Review of Possible Projects Towards a Higgs Factory

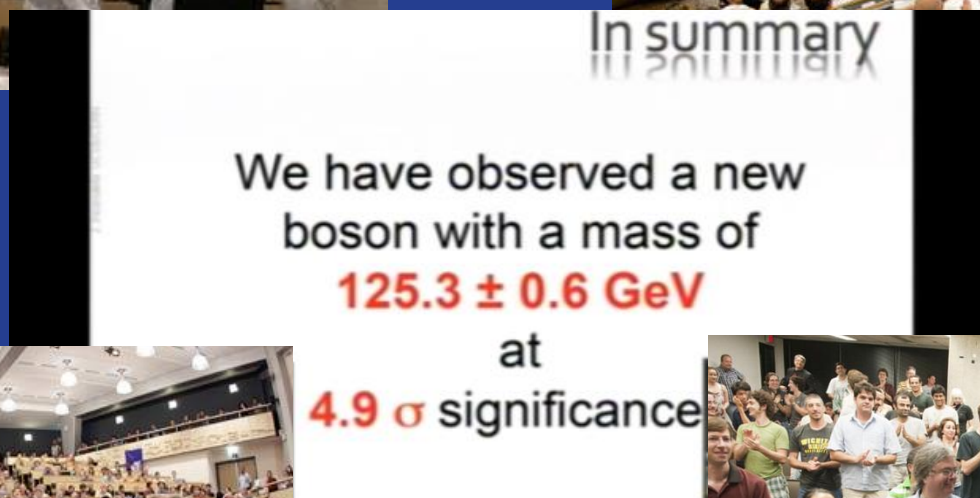
Stuart Henderson
September 30, 2013

Thanks to Mark Palmer, Frank Zimmermann, Patty McBride, Alain Blondel, Tanaji Sen, Katsunobu Oide

U.S. DEPARTMENT OF ENERGY

Fermilab

July 4, 2012 at CERN



Higgs Discovery!

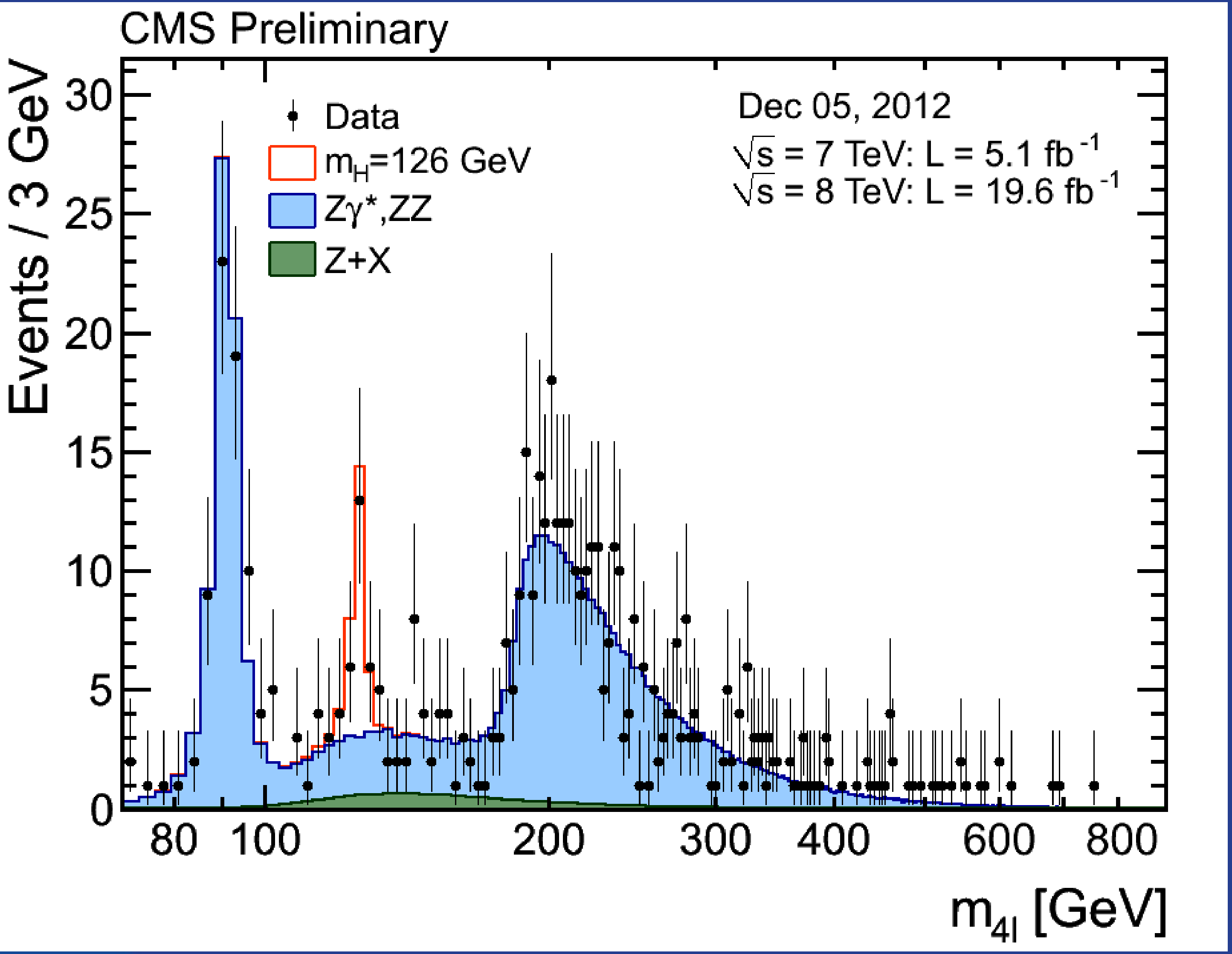
The announcement caused a global sensation

Press coverage after July 4th seminars at CERN

Fermilab

Higgs Discovery!

Higgs Discovery!




Hawking
Out $100 Over
Higgs Discovery
Jul 5, 2012 1:00 AM CDT


THE HIGGS BOSON
PROOF
THAT SMASHING STUFF WORKS


WOOHOO!
PEOPLE ARE STILL SCIENCING!


ONE DOES NOT SIMPLY FIND THE HIGGS BOSON
ONE SEES SOMETHING THAT MIGHT HAVE BEEN THE HIGGS BOSON AND THEN ONE COUNTS THE NUMBER OF TIMES ONE HAS SEEN SOMETHING THAT MIGHT HAVE BEEN THE HIGGS BOSON AND ONE COMPARES THAT NUMBER TO HOW MANY TIMES ONE WOULD HAVE SEEN SOMETHING THAT MIGHT HAVE BEEN THE HIGGS BOSON IF IN FACT THERE WAS NO HIGGS BOSON, AND IF THE DIFFERENCE IS LARGE ENOUGH THEN ONE HAS (PROBABLY) FOUND IT.
9GAG.COM/GAG/4792101


REACTIONS TO THE LATEST HIGGS BOSON ANNOUNCEMENT...
MAYBE WE WILL BEGIN TO UNDERSTAND HOW MATTER HOLDS TOGETHER!
MAYBE WE CAN DEVELOP A NEW GENERATION OF WEAPONS!
GOSH, I WONDER WHAT KIM KARDASHIAN IS DOING RIGHT NOW.
SCIENTISTS
MILITARY
THE PUBLIC


ONE DOES NOT SIMPLY FIND THE HIGGS
HIGGS BOSON
H
The HIGGS BOSON is the theoretical particle of the Higgs mechanism, which physicists believe will reveal how all matter in the universe gets its mass. Many scientists hope that the Large Hadron Collider in Geneva, Switzerland, which collides particles at 99.99% the speed of light, will detect the elusive Higgs Boson
Higgs boson
$10.49
PLUS SHIPPING
LIGHT
HEAVY
Wool felt, fleece with gravel fill for maximum mass.
GLUON PHOTON NEUTRINO TACHYON ELECTRON UP QUARK DOWN QUARK TAU NEUTRINO MUON
NEUTRON DOWN QUARK TAU GLUON HIGGS BOSON NEUTRINO TACHYON ELECTRON UP QUARK DOWN
NEUTRINO MUON UP QUARK PROTON NEUTRON DOWN QUARK TAU GLUON PHOTON NEUTRINO
The PARTICLE ZOO
GOSH, I WONDER WHAT KIM KARDASHIAN IS DOING RIGHT NOW.
PUBLIC
PEOPLE ARE STILL SCIENCING!

Why a Higgs Factory? (from Snowmass)

The Higgs Boson message

1. Direct measurement of the Higgs boson is the key to understanding Electroweak Symmetry Breaking.

   The light Higgs boson must be explained.

   An international research program focused on Higgs couplings to fermions and VBs to a precision of a few % or less is required in order to address its physics.

2. Full exploitation of the LHC is the path to a few % precision in couplings and 50 MeV mass determination.

3. Full exploitation of a precision electron collider is the path to a model-independent measurement of the width and sub-percent measurement of couplings.

Origin of EWSB | Origin of matter | Naturalness | Unification | New forces

Dark matter | Elementary?

Brock/Peskin Snowmass 2013

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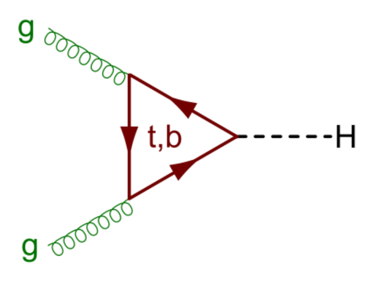
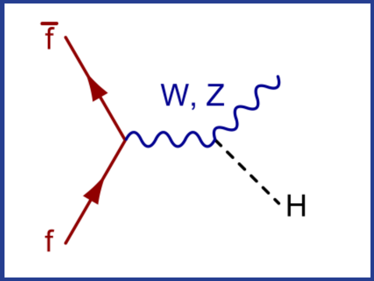
Higgs Production

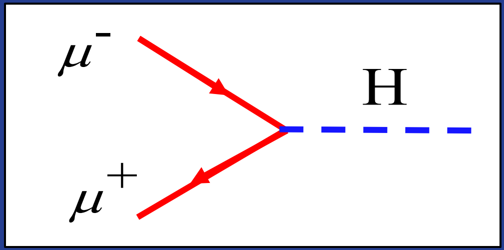


Gluon-gluon fusion: Proton-proton collisions (dominant at LHC)



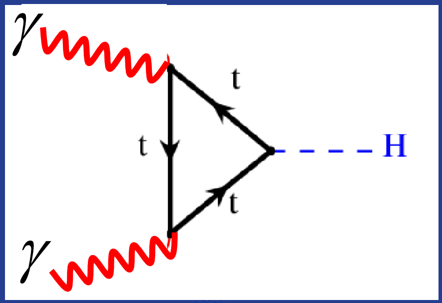
Higgs-strahlung: produced in association with Z, above ZH threshold:

- e+e- collisions near E_{cm} = 240 GeV, σ ~ 200 fb
- $\mathcal{L} = 10^{34}$ gives $100fb^{-1}$/yr = 20,000 *H*/year/IP



Direct s-channel production: muon colliders

- $\mu^+\mu^- \rightarrow H$; σ ~40pb
- Accounting for ΔE, ISR, need $\mathcal{L} = 1.2x10^{32}$ for 20,000 *H*/year

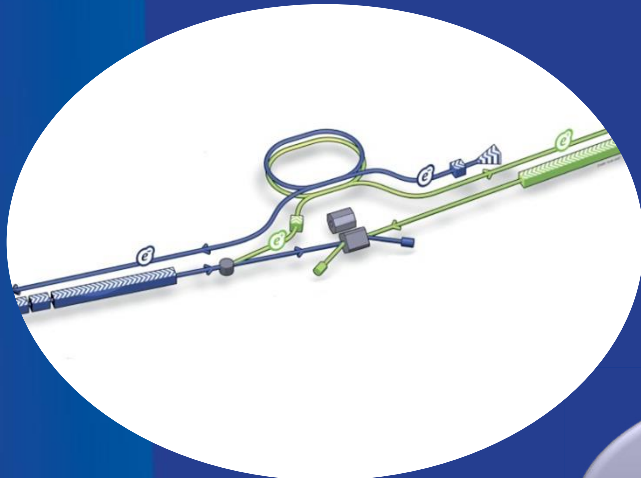


Photon-photon collisions

- $\gamma\gamma \rightarrow H$; σ ~200fb

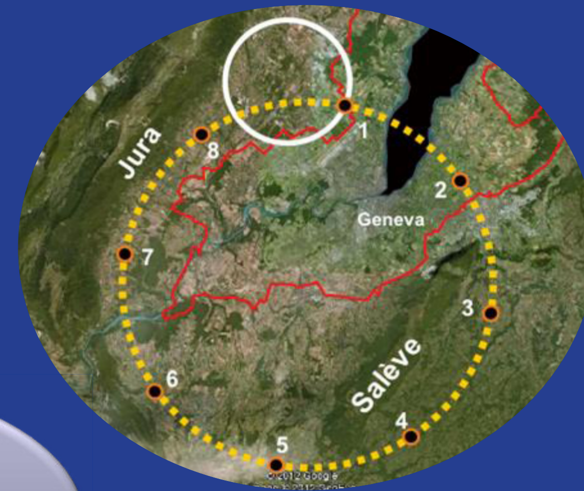
Linear Colliders

ILC, CLIC

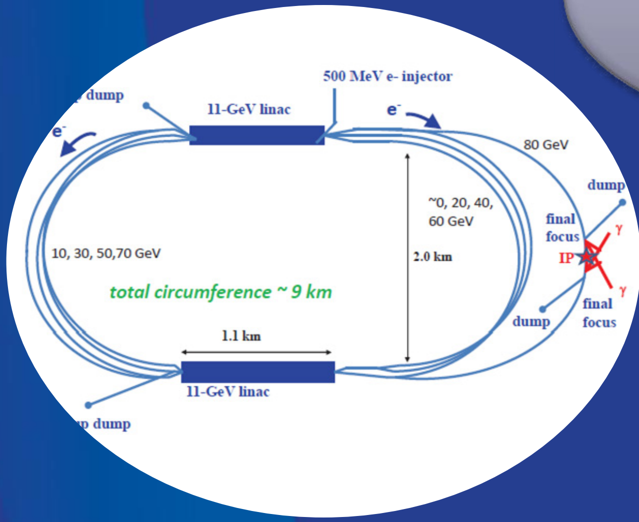


Circular e^+e^- Colliders

TLEP, SuperTristan, IHEP, …



Higgs Factories

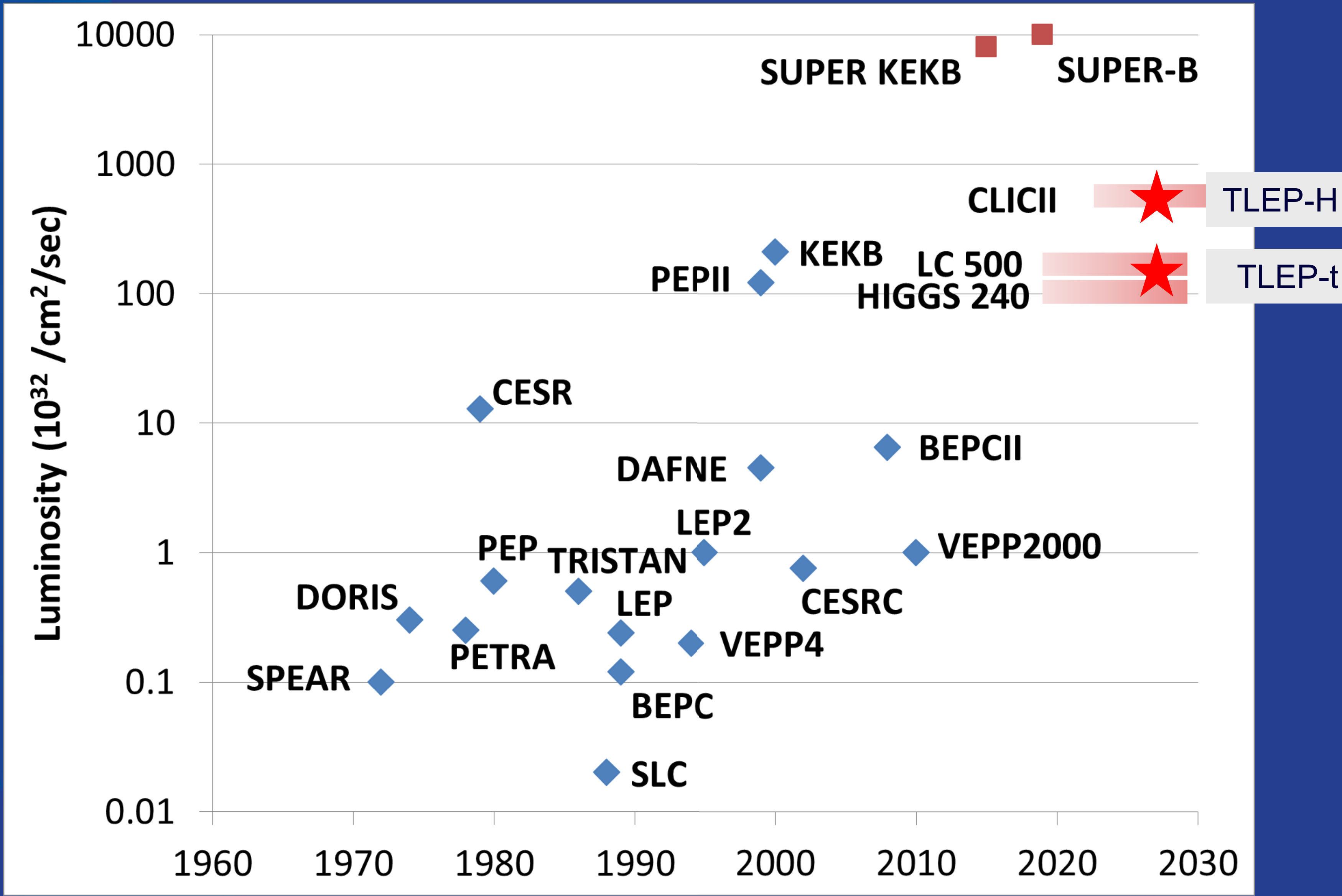


γ-γ Colliders

SAPPHIRE, CLICHÉ, HFiTT

Muon Colliders

Livingston Chart for e^+e^-: Luminosity



Linear Colliders

$$\mathcal{L} = \frac{N^2 f_c}{4\pi\sigma_x\sigma_y}$$

Number of particles

Collision frequency

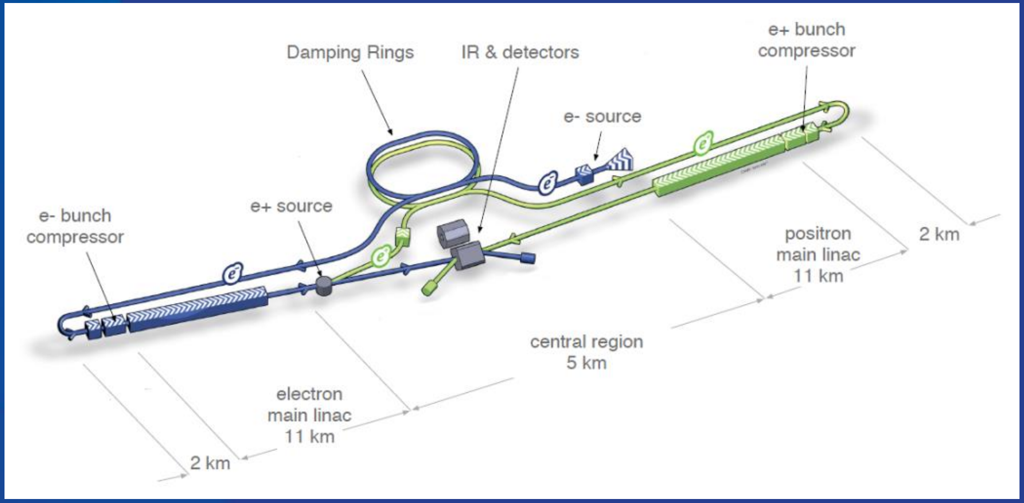
Beam sizes at collision point

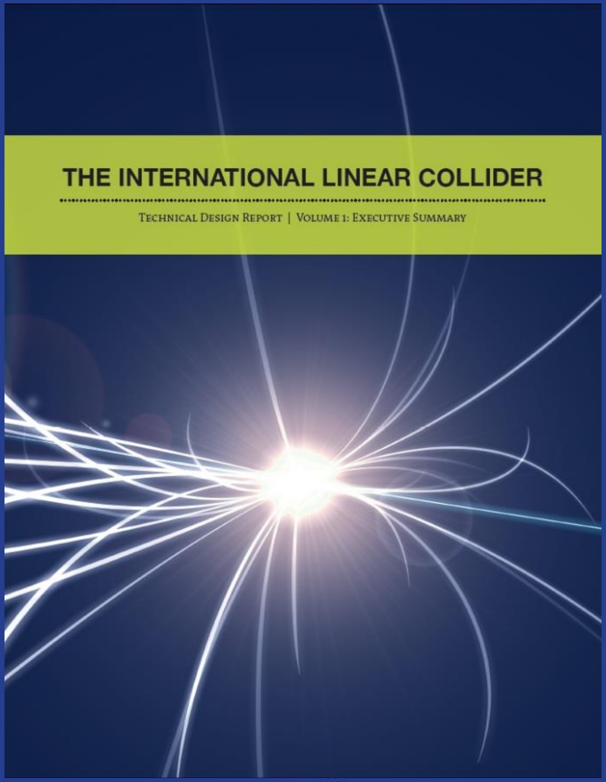
$$\mathcal{L} = \frac{P_b}{E_b}\left(\frac{N}{4\pi\sigma_x\sigma_y}\right)H_D$$

- Strong E-M fields at the collision point have important consequences:
  - Luminosity enhancement due to reduction in beam-size, quantified by H_D (pinch, disruption)
  - Beamstrahlung emission: background at the IP and energy spread at collision

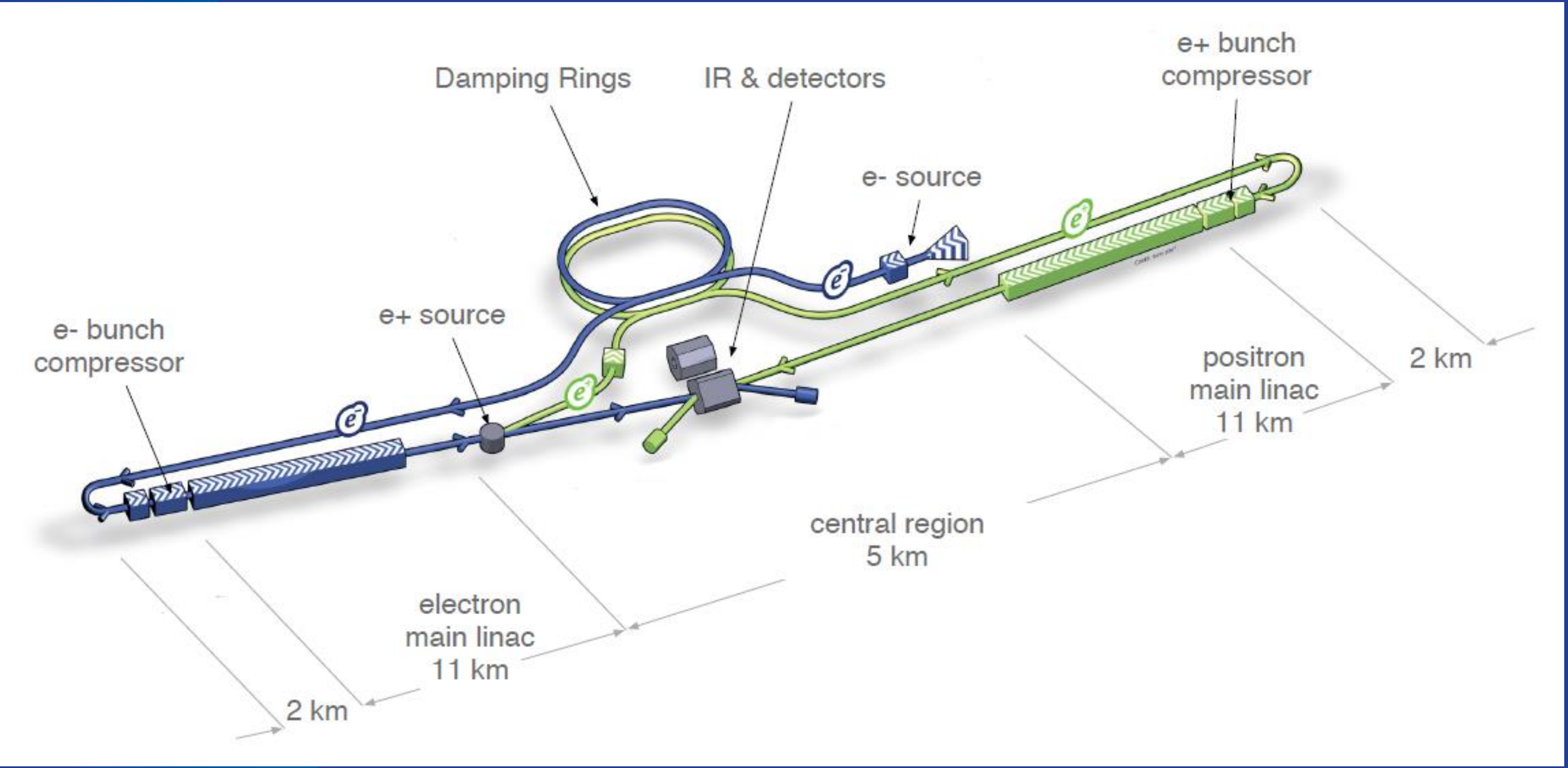
International Linear Collider

- 200-500 GeV (extendable to 1 TeV) CoM e+e- collider, based on 1.3 GHz Superconducting RF technology
- Builds upon two decades of R&D; TESLA collaboration, JLC/GLC, NLC concepts, unified within the Global Design Effort (since 2005).
- Over 300 national labs, universities and institutes contributed to the completion of the Technical Design Report documenting technical basis and value





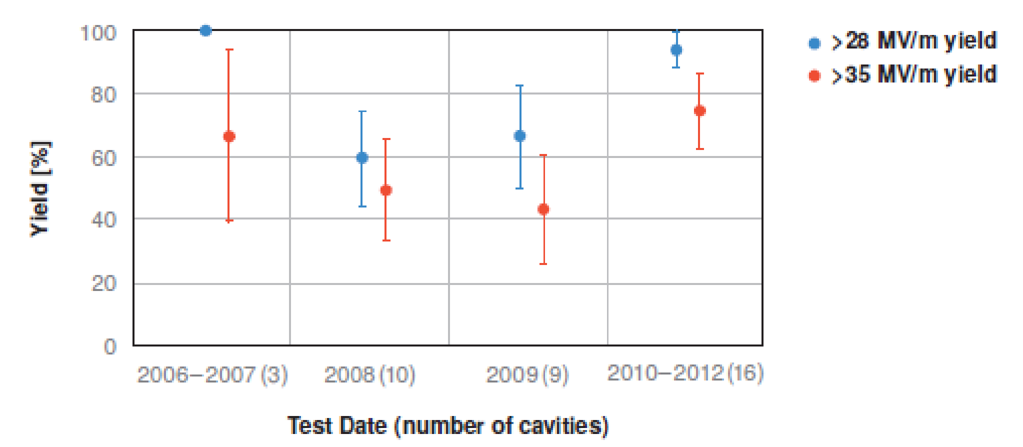
International Linear Collider



http://www.linearcollider.org/ILC/Publications/Technical-Design-Report

ILC: Challenges and R&D

- Most significant R&D issues addressed during ILC Technical Design Phase
- SRF cavity R&D for gradient/yield/industrialization
- Cryomodule prototype construction (global/regional)
- Beam tests at DESY/FLASH for ILC-like beams
- Damping ring studies for e-cloud mitigation (CESRTA)
- Generation of small emittance beams, preservation and focusing to nm-beamsize (KEK-ATF/ATF-2).



(a) PXFEL1 at DESY (b) CM2 at FNAL (c) S1-Global at KEK

- Some technical challenges remain (completion of ATF-2 program) but no showstoppers

ILC Key Parameters

	500 GeV	250 GeV
Luminosity	1.8×10^{34}	0.75×10^{34}
Total Beam Power [MW]	10.5	5.9
Rep-rate [Hz]	5	5
Horiz beam size [nm]	474	729
Vert beam size [nm]	5.9	7.7
Lumi enhancement factor	2.0	1.8
Estimated AC Power	163	122

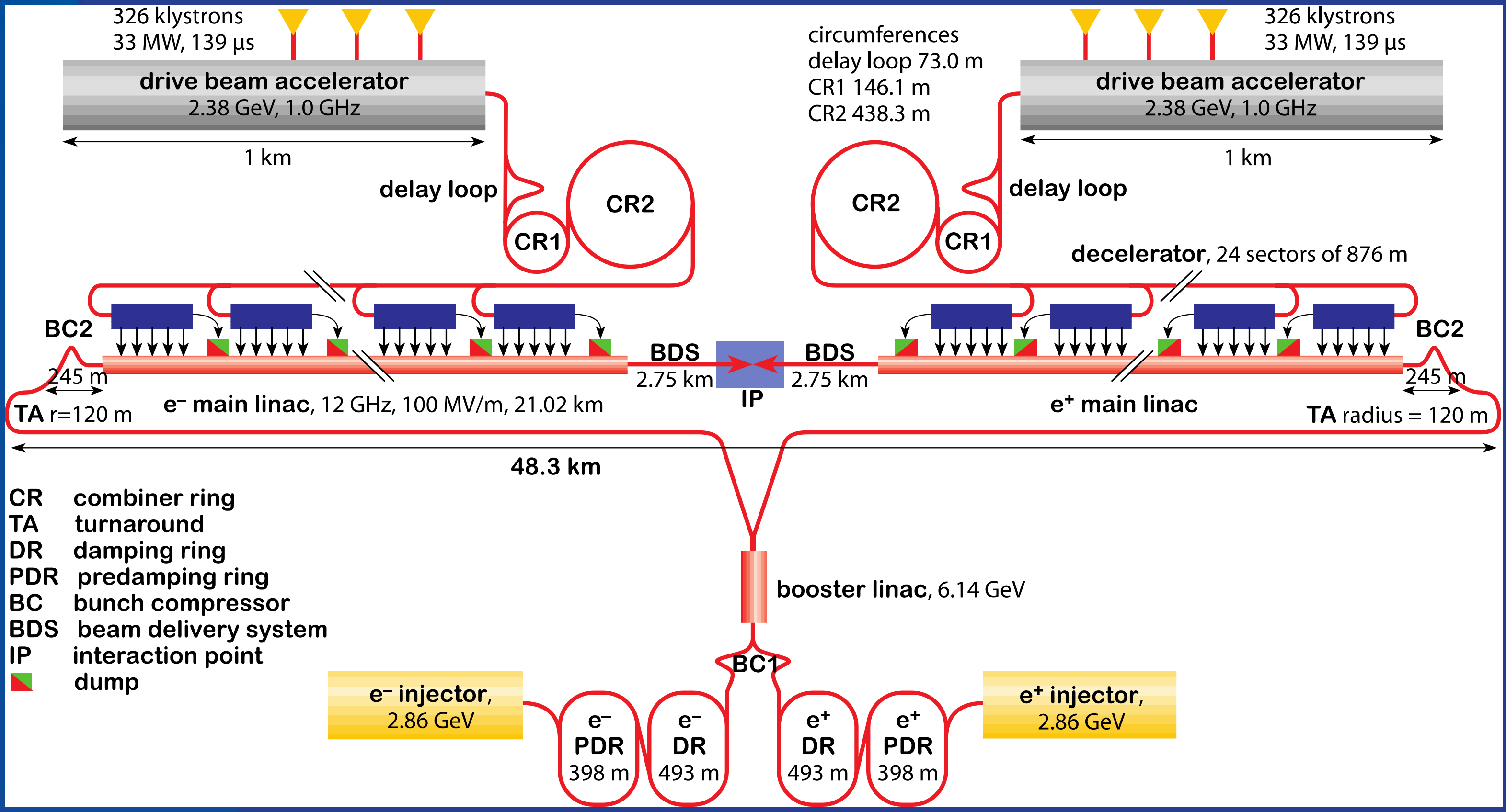
ILC Status – Recent Timeline

- **Political**: Japan has expressed strong support for hosting the ILC
  - ILC features in new gov’ts policy
  - PM Shinzo Abe and MEXT minister Shimomura have expressed strong support
  - Japan/US engagement at DOE level
  - LC team met with PM Abe 3/27/13

- **Technical**
  - Cost Review of the ILC TDR value estimate completed Feb 2013
  - Technical Design Report completed June 12, 2013
  - Site selection completed August 23, 2013: Kitakami site

Linear Colliders: CLIC

- Two-beam technology
  - Normal conducting RF,12 GHz, 100 MV/m
- Maximum energy 3 TeV CoM – Phase I at 0.5 TeV



Circular Colliders: Luminosity

$$\mathcal{L} = \frac{N^2 f_c}{4\pi\sigma_x\sigma_y}$$

Beam Current

Ratio of V/H beamsizes

Beam-beam tuneshift parameter

$$\mathcal{L} \approx \frac{EI(1+r)\xi_y}{\beta_y^*} F(\beta_y, \sigma_z)$$

Vertical beta-function at IP

Hourglass luminosity reduction factor if bunch length > beta*

Circular Colliders at Very High Energy

- For a high energy collider, main constraint is set by synchrotron radiation power, which must be replenished by the RF system, which in turn establishes power consumption
- Energy loss per turn:

$$\Delta E\,[\mathrm{GeV}] = 8.85x10^{-5}\,\frac{E^4[GeV^4]}{\rho[m]}$$

- Luminosity of a large collider of fixed energy increases linearly with circumference and SR power
- Example: 120 GeV e+e- collider in LEP tunnel has 7 GeV loss per turn (6% of beam energy!) compared to
  - 2.7 GeV for LEP2 and
  - 0.004 GeV for KEK-B

Circular Colliders: Why and How?

Why?

- Proven technology, pushed to extremes in B-factories
- Multiple interaction points
- A new large tunnel opens up prospects for a future, even larger, next hadron collider

How?

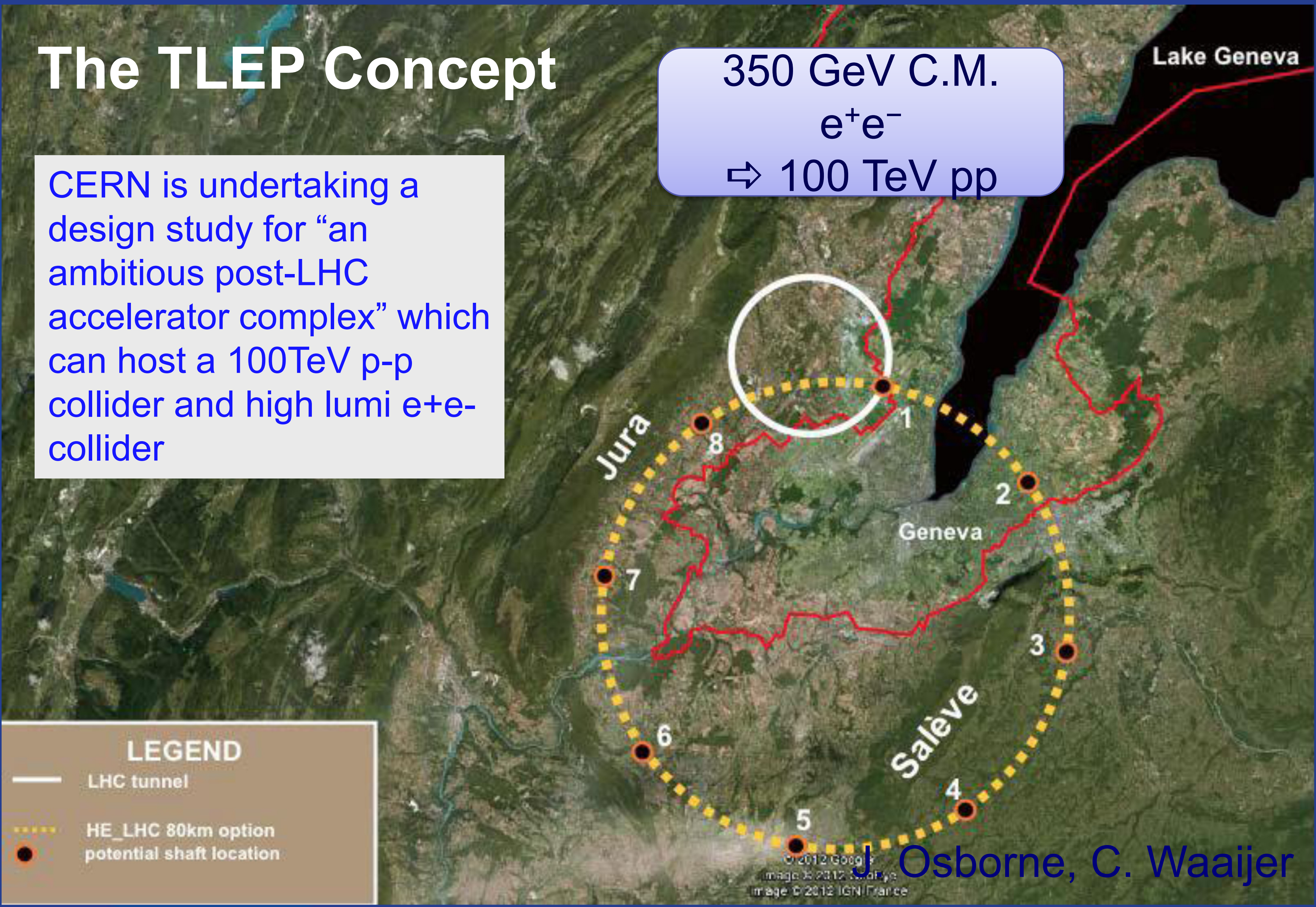
- Reuse a tunnel:
  - Use LEP tunnel to build LEP3, which coexists with LHC (27 km)
- Constrained to fit on a Site:
  - Fermilab Site Filler (16 km)
- “Green-field” Concepts
  - TLEP (80-100 km)
  - Super-Tristan (40, 60 km) at KEK
  - IHEP large collider
  - Very Large Lepton Collider (233 km in VLHC tunnel)
  - …and others….

Most active work for TLEP

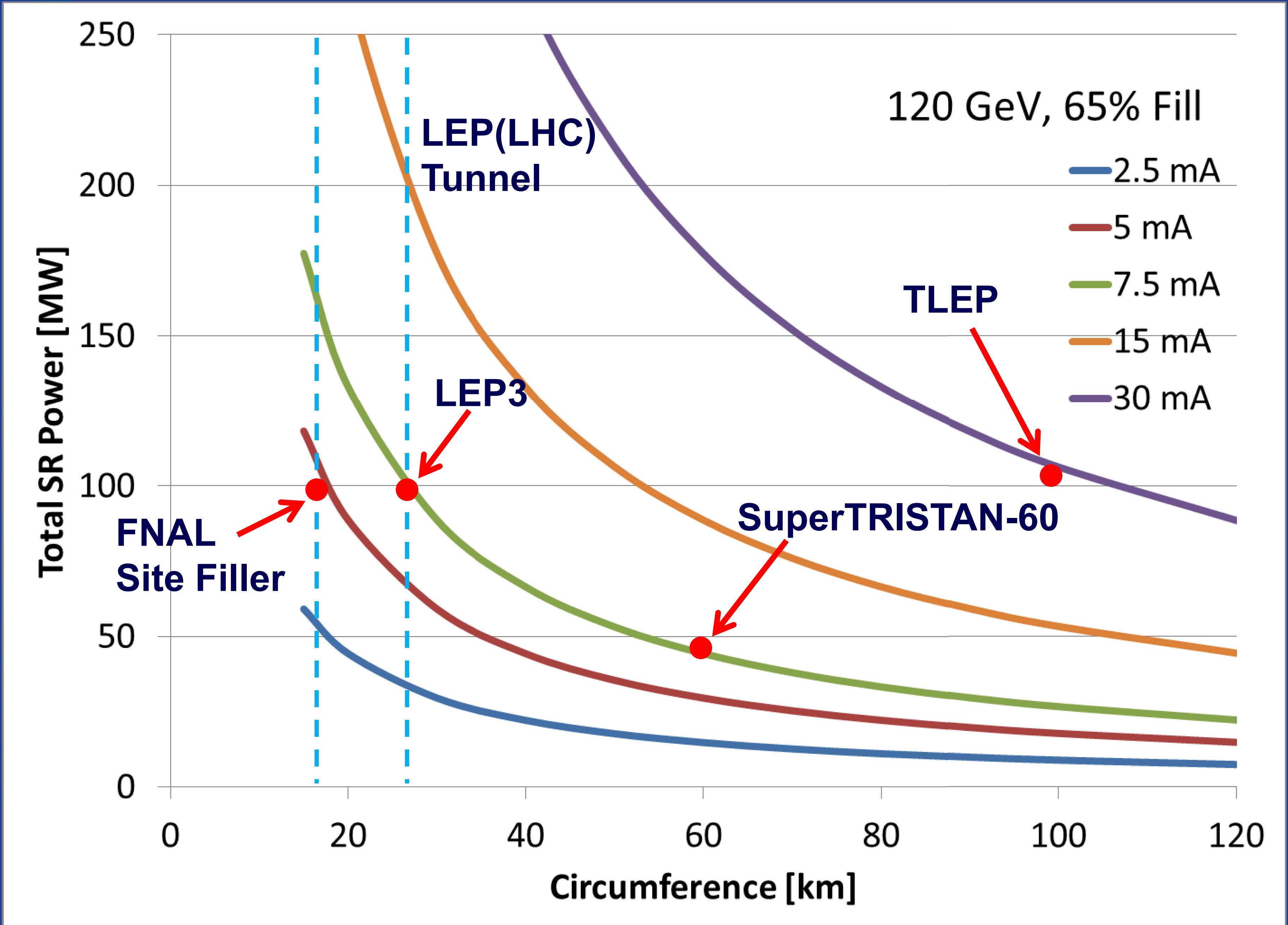
The TLEP Concept

350 GeV C.M.
e^+e^-
⇨ 100 TeV pp

CERN is undertaking a design study for “an ambitious post-LHC accelerator complex” which can host a 100TeV p-p collider and high lumi e+e- collider



J. Osborne, C. Waaijer


120 GeV, 65% Fill
2.5 mA
5 mA
7.5 mA
15 mA
30 mA
LEP(LHC)
Tunnel
LEP3
TLEP
FNAL
Site Filler
SuperTRISTAN-60
Total SR Power [MW]
Circumference [km]
0
50
100
150
200
250
0
20
40
60
80
100
120

Selected Circular Collider Parameters

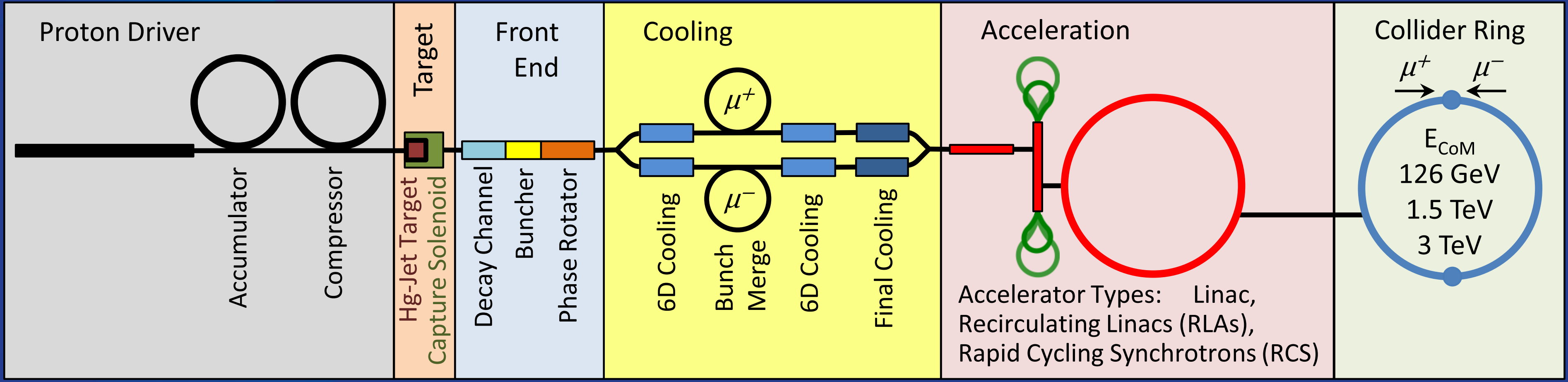
	KEK-B	LEP2	LEP3	FNAL Site Filler	TLEP
Circum [km]	3	27	27	16	100
Energy [GeV]	8/3.5	105	120	120	120
Current/beam [mA]	~1700	4	7.2	4.8	29.8
bunches	1600	4	4	2	167
Beta*x/y [mm]	1200/6	1500/65	200/1	200/2	500/1
Emit x/y [nm]	18/0.1	48/0.25	25/0.1	23/0.1	7.5/0.015
Bunch length [mm]	6	3	3	3	2.1
Beam-beam tuneshift	0.09	0.065	0.08	0.095	0.094
SR loss/turn [GeV/turn]	0.004/ 0.002	2.75	7.0	10.5	1.7
RF Voltage [GV]	0.010/.005	3.6	12	11.8	6.0
Total SR Power [MW]	5.6/3.4	22	100	100	100
Luminosity/IP [10^{34} /cm^2/sec]	2.1	0.013	1.0	0.52	5.0

Key Technical and Design Issues: Circular

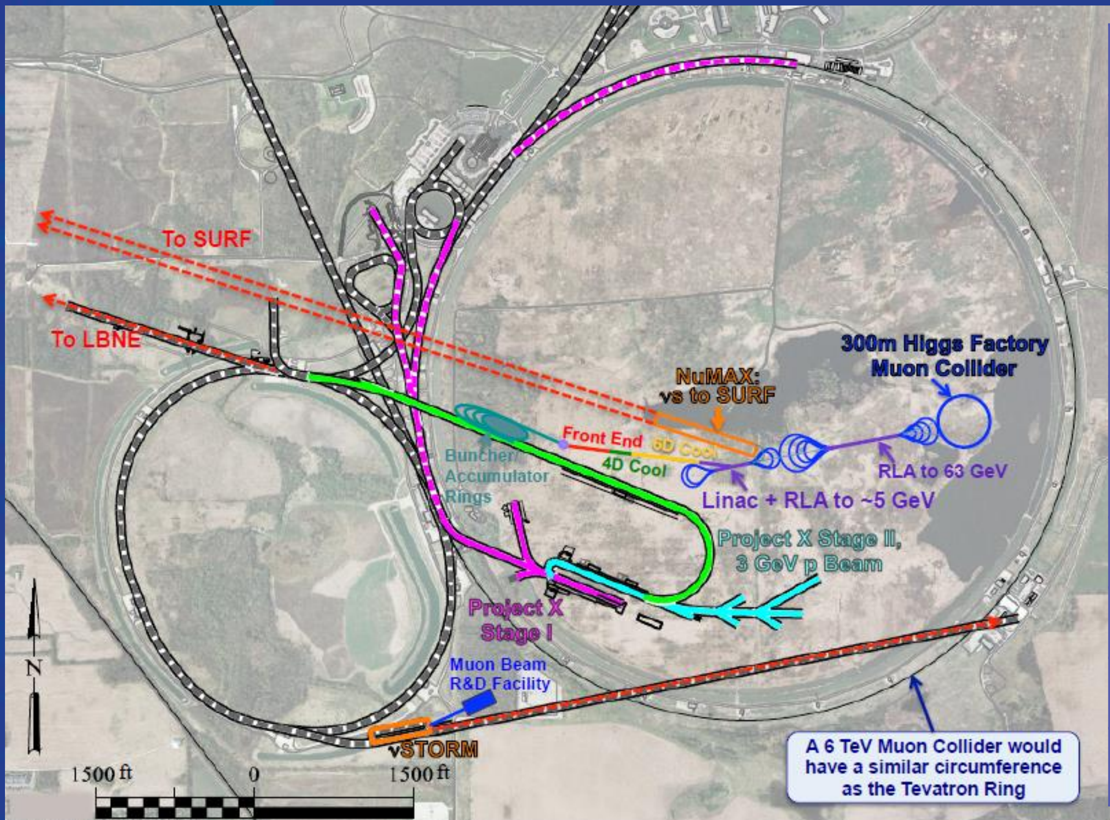
- Beamstrahlung
  - Short lifetime which requires large momentum acceptance (TLEP-H has 38 min lifetime for 2% acceptance)
  - Energy spread
  - Dynamic aperture
- Beam lifetime and Top-off Injection
  - At high luminosity, radiative Bhabha scattering is large, leading to short beam lifetime (24 mins for TLEP-H)
  - Topoff requires full-energy injector
- Achievable beam-beam tuneshift
  - Dependence of tuneshift limit on damping decrement observed at LEP (720 turns)/LEP2(60 turns): $\xi_y \approx \lambda^{0.4}$
- Vertical beta-star pushed to limits
  - Requires short bunches (2mm in TLEP-H) or crab-waist approach
- Very large radiated SR power, with high critical energy
  - Ex: LEP3 would have 3.7 kW/m, 1.5 MeV critical energy
  - Large, expensive CW SC RF system
- Lattice
  - Achievable emittance, IR Chromaticity, …

Muon Collider Concept

- Some advantages make muon colliders attractive for Higgs as well as TeV, multi-TeV colliders
  - Higgs: s-channel production, can achieve narrow energy spread, measure mass and resonance width with precision
  - No SR: Muon collider is compact relative to e+e- colliders; can fit e.g. on the Fermilab site; cost-effective, reasonable power consumption
  - Other important factors:
    - Synergistic with developing a cutting-edge neutrino capability
    - Good match to existing and planned infrastructure for intensity frontier



Higgs Muon Collider Parameters



Parameter	Value
Proton Driver Beam Power	4 MW
Repetition Rate	15 Hz
Number of muon bunches	1
$\mu^{+/-}$/ bunch	4×10^{12}
Transverse emittance	0.0002m
Collision β^*	0.017
Beam Energy Spread	0.004%
Center of Mass Energy	126 GeV
Luminosity	0.8×10^{32}
Higgs/ 10^7 seconds	13,500

Exquisite Energy Resolution Allows Direct Measurement of Higgs Width

See MAP collaboration Snowmass Whitepaper: “Enabling Intensity and Energy Frontier Science with a Muon Accelerator Facility in the U.S.” (http://arxiv.org/ftp/arxiv/papers/1308/1308.0494.pdf)

Key Technical Challenges

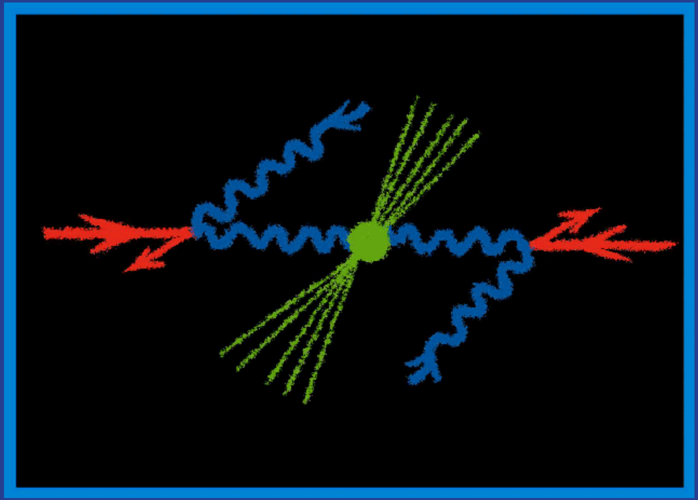
Many technical challenges to be overcome

- Muon production, manipulation, acceleration to high energy and into collision within muon lifetime
- Needs high-intensity proton driver (MW-class +)
- MW target system, pion to muon collection
- Needs muon cooling by large factors:
  - Cooling channel concepts
  - RF cavities in presence of magnetic fields, …
- Acceleration, collider ring, MDI and Detector, …

US Muon Accelerator Program (MAP) is carrying out a dedicated feasibility assessment of MC technology by the end of the decade

Gamma-Gamma Colliders

- High-power lasers are Compton backscattered from electron beams arranged as an e-e- or e+e- collider
- Equivalent e-e luminosity 1-2x10^{34}
- $\gamma\gamma \rightarrow H$ cross-section ~200fb
- Advantages:
  - Lower electron energy is needed (~80 GeV/beam)
  - Positrons are not required
- Concept is applicable to ILC/CLIC as a companion capability

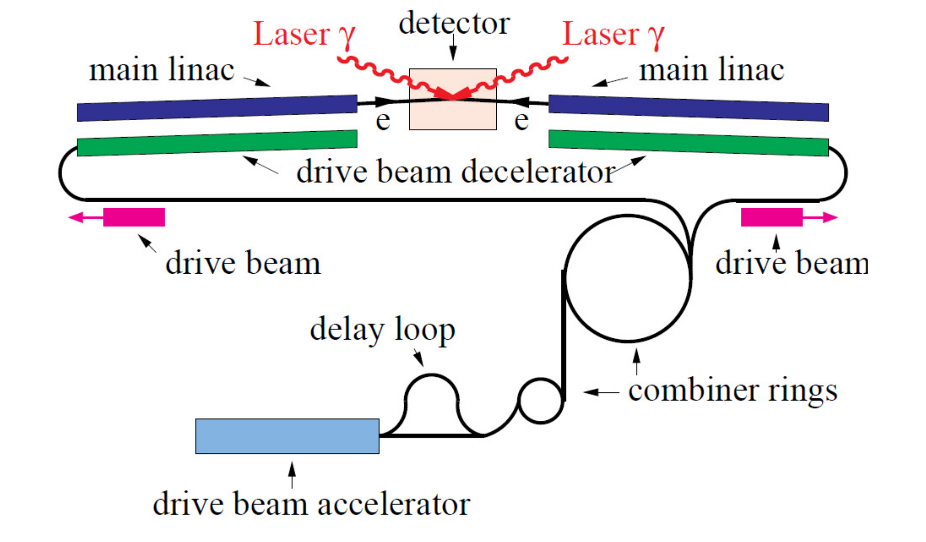


See, e.g., “SAPPHiRE, a small gamma-gamma Higgs factory,” S.A. Bogacz et. al., http://arxiv.org/abs/1208.2827

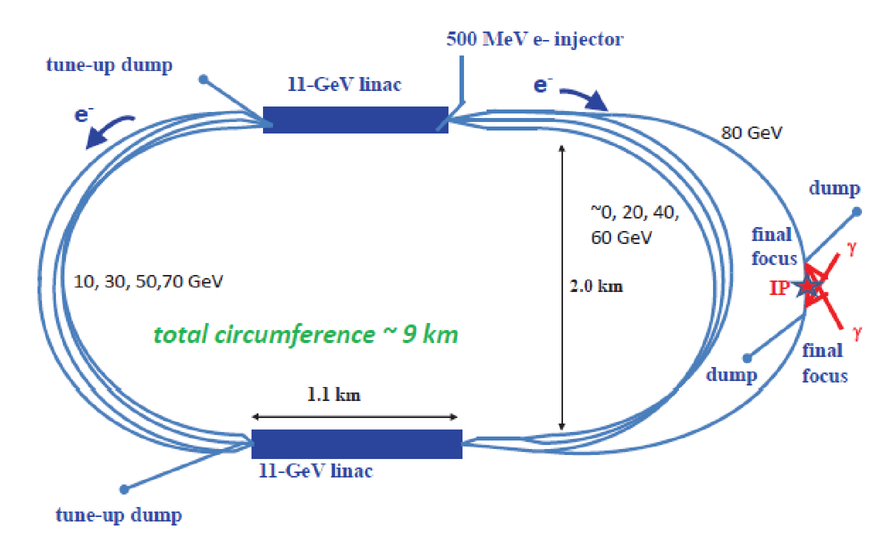
Gamma-Gamma Collider Concepts

- SAPPHiRE: ERL based gamma-gamma based on LHeC ERL concept
- HFiTT: Tevatron-sized factory
- Laser parameters are aggressive; requires optical cavity schemes

CLICHÉ: CLIC Higgs Experiment



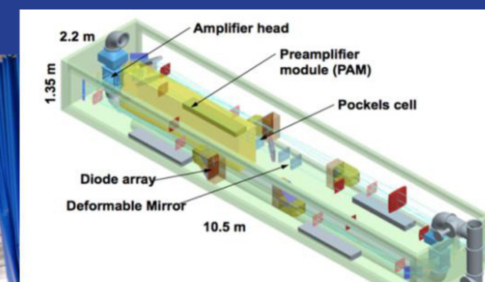
	SAPPHiRE
Beam Energy	80 GeV
Power Consumption	100 MW
Polarization	80%
Ave Beam Current	0.32 mA
E-e- geometric luminosity	2.2x10^34
Laser wavelength	351 nm
Repetition rate	200 kHz
Laser pulse energy	~5 J



Challenges

- One of the primary challenges is the laser system
  - Laser Inertial Fusion Energy (LIFE) system at 130 kW average power
  - Mourou et. al. propose developing networks of fiber lasers, combined coherently, to aim for >10J pulses at 10 kHz.

Figure 2: Principle of a coherent amplifier network (CAN) based on fiber laser technology. An initial pulse from a seed laser (1) is stretched (2), and split into many fibre channels (3). Each channel is amplified in several stages, with the final stages producing pulses of ~1 mJ at a high repetition rate (4). All the channels are combined coherently, compressed (5) and focused (6) to produce a pulse with an energy of >10 J at a repetition rate of 10 kHz (7). [3]

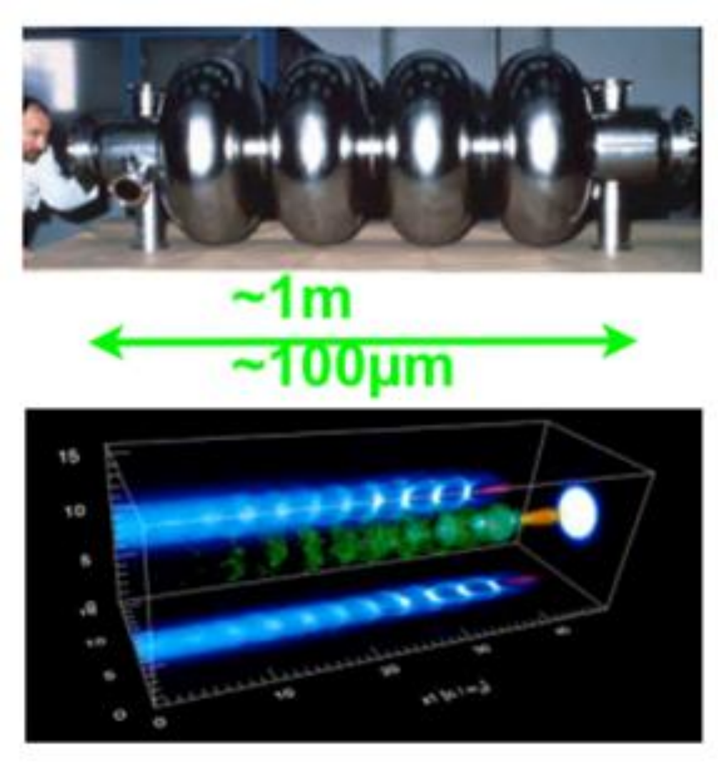


LIFE beam line :
- Pulses at 16 Hz
- 8.125 kJ / pulse
- 130 kW average power
- ns pulse width

Laser technology with comparable average power is under study now. Stay tuned!

Going to Higher Energies

- Linear collider and muon collider concepts are upgradeable in energy
  - ILC to 1 TeV
  - CLIC staging extends to 3 TeV (CDR completed)
  - Muon Collider could have a reach as high as 10 TeV
- Plasma wakefield acceleration (beam and laser-driven)
  - Potential for very high energies
  - First HEP application might be an ILC afterburner
  - Significant R&D remains in understanding the extrapolation parameters to the HEP regime (emittance preservation, energy spread, beam loading, repetition rate, positrons)



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Comparison

	Pros	Cons
Linear Collider	• Technically Mature; ready now • Upgradeable	• Large, expensive
Circular e+e-	• Extrapolation from established experience base • New tunnel provides path to next p-p collider	• Large power consumption • Requires large tunnel • B-factory like performance required
Muon Collider	• Small, less expensive • Good energy resolution • Upgradeable to high energy • Links with US HEP development path	• Requires substantial development • Challenging machine-detector interface
Gamma-gamma Collider	• Small, potentially less expensive	• Requires laser technology with aggressive parameters • Complicated machine-detector interface

Conclusions (including those from Snowmass)

- LHC will be fully exploited to learn as much about the Higgs as possible
- Higgs Factory concepts span a broad range of technical readiness

- The Japanese initiative to host a linear collider as a Higgs Factory is welcome
  - With the release of the TDR by the ILC GDE, the technical design is well developed and ready for a decision
  - The US accelerator community is capable of making significant contributions to a global ILC

Conclusions, cont'd

- A circular e+e- collider in a very large tunnel provides a promising path for a Higgs Factory, while enabling a ~100 TeV proton collider option.
  - This would be a challenging accelerator…it would be the largest collider ever built, and must operate like a B-factory at ~20x the energy; but the concept is very compelling
- Continued R&D toward a more compact lepton collider with multi-TeV upgradability is needed:
  - Muon collider, linear collider technologies including warm RF and wakefield approaches

This is an exciting time in particle physics. The Higgs Discovery is energizing the community in planning the next collider

To Learn More….

- ICFA Beam Dynamics Workshop Report on Higgs Factories (and ICFA Beam Dynamics Newsletter):
  - arXiv: 1302.3318 [physics.add-ph]

- ILC Technical Design Report:
  - http://www.linearcollider.org/ILC/Publications/Technical-Design-Report

- Snowmass Whitepapers and Presentations:
  - http://www.snowmass2013.org/tiki-index.php