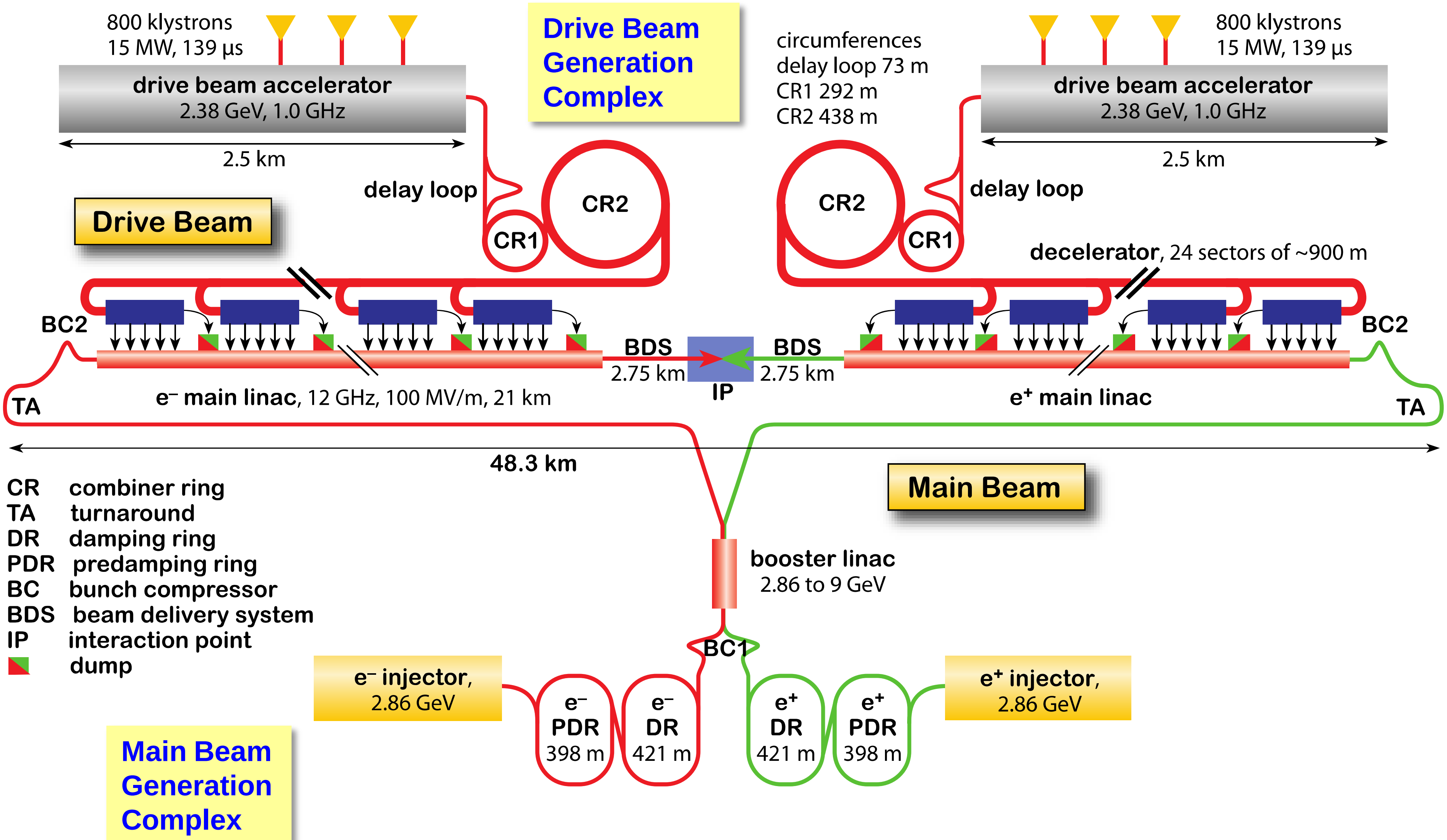
CLIC Interest in high Gradient FEL Design

D. Schulte for the CLIC collaboration

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

CLIC Layout at 3TeV



System Test Priorities

- Damping ring issues can be covered at existing light sources
- Beam delivery system is being tested at ATF2
- Main linac can only be covered to a limited extent at existing machines
  - Frequency matters for many components
  - Some components do not exist anywhere (e.g. wakemonitors, active alignment system, …)
- Hence, a larger scale main linac facility is of critical importance
- Ideal would be a combined low emittance ring, main linac and beam delivery system test facility
  - But linac alone would already be very valuable

Linac Considerations

- A drive beam to power the linac will only become available a long time from now
  - CLIC0 will need a long time to construct, main linac only comes at the end
  - CTF3 is not sufficient
  - Hence we will need to use klystrons or wait
- We are currently re-baselining CLIC
  - Focus for CDR has been on 3TeV, first stage has been derived from design optimised for 3TeV
  - Will now optimise first energy stage
  - Also consider alternative first energy stage based on klystrons
- Developing a klystron-based linac test facility seems very consistent
- The facility could turn into a user facility
  - Obvious candidate is an FEL

User and Test Facility Considerations

- CERN does not do light sources
  - Need to find one/several laboratories to build one and help them as needed (including RF, instrumentation, alignment, beam dynamics, test stands, industrial contacts …)

- Can optimise facility as
  - a test facility
  - as a user facility
  - or as any level of compromise
- Choice will depend largely on funding agencies

- Reasonable strategy is to explore the extremes and then understand possible compromises

- Made a very first exploration of X-FEL needs
  - Mainly based on CLIC components
  - Further optimisation will require more resources

FEL Required Photon Energies

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

Typically 8keV (0.15nm) are needed for atoms

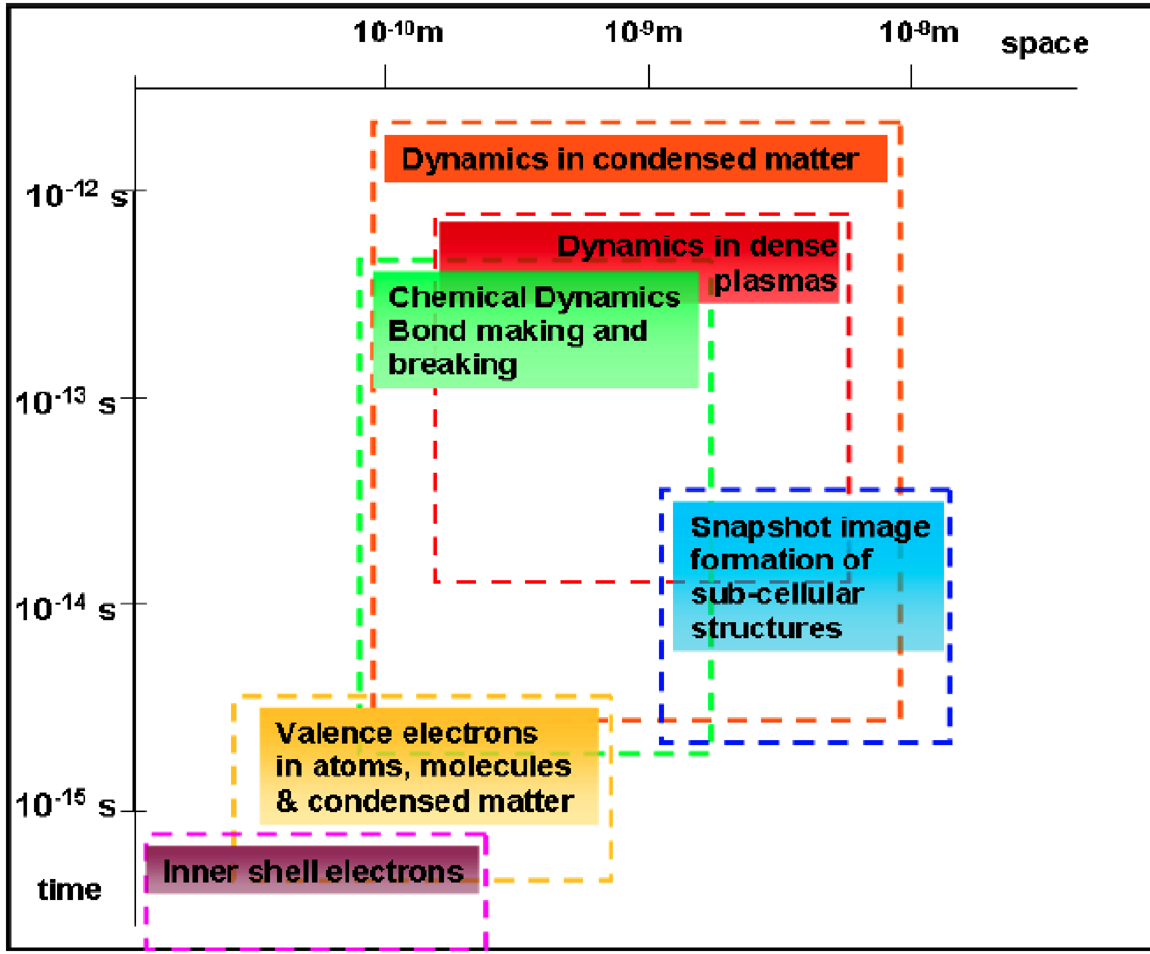
TESLA design report states 100keV as interesting for material science, but SUR is used profit from high energy and current

Need input from the user community

- wavelength
- brightness
- time structure
- …

Look into Angstrøm laser for now

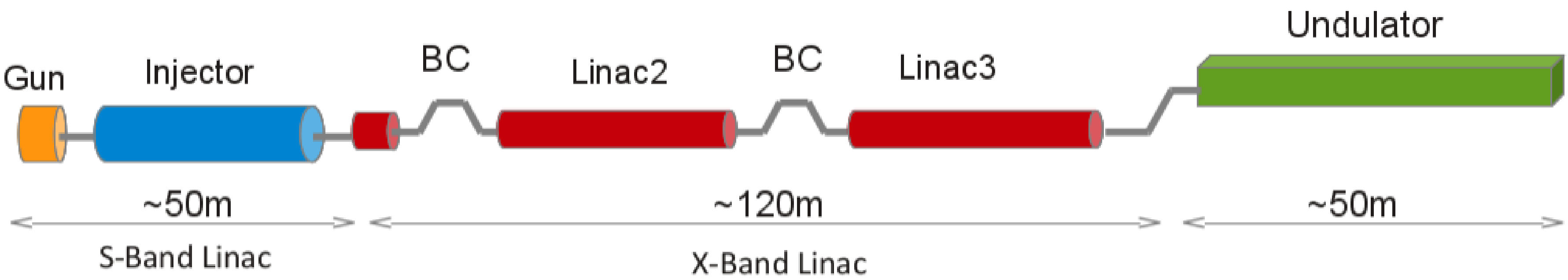
NLS report



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

FEL Overview

A. Aksoy



Other designs exist

Swiss FEL (C-band, approved):

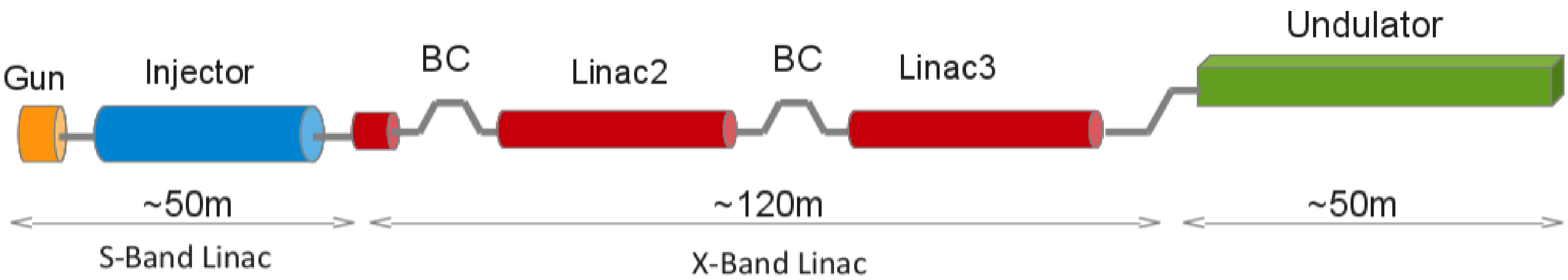
E=5.8GeV Q=200pC σ_z=7μm ε≈200nm-500nm

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

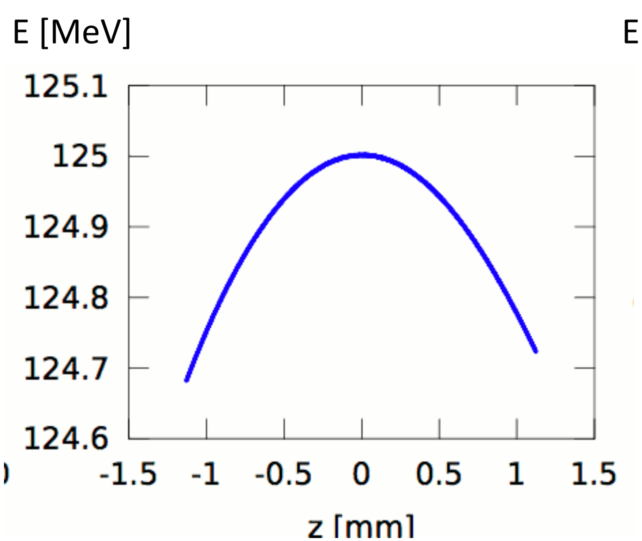
E=6GeV Q=250pC σ_z=8μm ε≈400nm-500nm

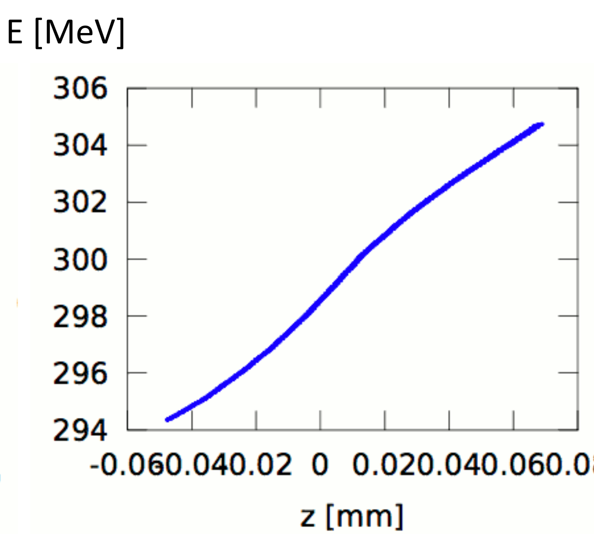
We did chose Q=250pC, E=6GeV and will go for similar bunch lengths
Do not study injector (use the one from PSI for now) or undulator

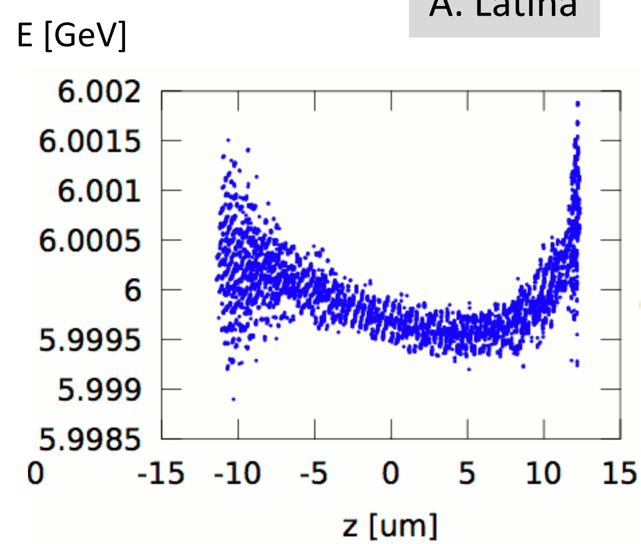
Longitudinal Dynamics



A. Latina

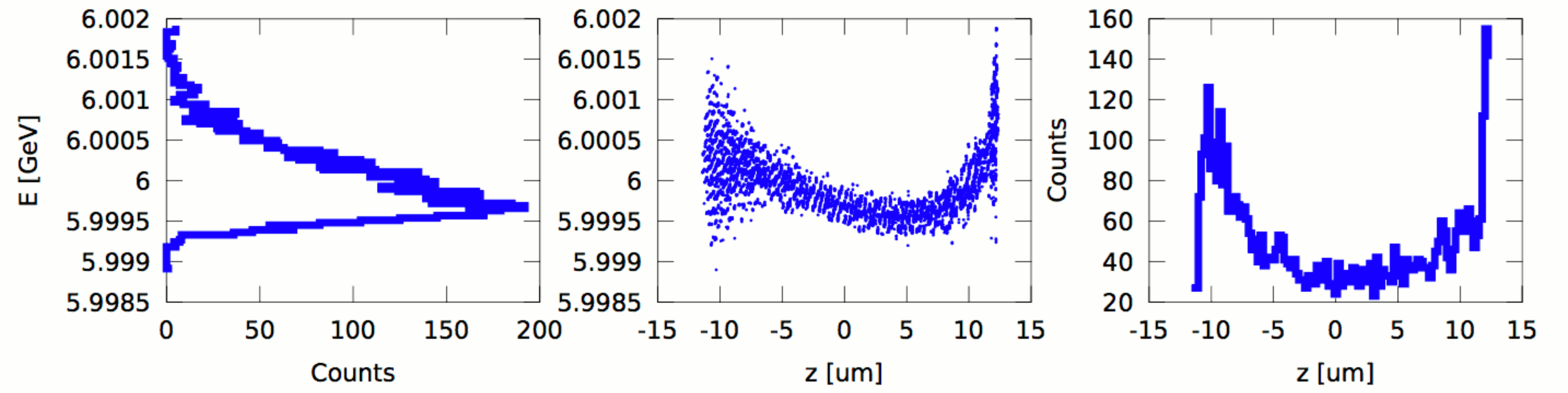






Longitudinal Dynamics (Example)

A. Latina



Structure with $a/\lambda=0.14$ and G=67.5MV/m used

σ_z = 7.96 µm, σ_E = 0.0071%, $\sigma_{E,slice}$ = 0.0027%

(for comparison Swiss FEL target at undulator $\sigma_{E,slice}$ = 0.006%)

Will need some realistic figure of merit for final beam distribution

Need to repeat for different structures and gradients

-> first indication is that similar values can be reached with all reasonable structures

Dependence on Structure Parameters

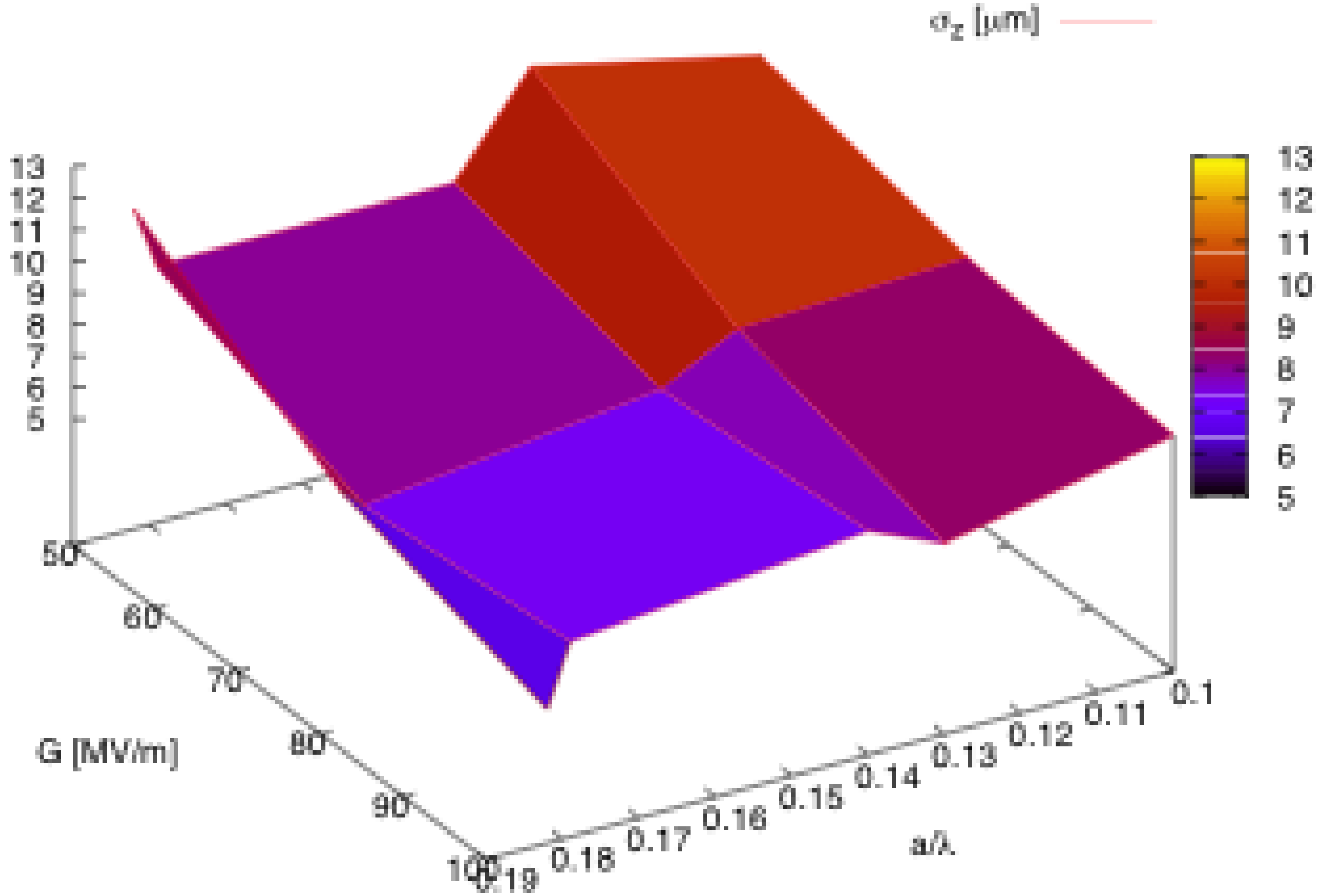
A. Latina

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

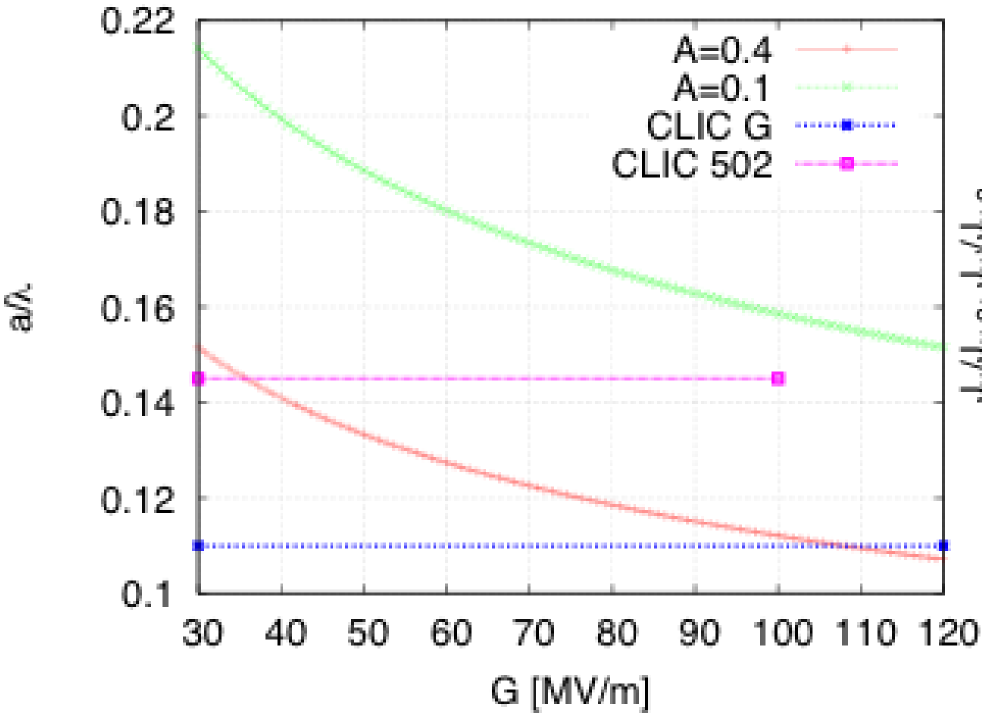
But optimisation routine does not seem to work consistently

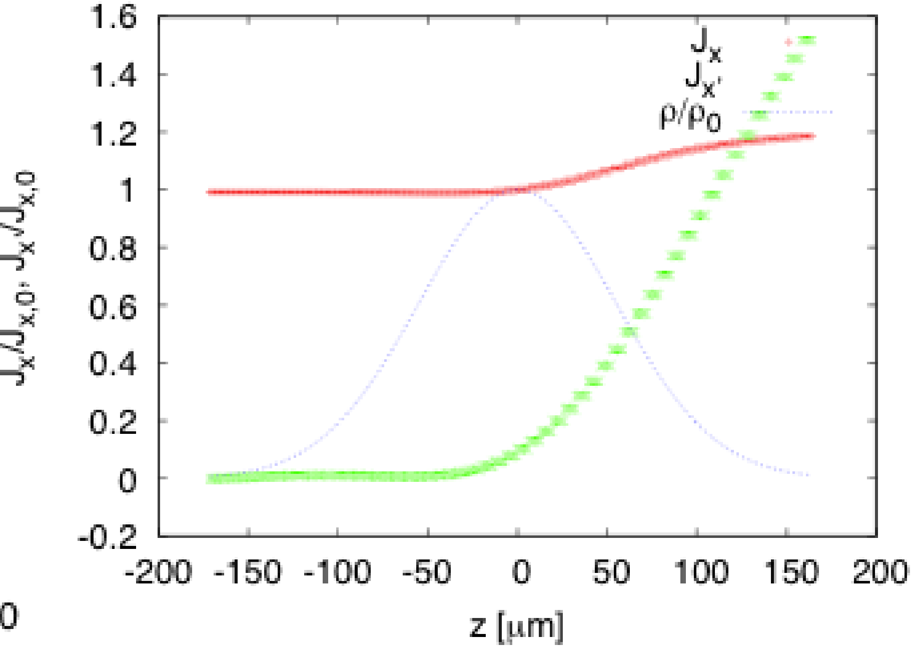
More work to be done

Will have constraint on G(a/λ) from transverse -> ignore longitudinal constraint for now



Transverse Dynamics





Stability requires

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

Note: in this case average angle is 0.2 times offset

Using simplified wakefield find 0.4

Calculate required a, using CLIC lattice and linearly rising wakefield

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

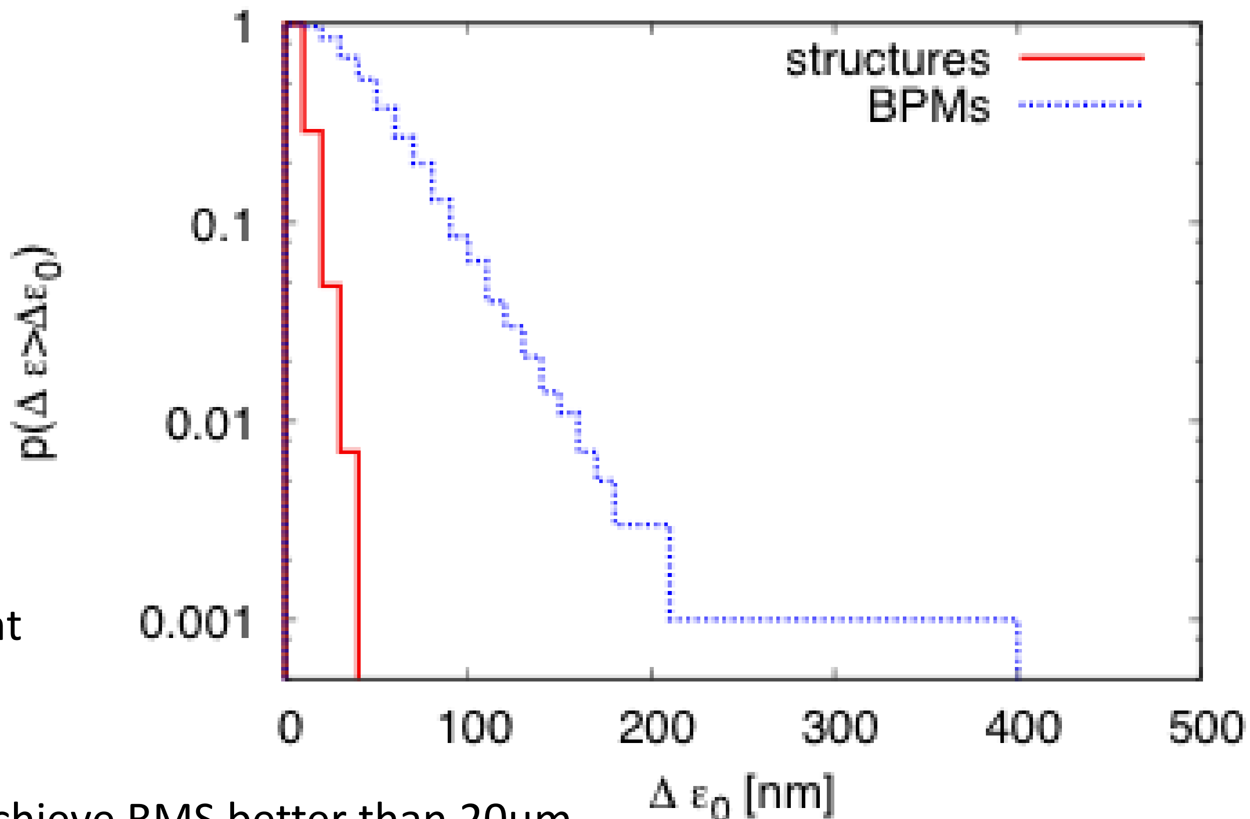
Transverse Emittance Growth

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

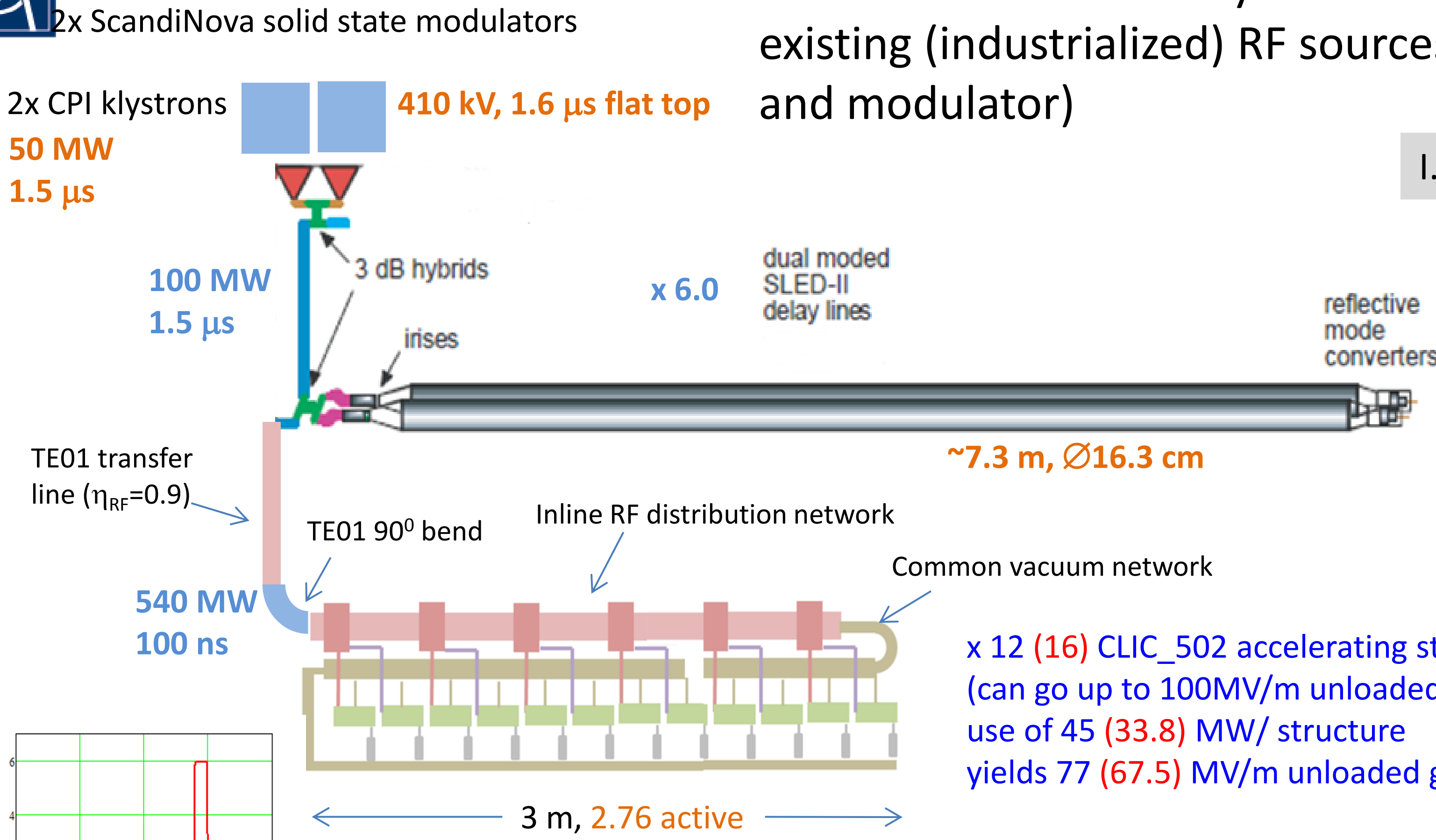
-> 16nm in the worst seed of BPM misalignment

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

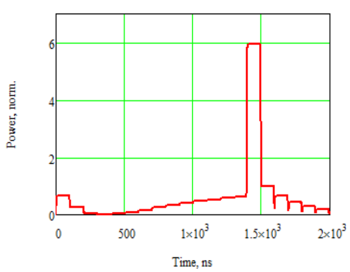
-> Limitation only from beam stability

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

I. Syratchev



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%)

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)
-> To be updated

Single bunch, no energy tunability

Stay below 83% of maximum gradient

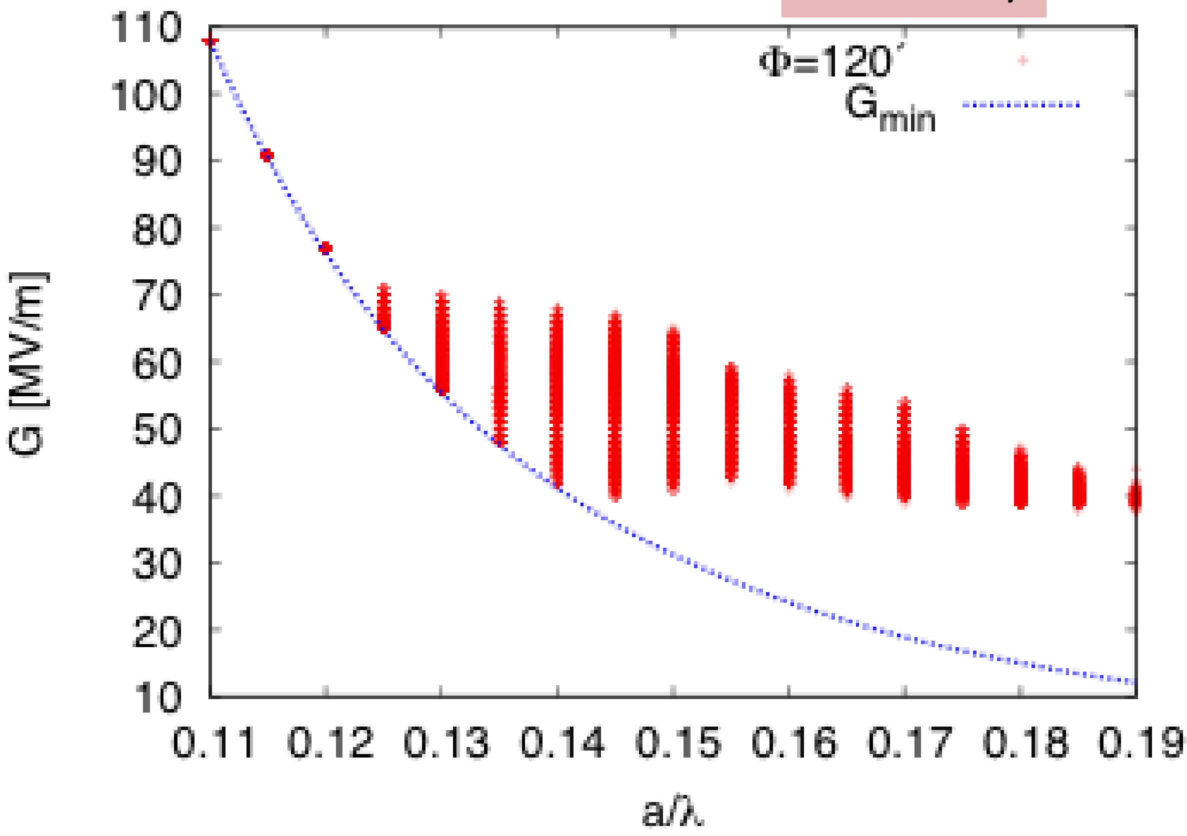
SLED II from Igor

Simple cost model

Transverse beam limitation used A=0.4

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

Preliminary

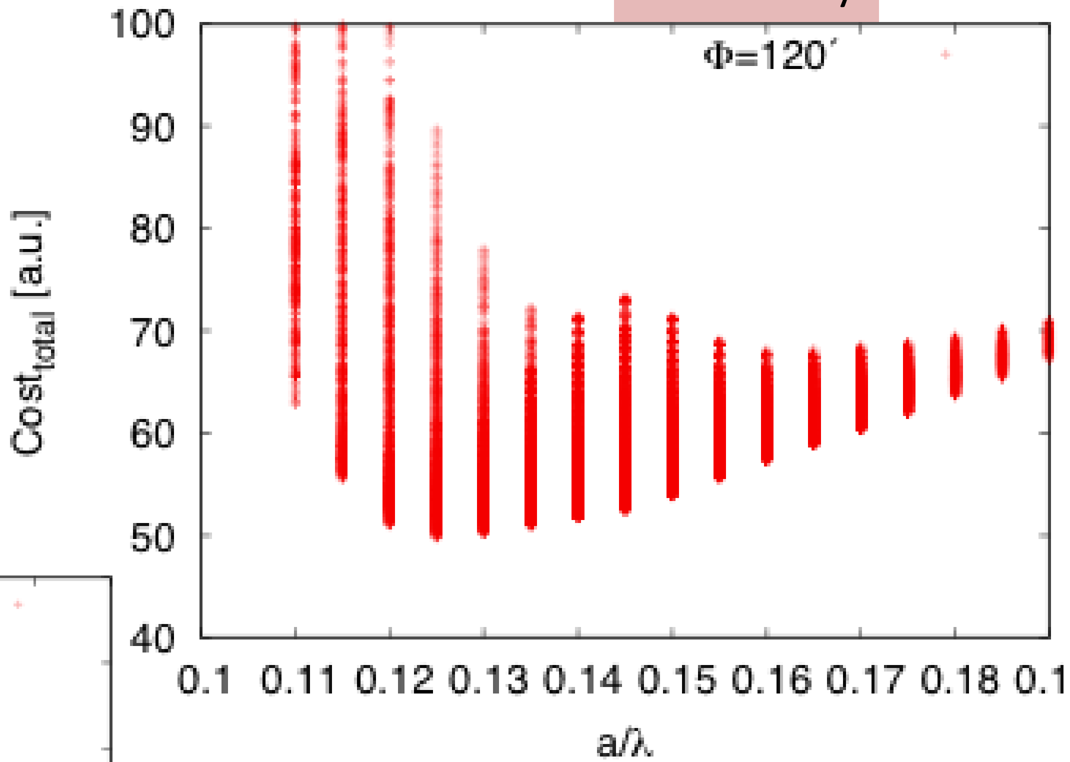


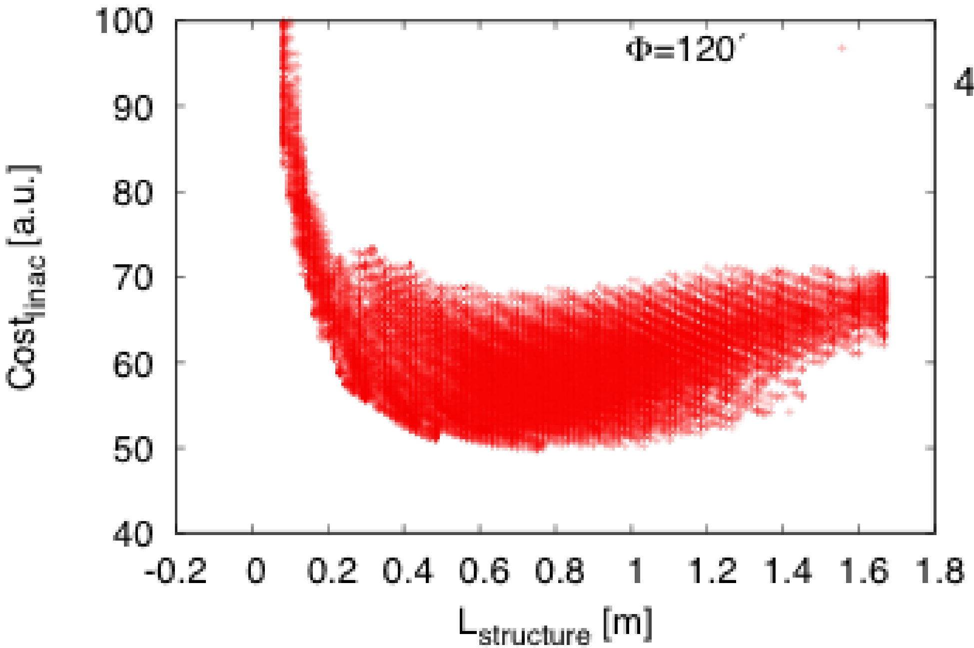
Note: only ϕ=120° shown
Similar calculation done for ϕ=150°
But slightly more costly

Cost Minimum

Preliminary

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.





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

2x ScandiNova solid state modulators

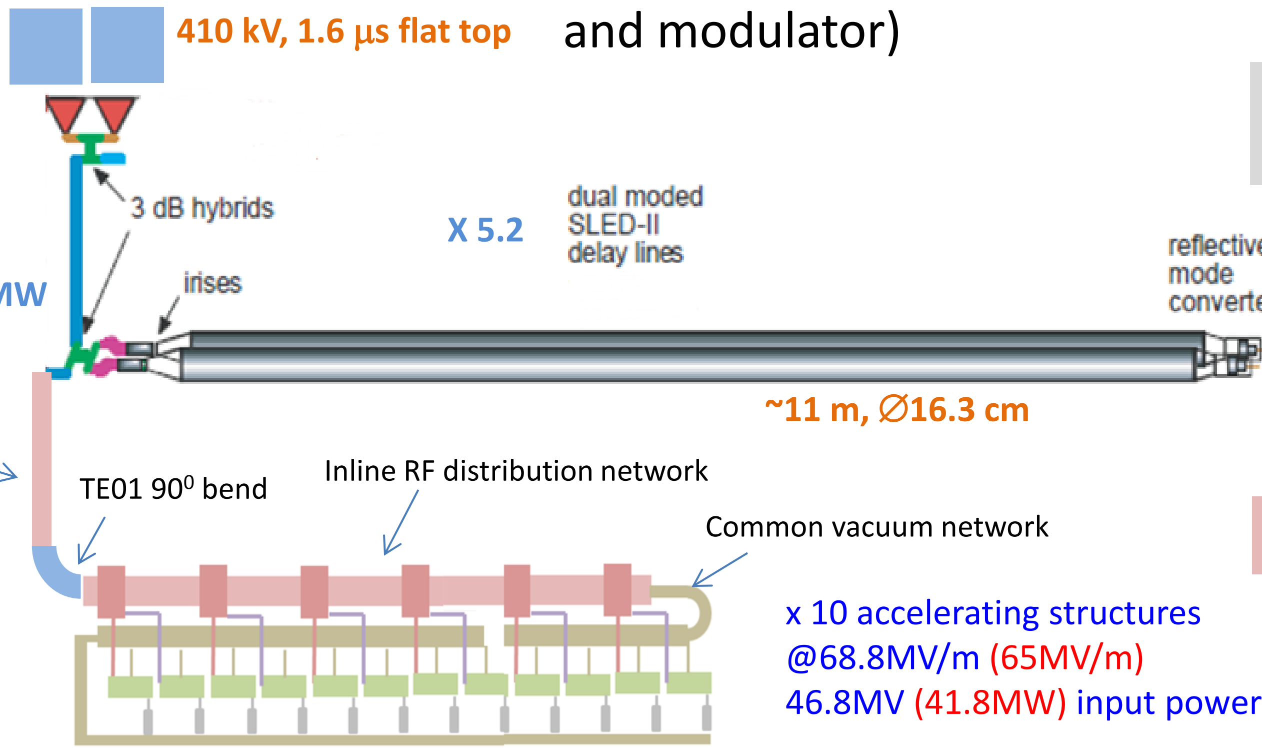
2x CPI klystrons

410 kV, 1.6 μs flat top

50 MW
1.5 μs
(Operated @45MW)

100 (90) MW
1.5 μs

X 5.2



~11 m, ∅16.3 cm

TE01 transfer line (η_{RF}=0.9)

TE01 90[0] bend

Inline RF distribution network

Common vacuum network

Preliminary

468 MW
(418 MW)
150 ns

x 10 accelerating structures
@68.8MV/m (65MV/m)
46.8MV (41.8MW) input power

10 m, 7.5 active

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	

Paths for Improvements

- A number of design improvements can be considered
  - Improved klystrons for CLIC could reduce required klystron number
  - Small klystrons could operate at O(1kHz)
    - 5-10MW per klystron
    - But might be a bit more expensive
  - Structures with no damping would be cheaper and slightly more efficient
    - Do we need more multi-bunch, which distance?
  - Cheaper pulse compressor options (see Igor)
    - No rectangular pulse is required

- Most important is user input
  - Need to understand what we optimise for

Synergy

- Accelerating structures
  - Have to understand the choice for FEL
    - Likely not at the RF limitations
    - But can test individual structures at full power
  - No multi-bunch/damping in FEL (or is there a case?)
  - High synergy for fabrication, conditioning, operation, dark current, vacuum, …
  - Could have some high performance RF unit in the FEL

- X-band RF components
  - Very high level of synergy on klystron and modulators, pulse compressors, instrumentation, …

- Other components
  - High synergy on magnets, alignment, supports, …

- Operation and beam dynamics
  - Many issues are very similar even if at a different level of difficulty
  - Operation with low emittance beam is highly synergetic
  - Validation and improvement of tuning and beam-based alignment procedures
  - Benchmarking of codes
  - …

Conclusion

- X-band seems a good technology for an X-FEL
  - CLIC structure and RF design and soon available commercial klystrons already promise good performance and cost

- Design study for FEL is required
  - Optimisation of the structure, pulse compressor and distribution system design for the FEL requires more work
    - E.g. high repetition rate klystrons should be investigated
    - …
  - The study will have synergy with CLIC re-baselining and klystron-based first stage

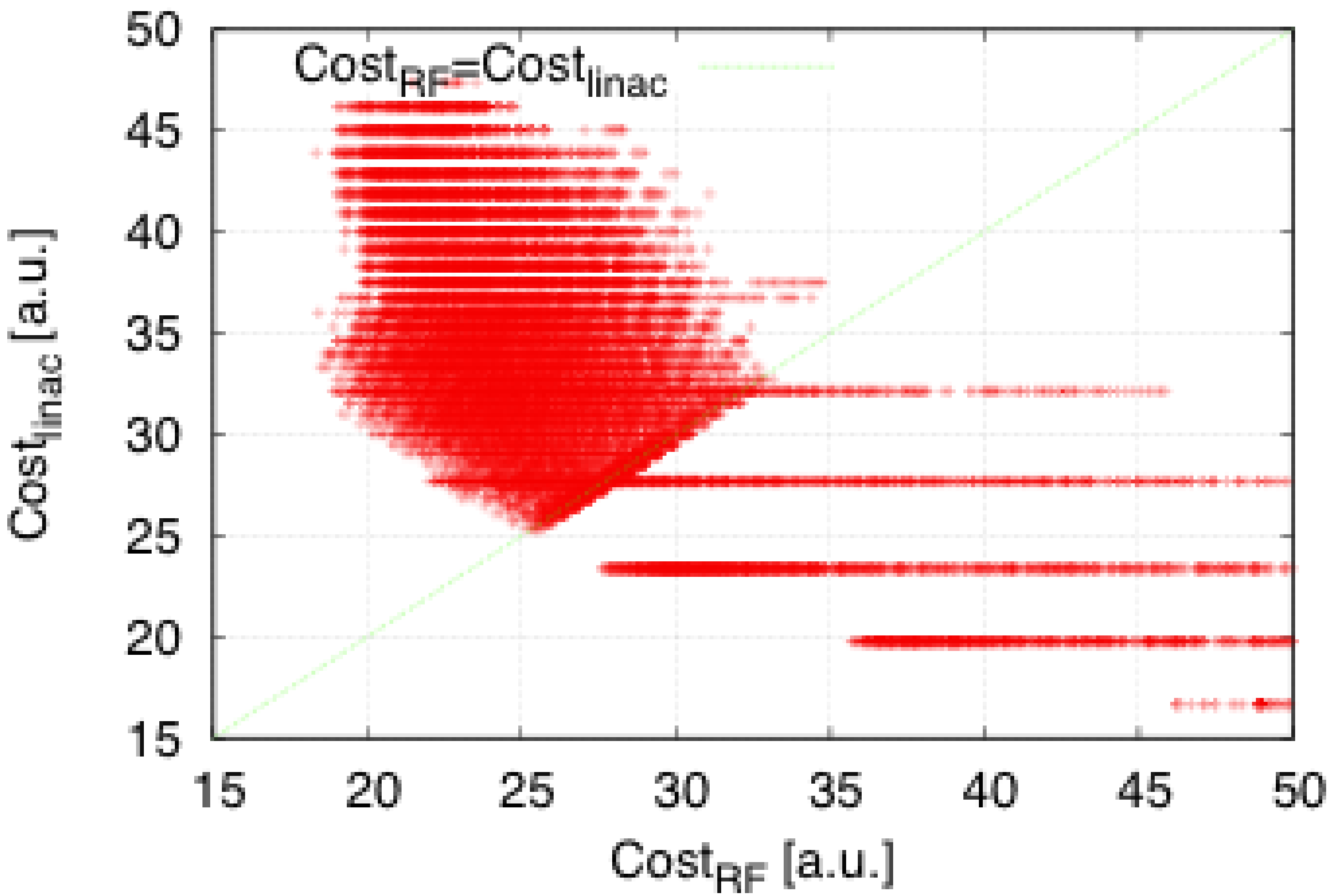
- Significant synergy with CLIC developments
  - Pulse compressor and distribution system design
  - Klystron and modulator development
  - Structure design
  - X-band operation
  - Beam dynamics
  - Need FEL design to fully asses level of synergy

- We are looking for collaborations on FELs
  - Discussions with Ankara, Australia, Shanghai

Reserve

Cost of Components

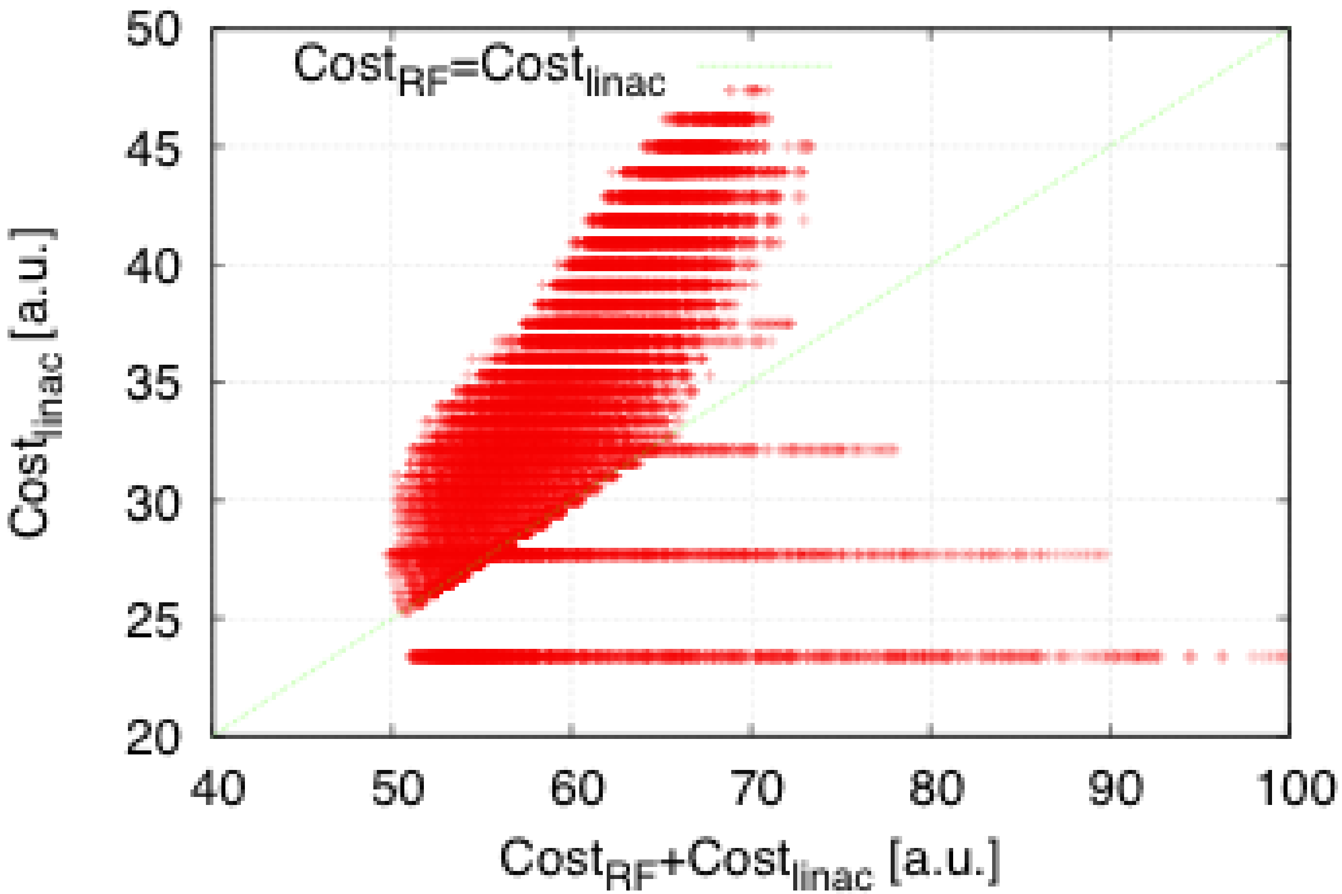
For given structure:
$Cost_{RF} \sim G$
$Cost_{linac} \sim 1/G$
-> optimum:
$Cost_{RF}=Cost_{linac}$



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

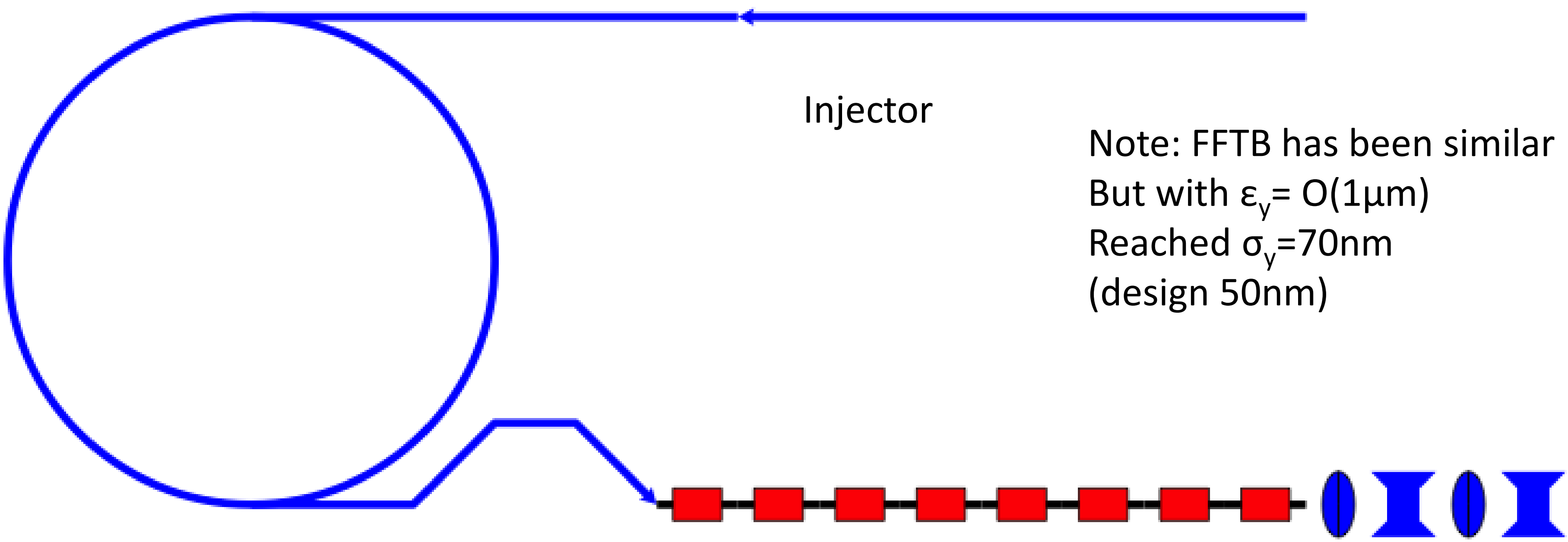
Higher $Cost_{linac}$:
Upper limit on G from RF constraints

Cost of Components II



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

Dream Test Facility Scheme



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

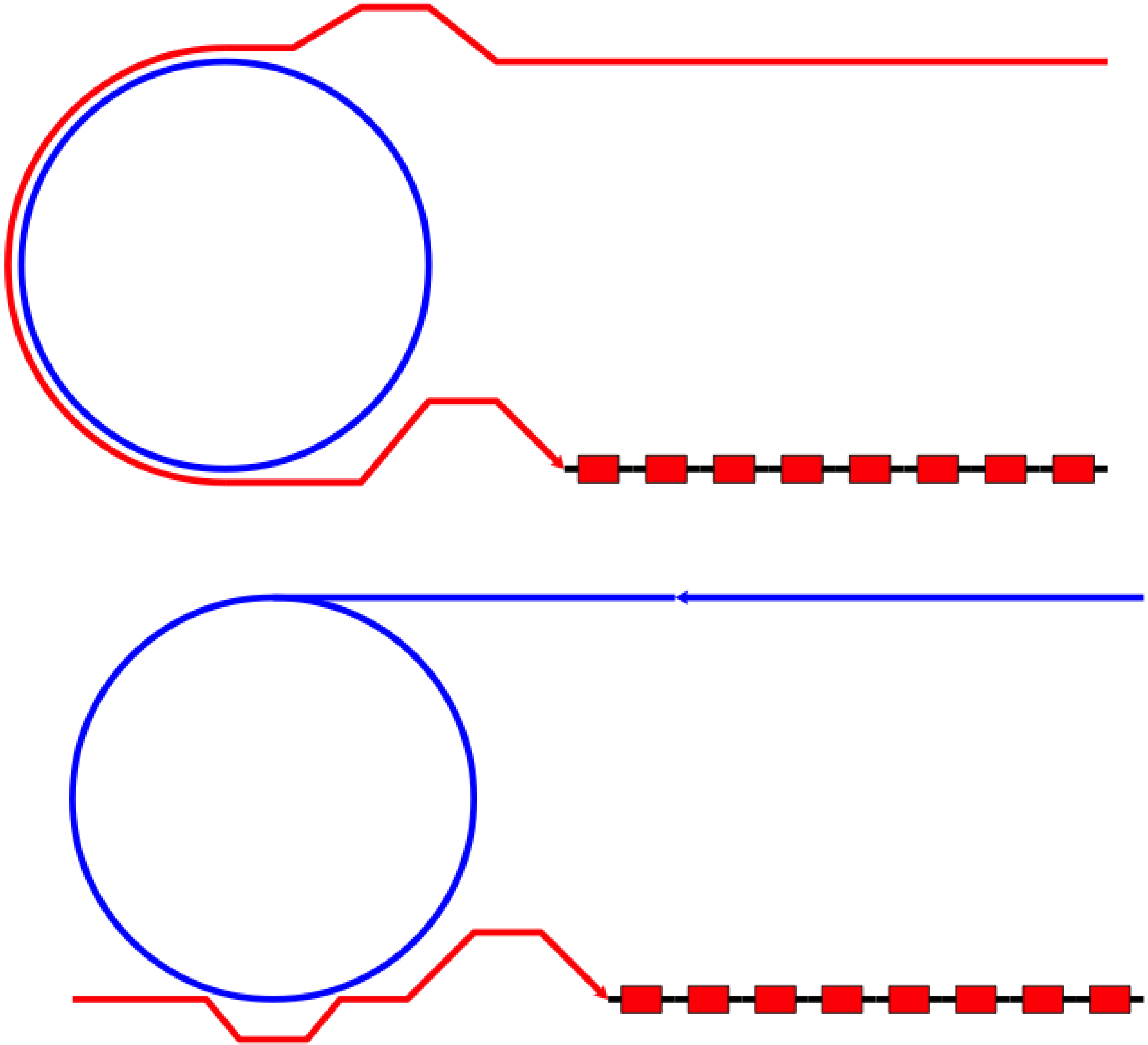
Example options: SPS as damping ring (combined with CLIC0?),
FACET with improved damping ring? ATF, PEP-II, ESRF, SLS, SPRING-8, …

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?

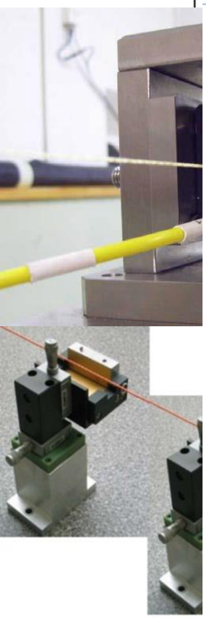
The ring can still be used almost independently, e.g. as a light source

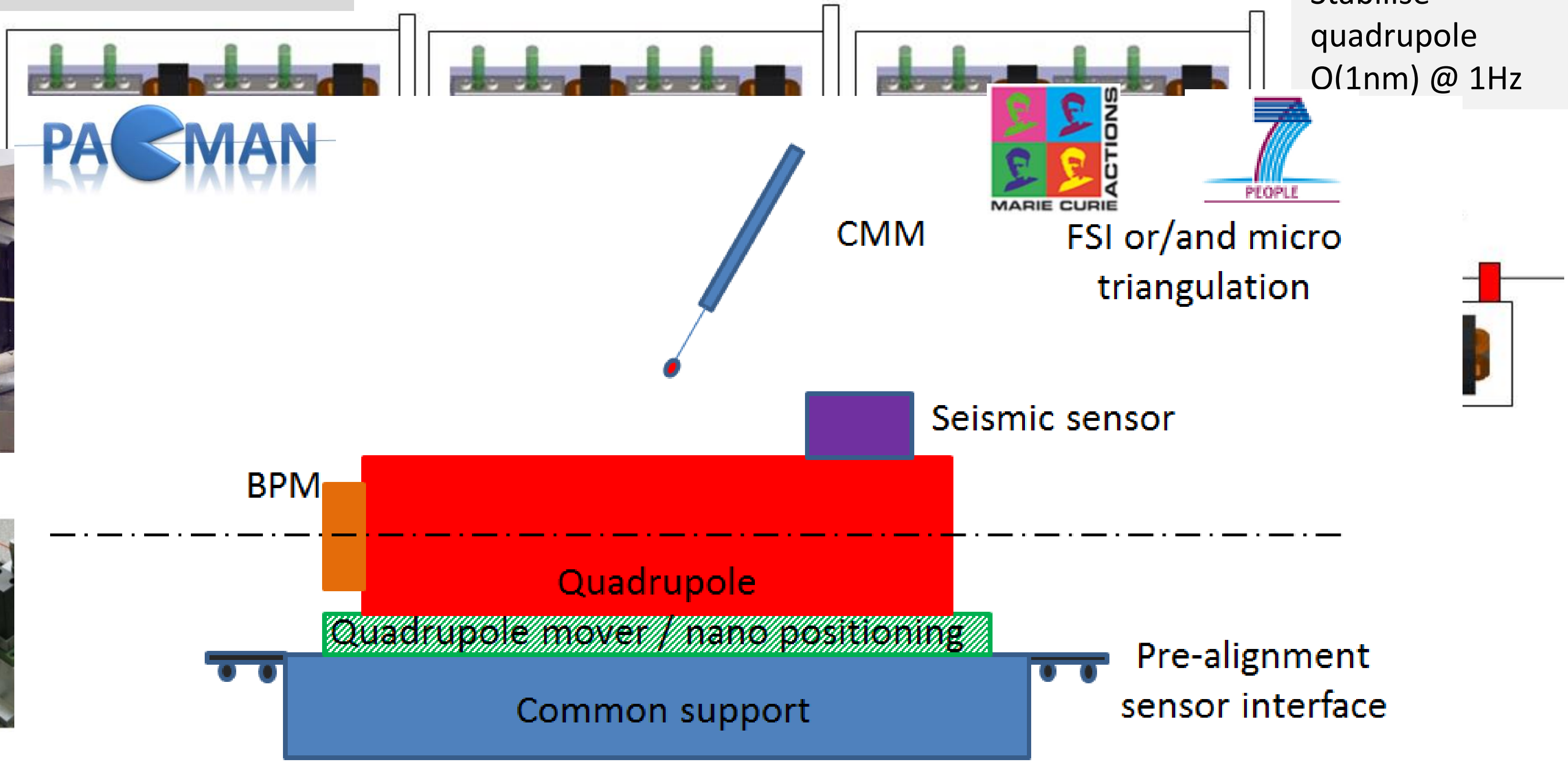


Main Linac Alignment

H. Mainaud Durand et al.

Stabilise quadrupole O(1nm) @ 1Hz

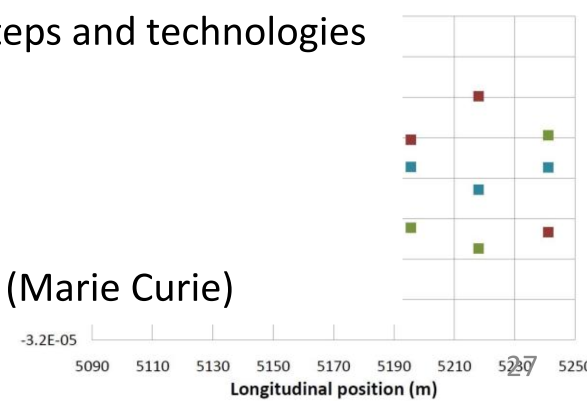




Develop an alternative solution integrating all the alignment steps and technologies at the same time and location (CMM machine)

Build a protoype

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

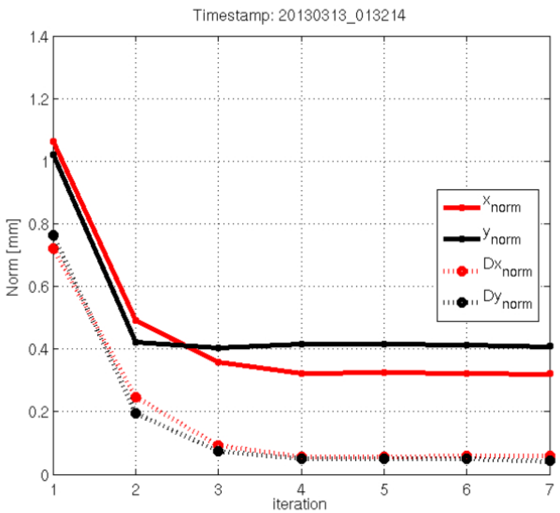


CLIC Beam-Based Alignment tests at FACET

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

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

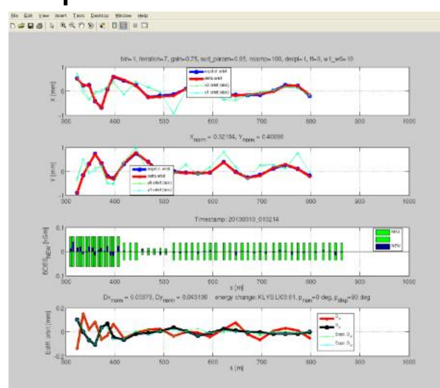
Orbit/Dispersion

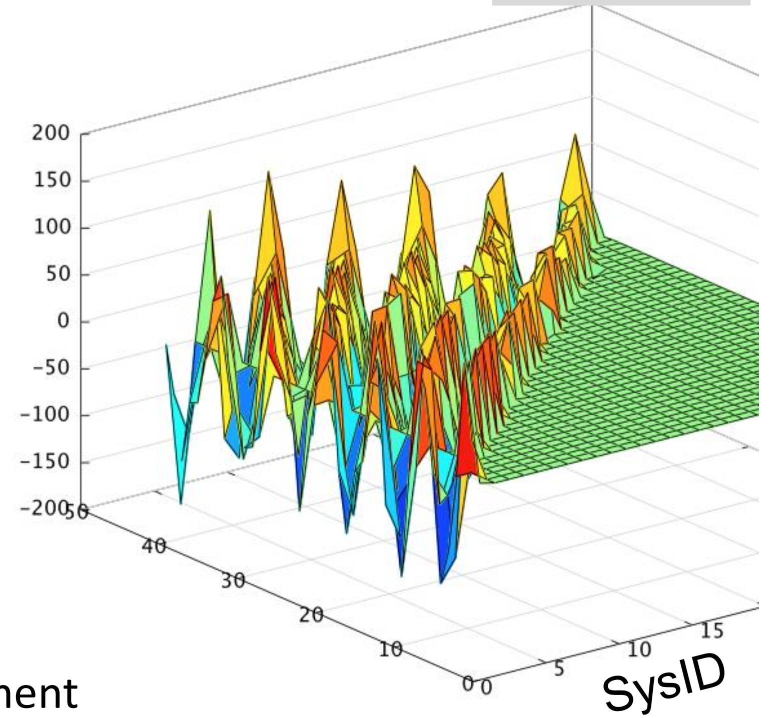


DFS correction applied to 500 meters of the SLC linac

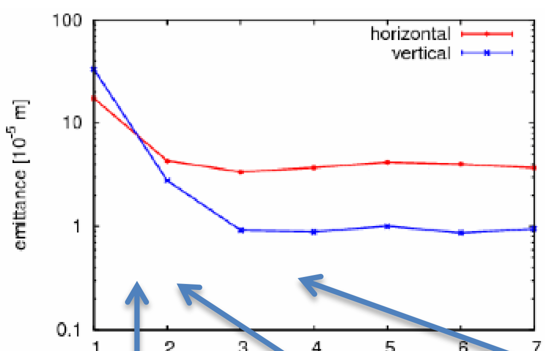
- SysID algorithms for model reconstruction
- DFS correction with GUI
- Emittance growth is measured

Graphic User Interface:

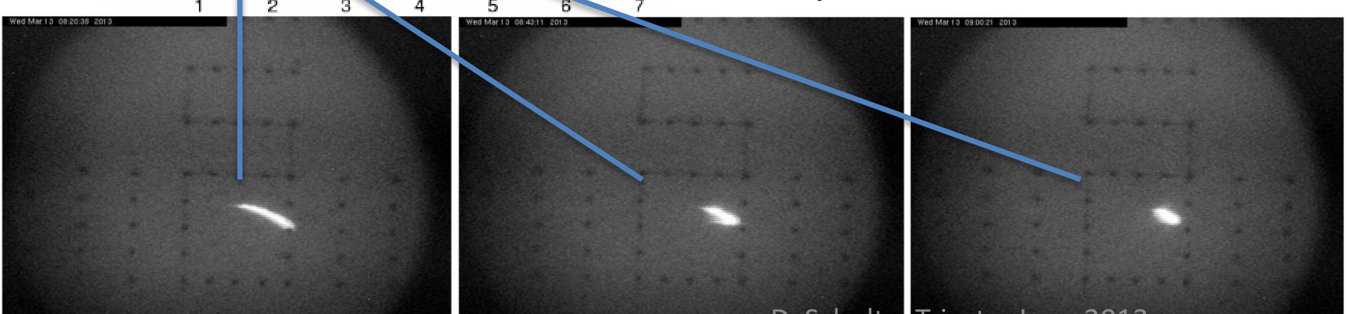




Emittance



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