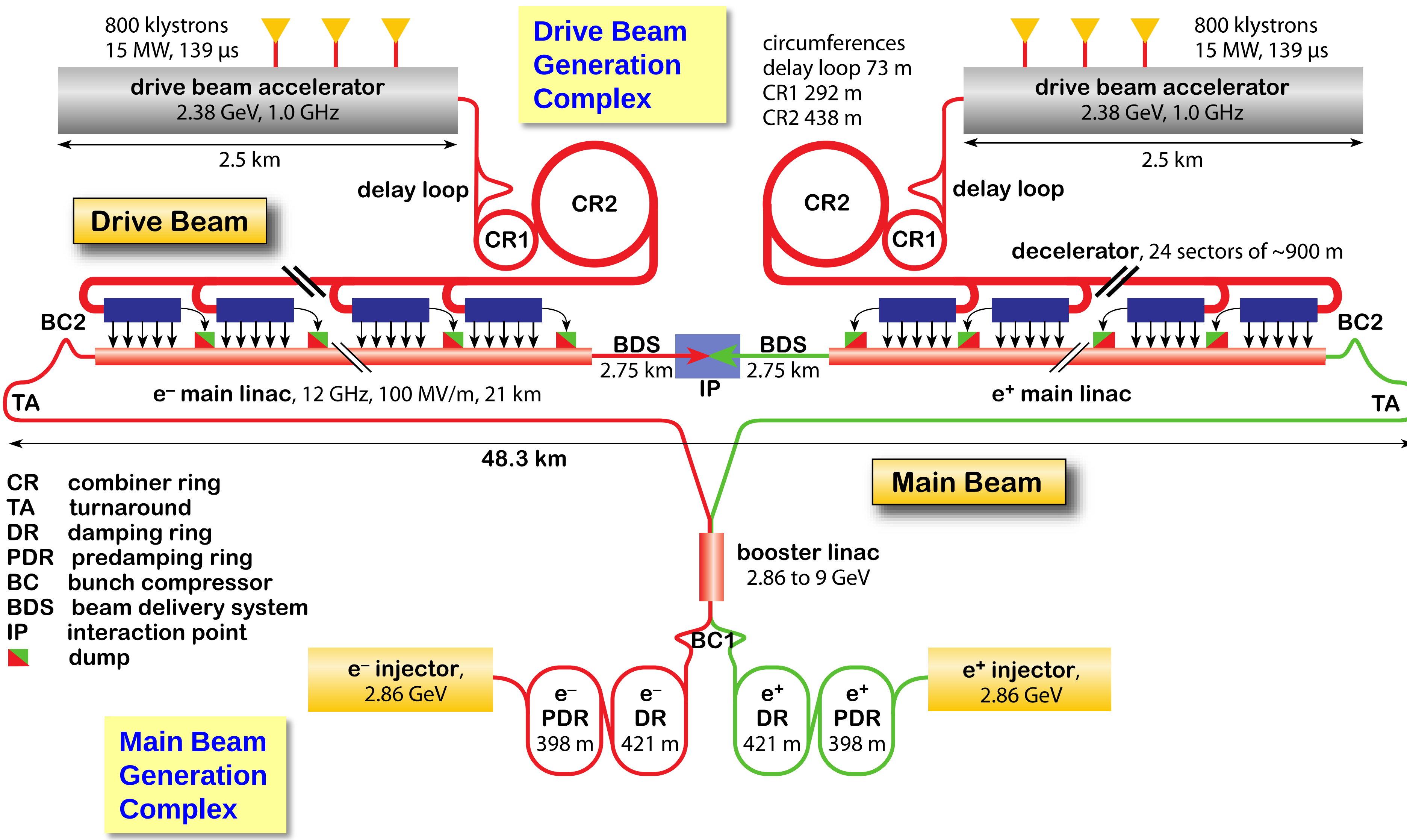
X-Band Technology, requirement for structure tests and its application for SASE FEL

D. Schulte for the CLIC collaboration

Special thanks to
A. Grudiev, A. Latina, Ph. Lebrun, I. Syratchev

CLIC Layout



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

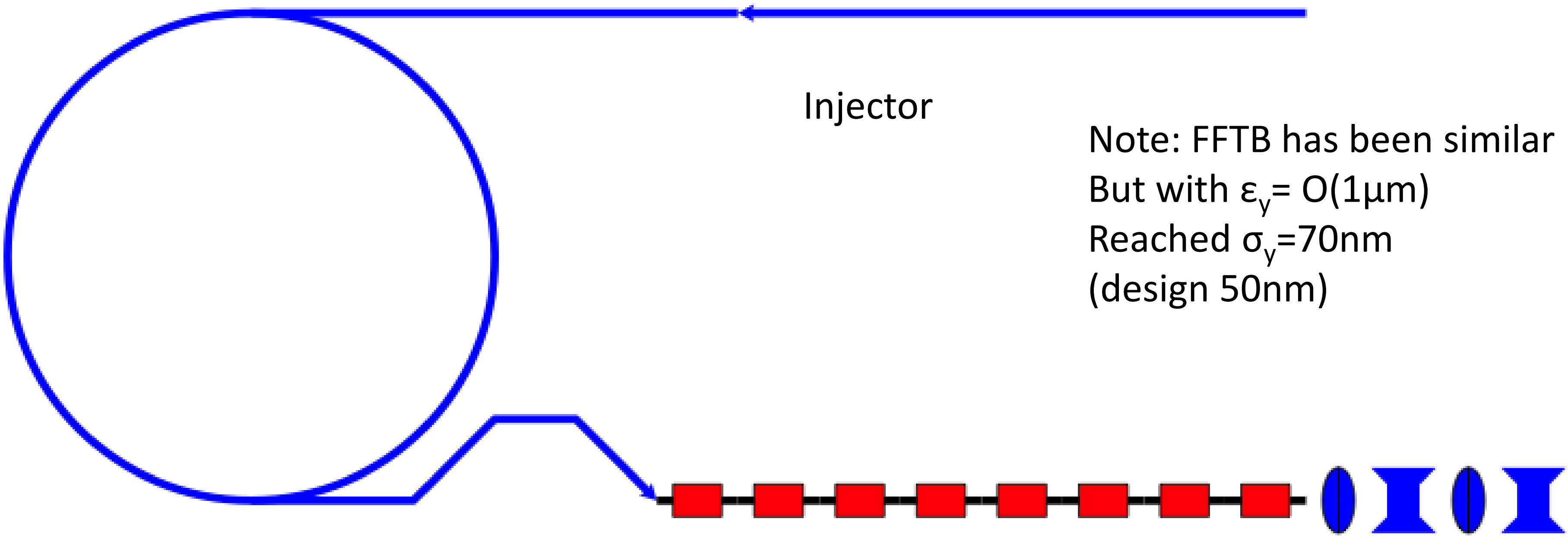
System Test Priorities

- 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 low emittance ring and a beam delivery system test facility

Dream Test Facility Scheme



Injector

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

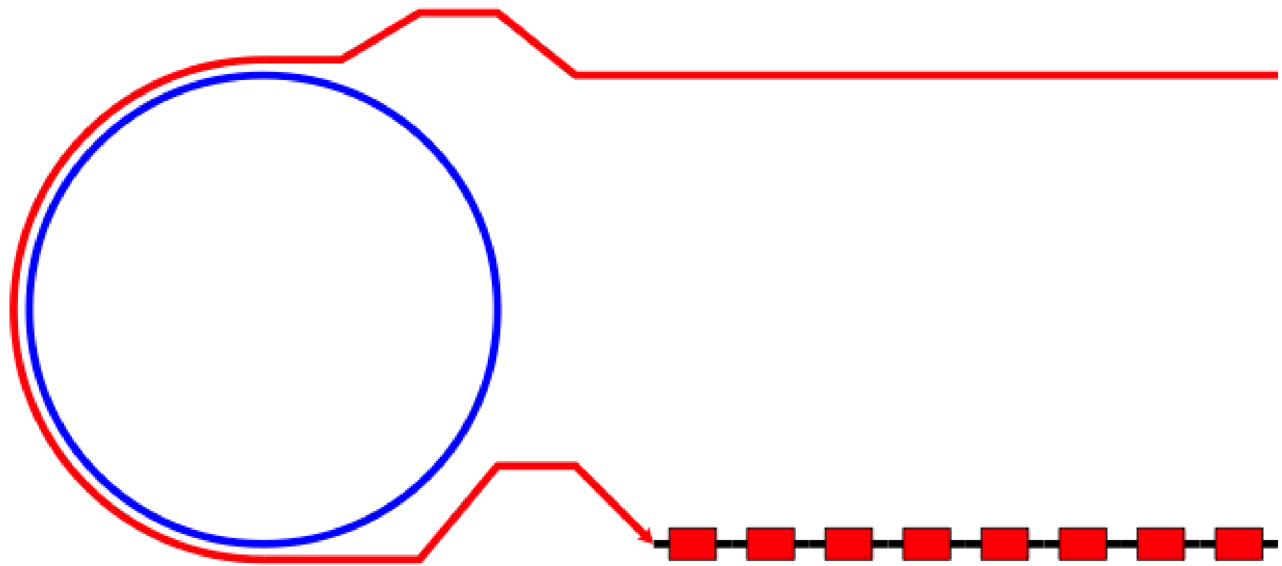
Example options: SPS as damping ring (combined with CLIC0?),
FACET with improved damping ring? ATF, PEP-II, ESRF, SLS, SPRING-8, …

Linac Considerations

- A drive beam to power the linac will only become available a long time from now
  - 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 Facility Operation

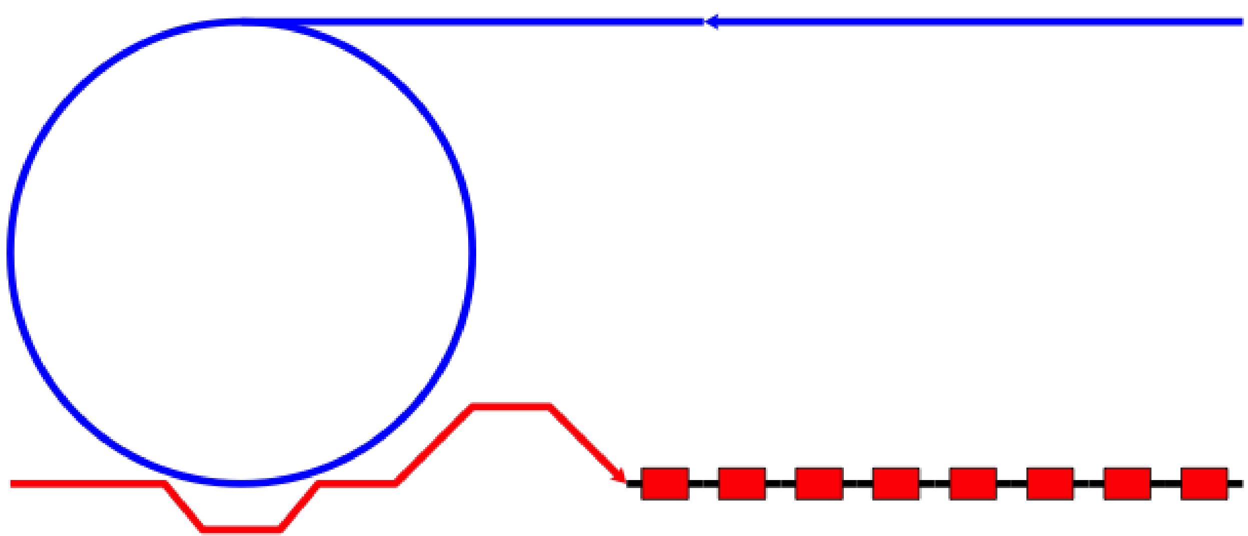
Bypassing the damping ring or with dedicated injector, one can use the linac as a 4th generation light source



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



User and Test Facility Considerations

- 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

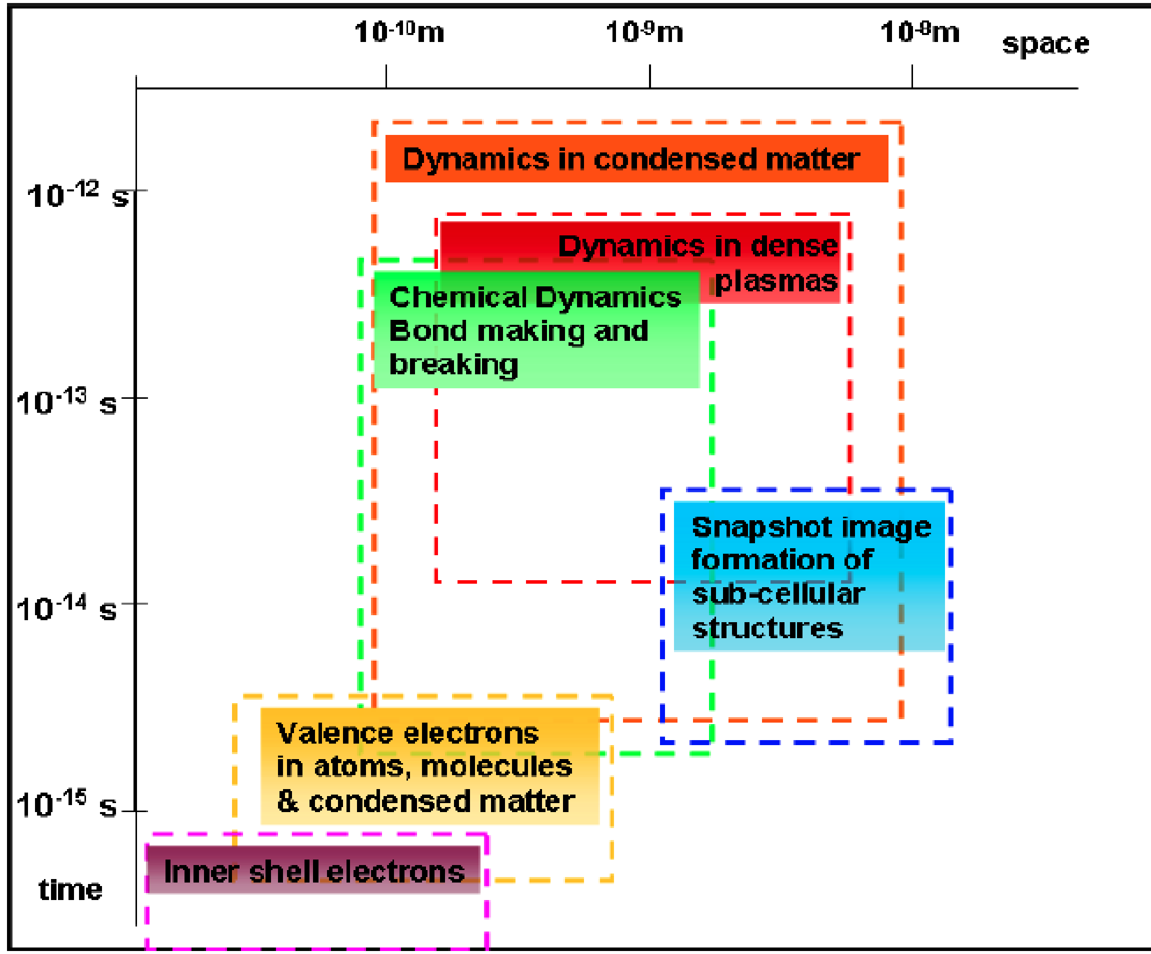
Seem to profit from below 1 a only for very short pulses

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
- …



NLS report

Look into Angstrøm laser for now

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)

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

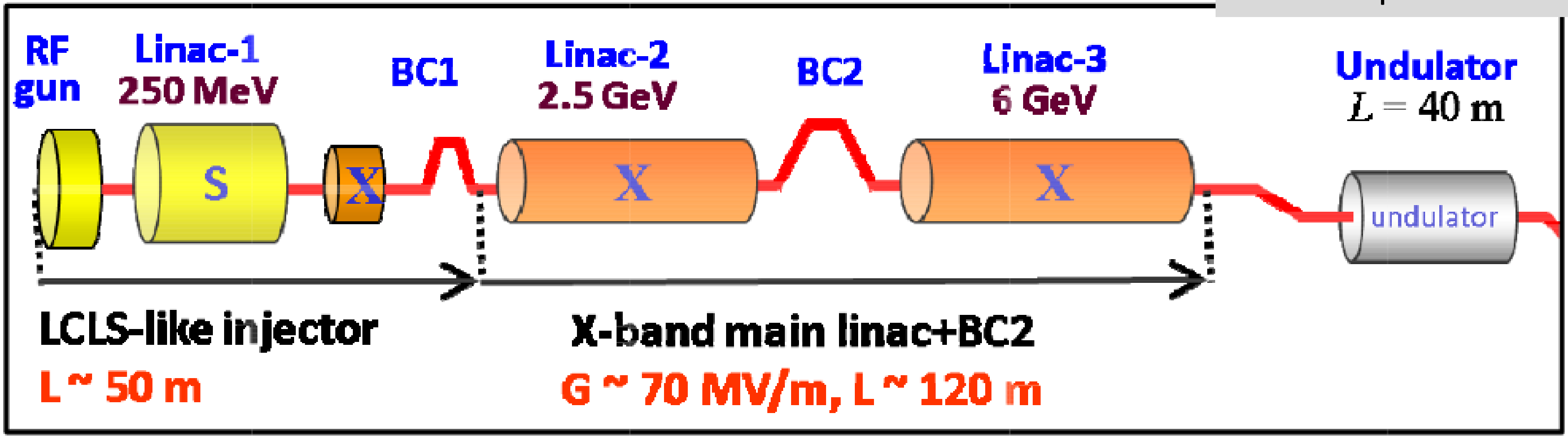
Consequently for λ=0.1nm

$$E \approx 6GeV$$

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

Overview

Chr. Adolphsen et al.



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 or undulator

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}

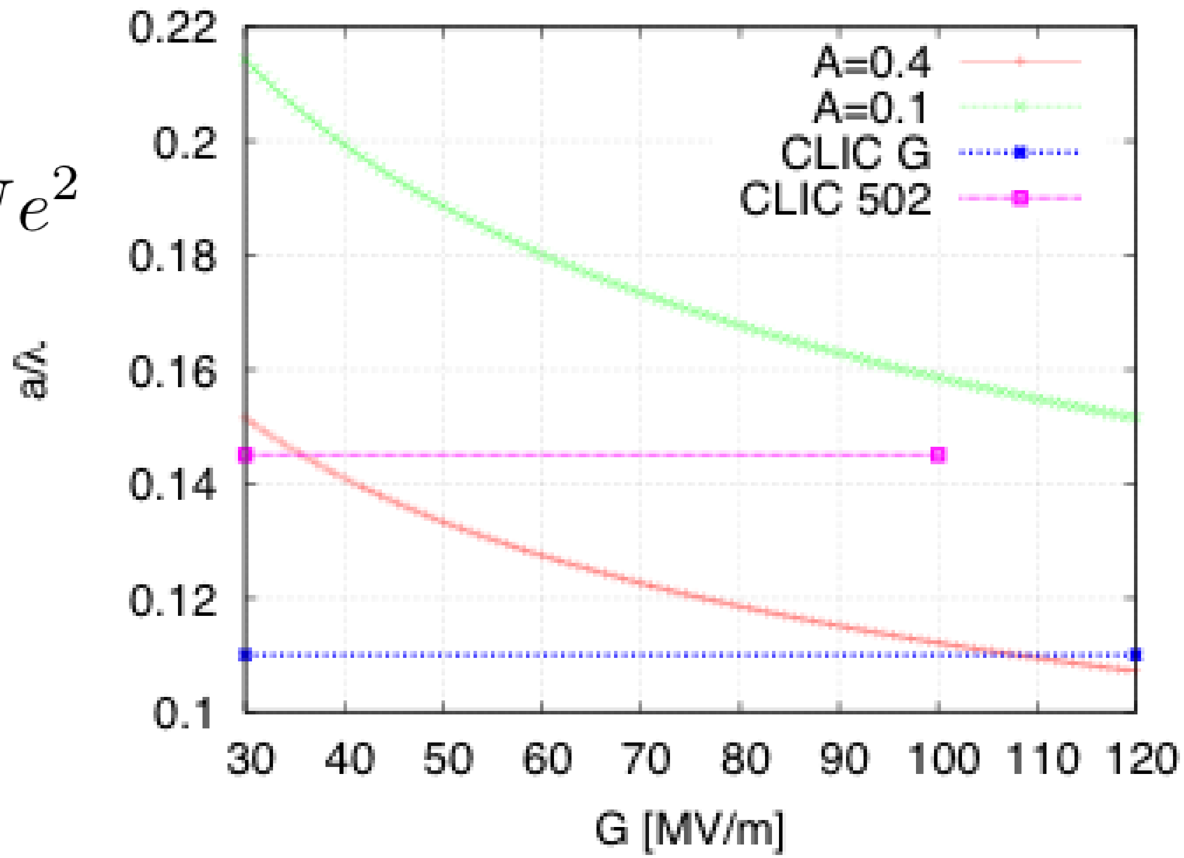
Structure Choice

Stability requires

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

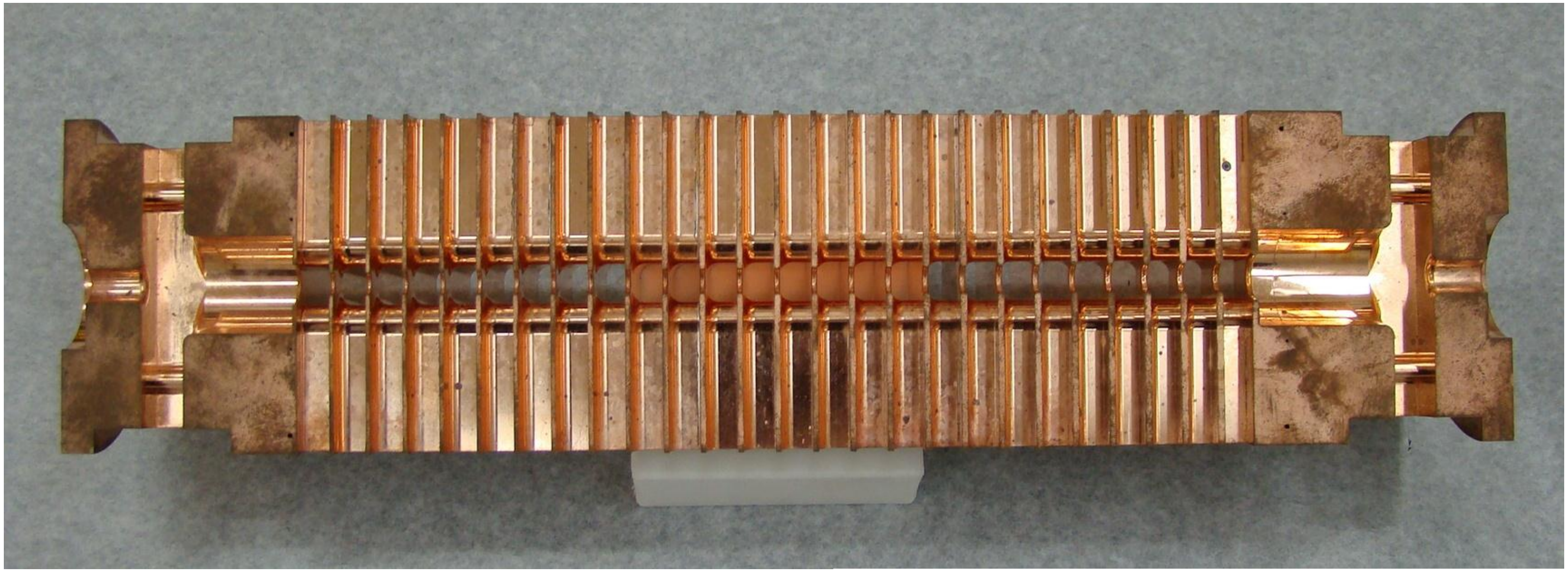
Linac 2 of SLAC proposal is most difficult

Calculate required a, using CLIC lattice



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

CLIC Accelerating Structure

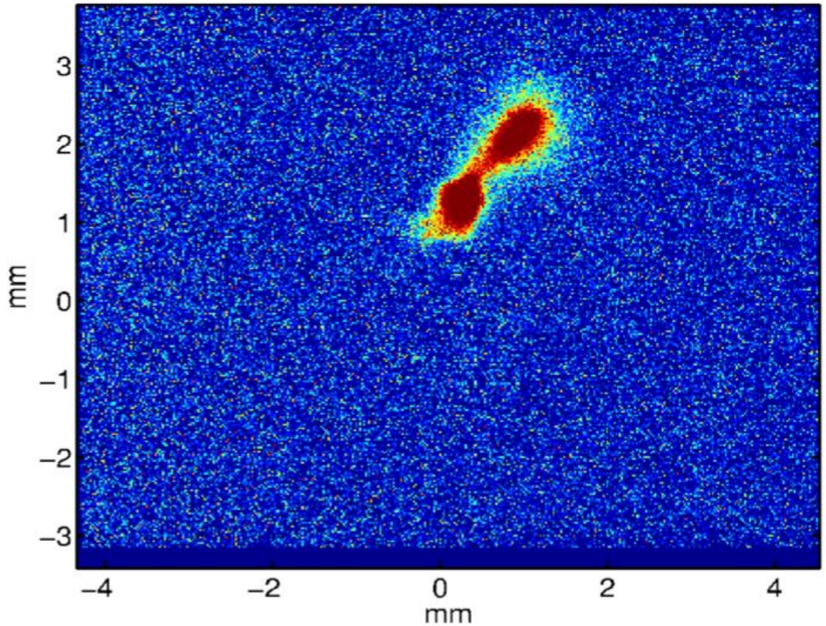


Loaded gradient 100MV/m

Require (soft) breakdown probability $p \leq 3 \times 10^{-7} m^{-1} pulse^{-1}$

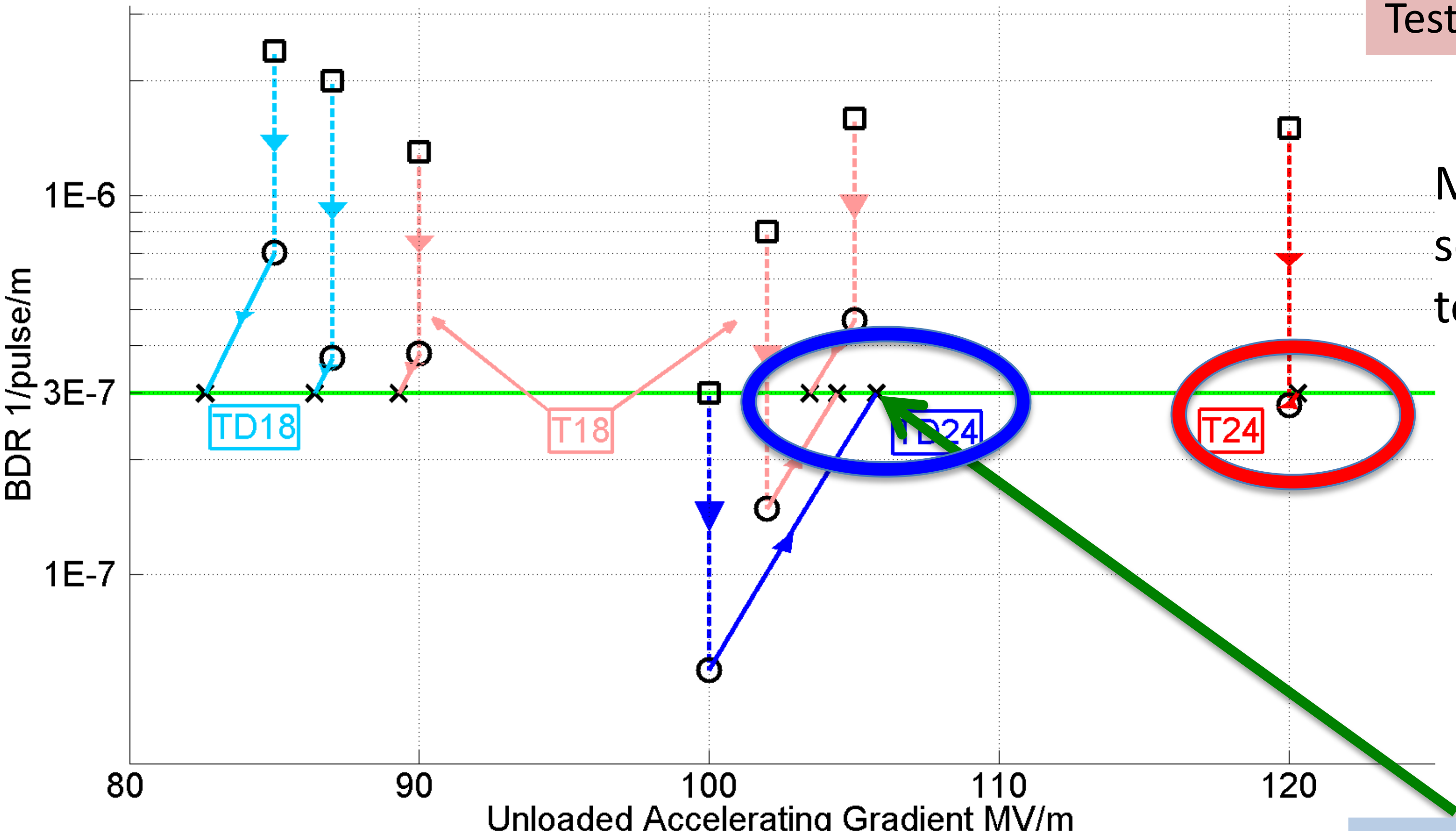
Structure design based on empirical constraints, not first principle

Experiments are essential to confirm the structure performance



Achieved Gradient for CLIC

Tests at KEK and SLAC



Measurements scaled according to

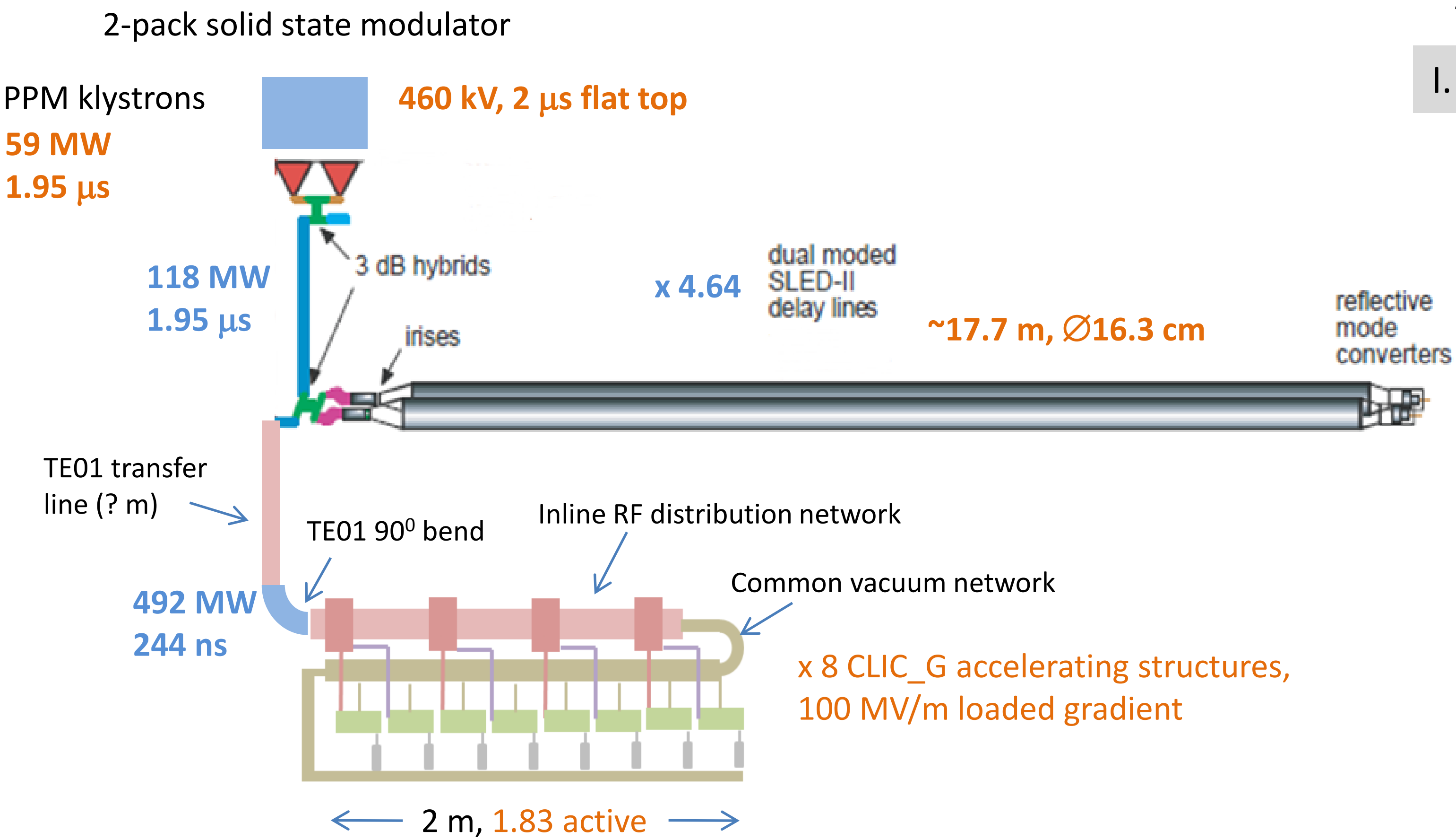
$$p \propto G^{30}\tau^{5}$$

Unloaded 106MV/m
With loading 0-16% less

	Simple early design to get started	More efficient fully optimised structure
No damping waveguides	T18	T24
Damping waveguides	TD18	TD24 = CLIC goal

CLIC'k RF unit layout

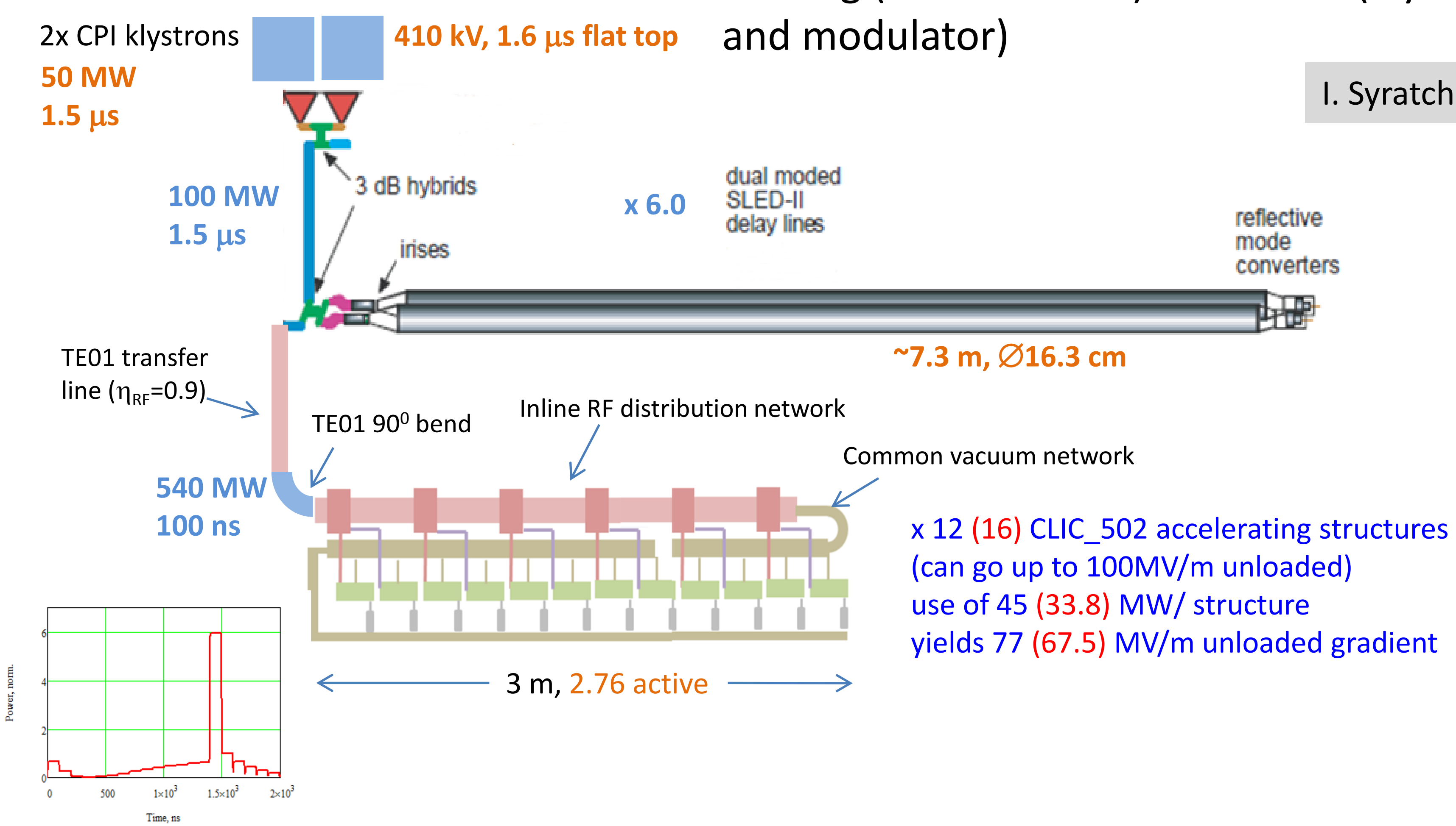
I. Syratchev



This unit should provide ~221 MeV acceleration without beam loading. The adopted components (klystron, modulator, RF network and structures), are expected to operate at the edge of demonstrated performance. Some of them (like 2-pack solid state modulator) need industrialization efforts.

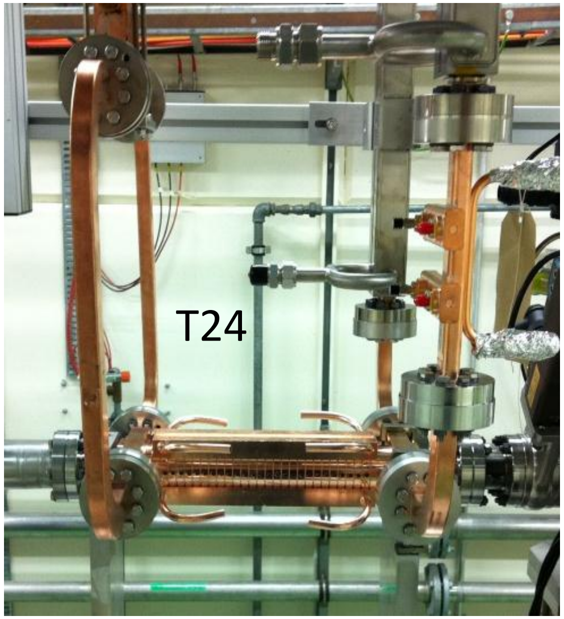
Electron linac RF unit layout based on the existing (industrialized) Rf sources (klystron and modulator)

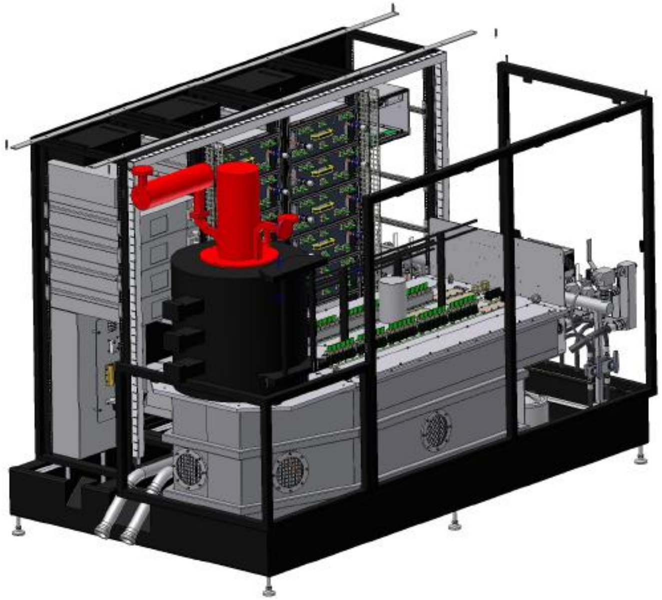
I. Syratchev



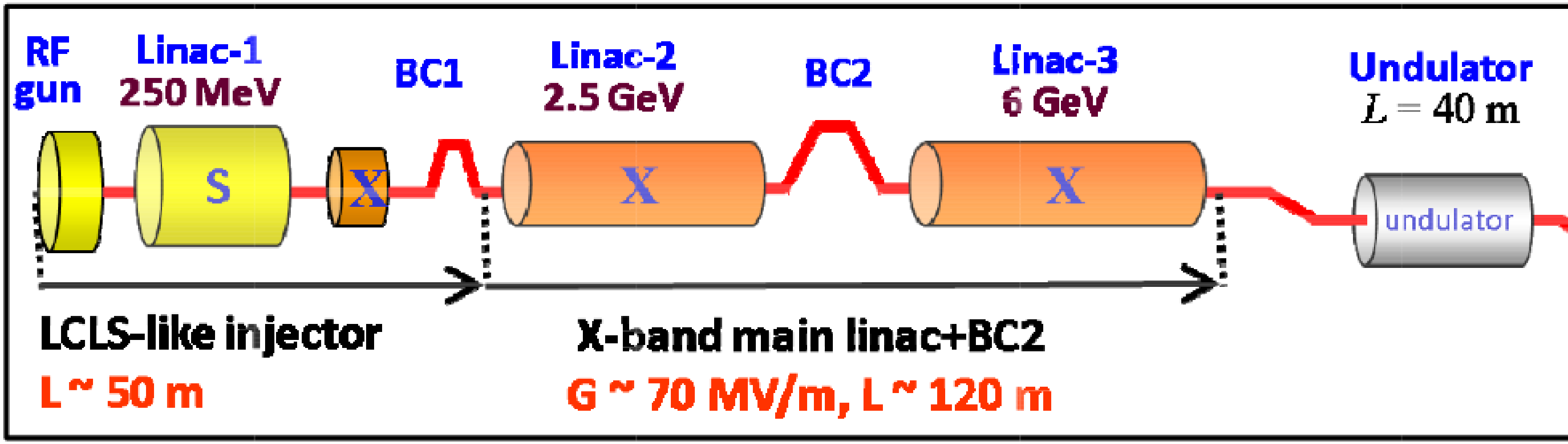
This unit should provide ~213 (248) MeV acceleration beam loading.
Need 27 (23) RF units.
Future CLIC klystrons would save O(20%)

Some Components

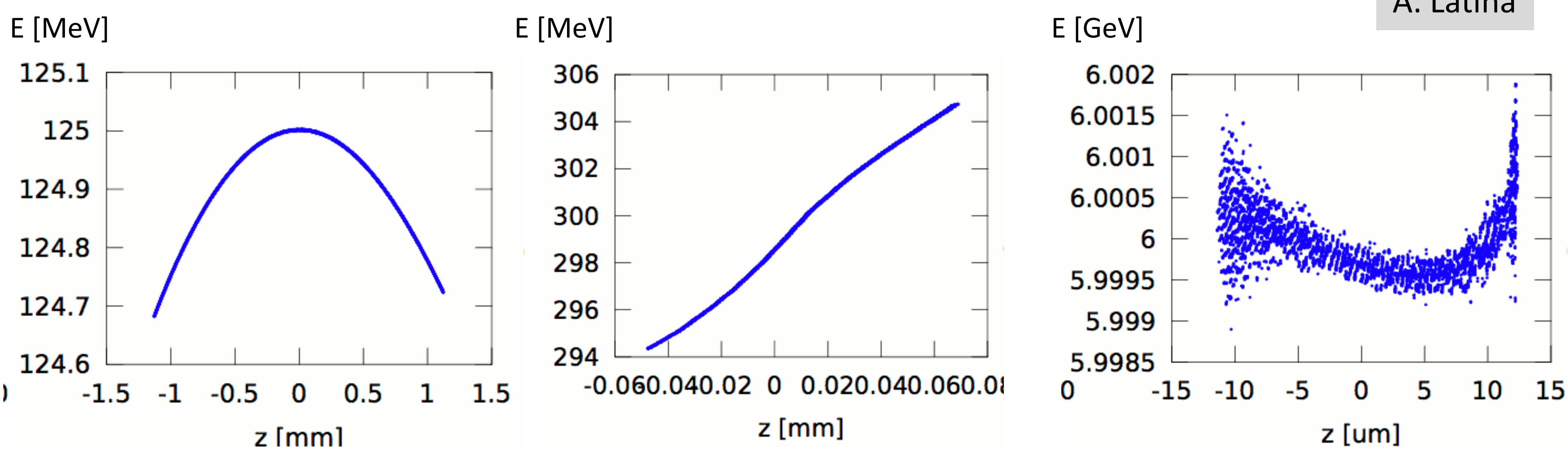




Longitudinal Dynamics

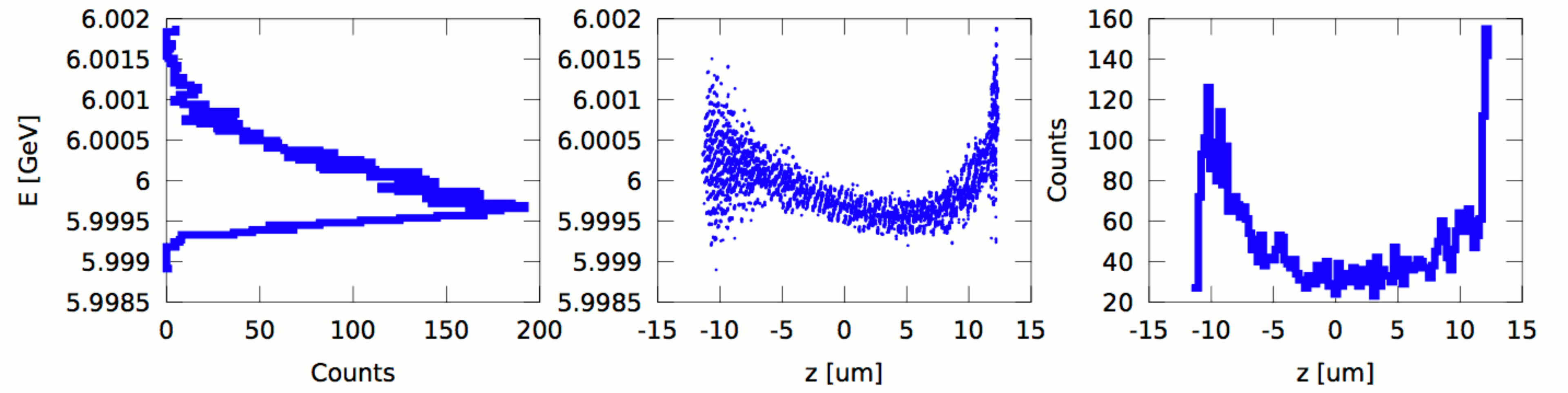


A. Latina



Longitudinal Dynamics (Example)

A. Latina



Structure with a/λ=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

Some 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 Considerations

Parameter	Unit	Swiss FEL	X-FEL (CLIC_502)		X-FEL (CLIC_L)	
Gradient	MV/m	27.5	77	67.5	59	51
Structure length	m	1.98	0.23	0.23	0.48	0.48
No of structures		104	368	368	204	240
Active length	m	208	74	85	98	115
No of klystrons		26	54	46	34	30
Cost est. 1	cu		91	88.5	83	87.5
Cost est. 2	cu		72.5	67.25	58.5	58.75

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

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

Thanks to Ph. Lebrun and I. Syratchev

Paths for Improvements

- Improved klystrons for CLIC
- Small klystrons could operate at O(1kHz)
  - 5-10MW per klystron
  - But might be a bit more expensive
- Longer structures might reduce klystron number
- Structures with no damping would be cheaper and slightly more efficient
- Cheaper pulse compressor options
  - No rectangular pulse is required
- Optimisation based on full

Future Work

- Technical proposal
  - Develop technical design (some months, depending on resources, 10 page document)
    - Coherent design
  - A more complete proposal (timescale and scope to be define, including cost, 30 pages on linac)
    - Contact with qualified industrial suppliers
    - Cost estimate based on industrial contacts

- Project preparation
  - Duration about three years
  - Design optimisation and finalisation
  - Prototype testing

- Project construction
  - Duration about five years

Future Work

- Technical proposal
  - CERN could take a leading role in linac design
  - Limited support for injectors, instrumentation etc.
  - Other system are to be covered by TAC
  - Help to identify qualified industrial suppliers and initiate contact

- Project preparation
  - CERN could take leading role in linac structure and power source design and transfer knowledge to TAC
  - Some support in other areas (instrumentation, …)
  - CERN can provide access to testing infrastructure
  - A number of CLIC components can be directly used for the FEL (power sources etc.) others need specific development

Future Work (cont.)

- Project construction (duration about 5 years)
  - CERN could provide support for reception tests
  - Depending on the scientific value of the FEL for the CERN R&D programme further support can be envisaged

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
  - …

High Gradient Day

During CLIC workshop on Thursday January 31

Thursday 31 January 2013

High Gradient Day: Presentations from laboratories, projects and studies concerning their plans and interests for development and use of normal conduction high gradient structures and associated power sources. - BE Auditorium Meyrin (09:00-12:15)

time	[id] title	presenter
09:00	[49] Introduction	
09:10	[36] CLIC activities/plans	
09:25	[37] PSI activities/plans	
09:45	[38] Trieste/Fermi plans	
10:00	[39] TERA activities/plans	
10:15	[40] Shanghai activities/plans	
10:30	Coffee	
11:00	[41] SLAC activities/plans	
11:15	[42] Ankara/Turkish activities/plans	
11:30	[56] ALBA	
11:45	[43] Frascati	
12:00	[173] MAX-lab	

High Gradient Day (cont)

During CLIC workshop on Thursday January 31

High Gradient Day: Presentations from laboratories, projects and studies concerning their plans and interests for development and use of normal conduction high gradient structures and associated power sources. : (Industrial presentations from the main producers of micron-precision high gradient RF structures or components) - BE Auditorium Meyrin (13:00-15:15)

time	[id] title	presenter
13:00	[50] Introduction	
13:10	[44] VDL	
13:25	[45] Bodycote	
13:40	[46] TEL Mechatronics	
13:55	[57] Mecachrome	
14:10	[55] CINEL	
14:25	[47] CERN in-house	
14:40	[59] Helsinki	

High Gradient Day: Presentations from laboratories, projects and studies concerning their plans and interests for development and use of normal conduction high gradient structures and associated power sources. : (main producers of high efficiency and high peak power klystron and modulators) - BE Auditorium Meyrin (15:30-18:15)

time	[id] title	presenter
15:30	[51] Introduction	
15:40	[52] CPI	
15:55	[53] Thales	
16:10	[58] Toshiba	
16:25	[60] Scandinova	
16:40	[147] JEMA	
16:55	[61] Ampegon	
17:10	[62] Transtechnik	
17:25	[148] Imtech	
17:40	[174] ITHPP	

Conclusion

- X-band seems a good technology for an X-FEL
  - CLIC structure and RF design and existing 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 remains to be done
    - E.g. can see improvements for the structure
    - 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