A Compact Inverse-Compton Scattering Source Based on X-band Technology and Cavity-Enhanced High-Average-Power Ultrafast Lasers

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- Storage-ring and Linac based
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Key technologies

- X-band high-gradient acceleration
- Fabry-Pérot resonator in burst mode

Proposed setup

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- Beam dynamics

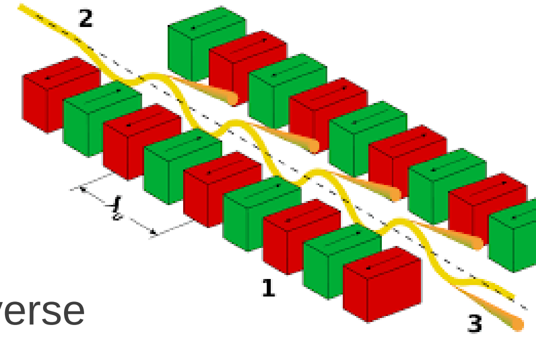
Estimated performance

Storage-ring-based X-ray sources

Storage rings X-ray sources offer high fluxes and large energy ranges, e.g. ESRF, Grenoble

Typical X-ray energies are from 5 to 60 keV.

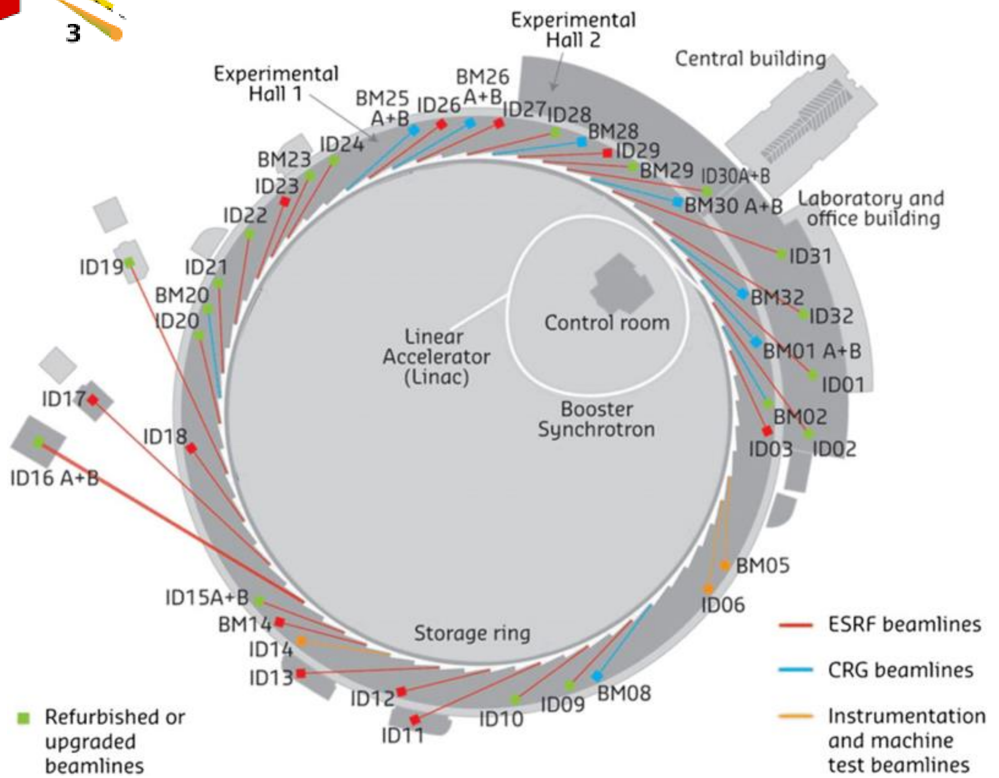
Research with **X-ray radiation** focuses on fields as diverse as protein **crystallography**, **earth science**, **palaeontology**, **materials science**, **chemistry** and **physics**.



Undulator

Energy	[GeV]	6.03
Maximum Current	[mA]	200
Horizontal emittance	[nm]	4
Vertical emittance (*minimum achieved)	[nm]	0.025 (0.010*)
Coupling (*minimum achieved)	[%]	0.6 (0.25*)
Revolution frequency	[kHz]	355
Number of bunches		1 to 992
Time between bunches	[ns]	2816 to 2.82

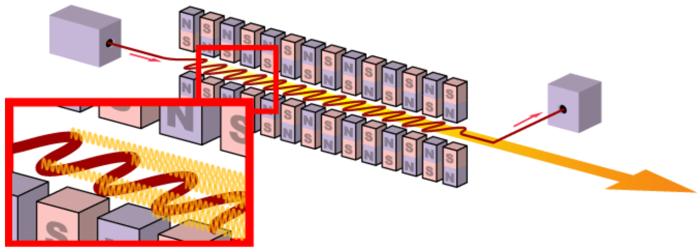
Circumference length 844 m



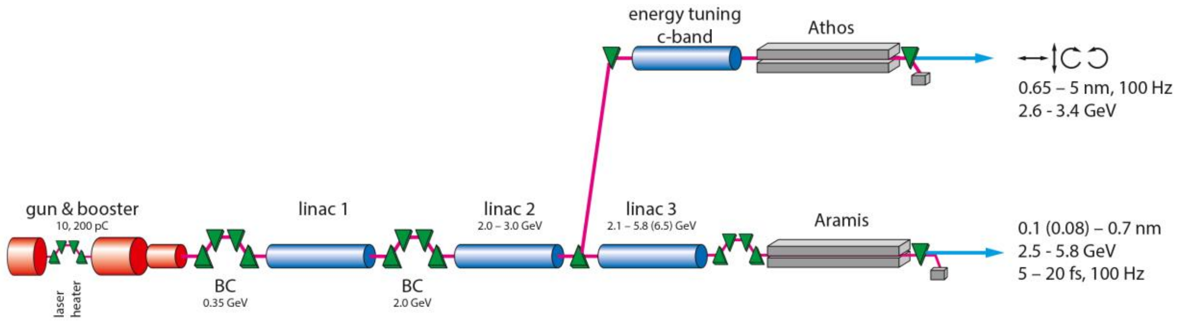
Linac-based X-ray sources: FEL

Free-Electron Lasers: e.g., SwissFEL

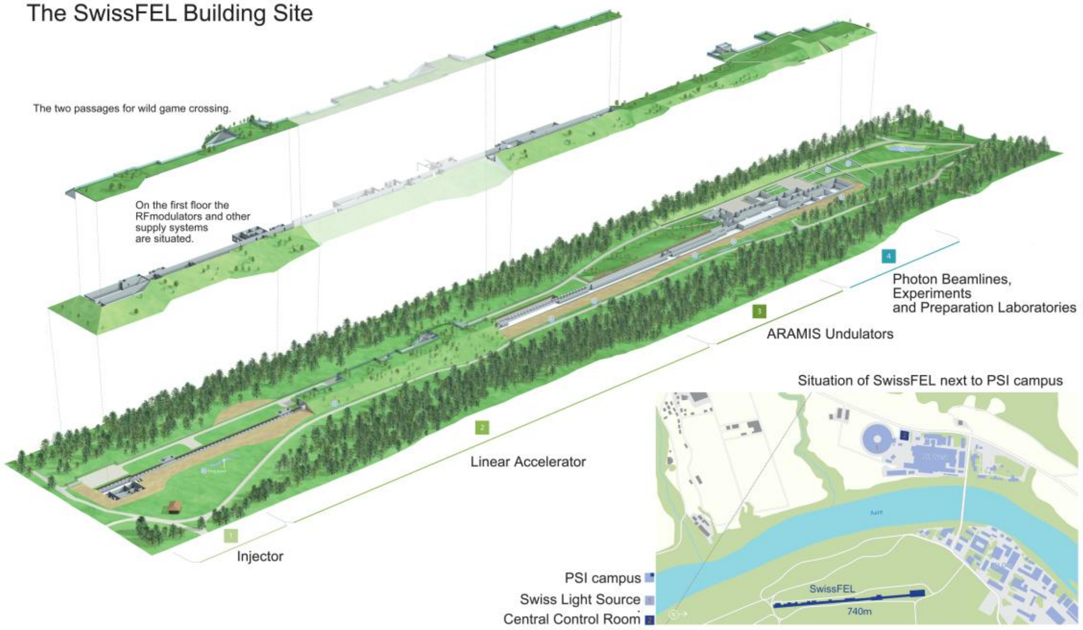
Main parameters	
Wave length	1A -50Å
Photon energy	0.25-12 keV
Pulse duration	1fs - 20fs
e Energy	5.8 GeV
e Bunch charge	10 - 200 pC
Repetition rate	100 Hz



FELs feature extremely high brilliance.



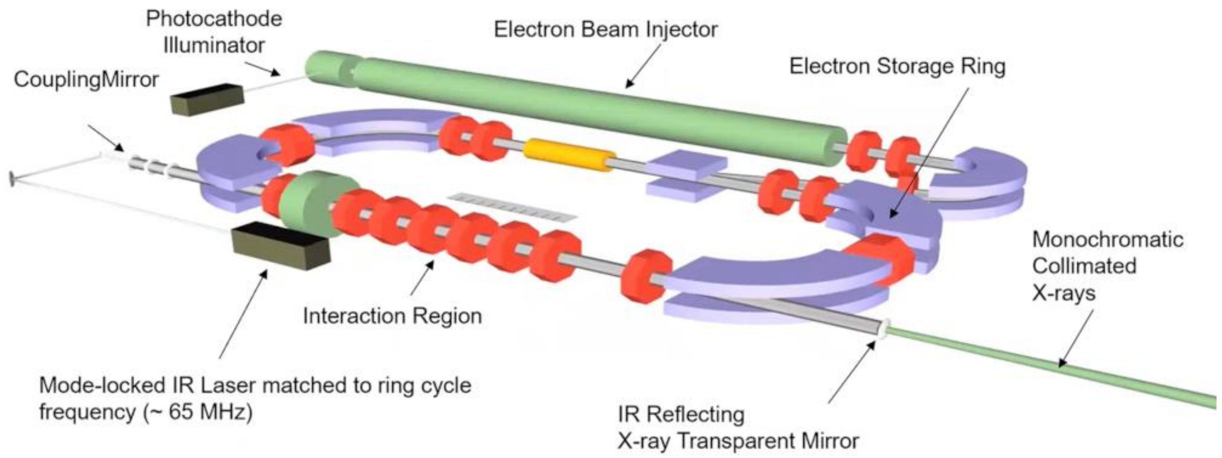
Total length of the facility 740 m



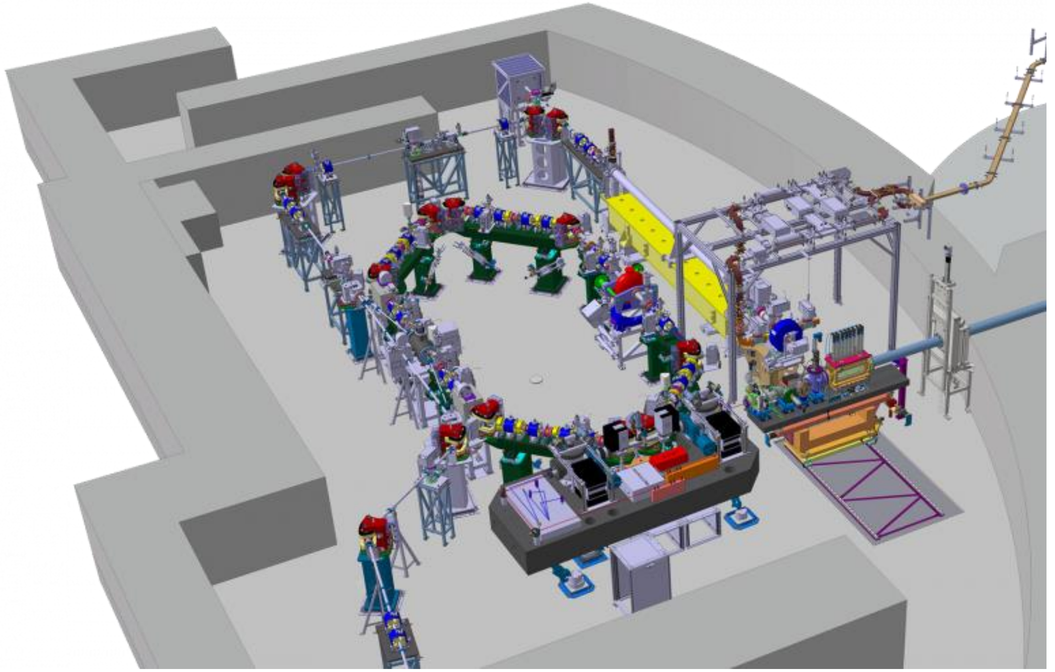
Storage-ring-based ICS sources

ICS = Inverse Compton Scattering (or Compton backscattering)

Lyncean Compact Light Source



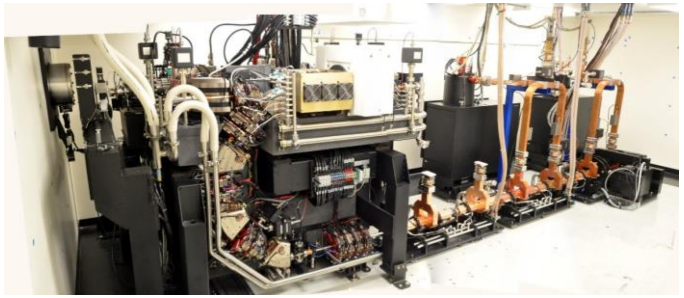
ThomX



Key subsystems:
- Short linac
- Compact storage ring
- Fabry-Pérot enhancement cavity in continuous-wave operation

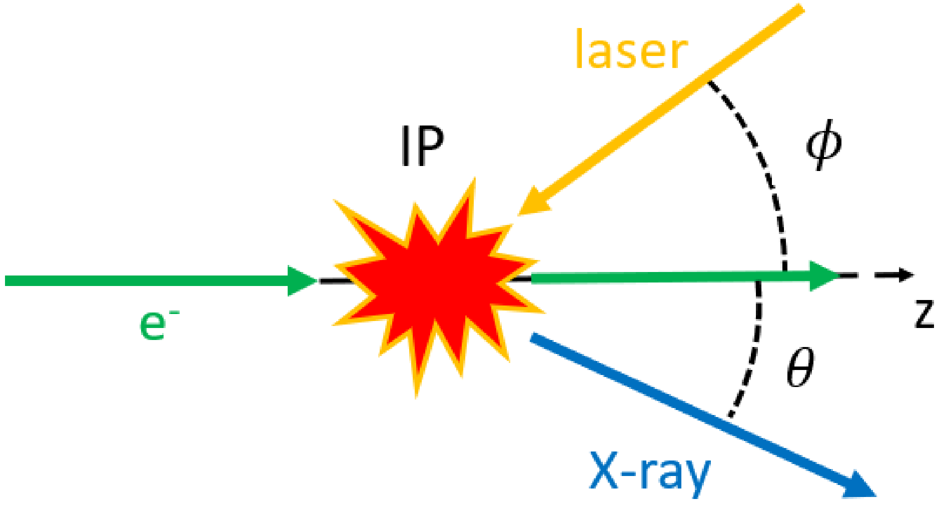
X-ray energy:
- 15 – 35 keV (Munich CLS, ~35 MeV e^- beam)
- 45 – 90 keV (ThomX, 50 MeV e^- beam)

More compact than Synchrotrons and FELs, but still **quite complex** to operate



Munich CLS

Inverse Compton scattering



= The conversion of a low energy photon from an EM field to a high-energy photon (X-ray or gamma ray) during the interaction (scattering) with a charged particle.

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

Total flux

$$\mathcal{B} = \frac{\mathcal{F}}{4\pi^2 \sigma_{\gamma,x}\sqrt{\epsilon_x/\beta_x}\,\sigma_{\gamma,y}\sqrt{\epsilon_y/\beta_y}}$$

Average brilliance

$$\frac{\sigma_{E_\gamma}}{E_\gamma} = \sqrt{\left(\frac{\sigma_{E_\theta}}{E_\theta}\right)^2 + \left(2\frac{\sigma_{E_e}}{E_e}\right)^2 + \left(\frac{\sigma_{E_{\text{laser}}}}{E_{\text{laser}}}\right)^2 + \left(\frac{\sigma_{E_\epsilon}}{E_\epsilon}\right)^2}$$

Photon bandwidth

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

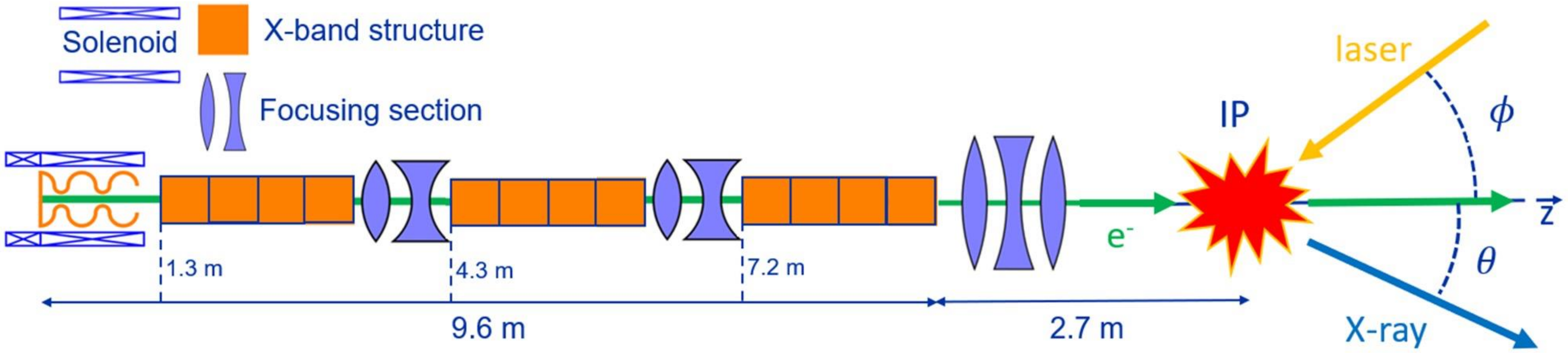
Photon energy

[Slide by V. Musat]

Linac-based ICS sources: extreme compactness

ICS = Inverse Compton Scattering (or Compton backscattering)

HPCI–ICS



RF Photoinjector X-band linac Beam delivery IP

HPCI: High-brilliance, compact X-ray sources

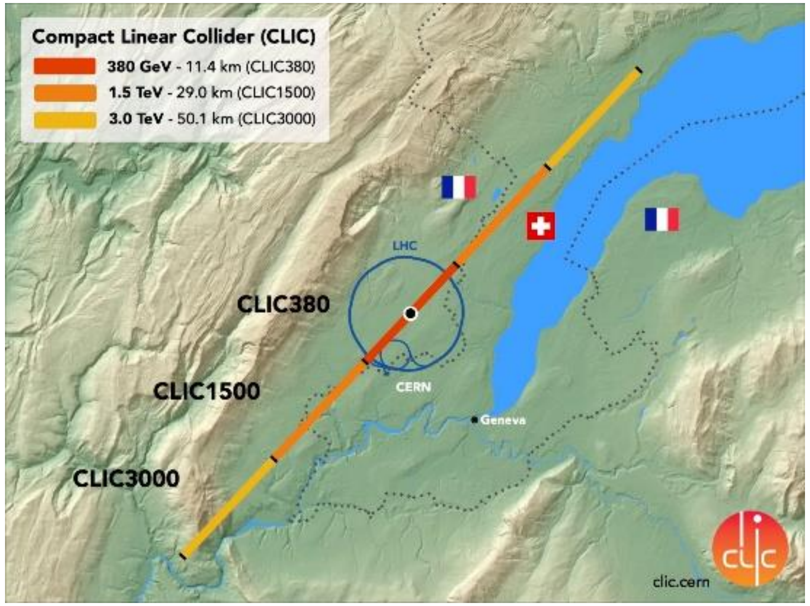
- Photoinjector -> high-brilliance
- X-band acceleration -> compactness, high flux, and high energy
- Fabry-Pérot -> high-flux
- Potential to generate soft X-rays up to gammas (~MeV)

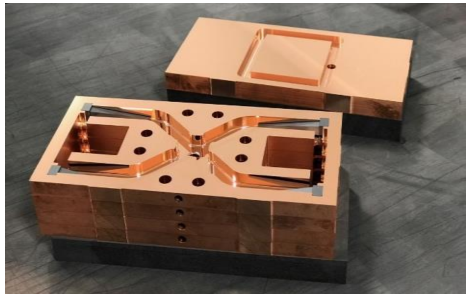
$$E_{\text{X-ray}} = 2\gamma^2 E_{\text{laser}} \frac{1+\cos\phi}{1+\gamma^2\theta^2}$$

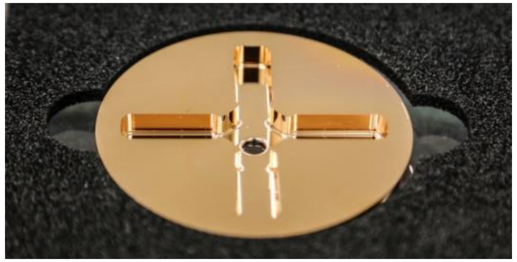
$$N_\gamma = \sigma_c \frac{N_e N_{\text{laser}} \cos(\phi/2)}{2\pi\sigma_{\gamma,y}\sqrt{\sigma_{\gamma,x}^2 \cos^2(\phi/2) + \sigma_{\gamma,z}^2 \sin^2(\phi/2)}}$$

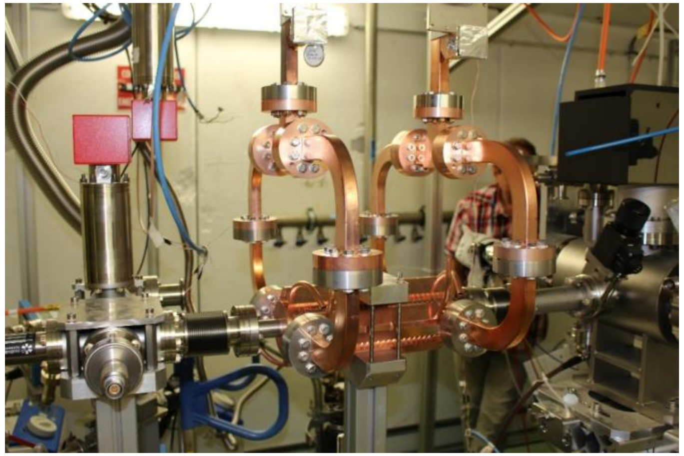
Significantly more compact than FELs and Synchrotrons.

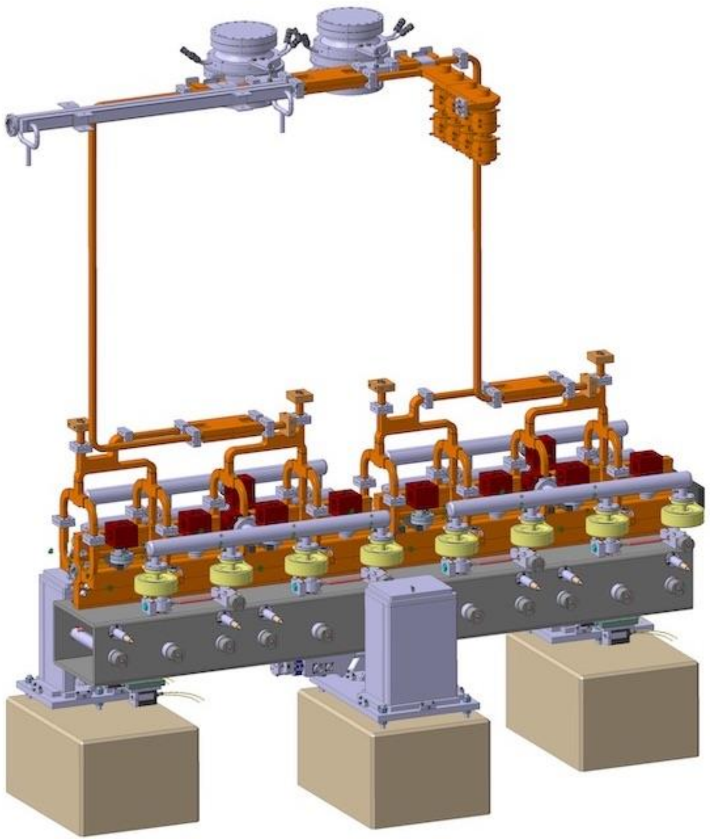
Enabling technology: X-band acceleration











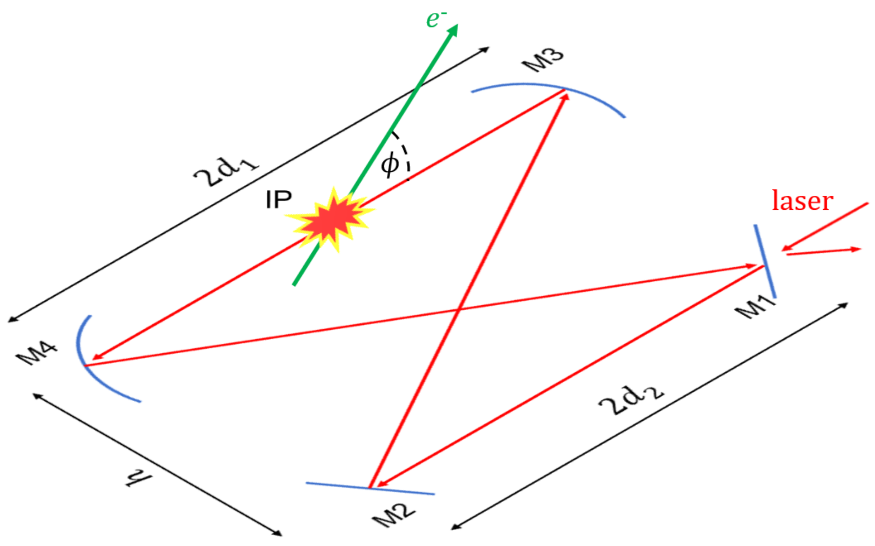
CLIC design study

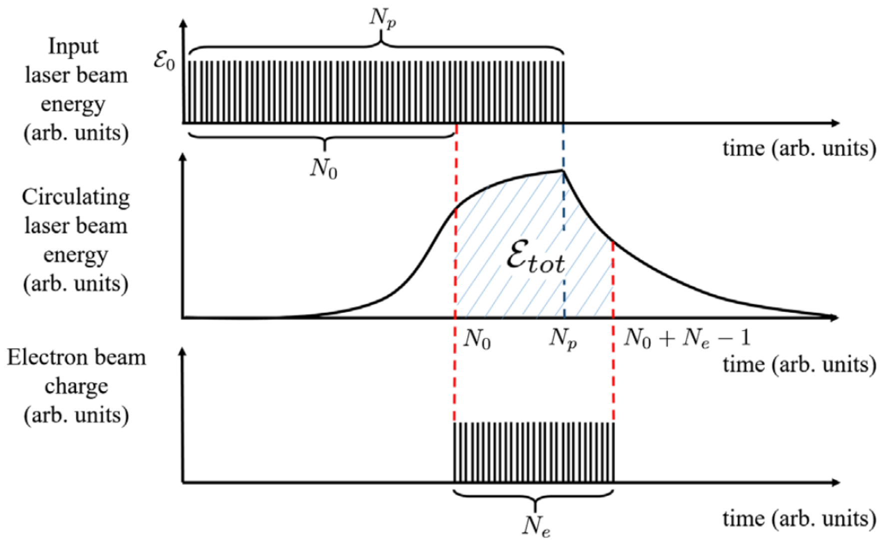
- Very high-accelerating gradient to make compact facility - 100 MV/m accelerating gradient - 12 GHz - normal conducting

- Efficiency a design goal from the beginning

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

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

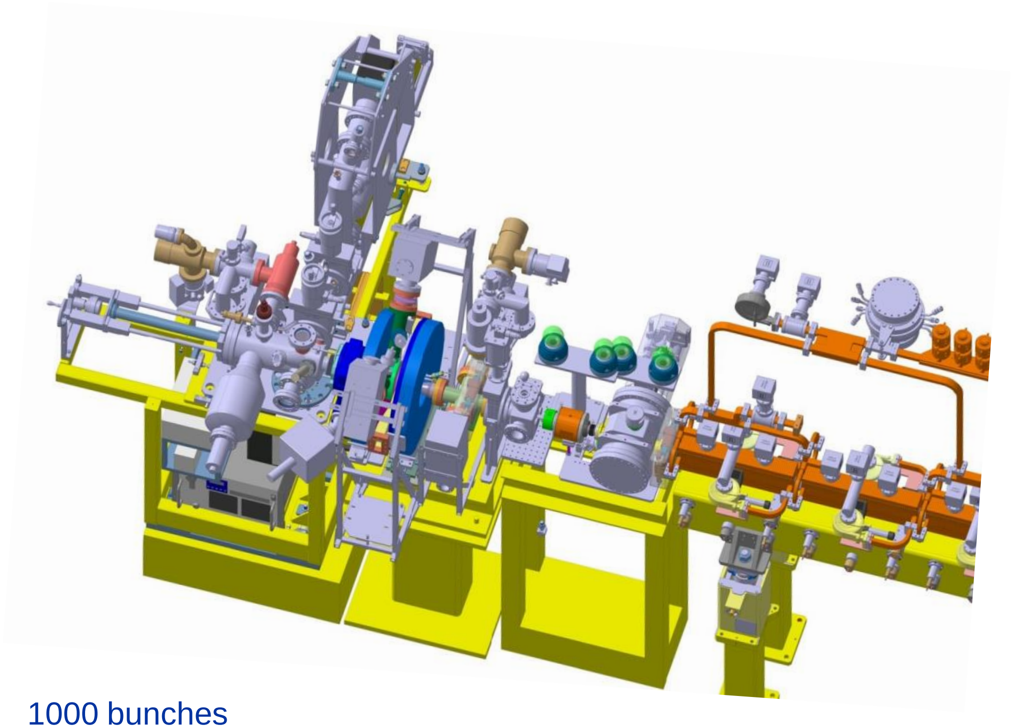
See V. Mușat, FLS2023, TU1C1

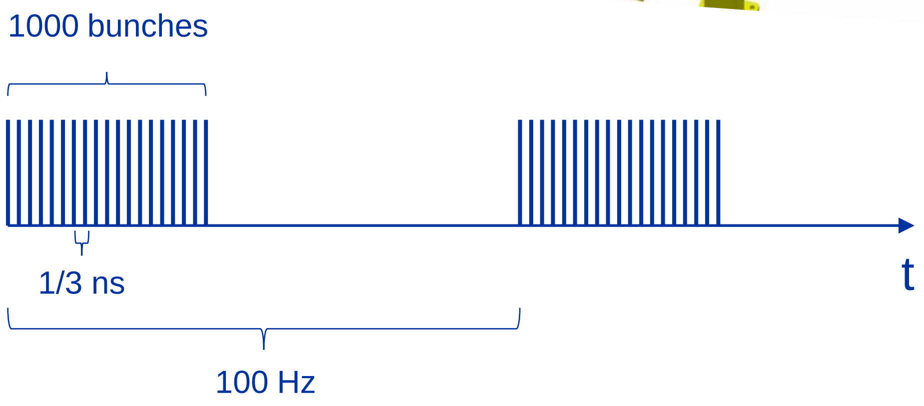
Key parameters of the HPCI–ICS source

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

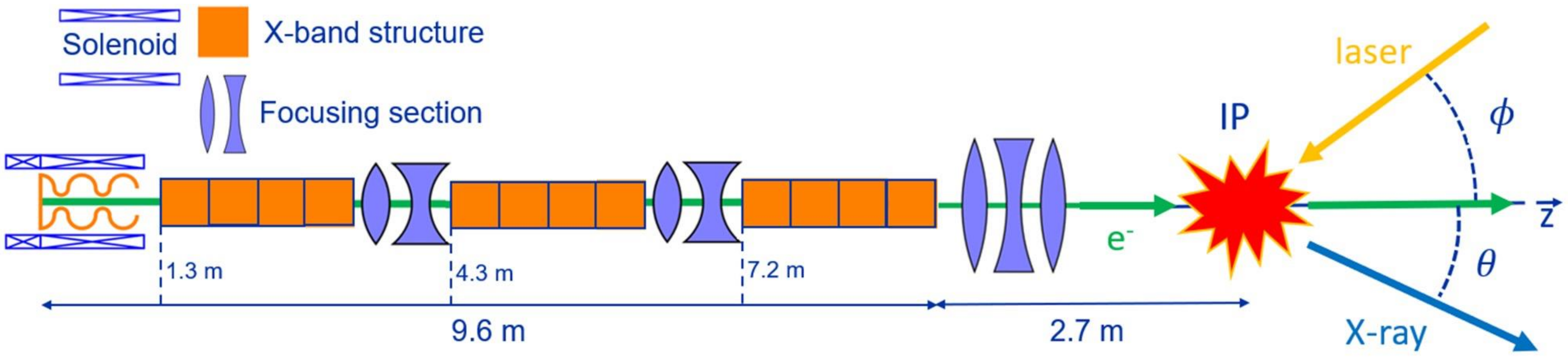




Photoinjector	Value	Unit
Gradient at cathode	90	MV/m
Frequency	3	GHz
Cathode	Cs_2Te	
Laser	UV	
Bunch charge	100	pC
Energy	6.5	MeV
Norm. transverse emittance	< 4	mm.mrad
Total length	1.3	m

S-band gun. 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 linac.

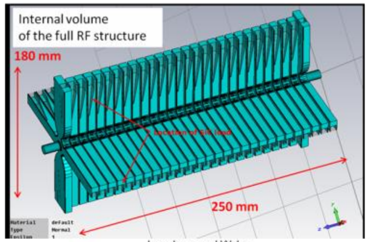
X-band => small iris apertures => strong wakefields

CLIC high current beam stability

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

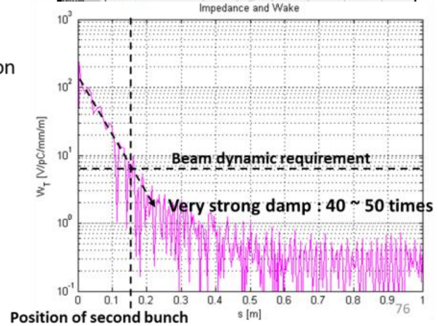
Transverse long-range Wakefield in CLIC-G structure

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



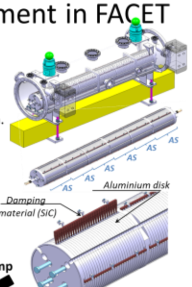
transverse long-range wakefield calculation using Gdfidl code:

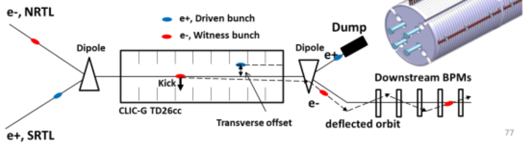
Peak value :
250 V/pC/m/mm
At position of second bunch (0.15m):
5~6 V/pC/m/mm
Beam dynamic requirement:
< 6.6 V/pC/m/mm



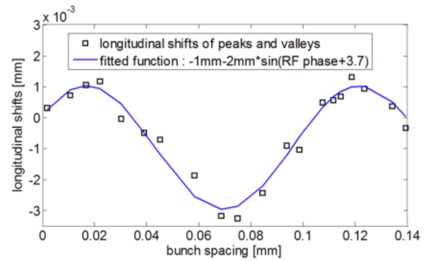
Direct wakefield measurement in FACET

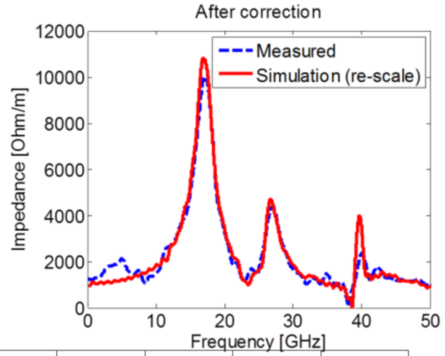
- Prototype structure are made of aluminium disks and SiC loads (clamped together by bolts).
- 6 full structures, active length = 1.38m
- FACET provides 3nC, 1.19GeV electron and positron.
- RMS bunch length is near 0.7mm.
- Maximum orbit deflection of e- due to peak transverse wake kick (1mm e+ offset): 5mm, BPM resolution: 50um

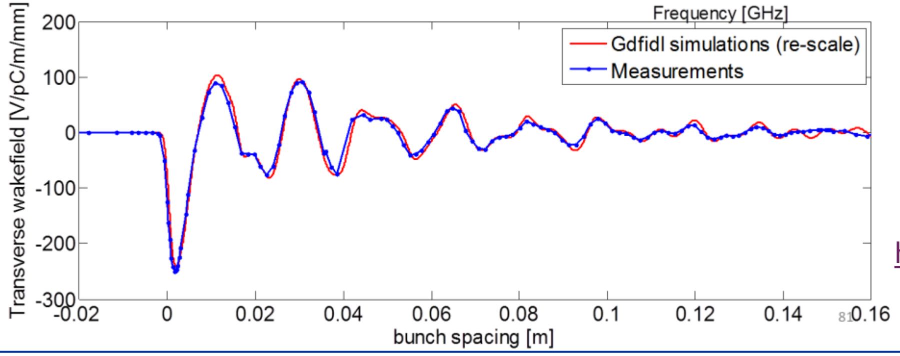


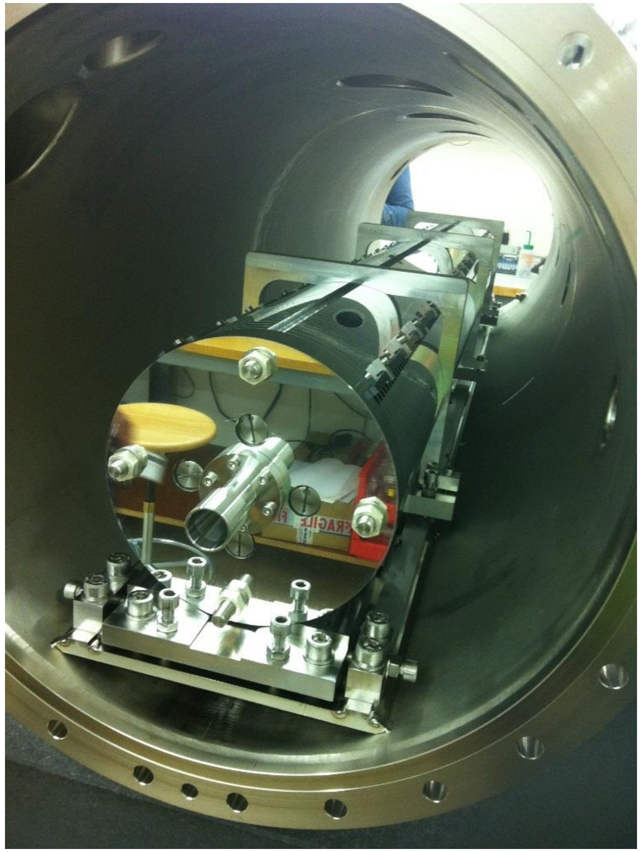


Timing correction





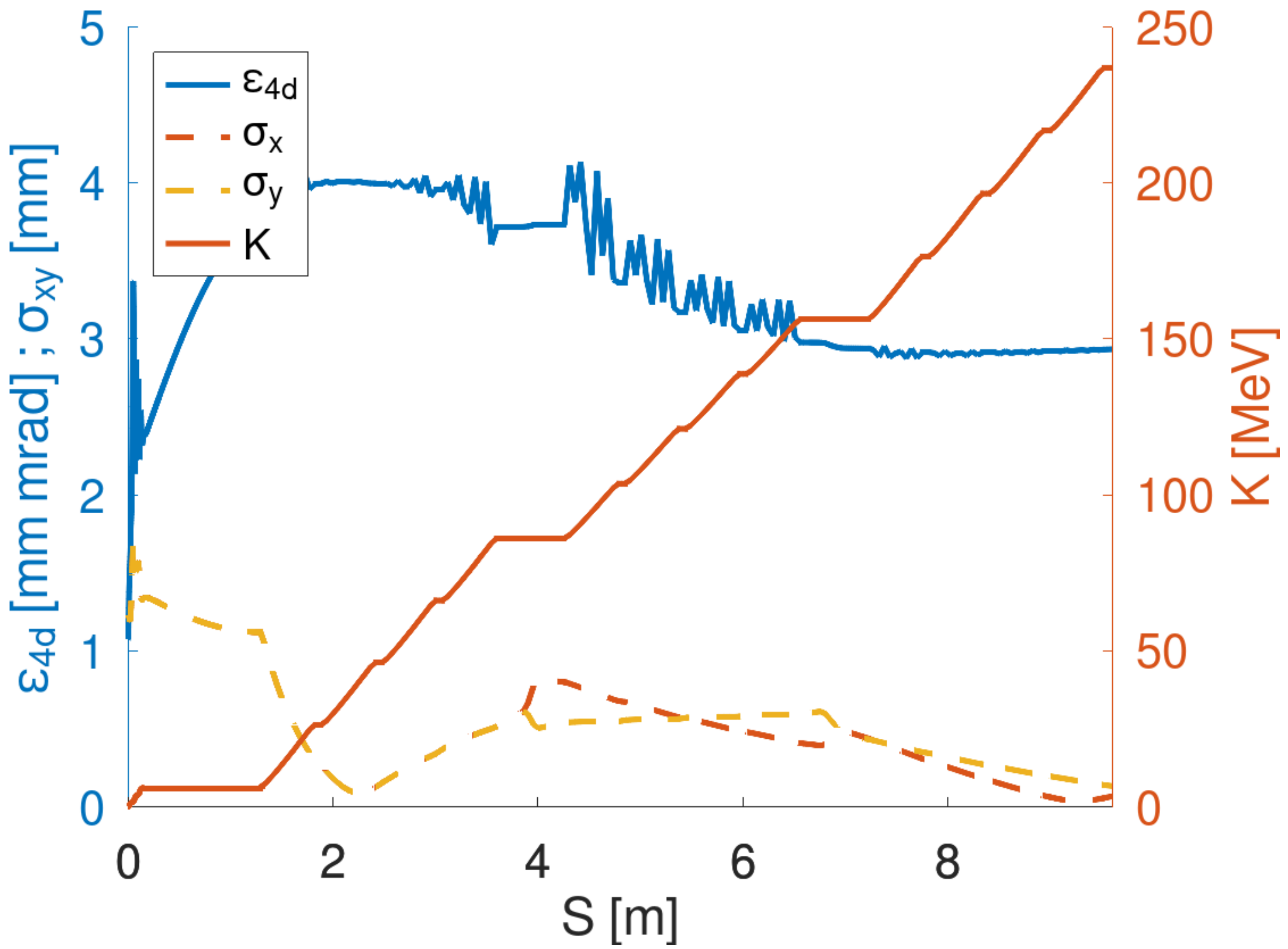




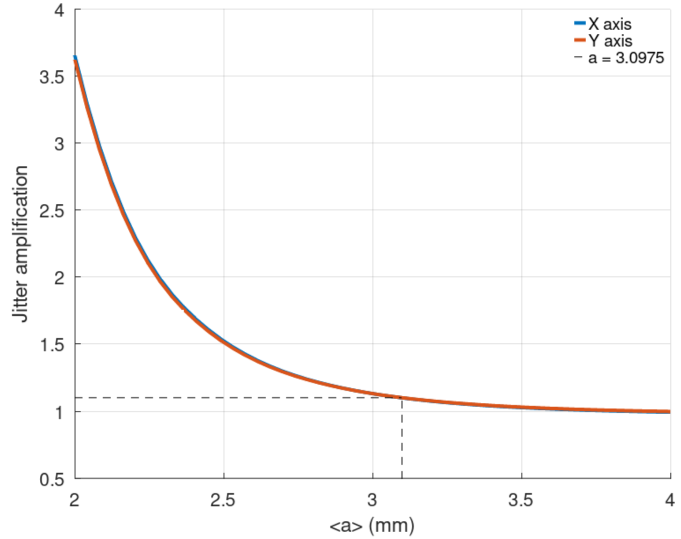
https://doi.org/10.1103/PhysRevAccelBeams.19.011001

Electron beam dynamics

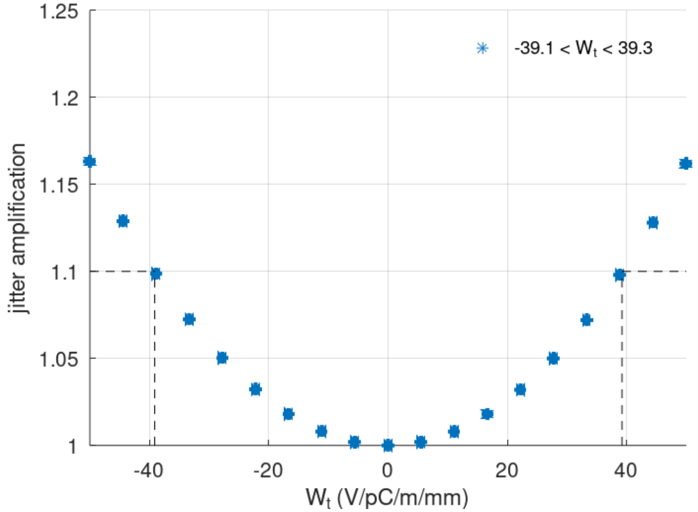
RF-Track simulation



Single-bunch jitter amplification



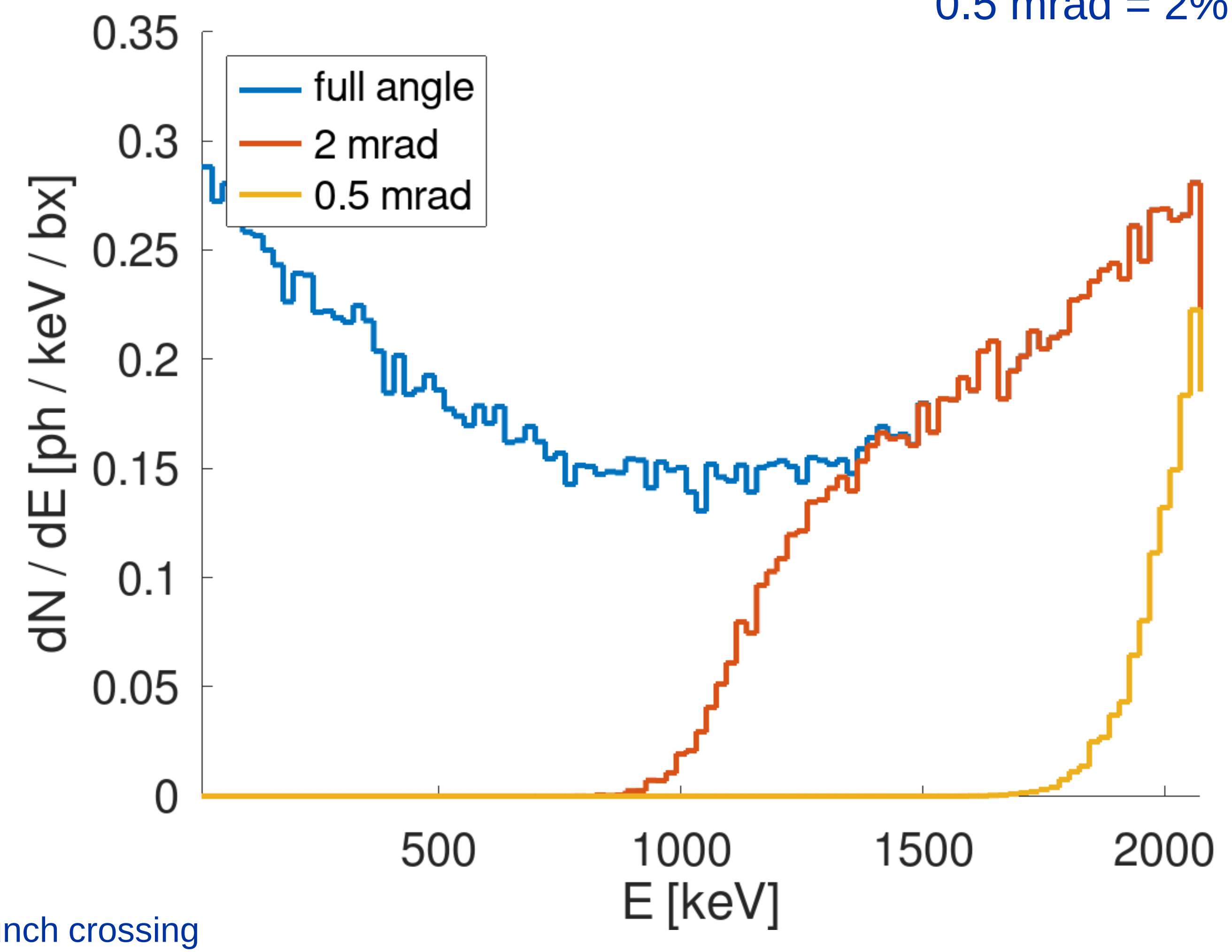
Multi-bunch jitter amplification

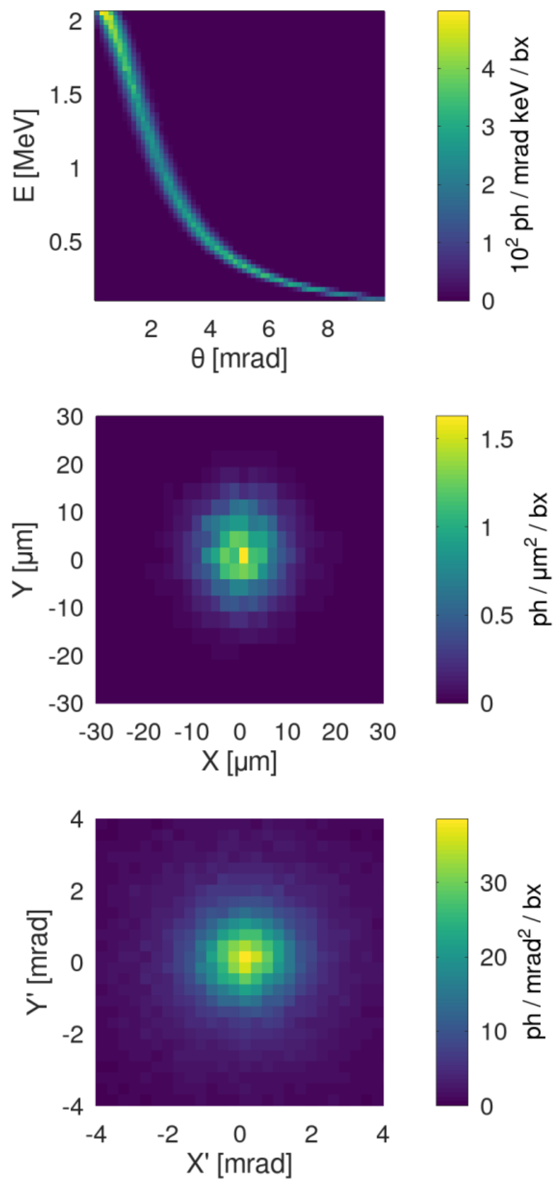


Photon performance

RF-Track simulation

0.5 mrad = 2% BW





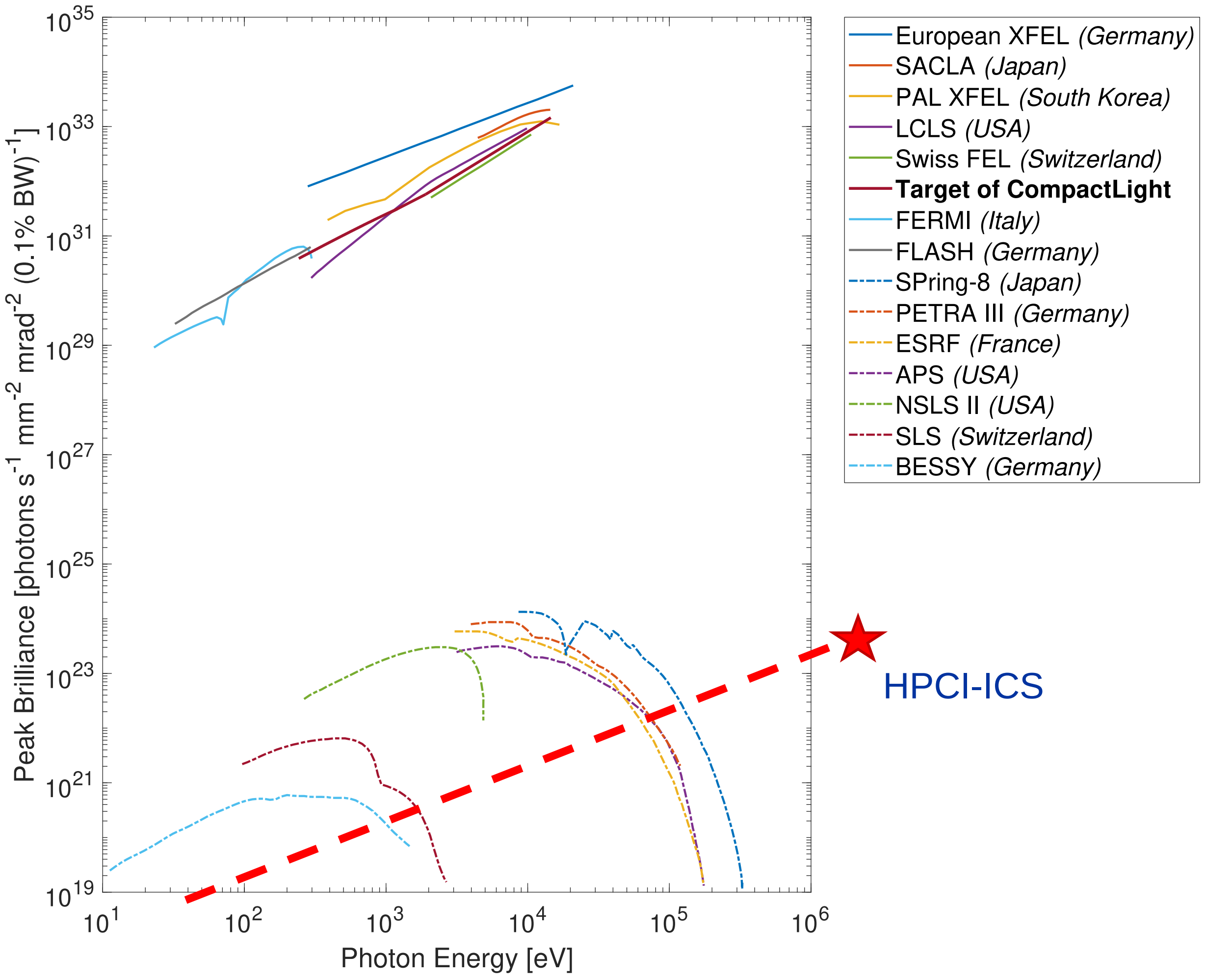
bx = bunch crossing

Photon performance

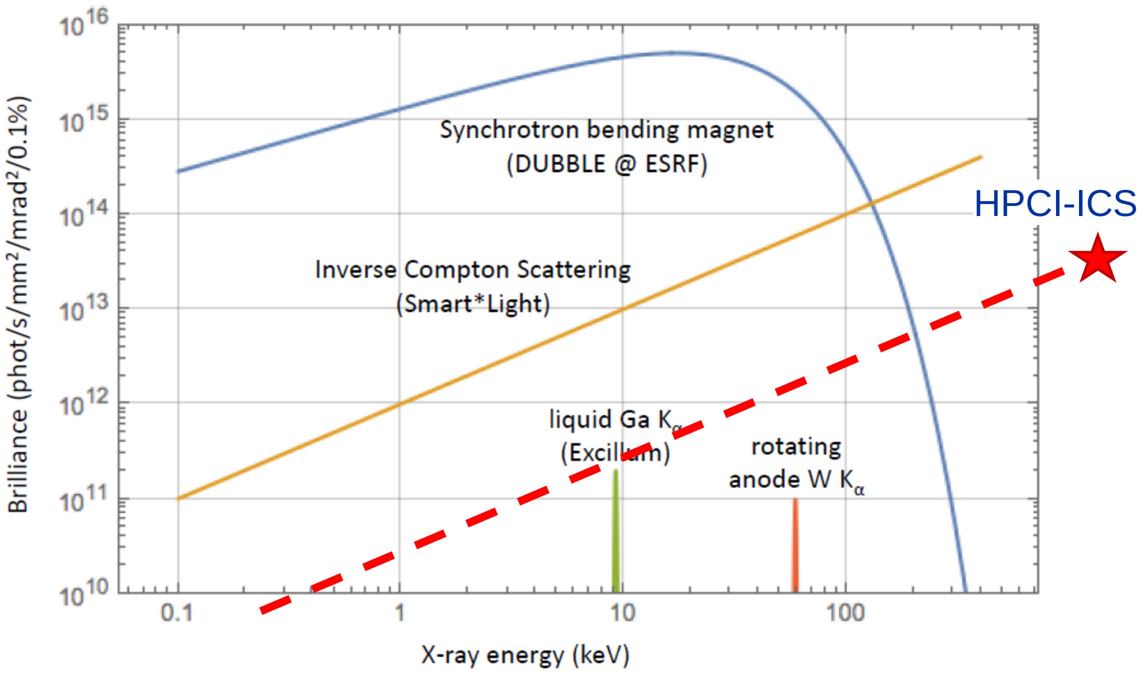
Outcoming photons	Value	Unit
Compton edge	2.1	MeV
Total flux	2.2×10^{13}	ph/s
Bandwidth (0.5 mrad)	2.0	%
Flux (0.5 mrad)	1.6×10^{12}	ph/s
Average Brilliance	4.4×10^{13}	(*)
Peak Brilliance	3.9×10^{23}	(*)

(*) 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

Enters the ballpark of facilities like **ELI-NP Gamma beam System**: a source of “up to 20 MeV Gamma Rays based on Compton back-scattering, i.e. collision of an intense high power laser beam and a high brightness electron beam with maximum kinetic energy of about 720 MeV”.

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