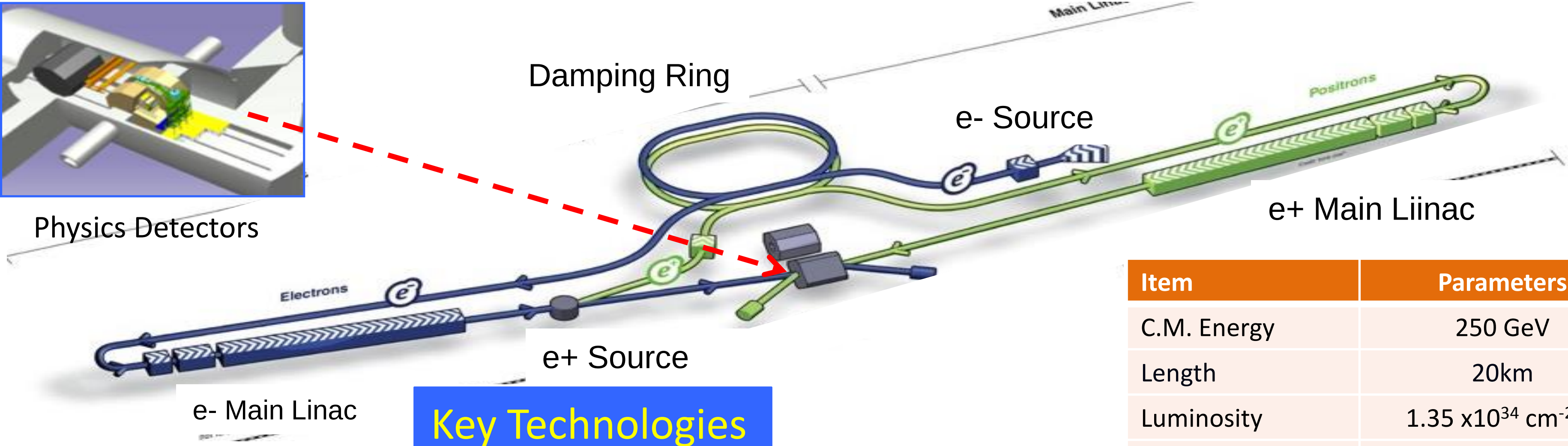
# Linear Colliders

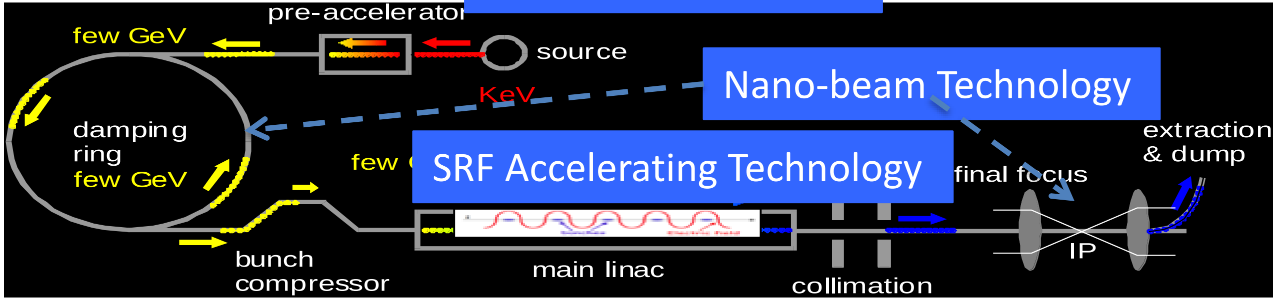
D. Schulte, CERN

# Key Parameters

| Parameter | Symbol [unit] | ILC | ILC | CLIC | CLIC |
|---|---|---|---|---|---|
| CMS energy | $E_{cm}$ [GeV] | 125 | 250 | 380 | 3000 |
| Luminosity | L [$10^{34}$ $cm^{-2}s^{-1}$] | 1.35 | 1.8 | 1.5 | 6 |
| Gradient | G [MV/m] | 31.5 | 31.5 | 72 | 100 |
| Repetition rate | $f_r$ [Hz] | 5 | 5 | 50 | 50 |
| Bunches per train | n | 1312 | 1312 | 352 | 312 |
| Particles/bunch | N [$10^9$] | 20 | 20 | 5.2 | 3.72 |
| Bunch length | $\sigma_z$ [μm] | 300 | 300 | 70 | 44 |
| Energy spread | [%] | 0.1-0.2 | 0.1-0.2 | 0.35 | 0.35 |
| Emittances | $\varepsilon_{x,y}$ [nm] | $5x10^3/35$ | $5x10^3/35$ | 950/30 | 660/20 |
| IP beam size | $\sigma_{x,y}$ [nm/nm] | 520/8 | 474/6 | 149/3 | 40/1 |
| Beta-functions | $b_{x,y}$[mm] | 13/0.41 | 22/0.48 | 8/0.1 | 6/0.07 |
| Assumed effective running time | [$10^7$ s/year] | 1.6 | 1.6 | 1.08 | 1.08 |

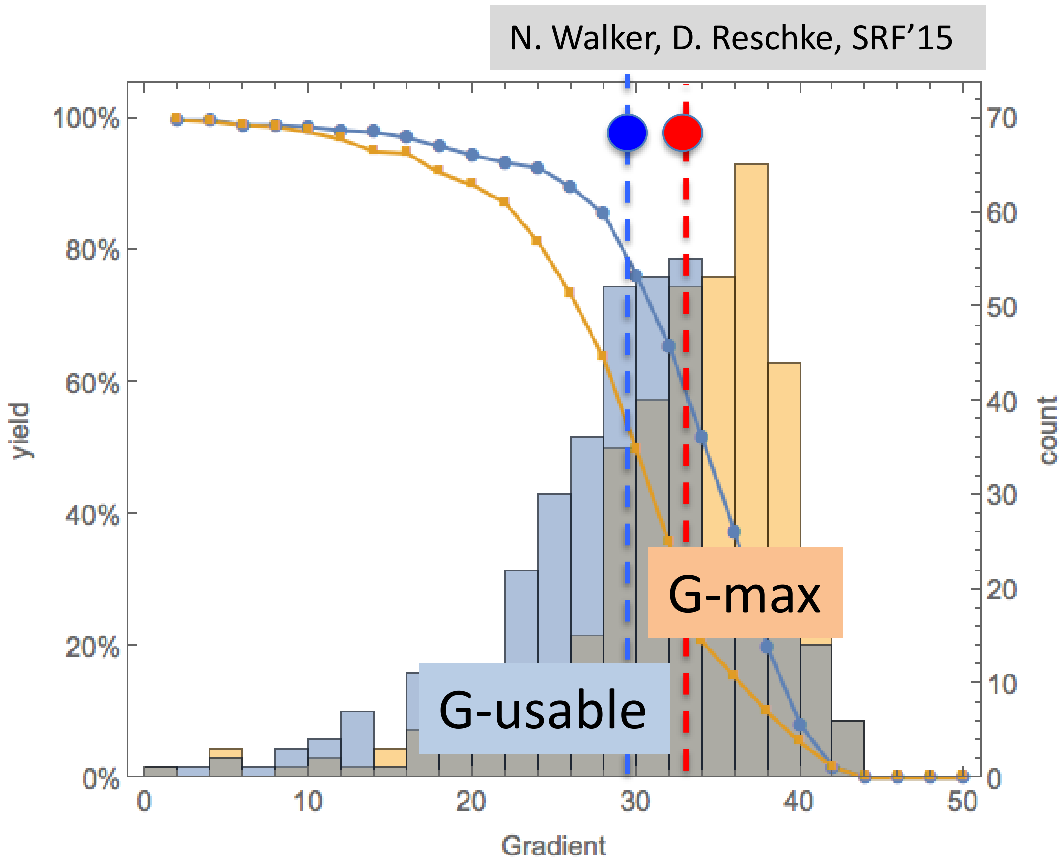
# ILC Overview




| Item | Parameters |
|---|---|
| C.M. Energy | 250 GeV |
| Length | 20km |
| Luminosity | 1.35 x10$^{34}$ cm$^{-2}$s$^{-1}$ |
| Repetition | 5 Hz |
| Beam Pulse | 0.73 ms |
| Beam Current | 5.8 mA (in pulse) |
| Beam size (y) at FF | **7.7** nm@250GeV |
| SRF Cavity G. | **31.5** MV/m (**35** MV/m) |
| $Q_0$ | $Q_0$ = 1x10$^{10}$ |

# ILC Cavities




800 cavities produced for European XFEL

Goal 24 MV/m

In vertical test stand (one Vendor):
Average gradient for $Q_0 > 10^{10}$
G = 29.4 MV/m

ILC goal 31.5 MV/m installed

# ILC Development

L. Evans
A. Yamamoto

Cost saving studies, e.g.

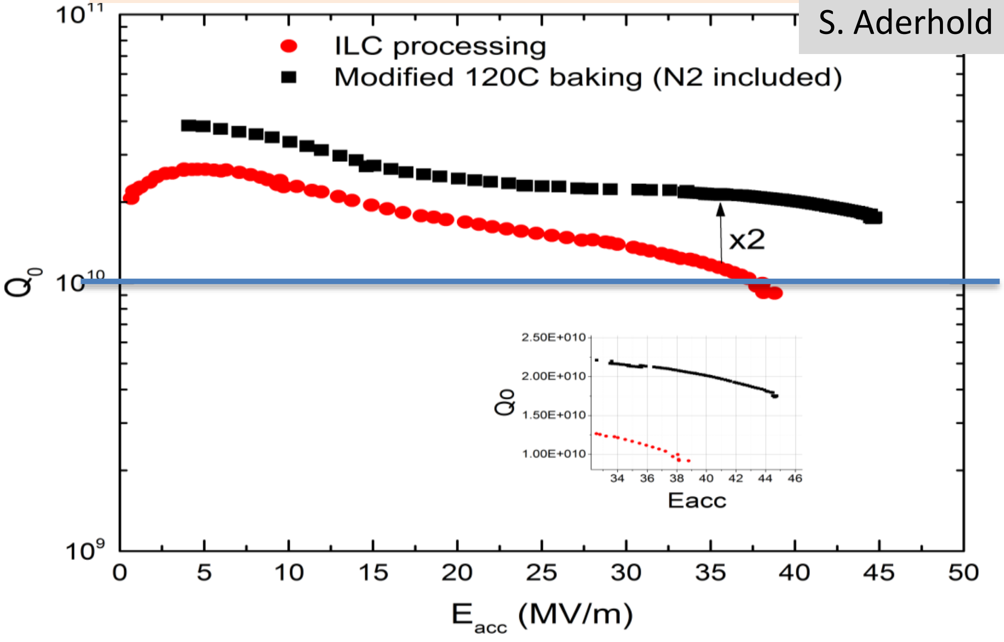
- Coupler design 1-2%
- Cavity material 2-3%
- No more hydrofluoric acid for chemical treatment 1-2%
- Higher gradient and more efficient cavities 4-5%
- …

Modified exposure to nitrogen (from FNAL)
Before: doping with few minutes at 800 °C
Now: a day or so at 120 °C

Nitrogen infusion appears very promising

- Increase in gradient
- Increase in $Q_0$

A. Grassellino,
S. Aderhold



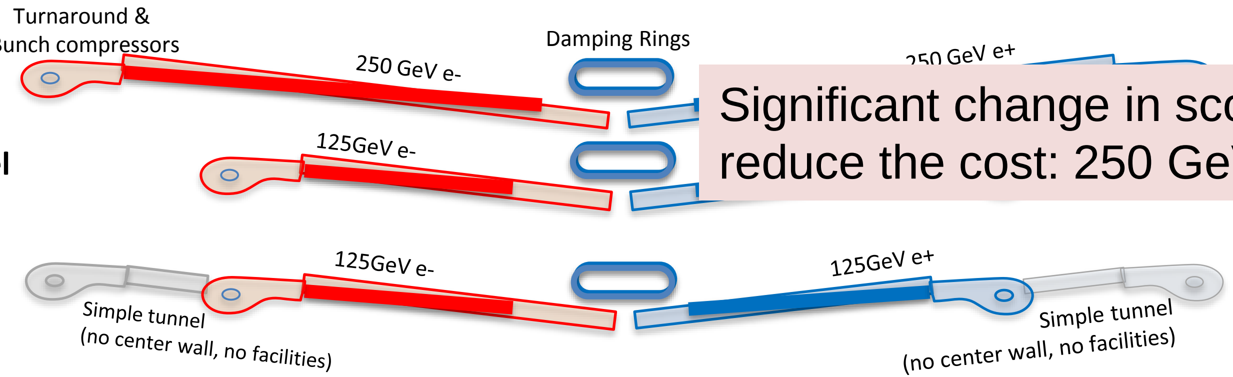
# ILC250 cost（in ILCU）

**TDR update:**

**Options A, A': 250 GeV tunnel**

**Options B, B': 350 GeV tunnel**

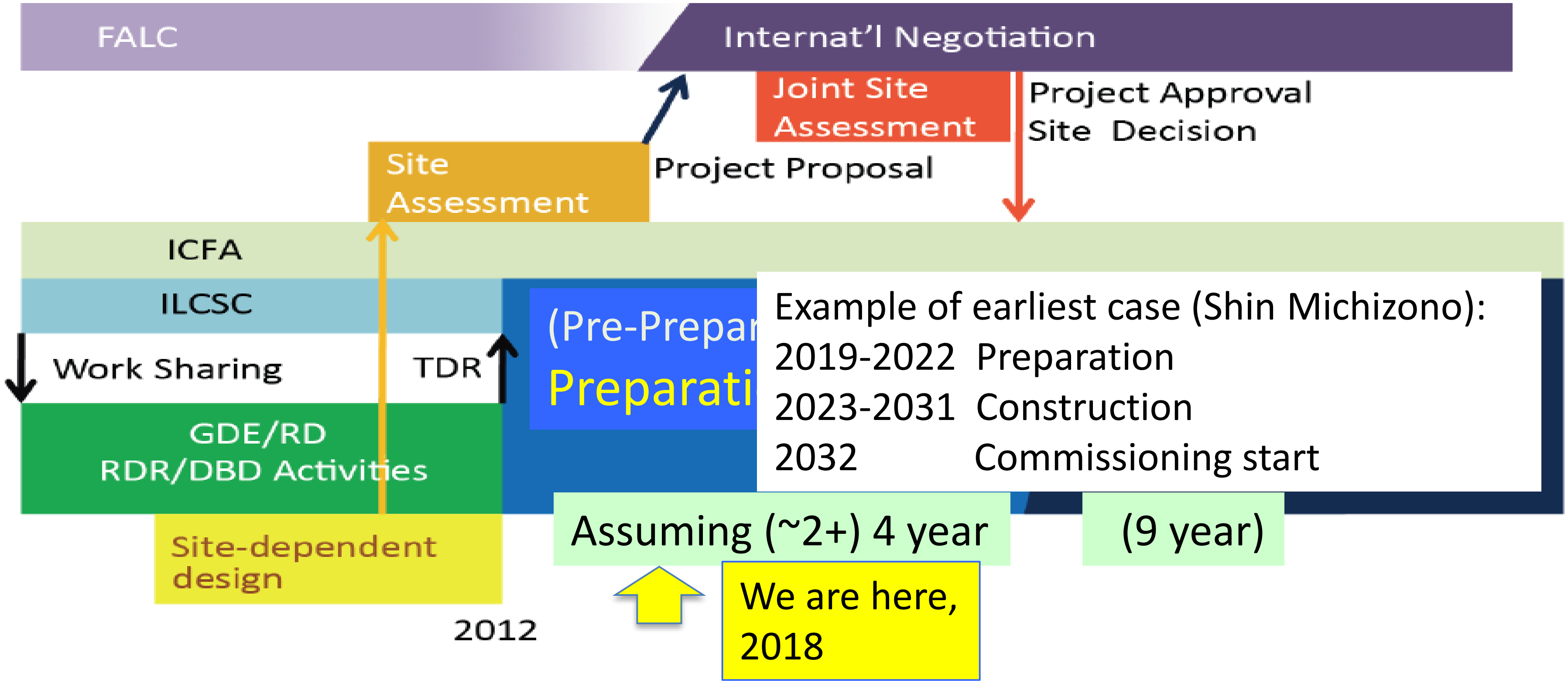
**Options C, C': 500 GeV tunnel**




Significant change in scope to reduce the cost: 250 GeV cms

| | e+/e- collision [GeV] | Tunnel Space for [GeV] | Value Total (MILCU) | Reduction [%] |
|---|---|---|---|---|
| TDR | 250/250 | 500 | 7,980 | 0 |
| TDR update | 250/250 | 500 | 7,950 | -0.4 |
| Option A | 125/125 | 250 | 5,260 | -34 |
| Option B | 125/125 | 350 | 5,350 | -33 |
| Option C | 125/125 | 500 | 5,470 | -31.5 |
| Option A' | 125/125 | 250 | 4,780 | -40 |
| Option B' | 125/125 | 350 | 4,870 | -39 |
| Option C' | 125/125 | 500 | 4,990 | -37.5 |

# ILC Time Line: Progress and Prospect



# CLIC (3 TeV)

## Drive beam time structure - initial

240 ns

140 μs train length - 24 × 24 sub-pulses

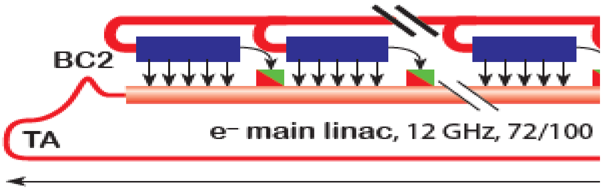
4.2 A - 2.4 GeV – 60 cm between bunch

## Drive beam time structure - final

240 ns

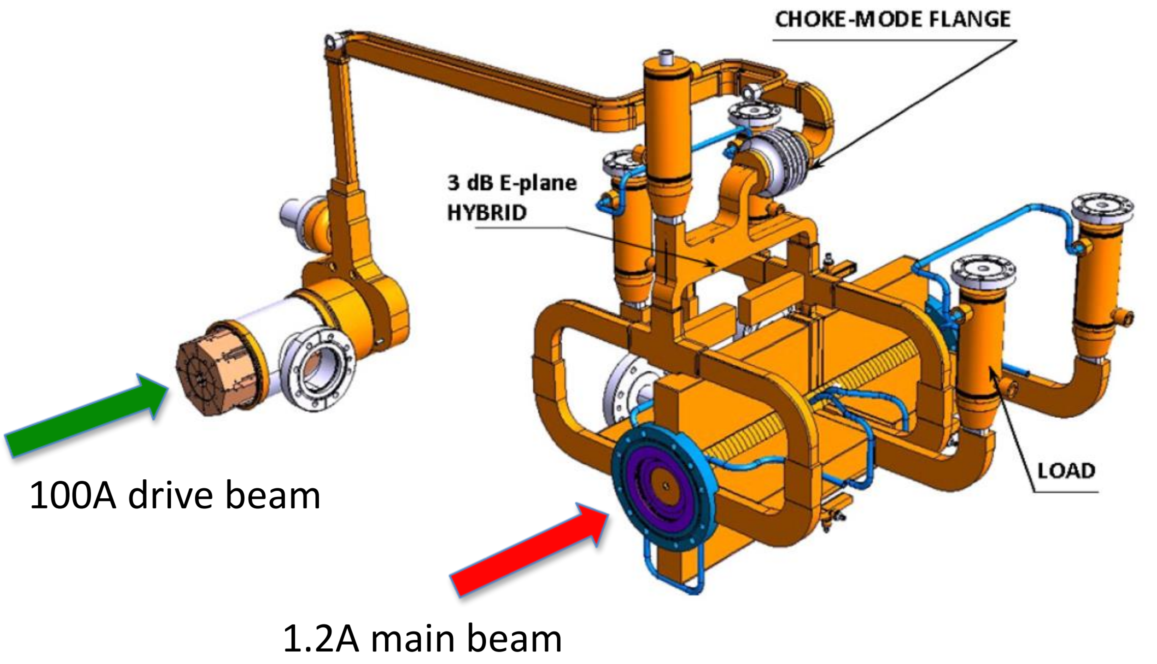
5.8 μs

delay loo




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

**1.5 Te**

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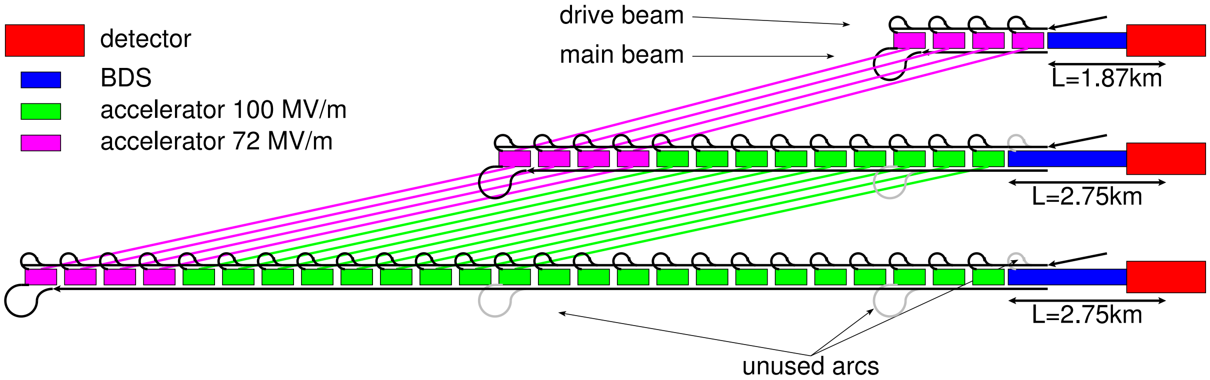
# CLIC Staged Design

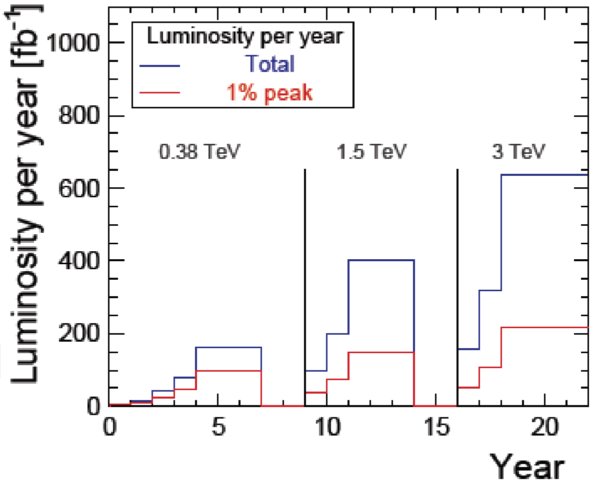
Staged design approach

Cost-optimised first energy stage

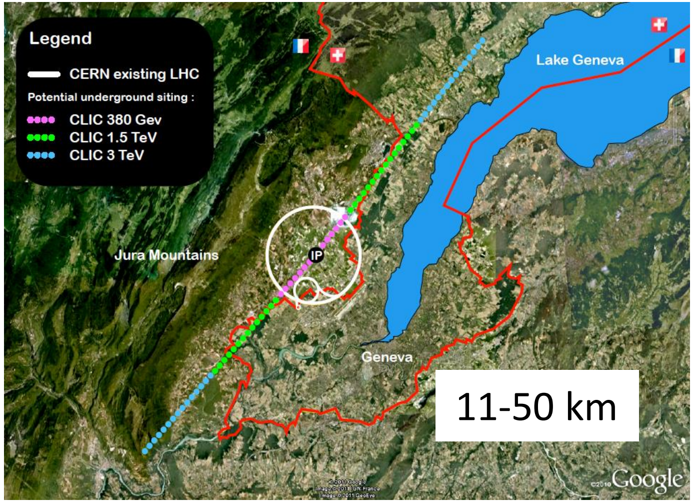
380 GeV: HZ, WW fusion, top asymmetry

Further stages re-use infrastructure and equipment

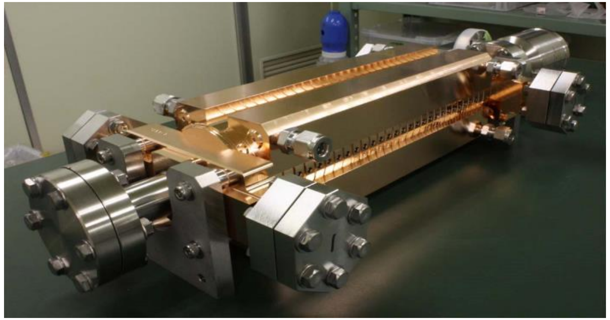



| Stage | $\sqrt{s}$ (GeV) | $\mathcal{L}_{int}$ ($fb^{-1}$) |
|---|---|---|
| 1 | 380 | 500 |
| | 350 | 100 |
| 2 | 1500 | 1500 |
| 3 | 3000 | 3000 |

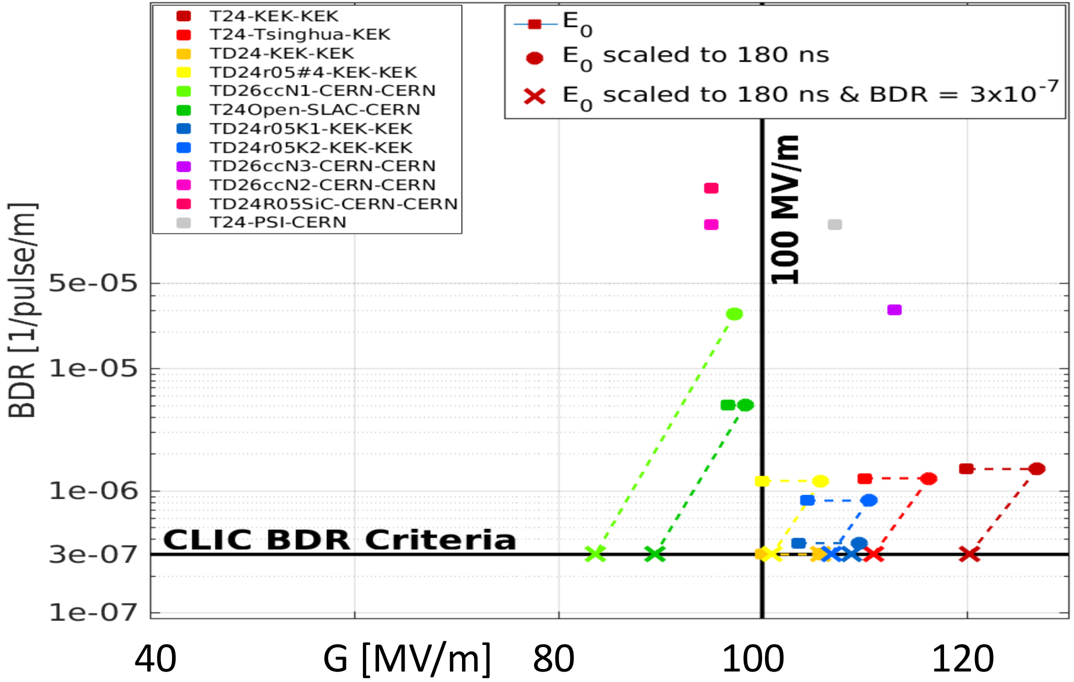


# CLIC Structure Development



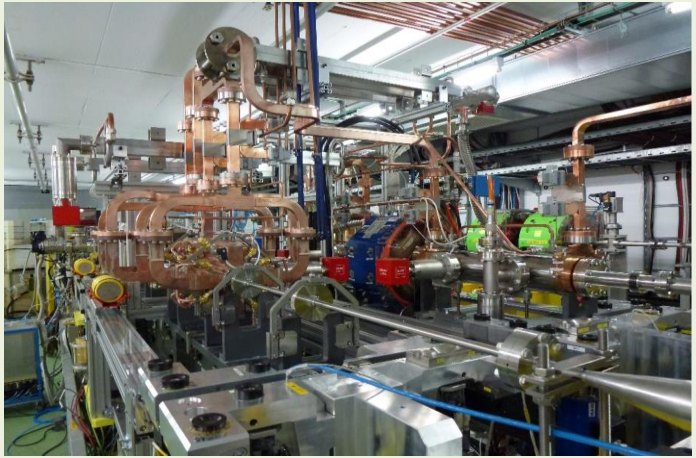
Structure testing takes long, conditioning required

Structures are quite reproducible
Details of manufacturing being worked out to improve further




Further optimisation ongoing of structure production for industrialisation
Several klystron-based test stands exist that test structures (X-boxes)

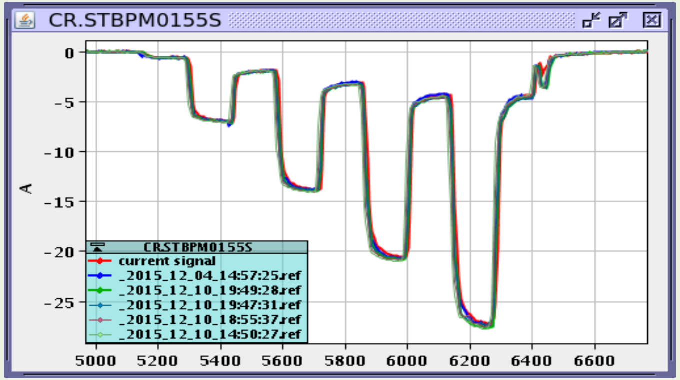
# From CTF3 to CLEAR



CTF3 has demonstrated drive beam production and main beam acceleration

- Technology
- Beam quality
- Operation

Now completed programme




New facility is coming online: CLEAR
CERN Linear Electron Accelerator for Research

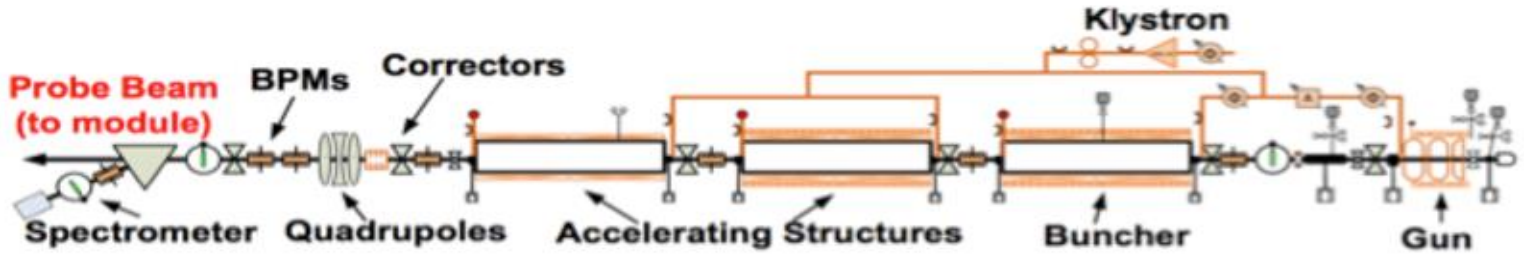
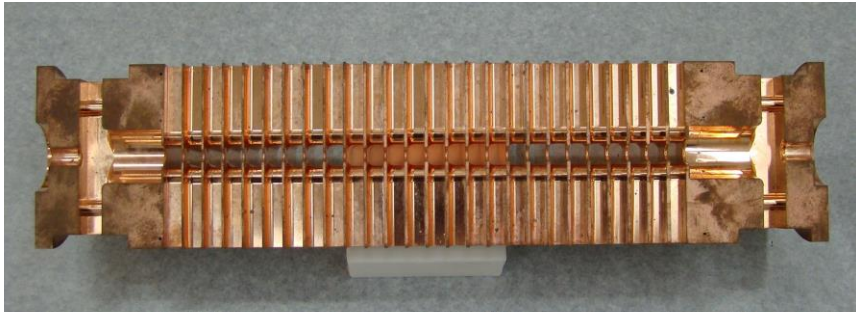



Figure 1: The current CALIFES beam line. The length of the facility (as shown) is ~20m.

# CLIC RF Technology Development



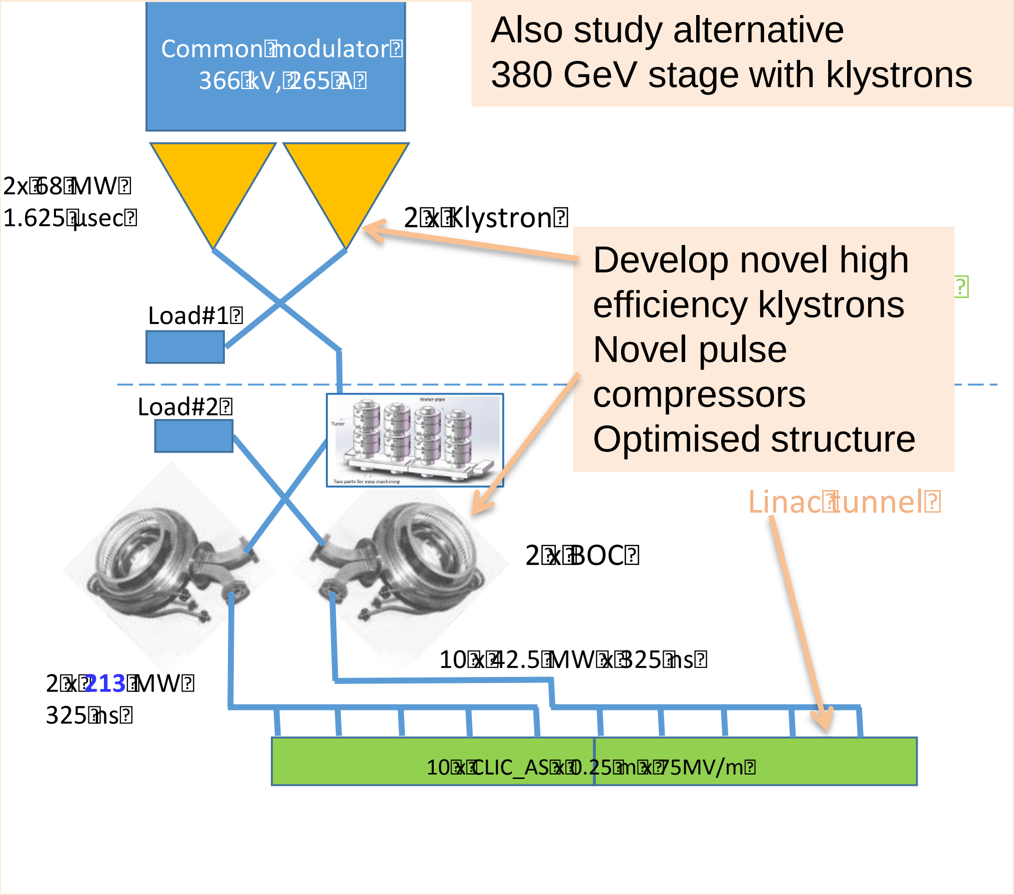
Further development and industrialisation of accelerating structures is ongoing

Several klystron-based test stands exist that test structures (X-boxes)

Growing use of X-band (FELs, novel technologies, …)

- E.g. at PSI, DESY, INFN, Cockcroft, …
- CompactLight proposal accepted by EU, 24 partners
- Sparc at INFN-LF

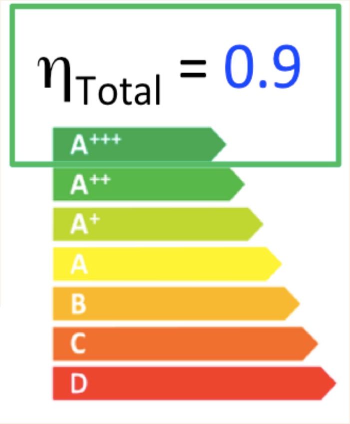
Also study alternative 380 GeV stage with klystrons

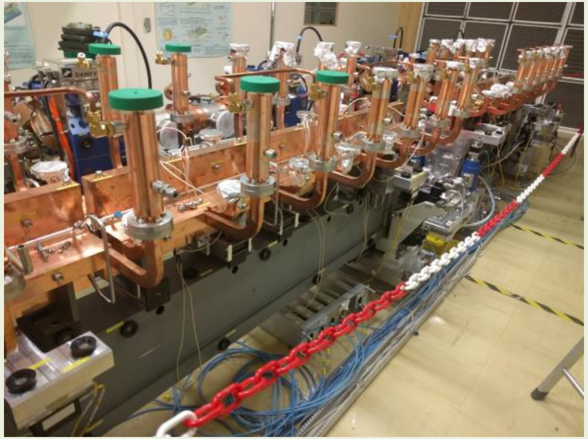



Develop novel high efficiency klystrons
Novel pulse compressors
Optimised structure

# Other CLIC Technology Development

**Redesign CLIC modulators and klystrons**
Aim: increase efficiency from 62% to 90%
⇒ Less power consumption
⇒ Also important cost saving
Shorter tubes, no oil in modulator, …
⇒ Important cost saving

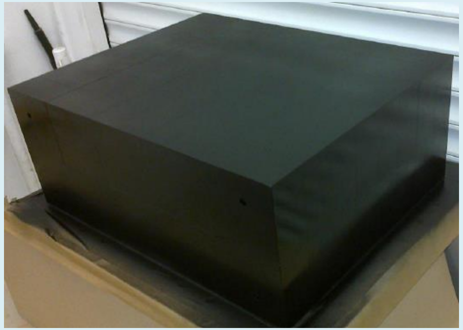


**New module design**
Reduce cost of mechanical system and control

**Permanent magnets**
Use tunable permanent magnets where possible

- Drive beam quadruoles
- Strongest permanent magnet developed in UK



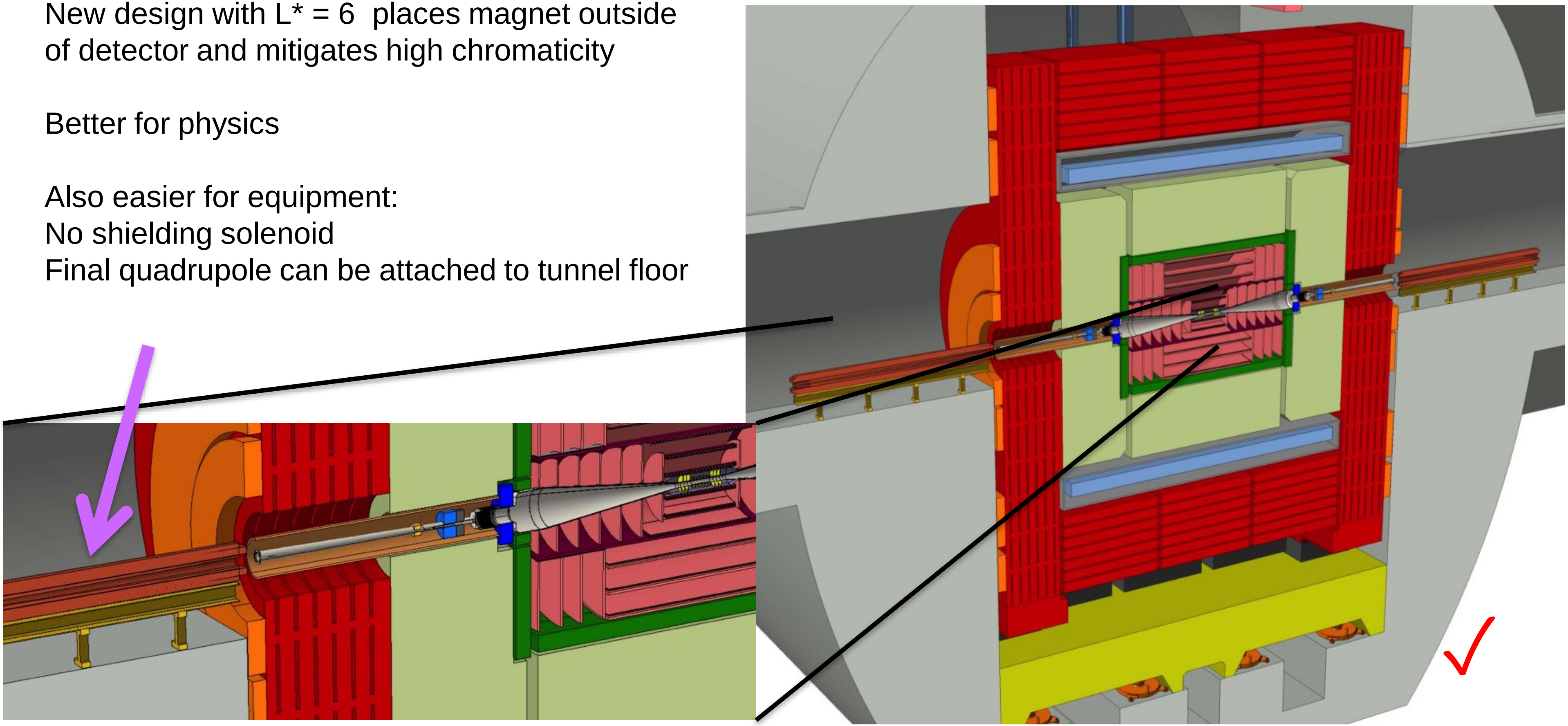
**Main beam injector**
e.g. halved power for positron production

# Beam Delivery System

New design with L* = 6  places magnet outside of detector and mitigates high chromaticity

Better for physics

Also easier for equipment:
No shielding solenoid
Final quadrupole can be attached to tunnel floor



# Cost

Goal set as “reasonable cost”: 6 GCHF

Preliminary cost estimate from rebaselining

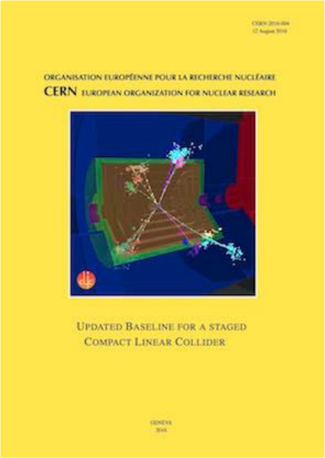
Performing bottom-up cost estimate

Also optimise the cost

- Module design is being improved
- Injector cost has been relatively high, is being reduced substantially by about halving number of klystrons
- Drive beam injector has already been optimised
- Civil engineering is being reviewed
- …

Preliminary value for 380 GeV (MCHF of Dec 2010)

| | |
|---|---|
| Main beam production | 1245 |
| Drive beam production | 974 |
| Two-beam accelerator | 2038 |
| Interaction region | 132 |
| Civil engineering etc. | 2112 |
| Control & operation | 216 |
| **TOTAL** | **6690** |



# Power

Goal set as “reasonable power”: 200 MW

Preliminary power estimate from rebaselining

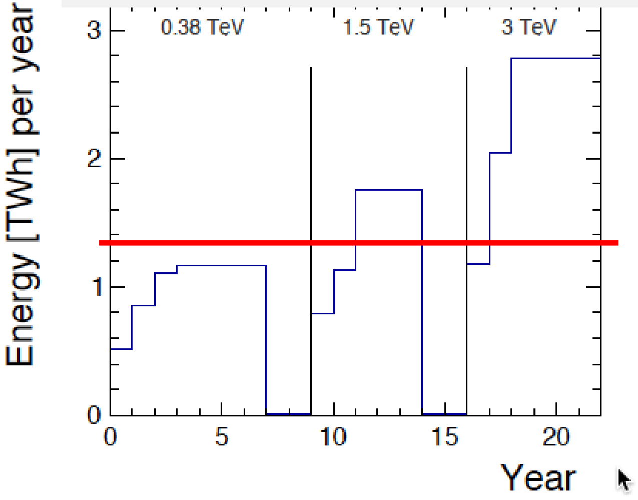
Performing bottom-up power estimate

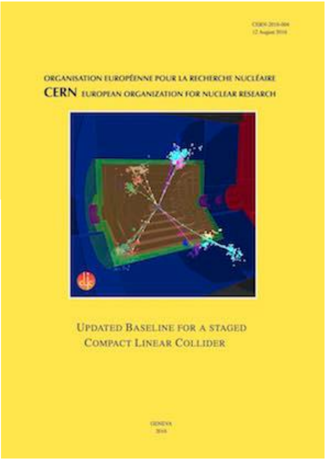
Also optimise the power

- Use of permanent magnets
- Reduction of injector power
- More efficient klystrons
- Use of green power: Ability to switch on and off to follow electricity availability
- …

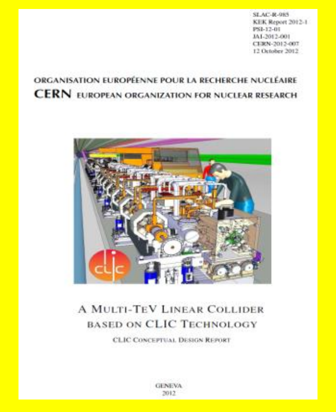
Preliminary Estimate 252 MW

CERN energy consumption 2012: 1.35 TWh



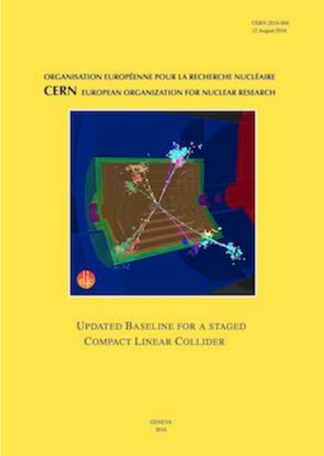



# CLIC Roadmap




CDR in 2012 established feasibility of 3 TeV design

Rebaselining document defined staged approach




**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

S. Stapnes

**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

# Novel Technologies

- Linear colliders based on novel technologies are being proposed

- Different acceleration media and powering schemes
  - Dielectric structures power by a beam
    - The continuation of CLIC with different means
  - Plasma cells powered by laser or beam, dielectric structures powered by laser
    - Quite different from existing studies

- Different ambitions
  - From cheaper alternative at lower energies
  - To long term goal proposed by Michael Peskin: $E_{cms}$ 30 TeV, L = $10^{36}$ $cm^{-2}s^{-1}$

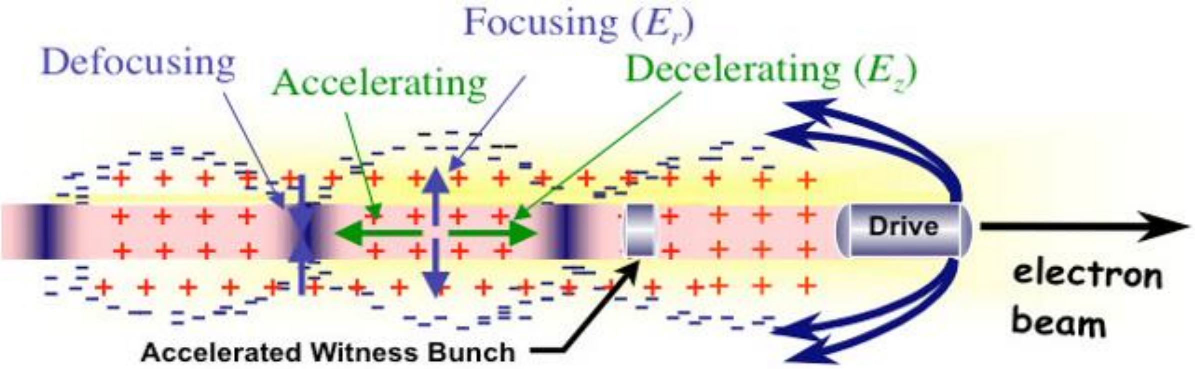
- From CLIC we are starting to explore the opportunities and challenges to make sure that CLIC is not inconsistent with a potential upgrade using novel technologies

# Plasma Acceleration

Very high gradients of 50 GV/m demonstrated

Can use laser or particle beam to generate field

R&D programmes are ongoing




Require also excellent beam quality and high efficiency

- For plasma acceleration this is new territory
- Theoretical studies and modelling is required
- Experimental programme is required
- First initiatives are ongoing (e.g. EUPRAXIA)
- This field can have high synergy with conventional linear colliders
  - E.g. could double CLIC luminosity if we could reduce imperfections b one order of magnitude

# Example Parameters

| Parameter | Symbol [unit] | ILC | CLIC | LPA | PWFA | DLA |
|---|---|---|---|---|---|---|
| CMS energy | $E_{cm}$ [GeV] | 500 | 3000 | 3000 | 3000 | 3000 |
| Luminosity | $L[10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}]$ | 1.8 | 6 | 10 | 6.3 | 10.7 (4.4) |
| Luminosity in peak | $L_{0.01}$ $[10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}]$ | 1 | 2 | ? | 2.5 | (3.8) |
| Total beam power | [MW] | 10.5 | 28 | 48 | 48 | 68.8 |
| Loaded gradient | $G$ [MV/m] | 31.5 | 100 | 3000 | 7600 | 1000 |
| Particles per bunch | $N$ $[10^9]$ | 20 | 3.72 | 1.19 | 10 | $3 \cdot 10^{-5}$ |
| Bunch length | $\sigma_z$ [$\mu$m] | 300 | 44 | 8 | 20 | 0.0028 |
| Interaction point beam size | $\sigma_x/\sigma_y$ [nm/nm] | 474/6 | 40/1 | 18/0.5 | 194/1.1 | 0.75/0.75 |
| Normalized emittances | $\epsilon_x/\epsilon_y$ [nm] | $10^4/35$ | 660/20 | 50/5 | $10^4/35$ | 0.1/0.1 |
| Beta functions | $\beta_x/\beta_y$ [mm] | 10/0.4 | 7/0.07 | -/- | 11/0.1 | 16.5/16.5 |
| Initial beam energy spread | $\sigma_E$ [%] | O(0.1) | 0.35 | — | — | — |
| Bunches per train | $n_b$ | 1312 | 312 | 1 | 1 | 159 |
| Bunch distance | $\Delta z$ [ns] | 554 | 0.5 | $11.9 \cdot 10^3$ | $10^5$ | $6.7 \cdot 10^{-6}$ |
| Repetition rate | $f_r$ [Hz] | 5 | 50 | $84 \cdot 10^3$ | $10^4$ | $3 \cdot 10^7$ |

LPA, PWFA, DLA parameters need important studies to be validated

My collection for RAST in 2016
PDFA: E. Adli et al.
LPA: D.B. Schroeder et al.
DLA: J. England

# Conclusion

Important progress toward the EU strategy

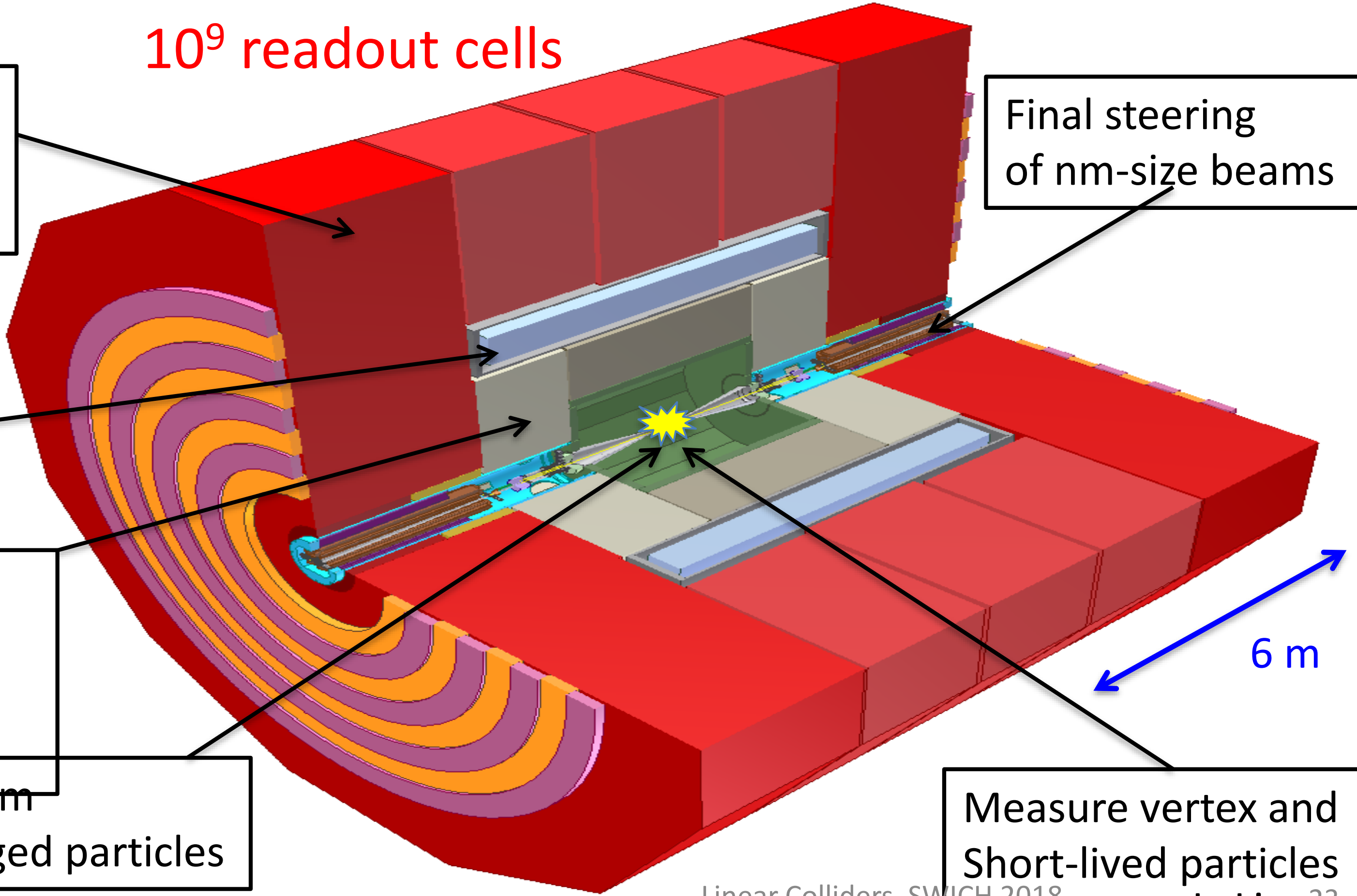
- ILC
  - Focus on cost reduction
  - Scope reduction to 250 GeV centre-of-mass
  - Political process ongoing
- CLIC
  - Further optimising 380 GeV first energy stage
  - Work on further stages, including novel technologies
  - Project Implementation Plan by end of 2018
- Novel acceleration technologies
  - Beam-driven dielectric acceleration could maybe be cheaper and higher gradient replacement of copper structures
  - Attention is moving also towards use of sequence multiple plasma cells, efficiency and beam quality
  - Interesting long-term development

Many thanks to L. Evans, S. Stapnes, W. Wuensch, Ph. Burrows, I. Syratchev,… the ILC and CLIC teams

# Reserve

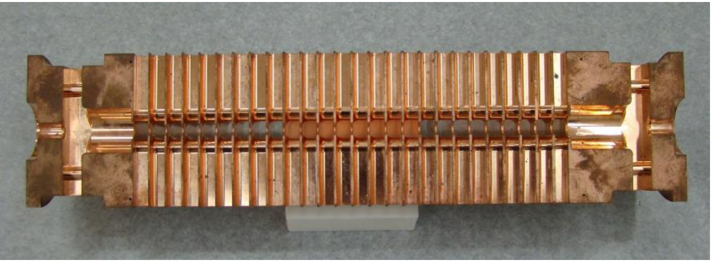
LHeC: J. Phys. G: Nucl. Part. Phys. 39 (2012)
FCC-eh :EDMS 17979910 FCC-ACC-RPT-0012075001

# Linear Collider Experiment

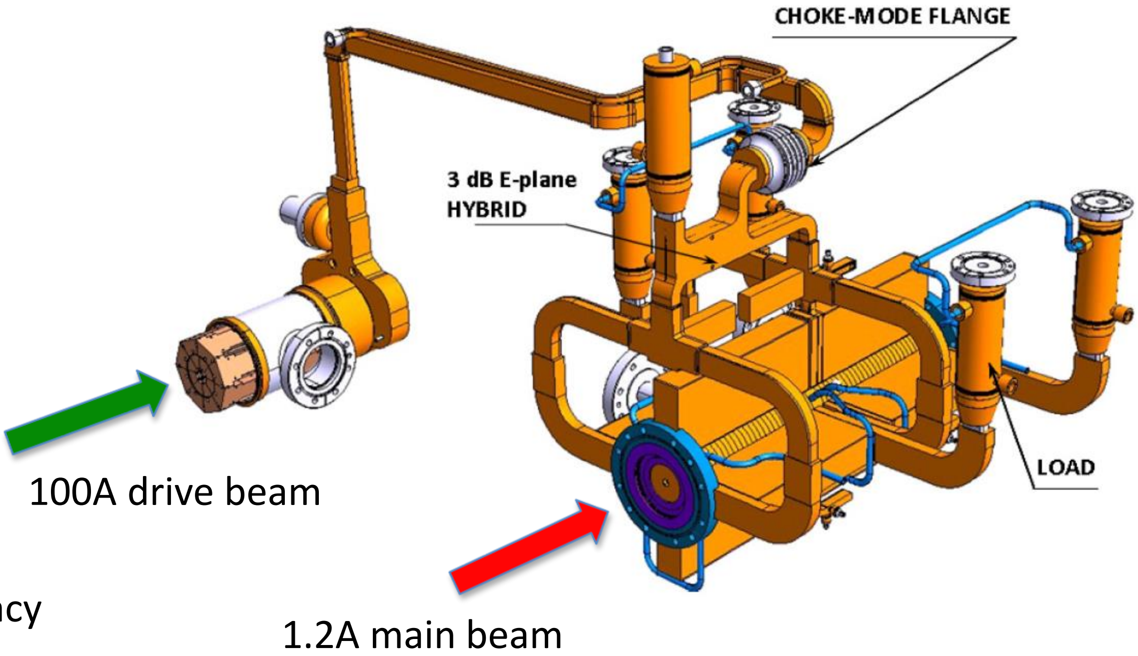


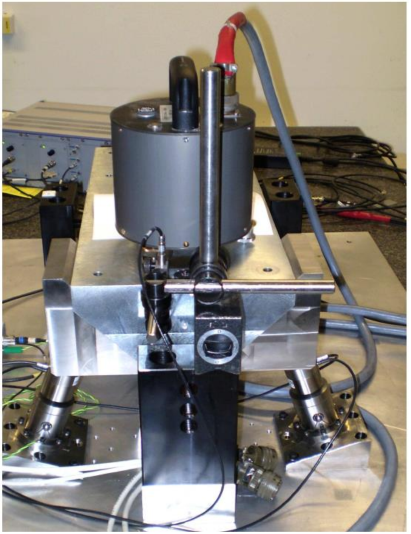
# CLIC Idea

High gradient makes machine cheap



Drive beam to produce short, high power RF pulse



Stabilise quadrupoles against groud motion

Novel, high-accuracy alignment scheme

And many more components

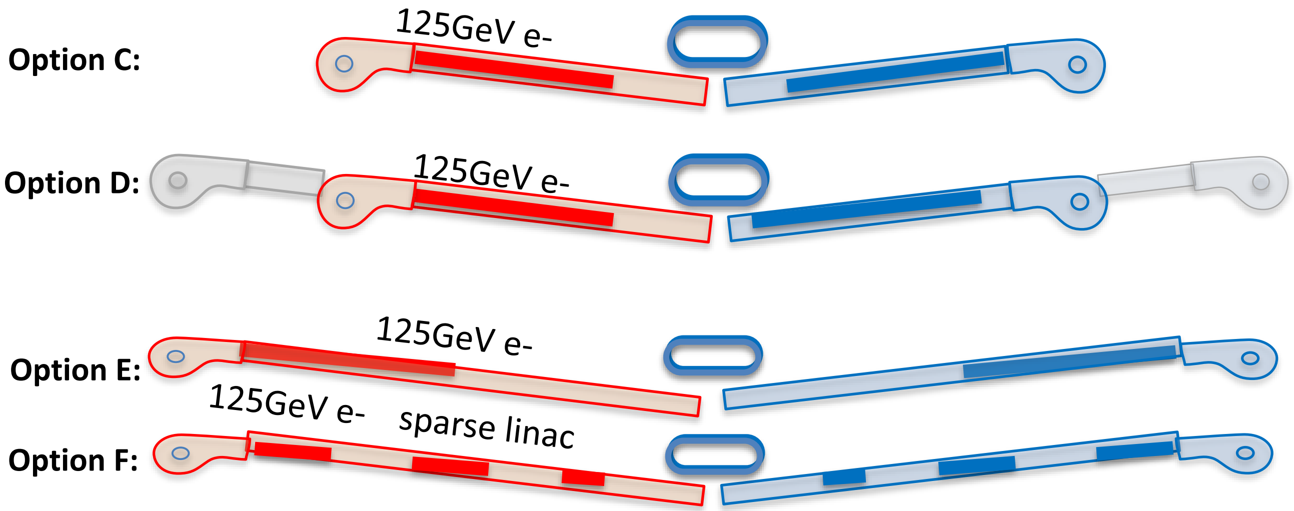
# ILC Staging Discussion

Technical improvements can decrease cost by 10-20%

More seems to be required, so staging is being considered

Discussions are ongoing

- Physics programme
- Optimum parameter choice at 250 GeV
- Positron source
- …




More options exist

Luminosity increase

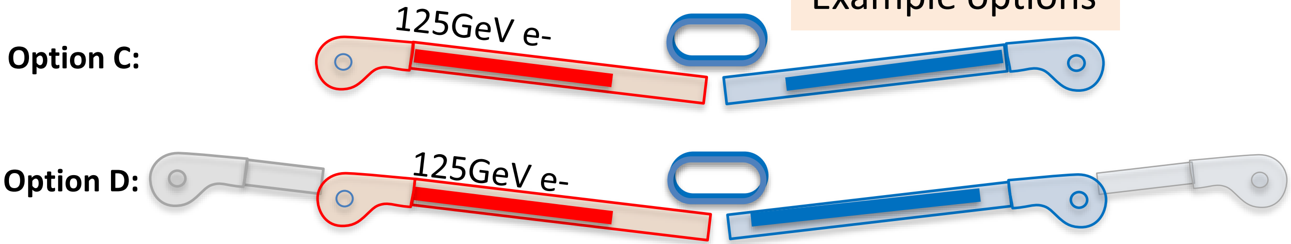
- 2 x by increasing RF
- 2 x by increasing cryogenics and repetition rate

# ILC Staging Scenarios

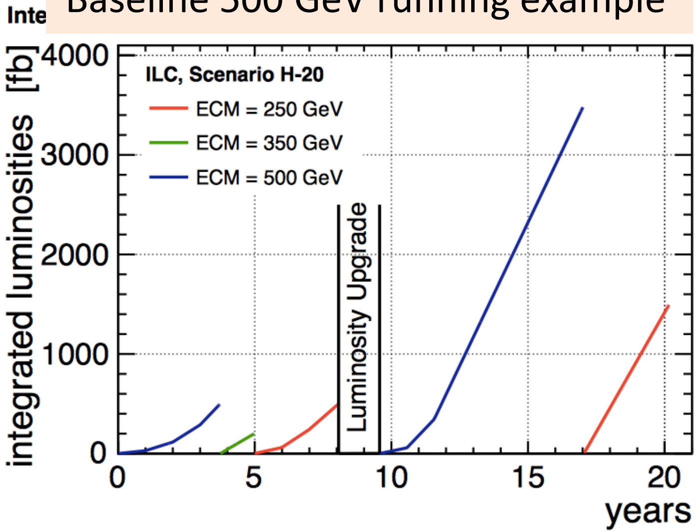
Technical improvements can decrease cost by 10-20%

More seems to be required, so staging is being considered

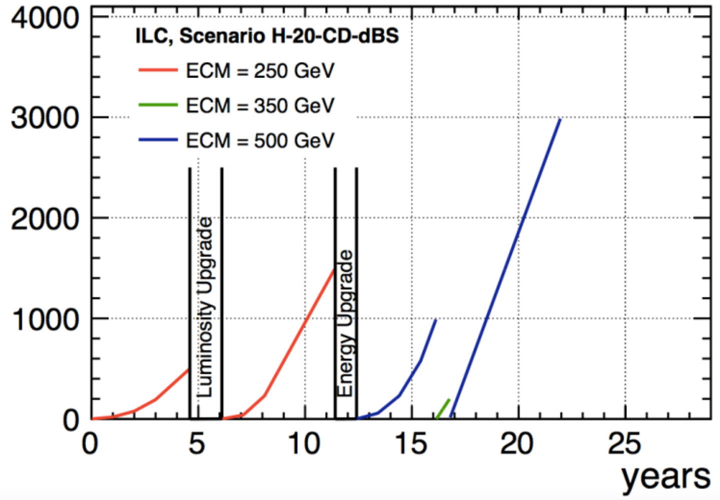
Example options




Baseline 500 GeV running example




Example: 250 GeV (F) and upgrade




Goal:
4 $ab^{-1}$ @ 500 GeV
100 $fb^{-1}$ @ 350 GeV
2 $ab^{-1}$ @ 250 GeV

Luminosity increase

- 2 x by increasing RF
- 2 x by increasing cryogenics and repetition rate