Introduction

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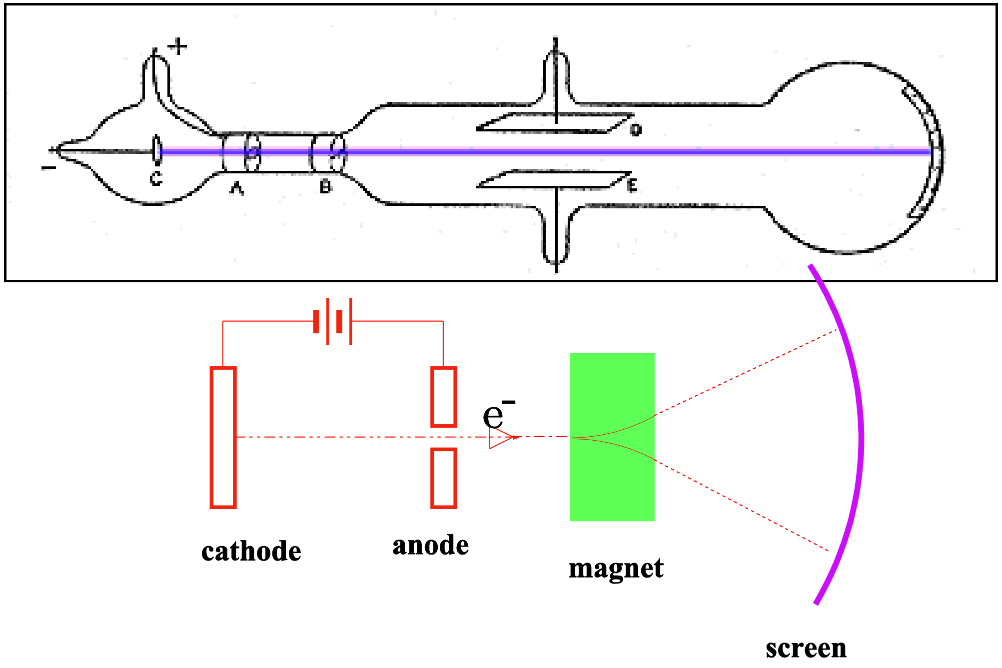
Part1: Accelerator Technology and Progress of High Energy Physics

- Mutual relation of physics and accelerator
- Physics demands have been pushing the accelerator technology
- Accelerator development has been pushing high energy physics

Will try to be extremely basic

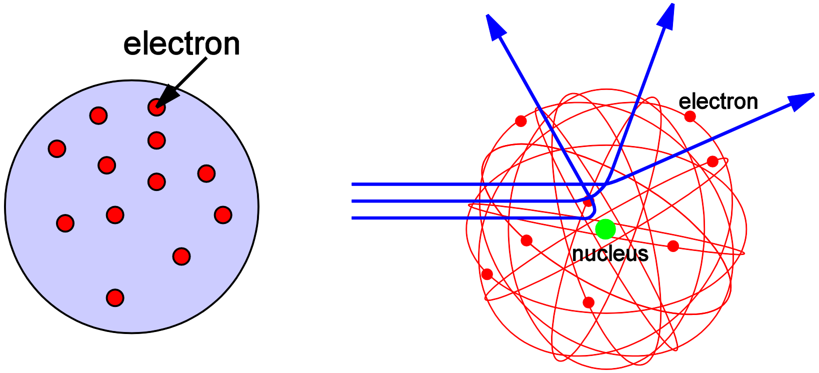
CRT: Cathode Ray Tube

- Electric voltage between two metallic plates
- Heat the cathode --- something emitted
- Proved the existence of electron in 1897
  J.J. Thompson
- TV monitor (until some years ago)



Use of Natural Radio Isotope

- Experiment by Rutherford
  - Hit “α” particles on gold foil to see atomic structure
  - Existence of nucleus in 1911



- Transformation of nucleus
  - Hit “α” particles on Nitrogen nucleus
  - Transformed to Oxygen nucleus

- Natural radio isotopes were used
- MeV accelerator did not exist

Cock-Croft Electro-Static Accelerator

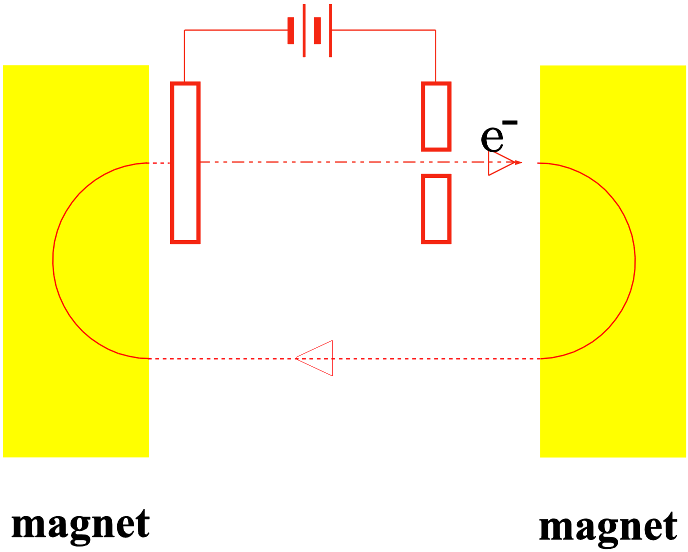
- High voltage by static electricity
- First nuclear transformation by accelerator
  H + Li → 2 He
- Cavendish institute in UK, 1932
- 800keV
- Breakdown limit

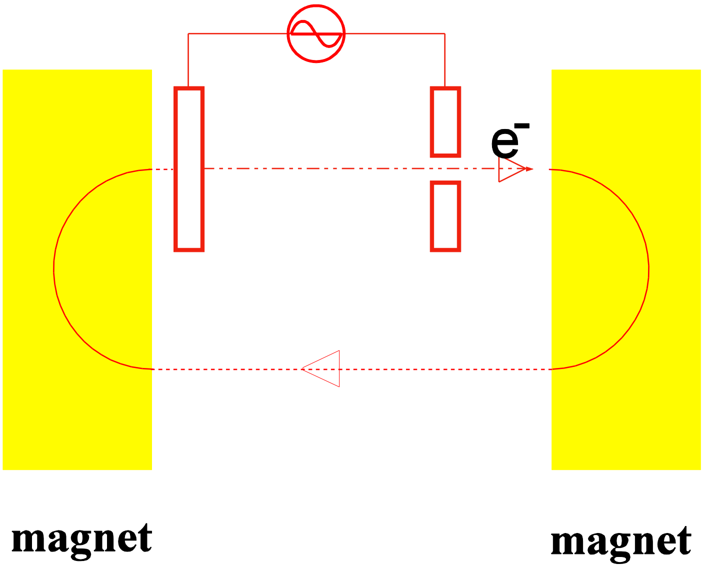
KEK 750keV Cockcroft-Walton

Repeated question:
How can we go to higher energies?

- reuse of CRT
- possible?

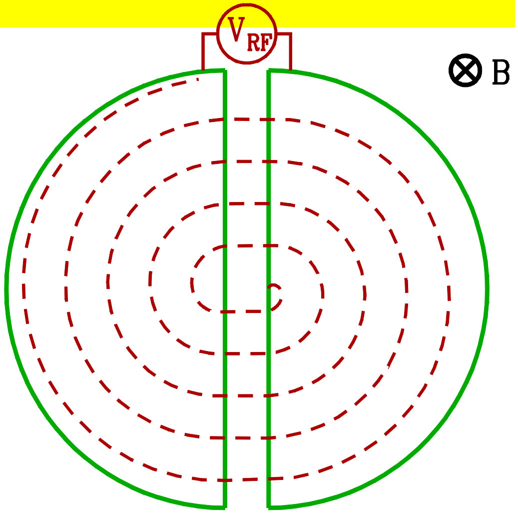
- use of alternating voltage
- high frequency needed

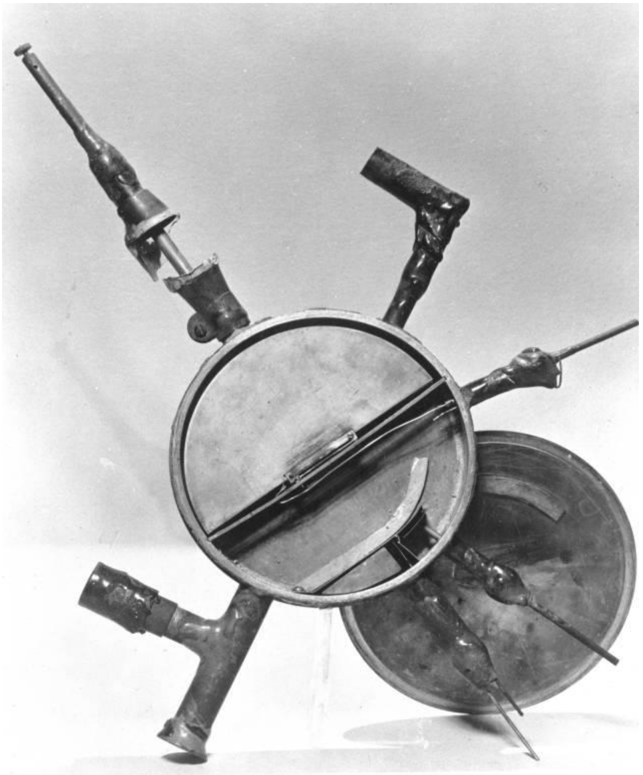




Cyclotron

- E.O.Lorence, 1931
  Berkeley, California
- Revolution period independent of energy





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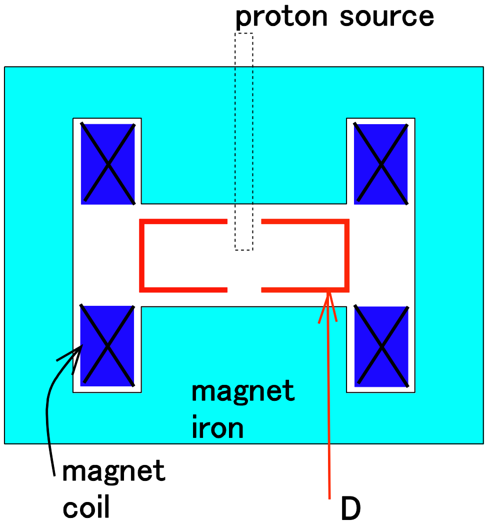
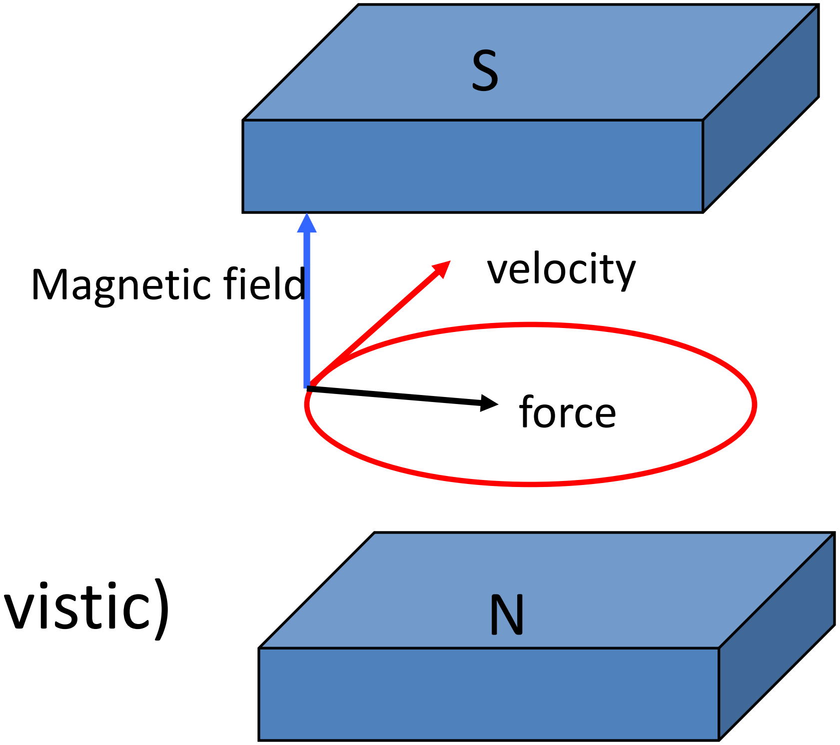


Relation : radius – magnetic field – beam energy – revolution time

- Radius

$$\rho[\mathrm{m}] = \frac{p[\mathrm{GeV/c}]}{0.3B[\mathrm{T}]}$$



- Revolution period (non-relativistic)

$$T = \frac{2\pi\rho}{v} = 2\pi\frac{m}{eB} = \mathrm{constant}$$

Limitation of cyclotron

- Bigger and bigger magnets for higher energies

$$\rho[\mathrm{m}] = \frac{p[\mathrm{GeV/c}]}{0.3B[\mathrm{T}]}$$

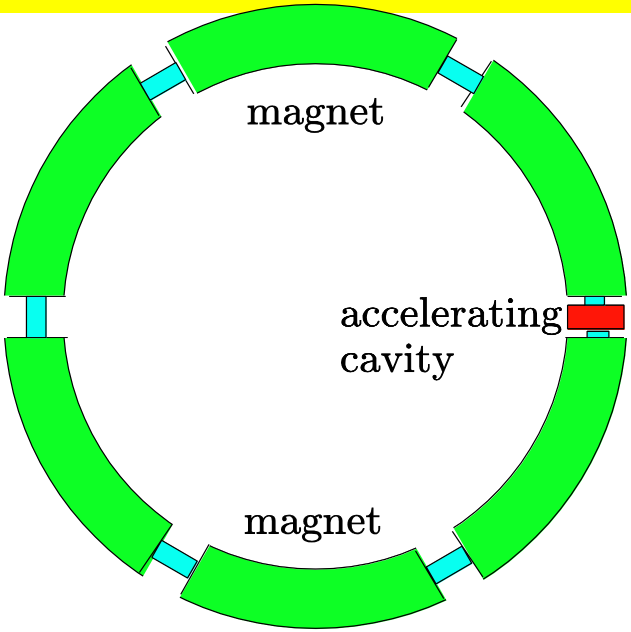
- Revolution time is not actually constant at high energies (special relativity) →
  - < 10 keV for electron
  - up to ~1GeV for proton

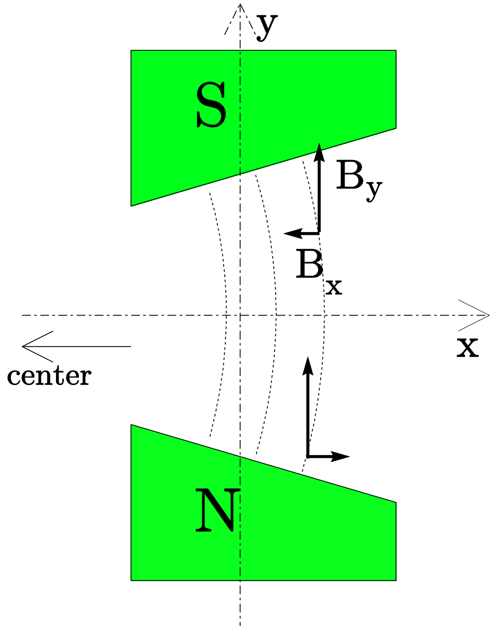
$$T = 2\pi\frac{m}{eB}\frac{1}{\sqrt{1-(v/c)^2}}$$

- Still being used at low energy physics
- advantage: continuous beam

Synchrotron

- Make orbit radius independent of energy
    - Raise magnetic field as acceleration
    - Save volume of magnets
    - Area of field is proportional to p (momentum), not p^2
- Gradient magnet needed for focusing
- Now main stream of circular accelerators





Particle Discoveries Before Accelerator Era

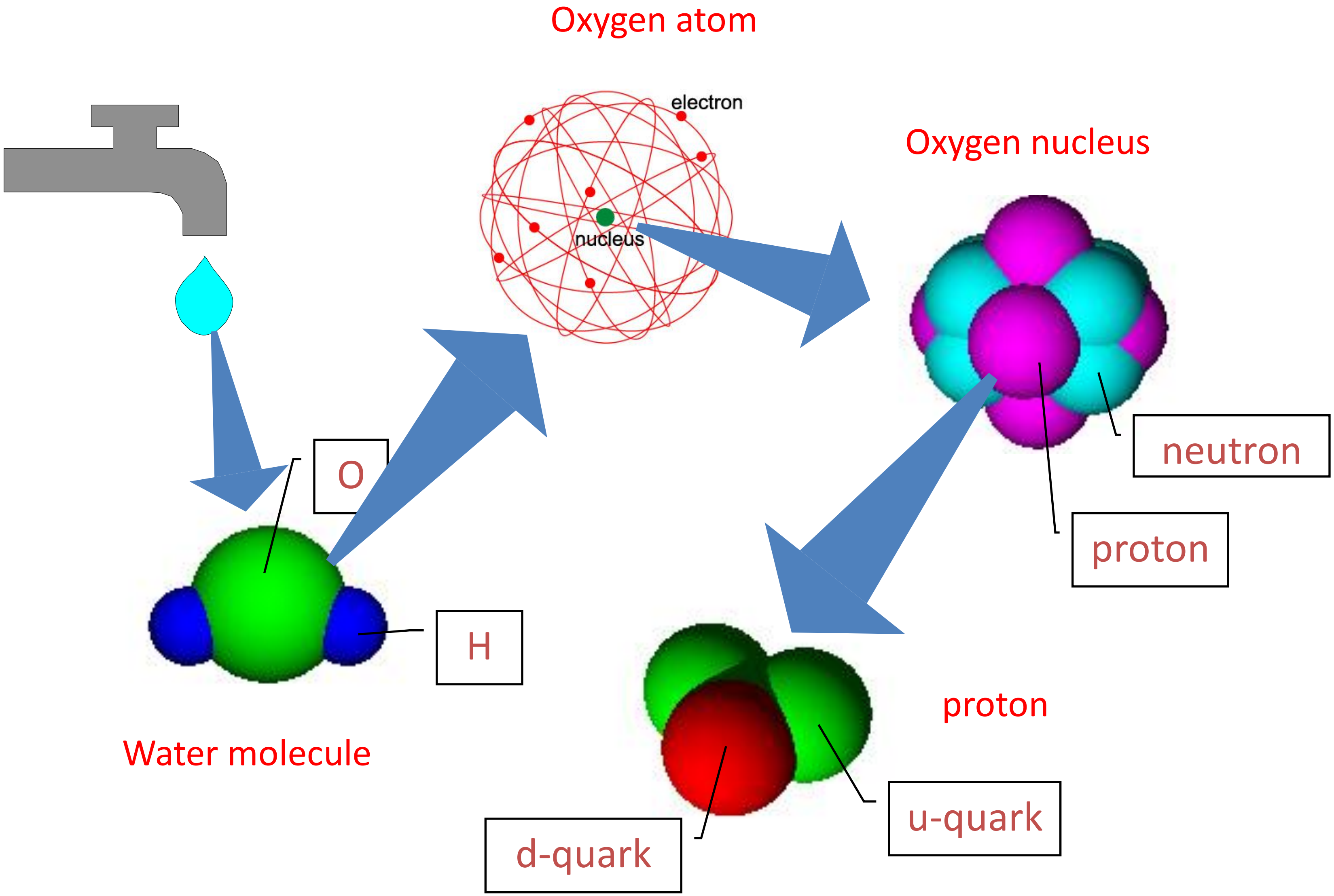
- electron 1897
- photon 1905
- proton 1911
- neutron 1932

----------------- Good Old Days --------------------

- positron 1932
- muon 1937
- pion 1947

These (after neutron) are discovered using cosmic ray particles

- New particle discoveries in 1950's by accelerators



Oxygen atom

Oxygen nucleus

O

H

neutron

proton

Water molecule

proton

u-quark

d-quark

1950’s

- A few GeV proton synchrotrons
  - Cosmotron (BNL) 3GeV
  - Bevatron (LBL) 6.2GeV

- Many new particles
  - anti-proton, anti-neutron
  - Λ, Σ, Ξ, Ω,....
  - Systematic description introducing “Quarks” by Gell-Mann in 1964

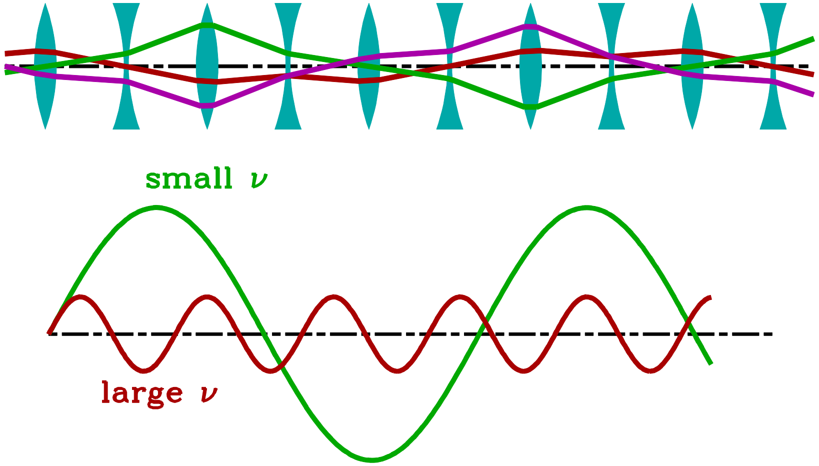
Bevatron

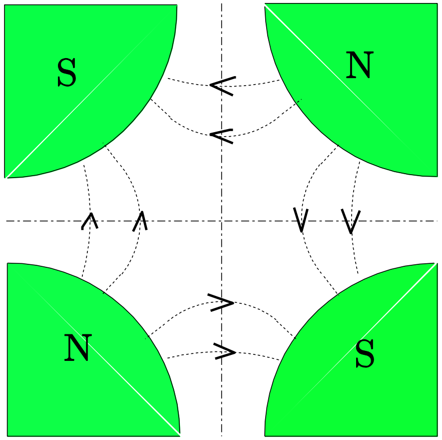
- Weak-focusing synchrotron
- Lorence Berkely Lab
- Operation start in 1954
- Bev.. = Billion Electron Volt
  = Giga Electron Volt (GeV)
- Up to 6.2 GeV
- Discovered anti-proton in 1955

http://www.lbl.gov/image-gallery/image-library.html

Principle of Strong Focusing

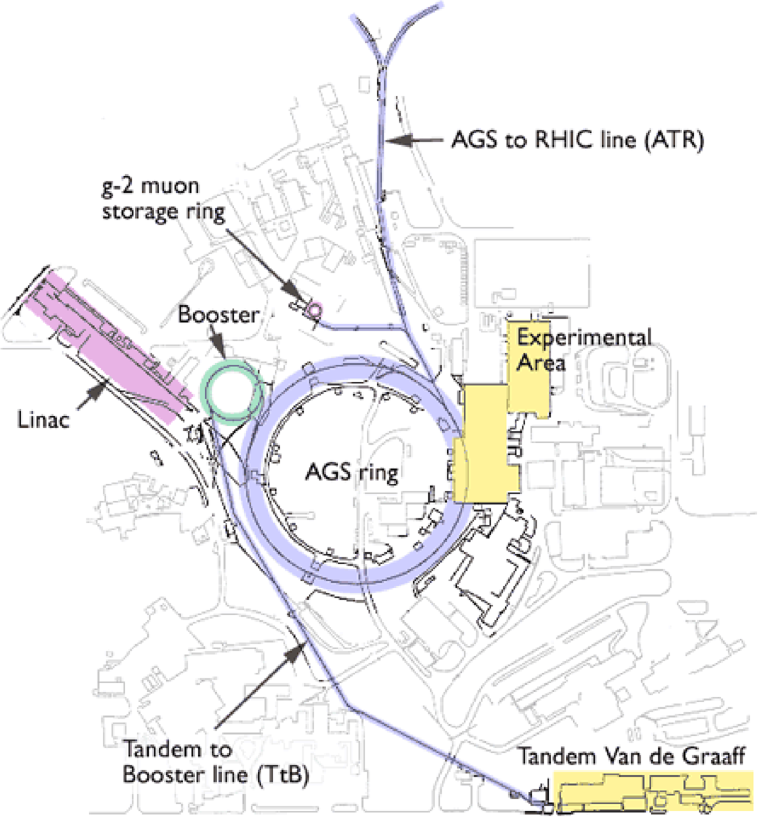
- Magnet size became an issue even for synchotron of a few GeV scale
- Combination of F-type magnet and D-type can reduce the beam size
- Around 1957
- Quadrupole magnets can also be used
- New issue: accuracy of field and alignment

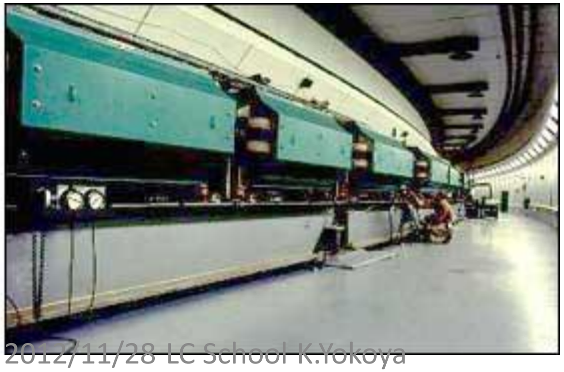




AGS: Alternating Gradient Synchrotron

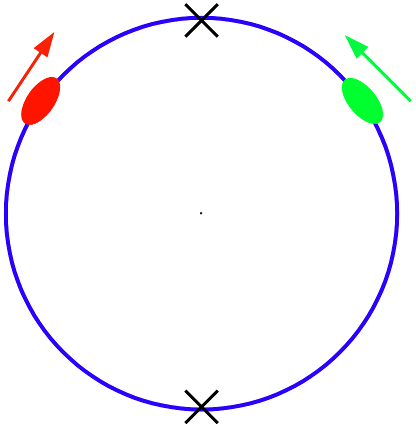
- Synchrotron based on strong-focusing principle
- BNL in US
- Operation start 1960, ~20GeV
- Up to ~33GeV
- Discovered
  - J/ψ
  - mu neutrino ν_μ



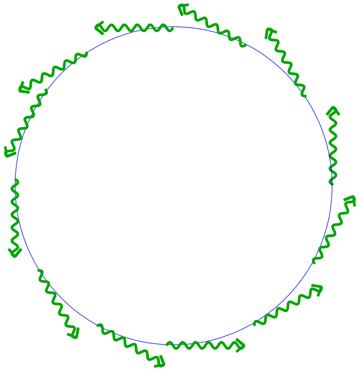


Sam Ting

Storage Ring

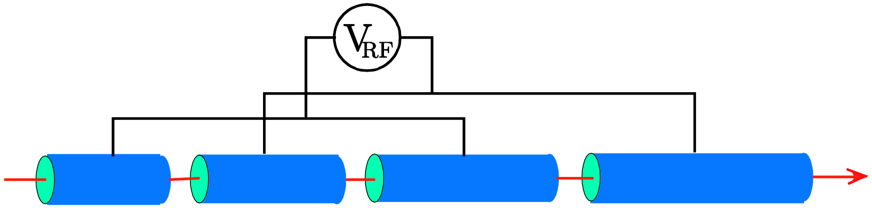


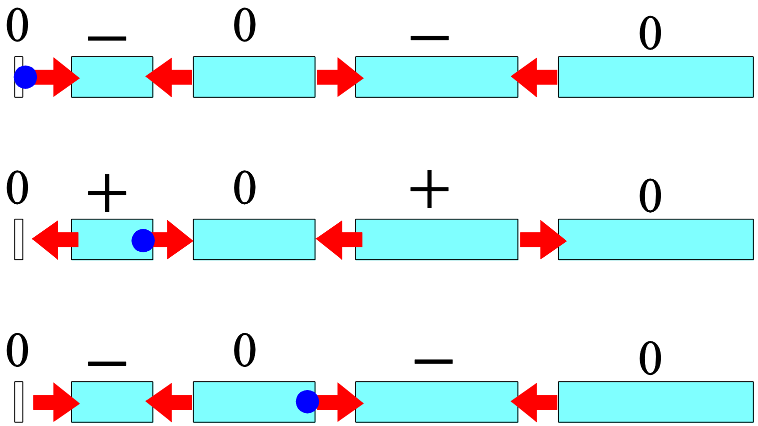
- Synchrotron can be used to store beams for seconds to days
- Usage
  - Collider
  - Synchrotron light source
- Principle same as synchrotron but
  - no need of rapid acceleration (even no acceleration)
  - longer beam life (e.g., better vacuum)
  - insertion structure (colliding region, undulator, etc)



Linear Accelerator (Linac)

- Drift tube type
  - The principle is old

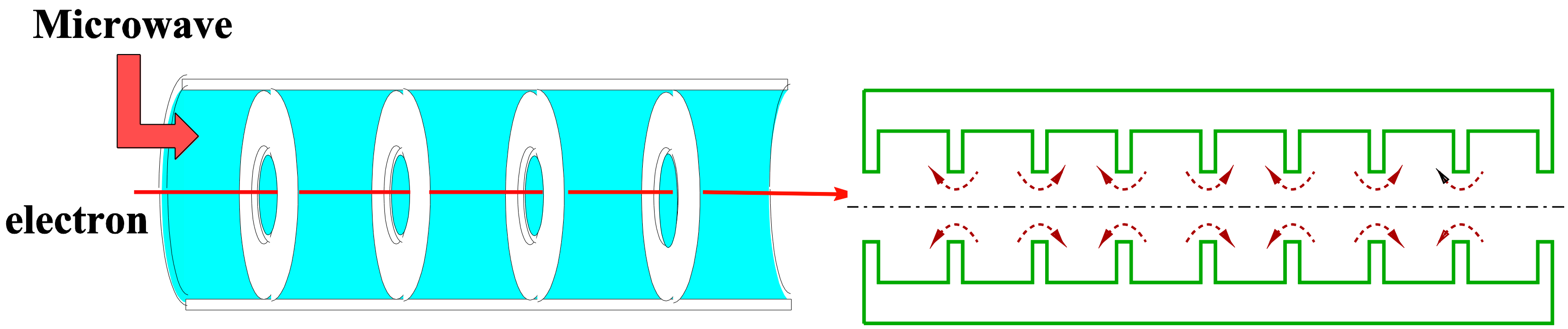




- The progress of microwave technology during World War II
- Application to accelerator after WW II

Electron Linac

- Velocity is almost constant above MeV
- No need of changing tube length
- Resonator type



SLAC: Stanford Linear Accelerator

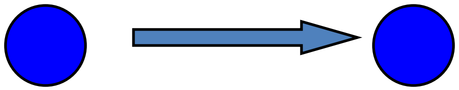
- Electron Linear Accelerator
- 2 miles
- Microwave frequency 2856MHz (wavelength 10.5cm)
- Operation start in 1967
- Study of deep inelastic scattering (to probe proton structure by electron-proton scattering) in ~1968
- Maximum energy ~50GeV (since 1989)
- Still now the longest and highest energy electron linac
- Still an active accelerator
  SPEAR, PEPII, SLC, LCLS, ...

Stanford Linear Accelerator

Collider

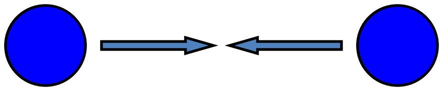
- What matters in physics is the Center-of-Mass energy

Fixed target



$$E_{CM} \approx \sqrt{2Em}$$

Collider



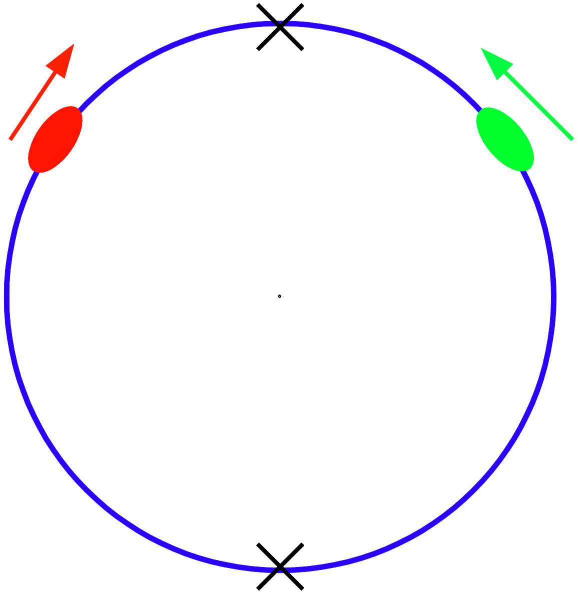
$$E_{CM} \approx 2E$$

- Energy of each beam can be lower in colliding scheme for given E_{CM}
- Colliding scheme much better in relativistic regime
  - e.g., for electrons, collision of 1GeV electrons is equivalent to 1TeV electron on sitting electron

How to Collide

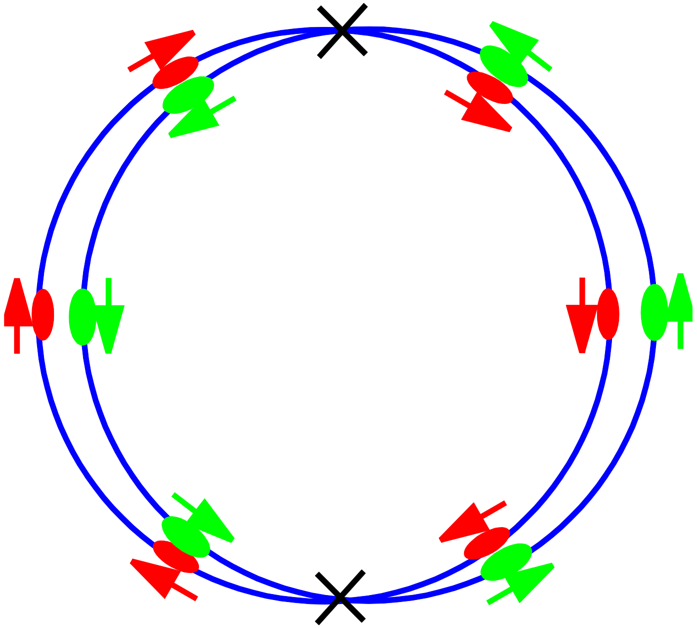
- Can be done in one ring for same energy beams and opposite charge (e.g., e+e-, proton-antiproton)

- More freedom with two rings



.... PETRA, TRISTAN, LEP,

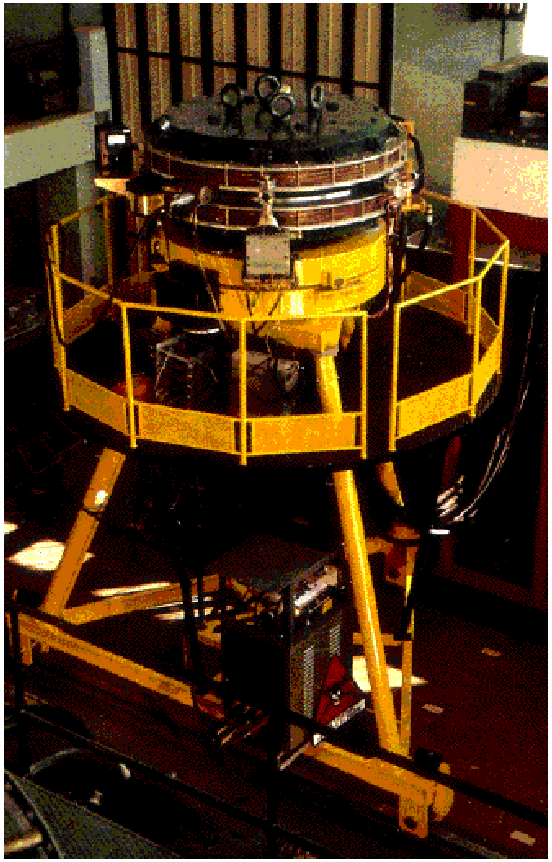
..... Spps, Tevatron



PEPII, KEKB, LHC, ...

The First Electron-Positron Collider: AdA

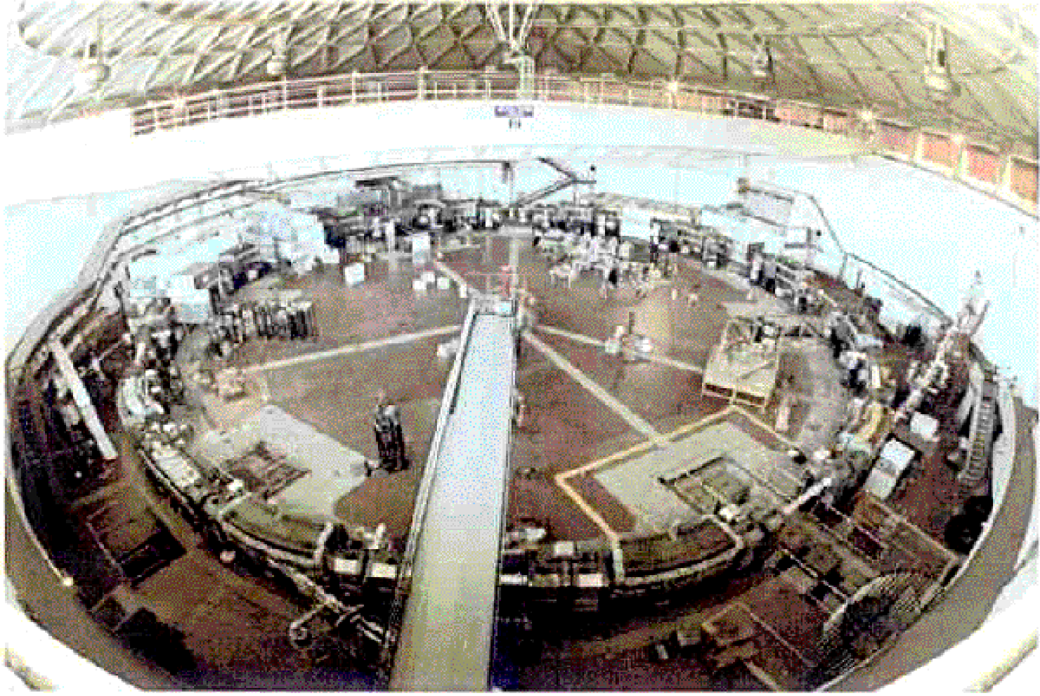
- First beam in 1961 in Italy
- Moved to Orsay, France
- The first beam collision in 1964
- Orbit radius 65cm, collision energy 0.5GeV



Now in the garden

The Second one : Adone

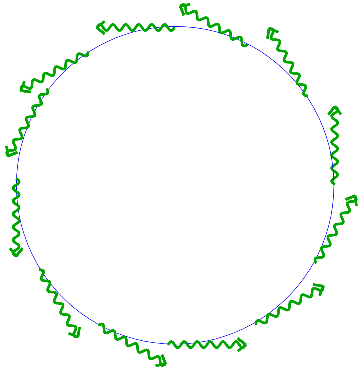
- First beam in 1967
- Circumference 105m
- Collision energy < 3GeV (Unlucky, did not reach J/ψ at 3.1GeV !!)
- Luminosity 3×10^{29} /cm^2/s



Synchrotron Radiation

- Charged particles lose energy by synchrotron radiation
- proportional to $1/m^4$
- Loss per turn (electron)

$$U = 0.088 \frac{E^4[\mathrm{GeV}]}{\rho[\mathrm{m}]} \quad [\mathrm{MeV}]$$



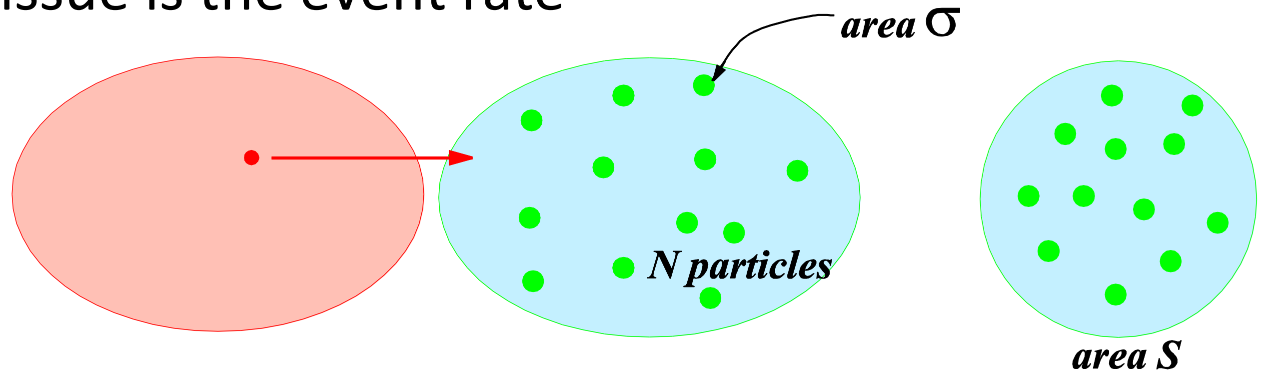
- Not only unwelcomed effects but
  - can be used as light source
  - radiation damping → Damping Ring lecture

Maximum Energy of Collider Ring

- Proton/antiproton
  - Ring size
  - Magnetic field
- Electron/positron
  - Ring size
  - Synchrotron radiation
    - Electric power consumption

Luminosity

- Colliders can reach higher energies compared with fixed target
- But issue is the event rate



$$\text{Number of events/sec} = \mathcal{L}\sigma$$

$$\mathcal{L} = f_{collision}\frac{N^2}{S}$$

For Gaussian beams

$$\mathcal{L} = f_{rep}\frac{n_b N^2}{4\pi\sigma_x^*\sigma_y^*}$$

Colliders demand small beams

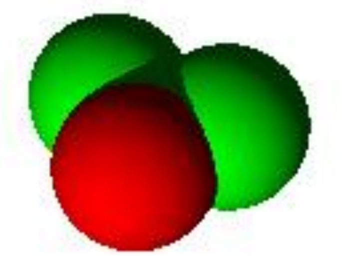
Quark Model: Gell-Mann, Zweig 1964

p charge=1
n charge=0
Λ charge=0

→

u quark charge = 2/3
d quark charge=-1/3
s quark charge = -1/3

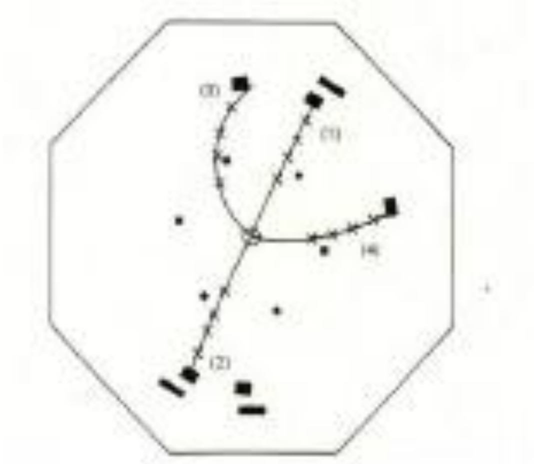
p = u + u + d charge = 2/3 + 2/3 – 1/3 = 1
n = u + d + d charge = 2/3 -1/3 -1/3 = 0

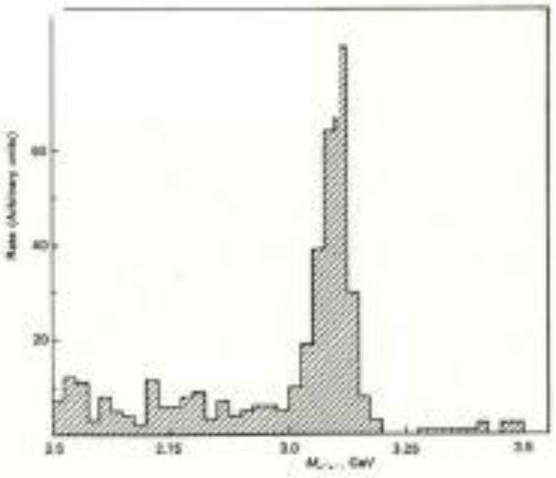


- Is this just mathematical model?
  - I thought so when I was a college student
- existence of quark
  - SLAC, late 1960's

Charm Quark

- Discovery of J/ψ in 1974
- $e^+e^- \rightarrow \psi$ at SLAC (Richter et.al.)
- $J \rightarrow e^+e^-$ at BNL (Ting et.al.)
- J/ψ = bound state of $c\bar{c}$



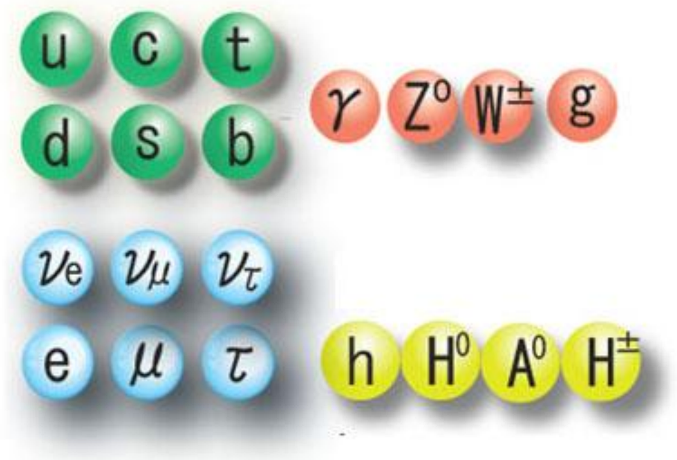


Present Particle Model: Standard Model

- Elementary particles consisting matter
  - 6 leptons
  - 6 quarks
  - in 3 generations
- forces between them mediated by bosons
  - weak interaction Z^0, W^+, W^-
  - electro-magnetic int. γ
  - strong interaction gluon
  - gravitation graviton

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$$

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$

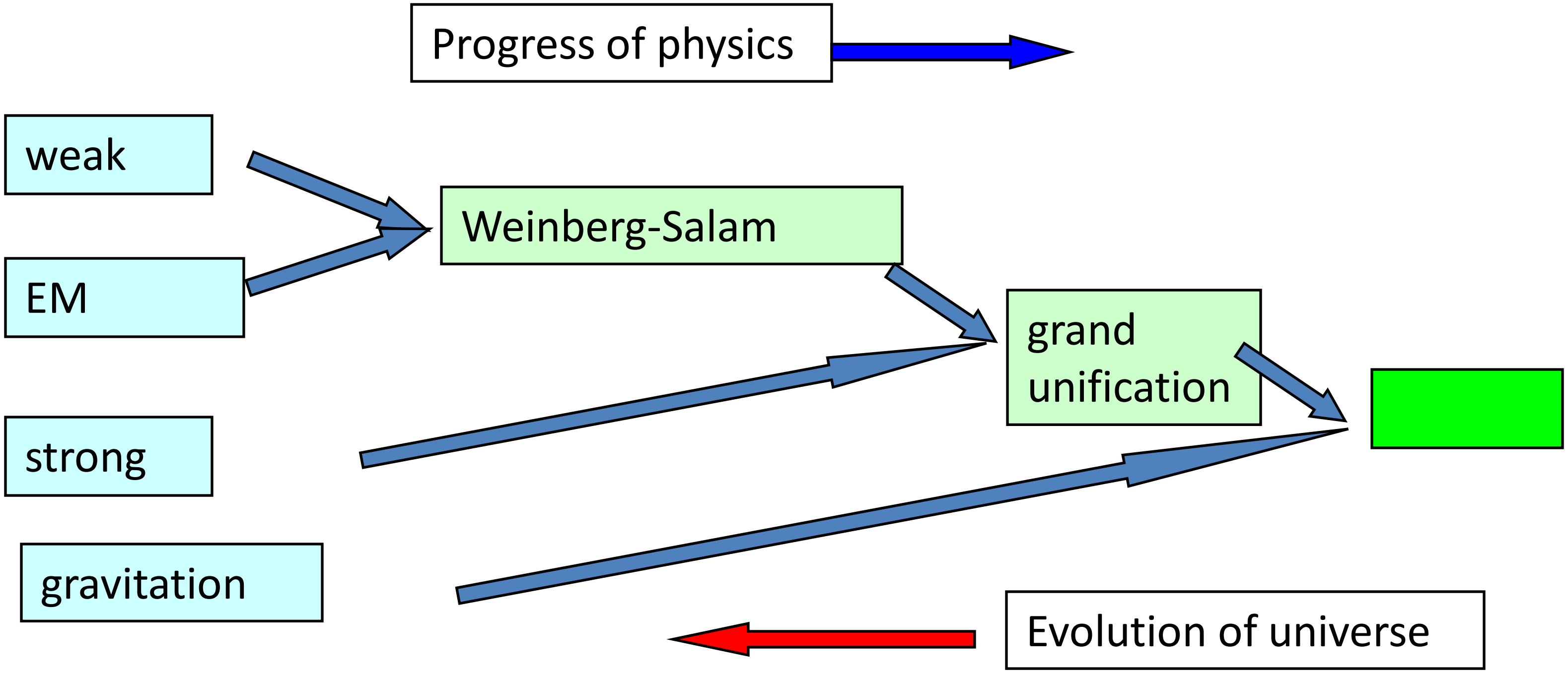


Unified Theory of Interactions

- Maxell theory
  - Unification of electric and magnetic fields into electromagnetism
- Weinberg-Salam model
  - end of 1960's
  - Unify electromagnetic and weak interactions
  - Introduced new particles Z^0, W^+, W^-
  - They are discovered in 1983
  - Advance of accelerator technology

Next Step of Unification

- Unification of remaining 2 interactions
- Further unification ay higher energies
- All forces be one at the beginning of universe?



Progress of physics

weak

EM

Weinberg-Salam

strong

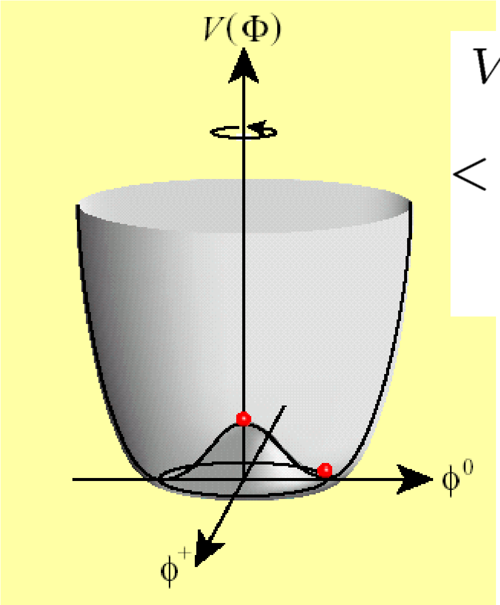
grand unification

gravitation

Evolution of universe

Higgs Particle

- Nambu-Goldstone model
- Higgs mechanism
  - Application of Namu-Goldstone
  - Starting with massless particles with symmetry
  - Spontaneous symmetry breaking introduced by Higgs potential;
  - Can create mass of particles coupled to Higgs
  - Applied to Weinberg-Salam
- Higgs: the only particle that had not been discovered in the Standard Model



$$\begin{aligned} V(\phi) &= -\mu^2\phi^2 + \lambda\phi^4 \\ <\phi> &= \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} \\ M_H &= 2\lambda v^2 \end{aligned}$$

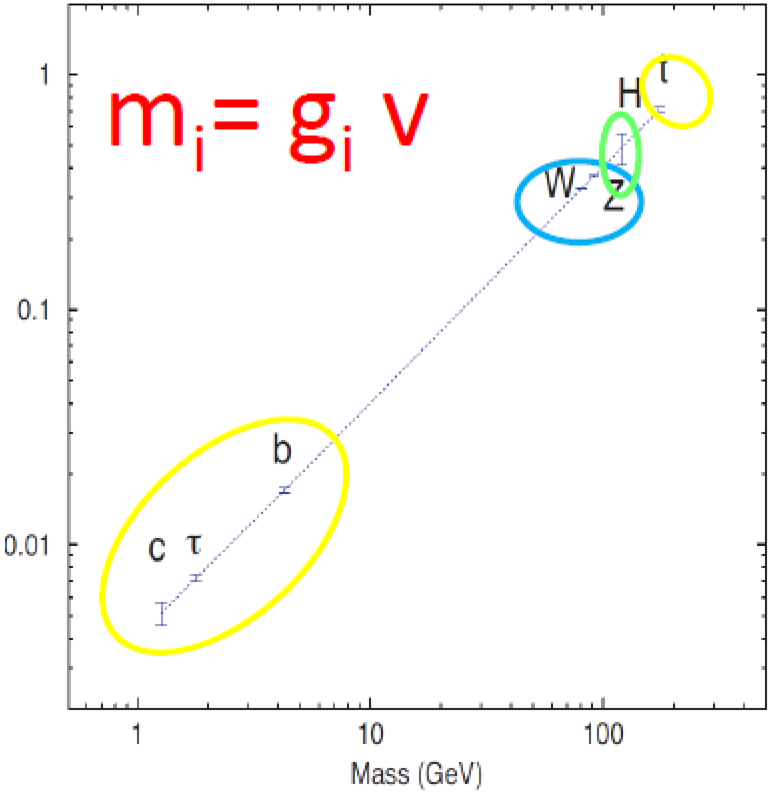
Y. Nambu

P. Higgs

Properties of Higgs

- Generate spontaneous breaking of electro-weak symmetry
- Scalar field coupled to all particles

- Mass of all particles come from the coupling to Higgs
    - Coupling to gauge fields (Z, W, g)
    - Coupling to quark and lepton (Yukawa coupling)
    - Self-coupling
- All these must be confirmed



$m_i = g_i v$

SPS: Super Proton Synchrotron

- Large proton synchrotron at CERN
- Operation start in 1976
- Reached 500GeV in
- Later remodeled into the first proton-antiproton collider

Stochastic Cooling

- Antiproton does not exist naturally
- must be created by collision using accelerators
- “Cooling” needed for collider
- Simon van der Meer invented cooling method in 1968
- Accumulated and cooled in AA (Antiproton Accumulator) and transported to SPS
- SPS → SppS
- First proton-antiproton collision in 1981年
- Discovered W^{+-}, Z^0 in 1983

Era of Huge Ring Colliders: Tevatron

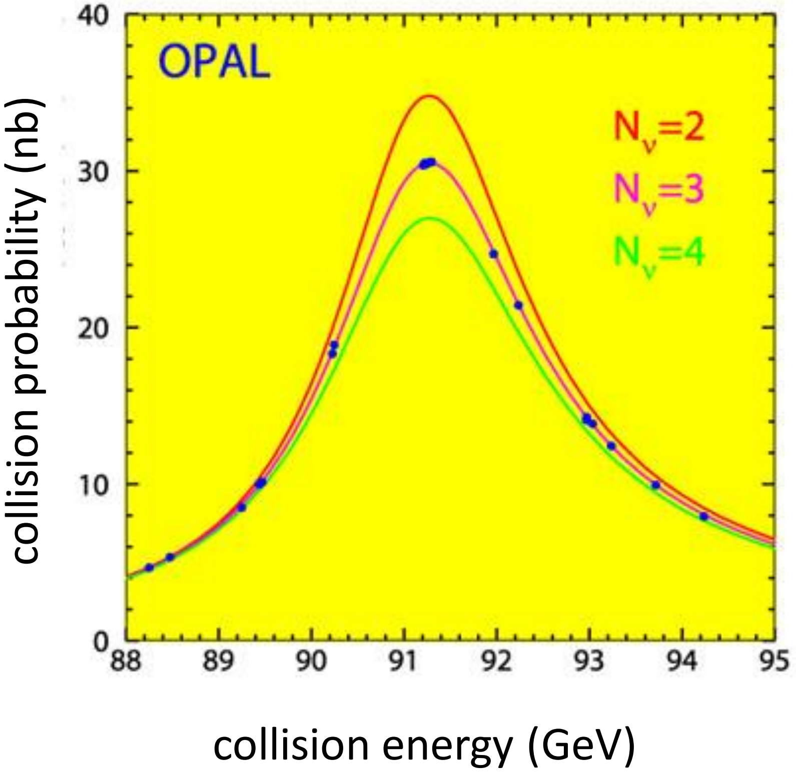
- FNAL
- Proton-antiproton
- circumference 6.3km
- up to ~1TeV
- Completed in 1983
- Superconducting magnet 4.2Tesla
- 1995 Top Quark
- 2009 shutdown

Main Injector in front and Tevatron hehind

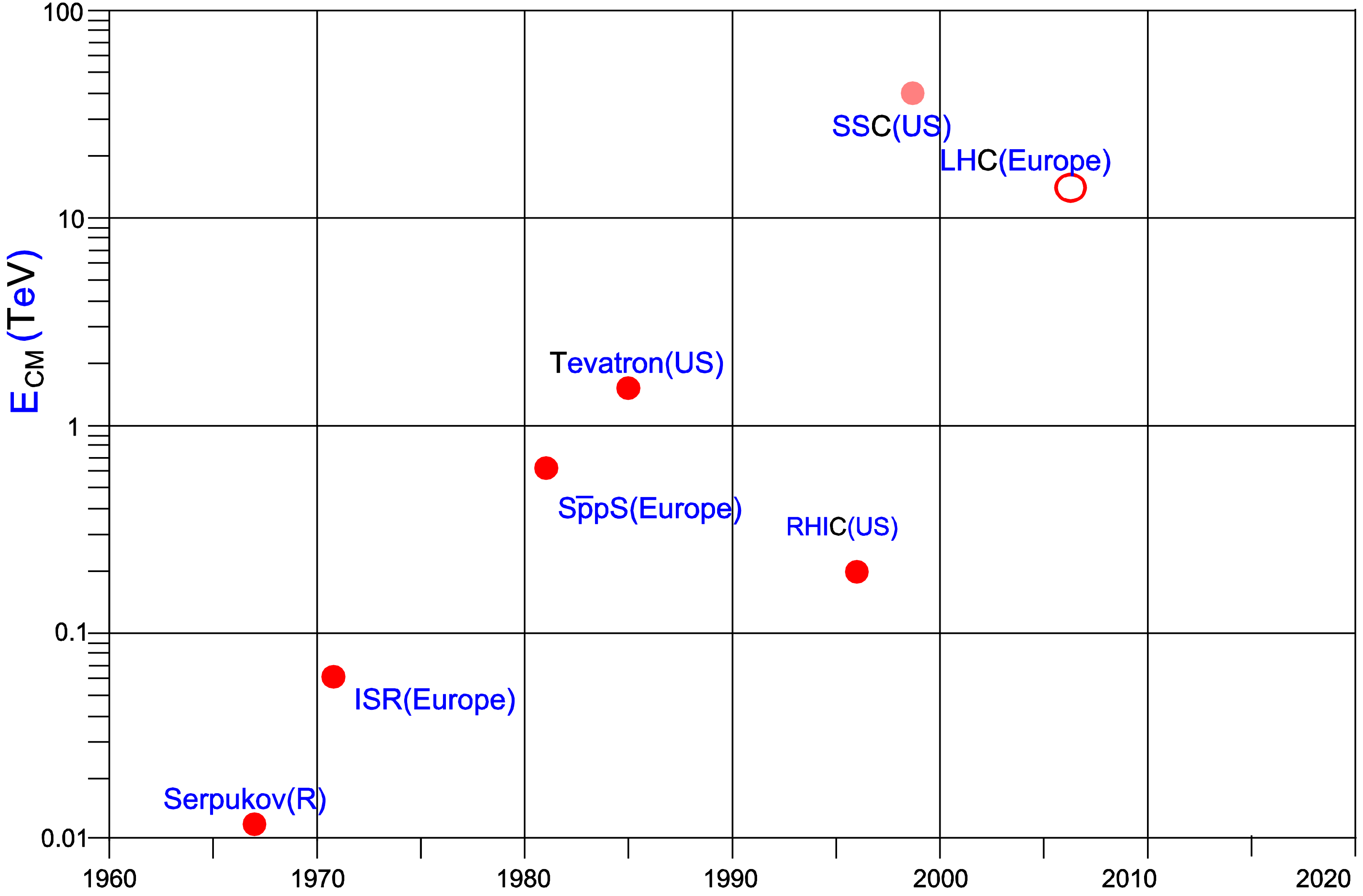
Era of Huge Ring Colliders: LEP

- LEP (Large Electron-Positron Collider)
  - CERN
  - Construction started in 1983, operation in 1989
- circumference 27km
  - First target Z^0 at 92GeV
  - Final beam energy 104.5GeV
  - end in 2000

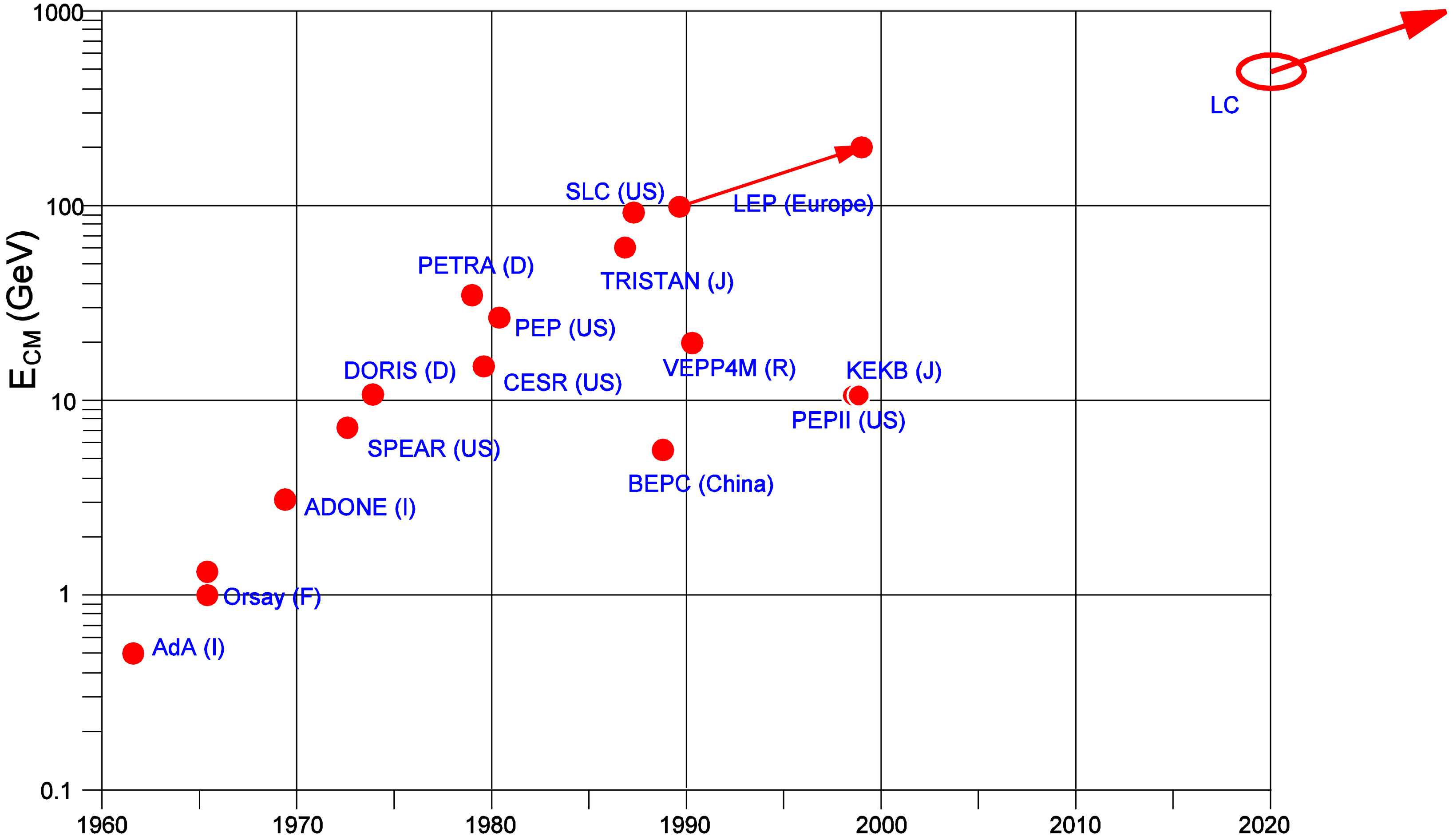
- LEP revealed Generation of elementary particles = 3
  n = 2.9841 +- 0.0083



Evolution of Proton/Antiproton Colliders

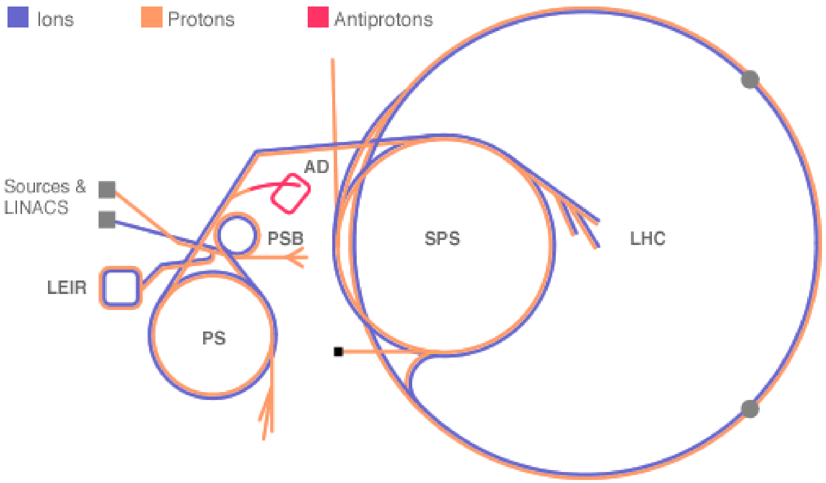


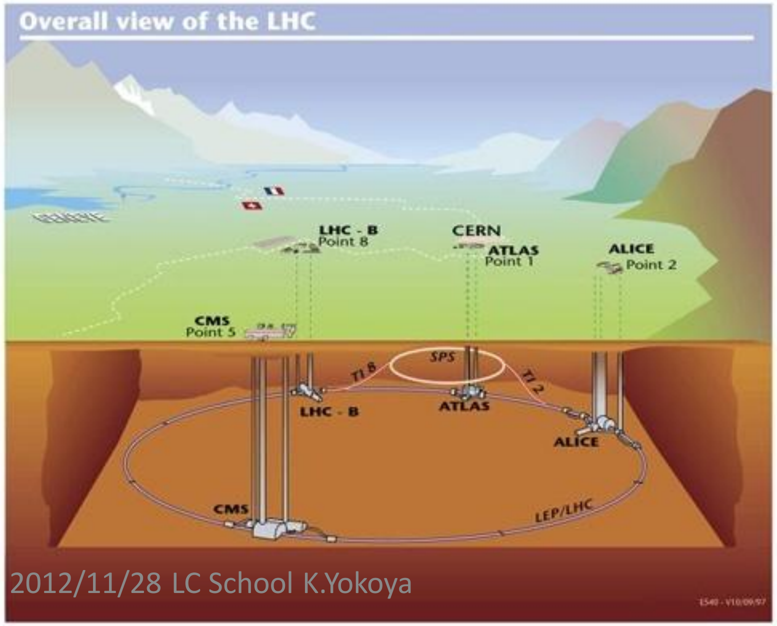
Evolution of Electron-Positron Colliders

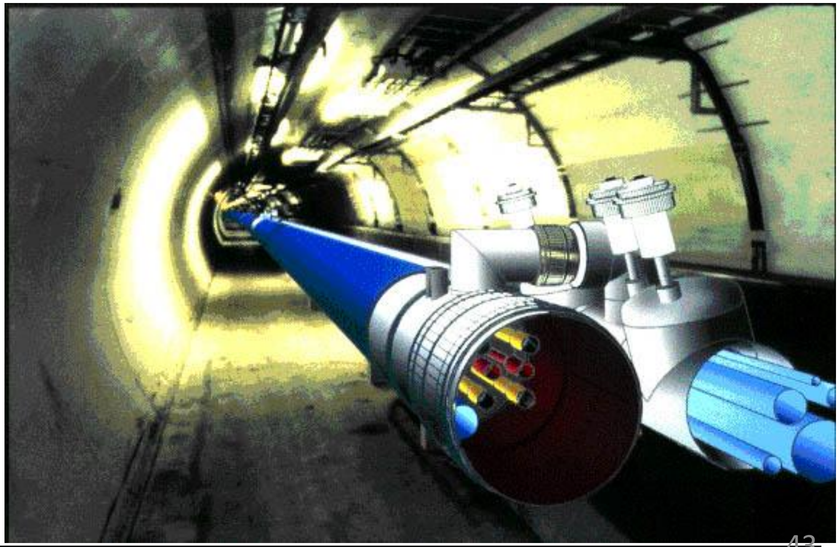


LHC

- Latest step to higher enegi
- Reuse of LEP tunnel
  - Circumference 27km
- 14TeV proton-proton
  - magnetic field 8.33 Tesla







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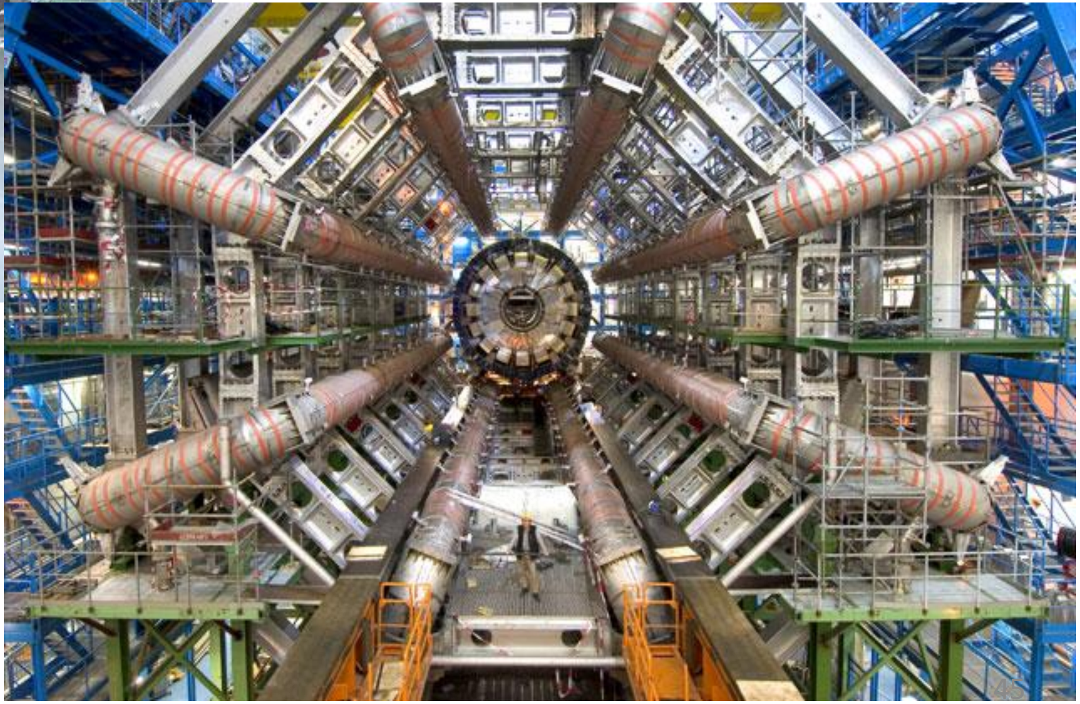
LHC

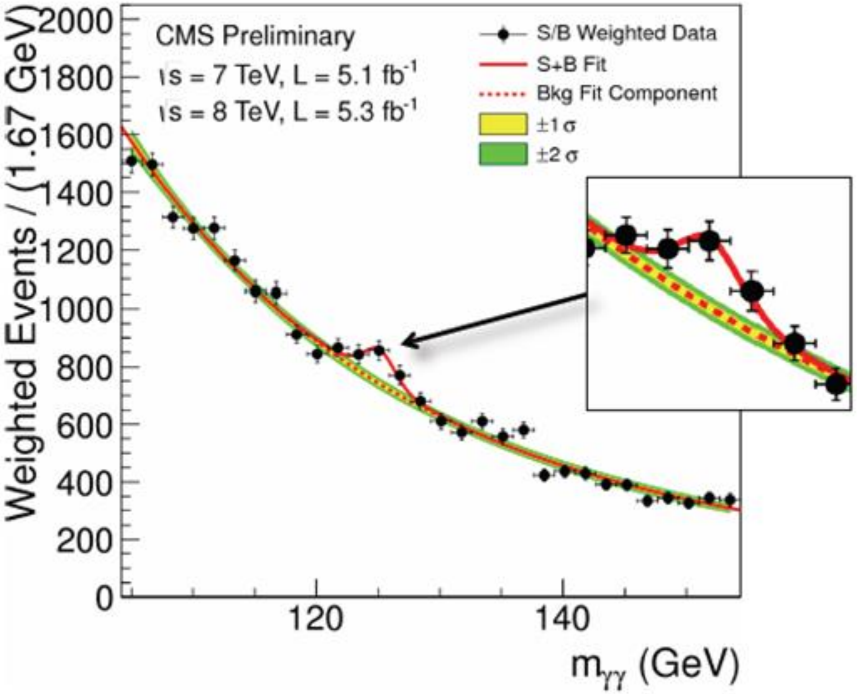
- Technology of Superconducting Magnet was essential

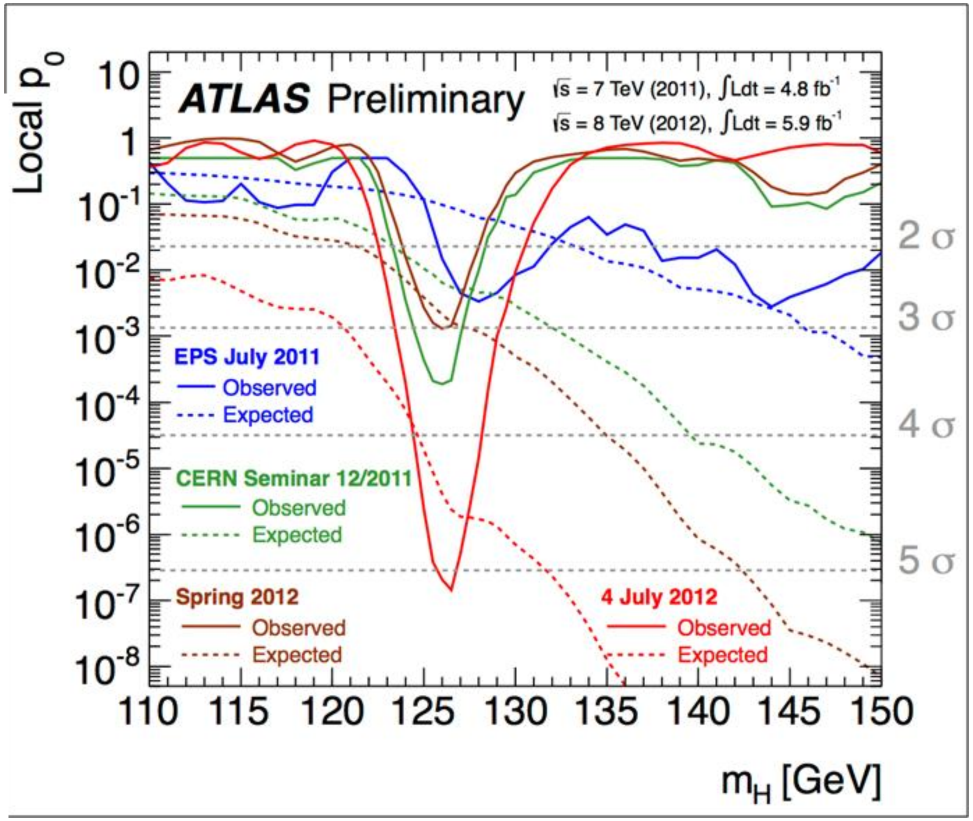
Atlas Detector



Discovery of Higgs-like Boson

- Reported Jul.4, 2012
- At ~126GeV



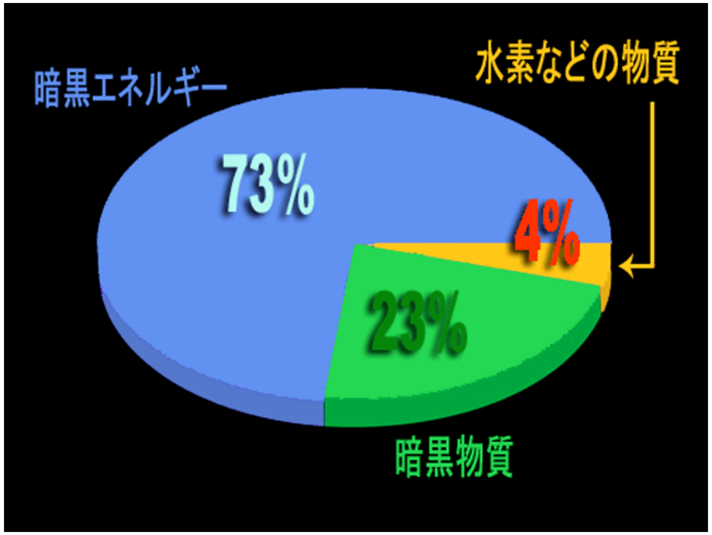


Part2: Future Accelerators

- Hadron Colliders
- Lepton Colliders
  - e+e-
    - Linear
    - Ring
  - μ+μ-
  - γγ
  - New acceleration mechanism

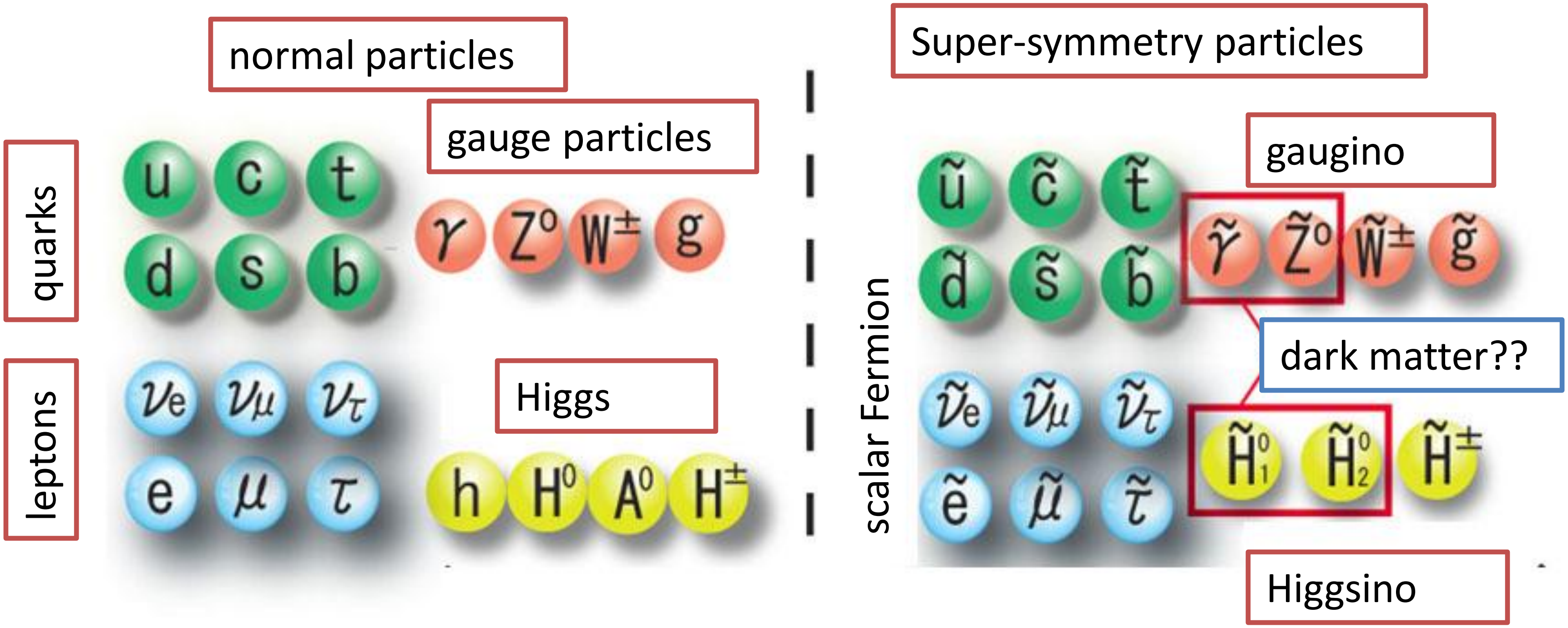
Physics Beyond Standard Model

- Grand Unification
- Super-symmetry
- Dark matter, dark energy
- Extra dimension
- Baryon number asymmetry



Super Symmetry (SUSY)

- Symmetry to exchange fermion and boson
- Important in unification to gravity
- Lightest SUSY particle is a candidate of dark matter
- No indication yet in LHC



normal particles

gauge particles

quarks

leptons

Higgs

Super-symmetry particles

gaugino

dark matter??

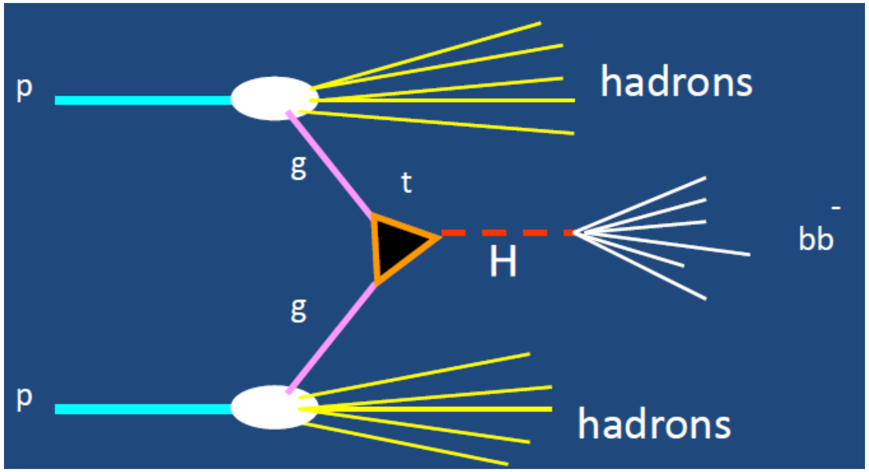
scalar Fermion

Higgsino

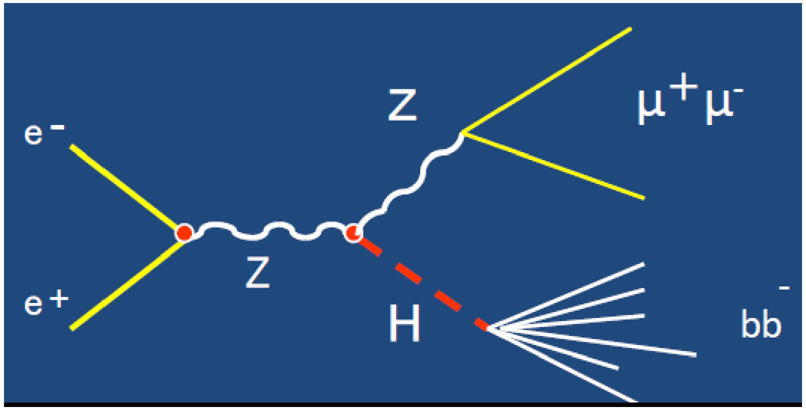
Hadron Collider

- Hadron (proton/antiproton) is easier to accelerate to high energies owing to the absence of synchrotron radiation
- Already 14TeV will be reached in a few years (LHC)
- Events are complicated because proton is not an elementary particle
  - p = uud
  - Very high event rate: most of them are unnecessary
- Higher energies are possible only by
  - Higher magnetic field
  - or larger ring

Higgs production in pp



Higgs production in e+e-



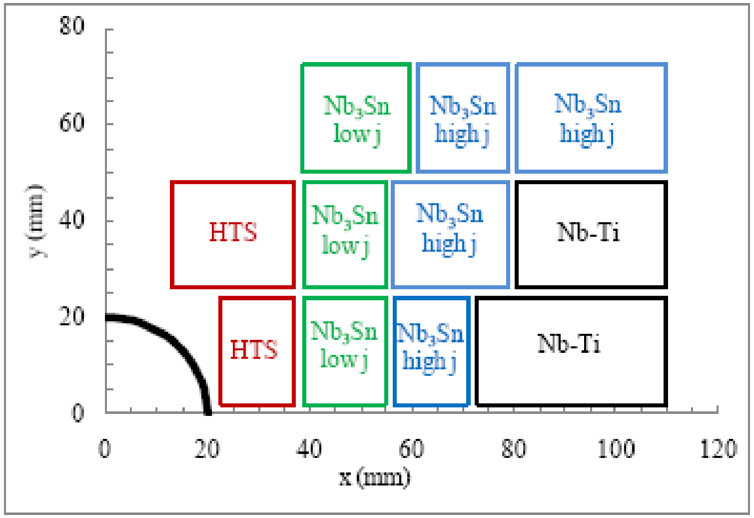
HELHC: Higher Energy LHC

- proposed after the luminosity upgrade to HL-LHC
- Upgrade the magnets of LHC
- 8.33 Tesla → 20 Tesla ?
- E_{CM} 33TeV
- According to the present price of magnet (if possible), 80km ring is cheaper

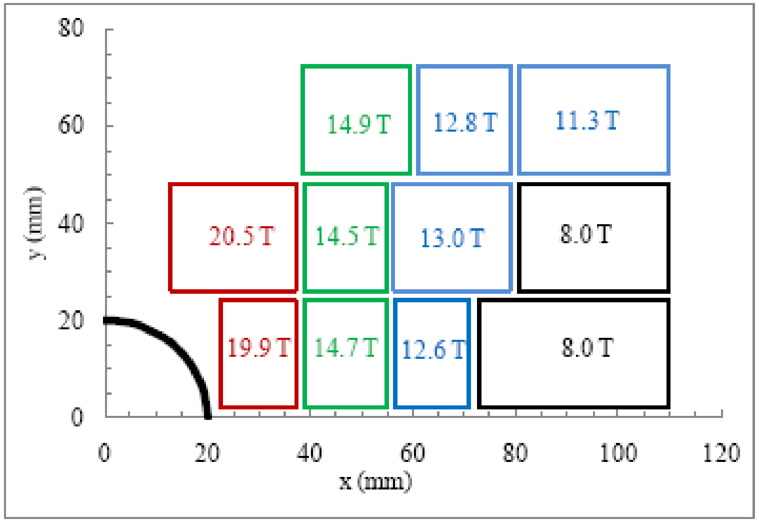
THE COIL

- Cable: 22 mm width, 1.62 mm thick, 0.8 mm strand (LBL HD2)
- Three layers are needed for field quality
  - 8 T → Nb-Ti (380 A/mm^2)
  - 13 T → Nb$_3$Sn (380 A/mm^2)
  - 15 T → Nb$_3$Sn (190 A/mm^2)
  - 20 T → HTS (380 A/mm^2)

	N. turns	%
Nb-Ti	41	27%
Nb$_3$Sn	85	57%
HTS	24	16%
Total	150	



Materials used in the coil (one quarter shown)

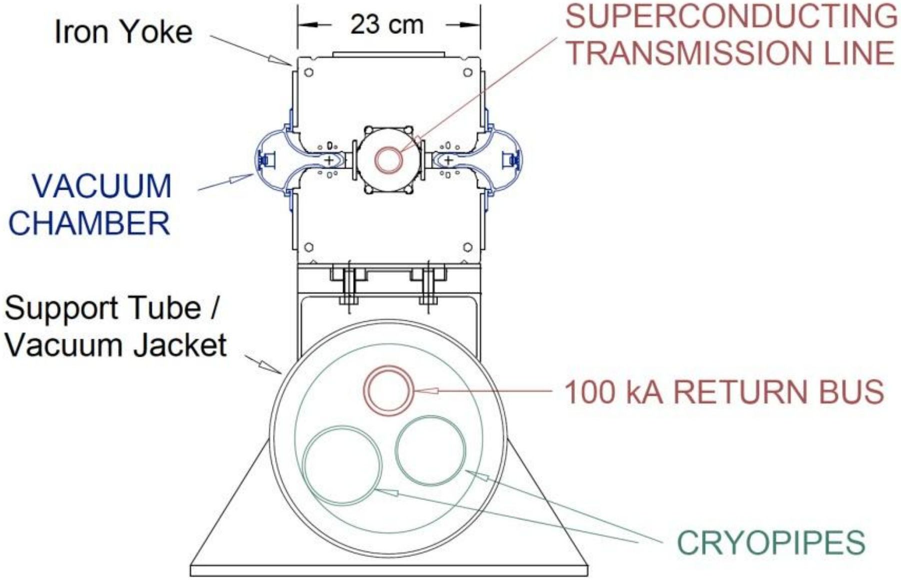


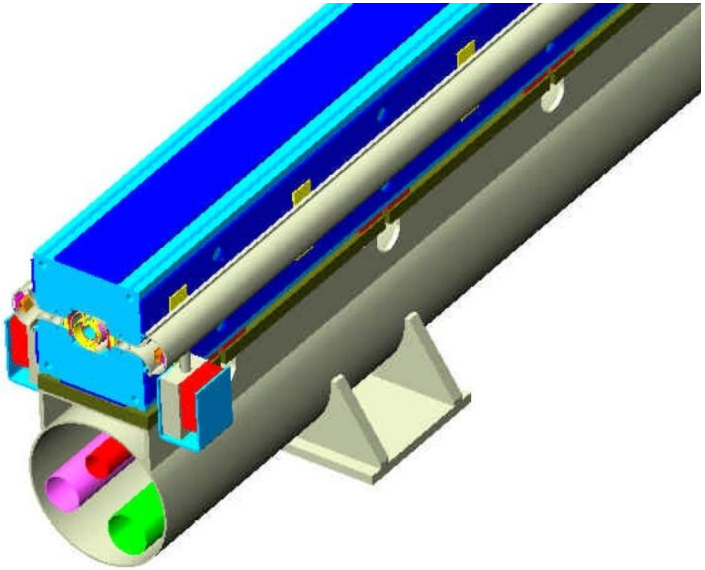
Field in the coil at 20 T operational field (one quarter shown)

from EzioTodesco (HELHC WS 2010)

VLHC

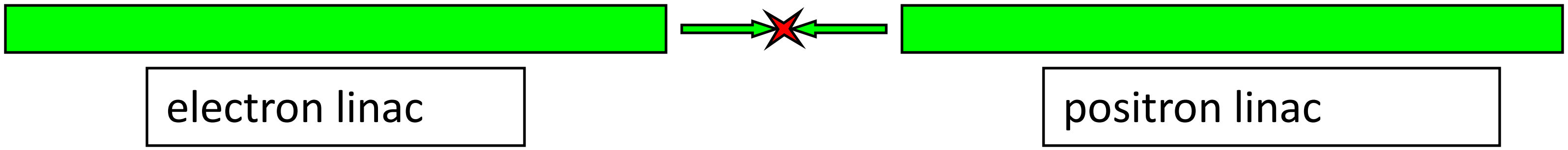
- Proposed long ago
- Circumference 233km
- Magnetic field 9.8T
- E_{CM} 175TeV





Electron-Positron Collider

- Ring collider is limited due to synchtrotron radiation (→ later slides)
  - LEP ended at E_{cm}=209GeV
- Beyond the radiation limit, the only possibility is linear collider
- First key issues of linear collider are
  - Acceleration gradient
  - Luminosity
    because of single-pass



Luminosity

- Quantity to be maximized

$$\text{Number of events/sec} = \mathcal{L}\sigma$$

$$(\sigma = \text{cross section of the event})$$

$$\mathcal{L} = f_{rep}\frac{n_b N^2}{4\pi\sigma_x^*\sigma_y^*}$$

( ): typical values for ILC

- f_{rep} repetition rate of beam pulse（5Hz）
- n_b number of bunches in a puilse (1312)
- N number of particles in a bunch (2x10^{10})
- σ_x*, σ_y* transverse beam size at the collision point (~6nm, ~500nm)

Beamstrahlung

- Synchrotron radiation during collision due to the field by the on-coming beam
- Causes
  - spread in the collision energy
  - background to the experiment
- The critical energy is characterized by the upsilon parameter

$$\Upsilon \equiv \frac{2}{3}\frac{\hbar\omega_c}{E} = \frac{\lambda_e \gamma^2}{\rho} = \gamma\frac{2B}{B_c} = \frac{e}{m^3}\sqrt{\left|(F_{\mu\nu}p^\nu)^2\right|}$$

$$B_c = m^2/e \approx 4.4\text{GTeslas}$$

Factor 2 in front of B comes from the sum of electric and magnetic fields

- Expressed by the beam parameters

$$\Upsilon_{average} = \frac{5}{6}\frac{N r_e^2 \gamma}{\alpha\sigma_z(\sigma_x + \sigma_y)}$$

- Order of 0.1 in 500GeV collider

Energy loss and number of photons by beamstrahlung

- Average number of photons per electron

$$n_\gamma \approx 1.08 \frac{2Nr_e\alpha}{\sigma_x+\sigma_y} U_0(\Upsilon),$$

$$U_0(\Upsilon) \approx \frac{1}{\sqrt{1+\Upsilon^{2/3}}}$$

- Average energy loss

$$\delta_E = \left\langle -\frac{\Delta E}{E} \right\rangle \approx 0.209 \frac{N^2 r_e^3 \gamma}{\sigma_z} \left(\frac{2}{\sigma_x+\sigma_y} \right)^2 U_1(\Upsilon)$$

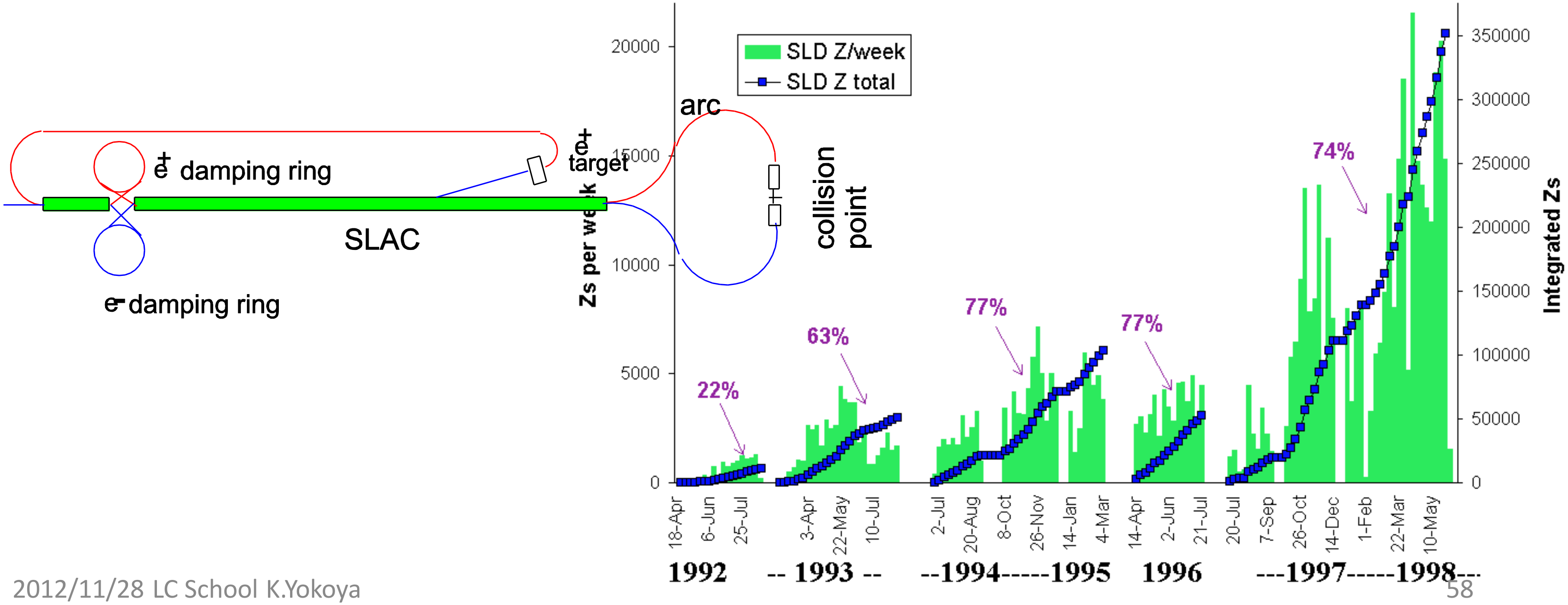
$$U_1(\Upsilon) \approx \frac{1}{[1+(1.5\Upsilon)^{2/3}]^2}$$

- Average photon energy

$$\left\langle \frac{\omega}{E} \right\rangle = \begin{cases} 0.462\Upsilon & (\Upsilon \to 0) \\ 16/23 = 0.254 & (\Upsilon \to \infty) \end{cases}$$

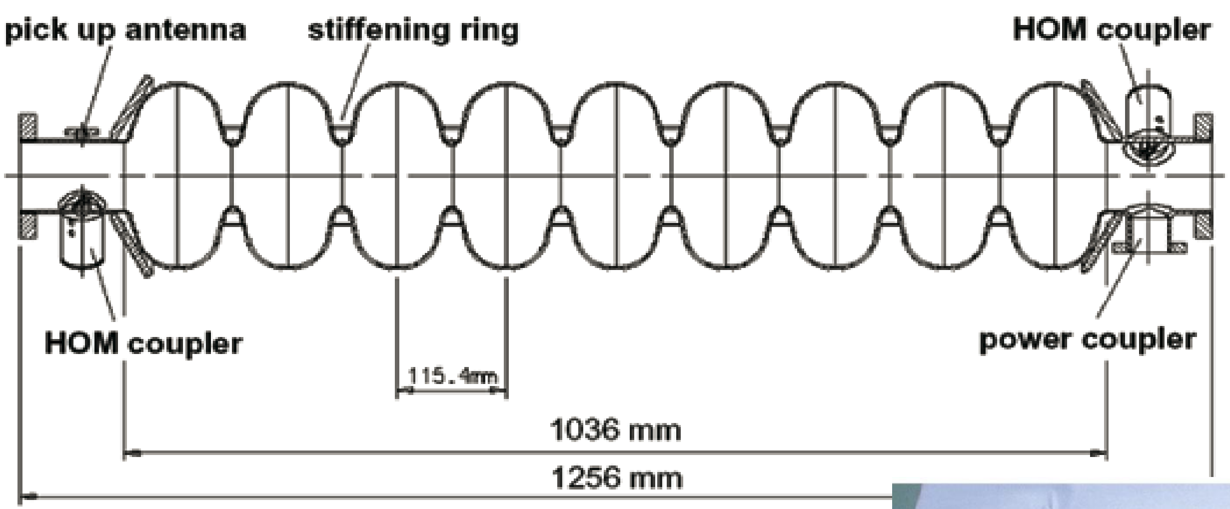
First Linear Collider: SLC

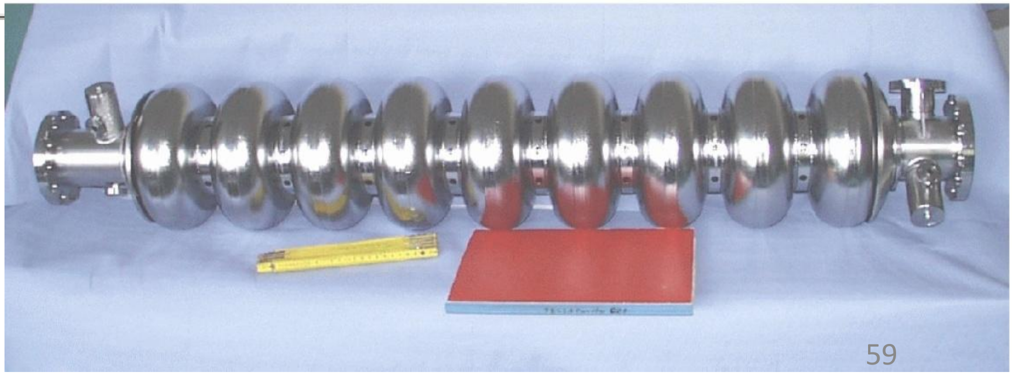
- Linear collider with one single linac
- completed in 1987 at SLAC
- First Z^0 event in April 1989
- polarized electron beam (~80%)
- end of run 1998
- luminosity $3x10^{30}$ /cm^2/s (design $6x10^{30}$)
    - high crossection at Z^0



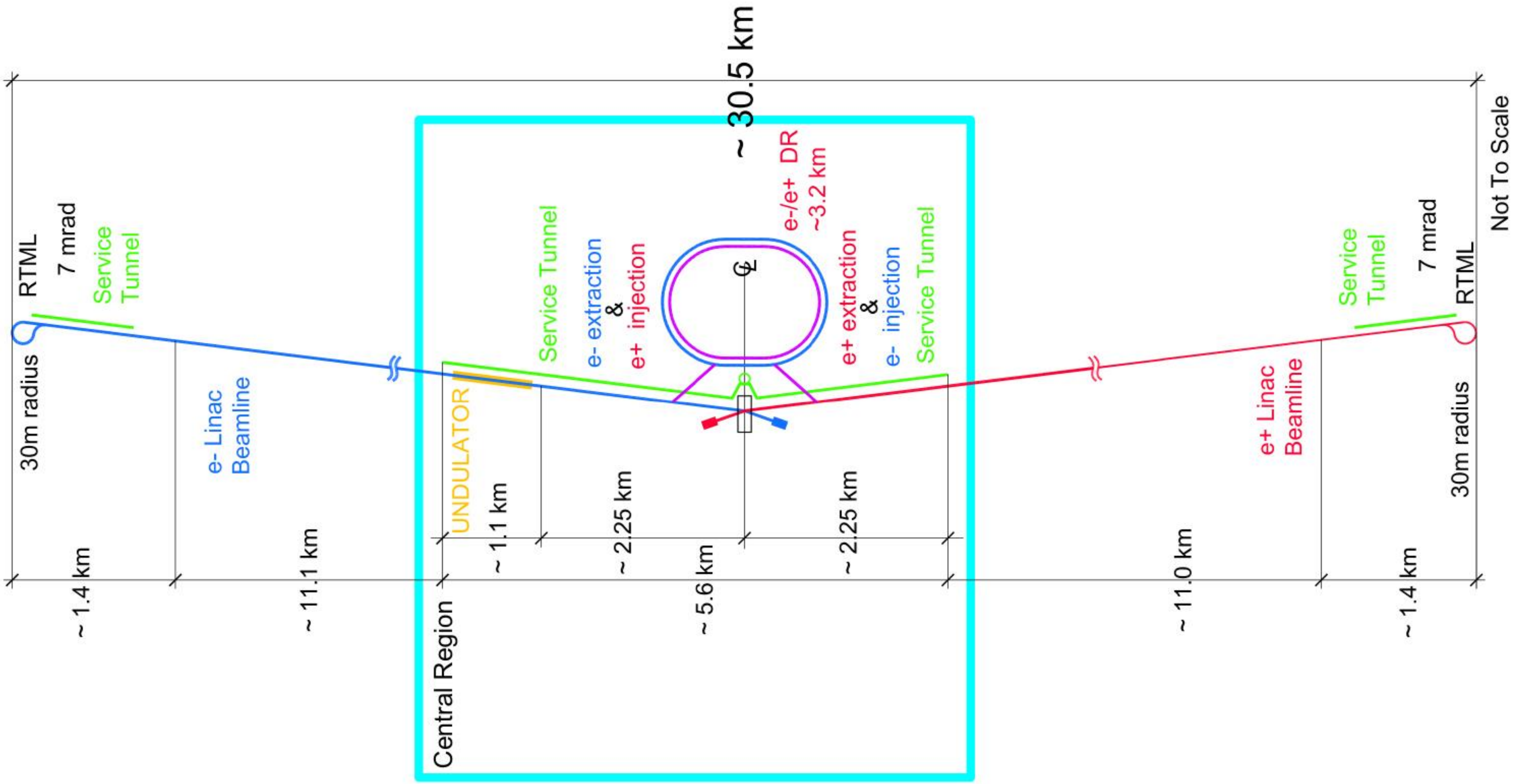
ILC: International Linear Collider

- Key technology: superconducting RF cavities
- Average accelerating gradient 31.5 MV/m
- Lecture by Barry Barish (this afternoon)





ILC Layout


~ 30.5 km
Not To Scale
RTML
7 mrad
Service Tunnel
30m radius
e- Linac Beamline
UNDULATOR
Service Tunnel
e- extraction & e+ injection
e-/e+ DR ~3.2 km
℄
e+ extraction & e- injection
Service Tunnel
e+ Linac Beamline
Service Tunnel
7 mrad
RTML
30m radius
~ 1.1 km
~ 2.25 km
~ 2.25 km
~ 1.4 km
~ 11.1 km
~ 5.6 km
~ 11.0 km
~ 1.4 km
Central Region

IP and General Parameters

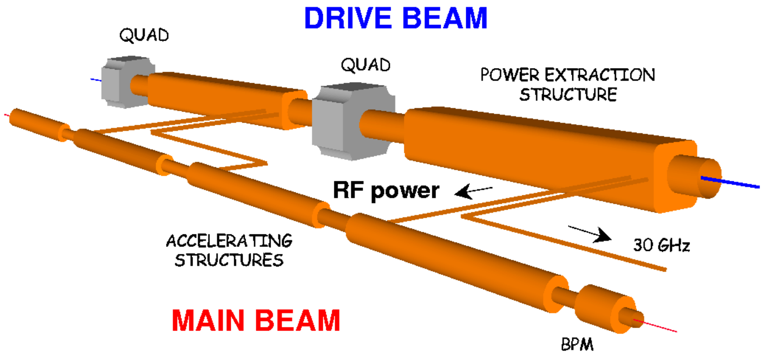
				TF = Traveling Focus						E_{cm} Upgrade	
									L Upgrade	A1	B1b
	Centre-of-mass energy	E_{cm}	**GeV**	**200**	**230**	**250**	**350**	**500**	**500**	**1000**	**1000**
	Beam energy	E_{beam}	GeV	100	115	125	175	250	500	500	500
	Collision rate	f_{rep}	Hz	5	5	5	5	5	5	4	4
	Electron linac rate	f_{linac}	Hz	10	10	10	5	5	5	4	4
	Number of bunches	n_b		1312	1312	1312	1312	1312	2625	2450	2450
	Electron bunch population	N_-	$\times 10^{10}$	2.0	2.0	2.0	2.0	2.0	2.0	1.74	1.74
	Positron bunch population	N_+	$\times 10^{10}$	2.0	2.0	2.0	2.0	2.0	2.0	1.74	1.74
	Bunch separation	Δt_b	ns	554	554	554	554	554	366	366	366
	Bunch separation $\times f_{RF}$	$\Delta t_b\ f_{RF}$		720	720	720	720	720	476	476	476
	Pulse current	I_{beam}	mA	5.8	5.8	5.8	5.8	5.79	8.75	7.6	7.6
	RMS bunch length	σ_z	mm	0.3	0.3	0.3	0.3	0.3	0.3	0.250	0.225
	Electron RMS energy spread	$\Delta p/p$	%	0.206	0.194	0.190	0.158	0.125	0.125	0.083	0.085
	Positron RMS energy spread	$\Delta p/p$	%	0.187	0.163	0.150	0.100	0.070	0.070	0.043	0.047
	Electron polarisation	P_-	%	80	80	80	80	80	80	80	80
	Positron polarisation	P_+	%	31	31	30	30	30	30	20	20
	Horizontal emittance	$\gamma\varepsilon_x$	μm	10	10	10	10	10	10	10	10
	Vertical emittance	$\gamma\varepsilon_y$	nm	35	35	35	35	35	35	30	30
	IP horizontal beta function	$\beta_x{}^*$	mm	16.0	14.0	13.0	16.0	11.0	11.0	22.6	11.0
	IP vertical beta function (no TF)	$\beta_y{}^*$	mm	0.34	0.38	0.41	0.34	0.48	0.48	0.25	0.23
	IP RMS horizontal beam size	$\sigma_x{}^*$	nm	904	789	729	684	474	474	481	335
	IP RMS veritcal beam size (no TF)	$\sigma_y{}^*$	nm	7.8	7.7	7.7	5.9	5.9	5.9	2.8	2.7
analytical estimates	Horizontal distruption parameter	D_x		0.2	0.2	0.3	0.2	0.3	0.3	0.1	0.2
	Vertical disruption parameter	D_y		24.3	24.5	24.5	24.3	24.6	24.6	18.7	25.1
	Horizontal enhancement factor	H_{Dx}		1.0	1.1	1.1	1.0	1.1	1.1	1.0	1.0
	Vertical enhancement factor	H_{Dy}		4.5	5.0	5.4	4.5	6.1	6.1	3.5	4.1
	Total enhancement factor	H_D		1.7	1.8	1.8	1.7	2.0	2.0	1.5	1.6
	Geometric luminosity	L_{geom}	$\times 10^{34}\ \mathrm{cm^{-2}s^{-}}$	0.30	0.34	0.37	0.52	0.75	1.50	1.77	2.64
	Luminosity	L	$\times 10^{34}\ \mathrm{cm^{-2}s^{-}}$	**0.50**	**0.61**	**0.68**	**0.88**	**1.47**	**2.94**	**2.71**	**4.32**
	Average beamstrahlung parameter	Υ_{av}		0.013	0.017	0.020	0.030	0.062	0.062	0.127	0.203
	Maximum beamstrahlung parameter	Υ_{max}		0.031	0.041	0.048	0.072	0.146	0.146	0.305	0.483
	Average number of photons / particl	n_γ		0.95	1.08	1.16	1.23	1.72	1.72	1.43	1.97
	Average energy loss	δE_{BS}	%	0.51	0.75	0.93	1.42	3.65	3.65	5.33	10.20
simulation	Luminosity	L	$\times 10^{34}\ \mathrm{cm^{-2}s^{-}}$	0.498	0.607	0.681	0.878	1.50	3.00	3.23	4.31
	Coherent waist shift	ΔW_y	μm	250	250	250	250	250	250	190	190
	Luminosity (inc. waist shift)	L	$\times 10^{34}\ \mathrm{cm^{-2}s^{-}}$	**0.56**	**0.67**	**0.75**	**1.0**	**1.8**	**3.6**	**3.6**	**4.9**
	Fraction of luminosity in top 1%	$L_{0.01}/L$		91.3%	88.6%	87.1%	77.4%	58.3%	58.3%	59.2%	44.5%
	Average energy loss	δE_{BS}		0.65%	0.83%	0.97%	1.9%	4.5%	4.5%	5.6%	10.5%
	Number of pairs per bunch crossing	N_{pairs}	$\times 10^3$	44.7	55.6	62.4	93.6	139.0	139.0	200.5	382.6
	Total pair energy per bunch crossing	E_{pairs}	TeV	25.5	37.5	46.5	115.0	344.1	344.1	1338.0	3441.0

Physics at ILC

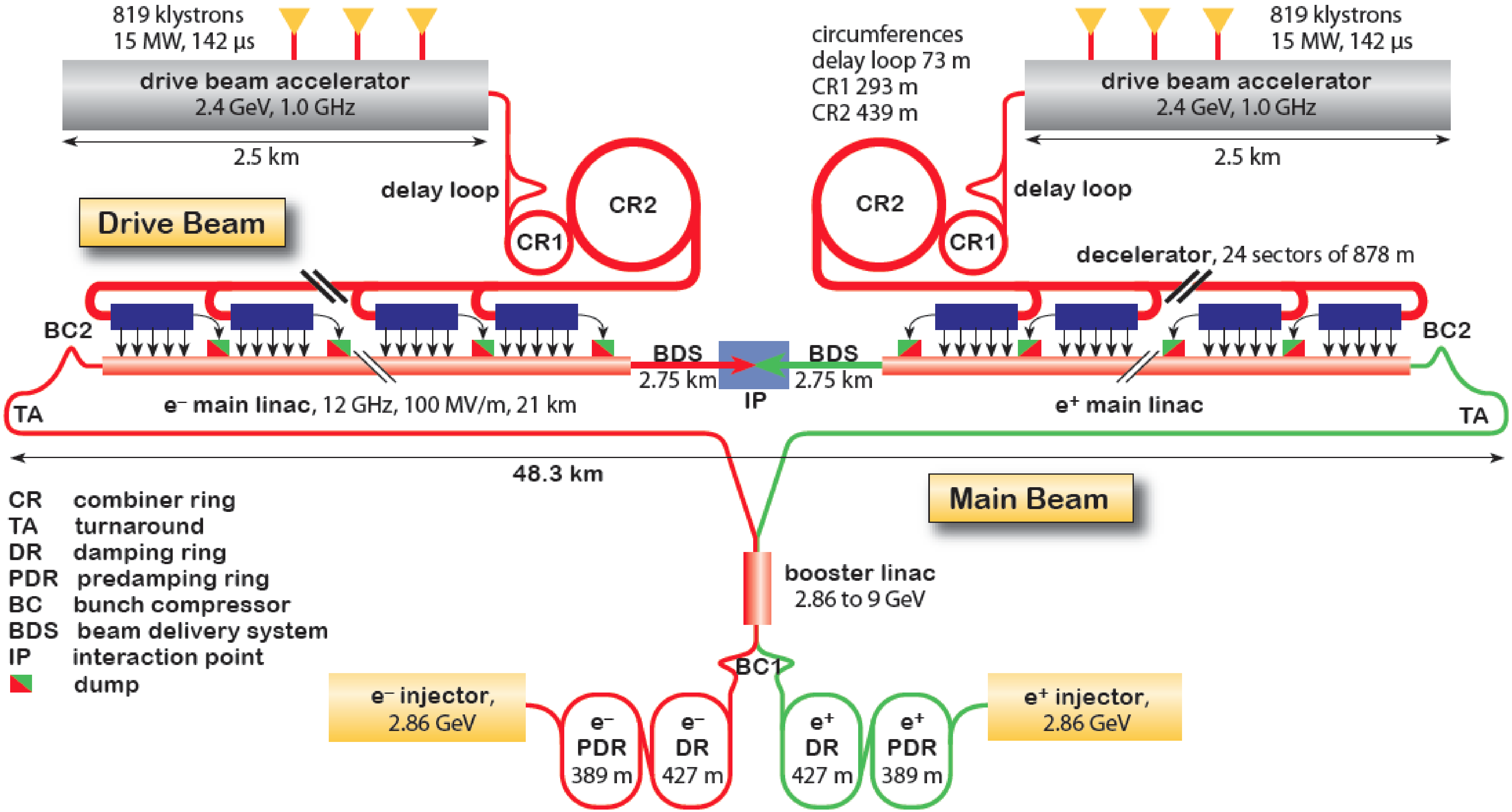
- Higgs factory (250-500GeV)
  - One single Higgs or more (SUSY) ?
  - Quantum number of vacuum?
  - Confirm the origin of mass
- Top quark (~350GeV)
  - Why heavy?
  - Determine the mass to O(100MeV), relation to H, W, Z
- Mass generation mechanism
  - Higgs self-coupling
- Direct search of new physics
  - Light dark matter invisible at LHC?

CLIC: Compact Linear Collider

- Two-beam scheme
  - Accelerate long train of electron beam to GeV
  - lead it to decelerating structure (PET: Power Extraction Structure)
  - transfer the generated microwave to linac (normal conducting) side by side with PET
  - Huge klystron
  - First proposed at CERN in 1987(?)
  - New scheme proposed by R. Ruth
    - Manipulation of long bunch train
    - Frequency determined by drive bunch interval and PET
- Lecture by Frank Tecker (tomorrow)



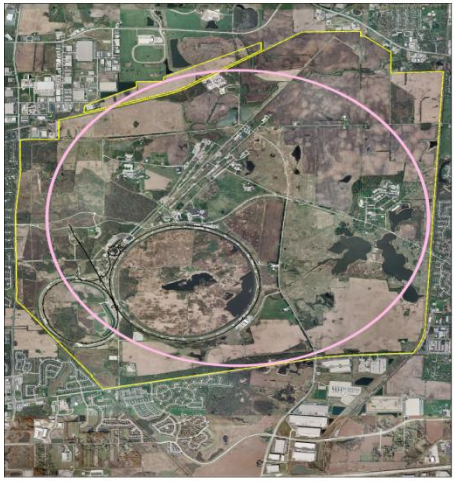
CLIC (CERN Linear Collider)



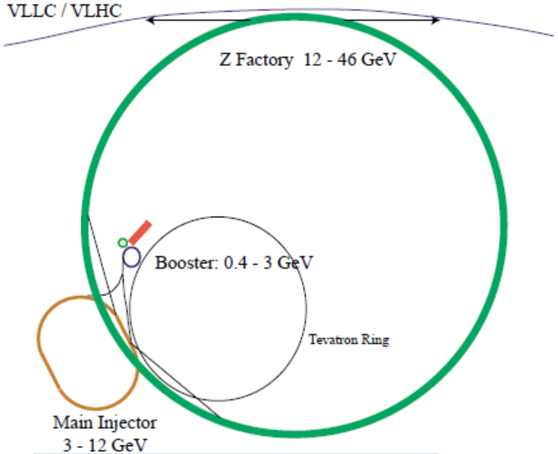
CR	combiner ring
TA	turnaround
DR	damping ring
PDR	predamping ring
BC	bunch compressor
BDS	beam delivery system
IP	interaction point
🟥	dump

Revival of e+e- Ring Colliders ?

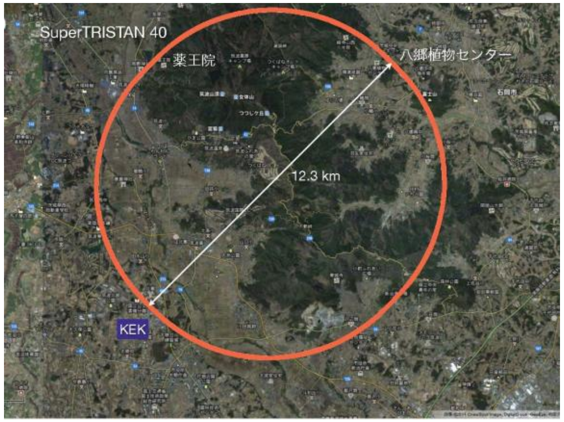
- To create Higgs by e+e- → ZH requires E_{CM}~240GeV
- This is not too high compared with the final energy 209GeV at LEP



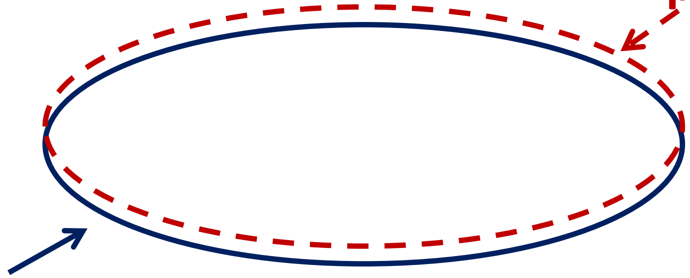
FNAL site filler (16km)



VLCC (233km)



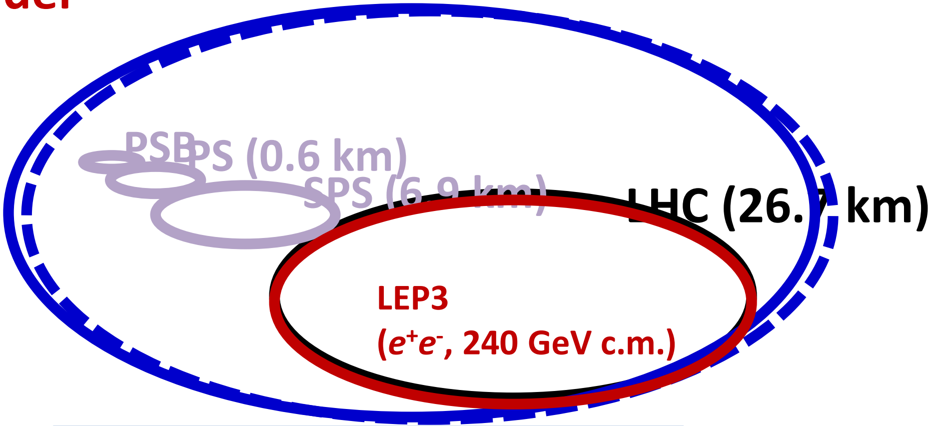
SuperTRISTAN (40km, 60km)



pp collider

e⁻e⁺ Higgs Factory

CHF (China) (50km, 70km)



LEP3 (27km), TLEP (80km)

2 Aspects of Synchrotron Radiation Loss

- Energy loss by individual particles must be compensated for

$$U = 0.088 \frac{E^4[\mathrm{GeV}]}{\rho[\mathrm{m}]} \quad [\mathrm{MeV}]$$

- This (almost) determines RF voltage per turn
  - ~7GeV in LEP tunnel
  - Still possible owing to the improvement of superconducting cavity technology
- But, to get required electric power, you must multiply the beam current
  - Real limitation comes from the wall-plug power
  - Reduce the beam current
  - Small beam size for high luminosity

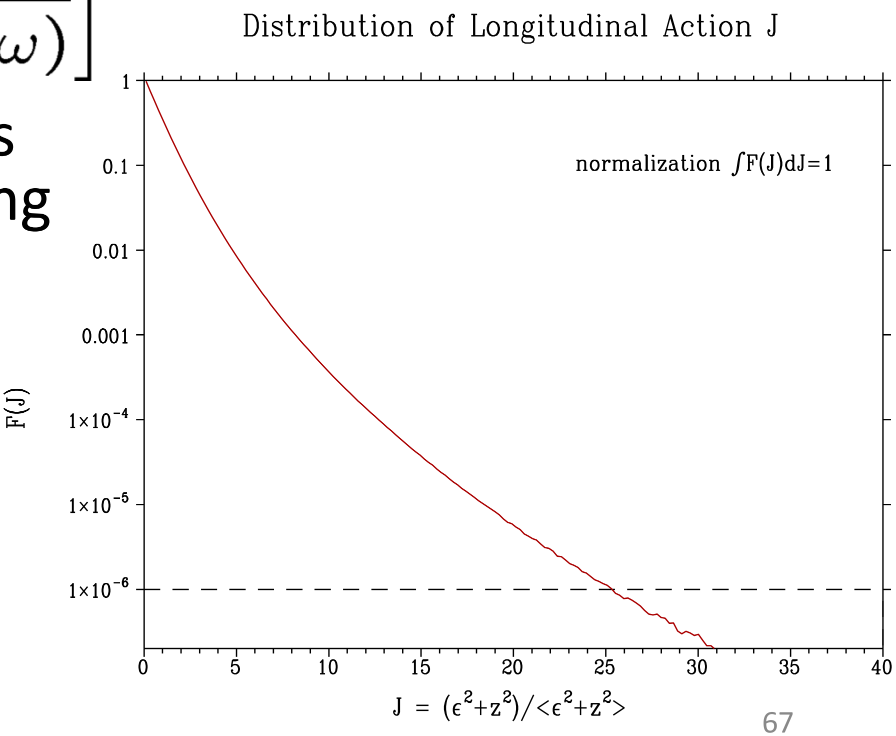
Beamstrahlung Limitation of e$^+$e$^-$ Ring Colliders

- Beamstrahlung at high-energy tail causes significant energy loss of electrons/positron

$$\Upsilon_{max} \approx \frac{2Nr_e^2\gamma}{\alpha\sigma_z(\sigma_x+\sigma_y)}$$

$$\frac{dW}{d\omega} \propto \exp\left[-\frac{2\omega}{3\Upsilon(E_e-\omega)}\right]$$

- Particles with large energy loss cannot circulate around the ring (momentum band-width)
- Affects the beam life time
- Hence, ring colliders are much more fragile than LCs against beamstrahlung



Luminosity Scaling of e⁺e⁻ Ring Colliders

V. Telnov, arXiv:1203.6563v, 29 March 2012

- For given Upsilon, the momentum band width must be

$$\eta \equiv [\Delta p/p]_{max} \gtrsim 15\Upsilon$$

- Then, the luminosity at beamstrahlung limit and tune-shift limit is given by

$$\mathcal{L} \propto \frac{\rho P_{SR}}{E^{13/3}} \left(\frac{\xi_y \eta^2}{\varepsilon_{g,y}} \right)^{1/3}$$

P_{SR} : syn.rad.power

ρ : bending radius

ξ_y : tune-shift

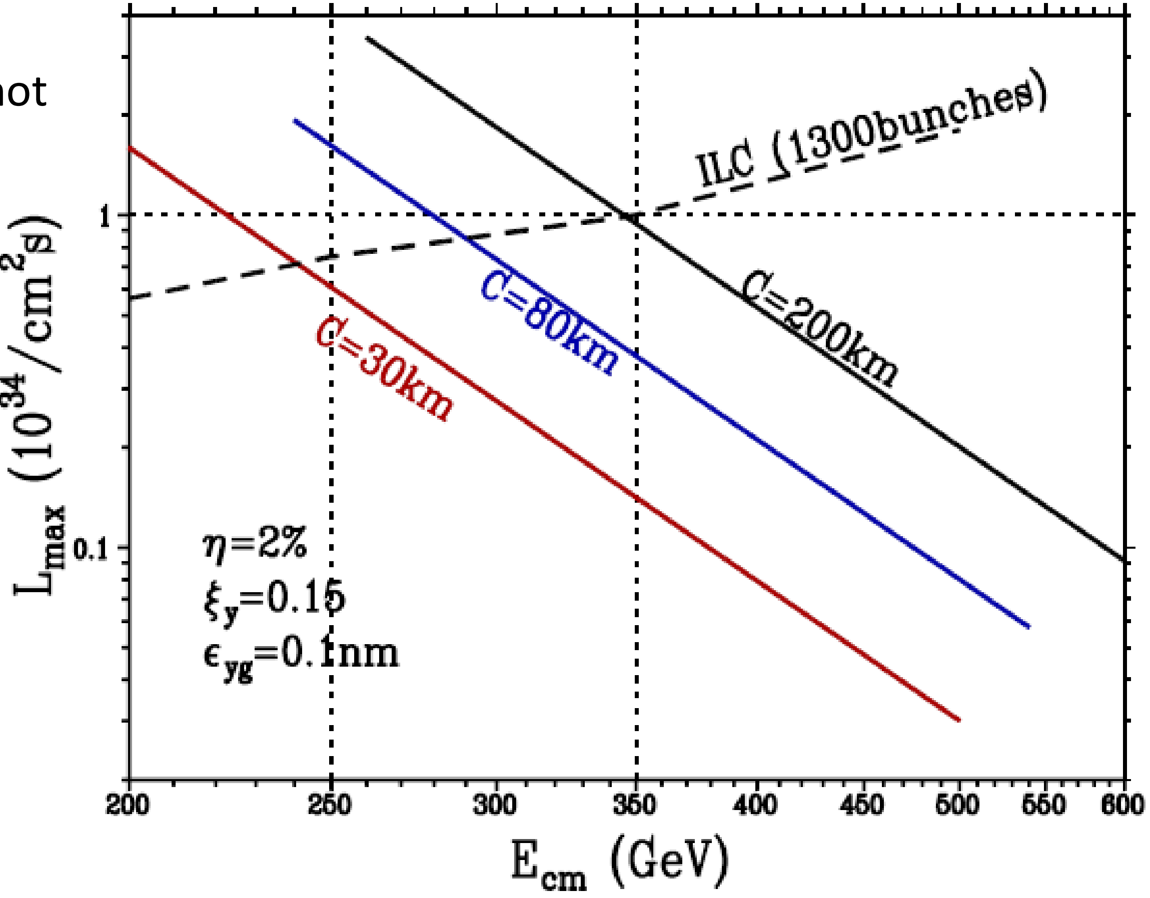
$\varepsilon_{g,y}$: geometric emit.

Luminosity vs. Energy

- Key parameters
  - momentum band width
  - vertical emittance
  - beam-beam tune-shift
- Ring Collider can be a choice ?
  if e+e- at >~350GeV is not needed at all

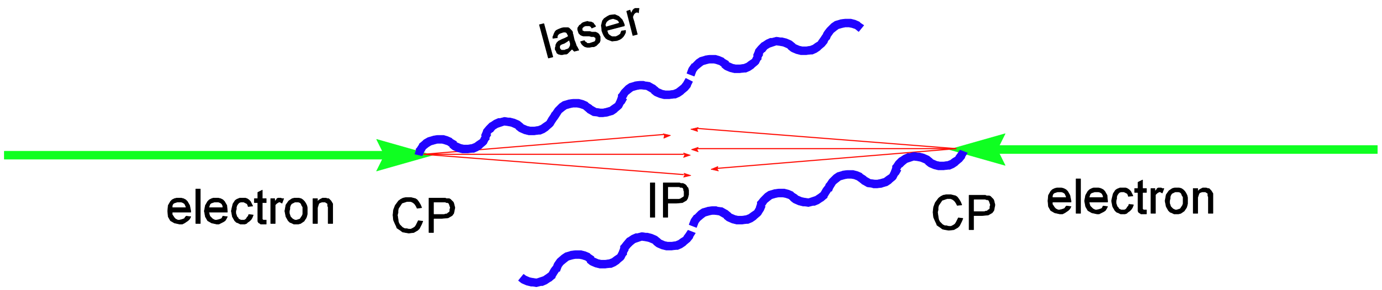
example with

- η=2%
- ξ_y=0.15
- ε_{gy}=0.1nm



Gamma-Gamma Collider

- electron-electron collider
- irradiate lasers just before ee collision
- create high energy photons, which made to collide
- no need of positrons



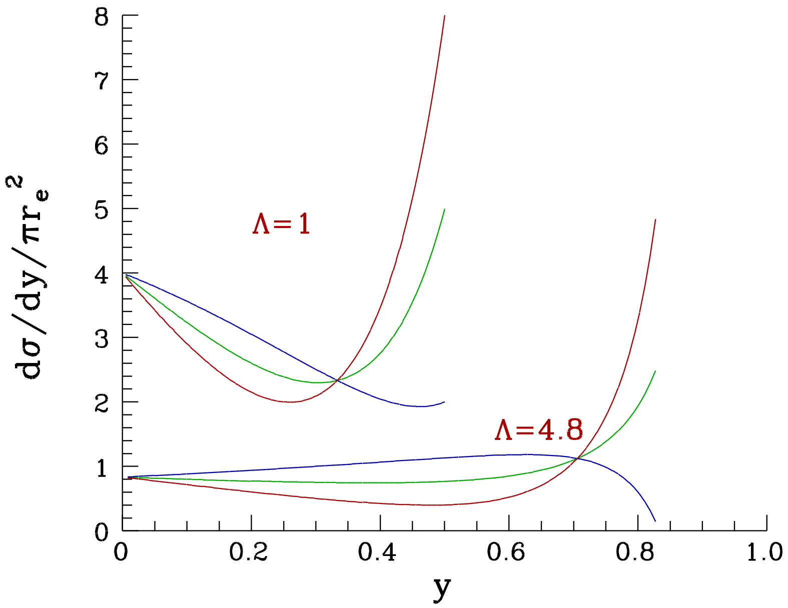
CP : conversion point
IP : interaction point

Kinetics of gamma conversion

- maximum photon energy

$$\omega = \frac{x}{1+x+\xi^2}E_e, \qquad x \equiv \frac{4E_e\omega_L}{m^2}$$

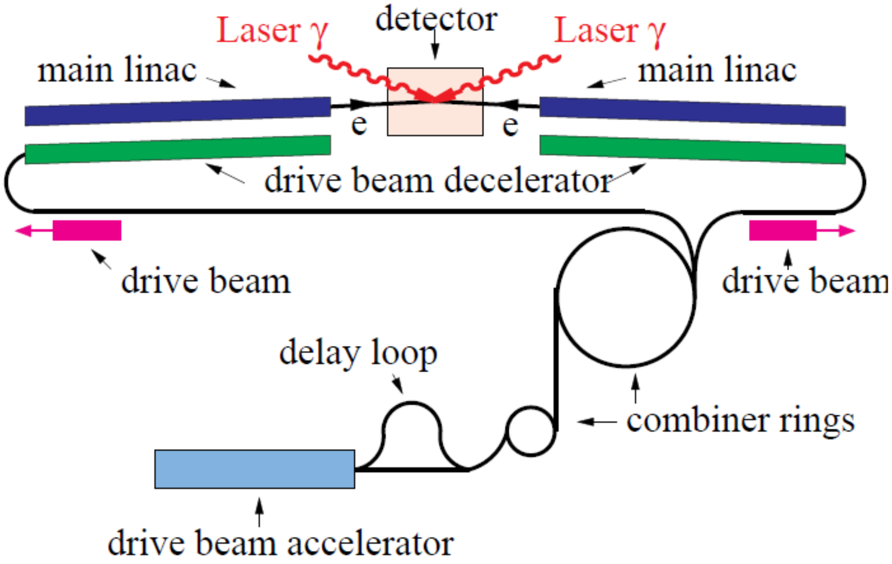
- electron polarization (longitudinal) is essential to create sharp photon energy spectrum

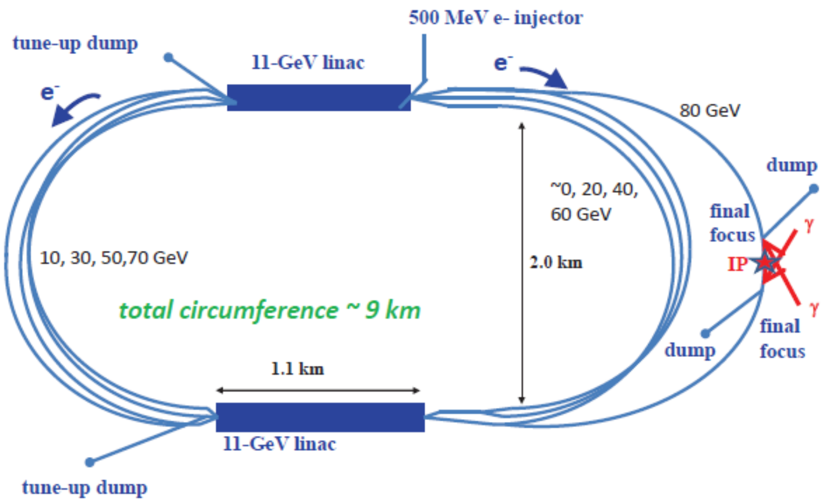


- Optimum laser wavelength $\lambda = \lambda_0$
  $\lambda_0 = 1\mu\text{m} * (E_e /250\text{GeV})$ corresponding to x=4.83
  - pair creation starts if $\lambda < \lambda_0$
  - photon energy lower if $\lambda > \lambda_0$
- required laser flush energy to convert most of the electrons is a few (5-10) Joules
  (weakly depends on electron bunch length)

Various Possibilities of γγ Colliders

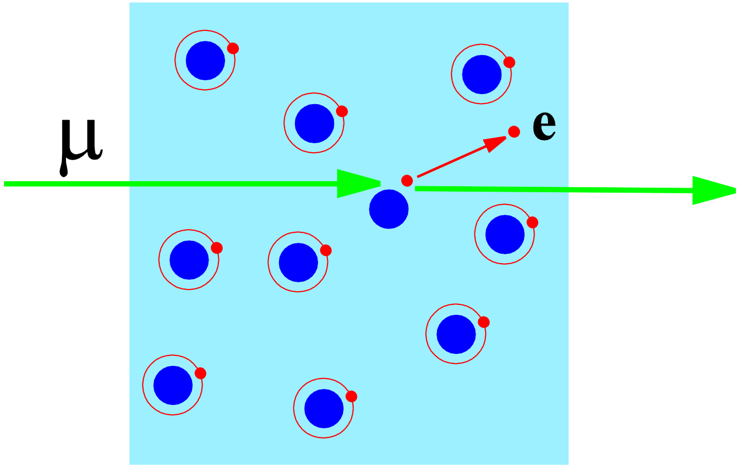
- e+e- linear collider can be converted to gamma-gamma collider
  - ILC
  - CLIC
- 80GeV e- on 80GeV e- converted by laser with x=4.83 gives 66GeV on 66 GeV γ-γ collider
  (lowest energy to produce H except muon collider)
- CLICHE (2003)
- SAPPHiRE (2012)



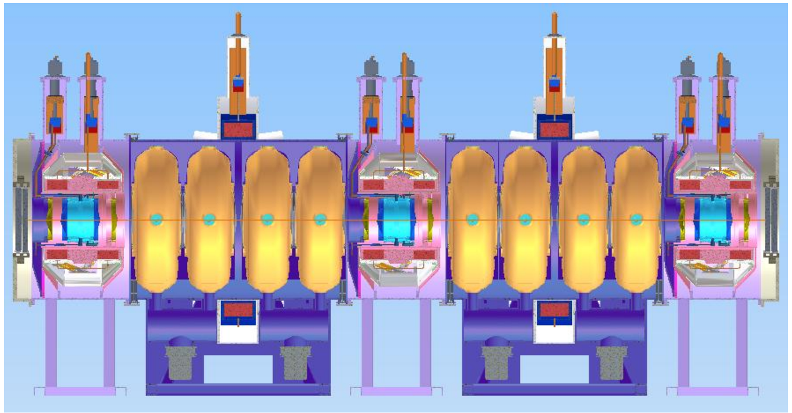


Muon Collider

- Properties of muons are quite similar to electron/positron
  - What can be done in e+e- can also be done in $\mu^+\mu^-$
- but muon is 200x heavier → can be accelerated to high energies in circular accelerator
- $\mu^+\mu^-$ collider is much cleaner than e+e- (beamstrahlung negligible)
  - except the problem of background from muon decay
- But muons do not exist naturally
  - need cooling like antiproton
- "Ionization cooling" invented by Skrinsky-Parkhomchuk 1981, Neuffer 1983

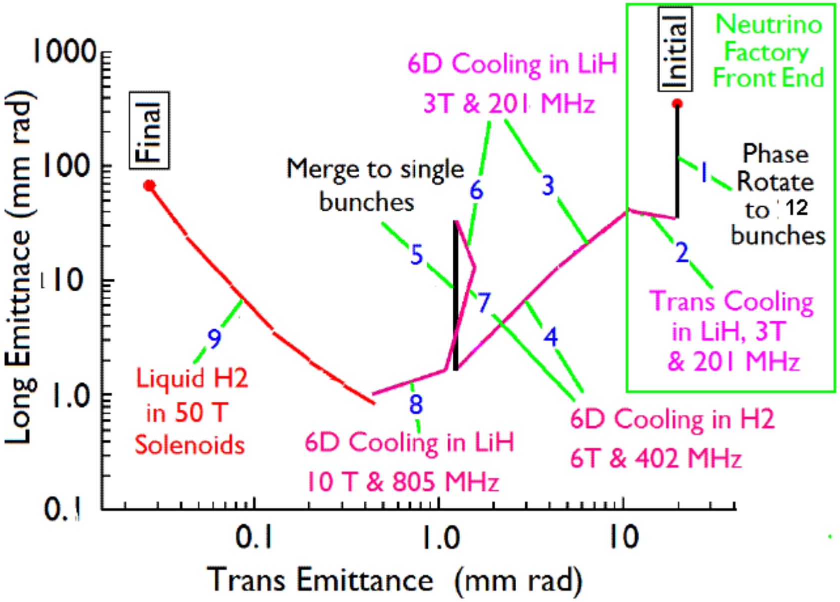


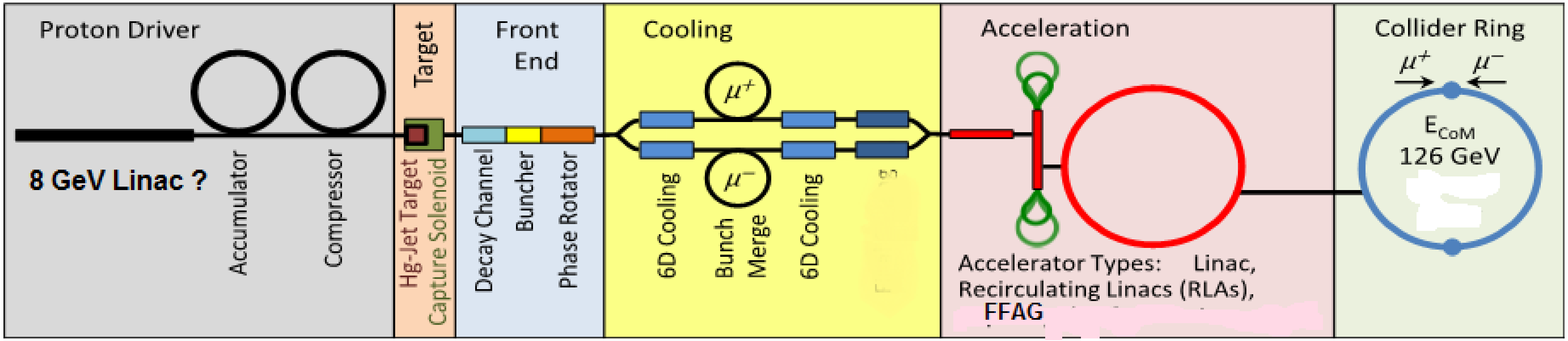
Ionization cooling test at MICE



Create and Cool Muon Beam

- Can be created by hadron collision
- Muons decay within 2μs in the rest frame
  - must be accelerated quickly
- Staging
  - Higgs factory at E_{cm}=126GeV
  - Neutrino factory
  - TeV muon collider
- Long way to collider
- B. Palmer's lecture





Plasma Accelerator

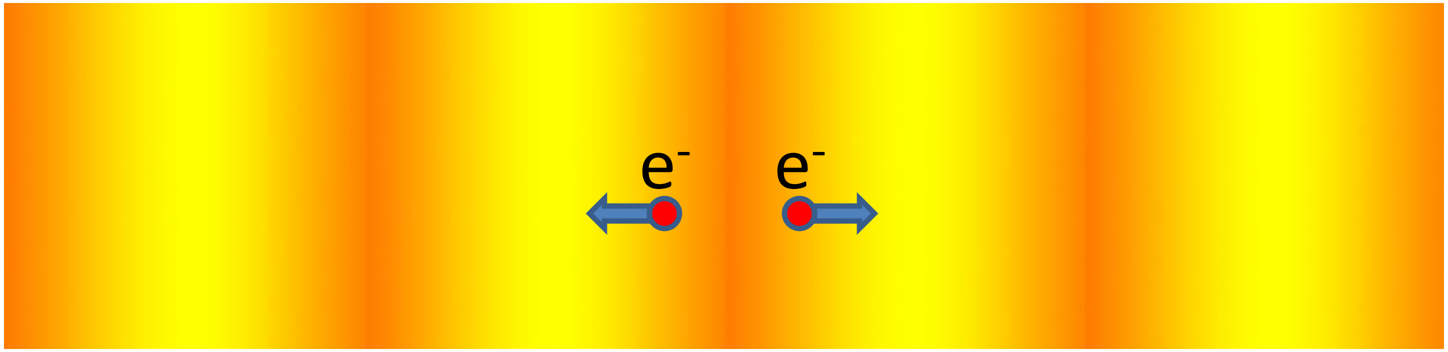
- Linac in the past has been driven by microwave technology
- Plane wave in vacuum cannot accelerate beams: needs material to make boundary condition
- Breakdown at high gradient
  - binding energy of matter: eV/angstrom = 10GeV/m
- Need not worry about breakdown with plasma
  - can reach > 10GeV/m

Plasma Wave

- Plasma is a mixture of free electrons and nucleus (ions), normally neutral
- By perturbation, electrons are easily moved while nuclei are almost sitting, density modulation created.
- The restoring force generates plasma wave
- Charged particles on the density slope are accelerated, like surfing.
- Plasma oscillation frequency and wavelength are given by

$$\omega_p = \sqrt{\frac{e^2}{\epsilon_0 m_e} n_0}, \qquad \lambda_p = \frac{2\pi c}{\omega_p} = \frac{3.3 \times 10^4}{\sqrt{n_e[\mathrm{cm}^{-3}]}} \quad [\mathrm{m}]$$

$$n_e = \text{plasma density}$$



How to Generate Plasma Wave

- PWFA (Plasma Wakefield Accelerator)
  - Use particle (normally electron) beam of short bunch
- LWFA (Laser Wakefield Accelerator)
  - Use ultra-short laser beam
- In both cases the driving beam
  - determines the phase velocity of plasma wave, which must be close to the velocity of light
  - must be shorter than the plasma wavelength required
  - can also ionize neutral gas to create plasma

LWFA

- laser pulse length ← plasma wave wavelength ← plasma density
- Laser intensity characterized by the parameter a_0
  - $a_0 < 1$: linear regime
  - $a_0 > 1$: blow-out regime

$$a_0 \approx 8.5 \times 10^{-10} \lambda_L[\mu\mathrm{m}] I^{1/2}[\mathrm{W/cm^2}]$$

- Accelerating field

$$E = E_0 \frac{a_0^2/2}{\sqrt{1 + a_0^2/2}}$$

$$E_0 = c m_e \omega_p / e = 96 n_0^{1/2}[\mathrm{cm}^{-3}]$$

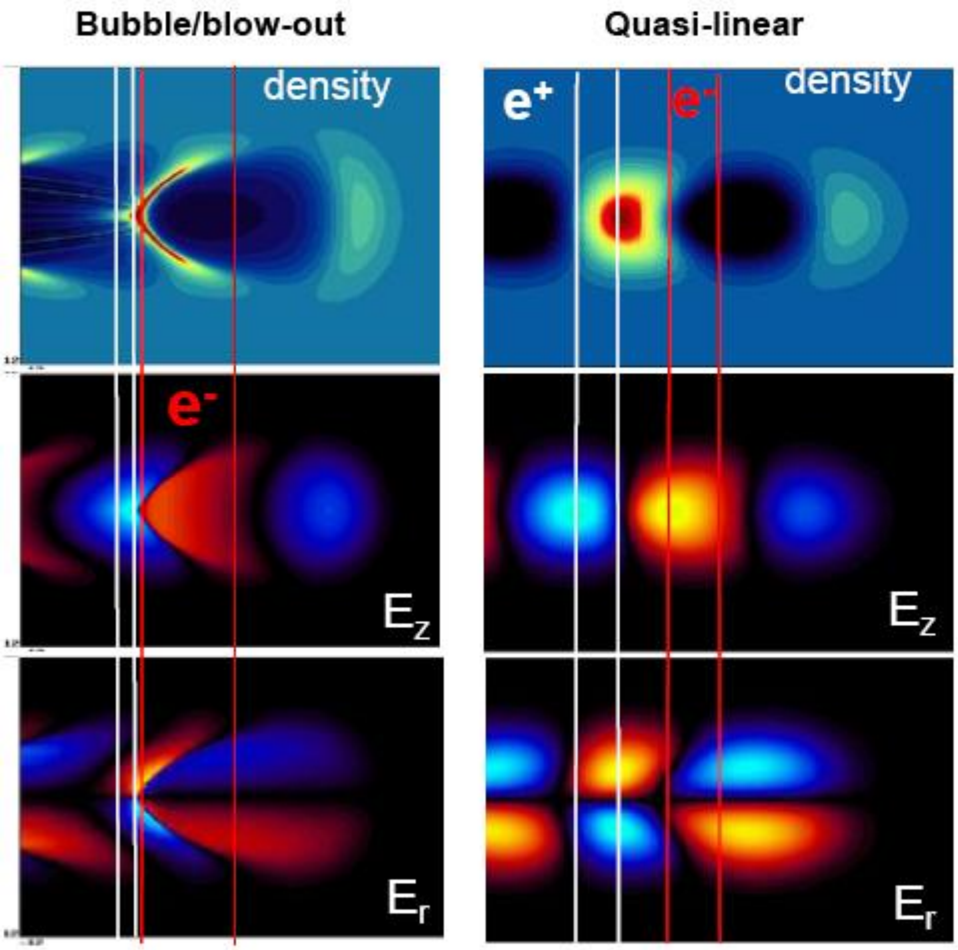
Blowout and Linear Regime

- The gradient can be higher in the blowout regime but
  - difficult to accelerate positron
  - very narrow region of acceleration and focusing

acceleration field

plasma density

transverse field



a=4

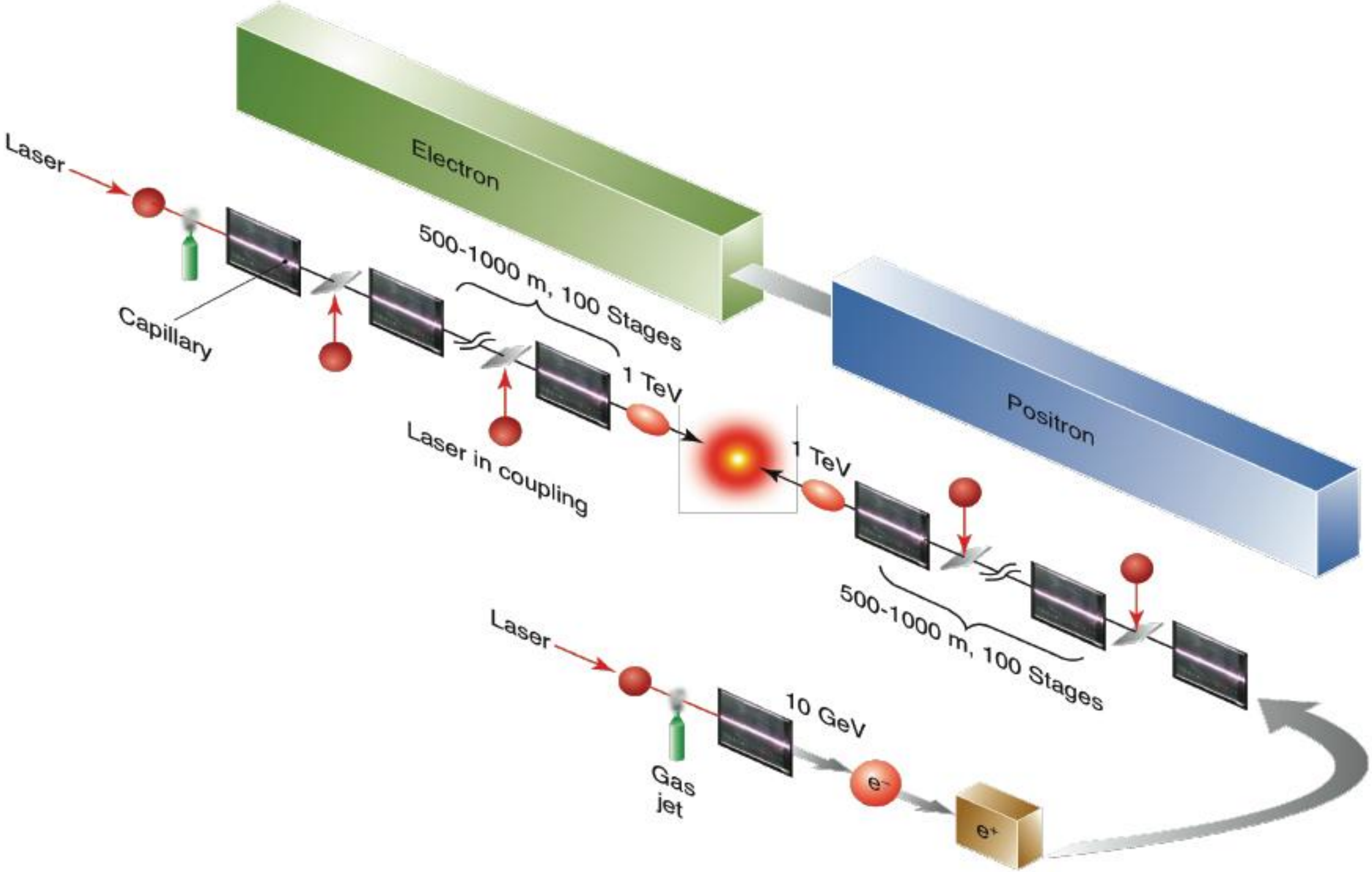
a=1

Figure from ICFA Beamdynamics News Letter 56

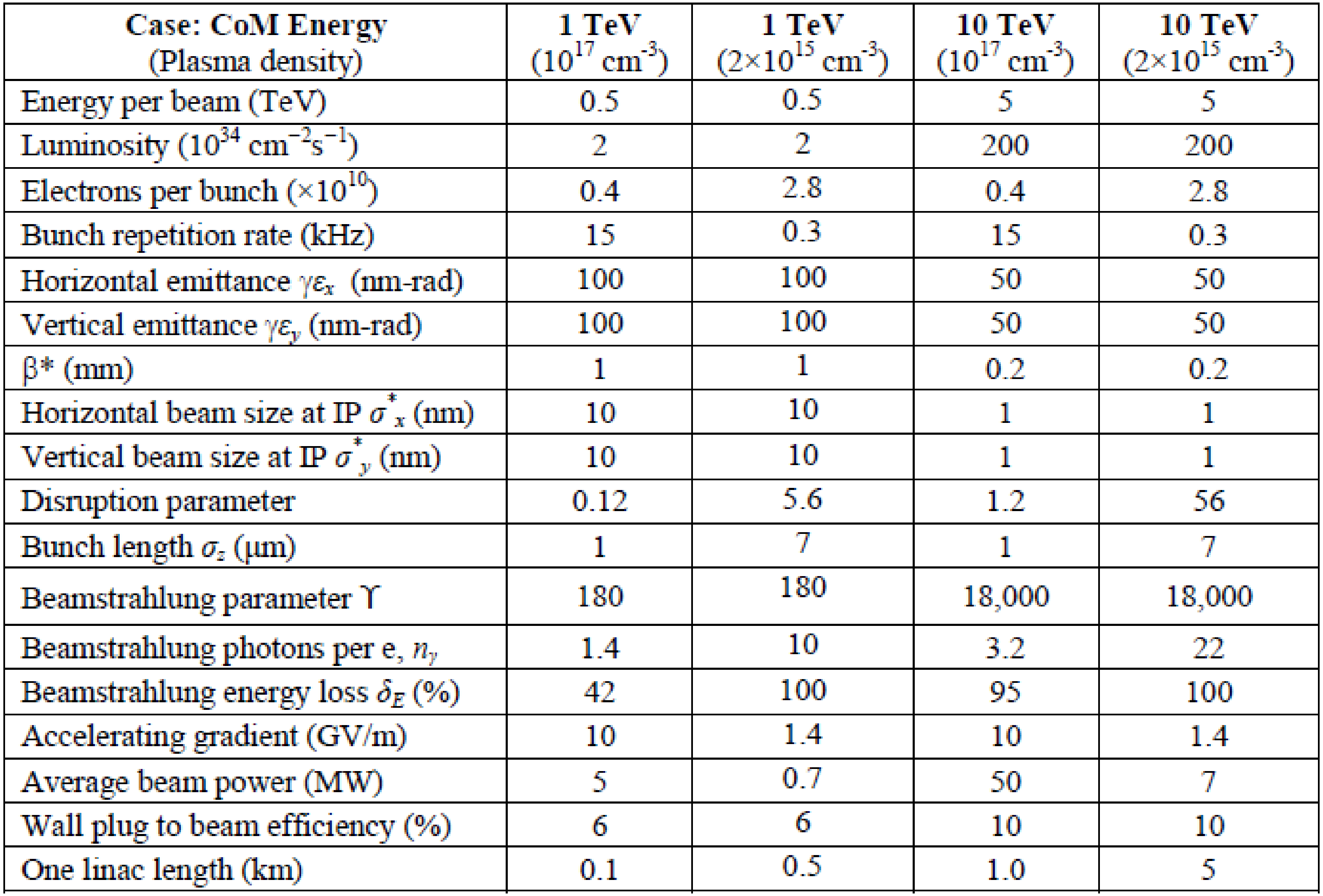
Limitation by Single Stage

- Laser must be kept focused (Rayleigh length)
  - solved by self-focusing and/or preformed plasma channel
- Dephasing: laser velocity in plasma
  - longitudinal plasma density control
- Eventually limited by depletion
  - depletion length proportional to $n_0^{-3/2}$
  - acceleration by one stage proportional to I/n_0
- Multiple stages needed for high energy, introducing issues
  - phase control
  - electron orbit matching

Concept of LWFA Collider



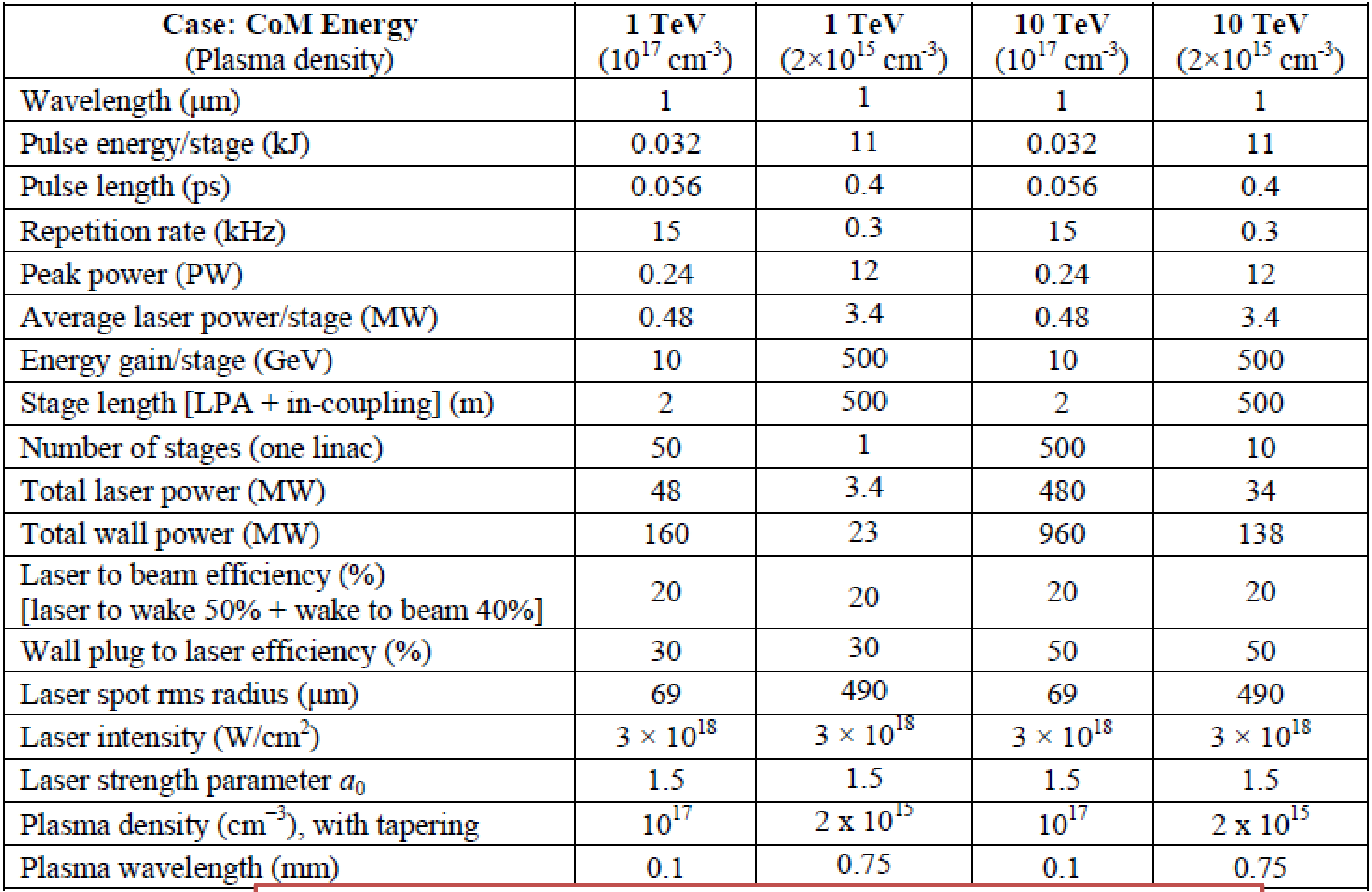
Example Beam Parameters of 1/10TeV Collider



Case: CoM Energy (Plasma density)	**1 TeV** (10^{17} cm^{-3})	**1 TeV** (2×10^{15} cm^{-3})	**10 TeV** (10^{17} cm^{-3})	**10 TeV** (2×10^{15} cm^{-3})
Energy per beam (TeV)	0.5	0.5	5	5
Luminosity (10^{34} cm^{-2}s^{-1})	2	2	200	200
Electrons per bunch ($\times10^{10}$)	0.4	2.8	0.4	2.8
Bunch repetition rate (kHz)	15	0.3	15	0.3
Horizontal emittance $\gamma\varepsilon_x$ (nm-rad)	100	100	50	50
Vertical emittance $\gamma\varepsilon_y$ (nm-rad)	100	100	50	50
β^* (mm)	1	1	0.2	0.2
Horizontal beam size at IP σ^*_x (nm)	10	10	1	1
Vertical beam size at IP σ^*_y (nm)	10	10	1	1
Disruption parameter	0.12	5.6	1.2	56
Bunch length σ_z (μm)	1	7	1	7
Beamstrahlung parameter Υ	180	180	18,000	18,000
Beamstrahlung photons per e, n_γ	1.4	10	3.2	22
Beamstrahlung energy loss δ_E (%)	42	100	95	100
Accelerating gradient (GV/m)	10	1.4	10	1.4
Average beam power (MW)	5	0.7	50	7
Wall plug to beam efficiency (%)	6	6	10	10
One linac length (km)	0.1	0.5	1.0	5

From ICFA Beamdynamics News Letter 56

Example Laser Parameters of 1/10TeV Collider



Case: CoM Energy (Plasma density)	**1 TeV** (10^{17} cm^{-3})	**1 TeV** (2×10^{15} cm^{-3})	**10 TeV** (10^{17} cm^{-3})	**10 TeV** (2×10^{15} cm^{-3})
Wavelength (μm)	1	1	1	1
Pulse energy/stage (kJ)	0.032	11	0.032	11
Pulse length (ps)	0.056	0.4	0.056	0.4
Repetition rate (kHz)	15	0.3	15	0.3
Peak power (PW)	0.24	12	0.24	12
Average laser power/stage (MW)	0.48	3.4	0.48	3.4
Energy gain/stage (GeV)	10	500	10	500
Stage length [LPA + in-coupling] (m)	2	500	2	500
Number of stages (one linac)	50	1	500	10
Total laser power (MW)	48	3.4	480	34
Total wall power (MW)	160	23	960	138
Laser to beam efficiency (%) [laser to wake 50% + wake to beam 40%]	20	20	20	20
Wall plug to laser efficiency (%)	30	30	50	50
Laser spot rms radius (μm)	69	490	69	490
Laser intensity (W/cm^2)	3×10^{18}	3×10^{18}	3×10^{18}	3×10^{18}
Laser strength parameter a_0	1.5	1.5	1.5	1.5
Plasma density (cm^{-3}), with tapering	10^{17}	2×10^{15}	10^{17}	2×10^{15}
Plasma wavelength (mm)	0.1	0.75	0.1	0.75

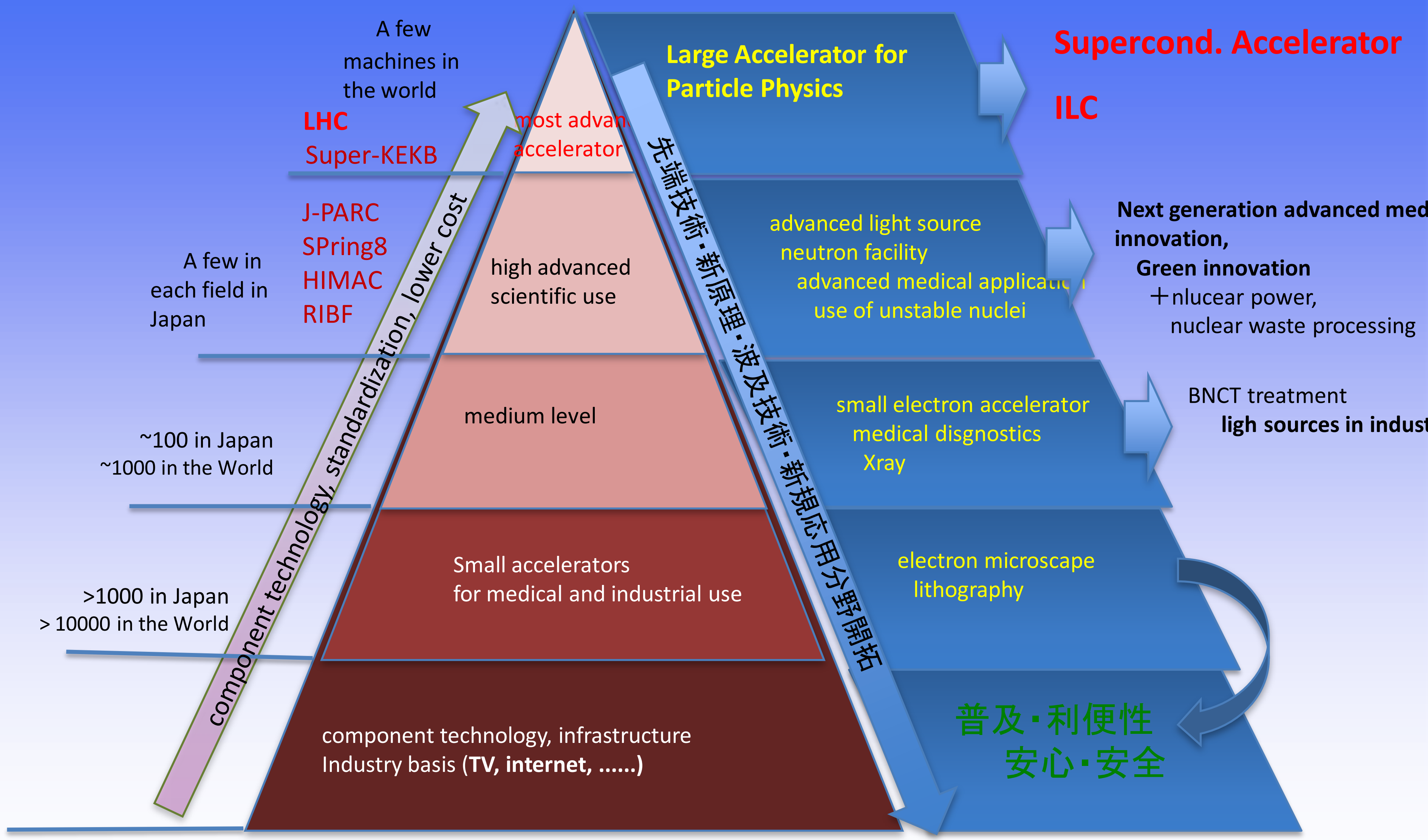
From ICFA Beamdynamics News Letter 56

What's Needed for Plasma Collider

- High rep rate, high power laser
- Beam quality
  - Small energy spread << 1%
  - emittance preservation
- High power efficiency from wall-plug to beam
  - Wall-plug → laser
  - Laser → plasma wave
  - plasma wave → beam
- Staging
  - laser phase
  - beam optics matching
- Very high component reliability
- Low cost per GeV
- Colliders need all these, but other applications need only some of these
- Application of plasmas accelerators would start long before these requirements are established

Piramid of Accelerators

Cannot replace the head only



A few machines in the world

LHC

Super-KEKB

most advan accelerator

Large Accelerator for Particle Physics

Supercond. Accelerator

ILC

A few in each field in Japan

J-PARC

SPring8

HIMAC

RIBF

high advanced scientific use

advanced light source
neutron facility
advanced medical application
use of unstable nuclei

Next generation advanced med
innovation,
Green innovation
＋nlucear power,
nuclear waste processing

~100 in Japan
~1000 in the World

medium level

small electron accelerator
medical disgnostics
Xray

BNCT treatment
ligh sources in indust

>1000 in Japan
> 10000 in the World

Small accelerators
for medical and industrial use

electron microscape
lithography

component technology, infrastructure
Industry basis (**TV, internet, ……)**

普及・利便性
安心・安全

component technology, standardization, lower cost

先端技術・新原理・波及技術・新規応用分野開拓

Original by S.Yamashita

Summary

- Accelerator Technology has been progressed in parallel with High Energy Physics
- New technologies are waiting for future development of high energy physics
- But each of them takes long time to realize
  - e+e- LC started in mid 1980’s
  - muon collider early 1990’s
- Progress of accelerator technology bas been backed-up by application