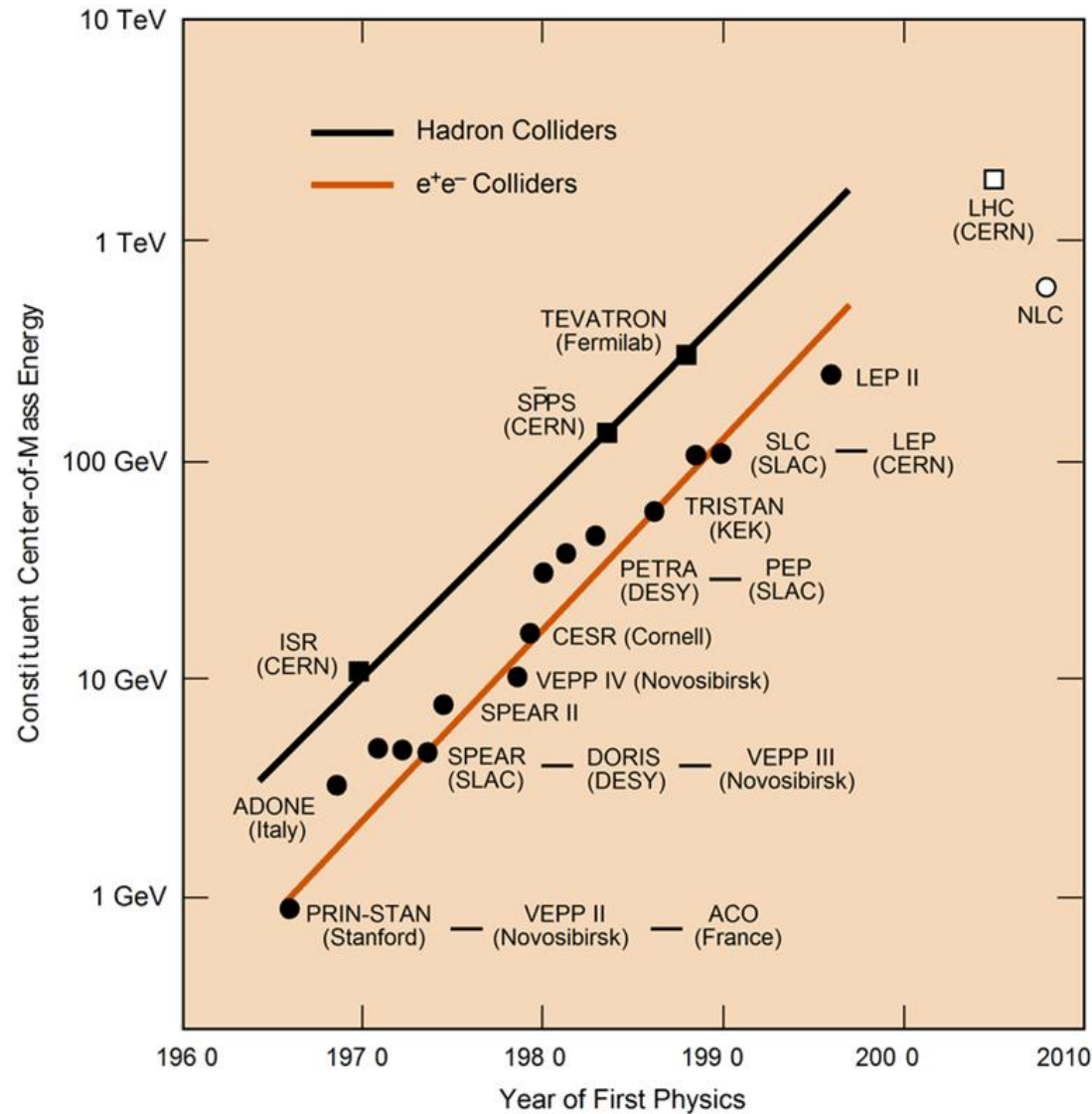


Physics 610

Adv Particle Physics

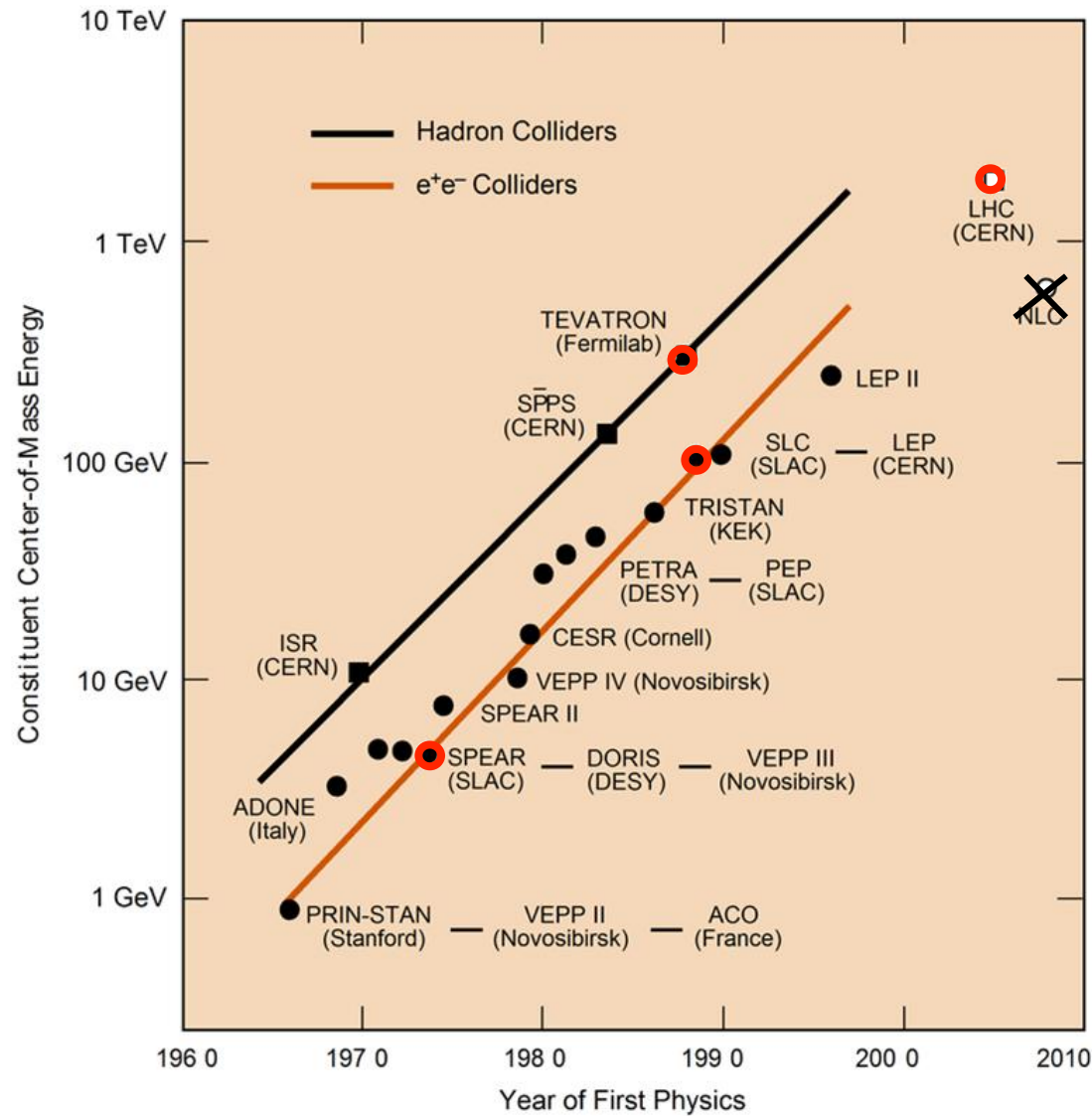
April 2014

Development of Accelerators



Symmetry
Magazine

Development of Accelerators



Symmetry
Magazine

The Largest Colliders

- Largest and highest energy colliders
 - Fermilab Tevatron (p/anti-p w/ 1 TeV beam energy - until 2011)
 - CERN Ring
 - LEP II (electron/positron with 104 GeV beam energy)
 - Large Hadron Collider -LHC (protons colliding with 3.5-4 TeV beam energy) - first collisions in 2009 - ~ 6.5-7 TeV beam in 2015



Large Hadron Collider

- Goal: 14 GeV center-of-mass collisions
began operations in 2008
- Luminosity lifetime limited by:
 - beam lifetime limit due to interactions of the two beams at the IPs
($\rightarrow$ total nuclear cross section)
 - beam size blowup due to intra-beam scattering
 - reduction in the beam intensity due to rest gas scattering
 - beam size reduction due to synchrotron radiation damping
 - beam size blowup due to the non-linear beam-beam interactions

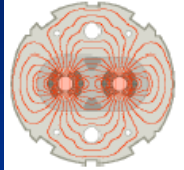


LHC Luminosity Design Lifetime

- Luminosity lifetime due to 2 high luminosity insertions (beam-beam interaction only; decay to $1/e$ of initial luminosity)
 - 84 h
- Vacuum beam lifetime
 - 100 h
- Horizontal intra-beam scattering (IBS) growth time at injection (without 200 MHz RF)
 - 146 h
- Longitudinal IBS growth time at injection
 - 94 h
- Horizontal IBS growth time at 7 TeV
 - 300 h
- Longitudinal IBS growth time at 7 TeV
 - 180 h
- Total luminosity lifetime due to IBS, beam-beam, restgas [radiation damping neglected]
 - 28 h



If the LHC did not use superconductivity

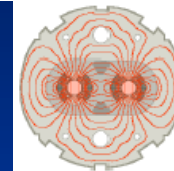


The LHC has a circumference of **26.7** km, with 20km filled with superconducting magnets operating at 8.3 T. The refrigerators producing the liquid helium to cool the magnets consume **40 MW** of power.

An equivalent machine with classical electromagnets would have a circumference of **100** km and would consume **1000 MW** of power.



LHC: Some of the Technical Challenges

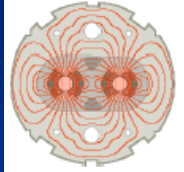


Circumference (km)	26.7	100-150m underground
Number of Dipoles	1232	Cable Nb-Ti, cold mass 37million kg
Length of Dipole (m)	14.3	
Dipole Field Strength (Tesla)	8.4	Results from the high beam energy needed
Operating Temperature (K)	1.9	Superconducting magnets needed for the high magnetic field Super-fluid helium
Current in dipole sc coils (A)	13000	Results from the high magnetic field 1ppm resolution
Beam Intensity (A)	0.5	$2.2 \cdot 10^{-6}$ loss causes quench
Beam Stored Energy (MJoules)	362	Results from high beam energy and high beam current 1MJ melts 2kg Cu
Magnet Stored Energy (MJoules)/ octant	1100	Results from the high magnetic field
Sector Powering Circuit	8	1612 different electrical circuits

How to Deal with the LHC self Destructive Power

- In case of a problem the stored energy in the magnets and in the beam must be transferred to and dissipated in a safe, clearly defined place
- **Magnet Protection system**
 - “Quench” Protection (measures resistance)
 - Energy dump triggered and energy dissipated as heat in resistors (after of course aborting the beams)
- **Machine Protection System**
 - All critical elements which could provoke a beam loss are equipped with an emergency beam abort signal which triggers the beam dump system. There is also a beam loss monitoring system all around the circumference which will abort the beam if anomalous losses occur
 - **The beam dump system is the last safety net**

September 10, 2008; It worked!



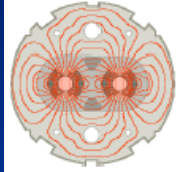
December 10, 2012

S. Myers Heraeus

10



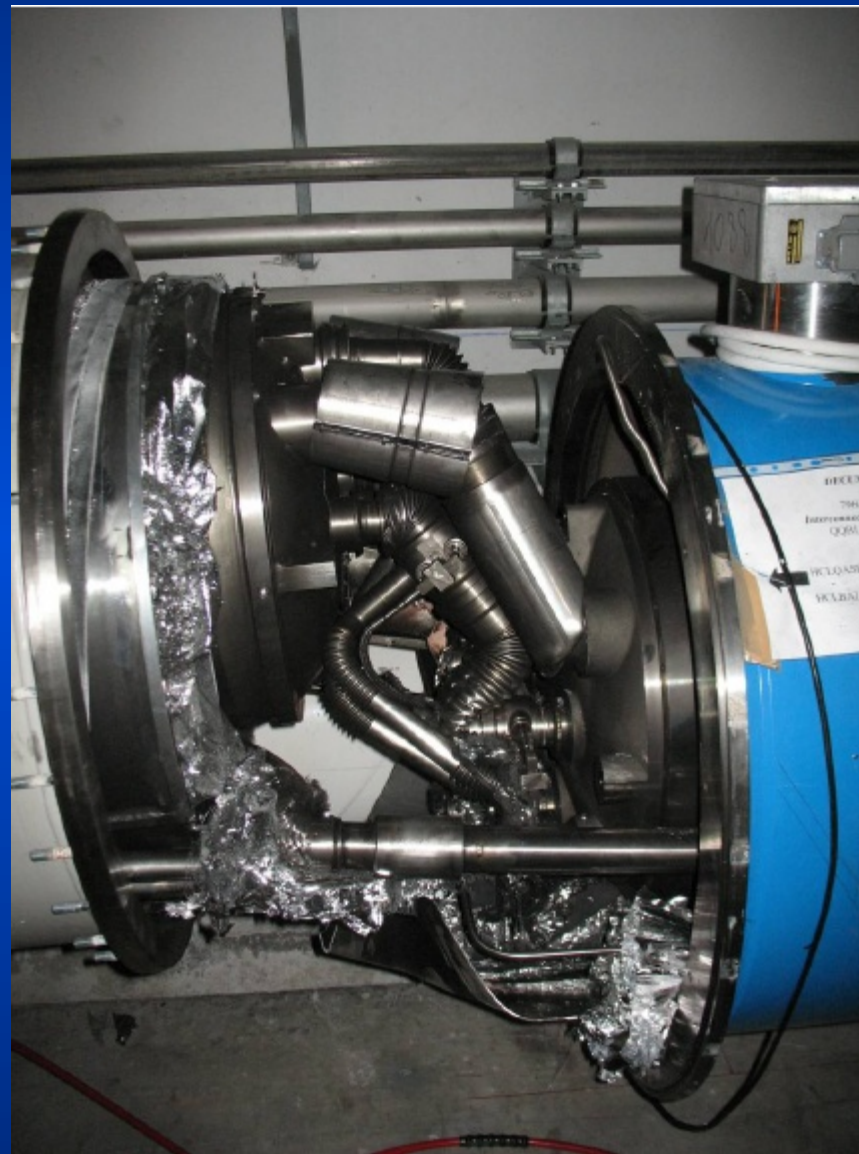
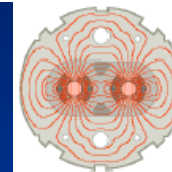
And 9 days later



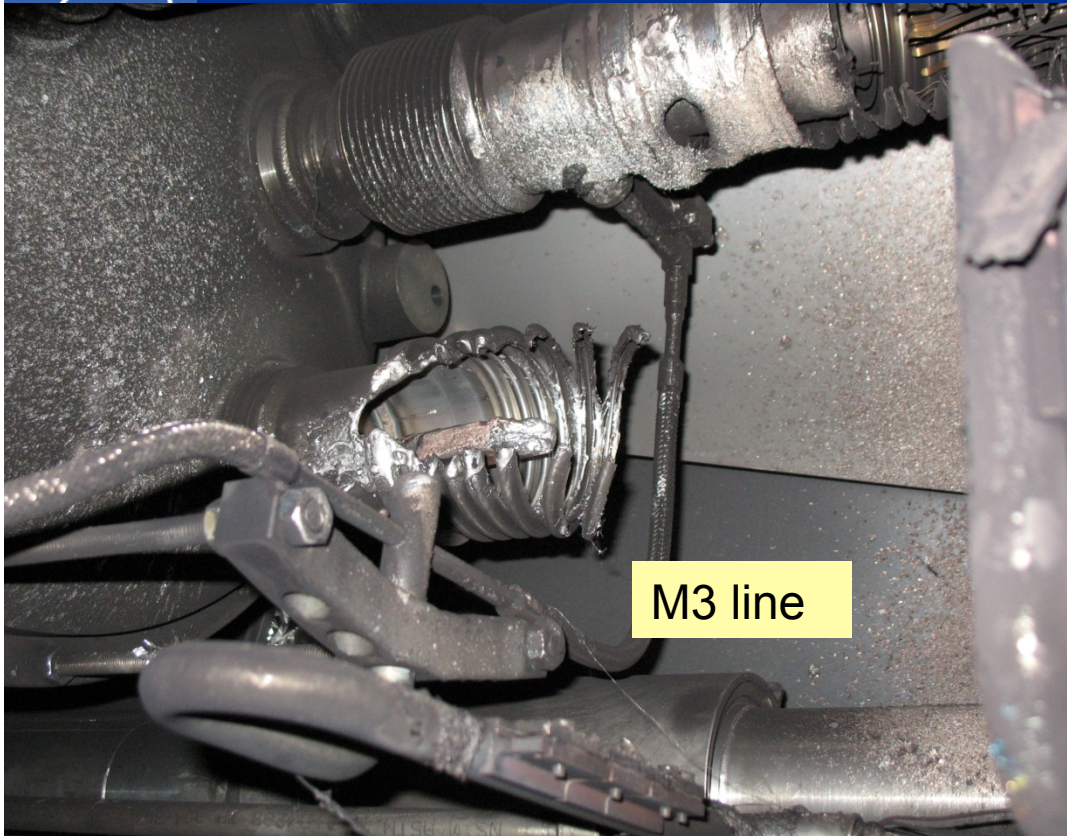
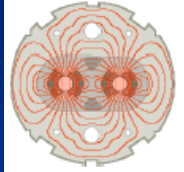
- Making the last step of dipole circuit in sector 34, to 9.3kA
- At 8.7kA, development of resistive zone in the dipole bus bar splice between Q24 R3 and the neighbouring dipole
- Electrical arc developed which punctured the helium enclosure

One inter-magnet connector (out of 100,000) was badly soldered and...

The magnet protection system did not protect

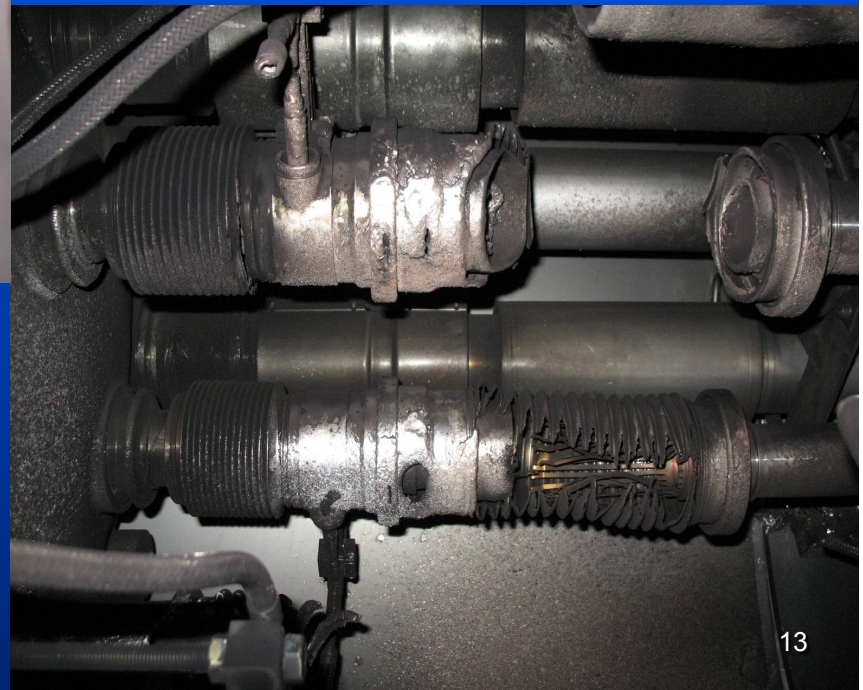


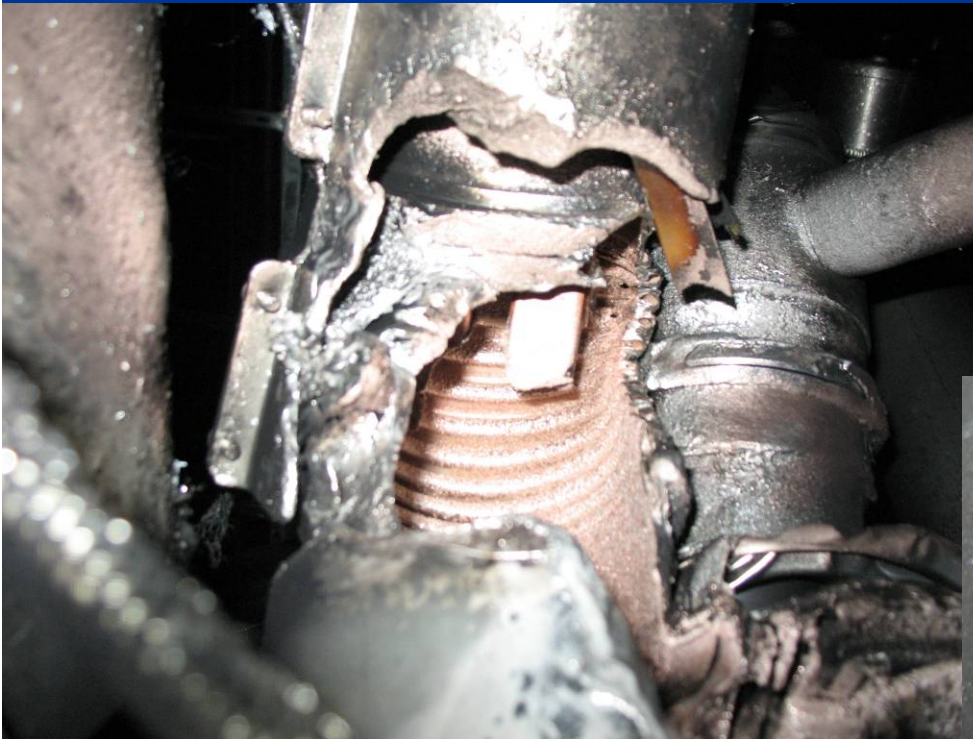
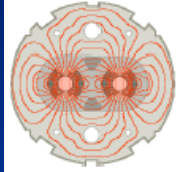
Electrical arc between C24 and Q24



M3 line

V lines



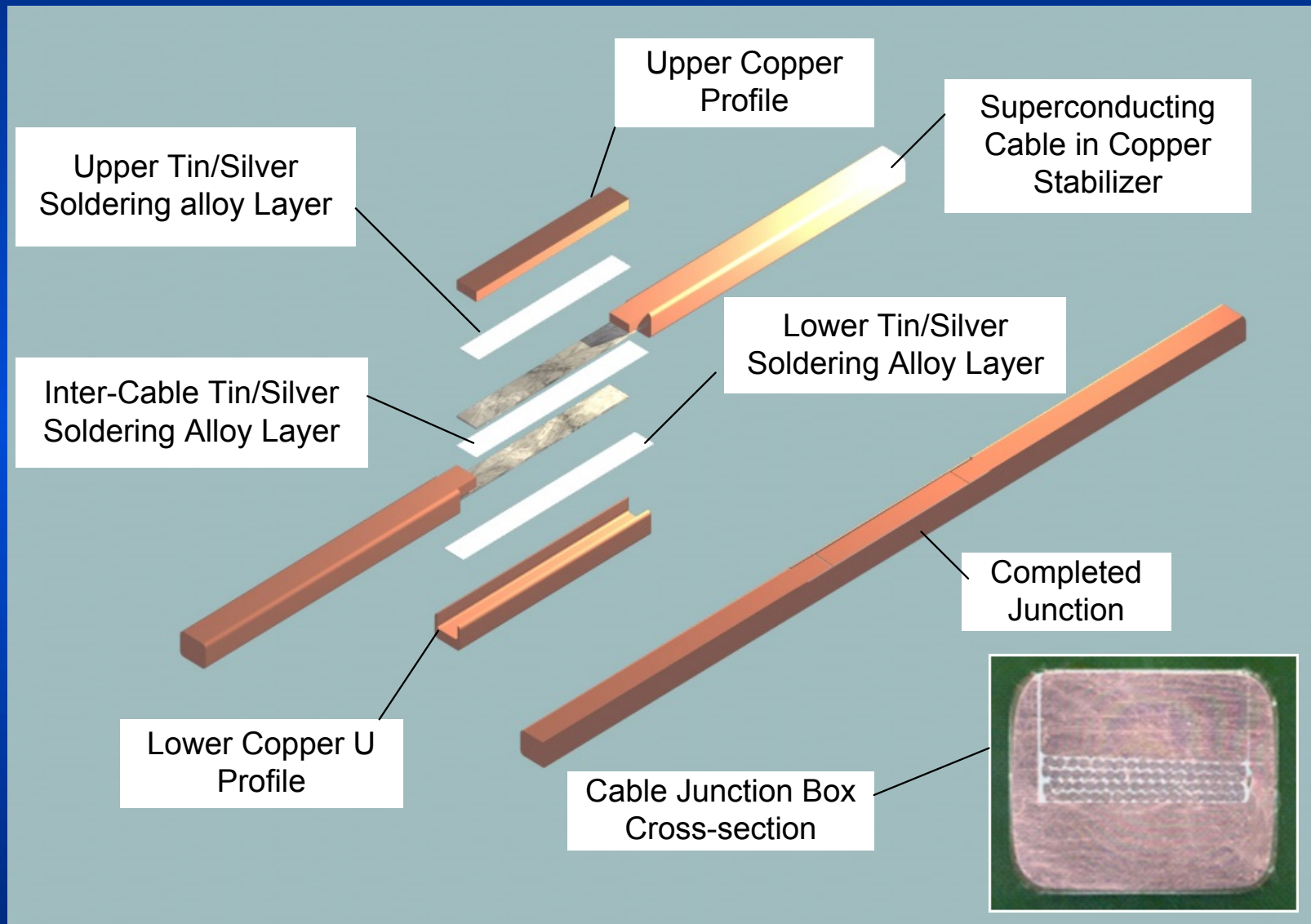
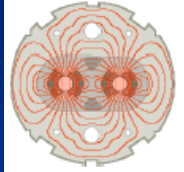


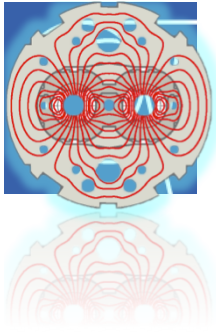
QQBI.27R3 M3 line

QBBI.B31R3 M3 line

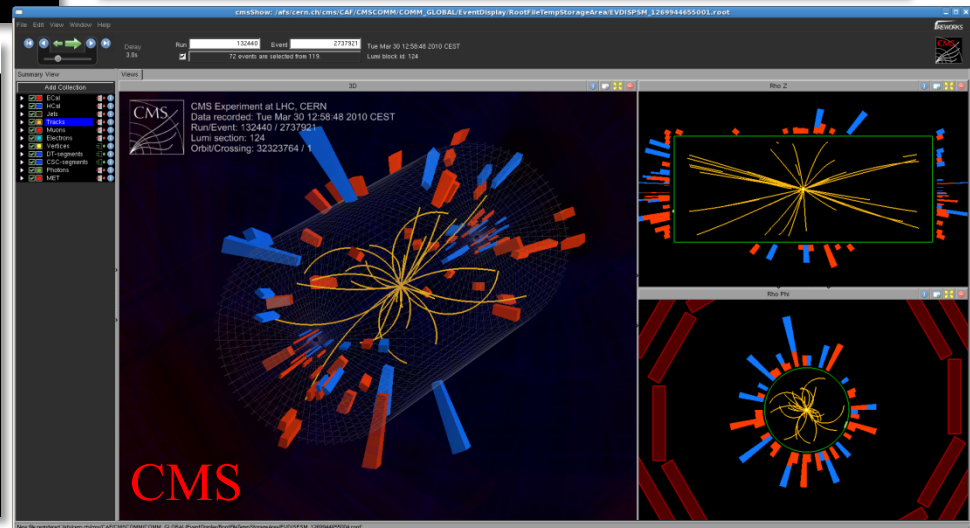
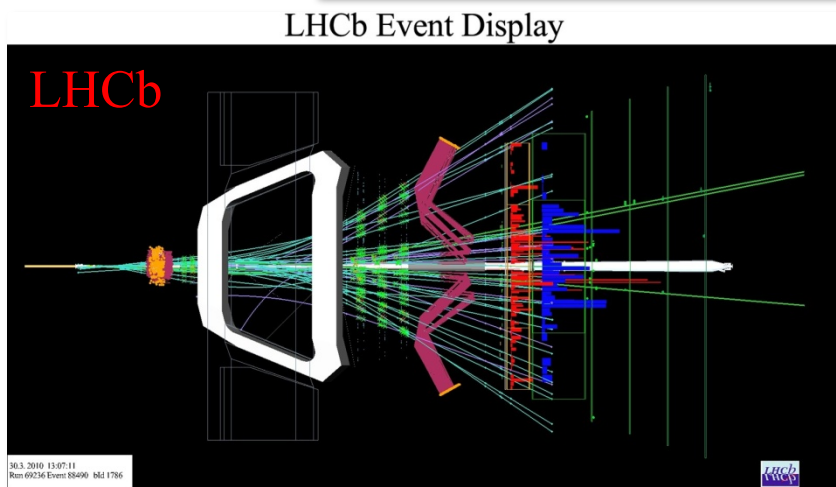
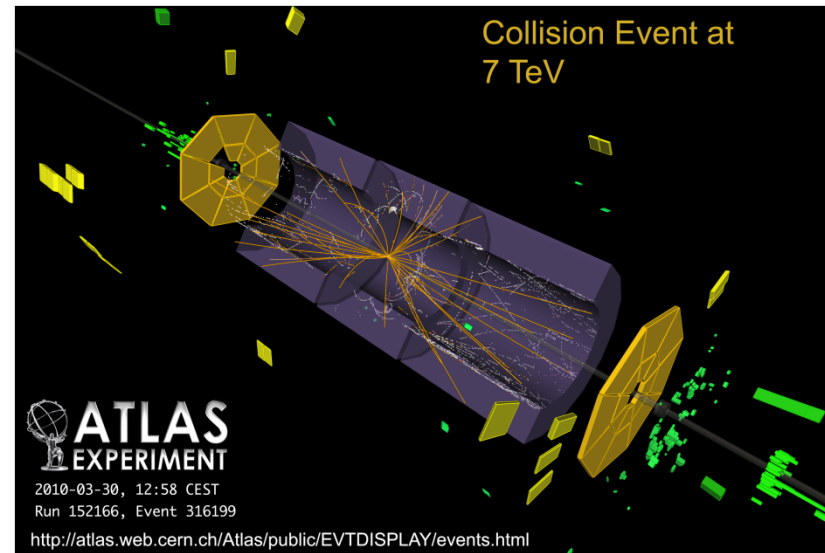
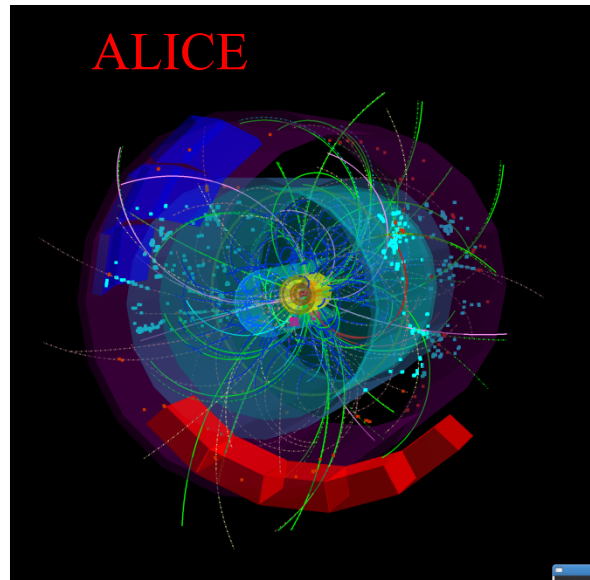
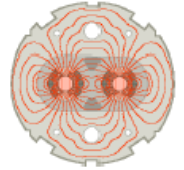


Bus bar splice

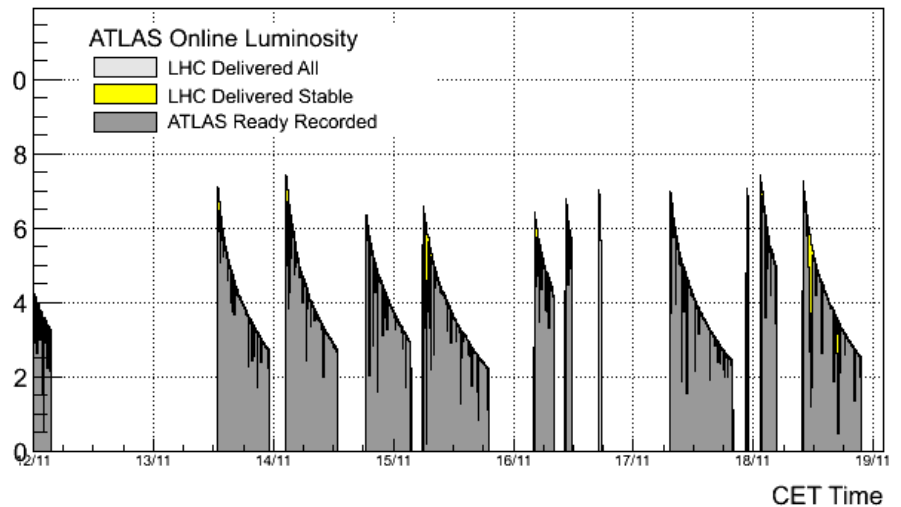
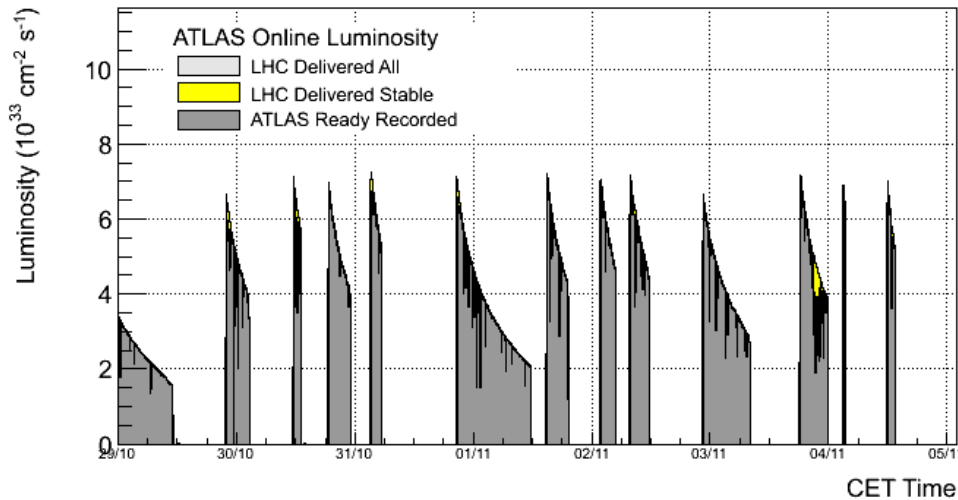
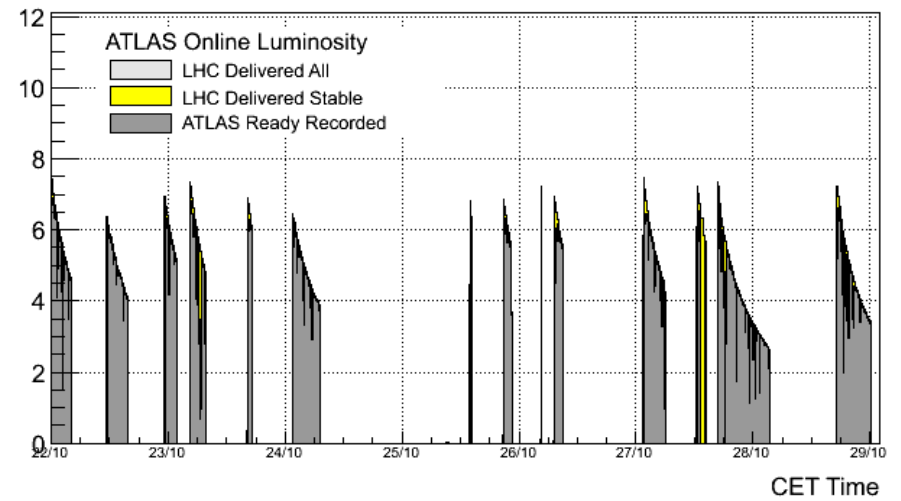
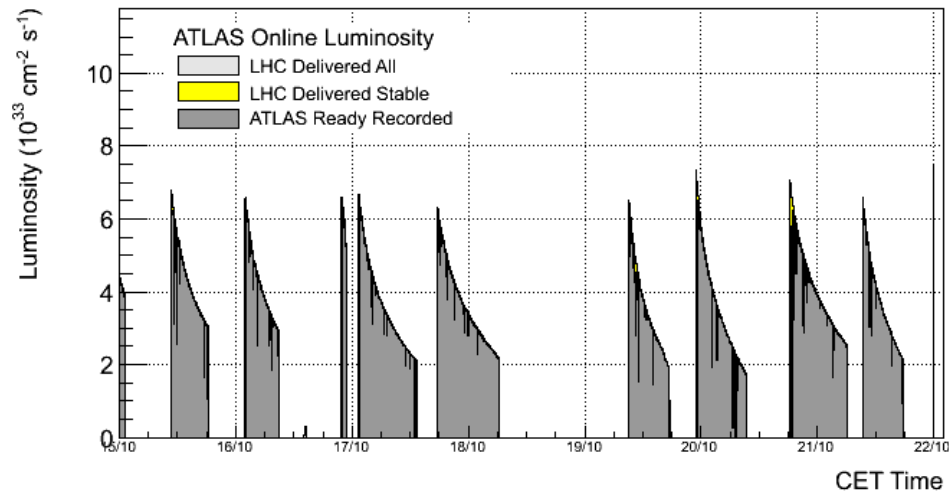




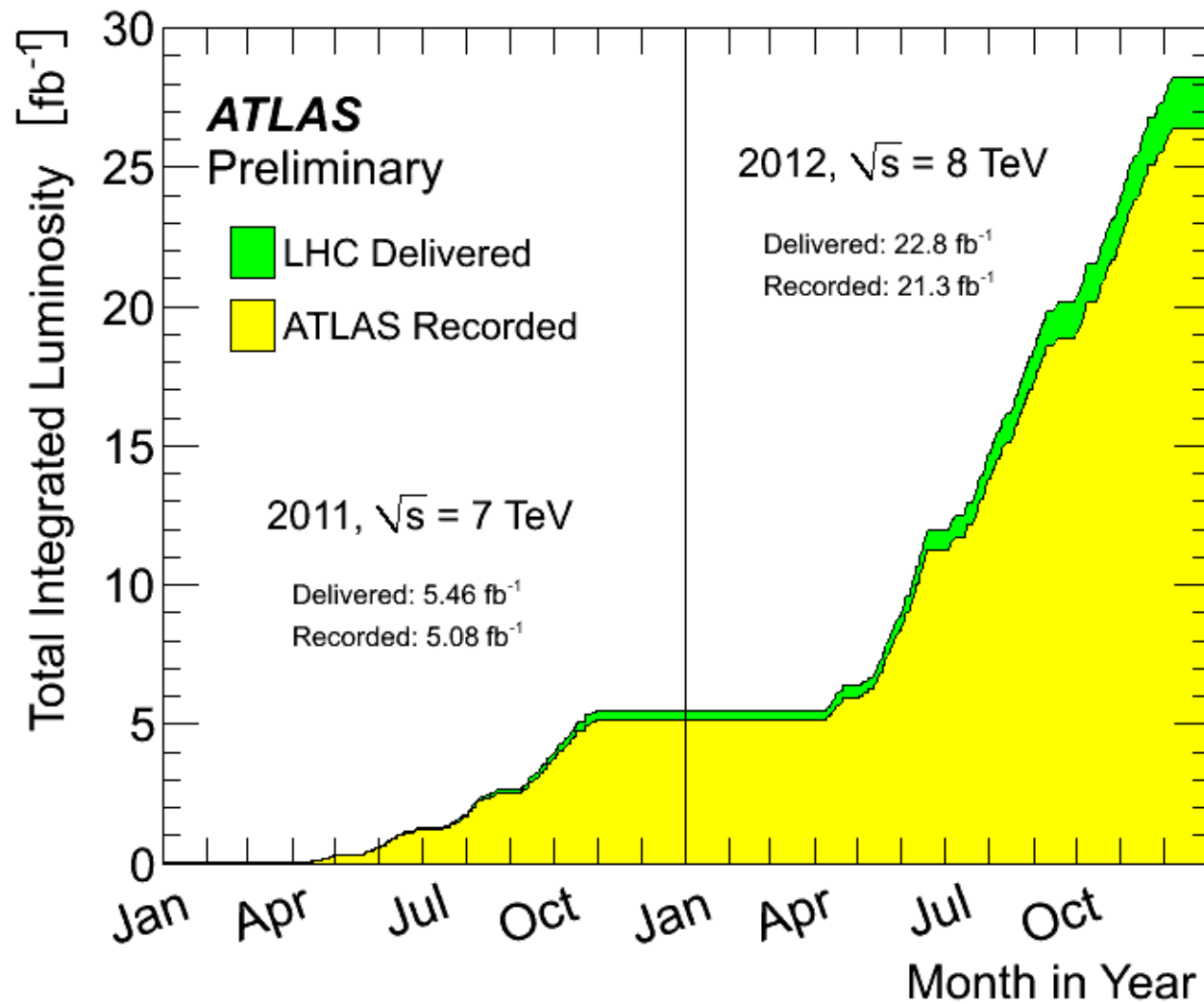
LHC: First collisions at 7 TeV on 30 March 2010



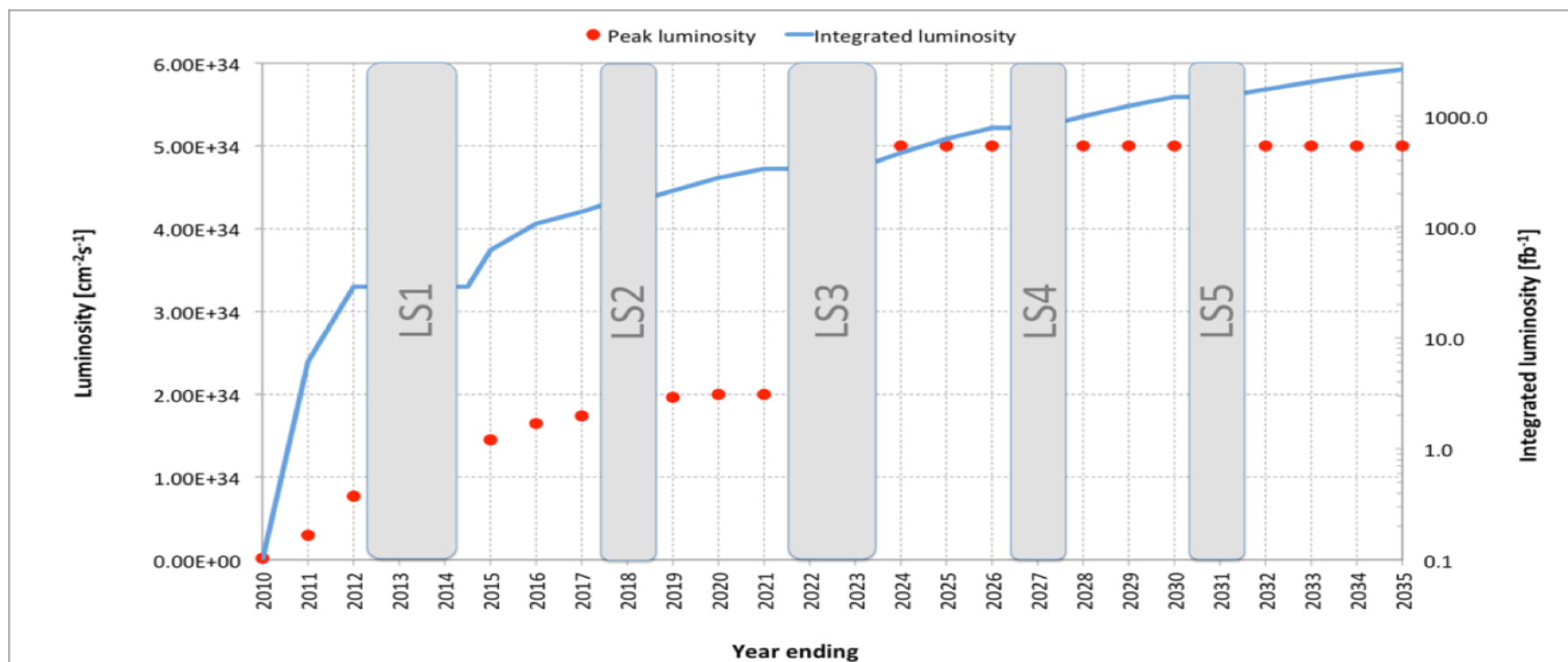
Typical Luminosities - 2012



2011-12 Summary



The plan of HL-LHC (baseline)

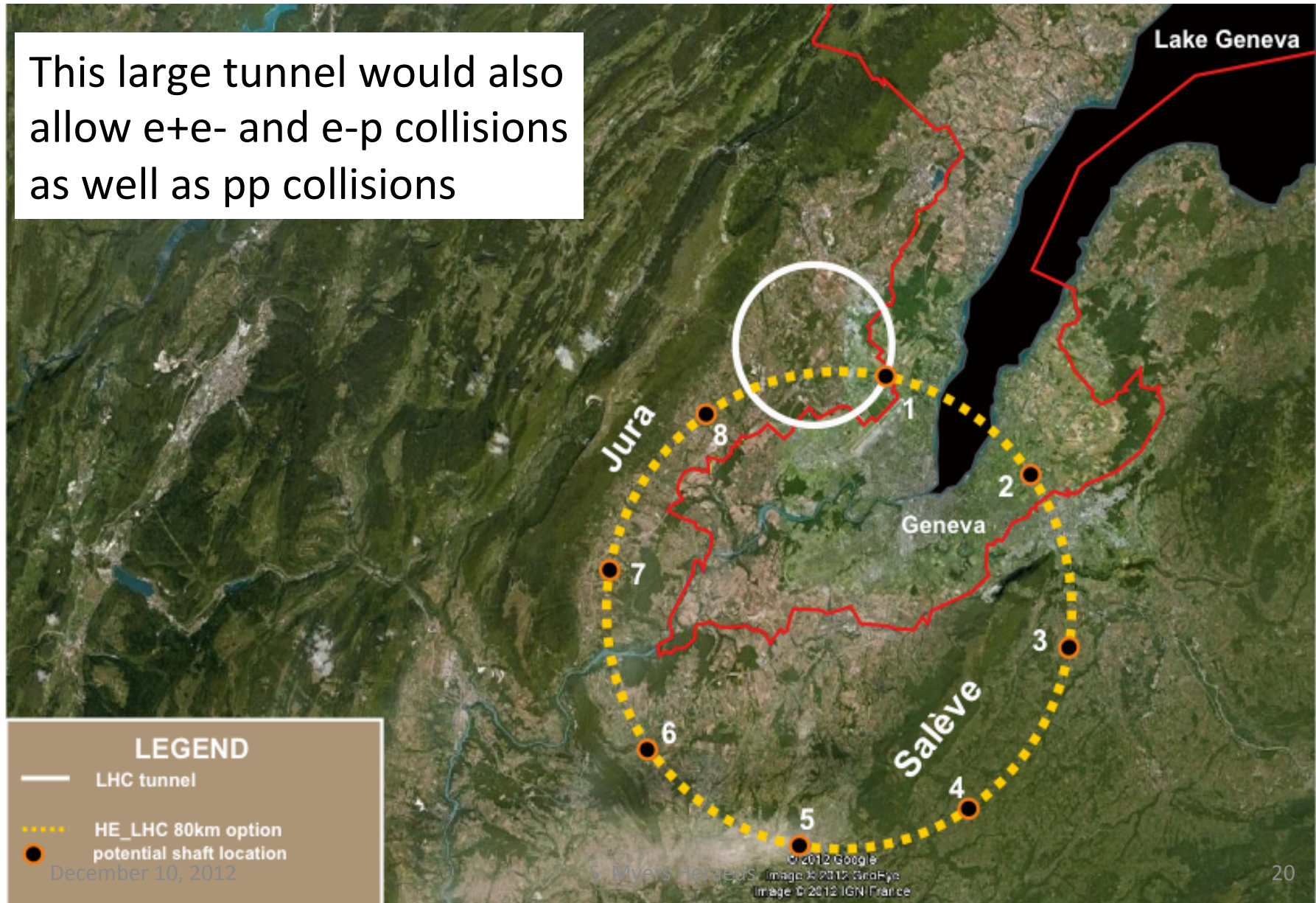


Levelling at $5 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$: 140 events/crossing in average, at 25 ns; several scenarios under study to limit to $1.0 \rightarrow 1.3 \text{ event/mm}$
(“Pile-up at HL-LHC and possible mitigation” Stephane Fartoukh on Wed. 2nd Oct.)

Total integrated luminosity of 3000 fb^{-1} for p-p by 2035, with LSs taken into account and 1 month for ion physics per year.

HE-LHC and SHE-LHC

This large tunnel would also allow e^+e^- and e - p collisions as well as pp collisions



Synchrotron Radiation

Radiation emitted by an electric charge travelling in a magnetic field, due to transverse acceleration. The total energy loss is given by

$$dW/dt = (2c/3)e^2\beta^4[E/(m_0c^2)]^4(1/r^2),$$

Consequently, the mean energy loss of electrons in a circular orbit due to synchrotron radiation is (per revolution)

$$W_r = t_r(dW/dt) = (4\pi/3)e^2\beta^3\gamma^4/r = CE^4/r$$

$$C = 8.85 \times 10^{-5} \quad [\text{GeV}^{-3}/\text{m}].$$

Synchrotron radiation produces a broad energy spectrum at low energies;

above a *critical energy* $\epsilon_c = 3\hbar c\gamma^3/2r$ the falloff is exponential.

ϵ_c is also the median of the power distribution

LHC Synchrotron Radiation Effects

S.R. Power deposition on cryogenic system

Photon stimulated outgassing -> dynamic pressure increase

Photoelectron production -> electron cloud effect

Power dissipation by bunched beam

Beam Induced Multipacting (BIM)

Electron stimulated outgassing

Beneficial effects of S.R. :

Cleaning of the vacuum system (beam cleaning effect)

Reduction of secondary electron coefficient by photons/
electrons

(beam scrubbing)

For the VLHC : Radiation damping -> Increase of Luminosity

Comparison of S.R Characteristics

		LEP200	LHC	SSC	HERA	VLHC
Beam particle		e ⁺ e ⁻	p	p	p	p
Circumference	km	26.7	26.7	82.9	6.45	95
Beam energy	TeV	0.1	7	20	0.82	50
Beam current	A	0.006	0.54	0.072	0.05	0.125
Critical energy of SR	eV	$7 \cdot 10^5$	44	284	0.34	3000
SR power (total)	kW	$1.7 \cdot 10^4$	7.5	8.8	$3 \cdot 10^{-4}$	800
Linear power density	W/m	882	0.22	0.14	$8 \cdot 10^{-5}$	4
Desorbing photons	s ⁻¹ m ⁻¹	$2.4 \cdot 10^{16}$	$1 \cdot 10^{17}$	$6.6 \cdot 10^{15}$	none	$3 \cdot 10^{16}$

Electron Synchrotrons

- Limited by growing synchrotron radiation
 - energy radiated per particle per turn

$$\Delta E = \frac{4\pi}{3} \left(\frac{e^2 \beta^3 \gamma^4}{\rho} \right)$$

- since energy loss scales as m^{-4} , radiation is $(M/m)^4 \approx 10^{13}$ times larger for electrons than protons
- LEP ($E_{\text{beam}} = 104 \text{ GeV}$) will be highest energy electron synchrotron
 - $\Delta E = 3.5 \text{ GeV}$
- This effect motivated the large electron linac at SLAC in the 1960's

Stanford Linear Accelerator Center (SLAC)

Located on Stanford campus

Operated by Stanford University under an agreement with DOE

Nobel Prizes

1976 – Burton Richter

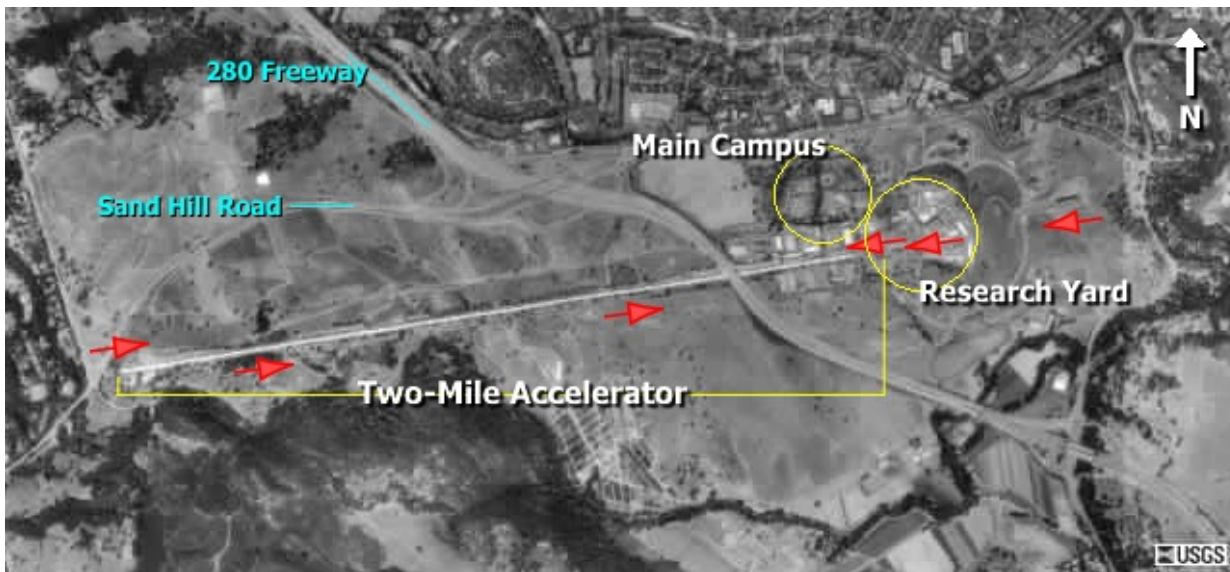
1990 - Richard Taylor, Jerome Friedman and Henry Kendall

1995 – Martin Perl



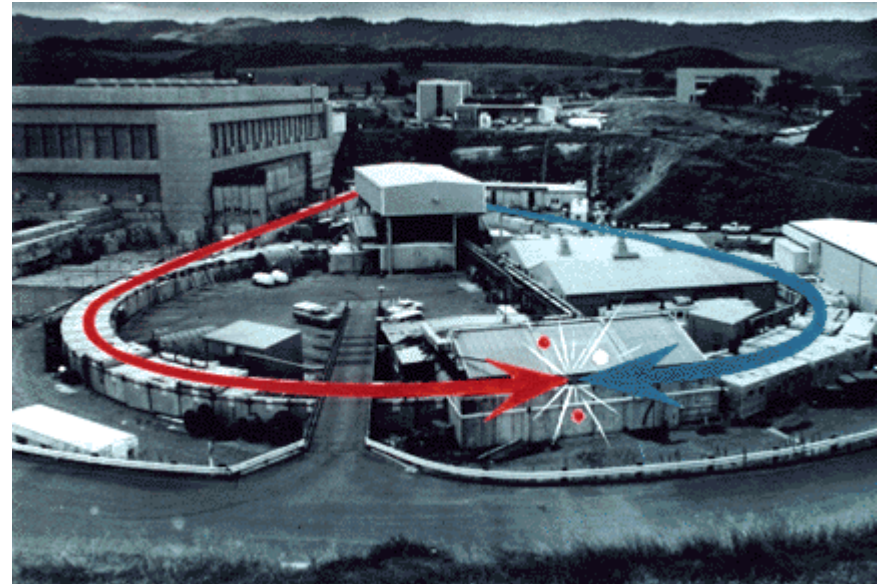
Electron Linear Accelerators

- SLAC was built for 25 GeV electrons with 240 klystrons
 - short 2 microsecond bursts of intense power at 60 Hz
 - eventually exceeded 50 GeV by shortening the pulse
 - also 120 Hz
- Avoids synchrotron radiation
- Loses advantage of multiple passes in circular accelerator



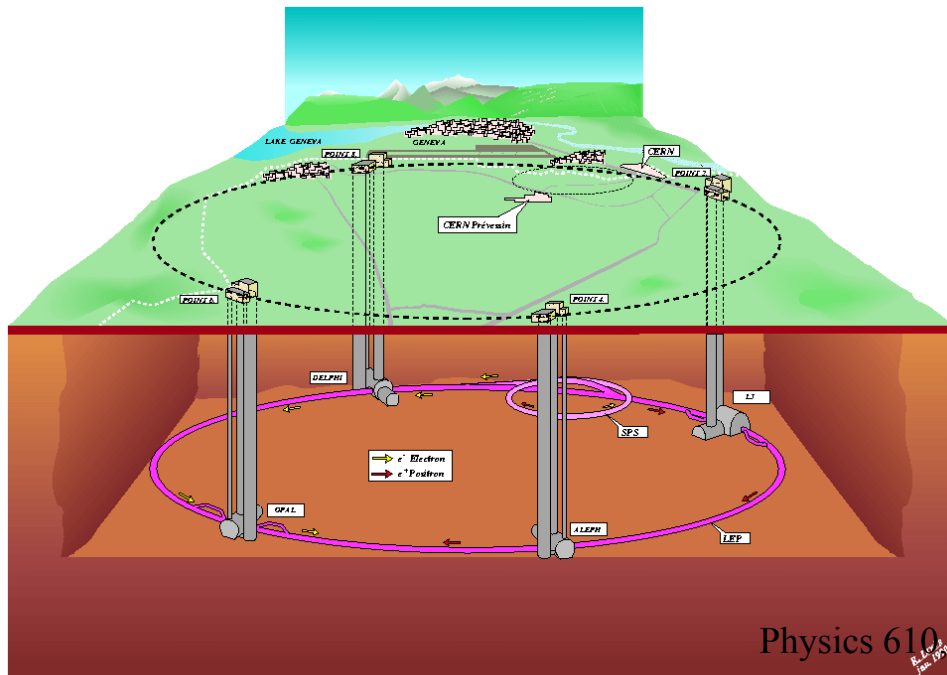
SPEAR Storage Ring & Collider

- SPEAR
 - completed in 1972
 - 80 meter diameter
 - E_{beam} up to 4 GeV
 - charm discovered in 1974
 - 1990 - dedicated to synchrotron radiation

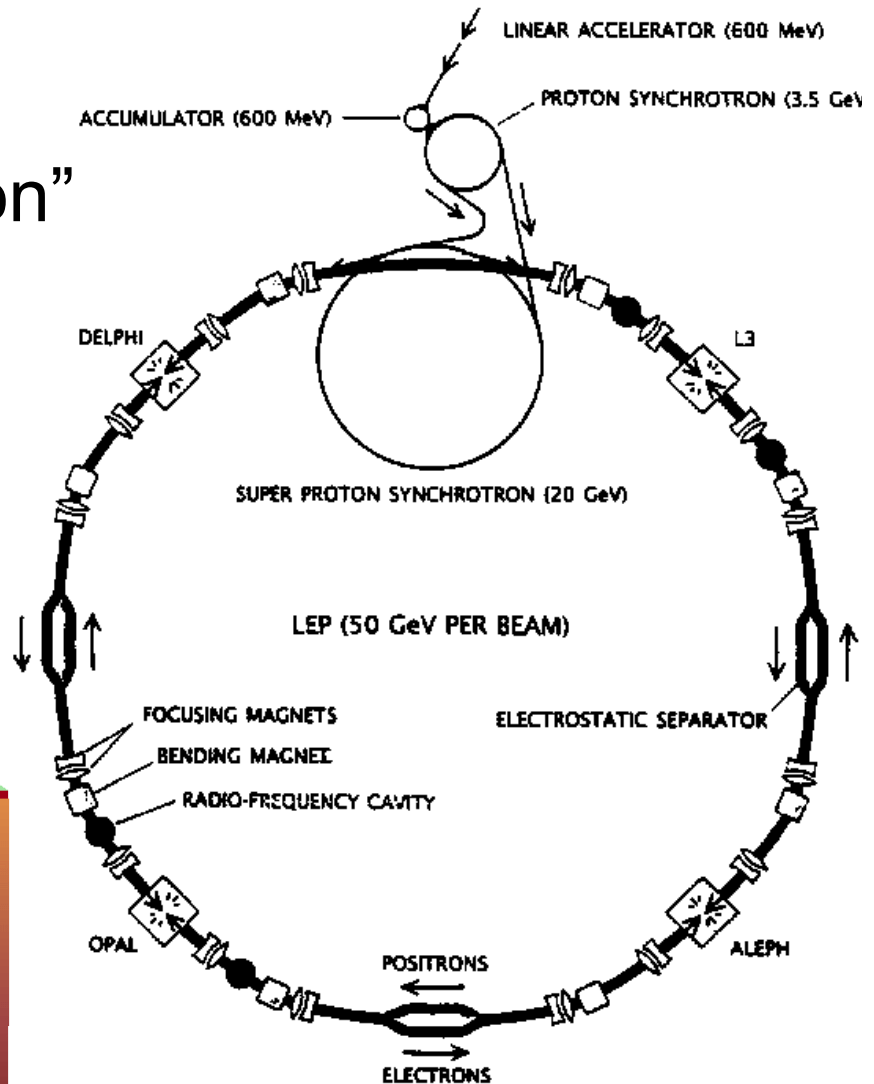


LEP Storage Ring

- LEP =
“large electron positron”
storage ring
- 26.67 km circumference



Physics 610 accelerators



LEP LUMINOSITY REVISITED: DESIGN AND REALITY

Ralph W. Assmann for the LEP team, CERN, Geneva, Switzerland

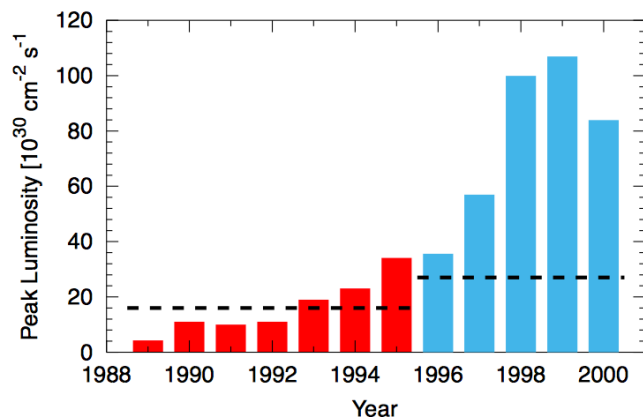


Figure 1: Peak luminosity for each year of LEP operation. The dashed lines indicate the design luminosities for LEP1 (red bars) and LEP2 (blue bars).

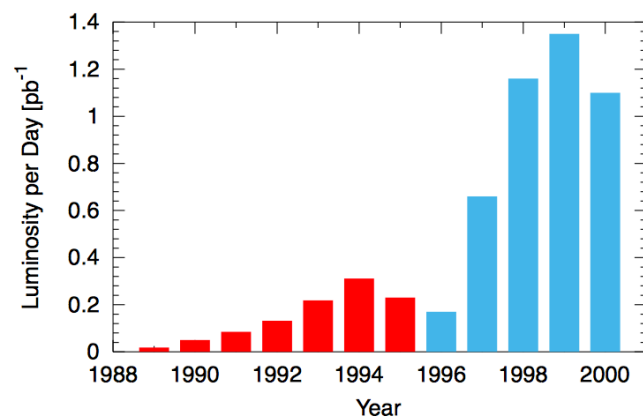


Figure 2: Average luminosity delivered per scheduled day of physics for each year of LEP operation. The red bars indicate LEP1 running, the blue bars LEP2 running.

Parameter	Design LEP1 / LEP2	Achieved LEP1 / LEP2
Bunch current	0.75 mA	1.00 mA
Total beam current	6.0 mA	8.4 / 6.2 mA
Vertical beam-beam parameter	0.03	0.045 / 0.083
Emittance ratio	4.0 %	0.4 %
Maximum luminosity	16 / 27 $10^{30} \text{ cm}^{-2} \text{ s}^{-1}$	34 / 100 $10^{30} \text{ cm}^{-2} \text{ s}^{-1}$
IP beta function β_x	1.75 m	1.25 m
IP beta function β_y	7.0 cm	4.0 cm
Max. beam energy	95 GeV	104.5 GeV
Av. RF gradient	6.0 MV/m	7.2 MV/m

Synchrotron Radiation

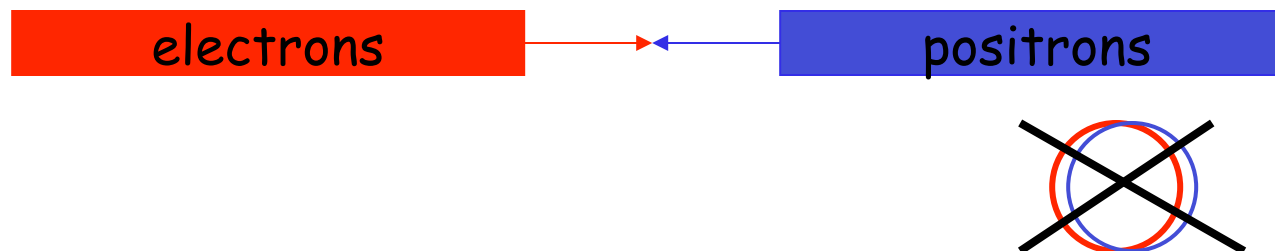
- Acceleration of electrons in a circular accelerator is plagued by Nature's resistance to acceleration
 - Synchrotron radiation
 - $\Delta E = 4\pi/3 (e^2 \beta^3 \gamma^4 / R)$
per turn
 $\gamma = E/m$, so $\Delta E \sim E^4/(m^4 R)$
 - LEP2
 $E \sim 100 \text{ GeV}$ $\Delta E = 3.5 \text{ GeV}$ Power $\sim 20 \text{ MW}$

Synchrotron Radiation

- Consider a 500 GeV ring
 - $\Delta E = 4\pi/3 (e^2\beta^3\gamma^4 / R)$
per turn
 $\gamma = E/m$, so $\Delta E \sim E^4/(m^4 R)$
 - Scale from LEP2
 - LEP2 ($E \sim 104.5$ GeV) $\Delta E = 3.5$ GeV Power ~ 20 MW
- For $E = 500$ GeV - assuming only LEP2 currents
 - $R = 4.2$ km Power $\sim (500/104.5)^4 20$ MW $\sim 10,500$ MW
 - $R = 100$ km Power $\sim 10,500$ MW $\cdot 4.2 / 100 \sim 441$ MW

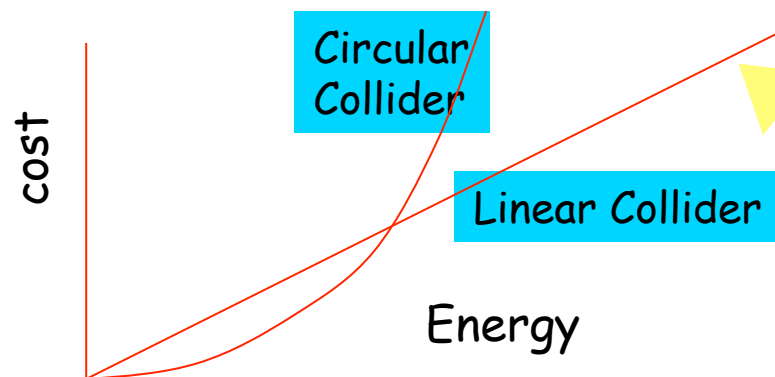
Linear Colliders

- 500 electron GeV ring collider doesn't look practical
- For this reason, at very high energy it is preferable to accelerate electrons in a linear accelerator, rather than a circular accelerator



Linear Colliders

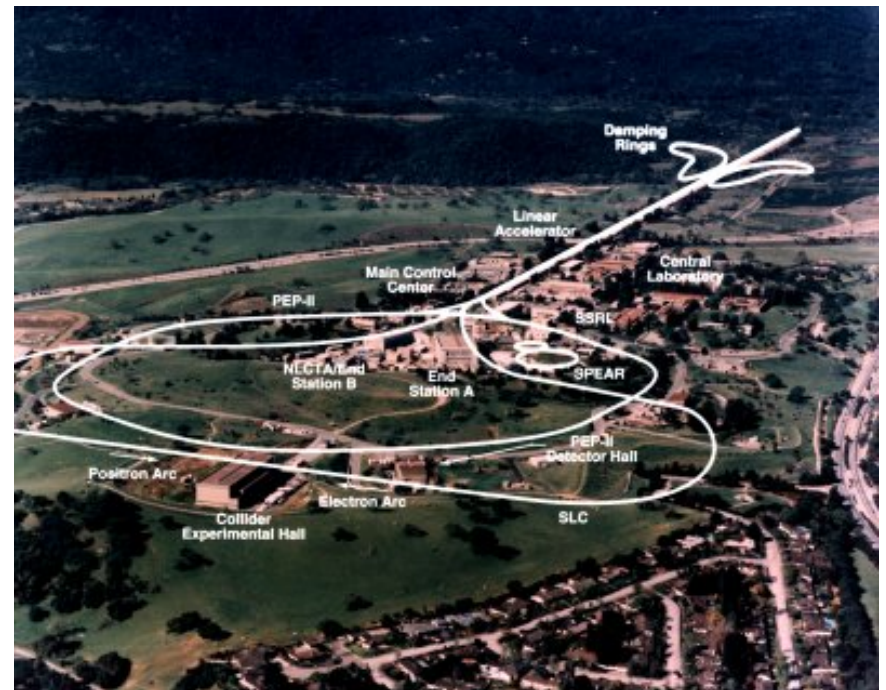
- Synchrotron radiation
 - $\Delta E \sim (E^4 / m^4 R)$
- Therefore
 - Cost (circular) $\sim a R + b \Delta E \sim a R + b (E^4 / m^4 R)$
 - Optimization $R \sim E^2 \Rightarrow \text{Cost} \sim c E^2$
 - Cost (linear) $\sim a' L$, where $L \sim E$



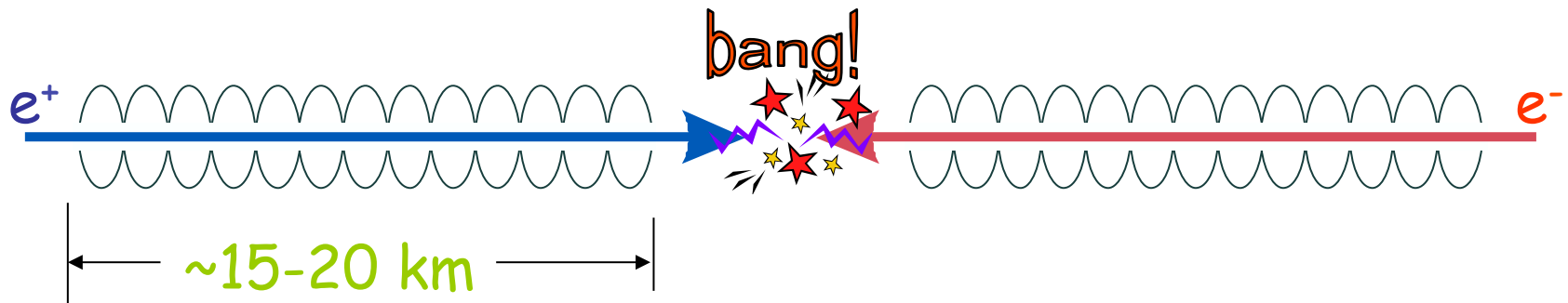
- At high energy, linear collider is more cost effective

The First Linear Collider (The SLC)

- This concept was demonstrated at SLAC (Stanford Linear Accelerator Center) in a linear collider prototype operating at ~ 91 GeV (the SLC)
- SLC was built in the 80's within the existing SLAC linear accelerator
- Operated 1989-98
 - precision Z^0 measurements
 - established LC concepts



Linear Collider = Two Linacs, No Bends!



For a $E_{\text{cm}} = 1 \text{ TeV}$ machine:

Effective gradient $G = 500 \text{ GV} / 15 \text{ km}$

= 34 MV/m real-estate gradient

Cost scaling:	storage ring	$\$_{\text{tot}} \propto E^2$
	linear collider	$\$_{\text{tot}} \propto E$

The “next” Linear Collider

THE NEXT LINEAR COLLIDER PROPOSALS INCLUDED PLANS TO DELIVER A FEW HUNDRED FB⁻¹ OF INTEGRATED LUM. PER YEAR

		 TESLA	 JLC-C	NLC/GLC-X* 
		(DESY-Germany)	(Japan)	(SLAC/KEK-Japan)
$\mathcal{L}_{\text{design}}$	(10^{34})	3.4 → 5.8	0.43	2.2 → 3.4
E_{CM}	(GeV)	500 → 800	500	500 → 1000
Eff. Gradient	(MV/m)	23.4 → 35	34	70
RF freq.	(GHz)	1.3	5.7	11.4
Δt_{bunch}	(ns)	337 → 176	2.8	1.4
#bunch/train		2820 → 4886	72	190
Beamstrahlung	(%)	3.2 → 4.4		4.6 → 8.8

There will only be one in the world
A the technology choice was made in 2004

* US and Japanese X-band R&D cooperation, but machine parameters may differ

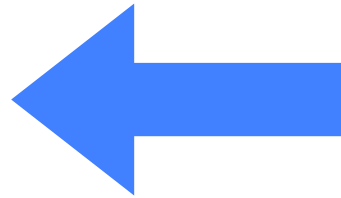
The *Luminosity* Issue

- High Beam Power
 - High current ($n_b N$)
 - High efficiency ($P_{RF} \rightarrow P_{beam}$)
- Small IP vertical beam size
 - Small emittance ϵ_y
 - strong focusing (small β_y^*)

The *Luminosity Issue*

Superconducting
RF Linac
Technology

(SCRF)



- High current ($n_b N$)
- High efficiency ($P_{\text{RF}} \rightarrow P_{\text{beam}}$)

- Small emittance ϵ_y
- strong focusing (small β_y^*)

the Big Jump from SLC to ILC:

In Beam Power (P_{beam}) $\times 100$,
collision beam size (σ_y^*) $1/100$
and Luminosity (L) $\times 10^4$

SLC / ILC Comparison

	SLC	ILC	
E_{cm}	100	500	GeV
P_{beam}	0.04	5	MW
σ_y^*	500	6	nm
$\delta E/E_{bs}$	0.03	4	%
L	3×10^{-4}	1.8	$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

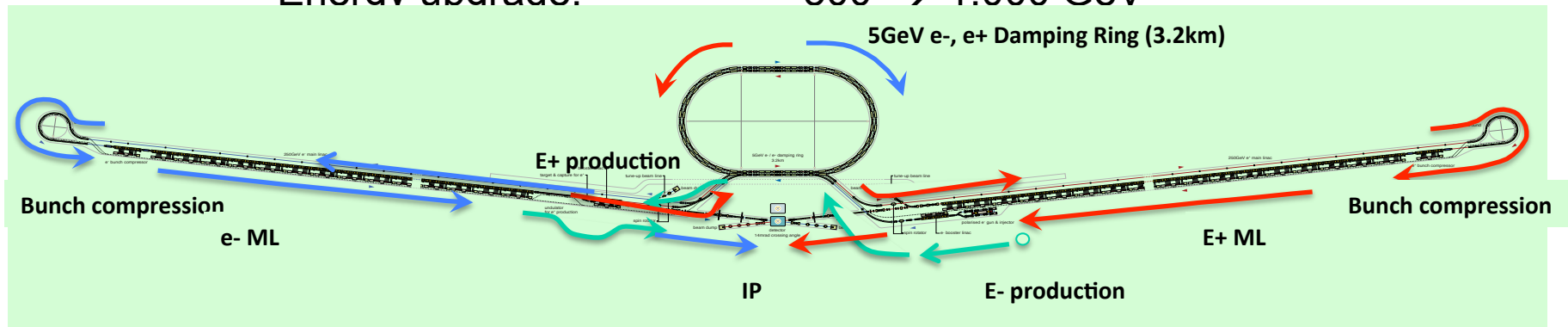
Requirements of Physics Experiments

- Basic requirements:

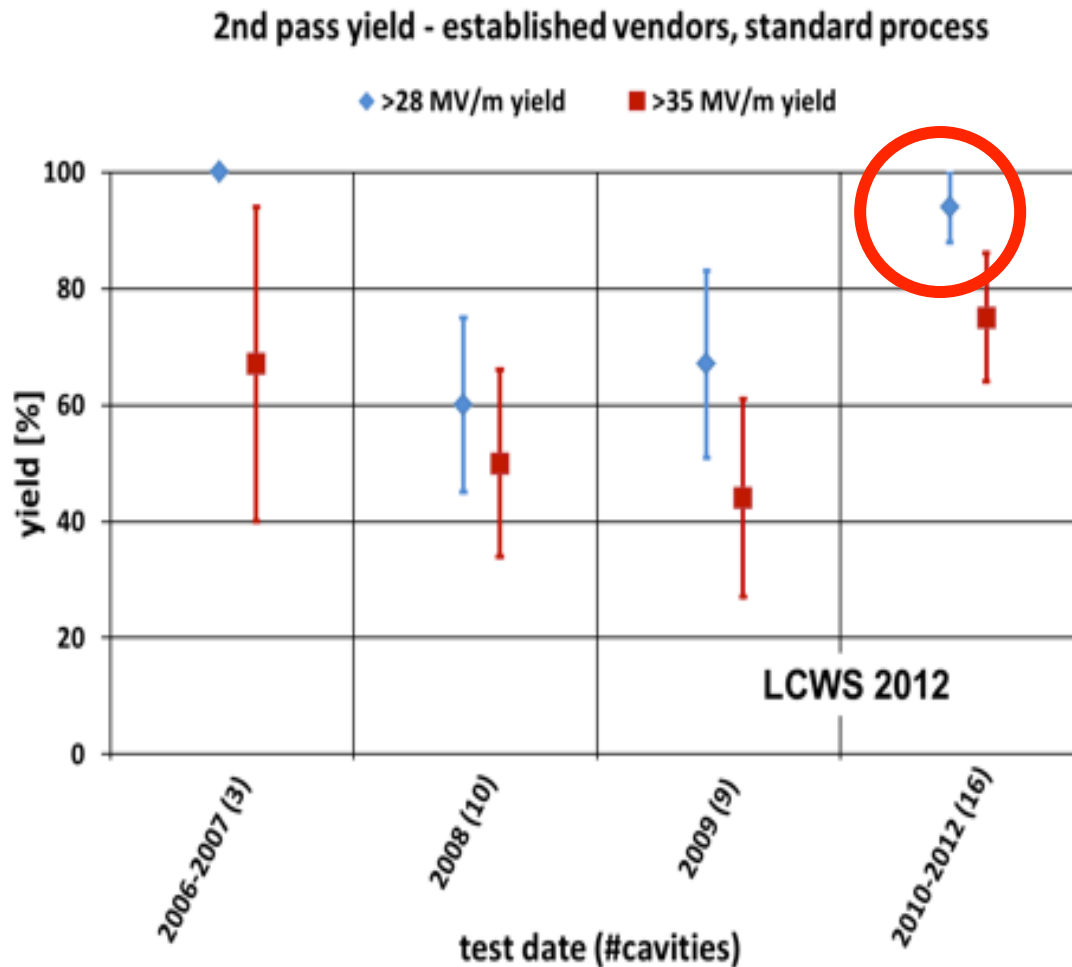
- Luminosity : $\int L dt = 500 \text{ fb}^{-1}$ in 4 years
- E_{cm} : 200 – 500 GeV and the ability to scan
- E stability and precision: $< 0.1\%$
- Electron polarization: $> 80\%$

- Extension capability:

- Energy upgrade: 500 $\rightarrow$ 1.000 GeV



Progress in SCRF Cavity Gradient



Production yield:
94 % at > 28 MV/m,

Average gradient:
37.1 MV/m

reached in 2012

Global Cooperation for ILC Accelerator Beam Demonstration

TTF/FLASH (DESY) ~1 GeV
ILC-like beam ILC RF unit
(* lower gradient)



DESY

STF (KEK) operation/
construction

ILC Cryomodule test: S1-Global
Experiment



KEK, Japan



CesrTA (Cornell)
electron cloud
low emittance

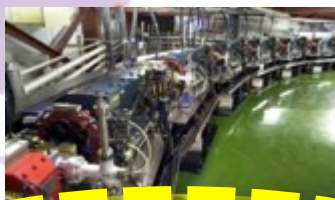
FNAL Cornell

INFN Frascati



DAFNE (INFN Frascati)
kicker development
electron cloud

Accelerator



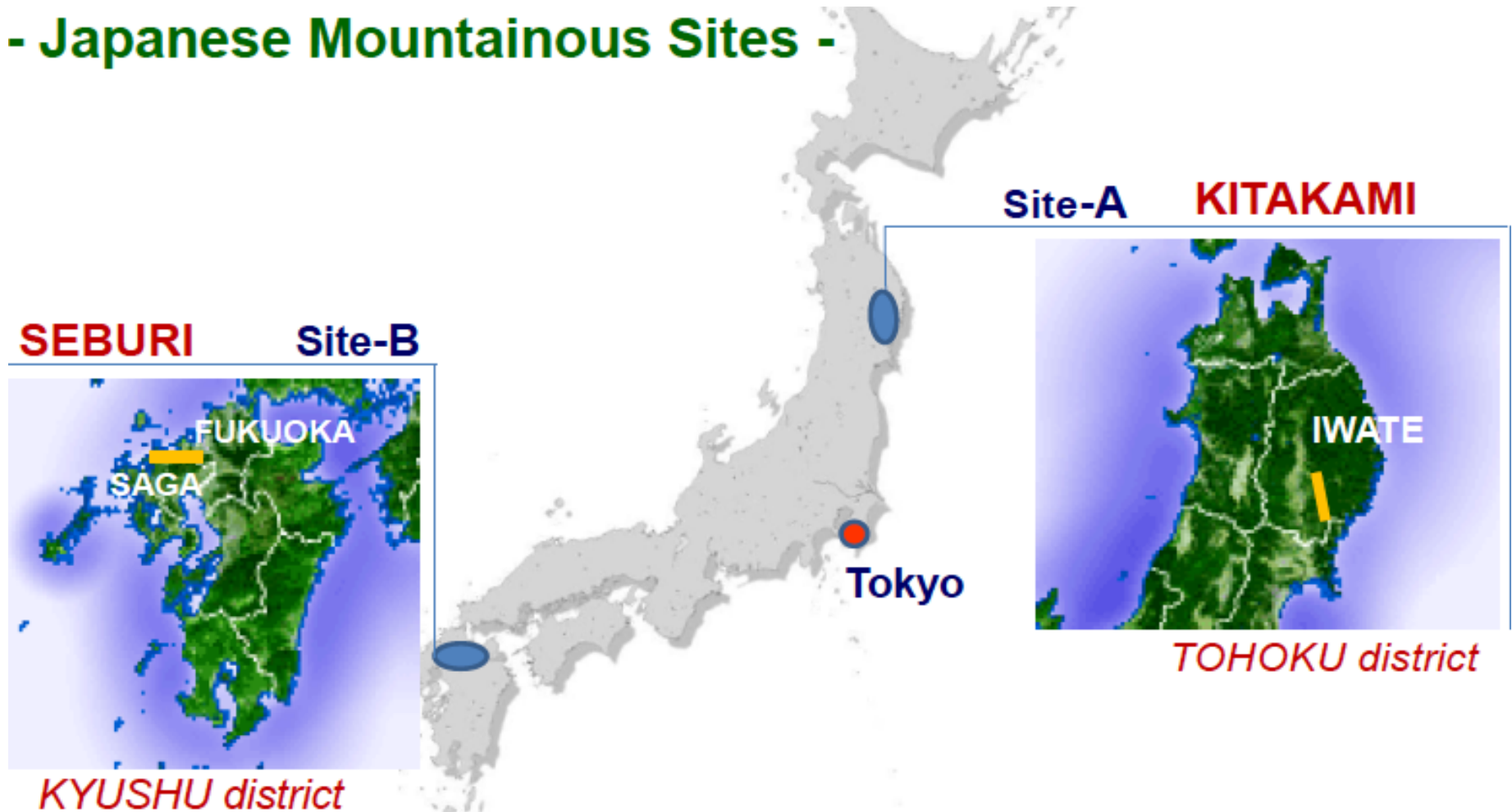
ATF & ATF2 (KEK)
ultra-low emittance
Final Focus optics
KEKB electron-cloud



NML facility ILC RF unit test
Under construction

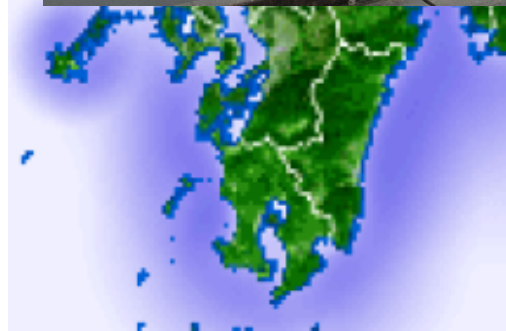
Japanese plans for a “Science City”

- Japanese Mountainous Sites -



Japanese plans for a “Science City”

- Japanese Mountainous Sites



KYUSHU district



Tokyo



TOHOKU district

Japanese plans for a “Science City”

- Jap



2-07

E

strict

KYUSHU district

What's next for ILC?

20 years from 1st idea to 1st prototype SLC

25 more years to a complete ILC design

2013

- TDR complete, Technical- and Cost-Reviews done
- Linear Collider Collaboration formed
- Japan selected the northern site

2013-2016

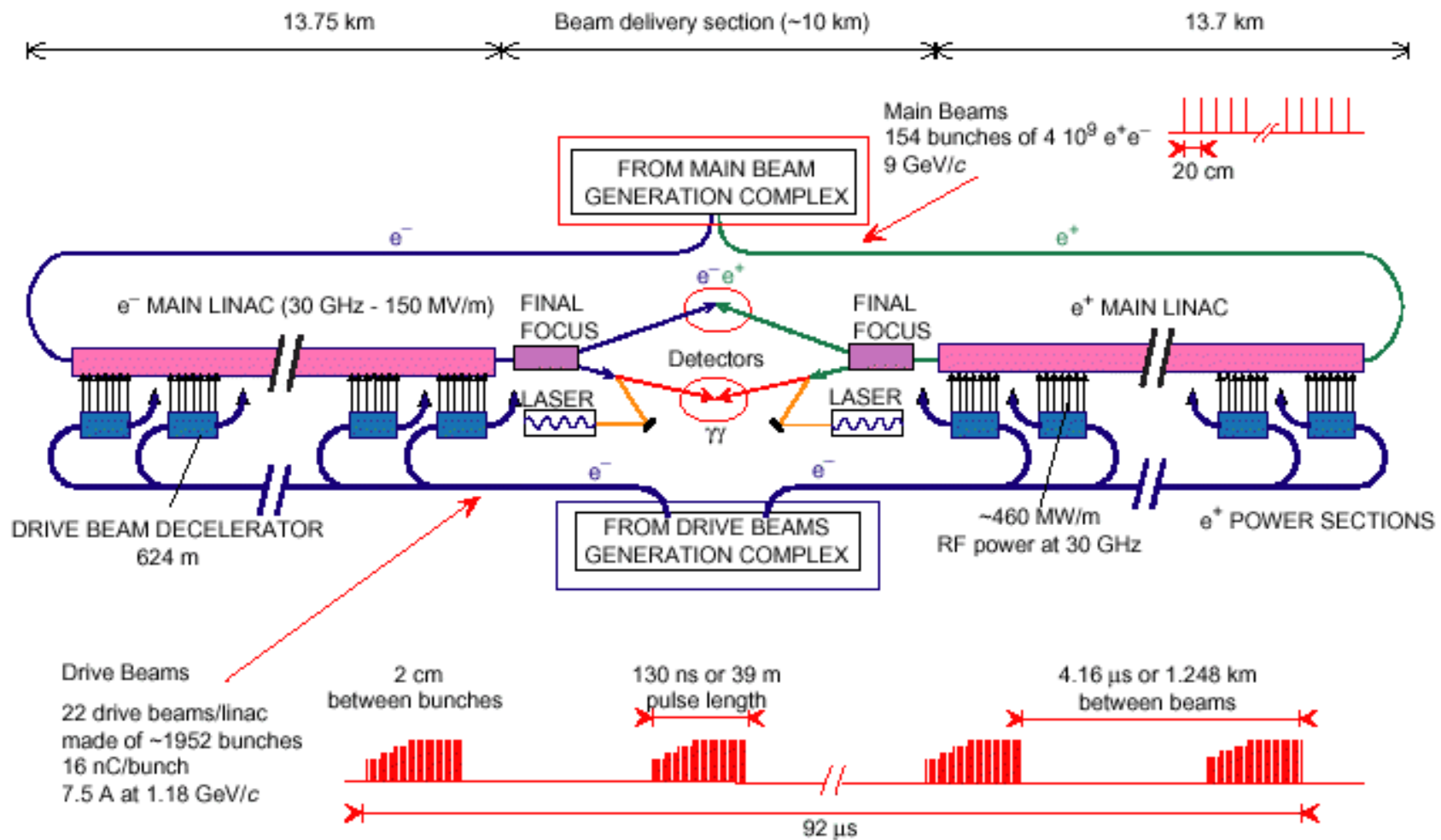
- Prepare a proposal to the funding agencies

2016 

The ILC is Good to Go

Quote from ILCSC chair Jonathan Bagger at LC2013 DESY

CLIC (Compact Linear Collider)



Possible CLIC stages studied in the CDR

Table 1: Parameters for the CLIC energy stages of scenario A.

Parameter	Symbol	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	$\sqrt{s}$	GeV	500	1400	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		354	312	312
Bunch separation	Δt	ns	0.5	0.5	0.5
Accelerating gradient	G	MV/m	80	80/100	100
Total luminosity	$\mathcal{L}$	$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$	2.3	3.2	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathcal{L}_{0.01}$	$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$	1.4	1.3	2
Main tunnel length		km	13.2	27.2	48.3
Charge per bunch	N	10^9	6.8	3.7	3.7
Bunch length	σ_z	μm	72	44	44
IP beam size	σ_x/σ_y	nm	200/2.6	$\sim 60/1.5$	$\sim 40/1$
Normalised emittance (end of linac)	ϵ_x/ϵ_y	nm	2350/20	660/20	660/20
Normalised emittance (IP)	ϵ_x/ϵ_y	nm	2400/25	—	—
Estimated power consumption	P_{wall}	MW	272	364	589

Table 2: Parameters for the CLIC energy stages of scenario B.

Parameter	Symbol	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	$\sqrt{s}$	GeV	500	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		312	312	312
Bunch separation	Δt	ns	0.5	0.5	0.5
Accelerating gradient	G	MV/m	100	100	100
Total luminosity	$\mathcal{L}$	$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$	1.3	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathcal{L}_{0.01}$	$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$	0.7	1.4	2
Main tunnel length		km	11.4	27.2	48.3
Charge per bunch	N	10^9	3.7	3.7	3.7
Bunch length	σ_z	μm	44	44	44
IP beam size	σ_x/σ_y	nm	100/2.6	$\sim 60/1.5$	$\sim 40/1$
Normalised emittance (end of linac)	ϵ_x/ϵ_y	nm	—	660/20	660/20
Normalised emittance	ϵ_x/ϵ_y	nm	660/25	—	48
Estimated power consumption	P_{wall}	MW	235	364	589

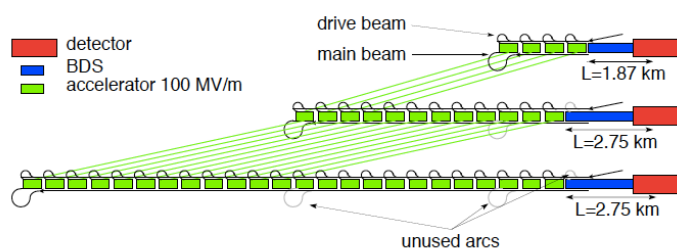


Fig. 3.6: Simplified upgrade scheme for CLIC staging scenario B.

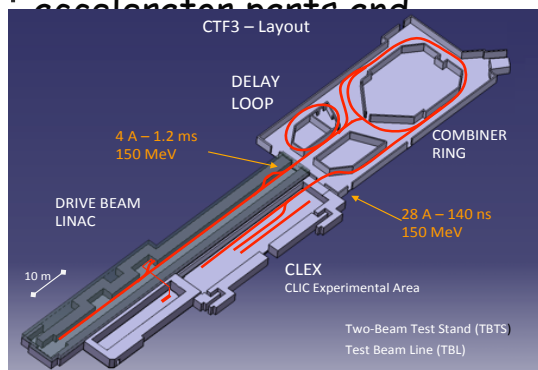
Key features:

- High gradient (energy/length)
- Small beams (luminosity)
- Repetition rates and bunch spacing (experimental conditions)

CLIC future system tests

2013-18 Development Phase

Develop a Project Plan for a staged implementation in agreement with LHC findings; further technical developments with industry, performance studies for accelerator parts and



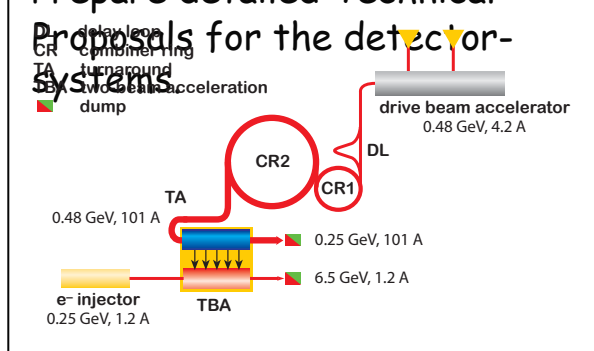
2018-19 Decisions

On the basis of LHC data and Project Plans (for CLIC and other potential projects), take decisions about next project(s) at the Energy Frontier.

4-5 year Preparation Phase

Finalise implementation parameters, Drive Beam Facility and other system verifications, site authorisation and preparation for industrial procurement.

Prepare detailed Technical Proposals for the detector-systems

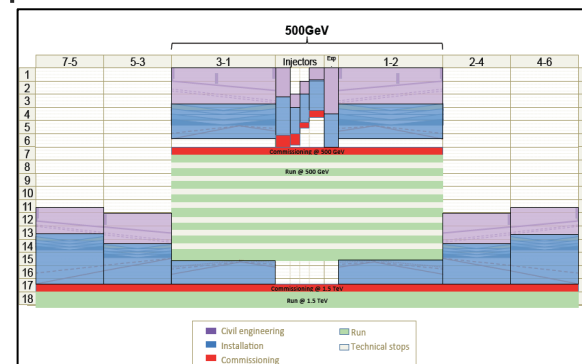


2024-25 Construction Start

Ready for full construction and main tunnel excavation.

Construction Phase

Stage 1 construction of CLIC, in parallel with detector construction. Preparation for implementation of further stages.



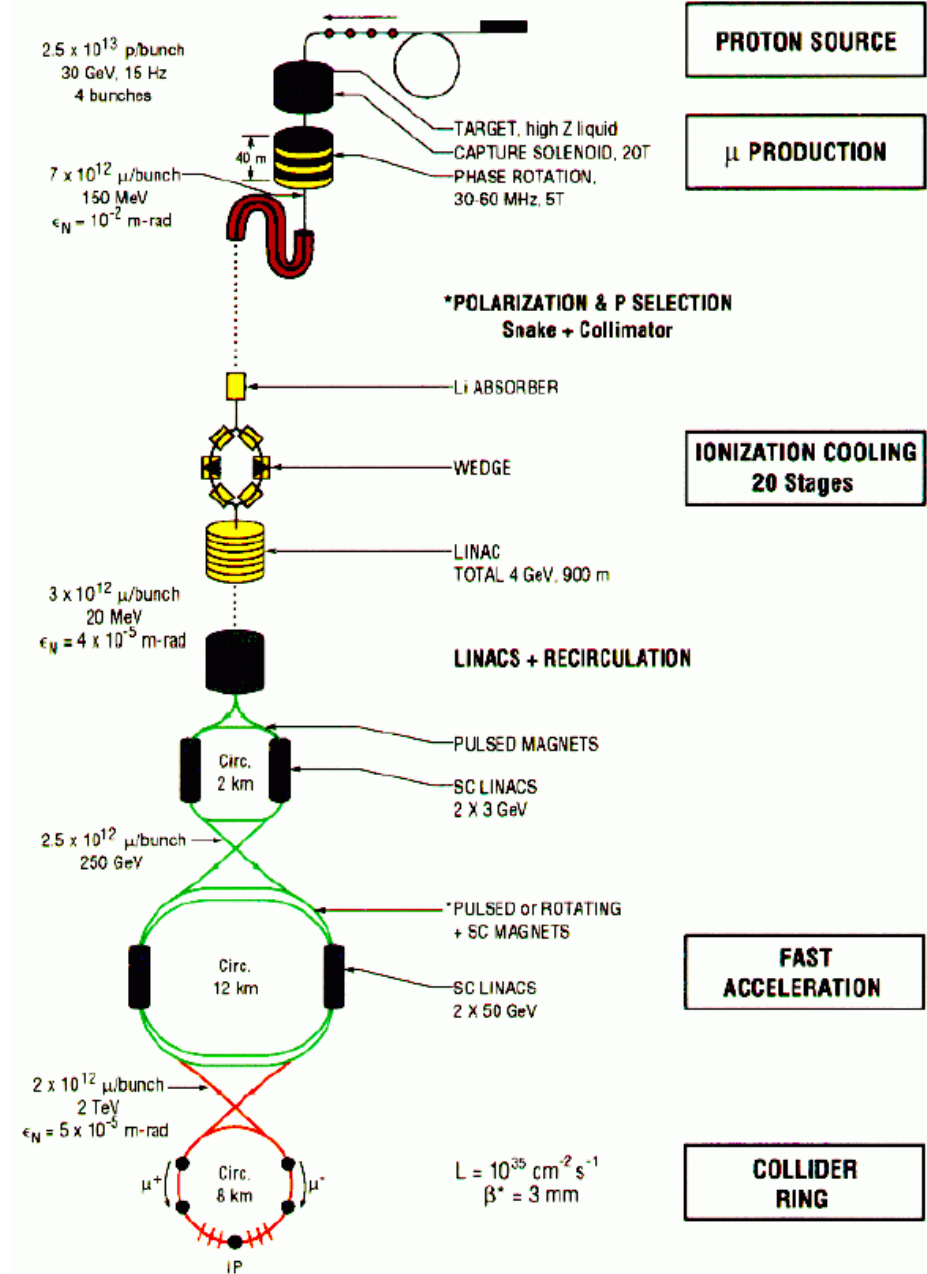
Commissioning

Becoming ready for data-taking as the LHC programme reaches completion.

Muon Collider

- Motivation: electron collider limited at high energy
 - length of linear collider $\rightarrow$ \$
 - beamstrahlung - limits L - but $\sigma \sim 1/s$ so need $L \sim s$
 - muons can be stored in a circular machine
- Problems for Muons
 - unstable 2×10^{-6} secs $\rightarrow \gamma c \tau \sim 6 \times 10^2 \gamma$ meters
 - produced as large beam $\rightarrow$ need to focus
- Higgs Factory
 - coupling to Higgs $\sim m_f^2$ $4 \times 10^4 \times$ electron

Muon Collider



Muon Collider

- Ionization Beam Cooling
- Neutrino Radiation
- Detector Radiation
- The Future
 - first step - neutrino factory
 - demonstrates storage and cooling

Need factor of $\sim 10^6$ in 6-D cooling $\equiv$ reduction of rel. invariant 6-D phase space volume: $\varepsilon_{6N} \equiv \prod_{i=x,y,z} \Delta p_i \Delta x_i$

(Illustration by David Neuffer)

Confining Magnetic Channel

Large Emittance Beam

Absorber

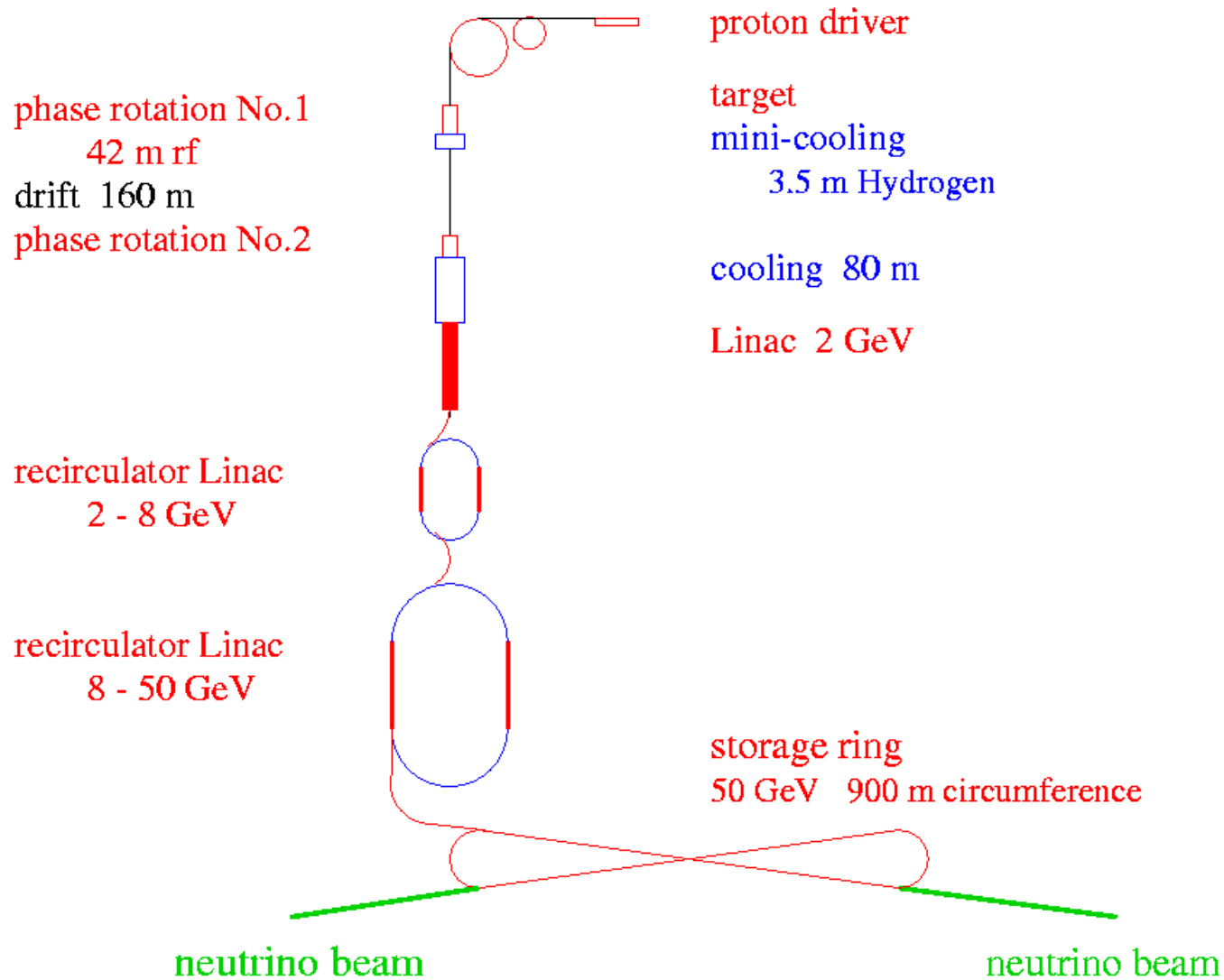
Acceleration

Smaller Emittance Beam

Diagram illustrating a dispersive region (inverted triangle) where wave packets with different momenta ($p + \Delta p$, p , $p - \Delta p$) enter from the left and emerge on the right with a spread $p' < p - \Delta p$.

[illegible]

Neutrino Factory



VLHC

- 30 TeV x 30 TeV
 - since LHC upgrade = 14 TeV = 7 TeV x 7 TeV
 - 8.4 T → 27 km circumference
- Options for 30 TeV x 30 TeV
 - low field, large ring
 - 1.8 Tesla → 388 km circumference
 - high field, small ring
 - 13 Tesla → 60 km circumference

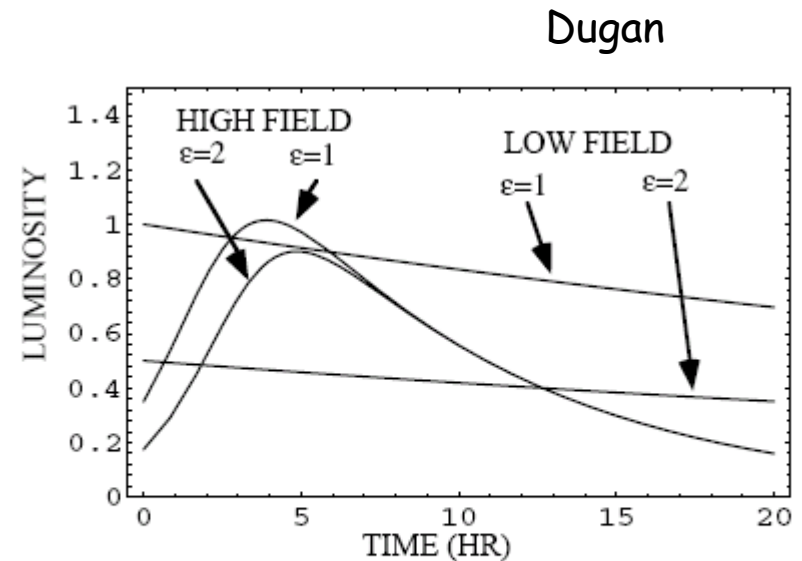
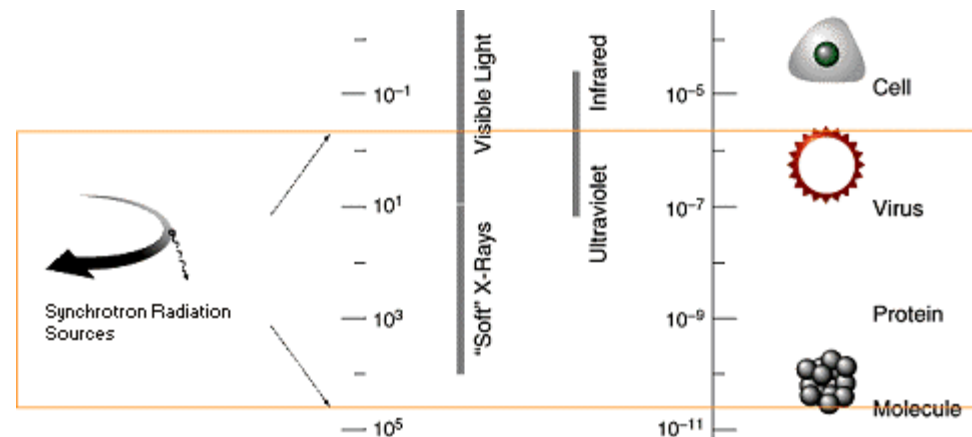
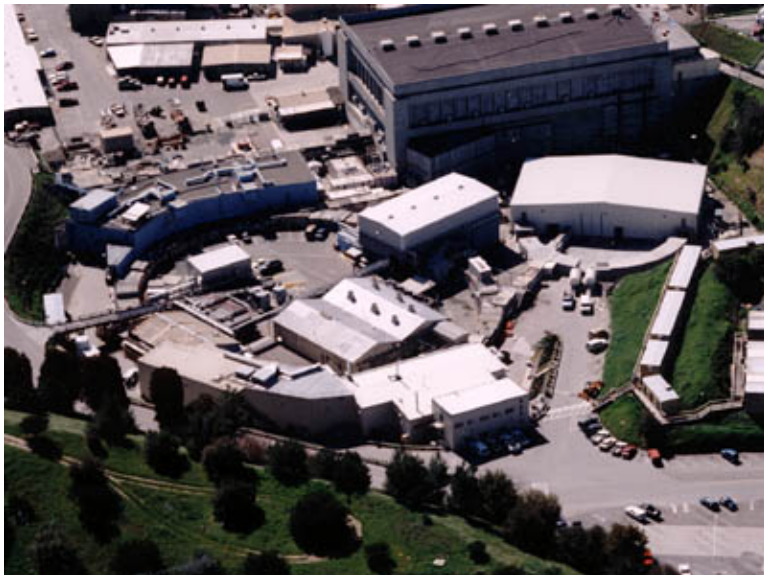


FIG. 2: Time evolution of the luminosity (in $10^{34} \text{cm}^{-2} \text{sec}^{-1}$).
Emittances are given in $\pi \mu\text{m-rad}$.

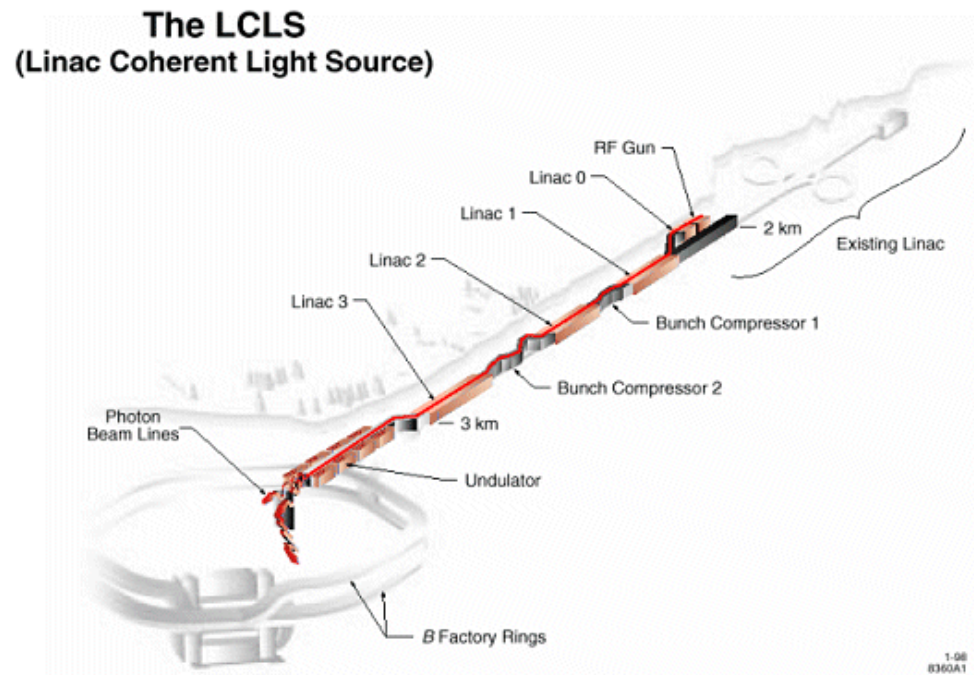
Synchrotron Radiation Facilities

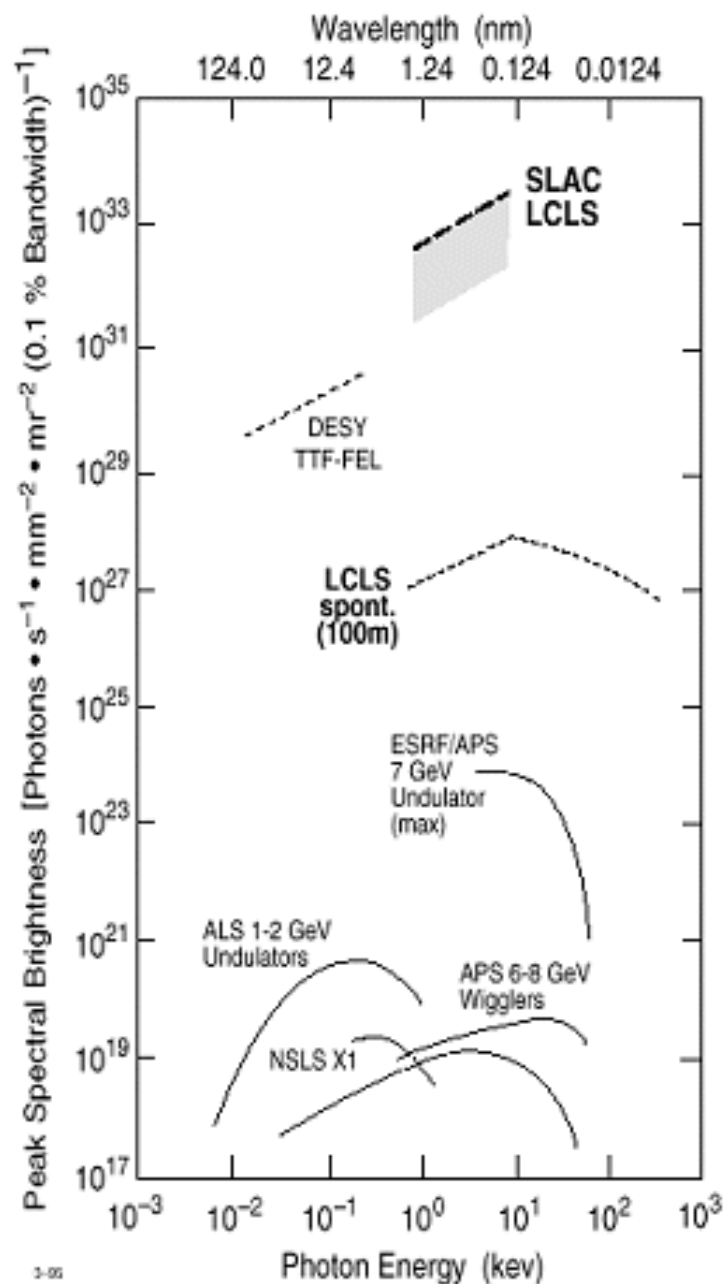
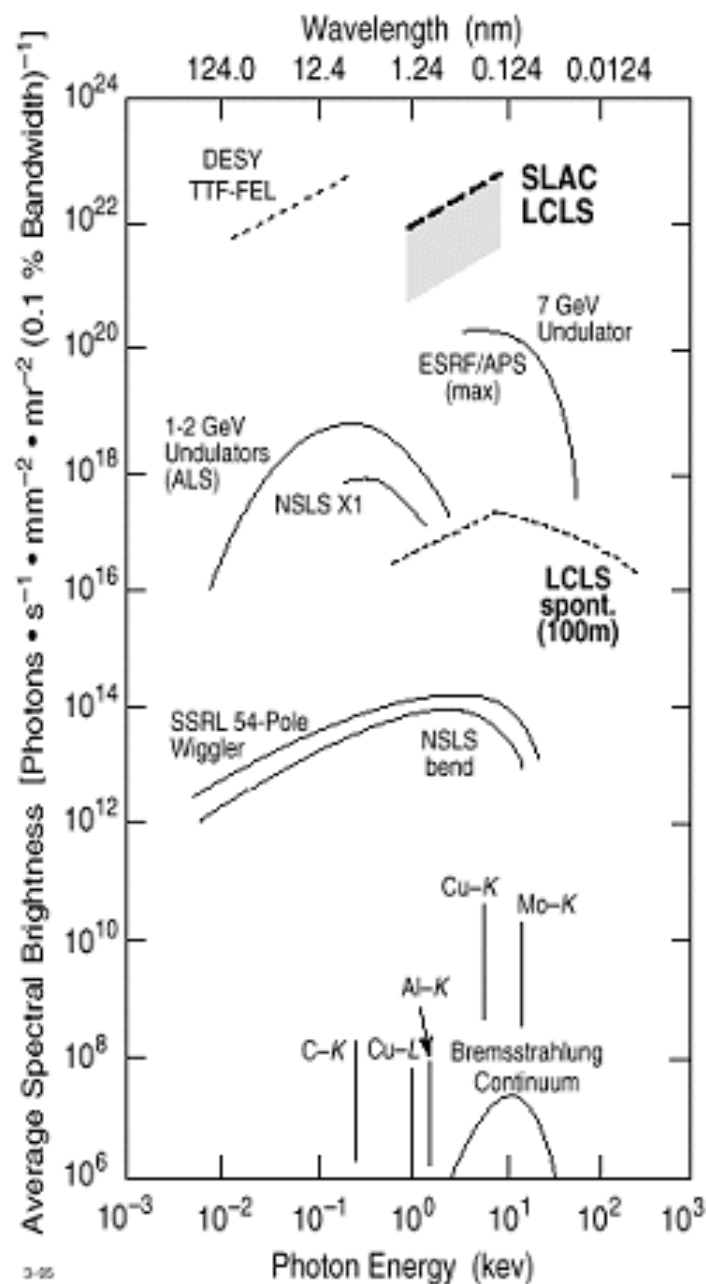
- A broad spectrum of science has benefited from the development of large storage rings for high energy physics
 - source of synchrotron radiation
 - initially parasitic operation from HEP facilities
 - dedicated facilities
- Latest: free electron lasers: XFEL@DESY, LCLS@SLAC



LCLS

- SLAC has been converted to a free electron laser – “Linac Coherent Light Source”
- Uses 1/3 of the linac to produce the brightest x-ray source in the world





Average and peak brightness calculated for the LCLS and for other facilities operating or under construction.