FELs of Europe Topical Workshop on Selected Problems in FEL Physics: from soft X-rays to THz
CSSB, DESY - Hamburg
November 17th, 2023

A Versatile THz Source from High-Brightness Electron Beams

Generation, Characterization and Applications at SPARC_LAB

Dipartimento di Scienze di Base e Applicate per l' Ingegneria

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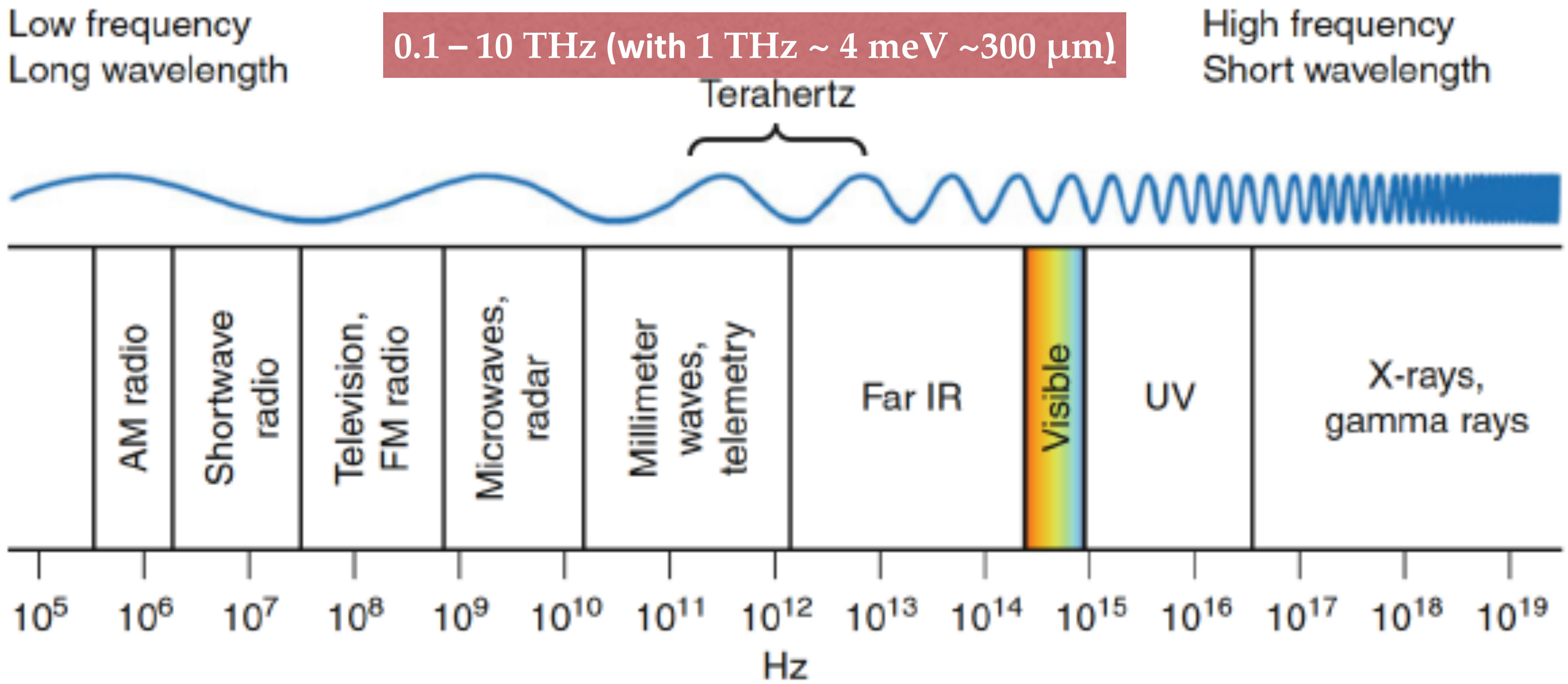
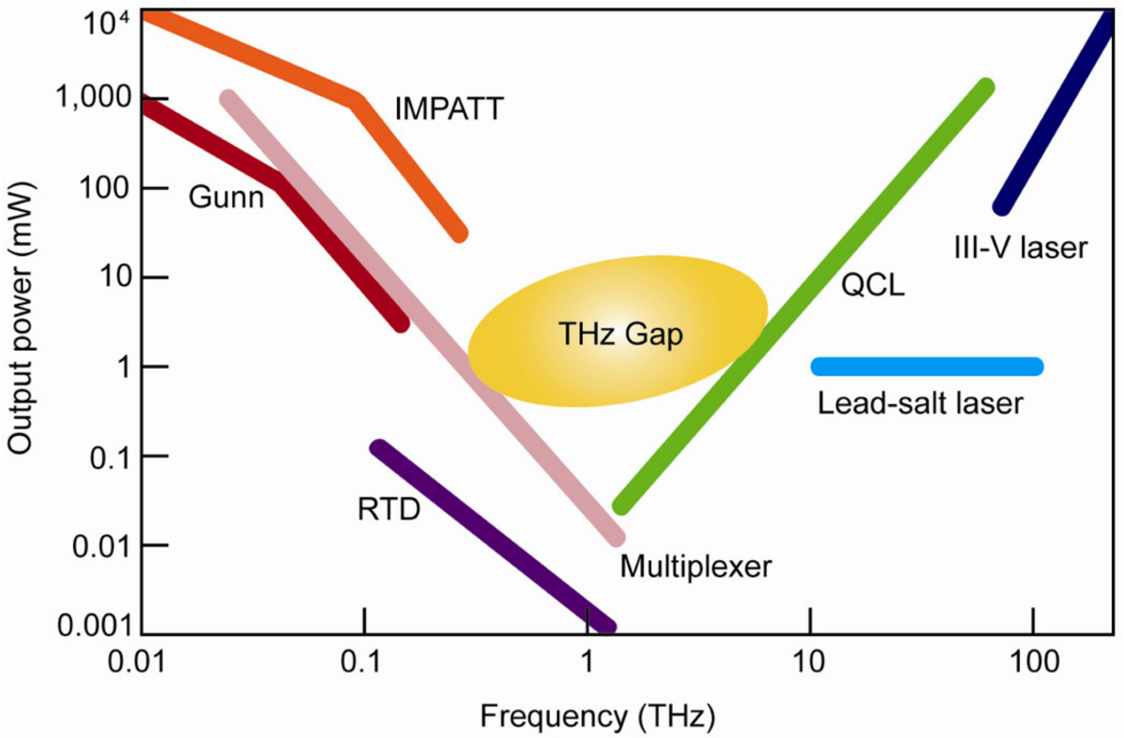
Sapienza Università di Roma

Outline

- Motivation for a THz radiation source
- Overview of the generation mechanism
- The THz radiation source at SPARC_LAB
  - Broad band from ultra-short high brightness electron bunches
  - Quasi-narrow band from longitudinally modulated bunches
  - Narrow band from SASE FEL process
    - The SABINA Project
- Conclusion

Motivation

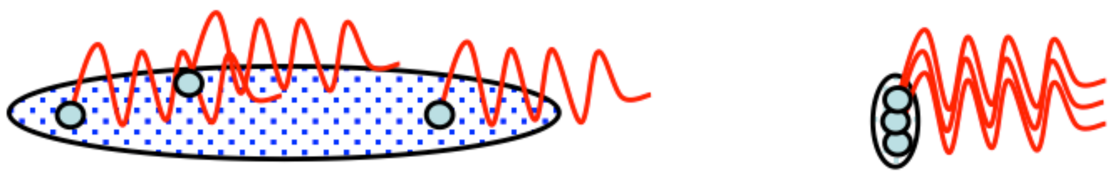




- **'THz Gap':** Challenges associated with the generation, manipulation and detection of THz radiation
- THz Sources:
  - Quantum Cascade Lasers (work mainly in CW, strict operational temperatures, small frequency tunability…)
  - Laser-based sources (pulsed radiation, frequency range limited by the non-linear crystals, high energy pulses…)
  - Particle Accelerator-based sources → High peak power and/or average power, …

Electron Beam-based THz Source

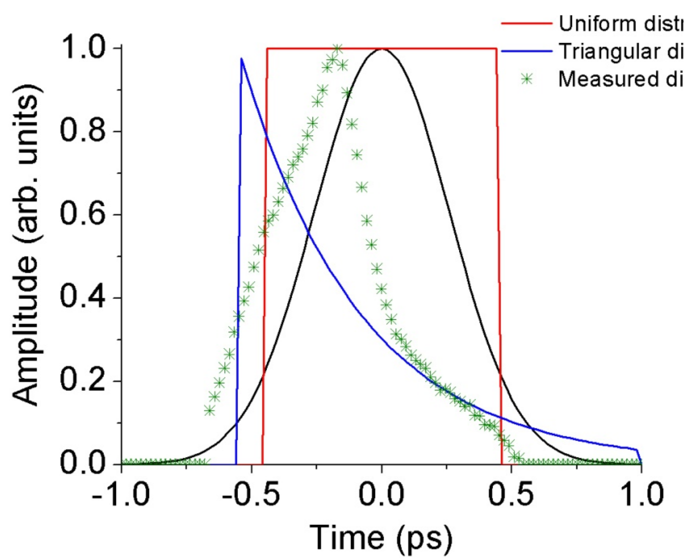
- **New generation of sources** that boost the peak power in the THz region up to **> 10^2 MW**
- Short, **sub-ps down to few tens of fs,** electron bunches produce **Coherent Radiation in the THz range**



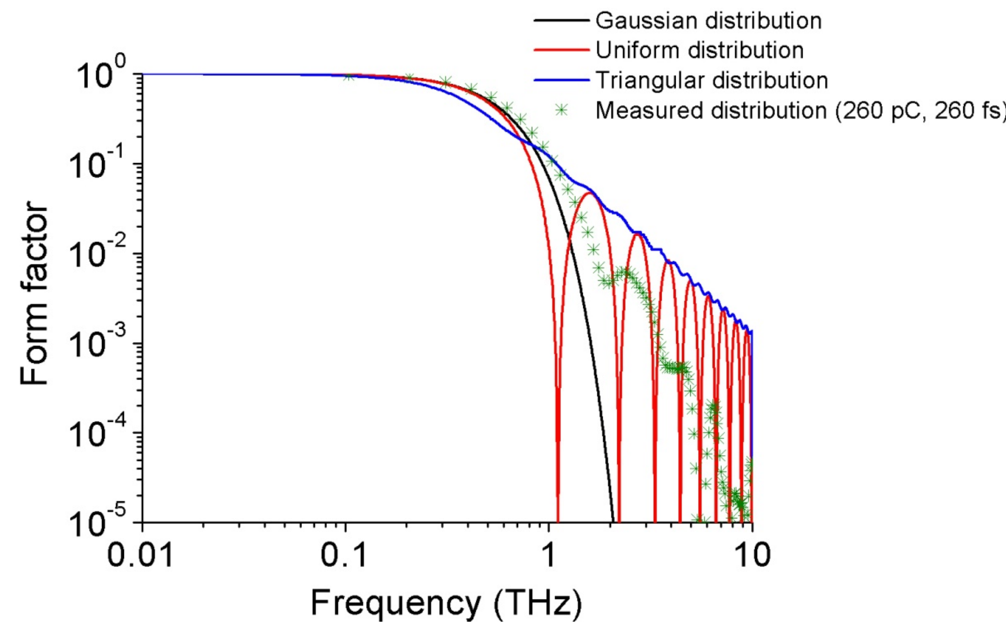
Coherent emission $\propto N^2$

- The **key for high efficiency** in a beam-based radiation source is to exploit the **coherence enhancement effect by beam profile tailoring**

Electron Beam Profile



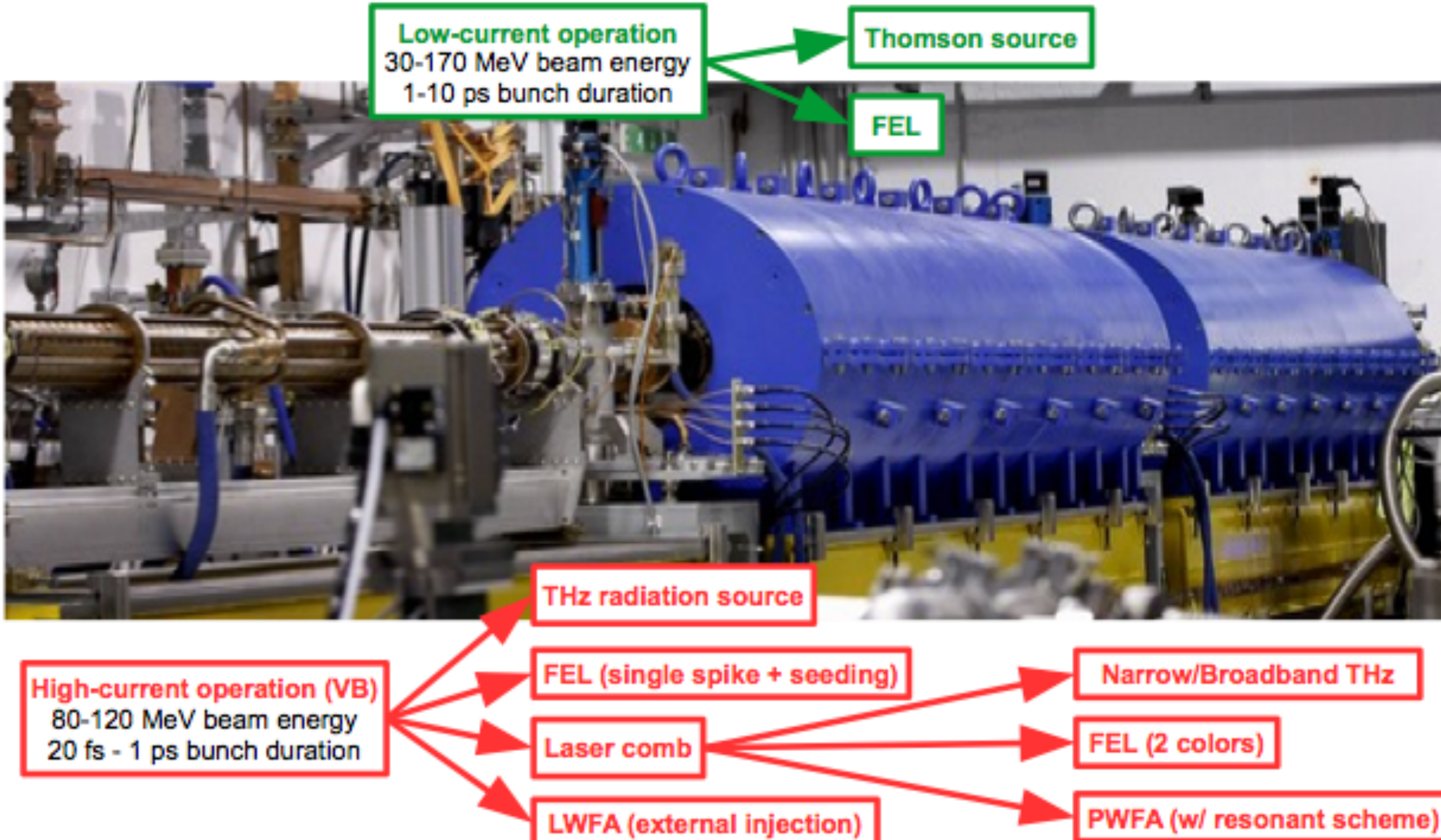
Coherent Radiation Spectrum



$$\frac{dU}{d\lambda} = \frac{dU_{sp}}{d\lambda}\left[N + N(N-1)|F(\lambda)|^2\right] \qquad F(\lambda) = \int_{-\infty}^{\infty} S(z)e^{i\frac{2\pi z}{\lambda}}dz$$

The SPARC_LAB Test Facility

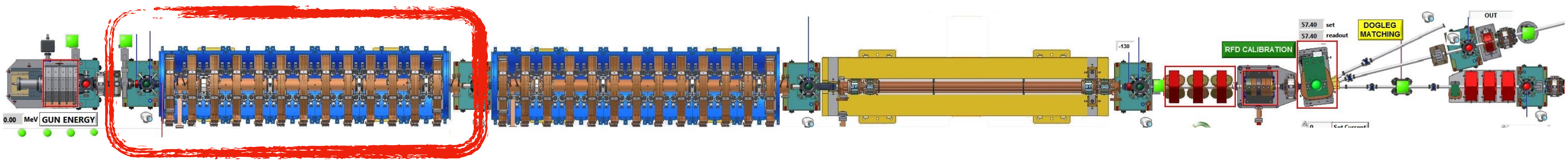
M. Ferrario et al., *SPARC_LAB present and future*, NIM B **309**, 183–188 (2013)

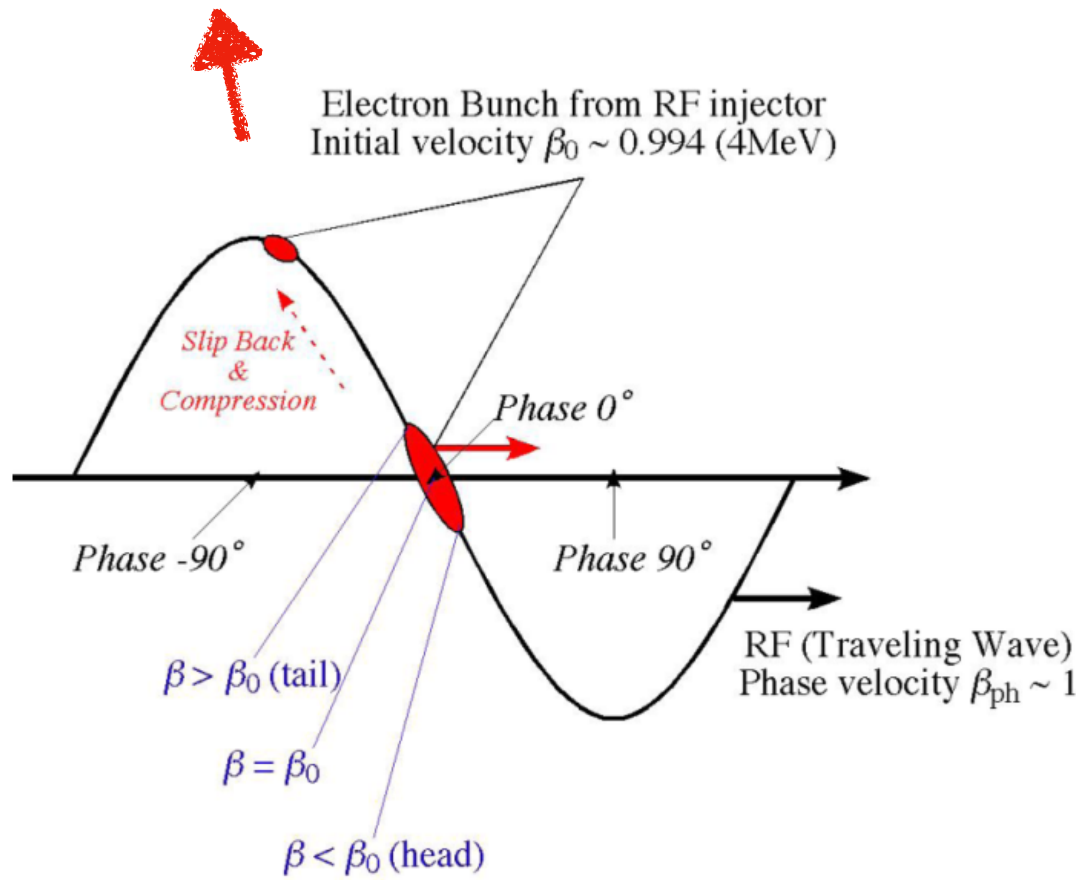


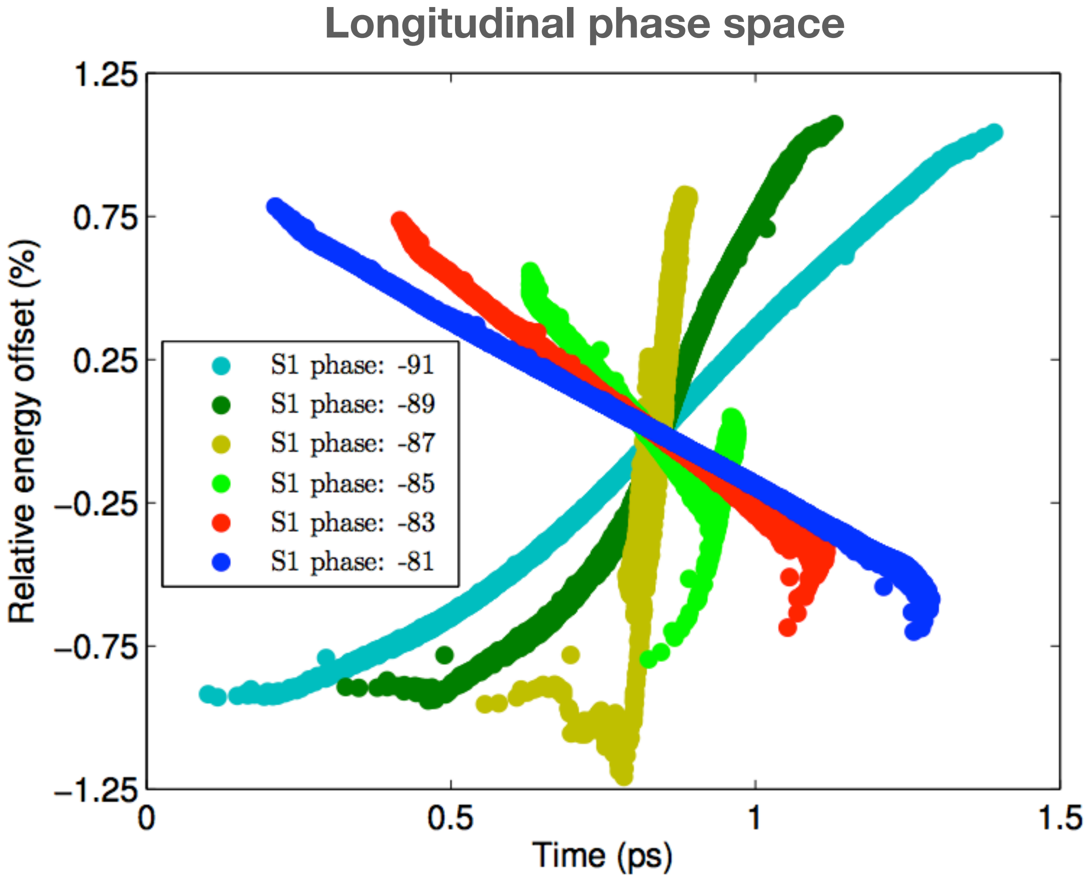
https://www.google.it/maps/@41.8231995,12.6743967,3a,69.7y,130.68h,76.68t/data=!3m6!1e1!3m4!1sYyB35yaBMxJgQ92-wp3oYQ!2e0!7i13312!8i6656?hl=en

Linac-based THz Radiation Source

Velocity Bunching Technique for Longitudinal Compression





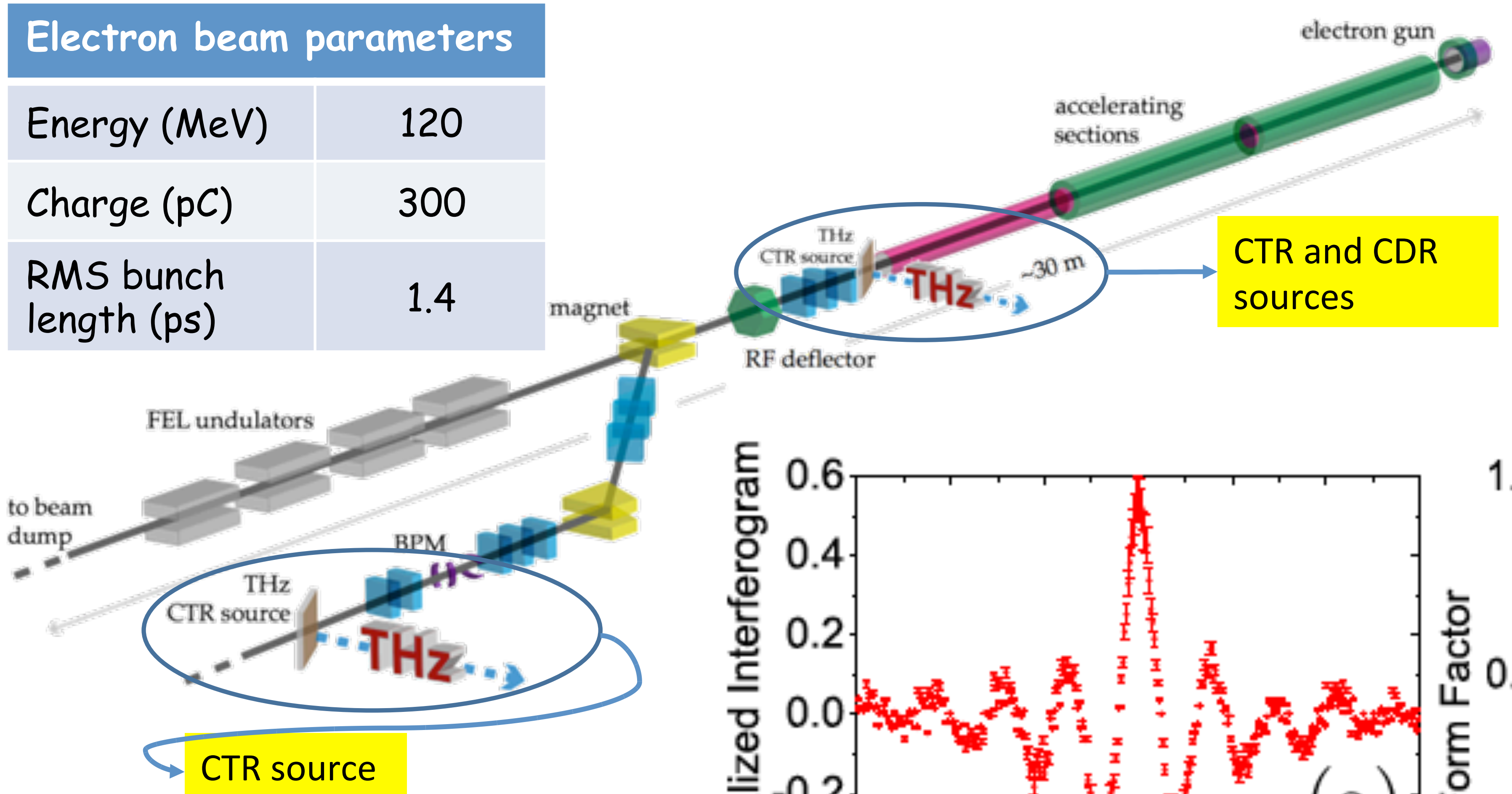


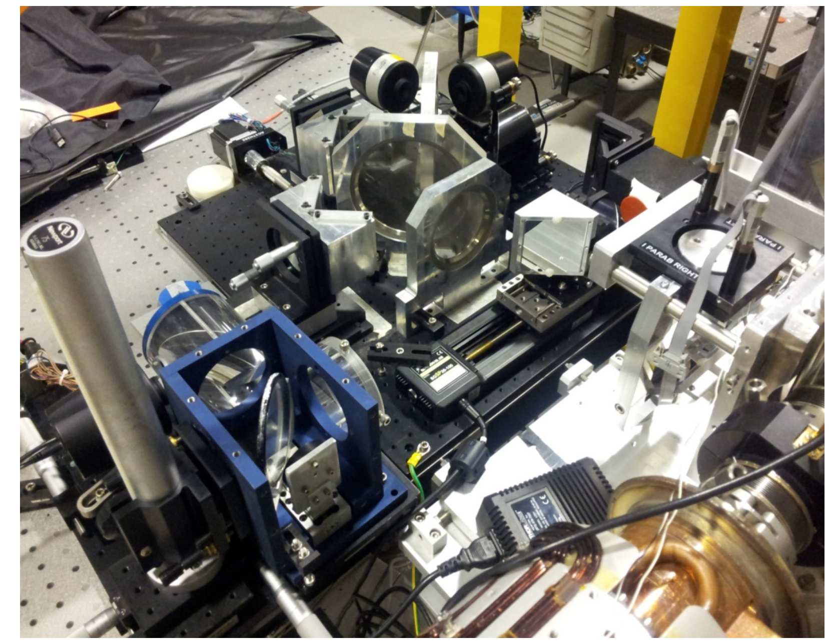
L. Serafini and M. Ferrario, *Velocity Bunching in Photo-injectors*, Physics of, and Science with the X-Ray Free-Electron Laser, edited.by S. Chattopadhyay et al. © 2001 American Institute of Physics

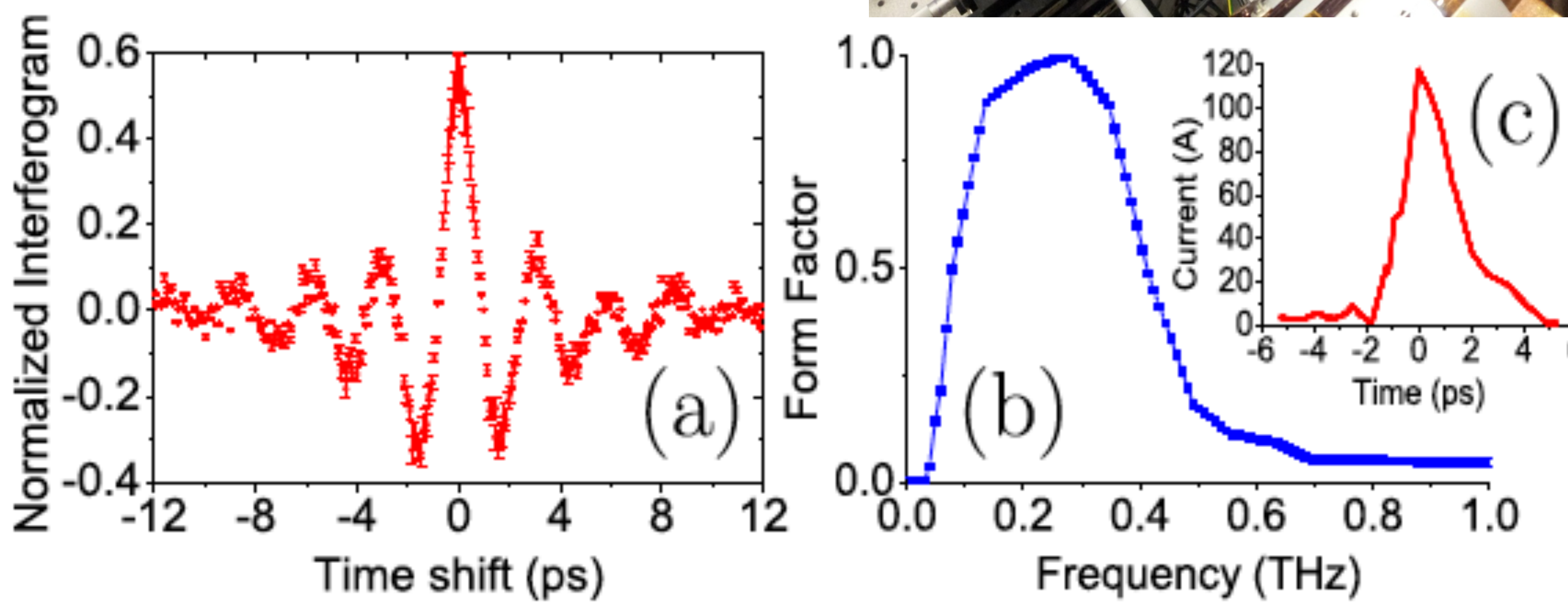
M. Ferrario et al., Experimental Demonstration of Emittance Compensation with Velocity Bunching, Phys. Rev. Lett. **104**, 054801 (2010)

THz Radiation as Longitudinal Beam Diagnostic

Electron beam parameters	
Energy (MeV)	120
Charge (pC)	300
RMS bunch length (ps)	1.4







$$\left(\frac{dI}{d\omega}\right)_{measured} \Rightarrow \frac{dI}{d\omega} \Rightarrow |F(\omega)| \Rightarrow F(\omega) \Rightarrow S(z)$$

Beam line transmission, instrument response

Phase reconstruction
Kramers-Kronig technique

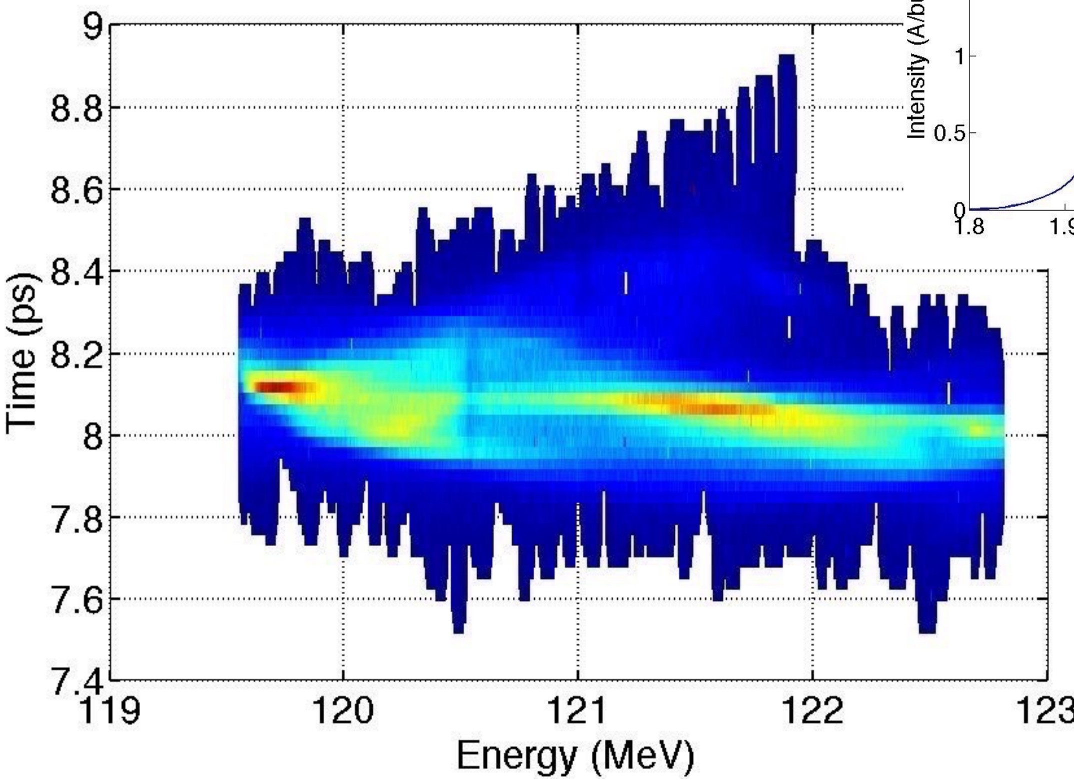
Inverse Fourier transform

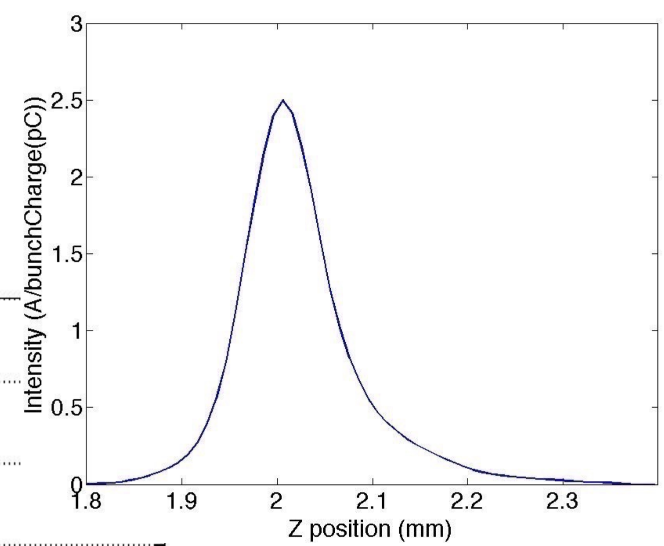
(a) Autocorrelation function measured by a Martin-Puplett interferometer
(b) Bunch form factor
(c) Retrieved longitudinal bunch profile: 1.4 (0.1) ps *rms*

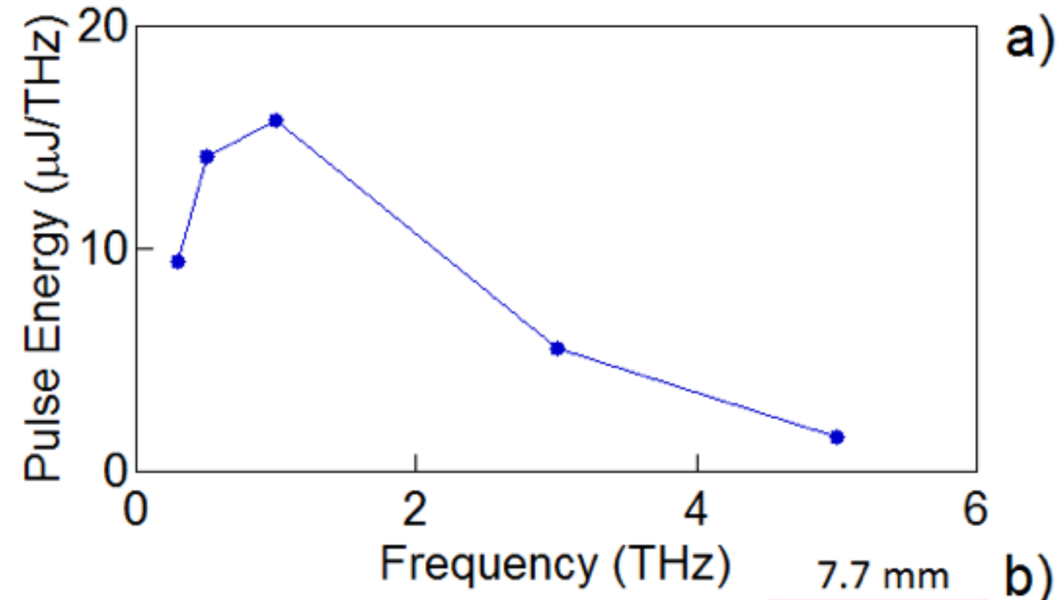
Broad-band High Peak Power Source

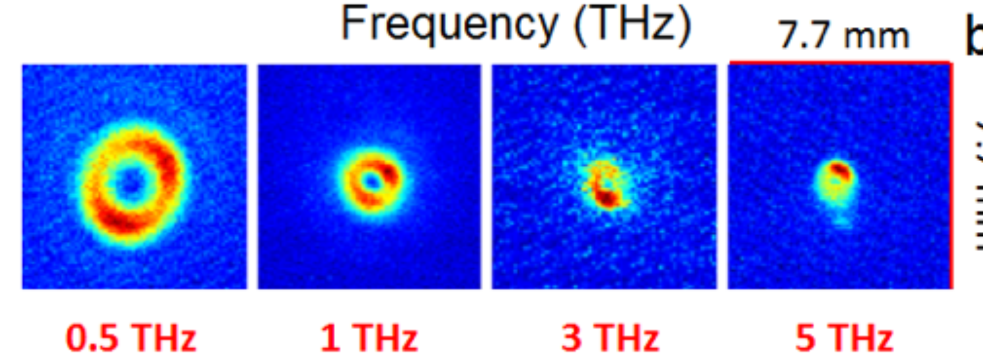
Velocity Bunching for Longitudinal Compression

E (MeV)	ΔE/E (%)	σ_t (fs)	Q (pC)
121 (0.03)	0.7	100(10)	500(25)







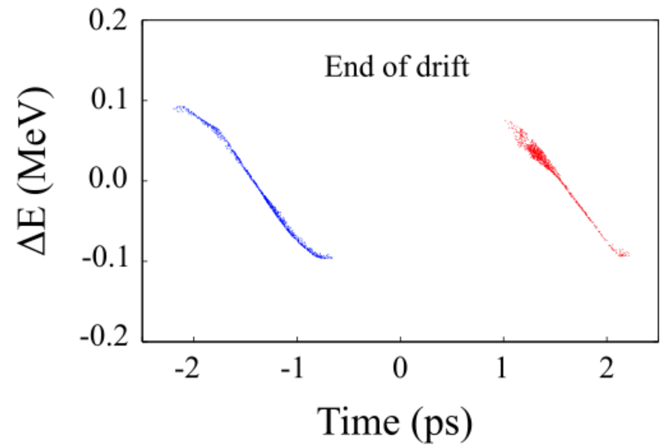


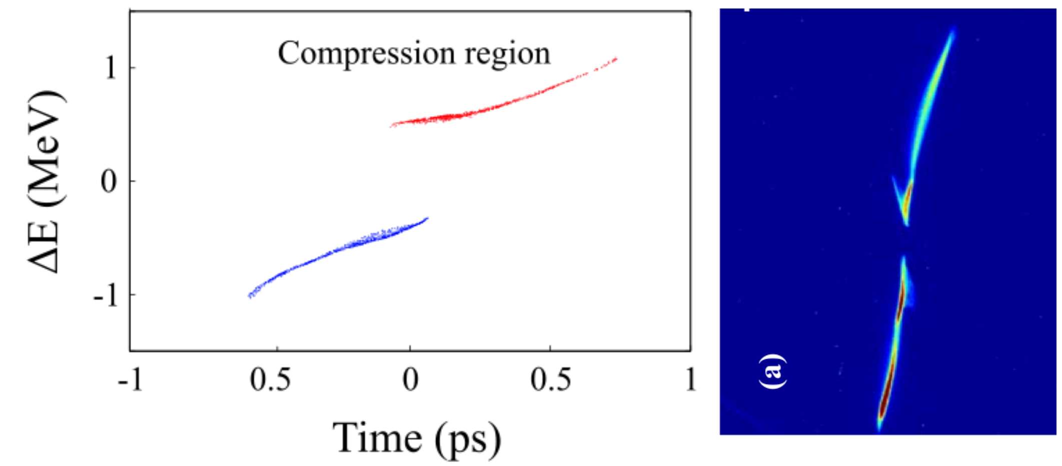
THz radiation parameters	
Integrated Energy/pulse (uJ)	35
Electric field (MV/cm)	1,6
Pulse duration (fs)	~100
BW (THz)	0.3* - 5**

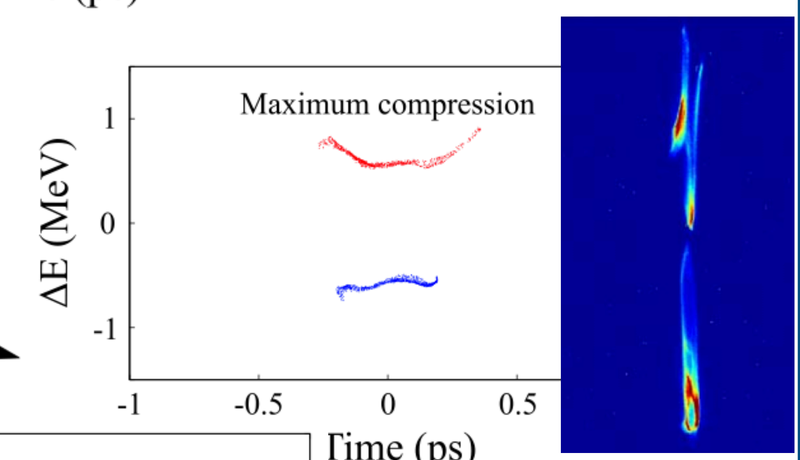
*Low frequency cut-off due to the extension of the source
**High frequency cut-off due to bunch length

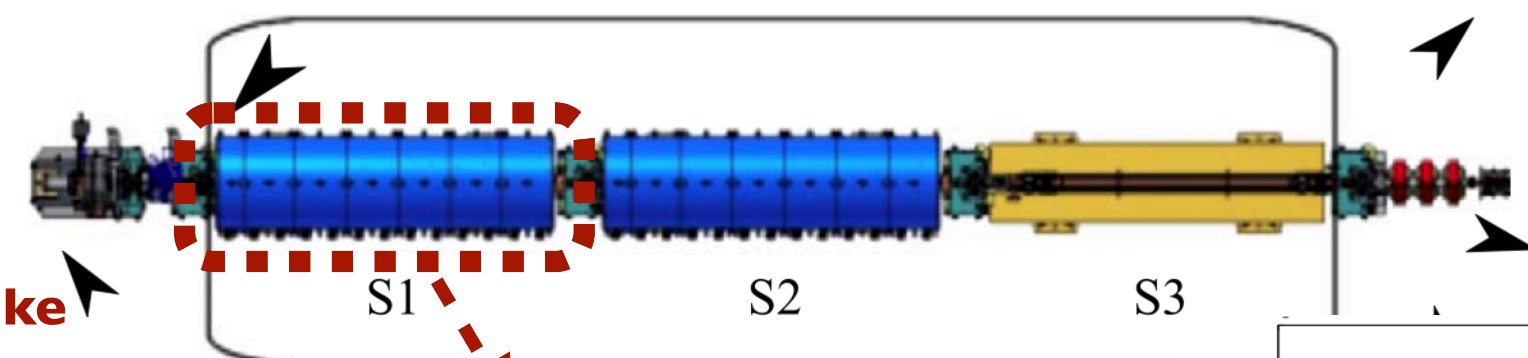
Linac-based THz Radiation Source

Laser Comb Technique for Longitudinally Modulated Beams

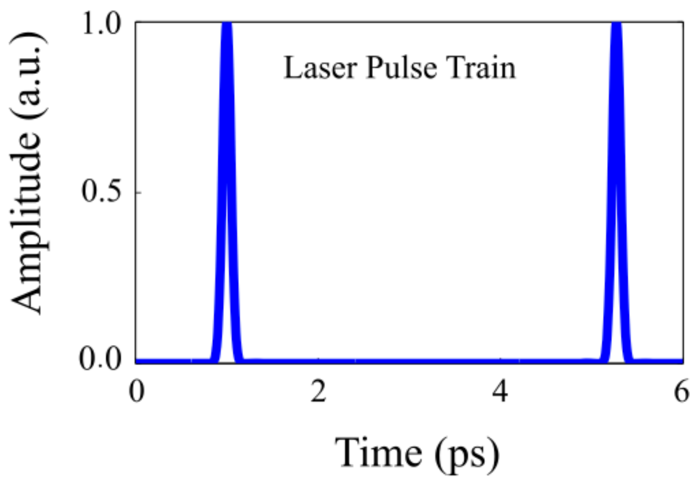




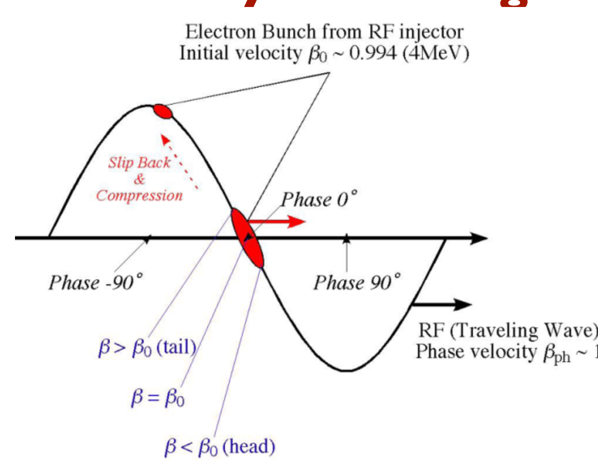


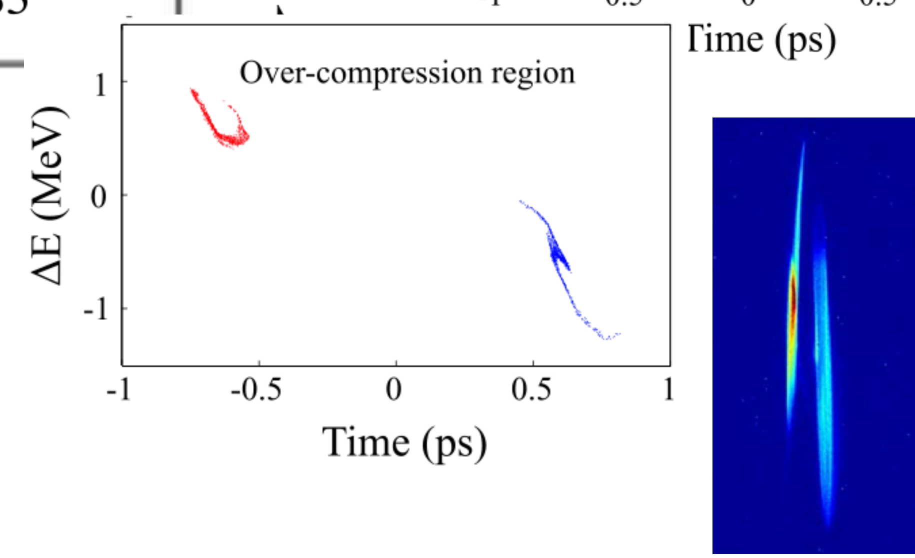


Comb-like laser



Velocity bunching



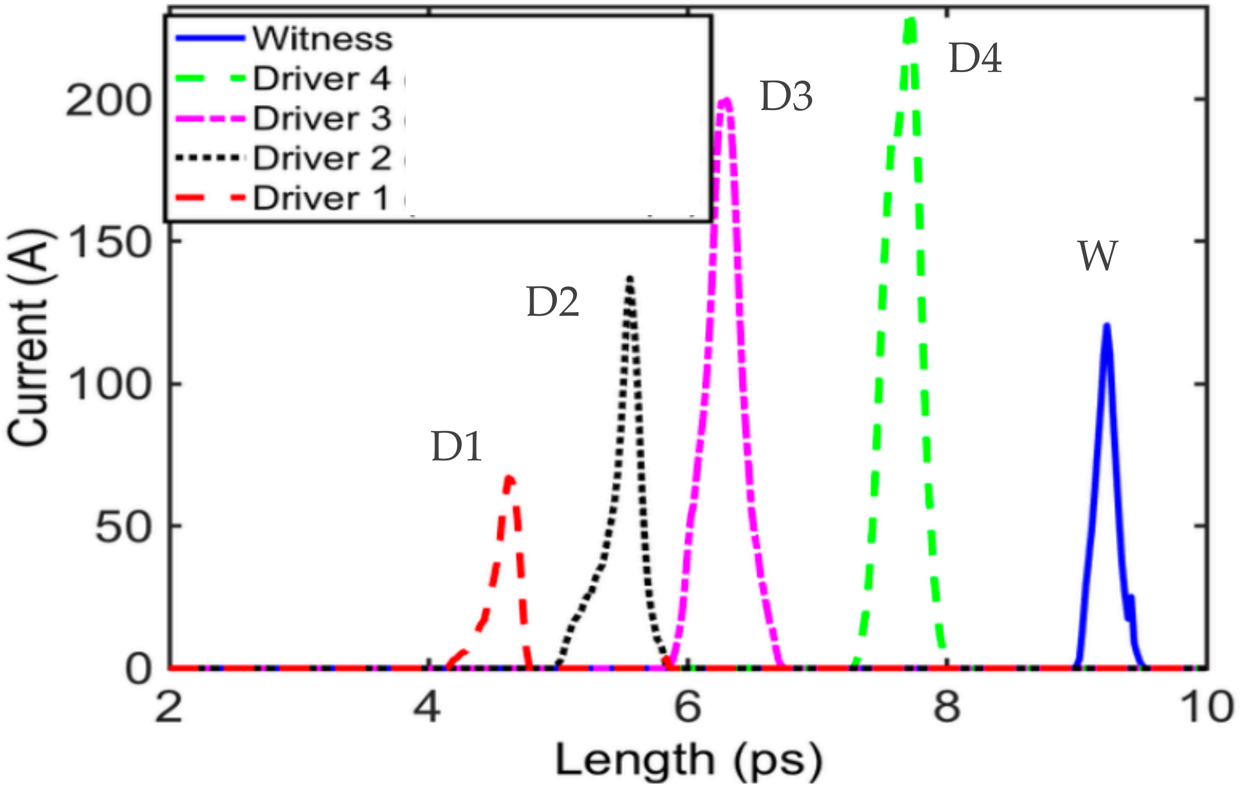


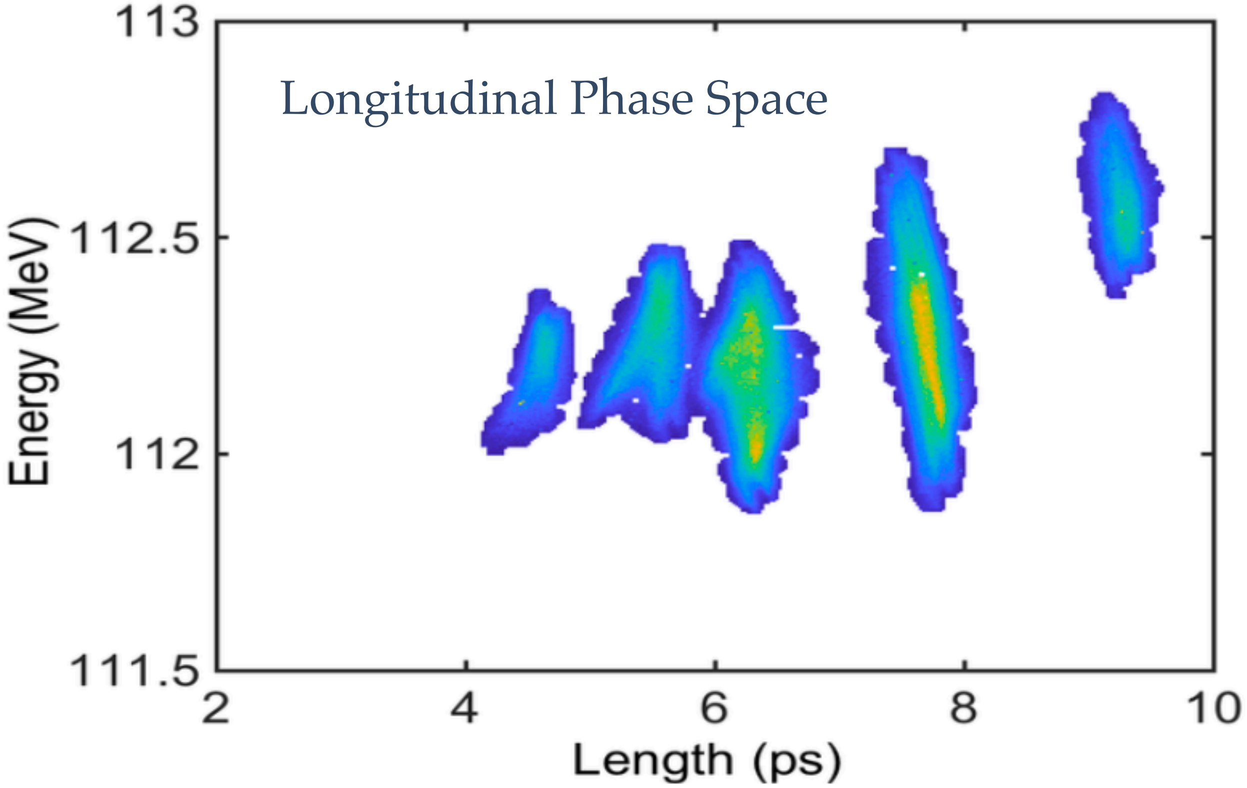
P. O. Shea et al., Proc. of 2001 IEEE PAC, Chicago, USA (2001) p.704.
M. Ferrario et al., Int. J. of Mod. Phys. B, 2006
M. Ferrario et al., PRL **104**, 054801 (2010)

Quasi-Narrow Band Tunable Source

Electron Beam Parameters

Total Charge = 240 pC



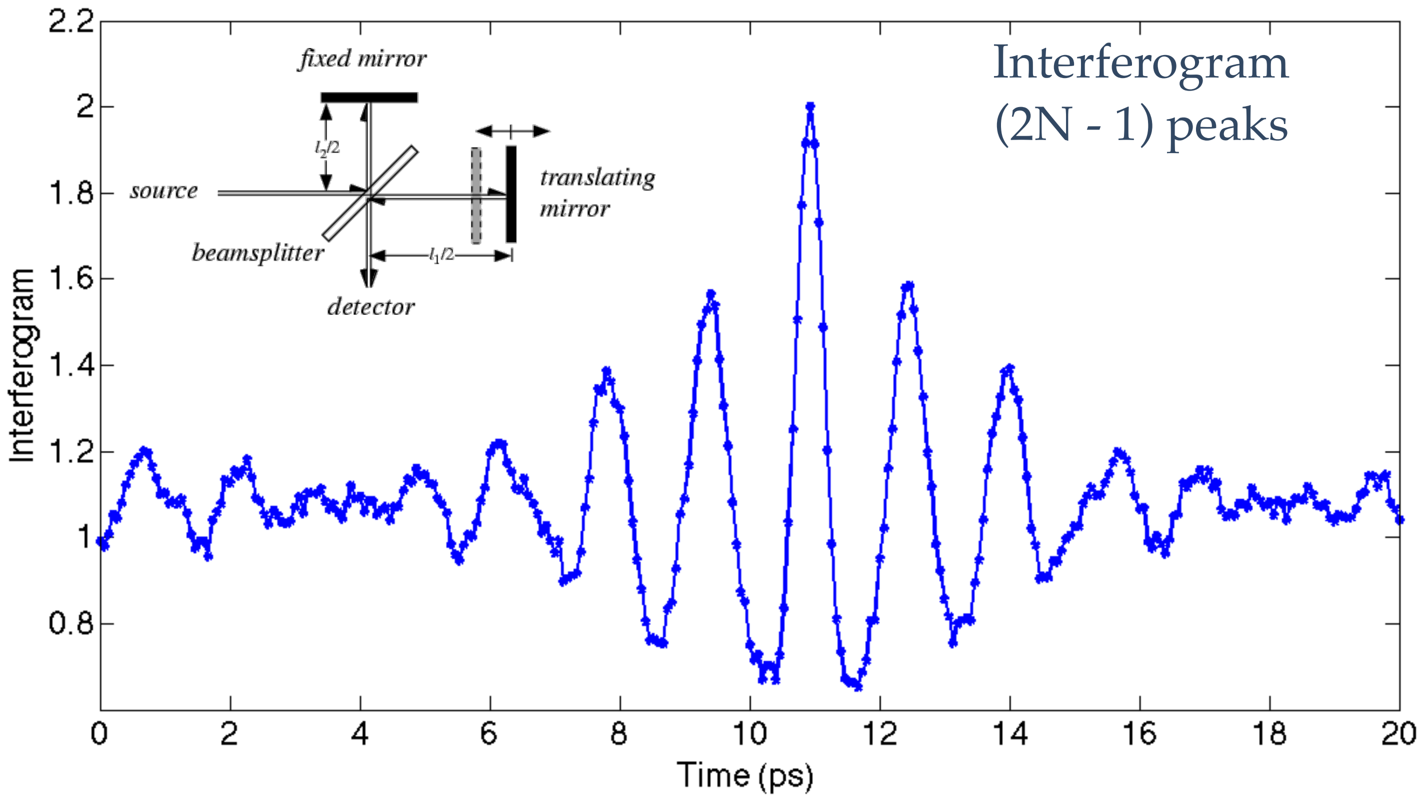


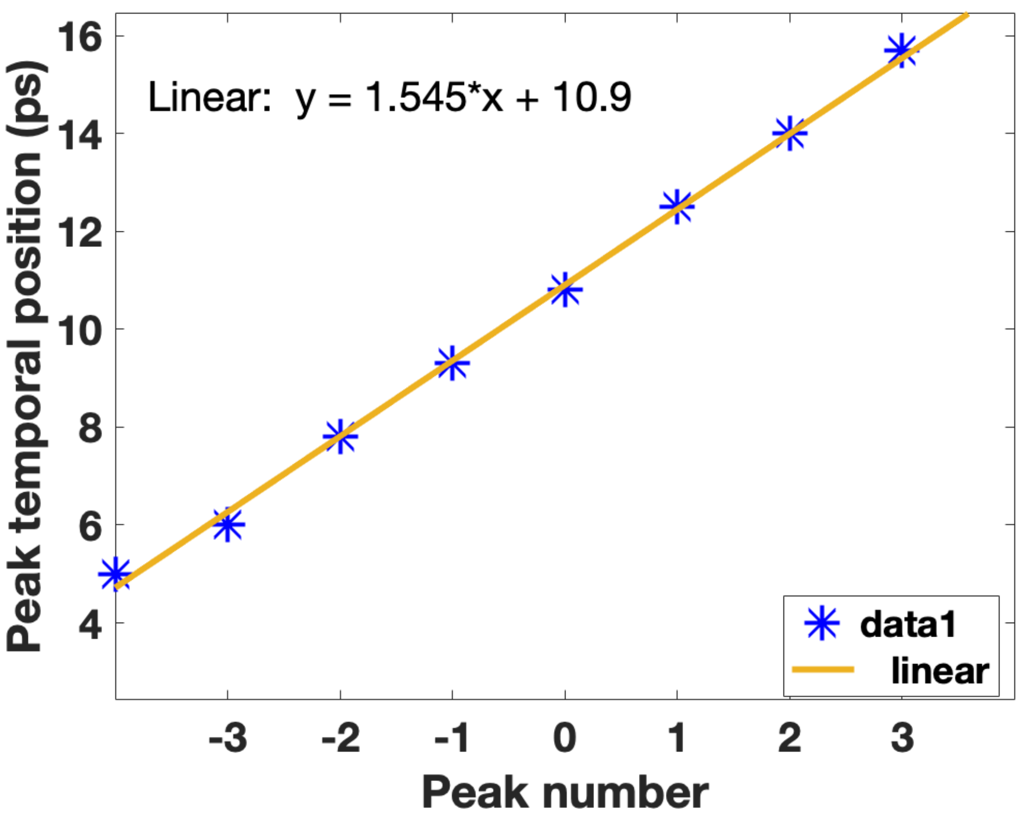
Time Separation(ps)
W-D4 =1.58 (0.02)
D4-D3 =1.38 (0.03)
D3-D2 =0.80 (0.03)
D2-D1 =0.91 (0.05)

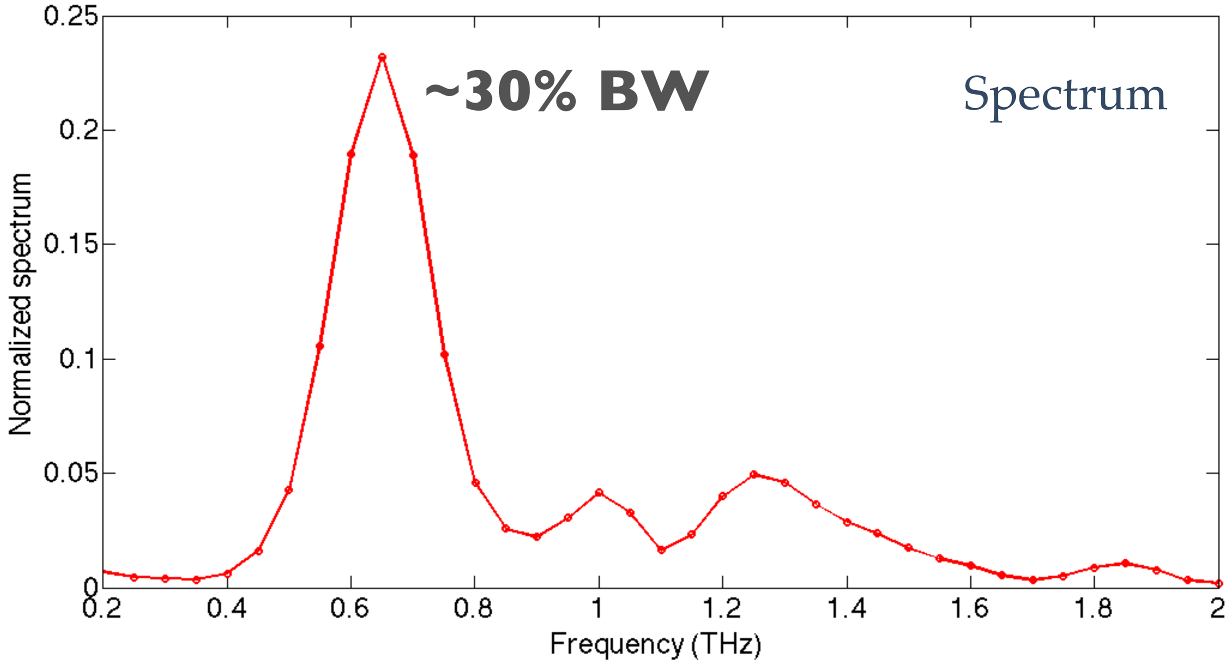
	E (MeV)	$\Delta E/E$ (%)	σ_t (fs)	Q (pC)	ε_{nx} (mm mrad)
W	112.6	0.084	80	24	1(0.09)
D4	112.3	0.159	42	75	0.8(0.1)
D3	112.2	0.112	92	69	1.7(0.1)
D2	112.3	0.087	113	36	2.7(0.6)
D1	112.2	0.045	100	36	2.8(0.3)

Quasi-Narrow Band Tunable Source

CTR Parameters

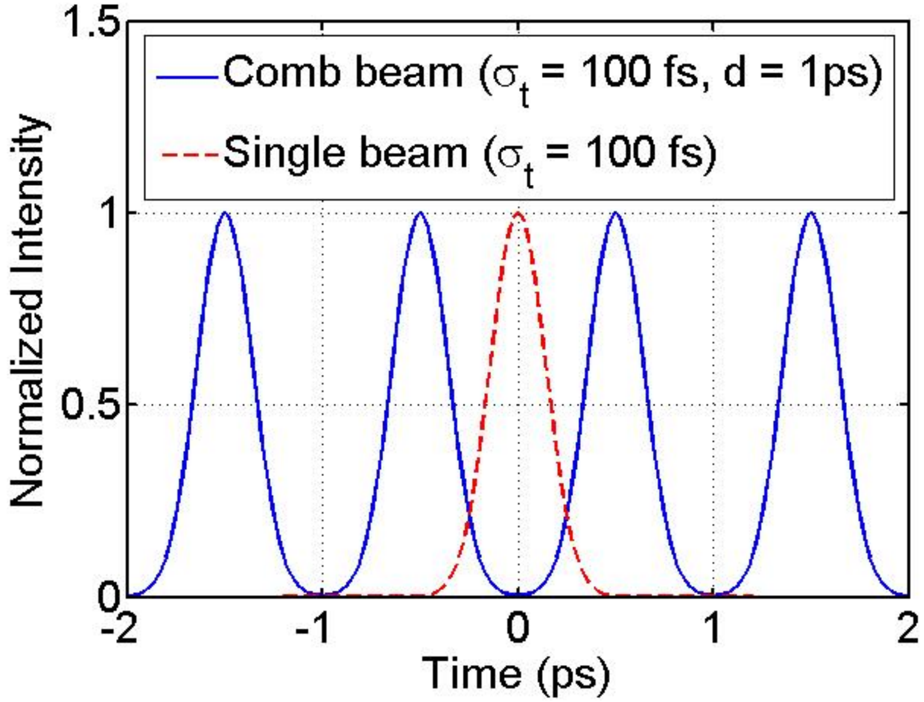


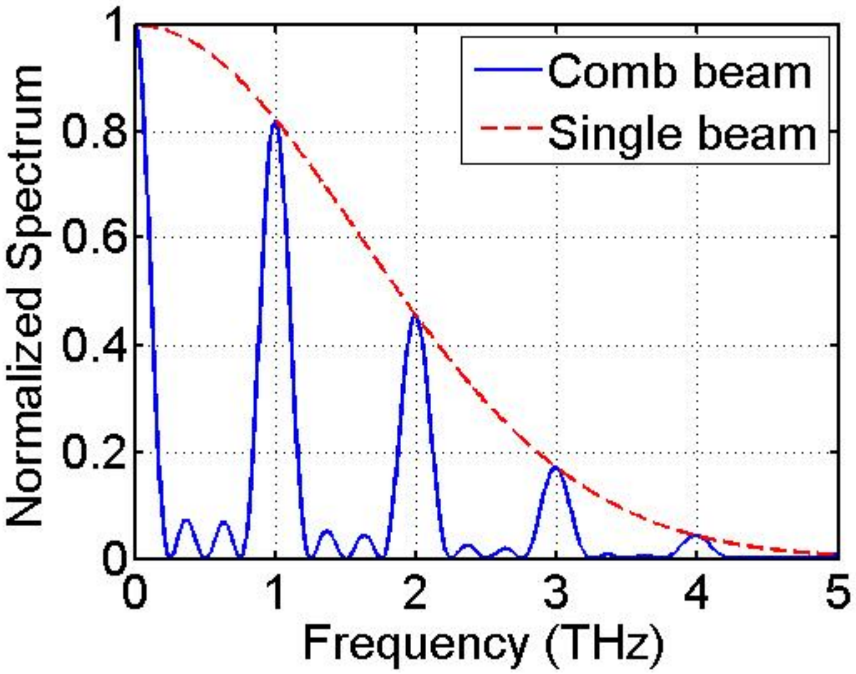


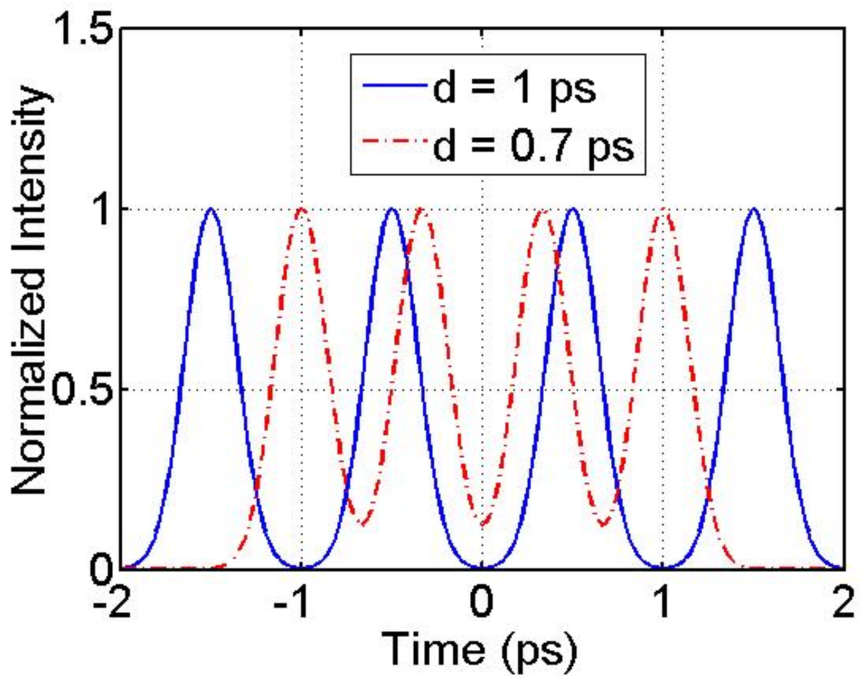


E. Chiadroni et al., Rev. Sci. Instrum. **84**, 022703 (2013)
B. Marchetti et al., Rev. Sci. Instrum. **86**, 073301 (2015)
F. Giorgianni et al., Appl. Sci. **6**, 2 (2016)

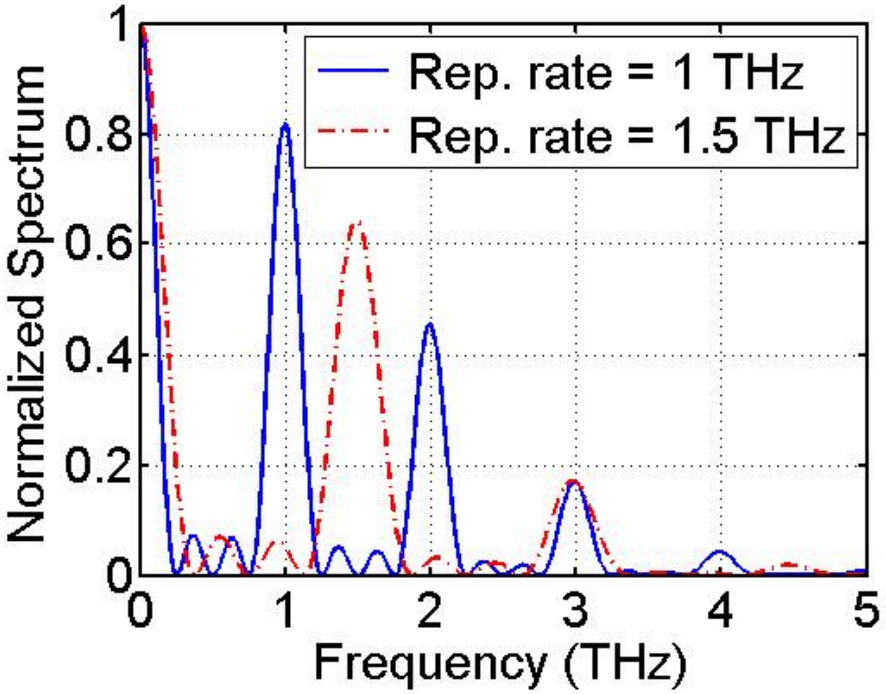
Tunable THz Source







M. Castellano and E. Chiadroni, **SPARC-BD-07/005** (2007).



Figures of Merit

CTR-based THz Source

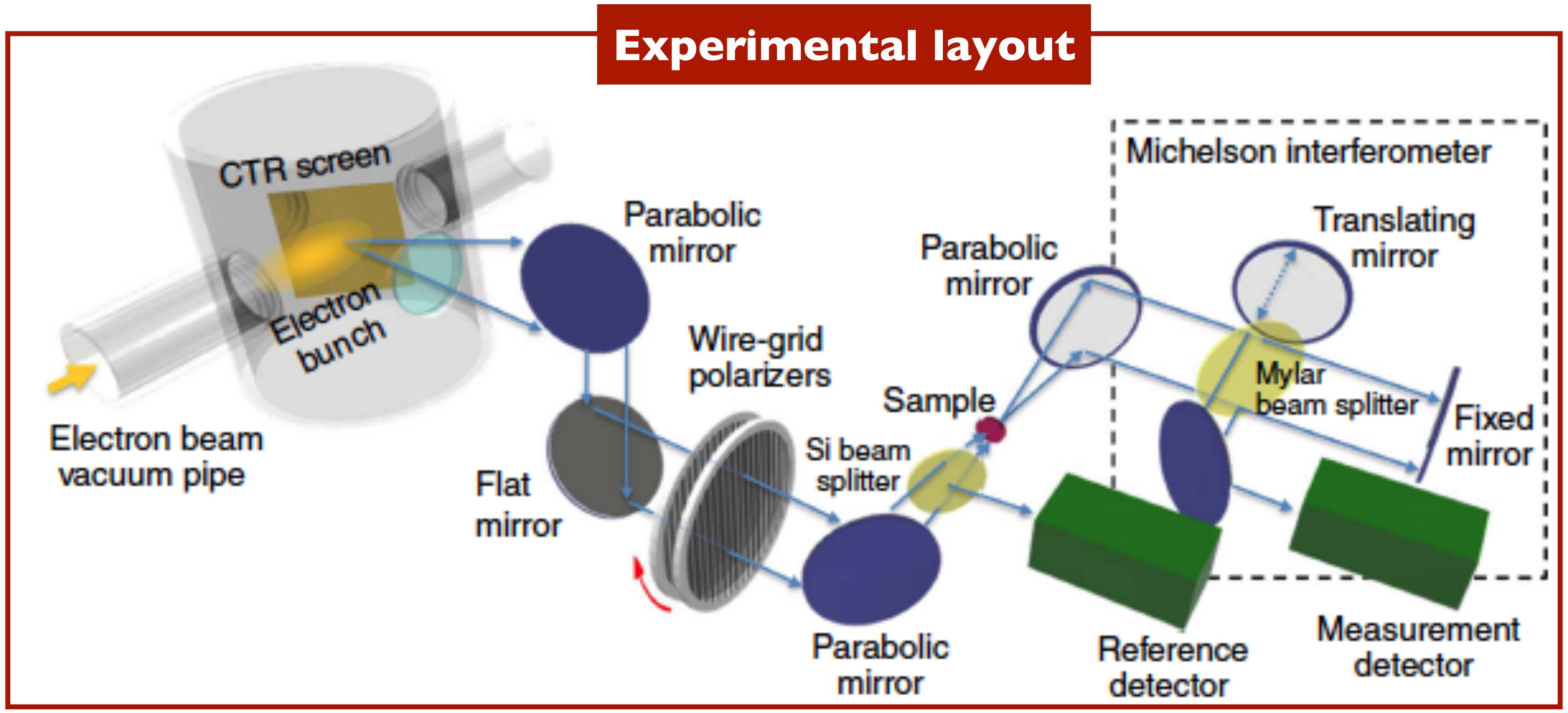
THz Radiation Parameters			Electron Beam Parameters		
	Single Bunch	**Ramped Comb**		**Single Bunch**	**Ramped Comb**
Energy per pulse (μJ)	35 †	∼1	Charge (pC)	500	220
Peak power (MW)	∼80 †	∼3	Energy (MeV)	121	110
Electric field (MV/cm)	>1 †	-	RMS Bunch duration (fs)	180	††
Bandwidth * (THz) $\Delta\nu$	∼2	0.25	Rep. Rate (Hz)	10	10
RMS Pulse duration t_p (ps)	∼0.18	∼1.23 **	Comb distance (ps)	-	1.3

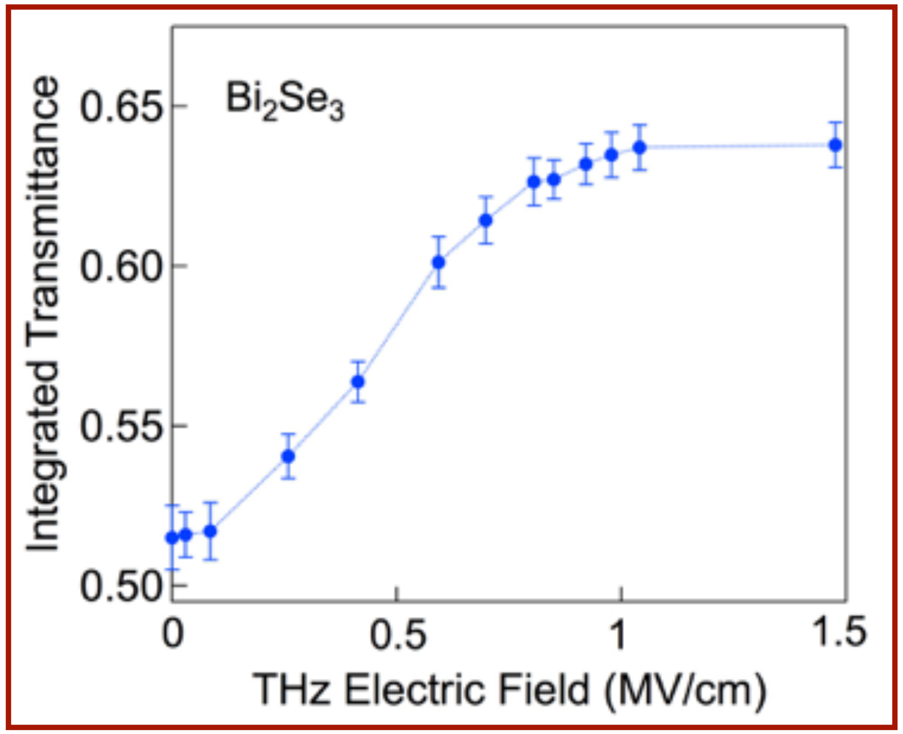
† Systematic uncertainty due to missing detector calibration below 0.61 THz; †† the RMS duration, σ_t, for each bunch in the train is reported in the table caption; * Defined as the FWHM; ** From measured results the time-bandwidth product is $\Delta\nu\ t_p = 0.72$.

First user's experiment at SPARC_LAB

Metal-to-insulator transition in topological insulators

Study of the non-linear electrodynamics properties on **topological insulators**: **strong reduction of the absorption of Bi_2Se_3** has been **observed for the first time increasing the THz electric field from few kV/cm up to 1.6 MV/cm** onto the sample



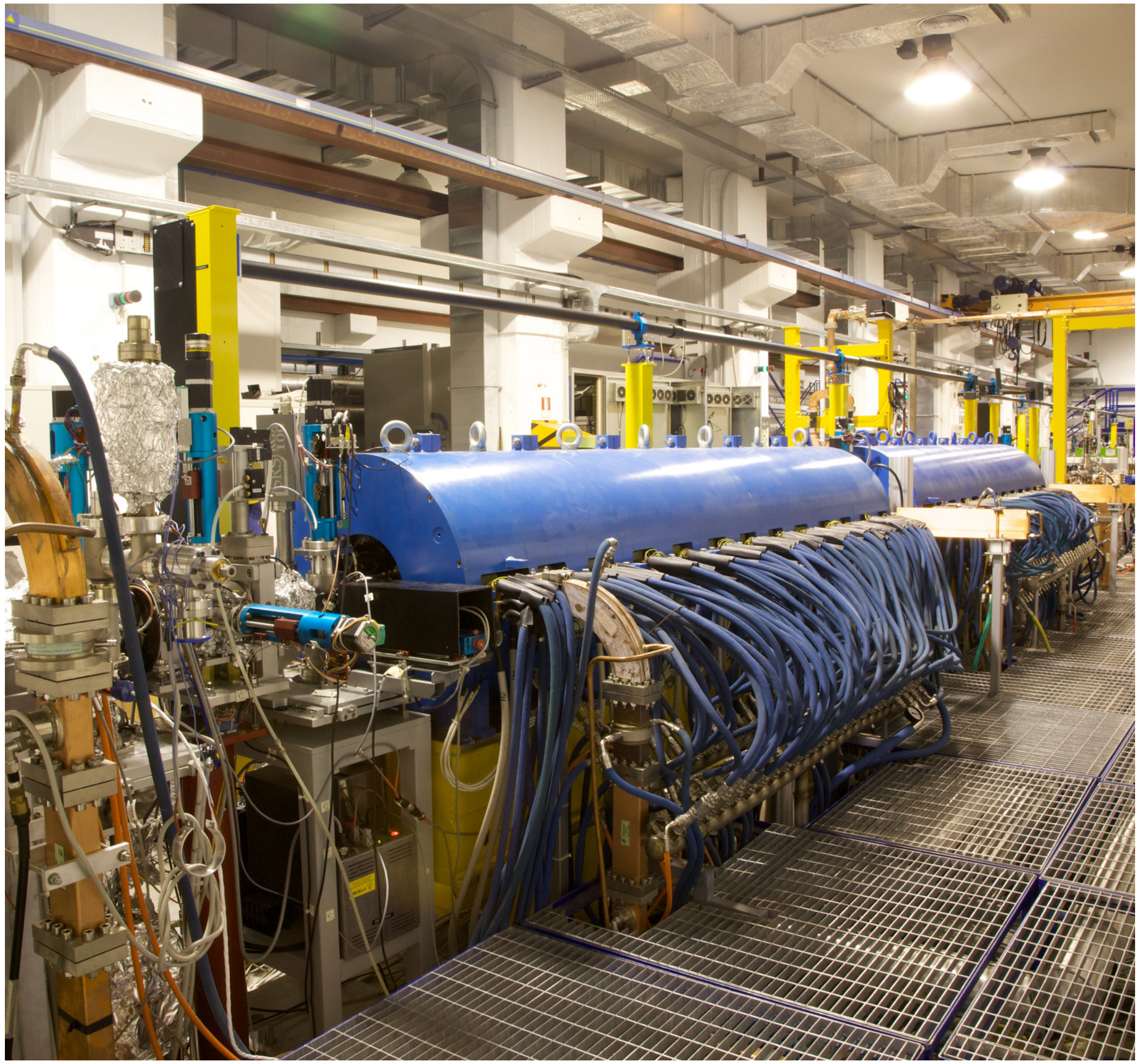


F. Giorgianni, E. Chiadroni et al., Nature Communications **7**:11421 (2016)

SABINA

Source of Advanced Beam Imaging for Novel Applications

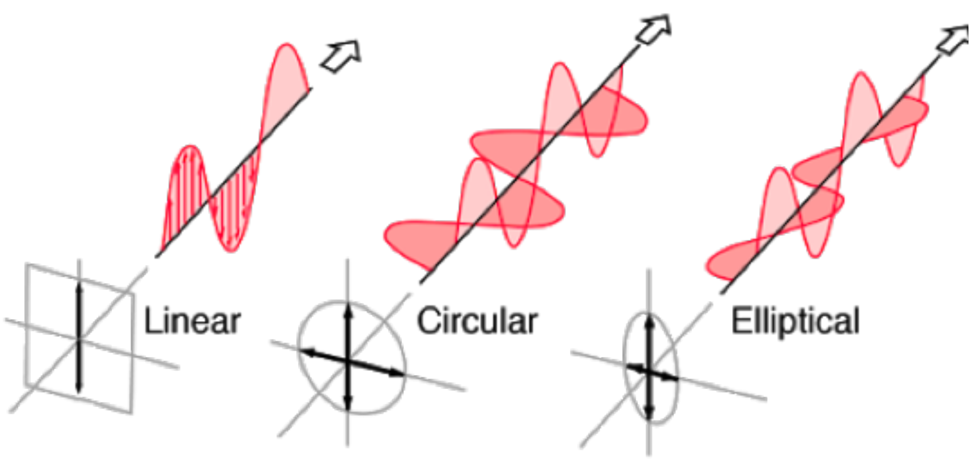
- **GOAL:** Enhancement of the SPARC_LAB research facility – increase of the uptime and improvement of the accelerator performances:
  - Technological plant renewal
  - Substitution of the ancillary systems and upgrade of the facility in terms of technology
  - Creation of two user facilities:
  - High power laser for solid target experiments
  - **THz/IR FEL**: radiation source for optical spectroscopy (pump probe), also at cryogenic T
- **STATUS:** kick off Sept. 2019, present deadline: end of 2023

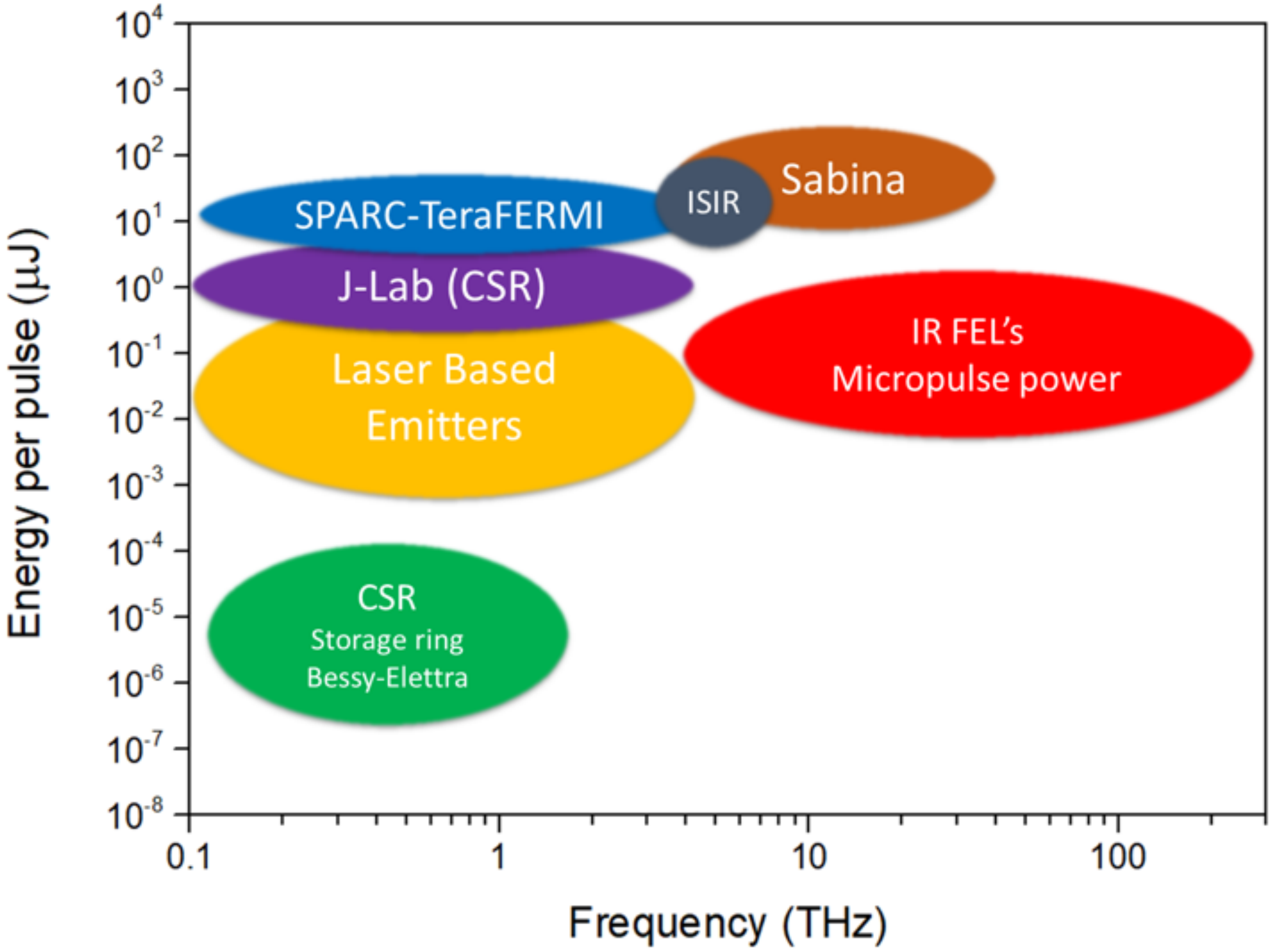


Spokesperson L. Sabbatini

The SABINA THz/IR SASE FEL

- **SABINA** aims to develop a THz/IR SASE FEL user facility delivering
  - monochromatic light with ~ps/sub-ps time duration
  - Tunable frequency between 3-30 THz
  - High energy per pulse, up to 100 μJ/pulse
  - Tunable polarization





Courtesy of L. Mosesso and S. Lupi

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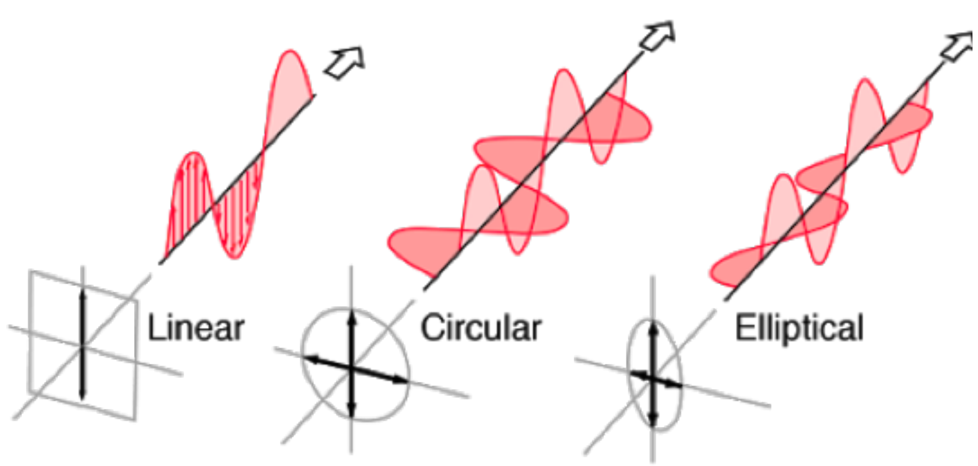
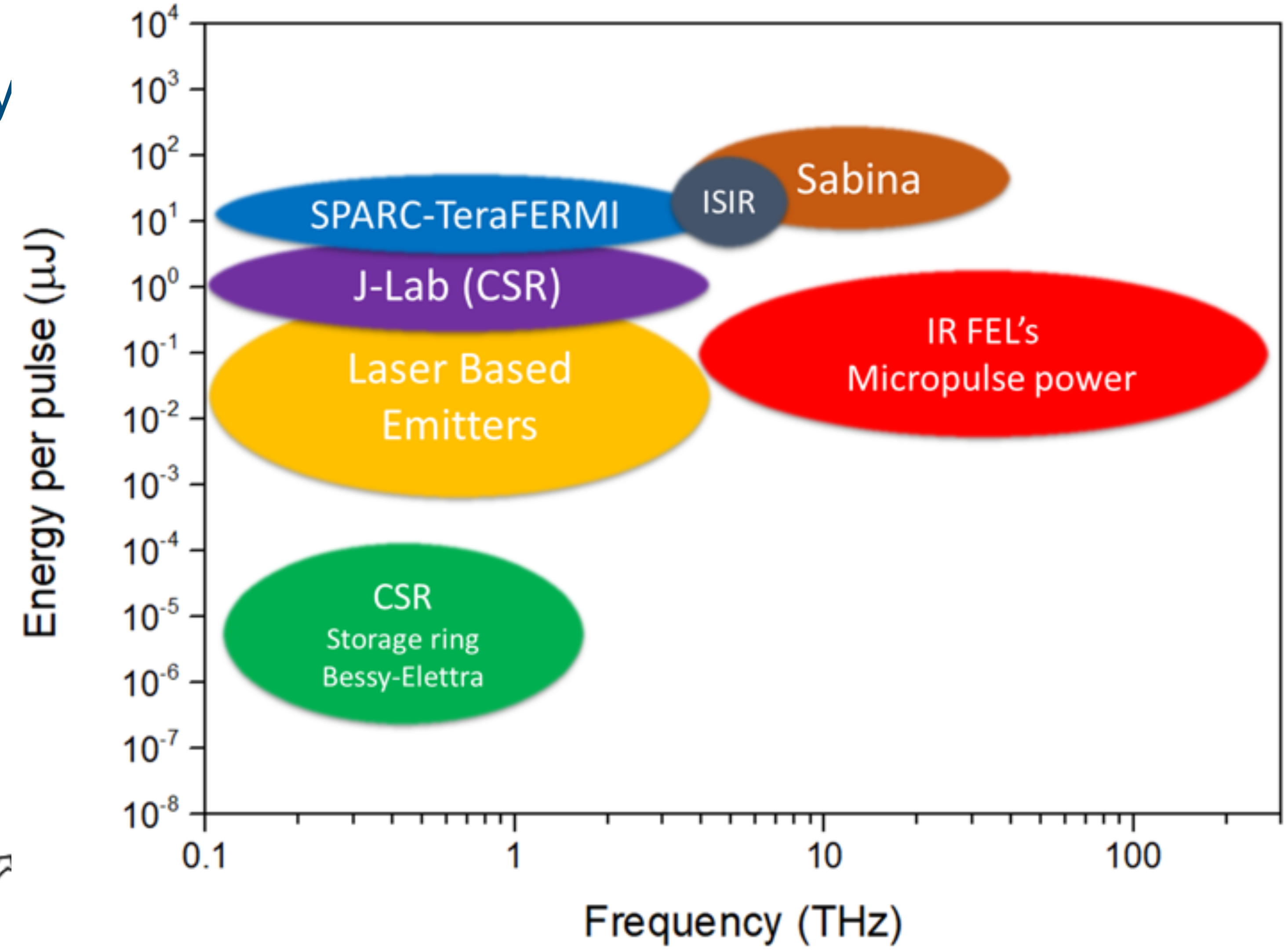
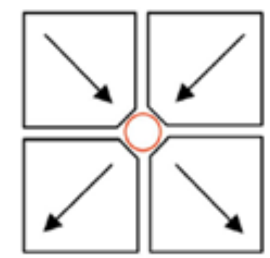


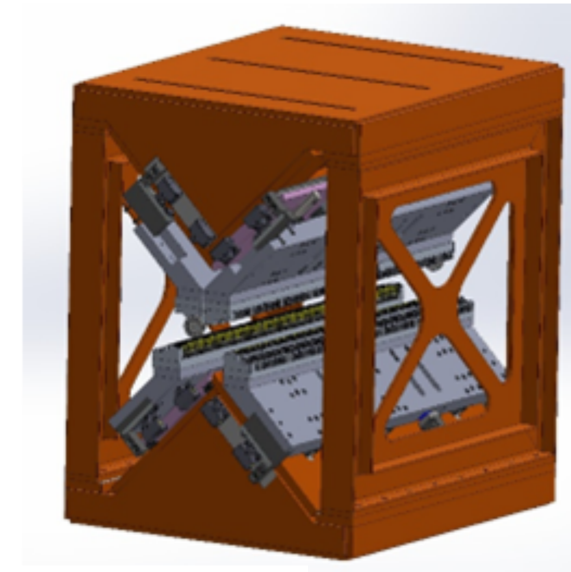


Courtesy of L. Mosesso and S. Lupi

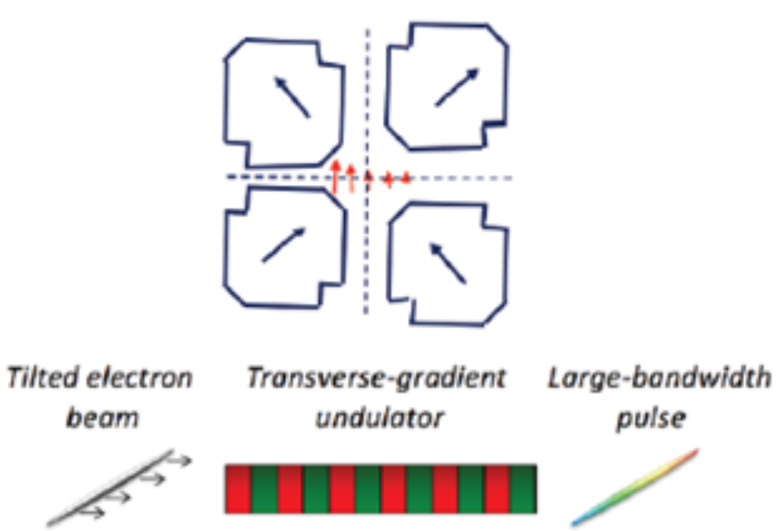
Apple X Undulator

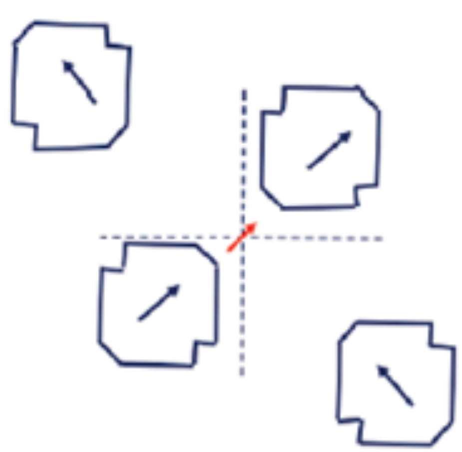
- Polarization and energy can be tuned with longitudinal shifts of the magnetic array pairs.
- The intensity of B along the undulator axis can be tuned by changing the gap





Magnetic period λ_u	55 mm
Total length of the single module	1.35 m
Number of periods	24
Number of period full size	22
Minimum vertical magnetic gap	1.22 mm
Minimum horizontal magnetic gap	1.22 mm
Maximum vertical magnetic gap	60 mm
Maximum horizontal magnetic gap	200 mm
Magnetic material	NdFeB





Advanced operational modes by means of asymmetric configurations

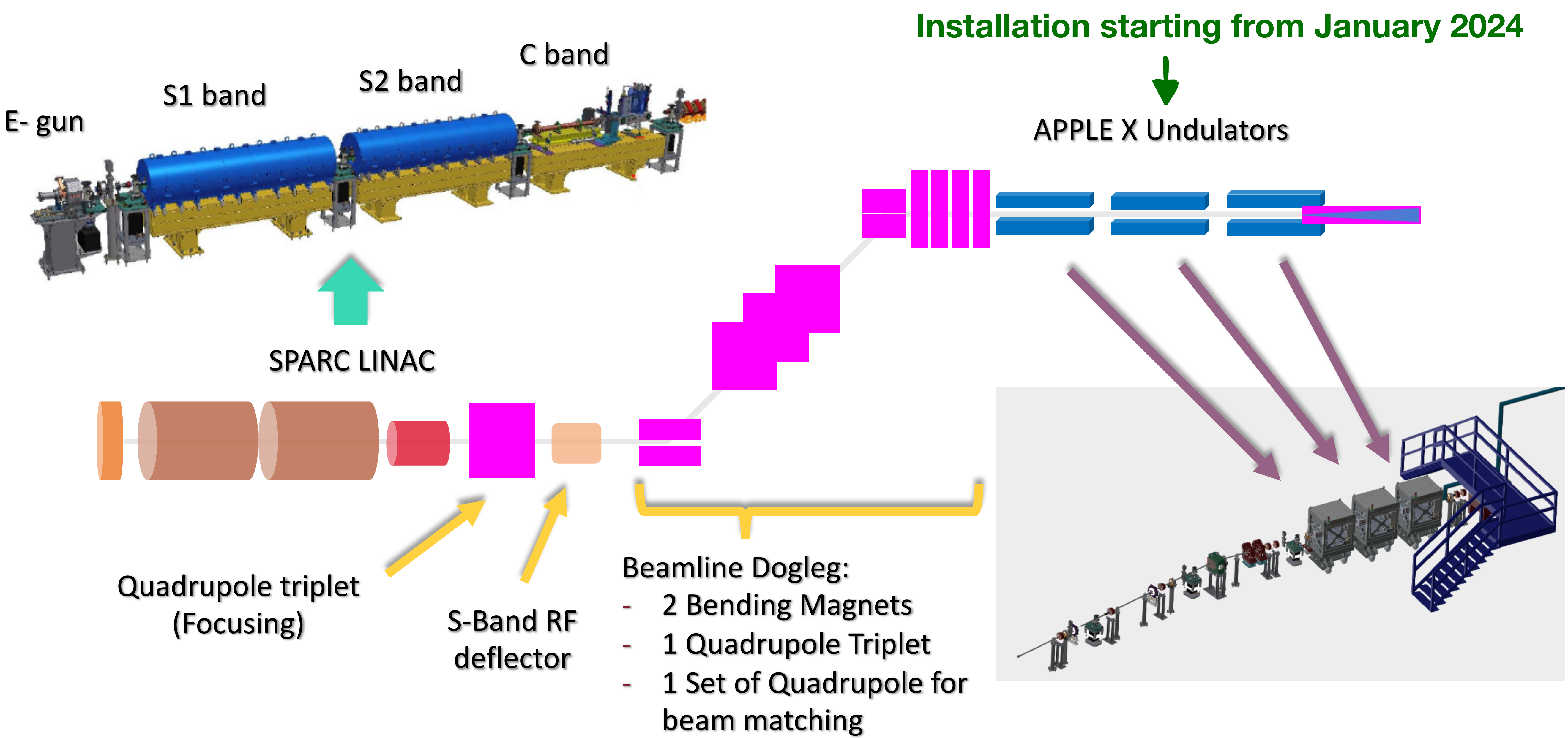
Courtesy of A. Petralia and L. Giannessi

Apple X Undulator from *Kyma*

First module arrived at LNF, now ready for magnetic measurements

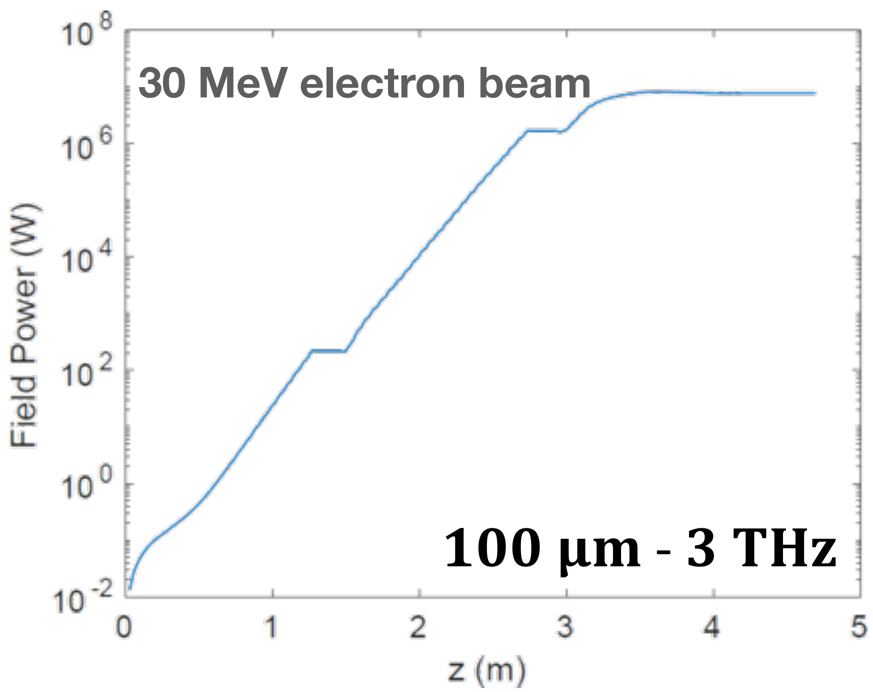
Courtesy of L. Giannessi

SABINA THz/IR FEL Beamline



Courtesy of A. Giribono and C. Vaccarezza

Expected Radiation Parameters



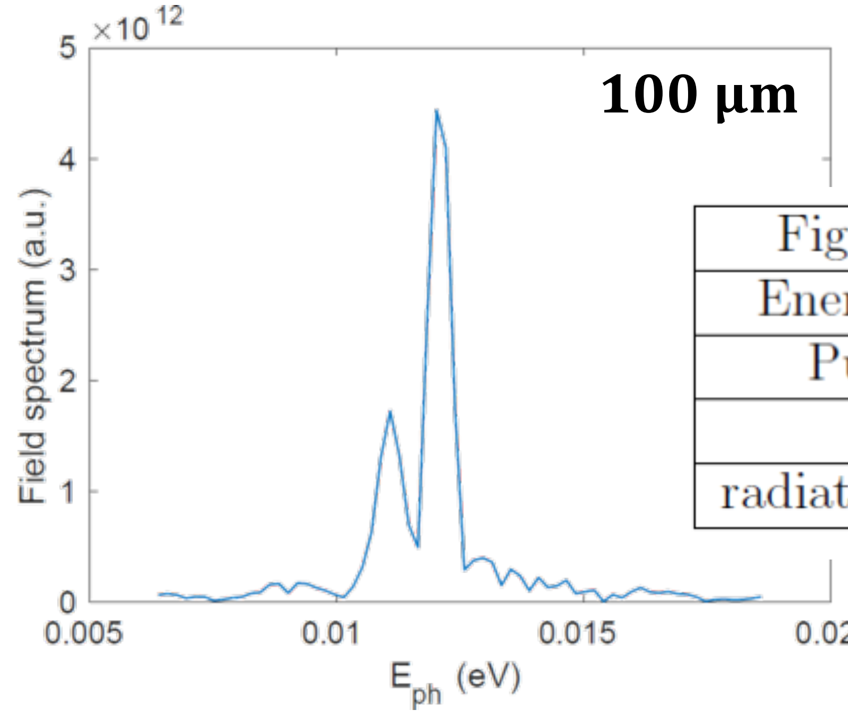
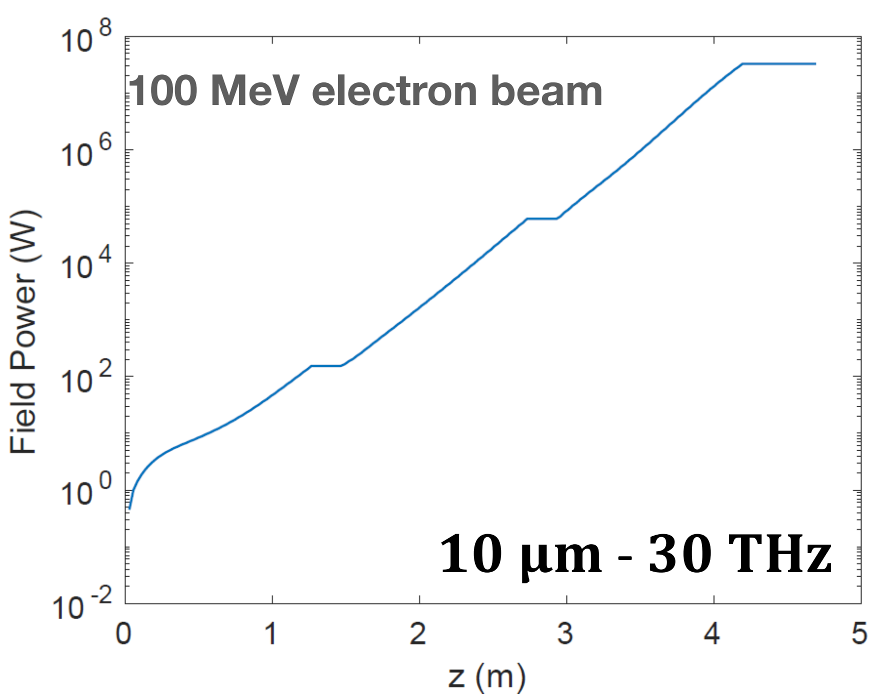


Figure of merit	Value
Energy per pulse	$(67 \pm 3)\ \mu$J
Pulse length	(6.2 ± 0.4) ps
w_0	(1.37 ± 0.05) mm
radiation divergence	(23 ± 1) mrad



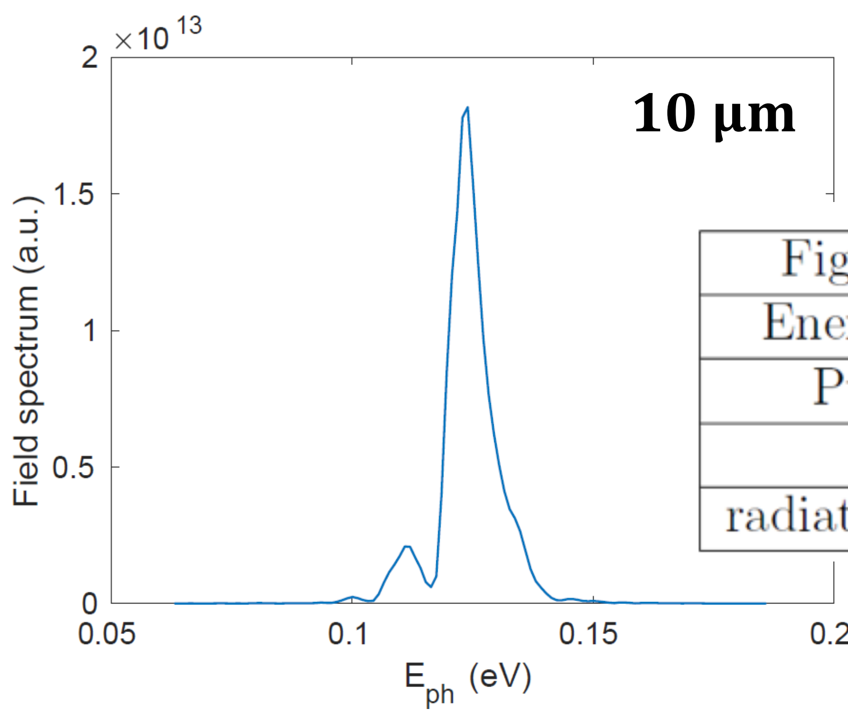


Figure of merit	Value
Energy per pulse	$(18 \pm 3)\ \mu$J
Pulse length	(300 ± 30) fs
w_0	$(680 \pm 60)\ \mu$m
radiation divergence	(4.7 ± 0.4) mrad

Courtesy of V. Petrillo

Conclusions

- The **SPARC_LAB** Test Facility is a **test bed for advanced high brightness beam research and applications,** e.g. novel acceleration techniques, advanced radiation sources, innovative diagnostic tools

- The most valuable results obtained at SPARC_LAB with both ultra-short single bunch and multi-bunches electron comb beams provide high energy per pulse and broad and narrow spectral bandwidth THz radiation, respectively for non-linear and pump-probe experiments in solid-state physics and material science

- **Next step** would be the operation of the **SABINA THz/IR SASE FEL** experiment hopefully end of next year for user experiments

Acknowledgement

- SPARC_LAB Collaboration
- LNF Accelerator Division

Thank You for the kind attention