Compact

The CompactLight Design Study (XLS)

Andrea Latina (CERN)
on behalf of the CompactLight Collaboration

EU's Horizon2020 research and innovation programme

Future Light Source 2018 – Shanghai – March 5-9, 2018

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CompactLight: Objectives and Relevant Dates

"Design a compact and cost-effective FEL, using very high-gradient acceleration and advanced undulators concepts"

FEL Facilities	Institutes
Hard X-ray	STFC, PSI, UA-IAT, SINAP, UoM, ANSTO.
Soft X-ray	ELETTRA-ST, INFN.
Compton Sources	TU/e, ANSTO.
Upgrading of existing facilities	ELETTRA-ST, INFN.

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The proposal was submitted in March 2017, and approved in August 2017

The CompactLight project started on 1st of January 2018

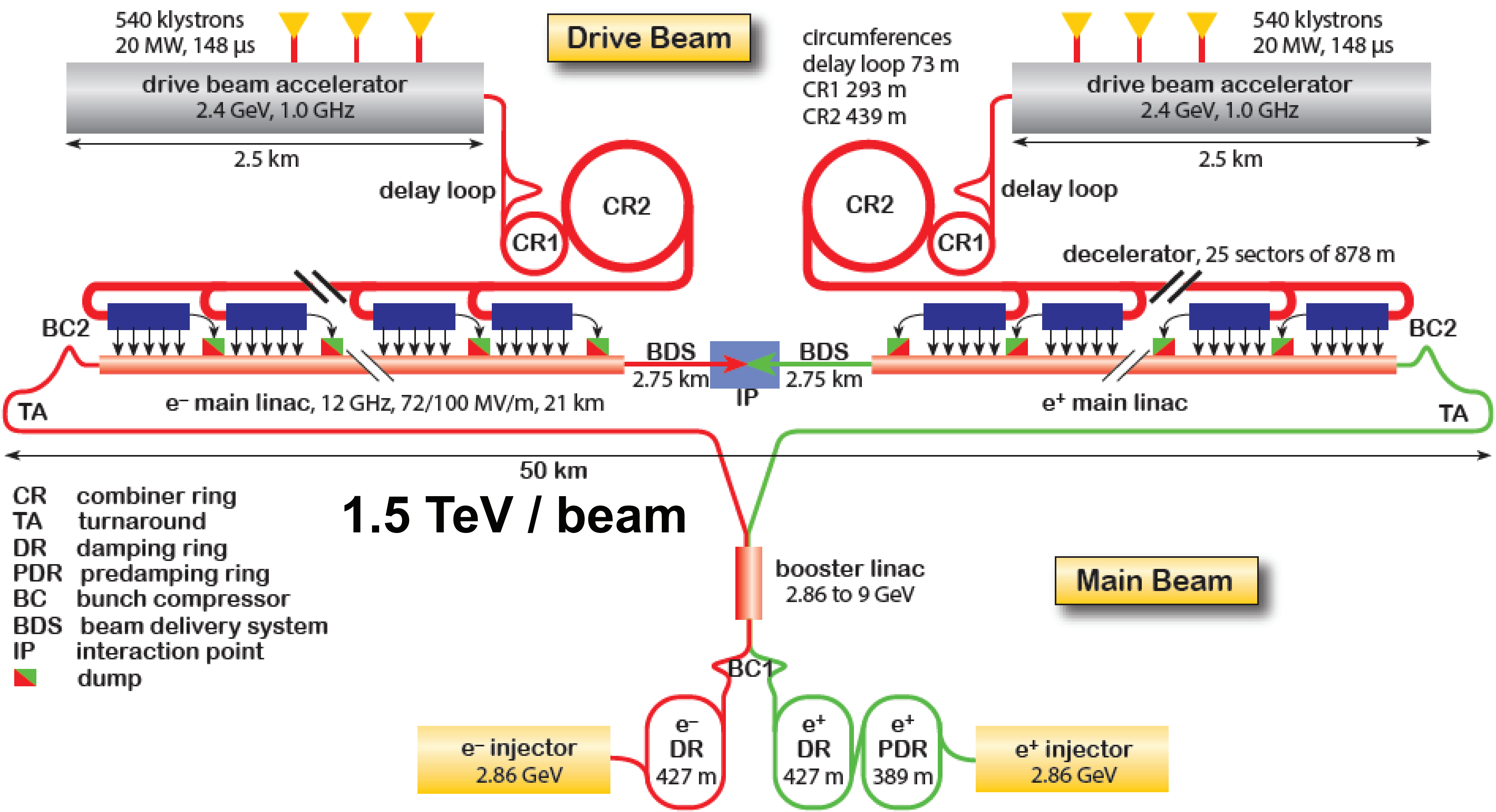
Official Kick-Off meeting was on the 25th of January 2018

⇛ Three years duration
⇛ Main deliverable: A CDR of the XLS facility

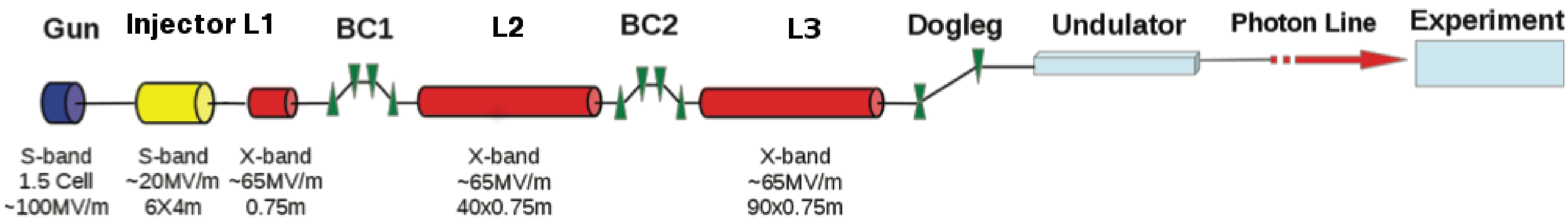
CLIC Study at CERN: e^+e^- linear collider for HEP

Compact

Layout at 3 TeV center-of-mass energy



CompactLight Layout & Parameters



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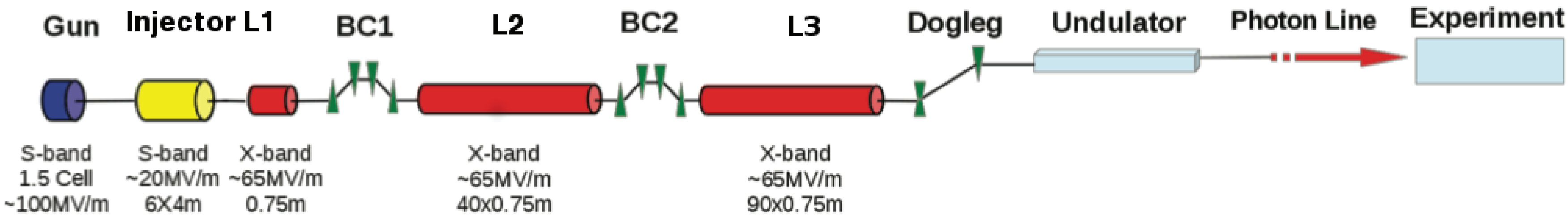
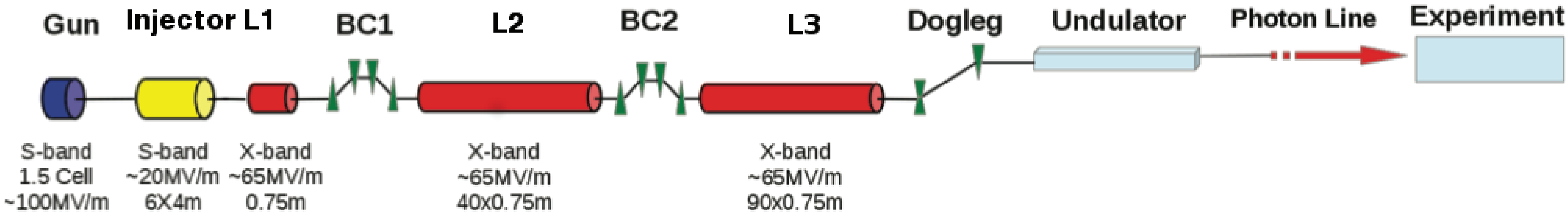


Preliminary Parameters and Layout of XLS hard X-ray FEL facility

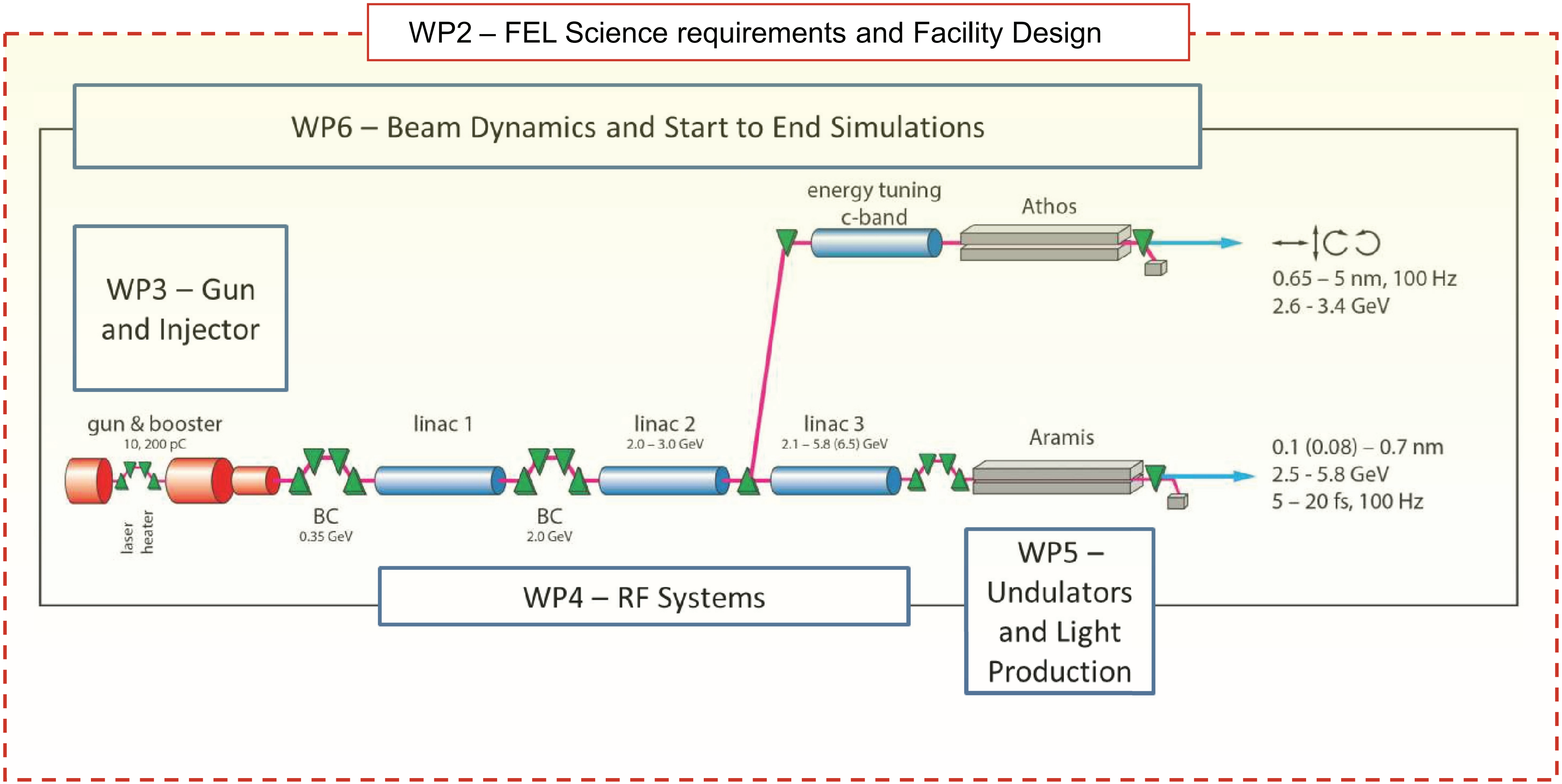
CompactLight Layout & Parameters



Preliminary Parameters and Layout of XLS hard X-ray FEL facility

Parameter	Value	Unit
Minimum Wavelength	0.1	nm
Photons per pulse	$>10^{12}$	
Pulse bandwidth	<<0.1	%
Repetition rate	100 to 1000	Hz
Pulse duration	<1 to 50	fs
Undulator Period	10	mm
K value	1.13	
Electron Energy	4.6	GeV
Bunch Charge	<250	pC
Normalised Emittance	<0.5	mrad

CompactLight: Technical Workpackages

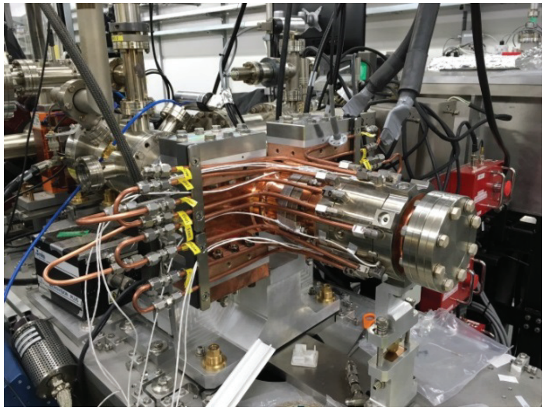


Using SwissFEL as an example https://www.psi.ch/swissfel

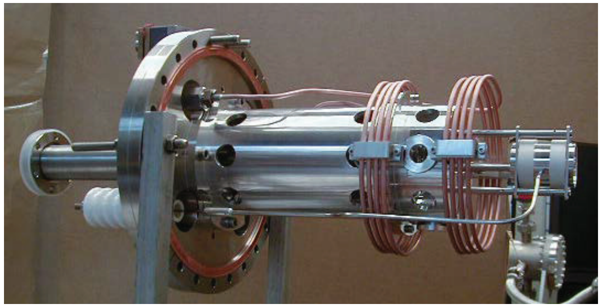
Courtesy of J. Clarke

WP3: Injector Gun

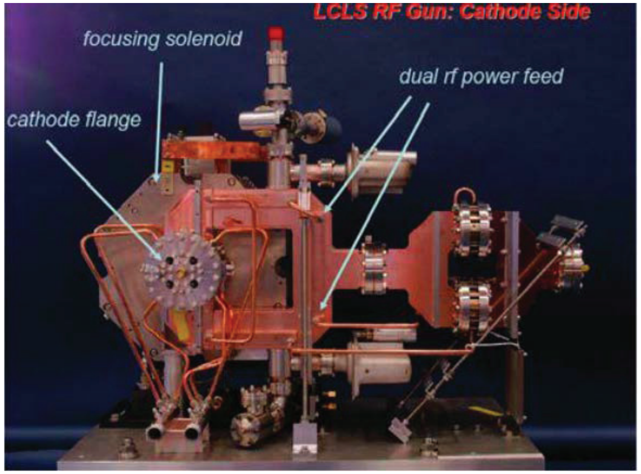
- Lead Institute: LNF-INFN (M. Ferrario)
- Main Tasks
  - Review State of the art Gun / Injector (S-, C-, X-band) and pick best for XLS
  - Develop of novel high-repetition rate gun / injector (w K-band linearizer)
  - Prototyping and test (if possible)



400Hz S-band rf gun in CLARA



Ultra-low emittance electron source, TU/e



LCLS S-band rf gun

WP3: Parameters (preliminary)

	Units	XLS Proposal 250 pC	More Photons 250 pC	More Photons 350 pC
Beam energy	GeV	4.6	4.6	4.6
Rms Bunch length	μm	40		
Rms Bunch matched spot	μm	17	7.5	6.7
Rms Energy Spread	%	<0.1	<0.1	<0.1
Rms norm. emittance	μm	<0.5	<0.5	<0.5
Slice length	μm	0.067	0.03	0.032
Slice Peak current	kA	2	5	3
Slice Energy Spread	%	0.01	0.01	0.01
Slice norm. emittance	μm	0.5	0.1	0.08
ρ_{3D}	x 10^{-4}	1.5	9.0	8.6
η		2.2	0.15	0.17
Radiation wavelength	nm	0.1	0.1	0.1
Undulator period	cm	1.2	1.2	1.2
K		1.	1	1
β undulator	m	5.	5	5
Saturation Active Length	m	60	11.0	11.6
Saturation power	GW	0.686	30	16
Photons/pulse	x 10^{11}	0.48	8.6	10

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

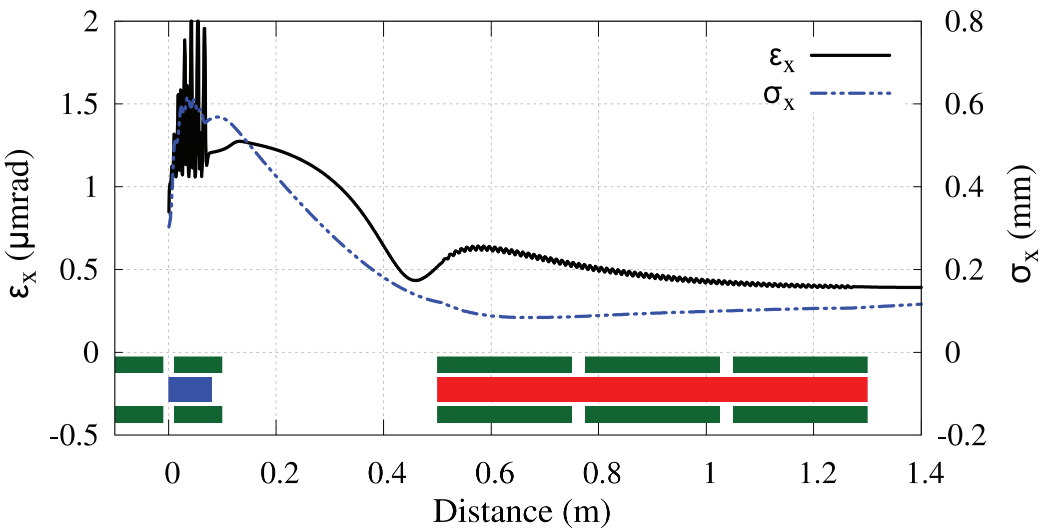
$$N_{ph} = 1.6\frac{E_b}{h\nu_{ph}}\frac{\rho N_e}{(1+\eta)^2}$$

$$\frac{\sigma_\gamma}{\gamma} \le \frac{\rho}{2}$$

$$\varepsilon \le \frac{\lambda_r}{4\pi}$$

WP3: Full X-band Gun (preliminary)

- Ankara's full X-band hard X-ray FEL design study
- Based on SLAC X-band rf photoinjector
  [R. A. Marsh et al., Phys. Rev. ST Accel. Beams 15, 102001 (2012)]
- Preliminary design: 5.6 cell photo-cathode rf gun operating at 12 GHz, with 200 MV peak accelerating voltage, followed by 6 CLIC-like X-band accelerating structures, 70 MV/m gradient
- The rf gun and solenoid magnets have been designed using 2D Poisson / Superfish code. Beam dynamics studies have been performed using ASTRA



Superfish + ASTRA simulation

Bunch charge of 250 pC

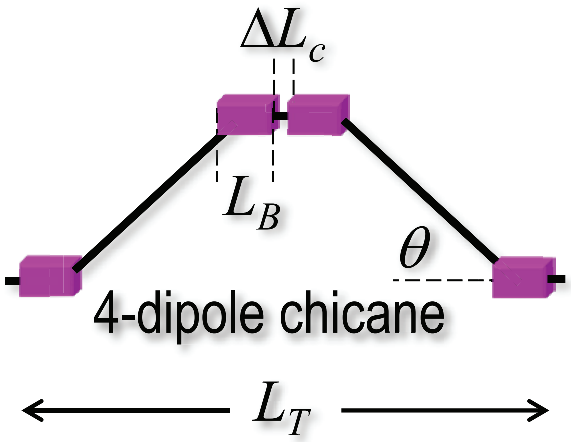
The cathode is excited by a

- flat top laser, which has a time FWHM of 3 ps, temporal rise/fall time of 0.3 ps

- $\sigma_z \approx 200$ µm
- $\sigma_{x,y} = 2$ mm spot size

Courtesy of A. Aksoy

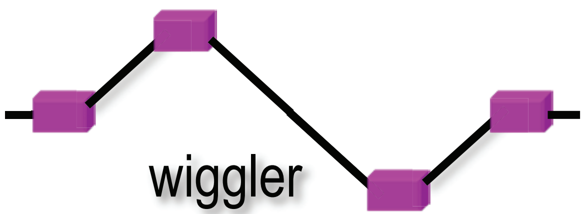
WP3: Magnetic Chicane



LEUTL,… LCLS, TTF-BC1,2, ILC, CLIC, …

$$R_{56} \approx -2\theta^2\left(\frac{L_T}{2} - \frac{4}{3}L_B - \frac{\Delta L_c}{2}\right) < 0$$

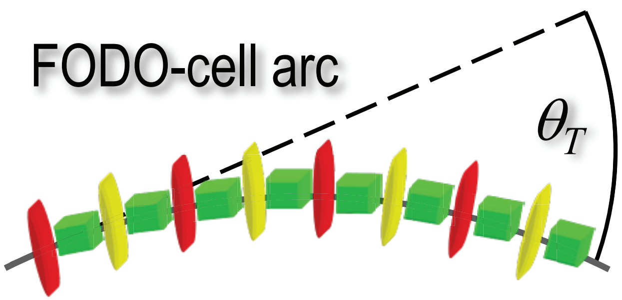
simple, achromatic



TESLA-BC2,3

$$R_{56} \approx -2\theta^2\left(\frac{L_T}{2} - \frac{4}{3}L_B\right) < 0$$

achromatic



SLC RTL, SLC arcs, NLC BC2

$$R_{56} \approx \frac{\theta_T^2 L_T}{4N_c^2 \sin^2(\mu_x/2)} > 0$$

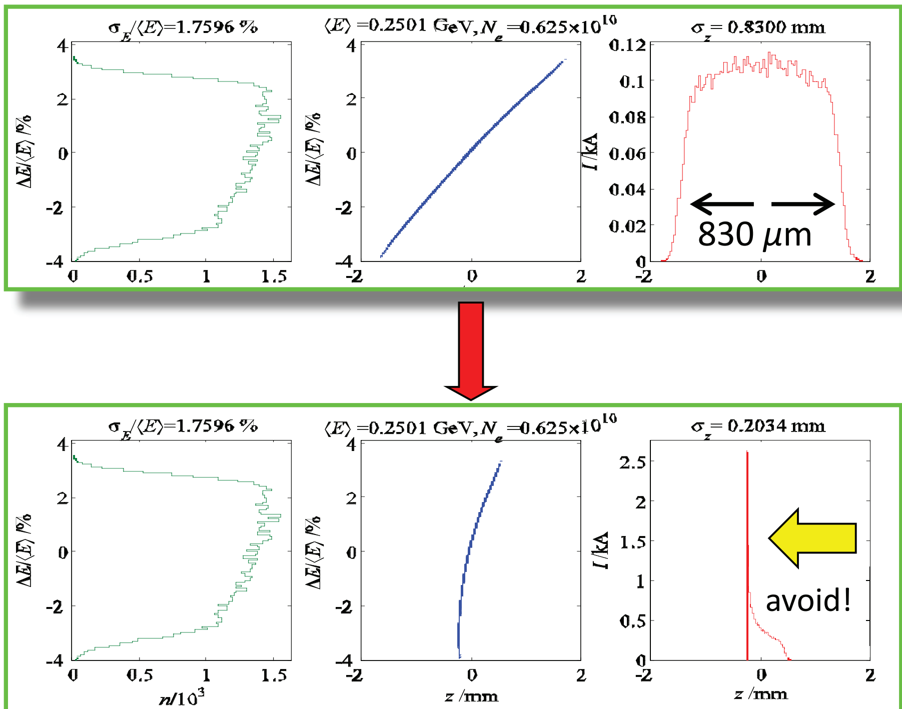
reverse sign

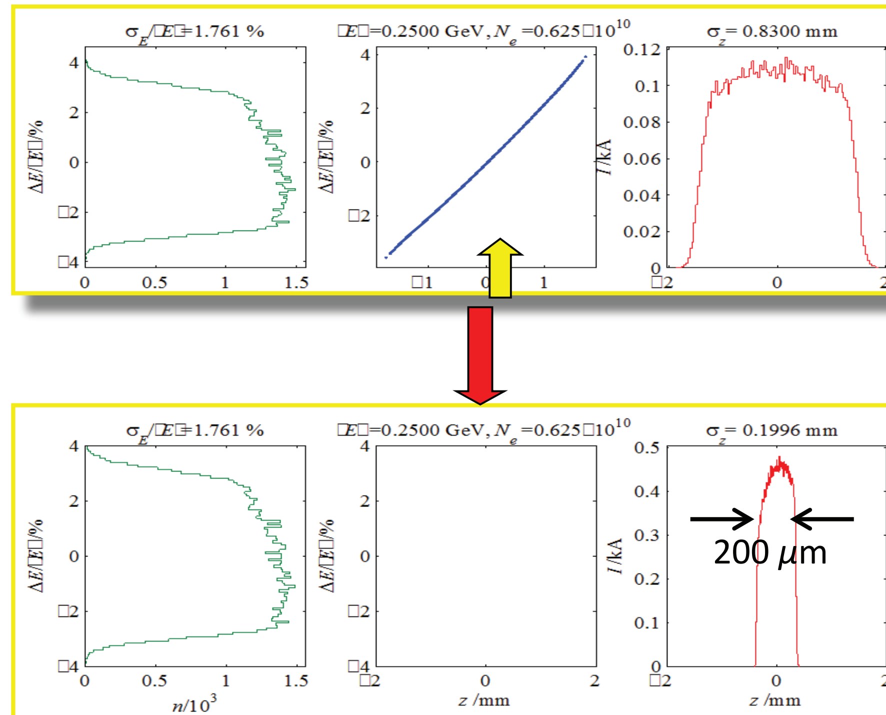
But CSR, and T_{566} **>** 0 in all cases…

WP3: Longitudinal Phase-space Linearization

RF curvature and 2nd-order compression cause current spikes

Harmonic RF at decelerating phase corrects 2nd-order and allows unchanged z-distribution

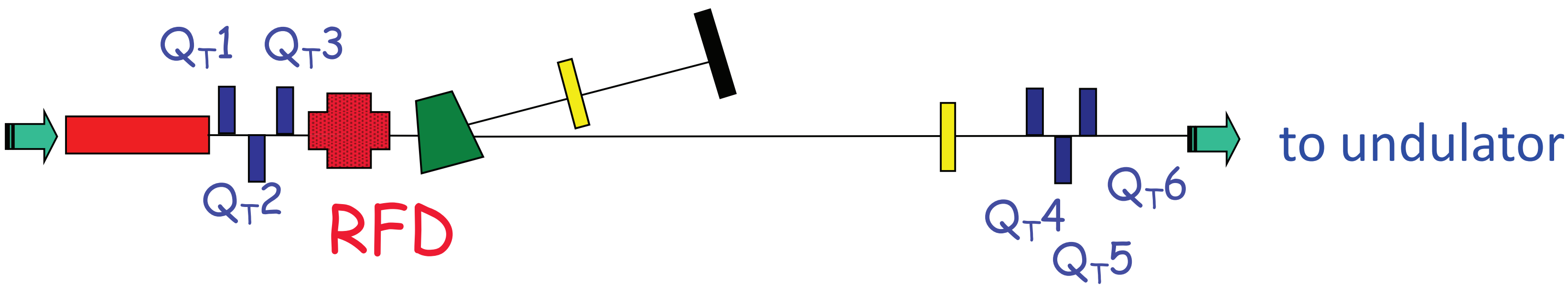




S-band injectors: X-band linearizer (ELETTRA, PSI)
X-band injectors: K-band linearizer (36 GHz)
Passive compensation with e.g. sextupoles

Courtesy of M. Ferrario

Example: SPARC Diagnostic Section



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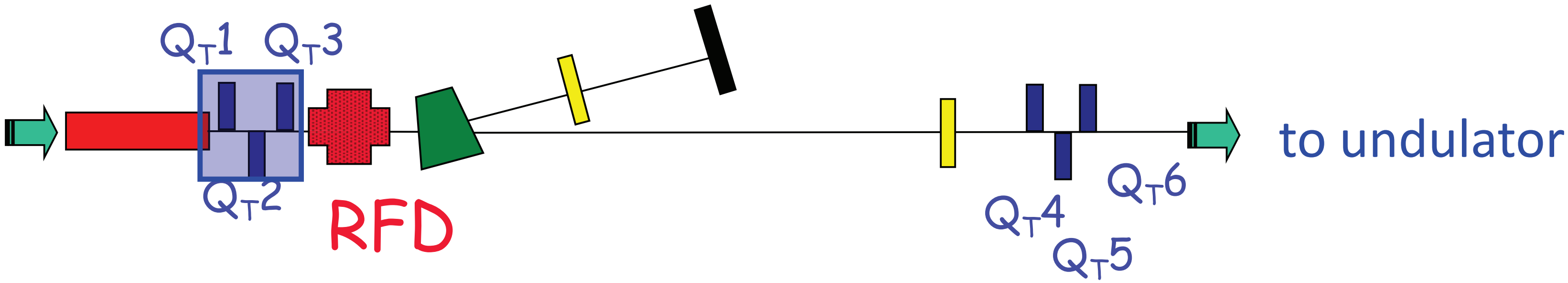

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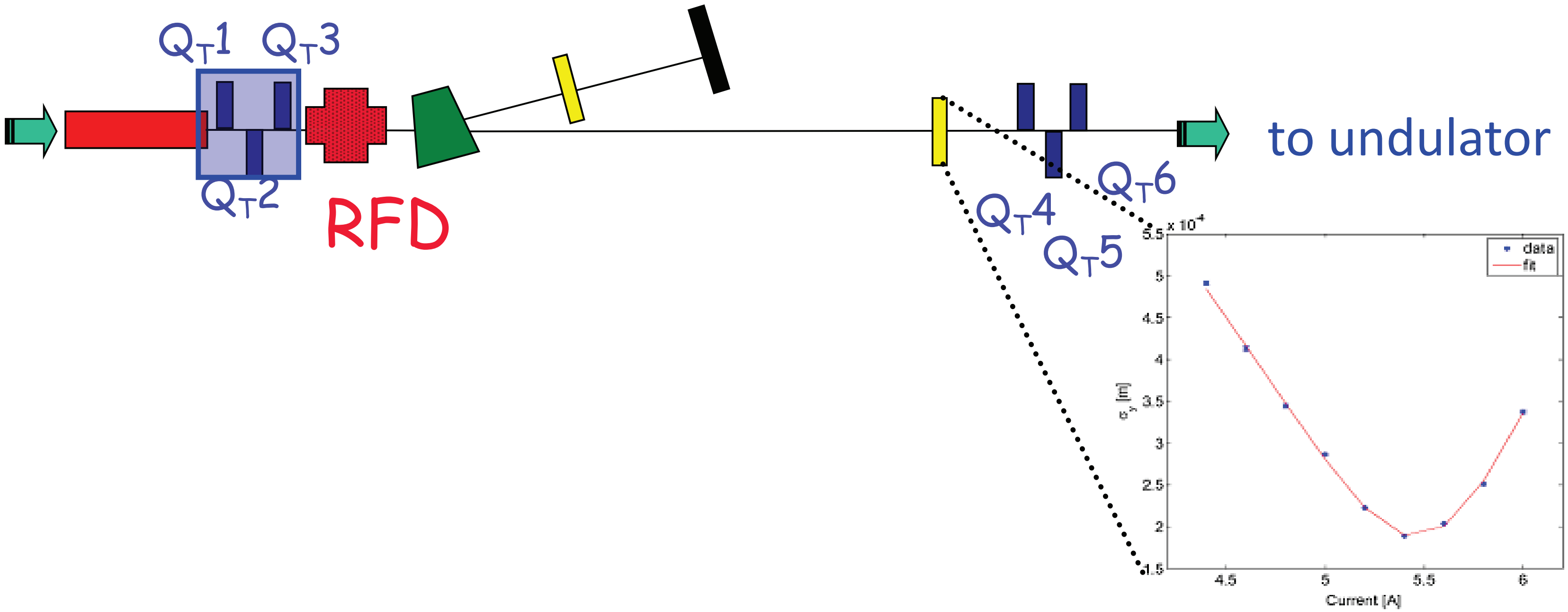

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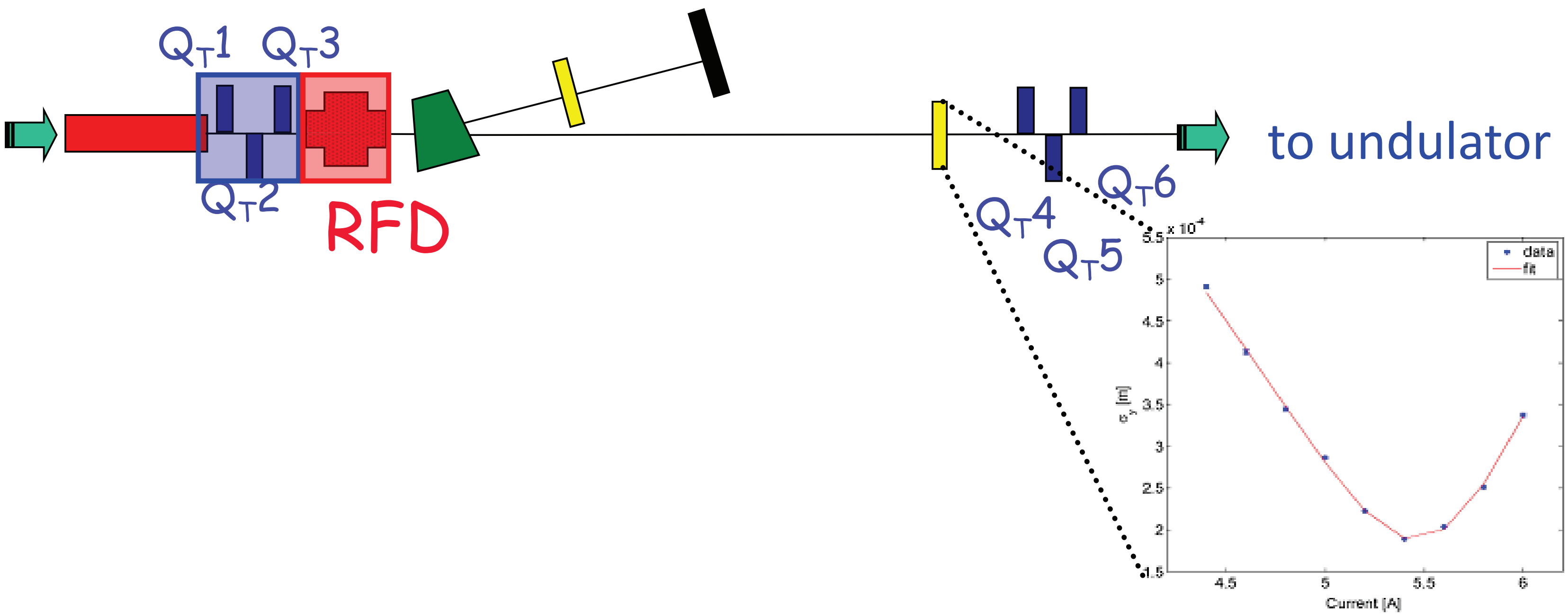

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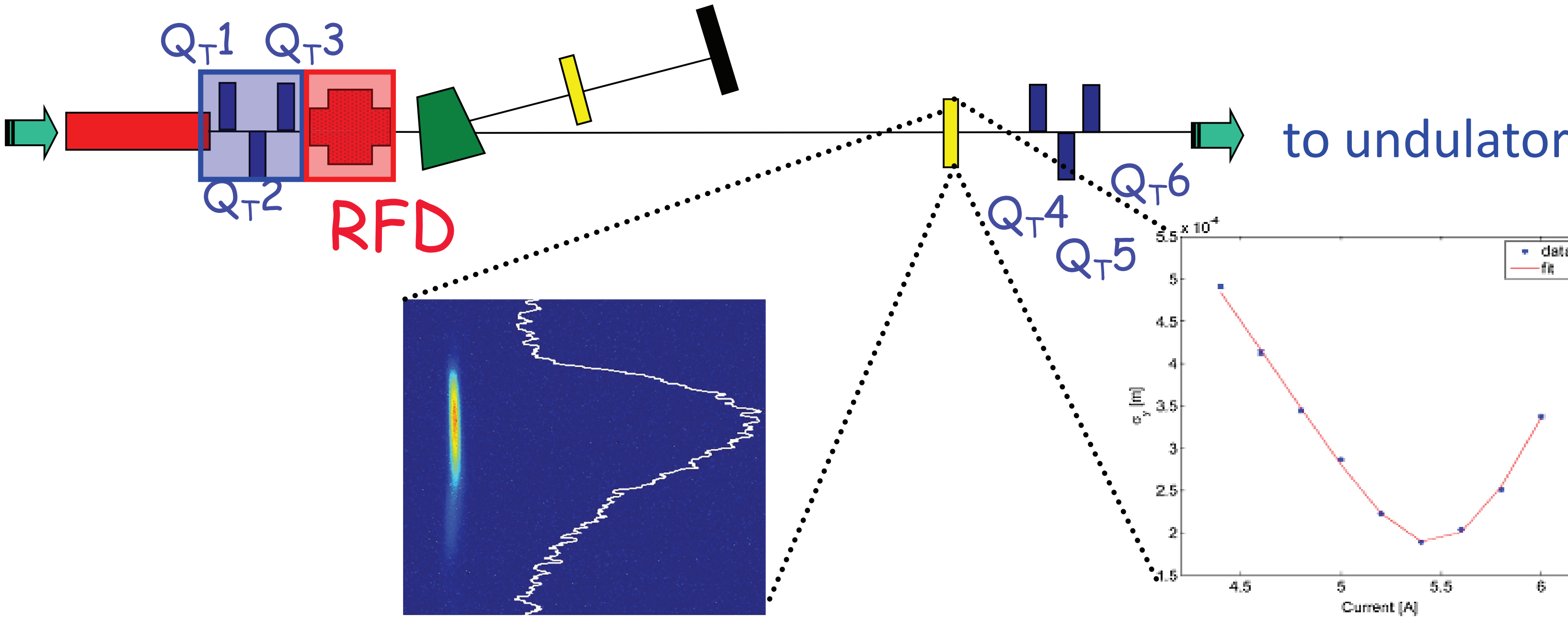

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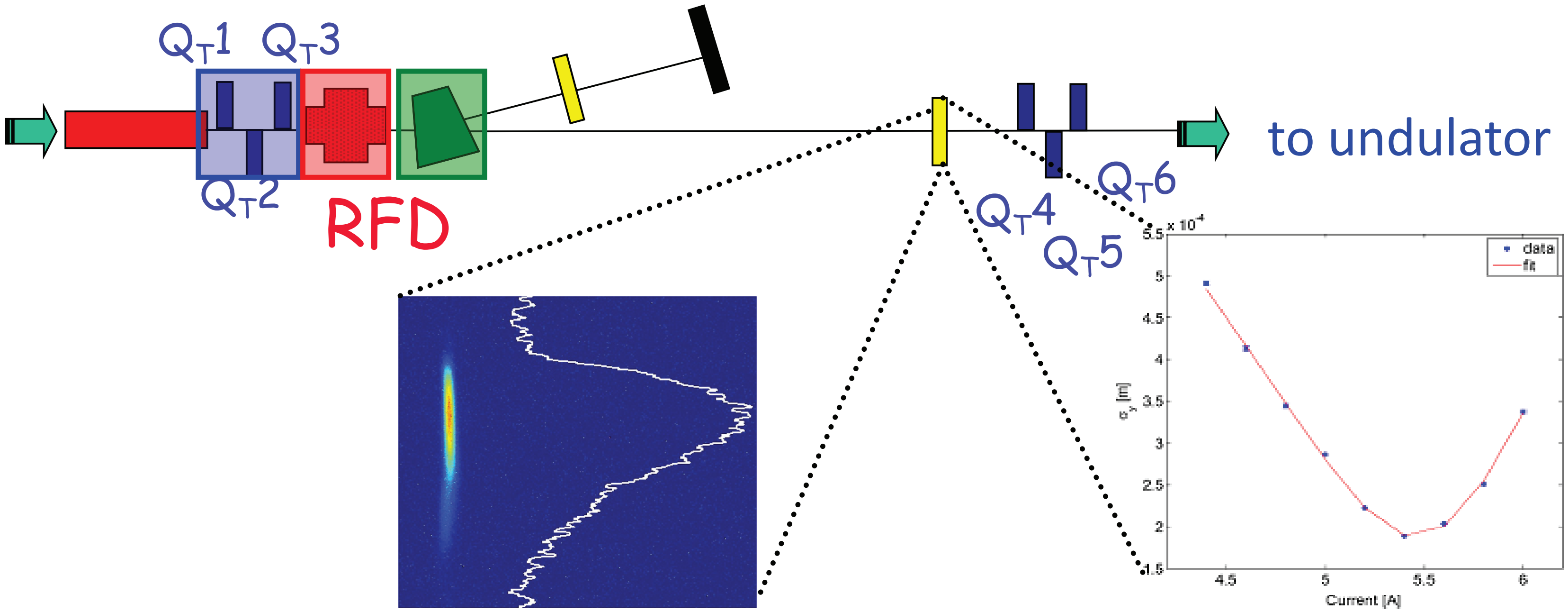

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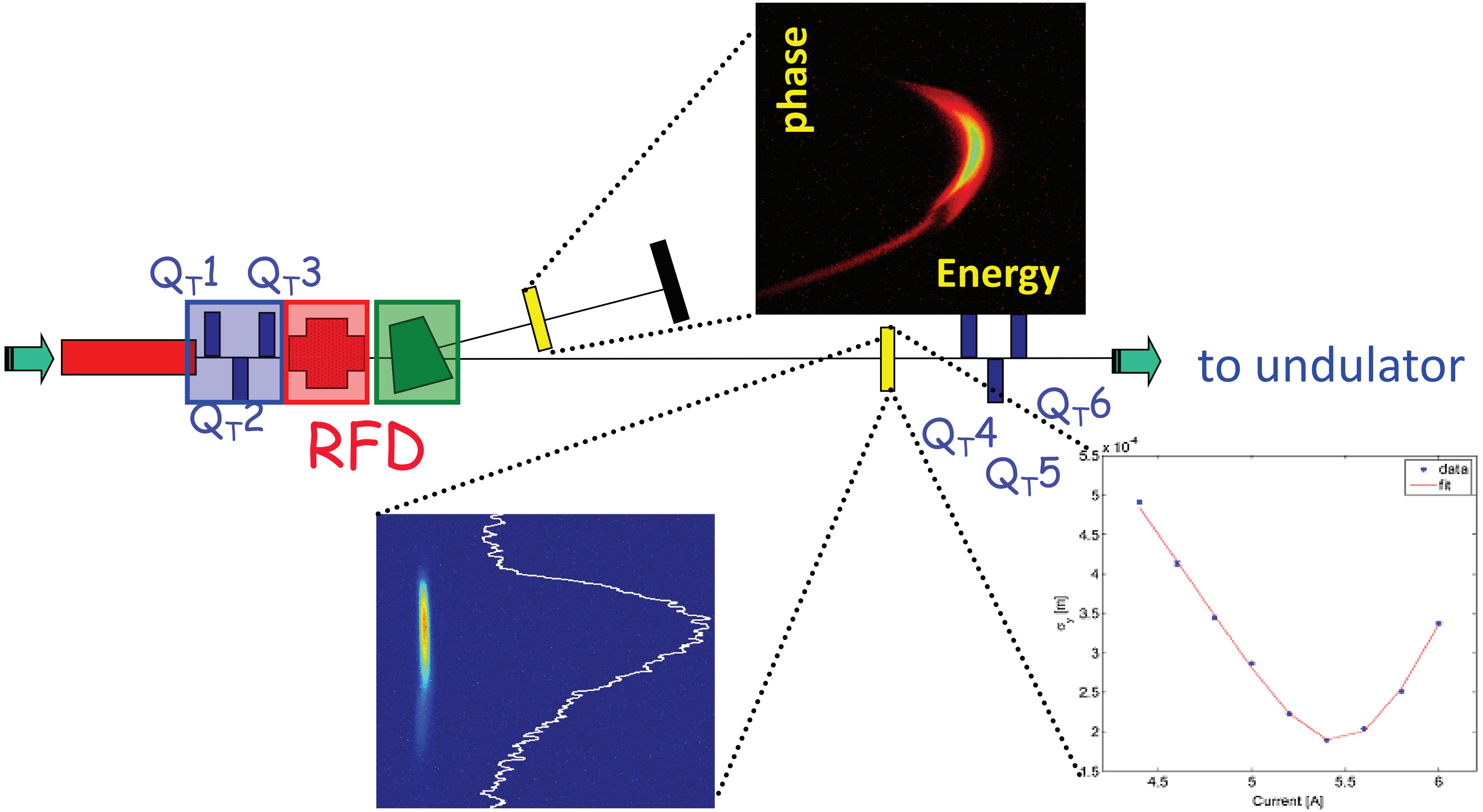

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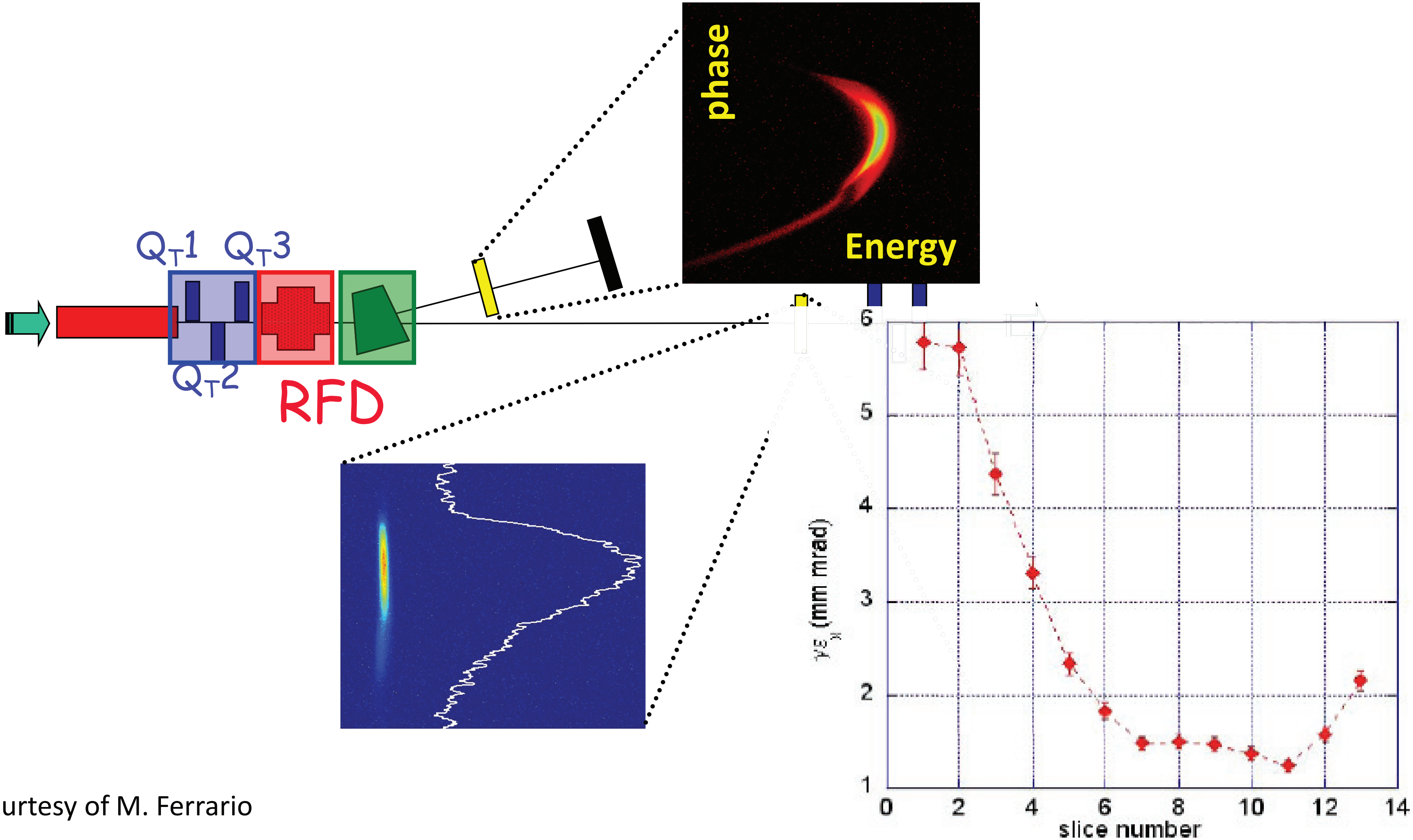


Courtesy of M. Ferrario

WP3: Summary

The work will be divided in four tasks:

- **Evaluation of a high-gradient C-band injector and S-band injector inclusive of X-band linearizer and a magnetic chicane.**

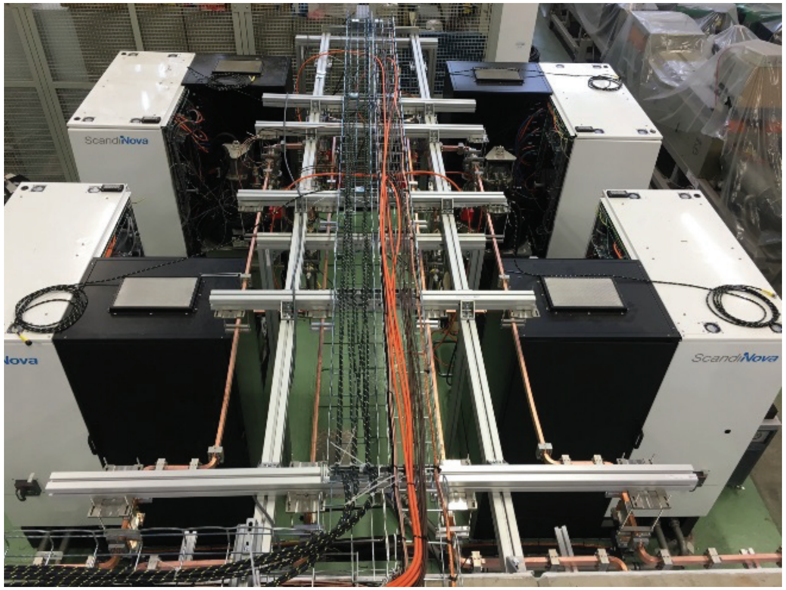
- **Evaluation of an innovative full-X-band injector, inclusive of a higher-harmonic linearization in the K band.** This ambitious goal aims to advance the recent achievements in the design of X-band guns and to explore the feasibility of RF components at unprecedented frequencies such as the K band.

- **Phase-space linearisers, and options for compact magnetic chicanes to achieve longitudinal bunch compression)**. Diagnostics tool based on X-band deflecting transverse cavity will also be considered

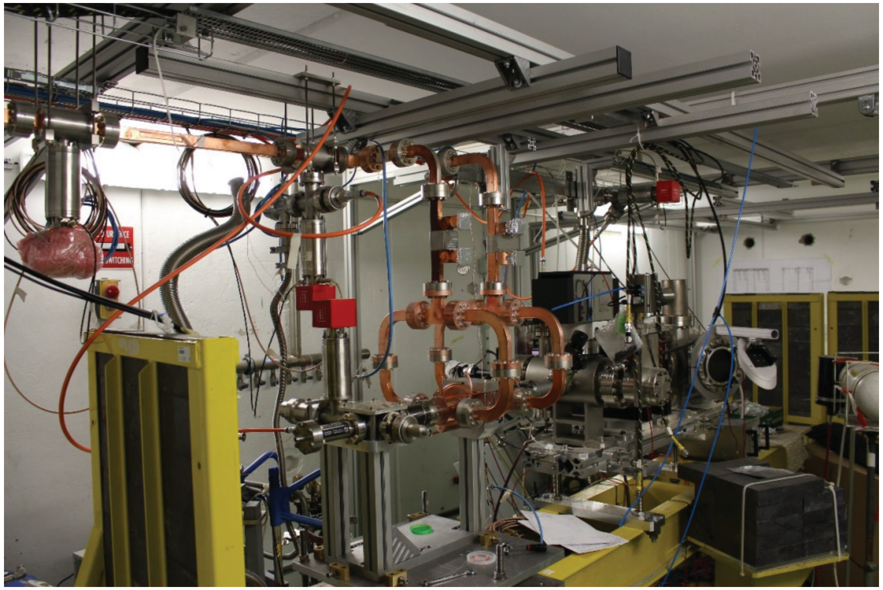
- **Design of CompactLight e-gun and injector inclusive of linearizer and a magnetic chicane**.

WP4: RF Systems

- Lead Institute: CERN (W. Wuensch)
- Main Tasks
  - Accelerator Structure design and optimization
  - Prototype testing in XBoxes and CLEAR, synergy with TNA in ARIES
  - High stability LLRF, timing, control
  - RF system studies including improvements exploiting new ideas on high efficiency klystrons

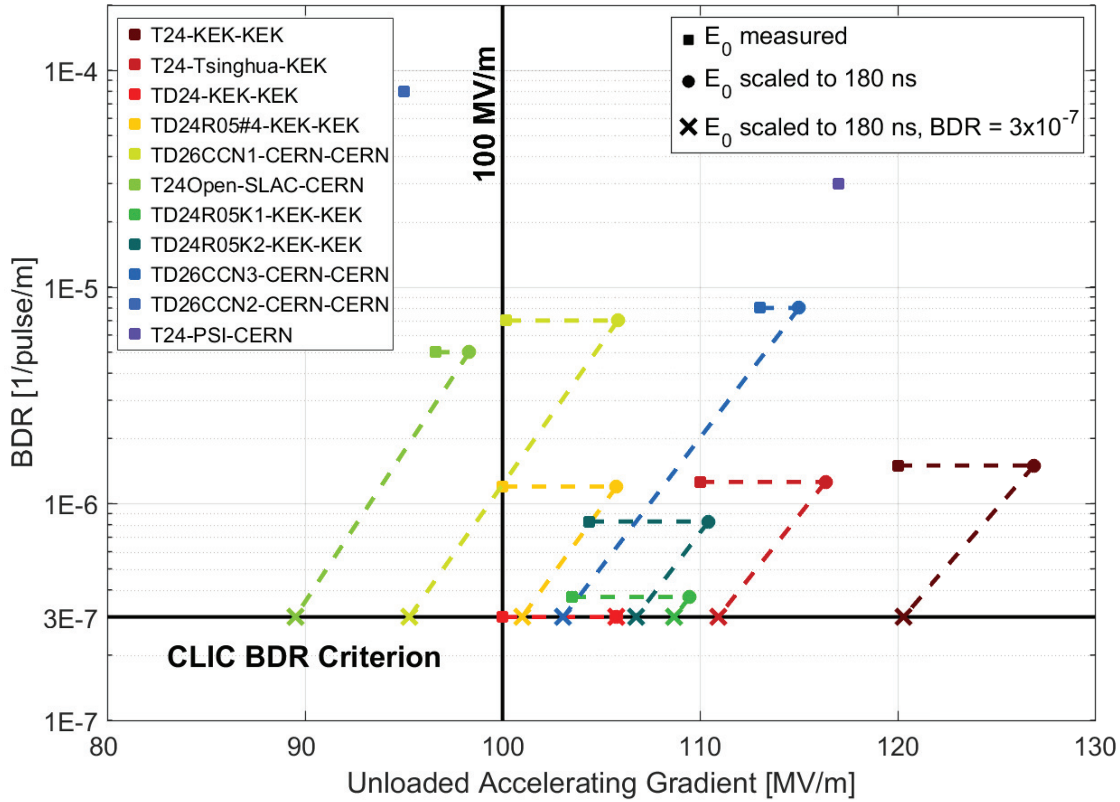


XBox-3: 50 MW, 400 Hz



XBox-3: Structure under test

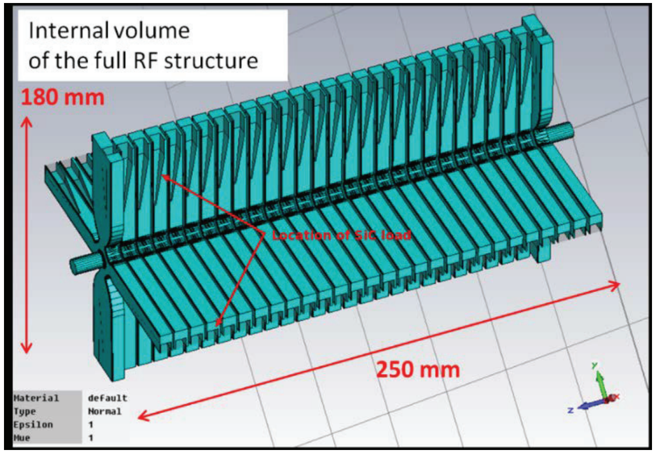
CLIC accelerating structure: Achieved 100 MV/m gradient in main-beam RF cavities



XLS Target : 65 - 70 MV/m

CLIC X-band Accelerating Structure

Structure name	CLIG-G TD26cc
Work frequency	11.994GHz
Cell	26 regular cells+ 2 couplers
Length (active)	230mm
Iris aperture	2.35mm - 3.15mm



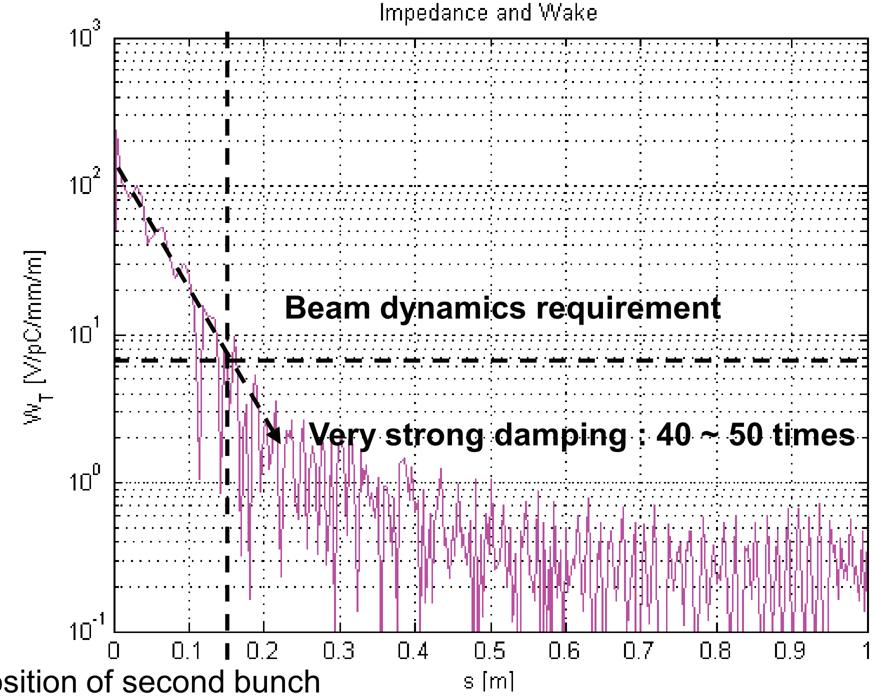
CLIC train: 354 bunches in 177 ns, 5 nm V emittance

Transverse long-range wakefield calculation using Gdfidl code:

Peak value :
250 V/pC/m/mm

At position of second bunch (0.15m):
5~6 V/pC/m/mm

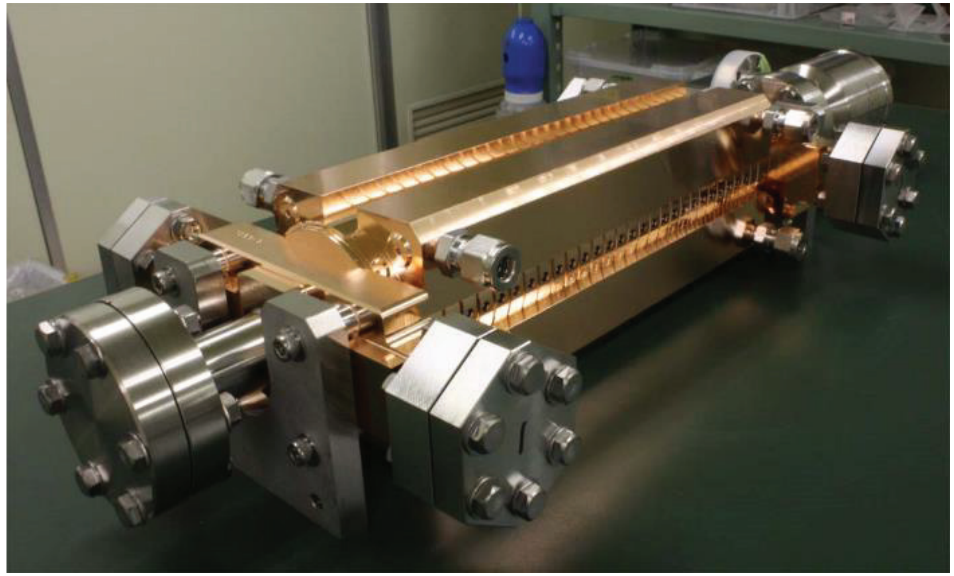
Beam dynamic requirement:
< 6.6 V/pC/m/mm



Position of second bunch

CLIC Accelerating Structure: Prototyping

Outside

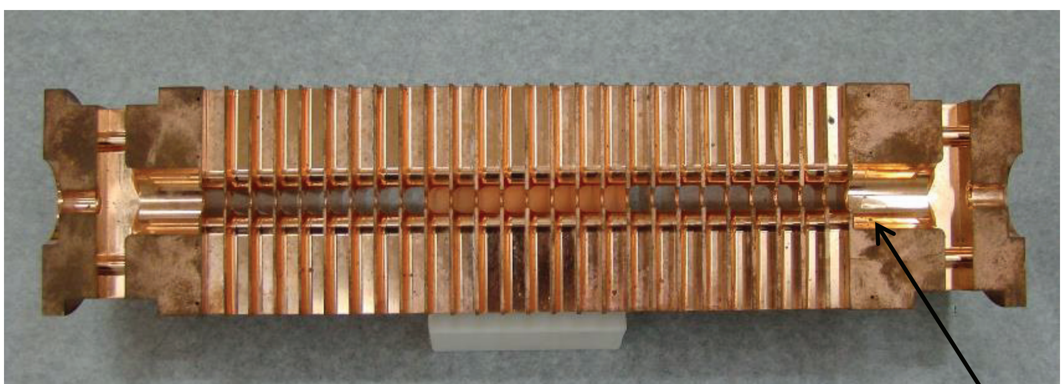


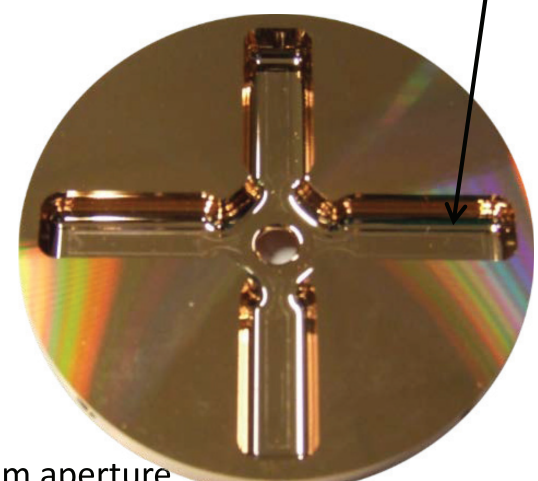
11.994 GHz X-band
100 MV/m
Input power ≈50 MW
Pulse length ≈ 200 ns
Repetition rate 50 Hz

HOM damping waveguide

Inside

Micron–precision disk





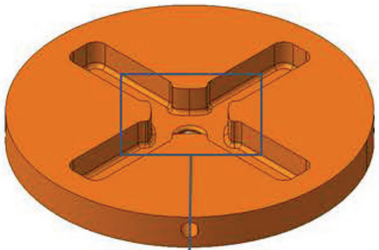
25 cm

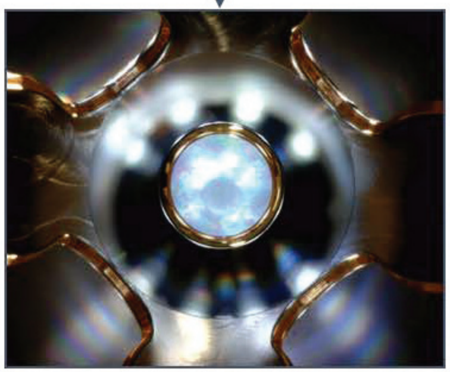
6 mm diameter beam aperture

CLIC AS: Assembly, towards industrialization

Compact

AS DISC



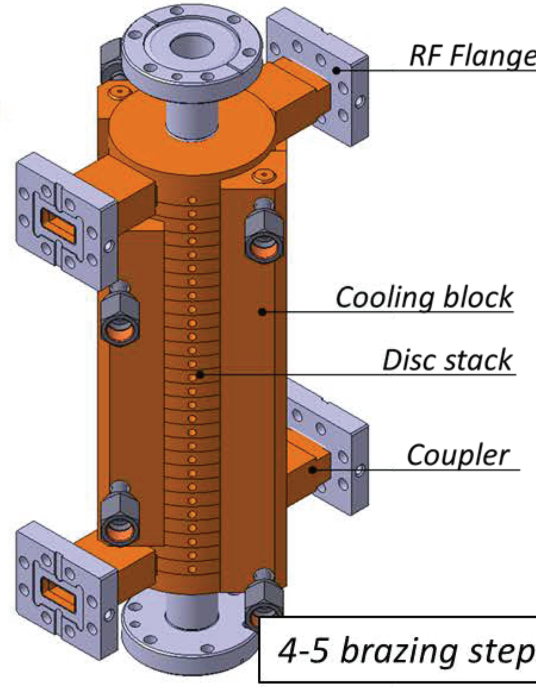


AS DISC STACK BONDING

Acceptance at CERN

AS ASSEMBLY

Acceptance at CERN



4-5 brazing steps

Cell shape accuracy - 0.004 mm
Flatness - 0.001 mm
Surface roughness - Ra 0.025 µm

REQUIREMENTS:

- Alignment
- Special tooling
- Clean environment

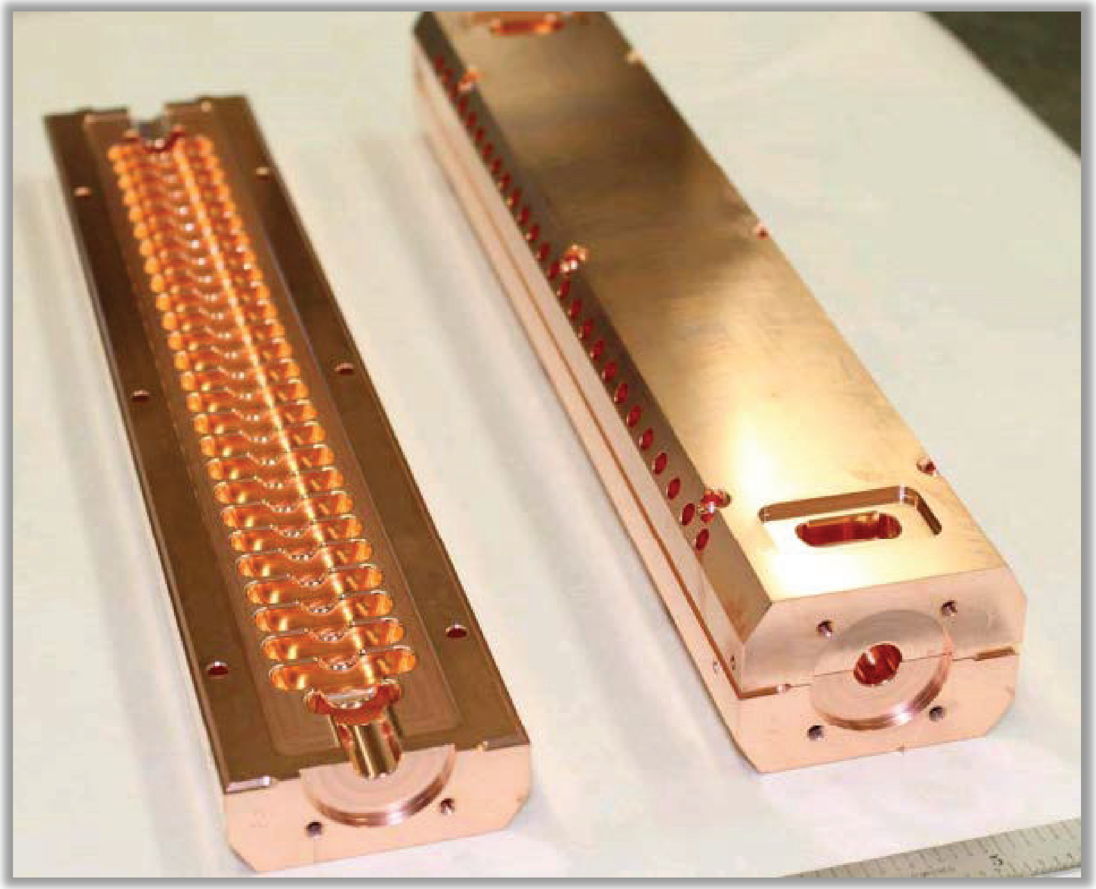
Commercial suppliers:

- 4 qualified companies for UP machining;
- Single-crystal diamond tool required.

Suppliers:

- 3 qualified companies for brazing/bonding operations, supervision by CERN;
- Collaborators.

CLIC AS: Assembly, towards industrialization



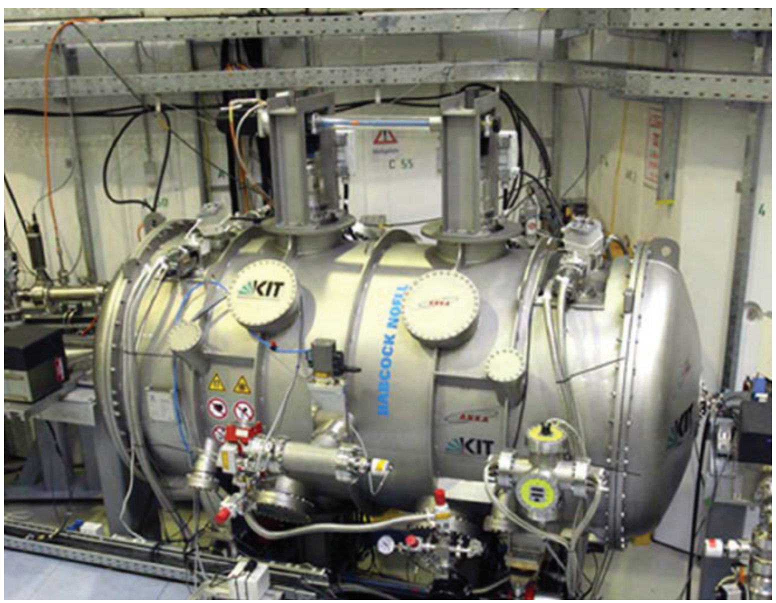
Alternative assembly scheme: building structures from two halves and using hard copper → significantly reduced fabrication costs, including vacuum brazing.

WP5: Undulators and Light Production

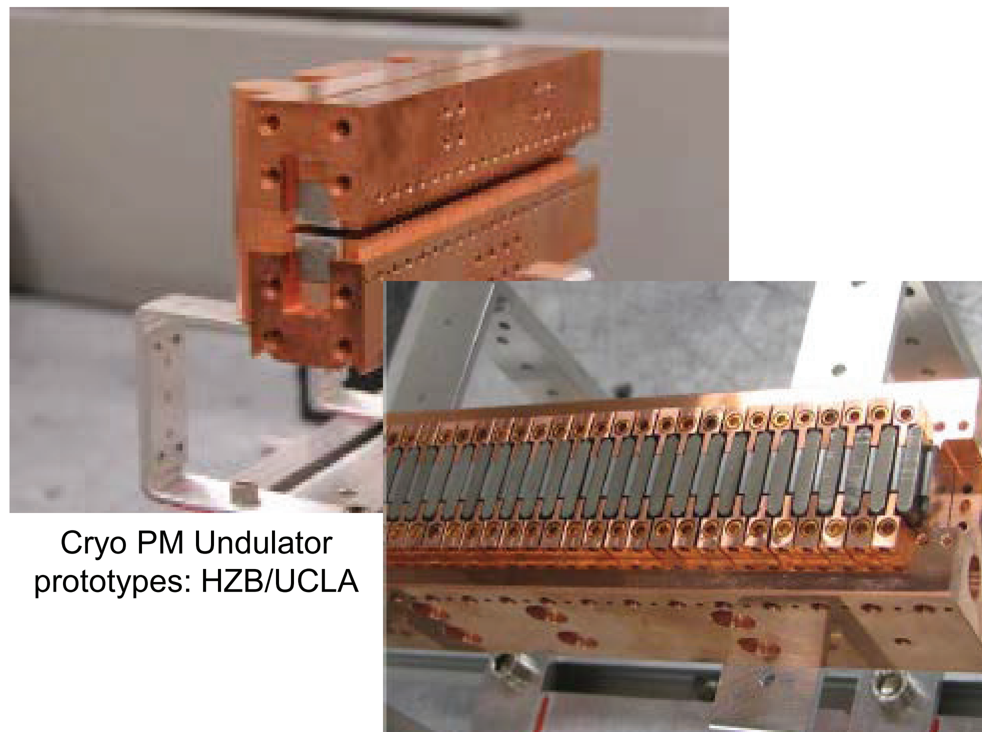
- The main cost driver for an FEL is the beam energy.
- By taking advantage of the latest technological undulator innovations, including anticipating further advances that will be proven in the coming few years, we will be able to lower the electron beam energy requirement significantly.
- A new generation of superconducting undulators for FELs with very low average beam currents, and consequently much smaller wakefield induced heat loads (taking account the much smaller bunch lengths) on the cryogenic vacuum beam screen, are able to operate with a similar magnet beam aperture as permanent magnet undulators.
- In this case preliminary calculations suggest that an XFEL could generate 0.1 nm wavelength output at only 4.6 GeV, a ~20% reduction in beam energy.

WP5: Undulators and Light Production

- Lead Institute: ENEA (G. Dattoli, F. Nguyen)
- Main Tasks
  - Comparative studies of “ambitious” undulators on the timescale of 4-5 years, matched to overall design: eg cryo permanent-magnet, super-conductive undulators
  - Similarly for Compton Back Scattering: state-of-the-art, future capabilities
  - FEL modelling and optimisation
  - CBS output modelling



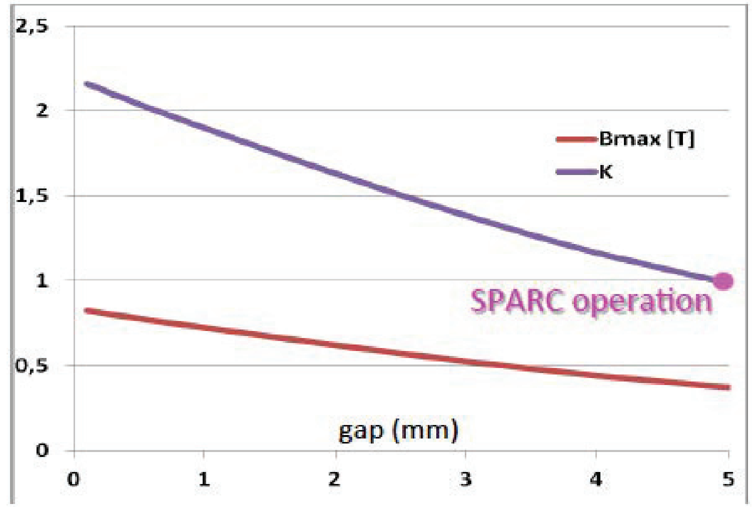
Superconducting Undulator installed at KIT

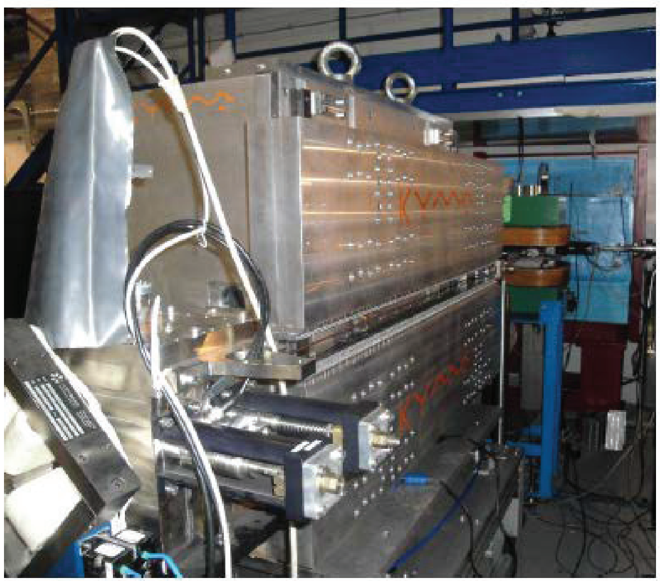

Cryo PM Undulator prototypes: HZB/UCLA

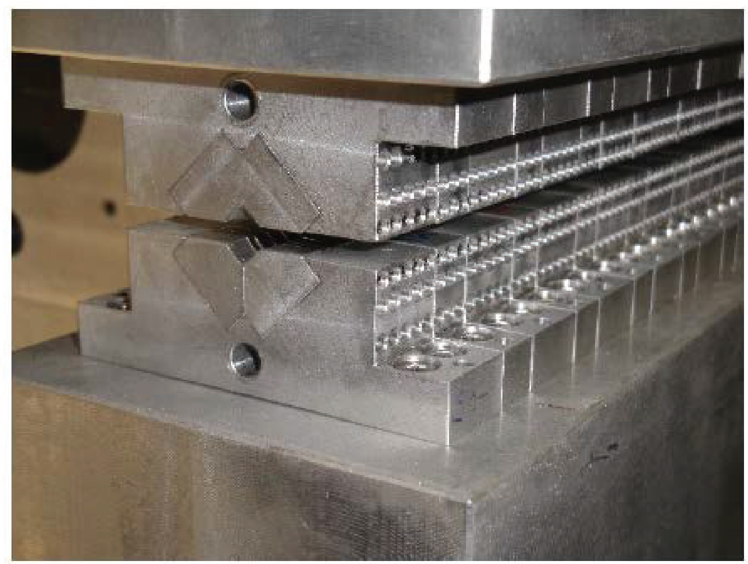
Kyma ∆ Undularor:
Designed by ENEA Frascati
Constructed dy Kyma Trieste
Tested with beam at SPARC_LAB

- DELTA like undulator
  λ_u = 1.4 cm, gap g = 5mm, Br = 1.22T.

Undulator tested in two stage SASE-FEL:
630nm to 315 nm

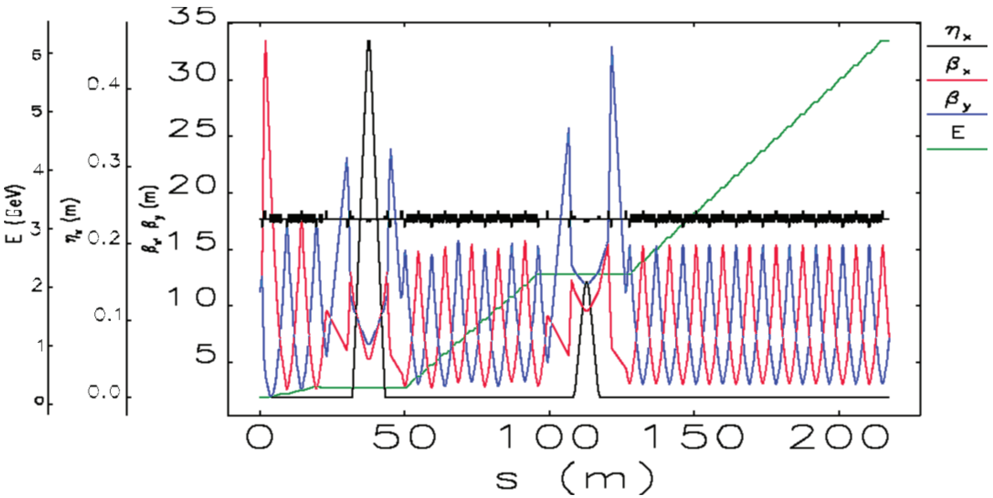






ENEA INFN

- Lead Institute: UA-IAT Ankara (A. Aksoy)
- Main Tasks
  - Modelling and optimisation of physics layout
  - Start-to-end simulations
  - Delivery of consistent tools, cost estimate, beam parameters for all options



Simulations for Turkish X-band FEL accelerator section, Ankara University

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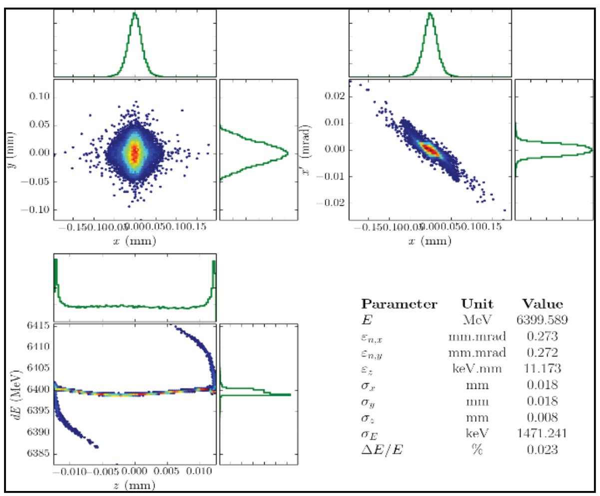
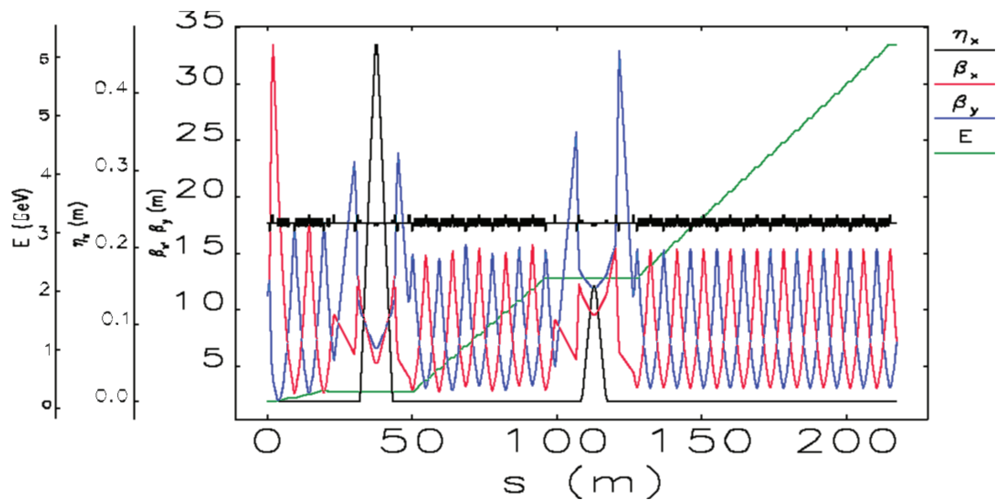
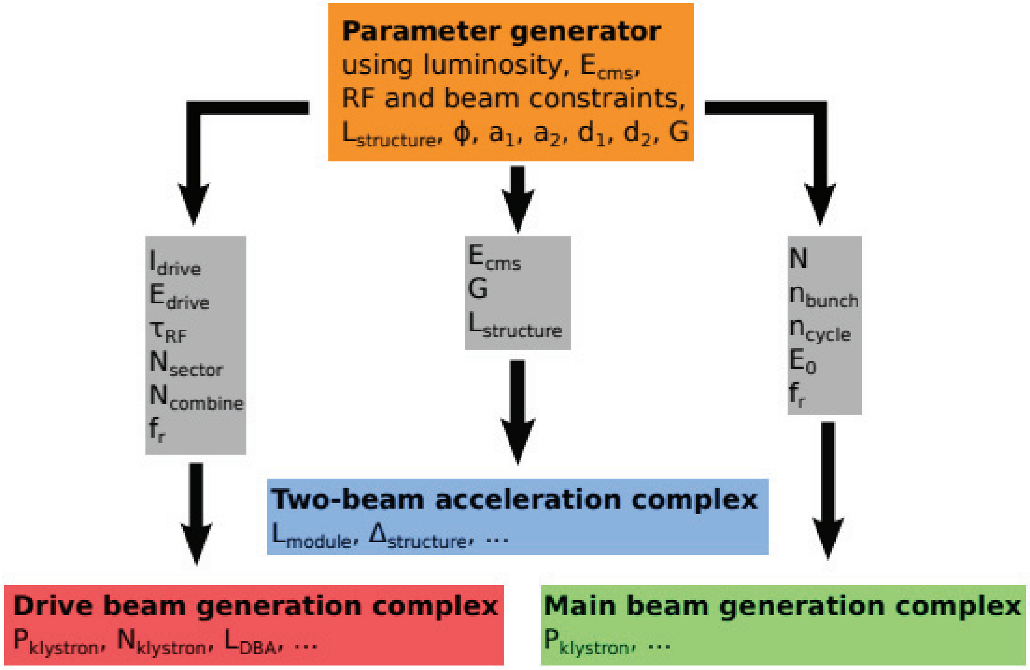




Simulations for Turkish X-band FEL accelerator section, Ankara University

CLIC Study

- Accelerator structure design fixed by few parameters ($L_{\text{structure}}$, Φ, ...)
- Find optimal parameter set for 380 GeV CLIC accelerator in parameter scan



- Evaluation tool exists, developed after CDR, based on methods already used in CDR
- Tested ~2 billion possible structures and resulting accelerator complexes based on these parameters

- All structures are checked for consistency with beam and RF constraints
- Gauging cost, power and luminosity (not including beam induced backgrounds)

Courtesy of the CLIC Study

WP6: RF Module (preliminary)

XLS Preliminary RF structure parameters

Parameter	Value
Length L	0.75m
Phase advance per cell φ	120°
First iris aperture a1/λ	0.15
Last iris aperture a2/λ	0.1
First iris thickness d1	0.9mm
Last iris thickness d2	1.7mm
Fill time τ	150ns
Operational gradient G	65MV/m
Input power Pin	41.8MW

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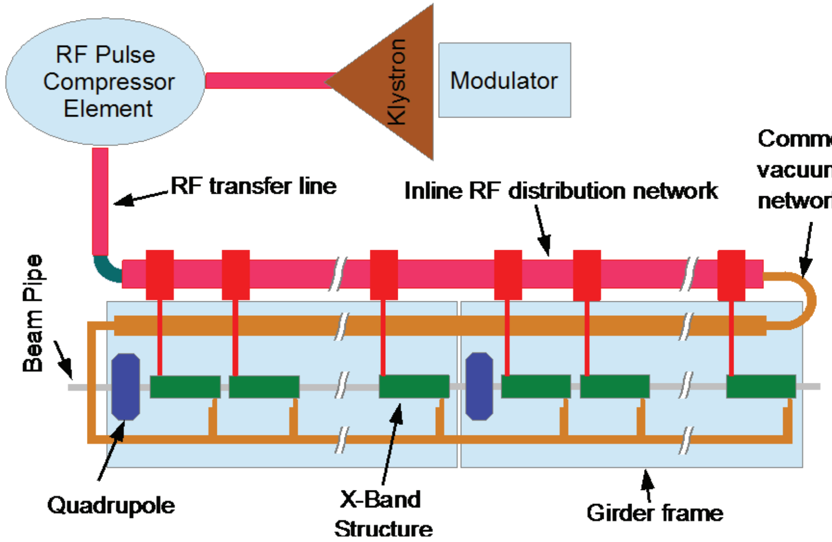

WP6: RF Module (preliminary)

Compact

XLS Preliminary RF structure parameters

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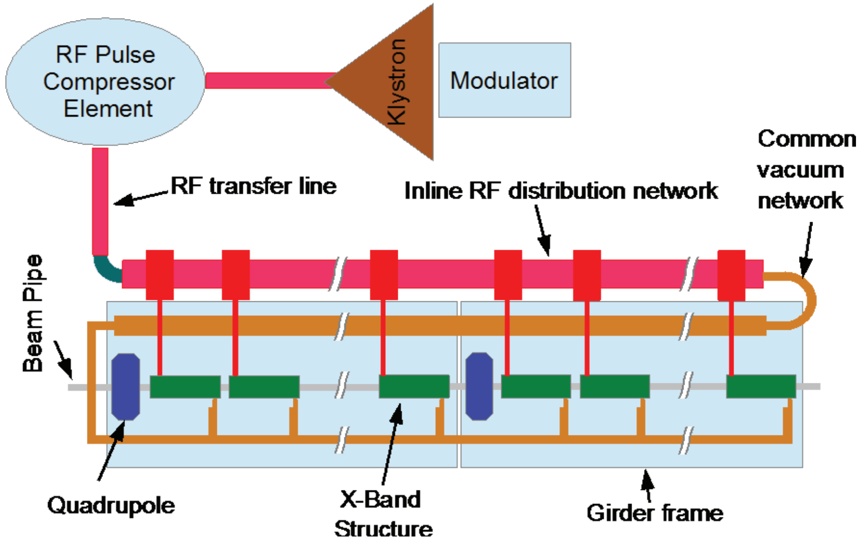

- Each RF units consists of a pair of 50 MW klystrons, like the commercial units currently in use in the CLIC X-Boxes, operated at 45MW and producing a 1.5 ⌠s long pulse.
- The pulses are combined and compressed to 150 ns in a pulse compressor, increasing its power by a factor 5.2.
- The final pulse then is distributed to feed 10 accelerating structures with 42MW (assuming a loss of 10% in the waveguide system).

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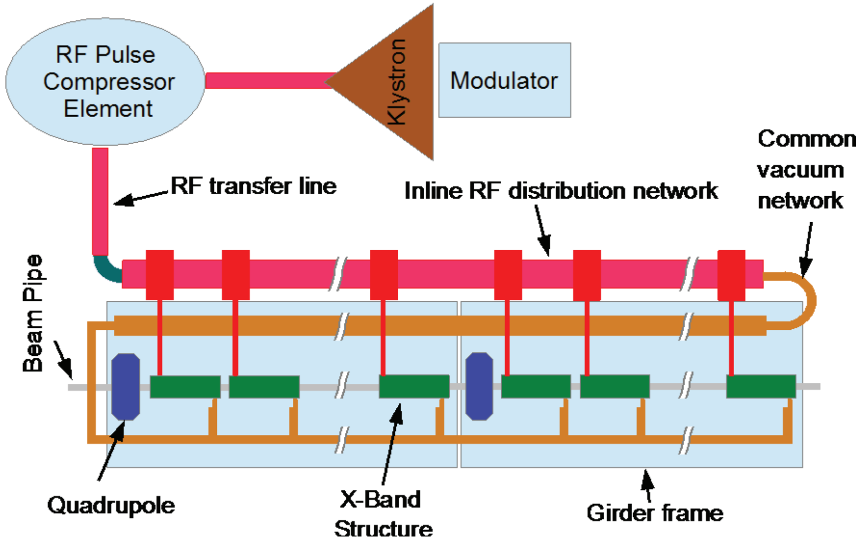

	unit	XLS X-band	SwissFEL C-band
Structures per RF unit		10	4
Klystrons per RF unit		2	1
Structure length	m	0.75	1.98
Allowed gradient	MV/m	80+	
Operating gradient	MV/m	65	27.5
Energy gain per RF unit	MV	488	203
Klystron nominal power	MW	50	50
Power in operation	MW	45	40
Klystron pulse length	µs	1.5	3
RF energy/pulse/GeV	J	277	591

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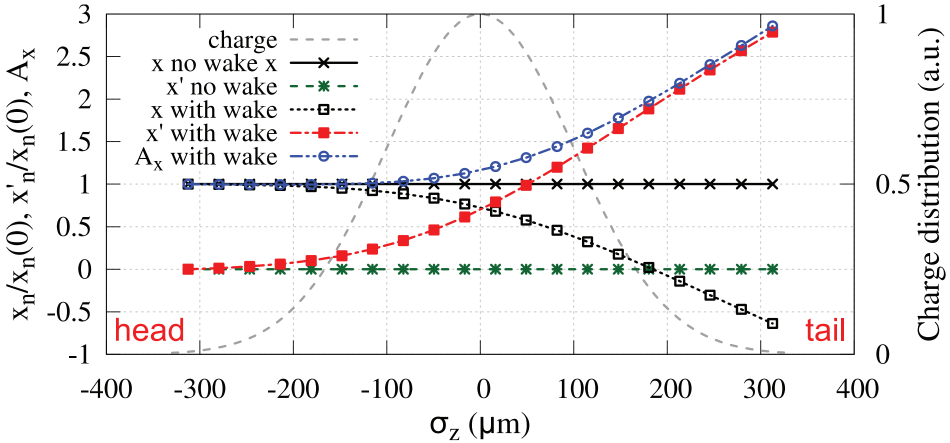
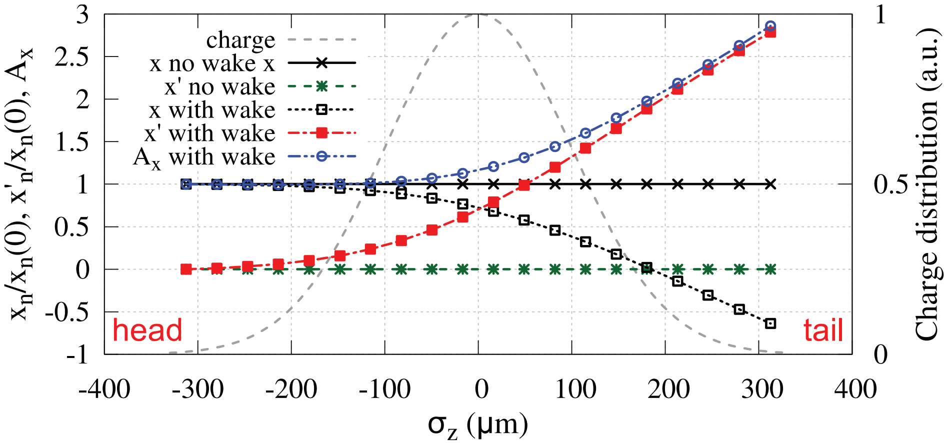
WP6: Beam Stability



Bunch stability to transverse wakefields

$$A_x \approx N\,e^2 \cdot \Delta W_{1,\perp} \cdot L_{\mathrm{struct}} \int_0^L \frac{\beta(s)}{E(s)} ds.$$

We target $A_x < 1.5$.



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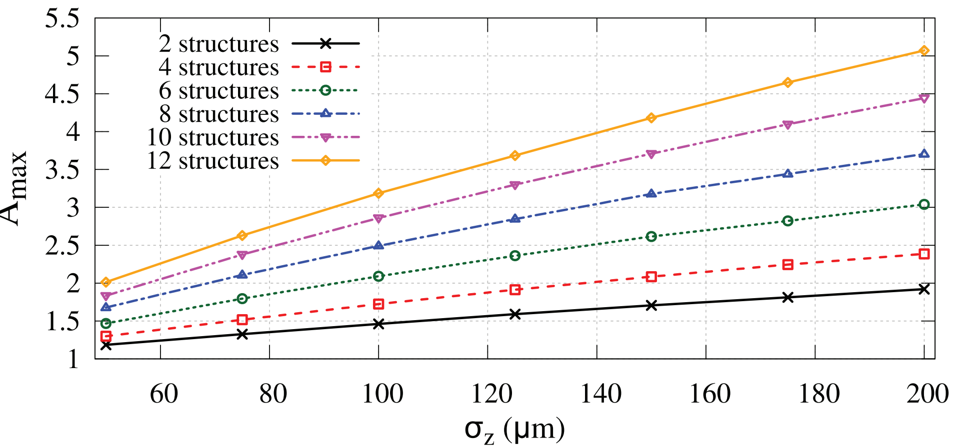

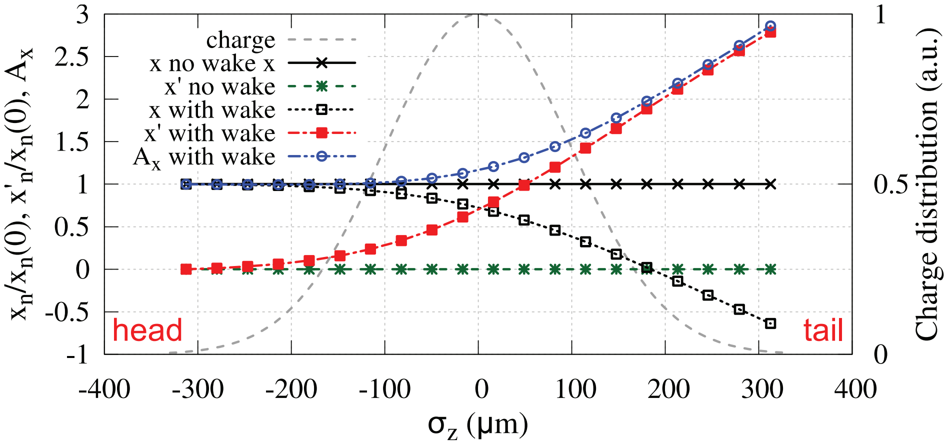

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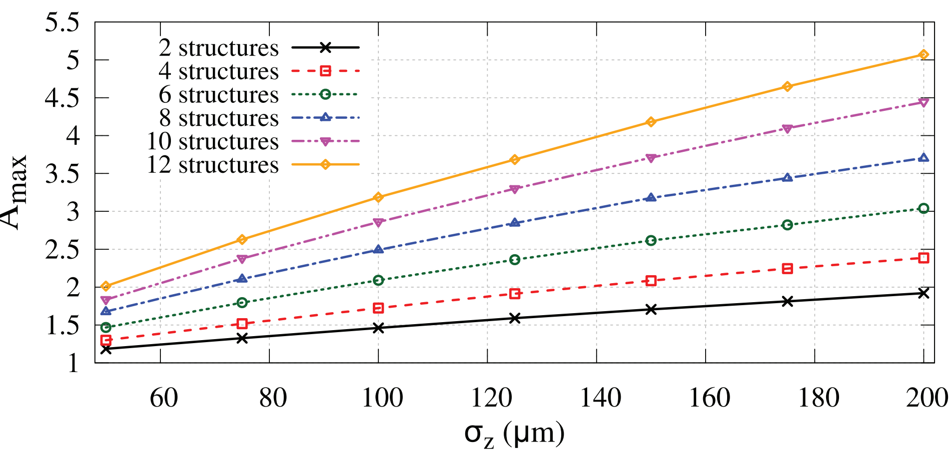
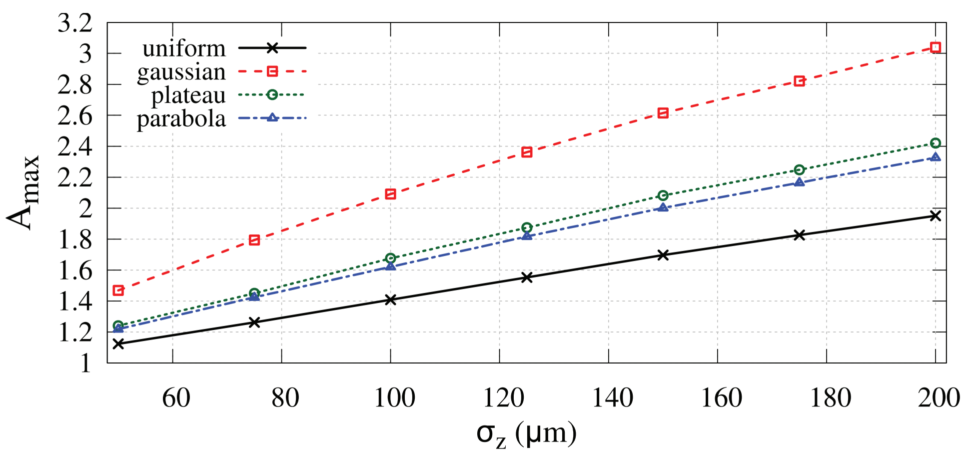
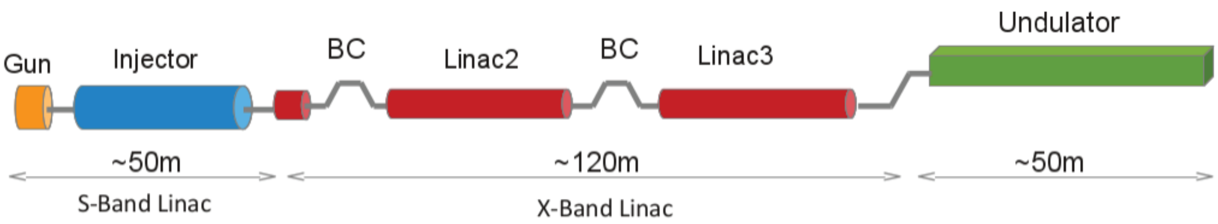
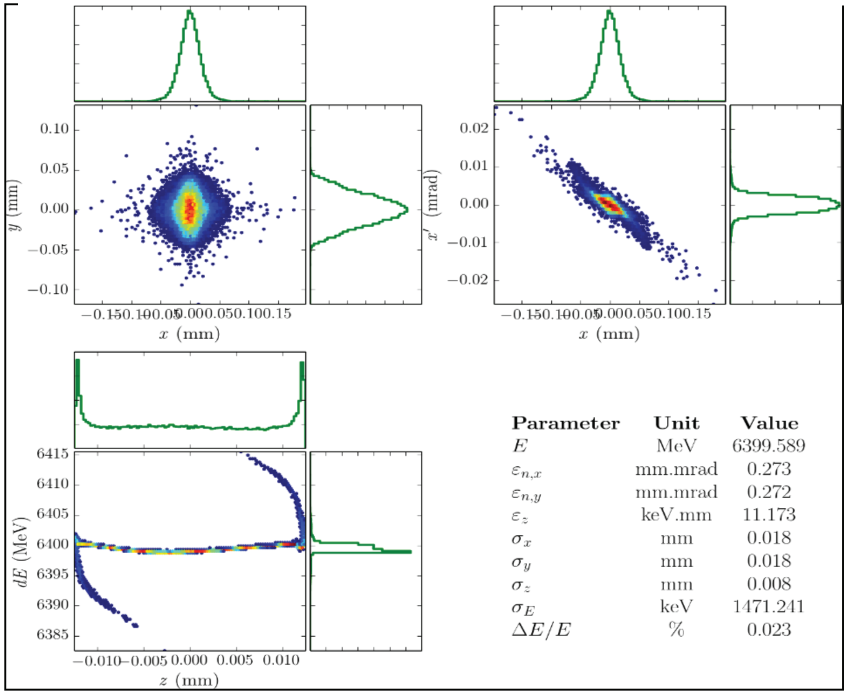




WP6: Start-to-end Electron Beam Simulation

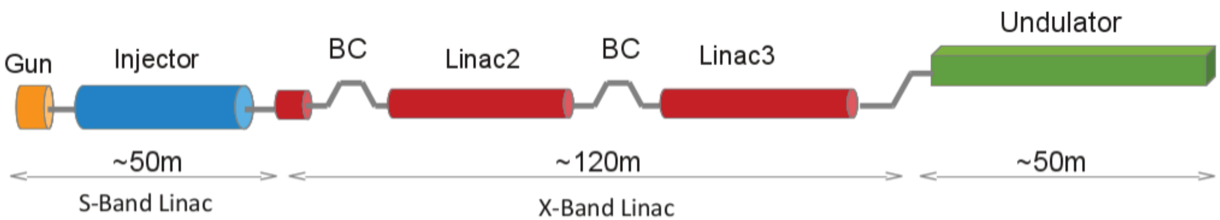


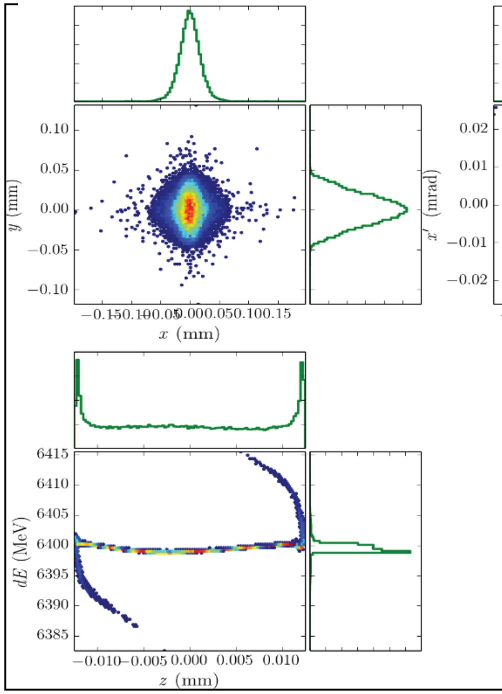


Parameter	Unit	Value
E	MeV	6399.589
$\varepsilon_{n,x}$	mm.mrad	0.273
$\varepsilon_{n,y}$	mm.mrad	0.272
ε_z	keV.mm	11.173
σ_x	mm	0.018
σ_y	mm	0.018
σ_z	mm	0.008
σ_E	keV	1471.241
$\Delta E/E$	%	0.023

ELEGANT simulation

WP6: Start-to-end Electron Beam Simulation





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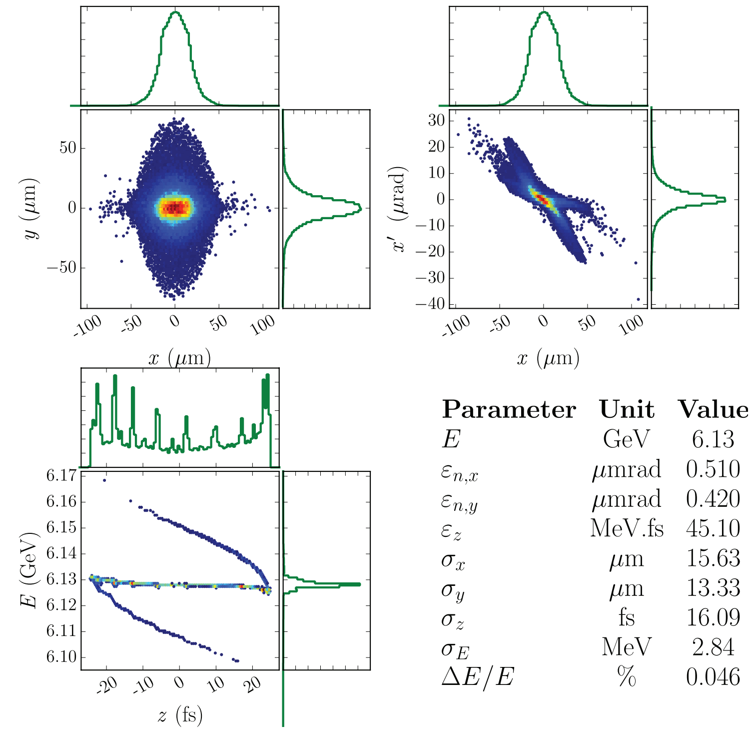
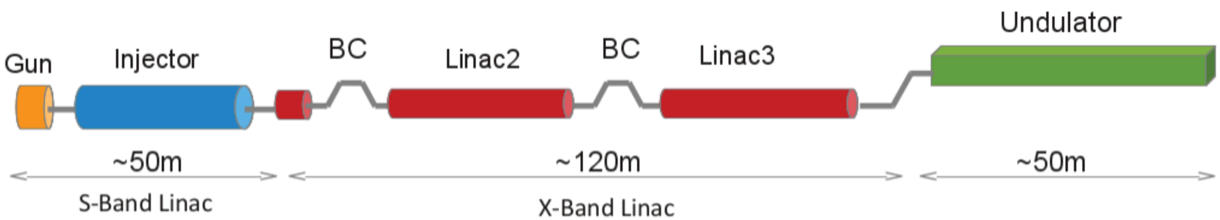


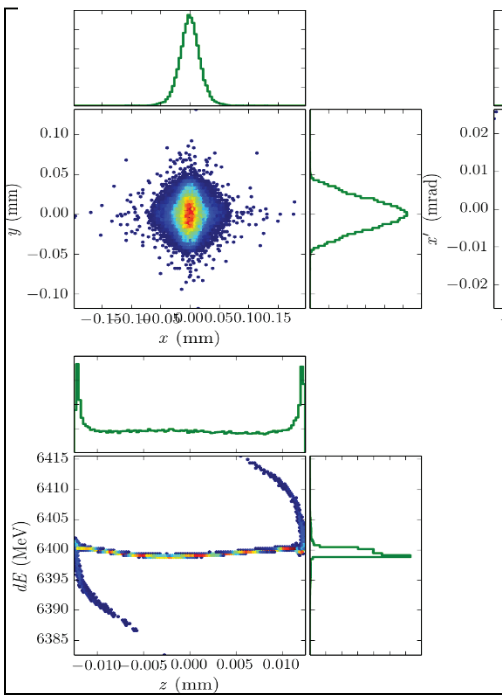
Parameter	Unit	Value
E	GeV	6.13
$\varepsilon_{n,x}$	μmrad	0.510
$\varepsilon_{n,y}$	μmrad	0.420
ε_z	MeV.fs	45.10
σ_x	μm	15.63
σ_y	μm	13.33
σ_z	fs	16.09
σ_E	MeV	2.84
$\Delta E/E$	%	0.046

ELEGANT simulation

WP6: Start-to-end Electron Beam Simulation

Compact





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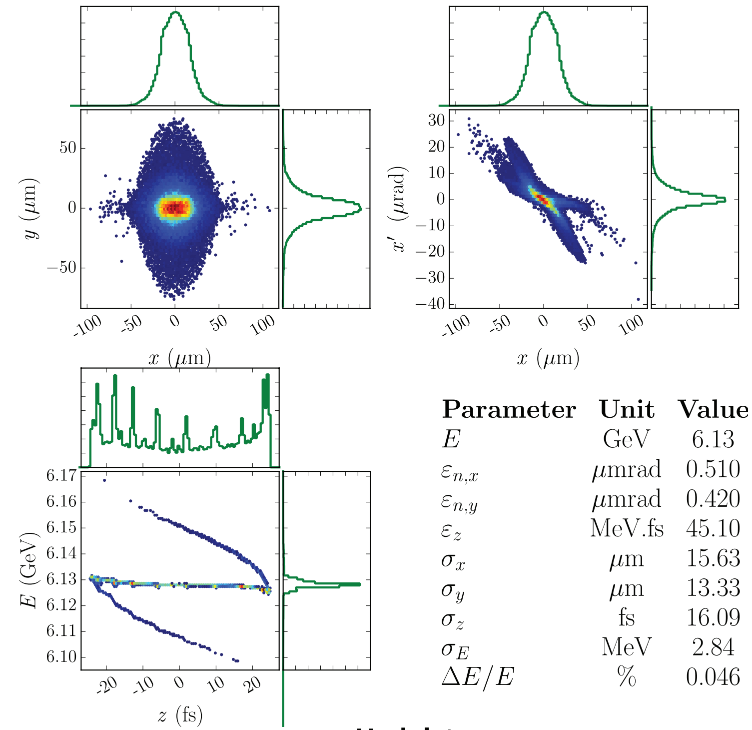

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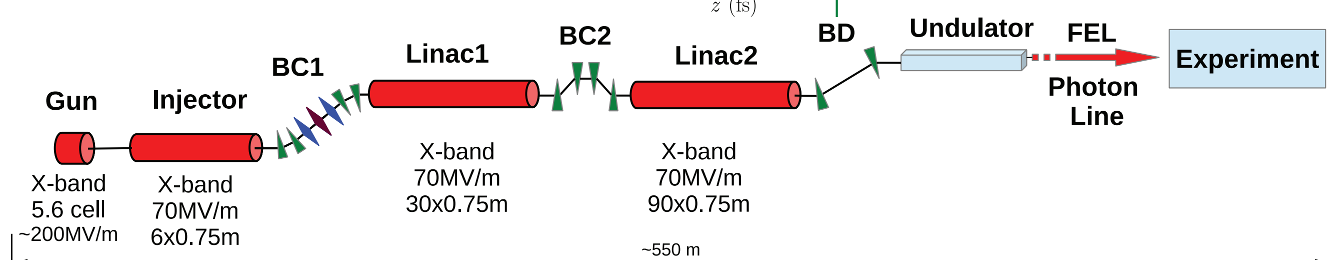
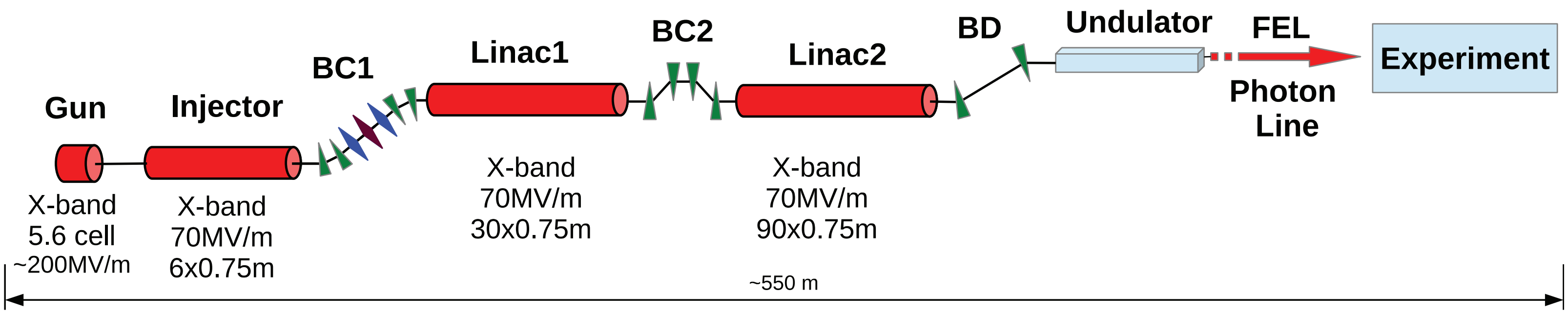


ELEGANT simulation

WP6: Electron Beam Performance

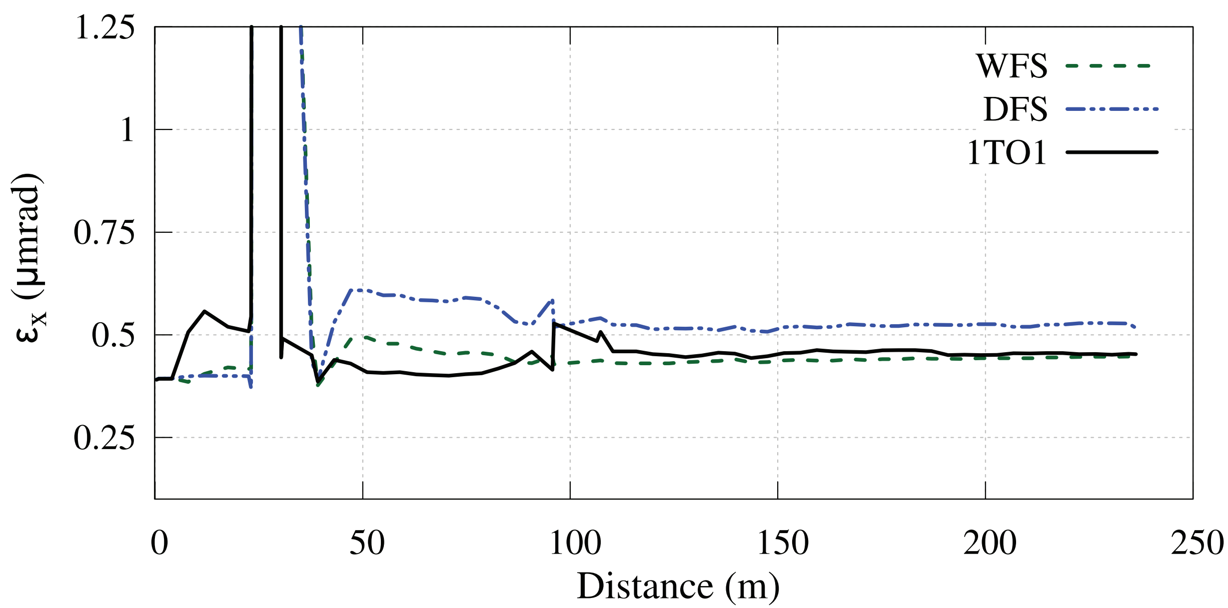


Static imperfections:

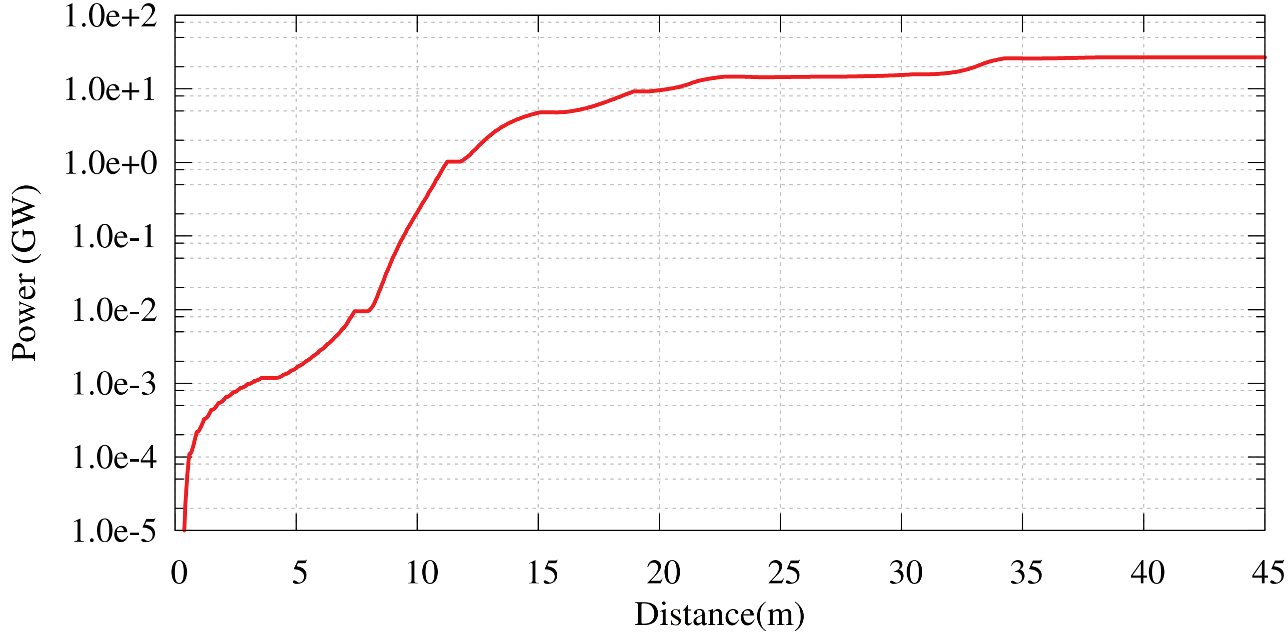
- 100 µm rms misalignment
- 5 µm bpm resolution
- 100 µrad rms pitch error

Beam-based alignment:

- Orbit steering
- Dispersion-free steering (DFS)
- Wakefield-free steering (WFS)
- (optionally, RF alignment)



PLACET simulation of 100 random configurations (average of)



Undulator parameters
λ_u= 1.5 cm period
K = 1
Average β-function = 10 m

Parameter	Value	Unit
Electron energy	6	GeV
Wavelength	0.1	nm
Photon energy	12.3	keV
Saturation length	35	m
Effective power	20	GW
Pulse duration	<50	fs
Photons per pulse	5e11	#

GENESIS simulation

Compact

- CompactLight has just started
- A lot of exciting work ahead
- First project review in Trieste June 19-20, 2018
- Stay tuned!

http://compact-light.web.cern.ch

Compact

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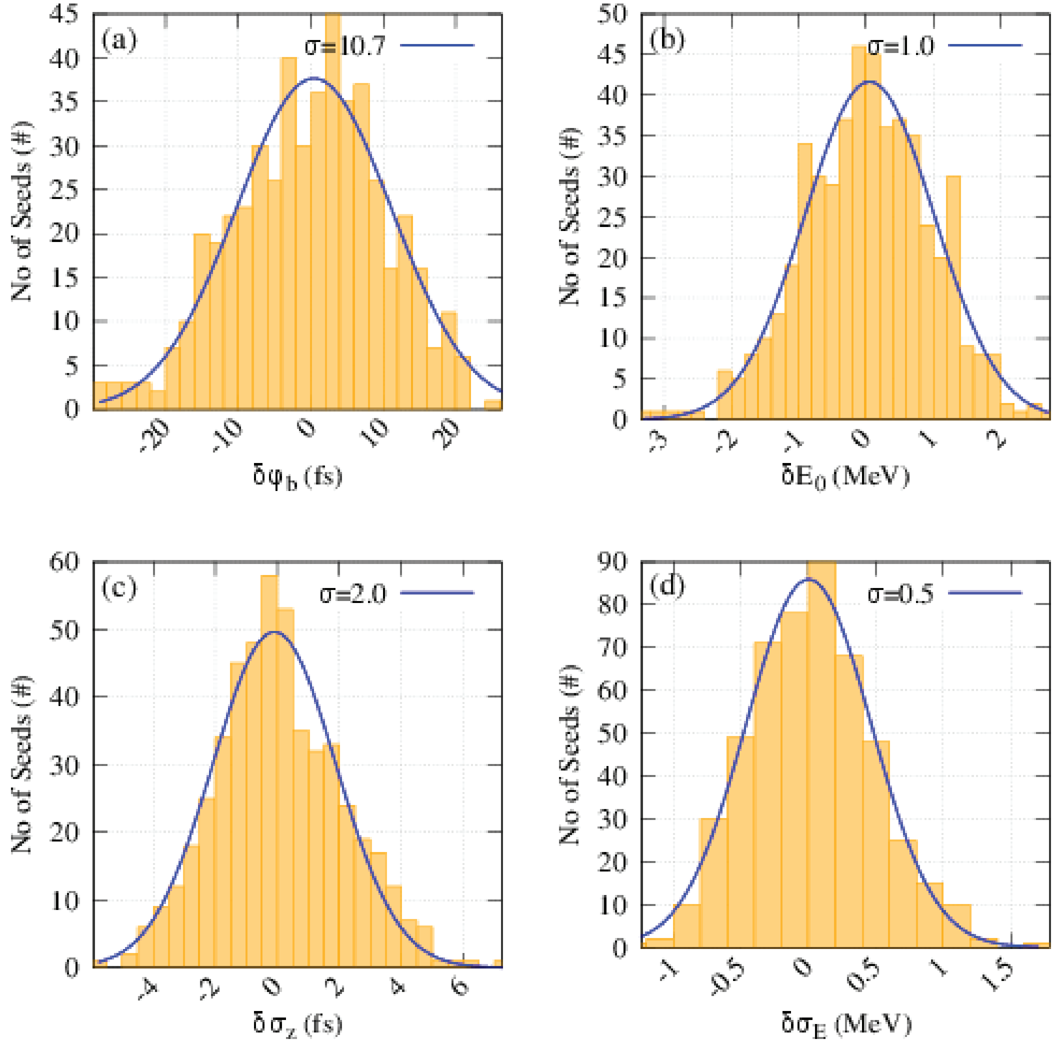
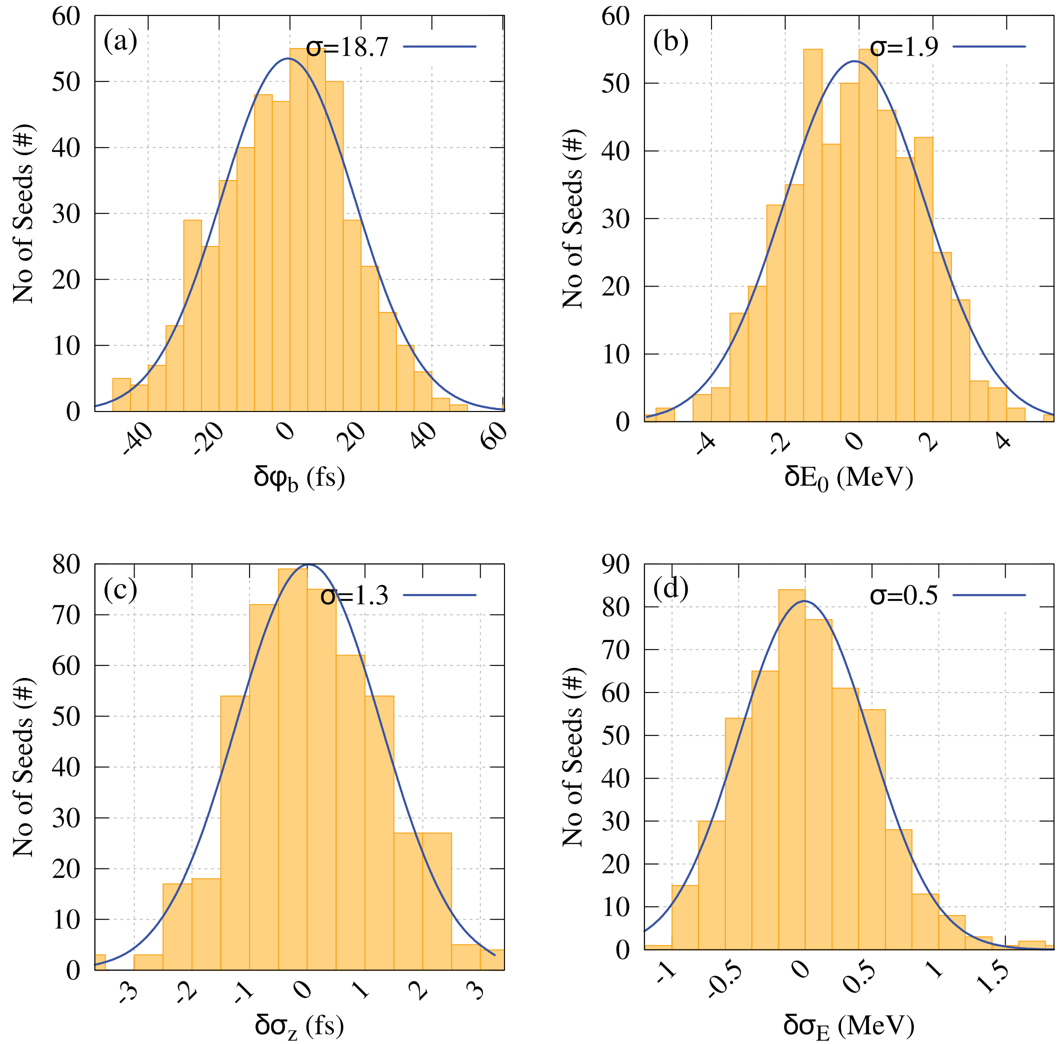
Extras: Longitudinal Stability – Gradient error



a) Bunch arrival time error, b) Beam energy error, c) Bunch length error d) Beam energy spread error versus 0.1% RF amplitude (RF gradient) error

Extras: Longitudinal Stability – Phase error



a) Bunch arrival time error, b) Beam energy error, c) Bunch length error d) Beam energy spread error versus 0.1% RF phase incoherent error