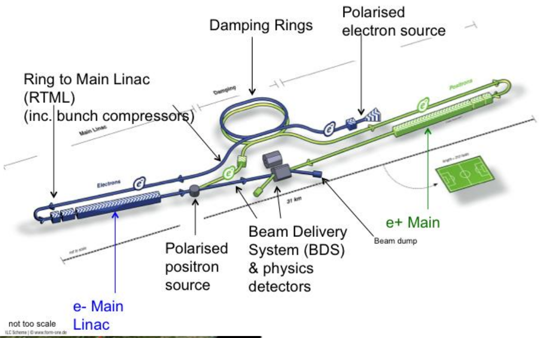
CLIC Interest in High Gradient FEL Design

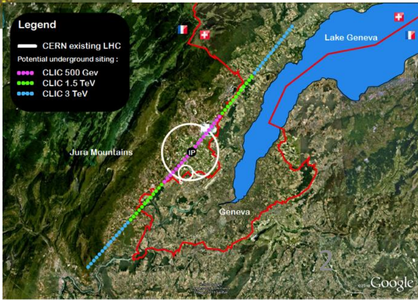
D. Schulte for the CLIC collaboration

Special thanks to
A. Grudiev, A. Latina, Ph. Lebrun, H. Schmickler, S. Stapnes,
I. Syratchev, W. Wuensch

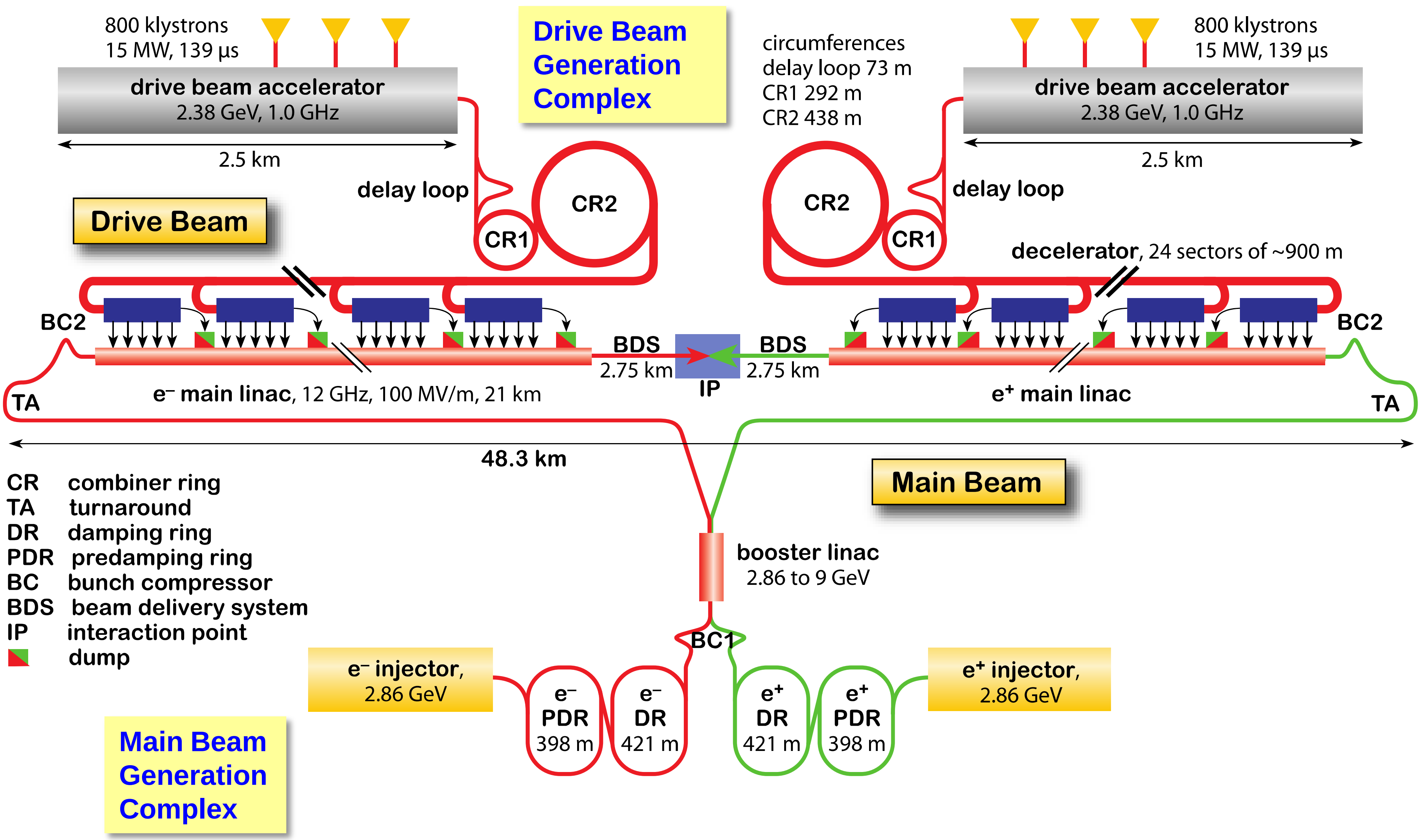
CLIC Study Context

- LHC and LHC luminosity upgrades (until ~2030)
  - Higgs and BSM physics
- Maybe ILC in Japan, a possibility for exploring the Higgs in detail, starting at 250 GeV
  - Requires significant integrated luminosities, and increased energies in steps (at least to 500 GeV), also long programme
- BSM – does it show up at LHC at 13-14 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
  - Two alternatives considered
    - higher energy hadrons (HE LHC or VHE LHC)
    - or highest possible energy e+e- (CLIC).

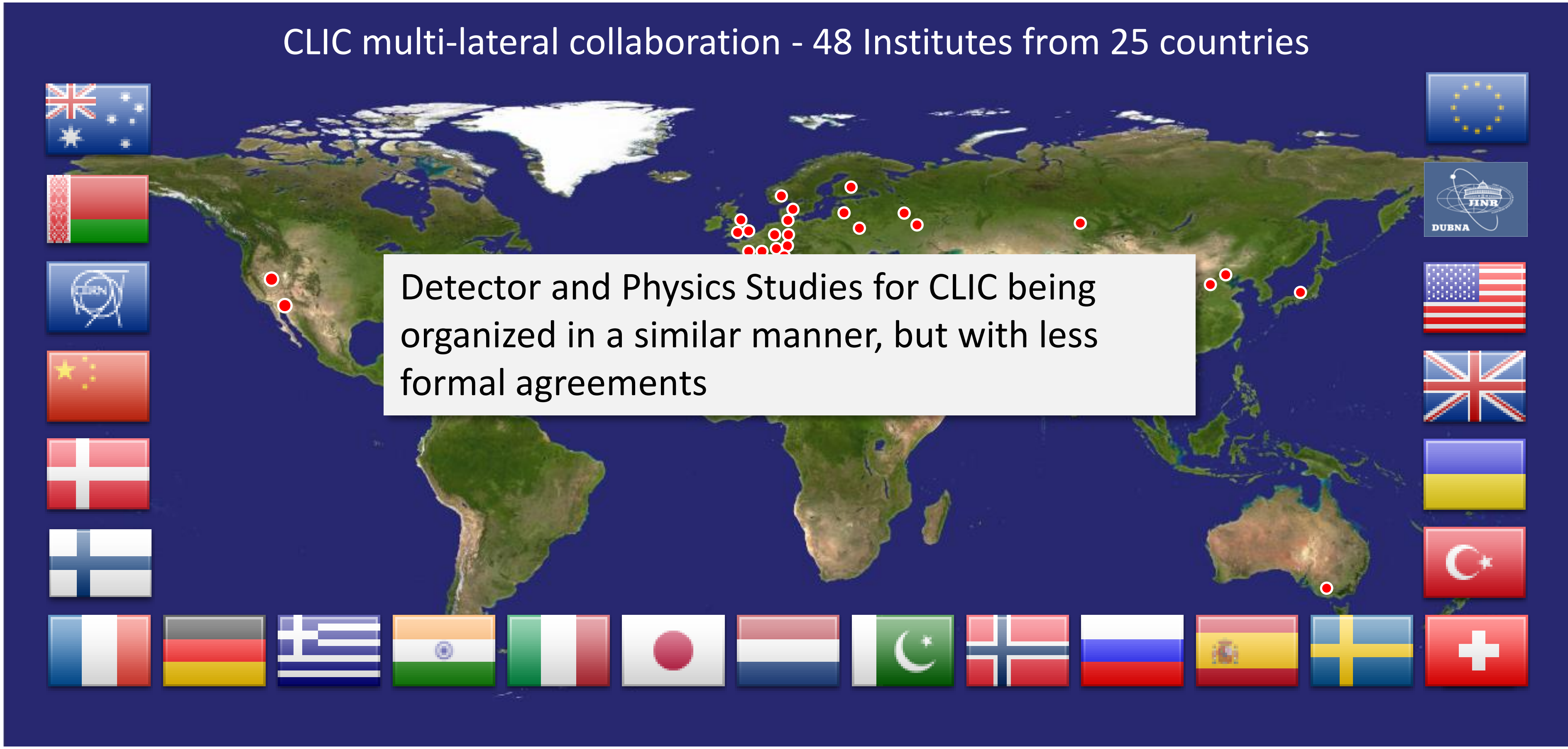




CLIC Layout at 3TeV



Current CLIC Collaboration



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)
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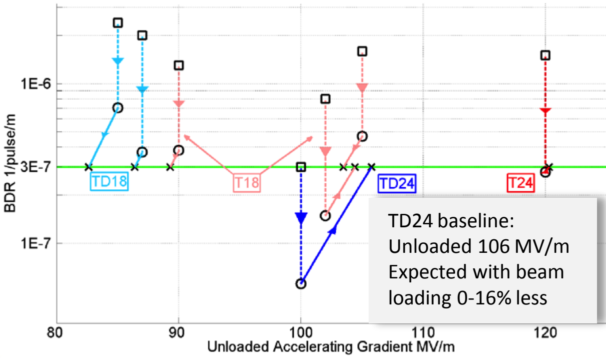
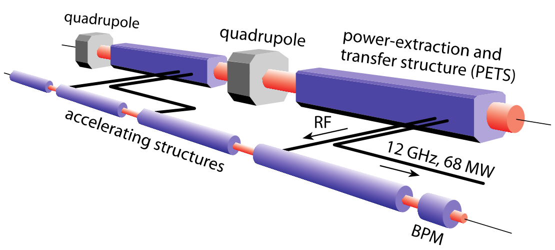
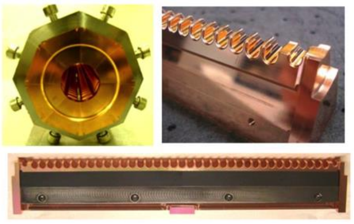
Tsinghua University (China)
University of Oslo (Norway)
University of Vigo (Spain)
Uppsala University (Sweden)
UCSC SCIPP (USA)

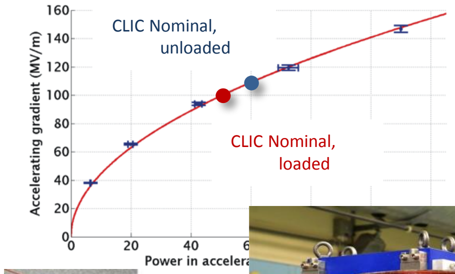
Conclusion of the Accelerator CDR Studies

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 above specifications, deceleration as expected – Improvements on operation, reliability, losses, more deceleration studies underway

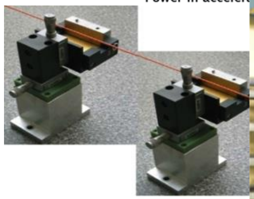


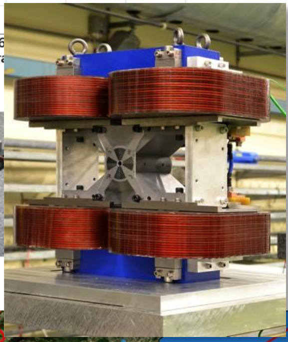


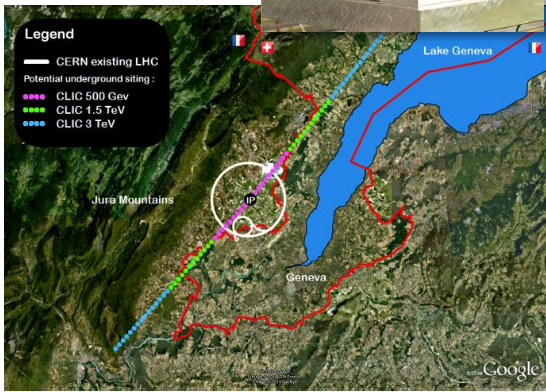




Luminosity	– Damping ring like an ambitious light source, no show stopper – Alignment system principle demonstrated – Stabilisation system developed, benchmarked, better system in pipeline – Simulations on or close to the target
Operation & Machine Protection	– Start-up sequence and low energy operation defined – Most critical failure studied and first reliability studies
Implementation	– Consistent staged implementation scenario defined – Schedules, cost and power developed and presented – Site and CE studies documented





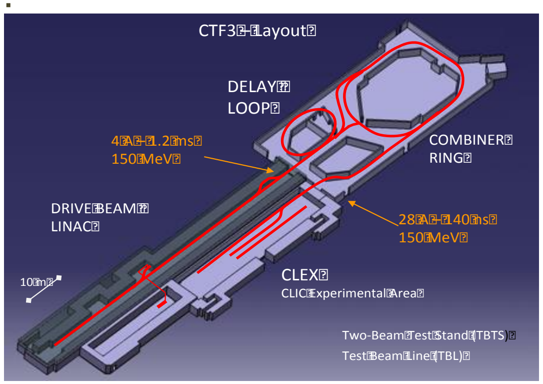


Accelerator	https://edms.cern.ch/document/1234244/
Physics and detector	http://arxiv.org/pdf/1202.5940v1
Summary	http://arxiv.org/pdf/1209.2543v1
EU strategy input	http://arxiv.org/pdf/1208.1402v1

CLIC Timeline

2012-18 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.



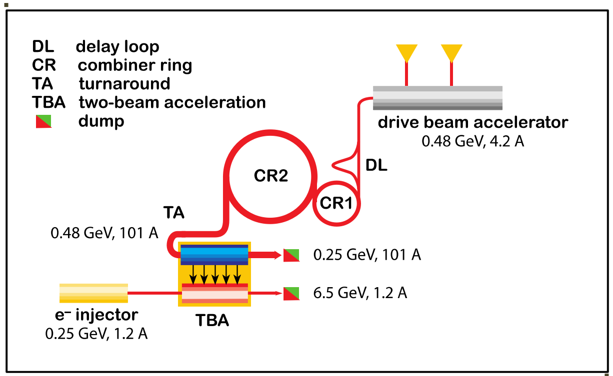
2018 Decisions

On the basis of LHC data and Project Plans (for CLIC and HiE LHC variants in particular), take decisions about next project(s) at the Energy Frontier.

2019-23 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.



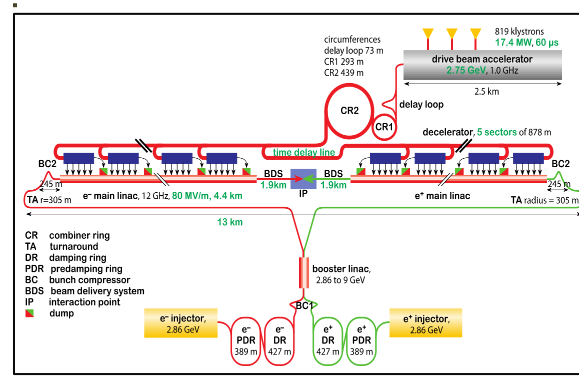
2023-24 Construction Start

Ready for full construction and main tunnel excavation.

2023-2030 Construction Phase

Stage 1 construction of a 500 GeV CLIC, in parallel with detector construction.

Preparation for implementation of further stages.



2030 Commissioning

From 2030, becoming ready for data-taking as the LHC programme reaches completion.

What is the Connection to FELs?

- CERN does not do light sources
  - It is not part of CERN's mandate

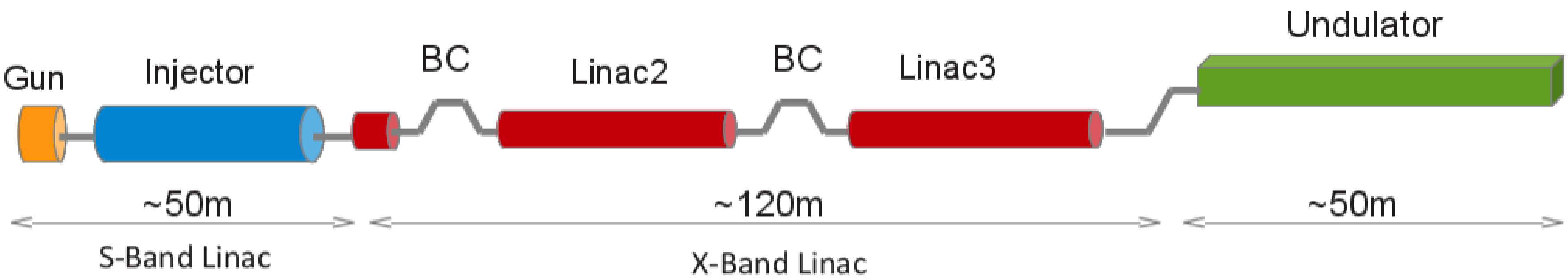
- But use of X-band in FELs in other labs would help CLIC for a number of tasks
  - Further technical developments with industry
    - Will create the industrial basis
  - Performance studies of accelerator parts and systems
    - From components up to large scale main linac system test

- We think that FELs can profit from X-band technology
  - For you to judge based on further studies

- Need to find one/several laboratories to build an FEL and help them as needed (including RF, instrumentation, alignment, beam dynamics, test stands, industrial contacts …)
  - This is why we are here

FEL Overview

A. Aksoy



Looked a bit into a linac design for a typical Angstrøm FEL

Swiss FEL (C-band, approved):

$E=5.8GeV$ $Q=200pC$ $\sigma_z=7\mu m$ $\varepsilon\approx 200nm-500nm$

Proposal of Ch. Adolphsen et al. shows concept for X-band

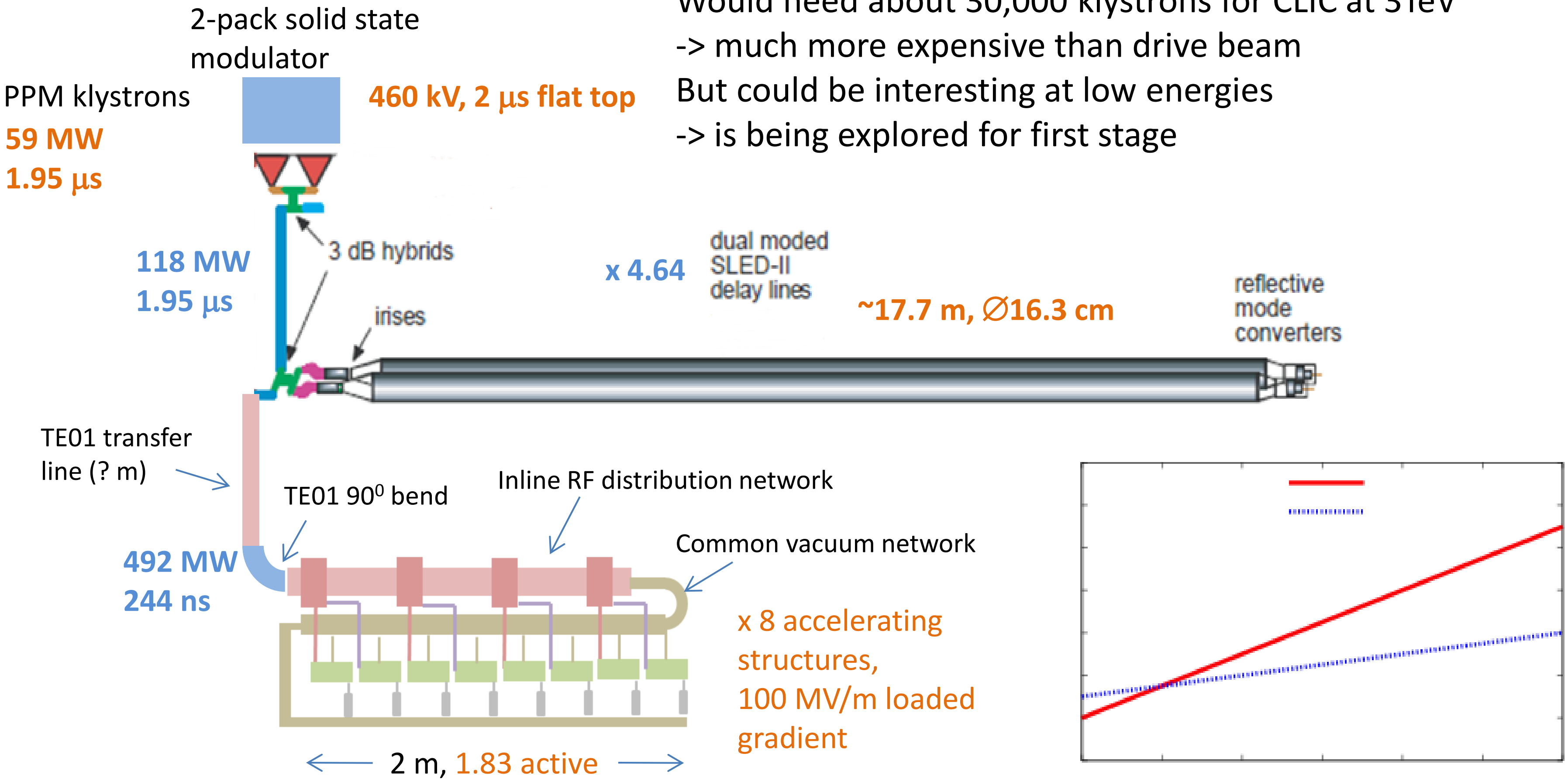
$E=6GeV$ $Q=250pC$ $\sigma_z=8\mu m$ $\varepsilon\approx 400nm-500nm$

As example we did chose Q=250pC, E=6GeV and will go for similar bunch lengths
Do not study injector (use the one from PSI for now) or undulator

Note: Klystron-based First CLIC Stage

Preliminary RF unit design

Would need about 30,000 klystrons for CLIC at 3TeV
-> much more expensive than drive beam
But could be interesting at low energies
-> is being explored for first stage

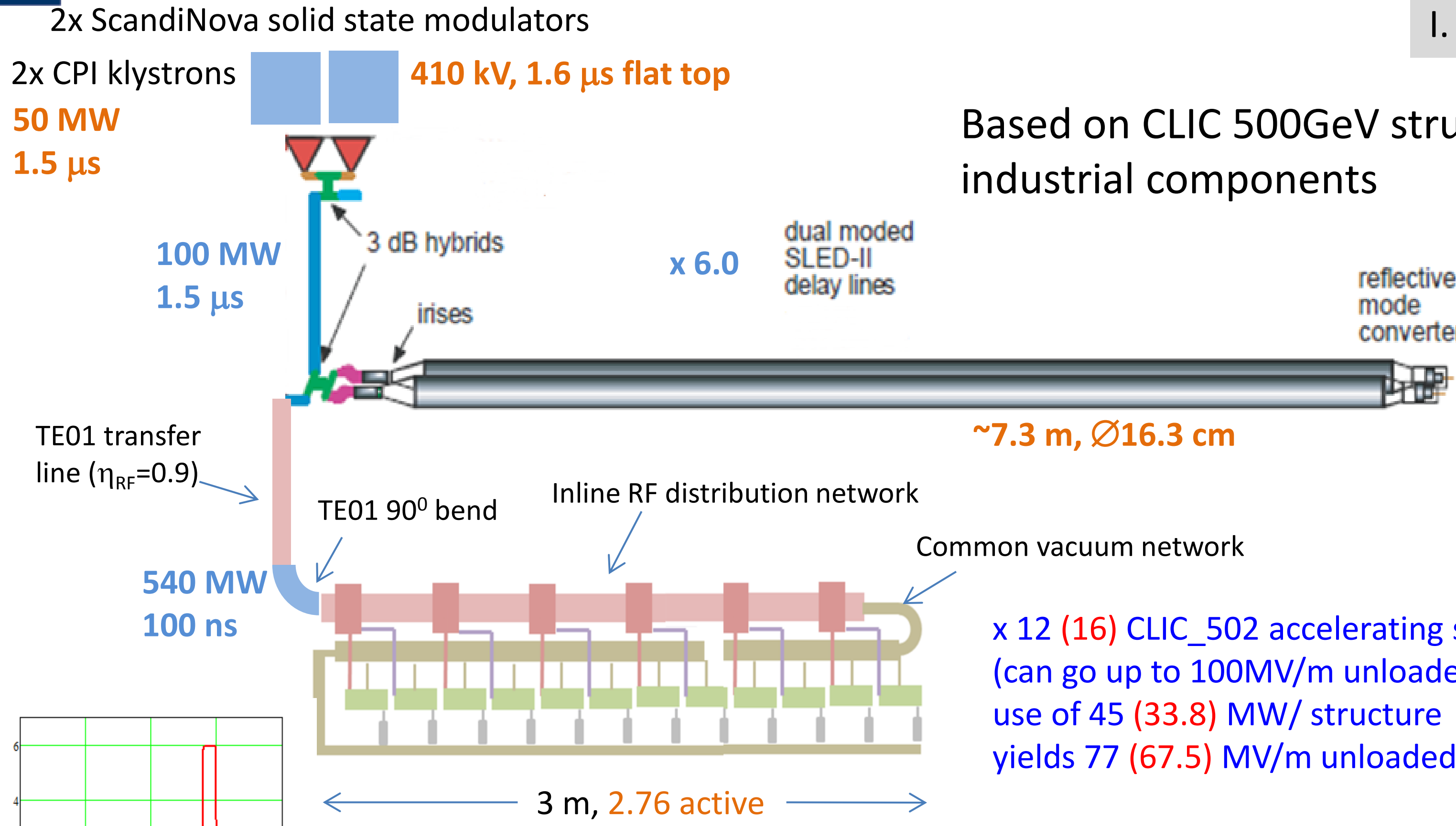


Compared to NLC, the energy gain per unit in CLIC'k case is 26% lower (need more klystrons per meter), but the unit length is ~ 3 time shorter.

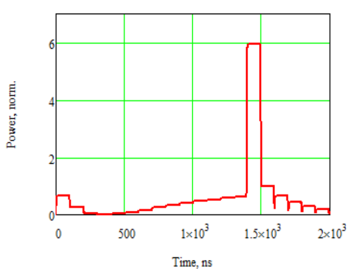
Example FEL RF Unit

I. Syratchev

Based on CLIC 500GeV structure and on industrial components

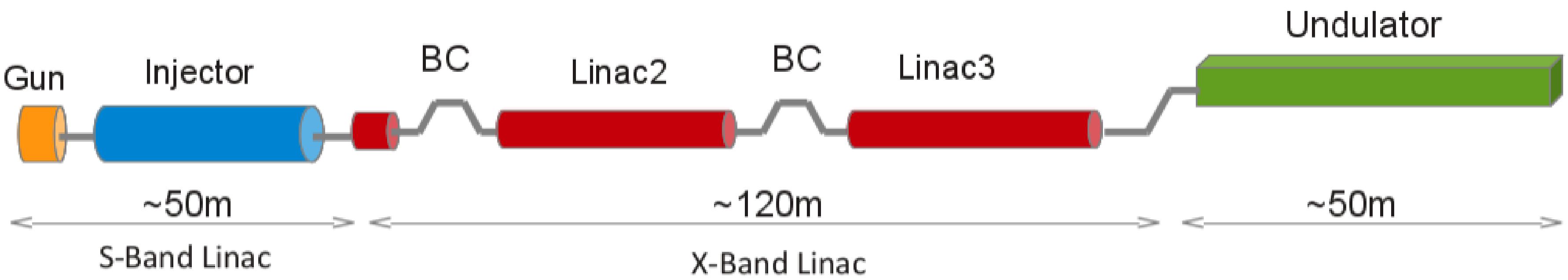


x 12 (16) CLIC_502 accelerating structures
(can go up to 100MV/m unloaded)
use of 45 (33.8) MW/ structure
yields 77 (67.5) MV/m unloaded gradient

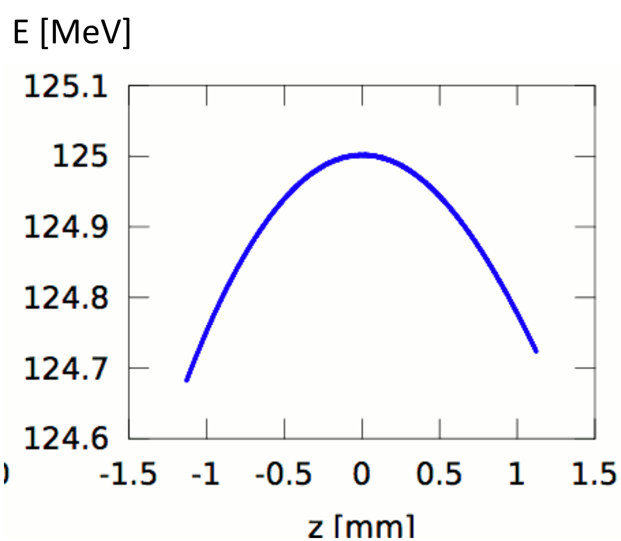


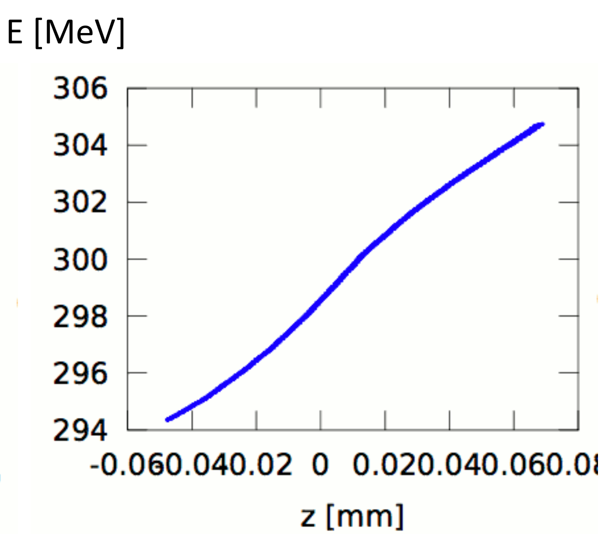
This unit should provide ~213 (248) MeV acceleration beam loading.
Need 27 (23) RF units.
Future CLIC klystrons would save O(20%)

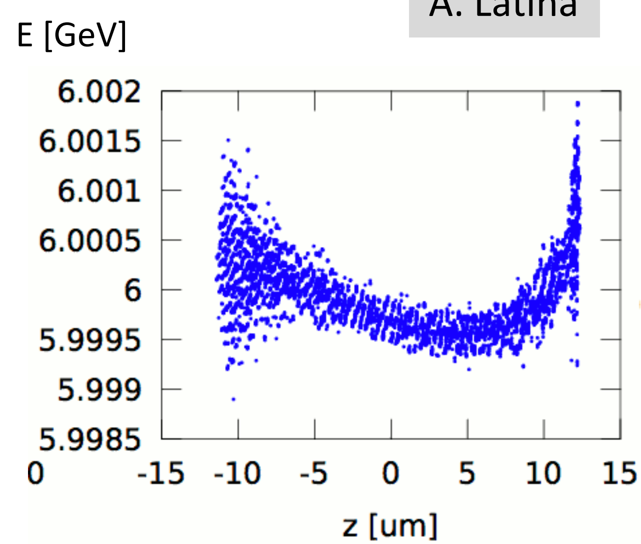
Longitudinal Dynamics



A. Latina

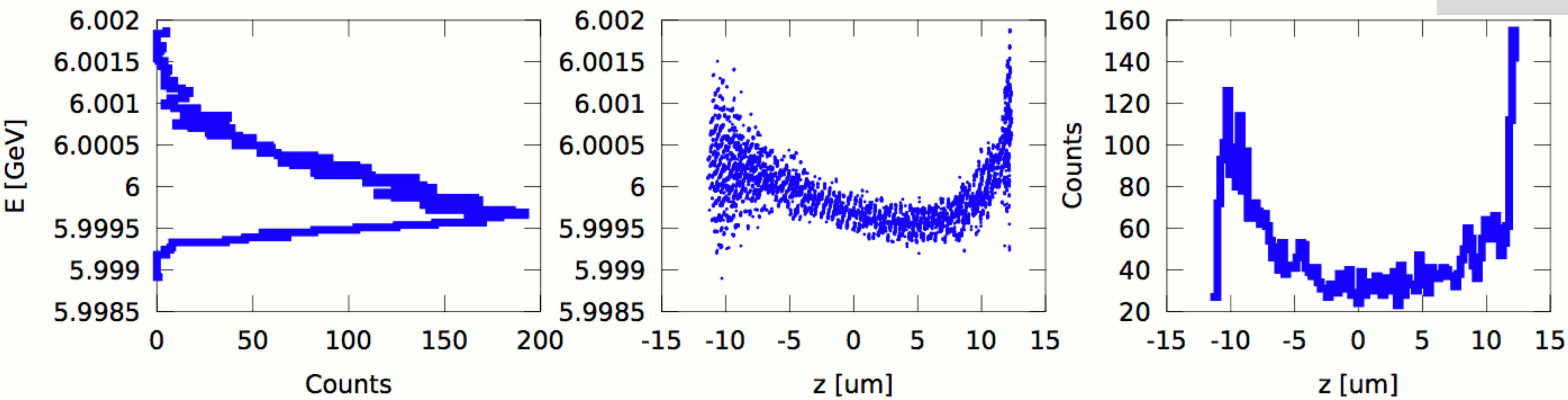






Longitudinal Dynamics (Example)

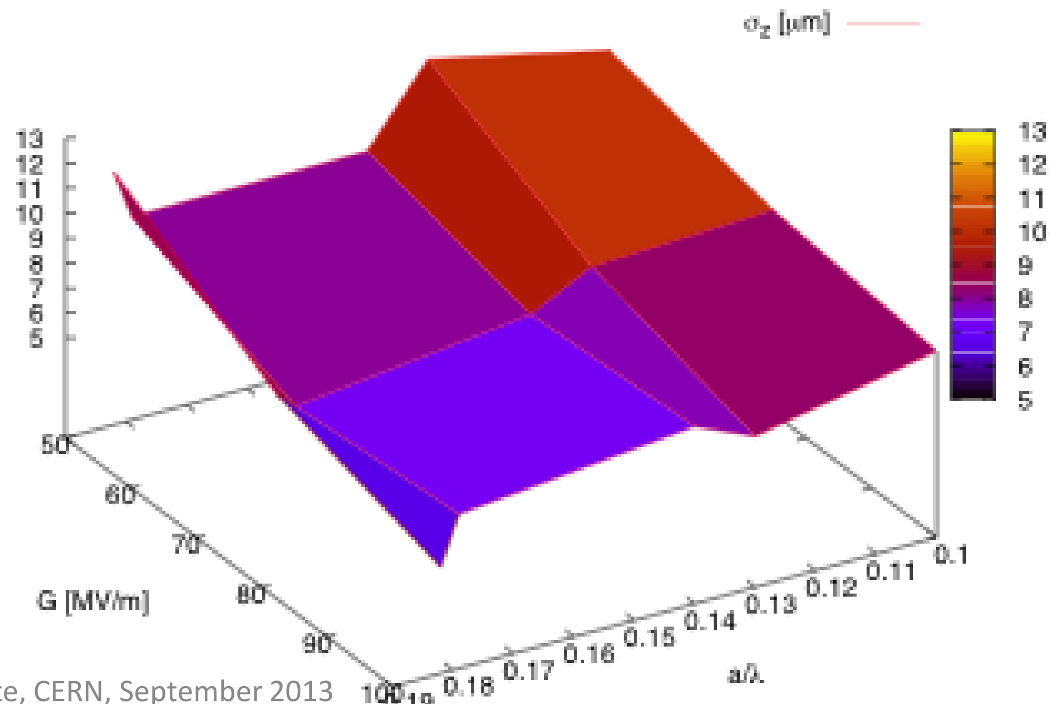
A. Latina



Example structure:
$a/\lambda=0.14$ and $G=67.5$MV/m

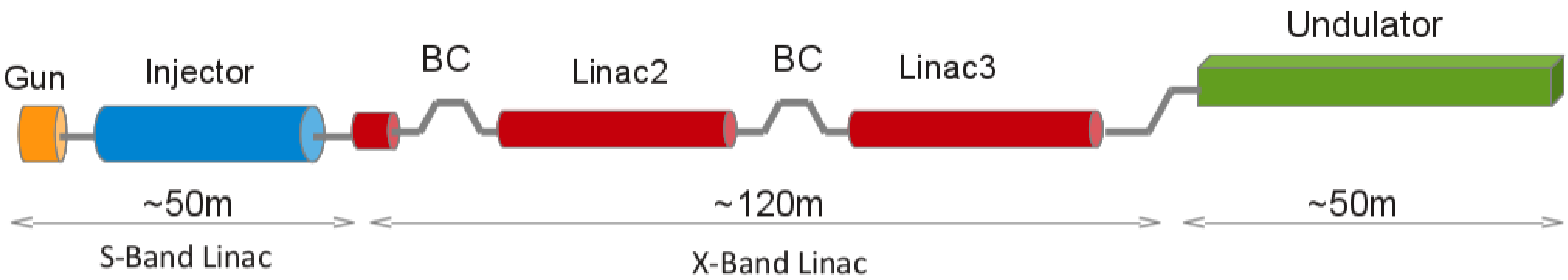
$\sigma_z = 7.96\ \mu m$, $\sigma_E = 0.0071\%$, $\sigma_{E,slice} = 0.0027\%$

(Swiss FEL: $\sigma_z=7\mu m$, $\sigma_{E,slice} = 0.006\%$)



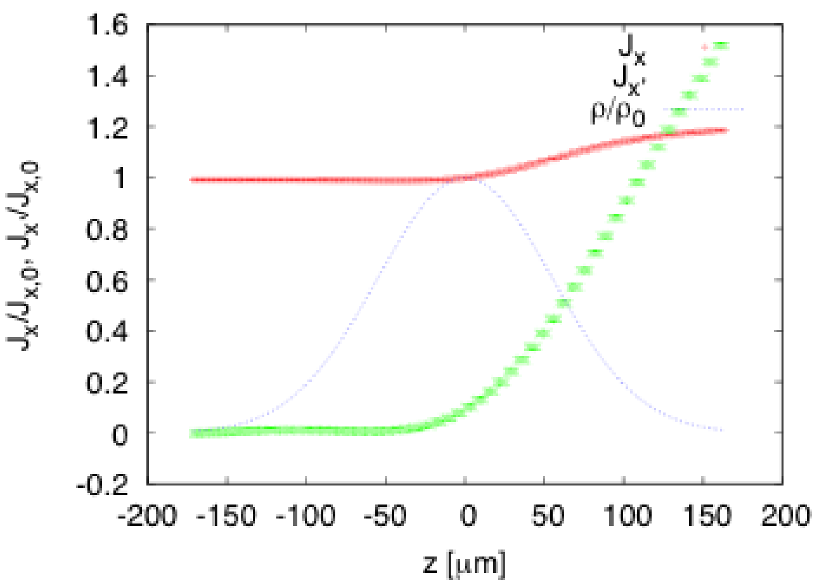
Looks promising but detailed studies needed
- realistic figure of merit for final beam distribution
- radiation in compressors
- operational margins
- …

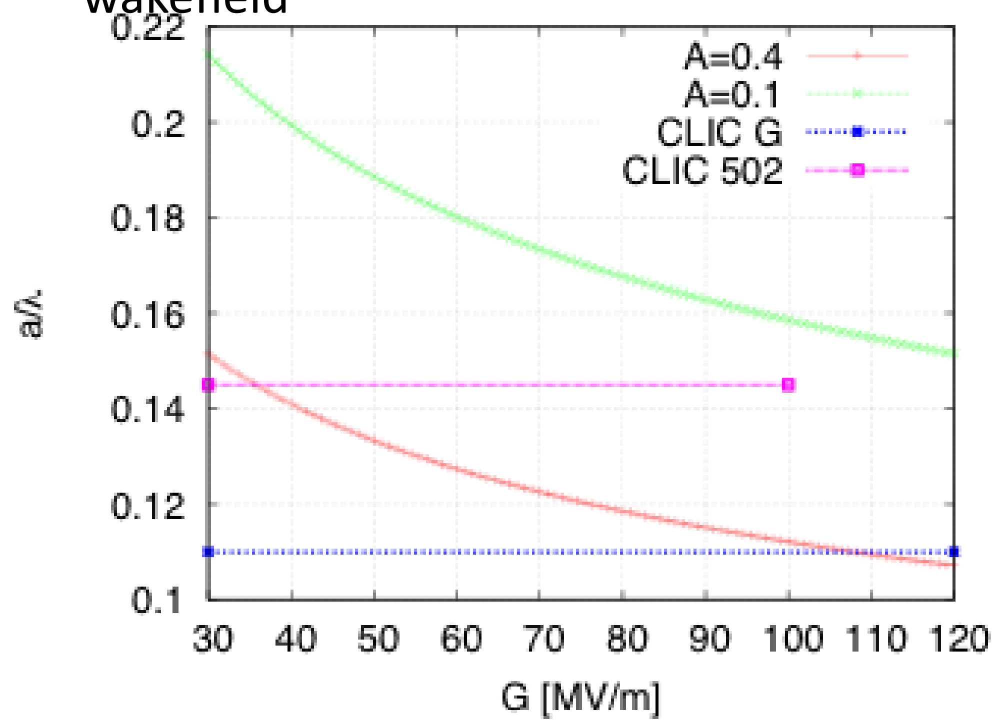
Transverse Dynamics



$$1 \gg A = \int_0^L \frac{\beta}{2E} ds \langle W_\perp \rangle N e^2$$

(Strong) CLIC lattice and simplified wakefield





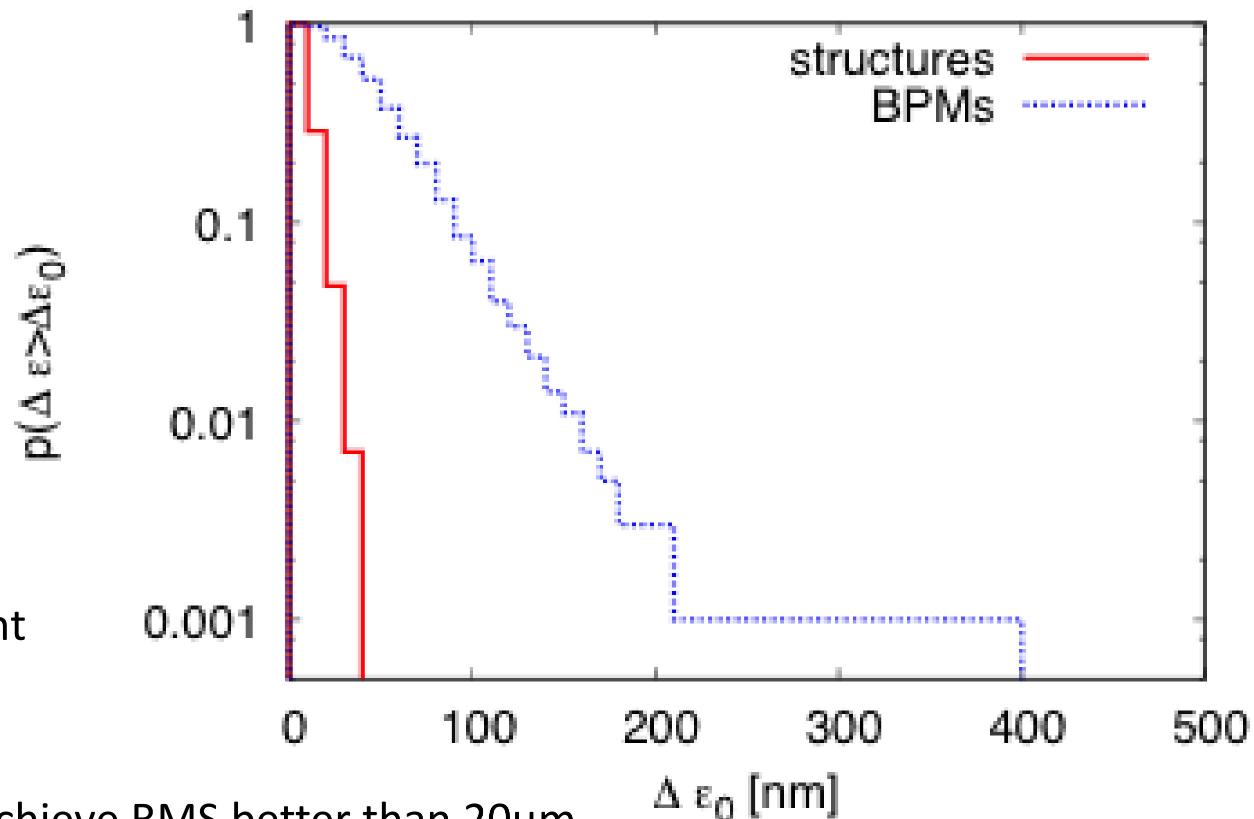
Transverse Emittance Growth (Example)

1000 runs for one example case

RMS misalignments of 100μm assumed

-> <Δε>=8nm for structures
Not more than 40nm in sample
-> > <Δε>=48nm for BPMs
Up to 400nm in sample

-> better alignment or more advanced beam-based alignment for BPMs needed



CLIC alignment team should achieve RMS better than 20μm

-> 16nm in the worst seed of BPM misalignment

Could also use advanced steering, e.g. the dispersion free steering that we tested at SLAC

-> Limitation only from beam stability

Some Examples for Basic Parameters

	unit	CLIC_502		Swiss
Structures per RF unit		12	16	4
Klystrons per RF unit		2	2	1
Structure length	m	0.23	0.23	1.98
a/lambda		0.145	0.145	
Allowed gradient	MV/m	100		
Operating gradient	MV/m	77	67.5	27.5
Energy gain per RF unit	MV	213	248	203
RF units needed		27	23	26
Total klystrons		54	46	26
Linac active length	m	74	85	206
Cost estimate	a.u.	76.2	71.5	

Preliminary estimates based on CLIC cost indicate:
cost of one RF unit C_{RF} (no accelerating structures) is approximately the same as 4m (estimate 1) to 8m (estimate 2) of active length, used 6.67m

- Needs to be reviewed
- Assume cost of RF unit is 2 cost units (cu)

Thanks to Ph. Lebrun and I. Syratchev

Cost Optimisation Example

Use CLIC structure database (K. Sjobak, A. Grudiev)
-> To be updated

Single bunch, no energy tunability

Stay below 83% of maximum gradient

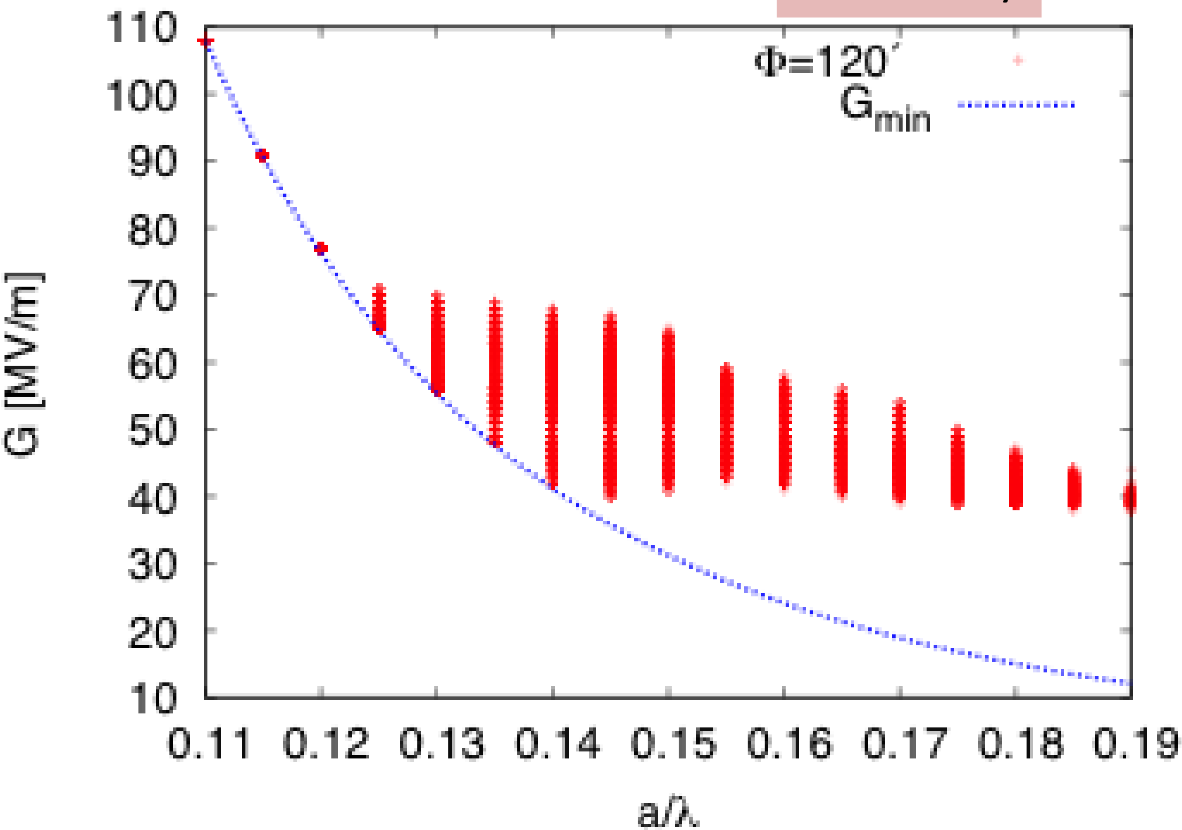
SLED II from Igor

Simple cost model

Transverse beam limitation used A=0.4

For each set (a1,a2,d1,d2) find optimum structure length and gradient

Preliminary

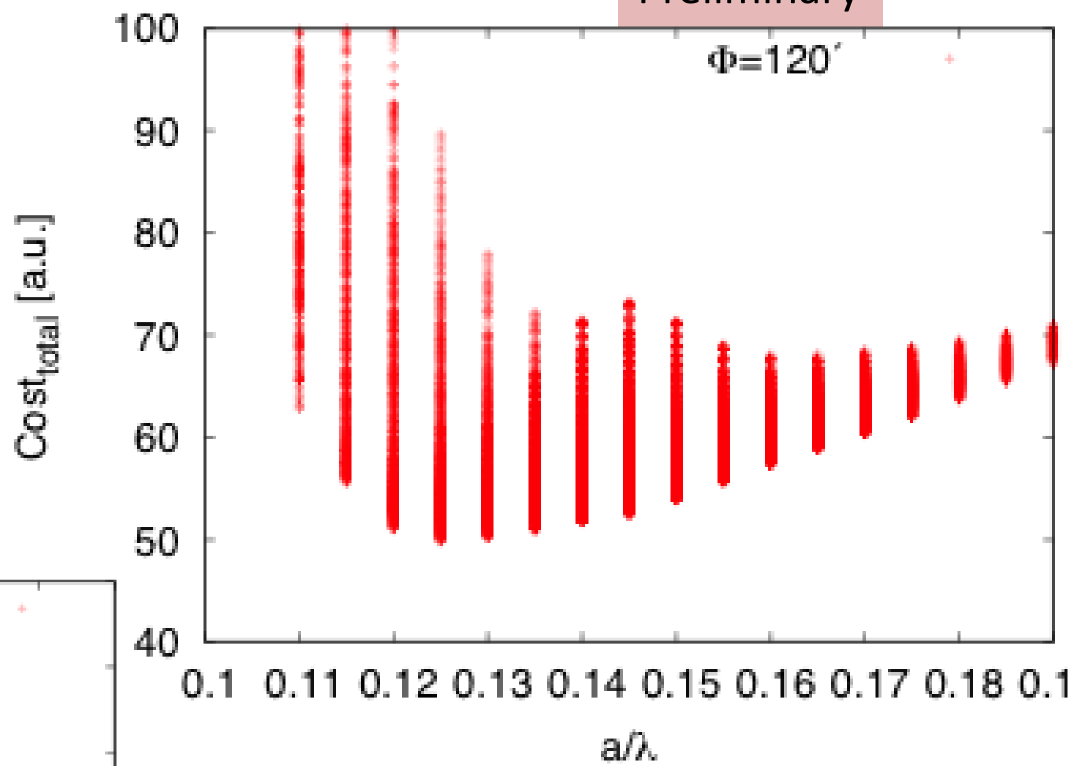


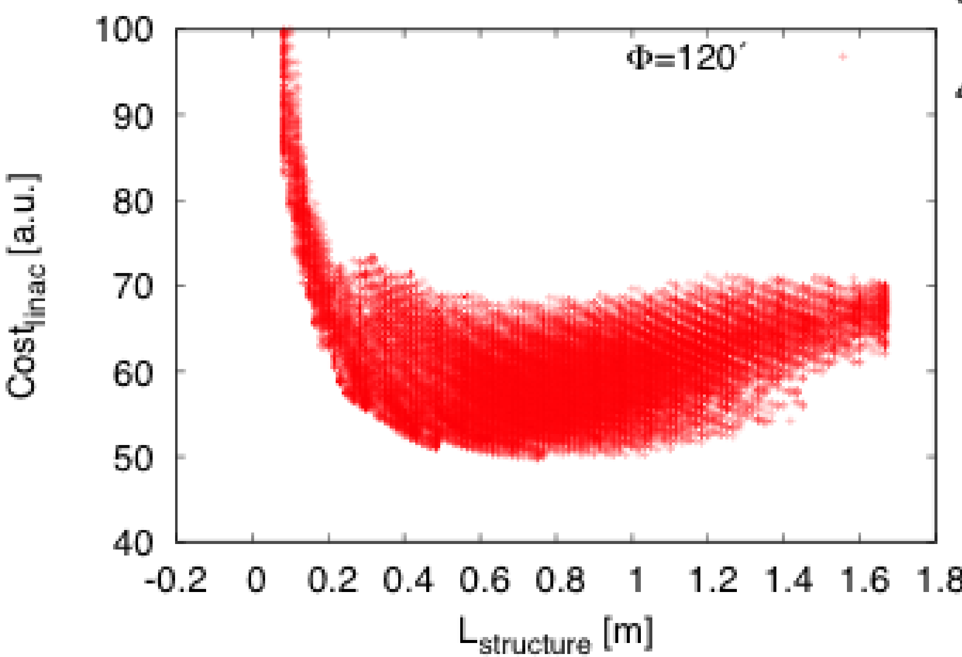
Note: only ϕ=120° shown
Similar calculation done for ϕ=150°
But slightly more costly

Cost Minimum

a_1/λ=0.15, a_2/λ=0.1
d_1/λ=0.9mm, d_2/λ=1.7mm
L=0.75m, G=65MV/m
P_{in}=41.8MW, τ=149.6ns
11 RF units
11 structure per unit?
Cost=49.7 a.u.

Preliminary



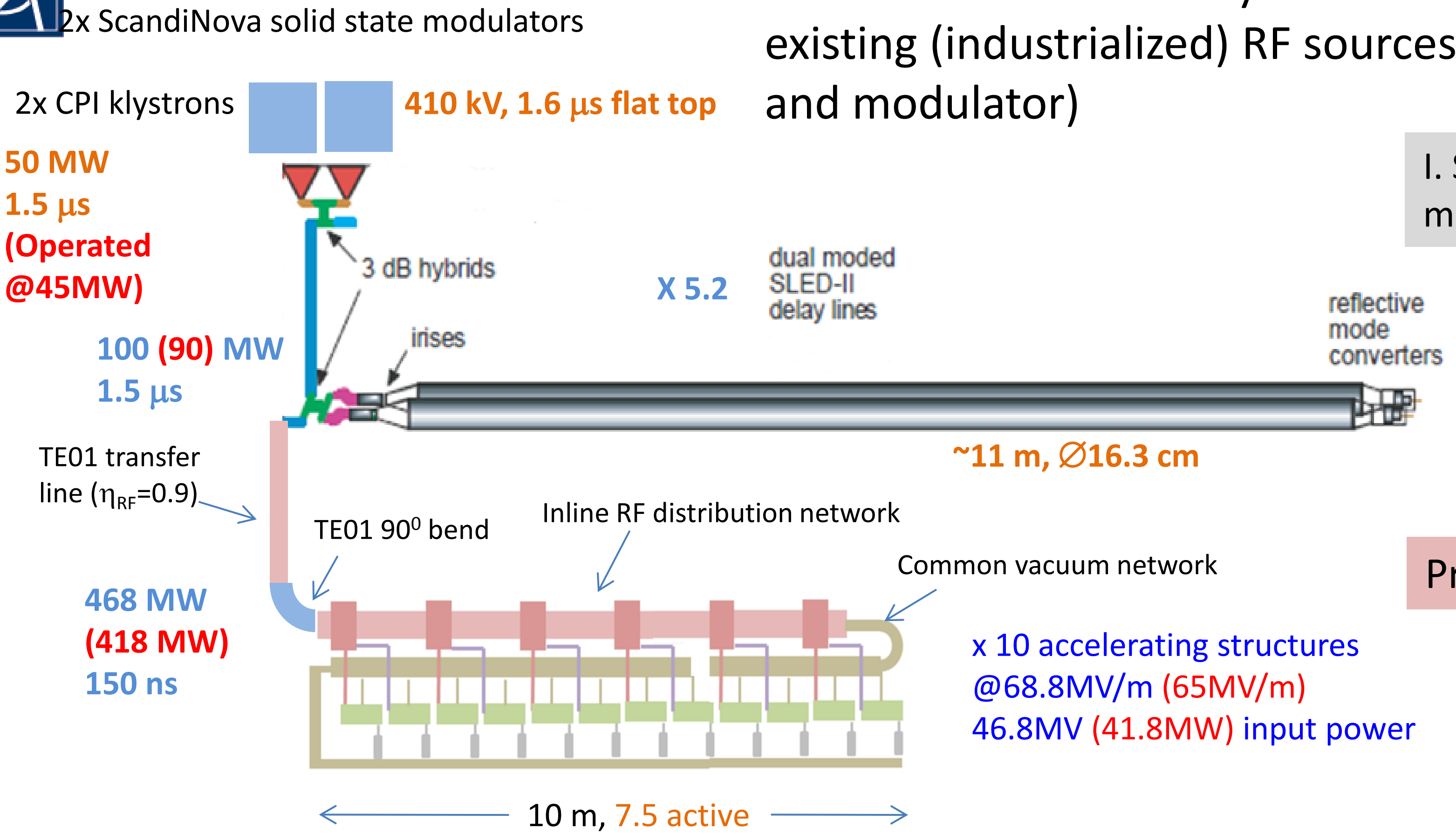


Many solutions at almost the same cost
Can chose most reasonable parameter set

Need to refine cost model design constraints

Electron linac RF unit layout based on the existing (industrialized) RF sources (klystron and modulator)

I. Syratchev, modified by me



Preliminary

This unit should provide ~516 (488) MeV acceleration beam loading.
Need 12 (12) RF units.
Cost 51.7 a.u., 4% more than optimum

More Examples for Basic Parameters

Preliminary

	unit	CLIC_502		Opt.	Swiss
Structures per RF unit		12	16	10	4
Klystrons per RF unit		2	2	2	1
Structure length	m	0.23	0.23	0.75	1.98
a/lambda		0.145	0.145	0.125	
Allowed gradient	MV/m	100		80+	
Operating gradient	MV/m	77	67.5	65	27.5
Energy gain per RF unit	MV	213	248	488	203
RF units needed		27	23	12	26
Total klystrons		54	46	24	26
Linac active length	m	74	85	88	206
Cost estimate	a.u.	76.2	71.5	51.7	

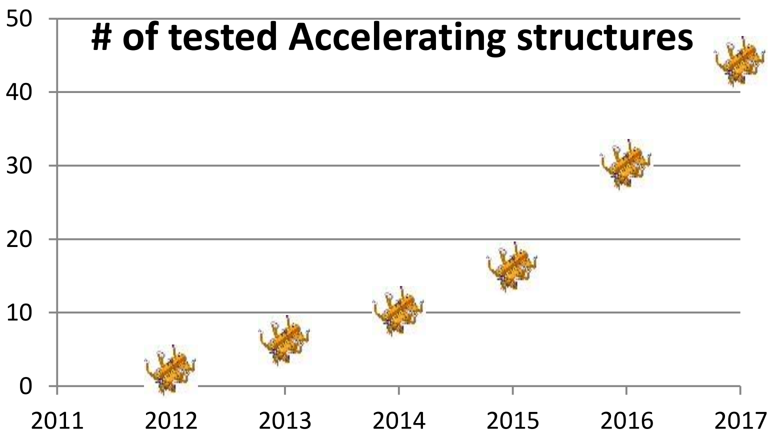
Potential Path Forward

- Prepare a CDR for each FEL project
  - To establish a project with an attractive scope and good, robust design and reasonable funding prospects
  - To propose and justify R&D phase toward a TDR and project proposal
  - Mainly theoretical work based on existing hardware experience and simulations
  - This work will profit from close collaboration between different FEL proponents and CLIC
  - One can imagine a "modular CDR", where parts are shared
- Prepare a project proposal/TDR
  - This will require hardware developments
    - E.g. an RF unit
  - There may be high potential for synergy between different FEL projects as well as CLIC in this phase
- Build plenty of great FELs
  - Also at this stage collaboration appears beneficial
- The level of mutual benefits will evolve with the designs

CLIC: Integrated Testing of X-band Structures

		2013				2014				2015				2016				2017			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
NEXTEF		TD24_R05	TD24_R05_4																		
ASTA		TD24_R05_1																			
TBTS	Slot 1	TD24_WFM_1				CFT3 technical stop	Module			CFT3 technical stop	Module			CFT3 technical stop				CFT3 technical stop			
	Slot 2	TD24_WFM_2																			
Xbox1	Dogleg	Inst.		Comm.			T24_1														
	CTF2	TD24_R05_1				TD24_R05_1		TD26_CC_1		TD24_R05_SiC_1		DDSA									
Xbox2	Slot 1	Procurement		Installation		Comm.	TD24_R05_3			Crab Cavity											
	Slot 2					New power splitter			Comm.												
Xbox3	Slot 1	Contract placement		Klystrons/modulator procurement								Inst.	Comm.								
	Slot 2																				
	Slot 3																				
	Slot 4																				

- Xbox1 first production tests lasted less than six months
- Conservative testing time (6 months) assumed for klystron based benches
- Double Xbox2 capacity thanks to a new power splitter. (see I. Syratchev)
- More than 40 accelerating structures tested by 2017



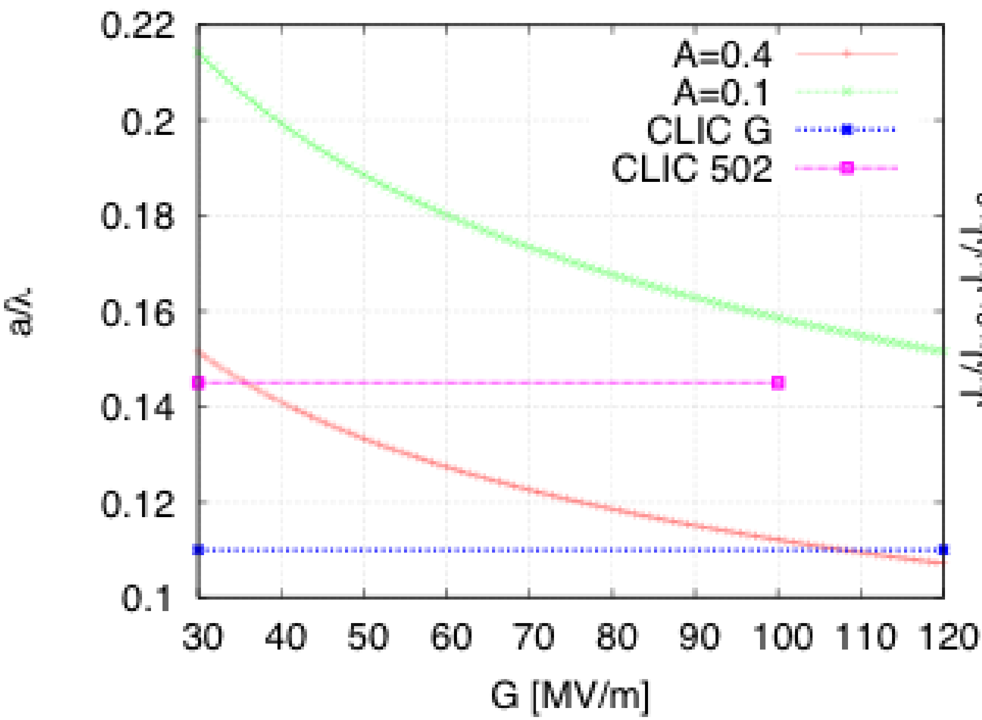
N. Catalan

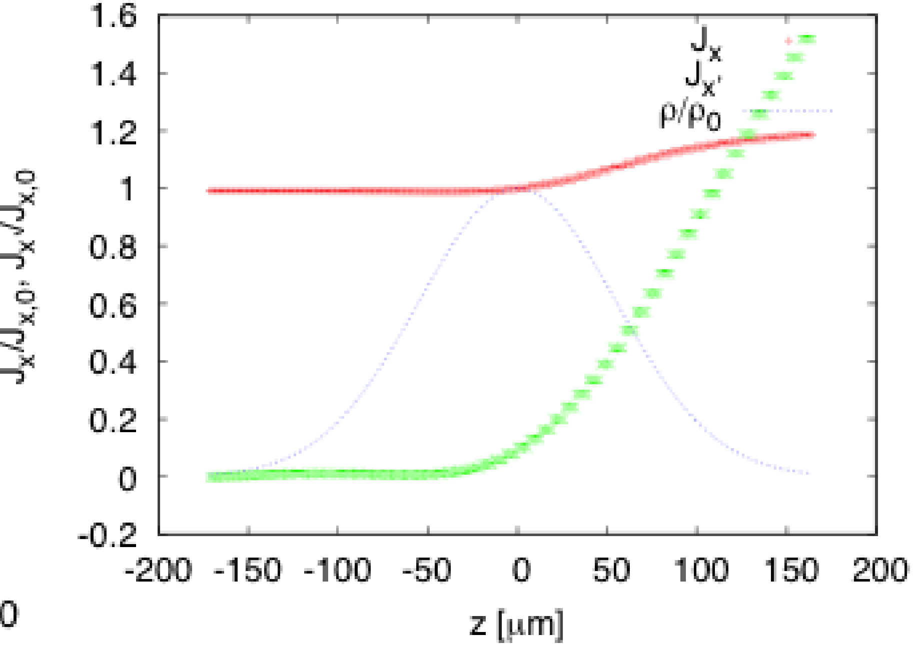
Conclusion

- X-band seems a good technology for an X-FEL
  - Simplistic example study with CLIC structure and RF design and soon available commercial klystrons already promises good performance and cost
  - Your FEL project might profit from X-band
- CLIC would profit from fostering the use of X-band technology
  - We are looking for collaborations on X-band FELs
- Let us hear your wishes and plans
- Maybe we can then join forces
  - To understand user needs
  - For the CDR writing
  - For the technical development

Reserve

Transverse Dynamics





Stability requires

$$1 >> A = \int_0^L \frac{\beta}{2E} ds \langle W_\perp \rangle N e^2$$

Note: in this case average angle is 0.2 times offset

Using simplified wakefield find 0.4

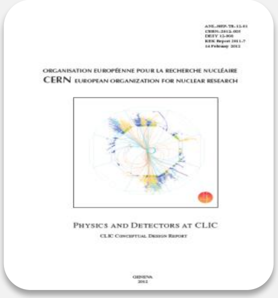
Calculate required aperture, using (strong) CLIC lattice and simplified wakefield

$$\int_0^L \frac{\beta}{2E} ds \langle W_\perp \rangle N e^2 \approx 3.25 \frac{\langle \beta \rangle}{\mathrm{m}} \frac{N}{10^9} \frac{\sigma_z}{\mu\mathrm{m}} \frac{\mathrm{mm}^4}{a^4} \frac{\mathrm{MV/m}}{G} \ln \frac{E_f}{E_0}$$

The physics and accelerator studies of CLIC have been documented in a CDR which was released last year:

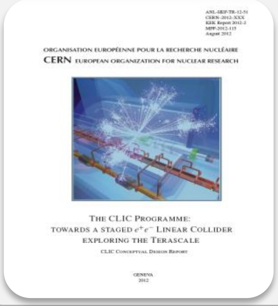
Vol 1: The CLIC accelerator and site facilities (H.Schmickler)

- 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
- Complete, presented in SPC in March 2012
  https://edms.cern.ch/document/1234244/



Vol 2: Physics and detectors at CLIC (L.Linssen)

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



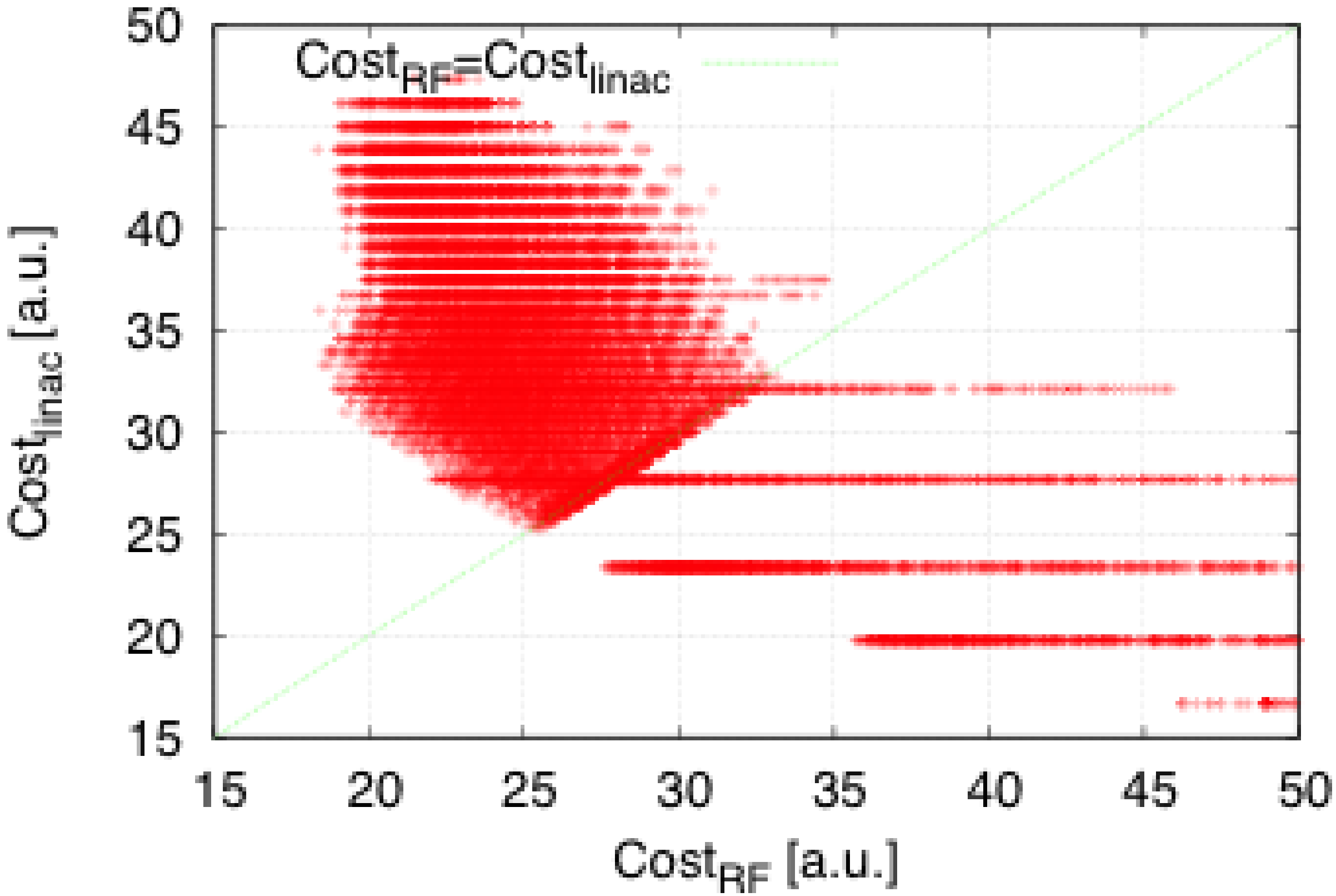
Vol 3: “CLIC study summary” (S.Stapnes)

- 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)
- Completed and printed, submitted for the European Strategy Open Meeting in September 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

Cost of Components

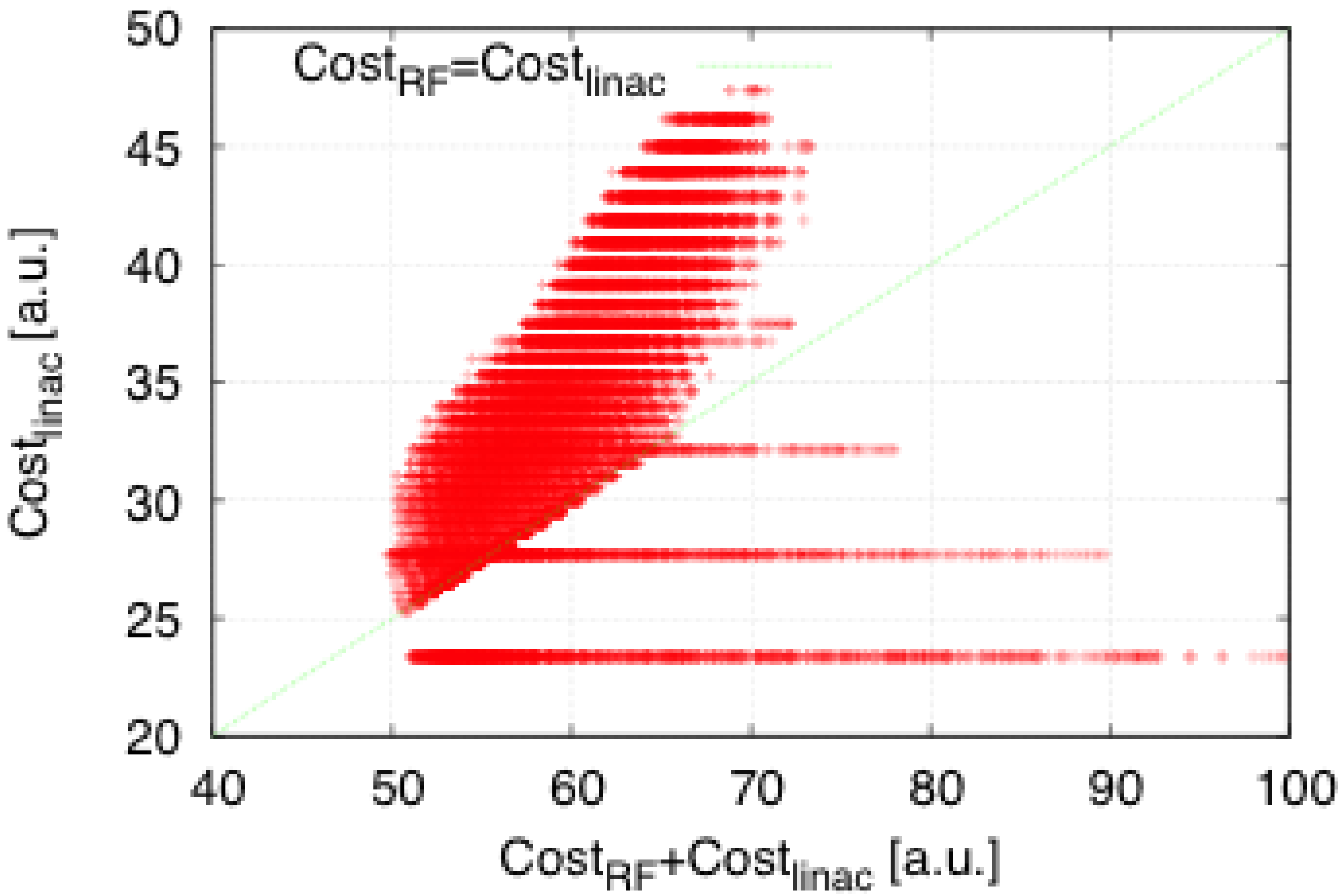
For given structure:
$Cost_{RF} \sim G$
$Cost_{linac} \sim 1/G$
-> optimum:
$Cost_{RF}=Cost_{linac}$



Higher $Cost_{RF}$:
Lower limit on G from beam dynamics

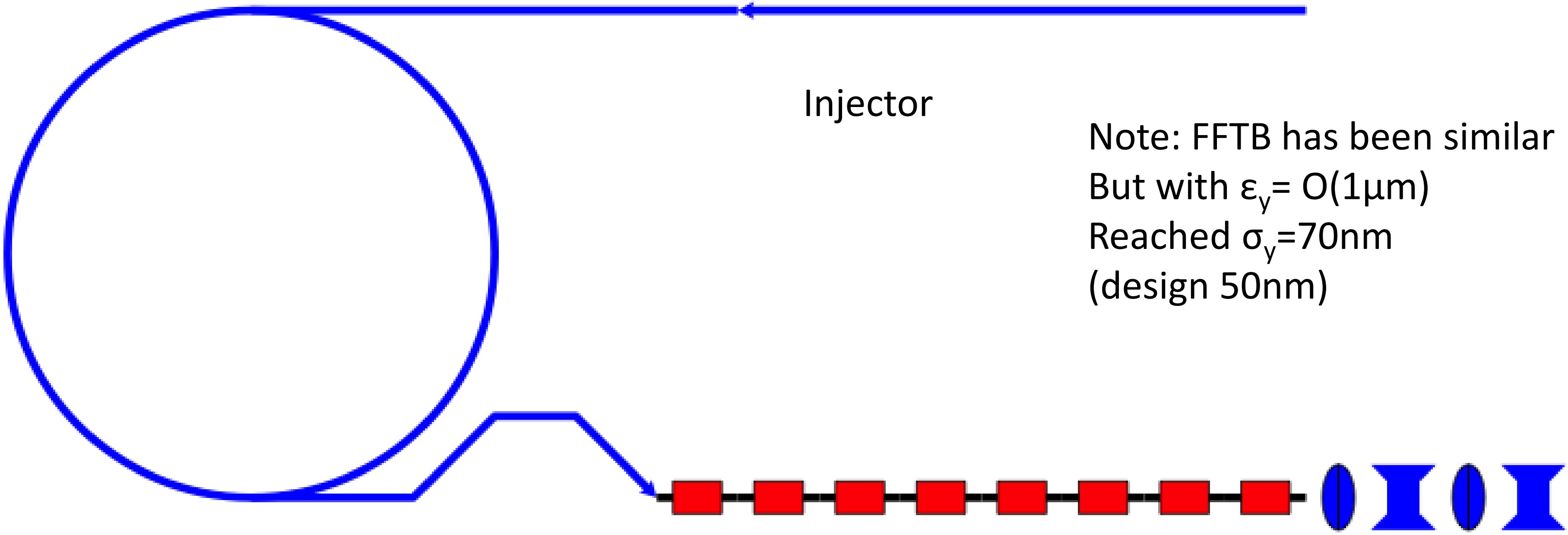
Higher $Cost_{linac}$:
Upper limit on G from RF constraints

Cost of Components II



Lowest cost machine has slightly larger linac cost compared to RF cost

Dream Test Facility Scheme



Note: FFTB has been similar
But with ε_y= O(1µm)
Reached σ_y=70nm
(design 50nm)

Low emittance ring,
e.g. CLIC damping ring,
3rd generation light source,
damping ring test facility

Main linac with bunch compressor
Powered with drive beam or X-band
klystrons

BDS test facility

Example options: SPS as damping ring (combined with CLIC0?),
FACET with improved damping ring? ATF, PEP-II, ESRF, SLS, SPRING-8, …

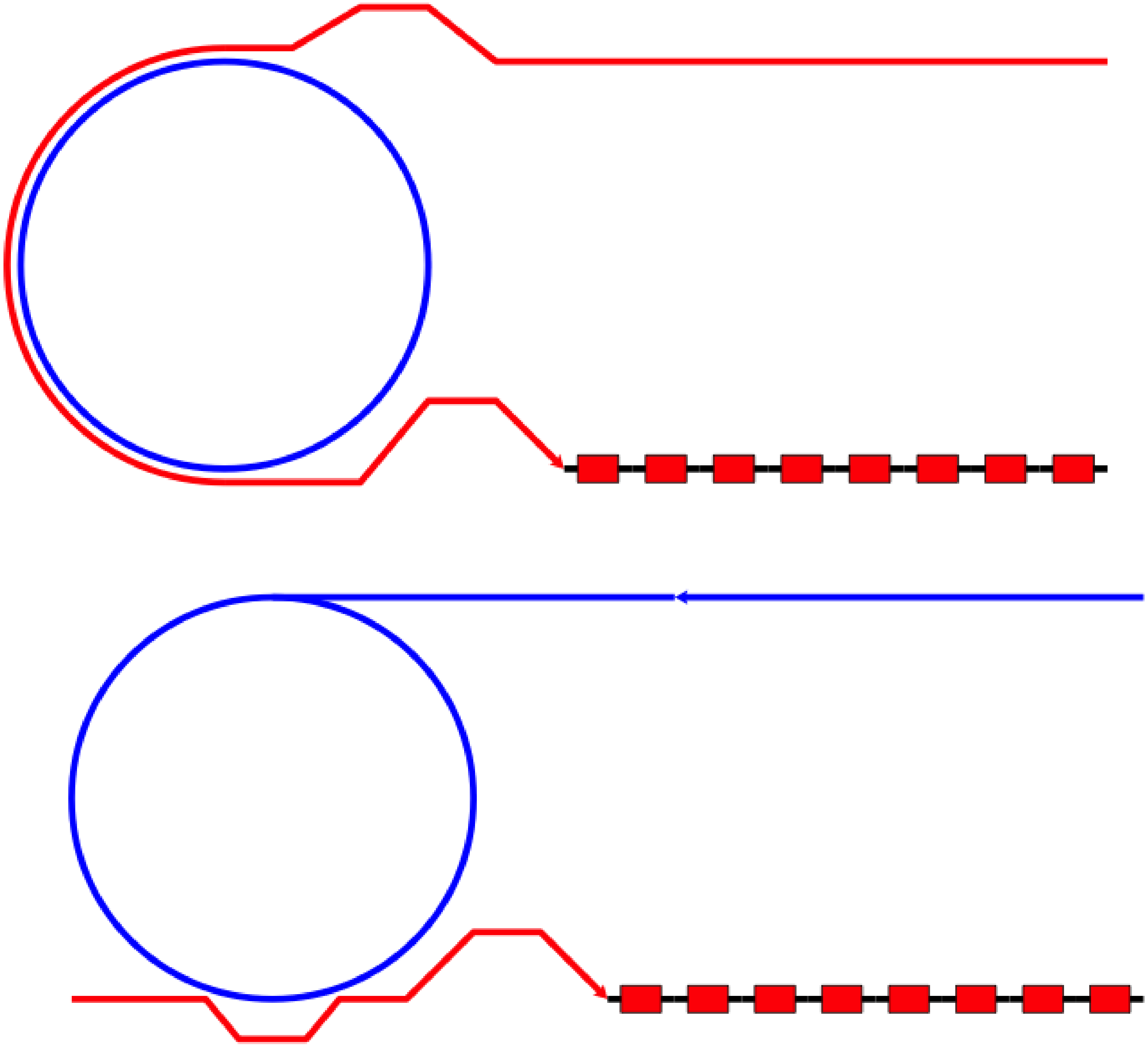
User Facility Operation

Bypassing the damping ring or with dedicated injector, one can use the linac as a 4th generation light source

Maybe some benefit in using ring and linac together as light source or for other experiments, e.g. ATF3 programme

Can we think of more?

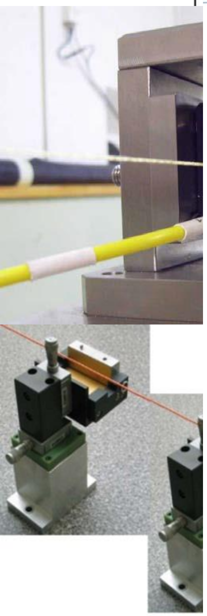
The ring can still be used almost independently, e.g. as a light source

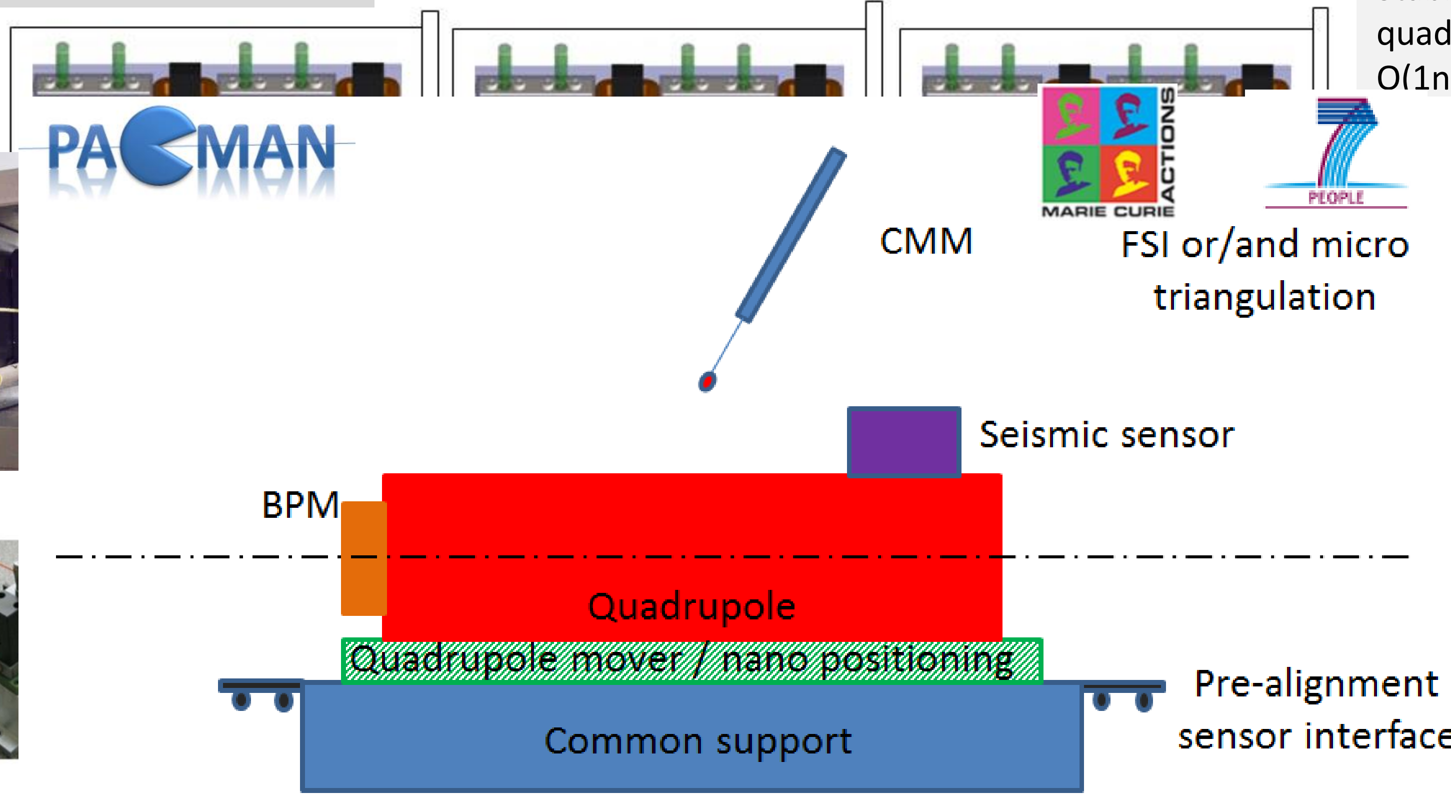


Main Linac Alignment

H. Mainaud Durand et al.

Stabilise quadrupole O(1nm) @ 1Hz

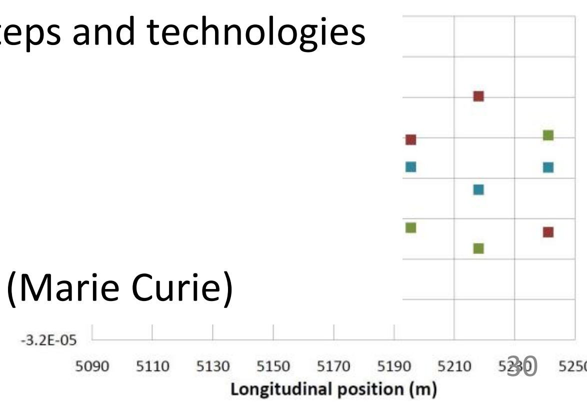




Develop an alternative solution integrating all the alignment steps and technologies at the same time and location (CMM machine)

Build a protoype

15 academic and industrial partners, EC funds 10PhD students (Marie Curie)

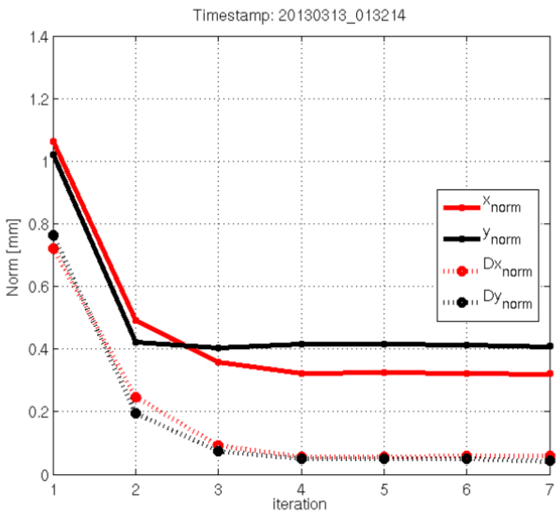


CLIC Beam-Based Alignment tests at FACET

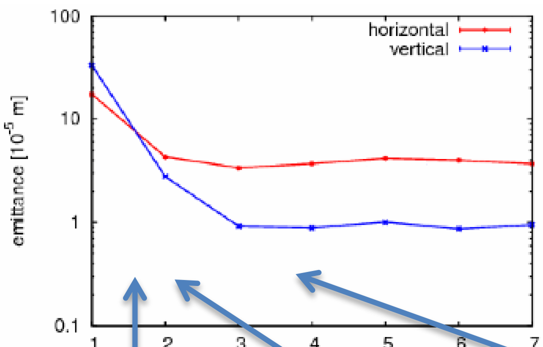
Dispersion-free Steering (DFS) proof of principle – March 2013

A. Latina,
J. Pfingstner,
E. Adli,
D. Schulte

Orbit/Dispersion



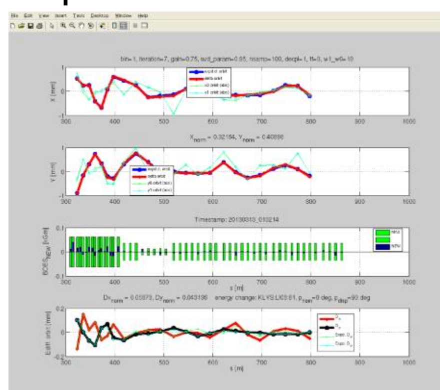
Emittance

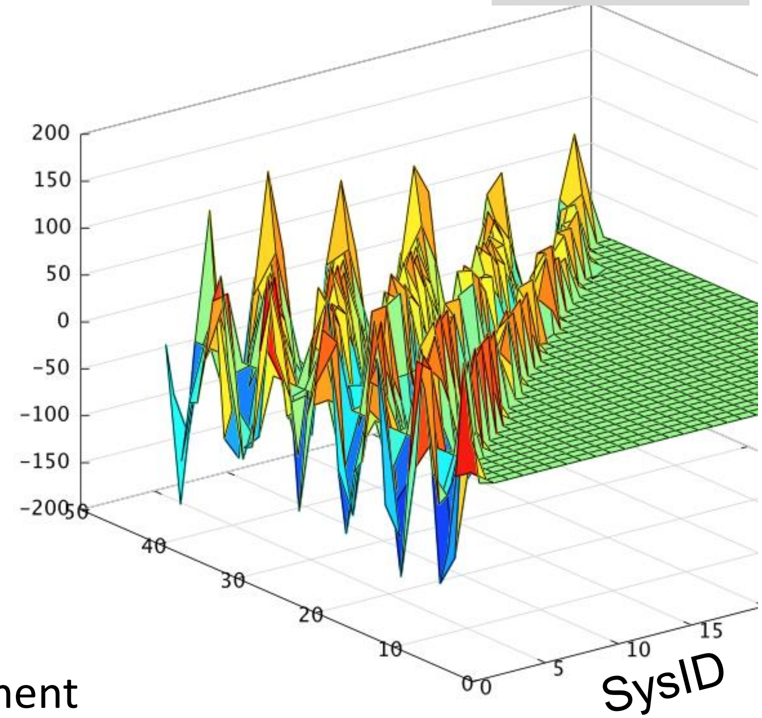


DFS correction applied to 500 meters of the SLC linac

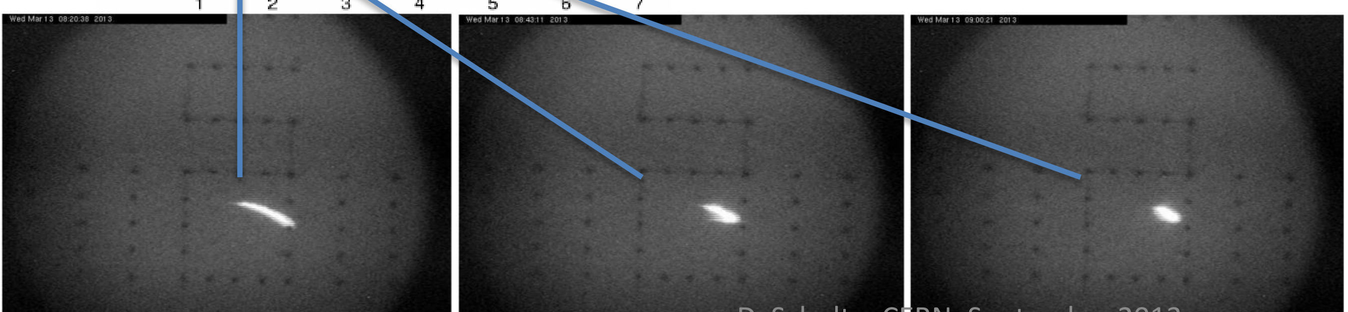
- SysID algorithms for model reconstruction
- DFS correction with GUI
- Emittance growth is measured

Graphic User Interface:





Beam profile measurement



Before correction After 1 iteration After 3 iterations

Incoming oscillation/dispersion is taken out and flattened; emittance in LI11 and emittance growth significantly reduced.

Required Beam Energy

Coherent wavelength is given by

$$\lambda = \lambda_u \frac{1}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

Typical best values are (e.g. Swiss FEL)

$$\lambda_u = 15mm \qquad K = \frac{e}{2\pi mc} B_u \lambda_u = 1.2$$

Consequently for λ=0.1nm

$$E \approx 6GeV$$

=> Gradient for CLIC test facility is about 40MV/m for 150m active length

Example of Basic Parameters (LCLS and SLAC study)

Parameter	symbol	LCLS	X-band FEL	unit
Bunch Charge	Q	250	250	pC
Electron Energy	E	14	6	GeV
Emittance	$\gamma\varepsilon_{x,y}$	0.4-0.6	0.4-0.5	µm
Peak Current	I_{pk}	3.0	3.0	kA
Energy Spread	σ_E/E	0.01	0.02	%
Undulator Period	λ_u	3	1.5	cm
Und. Parameter	K	3.5	1.9	
Mean Und. Beta	$\langle\beta\rangle$	30	8	m
FEL wavelength	λ_r	1.5	1.5	Å
Sat. Length	L_{sat}	60	30	m
Sat. Power	P_{sat}	30	10	GW
FWHM Pulse Length	ΔT	80	80	fs
Photons/Pulse	N_γ	2	0.7	10^{12}

Some Examples for Basic Parameters

	unit	CLIC_502		CLIC_L		Swiss
Structures per RF unit		12	16	12	16	4
Klystrons per RF unit		2	2	2	2	1
Structure length	m	0.23	0.23	0.48	0.48	1.98
a/lambda		0.145	0.145	0.14	0.14	
Allowed gradient	MV/m	100		80		
Operating gradient	MV/m	77	67.5	59	51	27.5
Energy gain per RF unit	MV	213	248	339	391	203
RF units needed		27	23	17	15	26
Total klystrons		54	46	34	30	26
Linac active length	m	74	85	98	115	206
Cost estimate	a.u.	76.2	71.5	63.4	64.5	

Preliminary estimates based on CLIC cost indicate:
cost of one RF unit C_{RF} (no accelerating structures) is approximately the same as 4m (estimate 1) to 8m (estimate 2) of active length, used 6.67m

- Needs to be reviewed
- Assume cost of RF unit is 2 cost units (cu)

Thanks to Ph. Lebrun and I. Syratchev

FEL Required Photon Energies

Seem to profit from below 1 a only for very short pulses

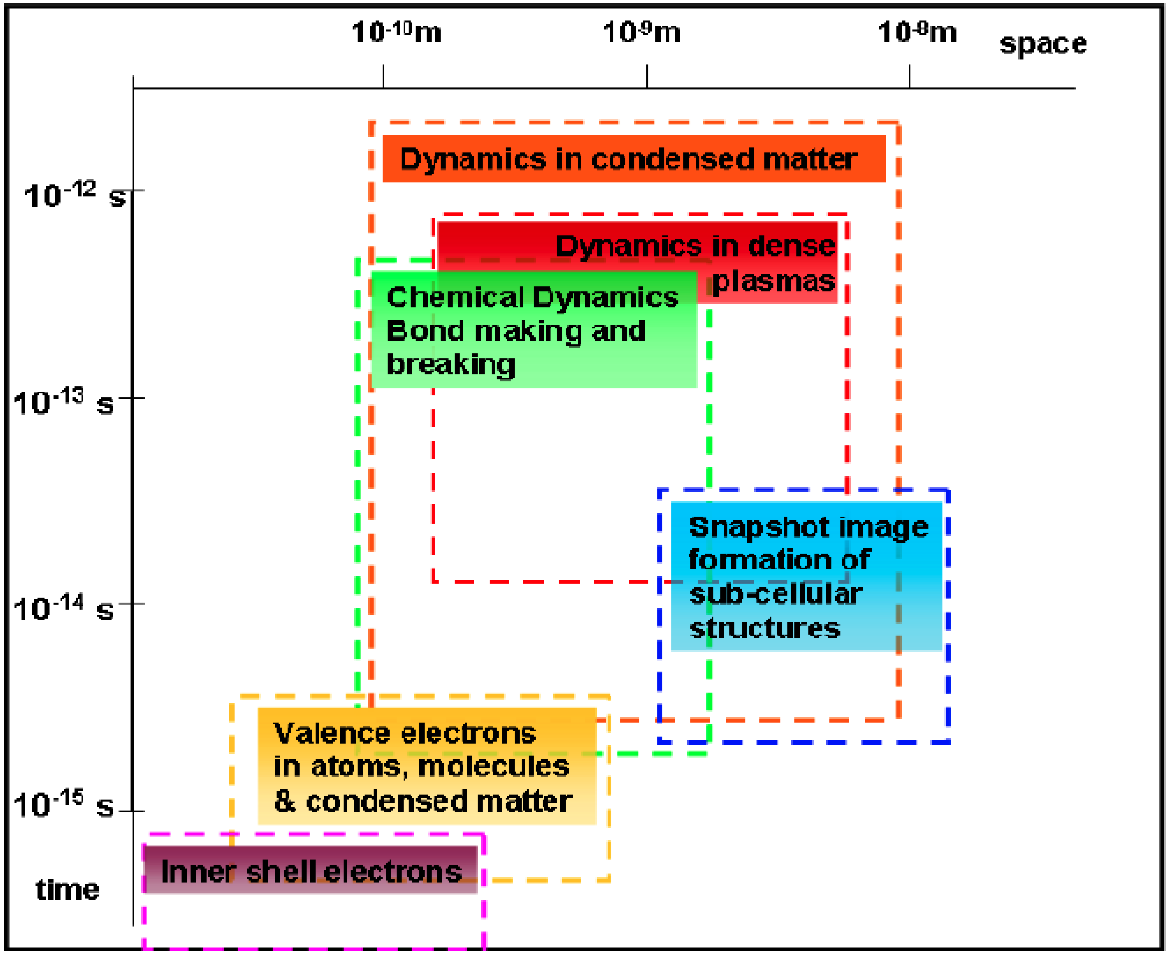
Typically 8keV (0.15nm) are needed for atoms

TESLA design report states 100keV as interesting for material science, but SUR is used profit from high energy and current

Need input from the user community
- wavelength
- brightness
- time structure
- …

Look into Angstrøm laser for now

NLS report



-> With advanced undulator requires 6GeV
But linac optimisation independent of energy

Dependence on Structure Parameters

A. Latina

Some dependence of final bunch length and energy spread on aperture and gradient

But optimisation routine does not seem to work consistently

More work to be done

Will have constraint on G(a/λ) from transverse

-> ignore longitudinal constraint for now