A Compact ICS Source Based on X-band Technology and Cavity-enhanced High-Average-Power Ultrafast Lasers

Andrea Latina, V. Muşat, R. Corsini, L.A. Dyks, E. Granados, A. Grudiev, S. Stapnes, P. Wang, W. Wuensch (CERN, Geneva, Switzerland), E. Cormier, G. Santarelli (LP2N, Talence, France)

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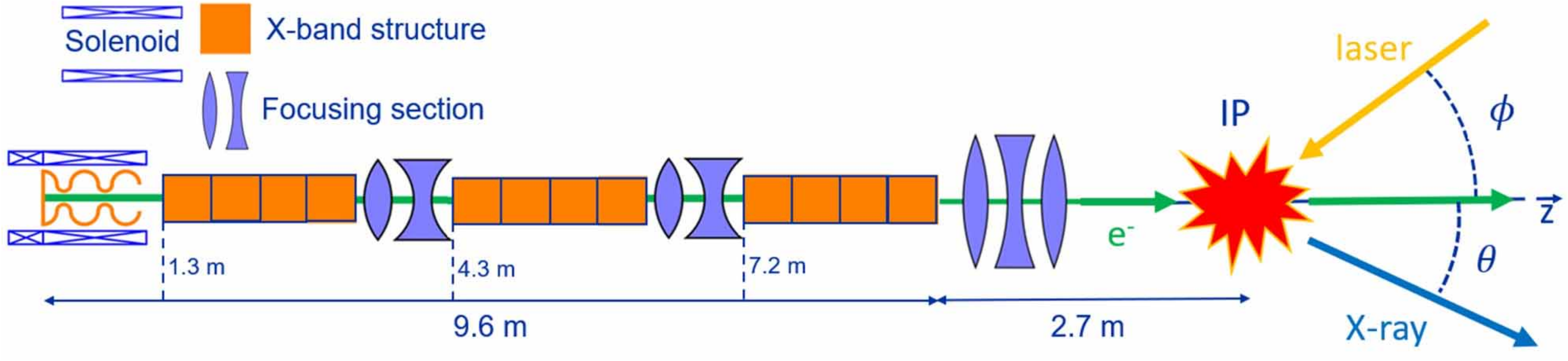
Linac-based ICS sources

HPCI–ICS



RF Photoinjector X-band linac Beam delivery IP

HPCI: High-brilliance, compact X-ray sources of X-rays

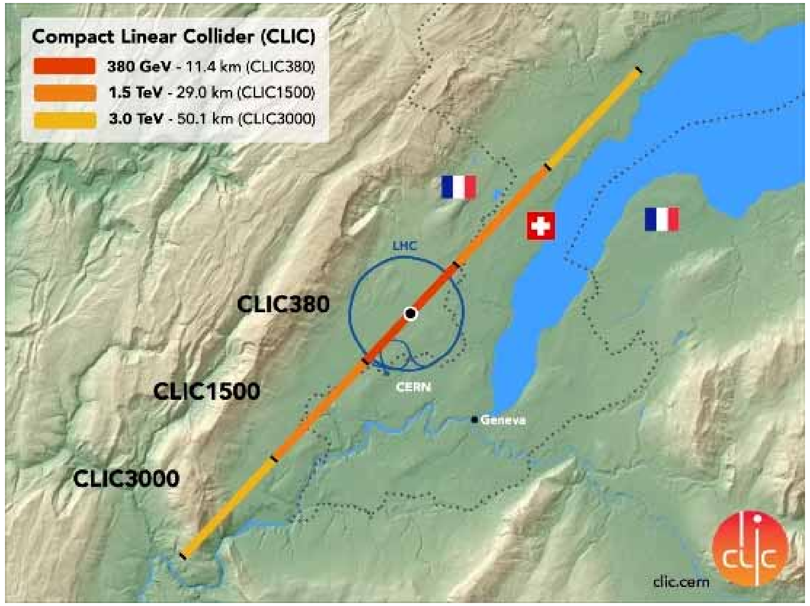
- Photoinjector -> high-brilliance
- X-band acceleration -> compactness, high flux, and high energy
- Fabry-Pérot -> high-flux
- Potential to generate soft X-rays up to gammas (~MeV)

$$E_{\text{X-ray}} = 2\gamma^2 E_{\text{laser}} \frac{1+\cos\phi}{1+\gamma^2\theta^2}$$

$$N_\gamma = \sigma_c \frac{N_e N_{\text{laser}} \cos(\phi/2)}{2\pi\sigma_{\gamma,y}\sqrt{\sigma_{\gamma,x}^2 \cos^2(\phi/2) + \sigma_{\gamma,z}^2 \sin^2(\phi/2)}}$$

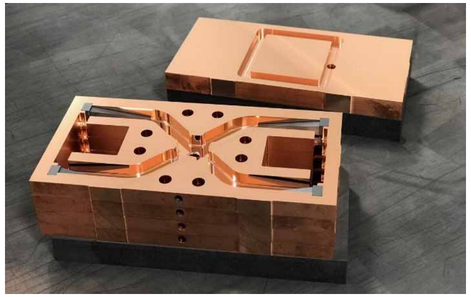
Significantly more compact than FELs and Synchrotrons

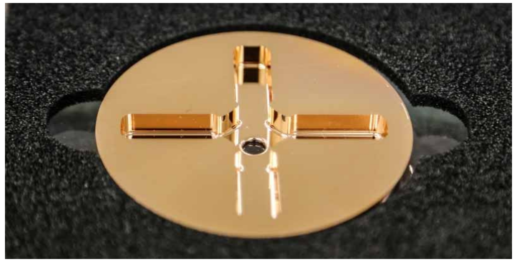
Enabling technology: X-band acceleration

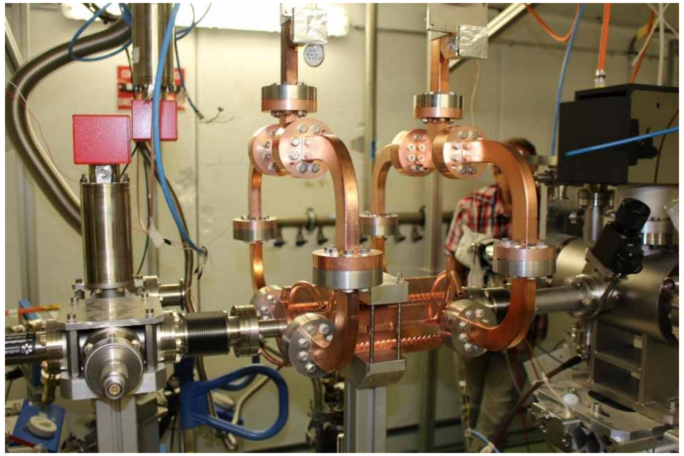


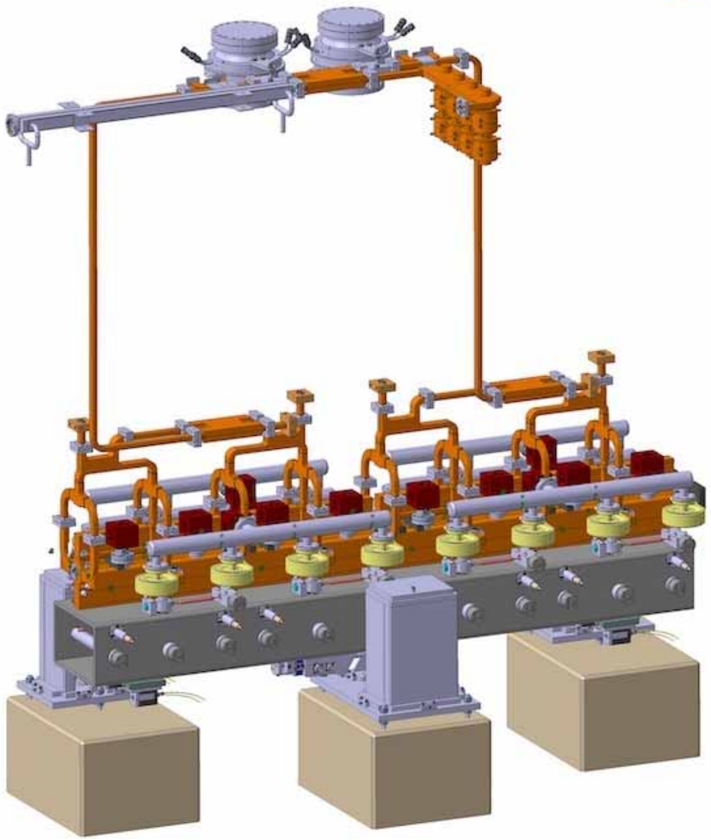
CLIC design study at CERN

- Very high-accelerating gradient to make compact facility - 100 MV/m accelerating gradient - 12 GHz - normal conducting
- Efficiency a design goal from the beginning



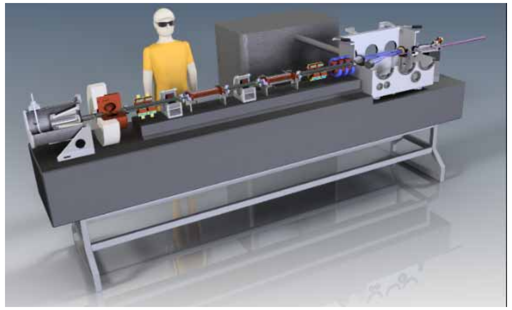




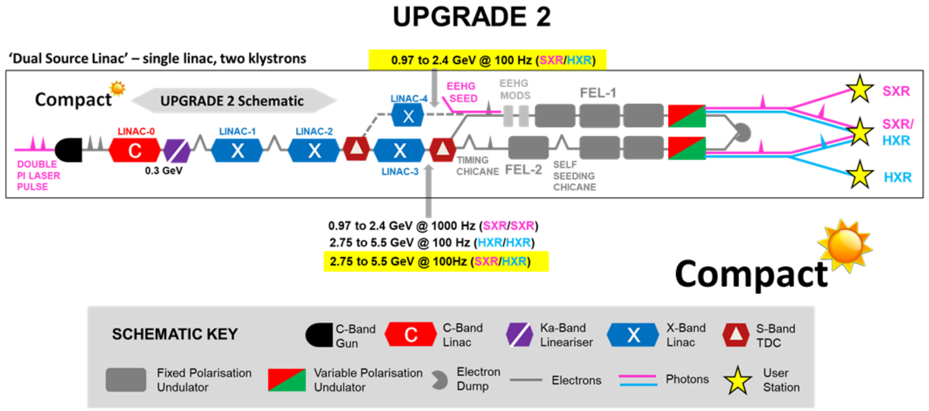


1m long accelerator structure is sufficient for generating up to ~100 keV monochromatic X-ray beams

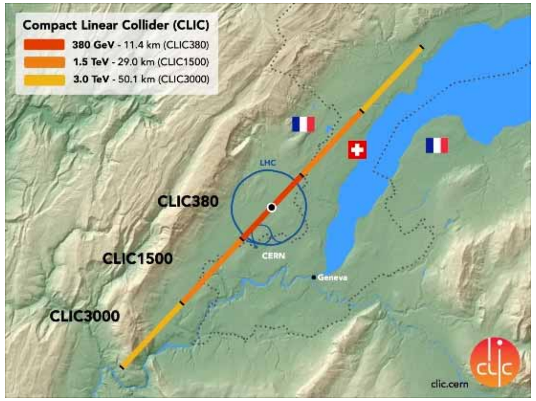
X-band and high-gradient applications



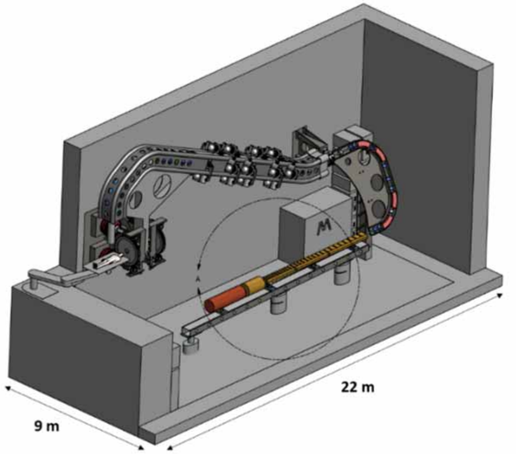
Light sources - ICS sources



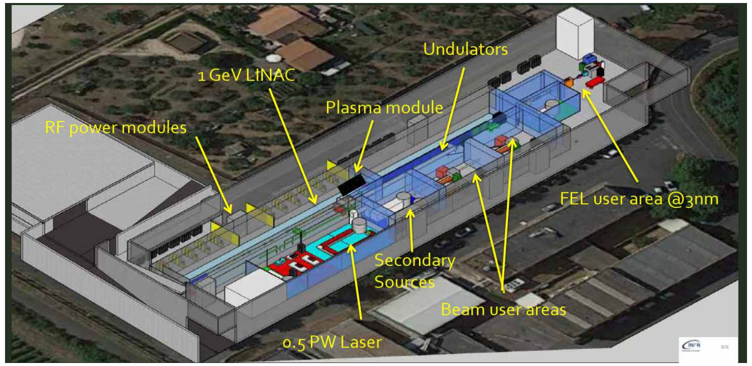
Light sources - XFEL



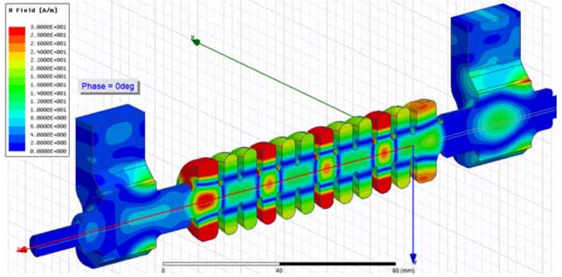
Linear collider

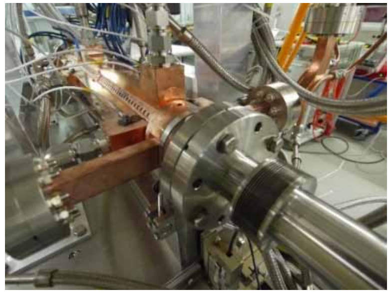


Medical applications



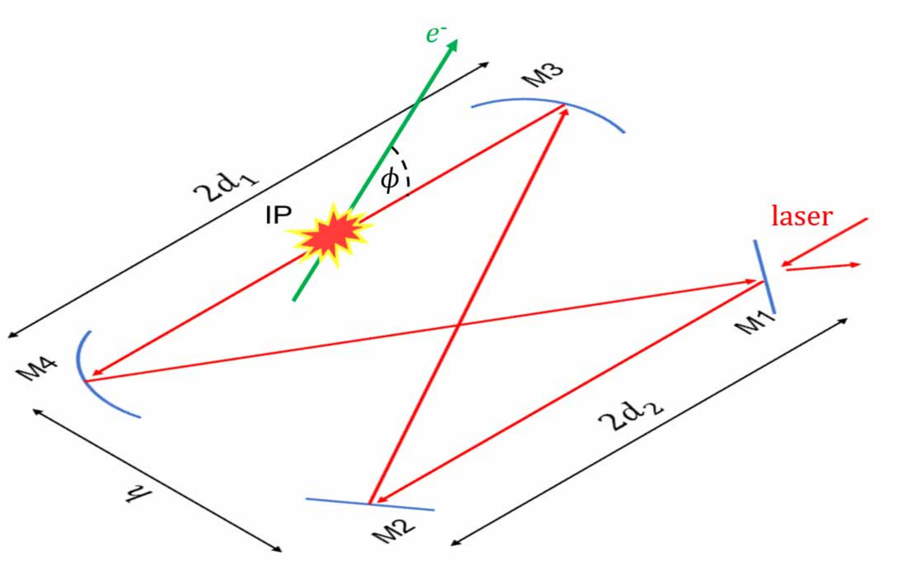
GeV-range research linacs

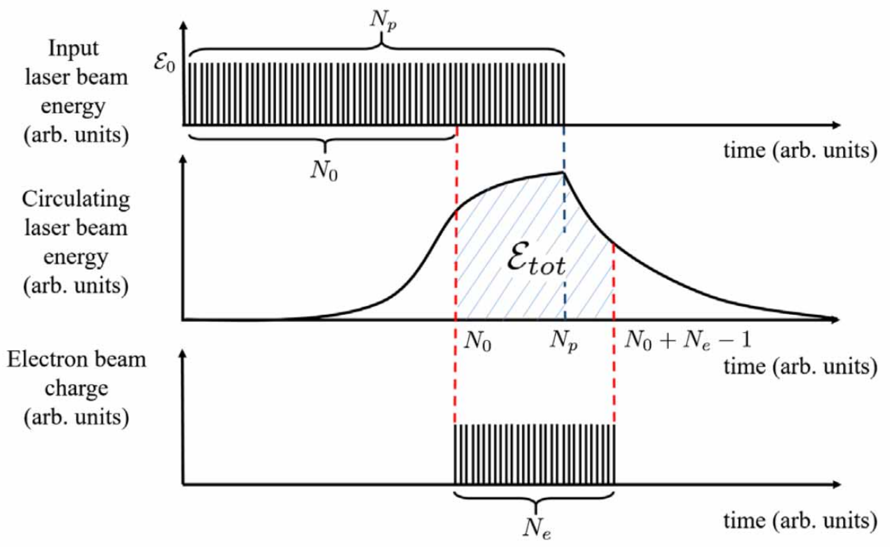




Beam manipulation

Enabling technology: burst-mode Fabry-Pérot





The burst mode operation of a Fabry-Perot cavity:

1. Has a temporal pattern of the laser pulses like the incoming electron train.
2. The effective gain is 2 to 3 orders of magnitude larger than the continuous wave mode.
3. Due to the lower intracavity average power, thermal effects on the cavity mirrors are minimised

FPC	Value	Unit
Micropulse energy	10	μJ
Effective gain	264	-
Macropulse energy	22.9	mJ
ε_{tot}	6	J

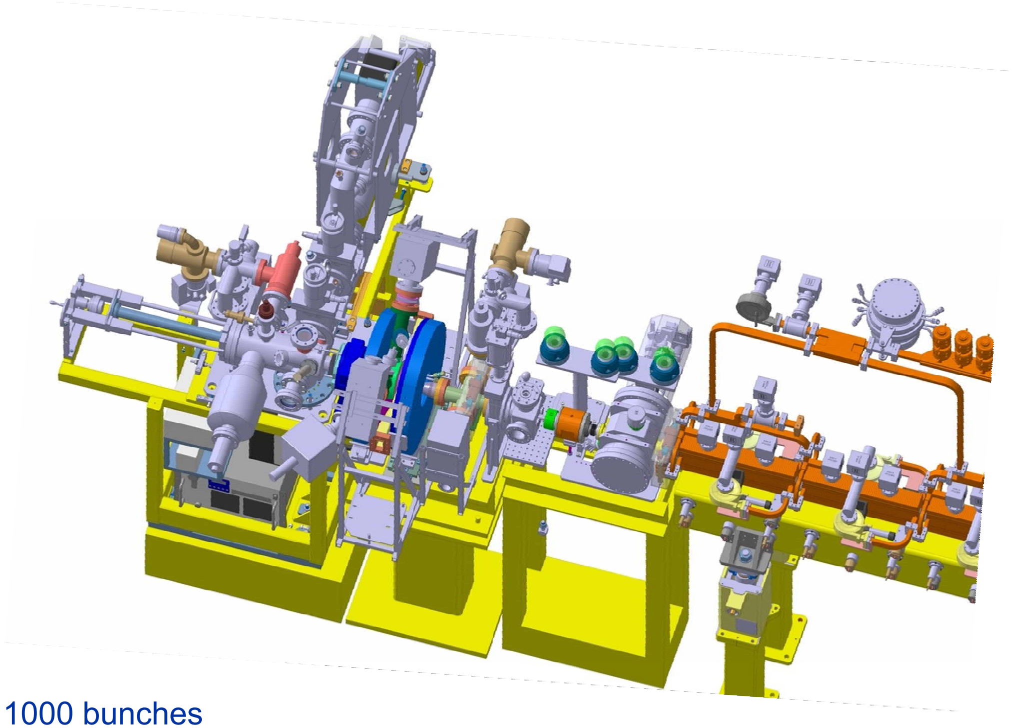
See V. Mușat, TU1C1

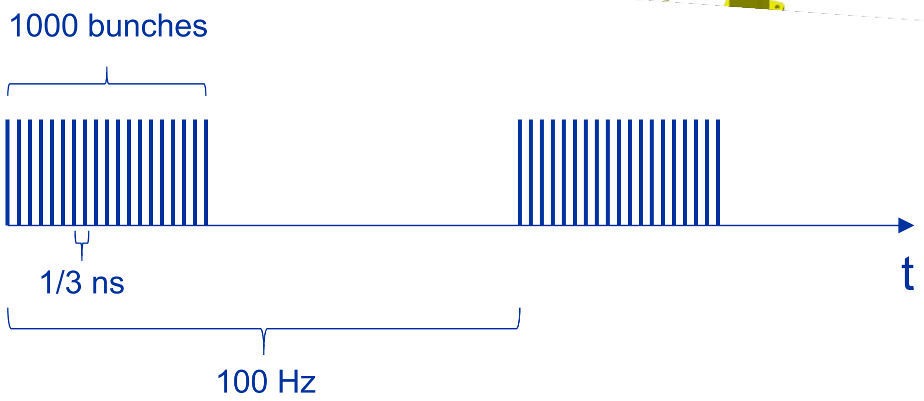
Key parameters of the HPCI–ICS source

Electron beam	Value	Unit
Energy	240	MeV
Single-bunch charge	100	pC
Repetition rate	100	Hz
Nb. of bunches per train	1000	
Bunch length	< 300	µm/c
Bunch spacing	1/3	ns
Norm. transverse emittance	< 3	mm.mrad
Final bunch energy spread	0.3	%

ICS Laser beam	Value	Unit
Wavelength	515	nm
Pulse energy	10	µJ
Pulse length	1.2	ps
Crossing angle	2	deg

Photoinjector

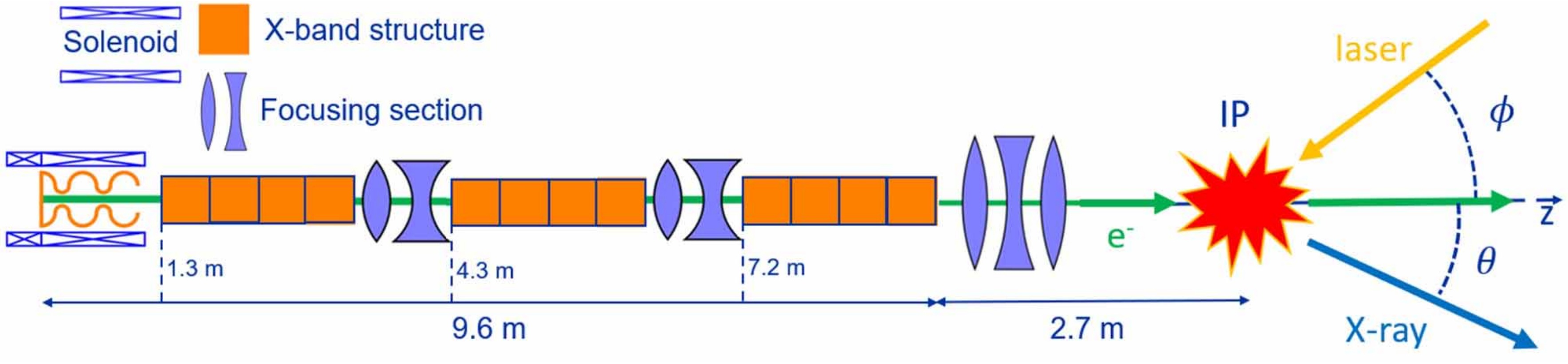




Photoinjector	Value	Unit
Gradient at cathode	90	MV/m
Frequency	3	GHz
Cathode	Cs_2Te	
Laser	UV	
Bunch charge	100	pC
Energy	6.5	MeV
Norm. transverse emittance	< 4	mm.mrad
Total length	1.3	m

S-band. Similar to the photoinjector of the CLEAR facility at CERN

Linac



RF Photoinjector X-band linac Beam delivery IP

X-band linac	Value	Unit
Frequency	12	GHz
Phase advance	2π/3	rad
Average loaded gradient	35	MV/m
Average iris aperture radius	3.8	mm
Structure length	0.5	nm
HOM damping	yes	-
Energy gain per module	~80	MeV

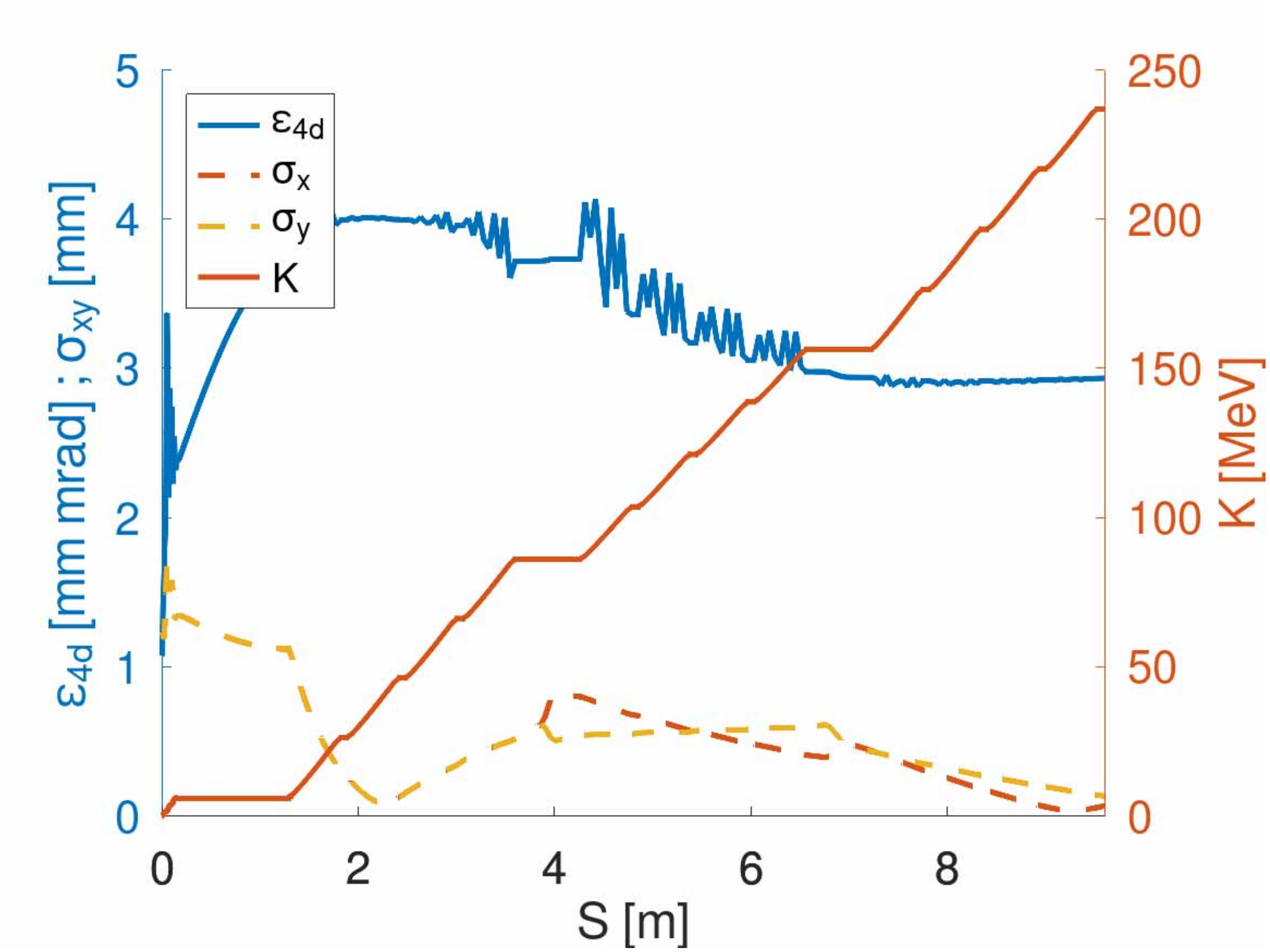
1 Klystron + 1 Pulse compressor can feed up to 8 structures.

It’s a wakefield-dominated machine.

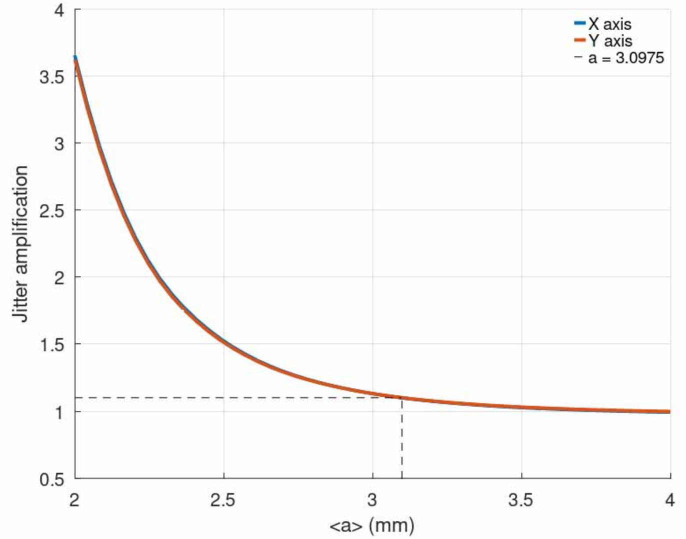
X-band = small iris apertures = strong wakefields

Electron beam dynamics

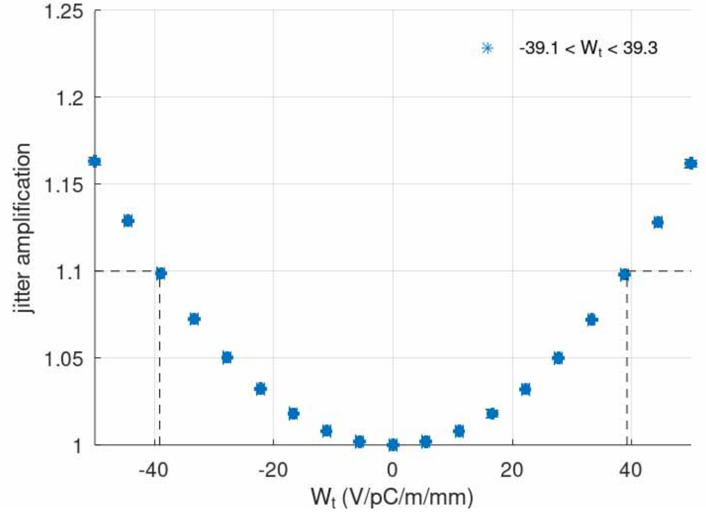
RF-Track simulation



Single-bunch jitter amplification

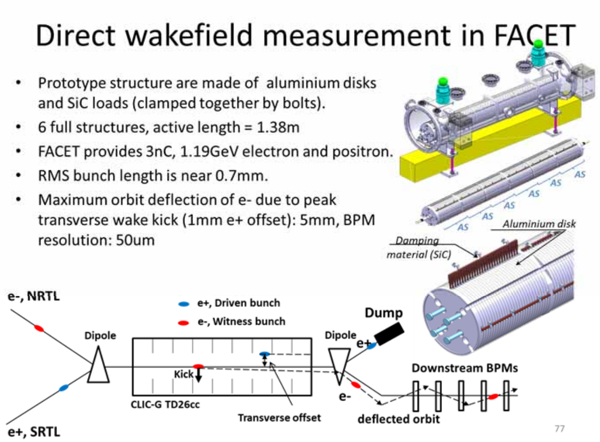


Multi-bunch jitter amplification



CLIC high current beam stability

High-current beam requires Higher-Order-Mode suppression for beam stability, just like CLIC

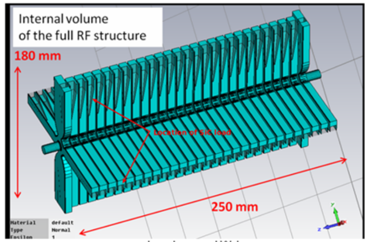


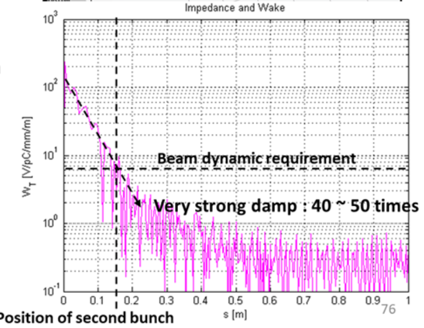
Transverse long-range Wakefield in CLIC-G structure

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

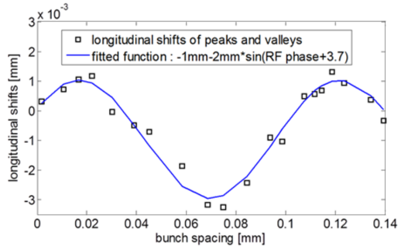
transverse long-range wakefield calculation using Gdfidl code:

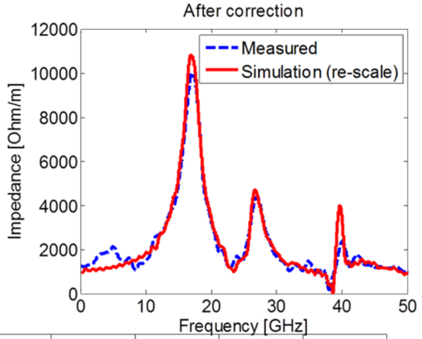
Peak value :
250 V/pC/m/mm
At position of second bunch (0.15m):
5~6 V/pC/m/mm
Beam dynamic requirement:
< 6.6 V/pC/m/mm

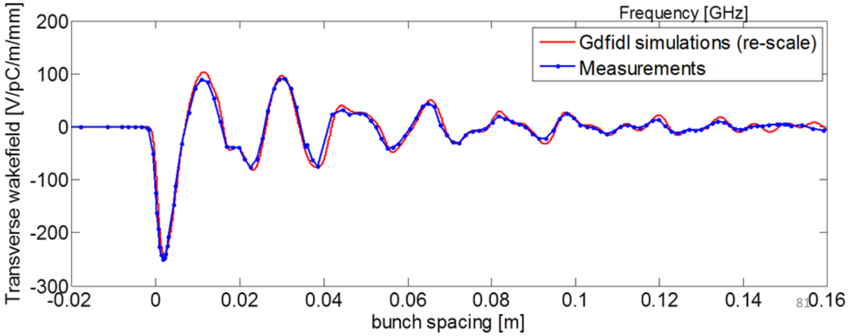


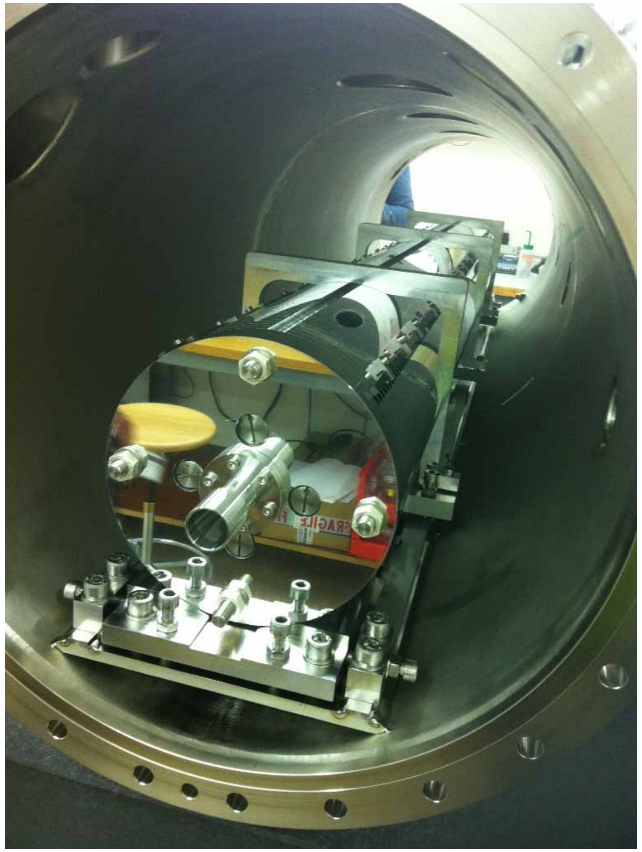


Timing correction







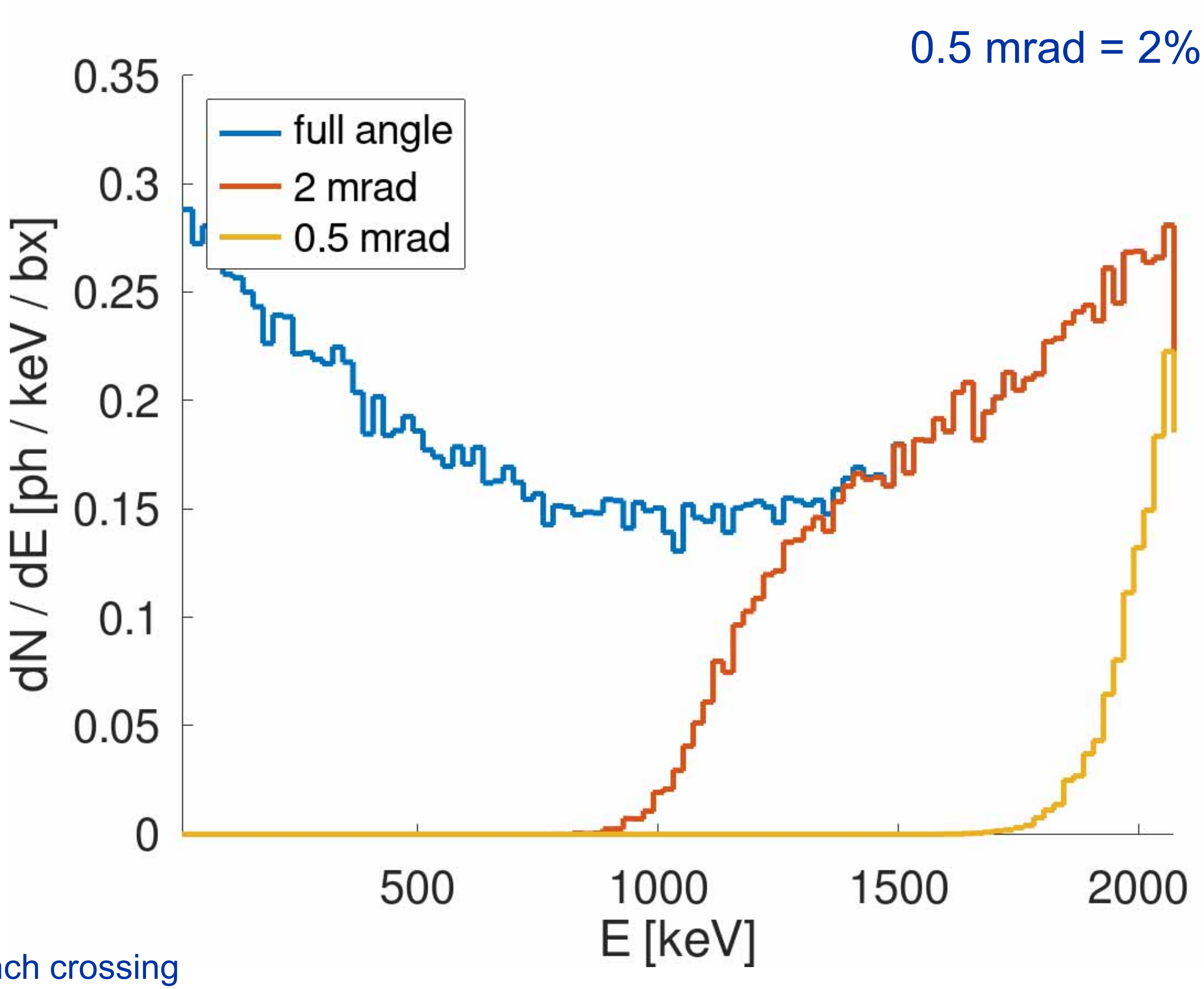


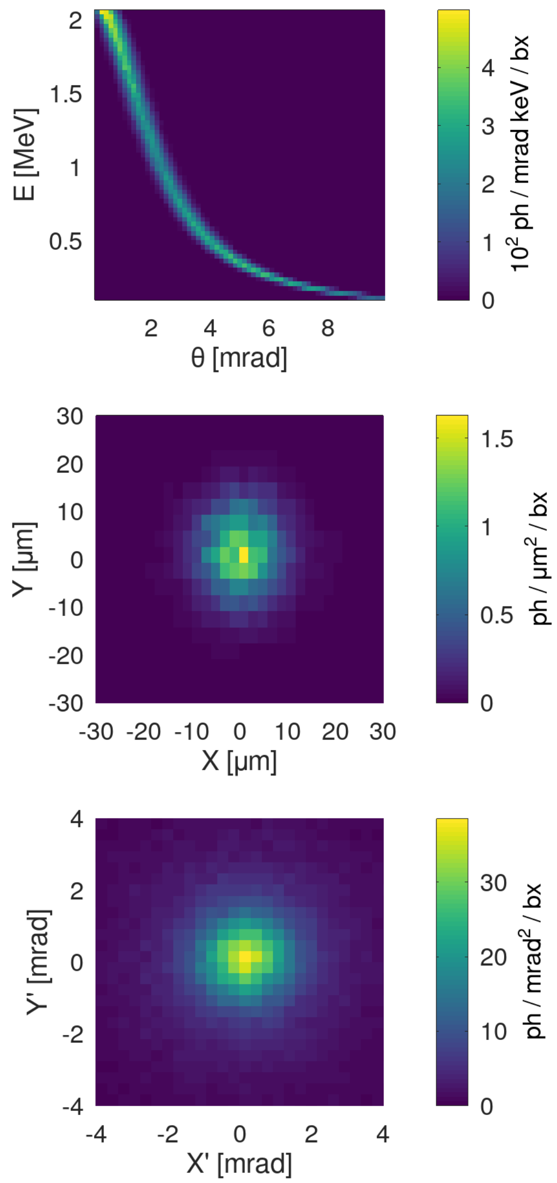
https://doi.org/10.1103/PhysRevAccelBeams.19.011001

Photon performance

RF-Track simulation

0.5 mrad = 2% BW





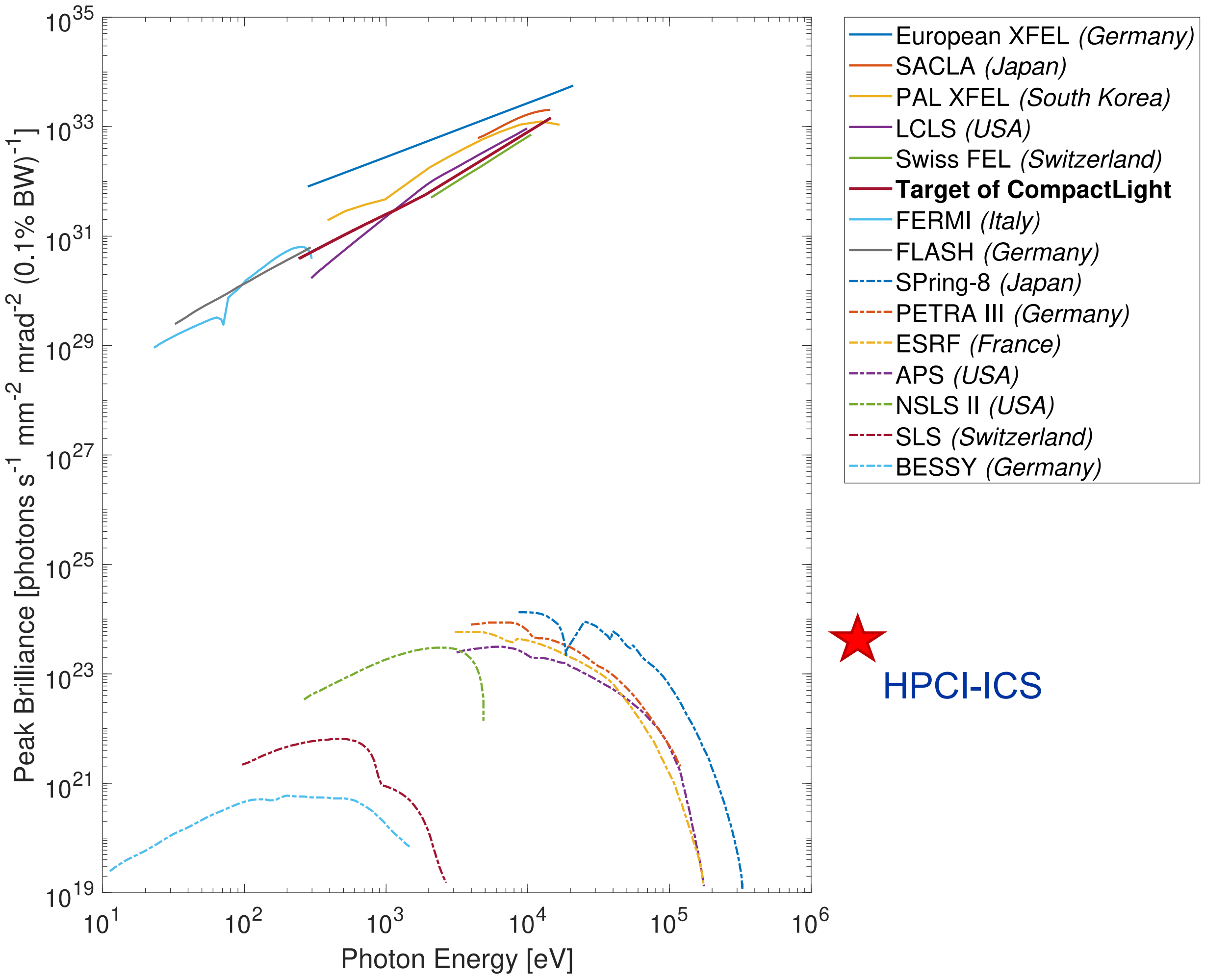
bx = bunch crossing

Photon performance

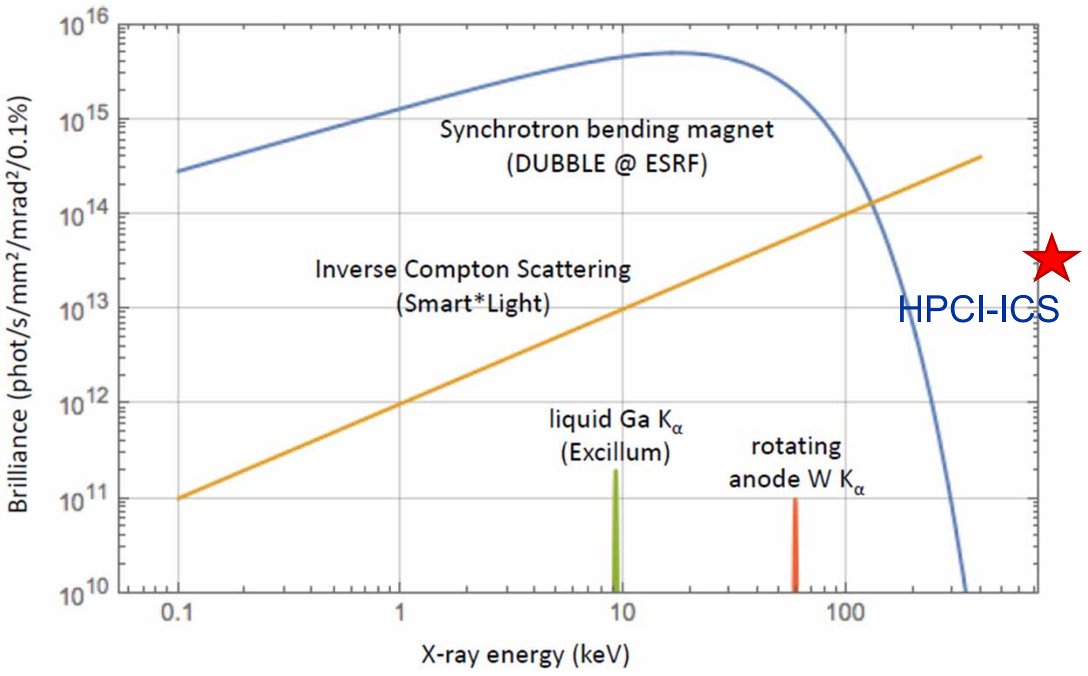
Outcoming photons	Value	Unit
Compton edge	2.1	MeV
Total flux	2.2×10^{13}	ph/s
Bandwidth (0.5 mrad)	2.0	%
Flux (0.5 mrad)	1.6×10^{12}	ph/s
Average Brilliance	4.4×10^{13}	(*)
Peak Brilliance	3.9×10^{23}	(*)

(*) ph / (s mm^2 mrad^2 0.1% BW)

Landscape of light sources



CompactLight CDR, https://doi.org/10.5281/zenodo.6375645



Courtesy Smart*Light

Conclusions

We presented an advanced conceptual design of a **compact ICS source:**

- S-band **photoinjector**
- High-gradient multi-bunch **X-band acceleration**
- **Fabry-Pérot** cavity operating **in burst mode**

Realistic start-to-end simulations were performed, showing that the HPCI-ICS source has the potential to produce 2 MeV gamma rays with a **total flux of 2.2 x 10^{13} ph/s in less than 15 meters** in length. It's one of the most compact, high energy and high flux sources in the landscape of existing and planned ICS sources.

MeV energy range gamma rays can have applications in various fields: material science, medicine, nuclear physics research, homeland security by nuclear resonance fluorescence inspection, and non-destructive testing of industrial materials.

CERN