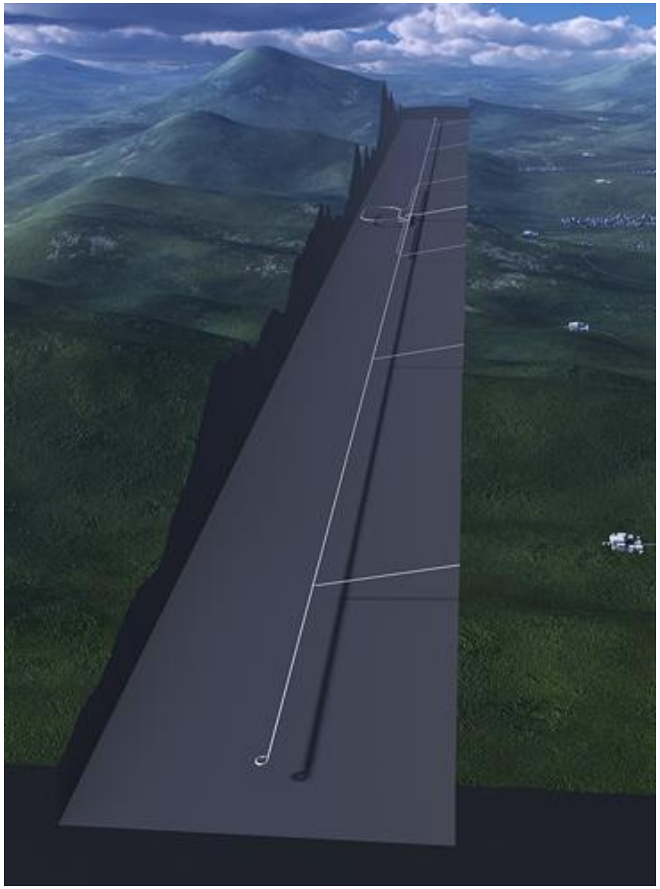
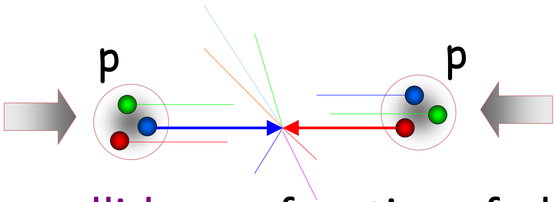
Future High Energy Linear Colliders

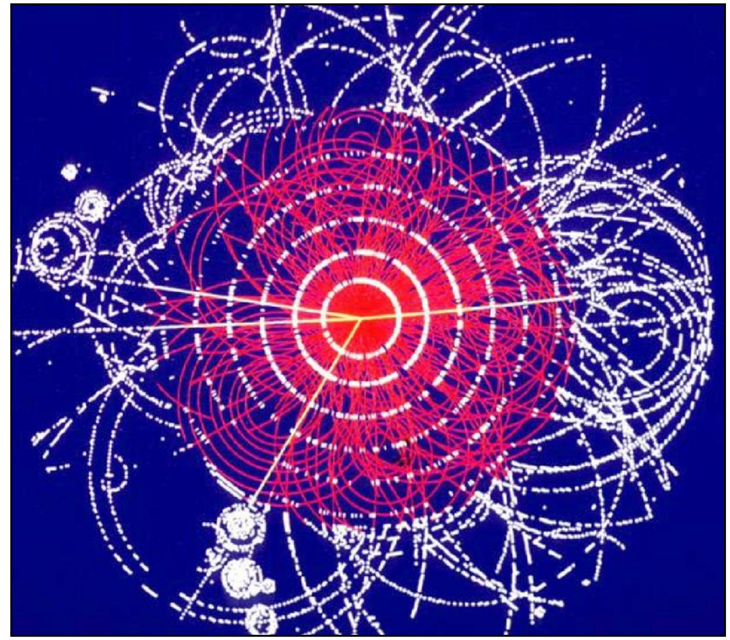
Louis Rinolfi

CERN

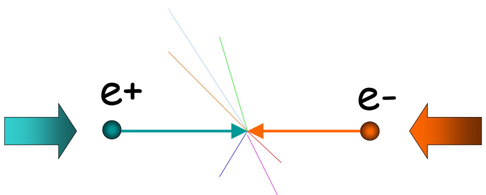


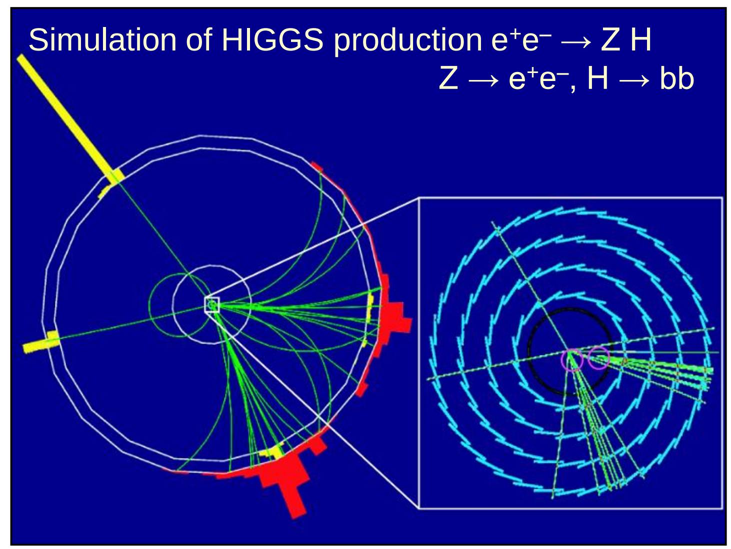
Hadrons versus leptons colliders





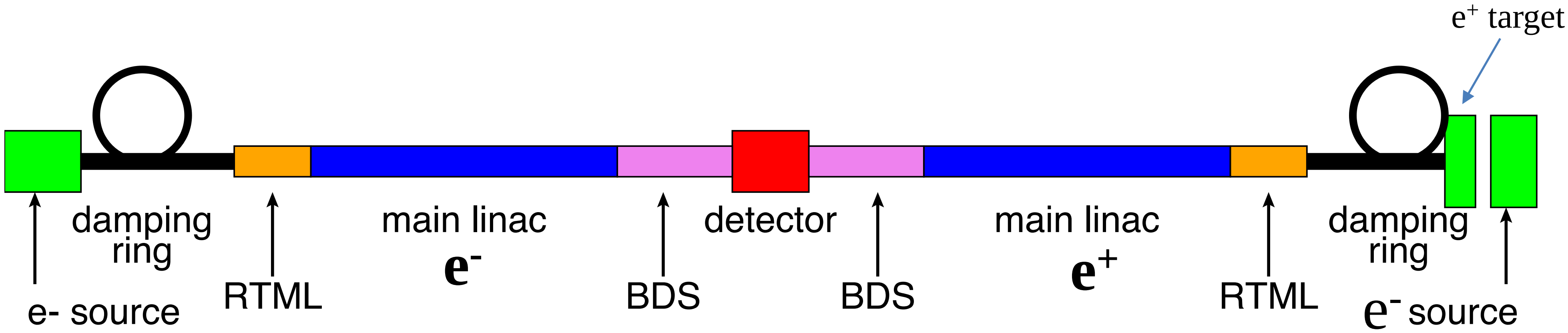
- hadron collider => frontier of physics
  - discovery machine
  - quarks collisions
  - not all nucleon energy available in collision
  - huge background





- lepton collider => precision physics
  - study machine
  - elementary particles collisions
  - well defined CM energy
  - polarization possible

Basic Linear Collider



Reach the highest collision energy

Reach the highest luminosity

With a reduced power consumption and a minimum cost

BDS = Beam Delivery System
RTML = Return To Main Linac

Luminosity

Number of events = L . σ_{event}

σ_{event} is the probability of producing a particular event
L is a measure of the total number of interactions

The unit of the cross-section (σ_{event}) is the barn (1 barn = 10^{-28} m^2)
=> 1fb = 10^{-43} m^2

If the cross-section to produce a given event is 1fb then we would need 1fb^{-1} of data to get 1 event!!

$$L = N_{events} / \sigma_{event}$$

Major parameters for linear colliders

Energy (center of mass) $$E_{cm} = 2\, F_{fill}\, L_{linac}\, G_{RF}$$

MeV — m — MV/m

Luminosity (basic) $$L = \frac{n_b\, N^+ N^-\, f_{rep}}{4\pi\, \sigma_x\, \sigma_y}$$

$cm^{-2}\, s^{-1}$ — Hz — cm

F_{fill} = Filling factor of the Linac; L_{linac} = Length of the linac; G_{RF} = accelerating gradient

n_b = number of bunches; N = number of particles per bunch; σ_x, σ_y = beam size parameters

Brief history of high energy linear colliders $e^+ e^-$

1985: **CLIC =** CERN Linear Collider **=>** Compact Linear Collider

1989: **SLC = Stanford Linear Collider**

Start operation with the beam

1995: **Six linear colliders studies at high energy, in parallel:**

=> TESLA (1.3 GHz, superconducting, SC)

=> SBLC (3 GHz, normal conducting, NC)

=> NLC (11.4 GHz, normal conducting, NC)

=> JLC (11.4 GHz, normal conducting, NC)

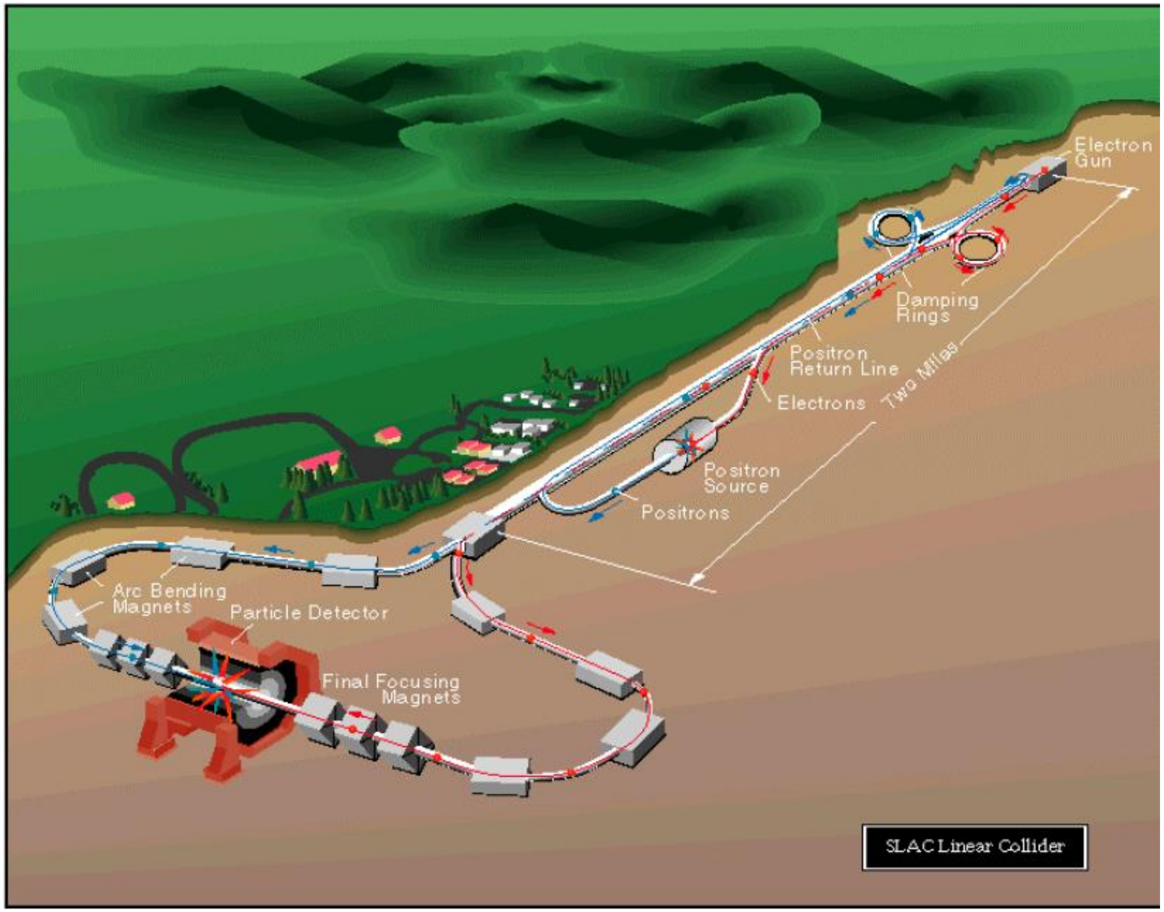
=> VLEPP (14 GHz, normal conducting, NC)

=> CLIC (30 GHz, normal conducting, NC)

2004: International Technology Recommendation Panel selects the Superconducting RF technology versus room temperature technology
=> ILC (International Linear Collider) based on TESLA technolgy

2018: **Two studies, on high energy linear colliders:**
ILC at 1.3 GHz (SC) for the multi(100's)-GeV and CLIC study at 12 GHz (NC) for the multi-TeV

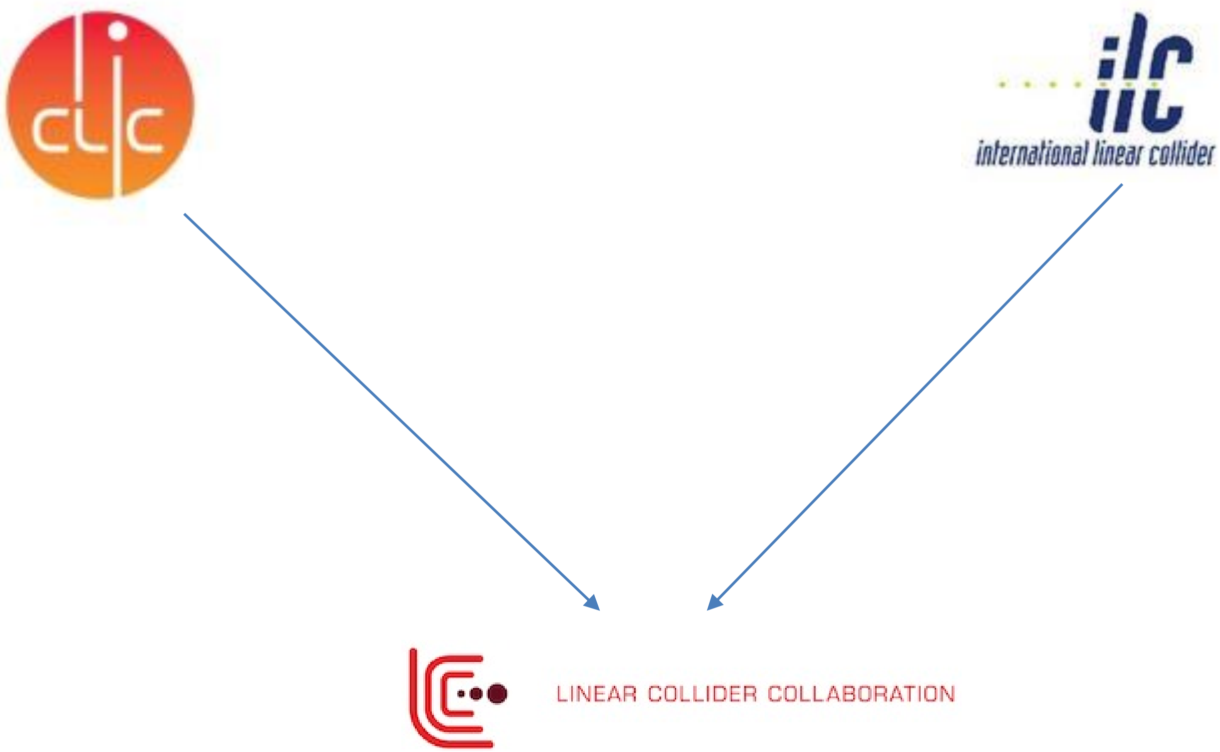
SLC (Stanford Linear Collider) – California - USA



2 experiments: MARK II, SLD
Energy: 92 GeV
Peak Luminosity: $2 \times 10^{30} cm^{-2} s^{-1}$

The only Linear Collider who was running with a beam (up to now)
e^- (45 GeV) and e^+ (45 GeV)

Operation: 1989-1998

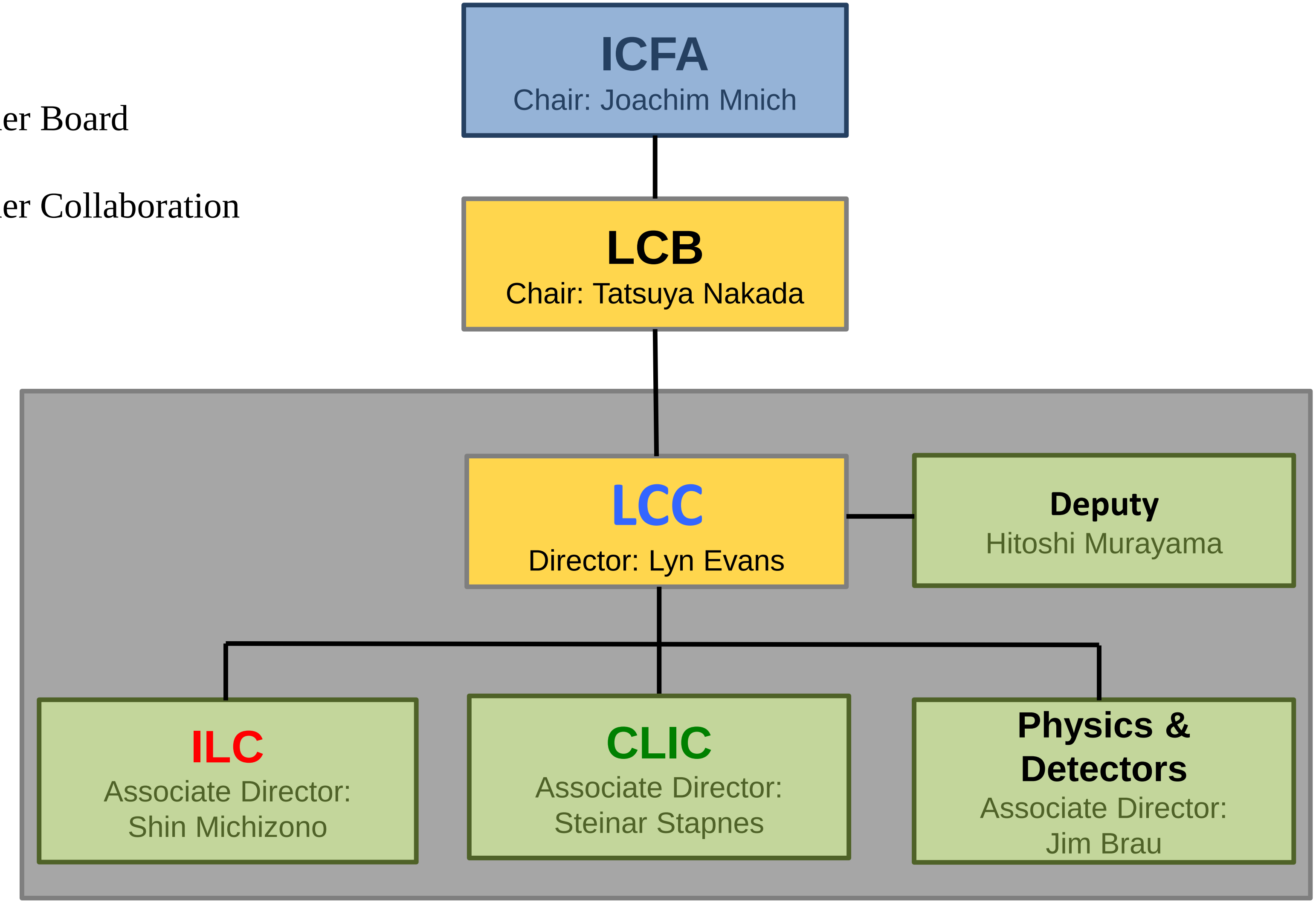

CLIC
ilc
international linear collider
LINEAR COLLIDER COLLABORATION

ICFA/LCB/LCC Organization in 2017

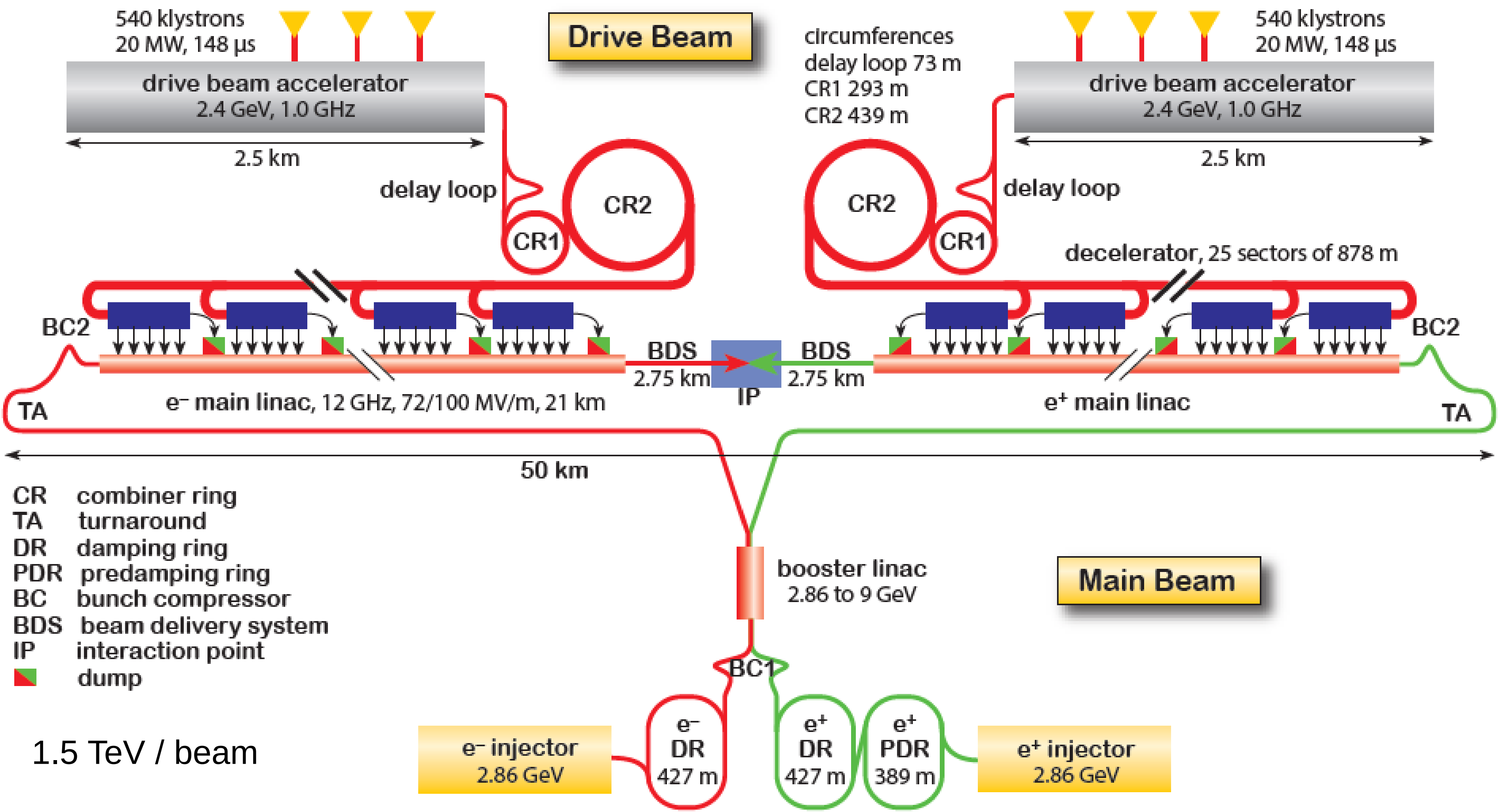
ICFA = International Committee for Future Accelerators

LCB = Linear Collider Board

LCC = Linear Collider Collaboration



CLIC (Compact Linear Collider) $e^+ e^-$



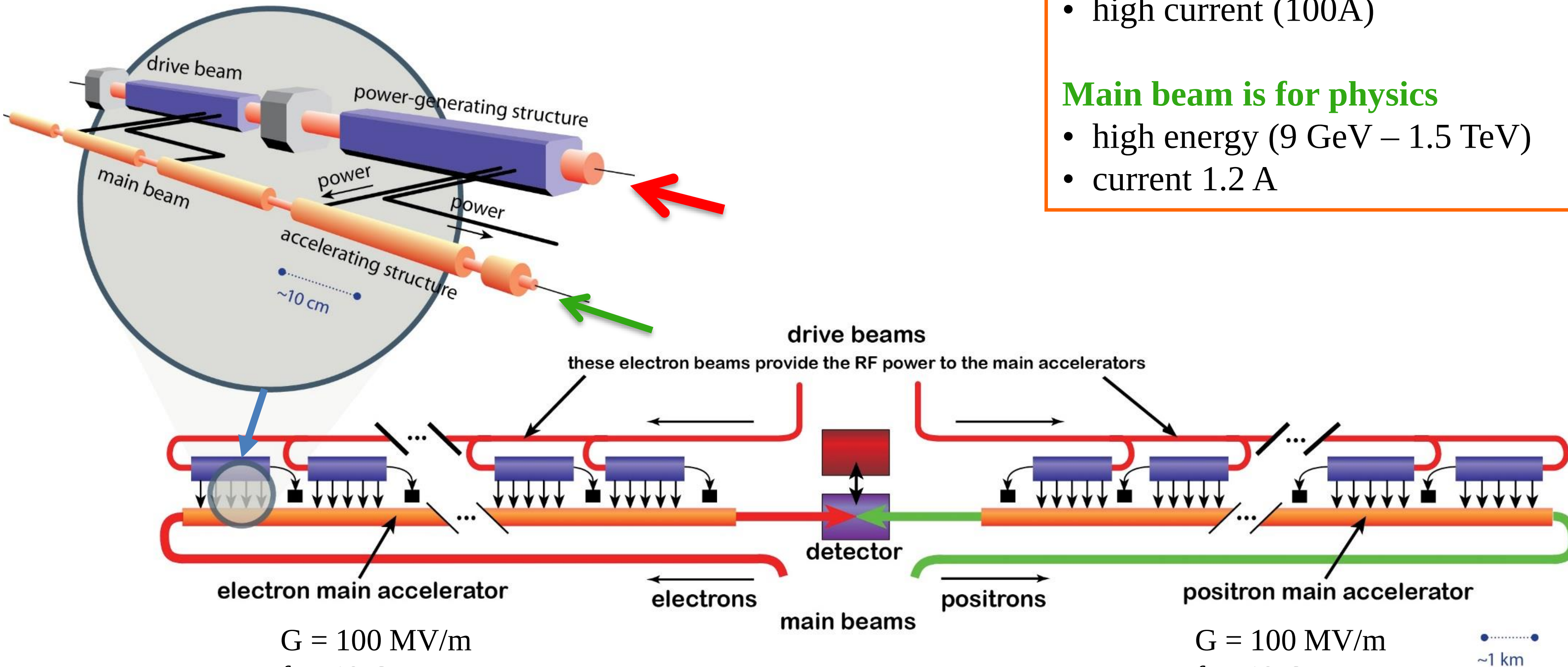
1.5 TeV / beam

Layout for 3 TeV center of mass (cm)

CLIC basic scheme

Drive Beam supplies RF power
- 12 GHz bunch structure
- low energy (2.4 GeV - 240 MeV)
- high current (100A)

Main beam is for physics
- high energy (9 GeV – 1.5 TeV)
- current 1.2 A



G = 100 MV/m
f = 12 GHz

G = 100 MV/m
f = 12 GHz

CLIC project

Phil Burrows / CERN workshop 2018

Optimize machine design w.r.t. cost and power for a staged approach to reach multi-TeV scales:

~ 380 GeV (optimised for Higgs + top physics)
~ 1500 GeV
~ 3000 GeV

Adapting appropriately to LHC + other physics findings

Possibility for first physics no later than 2035

Project Plan to include accelerator, detector, physics

CLIC parameters

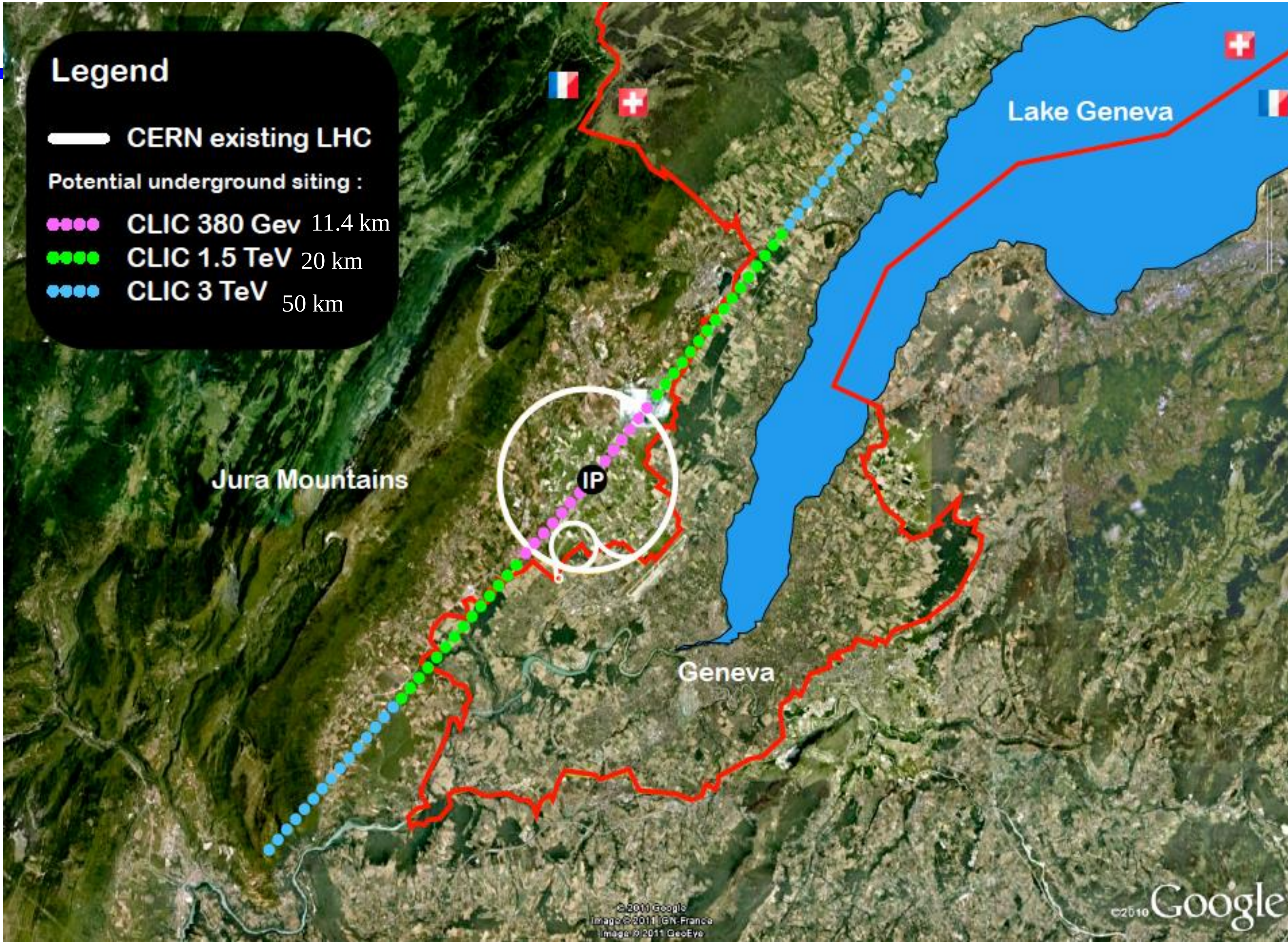
Parameter	380 GeV	1.5 TeV	3 TeV
Total luminosity L ($10^{34}cm^{-2}sec^{-1}$)	1.5	3.7	5.9
L above 99% of √s ($10^{34}cm^{-2}sec^{-1}$)	0.9	1.4	2.0
Accelerating gradient (MV/m)	72	72/100	72/100
Site length (km)	11.4	29.0	50.1
Number of bunches per train	352	312	312
Number of particles per bunch (10^9)	5.2	3.7	3.7
Normalized emittance (end of linac) $\varepsilon_x/\varepsilon_y$ (nm.rad)	920/20	660/20	660/20
Beam size at IP σ_x/σ_y (nm)	150/2.9	~60/1.5	~40/1
Beam size at IP σ_z (µm)	70	44	44
Estimated power consumption (MW)	252	364	589

For the 3 stages:

Repetition frequency
f = 50 Hz

RF pulse length
τ = 244 ns

Bunch separation
Main beam
Δt = 0.5 ns


Legend
CERN existing LHC
Potential underground siting :
CLIC 380 Gev 11.4 km
CLIC 1.5 TeV 20 km
CLIC 3 TeV 50 km
Lake Geneva
Jura Mountains
IP
Geneva
Google

CLIC Collaborations

32 Countries – over 70 Institutes

Some challenging parameters

Accelerating gradient ($G = 100$ MV/m)

Very low break down rate in the accelerating cavities (BDR < 10^{-7})

Beam emittance production and preservation ($\gamma\varepsilon_n = 5$ nm.rad at Damping ring exit)

Ground motion and stability requirements

Positron flux ($1.1\ 10^{14}$ e^+/s => 20 times more than the SLC machine produced)

Beam size at IP ($\sigma_y = 1$ nm)

Power consumption (~ 600 MW)

Cost (several billions of €, $, CHF,…..)

……..

CLIC Timeline

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

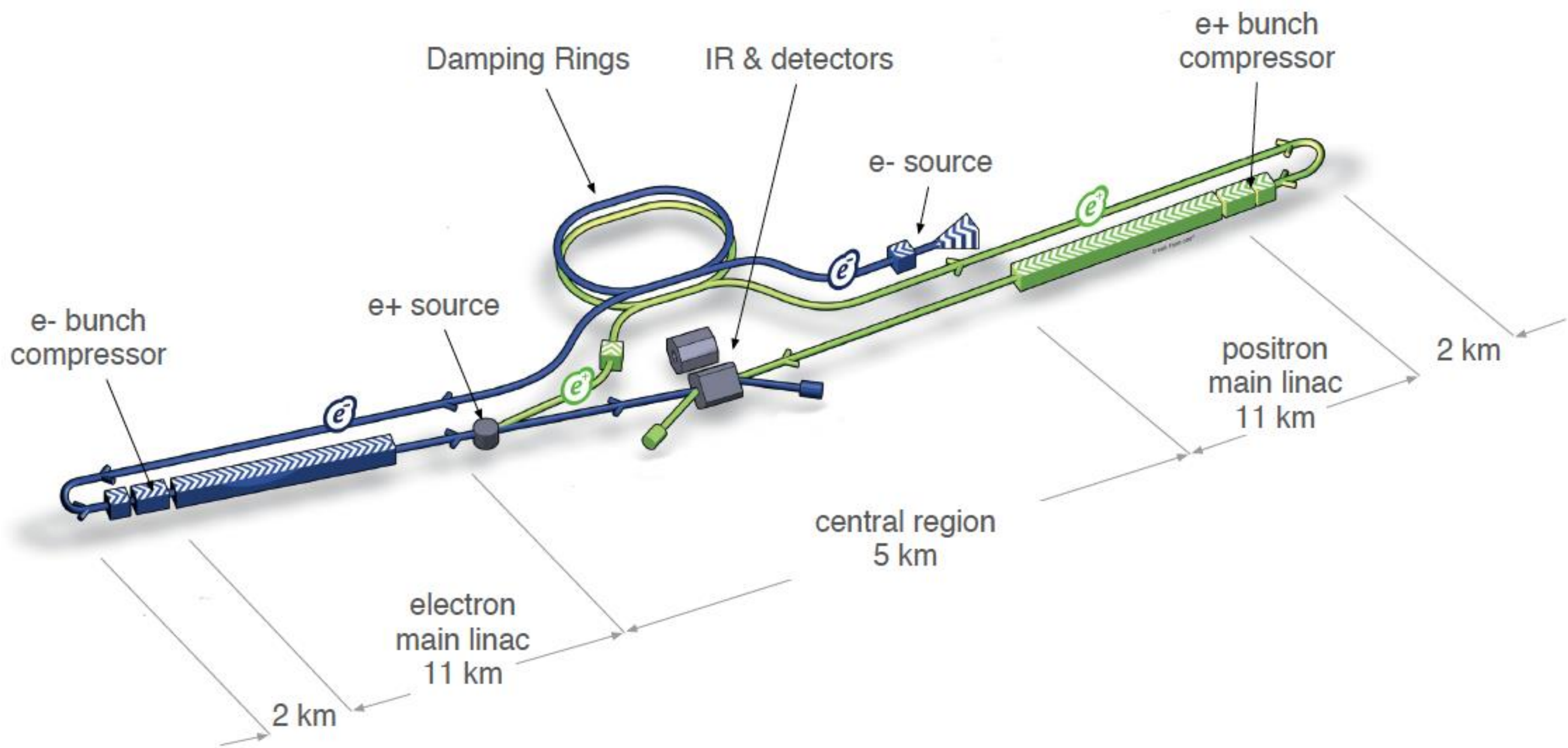
Ready for construction; start of excavations

2035 First Beams

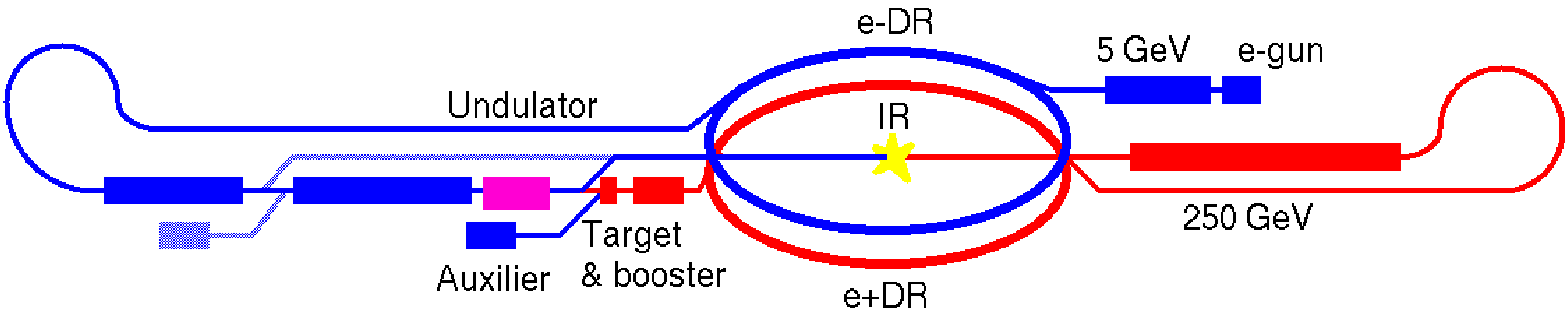
Getting ready for data taking by the time the LHC programme reaches completion

CLIC Workshop 2018 : https://indico.cern.ch/event/656356/

ILC (International Linear Collider) $e^+ e^-$



ILC accelerator overview

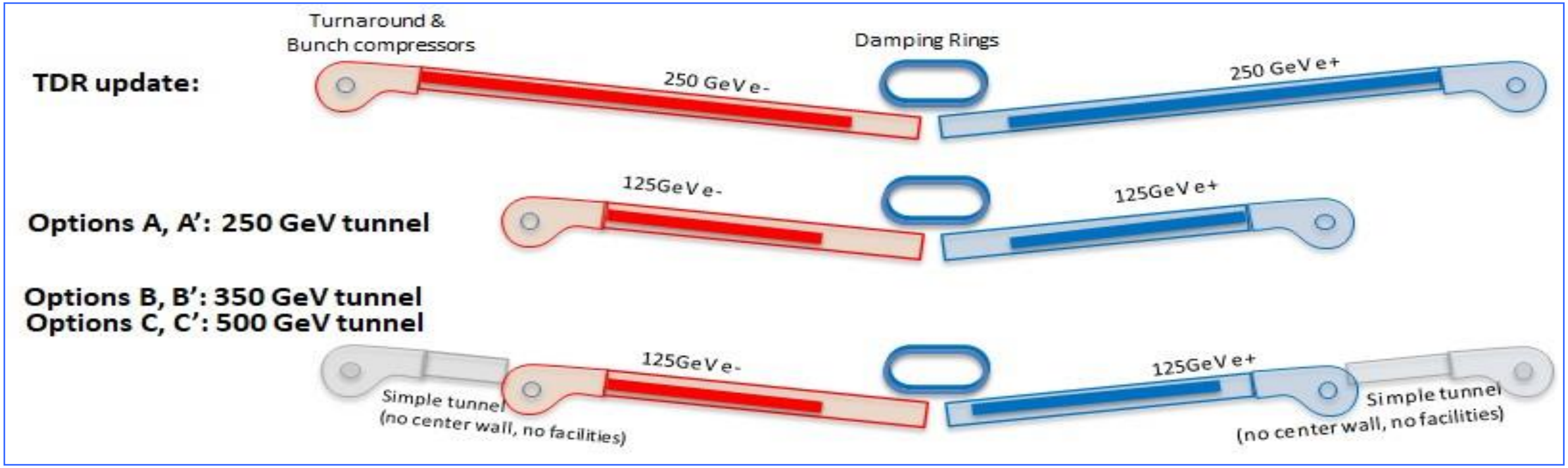


- High gradient acceleration with super-conducting RF cavities $G = 31.5$ MV/m
- High luminosity $L = 1.8\ 10^{34}\ cm^{-2}s^{-1}$
- Polarized beams

ILC parameters

Parameter	Symbol	ILC	Unit
Center of mass energy	E_{cm}	500	GeV
Total luminosity	**L**	**2**	**10^{34} cm^{-2} s^{-1}**
Luminosity (in 1% of energy)	$L_{99\%}$	1	10^{34} cm^{-2} s^{-1}
Main Linac RF Frequency	f_{RF}	1.3	GHz
Linac repetition rate	f_{rep}	5	Hz
No. of particles / bunch	N_b	20	10^9
No. of bunches / pulse	k_b	1312	
Beam pulse length	Δt	730	ms
Main beam current	I	5.8	mA
Accelerating gradient	G	31.5	MV/m
Beam power / beam	P_b	10.8	MW
IP beam size before pinch	σ^*_x / σ^*_y	640 / 5.7	nm
Transverse emittances	$\gamma\varepsilon_x$ / $\gamma\varepsilon_y$	8000 / 40	nm rad
Proposed site length	l_{tot}	31	km
Wall-plug power to beam efficiency	η_{wp-rf}	9.4	%
Total site AC power	P_{tot}	230	MW

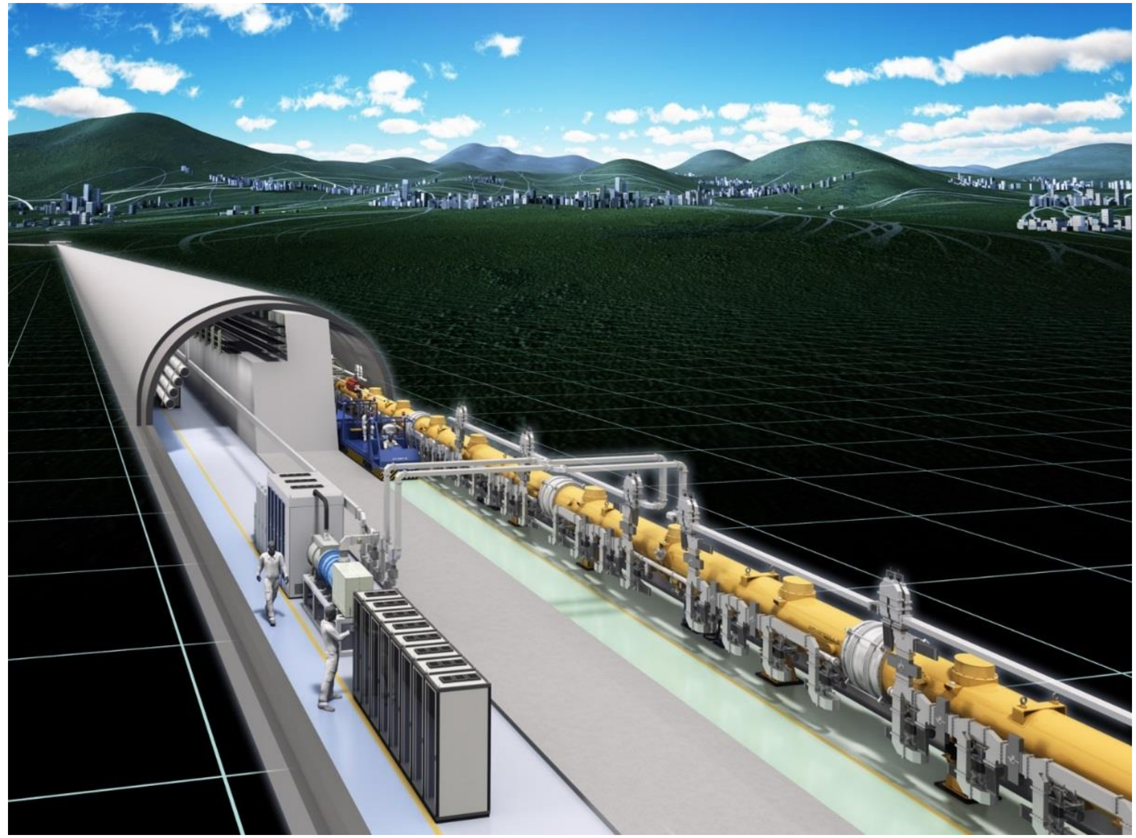
ILC staging options

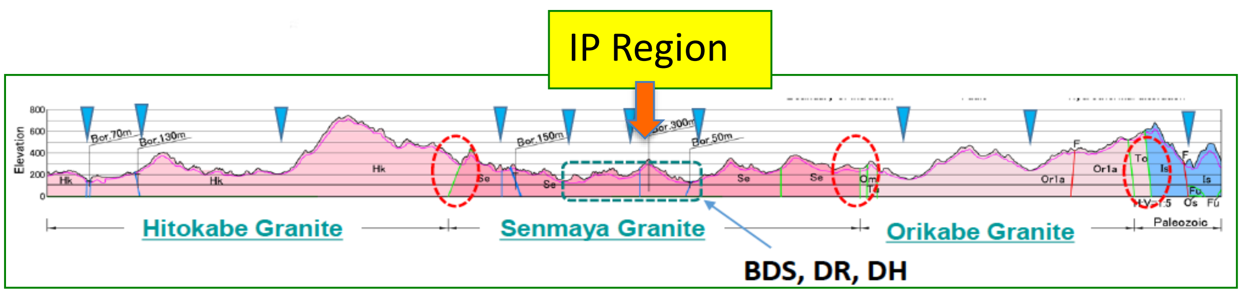


To cover with high precision Higgs and top quark physics

ILC in Japan

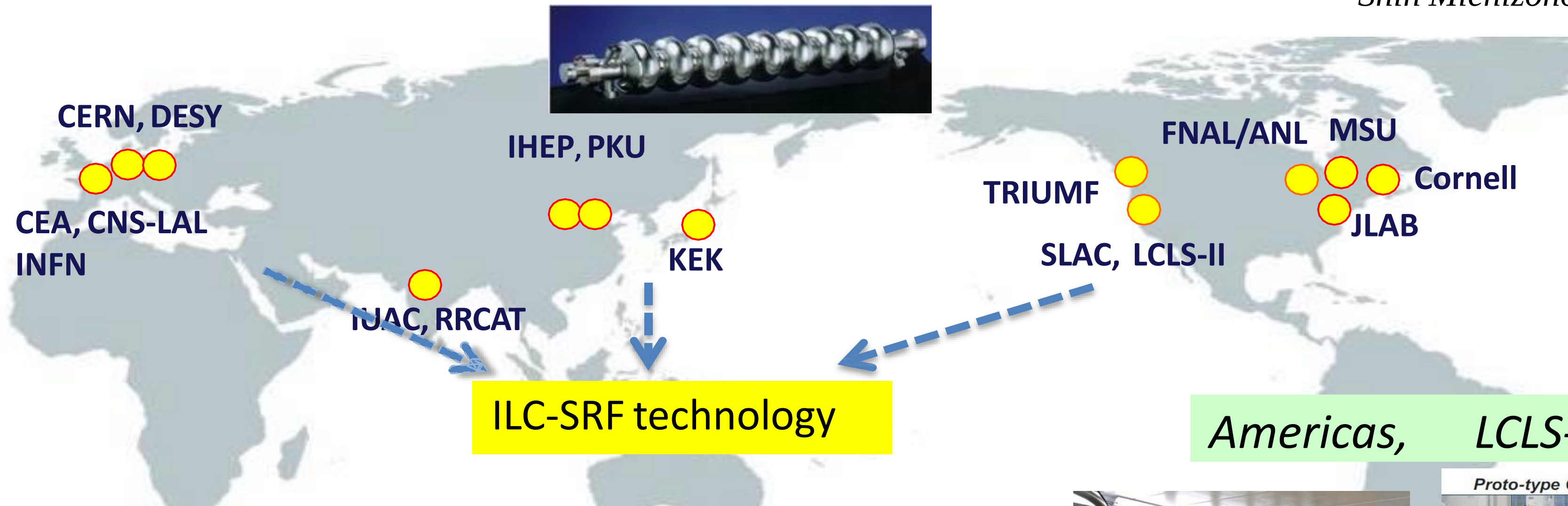

Kitakami site




IP Region
Elevation
Hitokabe Granite
Senmaya Granite
Orikabe Granite
Paleozoic
BDS, DR, DH

Worldwide SRF Collaboration

Shin Michizono / KEK



European XFEL

Asia,
PAPS@IHEP   CFF/STF@KEK

Americas,   LCLS-II

Some challenging parameters

Accelerating gradient in SC cavities (G = 31 MV/m)

Beam emittance production and preservation ($\gamma\varepsilon_n$ = 10 nm.rad at Damping ring exit)

Ground motion and stability requirements

Positron flux (3.9 10^{14} e^+/s => 70 times more than the SLC machine produced)

Beam size at IP (σ_y = 6 nm)

Power consumption (~ 230 MW)

Cost (several billions of €, $, CHF,…..)

…..

Decision on ILC in 2018 ?

Fabiola Gianotti / 16/01/2018 CERN

Crucial input will come also from facilities, projects and experiments across the world.

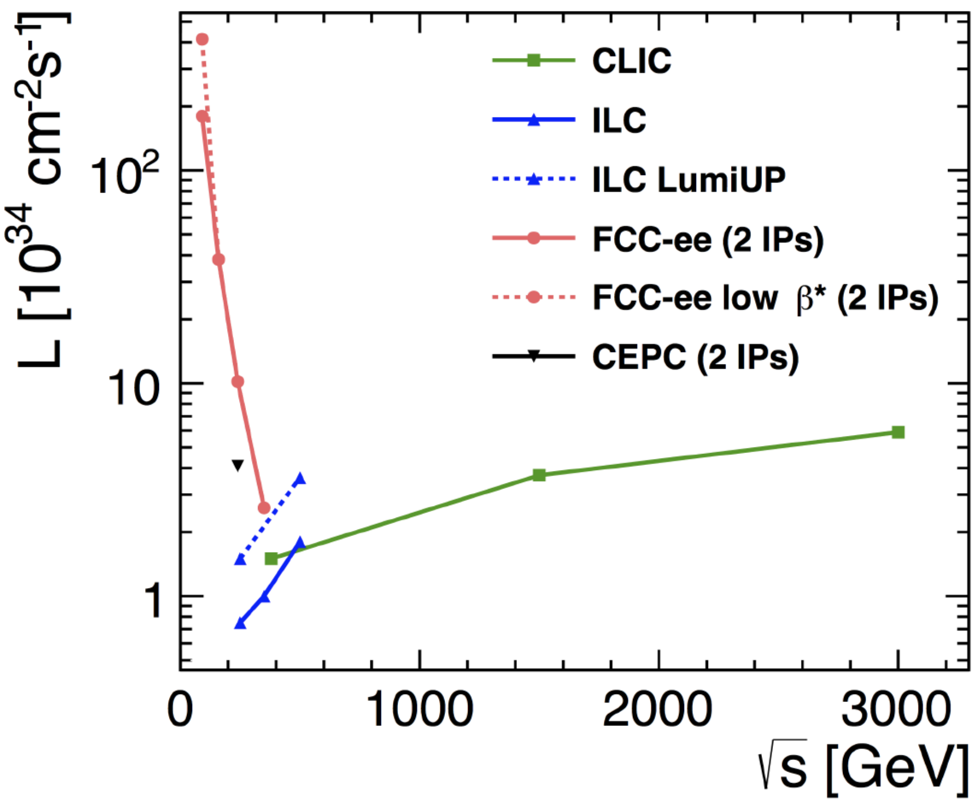
For instance: Japan's decision to build (or not) an ILC, expected by end 2018, will have an impact on which future high-E accelerators CERN should consider

ICFA statement in November 2017: "*ICFA … very strongly encourages Japan to realize the ILC in a timely fashion as a Higgs boson factory with a centre-of-mass energy of 250 GeV as an international project, led by Japanese initiative*… ICFA emphasizes the extendibility of the ILC to higher energies …* "

* It means that the host country is expected to make the majority financial contribution

https://agenda.linearcollider.org/event/7645/overview

Luminosity performance e^+e^- colliders



Note 1: Peak luminosity at SLC (92 GeV) was ~10^{30} cm^{-2}s^{-1}
Note2: Peak luminosity at LEP2 (209 GeV) was ~10^{32} cm^{-2}s^{-1}

Other possible future linear colliders

LWFA = Laser Wake Field Accelerator

PWFA = Plasma Wake Field Accelerator

SWFA = Structure Wake Field Accelerator

DLA = Dielectric Laser Accelerator

JUAS Seminar on The future of particle accelerators (European context) 11th January 2018 by M. Vretenar /CERN

JUAS Seminar on Laser Plasma Accelerator 31st January 2018 by R. Aßmann / DESY

EAAC workshop – Elba - Italy

EAAC 2017 3rd European Advanced Accelerator Concepts Workshop

Wakefields for higher accelerating fields

LWFA = Wakefields are driven in plasma by intense laser beams

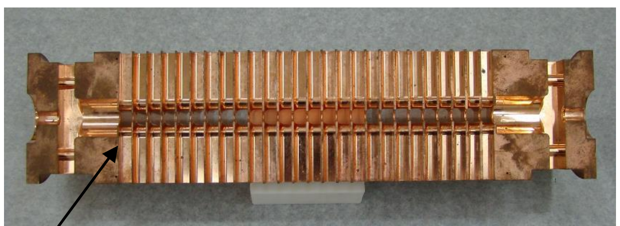
PWFA = Wakefields are driven in plasma by particle beams

SWFA = Wakefields are driven in dielectric structures by particle beams

DLA = Wakefields are driven in dielectric structures by very short laser pulses

RF accelerating structure

100 MV/m

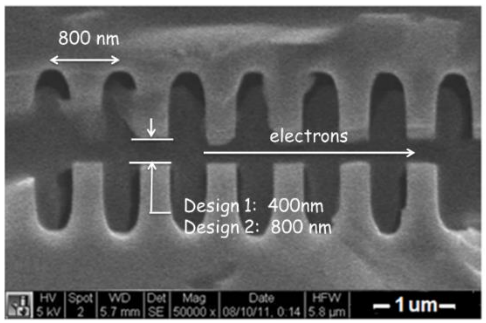


25 cm

Φ 6 mm

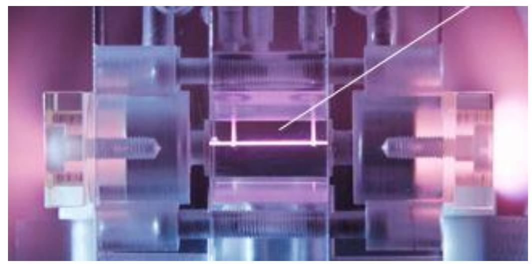
Dielectric accelerating structure

~ 2 GV/m



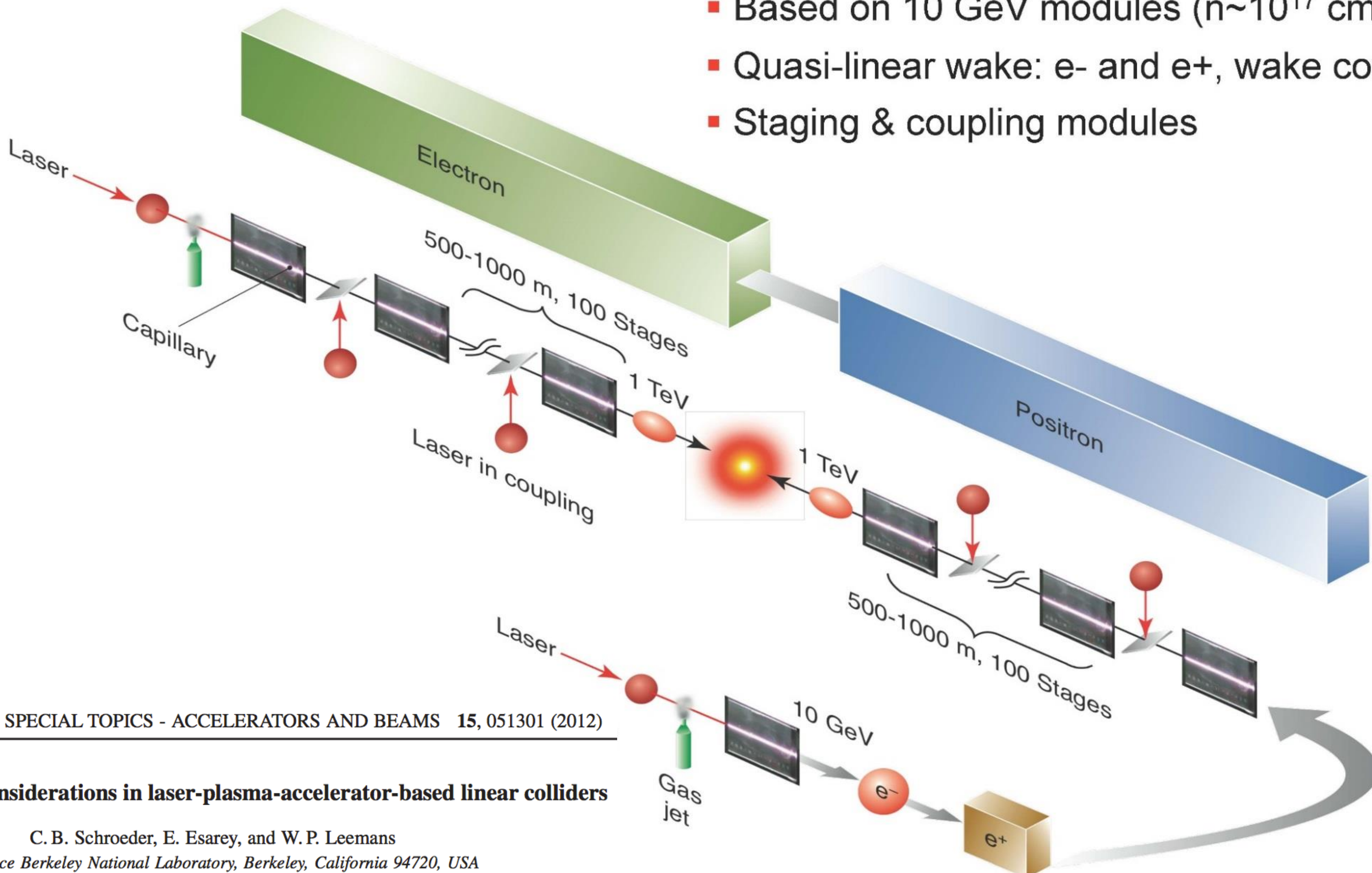
Plasma accelerating structure

~ 100 GV/m



LWFA for Linear Collider

- Based on 10 GeV modules ($n \sim 10^{17}$ cm^{-3})
- Quasi-linear wake: e- and e+, wake control
- Staging & coupling modules



PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **15**, 051301 (2012)

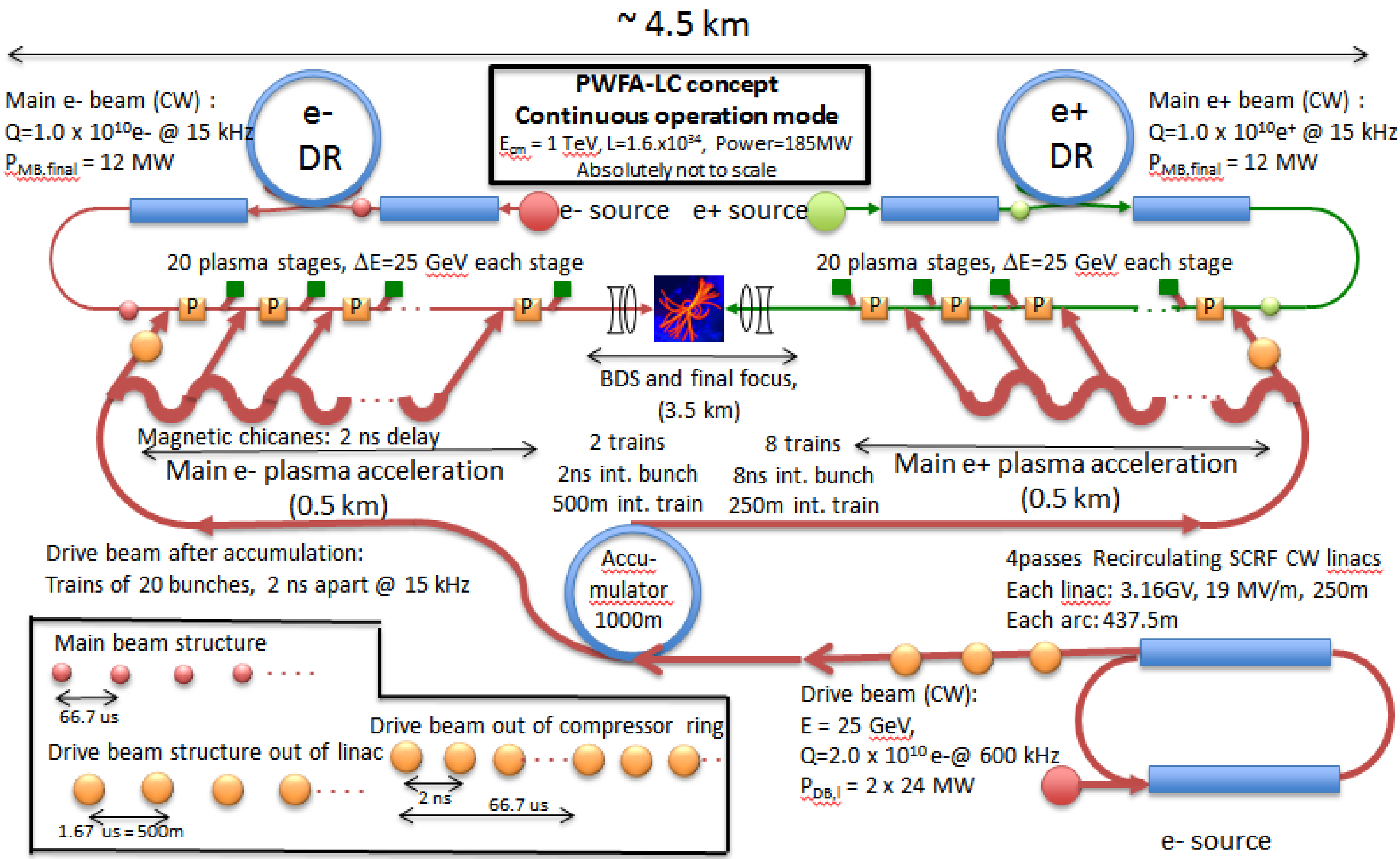
Beamstrahlung considerations in laser-plasma-accelerator-based linear colliders

C. B. Schroeder, E. Esarey, and W. P. Leemans

Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA

(Received 23 November 2011; published 4 May 2012)

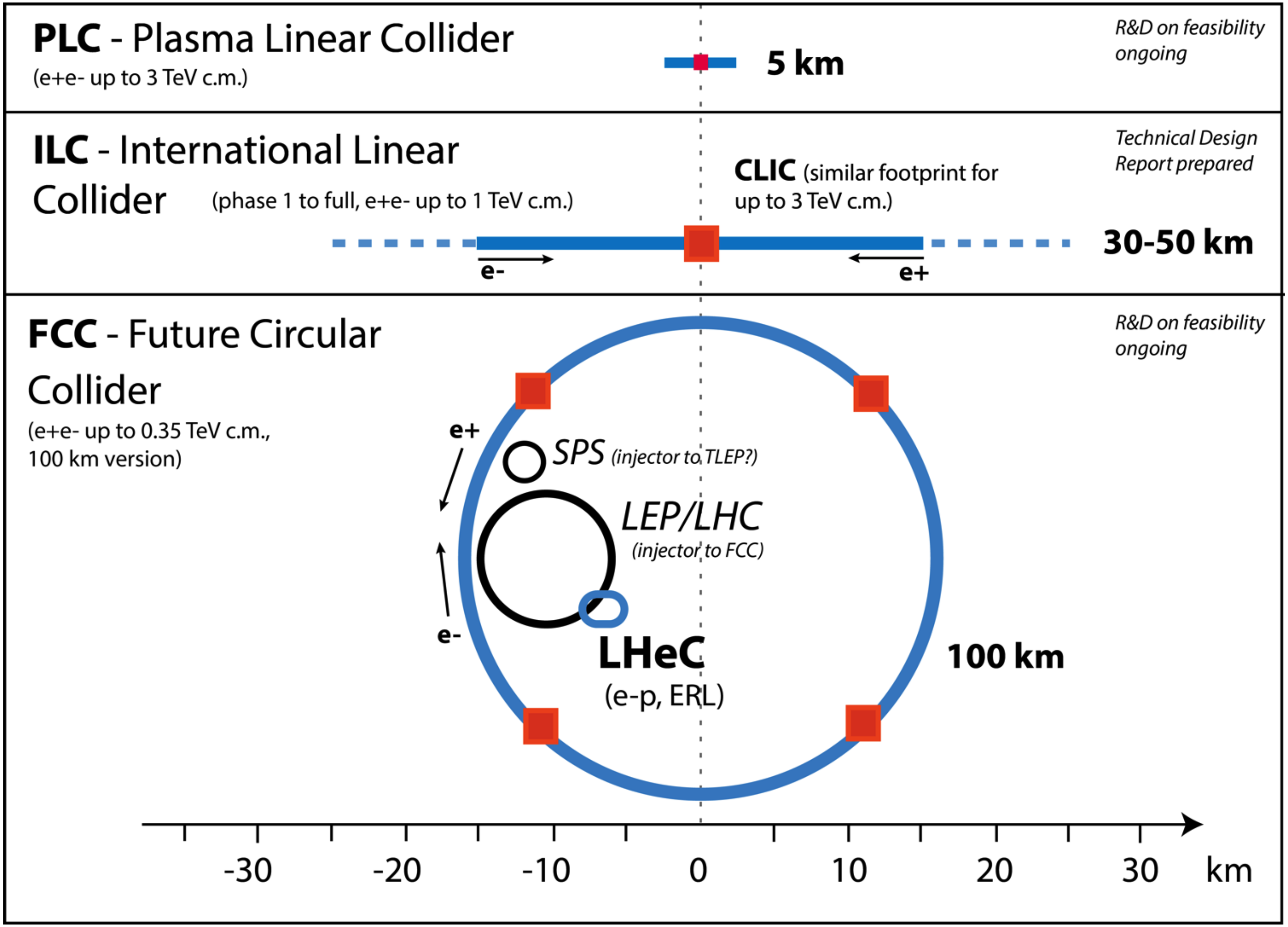
PWFA for Linear Collider



Concept for PWFA-LC layout for 1TeV. Based on earlier work from 2009 by Raubenheimer et al.

E. Adli et al., "A beam driven Plasma Wake-Field Linear Collider", CSS2013 and arXiv:1308.1145

Which future collider ?



Linear muon collider ?

F. Zimmermann, “Final Focus Challenges for Muon Colliders at Highest Energies,” CERN-SL-99-077-AP.- AIP Conf. Proc.: 530 (1999) , pp. In : Colliders and Collider Physics at the Highest Energies : Muon Colliders at 10 TeV to 100 TeV, Montauk, NY, USA, 27 Sep - 1 Oct 1999, pp.347-367

9 Single-Pass Muon Collider

The design of a muon ring collider at multi-TeV energies faces severe, perhaps insurmountable problems:

- The neutrino radiation is likely to limit a ring collider to energies below a few TeV. The radiation hazard arises because the neutrino cross sections increase almost linearly with energy, while the angular divergence of the emitted neutrinos decreases as $1/\gamma$. As a net result the neutrino radiation dose increases as the 3rd power of energy [25], and at multi-TeV energies easily exceeds the US Federal limit [26].
- The beam has to survive hundreds of passes through a final-focus system more challenging than that of the SLC, retaining the same constant emittance. This appears non-trivial, as already the extracted beam at the SLC showed large emittance degradation even in the absence of collisions.

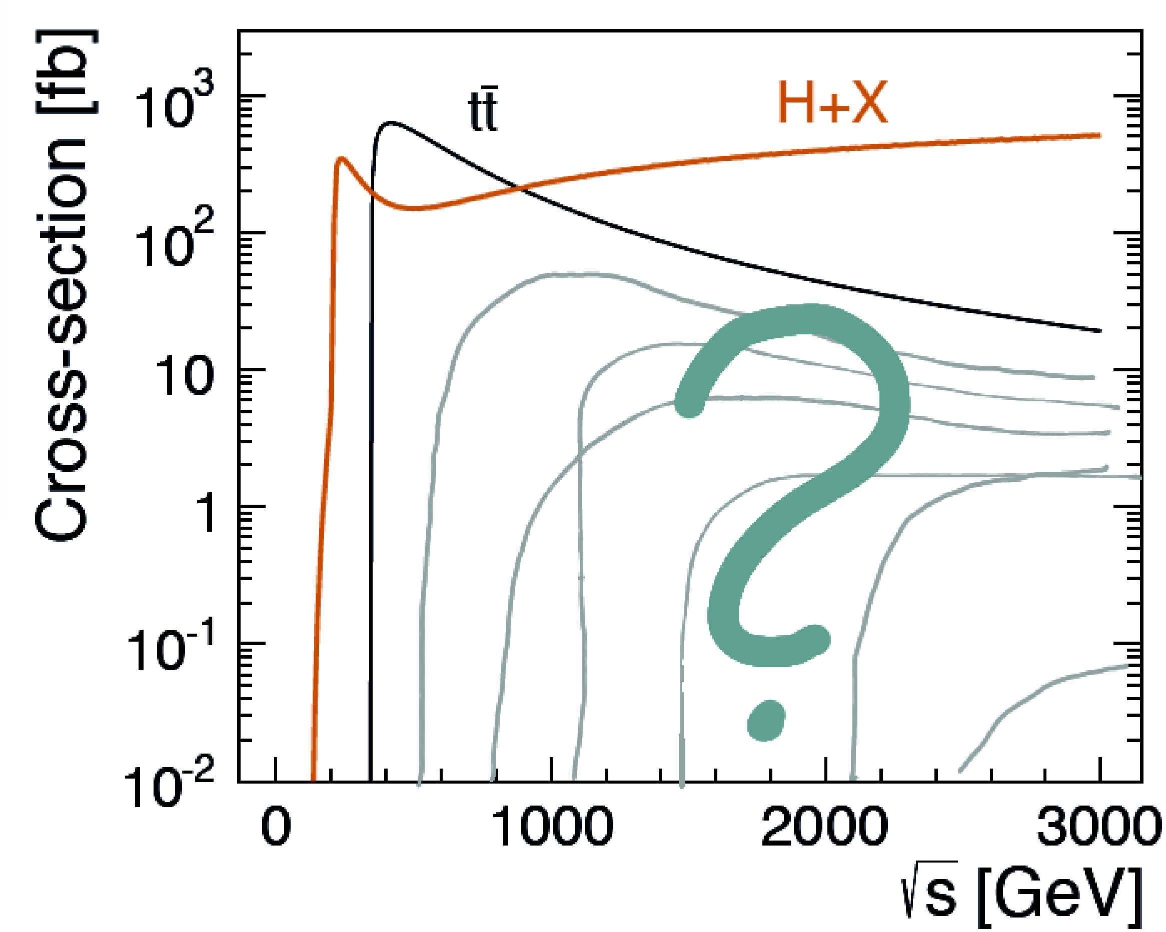
Similarly, several difficulties lie in the way of an electron-positron linear collider at multi-TeV energies. The most dramatic is the effect of beamstrahlung,

A single-pass muon collider (SPMC) solves all the above problems: Because of the larger muon mass, the beamstrahlung at 10 TeV or 100 TeV is still contained. There is no need to preserve the emittances after the collision, and the beam can be dispersed onto a dump (downwards, or upwards), thereby reducing the density of neutrino radiation by orders of magnitude. Note that, as an option, the beams could still be accelerated in a ring [31], from which they might then be extracted, focused to a small spot size, and collided only once.

Table 4: Example parameters for single-pass muon colliders at 10, 100 and 1000 TeV.

parameter	symbol	SPMC-0	SPMC-I	SPMC-II	SPMC-III
cm energy [TeV]	E_{cm}	3	10	100	1000
luminosity [10^{35} cm^{-2} s^{-1}]	L	1.2	2.1	7.2	5.4
beam energy [TeV]	E_b	1.5	5	50	500
muons/bunch [10^{12}]	N_b	5	3	0.8	0.2
bunches/train	n_b	1	1	1	1
repetition rate [Hz]	f_{rep}	160	27	7.9	3.2
normalized tr. emittances [μm]	$\gamma\epsilon_{x,y}$	15	2	0.5	0.25
6-dim. normalized emittance [10^{-12} m^3]	$\gamma^3\epsilon_{6d}$	16	1.5	0.23	0.30
rms energy spread	$\delta_{\rm rms}$	1%	1%	1%	1%
rms bunch length [mm]	σ_z	0.5	0.8	0.2	0.1
relativistic Lorentz factor [10^4]	γ	1.41	4.7	47	473
IP beta functions [mm]	$\beta^*_{x,y}$	0.5	0.8	0.2	0.1
IP spot sizes [nm]	$\sigma_{x,y}$	730	184	14.5	2.3
beamstrahlung energy loss	δ_B	7×10^{-7}	8×10^{-6}	4×10^{-3}	0.14
Upsilon parameter	Υ	2×10^{-6}	1.0×10^{-5}	1.4×10^{-3}	0.04
beamstrahlung photons/lepton	N_γ	0.71	1.67	5.61	8.43
luminosity enhancement factor	H_D	2.00	3.67	3.77	2.83

Future physics ?



LHC continues to investigate what physics is behind the Higgs boson and what energy scale should be considered.

Many fundamental questions remain open

Fabiola Gianotti / 16/01/2018 CERN

PUZZLING: the SM is not a complete theory of particle physics, as several outstanding questions remain that cannot be explained within the SM

What is the composition of dark matter (~25% of the Universe) ?
What is the cause of the Universe's accelerated expansion (today: dark energy?; primordial: inflation?)
What is the origin of neutrino masses and oscillations ?
Why 3 fermion families ? Why do neutral leptons, charged leptons and quarks behave differently?
What is the origin of the matter-antimatter asymmetry in the Universe ?
Why is the Higgs boson so light (so-called "naturalness" or "hierarchy" problem) ?
Why is Gravity so weak ?
Etc. etc.

These questions require NEW PHYSICS
→ but where is the new physics in terms of E-scale and couplings to SM particles ???

The future of high energy physic seems very exciting !!!

Looking the future

Conclusion

JUAS students are the future machine builders …..

…. for future high energy particle accelerators !

Acknowledgements

Thanks to Erik Adli, Ralph Assmann, Fabiola Gianotti, Phil Burrows, Paul Emma, Andrea Latina, W.P. Leemans, Lucie Linssen, Shin Michizono, Tsunehiko Omori, John Osborne, Roger Ruber, Nick Walker, Akira Yamamoto, Frank Zimmermann