Foundation of Collider

Circular Collider
Linear Collider
Muon Collider
Plasma Accelerator

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Limitation of Target Experiments

- By using synchrotrons/linacs we can accelerate particles (proton/electron, etc) up to some tens of GeV, even some 100’s of GeV
- However, the center-of-mass energy of a 1000GeV proton and a proton at rest is only some 40GeV
- High energy physics demands higher and higher energies
- How can we reach such energies?

Collider

- What is important in high energy physics is the collision energy (or, center-of-mass energy E_{CM}), not the single beam energy
- Consider a collision of two beams

- Either scheme is equivalent if the collision energy is the same
- Energy of each beam is lower in the right-hand scheme
- When the particle energy is so high ($E \gg mc^2$) that the special relativity has to be used, the right-hand scheme is by far better

$$E_{CM} \approx \sqrt{2mE}$$ target experiment

$$E_{CM} = 2E$$ colliding beam

note: here mc^2 is simplified to m

- For example, a collision of two 0.5GeV electrons is equivalent to collision of 1TeV electron with an electron at rest

Exercise

- To create a muon pair $\mu^+\mu^-$ in an electron-positron collider by $e^+e^- \rightarrow \mu^+\mu^-$, you need the electron energy (=positron energy) 105.66MeV (=mc^2 of $\mu^{\pm}$).
- Now, you want to create a muon pair from an accelerated positron colliding with an electron at rest.
- What is the required energy of the positron?
- See muon collider section for the answer

Answer

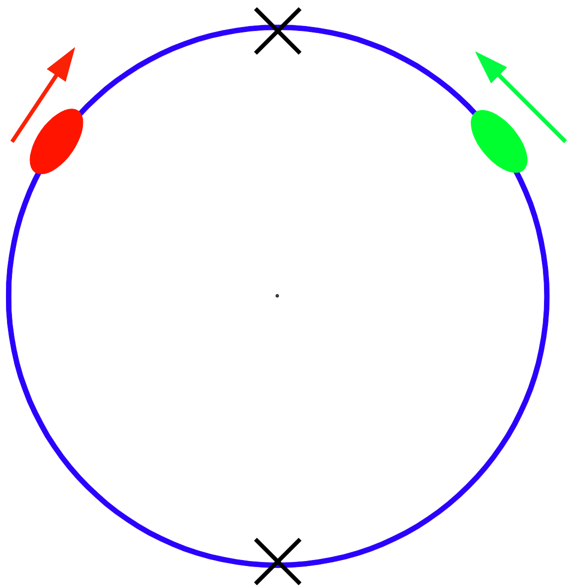
$$E_{CM} = \sqrt{2m_e E} = 2m_\mu$$

$$E = \frac{2m_\mu^2}{m_e} = \frac{2 \times (105.66\mathrm{MeV})^2}{0.511\mathrm{MeV}} = 43.7\mathrm{GeV}$$

How to make particles collide?

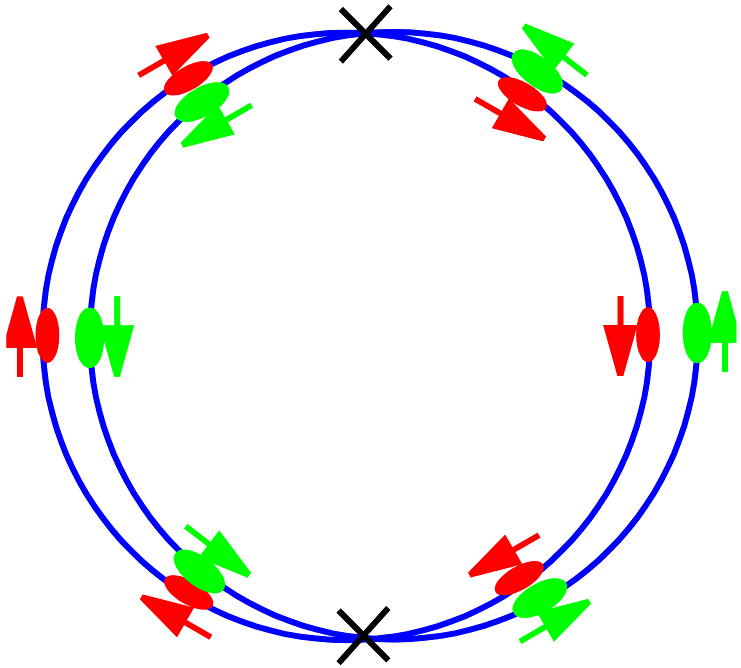
- Beams of same energy and opposite charge
- Can use a single ring
- You need (electro-static) separators to avoid unnecessary collisions

- Much more freedom by using two rings



.... PETRA, TRISTAN, LEP,

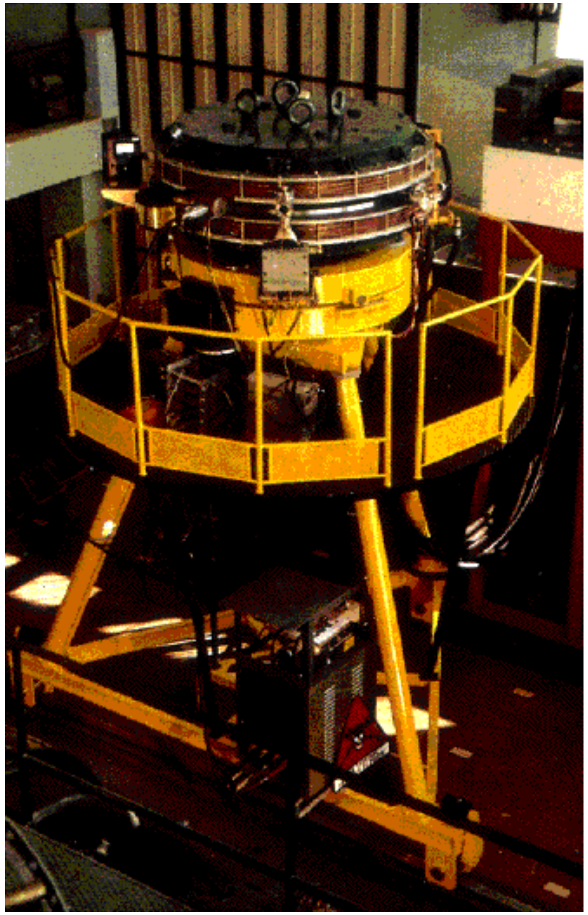
..... SppS, Tevatron



PEPII, KEKB, LHC, ...

First Electron-Positron Collider: AdA

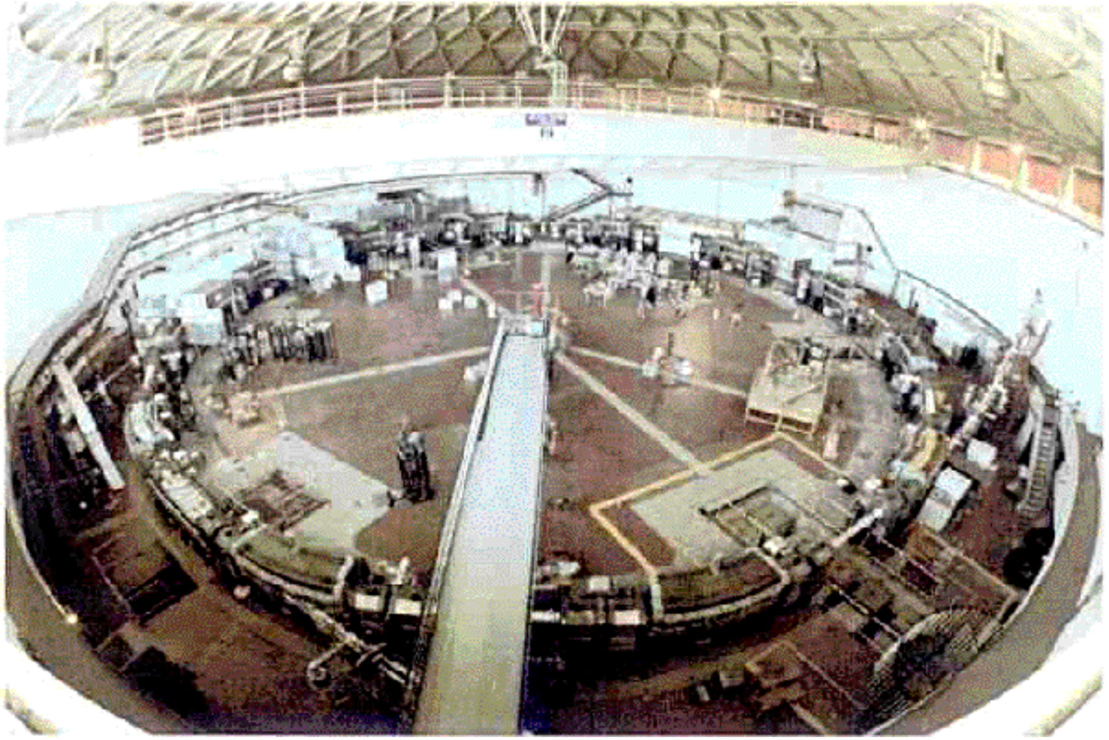
- First beam in Italy in 1961
- Moved to Orsay (France) and the first collision in 1964
- Orbit radius 65cm, collision energy 0.5GeV



Now exhibited in a garden in Frascati, Italy

The second：Adone

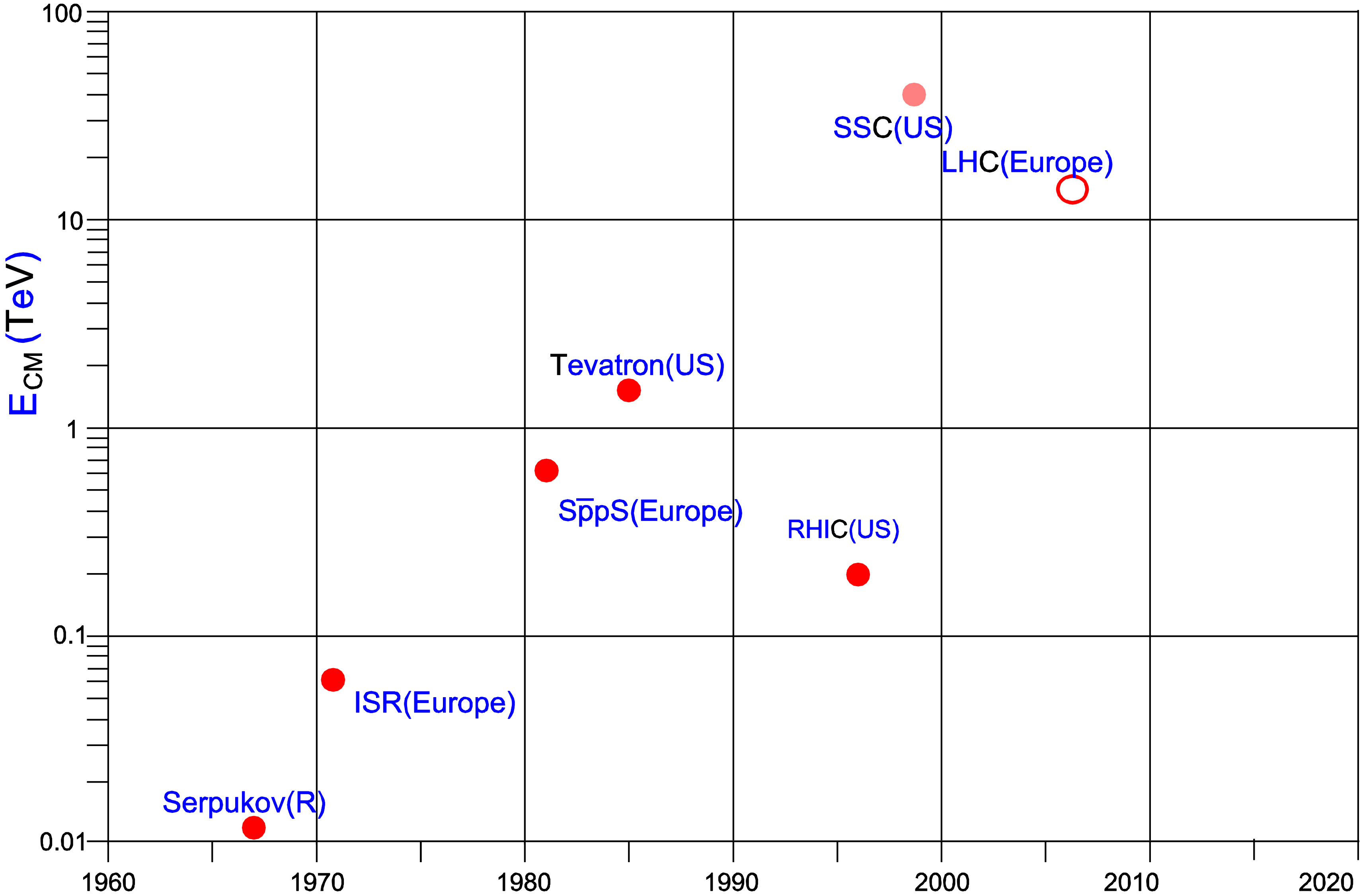
- The first beam in 1967
- Circumference 105m
- Collision energy < 3GeV
  （Did not reach J/ψ at 3.1GeV)
- Luminosity
  $3x10^{29}$ /cm^2/s



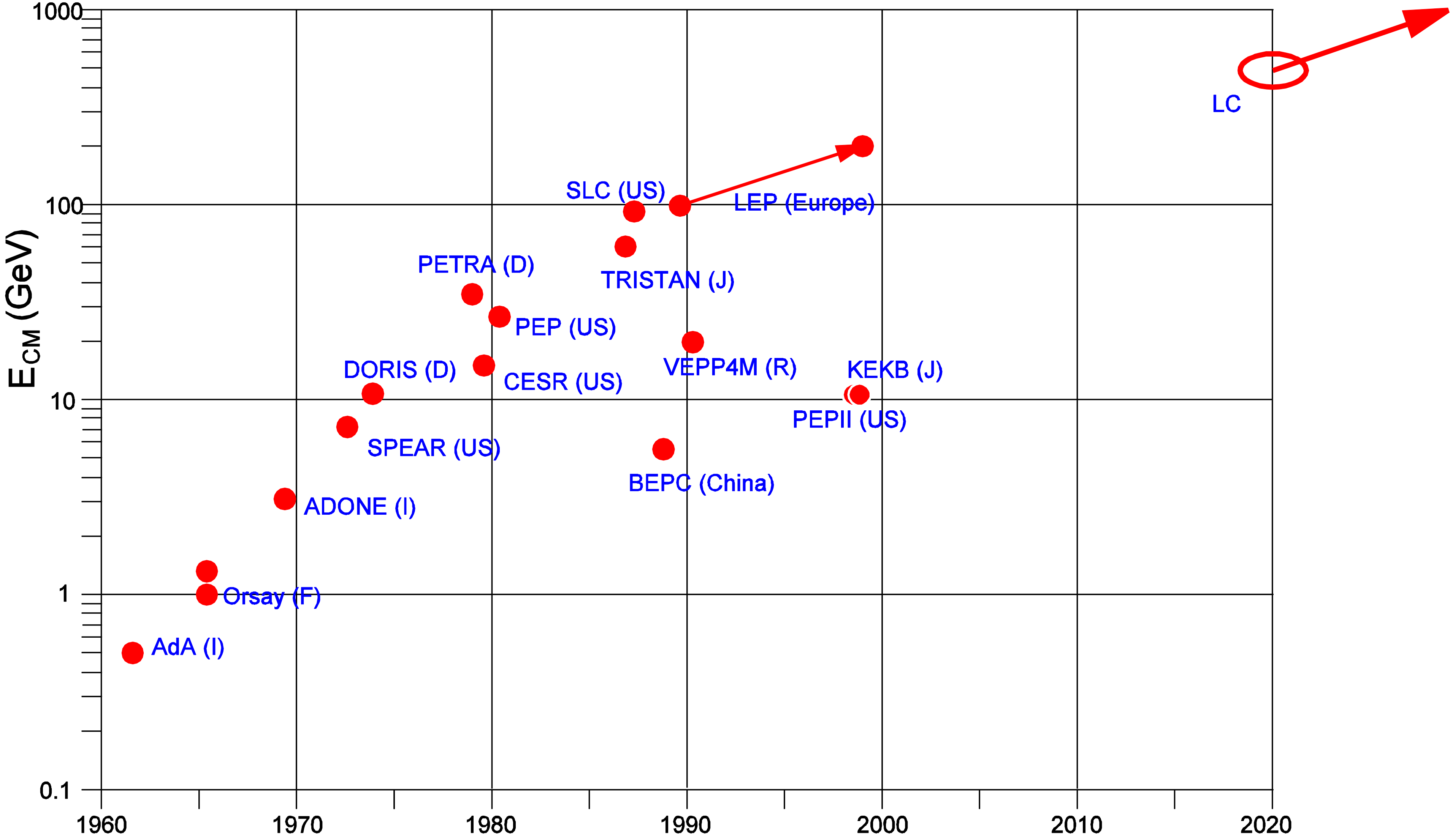
Many Colliders Built Since Then

- e+e-
- pp
- ppbar
- ions
- ep

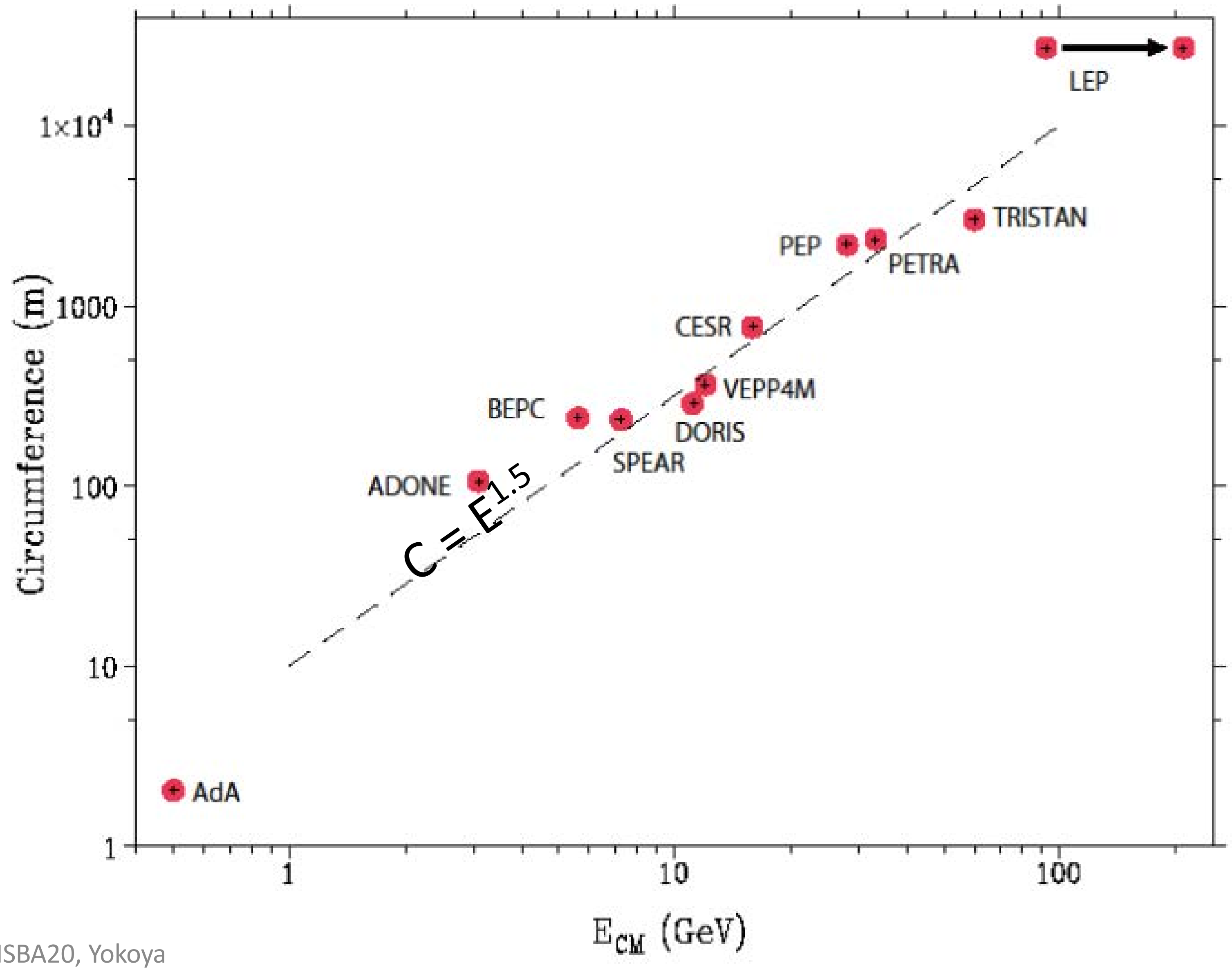
History of Proton/Antiproton Colliders



History of Electron-Positron Colliders



Energy vs. Ring Radius



Difficulty of Colliders

- Number of events per second
  - Fixed target
    $$F\times n\times d\times \sigma$$
    - F: particle flux (number of particles per second)
    - n: density of target (atoms / m^3) , not the density of projectile
    - d: target thickness
    - σ: event cross-section
  - Collider
    $$L\times\sigma, \qquad L = fcol\times\frac{N^2}{S} = \frac{FN}{S}$$
    - L: Luminosity
    - f_{col}: bunch collision frequency (F=$f_{col}N$)
    - N: number of particles per bunch
    - S: transverse cross-section of the bunch
- Essential difference: $n\times d$ → N / S
  i.e., target density vs. beam density
- Need to pack many particles in a small area (firstly, the transverse are)

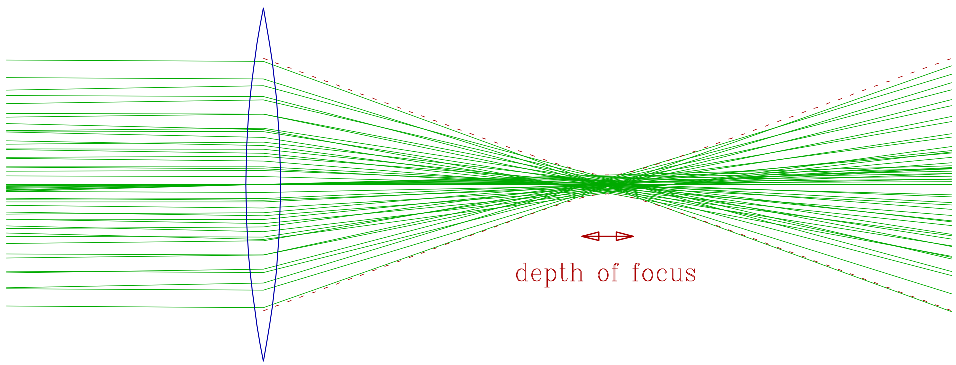
ABC of Circular Collider Dynamics

- Beam dynamics in a circular collider is basically similar to that of storage rings except for the conditions coming from the collision point
- Luminosity

$$\mathcal{L} = \frac{f_{col} N^2}{4\pi\sigma_x\sigma_y}, \quad \sigma_x^* = \sqrt{\epsilon_x\beta_x^*}, \quad \sigma_y^* = \sqrt{\epsilon_y\beta_y^*}$$

The asterisk * indicates a quantity at the exact collision point

- Hour-glass Effect



$$\beta_y^* >\approx \sigma_z$$

$$\beta(s) = \beta^* \sqrt{1 + \frac{s^2}{\beta^{*2}}}$$

Beam-beam tune-shift

- The beam is focused (assume oppositely charged beams like e+e-) by the on-coming bunch
- This causes a shift of betatron frequency as well as its spread
- Their magnitude can be characterized by the parameter ξ_x,ξ_y . In the simple case of head-on collision of equal size Gaussian bunches

$$\xi_{x(y)} = \frac{r_e}{2\pi} \frac{N\beta^*_{x(y)}}{\gamma} \frac{1}{\sigma^*_{x(y)}(\sigma^*_x + \sigma^*_y)}$$

- There has been a limit of $\xi_{x,y}$ empirically to be around 0.06, but these days we can predict it by computer simulations
- It is larger when the radiation damping is strong (so, it is small for proton collider)

Era of Huge Circular Colliders: Tevatron

- Fermi National Lab
- Proton - antiproton
- Circumference 6.3km
- 1TeV
- Completed in 1983
- Superconducting magnet 4.2Tesla
- 1995 Top Quark
- 2009 shutdown

Tevatron behind and Main Injector front

Era of Huge Circular Colliders: LEP

- LEP (Large Electron-Positron Collider)
  - CERN
  - Construction started in 1983
  - Operation started in 1989
  - Circumference 27km
  - Ultimate beam energy about 100GeV
  - Closed in 2000

- LEP revealed Generation of elementary particles =3

  n = 2.9841 +- 0.0083

SPS: Super Proton Synchrotron

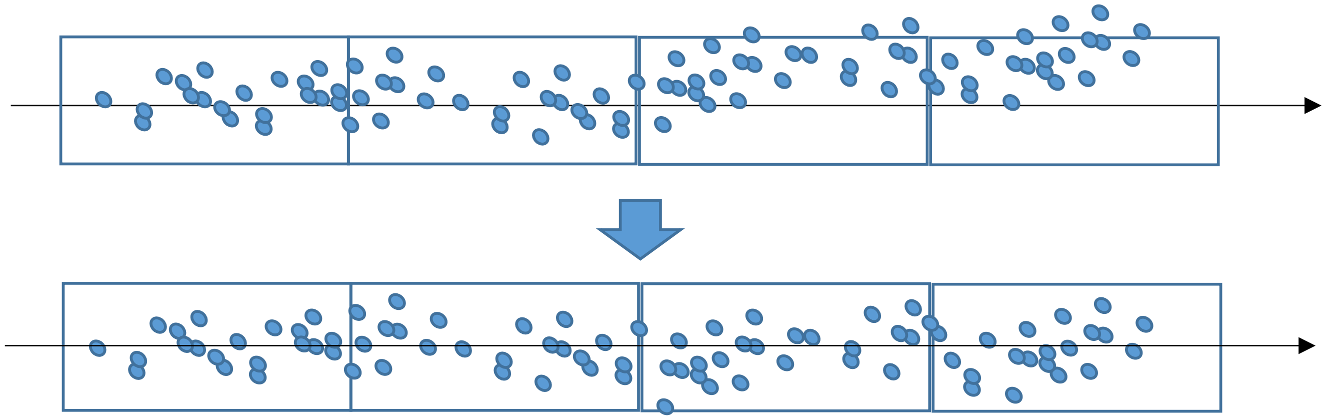
- Large proton synchrotron at CERN
- Operation started in 1976
- Achieved 500GeV in 1978
- Then, converted to the first proton-antiproton collider

Stochastic Cooling

- Is a collider of proton and antiproton possible?
- Antiproton does not naturally exist
- Must be created by accelerator
- Anti-protons can be produced by accelerators >> GeV, but the anti-proton beam is too big (low density)
- “Cooling” is needed for using it in colliders
- Cooling method (stochastic cooling) invented in 1968 by Simon van der Meer
- At CERN
  - Antiproton beam was cooled and accumulated in AA (Antiproton Accumulator) and transferred to SPS
  - SPS → Sp$\bar{p}^{bar}$ S
  - The first p p^{bar} collision in 1981
  - Discovery of W^{+-}, Z^0 in 1983

Concept of Stochastic Cooling

- Repeat the following process
  1. Measure the average beam position of the slices
  2. Kick the each slice so that the center-of-mass comes to zero
  3. Shuffle the particles (actually, synchrotron oscillation)
- Average position approaches zero
- Speed proportional to 1/*N*
  - *N*: number of particles in a slice
  - No cooling if *N*=infinite

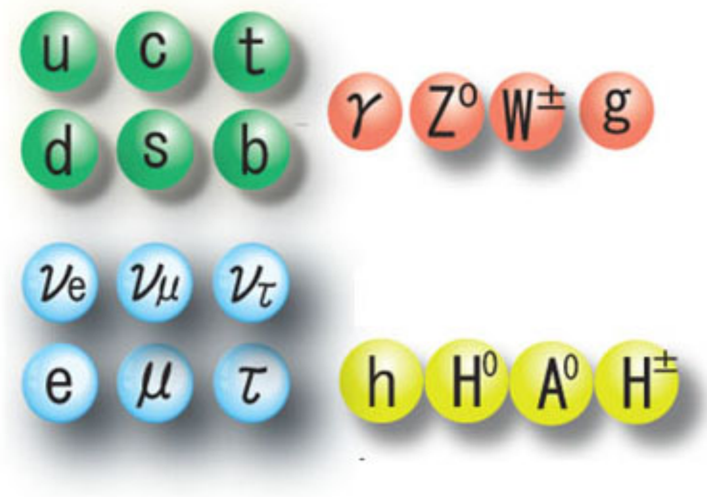


Elementary Particle Model

- Standard model now
  - Much more complex than the “4 particle model (p,n,e,γ)”
  - But simpler than the periodic table by Mendelejev
- Fundamental particles as constituents of Matter
  - ➢ 6 Leptons
  - ➢ 6 quarks
- The force between them are intermediated by Bosons
  - ➢ Weak interaction Z^0, W^+, W^-
  - ➢ Electro-magnetic interaction γ (light)
  - ➢ Strong interaction gluon
  - ➢ Gravitation graviton
- All of these, except γ and perhaps $\mu/\nu_e/\nu_\mu$, have been found with the help of accelerators.
- Standard model needs “Higgs particle”

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

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

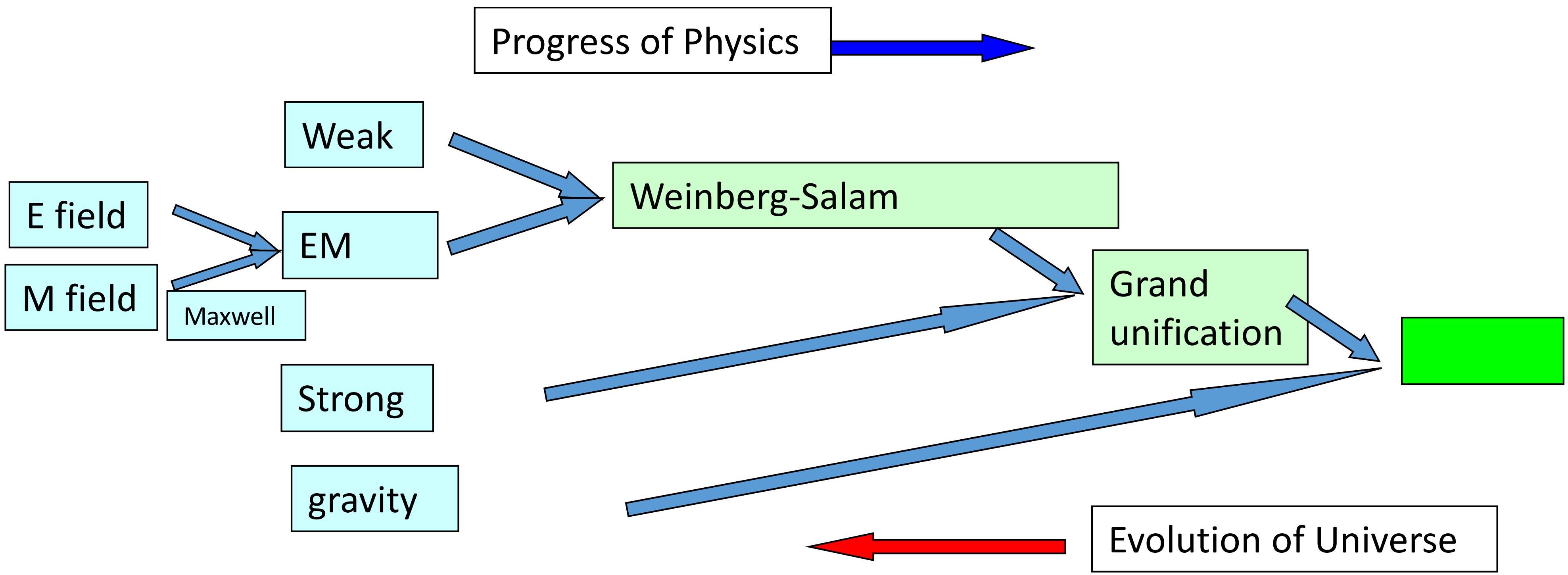


Unified Theories

- Maxwell Equation (19th century)
  - Unified electric and magnetic fields
- Weinberg-Salam model
  - Late 1960's
  - Unified Electro-magnetic and weak interaction
  - Z^0, W^+, W^- were predicted as new intermediate bosons and discovered in 1983
  - Technology jump of accelerator was needed

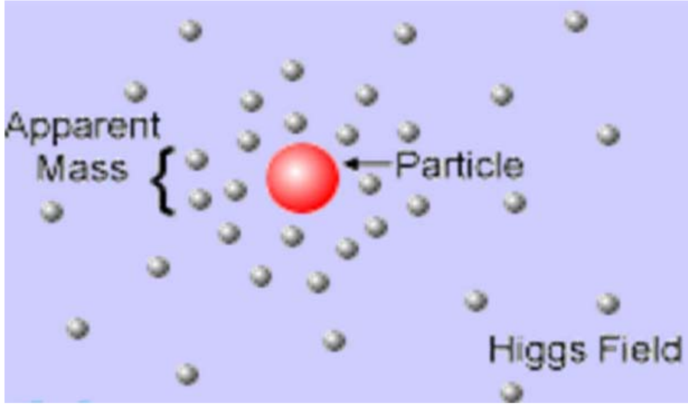
Towards Unification

- How to unify the other two: strong and gravity
- At higher energies
- Only one interaction at the beginning of the universe?

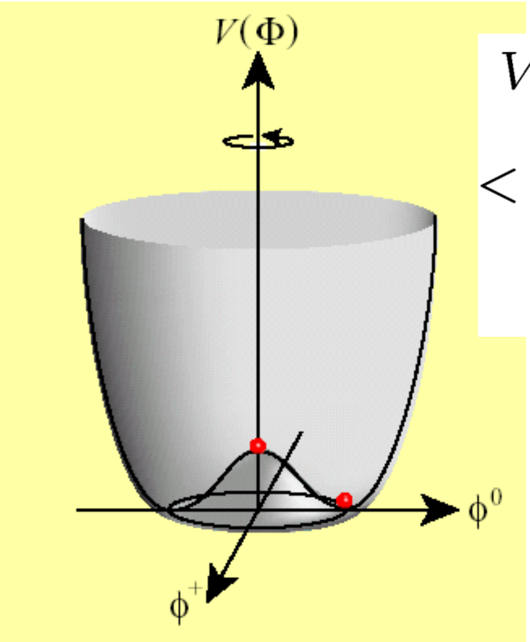


Higgs Particle

- Nambu-Goldstone Model
- Higgs mechanism
  - Application of Nambu-Goldstone theory
  - Start with zero-mass particles with symmetry
  - Spontaneous symmetry breaking due to Higgs potential
  - All particles coupled to Higgs acquire mass
  - Applied to Weinberg-Salam theory



- Higgs particle: the only particle that had not been discovered in the Standard Model



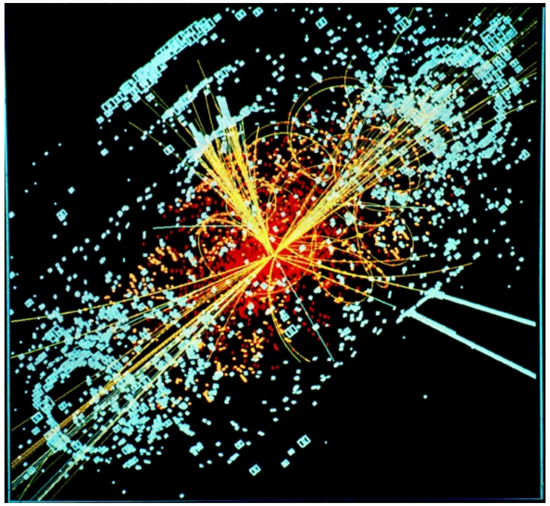
$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$
$$<\phi> = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$$
$$M_H = 2\lambda v^2$$

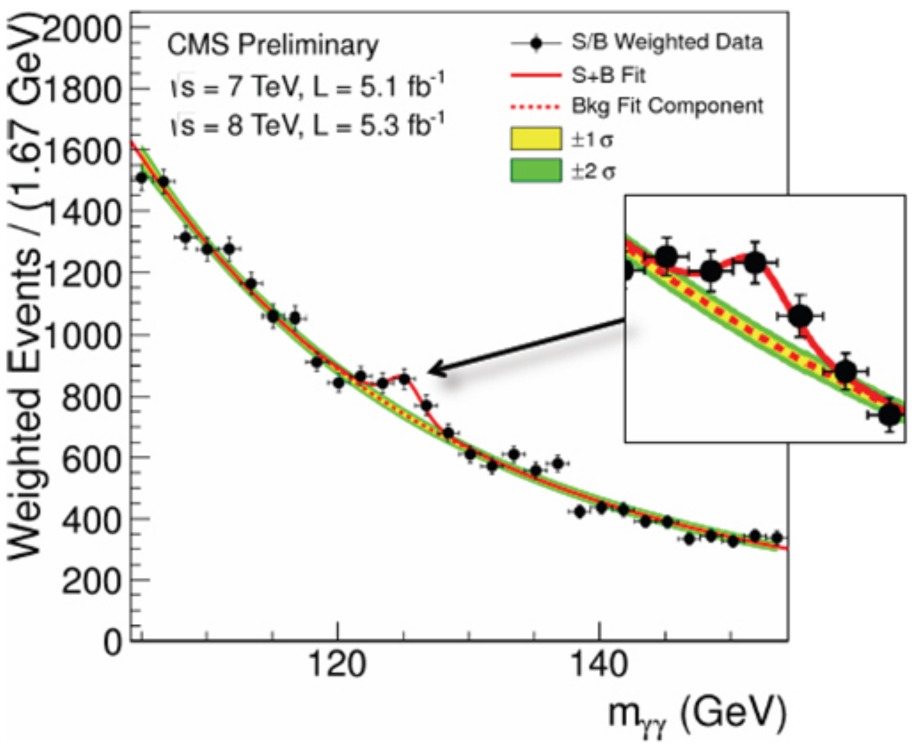
Y. Nambu

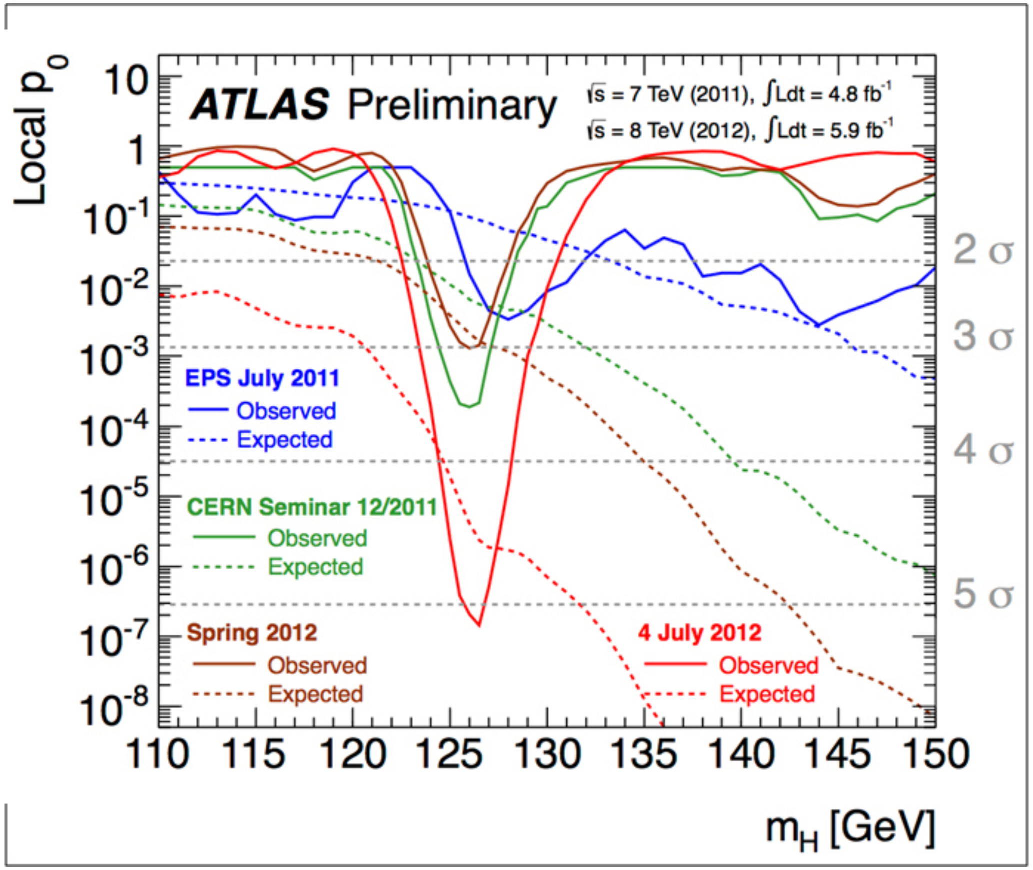
P. Higgs

Discovery of “Higgs”

- Announced on Jul.4, 2012
- ~125GeV

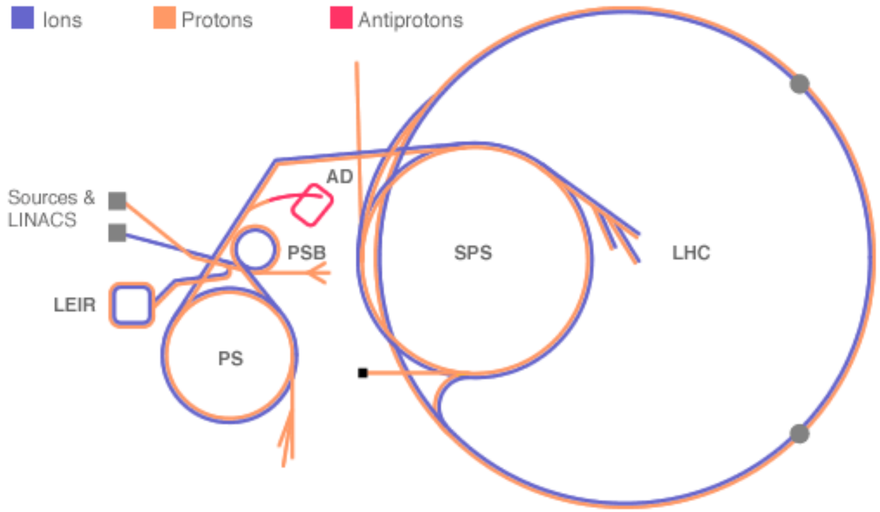


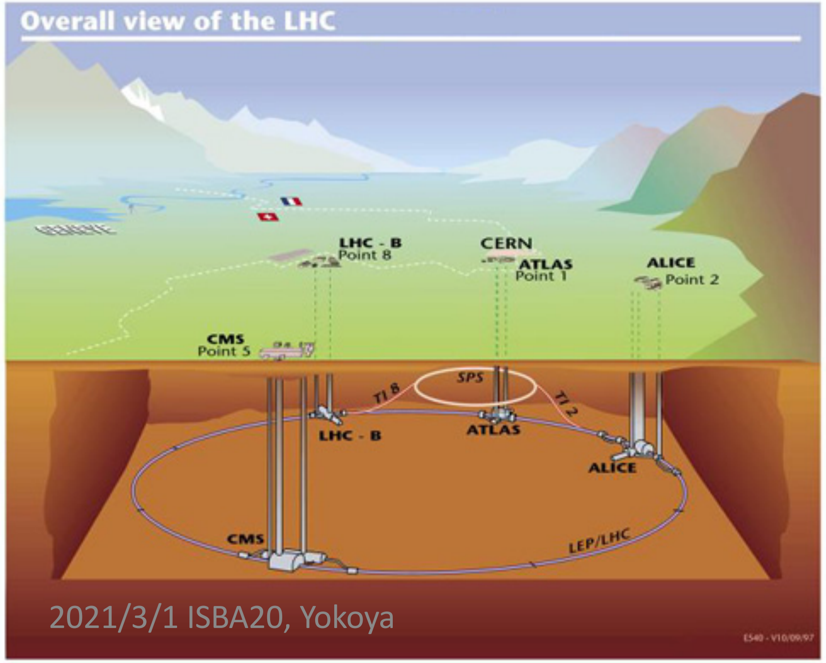


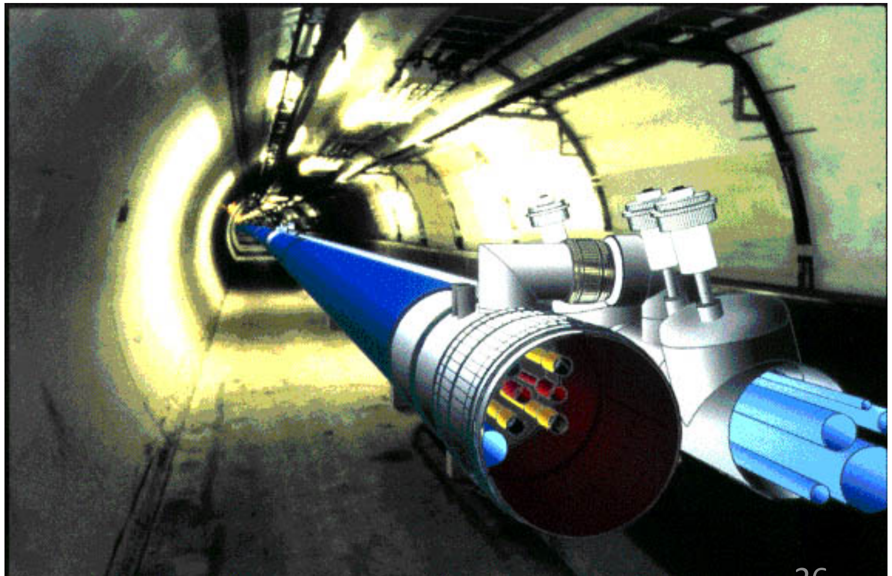


Huge Colliders Era (continued)

- LHC
- Recycle of LEP tunnel
- 14TeV proton-proton
- Discovered Higgs particle in 2012



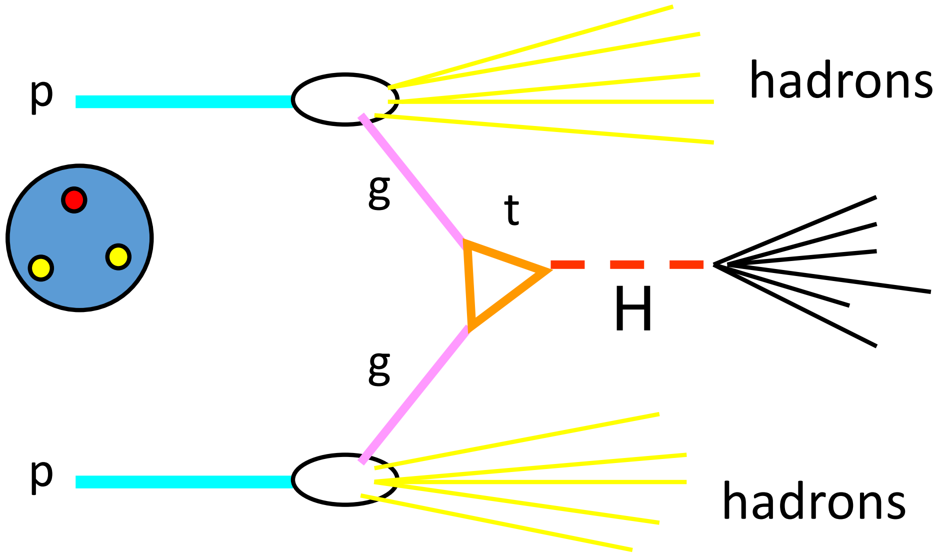




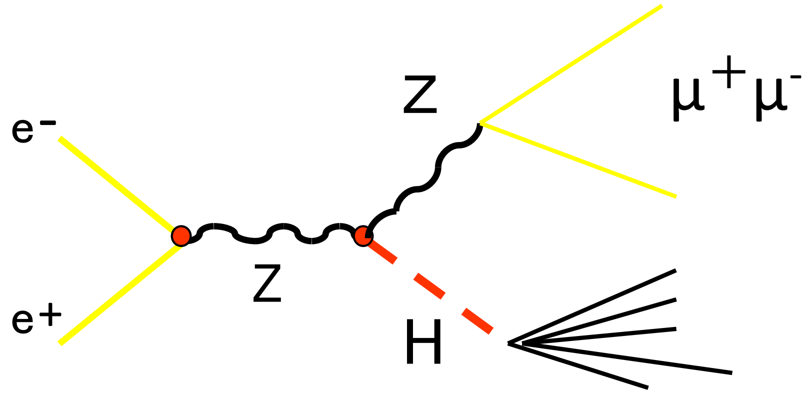
http://athome.web.cern.ch/athome/LHC/lhc.html

LHC is not the End

- LHC discovered Higgs
  - LHC is a proton collider
  - Protons are easier to accelerate to high energies
  - But the collision is complex due to the complexity of proton
- On the other hand, e+e- collider is:
  - Particle structure is simple
  - Better for probing particle properties
  - e+e- colliders are useful for precision measurement

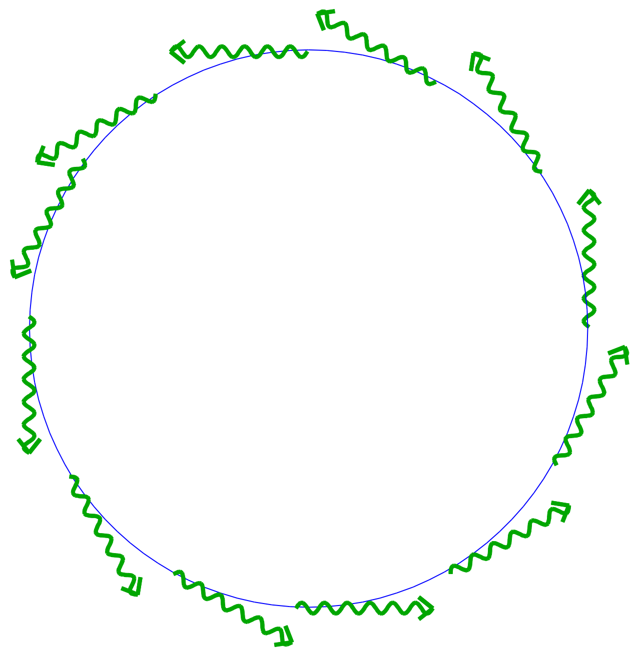


これはだいぶむずかしい図ですが



Limitation of Circular Accelerator

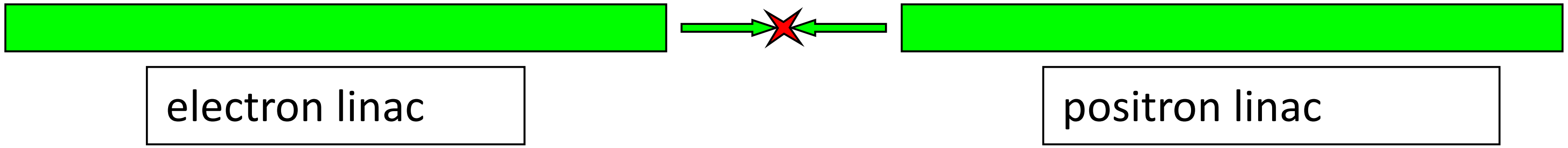
- High energy electron (positron) in a circular orbit emits photons (synchrotron radiation) in forward direction and loses energy
- Energy loss in one second is proportional to
  E^4 / ρ^2



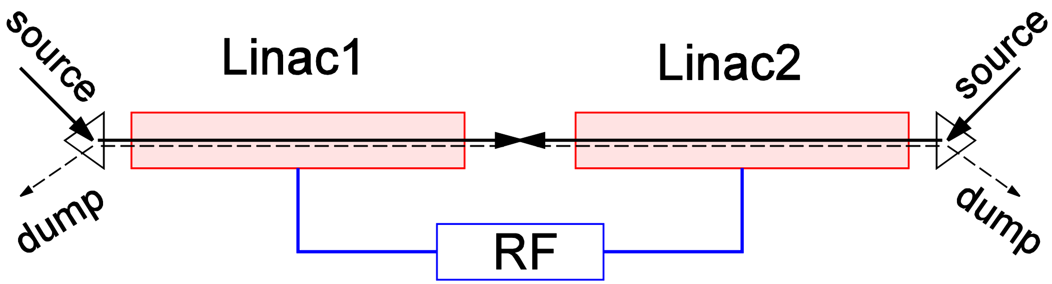
- This is useful for some purposes
  - Use synchrotron light for material physics
- But is a big obstacle for getting high energy electron

Electron-Positron Linear Collider

- To go beyond E_{CM} = 209GeV, linear collider is the natural choice



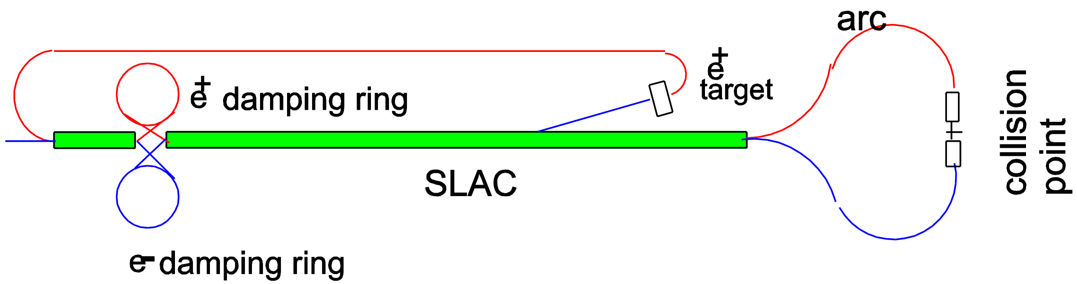
- Proposal in early 1960's
  - About the same time as the first circular collider AdA
  - Energy recovery was the original concern

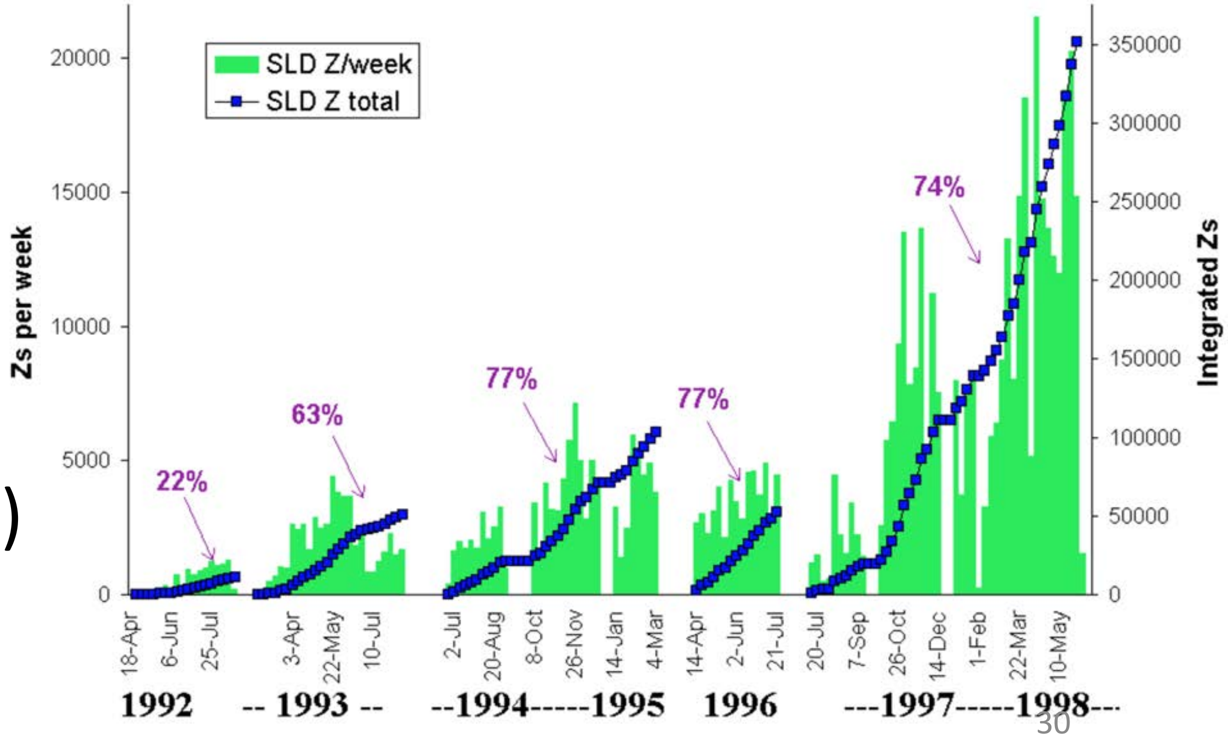


M. Tigner, Nuovo Cimento **37** (1965) 1228

SLC : The First Linear Collider

- Single linac
  - One revolution was possible if up to 46GeV
- Completed in 1987 at SLAC
- First Z^0 event in May 1989
- Competition with LEP
- Polarized electron beam (~80%)
- Finished in 1998
- luminosity $3x10^{30}$ $/cm^2/s$ (design $6x10^{30}$)



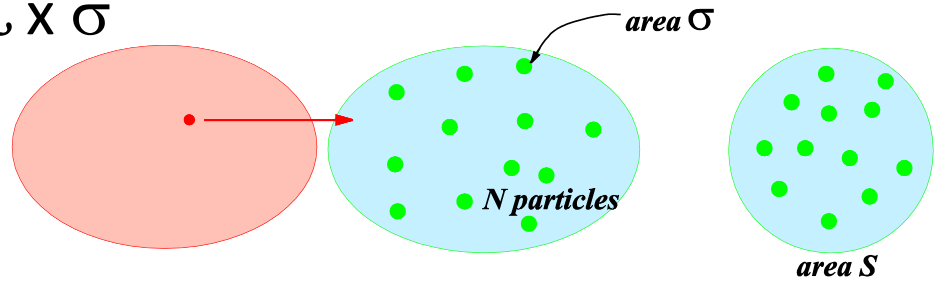


Why LC was not built till 1987 ?

- Difference from Ring collider : single pass
  - Pass accelerating structure only once
  - Beam is thrown away after one collision
- 2 Issues come from this nature of LC
  - High gradient acceleration
    - Total length is decided by the accelerating gradient
  - Fine beam
    - Low collision rate
    - Beam must be focused to a tiny spot at the collision point

Luminosity

- Number of events in unit time = $\mathcal{L} \times \sigma$
  - σ comes from physics
  - $\mathcal{L}$ accelerator parameter



- Luminosity

$$\mathcal{L} = \frac{f_{col} N^2}{\text{beam crosssection}}$$

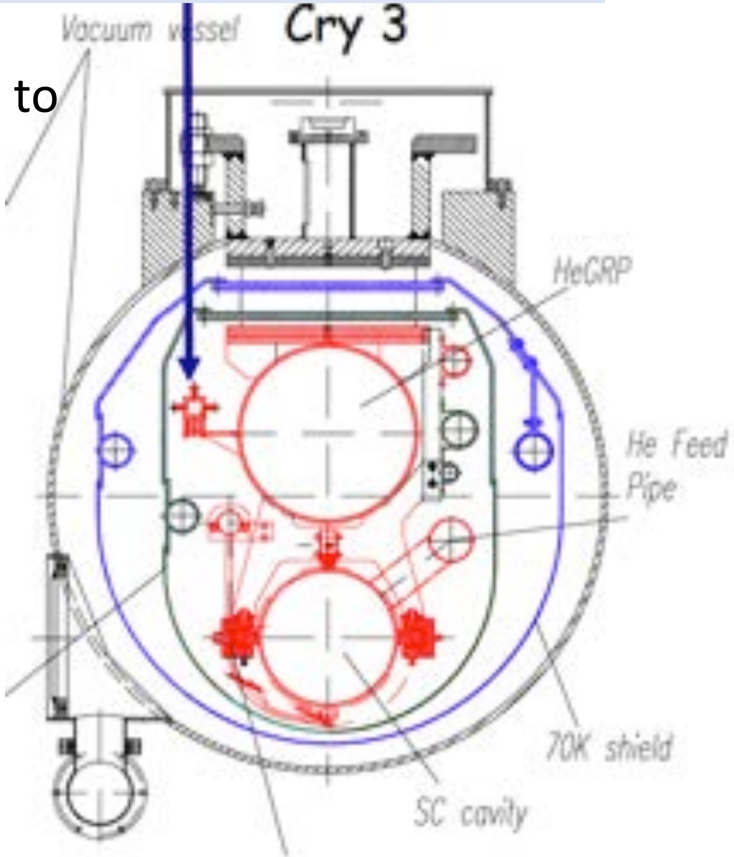
- N: number of particles per bunch
- f_{col} bunch collision frequency
  - Circular: number of bunches x revolution frequency
  - Linear: number of bunches x pulse repetition frequency
  - LC loses factor 100-10000
- To compensate for this difference, LC must squeeze the beam to a tiny spot at the interaction point (IP)

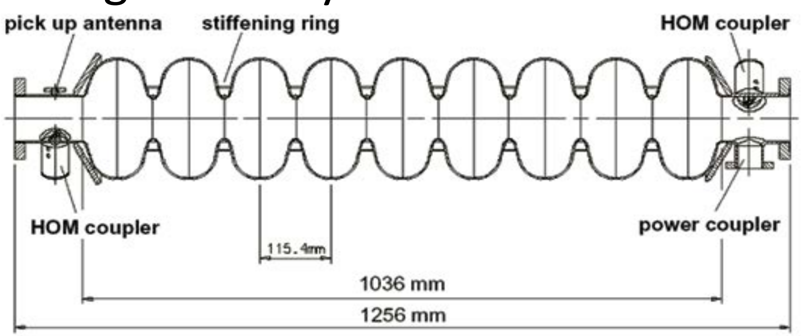
Development of LC Technology

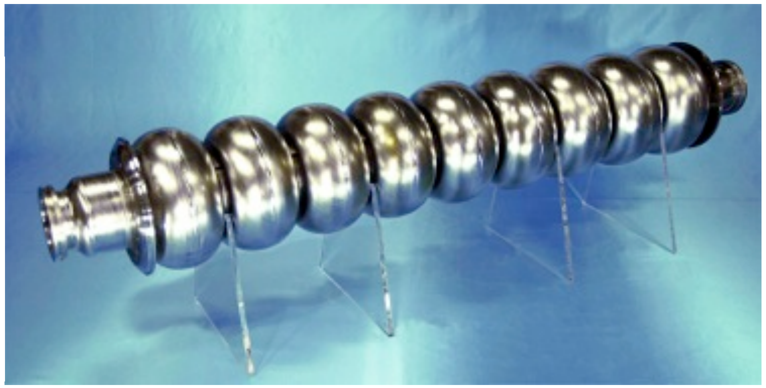
- Serious R&D started in mid 1980's
  - US, Germany, Soviet Union, CERN, Japan
  - Many machine names were born
    NLC, TESLA, VLEPP, CLIC, JLC
- Acceleration method
  - New advanced schemes proposed in early stages
    - Laser grating, inverse FEL, dielectric accelerator, plasma
  - Settled to the conventional microwave method but with improved technologies
  - SCRF, Xband NC, C-band NC, Xband single bunch, two beam
  - R&D's unified to SCRF for the next (after SLC) generation LC in 2004

Advantages of SCRF

- Low loss
  - The Ohmic energy loss per unit time proportional to $1/Q_0$
  - $Q_0 \sim 10^{10}$ (SC), 10^4 (NC)
  - But, keep in mind
    - Pulse length ~ ms (SC), ~μs (NC)
    - To remove 1W of heat, SC required 1kW AC power
    - So, the difference between SC and LC is small (see the next page)
- Long pulse
  - Easier intra-pulse feedback
  - Detector deadtime
- Disadvantages of SC
  - Lower accelerating gradient
    - ~30 MV/m (ILC), ~100 MV/m (CLIC)
  - Large refrigeration system





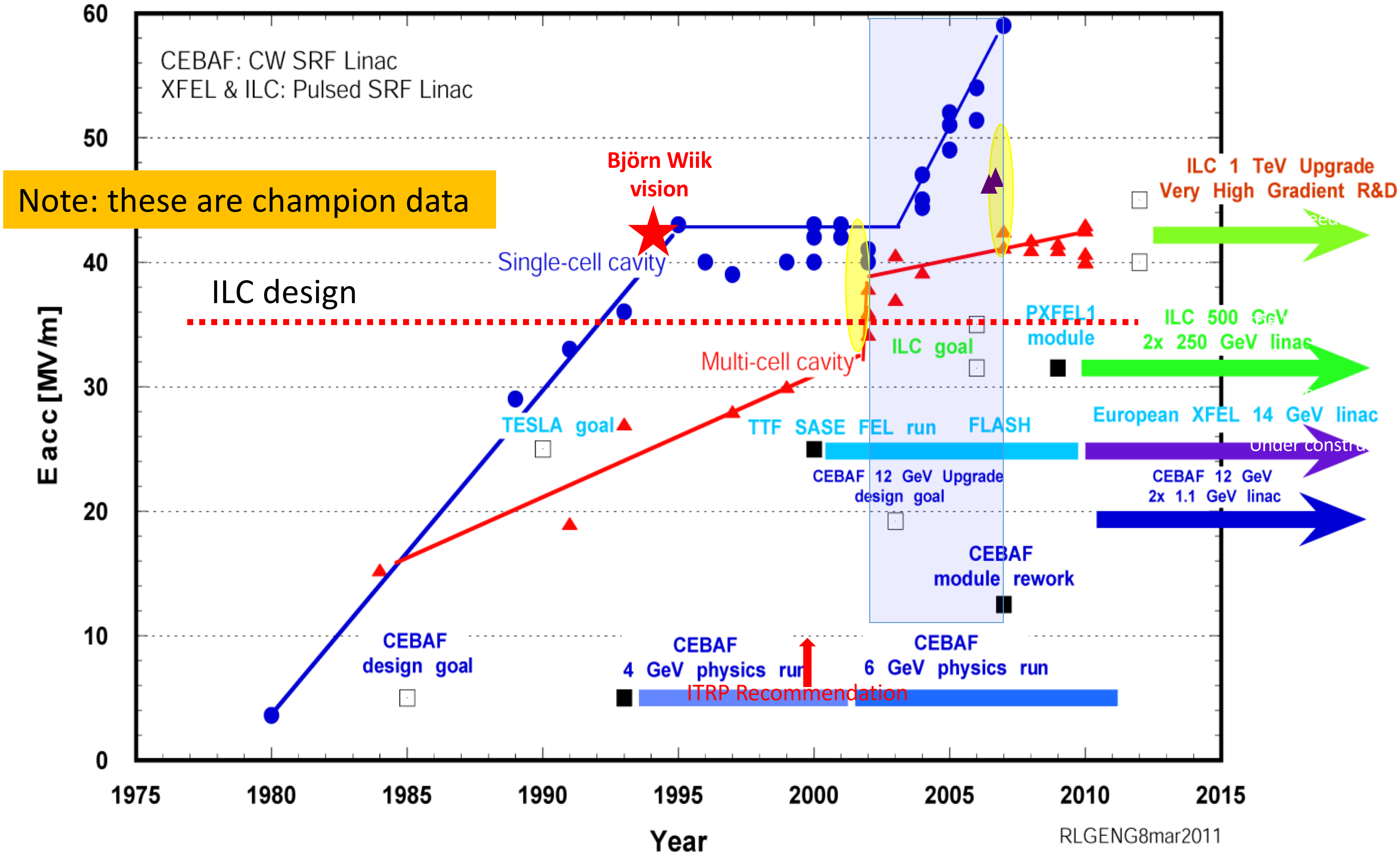


NC vs. SC --- Power Efficifiency

		ILC 500GeV	CLIC 3TeV
Loaded gradient	MV/m	31.5	100
Beam power/beam	MW	5.2	14
Total power consumption	MW	163	582
Beam power/total AC power	%	6.4	4.8
Main linac power efficiency*)	%	12	6

- *) = beam power gain / AC power for main linac
  - Including cryogenics (ILC), drive linac and drive beam manipulation (CLIC), linac magnets,
  - Not including AC high power line

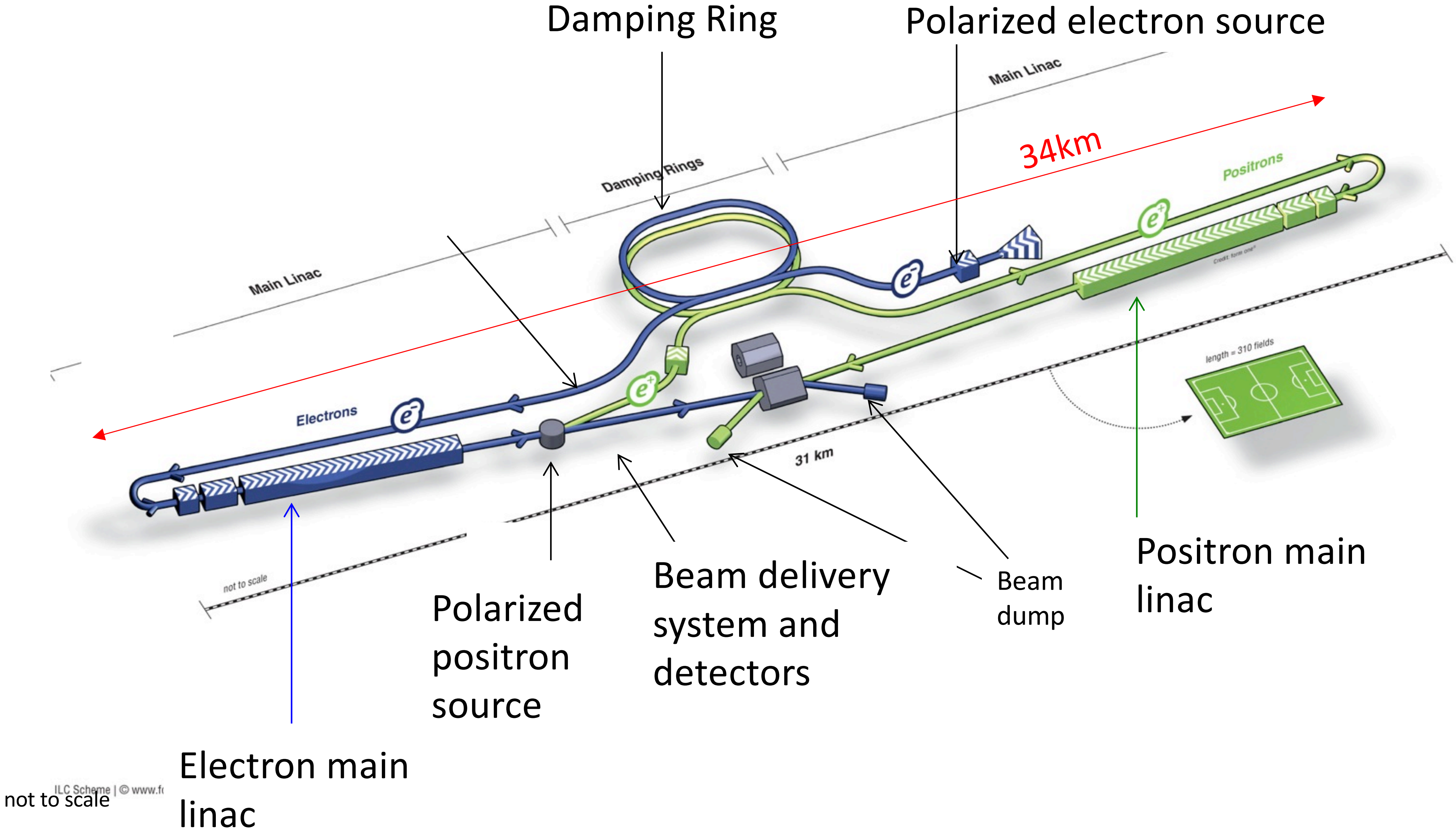
History of Gradient of SCRF Cavities



ILC

- e+e- linear collider using superconducting acceleration technology
- Start with E_{CM}=250GeV, to be later upgraded to 500GeV/1TeV
  - Site length ~20km (~30km for 500GeV, ~50km for 1TeV)
- Average accelerating gradient 31.5MV/m
  - Site length for E_{CM}=500GeV is ~30km
  - Now under R&D for higher gradient
    - Even to 2-3 TeV?
- I will not describe it in detail
  - You will hear many times in this school

ILC Layout



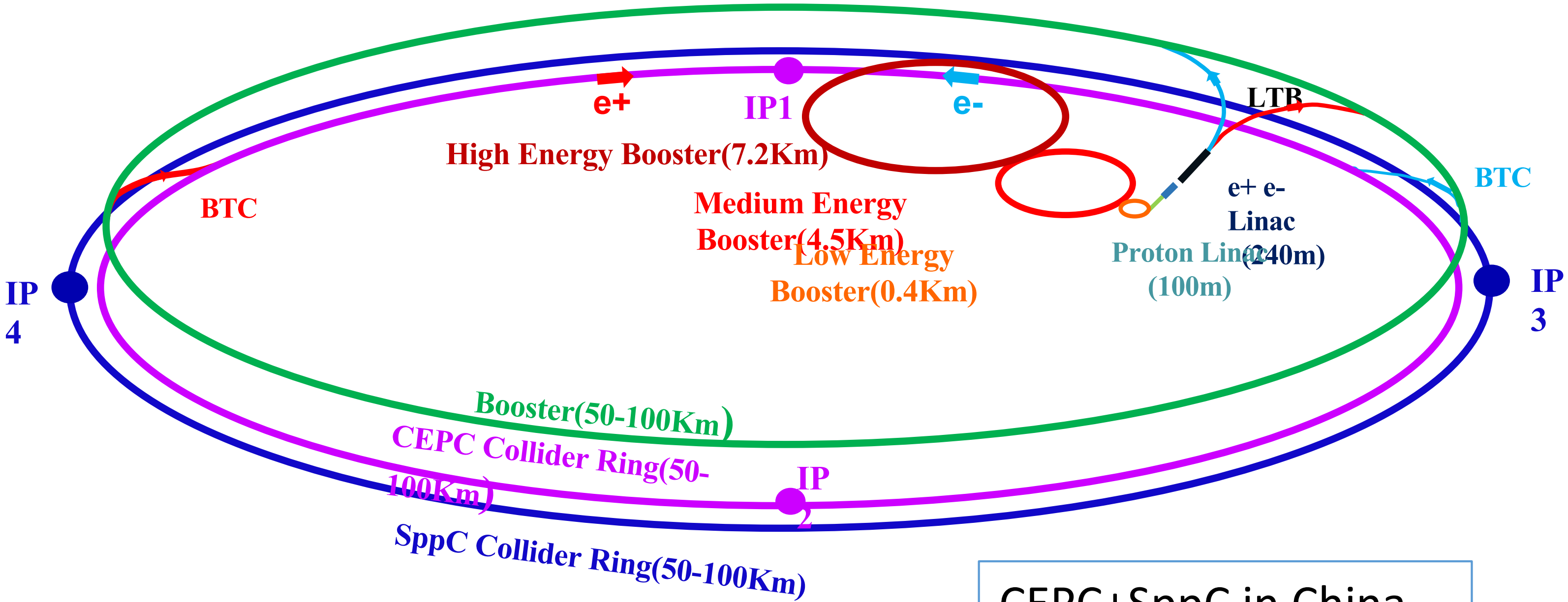
Damping Ring
Polarized electron source
Main Linac
Damping Rings
Main Linac
34km
Positrons
Electrons
length = 310 fields
31 km
not to scale
Polarized positron source
Beam delivery system and detectors
Beam dump
Positron main linac
Electron main linac
not to scale
ILC Scheme | © www.f

Future Accelerators

- ILC
- ILC upgrade
- Circular Accelerator
- CLIC
- Gamma-gamma collider
- Muon collider
- Dielectric accelerator (DLA)
- Plasma collider (PWFA,LWFA)

p-p Collider

- For p-p there is still a possibility to increase the magnetic field from 8Tesla (LHC) to 15T or even to 20T.
- R&D would take long time
- Cost is also a problem. 100km ring (4 times LHC) would cost too much.
- A possible choice would be to replace magnets in LHC

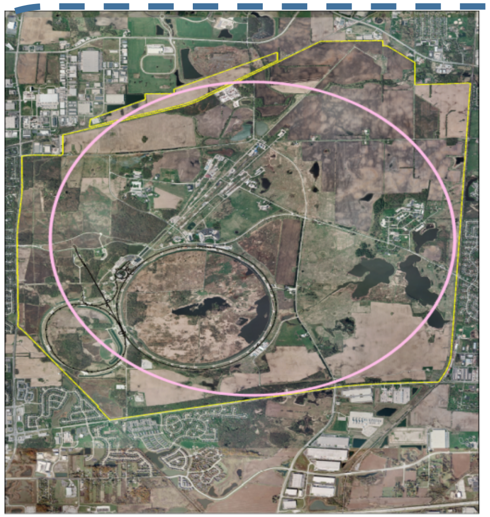


CEPC+SppC in China

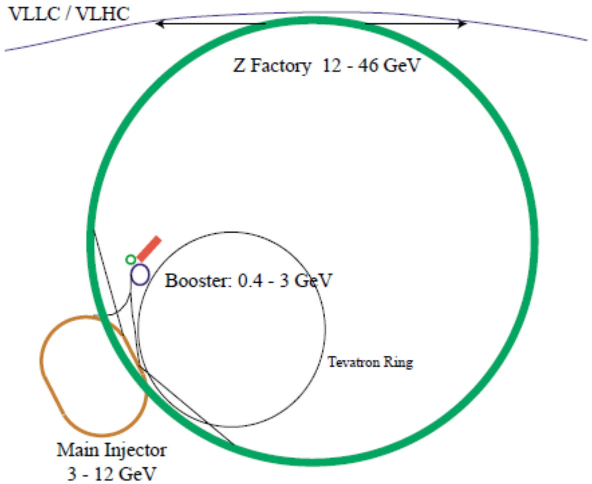
Revival of e+e- Ring Colliders ?

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

These ones died already

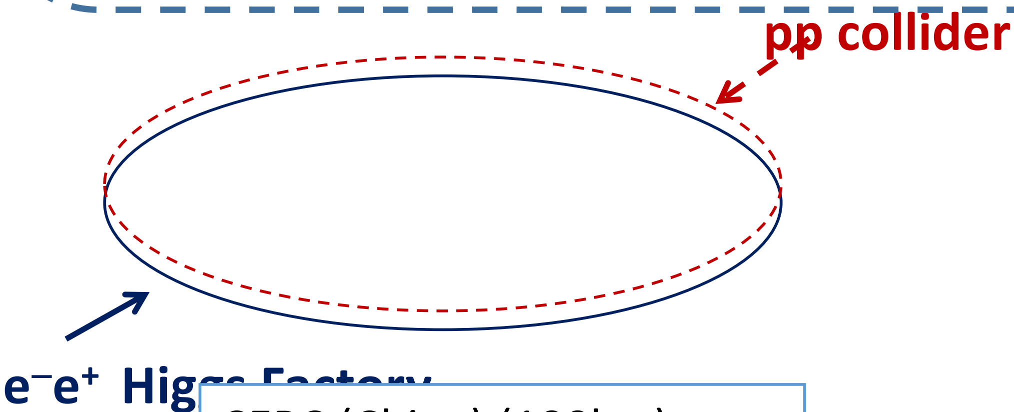


FNAL site filler (16km)

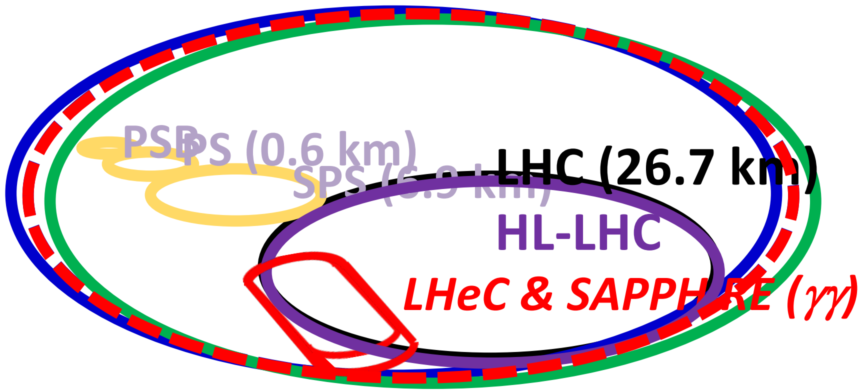


VLCC (233km)

SuperTRISTAN (40km, 60km)



CEPC (China) (100km)



FCCee (100km)

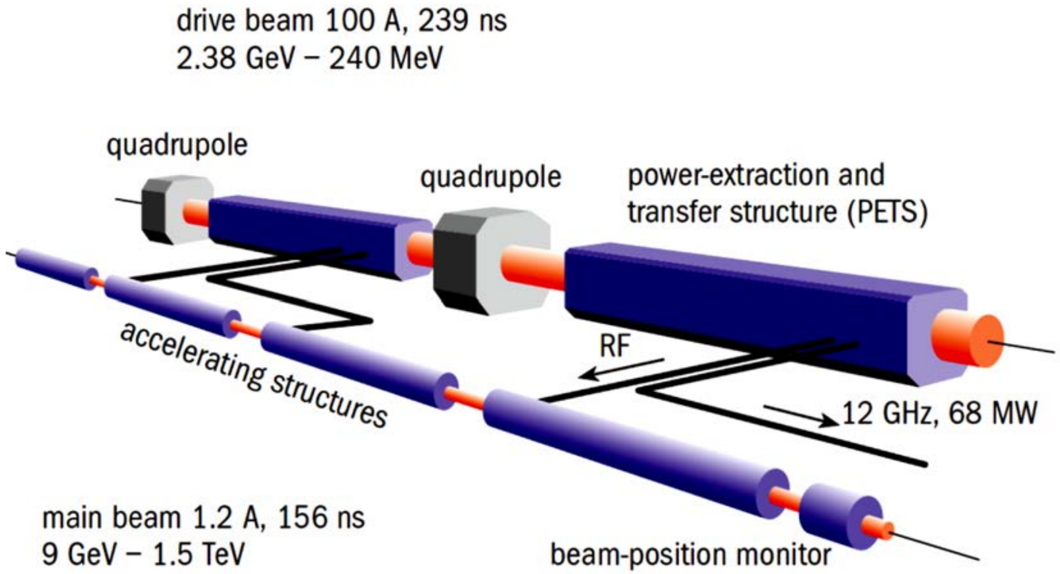
e+e- Ring Colliders

- e+e- Ring Colliders above LEP has been considered to be unreasonable extension
- But, knowing the mass of Higgs not too high, intensive studies are now being done, in particular FCC (CERN) and CEPC (China)
- These include the far-future scope to use the same tunnel for proton-proton collision at ~100TeV.
- Accept ~100MW synchrotron radiation
- Their designs seem to converge to a 100km ring.
- Can reach E_{CM}~350GeV

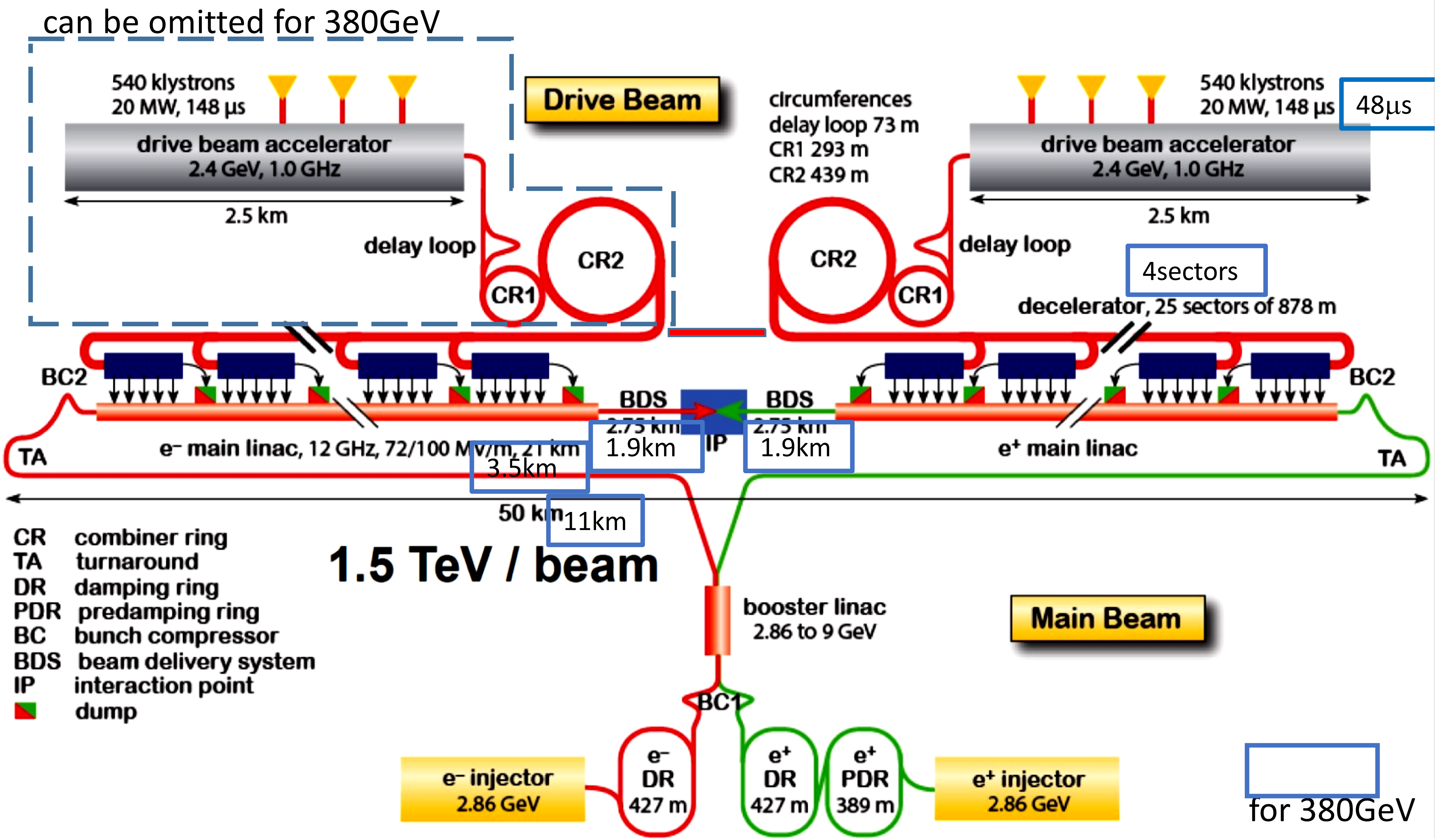
CLIC Concept

- 2-Beam Concept
  - Accelerate electrons by linac (Drive Linac) with low energy (~2.4GeV), low frequency (1GHz), high current（~4A), and long pulse (~140μs)
  - Compress the bunch interval by using delay loop/combiner ring (-->100A)
  - Leading these electrons into deceleration cavities (called PET:Power Extraction and Transfer Structure), generate high frequency microwave of 12GHz
  - Accelerate electron and positron by this 12GHz microwave to high energies
  - Equivalent to replace huge number of klystrons with one huge klystron

- High gradient acceleration (72-100MV/m) is feasible
  - 3TeV in 50km site
- To increase energy,
  - Extend Collider linac (but no additional power source)
  - Lengthen the Drive Lina pulse



CLIC layout (3 TeV)



CLIC Design Parameters

Parameter	Symbol	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	$\sqrt{s}$	GeV	380	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		352	312	312
Bunch separation	Δt	ns	0.5	0.5	0.5
Pulse length	τ_{RF}	ns	244	244	244
Accelerating gradient	G	MV/m	72	72/100	72/100
Total luminosity	$\mathscr{L}$	10^{34} cm^{-2}s^{-1}	1.5	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	10^{34} cm^{-2}s^{-1}	0.9	1.4	2
Main tunnel length		km	11.4	29.0	50.1
Number of particles per bunch	N	10^9	5.2	3.7	3.7
Bunch length	σ_z	μm	70	44	44
IP beam size	σ_x/σ_y	nm	149/2.9	$\sim$ 60/1.5	$\sim$ 40/1
Normalised emittance (end of linac)	ϵ_x/ϵ_y	nm	920/20	660/20	660/20
Normalised emittance (at IP)	ϵ_x/ϵ_y	nm	950/30	—	—
Estimated power consumption	P_{wall}	MW	252	364	589

P. Burrows, LCWS2018, Arlington, Texas

CLIC Technology Maturity

- CDR published
- Cavity with accelerating gradient ~100MV/m almost confirmed
- Drive Beam generation demonstrated. Emittance and stability to be further improved
- Deceleration in PETS in progress
- Emittance preservation in linac with stabilization system developed
- Linac beam dynamics being tested at FACET
- Final Focus System to be tested at ATF2

LINEAR COLLIDER COLLABORATION

CLIC roadmap

P. Burrows, LCWS2018, Arlington, Texas

2013 - 2019 Development Phase

Development of a Project Plan for a staged CLIC implementation in line with LHC results; technical developments with industry, performance studies for accelerator parts and systems, detector technology demonstrators

2020 - 2025 Preparation Phase

Finalisation of implementation parameters, preparation for industrial procurement, Drive Beam Facility and other system verifications, Technical Proposal of the experiment, site authorisation

2026 - 2034 Construction Phase

Construction of the first CLIC accelerator stage compatible with implementation of further stages; construction of the experiment; hardware commissioning

2019 - 2020 Decisions

Update of the European Strategy for Particle Physics; decision towards a next CERN project at the energy frontier (e.g. CLIC, FCC)

2025 Construction Start

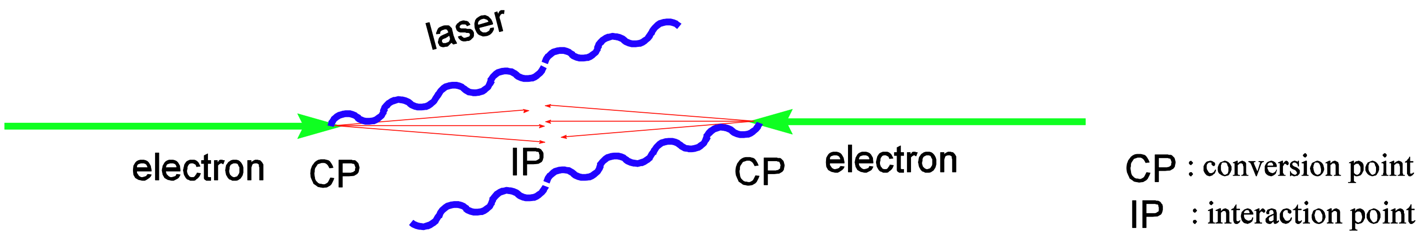
Ready for construction; start of excavations

2035 First Beams

Getting ready for data taking by the time the LHC programme reaches completion

Gamma-Gamma Collider

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



- Lots of recent proposals of $\gamma\,\gamma \rightarrow$ H (not "beyond LHC")
  - Recent proposal: 62.8GeV electron x 1keV FEL to produce 62.5GeV γ
    T. Barklow, et.al., "An Xray FEL-Based $\gamma\gamma$ Collider Higgs Factory – Material for AF03 Summary Report", Dec.2020
- ILC and CLIC can be converted to γ-γ collider if physics demands
- In principle, advanced linear colliders (plasma, etc) can also be converted to γ-γ collider. In particular when positron acceleration is difficult.

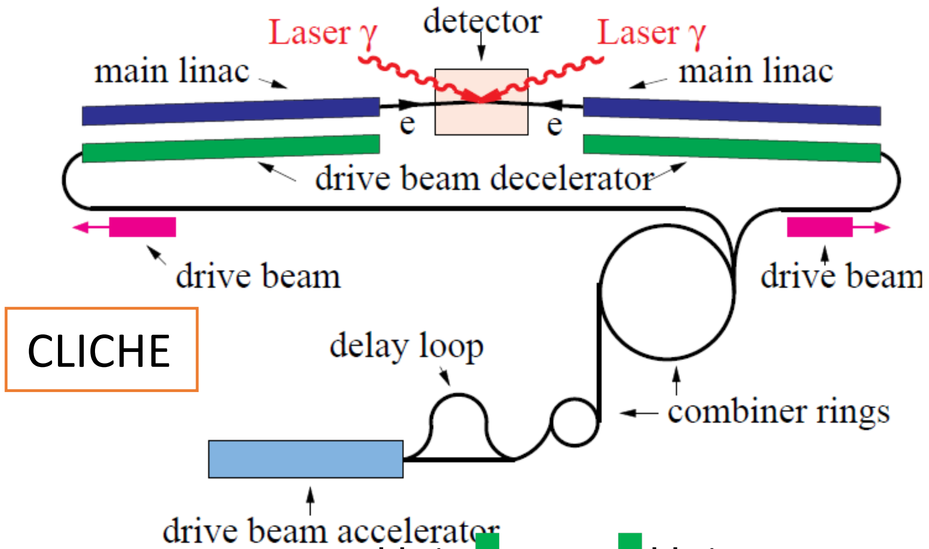
Technology for Gamma-Gamma

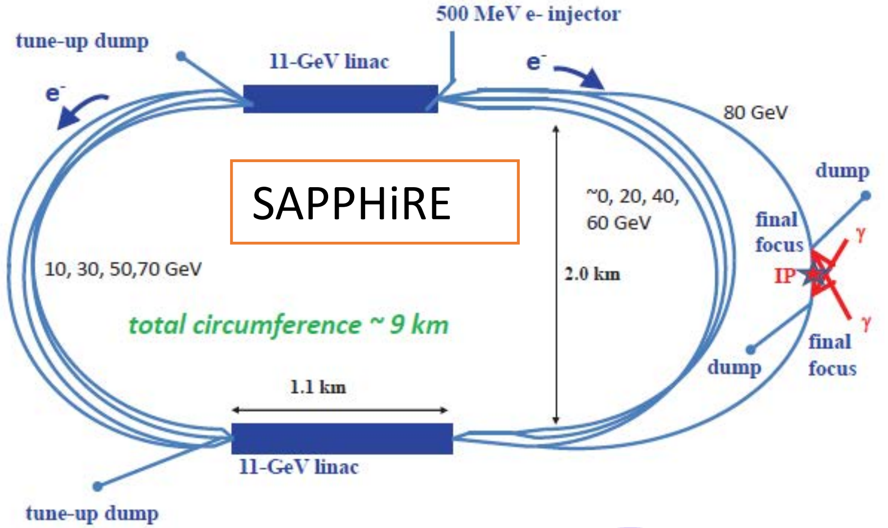
- Laser
  - Pulse structure must match with the electron beam (difference between NC and SC linacs)
  - Flash energy : a few to 10 Joules
  - Some lasers close to gamma-gamma application
    - LIFE (fusion), fiber
    - But still needs years of R&D including the adaptation of pulse structure
- Optical cavity
  - Can accumulate laser pulse from relatively weak lasers (mostly for SC linac case)
  - Many R&D studies in the world for other applications
- FEL
- IR design
  - Path of laser beam
  - In particular complex with optical cavity is used
  - background studies

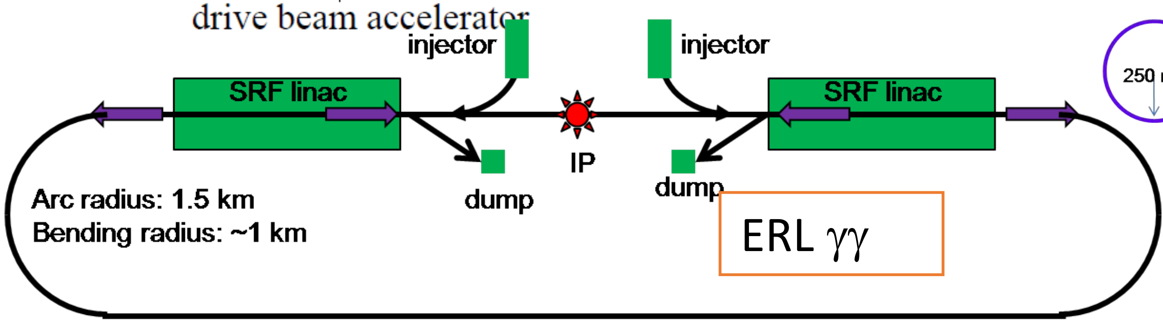
Various Possibilities of γγ Colliders

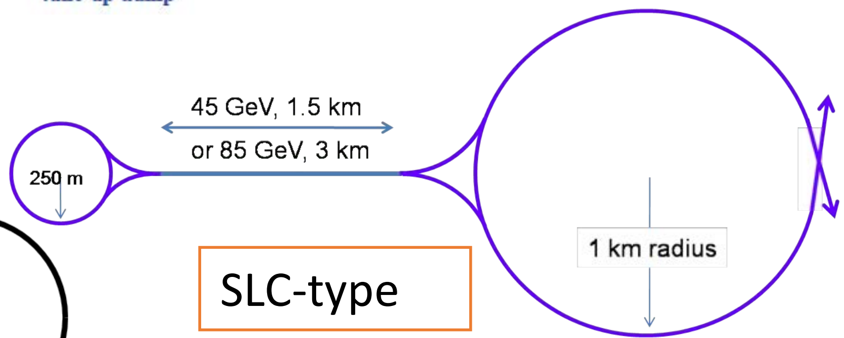
- e+e- linear collider (ILC, CLIC) can be converted to γ-γ collider
- 80GeV e- on 80GeV e- converted by laser with x=4.83 gives 66GeV on 66 GeV γ-γ collider
  (lowest energy to produce H except muon collider)
- CLICHE (2003)
- SAPPHiRE (2012)

Presumably, most of these are dead

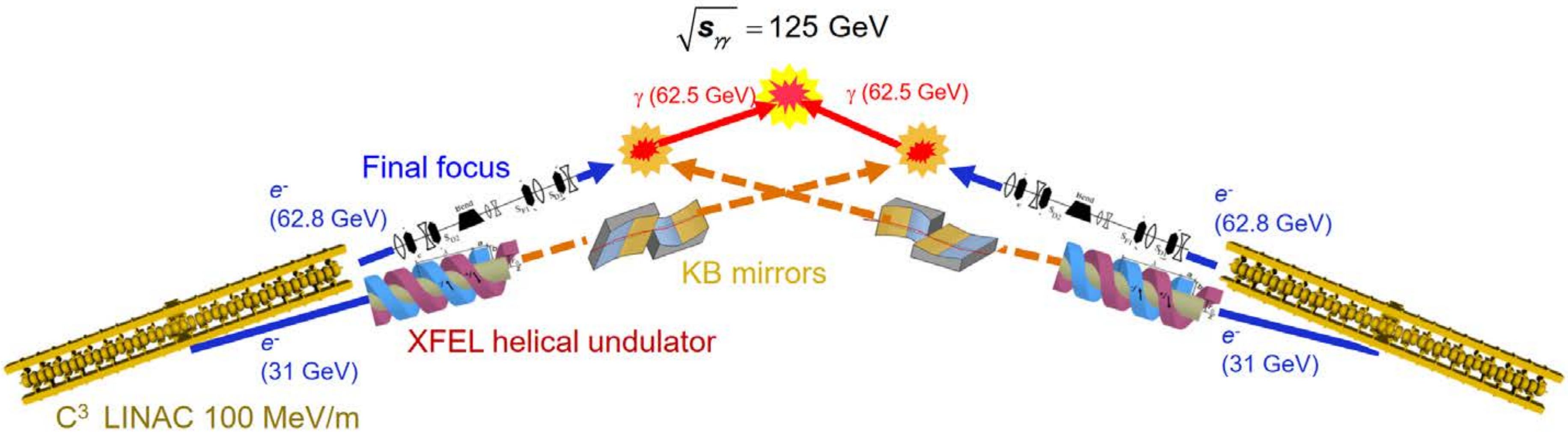








- New proposal
- FEL-based $\gamma\gamma$ collider
  - ~1keV FEL
  - x ~ 1000

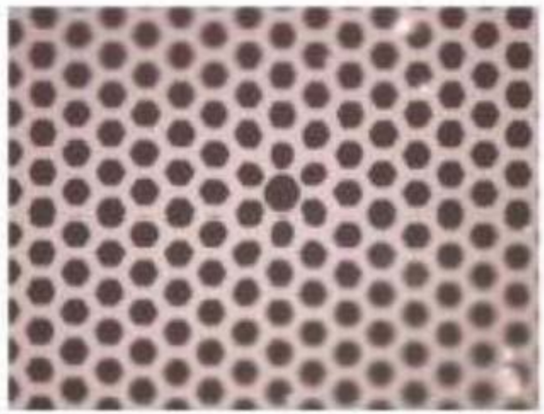


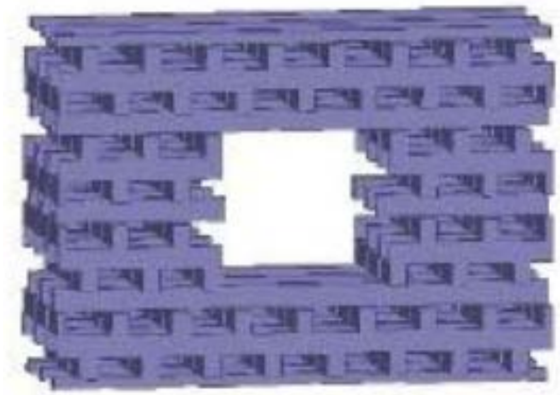
Advanced Acceleration Mechanisms

- Dielectric material
  - Laser-driven (DLA)
  - Beam driven
- Plasma wakefield acceleration
  - Laser-driven (LWFA)
  - Beam driven (PWFA)

Dielectric Laser Accelerator (DLA)

- Direct extension of present accelerator concept (microwave + resonant structure)
  - Klystron → laser
  - Resonant cavity → micron scale dielectric crystal (semiconductor technology)
  - less power loss than metal at optical frequencies
  - expected higher breakdown thresholds (> 1 order of magnitude than Cu structure)
- Very short wavelength (micron)
- Require very low bunch charge $O(10^4)$ plus very high repetition rate O(GHz)
  - In one hand this relaxes the beam-beam interaction





DLA

- Challenges
  - material to ensure the gradient
  - power coupler of high efficiency
  - electron beam with required bunch pattern (hundred bunchlets in pico-second repeated a few MHz)
  - for colliders
    - emittance growth by transverse wake (alignment)
    - positron beam
      almost impossible to create the beam structure?
    - Can go to γ-γ collider?
      But require extreme laser (~5TW x 1ps, average ~50MW)

An example of 10TeV collider

Bunch population	3.80E+04
bunches per train	159
rep rate	5 MHz
macro bunch length	150 μm
wavelength	1.89 μm
normalized emittance	1e−10 m
IP spot size	0.06nm
Luminosity	4.90E+36
Beam power	24.2MW
Wall−plug power	242MW
Gradient	400MV/m
Total linac length	25km
Laser pulse energy	1μJ
Average power	1kW
Pulsewidth	1ps
Wall−plug efficiency	30−40%

one of the examples in ICFA-ICUIL report

Plasma Wakefield Accelerator

Linac in the past has been driven by **microwave technology**

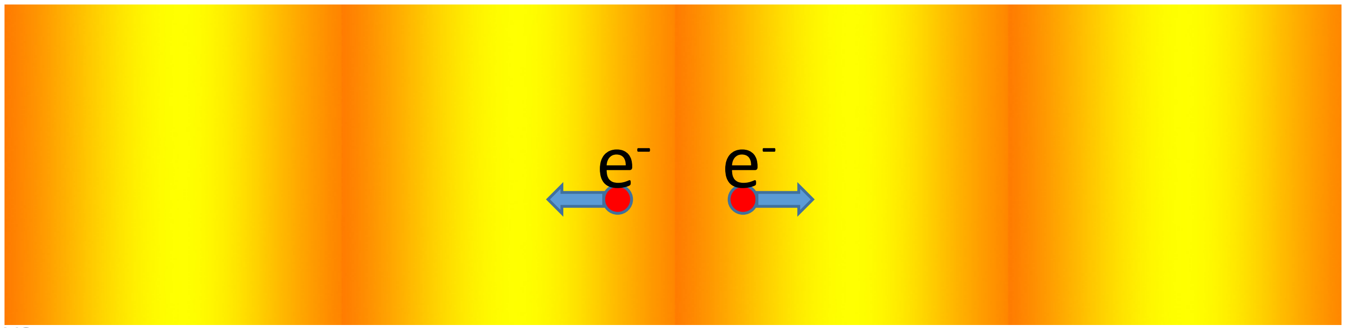
- Plane wave in vacuum cannot accelerate beams: needs material to make boundary condition
- Breakdown at high gradient

Excite **plasma wave** by some way (electron beam, laser beam)

- Charged particles on the density slope are accelerated, like surfing.
- Need not worry about breakdown with plasma
  - can reach > 10GeV/m
- Plasma oscillation frequency and wavelength are related to plasma density

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

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



How to Generate Plasma Wave

- Beam-Driven (PWFA)
  - Use particle (normally electron) beam of short bunch
- Laser-Driven (LWFA)
  - 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

- kick out plasma electrons by pondermotive force of laser
- Laser intensity characterized by the parameter a_0
  - $a_0 < 1$: linear regime
  - $a_0 > 1$: blow-out regime (all electrons expelled out of the drive beam region)

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

- Accelerating field

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

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

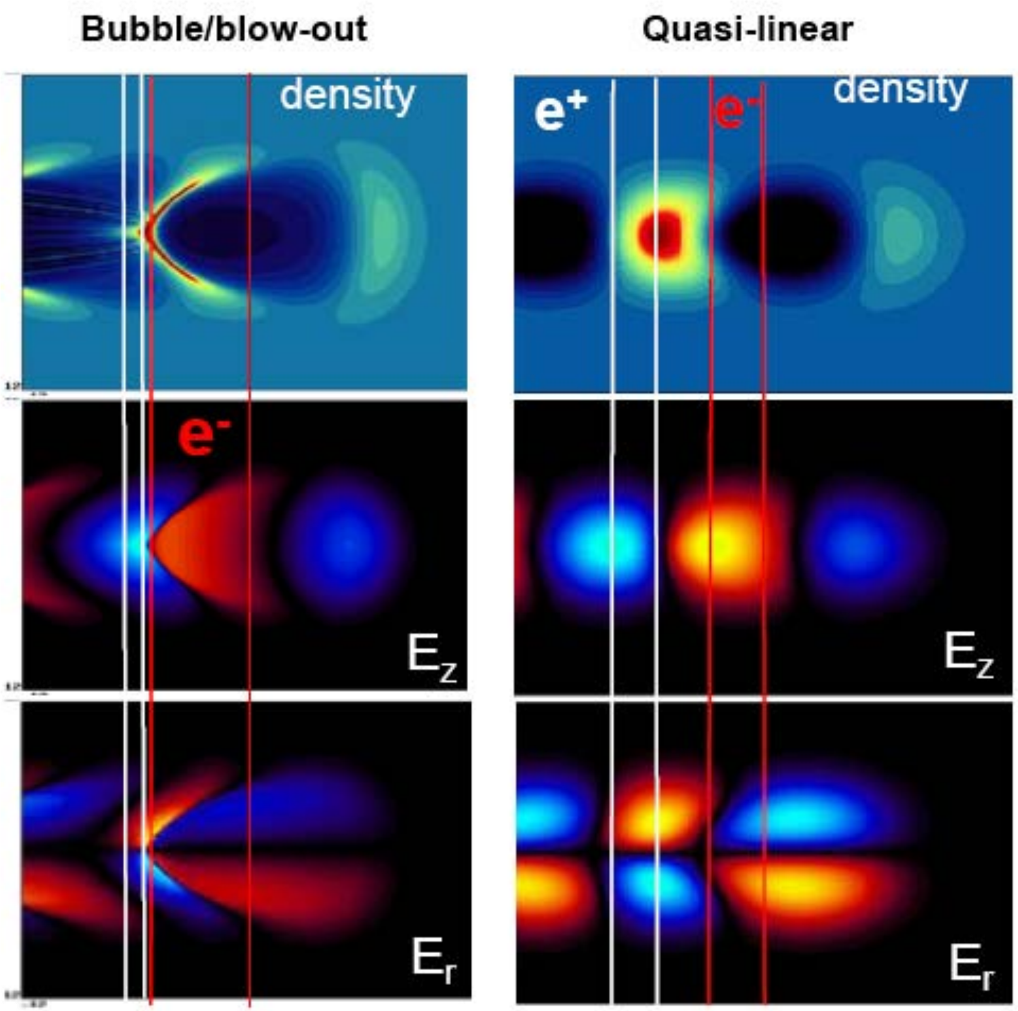
Blowout and Linear Regime

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

acceleration field

plasma density

transverse field



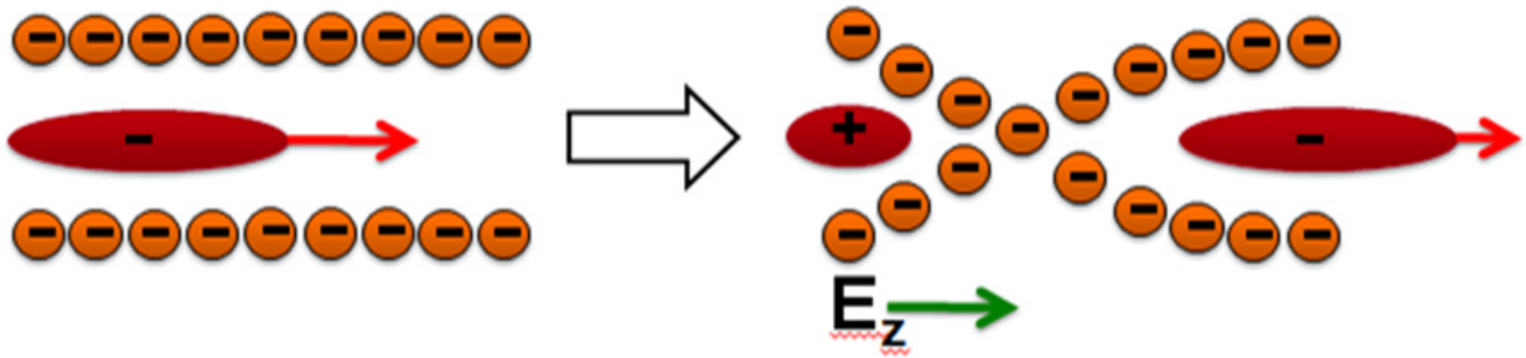
a=4

a=1

Figure from ICFA Beamdynamics News Letter 56

Positron Acceleration

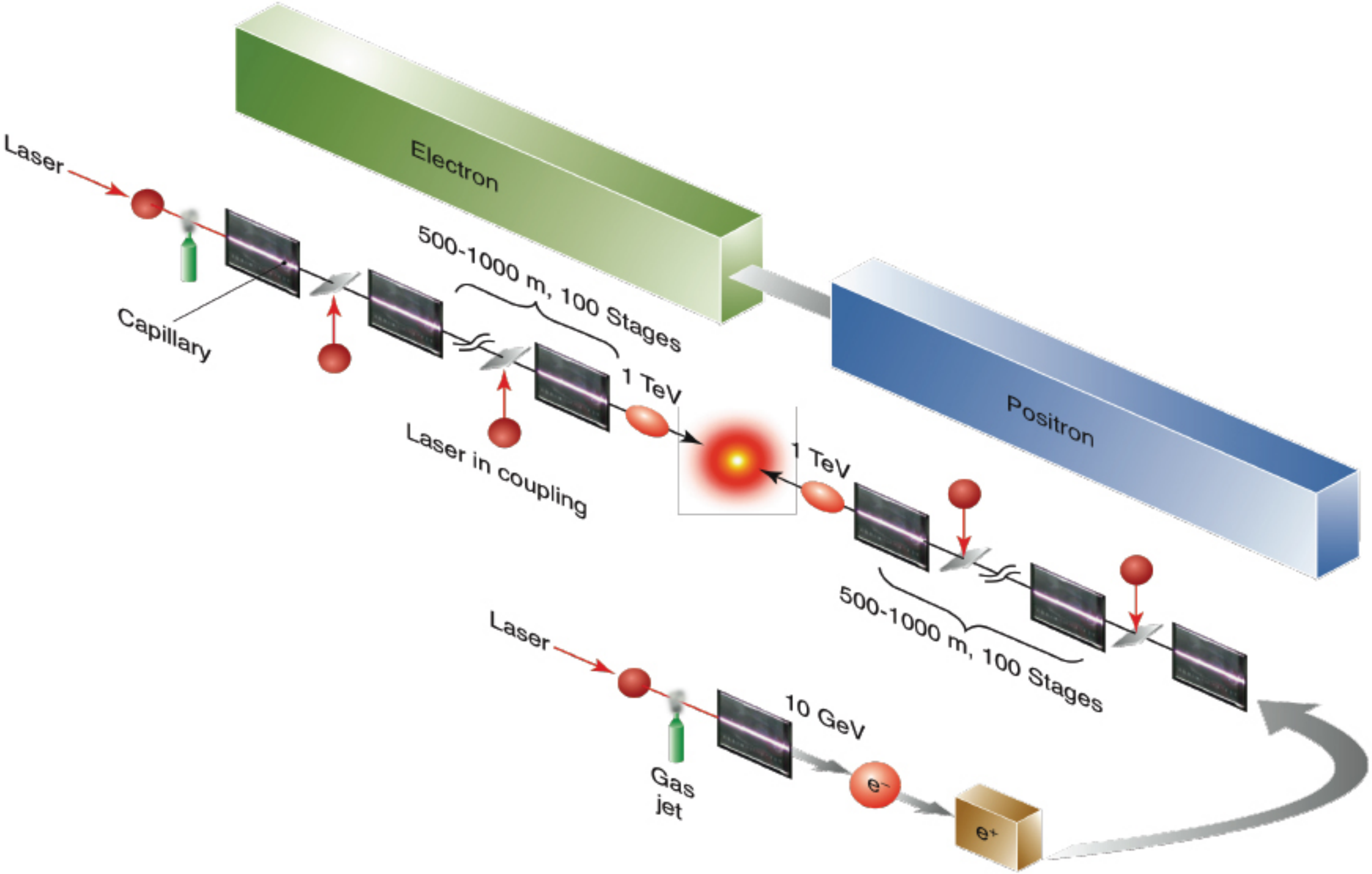
- Positron beam is defocused in the acceleration phase
- Use hollow plasma channel
- Acceleration+focusing phase created when plasma electrons go back to the axis



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 of
  - phase control
  - electron orbit matching

Concept of LWFA Collider



Example Beam Parameters of 1-10TeV LWFA

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 (ICFA-ICUIL White paper)

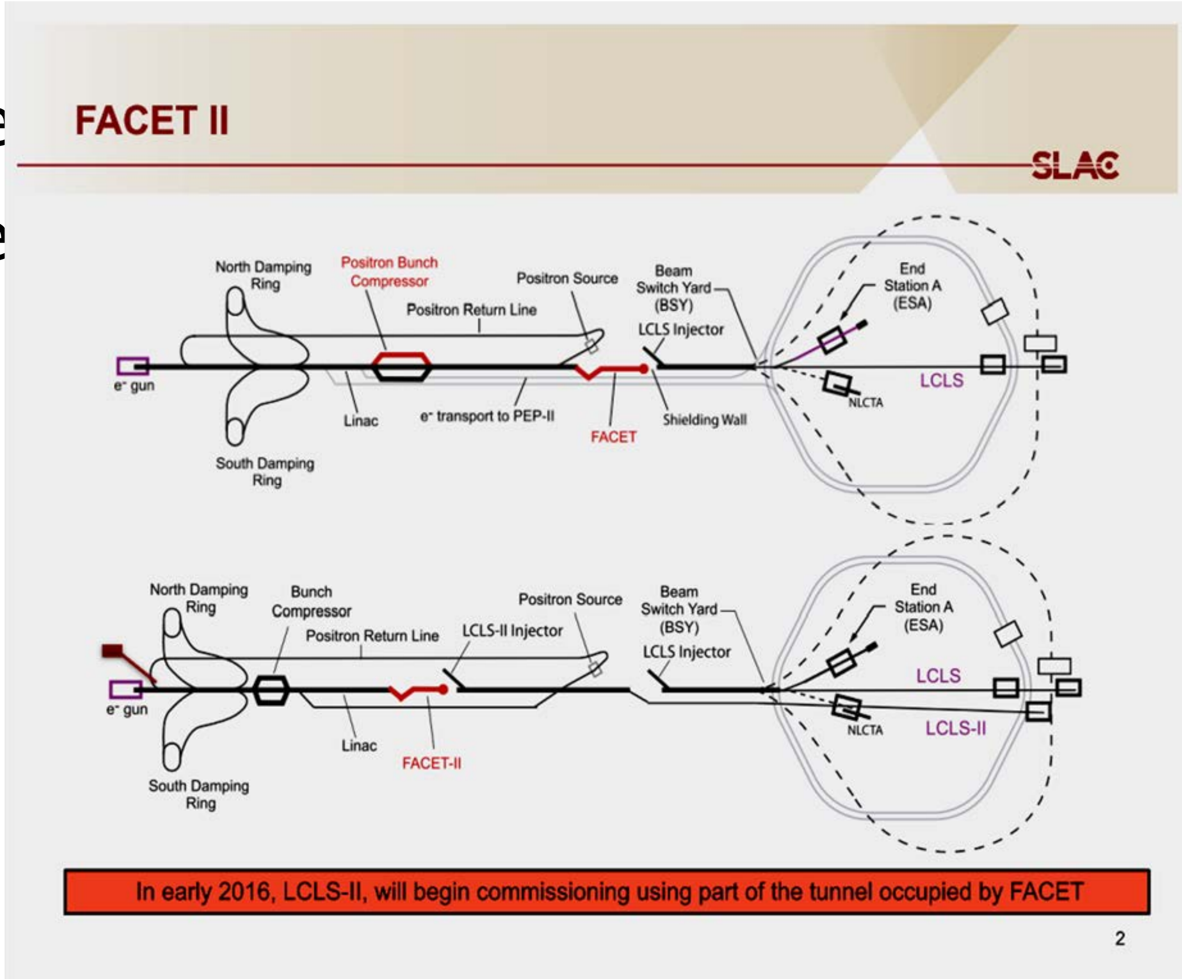
Example Laser Parameters of 1/10TeV LWFA

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

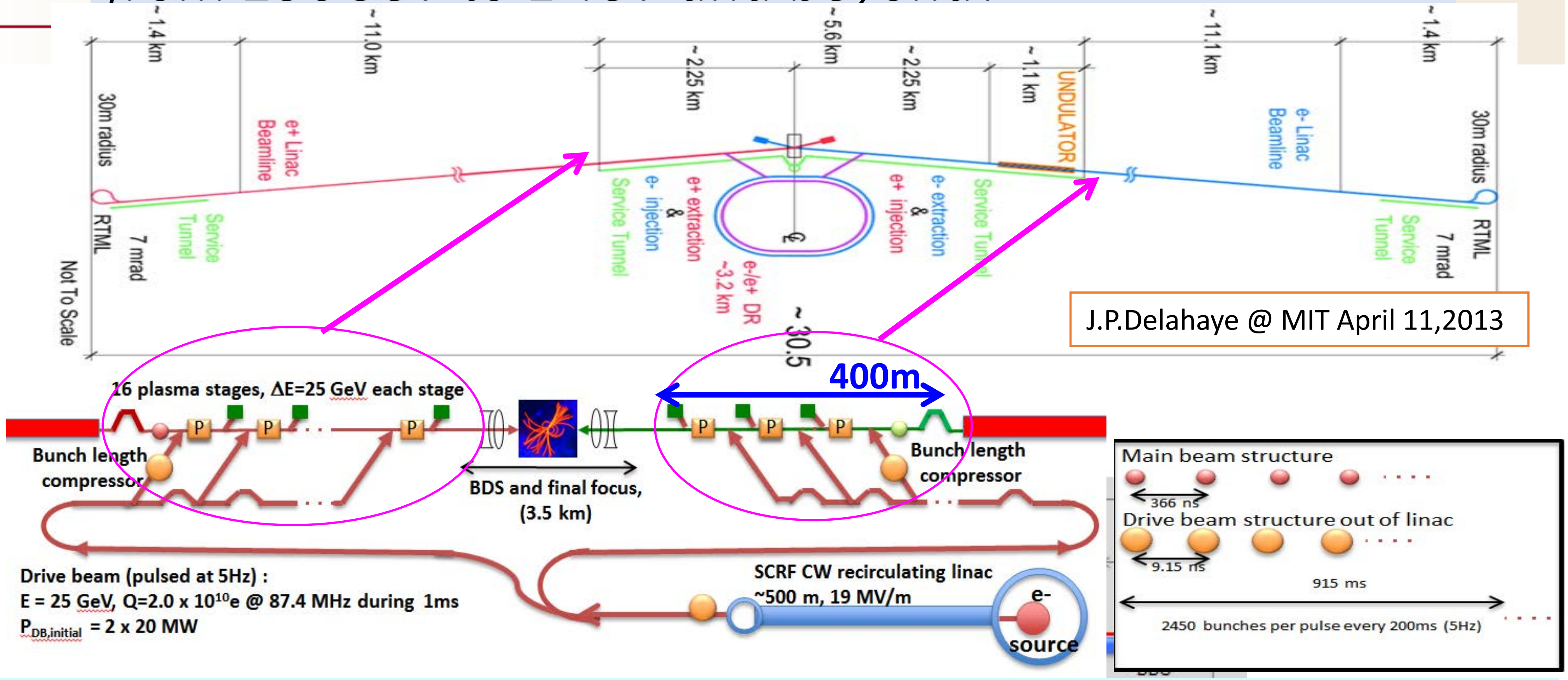
From ICFA Beamdynamics News Letter 56

Beam-Driven Plasma Accelerator

- Use electron beam to generate plasma wave
- Bunch pattern is more flexible than in LWFA (not constrained by the laser technology)
- R&D works led by SLAC (FACET/FACET2)



An alternative ILC upgrade by PWFA from 250GeV to 1 TeV and beyond?



One possible scenario could be:

1) **Build & operate the ILC as presently proposed up to 250 GeV (125 GeV/beam): total extension 21km**
2) **Develop the PFWA technology in the meantime (up to 2025?)**
3) **When ILC upgrade requested by Physics (say up to 1 TeV), decide for ILC or PWFA technology:**
4) **Do not extend the ILC tunnel but remove latest 400m of ILC linac (beam energy reduced by 8 GeV)**
5) **Reuse removed ILC structures for PWFA SC drive beam accelerating linac (25 GeV, 500m@19MV/m)**
6) **Install a bunch length compressor and 16 plasma cells in latest part of each linac in the same tunnel for a 375+8 GeV PWFA beam acceleration (382m)**
7) **Reuse the return loop of the ILC main beam as return loop of the PWFA drive beam**

ILC upgrade from 250 GeV to 1 TeV by PWFA

Parameter	Unit	ILC	ILC	ILC (to 250GeV) + PWFA
Energy (cm)	GeV	250	1000	PFWA = 250 to 1000
Luminosity (per IP)	$10^{34}cm^{-2}s^{-1}$	0.75	4.9	4.9
Peak (1%)Lum(/IP)	$\mathbf{10^{34}cm^{-2}s^{-1}}$	0.65	2.2	2.2
# IP	-	1	1	1
Length	km	21	52	21
Power (wall plug)	MW	128	300	128+135*1.2=290?
Polarisation (e+/e-)	%	80/30	80/30	80/30
Lin. Acc. grad. (peak/eff)	MV/m	31.5/25	36/30	7600/1000
# particles/bunch	10^{10}	2	1.74	1.74
# bunches/pulse	-	1312	2450	2450
Bunch interval	ns	554	366	366
Average/peak current	nA/mA	21/6	22.9/7.6	22.9/7.6
Pulse repetition rate	Hz	5	4	5
Beam power/beam	MW	2.63	13.8	13.8
Norm Emitt (X/Y)	10^{-6}/$\mathbf{10^{-9}}$rad-m	10/35	10/30	10/30
Sx, Sy, Sz at IP	nm,nm,µm	729/6.7/300	335/2.7/225	485/2.7/20
Crossing angle	mrad	14	14	14
Av # photons	-	1.17	2.0	1.0
δb beam-beam	%	0.95	10.5	16
Upsilon	-	0.02	0.09	0.8

J.P.Delahaye @ MIT April 11,2013

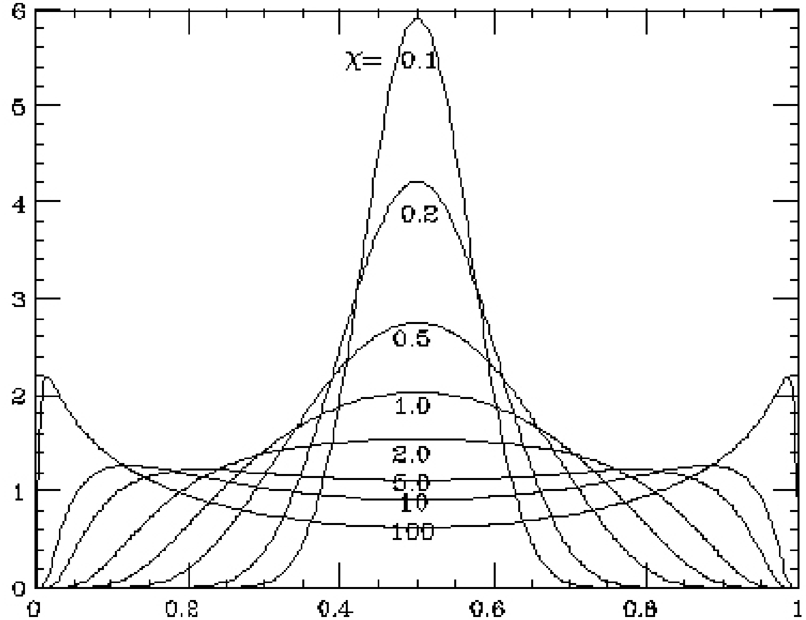
What's Needed for Plasma Collider

- High rep rate, high power laser (Laser-driven)
- Beam quality
  - Small energy spread << 1%
  - emittance preservation (alignment, instabilities, laser stability, Coulomb scattering)
- High power efficiency from wall-plug to beam
  - Wall-plug → laser (Laser-driven)
  - Laser (beam) → plasma wave
  - plasma wave → beam (high-beam loading required)
- Staging
  - laser phase (Laser-driven)
  - beam optics matching
  - Beam transmission >~99.9%
- Positron acceleration
- Beam-beam interaction (extremely large Υ)
- Very high component reliability
- Low cost per GeV
- **Colliders need all these, but other applications need only some of these**
  - Advantage of LWFA (PWFA requires big drive linac)
- Application of plasma accelerators would start long before these requirements are established

A Challenge for Detectors

- Wakefield accelerators adopt short wavelength
  - The bunch length inevitably short
  - High beamstrahlung parameter

$$\Upsilon \equiv \frac{\text{critical energy}}{E_0} \propto \frac{N\gamma}{\sigma_z(\sigma_x + \sigma_y)}$$

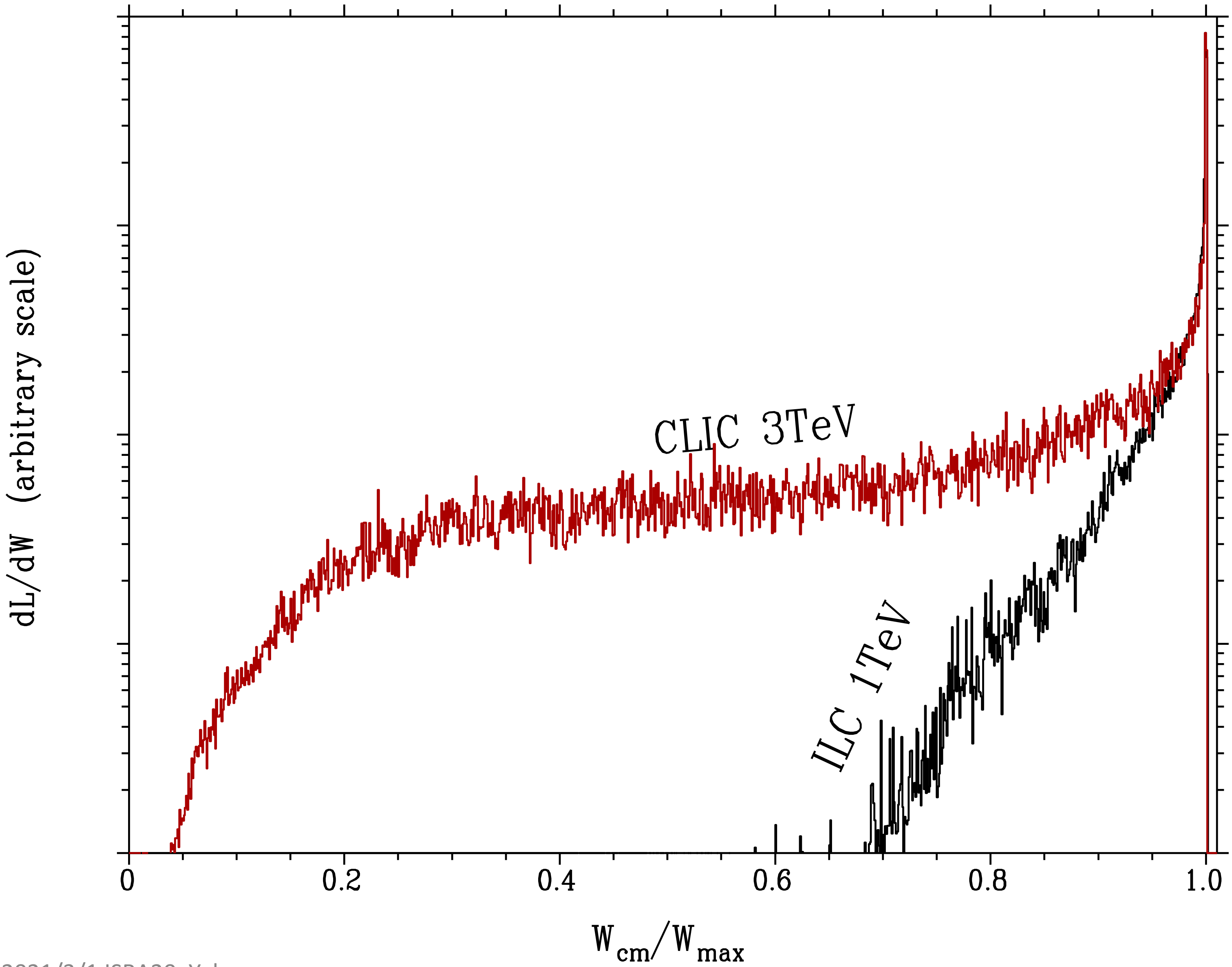


- High field effects
  - Beamstrahlung $e \rightarrow e + \gamma$
  - Coherent pair creation $\gamma \rightarrow e^+ e^-$
  - Minimum electron energy

$$E_{min} \sim E_0/\Upsilon, \qquad (\Upsilon \ll 1)$$

  - Come out with very large angles
  - Previous LWFA example gives Υ=18000, E_{min} ~ 300MeV, angle = O(1radian)
  - Much more abundant than the pairs from particle-particle collision

Luminosity Spectrum (e^-,e^+)



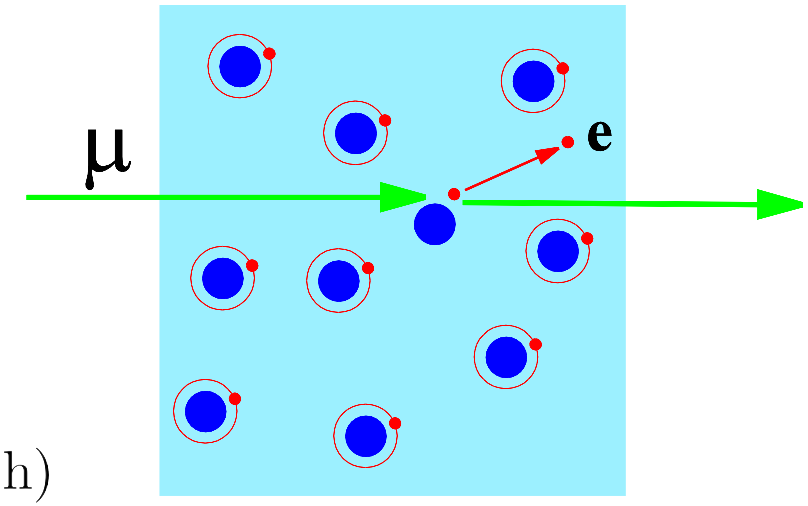
Muon Collider

- 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

- Make use of energy loss dE/dx by ionization
- Coulomb scattering heats the beam

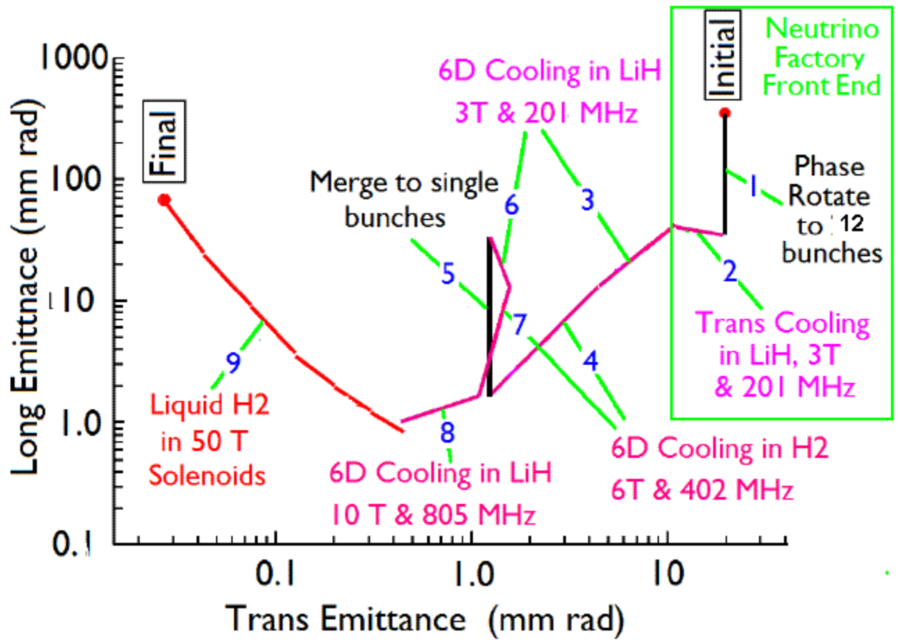
$$\frac{d\varepsilon_n}{ds} = -\frac{1}{\beta^2}\frac{dE}{ds}\frac{\varepsilon_n}{E} + \frac{1}{\beta^3}\frac{\beta_\perp (0.014)^2}{2EmX_0}$$

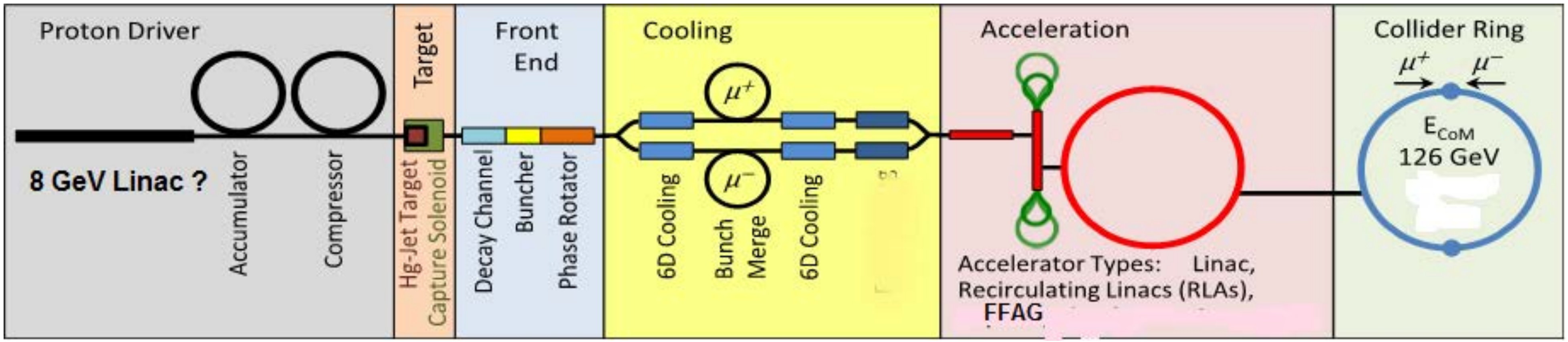
$$(\beta = v/c,\ X_0 = \text{radiation length})$$



Create and Cool Muon Beam

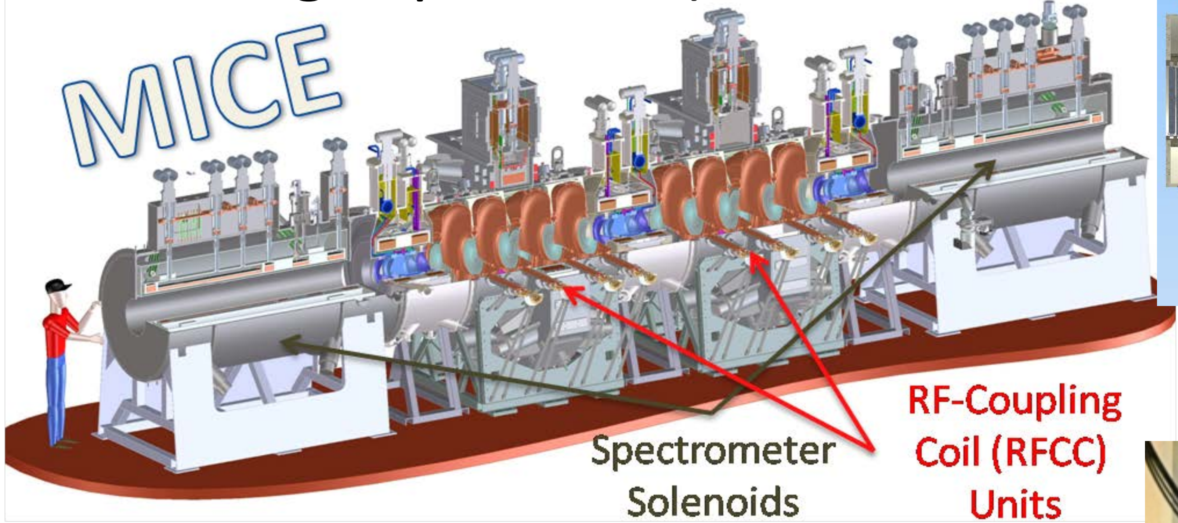
- Muons created by hadron collision
- Muons decay within 2μs in the rest frame
  - must be accelerated quickly
- Staging
  - Higgs factory at E_{cm}=126GeV (Z-pole used to be the first target)
  - Neutrino factory
  - TeV muon collider

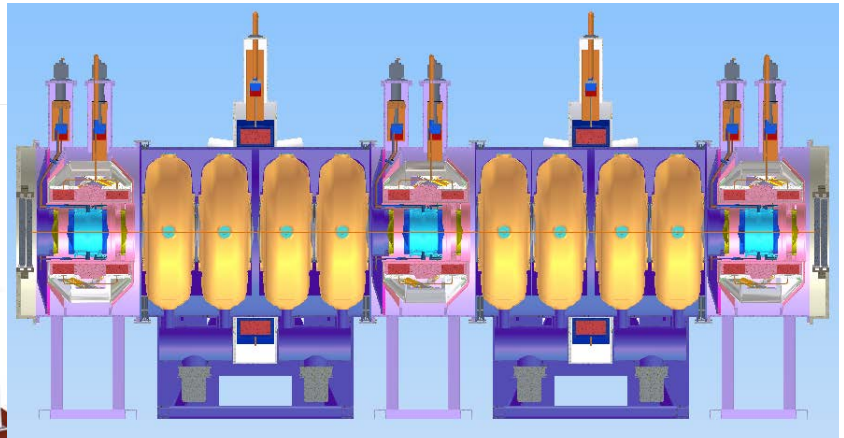




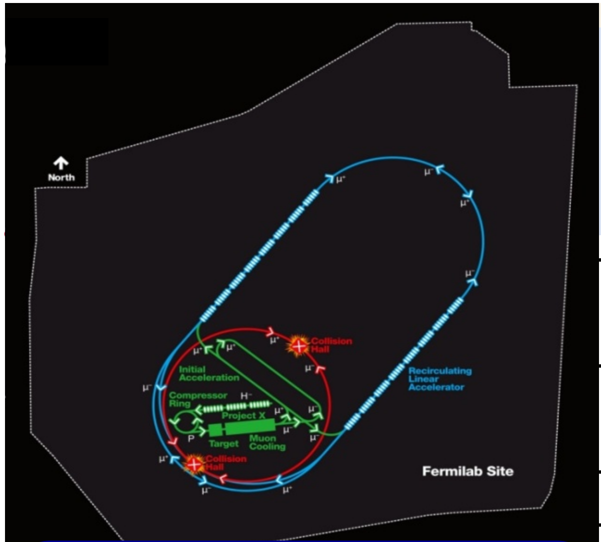
Cooling Test Facilities

- MICE (Muon Ionization Cooling Experiment) @RAL





- MTA (MuCool Test Area) @FNAL
  - cavity test



MAP Designs for a Muon-Based Higgs Factory and Energy Frontier Colliders

This page is already out of date

Range of Top Params:
$\delta E/E \sim 0.01 - 0.1\%$
$L_{avg} \sim 0.7 - 6 \cdot 10^{33}$

Exquisite Energy Resolution Allows Direct Measurement of Higgs Width

Site Radiation mitigation with depth and lattice design: ≤ 10 TeV

Muon Collider Baseline Parameters

Parameter	***Units***	**Higgs Factory** Startup Operation	**Higgs Factory** Production Operation	**Multi-TeV Baselines**	**Multi-TeV Baselines**
CoM Energy	TeV	0.126	0.126	1.5	3.0
Avg. Luminosity	$10^{34}cm^{-2}s^{-1}$	0.0017	0.008	1.25	4.4
eam Energy Spread	%	0.003	0.004	0.1	0.1
Higgs/10^7sec		3,500	13,500	37,500	200,000
Circumference	km	0.3	0.3	2.5	4.5
No. of IPs		1	1	2	2
Repetition Rate	Hz	30	15	15	12
β^*	cm	3.3	1.7	1 (0.5-2)	0.5 (0.3-3)
No. muons/bunch	10^{12}	2	4	2	2
No. bunches/beam		1	1	1	1
Norm. Trans. Emittance, ε_{TN}	π mm-rad	0.4	0.2	0.025	0.025
Norm. Long. Emittance, ε_{LN}	π mm-rad	1	1.5	70	70
Bunch Length, σ_s	cm	5.6	6.3	1	0.5
Beam Size @ IP	μm	150	75	6	3
Beam-beam Parameter / IP		0.005	0.02	0.09	0.09
Proton Driver Power	MW	4#	4	4	4

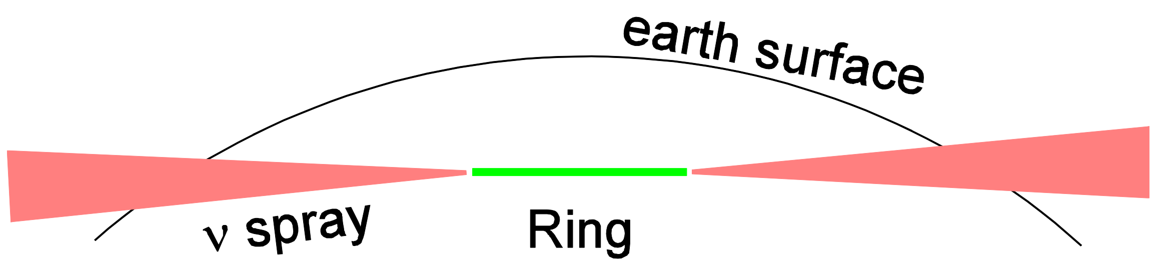
Could begin operation with Project X Stage 2 beam

Success of advanced cooling concepts ⇨ several ⇙ 10^{32}

M.Palmer, Jul.30

Technical Challenges of Muon Collider

- Proton driver of several MW
- Target at several MW
- Ionization cooling
  - ~10^7 in 6D emittance
  - High field HTS solenoid (>30T)
  - High gradient acceleration in magnetic field (Teslas)
- collider ring issues
  - High field dipole (10-20T)
  - muon decay (background, magnet shielding)
- Will require tens of years of R&D
- Energy limit comes from radiation (~10TeV?)



A New Concept of Muon Collider (1)

- Muon beam from
  proton + target → π → $\mu + \nu$
  has a big emittance. Must be cooled for a collider
- But muon cooling is not an easy task
- Instead, create $\mu^+\mu^-$ at the pair creation threshold from >44GeV e^+ colliding with e^- at rest
  - e+e- → $\mu^+\mu^-$
  - $\mu^+\mu^-$ is nearly at rest in the center-of-mass system
  - expected to be of very low emittance
- Quickly accelerate to high energies by FFAG/RLA

Exercise Solution

- Compute the minimum positron energy for creating a $\mu^+\mu^-$ pair by a collision with an electron at rest.

$$e^+ + e^- \to \mu^+ + \mu^-$$

$$p_1 + p_2 \;=\; q_1 + q_2$$

$$(p_1 + p_2)^2 = (q_1 + q_2)^2$$

$$\text{l.h.s} = 2m_e^2 + 2p_1 \cdot p_2 = 2m_e^2 + 2E_1 \cdot m_e$$

$$\text{r.h.s} = (2m_\mu)^2 \qquad \text{(just at threshold)}$$

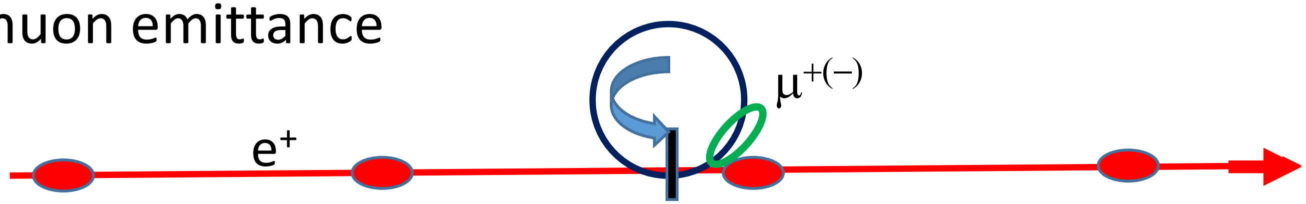
$$E_1 = \frac{2m_\mu^2 - m_e^2}{m_e}$$

$$m_e = 0.511\text{MeV}, \qquad m_\mu = 105.66\text{MeV}$$

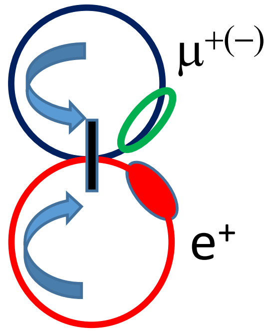
$$E_1 = 43.7\text{GeV}$$

A New Concept of Muon Collider (2)

- Problem is the crosssection of $e^+e^- \rightarrow \mu^+\mu^-$ is much smaller than that of p+target$\rightarrow\pi$
  - Need to accumulate $\mu^+(\mu^-)$ in small number of bunches
- Muon creation on the same bunch repeatedly
  - Target heating
  - Increase of muon emittance



- Too many positrons are needed (more than those for e+e- linear collider)
  - This may be solved by using a positron storage ring (45GeV)
  - But positron life time?
- Problem of collider issues are still there



Far Future of Accelerators for High Energy Physics

- The cost is becoming higher and higher
- Cost of LHC is about 6B$, but nearly 10B$ if it was built from scratch (tunnel, injectors, etc)
- Cost of ILC (250GeV) is around 6B$
  - 500GeV machine around 9B$
  - CEPC is similar to ILC 250GeV
    - This is Chinese price.
    - FCCee is much more expensive = 10.5 BCHF for 240GeV

$\mathrm{CHF(Swiss\ franc)} \approx \mathrm{US\$}$

  - Operation cost is also expensive .
    - ~2-300M$/year for ILC250
    - Presumably more for CEPC (more power but may be less price?).
- CEPCpp, FCCpp ???
- Plasma, not obviously cheaper
- Hope it is possible to reach up to ~100TeV for pp, 3-10TeV for e^+e^- and $\mu^+\mu^-$
- No idea beyond!!   End of High Energy Physics??