Latest results on critical-path R&D towards CLIC

Philip Burrows

John Adams Institute

Oxford University

On behalf of the CLIC Accelerator Collaboration

Thanks to all colleagues for materials

LINEAR COLLIDER COLLABORATION

CLIC Accelerator Collaboration

31 Countries – over 50 Institutes

Outline

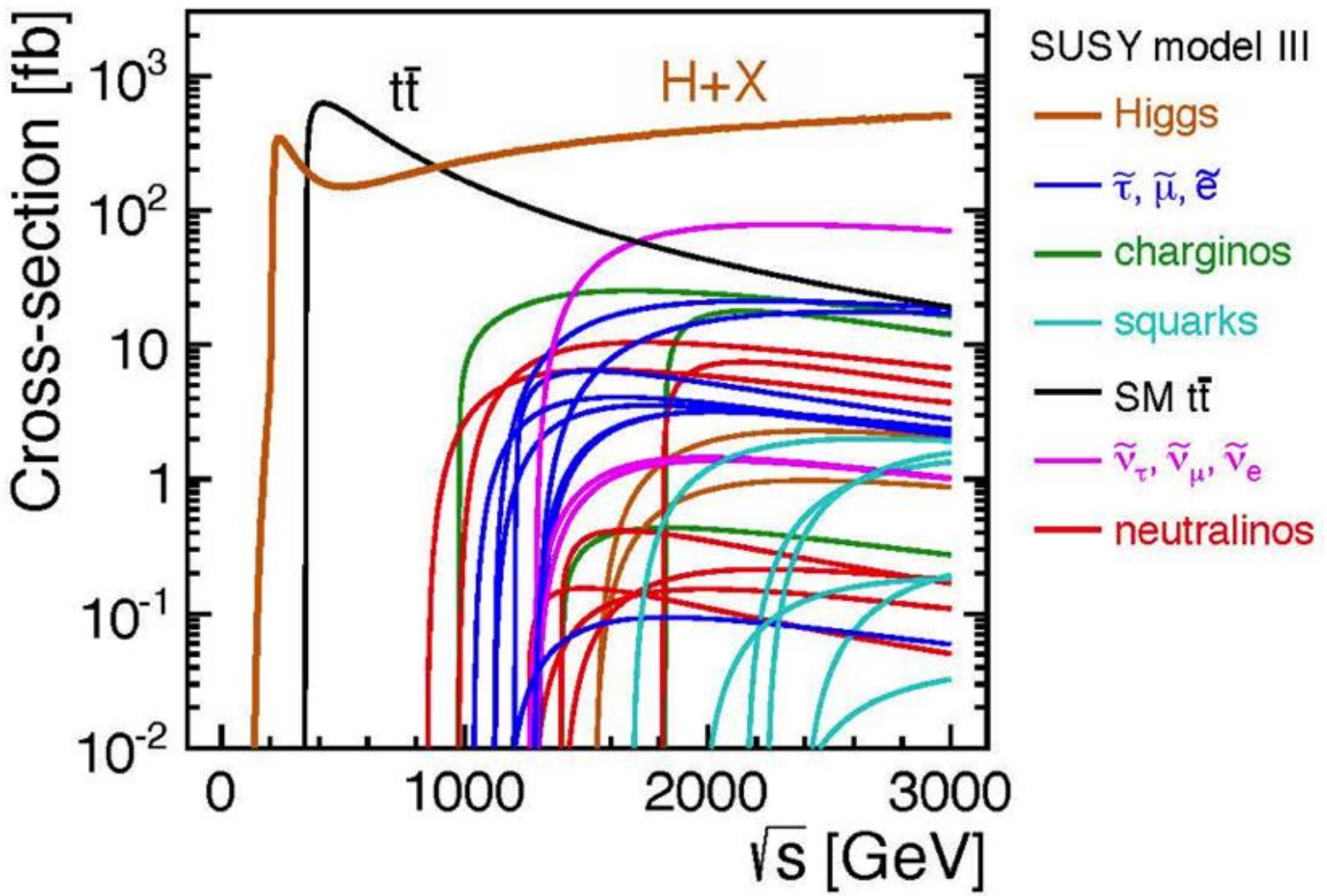
- Brief context and introduction
- Reminder of CLIC CDR 2012
- Rebaselining + project staging
- R&D status + highlights
- Strategic plan → 2018/19 and beyond
- Outlook

Apologies for skipping many results + details!

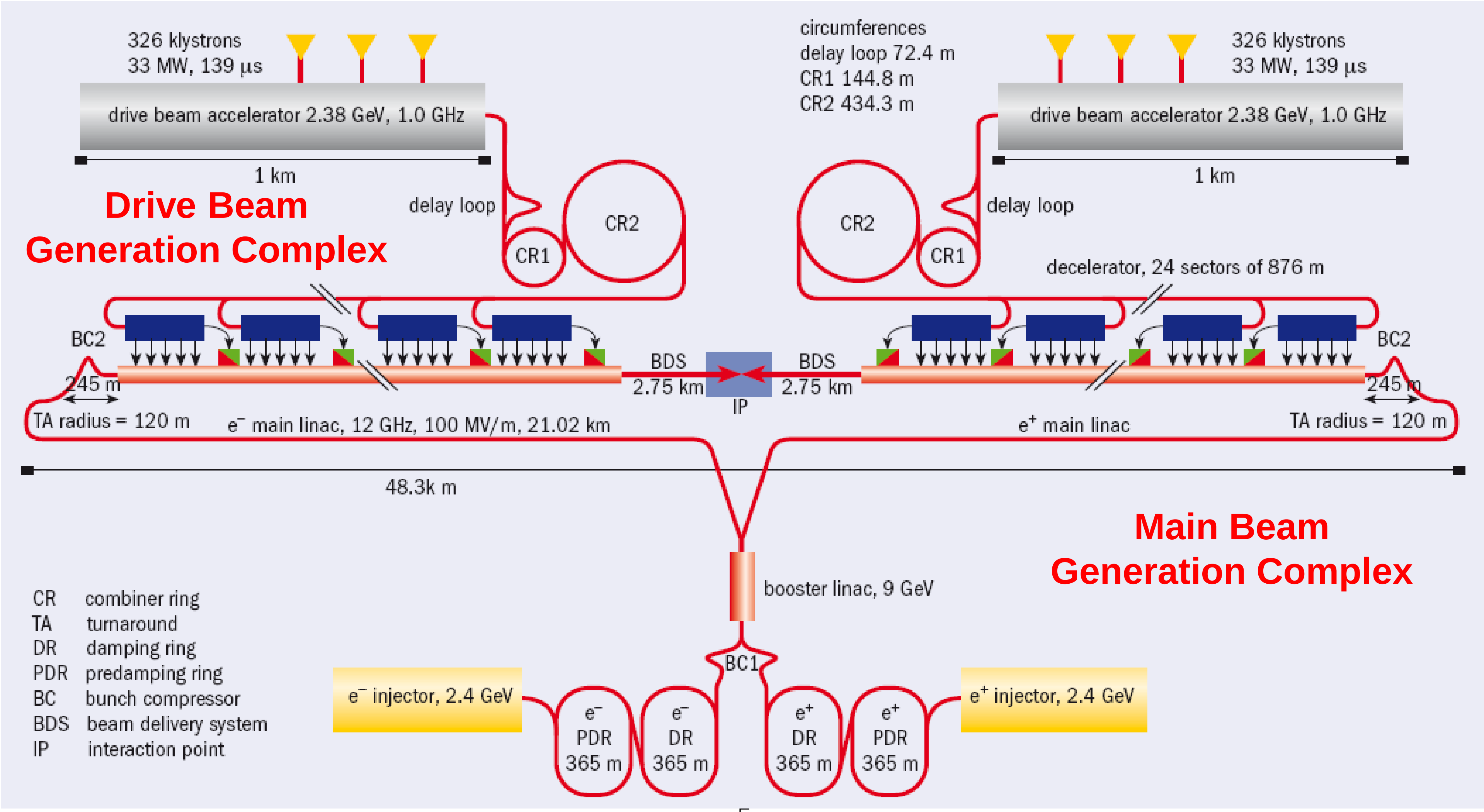
CLIC physics context

Energy-frontier capability for electron-positron collisions,

for precision exploration of potential new physics that may emerge from LHC



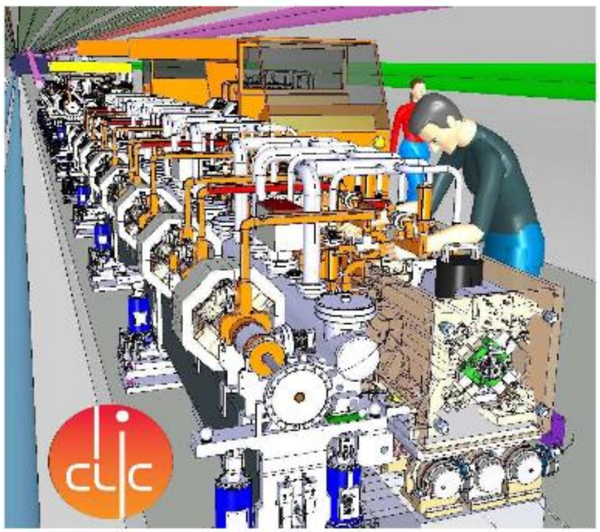
CLIC layout 3 TeV



CDR (2012)

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

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH



A MULTI-TEV LINEAR COLLIDER BASED ON CLIC TECHNOLOGY

CLIC CONCEPTUAL DESIGN REPORT

GENEVA
2012

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

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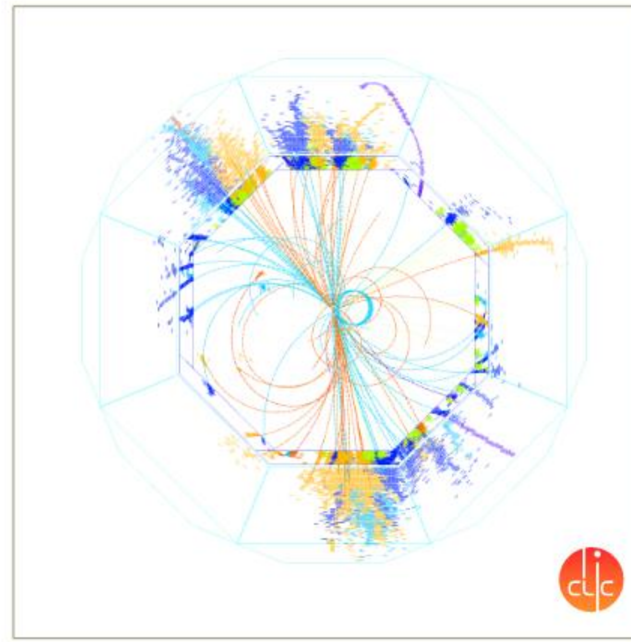
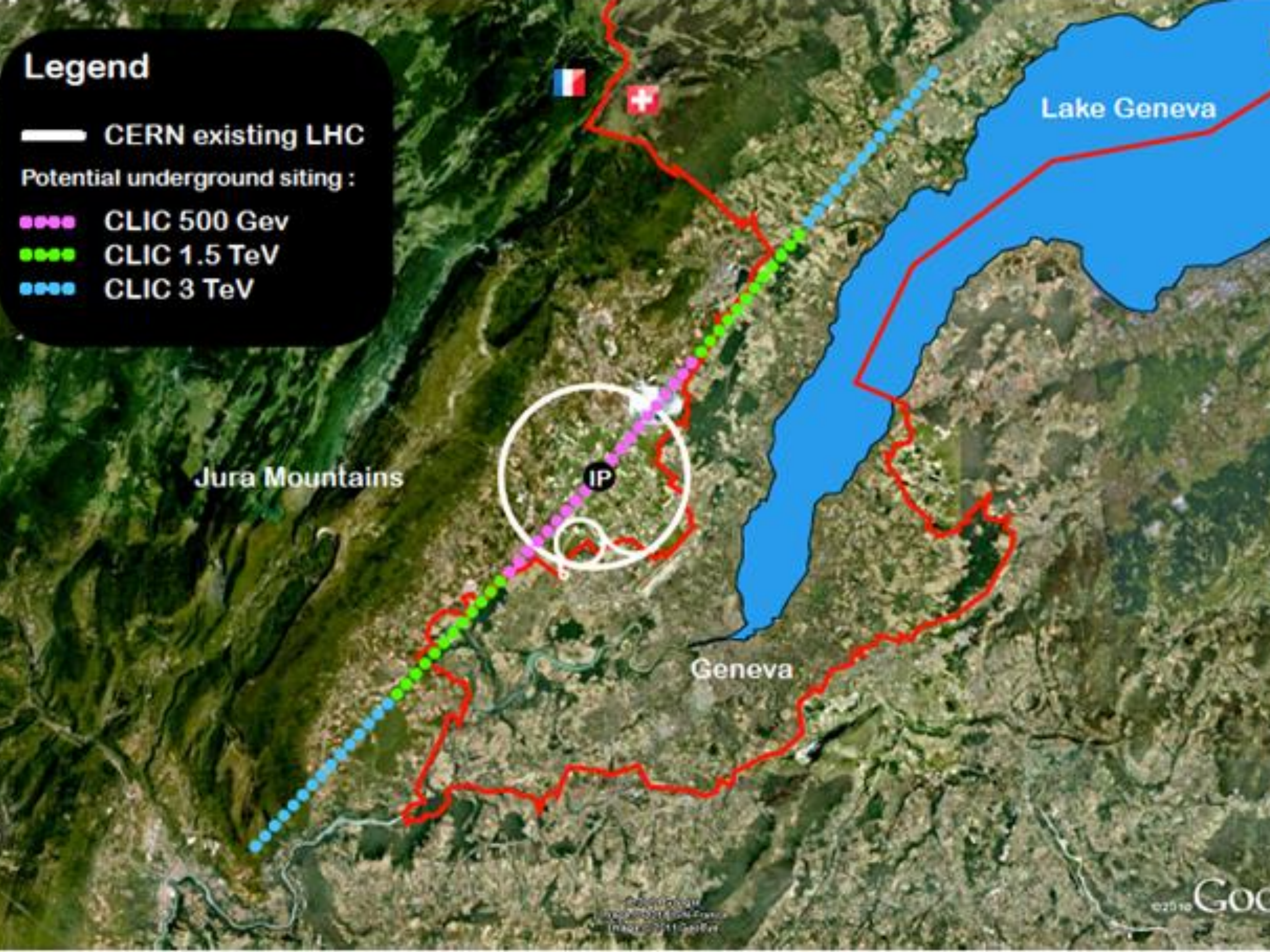


PHYSICS AND DETECTORS AT CLIC

CLIC CONCEPTUAL DESIGN REPORT


Legend
CERN existing LHC
Potential underground siting :
CLIC 500 Gev
CLIC 1.5 TeV
CLIC 3 TeV
Lake Geneva
Jura Mountains
IP
Geneva

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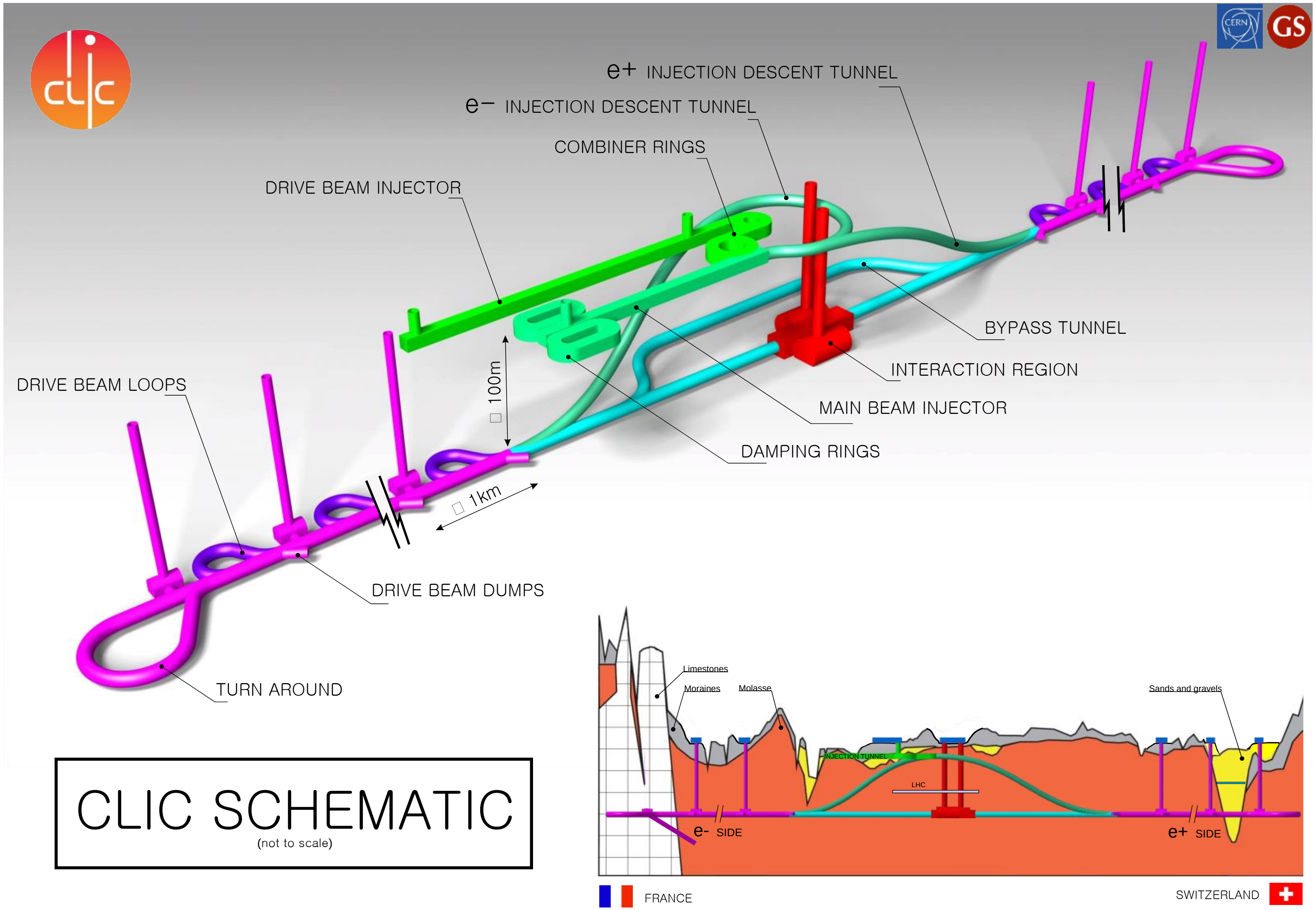
CDR tunnel layout



CDR

- Pre-Higgs discovery
- Optimised design for 3TeV, but not lower energies
- First look at power/energy requirements
- Some industrial costing, overall cost not optimised
- Some component reliability studies
- X-band demonstration limited by test capacity
- Initial system tests

→ Already a lot more has been (and will be) done!

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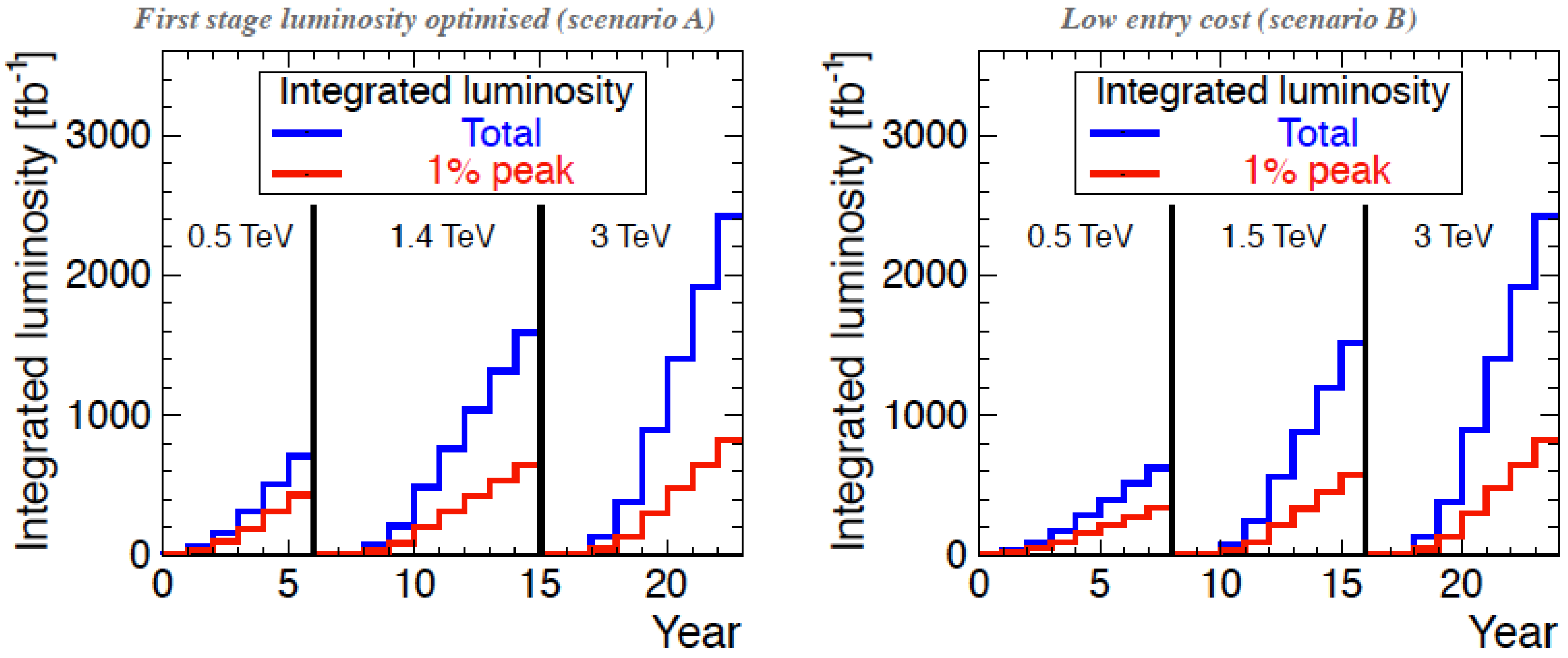
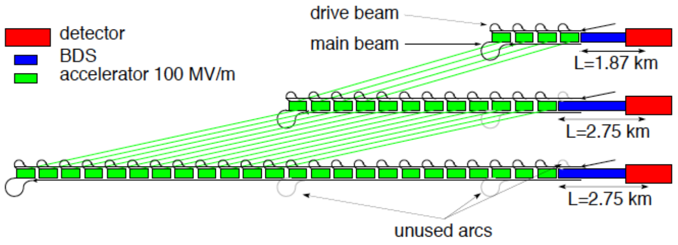
CLIC energy staging (CDR)

Energy-staging exercise started for CDR



CLIC energy staging (CDR)

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	$\sim$ 60/1.5	$\sim$ 40/1
Normalised emittance (end of linac)	$\varepsilon_x/\varepsilon_y$	nm	—	660/20	660/20
Normalised emittance	$\varepsilon_x/\varepsilon_y$	nm	660/25	—	—
Estimated power consumption	P_{wall}	MW	235	364	589



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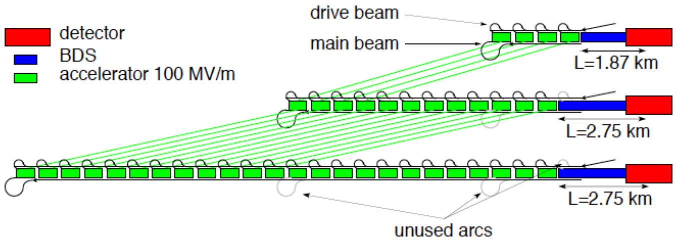
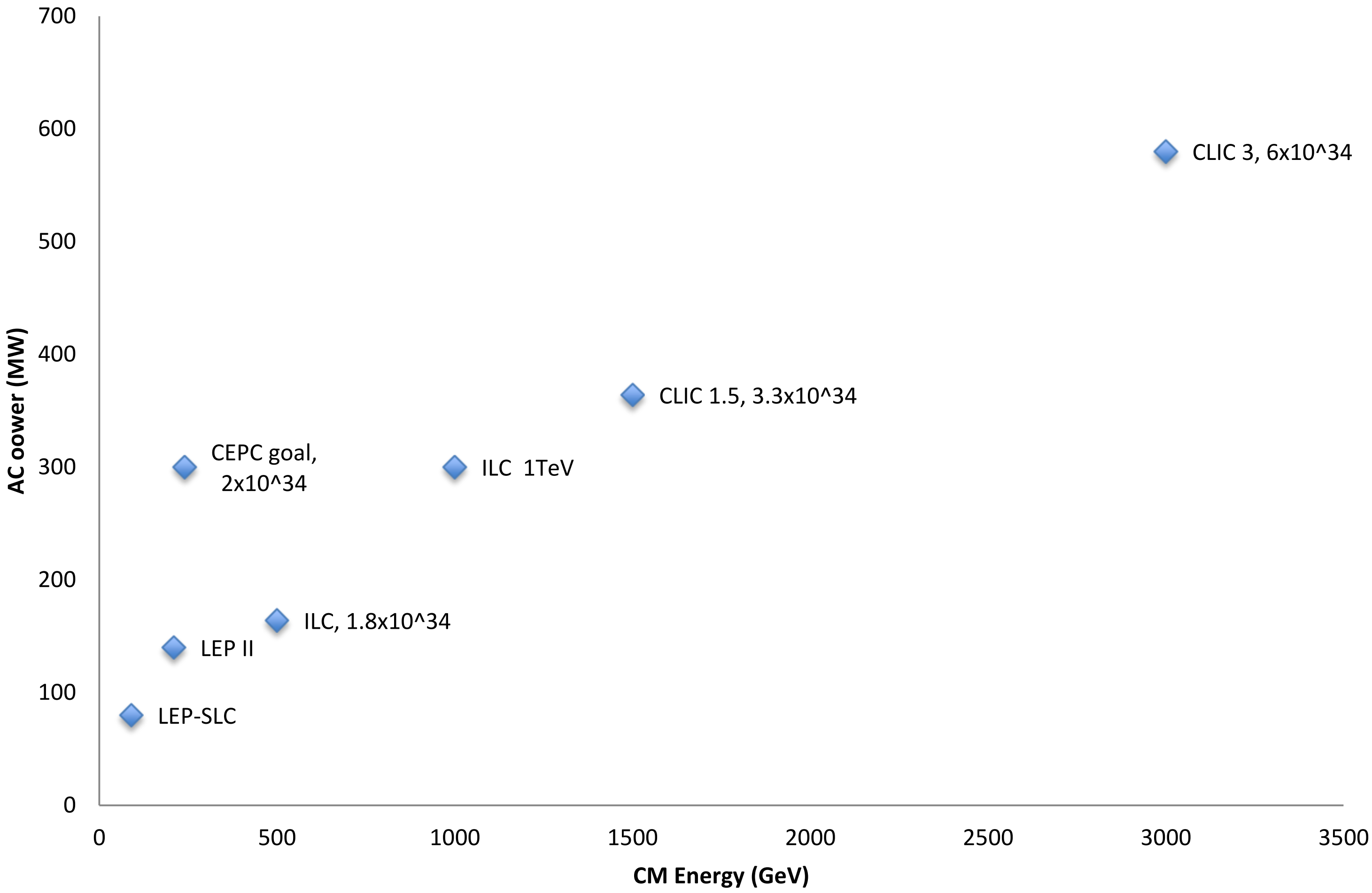
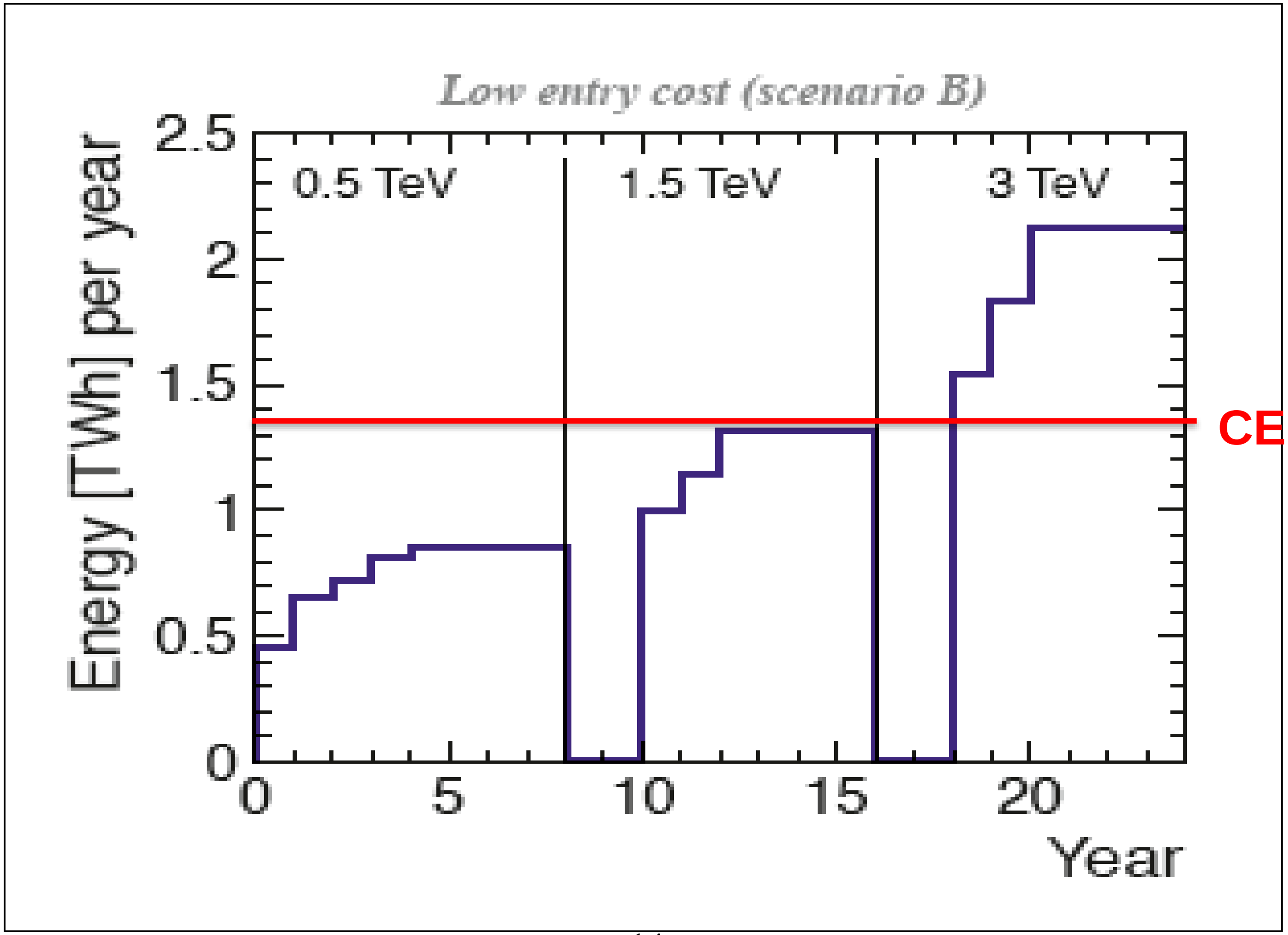


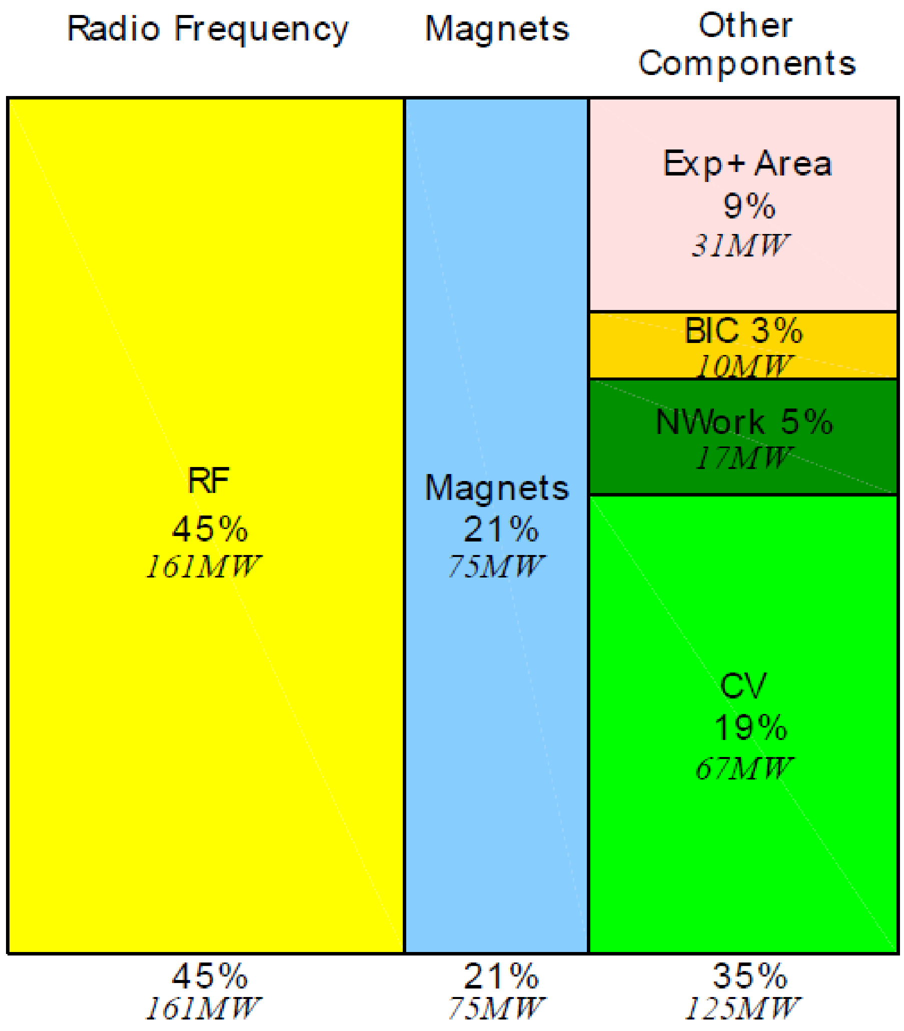
AC power


AC oower (MW)
700
600
500
400
300
200
100
0
0
500
1000
1500
2000
2500
3000
3500
CM Energy (GeV)
CLIC 3, 6x10^34
CLIC 1.5, 3.3x10^34
CEPC goal,
2x10^34
ILC 1TeV
ILC, 1.8x10^34
LEP II
LEP-SLC

Energy consumption



AC power (1.5 TeV)



Beyond the CDR

Develop a Project Plan for a staged implementation of CLIC, consistent with LHC findings, as an option for CERN in post-LHC era – for consideration in next European Strategy update 2018/19

- **Update physics studies in light of LHC results**
- **Complete key technical feasibility R&D**
- **Perform more system tests + verification**
- **More advanced industrialisation studies**
- **Rebaseline, cost/staging strategy with a 20-30 year perspective**

Rebaselining: goals

Optimize machine design w.r.t. cost and power for:

~ 380 GeV (optimised for Higgs + top physics)
~ 1500 GeV
3000 GeV (working assumption, pending LHC results)

for various luminosities and safety factors

Expect to make significant cost and power reductions for the initial stages

Choose new staged parameter sets, with a corresponding consistent upgrade path, also considering the possibility of the initial-stage being klystron-powered

‘Automatic’ parameter determination

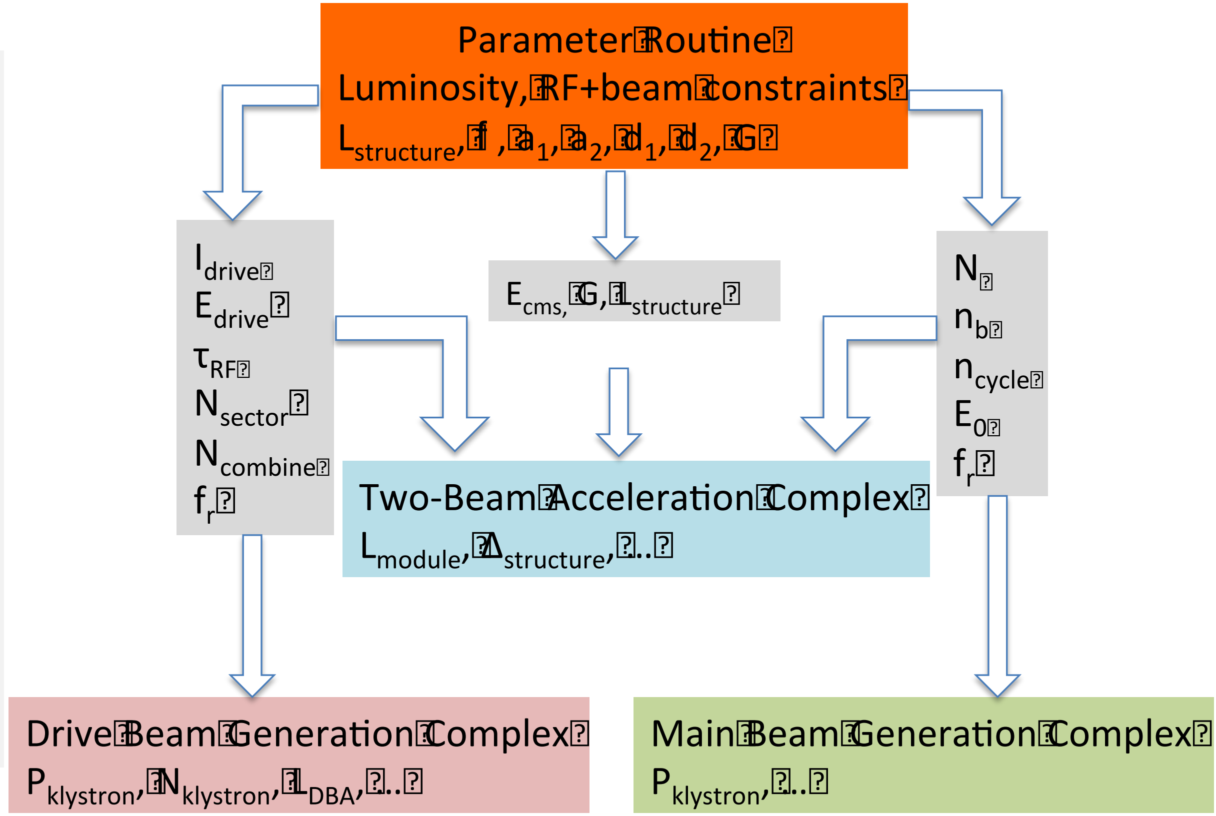
Structure design fixed by few parameters

$a_1, a_2, d_1, d_2, N_c, \phi, G$

Beam parameters derived automatically to reach specific energy and luminosity

Consistency of structure with RF constraints is checked

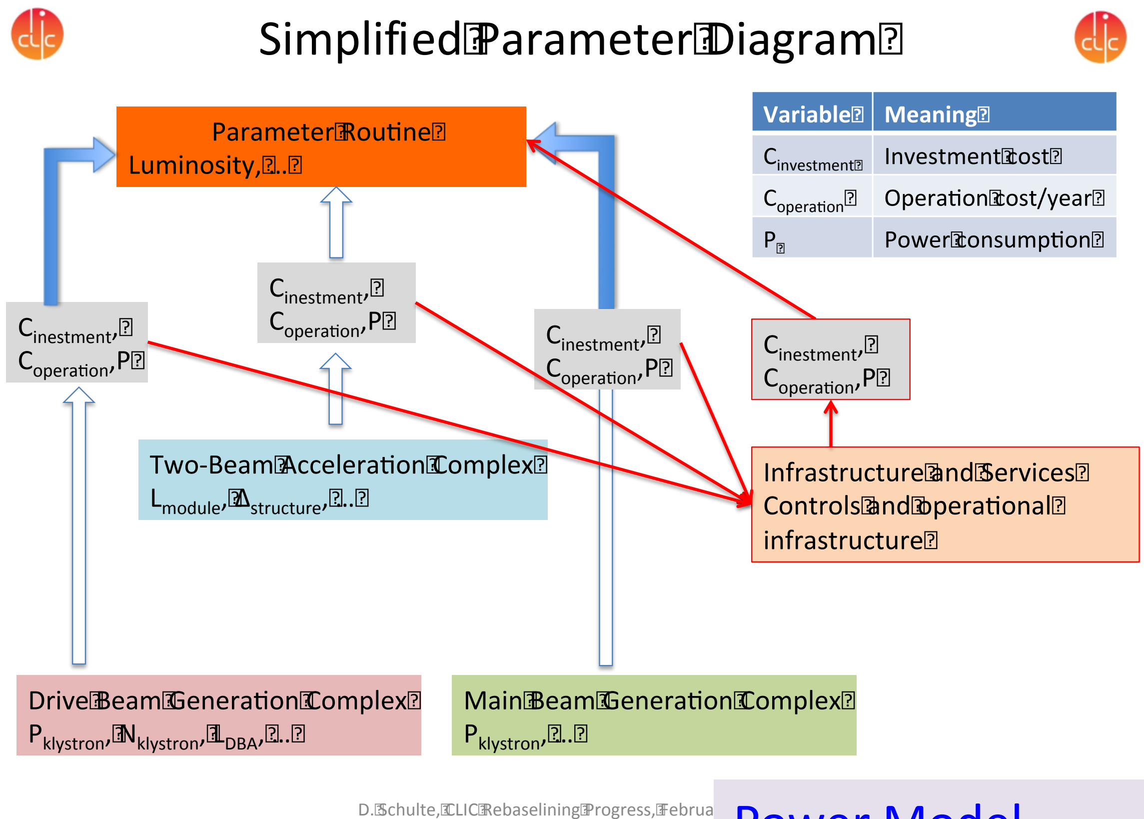
Repeat for 1.7 billion cases



Design choices and specific studies

- Use 50Hz operation for beam stability
- Scale horizontal emittance with charge to keep the same risk in damping ring
- Scale for constant local stability in main linac, i.e. tolerances vary but stay above CDR values
- BDS design similar to CDR, use improved β_x-reach as reserve

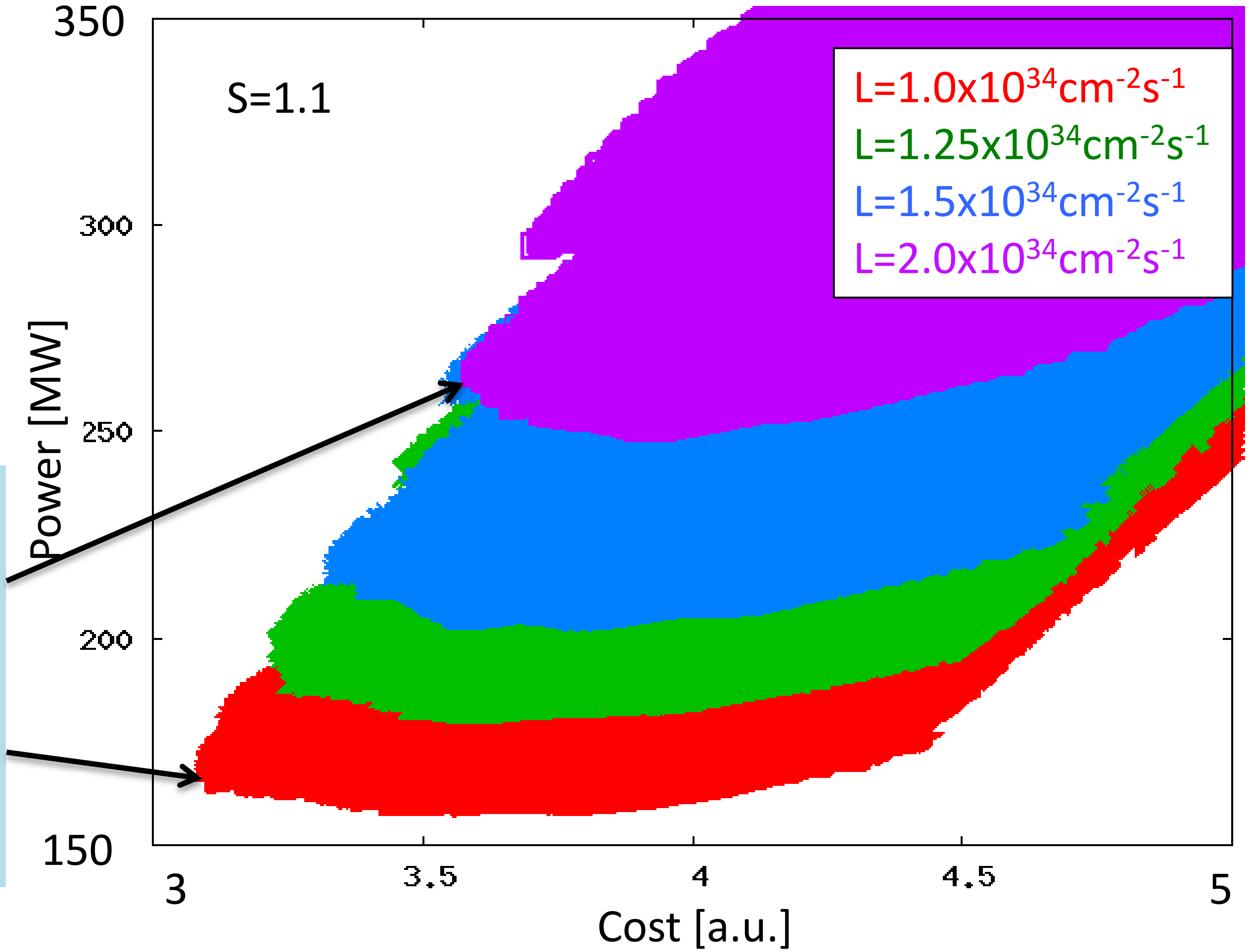
Cost / power model



Power Model

- Does not contain BDS and experiments
- Main beam injector power scaled with charge per train
- Some improvement is possible (e.g. drive beam turn-around magnets, booster linac, …)

Example output (360 GeV)



Luminosity goal impacts minimum cost
For $L=1\times10^{34}cm^{-2}s^{-1}$ to $L=2\times10^{34}cm^{-2}s^{-1}$:

Costs 0.5 a.u.
And O(100MW)

Cheapest machine is close to lowest power consumption => small potential for trade-off

Rebaselining: ongoing studies

Use of permanent or hybrid magnets for the drive beam (order of 50,000 magnets)

Optimize drive beam accelerator klystron system

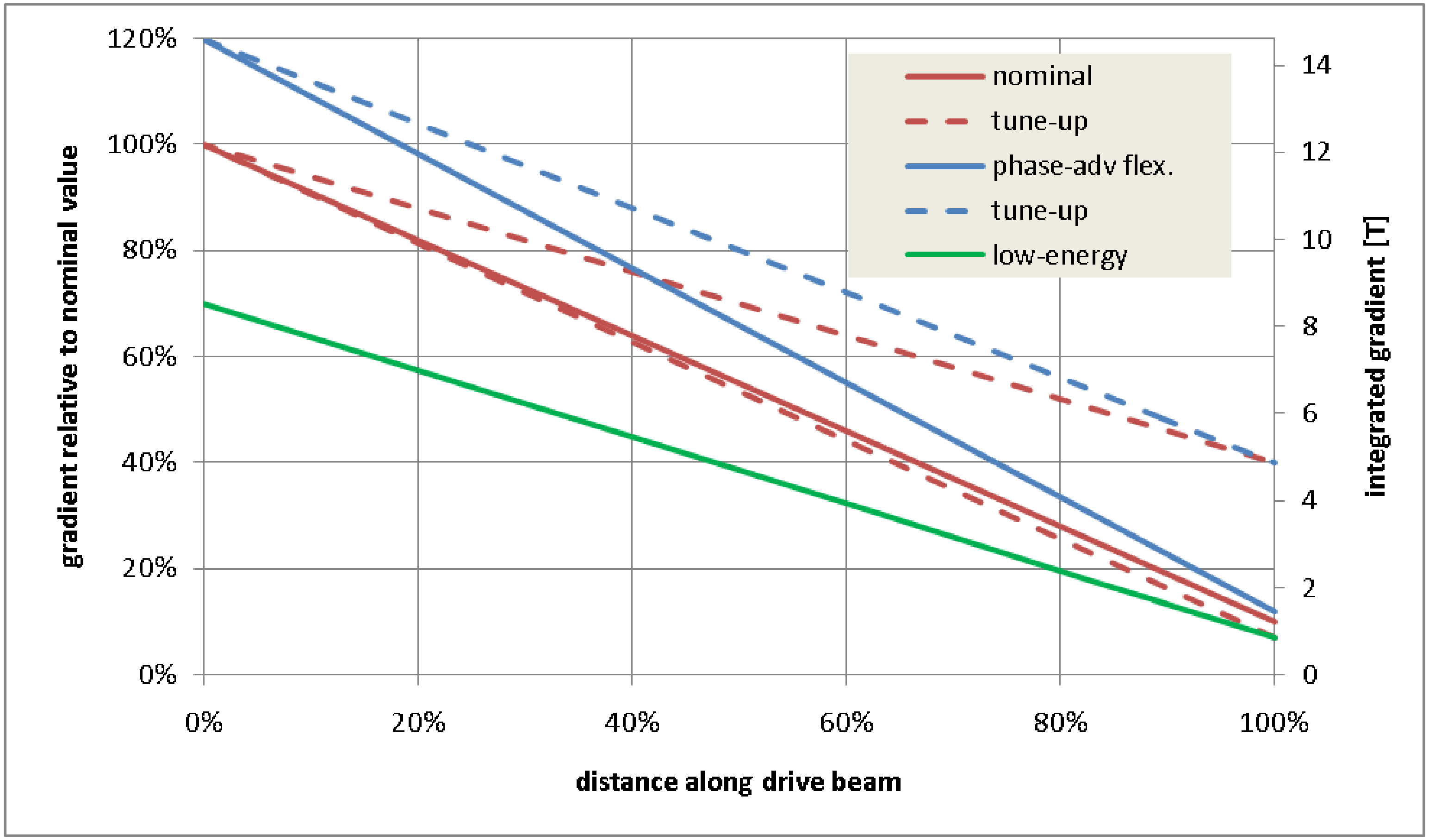
Eliminate electron pre-damping ring (better electron injector)

Systematic optimization of injector-complex linacs

Optimize / reduce power overhead estimates

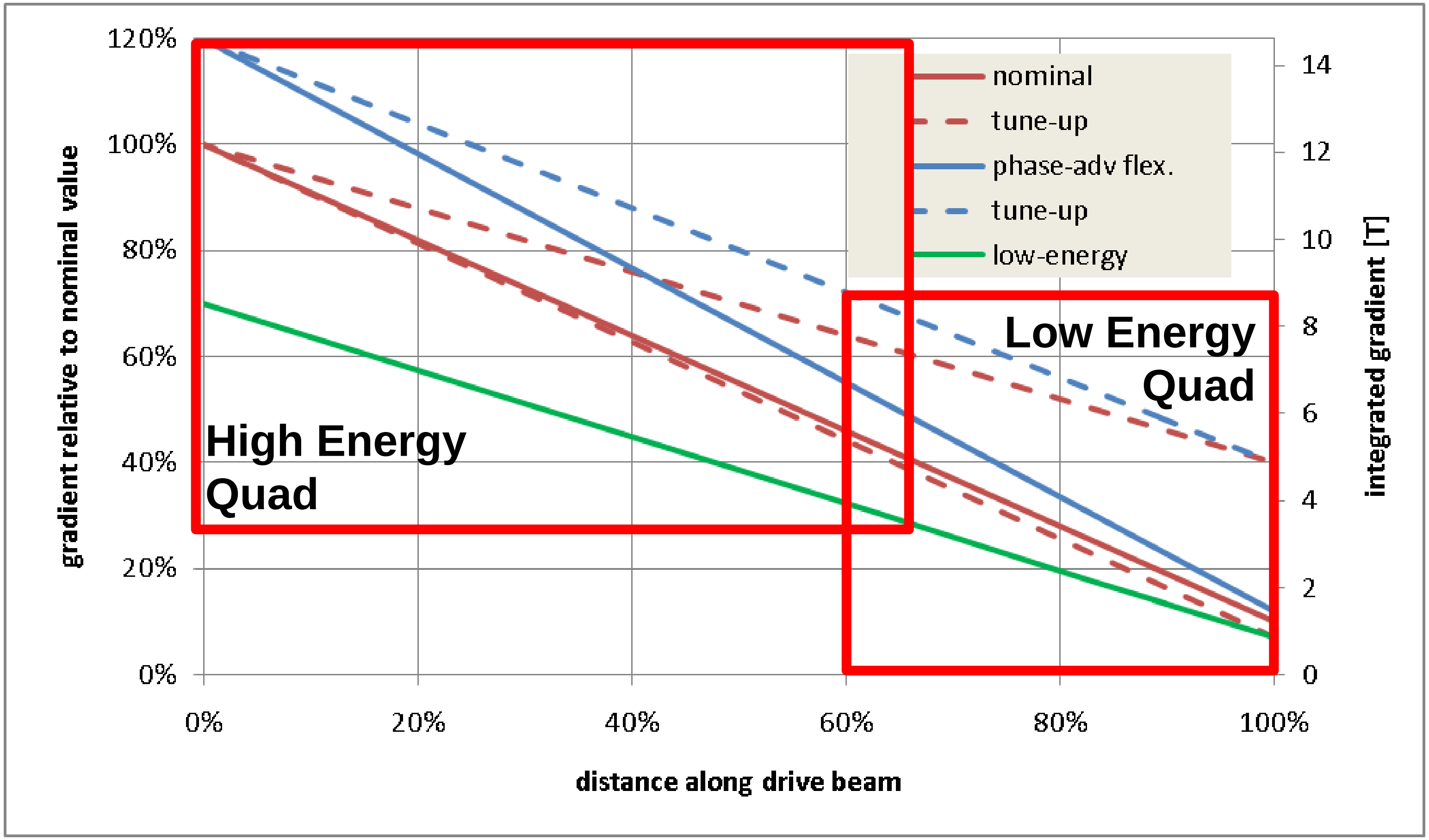
… … …

Drive beam quadrupoles (40 MW @ 3 TeV)



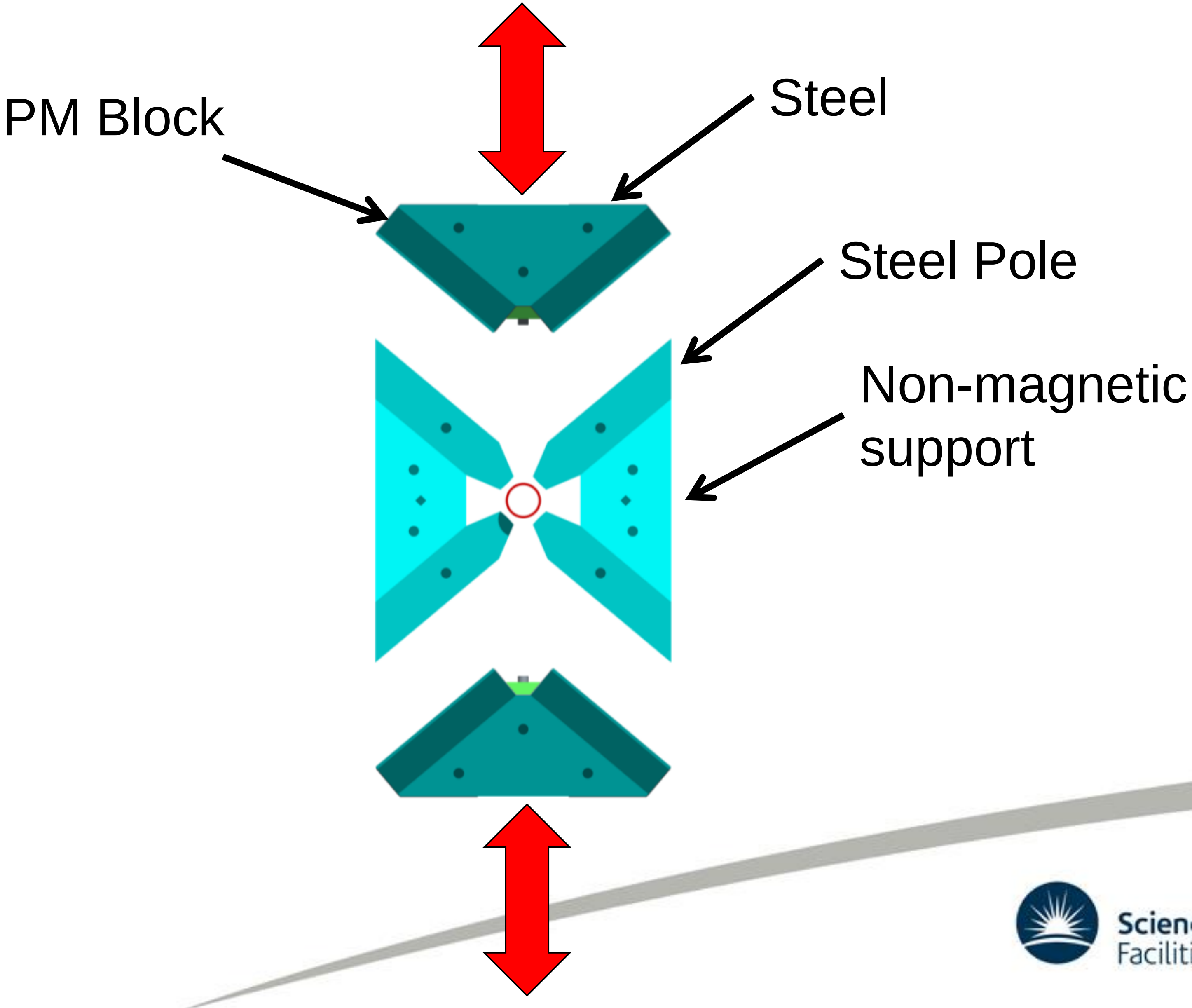
High energy quad – Gradient very high
Low energy quad – Very large dynamic range

Permanent Magnet solution



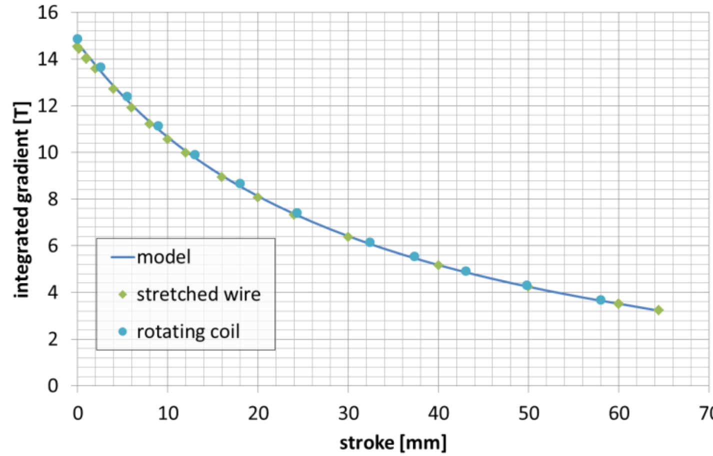
High energy quad – Gradient very high
Low energy quad – Very large dynamic range

PM engineering concept



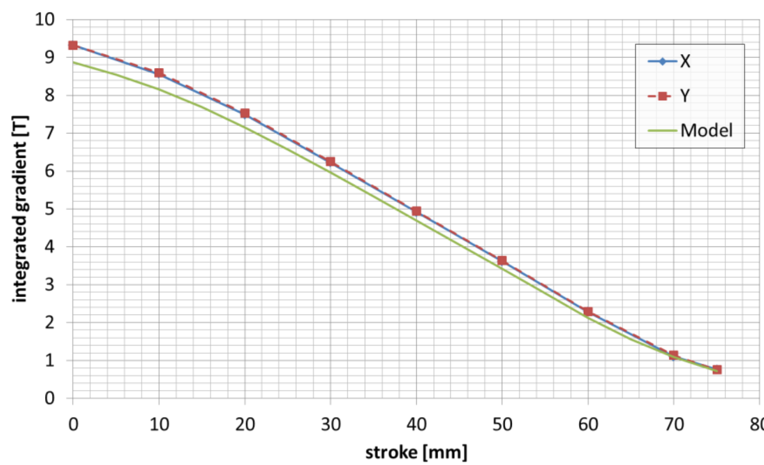
Permanent Magnet prototypes

High Energy Quad



BJA Shepherd et al, Tunable high-gradient permanent magnet quadrupoles, 2014 JINST 9 T11006

Low Energy Quad



Patent granted to cover both designs

Team now focussed on PM Dipoles

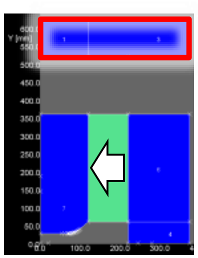
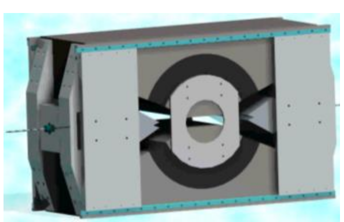
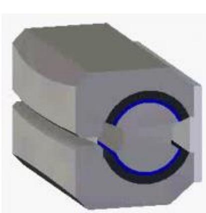
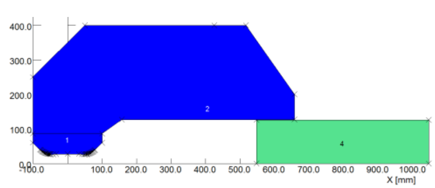
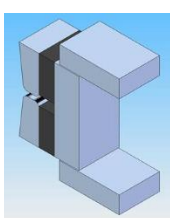
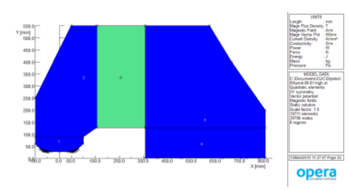
Now looking at PM dipoles

Type	Quantity	Length (m)	Strength (T)	Pole Gap (mm)	Good Field Region (mm)	Field Quality	Range (%)
MB RTML	666	2.0	0.5	30	20 x 20	1 x 10^{-4}	± 10
DB TAL	576	1.5	1.6	53	40 x 40	1 x 10^{-4}	50–100

- **Drive Beam Turn Around Loop (DB TAL)**
- **Main Beam Ring to Main Linac (MB RTML)**

Total power consumed by both types: 15 MW

Several possible designs considered:

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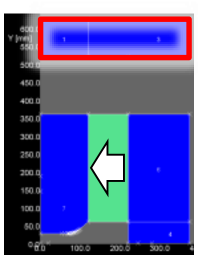
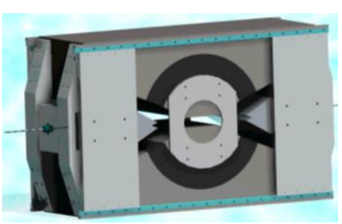
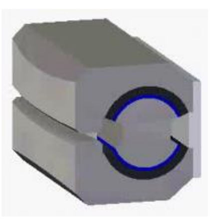
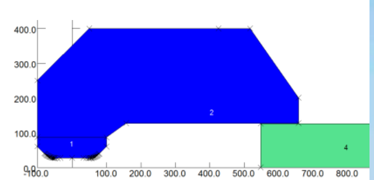
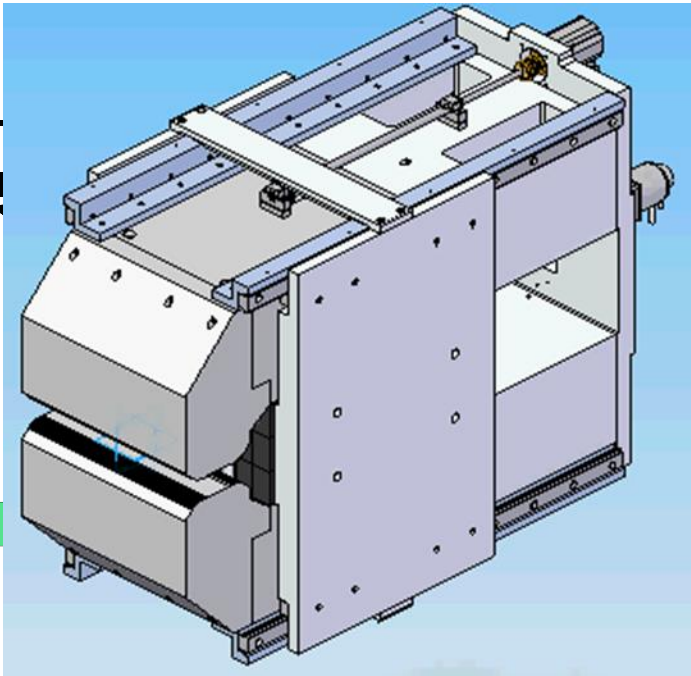
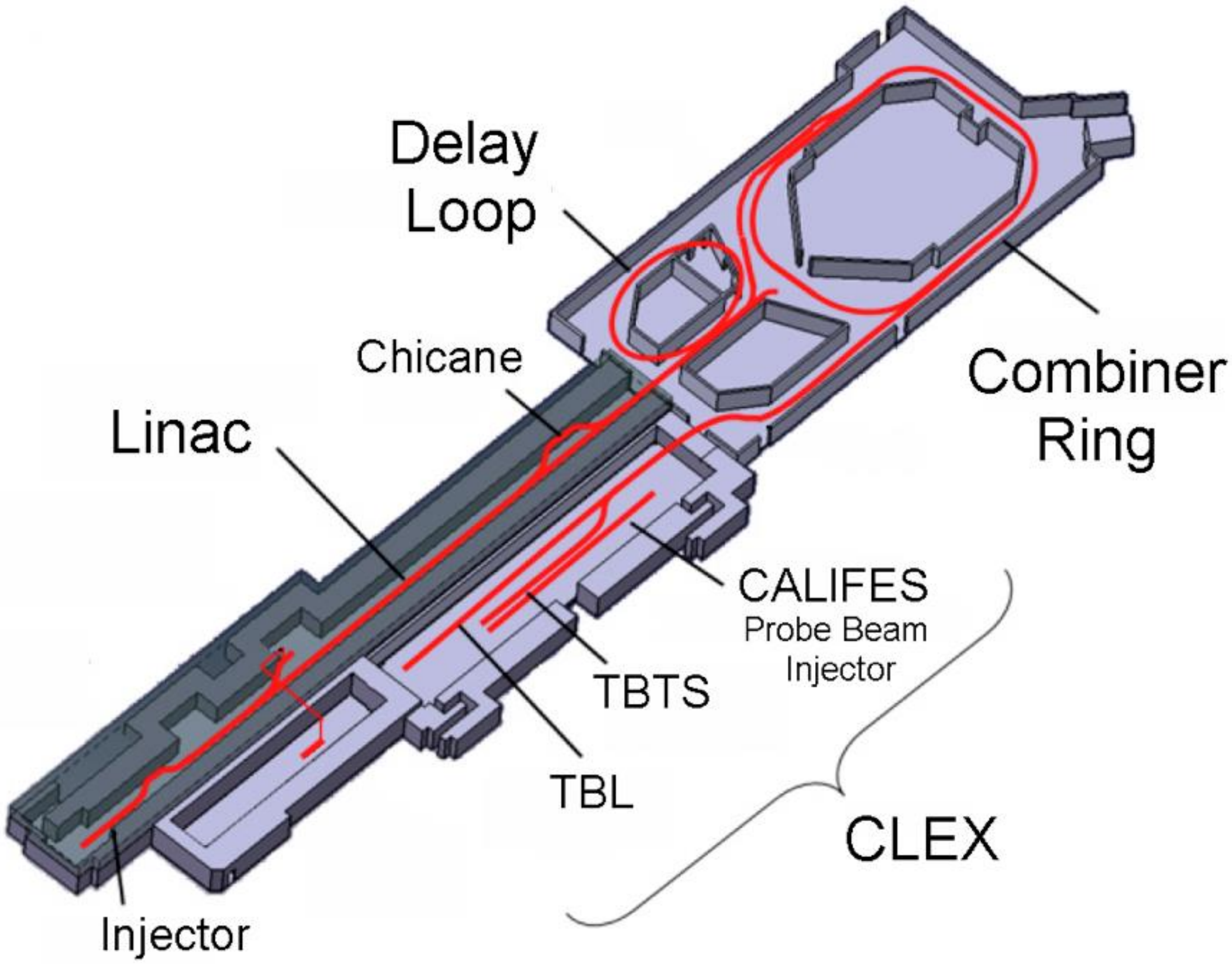
- Drive Beam Turn Around Loop (DB TAL)
- Main Beam Ring to Main Linac (MB RTML

Total power consumed by both types: 1

Several possible designs considered:

CTF3



Delay Loop
Chicane
Linac
Combiner Ring
CALIFES
Probe Beam Injector
TBTS
TBL
CLEX
Injector

Main achievements of CTF3

Drive beam generation:

- Linac operation (4A) with full beam loading
- Phase-coding of beam with sub-harmonic buncher system
- Factor of ~8 current amplification by beam recombination
- Power extraction from drive beam at 2 x CLIC nominal

Two-beam test stand + TBL:

- 2-beam acceleration in CLIC structures up to 1.5 x nominal
- Drive-beam stable deceleration to 35% of initial energy
- 12 GHz RF power @ ~ 1 GW in string of 13 decelerators

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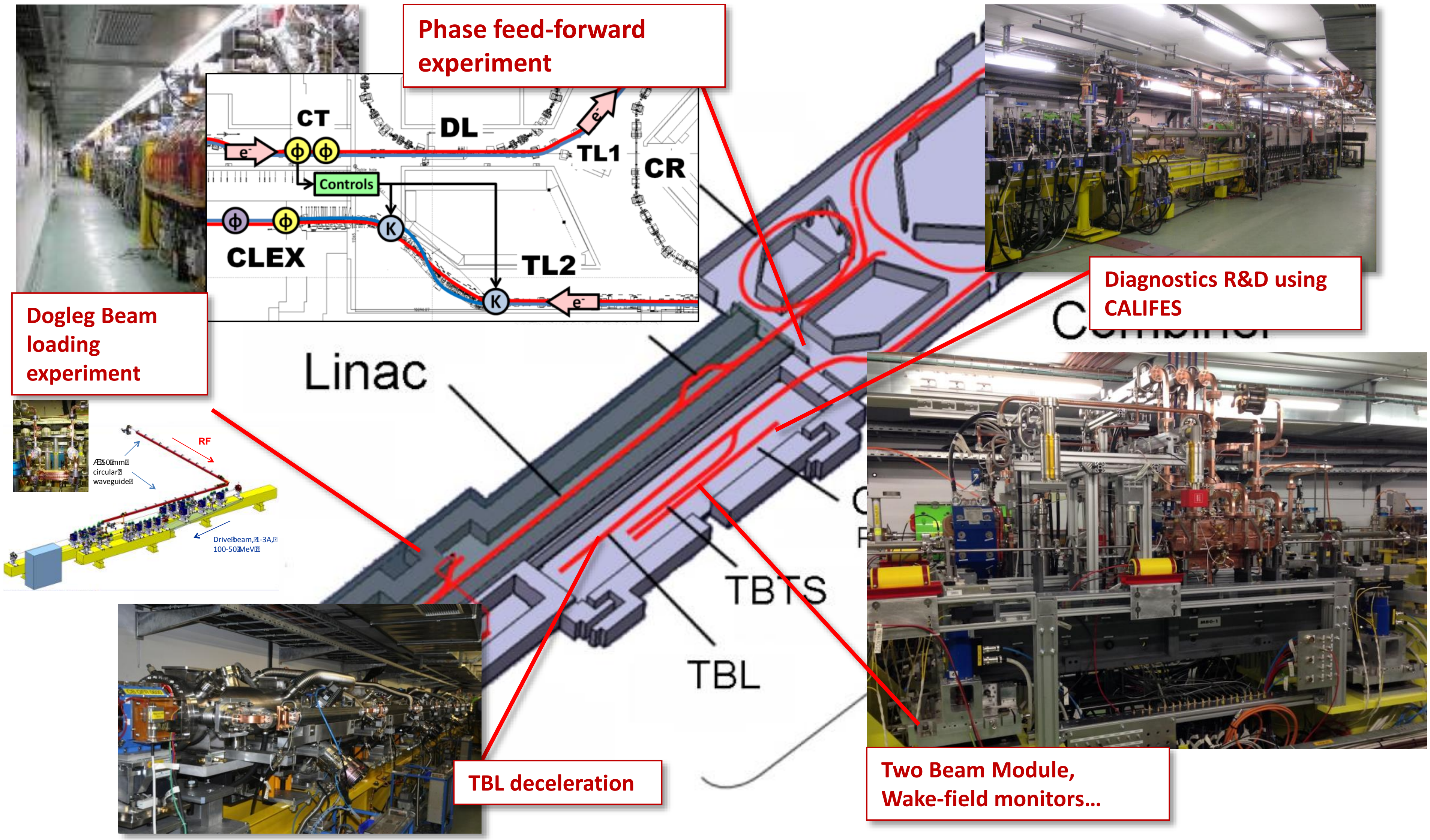
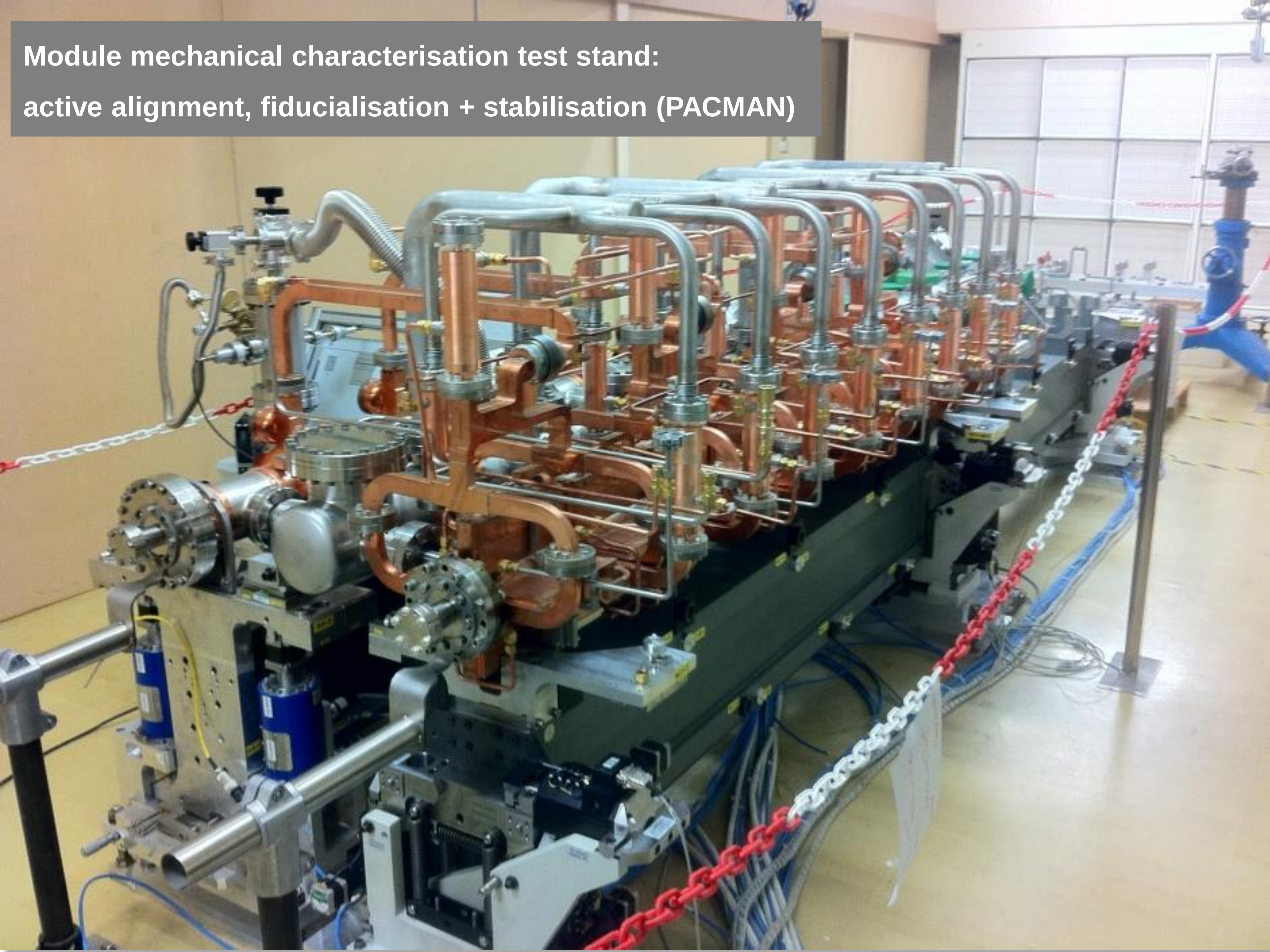
CTF3: 2015 - 2016



Recently installed 2-beam acceleration module in CTF3
(according to latest CLIC design)

Module mechanical characterisation test stand:

active alignment, fiducialisation + stabilisation (PACMAN)



CTF3 programme 2015-16

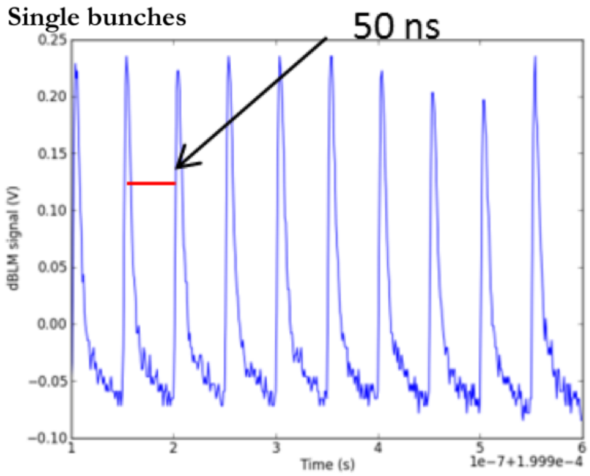
Power production:

- **stability + control of RF profile (beam loading comp.)**
- **RF phase/amplitude drifts along TBL**
- **PETS switching at full power**
- **beam deceleration + dispersion-free steering in TBL**
- **routine operation**
- **…**

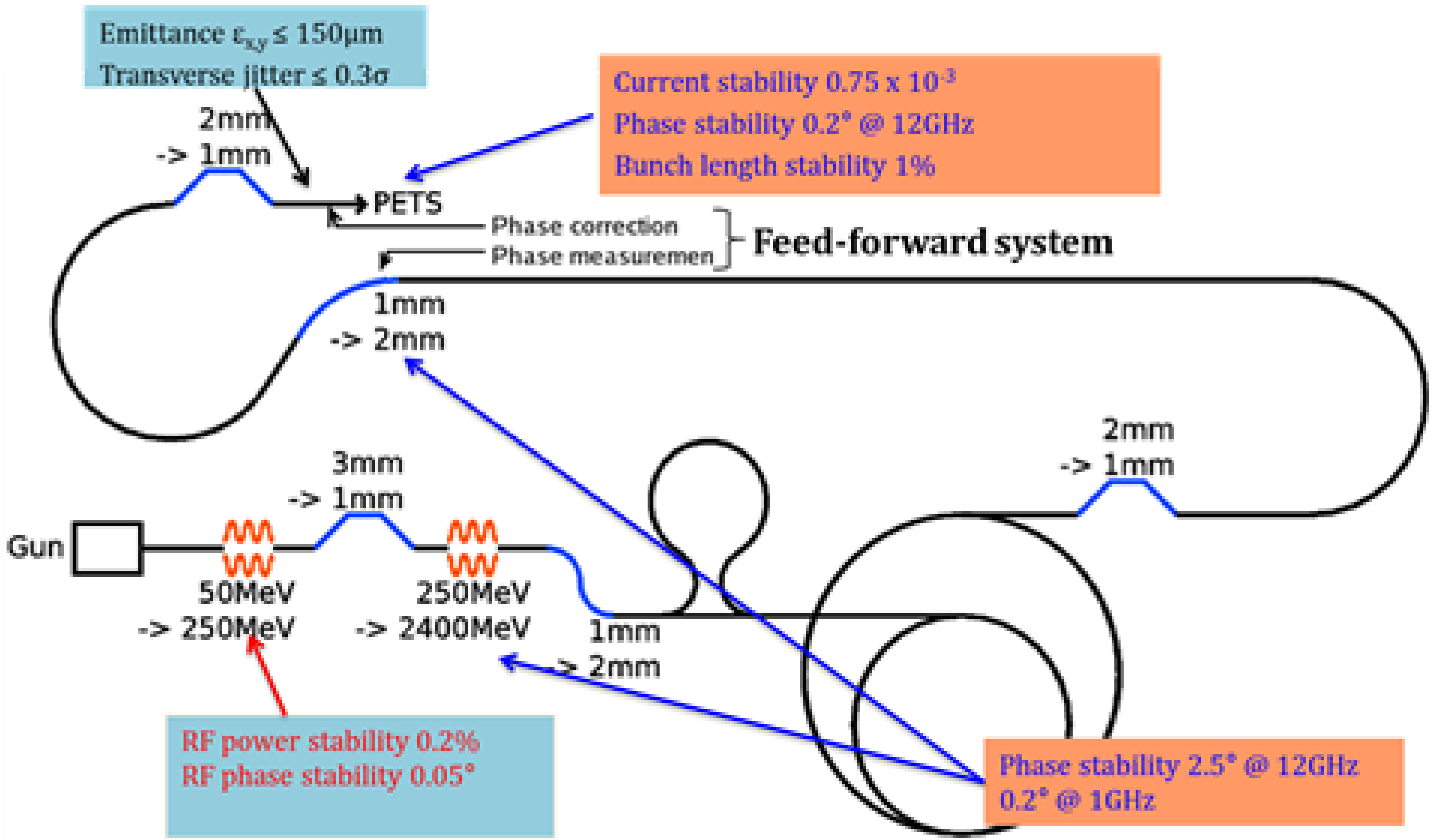
CTF3 programme 2015-16

Diagnostics tests:

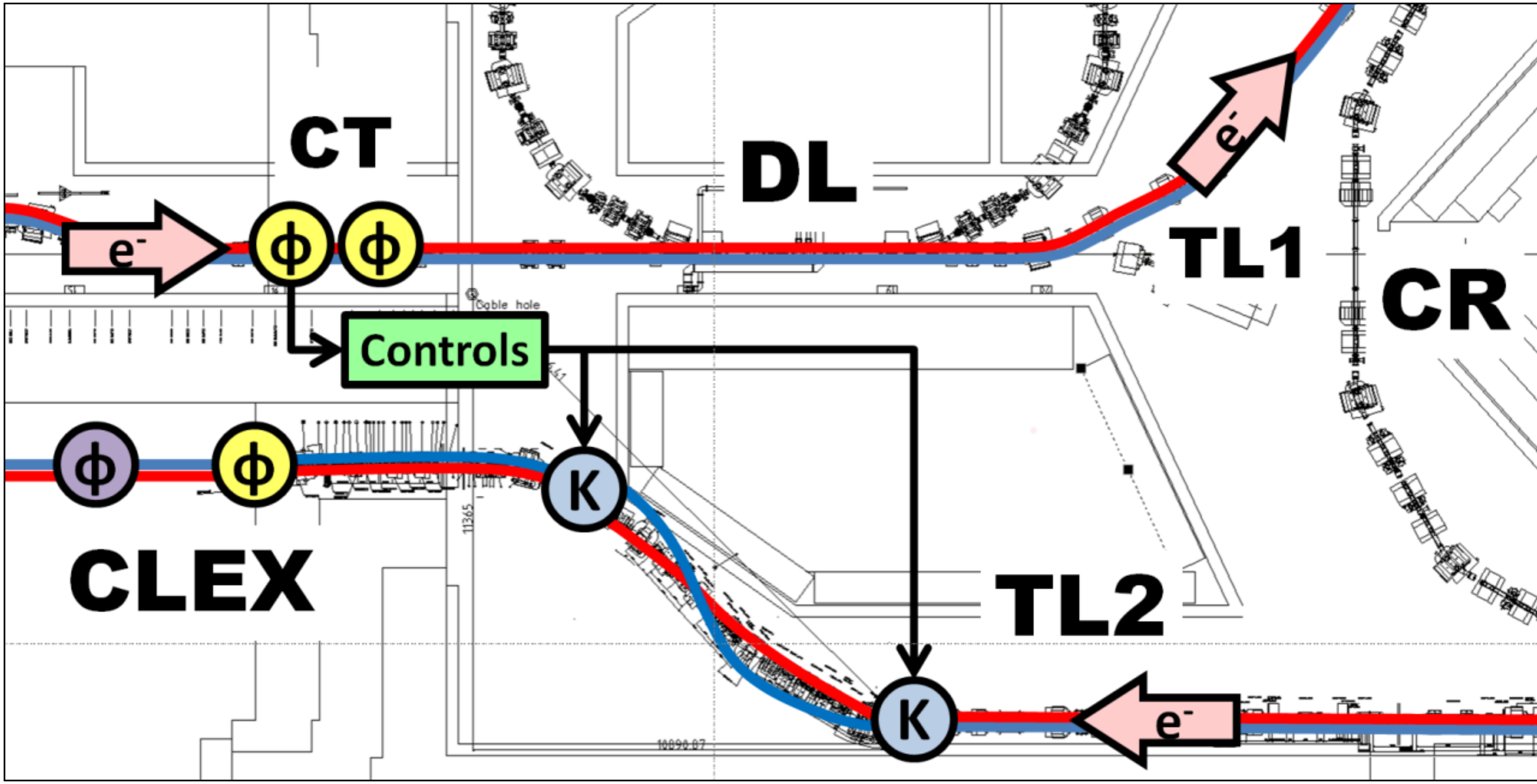
- **main-beam cavity BPMs (TBTS)**
- **drive-beam stripline BPMs (TBL)**
- **electro-optic bunch-profile monitors (CALIFES)**
- **optical transition radiation beam size monitor**
- **diamond beam-loss detectors**
- **…**



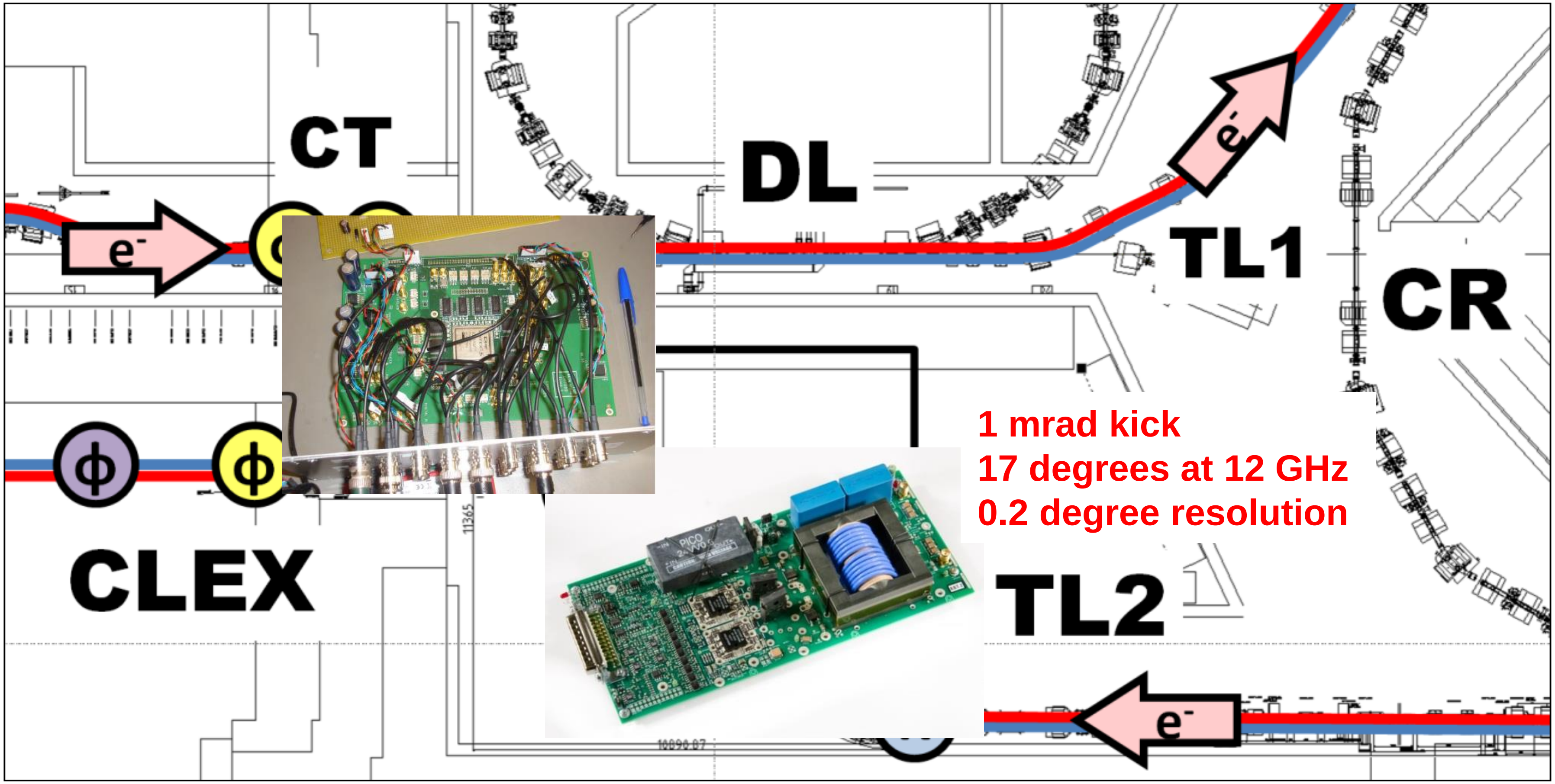
Drive-beam phase feed-forward



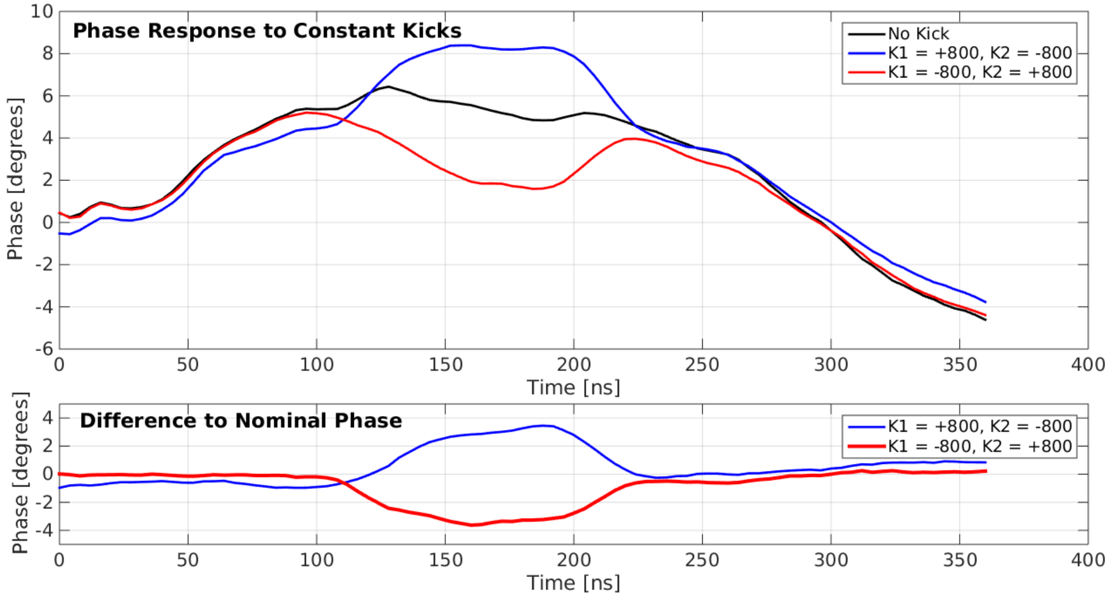
CTF3 phase FF prototype

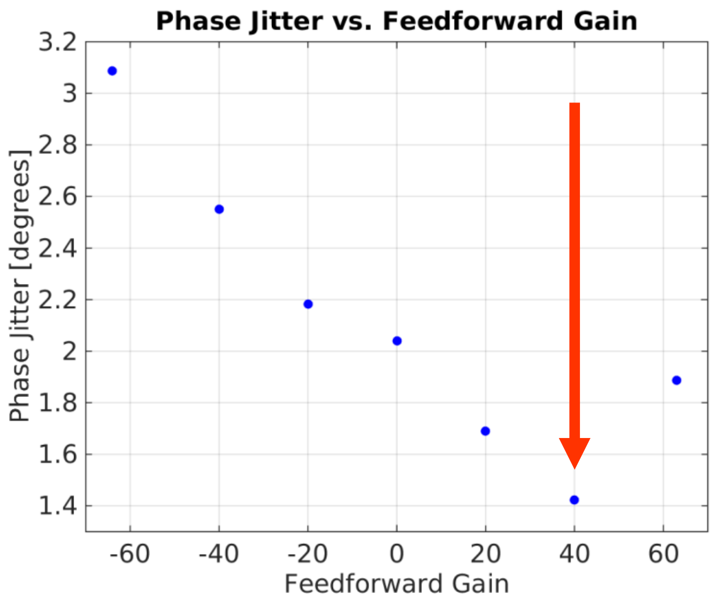


CTF3 phase FF prototype



Initial FF tests: phase correction

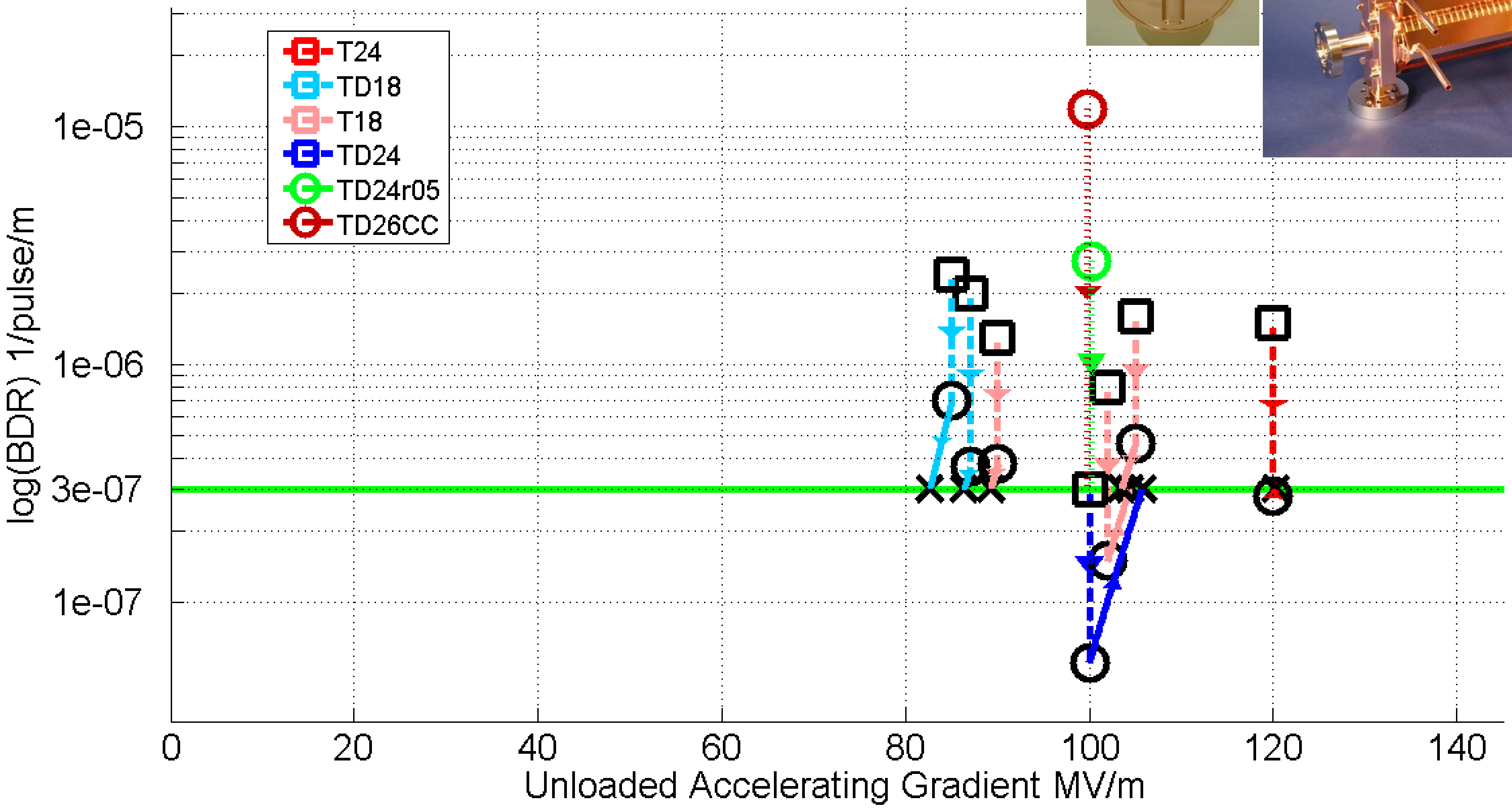


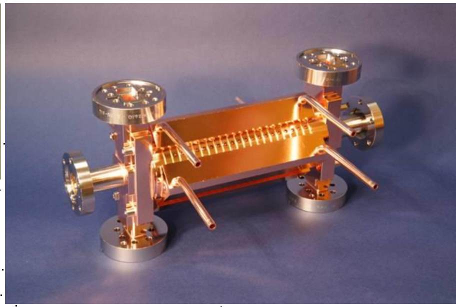


System works:

- → **improve phase propagation**
- → **improve system performance**
- → **2015 tests starting**

High-gradient structure tests





High-gradient structure tests

- **Results generally very promising**
- **Understanding of breakdown mechanism improving**

Limitations on gradient

- **Surface magnetic field**
  - **Pulsed surface heating => material fatigue => cracks**
- **Field emission due to surface electric field**
  - **RF break downs**
  - **Break down rate => Operation efficiency**
  - **Local plasma triggered by field emission => Erosion of surface**
  - **Dark current capture**
    => Efficiency reduction, activation, detector backgrounds
- **RF power flow**
  - **RF power flow and/or iris aperture have a strong impact on achievable E_{acc} and on surface erosion. Ongoing studies.**

High-gradient structure tests

- Results generally very promising
- Understanding of breakdown mechanism improving
- Numbers of structures still limited
- Limited experience with industrial production
- Gain more experience in conditioning / acceptance testing
- Exploring industrial-scale fabrication
- Exploring potential applications (XFEL, medical …)
- NB: availability of high-power RF test capacity

X-band test stands

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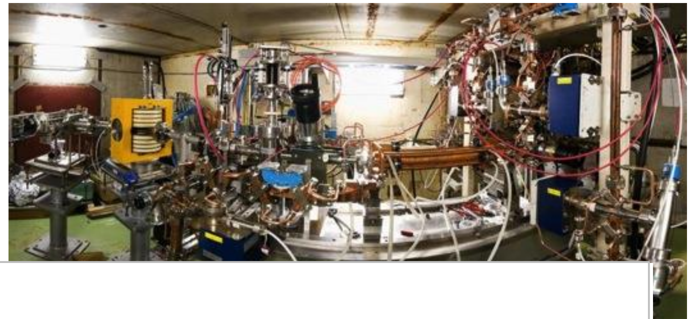
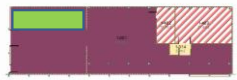
Previous:
Scaled 11.4 GHz
tests at SLAC and KEK.



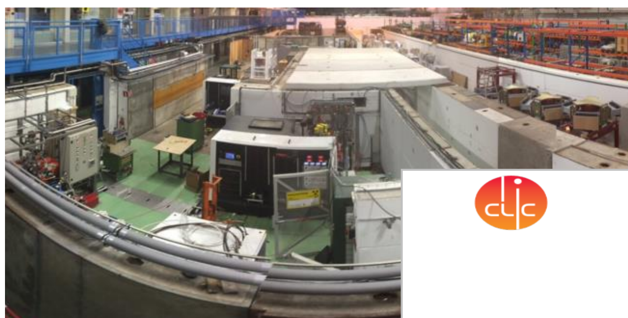
NEXTEF at KEK

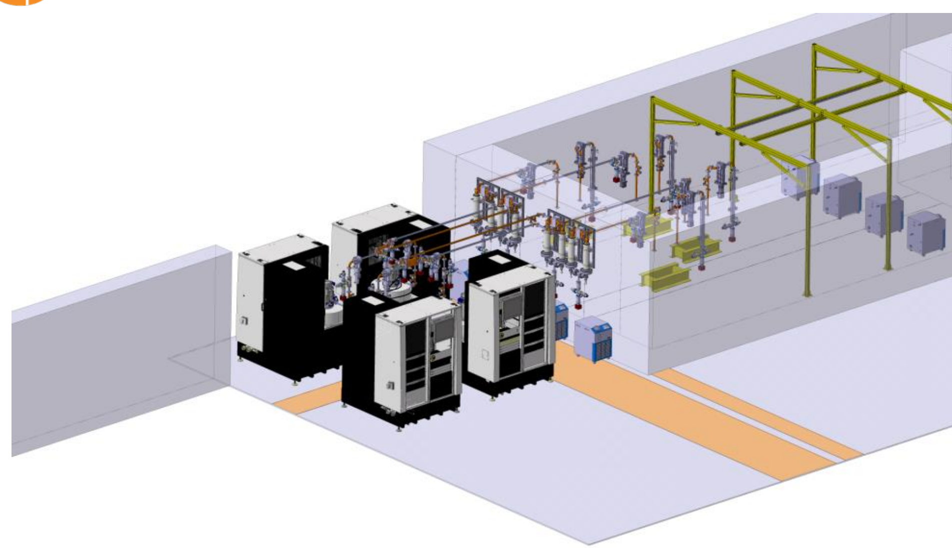
ASTA at SLAC

… remain important, also linked to testing of X-band structures from Tsinghua and SINAP



CTF3 klystron gallery





Very significant increase of test-capacity:
- First commercial 12 GHz klystron systems available
- Confidence that one can design for good (and possibly better) gradient performance

As a result: now possible to consider X-band for smaller-scale accelerator systems

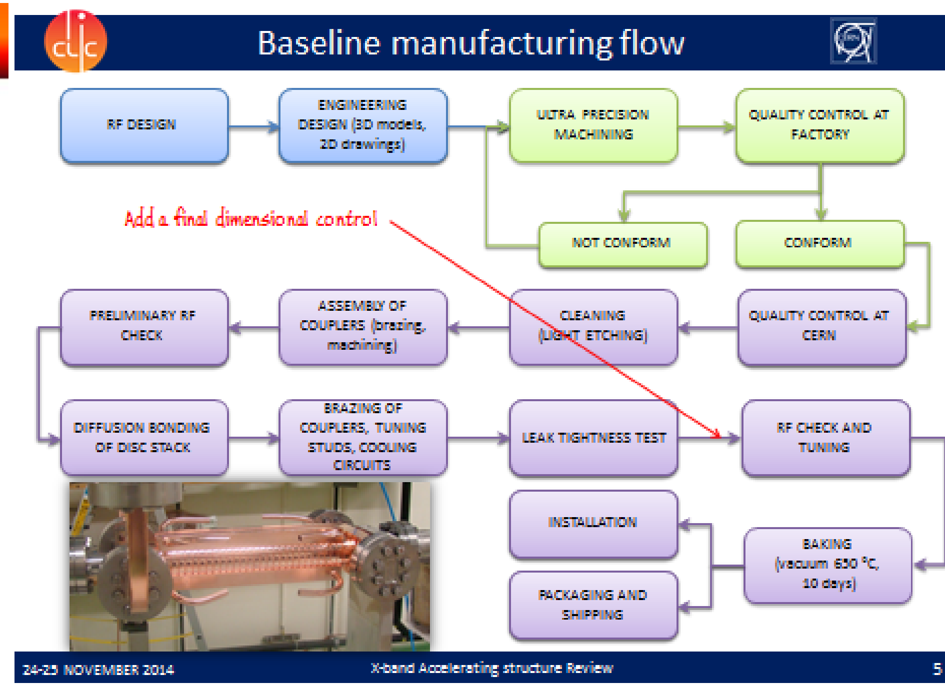
Structures in the pipeline

CLIC structures:

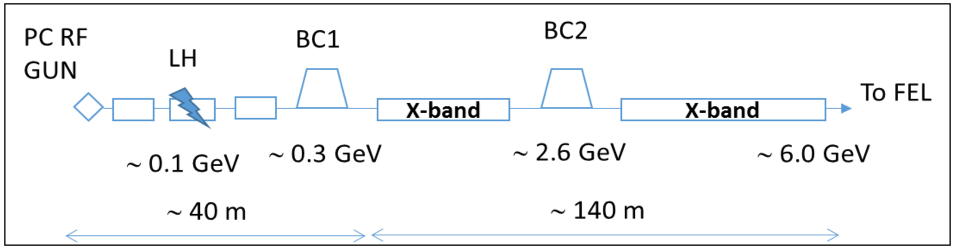
- Two TD26CC built and tested by KEK. *Still superb production*
- One TD26CC built by CIEMAT. *Next step after PETS.*
- Two T24s built by PSI in their production run. *Vacuum brazing alternative, benchmark for their production line.*
- One T24 built by SINAP. *Potentially leads to large X-band installation.*
- Whole structure in industry – Technical specifications are under preparation. *Industrialization, cost estimate.*

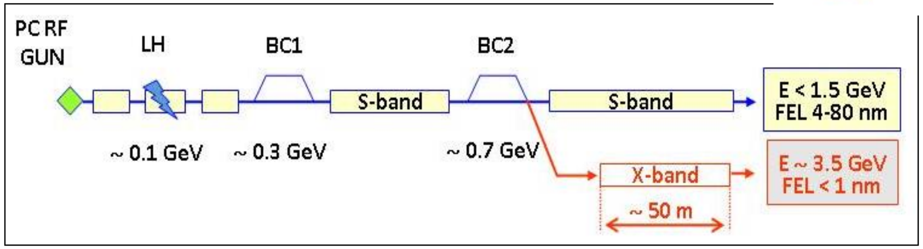
Other related structures:

- Structure in halves by SLAC. *Potentially cheaper, hard materials, preconditioned surfaces possible.*
- Choke-mode damping by Tsinghua. *Potentially cheaper*
- Four XFEL structures by SINAP. *New application with large potential.*
- High-gradient proton funded by KT (CERN technology transfer). *New application.*



Possible X-band FELs

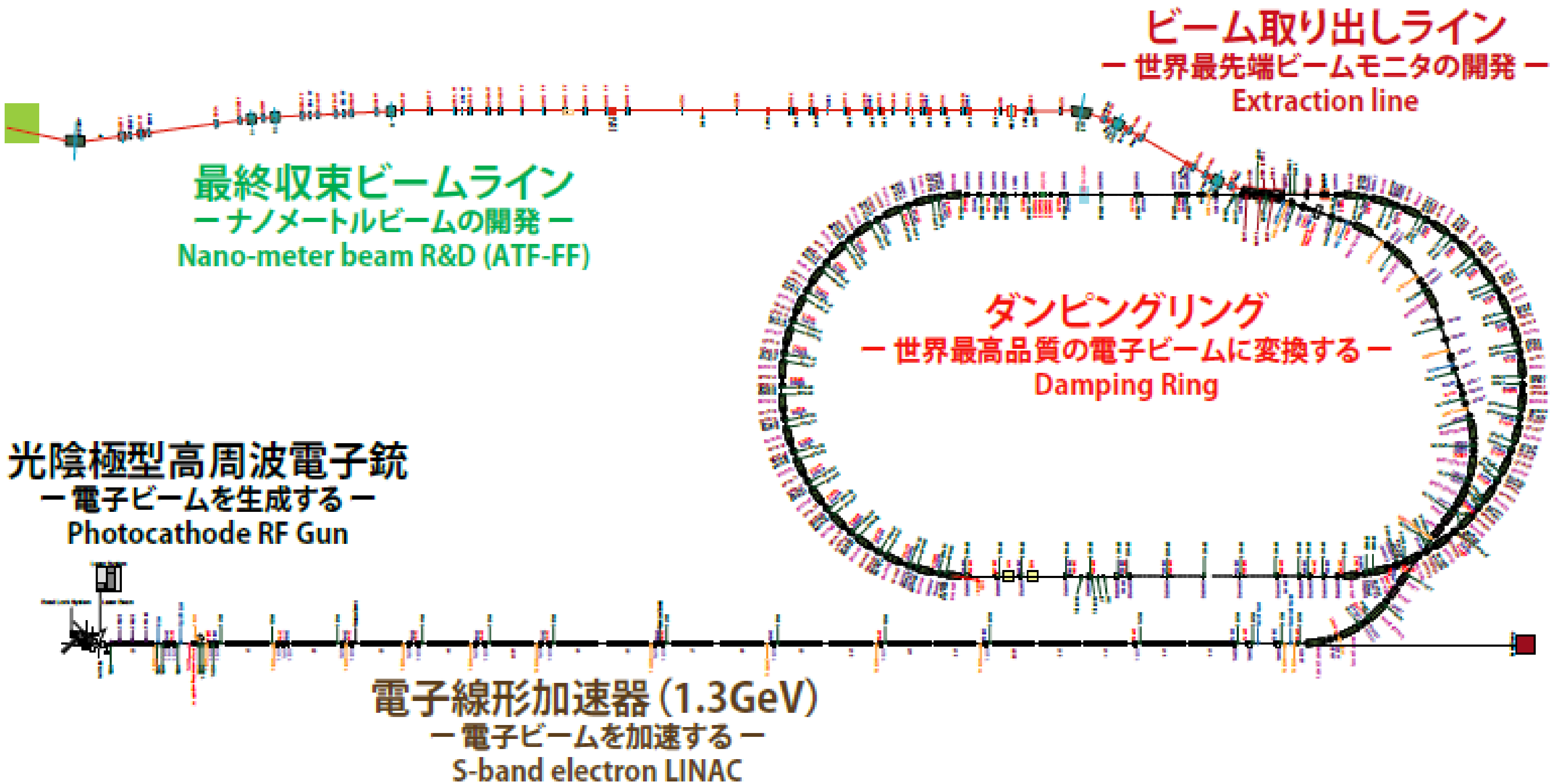




- X-band technology appears interesting for compact, relatively low cost FELs – new or extensions
  - Logical step after S-band and C-band
  - Example similar to SwissFEL: E=6 GeV, Ne=0.25 nC, σ_z=8μm
- Use of X-band in other projects will support industrialisation
  - They will be klystron-based, additional synergy with klystron-based first energy stage
- Started to collaborate on use of X-band in FELs
  - Australian Light Source, Turkish Accelerator Centre, Elettra, SINAP, Cockcroft Institute, TU Athens, U. Oslo, Uppsala University, CERN
- Share common work between partners
  - Cost model and optimisation
  - Beam dynamics, e.g. beam-based alignment
  - Accelerator systems, e.g. alignment, instrumentation…
- Define common standard solutions
  - Common RF component design, -> industry standard
  - High repetition rate klystrons (200->400 Hz now into test-stands)

Important collaboration for X-band technology

ATF/ATF2 (KEK)



ビーム取り出しライン
ー 世界最先端ビームモニタの開発 ー
Extraction line
最終収束ビームライン
ーナノメートルビームの開発ー
Nano-meter beam R&D (ATF-FF)
ダンピングリング
ー 世界最高品質の電子ビームに変換する ー
Damping Ring
光陰極型高周波電子銃
ー 電子ビームを生成する ー
Photocathode RF Gun
電子線形加速器（1.3GeV）
ー 電子ビームを加速する ー
S-band electron LINAC

CLIC + ATF/ATF2

Demonstration of nanometer-scale beam (~44nm achieved)

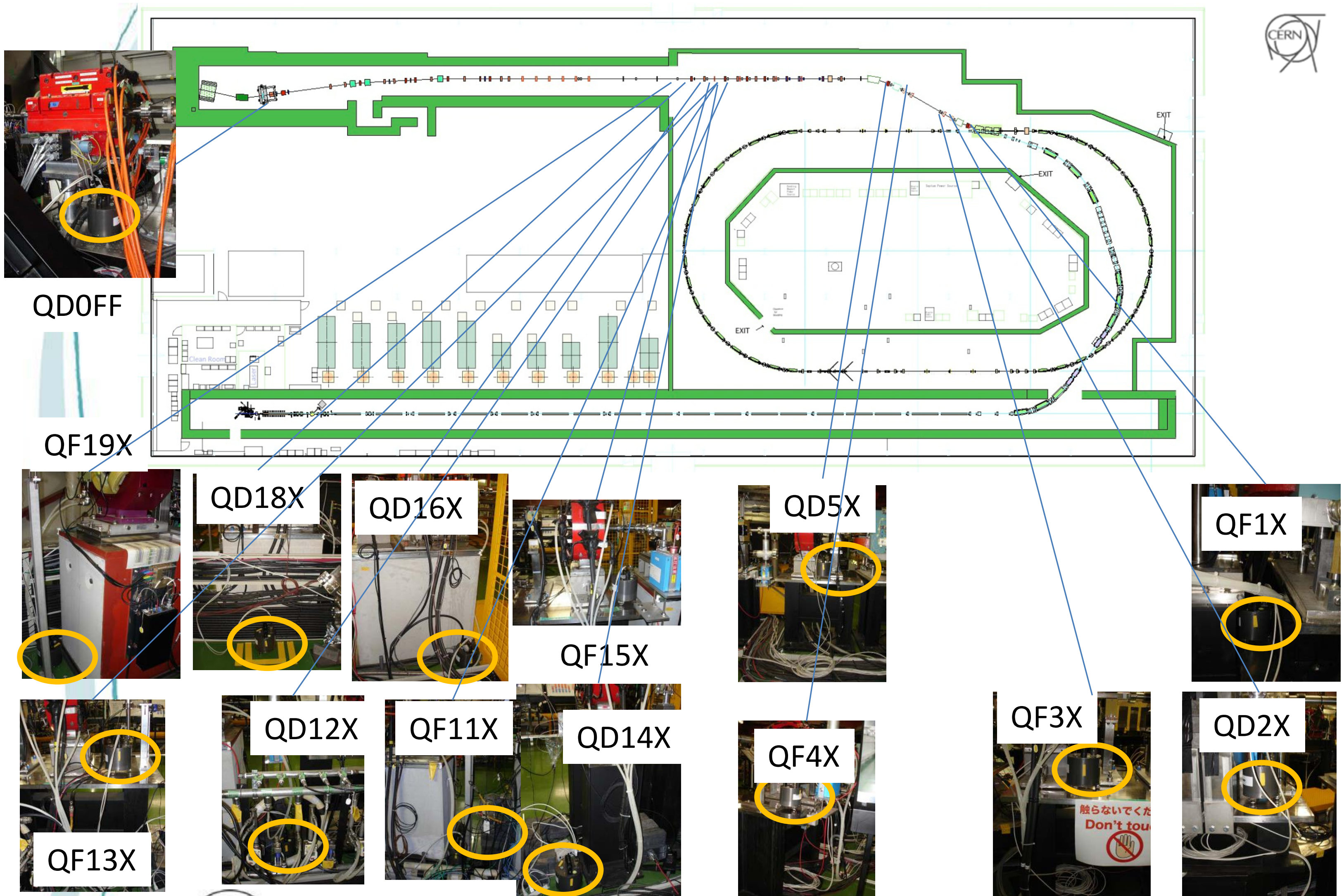
Beam stabilisation at nanometre level

Also:

- **Beam tuning techniques**
- **Beam jitter characterisation and amelioration**
- **Beam feedback + feed-forward**
- **Magnet development (hybrid QD0, PM octupoles)**
- **Beam instrumentation: BPMs, transverse beam size …**
- **DR extraction kicker tests …**

LINEAR COLLIDER COLLABORATION

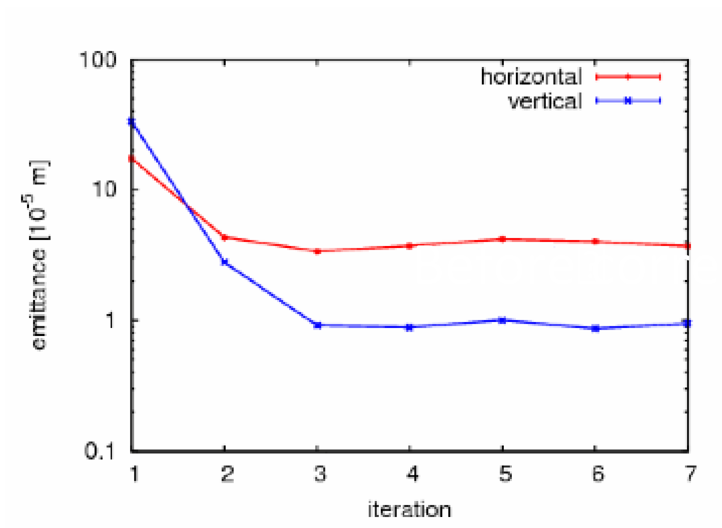
Ground-motion sensor array



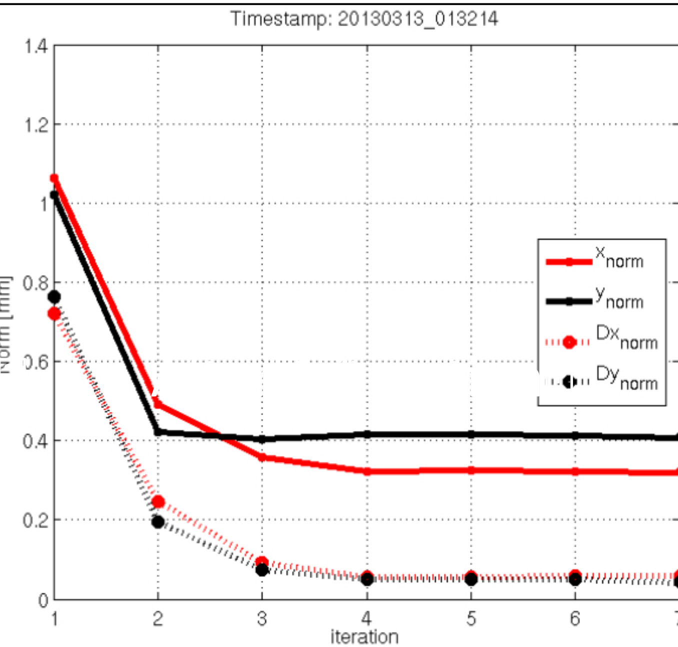
Beam tuning at FACET (SLAC)

Dispersion-free steering

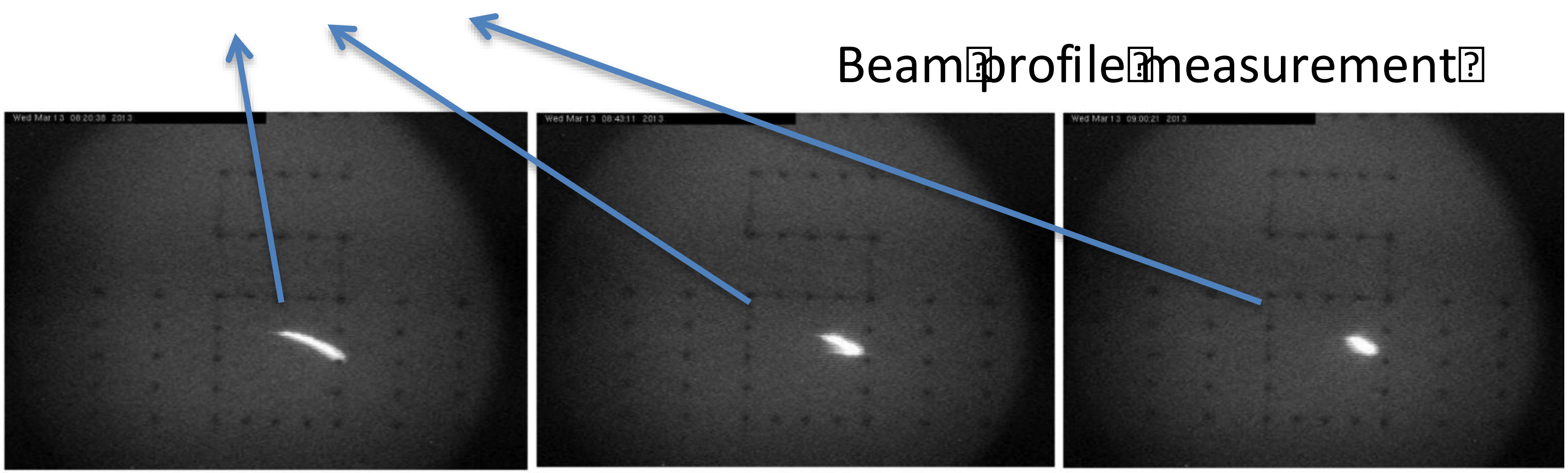
Emittance



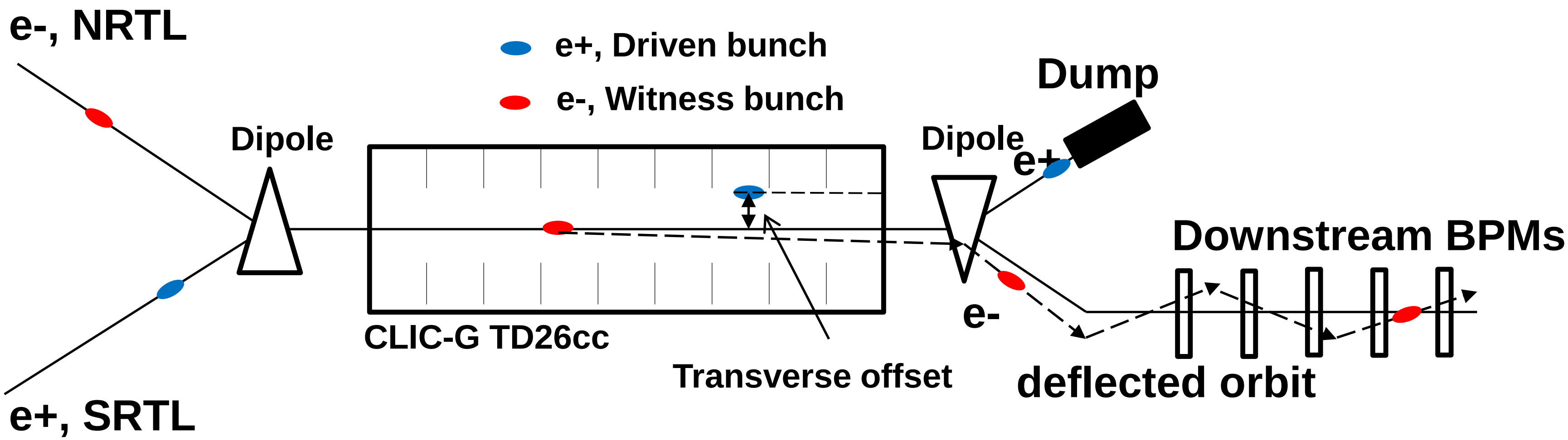
Orbit/Dispersion

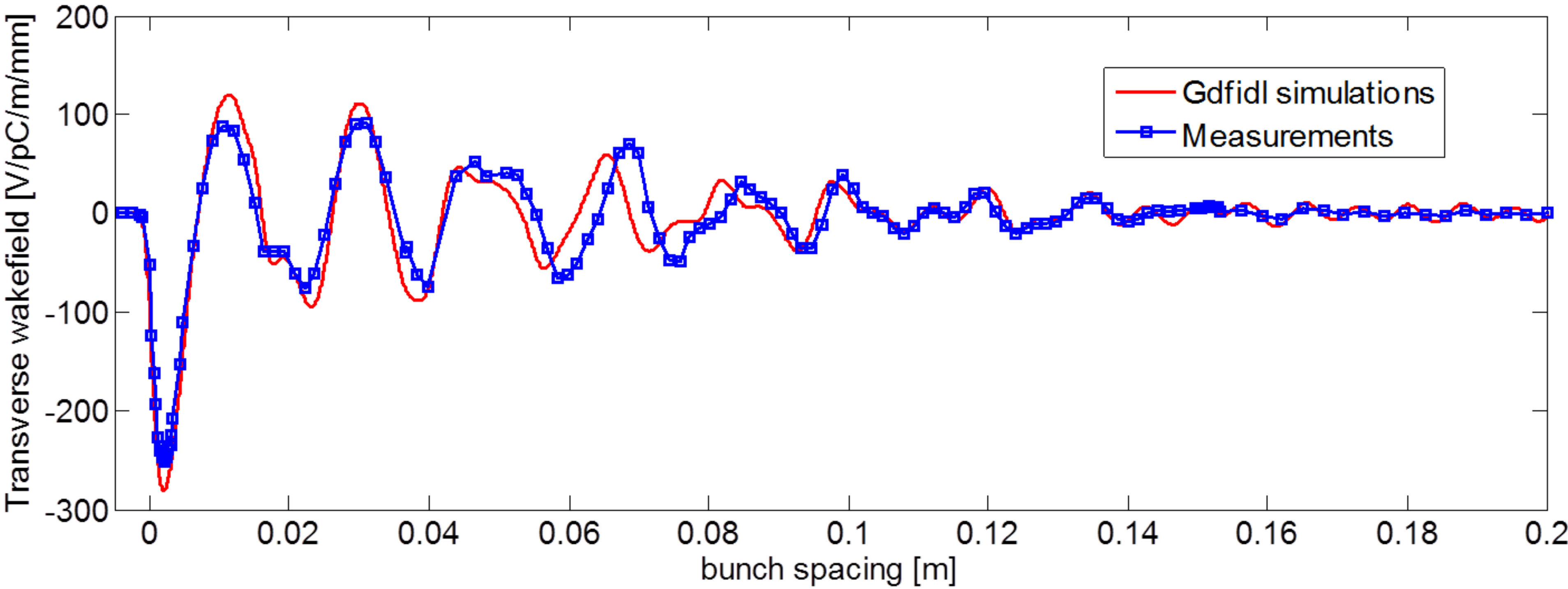


Beam profile measurement



FACET measurements of wakefields





Summary

Goals and plans for 2015-18 are well defined + aligned with European Strategy

Prepared to align with LHC physics outcomes

- **Aim provide optimized staged approach up to 3 TeV with costs and power not excessive compared with LHC**
- **Very good progress on X-band technology, better availability of power sources, and increased understanding of structure design parameters**
  - **Applications in smaller systems; FEL linacs key example – with considerable interest in the CLIC collaboration**
- **Also recent good progress on performance verifications, drive beam (CTF3), main beam emittance conservation (FACET) and final focus studies (ATF)**
  - **CTF3 running planned until end 2016; need a strategy for system tests beyond**
- **Technical developments of key parts well underway – with increasing involvement of industry – largely limited by funding**
- **Collaborations for CLIC accelerator and detector & physics studies are growing**

LINEAR COLLIDER COLLABORATION

CLIC roadmap

2013-18 Development Phase

Develop a Project Plan for a staged implementation in agreement with LHC findings; further technical developments with industry, performance studies for accelerator parts and systems, as well as for detectors.

4-5 year Preparation Phase

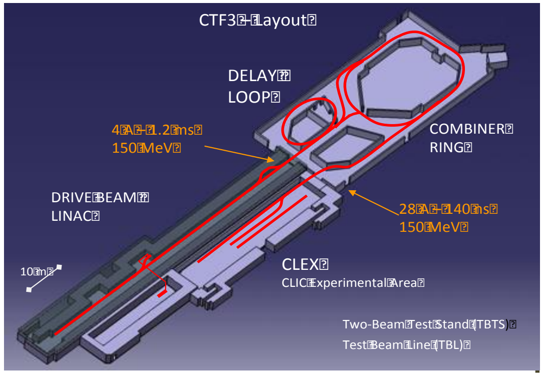
Finalise implementation parameters, Drive Beam Facility and other system verifications, site authorisation and preparation for industrial procurement.

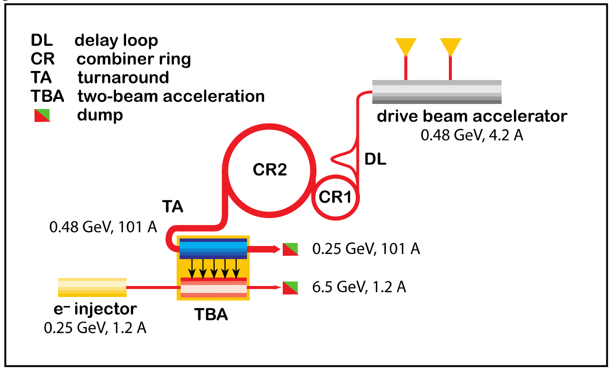
Prepare detailed Technical Proposals for the detector-systems.

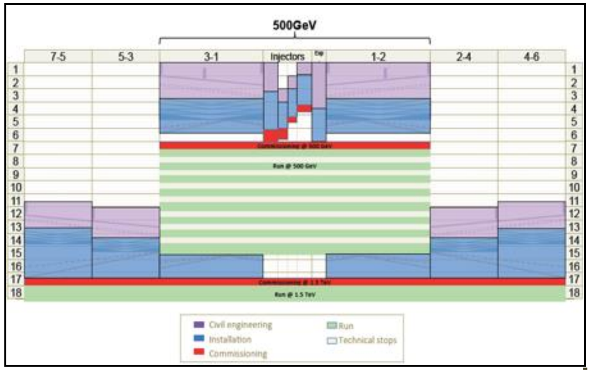
Construction Phase

Stage 1 construction of CLIC, in parallel with detector construction.

Preparation for implementation of further stages.







2018-19 Decisions

On the basis of LHC data and Project Plans (for CLIC and other potential projects as FCC), take decisions about next project(s) at the Energy Frontier.

2024-25 Construction Start

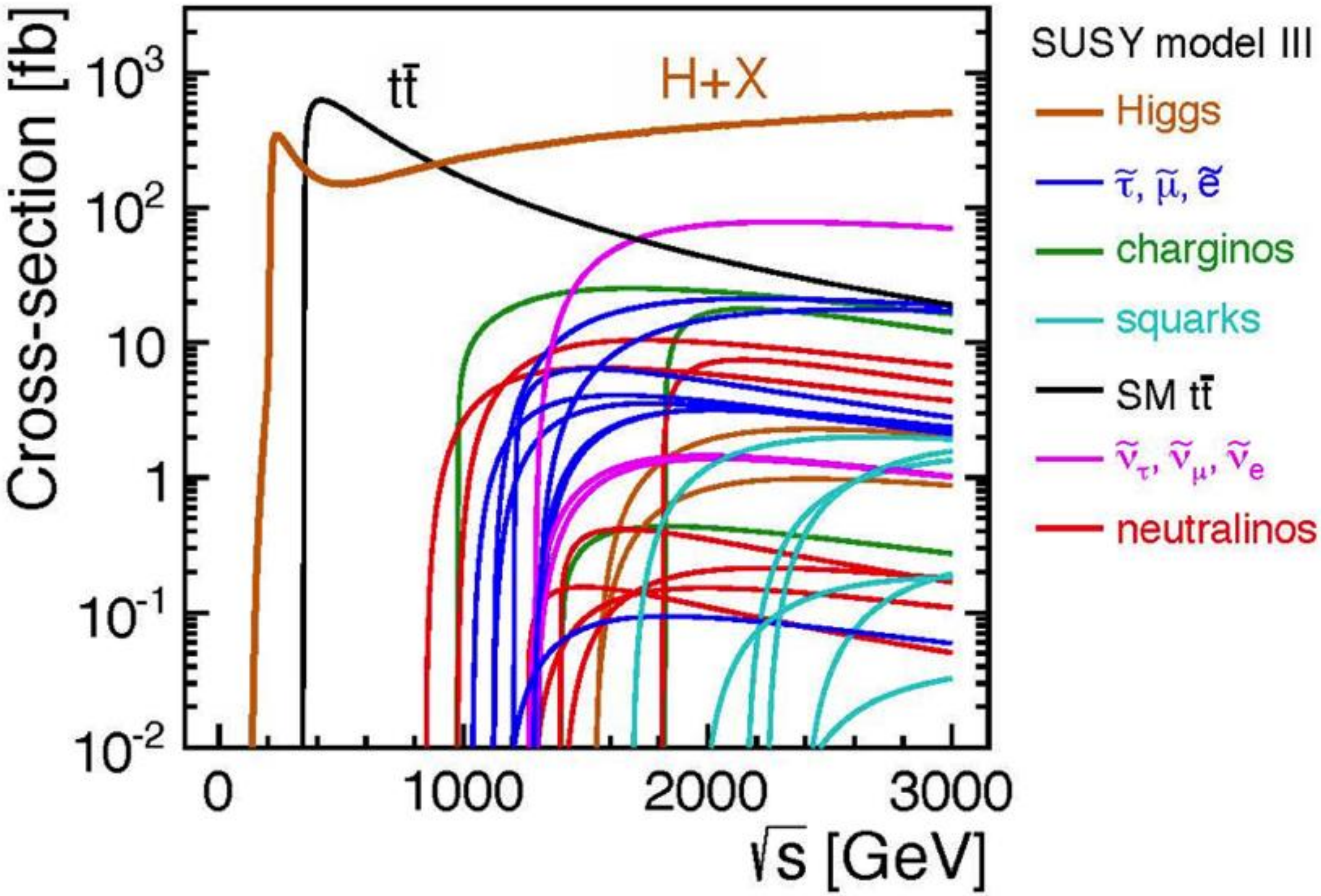
Ready for full construction and main tunnel excavation.

Commissioning

Becoming ready for data-taking as the LHC programme reaches completion.

LINEAR COLLIDER COLLABORATION

While waiting for LHC results … planning a strategy for delivery

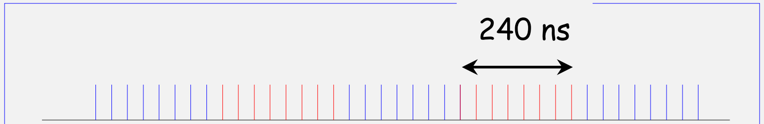


Backup

CLIC Layout at 3 TeV

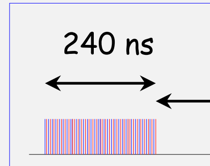
Drive Beam Generation

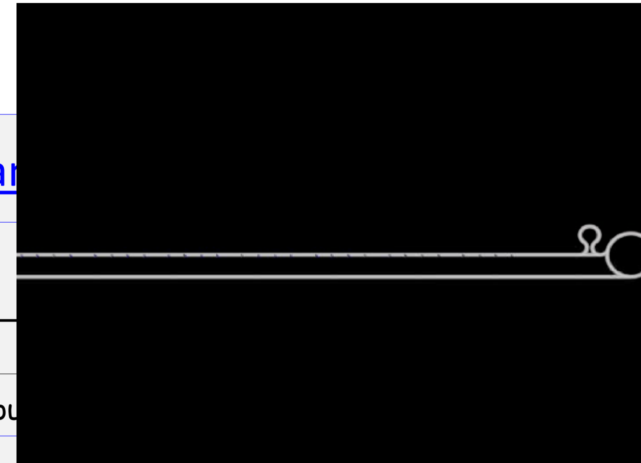
Drive beam time structure - initial

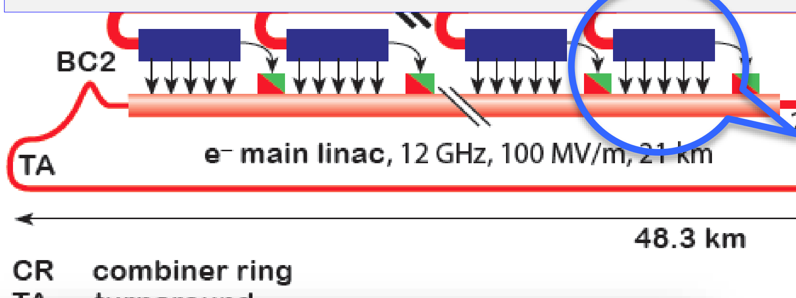


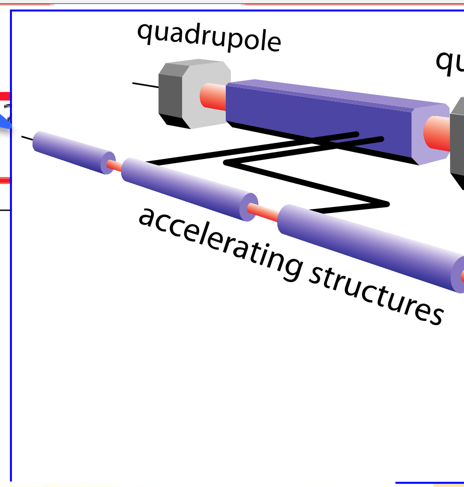
140 μs train length - 24 × 24 sub-pulses
4.2 A - 2.4 GeV – 60 cm between bunches

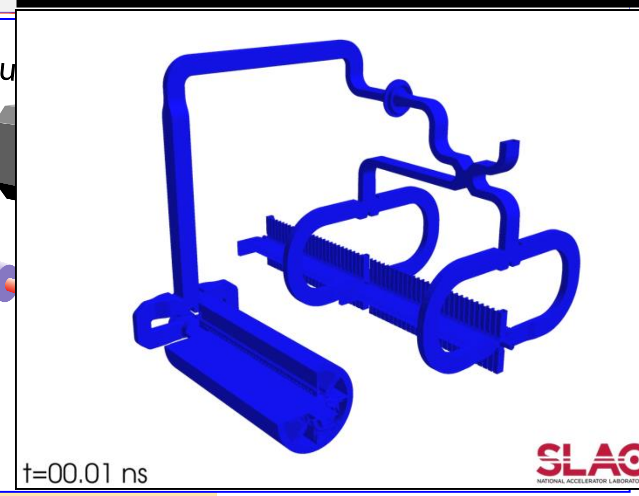
Drive bea

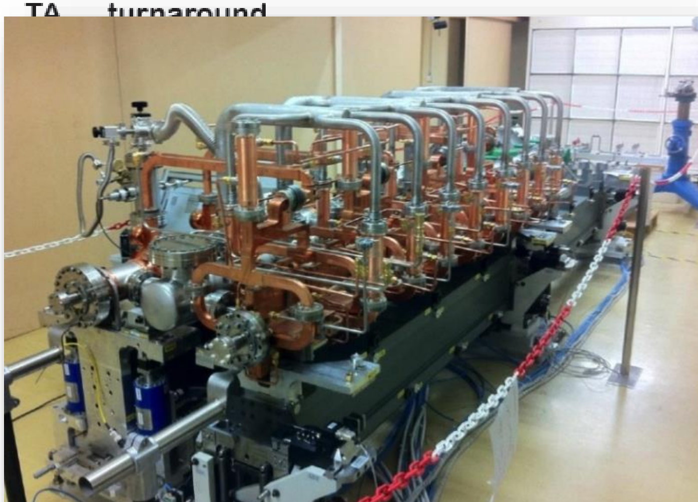


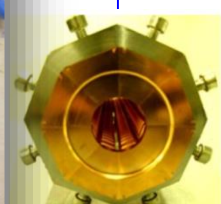


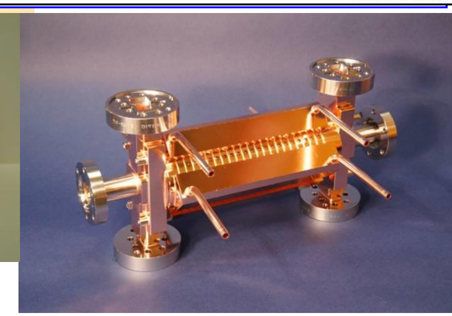


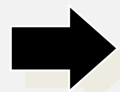








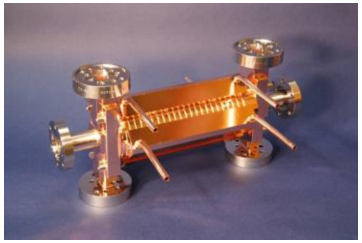


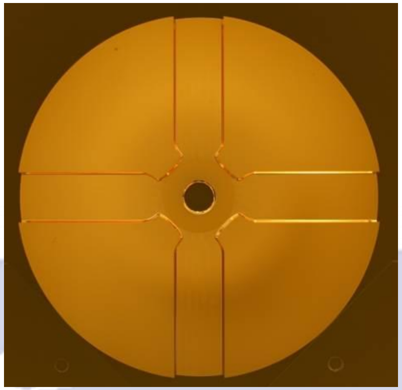


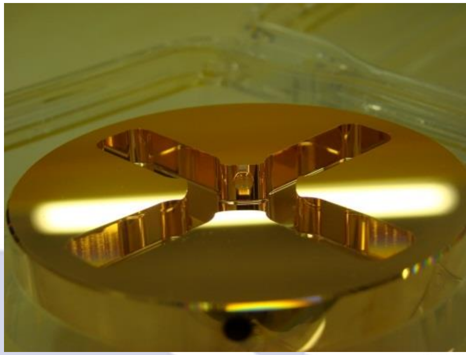
X-band structures and testing

X-band Technologies:

- High gradient structures and high efficiency RF (structure prod. in green)
- X-band High power Testing Facilities (x3 increase) (in red)
- Use of X-band technologies for FELs





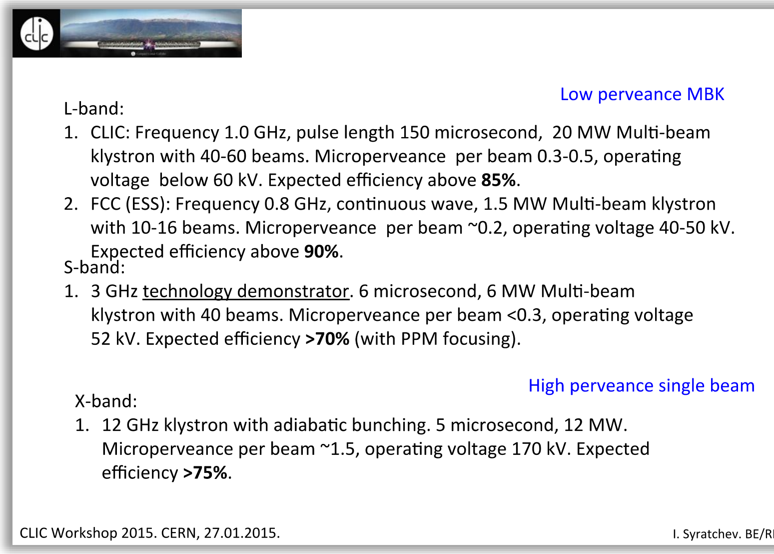


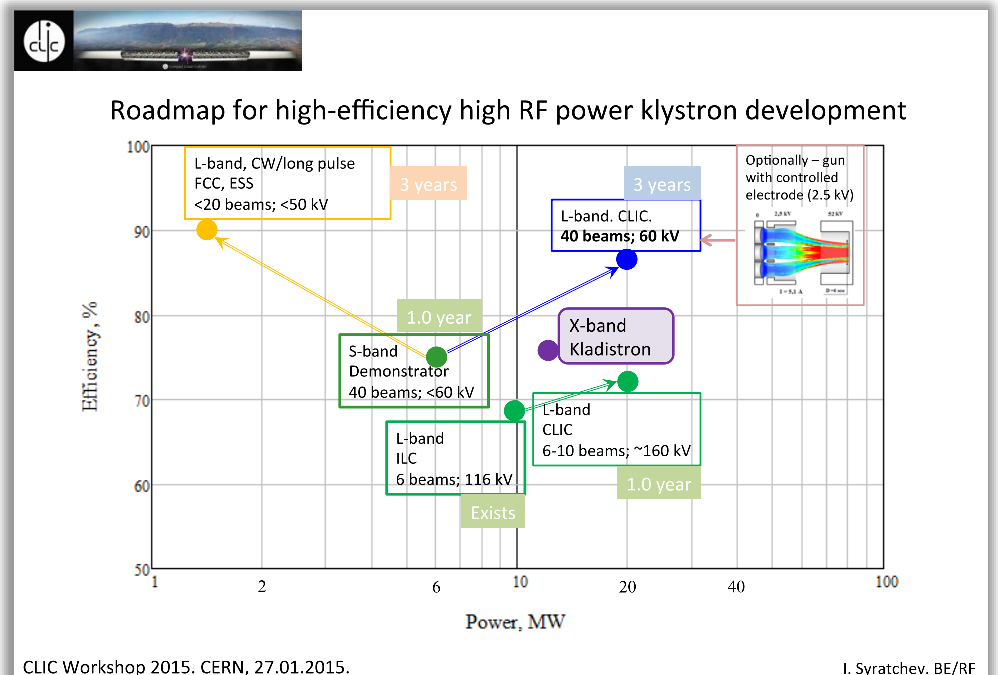
Institute	Structure	Status
KEK	Long history – latest TD26CC	Mechanical design
Tsinghua	T24 - VDL machined, Tsinghua assembled, H bonding, KEK high-power test	At KEK
	CLIC choke	manufacturing tests
SINAP	XFEL structure, KEK high-power test	rf design phase
	T24, CERN high-power test	Agreement signed
	Four XFEL structures	H2020 proposal
CIEMAT	TD24CC	Agreement signed
PSI	Two T24 structures made at PSI using SwissFEL production line including vacuum brazing	Mechanical design work underway
VDL	XFEL structure	H2020 proposal
SLAC	T24 in milled halves	machining
CERN	Structures and Test-stands	
	KT (Knowledge Transfer) funded medical linac	machining

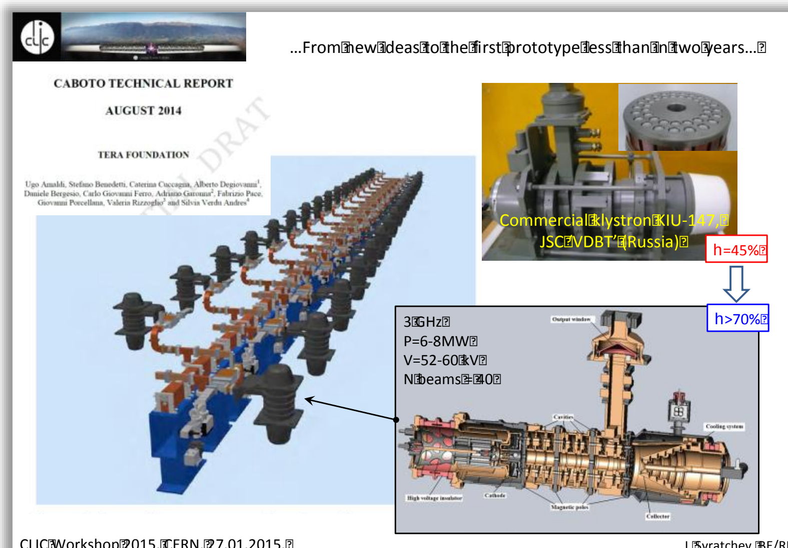
Novel RF developments

Work shared between researchers and industry at CERN, in the US, UK, France, Sweden, Russia … covering much wider than CLIC but seed funded from the CERN LC budget:

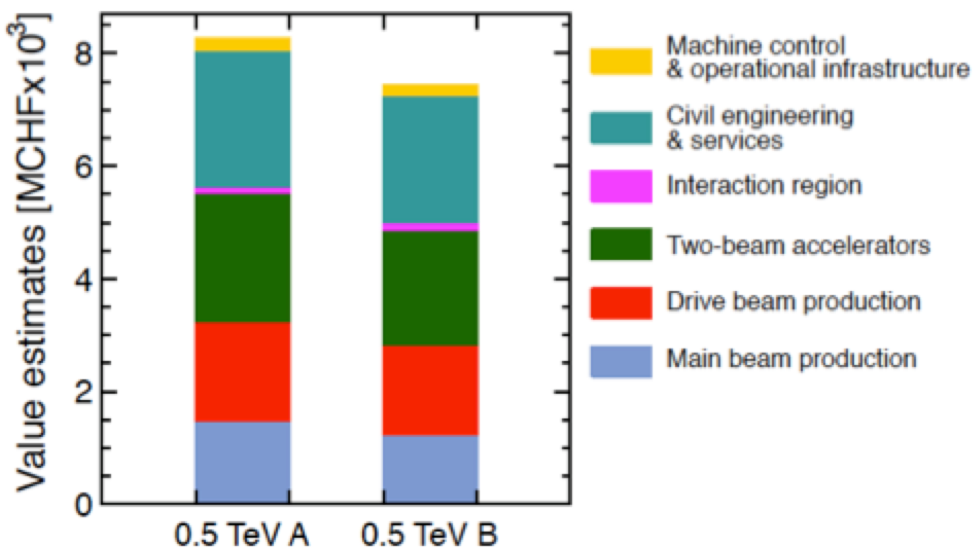
- ➢ The increase in efficiency of RF power generation for the future large accelerators such as CLIC, ILC, ESS, FCC and others is considered a high priority issue.
- ➢ The deeper understanding of the klystron physics, new ideas and massive application of the modern computation resources are the key ingredients to deign the klystron with RF power production efficiency at a level of 90% and above.







Developments for 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

CDR costs can now be updated

- New parameters optimizing costs, affect mostly initial stages
- Technical developments, affects all stages
- Too early for updated industrial quotes in some areas (other areas can be updated)

2012 CHF versus 2015 CHF ?