High energy frontier: Linear colliders ILC – CLIC

Lenny Rivkin
PSI & EPFL

CERN Council open session in Bruxelles adopted the European Particle Physics Strategy Update in May 2013

Three points worth noting

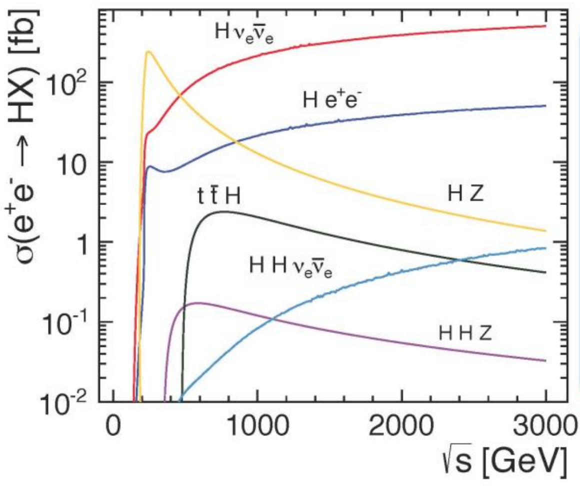
- It sets the priority for the large projects explicitly stating four issues which should be done, rather than discussing all the projects we would like to do
- While expressing the European ambitions, i.e. physics at the highest energy (exploitation of LHC and R&D for the post LHC machines), declaring the readiness of Europe to participate in the large projects outside of Europe in a concrete way (ILC construction in Japan, long baseline experiment in the US or Japan)
- Unique opportunities at the national laboratories (worldwide) are fully acknowledged and encouraged for the precision experiments

Physics at Linear Colliders from 250 GeV to 3000 GeV

- **Physics case for the Linear Collider:**
  - **Higgs physics (SM and non-SM)**
  - **Top**
  - SUSY
  - Higgs strong interactions
  - New Z’ sector
  - Contact interactions
  - Extra dimensions
  - ….

Stage 1: ~350-375 GeV => Higgs and top physics
Stage 2: ~1.5 TeV => ttH, ννHH + New Physics (lower mass scale)
Stage 3: ~3 TeV => New Physics (higher mass scale)

Higgs boson Production Cross-Sections



Several thresholds:

126 GeV Hνν, He^+e^-

217 GeV HZ

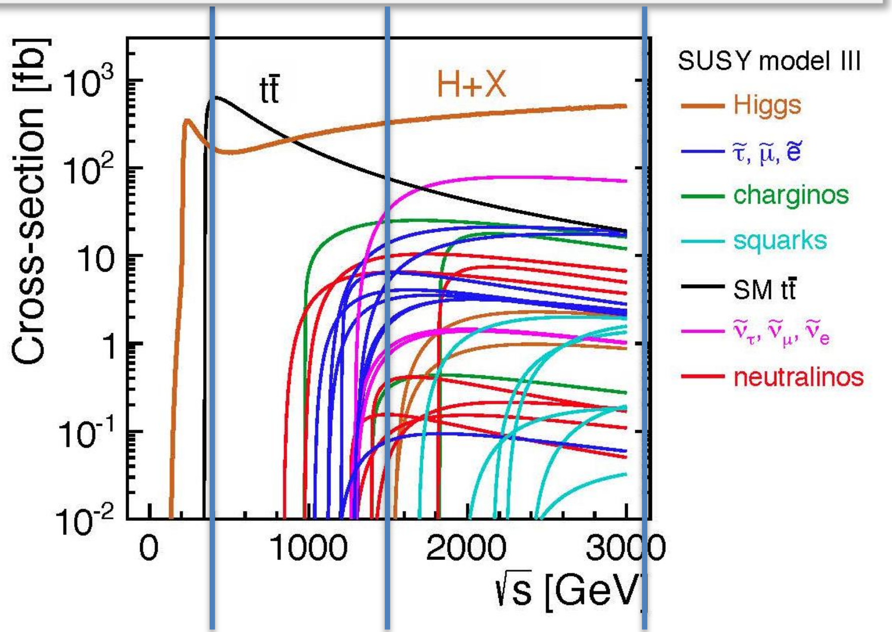
252 GeV HHνν

343 GeV HHZ

472 GeV Htt

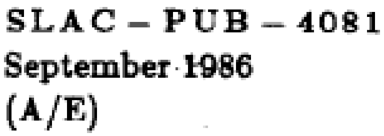
Optimization determines optimal signal to bkgd

Lebrun et al., arXiv:1209.2543



ILC ⇒ CLIC

Pushing high energy frontier with linear collider



SLAC – PUB – 4081
September 1986
(A/E)

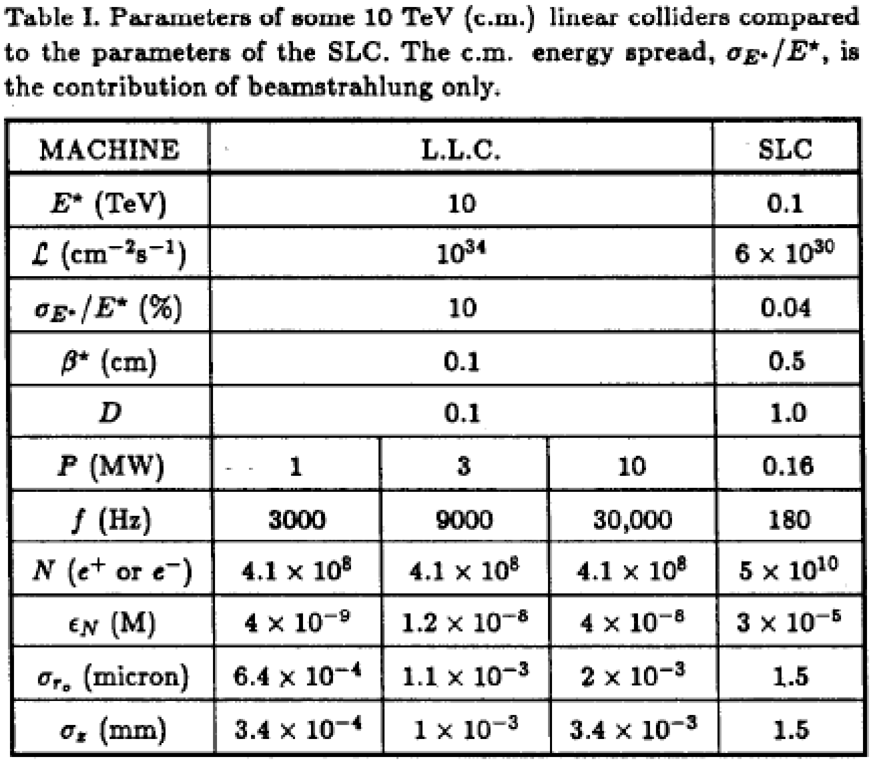
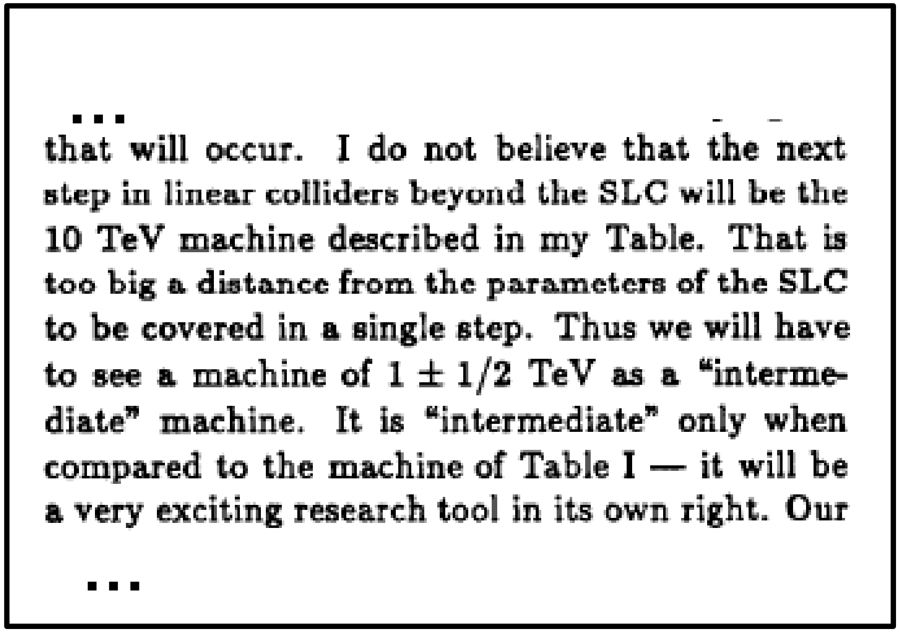


Table I. Parameters of some 10 TeV (c.m.) linear colliders compared to the parameters of the SLC. The c.m. energy spread, σ_{E^*}/E^*, is the contribution of beamstrahlung only.

MACHINE	L.L.C.			SLC
E^* (TeV)	10			0.1
$\mathcal{L}$ ($cm^{-2}s^{-1}$)	10^{34}			6×10^{30}
σ_{E^*}/E^* (%)	10			0.04
β^* (cm)	0.1			0.5
D	0.1			1.0
P (MW)	1	3	10	0.16
f (Hz)	3000	9000	30,000	180
N (e^+ or e^-)	4.1×10^8	4.1×10^8	4.1×10^8	5×10^{10}
ϵ_N (M)	4×10^{-9}	1.2×10^{-8}	4×10^{-8}	3×10^{-5}
σ_{r_o} (micron)	6.4×10^{-4}	1.1×10^{-3}	2×10^{-3}	1.5
σ_z (mm)	3.4×10^{-4}	1×10^{-3}	3.4×10^{-3}	1.5



…

that will occur. I do not believe that the next step in linear colliders beyond the SLC will be the 10 TeV machine described in my Table. That is too big a distance from the parameters of the SLC to be covered in a single step. Thus we will have to see a machine of 1 ± 1/2 TeV as a "intermediate" machine. It is "intermediate" only when compared to the machine of Table I — it will be a very exciting research tool in its own right. Our

…

Burt Richter

The context of the LC projects – strategy

European Strategy priorities related to the Energy Frontier:

LHC and LHC luminosity upgrades (until ~2030)

- Higgs and Beyond the Standard Model physics in long term programme

BSM – does it show up at LHC at 14 TeV, 2015 onwards ?

- What are the best machines to access such physics directly post-LHC …. we don't know but we can prepare main options the next years towards next strategy update (~2018)
- Two alternatives considered; higher energy hadrons (HE LHC or VHE LHC), or highest possible energy e+e- with CLIC

ILC in Japan, a possibility for exploring the Higgs in detail, starting at 250 GeV

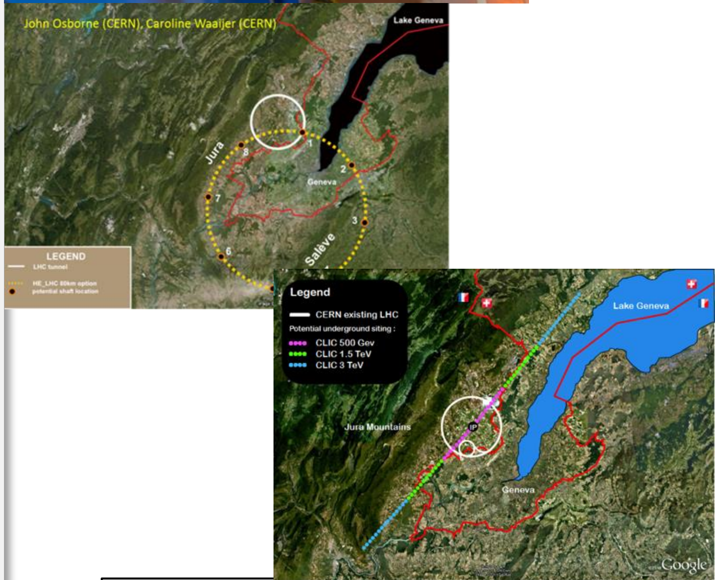
- If implemented a comprehensive programme that can map out the Higgs sector in particular

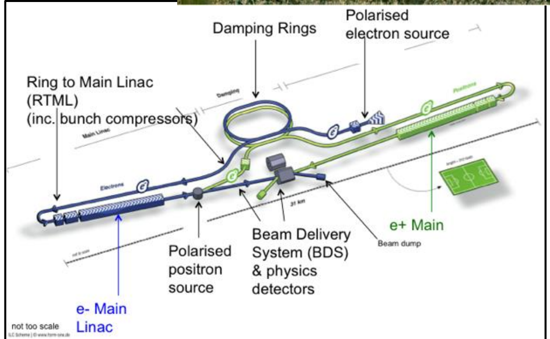
In accordance with this, pursue three connected activities in the period towards 2017-18 (when LHC results at nominal energy are becoming mature):

CLIC as option for the energy frontier

ILC project development – towards a construction project

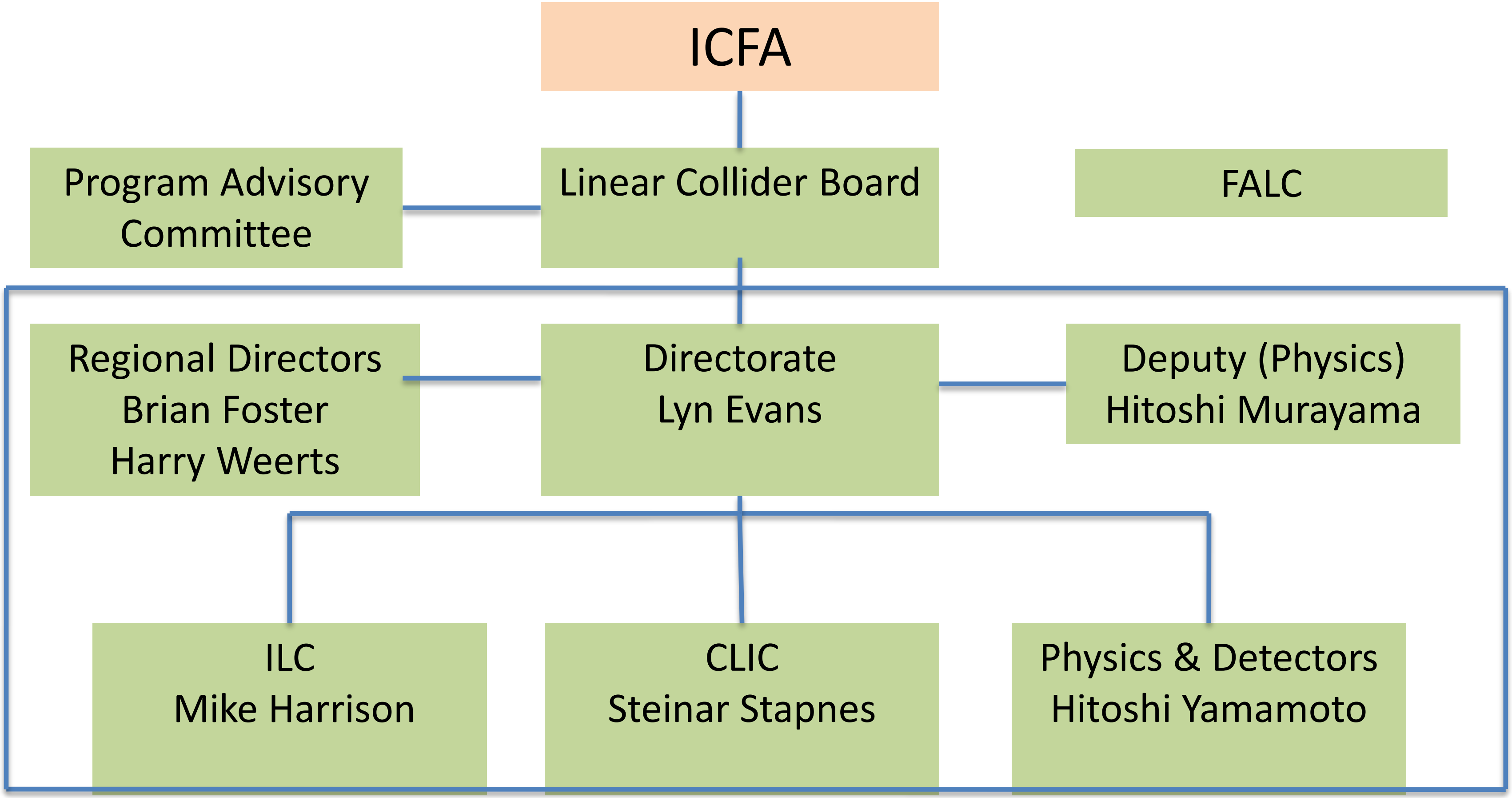
Common activities wherever possible





S. Stapnes

Linear Collider Collaboration Organization



ICFA

Program Advisory Committee

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ILC
Mike Harrison

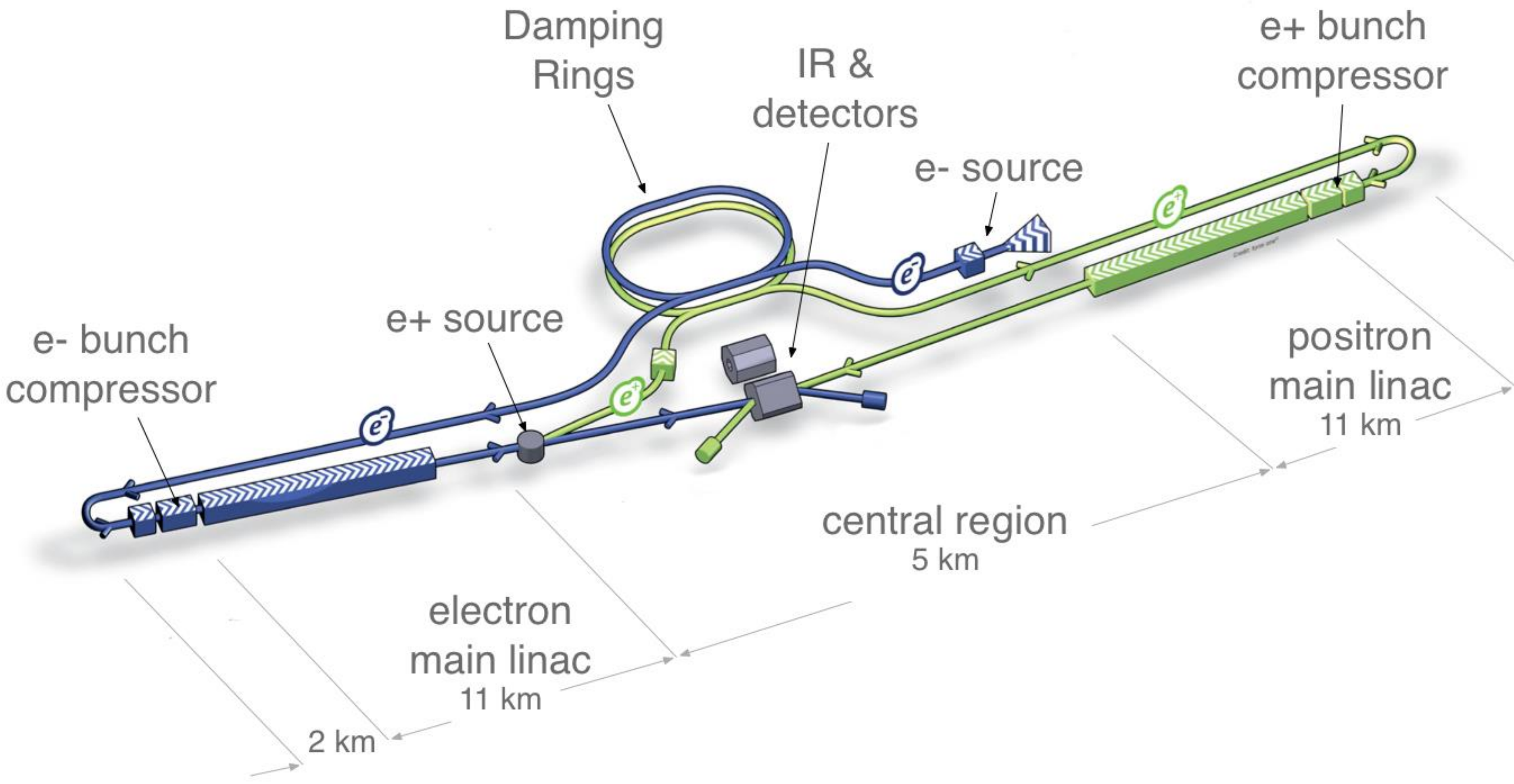
CLIC
Steinar Stapnes

Physics & Detectors
Hitoshi Yamamoto

Linear Collider Collaboration

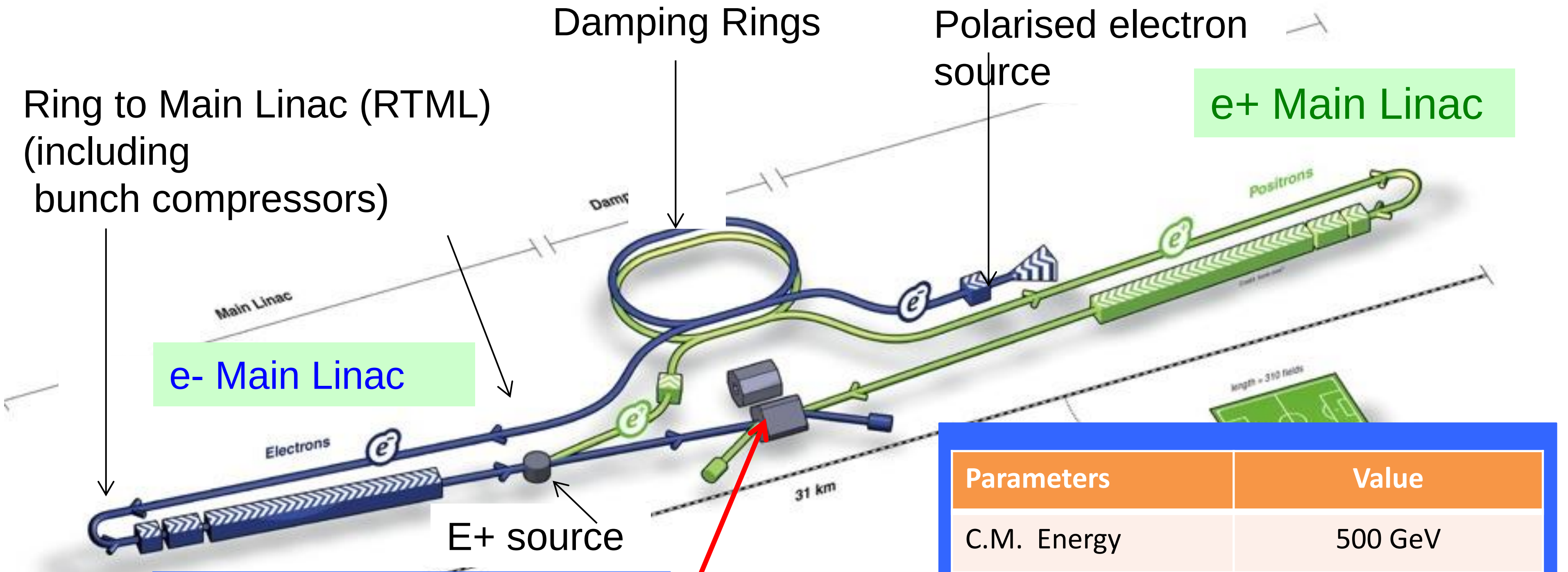
http://www.linearcollider.org

Generic layout of a Linear Collider



ILC Scheme | © www.form-one.de

ILC TDR Layout



Damping Rings

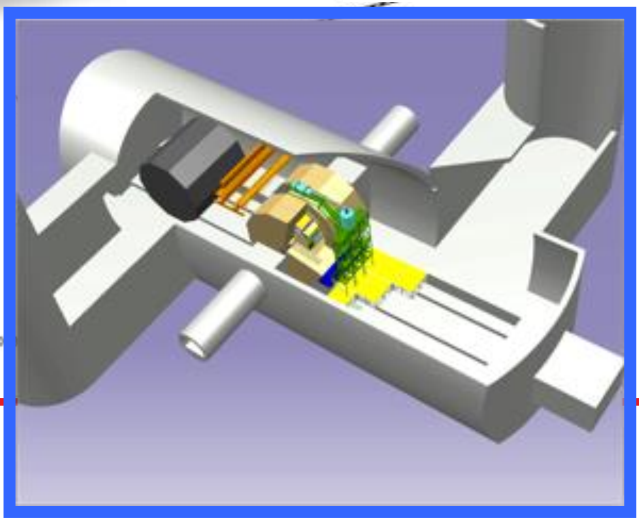
Polarised electron source

e+ Main Linac

Ring to Main Linac (RTML) (including bunch compressors)

e- Main Linac

E+ source

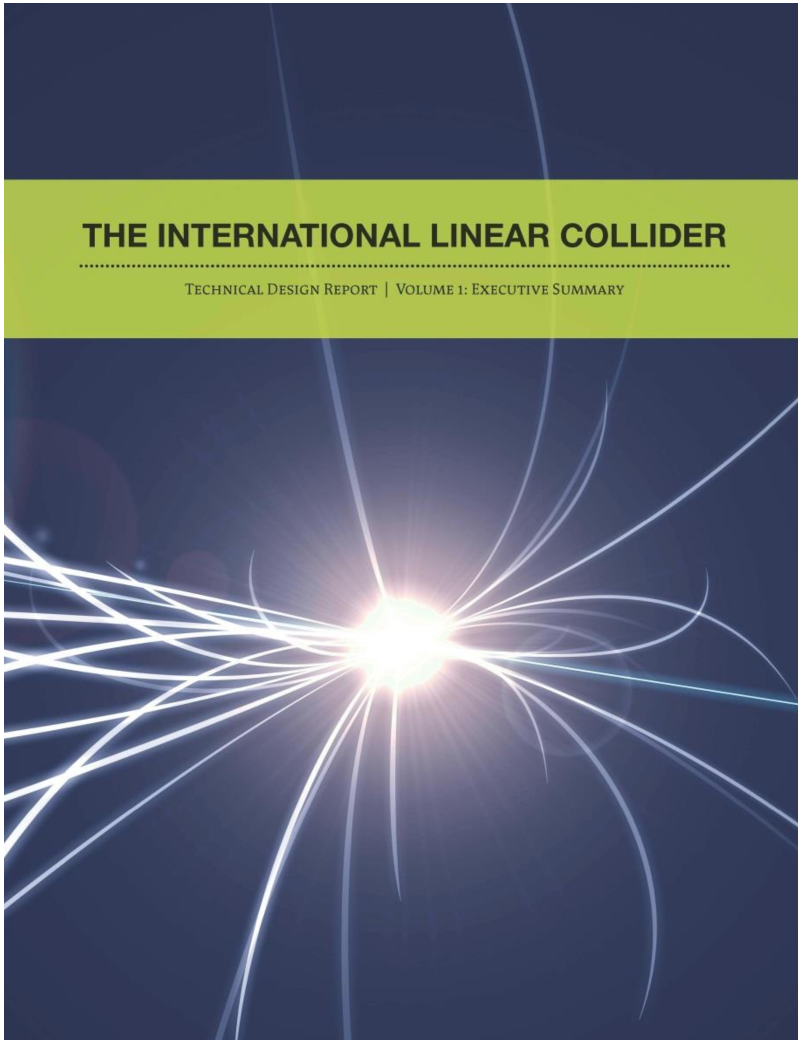


ILC Scheme | © www.form-o

Parameters	Value
C.M. Energy	500 GeV
Peak luminosity	1.8 x10^{34} $cm^{-2}s^{-1}$
Beam Rep. rate	5 Hz
Pulse duration	0.73 ms
Average current	5.8 mA (in pulse)
E gradient in SCRF acc. cavity	31.5 MV/m +/-20% Q_0 = 1E10

ILC Technical Status

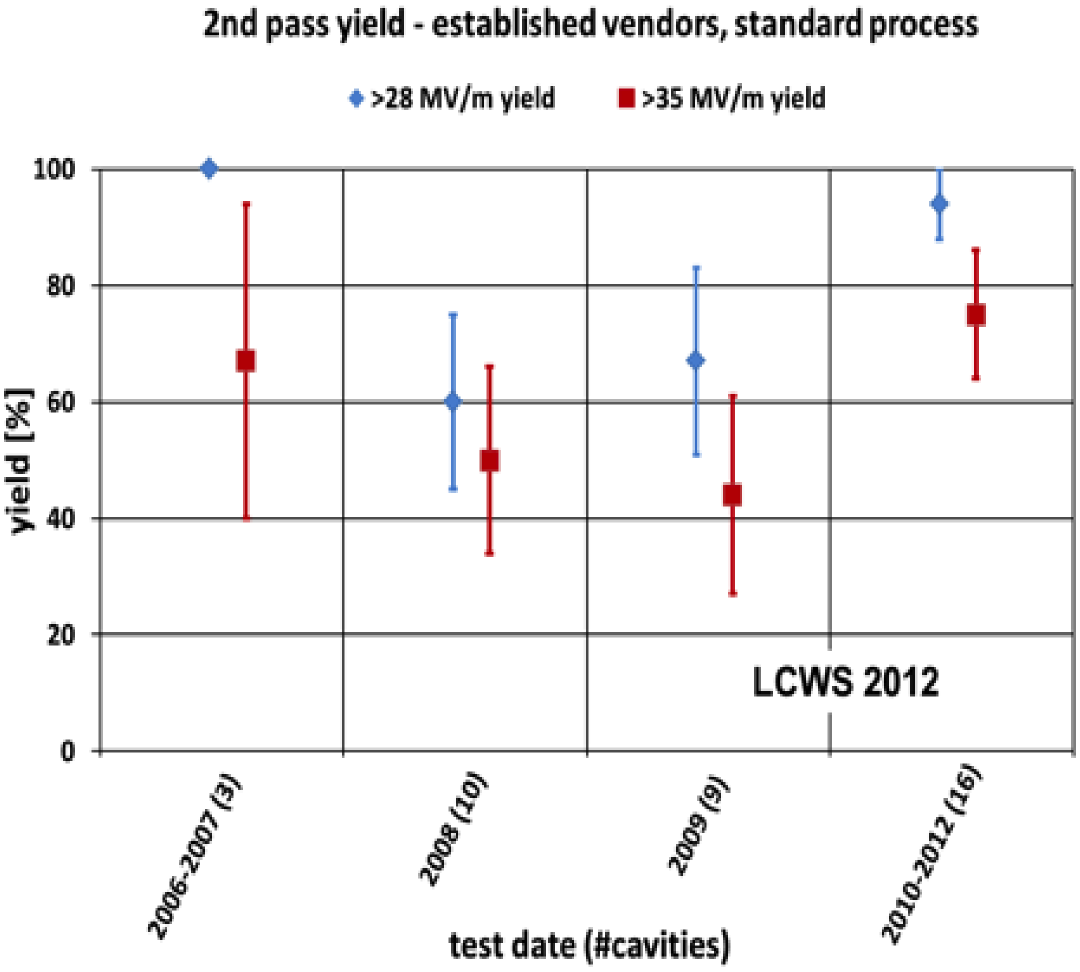
- Technical design completed and TDR published this month.
- Value cost estimate of $7.8B based on the TDR + 22.9M man-hrs of explicit labor (~$2B). Value estimate does not include cost elements such as escalation, contingency, pre-ops, detectors, etc. The costs were reviewed in Jan 2013
- Generic site(s):
  flat terrain & mountainous
- Using "reasonable" assumptions, ~9 years from ground breaking to start of beam commissioning



THE INTERNATIONAL LINEAR COLLIDER

Technical Design Report | Volume 1: Executive Summary

Progress in SCRF Cavity Gradient



Production yield:
94 % at > 28 MV/m,

Average gradient:
37.1 MV/m

reached (2012)

Progress in 1.3 GHz ILC Cavity Production

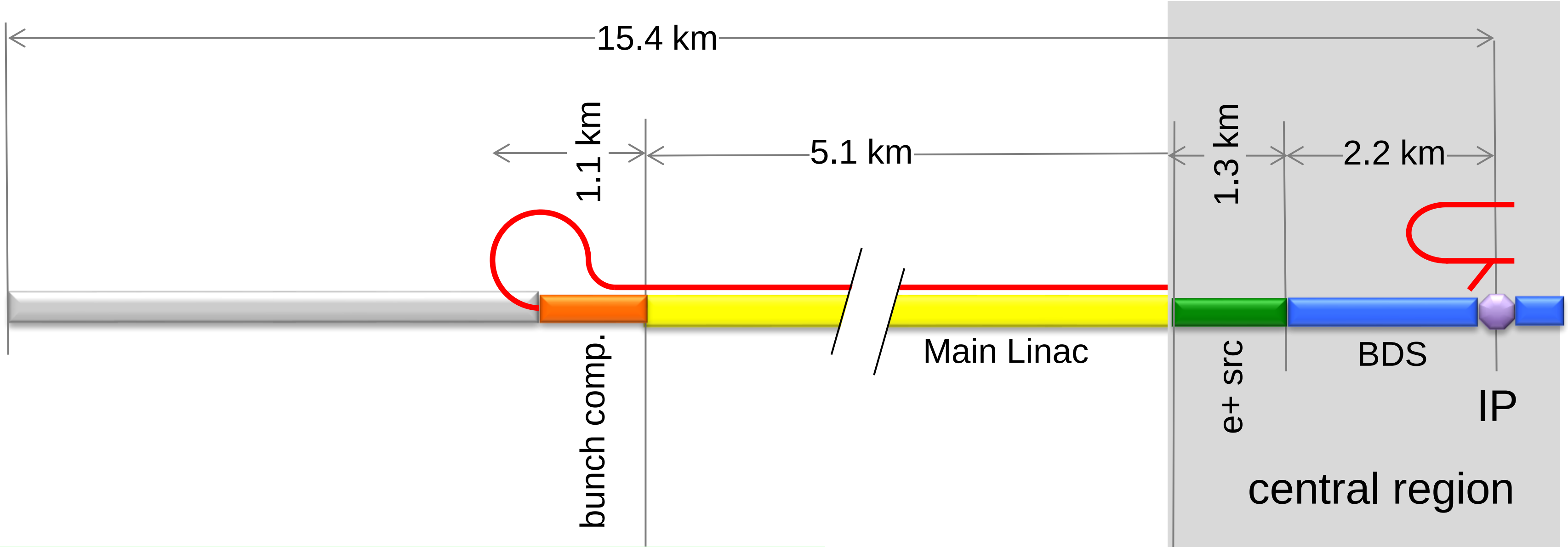
year	# 9-cell cavities qualified	Capable Lab.	Capable Industry
2006	10	1 DESY	2 ACCEL, ZANON
2011	41	4 DESY, JLAB, FNAL, KEK	4 RI, ZANON, AES, MHI,
2012	(45)	5 DESY, JLAB, FNAL, KEK, Cornell	5 RI, ZANON, AES, MHI, Hitachi

- **Progress in EXFEL (800 cavity construction as of 2012/10):**

  (courtesy by D. Reschke: the 2nd EP at DESY)

  - RI: 4 reference cavities with Eacc > 28 MV/m, (~ 39 MV/m max.)
  - Zanon: 3 reference cavities with Eacc > 30 MV/m (~ 35 MV/m max.)

250 GeV staged (scenario 1)

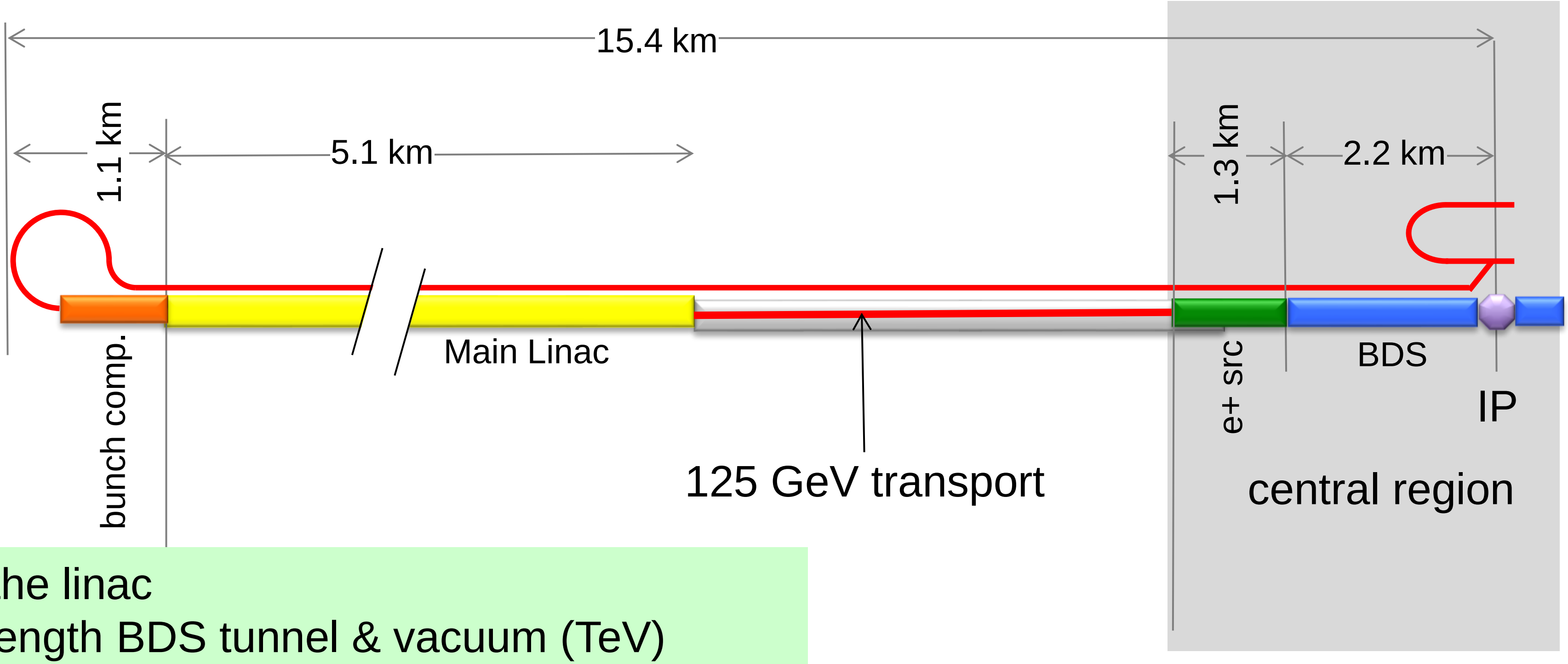


Half the linac
Full-length BDS tunnel & vacuum (TeV)
½ BDS magnets (instrumentation, CF etc)
½ RTML LTL

Extended tunnel/CFS already 500 GeV stage

10Hz mode e- linac

250 GeV staged (scenario 2)



Half the linac
Full-length BDS tunnel & vacuum (TeV)
½ BDS magnets (instrumentation, CF etc)
1 RTML LTL
5km 125 GeV transport line

Extended tunnel/CFS already 500 GeV stage

10Hz mode e- linac

quasi-adiabatic energy upgrade?

Japanese initiative

advantage of this situation.

An Assumption for Numbers of Persons at ILC (whole) Laboratory

(more than the number in TDR)

	Under construction Peak (8Th year.)	Operation start (11Th year.)	In operation (15Th year.)	In operation (20Th year.)
Laboratory Staffs *#1*	1,600	1,200	1,200	1,200
Experiment participants *#2*	500	700	800	1,000
Laboratory Support *#3*	300	300	400	500
Total	2,400	2,200	2,400	2,700

#1**:** including the regular/permanent staff and temporary staff (Post-Doc),
#2: including researchers, engineers and students for two experiments,
#3: including subcontracted specialist to support acc. & exp. activities

Accelerator System Tests

2009 ~

NML (FNAL)

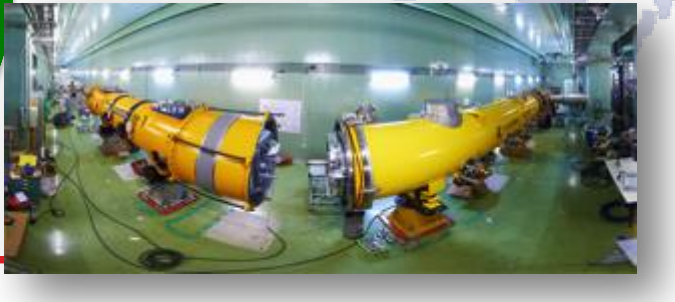
- Under construction
- Up to 6 cryomodules
- Operation: end 2012
  - (3 CM)

FLASH (DESY)

- TDP focus
- 7 CM → 1.2 GeV beam
- photon user facility

STF (KEK)

- "Quantum Beam" experiment 2011
- 1 CM with beam 2013
- (2 CM 2015)

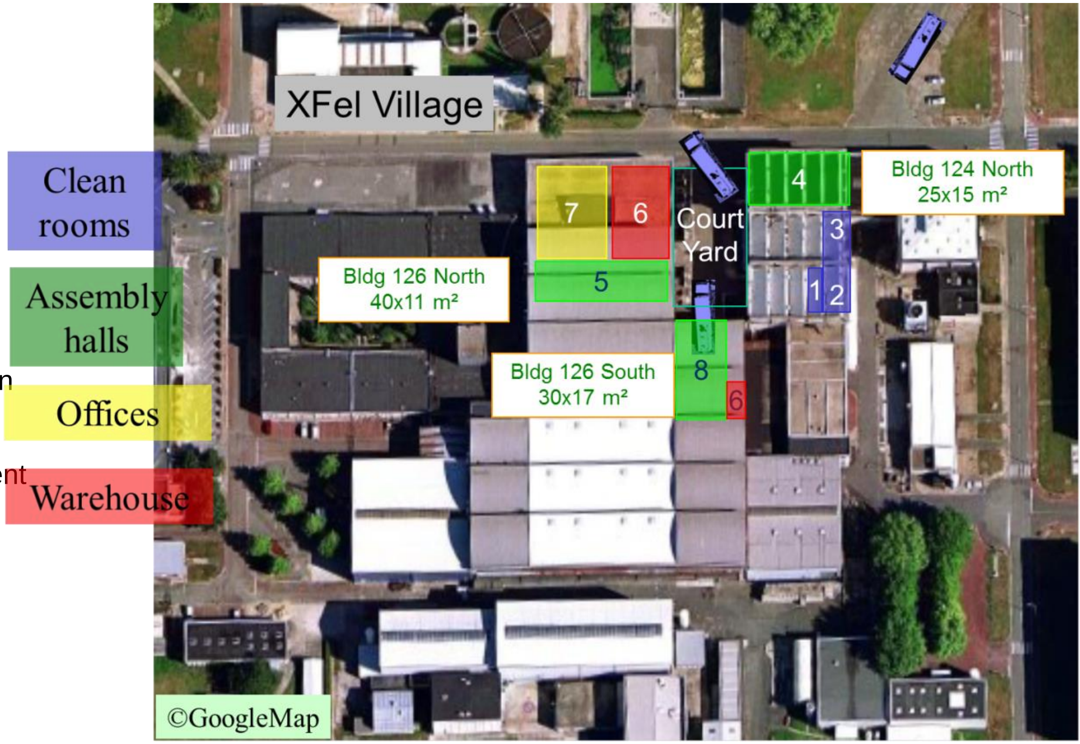


Full systems integration testing

XFEL challenges experience, module assembly

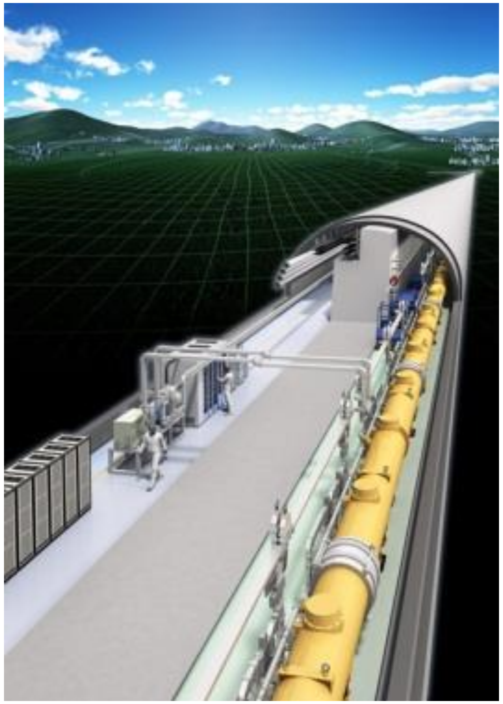
New and complex infrastructure build at CEA, Saclay

1. **Clean Room Cold Coupler Area** (IS04-CC-WS1)
    - Cold coupler assembly
2. **Clean Room String Assembly Area** (ISO4-SA-WS1, ISO4-SA-WS2)
    - String connections (1 gate valve + 8 cavities + 1 Qpole unit)
3. **Roll-out Area** (RO-WS1, RO-WS2)
    - HOM tuning, magnetic shielding, tuners,…
    - 2Ph-tube welding, cold-mass connection
4. **Alignment Area** (AL-WS1, AL-WS2)
    - Cavity and quadrupole fine alignment
    - Coupler shields and braids, tuner electric tests
5. **Cantilever Area** (CA-WS1)
    - Welding of 4K and 70 K shields, super insulation
    - Quad current lead
    - Insertion into vacuum vessel and string alignment
6. **Coupler Area** (CO-WS1, CO-WS2)
    - Warm couplers + coupler pumping line
    - Control operations (electrical, RF)
7. **Shipment Area** (SH-WS1, SH-WS2)
    - CEA-Alsyom “acceptance test”
    - End-caps closing, N2-insulation, loading.



In full production, this chain of workstations will be fully occupied with 7 cryomodules (XM_{n-6} @ WS1,…, XM_n @ WS7) stationed for one week.

European XFEL cryomodule assembly in Saclay



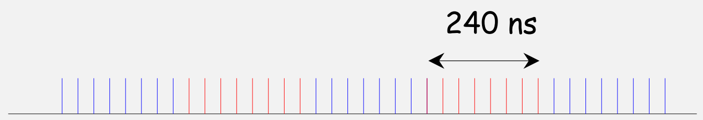
CLIC

Compact LInear Collider

CLIC Layout at 3 TeV

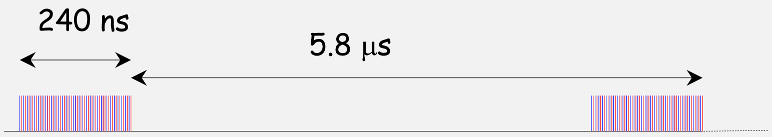
Drive Beam Generation

Drive beam time structure - initial

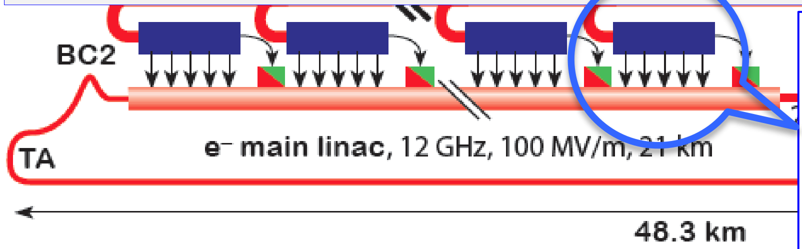


140 µs train length - 24 × 24 sub-pulses
4.2 A - 2.4 GeV – 60 cm between bunches

Drive beam time structure - final

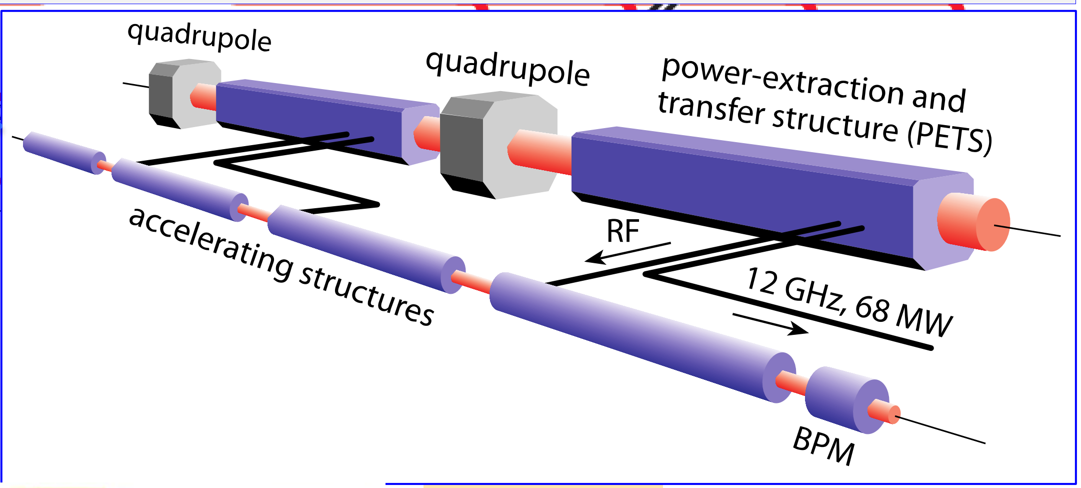


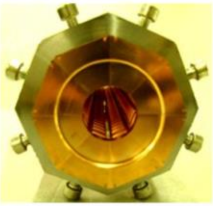
24 pulses – **101 A** – 2.5 cm between bunches

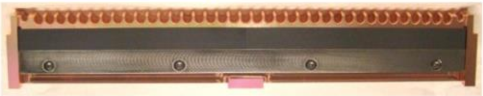


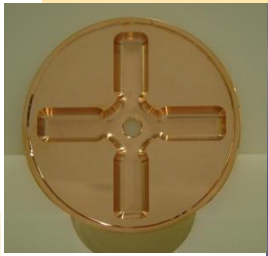
CR	combiner ring
TA	turnaround
DR	damping ring
PDR	predamping ring
BC	bunch compressor
BDS	beam delivery system
IP	interaction point
🟥	dump

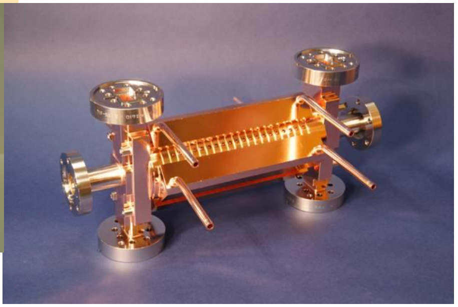
e^- injector,
2.86 GeV









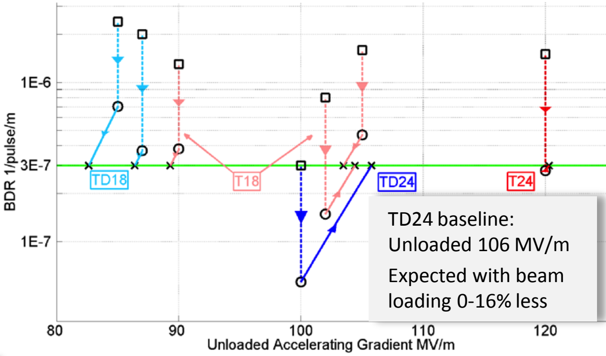


Main Beam Generation Complex

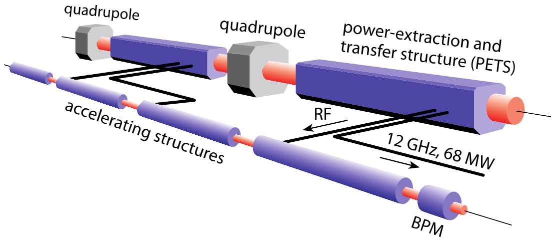
Conclusion of the accelerator CDR studies

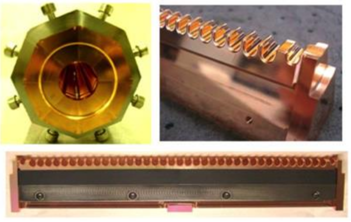
Main linac gradient
- Ongoing test close to or on target
- Uncertainty from beam loading being tested

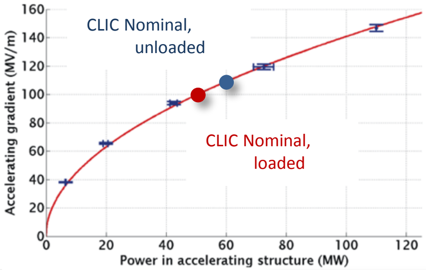
Drive beam scheme
- Generation tested, used to accelerate test beam abov specifications, deceleration as expected
- Improvements on operation, reliability, losses, more deceleration studies underway



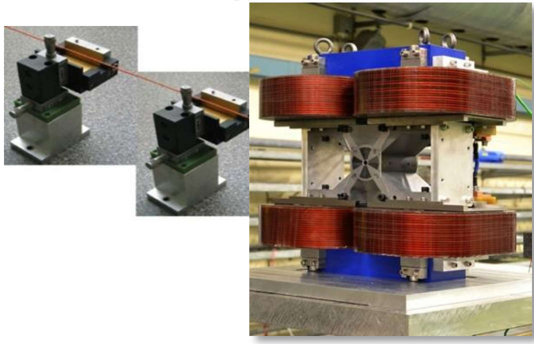
TD24 baseline:
Unloaded 106 MV/m
Expected with beam loading 0-16% less







Luminosity
- Damping ring like an ambitious light source, no show stopper
- Alignment system principle demonstrated
- Stabilisation system developed, benchmarked, better system in pipeline
- Simulations on or close to the target



Operation & Machine Protection
- Start-up sequence and low energy operation defined
- Most critical failure studied and first reliability studies

Implementation
- Consistent three stage implementation scenario defined
- Schedules, cost and power developed and presented
- Site and CE studies documented

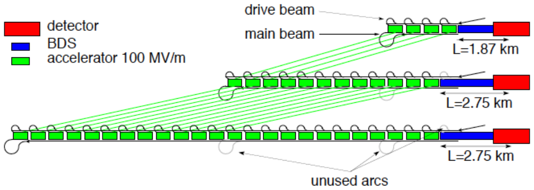
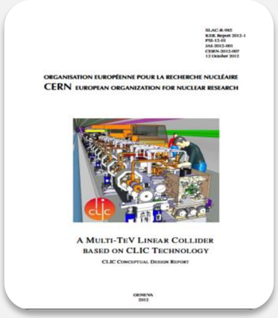


Fig. 3.6: Simplified upgrade scheme for CLIC staging scenario B.

The CLIC CDR documents



SLAC-R-985
KEK Report 2012-1
PSI-12-01
JAI-2012-001
CERN-2012-007
12 October 2012

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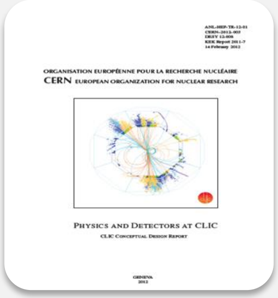
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

A MULTI-TEV LINEAR COLLIDER
BASED ON CLIC TECHNOLOGY
CLIC CONCEPTUAL DESIGN REPORT

GENEVA
2012

Vol 1: The CLIC accelerator and site facilities

- CLIC concept with exploration over multi-TeV energy range up to 3 TeV
- Feasibility study of CLIC parameters optimized at 3 TeV (most demanding)
- Consider also 500 GeV, and intermediate energy range
- https://edms.cern.ch/document/1234244/



ANL-HEP-TR-12-01
CERN-2012-003
DESY 12-008
KEK Report 2011-7
14 February 2012

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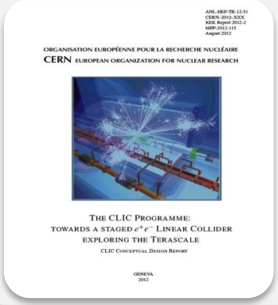
PHYSICS AND DETECTORS AT CLIC
CLIC CONCEPTUAL DESIGN REPORT

GENEVA
2012

Vol 2: Physics and detectors at CLIC

- Physics at a multi-TeV CLIC machine can be measured with high precision, despite challenging background conditions
- External review procedure in October 2011
- http://arxiv.org/pdf/1202.5940v1



ANL-HEP-TR-12-51
CERN-2012-XXX
KEK Report 2012-2
MPP-2012-115
August 2012

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THE CLIC PROGRAMME:
TOWARDS A STAGED e^+e^- LINEAR COLLIDER
EXPLORING THE TERASCALE
CLIC CONCEPTUAL DESIGN REPORT

GENEVA
2012

Vol 3: “CLIC study summary”

- Summary and available for the European Strategy process, including possible implementation stages for a CLIC machine as well as costing and cost-drives
- Proposing objectives and work plan of post CDR phase (2012-16)
- http://arxiv.org/pdf/1209.2543v1

In addition a shorter overview document was submitted as input to the European Strategy update, available at: http://arxiv.org/pdf/1208.1402v1

An input document to Snowmass 2013 has also been submitted: http://arxiv.org/abs/1305.5766

Possible CLIC stages studied

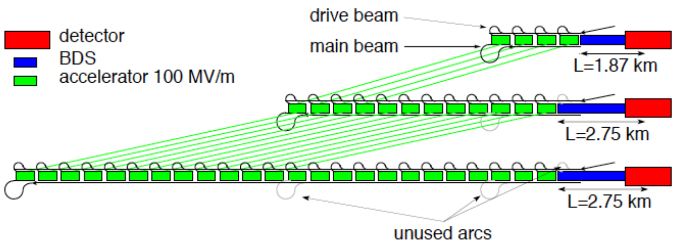
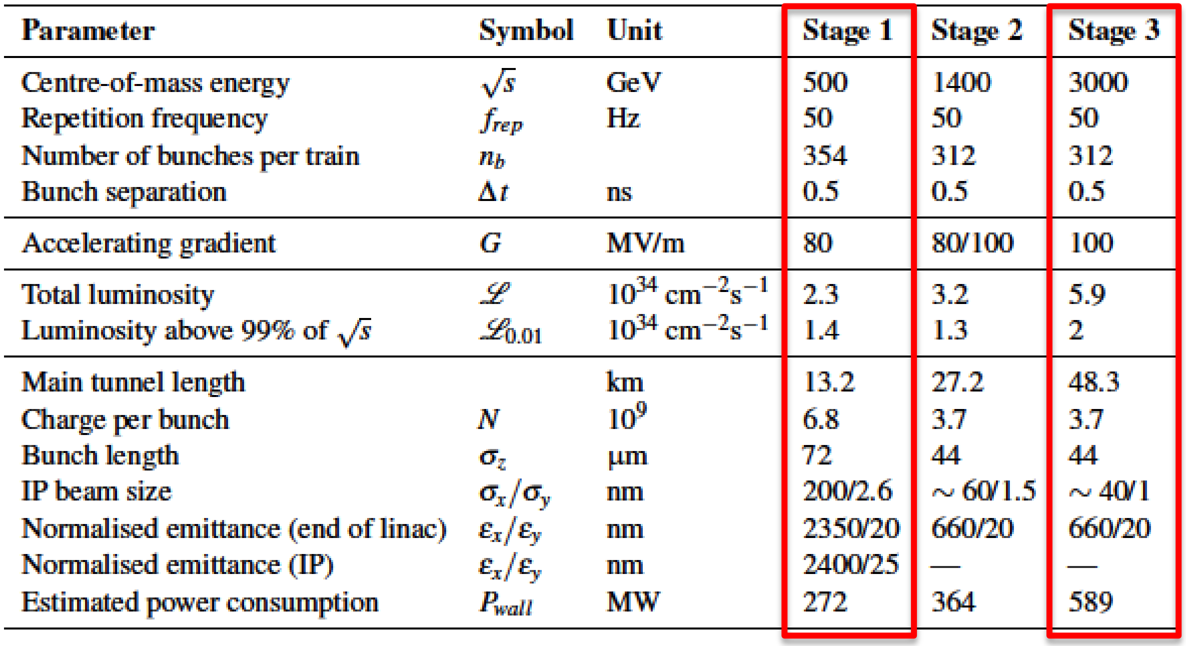


Fig. 3.6: Simplified upgrade scheme for CLIC staging scenario B.

Key features:

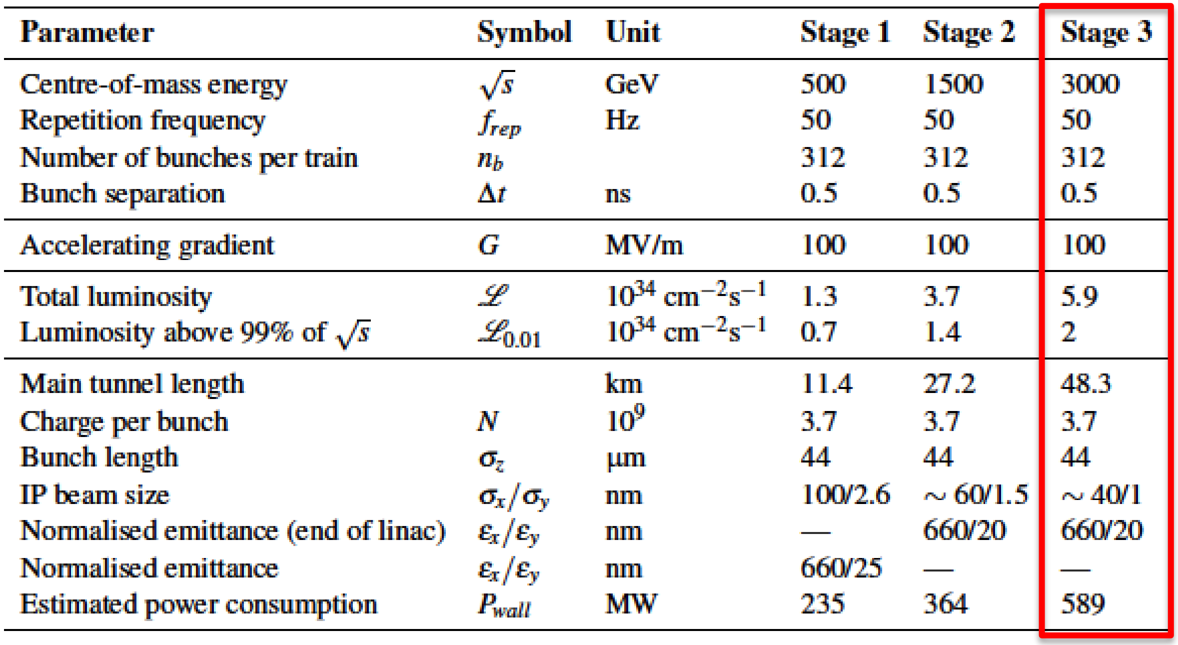
- High gradient (energy/length)
- Small beams (luminosity)
- Repetition rates and bunch spacing (experimental conditions)

Table 1: Parameters for the CLIC energy stages of scenario A.



Parameter	Symbol	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	$\sqrt{s}$	GeV	500	1400	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		354	312	312
Bunch separation	Δt	ns	0.5	0.5	0.5
Accelerating gradient	G	MV/m	80	80/100	100
Total luminosity	$\mathscr{L}$	10^{34} cm^{-2}s^{-1}	2.3	3.2	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	10^{34} cm^{-2}s^{-1}	1.4	1.3	2
Main tunnel length		km	13.2	27.2	48.3
Charge per bunch	N	10^9	6.8	3.7	3.7
Bunch length	σ_z	μm	72	44	44
IP beam size	σ_x/σ_y	nm	200/2.6	~ 60/1.5	~ 40/1
Normalised emittance (end of linac)	ϵ_x/ϵ_y	nm	2350/20	660/20	660/20
Normalised emittance (IP)	ϵ_x/ϵ_y	nm	2400/25	—	—
Estimated power consumption	P_{wall}	MW	272	364	589

Table 2: Parameters for the CLIC energy stages of scenario B.



Parameter	Symbol	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	$\sqrt{s}$	GeV	500	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		312	312	312
Bunch separation	Δt	ns	0.5	0.5	0.5
Accelerating gradient	G	MV/m	100	100	100
Total luminosity	$\mathscr{L}$	10^{34} cm^{-2}s^{-1}	1.3	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	10^{34} cm^{-2}s^{-1}	0.7	1.4	2
Main tunnel length		km	11.4	27.2	48.3
Charge per bunch	N	10^9	3.7	3.7	3.7
Bunch length	σ_z	μm	44	44	44
IP beam size	σ_x/σ_y	nm	100/2.6	~ 60/1.5	~ 40/1
Normalised emittance (end of linac)	ϵ_x/ϵ_y	nm	—	660/20	660/20
Normalised emittance	ϵ_x/ϵ_y	nm	660/25	—	—
Estimated power consumption	P_{wall}	MW	235	364	589

Possible luminosity examples

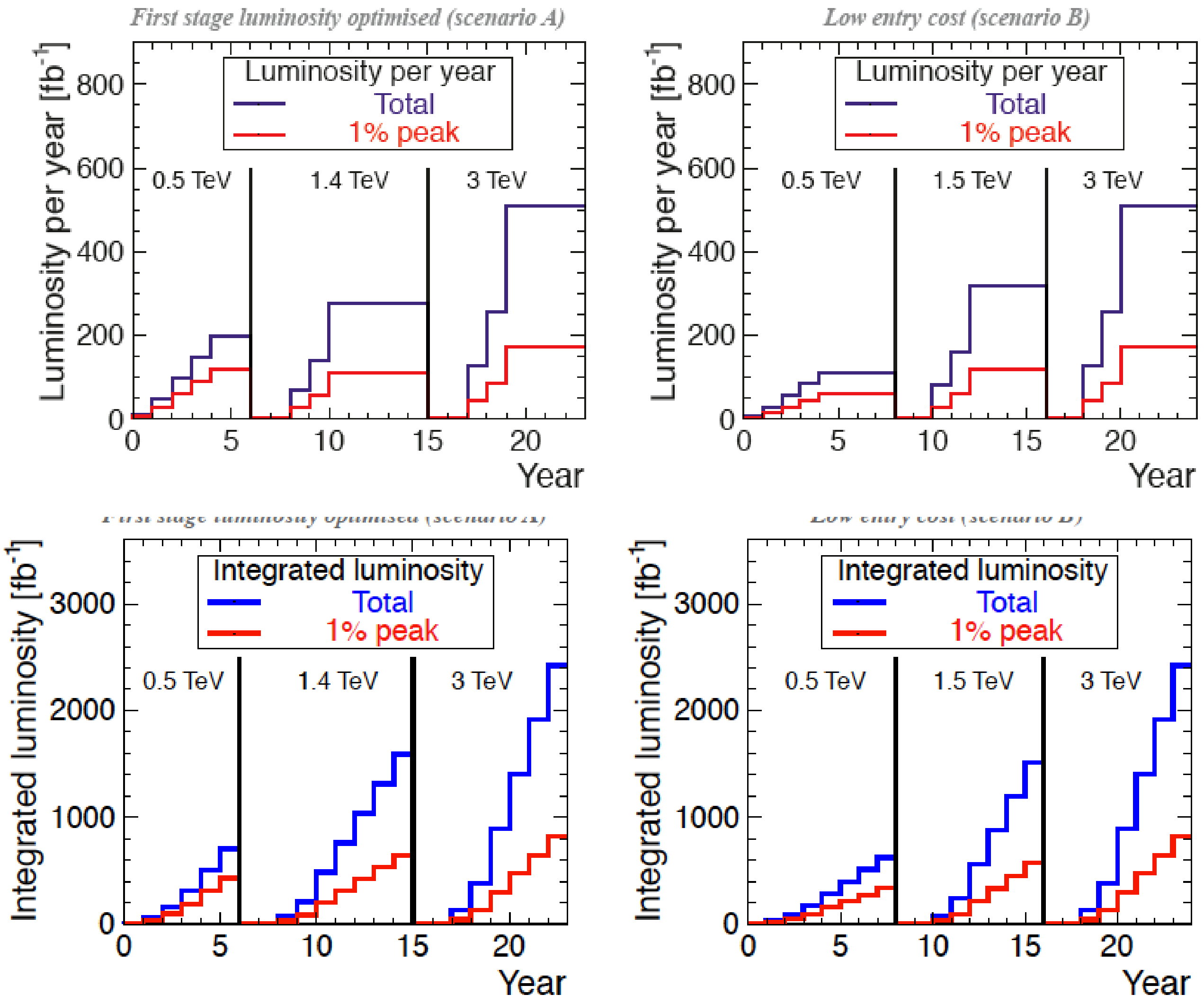
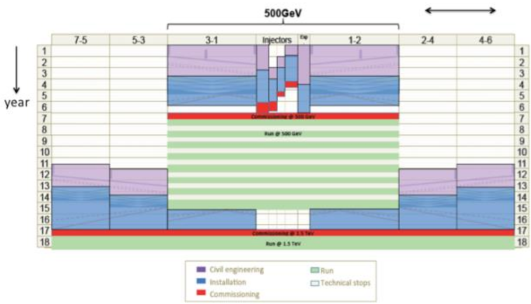


Fig. 5.2: Integrated luminosity in the scenarios optimised for luminosity in the first energy stage (left) and optimised for entry costs (right). Years are counted from the start of beam commissioning. These figures include luminosity ramp-up of four years (5%, 25%, 50%, 75%) in the first stage and two years (25%, 50%) in subsequent stages.

Based on 200 days/year at 50% efficiency (accelerator + data taking combined)

Target figures: >600 fb^{-1} at first stage, 1.5 ab^{-1} at second stage, 2 ab^{-1} at third stage

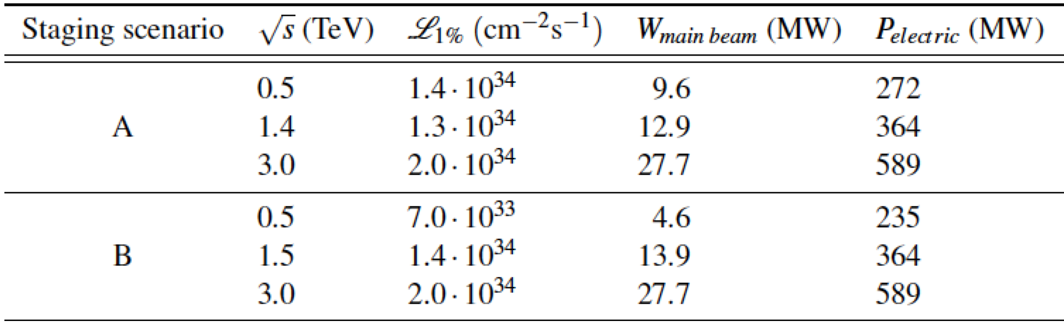


Power/energy consumption

Considering 150 days per year of normal operation at nominal power and a luminosity ramp-up in the early years at each stage of collision energy, the development of yearly energy consumption can be sketched.

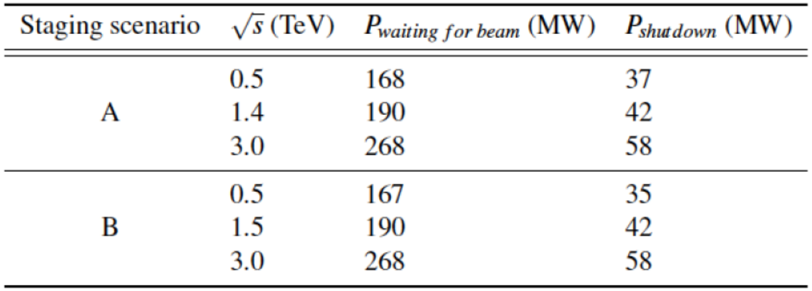
- Re-optimize parts
  - Reduced current density in normal-conducting magnets
  - Reduction of heat loads to HVAC
  - Re-optimization of accelerating gradient with different objective function
- Efficiency
  - Grid-to-RF power conversion
  - Permanent or super-ferric superconducting magnets
- Energy management
  - Low-power configurations in case of beam interruption
  - Modulation of scheduled operation to match electricity demand: Seasonal and Daily
  - Power quality specifications
- Waste heat recovery
  - Possibilities of heat rejection at higher temperature
  - Waste heat valorization by concomitant needs, e.g. residential heating, absorption cooling

Beyond:
Scale with inst. luminosity – i.e. running at the very end of the project lifetime might be power limited and require more time.



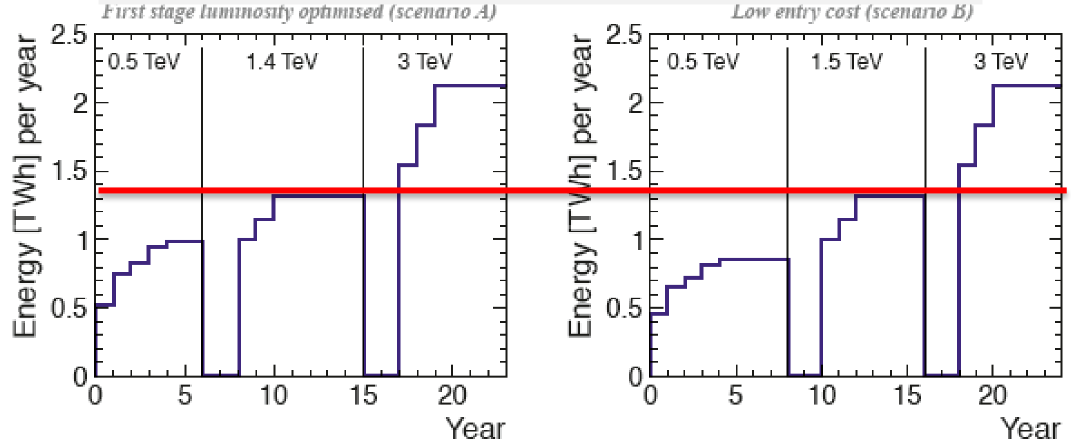
Staging scenario	$\sqrt{s}$ (TeV)	$\mathscr{L}_{1\%}$ ($\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	$W_{main\ beam}$ (MW)	$P_{electric}$ (MW)
A	0.5	$1.4 \cdot 10^{34}$	9.6	272
	1.4	$1.3 \cdot 10^{34}$	12.9	364
	3.0	$2.0 \cdot 10^{34}$	27.7	589
B	0.5	$7.0 \cdot 10^{33}$	4.6	235
	1.5	$1.4 \cdot 10^{34}$	13.9	364
	3.0	$2.0 \cdot 10^{34}$	27.7	589

Table 5.2: Residual power without beams for staging scenarios A and B.

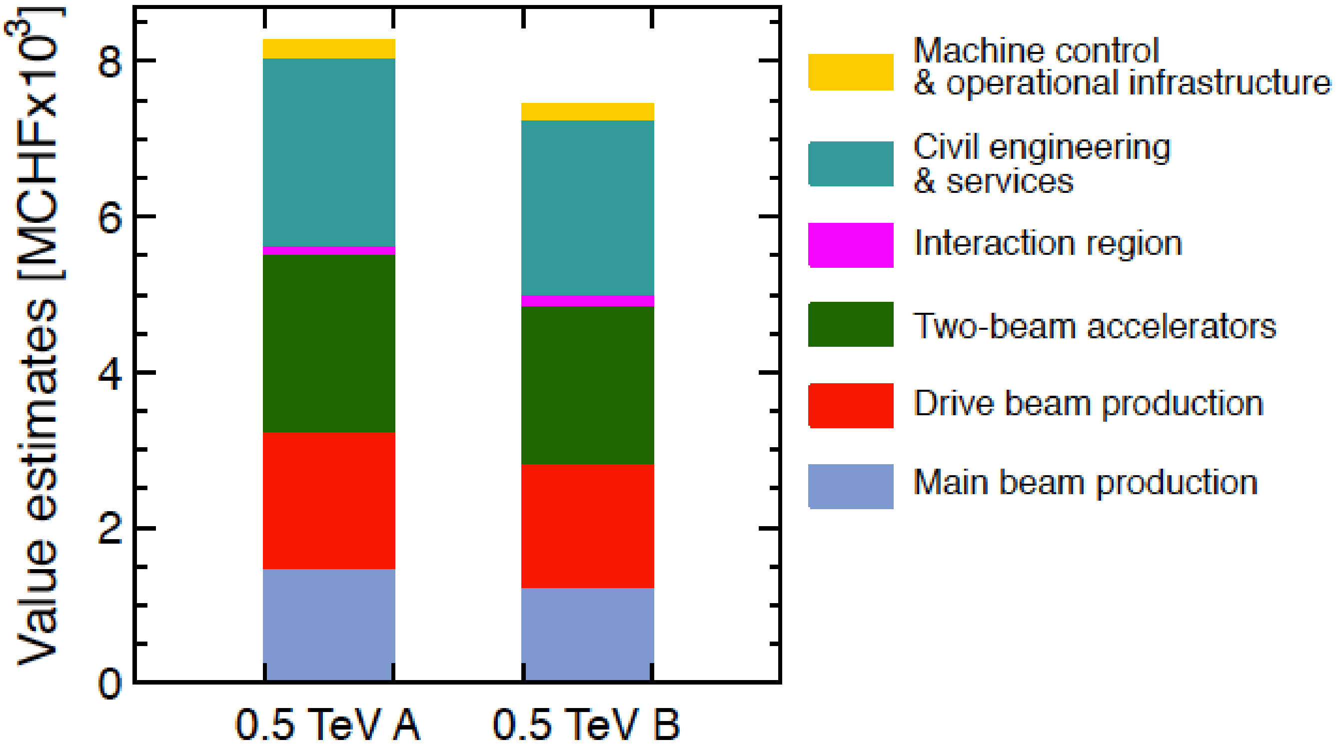


Staging scenario	$\sqrt{s}$ (TeV)	$P_{waiting\ for\ beam}$ (MW)	$P_{shutdown}$ (MW)
A	0.5	168	37
	1.4	190	42
	3.0	268	58
B	0.5	167	35
	1.5	190	42
	3.0	268	58

CERN energy consumption 2012: 1.35 TWh



Costs

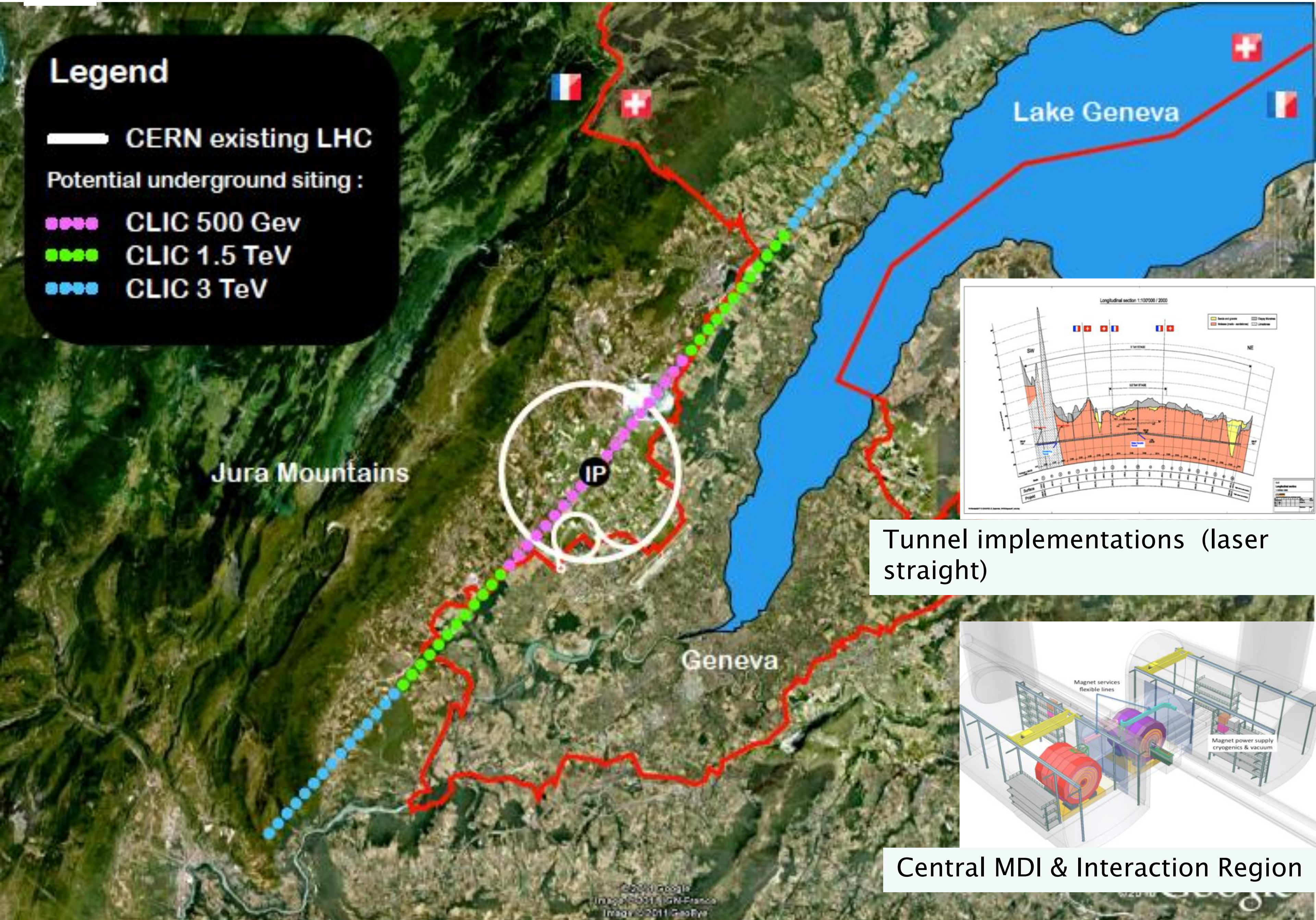


First to second stage: 4 MCHF/GeV (i.e. initial costs are very significant)

Caveats:

- Uncertainties 20-25%
- Possible savings around 10%
- However – first stage not optimised (work for next phase), parameters largely defined for 3 TeV final stage

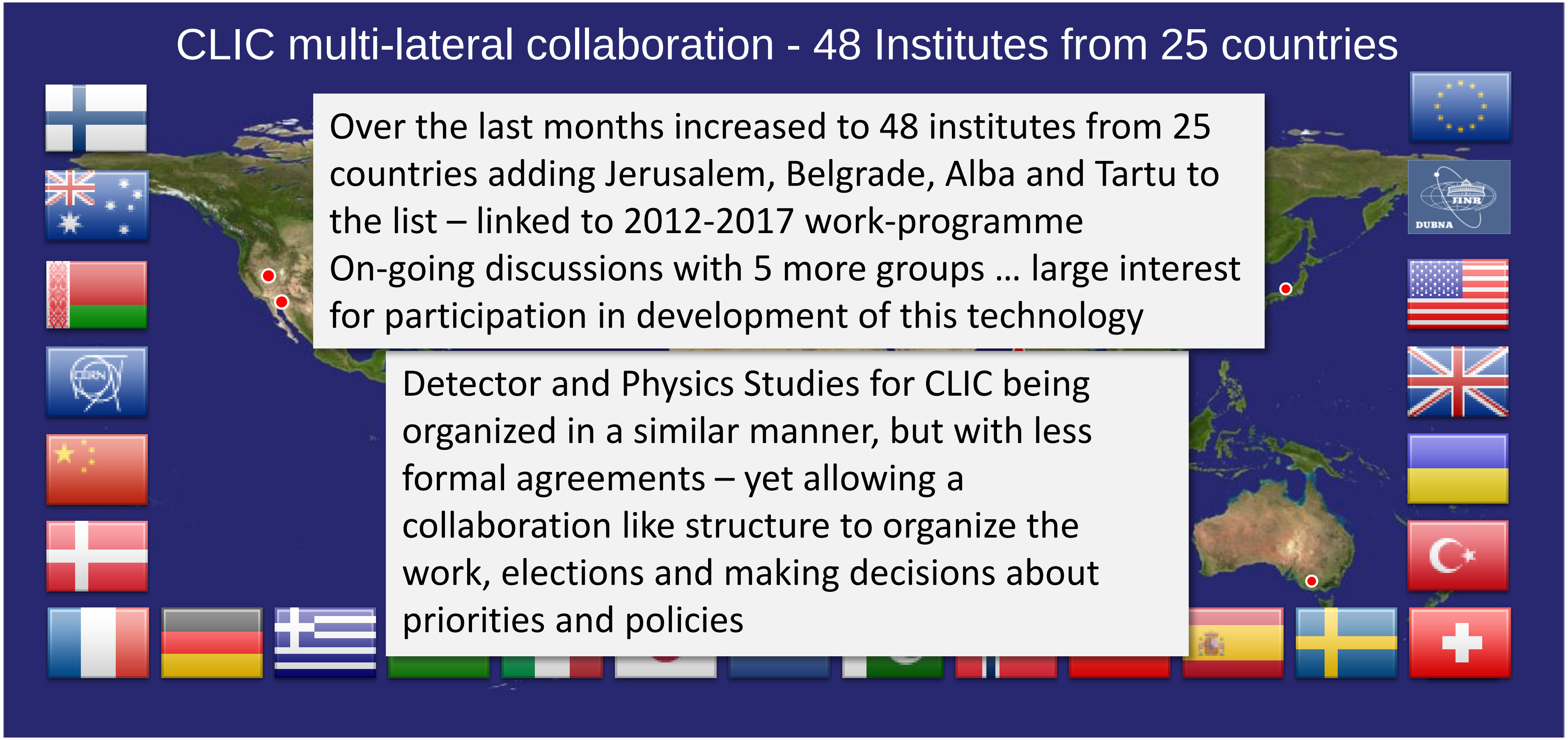
CLIC near CERN and EPFL



Tunnel implementations (laser straight)

Central MDI & Interaction Region

Current CLIC Collaboration



CLIC multi-lateral collaboration - 48 Institutes from 25 countries

Over the last months increased to 48 institutes from 25 countries adding Jerusalem, Belgrade, Alba and Tartu to the list – linked to 2012-2017 work-programme

On-going discussions with 5 more groups … large interest for participation in development of this technology

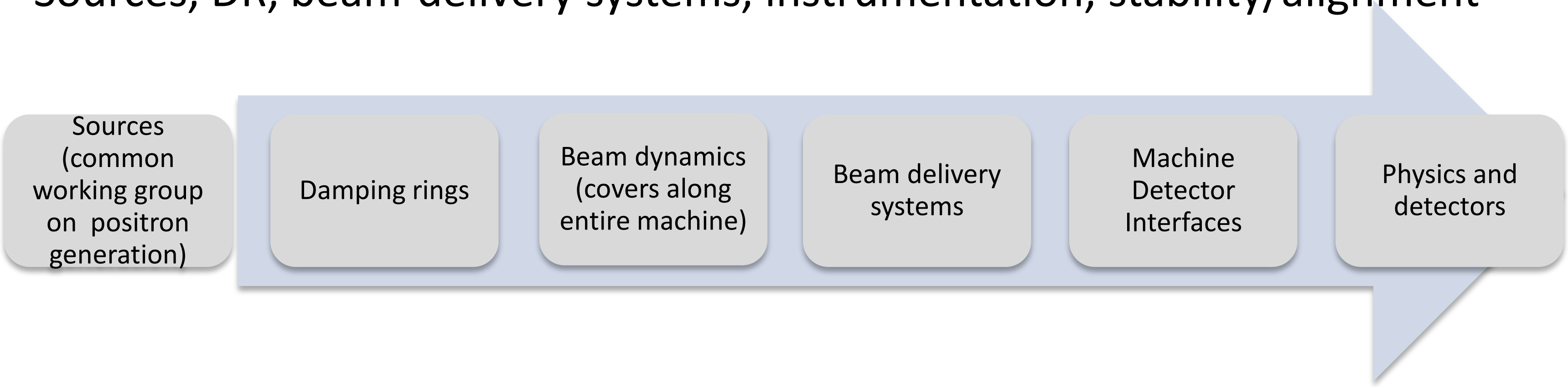
Detector and Physics Studies for CLIC being organized in a similar manner, but with less formal agreements – yet allowing a collaboration like structure to organize the work, elections and making decisions about priorities and policies

ACAS (Australia)
Aarhus University (Denmark)
Ankara University (Turkey)
Argonne National Laboratory (USA)
Athens University (Greece)
BINP (Russia)
CERN
CIEMAT (Spain)
Cockcroft Institute (UK)
ETH Zurich (Switzerland)
FNAL (USA)
Gazi Universities (Turkey)
Helsinki Institute of Physics (Finland)
IAP (Russia)
IAP NASU (Ukraine)
IHEP (China)
INFN / LNF (Italy)
Instituto de Fisica Corpuscular (Spain)
IRFU / Saclay (France)
Jefferson Lab (USA)
John Adams Institute/Oxford (UK)
Joint Institute for Power and Nuclear Research SOSNY /Minsk (Belarus)
John Adams Institute/RHUL (UK)
JINR
Karlsruhe University (Germany)
KEK (Japan)
LAL / Orsay (France)
LAPP / ESIA (France)
NIKHEF/Amsterdam (Netherland)
NCP (Pakistan)
North-West. Univ. Illinois (USA)
Patras University (Greece)
Polytech. Univ. of Catalonia (Spain)
PSI (Switzerland)
RAL (UK)
RRCAT / Indore (India)
SLAC (USA)
Sincrotrone Trieste/ELETTRA (Italy)
Thrace University (Greece)
Tsinghua University (China)
University of Oslo (Norway)
University of Vigo (Spain)
Uppsala University (Sweden)
UCSC SCIPP (USA)

Obvious European contributions possible to ILC construction – based on XFEL construction (not only cryo-module examples shown on previous slides)

Significant work and expertise – and huge common potential with CLIC related to “luminosity performance/critical systems and associated system tests”:

CERN, Spain, UK, Italy, France, Switzerland … :
Sources, DR, beam-delivery systems, instrumentation, stability/alignment



Sources (common working group on positron generation)

Damping rings

Beam dynamics (covers along entire machine)

Beam delivery systems

Machine Detector Interfaces

Physics and detectors

Summary

- Major milestones achieved for CLIC (CDR 2012) and ILC (TDR 2013)
- ILC and CLIC have different main goals and timescales
- European Strategy: very high energy linear collider needs an intermediate step like 250 – 500 GeV ILC or CLIC (klystron based?)

- CLIC program for 2018 defined (being revised now after the Strategy document), collaboration based developments of key aspects of the technology

- ILC might enter construction (or preparation for construction) in Japan
    - Site choice next, followed by statements by government ? Involvement by other regions a key
    - Europe well prepared to contribute (technically) – finances another challenge

Thank you
for your attention

Many thanks to all the people for their slides