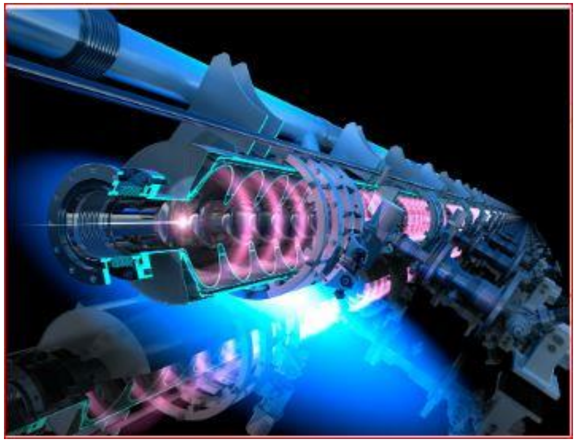
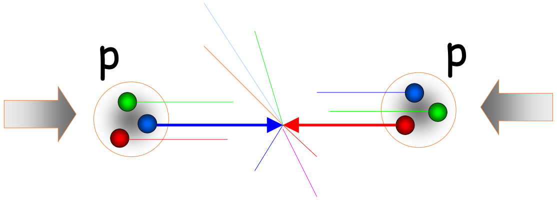
Future High Energy Linear Colliders

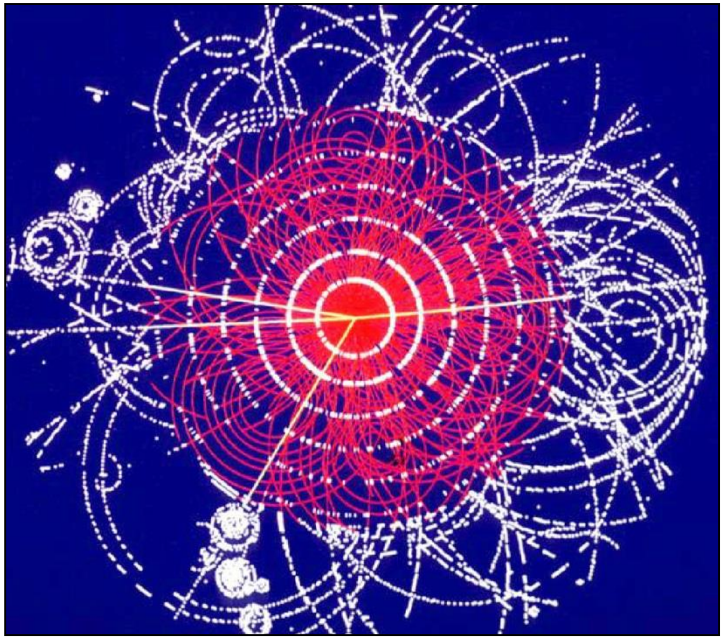
Louis Rinolfi

CERN



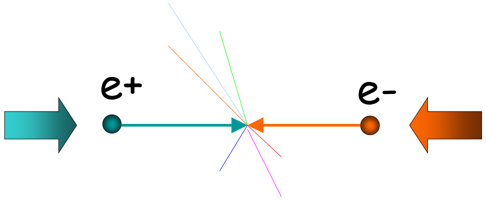
Hadrons versus leptons colliders

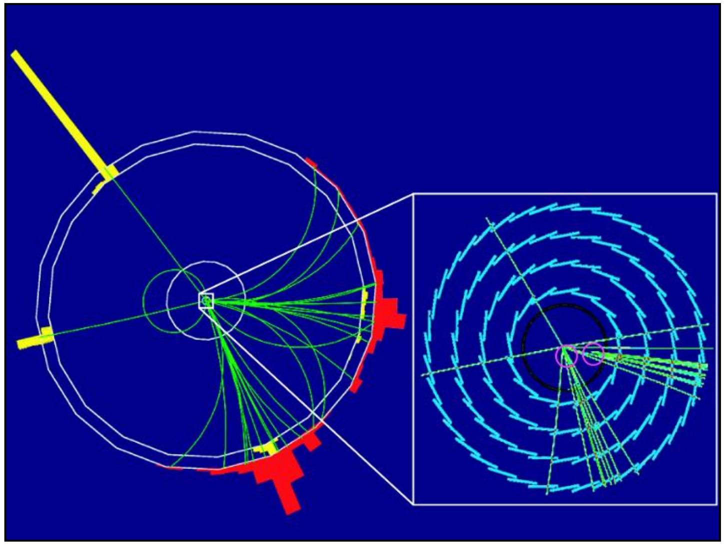




hadron collider => frontier of physics

- 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

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)	DESY (Germany)
=> SBLC	(3 GHz, normal conducting, NC)	DESY (Germany)
=> NLC	(11.4 GHz, normal conducting, NC)	SLAC (California)
=> JLC	(11.4 GHz, normal conducting, NC)	KEK (Japan)
=> VLEPP	(14 GHz, normal conducting, NC)	Novosibirsk (Russia)
=> CLIC	(30 GHz, normal conducting, NC)	CERN (Switzerland)

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

2019: CLIC (12 GHz) and ILC (1.3 GHz) studies are ongoing

Future high energy colliders

as seen in 2000

LONGITUDINAL BEAM DYNAMICS

Application to synchrotron

CERN/PS 2000-008 (LP)

Course given at JUAS (Joint Universities Accelerator School) at Archamps (France)

January 2000

The milestones with a possible future scenario are given below:

1989: SLC first beam (50 GeV)

1989: LEP first beam (45 GeV)

1998: End of SLC (50 GeV with polarised electrons)

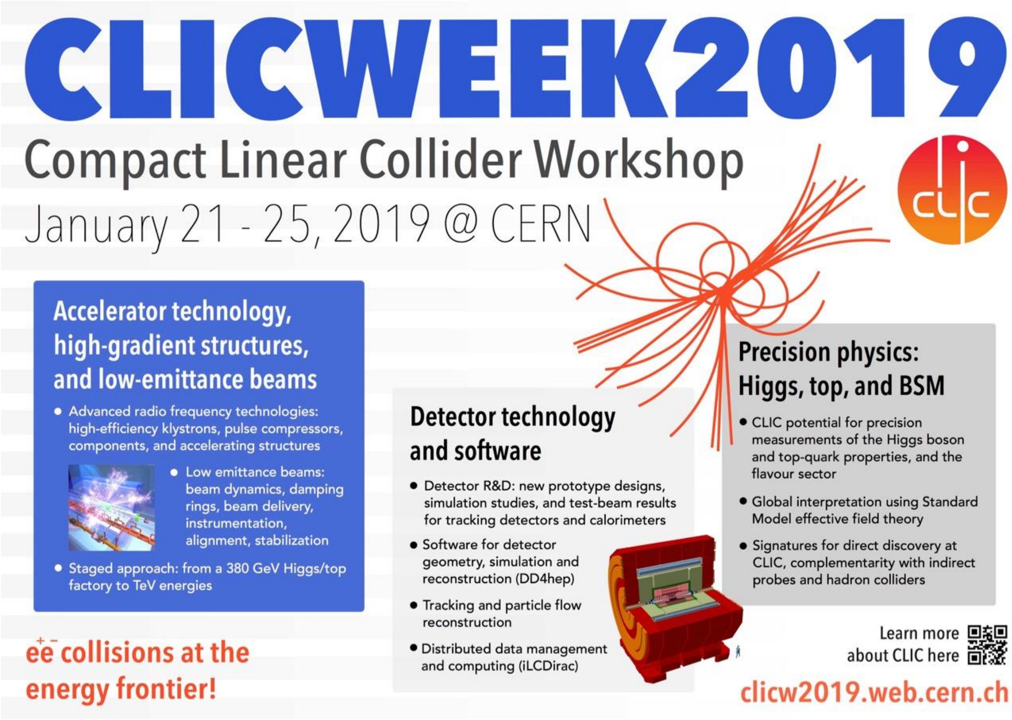
2000: End of LEP (104 GeV)

2005: LHC first beam p^+/p^+ (7 TeV)) (approved in 1994)

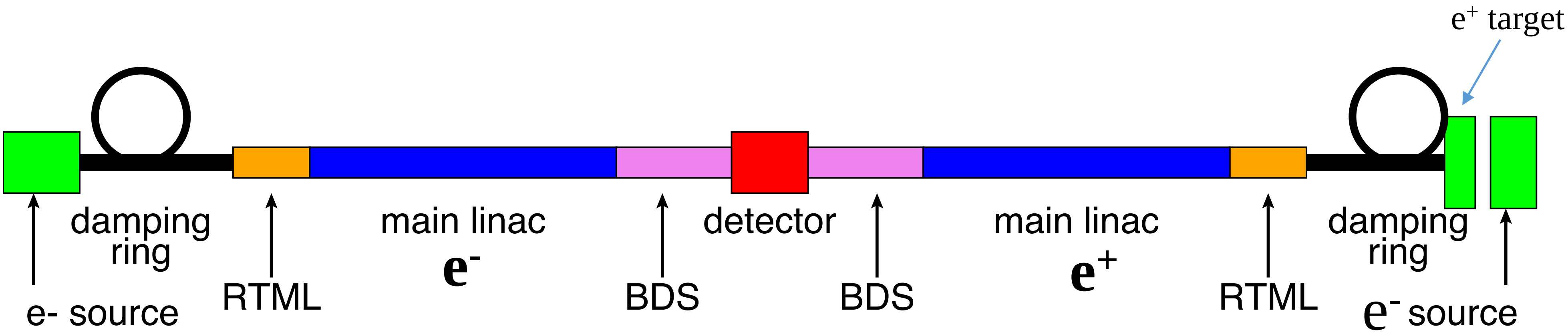
2010: Linear Collider e^-/e^+ (up to 3 TeV) (?)

2030: Muons Collider μ^-/μ^+ (?)

Recent workshops on high energy linear colliders



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

Energy center of mass for linear colliders

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

MeV

m

MV/m

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

Luminosity

Number of events = σ_{event} x $\int L(t)\,dt$

σ_{event} is the probability of producing a particular event
$\int L(t)\,dt$ is a measure of the total number of interactions
with L the instantaneous luminosity

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

Basic expression for luminosity

$$L = \frac{n_b \; N^+ N^- \; f_{rep}}{4 \pi \sigma_x \sigma_y}$$

L: cm^{-2} s^{-1}; f_{rep}: Hz; σ_x, σ_y: cm

n_b = number of bunches; N = number of particles per bunch; σ_x, σ_y = rms transverse beam sizes

Re-write luminosity for linear colliders

$$L = \frac{n_b \; N^+ N^- \; f_r}{4 \pi \sigma_x \sigma_y}$$

$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \frac{1}{\sigma_y}$$

Luminosity spectrum (Physics)

Beam current (Power and RF limits, beam stability)

Beam Quality (Many systems)

$$\mathcal{L} \propto \frac{P_{wall}}{E_{cm}} \frac{\eta}{\sigma_y} N_\gamma \; H_D$$

P_{wall} = total wall-plug power; E_{cm} = center mass energy;

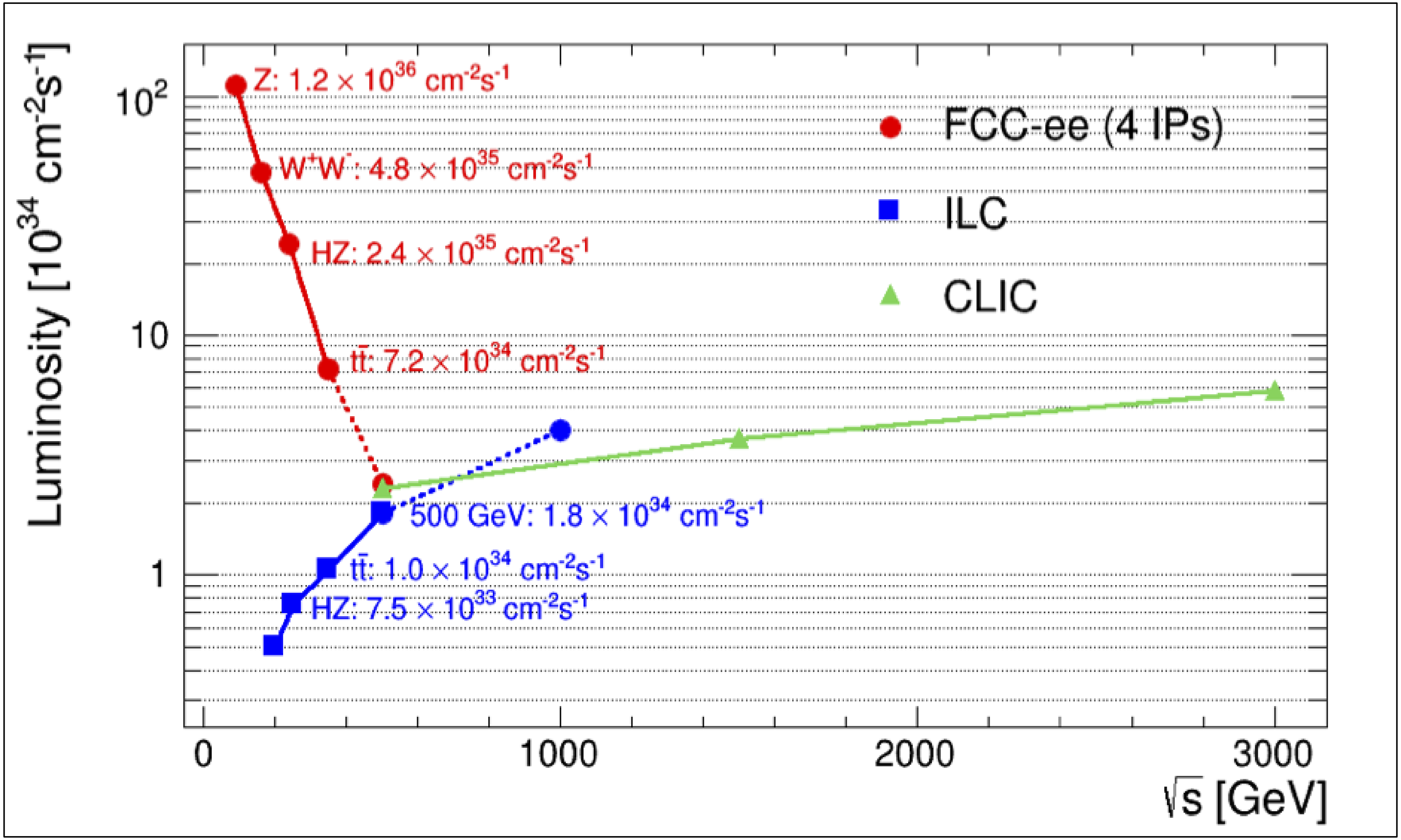
η = efficiency of converting wall-plug power into beam power

$N\gamma$ = number of beamstrahlung photons emitted per e+/-

H_D = enhancement of luminosity due to the pinch effect during bunch crossing

Luminosity performance for e^+e^- colliders

F. Gianotti



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}

SLC (Stanford Linear Collider) – California - USA

The first and only Linear Collider who was running with a beam
e^- (45.6 GeV) and e^+ (45.6 GeV)

3.2 km (2 miles) S-band linac

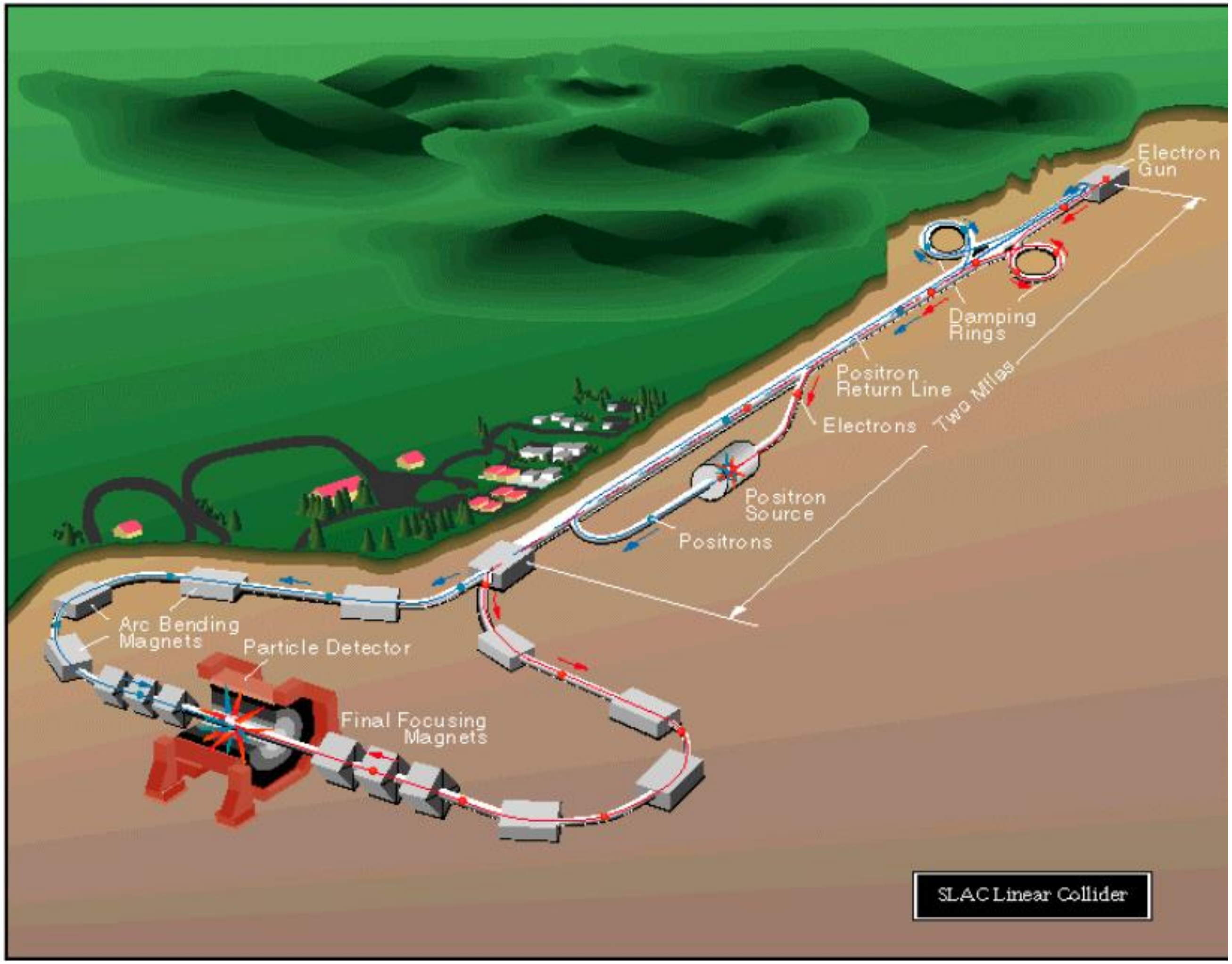
Operation: 1989-1998

SLC (Stanford Linear Collider) – California - USA

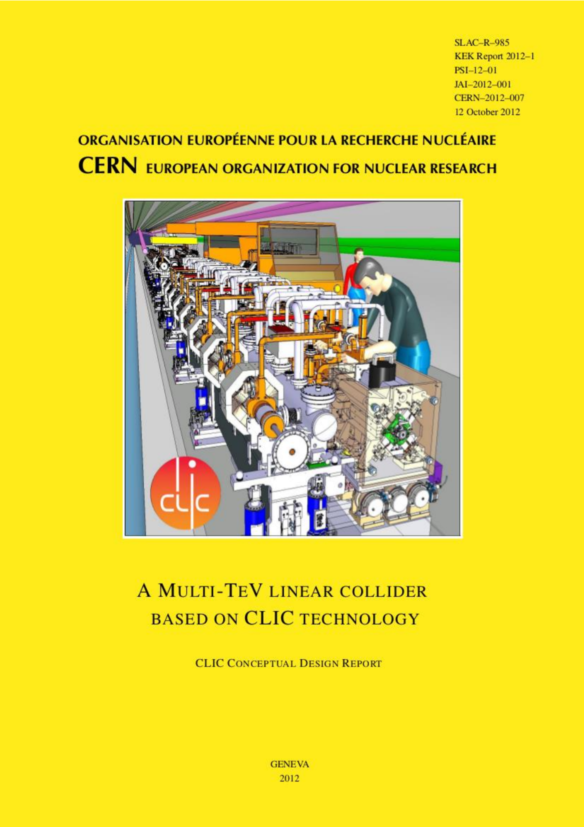
Final beam energy
E_{cm} = 92 GeV

2 experiments: MARK II, SLD
Peak Luminosity: $2x10^{30}cm^{-2}s^{-1}$

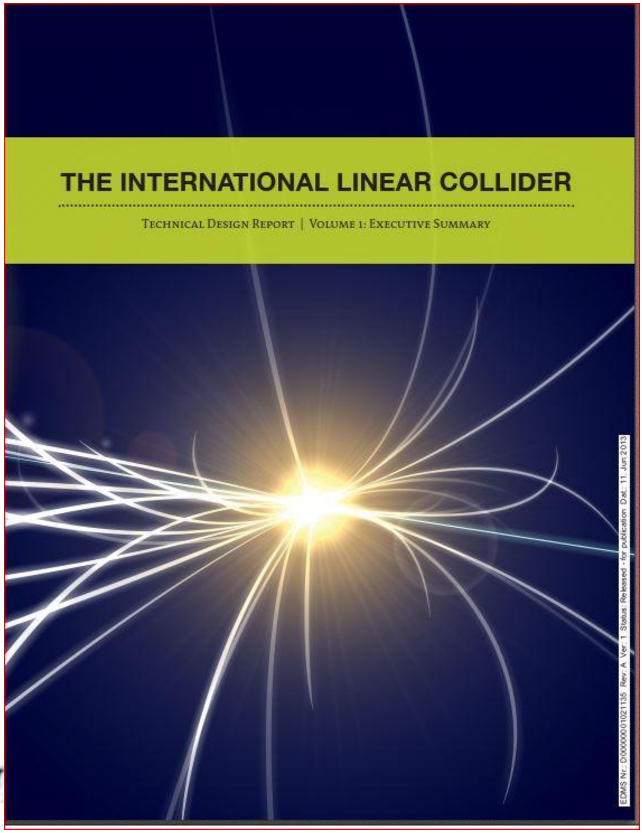
80% electron-beam polarization



The Linear Collider Collaboration



CLIC Conceptual Design Report published in 2012



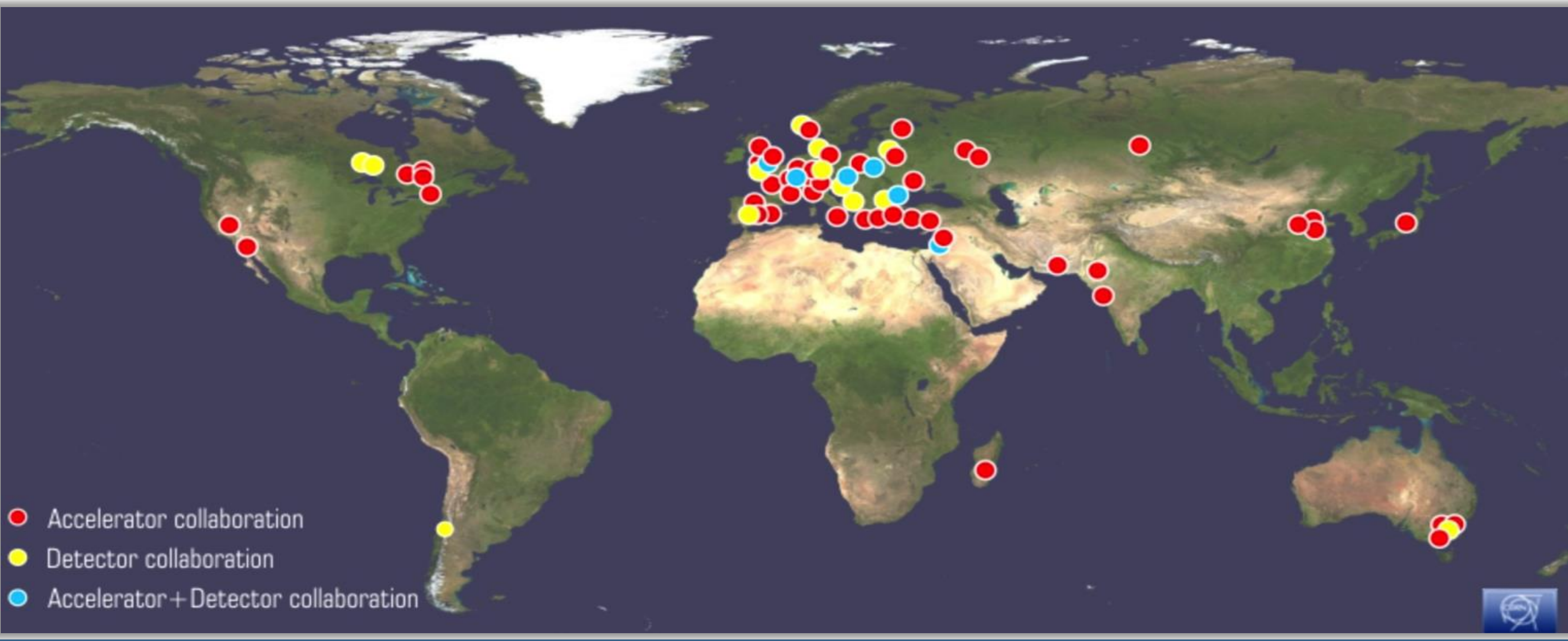
ILC Technical Design Report published in 2013

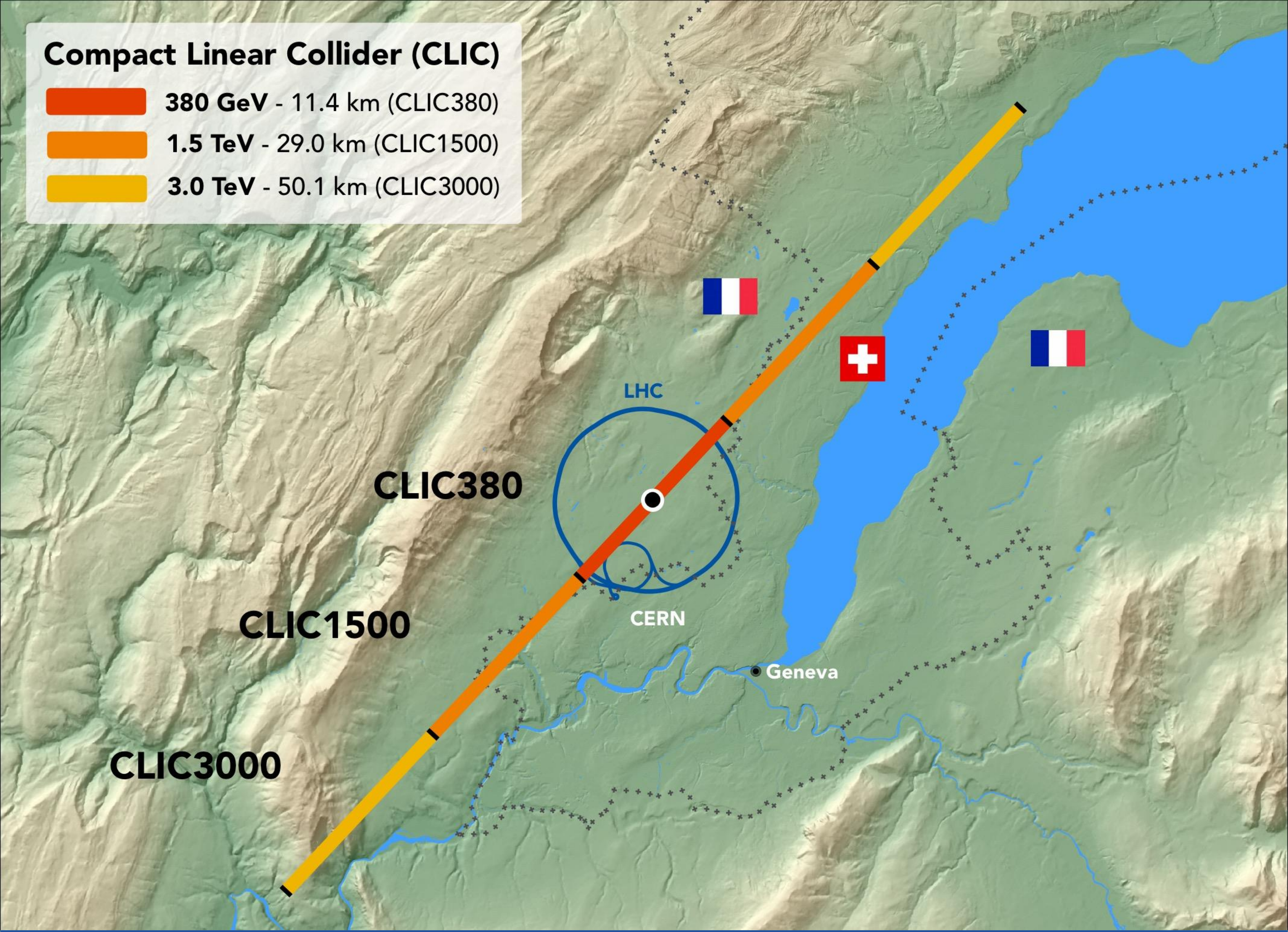
LINEAR COLLIDER COLLABORATION 2012

CLIC Collaborations

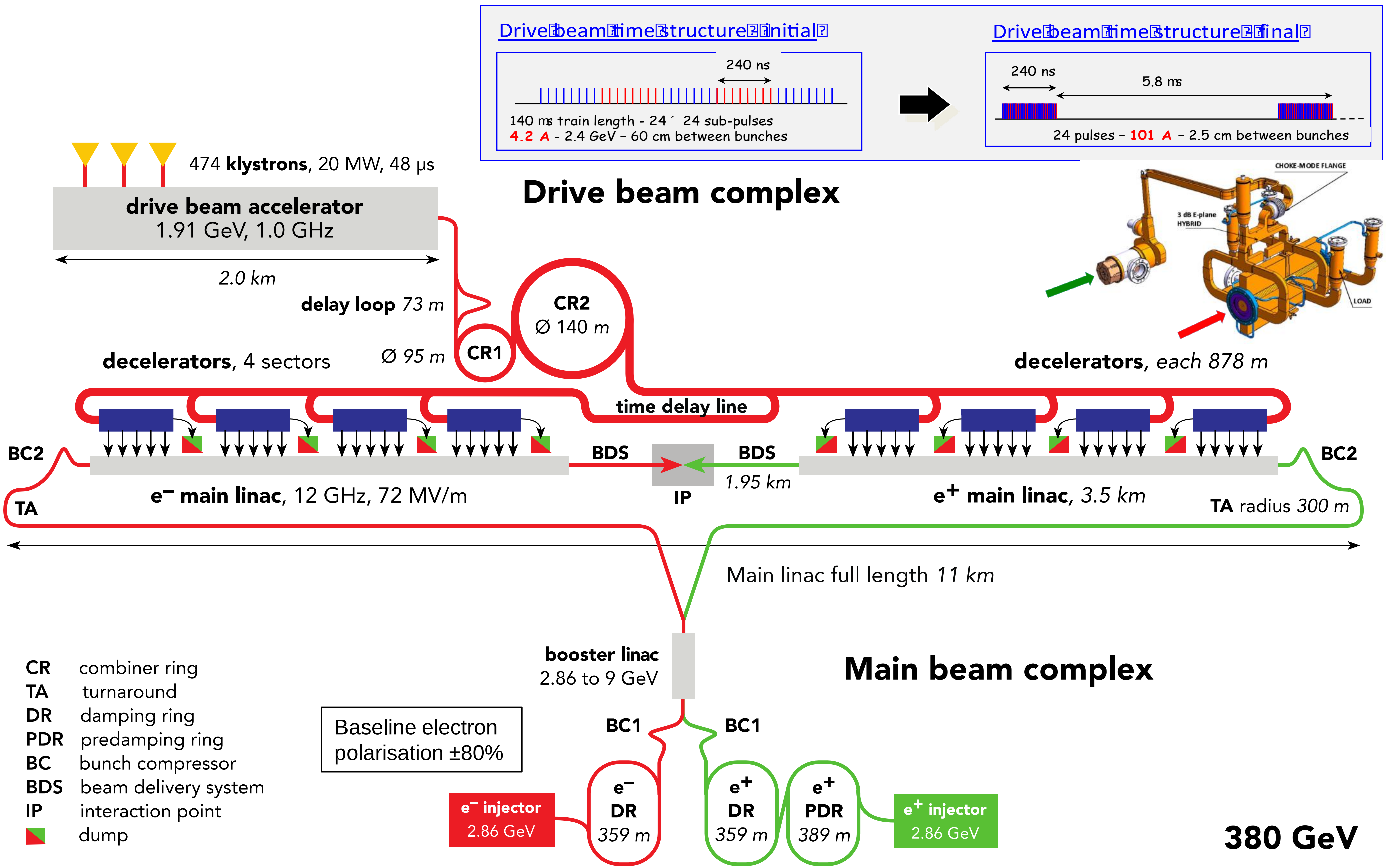
CLIC accelerator collaboration
70 institutes from **32 countries**

CLIC detector and physics (CLICdp)
30 institutes from **18 countries**

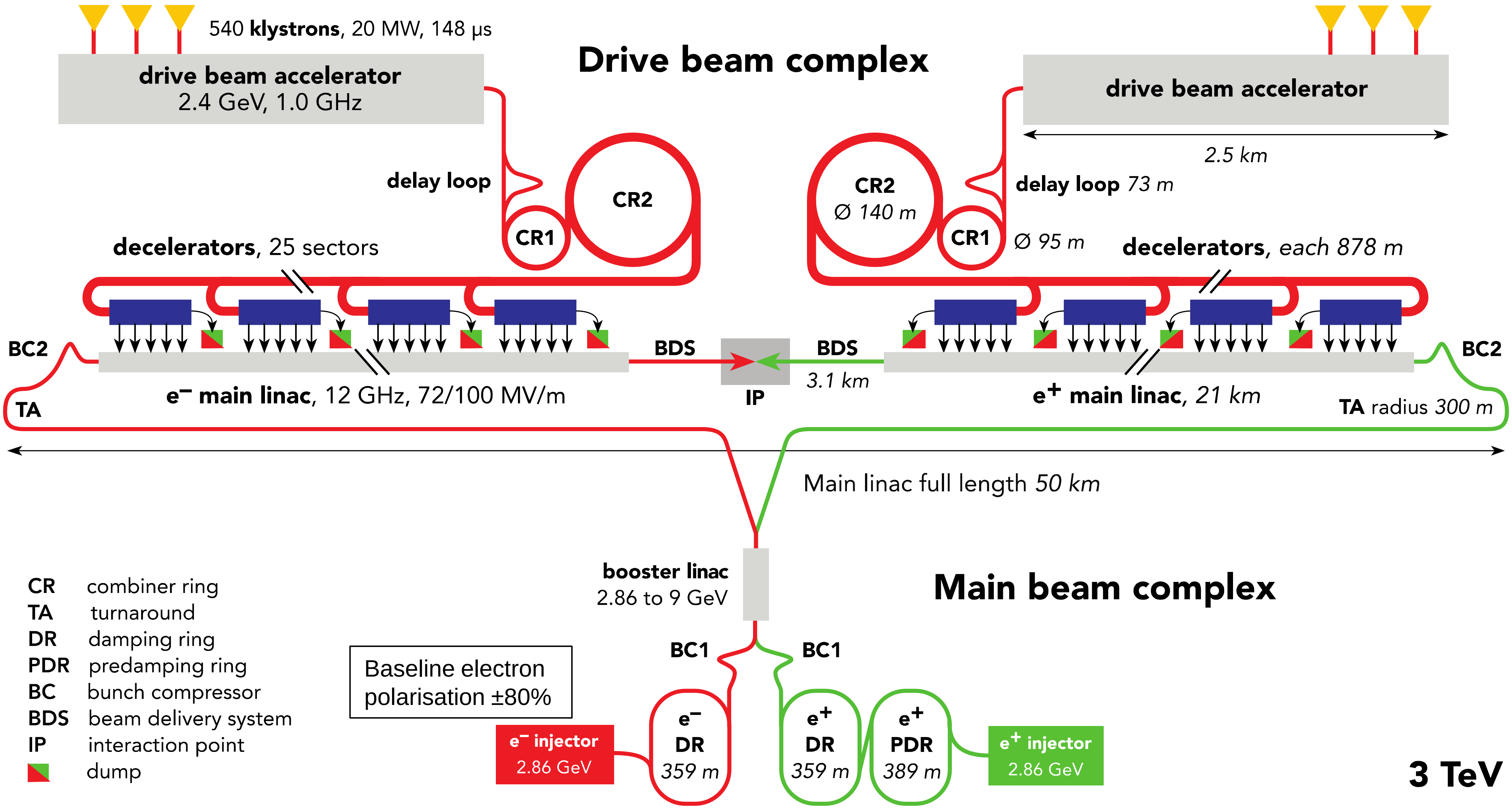



Compact Linear Collider (CLIC)
380 GeV - 11.4 km (CLIC380)
1.5 TeV - 29.0 km (CLIC1500)
3.0 TeV - 50.1 km (CLIC3000)
CLIC380
CLIC1500
CLIC3000
LHC
CERN
Geneva

CLIC layout – 380 GeV



CLIC layout – 3TeV

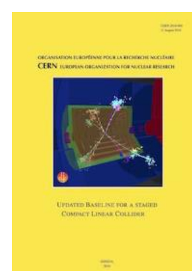


CLIC parameters

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	$\mathscr{L}$	$10^{34}\ \text{cm}^{-2}\text{s}^{-1}$	1.5	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	$10^{34}\ \text{cm}^{-2}\text{s}^{-1}$	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	—	—

CDR 2012

https://cds.cern.ch/record/1500095
https://cds.cern.ch/record/1425915
https://cds.cern.ch/record/1475225



Updated Staging Baseline 2016

http://dx.doi.org/10.5170/CERN-2016-004

Project Implementation Plan 2018

CLIC roadmap

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

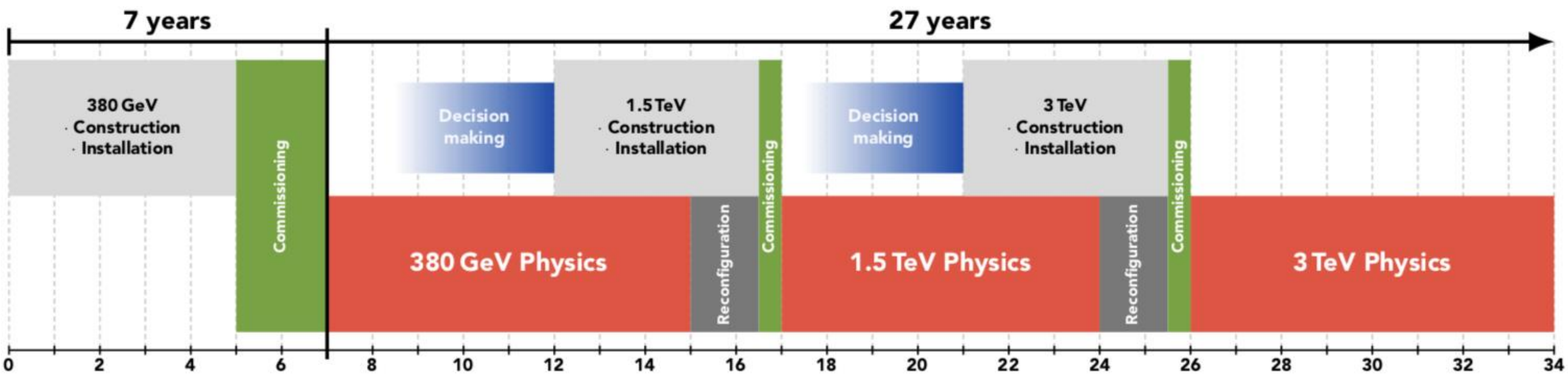
2020 - 2025 Preparation Phase
Finalisation of implementation parameters, preparation for industrial procurement, Drive Beam Facility and other system verifications, Technical Proposal of the experiment, site authorisation

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

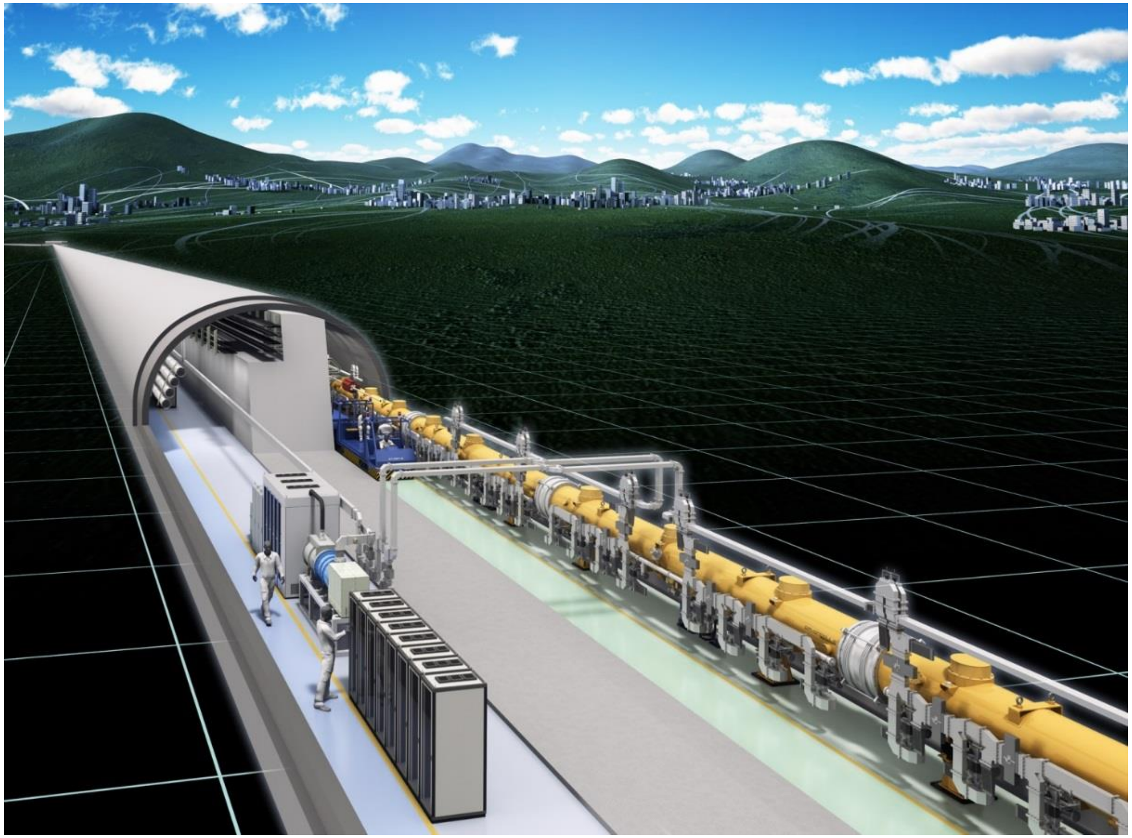
2035 First Beams
Getting ready for data taking by the time the LHC programme reaches completion



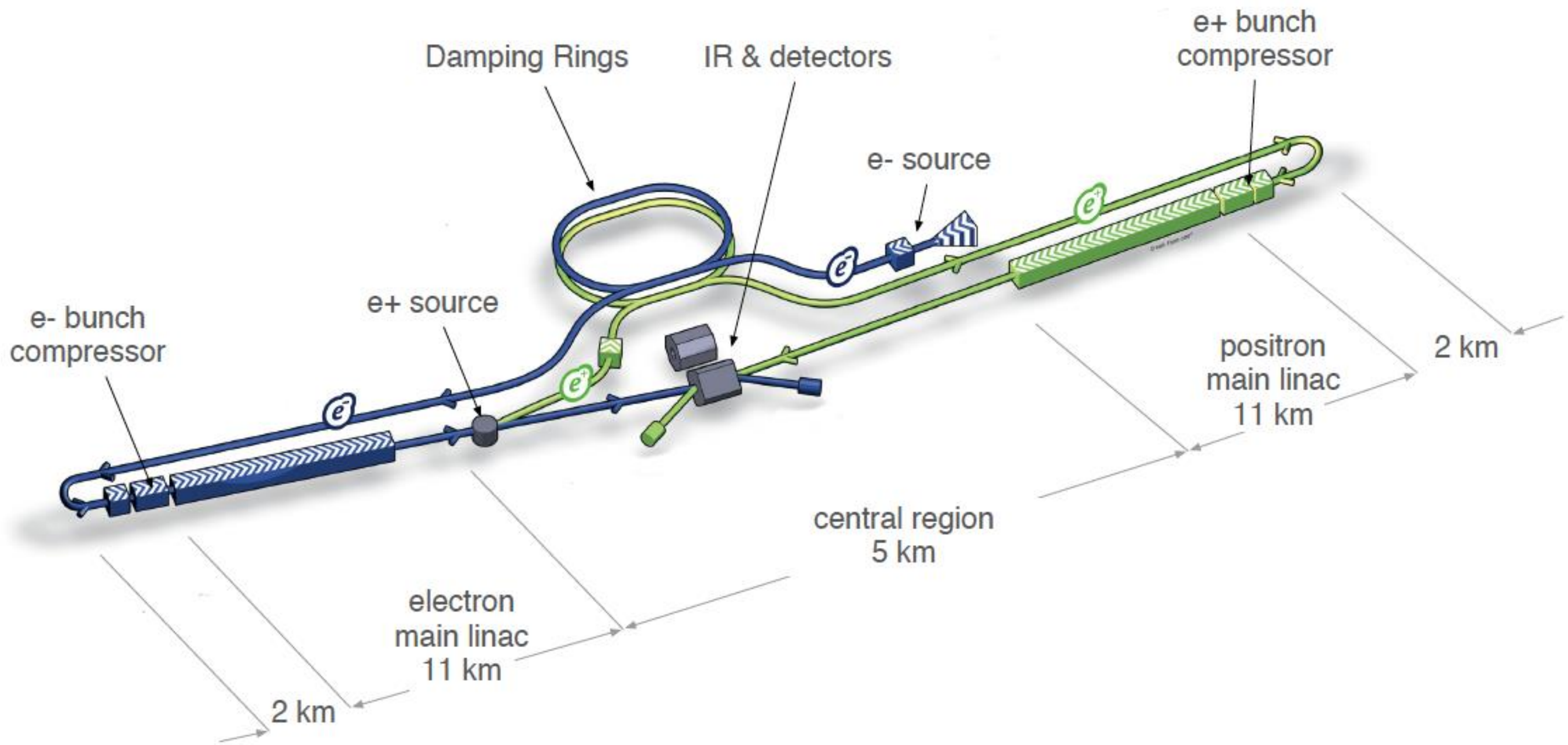
ILC Collaborations

ILC in Japan

Kitakami mountains



ILC layout



8370 superconducting cavities in 930 cryo-modules
Gradient 31.5 MV/m   RF Frequency 1.3 GHz
Beam polarization: e- 80%, e+ 30%

ILC parameters

Quantity	Unit	ILC250	ILC500	ILC1000
Centre-of-mass energy	GeV	250	500	1000
Luminosity	$10^{34} cm^{-2} s^{-1}$	1.35	1.8	4.9
Repetition frequency	Hz	5	5	4
Bunches per pulse	1	1312	1312	2450
Bunch population	10^{10} e-	2	2	1.74
Linac bunch interval	ns	554	554	366
Beam current in pulse	mA	5.8	5.8	7.6
Beam pulse duration	s	727	727	897
Average beam power	MW	5.3	10.5	27.2
Norm. hor. emitt. at IP	μm	5	10	10
Norm. vert. emitt. at IP	nm	35	35	35
RMS hor. beam size at IP	nm	516	474	335
RMS vert. beam size at IP	nm	7.7	5.9	2.7
Site AC power	MW	129	163	300
Site length	km	20.5	31	40

Extendability built-in

Going fom 250 GeV to 1 TeV

ILC Site & Infrastructure

- 67 km maximal length of tunnel
- Beam dumps, etc designed for 1 TeV operation
- Overall recommended ILC power limit for the 1 TeV ILC : 300 MW

Luminosity upgrades

- Straightforward: Increasing the number of bunches from 1312 to 2624
- Power Increase 129 MW → 164 MW

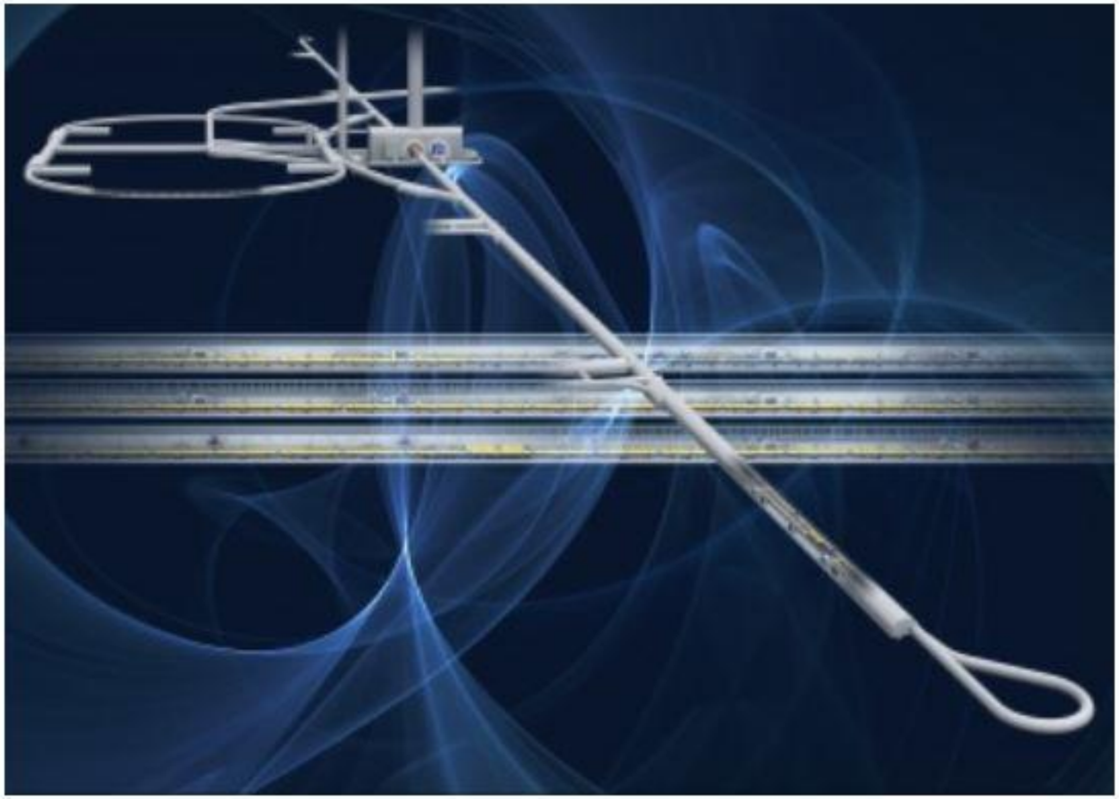
Energy upgrades

- Energy upgrades to 350 GeV ($t\bar{t}$ threshold) and ~500 GeV being discussed
- 1 TeV for longer-term plan

DESY. | ILC |103rd Plenary ECFA |Marcel Stanitzki

DIRECTOR'S UPDATE

Clarifications on the report from the Science Council of Japan regarding the ILC



The report released by the Science Council of Japan on 19 December on the realisation of the ILC raised many questions within the linear collider community. The ILC Planning Office at KEK asks for continuing support.

Special issue

21 December 2019

LC NEWSLINE

THE NEWSLETTER OF THE LINEAR COLLIDER COMMUNITY

What does this report mean to the ILC project ?

http://newsline.linearcollider.org/

Comparison

Parameter	Symbol [unit]	SLC	ILC	CLIC
Centre of mass energy	E_{cm} [GeV]	92	500	3000
luminosity	L [$10^{34}cm^{-2}s^{-1}$]	0.0003	1.8	6
Luminosity in peak	$L_{0.01}$ [$10^{34}cm^{-2}s^{-1}$]	0.0003	1	2
Gradient	G [MV/m]	20	31.5	100
Particles per bunch	N [10^9]	37	20	3.72
Bunch length	σ_z [μm]	1000	300	44
Collision beam size	$\sigma_{x,y}$ [nm/nm]	1700/600	474/5.9	40/1
Vertical emittance	$\varepsilon_{x,y}$ [nm]	3000	35	20
Bunches per pulse	n_b	1	1312	312
Distance between bunches	Δz [mm]	-	554	0.5
Repetition rate	f_r [Hz]	120	5	50

Other possible future linear colliders

LWFA = Laser Wake Field Accelerator
=> *Wakefields driven in plasma by intense laser beams*

PWFA = Plasma Wake Field Accelerator
=> *Wakefields driven in plasma by particle beams*

SWFA = Structure Wake Field Accelerator
=> *Wakefields driven in structures (*dielectric tubes*) by particle beams*

DLA = Dielectric Laser Accelerator
=> *Wakefields driven in dielectric structures by short-pulse laser*

Gamma-gamma factory:
=> e- e- collisions
=> e- ions collisions (partially stripped ions)

Seminars on future linear colliders

JUAS Seminar on Particle accelerators (European context)
16th January 2019 by M. Vretenar / CERN

JUAS Seminar on Novel high gradient particle accelerator
30th January 2019 by R. Aβmann / DESY

[EAAC workshop – Elba - Italy]

EAAC 2017 3rd European Advanced Accelerator Concepts Workshop

ICFA

ALEGRO 2018

ALEGRO for Advanced LinEar collider study GROup, has been set up to coordinate preparation of **proposal for an Advanced Linear Collider in multi-TeV energy range**.

Workshop 25-28 April 2017 at CERN
https://indico.cern.ch/event/569406/

Workshop 26-29 March 2018 at University of Oxford, JAI
https://indico.cern.ch/event/677640/overview

Future workshop at CERN 26-29 March 2019

https://indico.cern.ch/event/732810/overview

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

Table 4: Parameters for Single Pass Muon collider

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

1-3 July 2018
Università di Padova - Orto Botanico

Muon Collider workshop Italy

Muon colliders

Carlo Rubia / INFN / CERN
Padova workshop 2018

Advantages

- Large cross sections σ ($\mu^+\mu^- \to h$) = 35 pb in s-channel resonance and 0.2 pb for $\mu^+\mu^- \to ZH$ of at ≈ ½ TeV.
- Small size footprint: they may fit within the ESS site
- No synchrotron radiation and beamstrahlung problems
- Precise measurements of line shape and total decay width Γ
- Exquisite measurements of all channels and tests of SM.
- The cost of the facility, provided cooling will be successful, is of the order of a fraction of one of the LHC.

Challenges

- A low cost demonstration of muon cooling must be done first
- Muon 2D and 3D cooling needs to be demonstrated
- Need ultimately very small c.o.m energy spread (0.003%)
- Backgrounds from constant muon decay
- Significant R&D required towards end-to-end design

Questions for a future high energy linear collider

For electron-positron collisions, what are the goals for the energy and the luminosity ? Probably the higher is better but for a future project, the justifications are crucial (cost, power consumption,….)

For gamma-gamma collisions, some issues relative to positrons can be solved and beamstrahlung limit can be avoided. Can one justify a stand-alone project ?

For the Novel Acceleration Technologies, what are the remaining R&D's to make a jump between the facility and the real machine ?

For a future high energy linear colliders => which types of particles ?

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 is very exciting !!!

Conclusion

The forthcoming physic results are decisive to define a precise roadmap for the future.

For an high energy collider, we cannot test and demonstrate everything => various test facilities are essential.

Two crucial parameters: make high energies cheaper and increase the luminosity as much as possible.

Try to make credible an high energy collider.

JUAS students are the future machine builders …..

…. for future high energy particle accelerators !

Acknowledgments

Several slides from:

F. Gianotti, A. Latina, P. Mugli, T. Omori, C. Rubia,
D. Schulte, J. Sheppard, S. Stapnes, M. Stanitzki,
F. Zimmermann

Spares

CLIC Cost

Domain	Sub-Domain	Cost [MCHF] Drive-Beam	Cost [MCHF] Klystron
Main Beam Production	Injectors	175	175
	Damping Rings	309	309
	Beam Transport	409	409
Drive Beam Production	Injectors	584	—
	Frequency Multiplication	379	—
	Beam Transport	76	—
Main Linac Modules	Main Linac Modules	1329	895
	Post decelerators	37	—
Main Linac RF	Main Linac Xband RF	—	2788
Beam Delivery and Post Collision Lines	Beam Delivery Systems	52	52
	Final focus, Exp. Area	22	22
	Post-collision lines/dumps	47	47
Civil Engineering	Civil Engineering	1300	1479
Infrastructure and Services	Electrical distribution	243	243
	Survey and Alignment	194	147
	Cooling and ventilation	443	410
	Transport / installation	38	36
Machine Control, Protection and Safety systems	Safety system	72	114
	Machine Control Infrastructure	146	131
	Machine Protection	14	8
	Access Safety & Control System	23	23
Total (rounded)		**5890**	**7290**

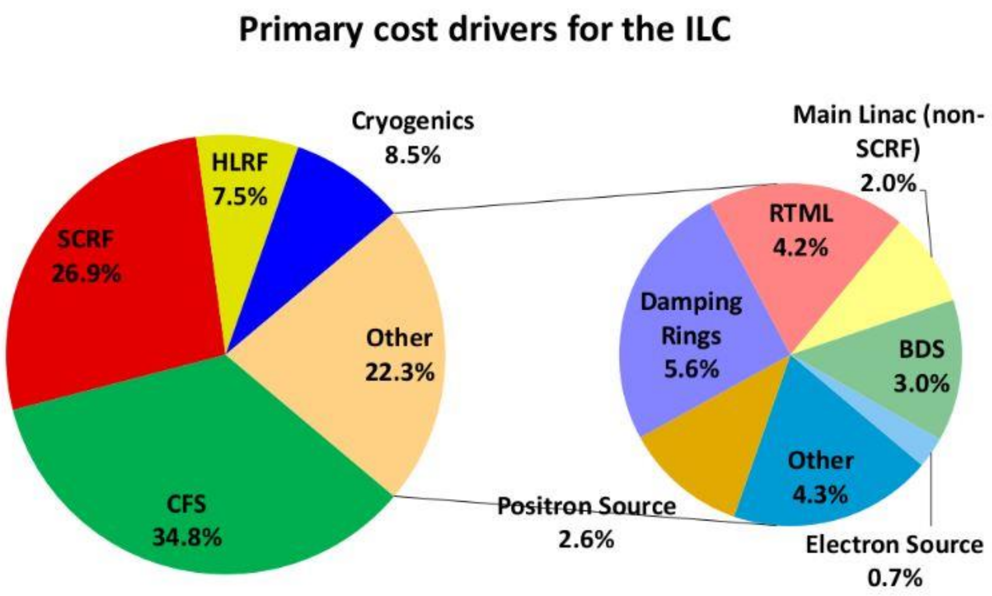
ILC Cost

Accelerator Costing

ILC250 Baseline

ILC costing model

- Established for the TDR
  - Including set-up and learning curves
- TDR (500 GeV)
  - 7.98 Billion US-$
- Updates since
  - All experiences from the E-XFEL, ESS, LCLS-II
  - Higher Gradient Cavities
- ILC 250 baseline
  - 40% cost reduction
  - 1/3 Construction (CFS)



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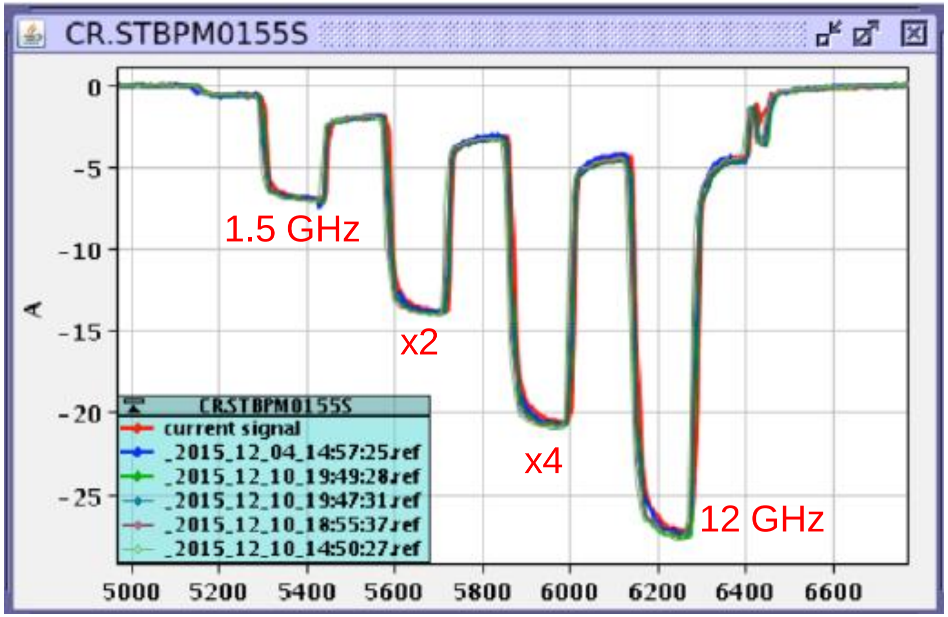
Page 19

Results obtained in CTF3

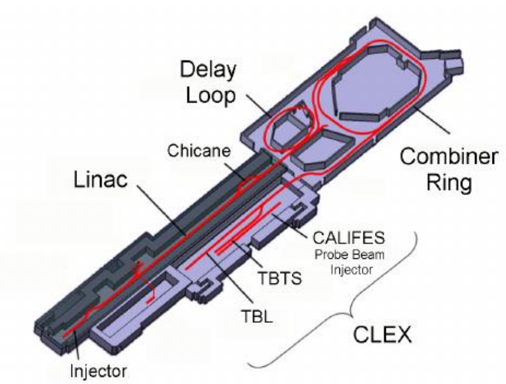
Drive beam quality:
Produced high-current drive beam bunched at 12GHz



← 28A

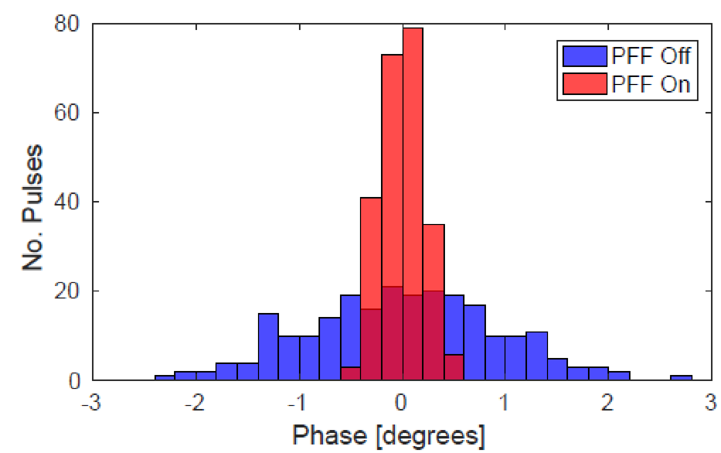
Current in combiner ring

Drive beam arrival time stabilised to CLIC specification of 50fs:



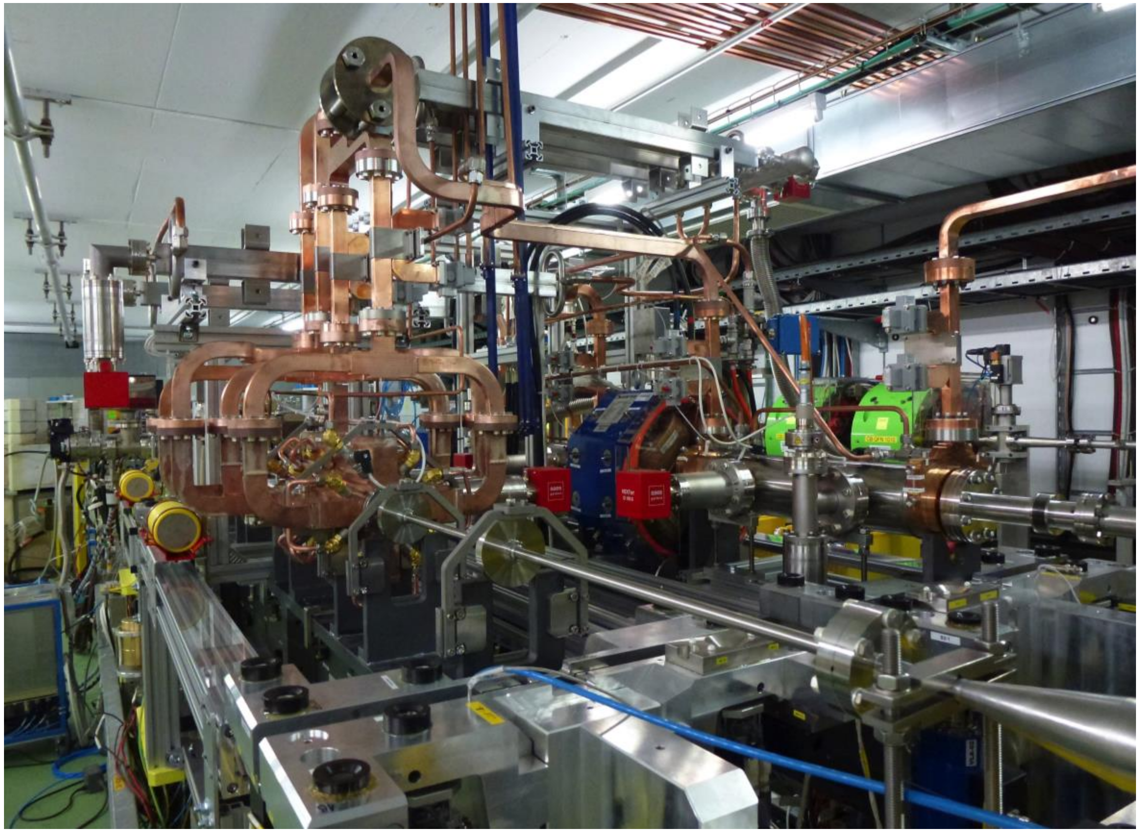
Examples of measurements from CTF3 (CLIC Test Facility)

CTF3 modified => CLEAR (CERN Linear Electron Accelerator for Research)

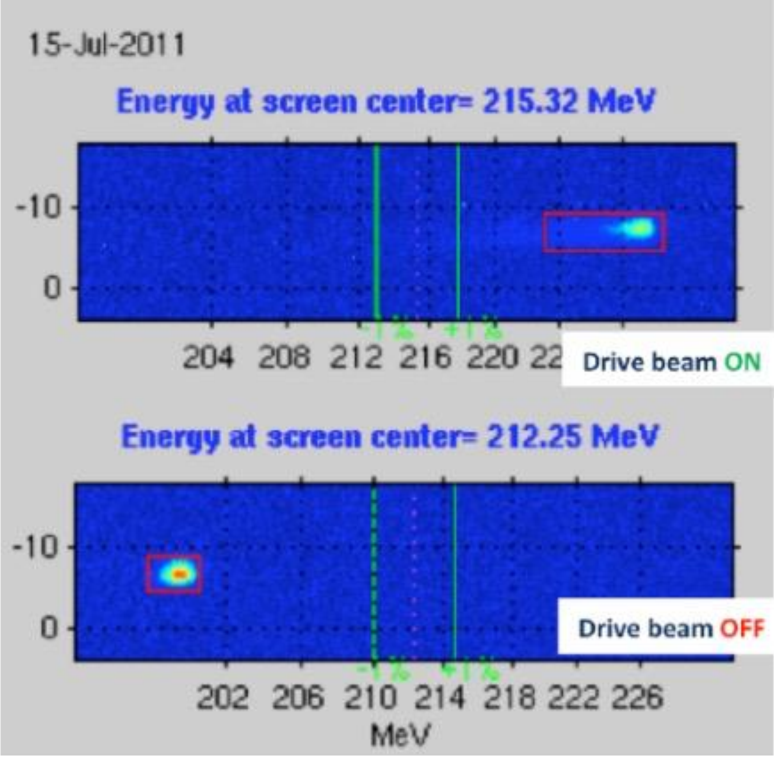


Results obtained in CTF3

Demonstrated 2-beam acceleration



31MeV = 145MV/m



Accelerator challenges

X-band performance: achieved 100MV/m gradient in main-beam RF cavities

Key challenges:

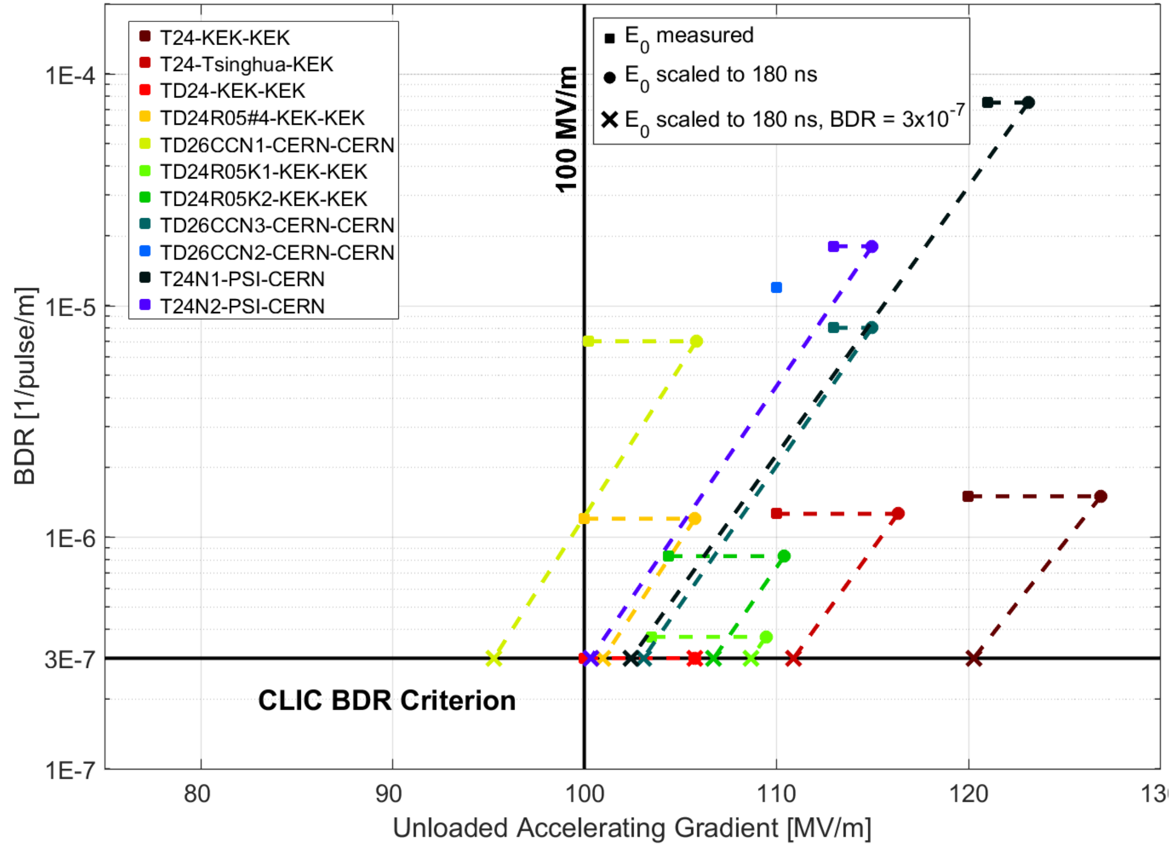
High-current drive beam bunched at 12 GHz

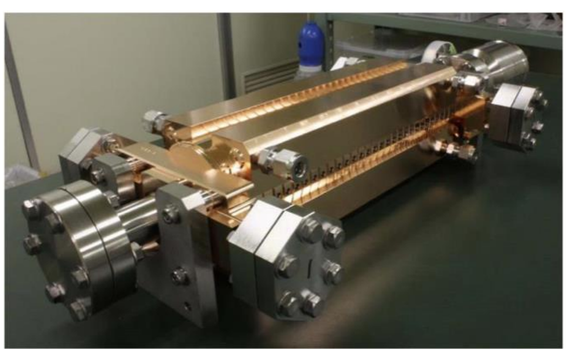
Power transfer + main-beam acceleration

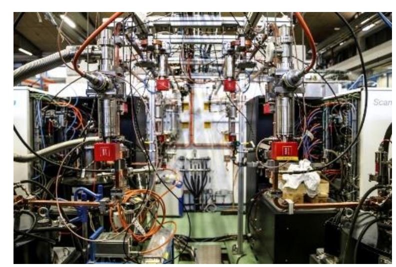
~100 MV/m gradient in main-beam cavities

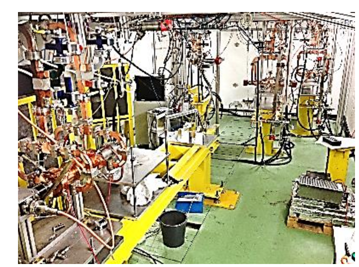
Low emittance generation

Alignment & Stability









Accelerator challenges

Nano-beams

Key challenges:

High-current drive beam bunched at 12 GHz

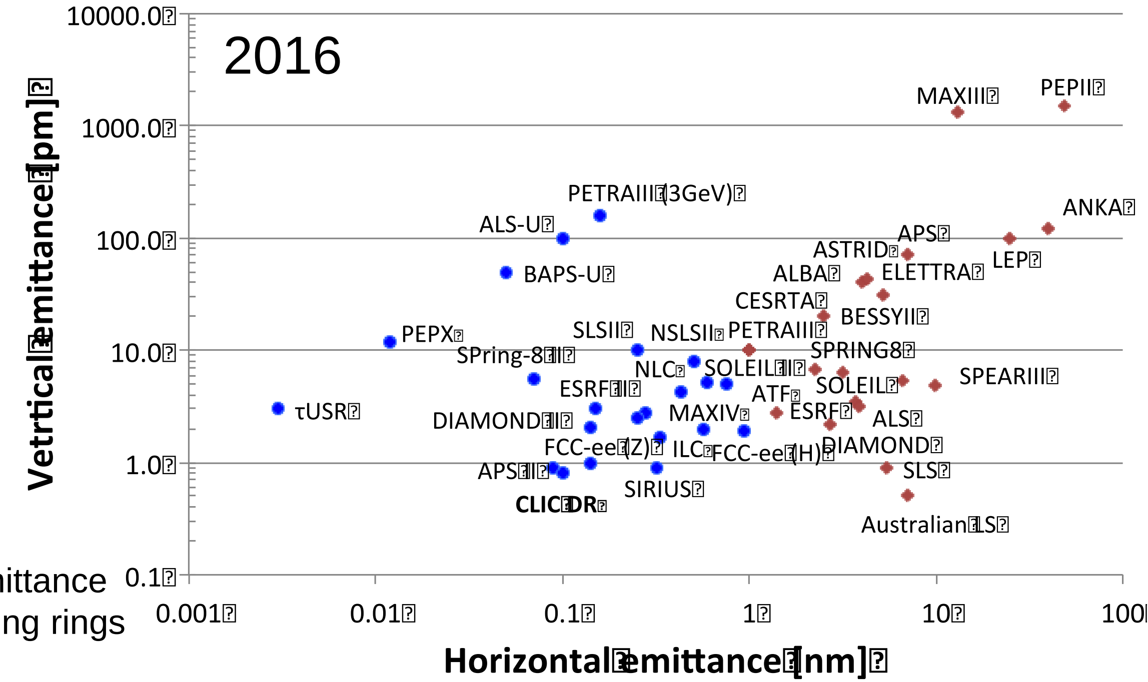
Power transfer + main-beam acceleration

~100 MV/m gradient in main-beam cavities

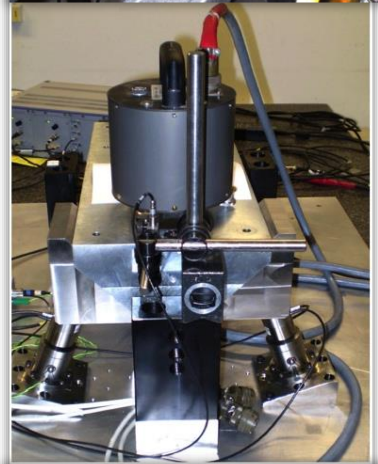
Low emittance generation

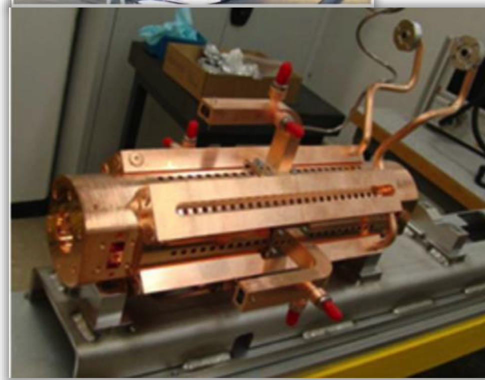
The CLIC strategy:

- Align components (10μm over 200m)
- Control/damp vibrations (from ground to accelerator)
- Measure beams well – allow to steer beam and optimize positions
- Algorithms for measurements, beam and component optimization, feedbacks
- Tests in existing accelerators of equipment and algorithms (FACET at Stanford, ATF2 at KEK, CTF3, Light-sources)



CLIC emittance at damping rings





European Strategy Input

Updated Baseline for a Staged Compact Linear Collider ✓
arXiv: 1608.07537, CERN-2016-004

Higgs Physics at the CLIC Electron-Positron Linear Collider ✓
arXiv: 1608.07538, Eur. Phys. J. C77 (2017) 475

The optimised CLIC detector model CLICdet
CLICdp-Note-2017-001 ✓ and CLICdet detector validation note ✓

Top-quark physics at the CLIC electron-positron linear collider ✓
arXiv: 1807.02441, in journal review

CLIC Project Implementation Plan
2018

The CLIC Potential for New Physics
2018

Detector Technologies for CLIC
early 2019

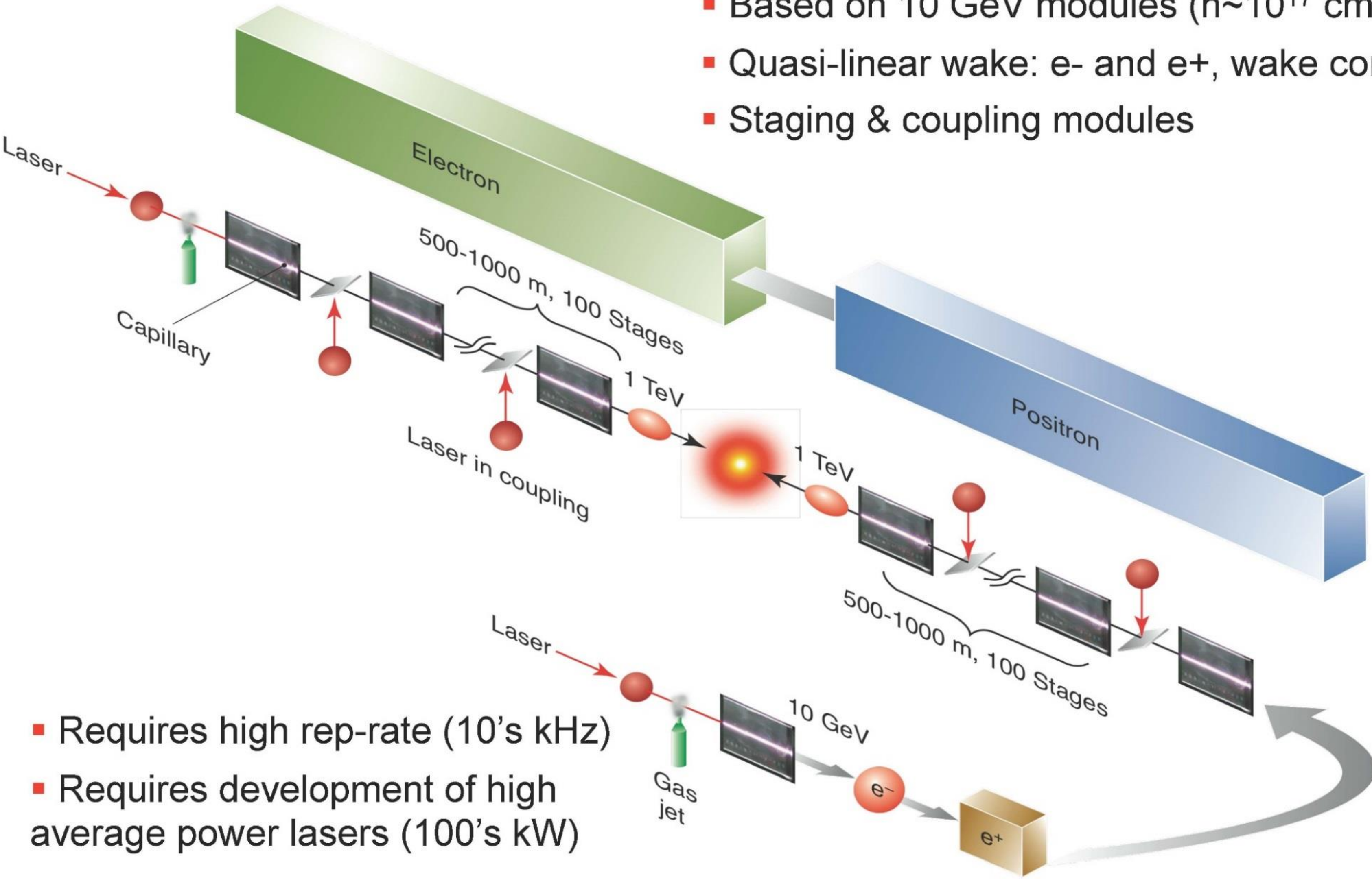
Four new CERN Yellow Reports

CLIC 2018 Summary Report
2018

Official short ESU submissions (~10 pages):
1) CLIC project (accelerator + detector)
2) CLIC physics

Laser Wake Field linear collider

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



- Requires high rep-rate (10's kHz)
- Requires development of high average power lasers (100's kW)

W.P. Leemans & E. Esarey, Physics Today, March 2009

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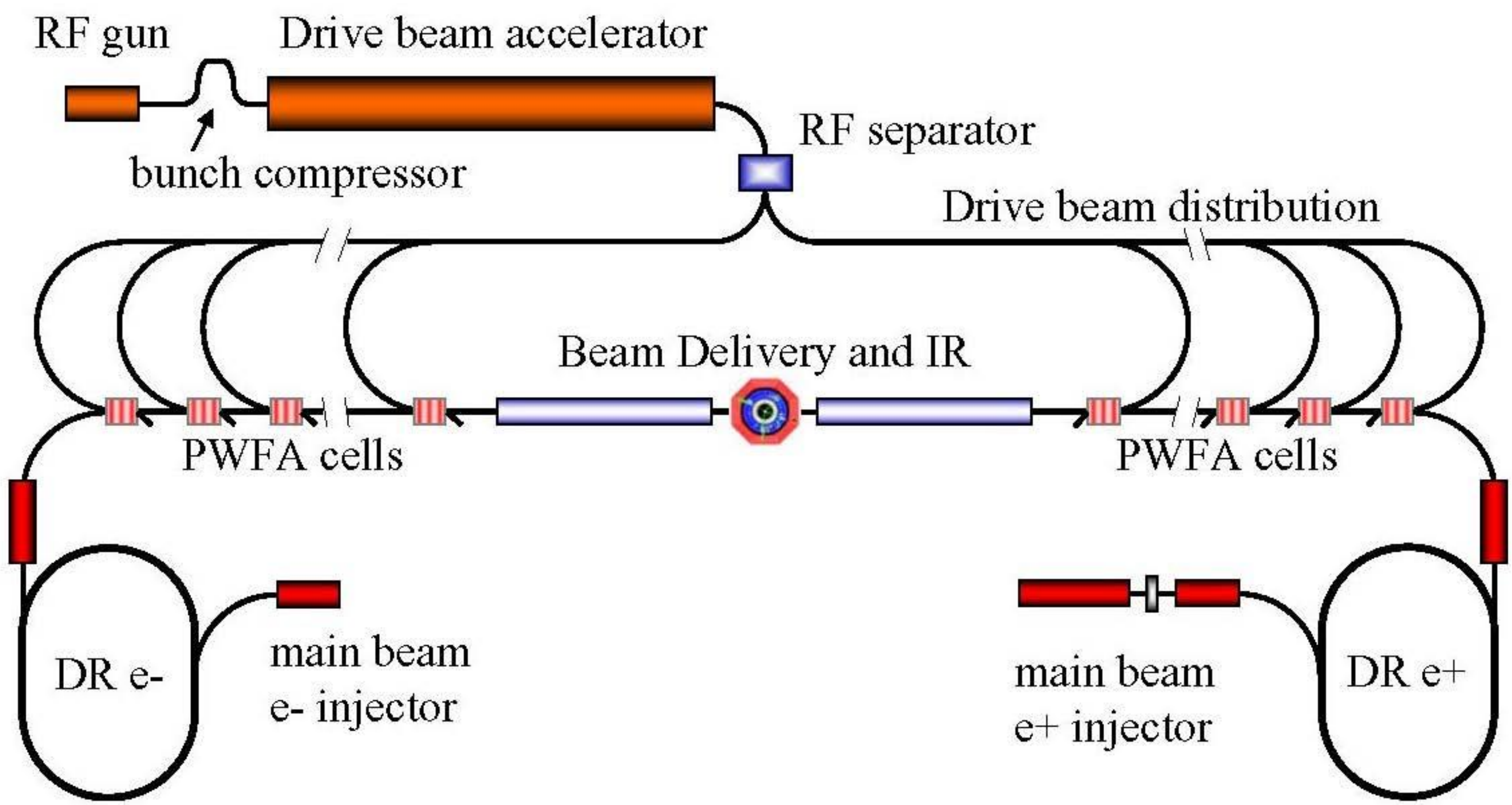
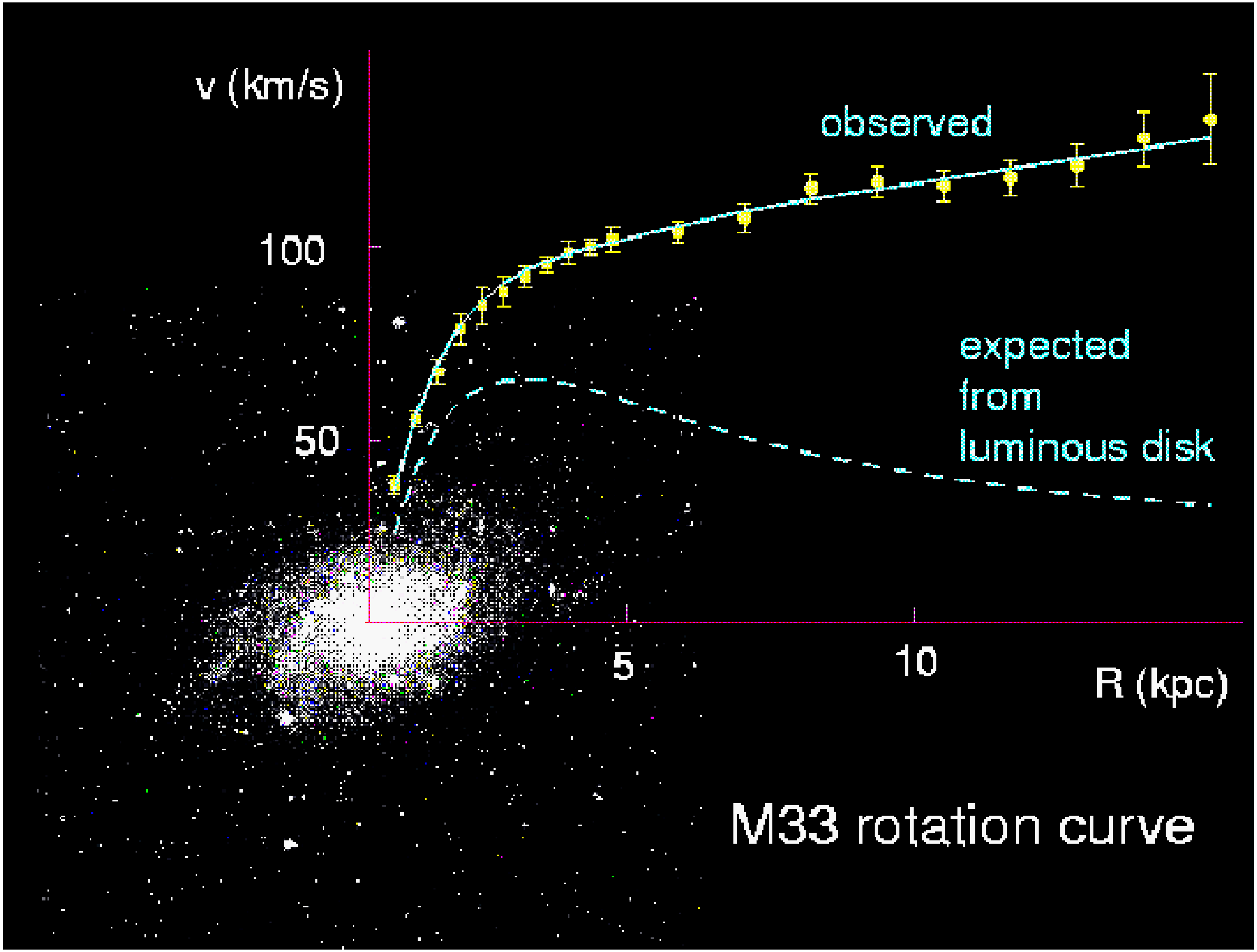
Plasma Wake Field linear collider

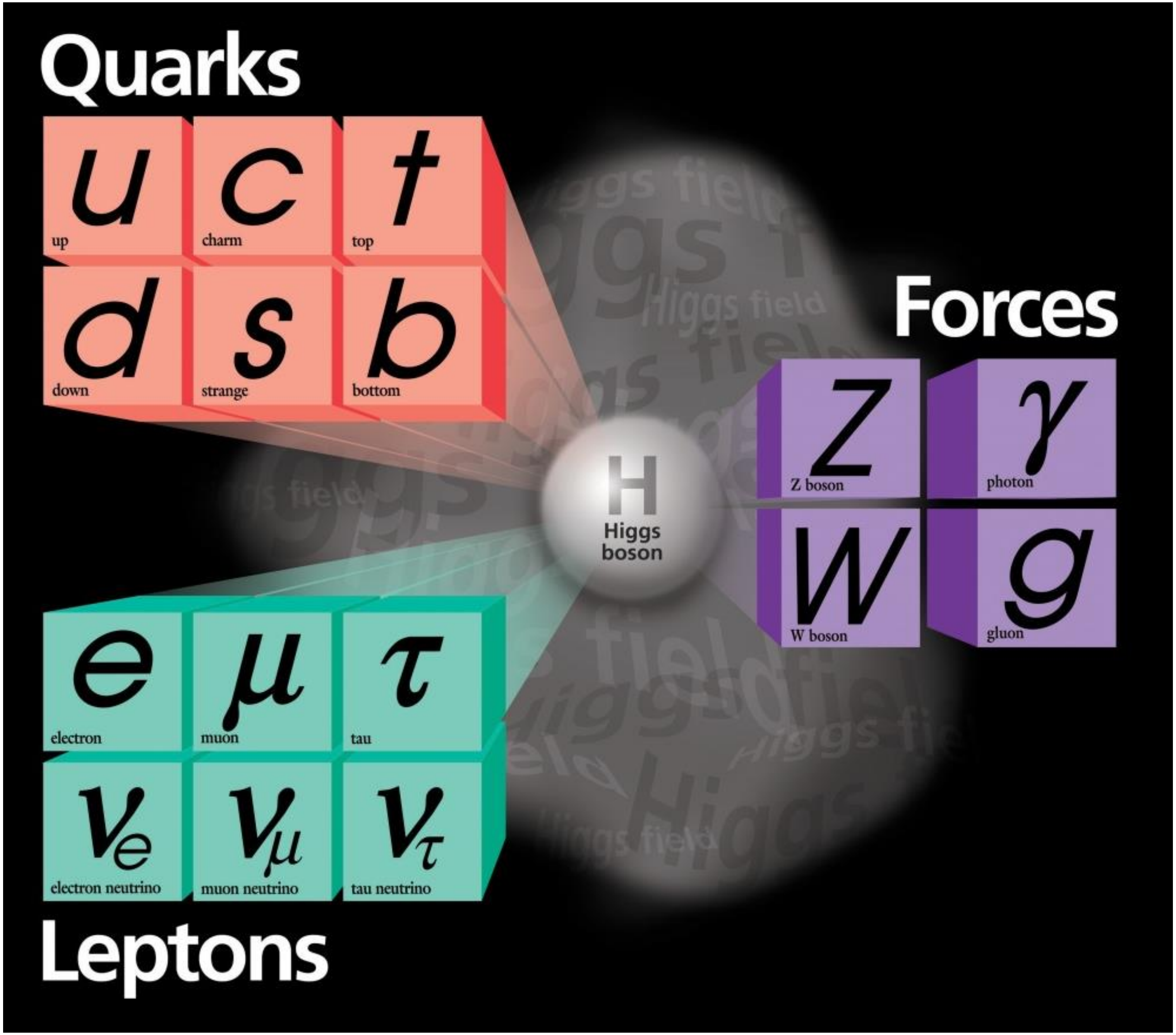


Concept for a multi-stage PWFA-based Linear Collider (A. Seryi, T. Raubenheimer et al., 2009)

Dark matter



Corbelli & Salucci (2000);
Bergstrom (2000)


Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
Forces
Z
Z boson
γ
photon
W
W boson
g
gluon
H
Higgs boson
e
electron
μ
muon
τ
tau
νe
electron neutrino
νμ
muon neutrino
ντ
tau neutrino
Leptons
Higgs field