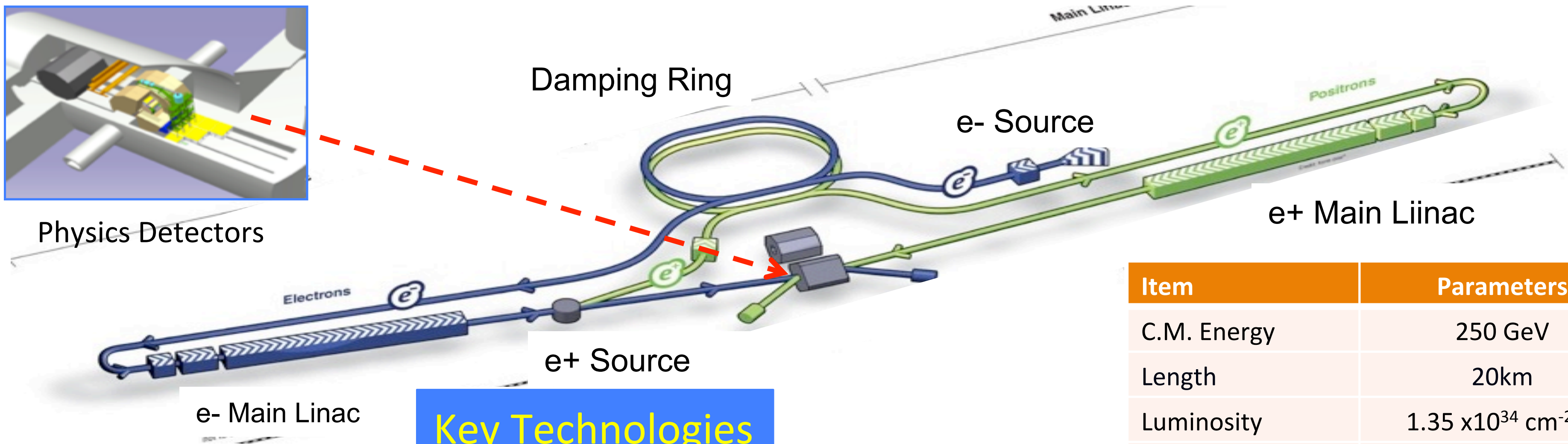
Linear Colliders

D. Schulte, CERN

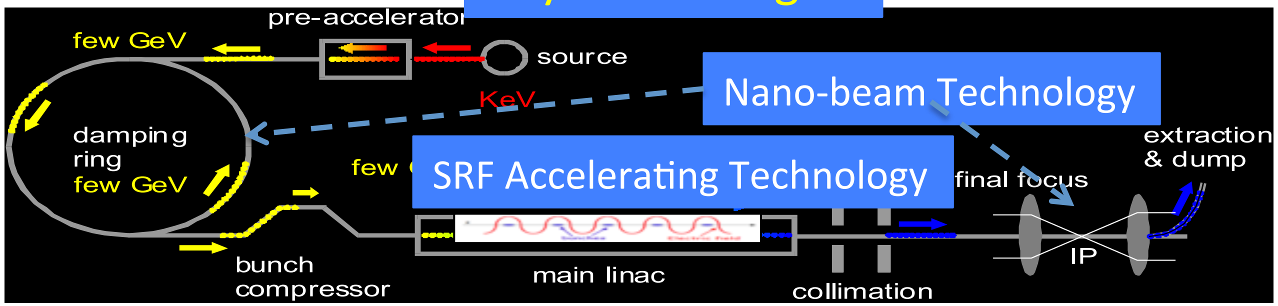
Key Parameters

Parameter	Symbol [unit]	ILC	ILC	CLIC	CLIC
CMS energy	E_{cm} [GeV]	250	500	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	σ_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]	5×10^3/35	5×10^3/35	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



Key Technologies

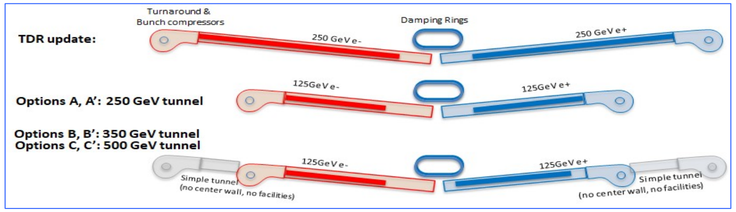


Item	Parameters
C.M. Energy	250 GeV
Length	20km
Luminosity	1.35 x10^{34} $cm^{-2}s^{-1}$
Repetition	5 Hz
Beam Pulse	0.73 ms
Beam Current	5.8 mA (in pulse)
Beam size (y) at FF	**7.7** nm@250GeV
SRF Cavity G. Q_0	**31.5** MV/m (**35** MV/m) Q_0 = 1x10^{10}

ILC since the TDR in 2012-13: Technical focus and changes

- Site specific studies
- Technical developments for most accelerator systems - high Q improvements for example
- E-XFEL at DESY successfully constructed and put into operation – a key technology demonstration

Options for ILC Staging at 250GeV



Options	Gradient [MV/m]	E_{CM} [GeV]	Total E_{CM} Margin	n	Space margin	Reserved tunnel	Total tunnel
TDR update	31.5	500	2%	10	1,473 m	0 m	33.5 km
Option A		250	6%	6	583 m	0 m	20.5 km
Option B				6&8		3,238 m	27 km
Option C				6&10		6,477 m	33.5 km
Option A'	35			6	1,049 m	0 m	20.5 km
Option B'				6&8		3,238 m	27 km
Option C'				6&10		6,477 m	33.5 km

A. Yamamoto, 171106 2

Recent proposal to start with an initial energy of 250 GeV (physics impact report) – key issues:

- Higgs precision depends significantly on HiLumi performance and theory assumptions (link)
- Below ttbar threshold
- Reduced search capabilities

Nevertheless, provides impressive precision, and remains upgradable.

TDR costs of ~8 BILCU for 500 GeV (ILCU = 2012 US$ estimate used in the TDR) can be reduced by up to ~40%

The European-XFEL

H. Weise

Progress:

2013: Construction started

…

2016: E- XFEL Linac completion

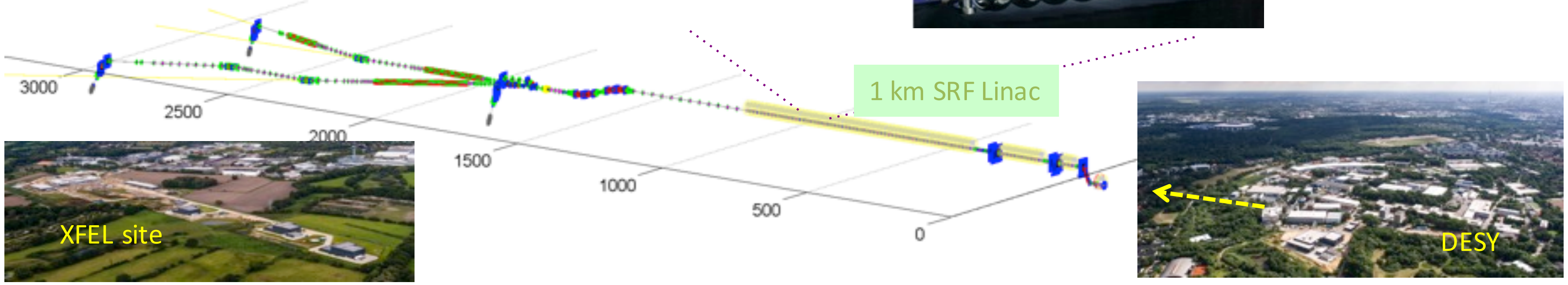
2017: E-XFEL beam start

1.3 GHz / 23.6 MV/m

800+4 SRF acc. Cavities

100+3 Cryo-Modules (CM)

: ~1/10 scale to ILC-ML

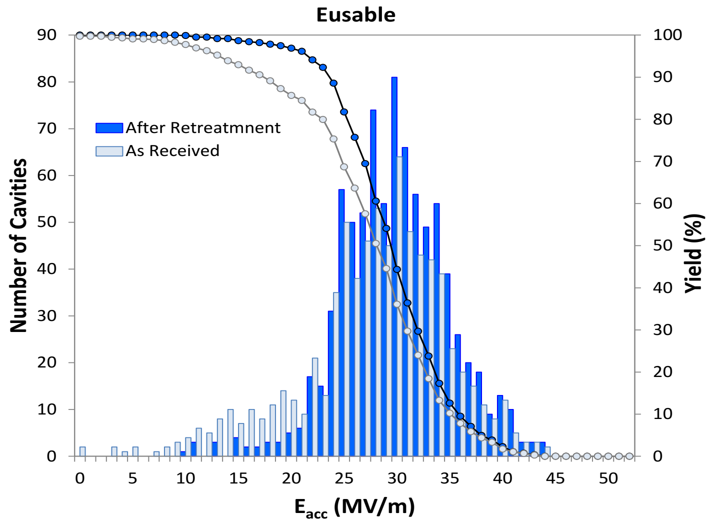


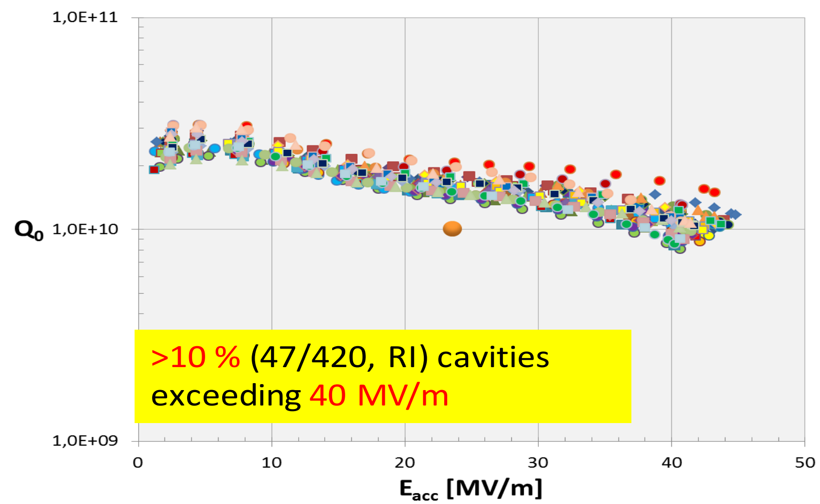
SRF Cavity Performance

ILC goal:
31.5 MV/m

FEL goal:
24 MV/m

Achieved:
29.8 MV/m





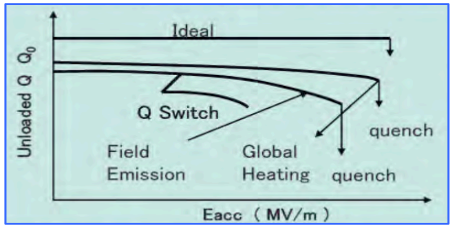
After Retreatment:

E-usable: 29.8 ± 5.1 [MV/m]

(RI): E usable 31.2 ± 5.2 [MV/m]), w/ 2nd EP

(EZ): E usable 28.6 ± 4.8 [MV/m]) , w/ BCP (instead of 2nd EP)

A. Yamamoto, 171106



N. Walker, D. Reschke, C. Pagani

ILC Development

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%
- …

L. Evans
A. Yamamoto

Modified exposure to nitrogen (from FNAL)

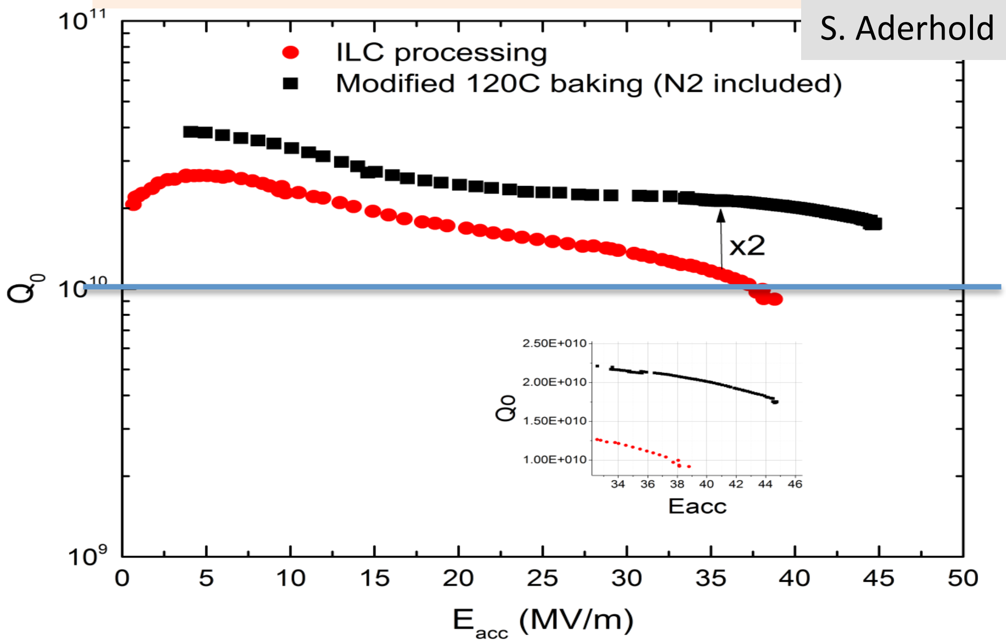
Before: doping with few minutes at 800 °C

Now: a day or so at 120 °C

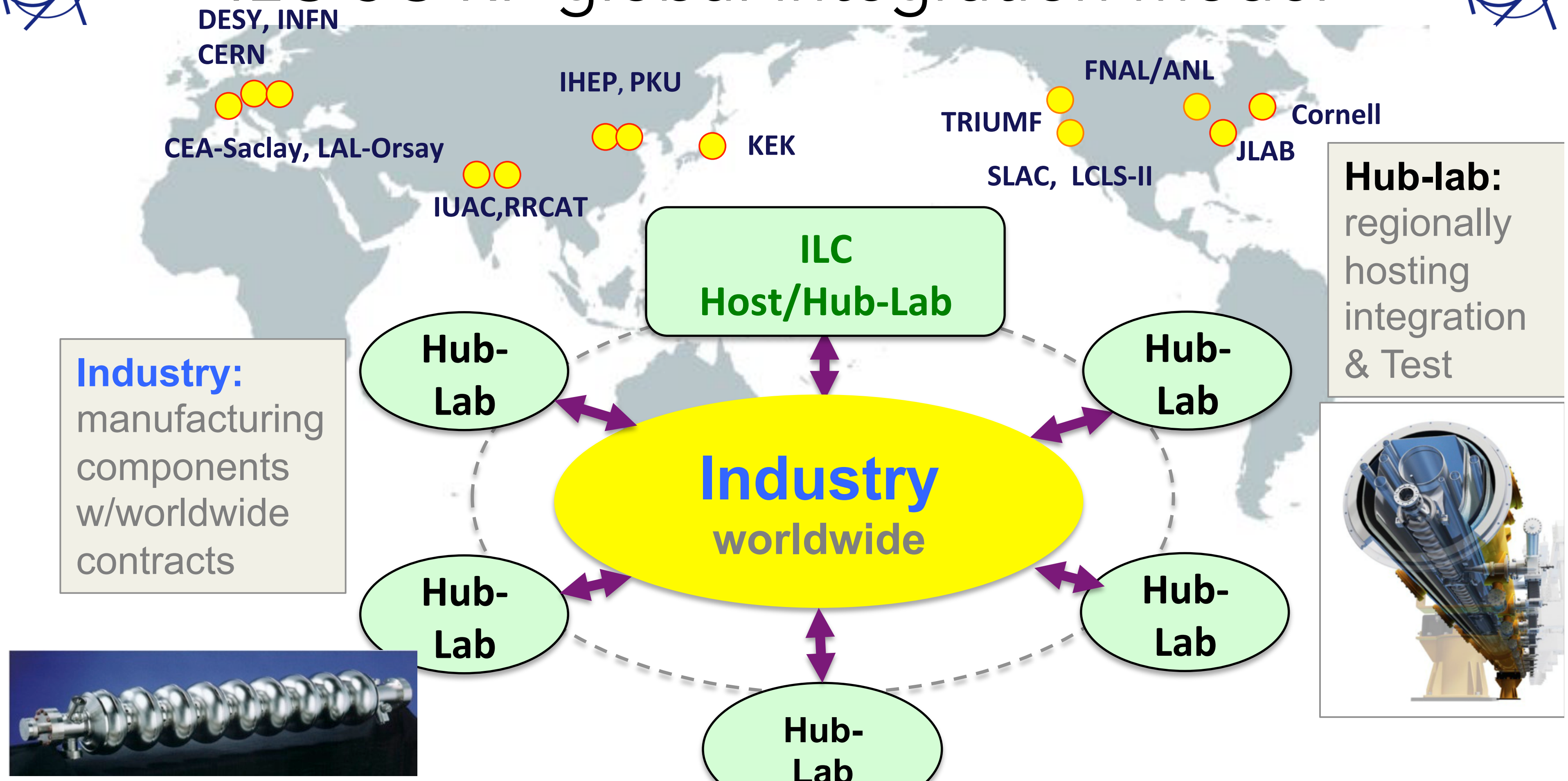
Nitrogen infusion appears very promising

- Increase in gradient
- Increase in Q_0

A. Grassellino, S. Aderhold



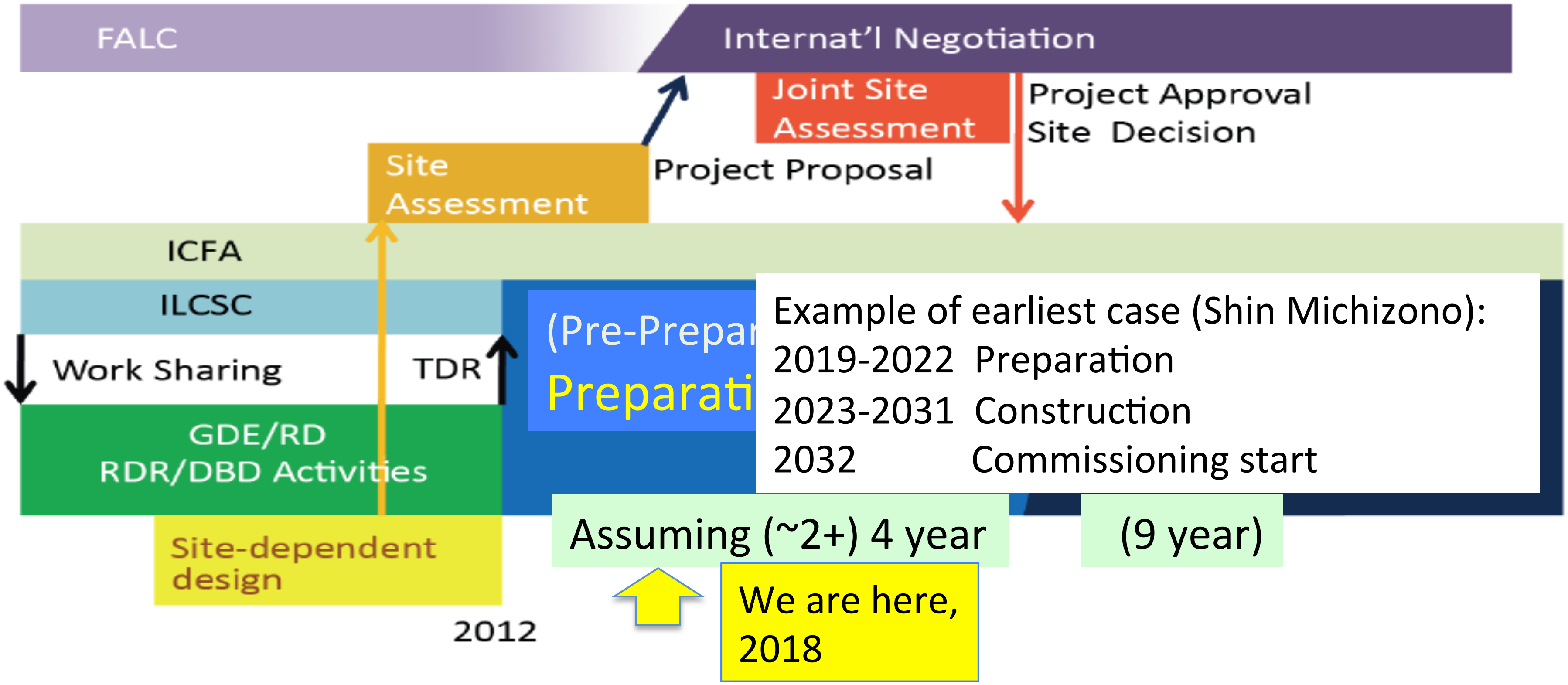
ILC SC RF global integration model



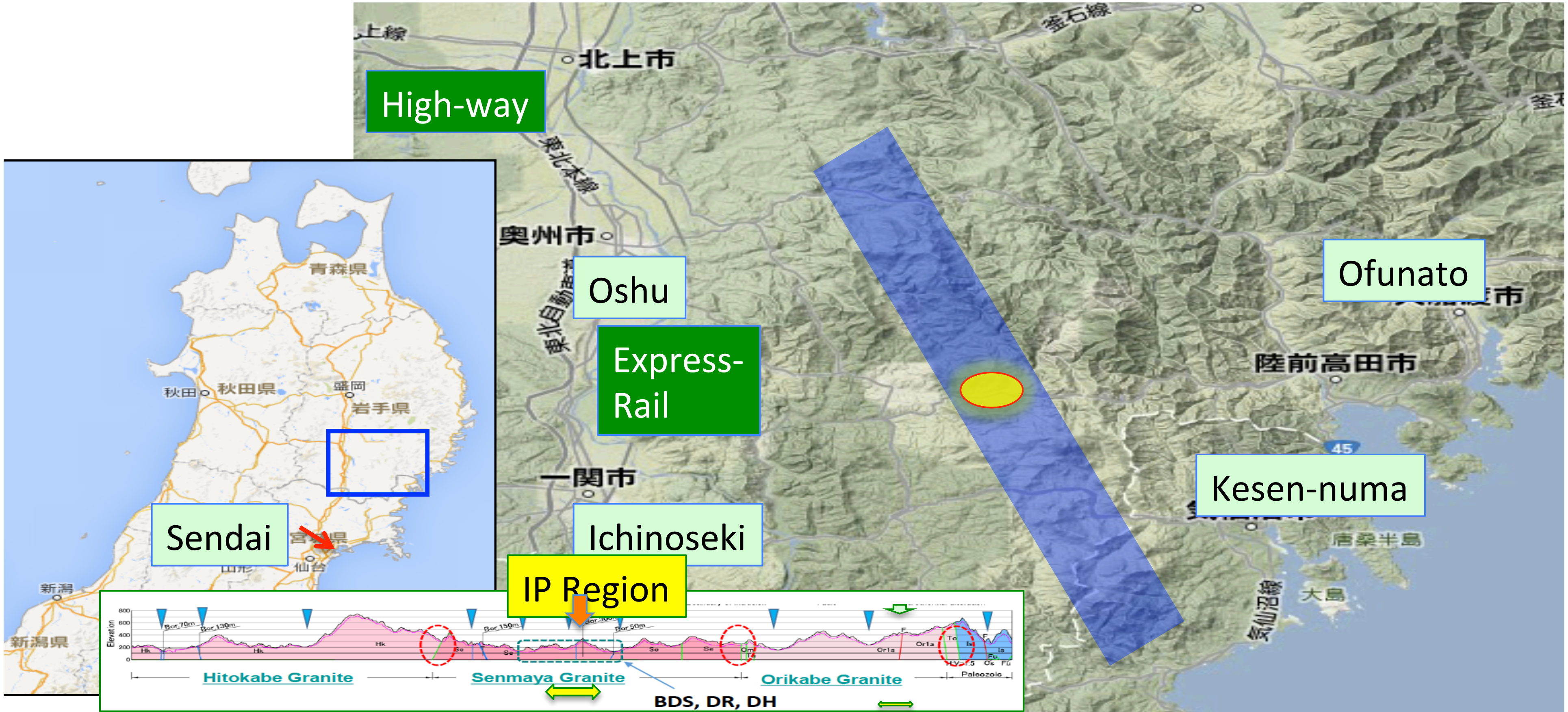
ILC Parameter Demonstration

Characteristics	Parameter	Unit	Demonstrated
ATF-FF equiv. beam size (y) ILC-FF beam size (y)	37 (reaching **41**) 5.9 (correspond. 7)	nm nm	KEK-ATF
Average accelerating gradient	31.5 (±20%)	MV/m	DESY, FNAL, JLab, Cornell, KEK,
Cavity Q_0	10^{10}		
(Cavity qualification gradient	35 (±20%)	MV/m)	
Beam current	5.8	mA	DESY-FLASH), KEK-STF
Number of bunches per pulse	1312		DESY
Charge per bunch	3.2	nC	
Bunch spacing	554	ns	
Beam pulse length	730	ms	DESY, KEK
RF pulse length (incl. fill time)	1.65	ms	DESY, KEK, FNAL
Efficiency (RF→beam)	0.44		
Pulse repetition rate	5	Hz	DESY, KEK

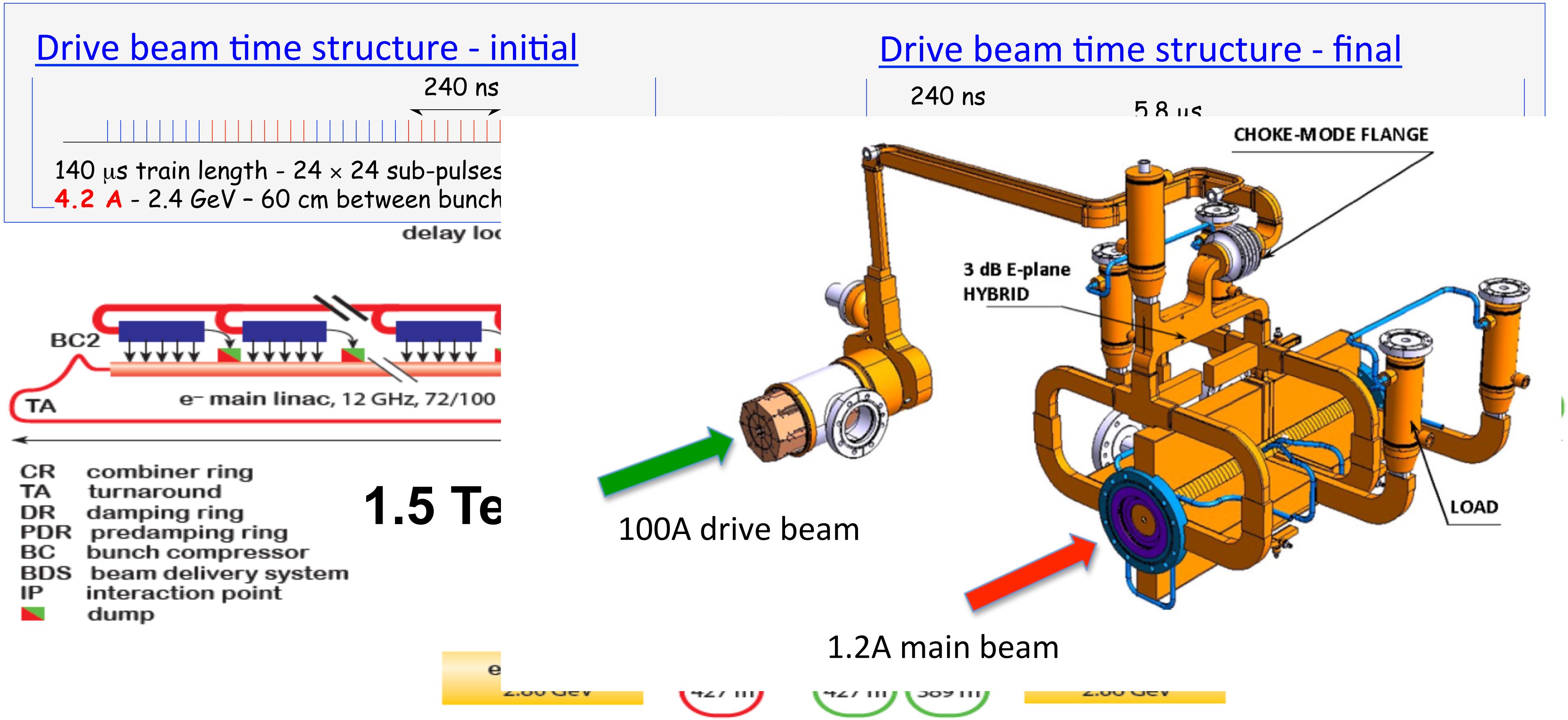
ILC Time Line: Progress and Prospect



ILC Candidate Location: Kitakami, Tohoku

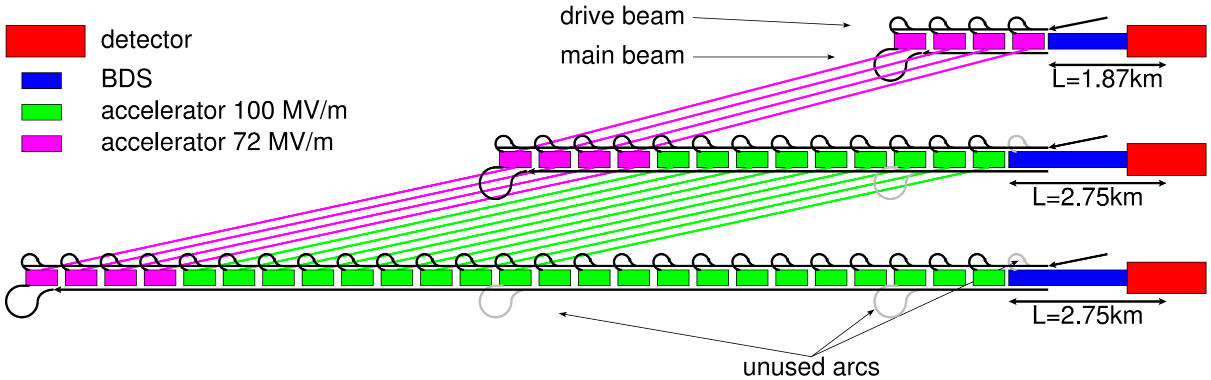


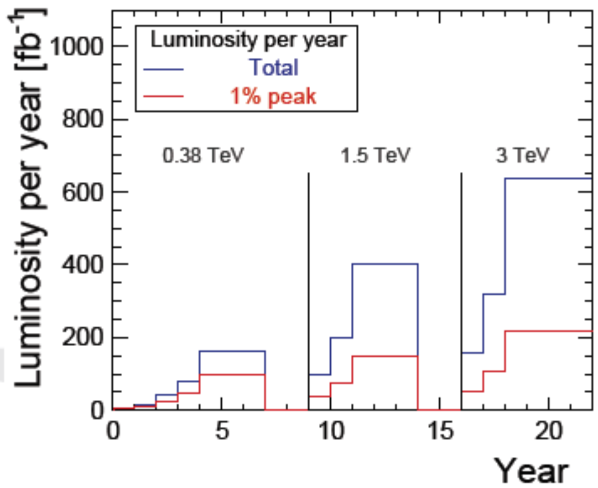
CLIC (3 TeV)


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
delay loo
BC2
TA
e⁻ main linac, 12 GHz, 72/100
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
CHOKE-MODE FLANGE
3 dB E-plane
HYBRID
LOAD
100A drive beam
1.2A main beam

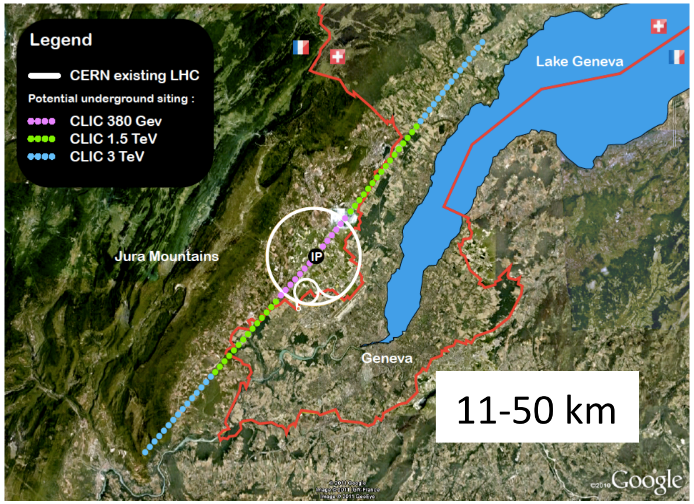
CLIC Staged Design

Staged design approach
Cost-optimised first energy stage
380 GeV: HZ, WW fusion, top asymmetry
Further stages re-use infrastructure and equipment

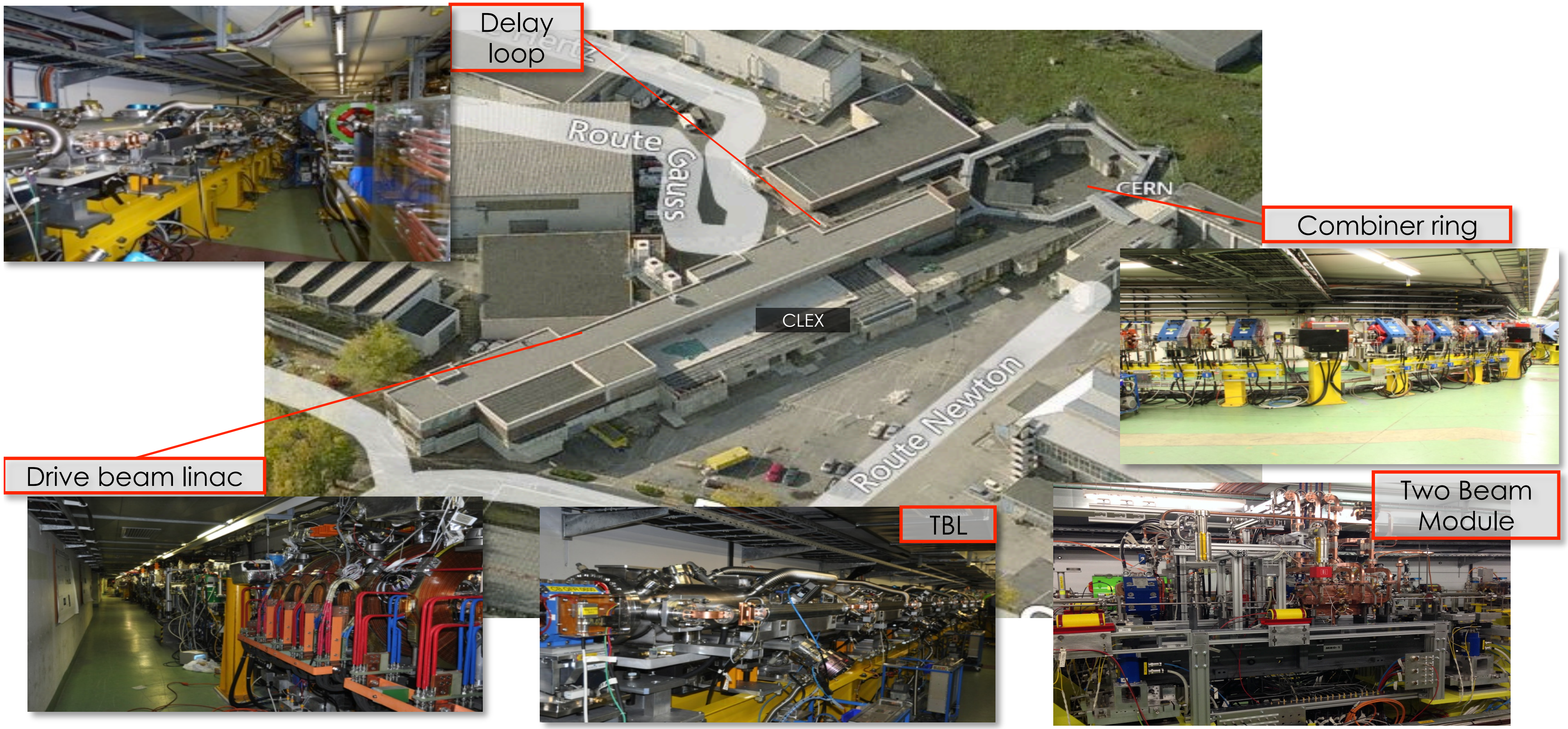




Stage	$\sqrt{s}$ (GeV)	$\mathscr{L}_{int}$ (fb^{-1})
1	380	500
	350	100
2	1500	1500
3	3000	3000

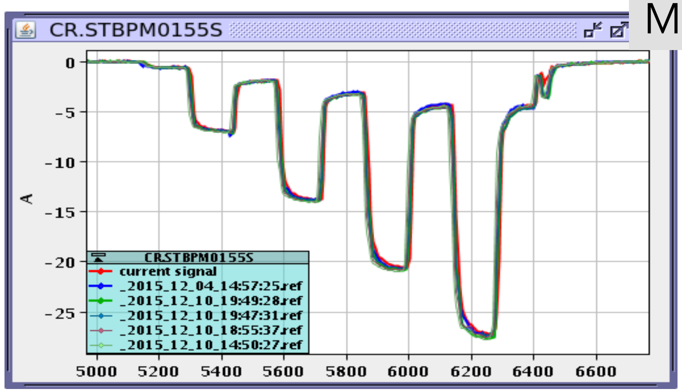


CLIC Test Facility (CTF3)

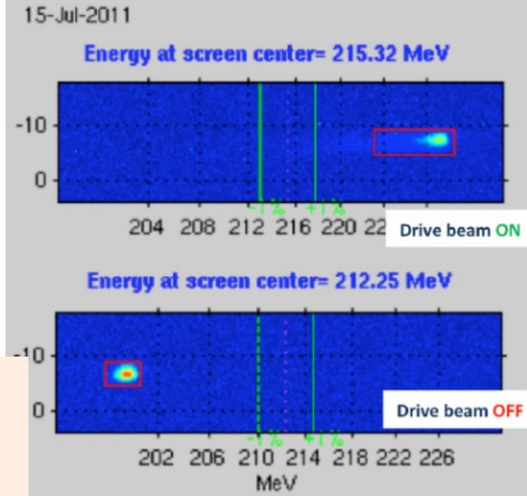


Drive Beam Scheme Performance

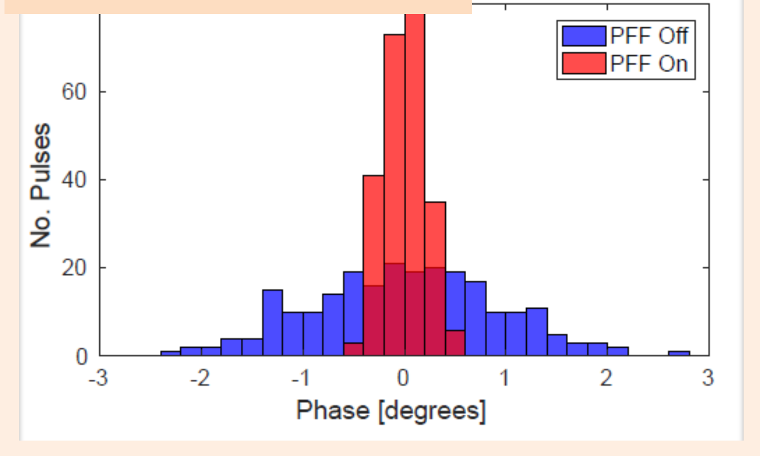
CTF3 measurements:
- RF to drive beam efficiency > 95%
- Current multiplication factor 8
- Most of beam quality
- 145 MV/m X-band acceleration



Measured 145 MV/m gradient



Arrival time with feedback

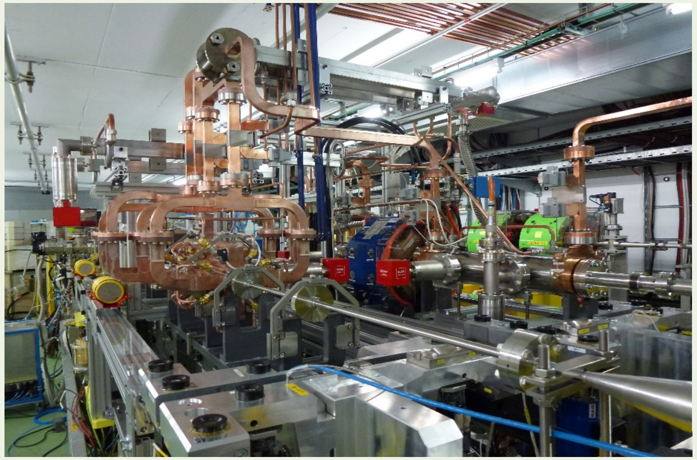


Current stability affected by very low CTF3 energy, 3 x larger beam and delay loop design different from CLIC

Detailed simulations of drive beam performance in CLIC

Parameter	CLIC goal	CTF3 meas
Arrival time	50 fs	50 fs
Current after linac	0.75×10^{-3}	$0.2\text{-}0.4 \times 10^{-3}$
Energy	1.0×10^{-3}	0.7×10^{-3}

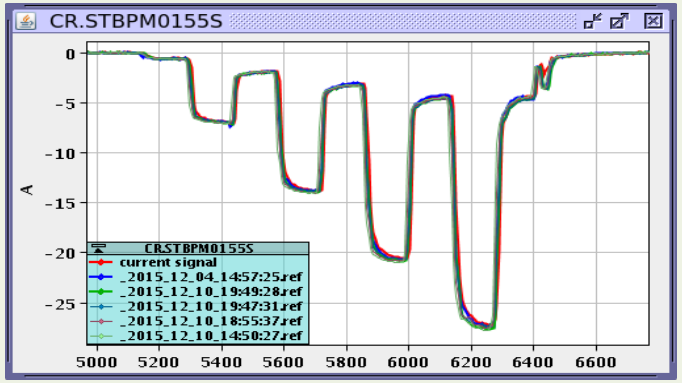
From CTF3 to CLEAR



CTF3 has demonstrated drive beam production and main beam acceleration

- Technology
- Beam quality
- Operation

Now stopped



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

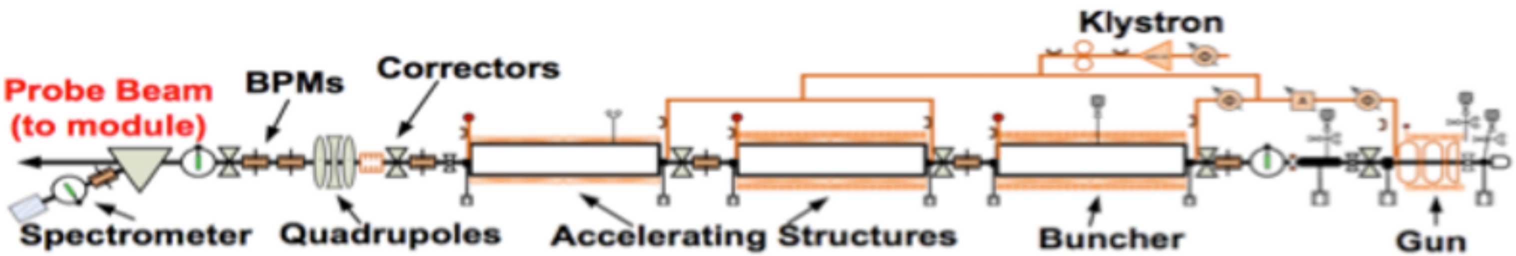
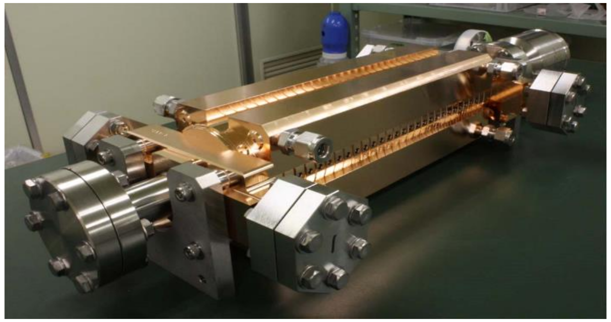


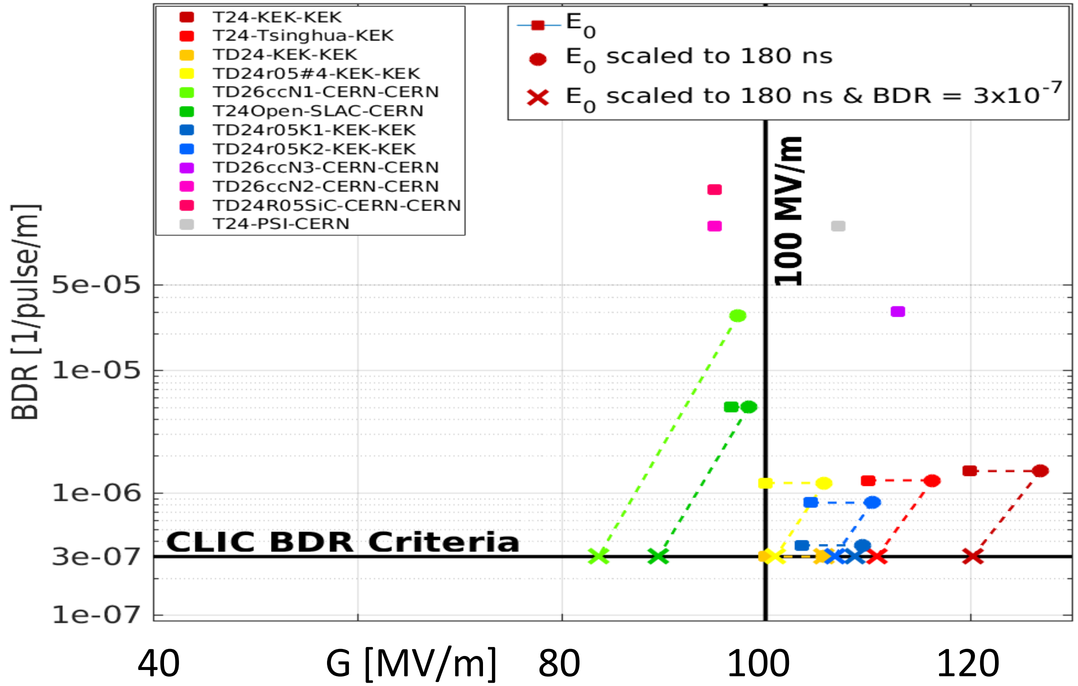
Figure 1: The current CALIFES beam line. The length of the facility (as shown) is ~20m.

CLIC Structure Development



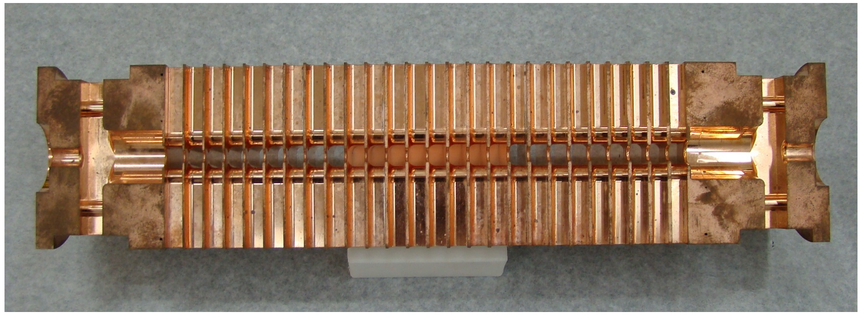
Structure testing takes long, conditioning required

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)

CLIC RF Technology Development

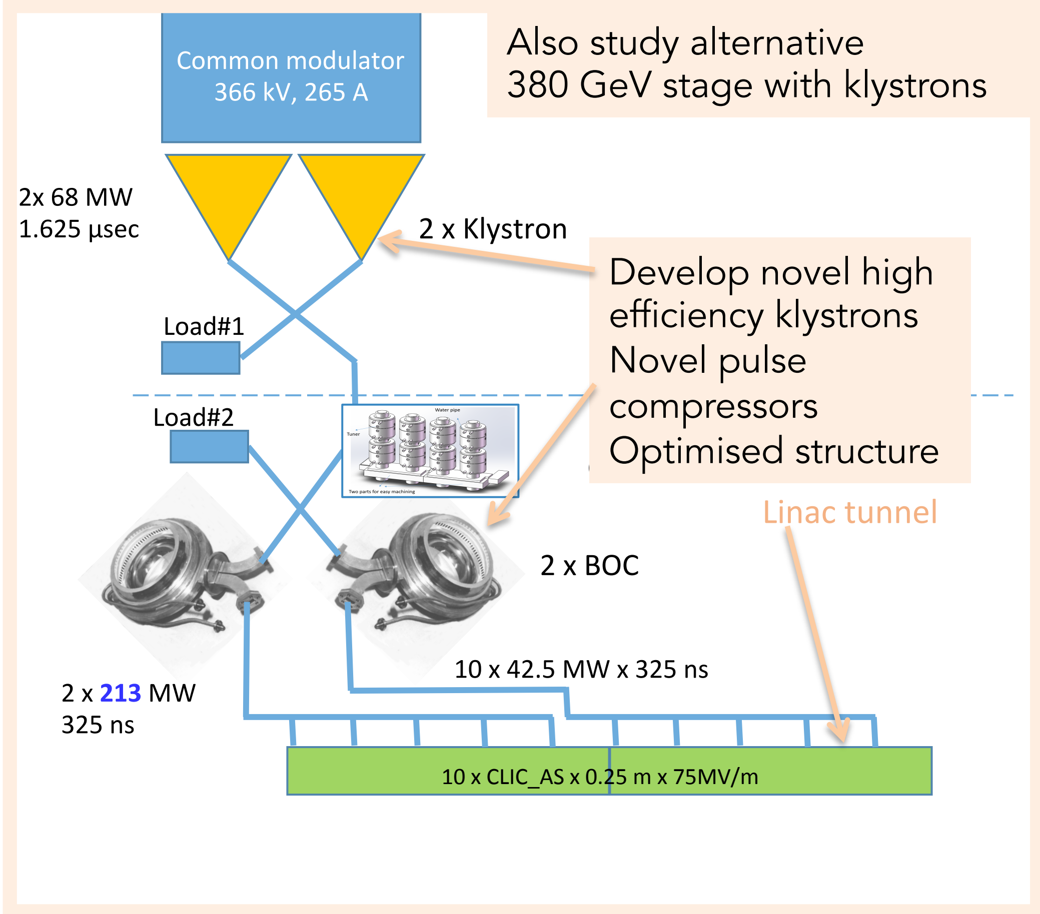


Further development and industrialisation of accelerating structures is ongoing

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

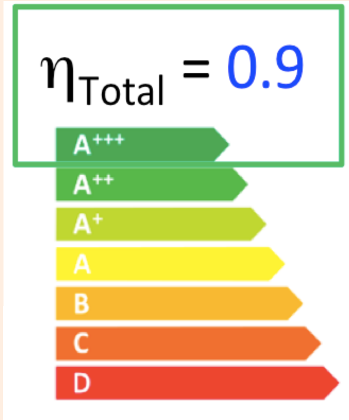
Growing use of X-band (FELs, novel technologies, …)

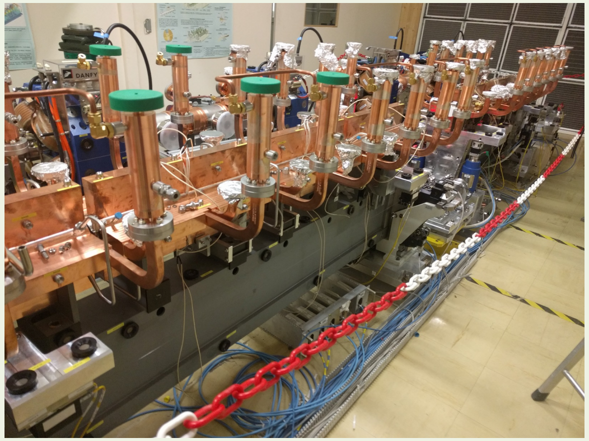
- E.g. at PSI, DESY, INFN, Cockcroft, …
- CompactLight proposal accepted by EU, 24 partners
- Sparc at INFN-LF



Other CLIC Technology Development

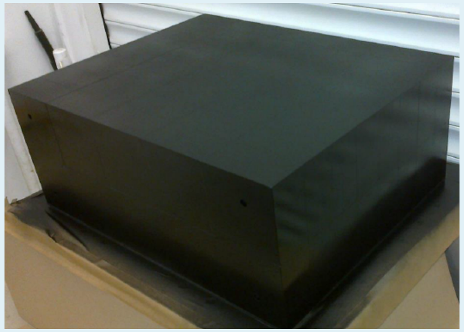
Redesign CLIC modulators and klystrons
Aim: increase efficiency from 62% to 90%
⇒ Less power consumption
⇒ Also important cost saving
Shorter tubes, no oil in modulator, …
⇒ Important cost saving





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

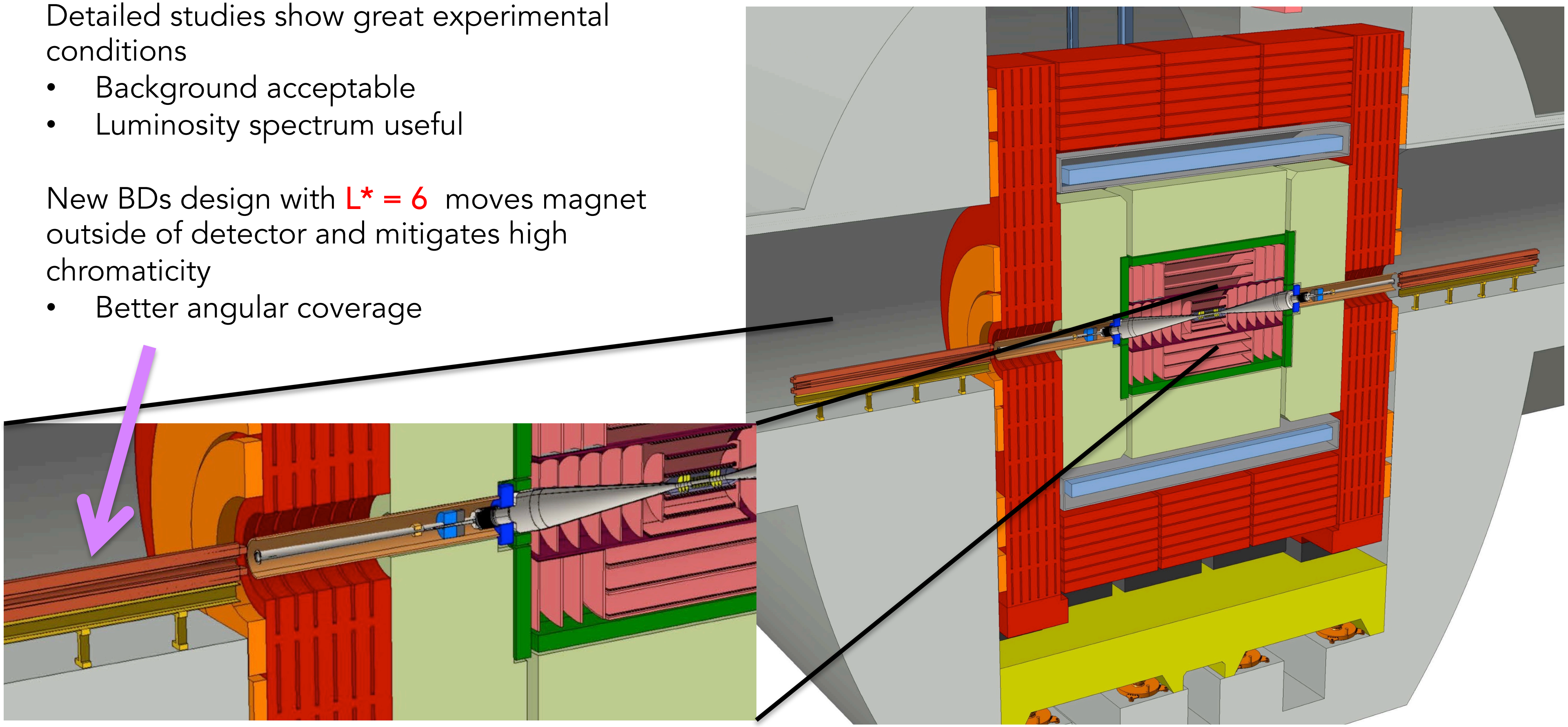
Experimental Conditions

Detailed studies show great experimental conditions

- Background acceptable
- Luminosity spectrum useful

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

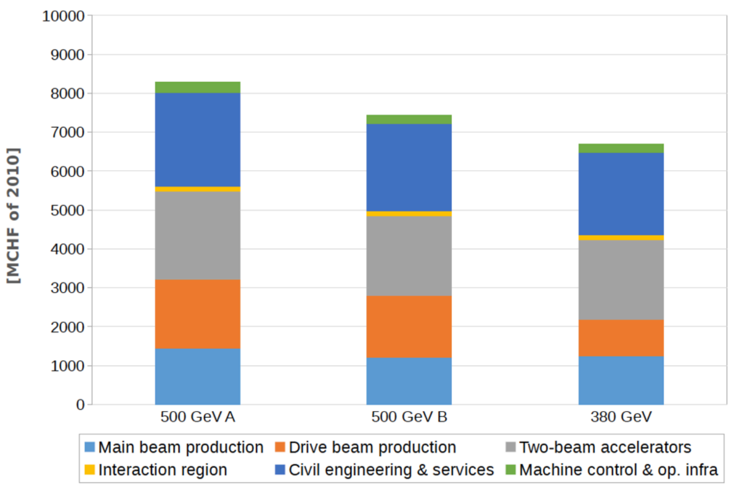
- Better angular coverage

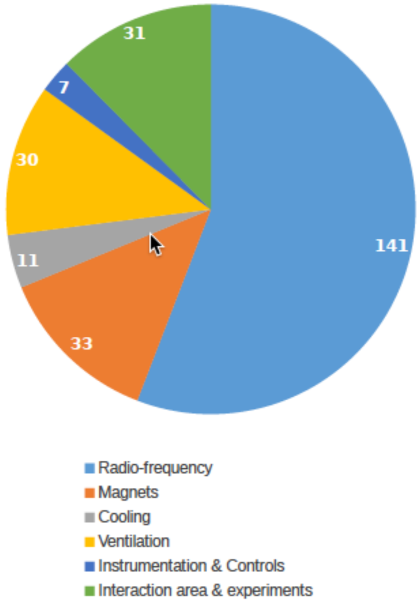


Cost and Power

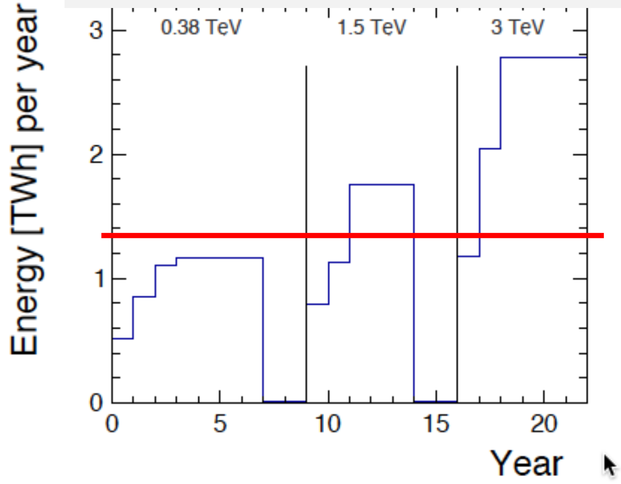
Table 11: Value estimate of CLIC at 380 GeV centre-of-mass energy.

	Value [MCHF of December 2010]
Main beam production	1245
Drive beam production	974
Two-beam accelerators	2038
Interaction region	132
Civil engineering & services	2112
Accelerator control & operational infrastructure	216
Total	6690



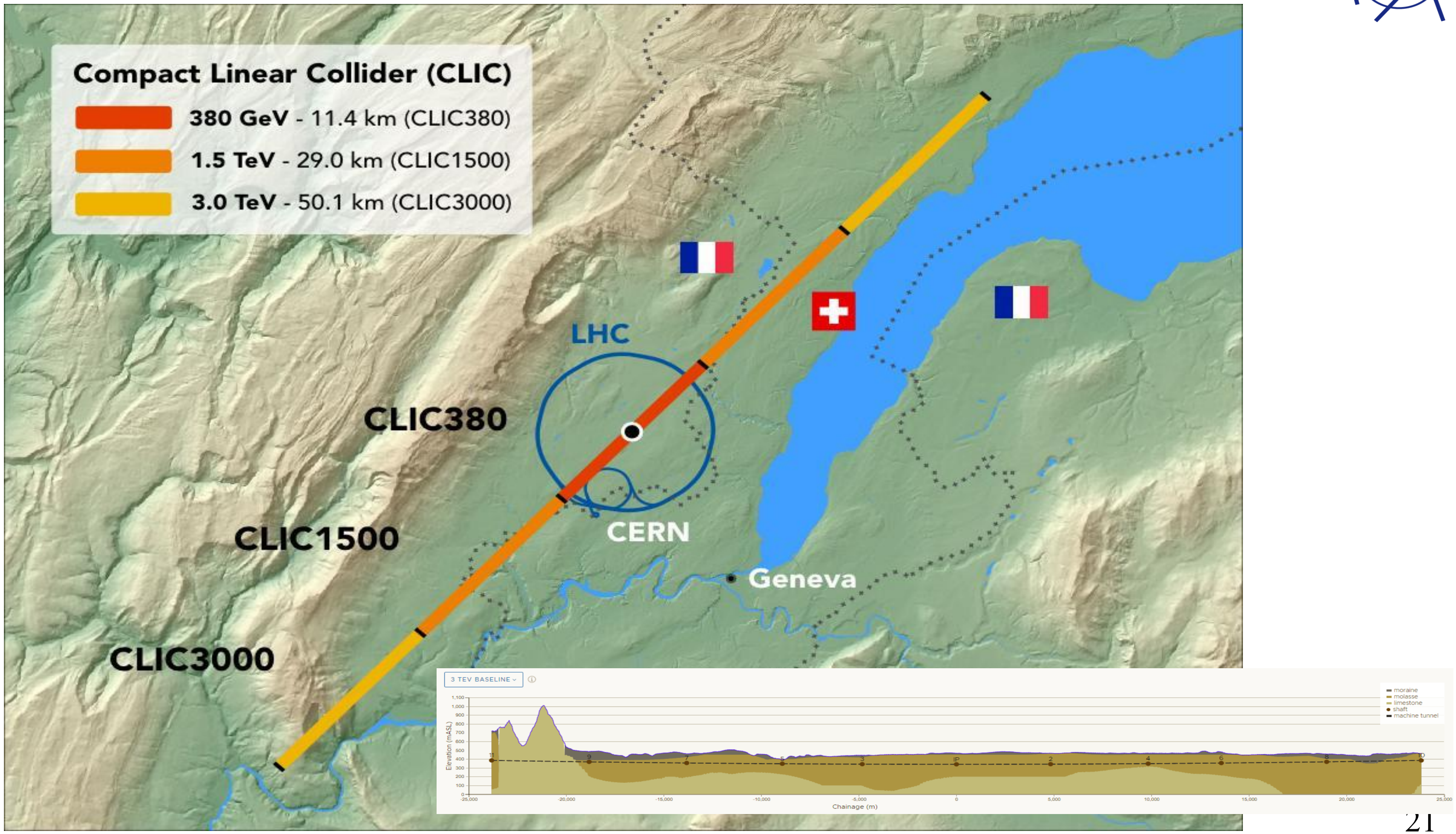


CERN energy consumption 2012: 1.35 TWh



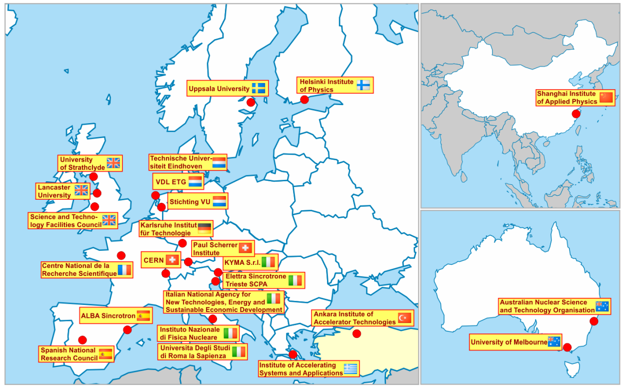
A cost of ~6 BCHF and power ~200 MW are “reasonable” values
→ Continue work on modules, RF and CE for costs; for power RF and magnets

CLIC Site



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

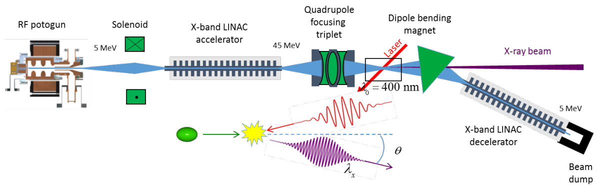
CLIC Technology and FELs



CLIC technology for different applications

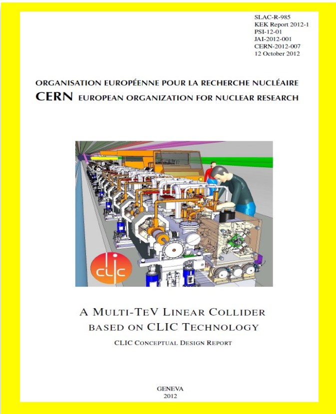
- EU co-funded FEL design study
- SPARC at INFN-LF
- …

INFN Frascati advanced acceleration facility
EuPARXIA@SPARC_LAB



Eindhoven University led
SMART*LIGHT Compton Source

CLIC Roadmap



CDR in 2012 established feasibility of 3 TeV design

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)

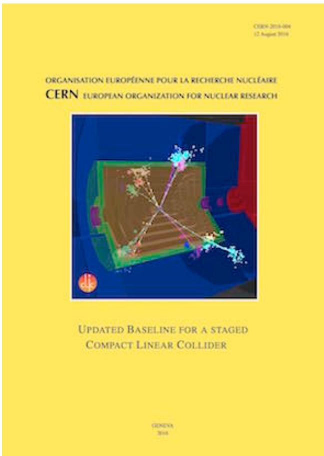
2025 Construction Start

Ready for construction; start of excavations

2035 First Beams

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

Rebaselining document defined staged approach

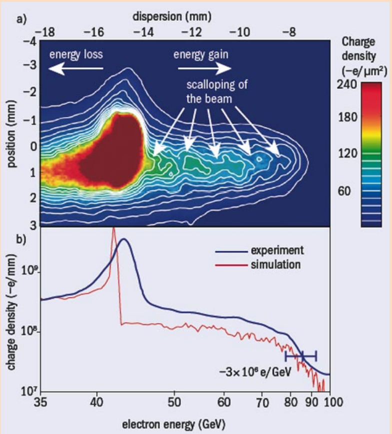


Novel Technologies

Beam-driven plasma

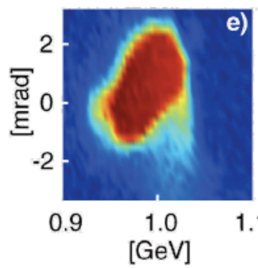
SLC beam L=0.85m,
G=O(50 GV/m)
⇒ 42 GeV

I. Blumenfeld et al,
Nature 445, p. 741
(2007)



Laser-driven plasma

Using laser beam to generate the plasma at Berkeley
=> 1GeV



Beam energy =1.0 GeV
Charge= Q~30 pC
1.6 mrad rms divergence
2.5% rms energy spread

Leemans *et al.*, Nature Phys. (2006).
Nakamura *et al.*, Phys. Plasmas (2007).

Proton-driven plasma

Planned in AWAKE
Using a proton bunch to create many minibunches

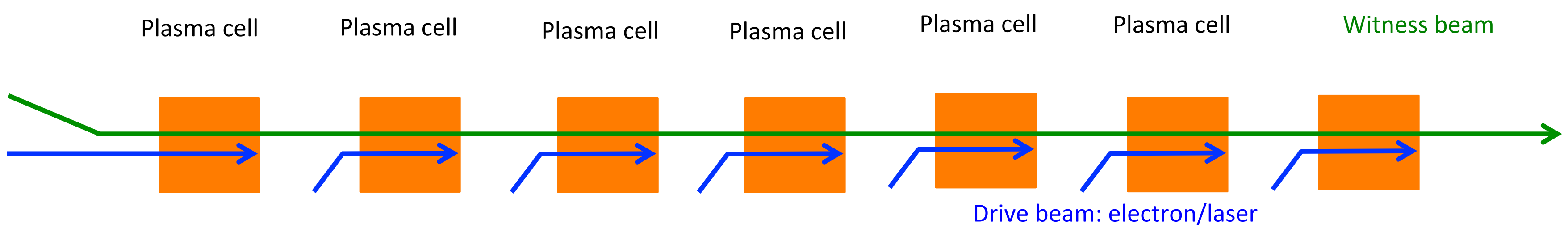
Laser-driven dielectric accelerating structures

Beam-driven dielectric accelerating structures

High gradients can be reached

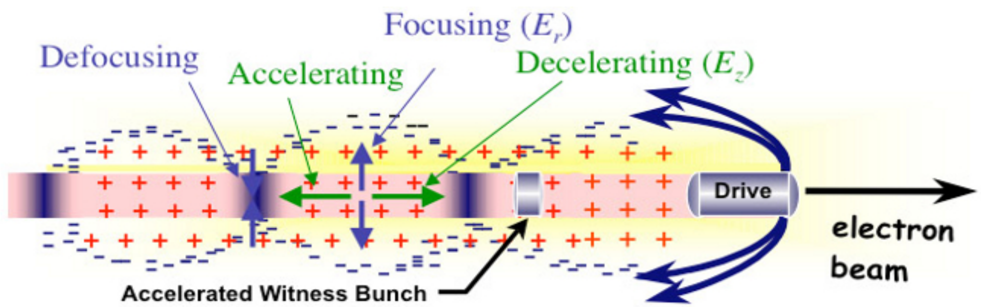
Could become viable technologies for linear colliders

Use for Linear Colliders



A long way to go from small scale to colliders
But important to pursue

Working group at CLIC to make sure that design is consistent with later upgrade using novel technlogies



Conclusion

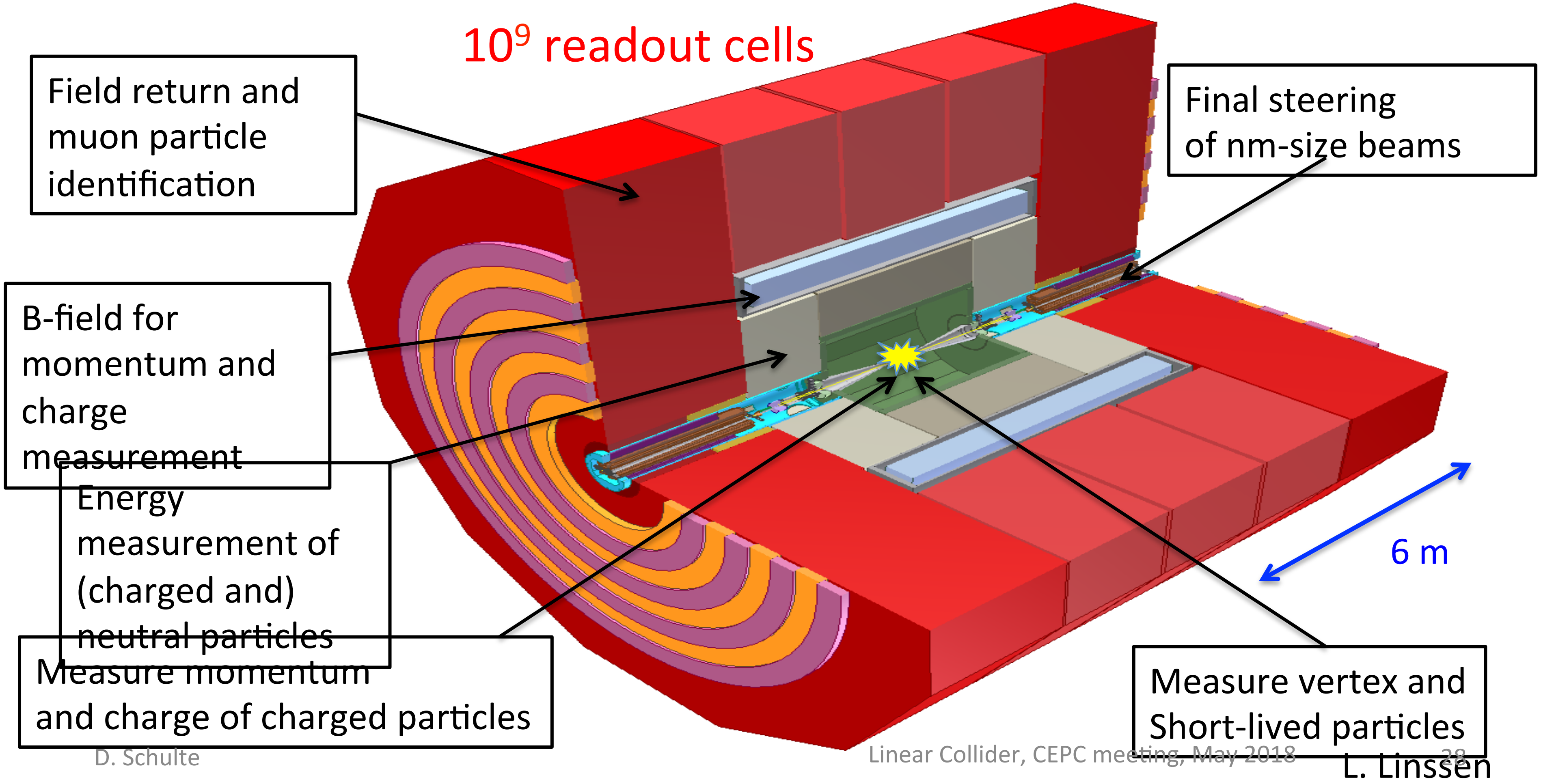
Important progress toward the EU strategy

- ILC
  - European XFEL is large-scale prototype
  - Focus on cost reduction
  - Scope reduction to 250 GeV centre-of-mass
  - Political process ongoing
- CLIC
  - Normal conducting FELs are prototypes, e.g. Swiss FEL
  - Further optimising 380 GeV first energy stage
  - Work on further stages, including considerations of novel technologies
  - Project Implementation Plan by end of 2018

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

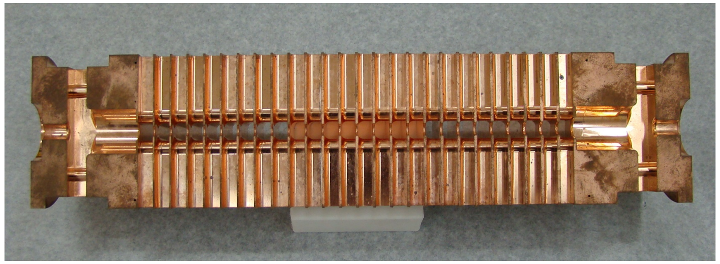
Reserve

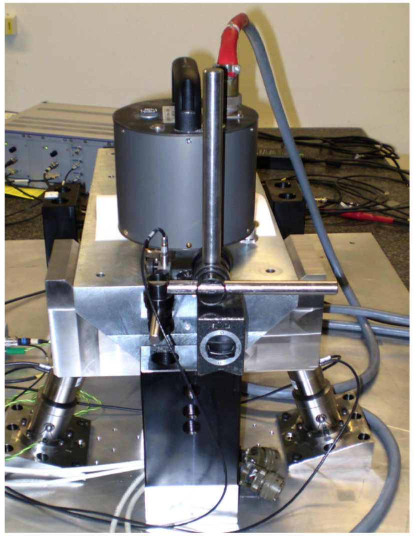
Linear Collider Experiment



CLIC Idea

High gradient makes machine cheap

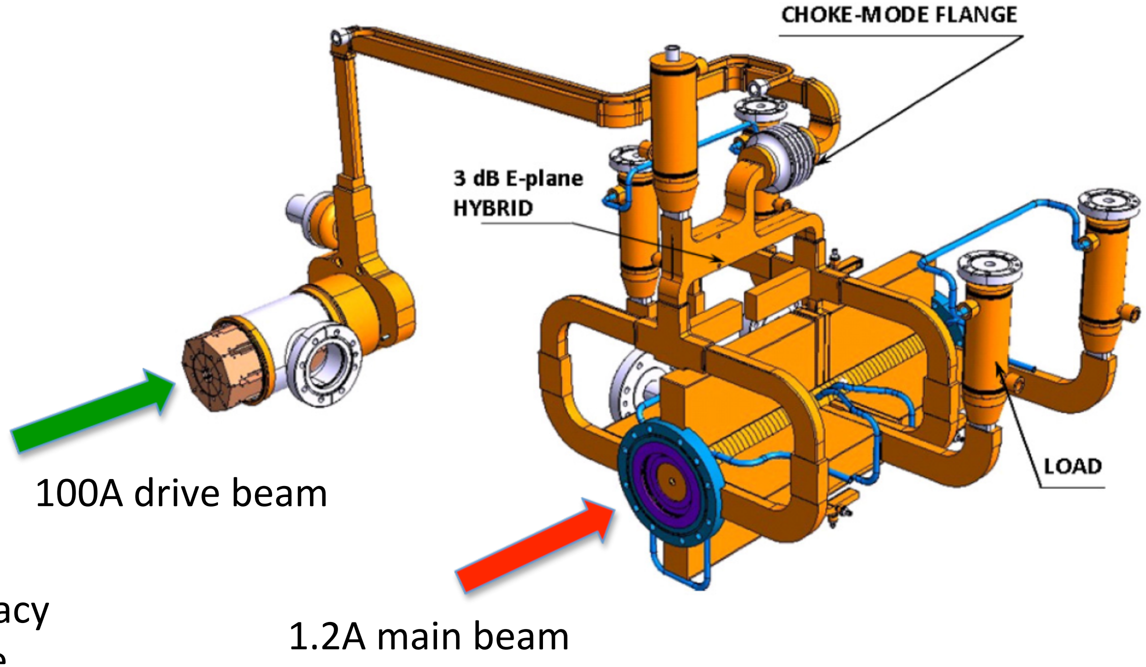




Stabilise quadrupoles against groud motion

Novel, high-accuracy alignment scheme

Drive beam to produce short, high power RF pulse



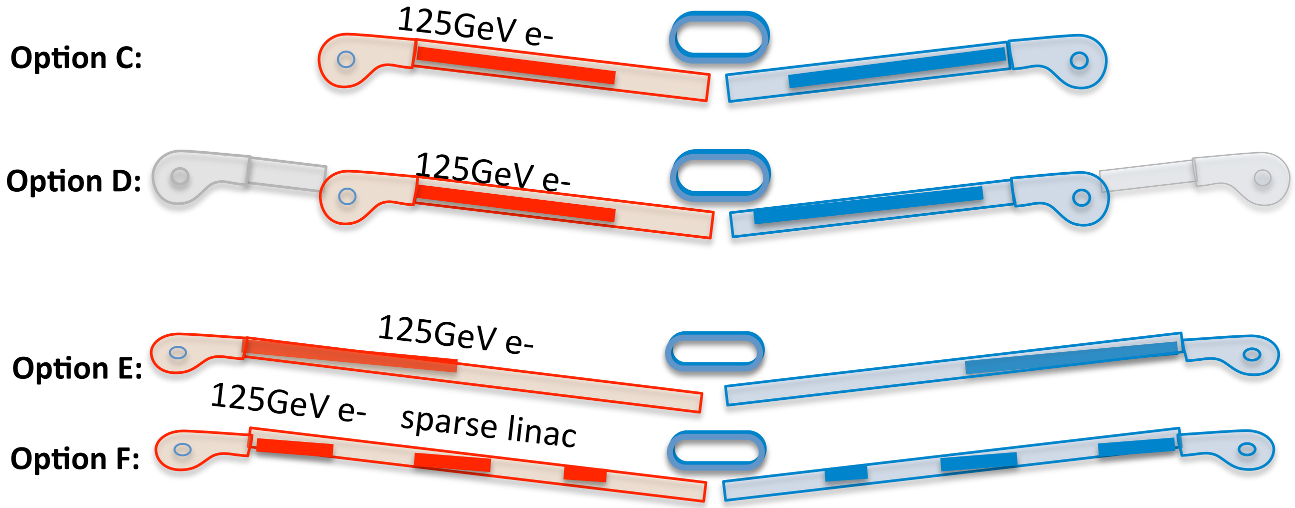
And many more components

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

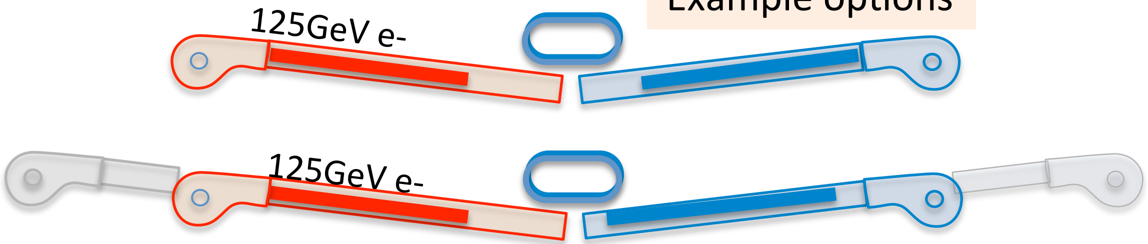
Technical improvements can decrease cost by 10-20%

More seems to be required, so staging is being considered

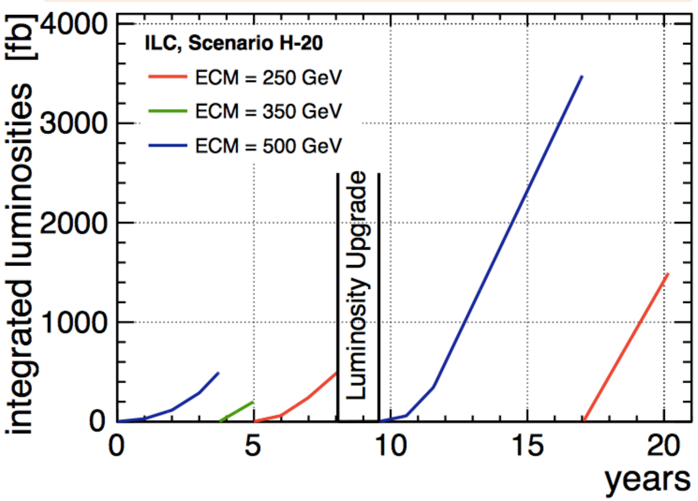
Example options

Option C:

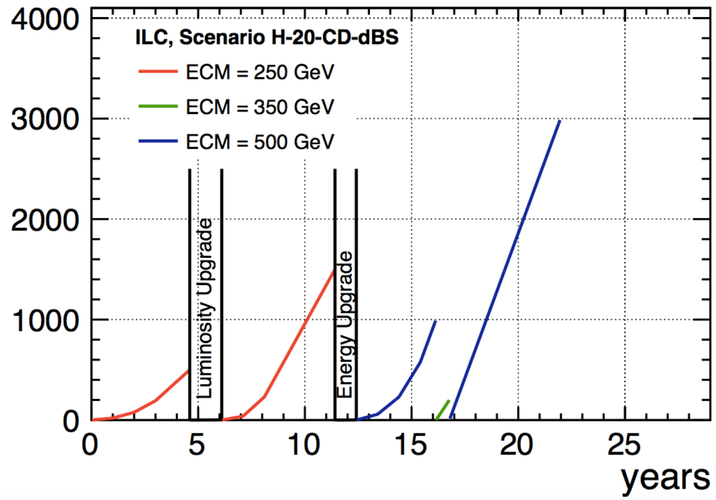
Option D:



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

Cost

Goal set as "reasonable cost": 6 GCHF

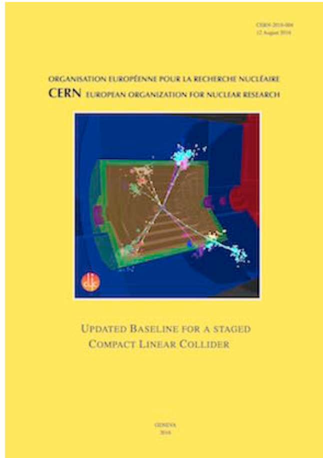
Preliminary cost estimate from rebaselining

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

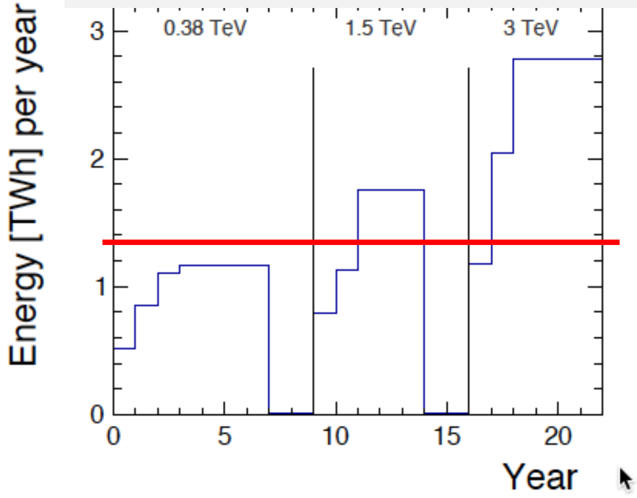
Performing bottom-up power estimate

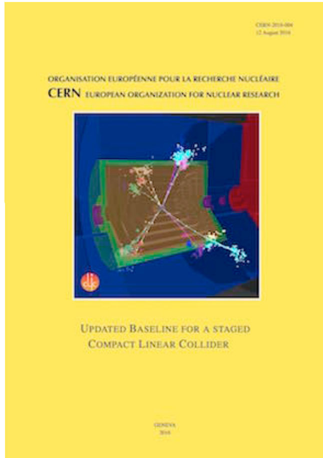
Also optimise the power

- 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

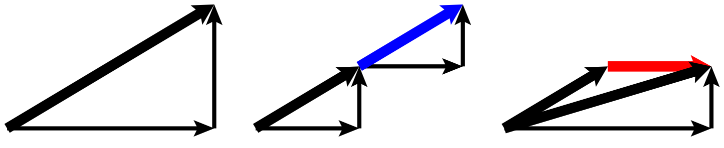
CERN energy consumption 2012: 1.35 TWh

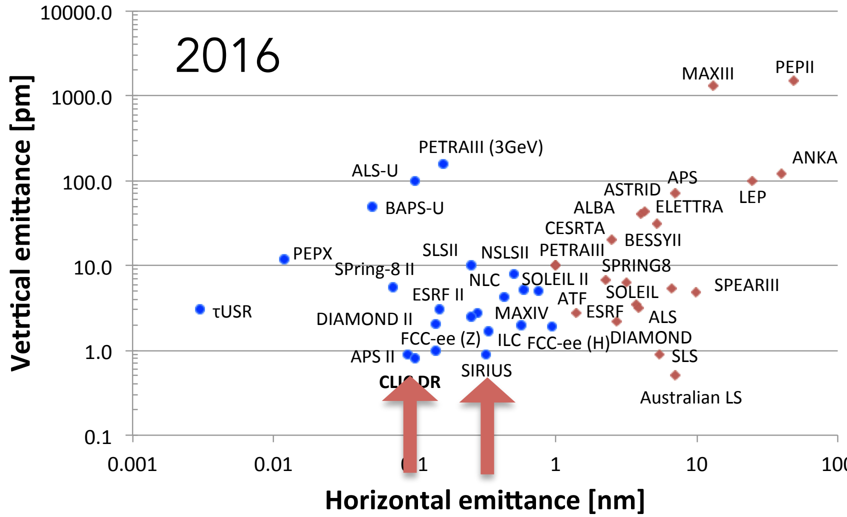




Damping Rings

Cool the beams from the sources





Important progress in collaboration with light source community

Studies of lattice and collective effects show that emittance targets can be reached for 3TeV

Currently optimising for 380 GeV

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}

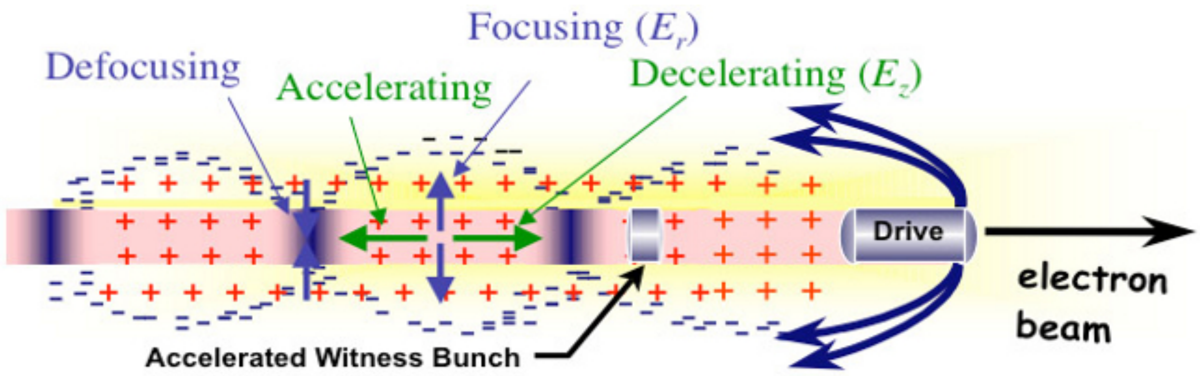
- From CLIC we are starting to explore the opportunities and challenges to make sure that CLIC is not inconsistent with a potential upgrade using novel technologies

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	σ_z [μm]	300	44	8	20	0.0028
Interaction point beam size	σ_x/σ_y [nm/nm]	474/6	40/1	18/0.5	194/1.1	0.75/0.75
Normalized emittances	ϵ_x/ϵ_y [nm]	$10^4/35$	660/20	50/5	$10^4/35$	0.1/0.1
Beta functions	β_x/β_y [mm]	10/0.4	7/0.07	-/-	11/0.1	16.5/16.5
Initial beam energy spread	σ_E [%]	O(0.1)	0.35	—	—	—
Bunches per train	n_b	1312	312	1	1	159
Bunch distance	Δz [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