Workshop on THz Sources for Time-Resolved Studies of Matter
Argonne National Laboratory
July 30th-31st, 2012

Characterization of the THz Radiation Source at SPARC_LAB

Abstract

The linac-driven coherent THz radiation source at the SPARC_LAB facility is able to deliver broadband THz pulses with sub-ps shaping. In addition, high peak power, narrow-band THz radiation can be also generated. The technique, we have proposed and applied to generate a train of short electron bunches with THz repetition rate, relies on low energy RF compression (the velocity bunching) and on the use of properly shaped trains of UV laser pulses hitting the cathode of the RF gun (comb laser beam). The status of the THz beam lines will be reported, with a deep insight on the generation and properties of the SPARC_LAB THz radiation.

Enrica Chiadroni (INFN-LNF)

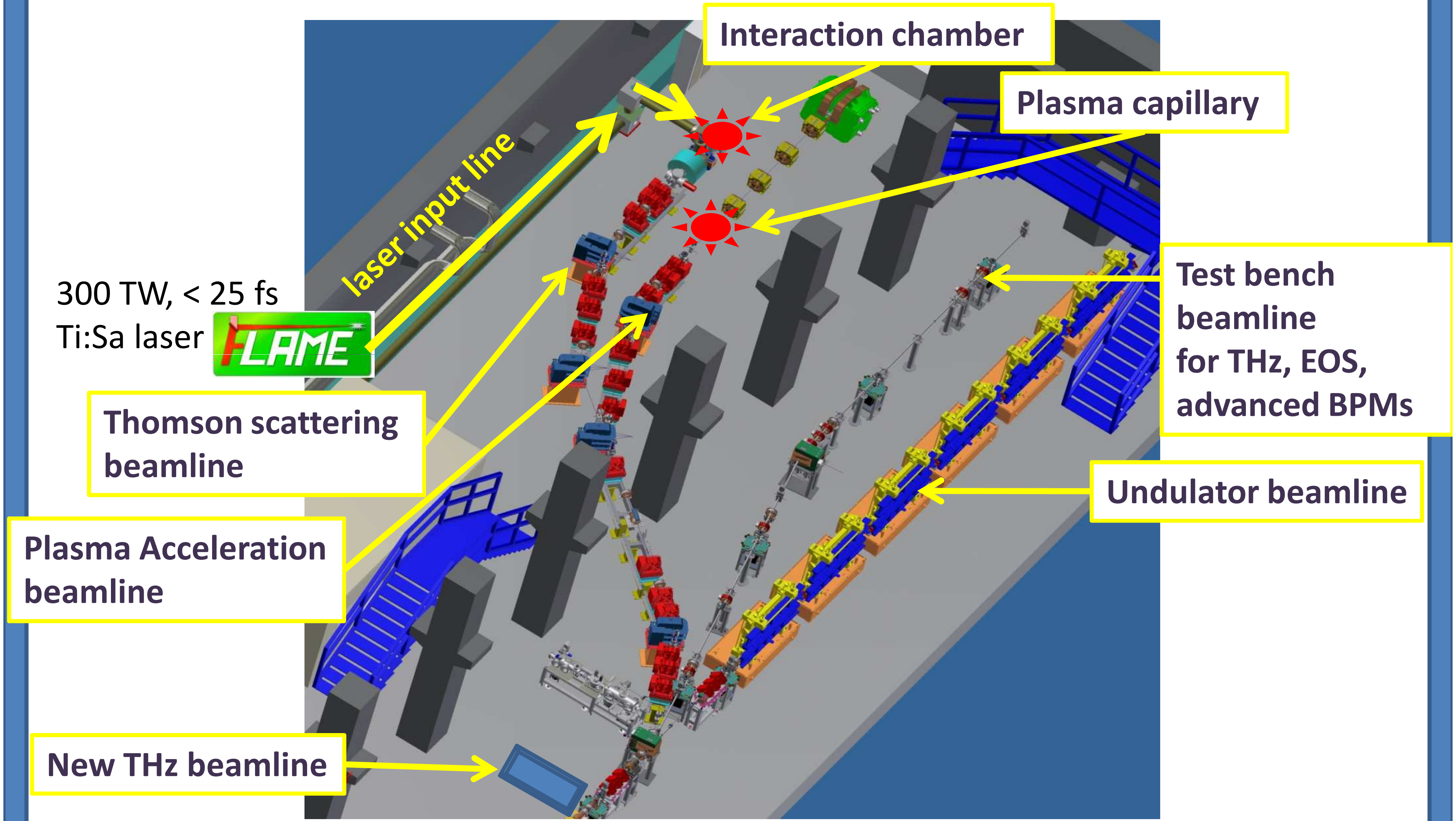
on behalf of the SPARC_LAB collaboration

Outline

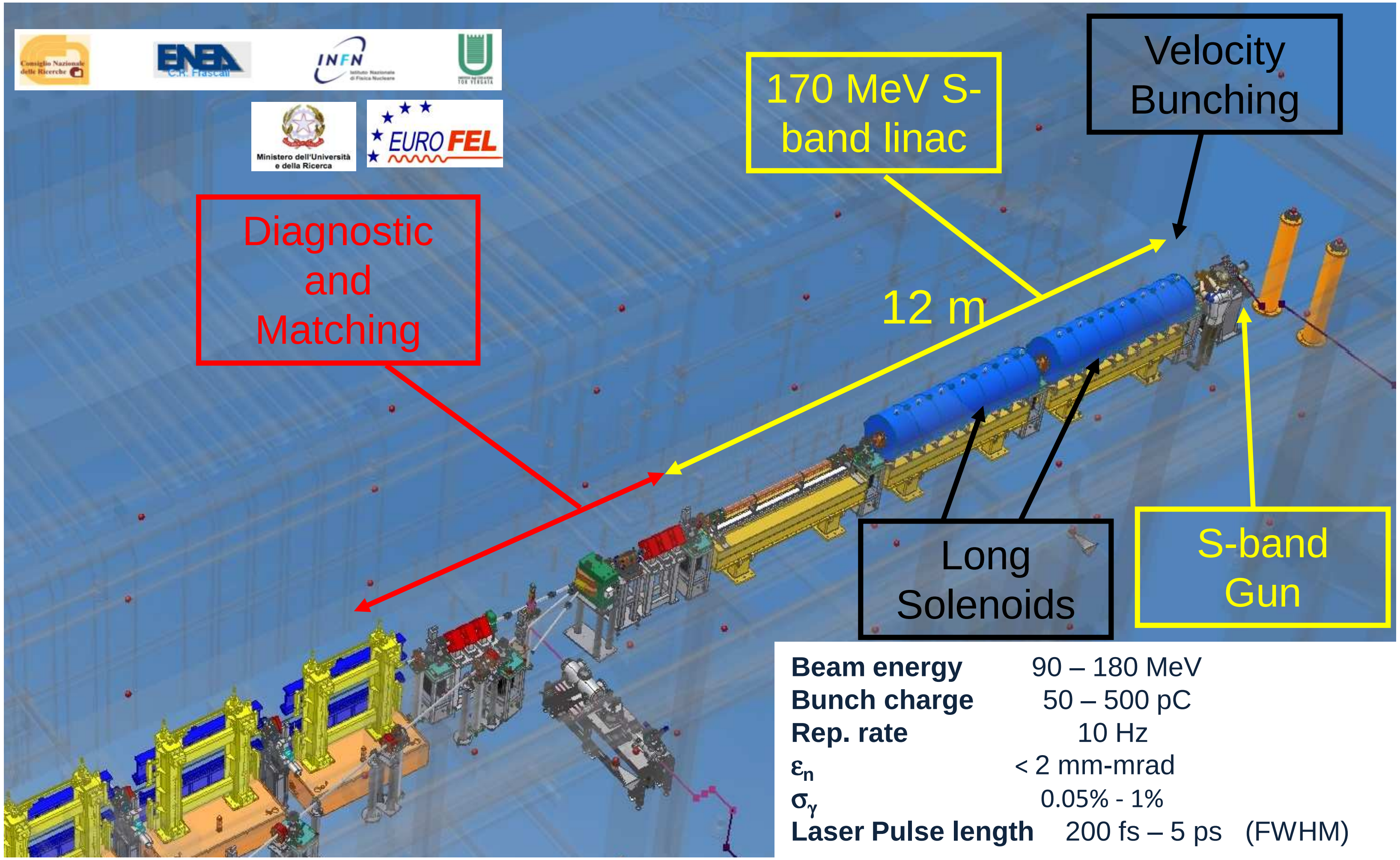
- INTRODUCTION
  - The SPARC_LAB Facility: SPARC photo-injector
  - The THz radiation beamlines at SPARC_LAB
    - Experimental setup: Frequency domain measurements (Martin-Puplett interferometer and band-pass THz filters)
    - SPARC_LAB houses a dedicated INFN-funded experiment in collaboration with the Univ. of Rome La Sapienza and CNR/IFN
  - Motivation
- THE SPARC_LAB THz RADIATION
  - Coherent Radiation
  - Broad-band from ultra-short high-brightness electron bunches
  - Narrow-band and tunable from comb beams
- CONCLUSIONS

INTRODUCTION

The SPARC_LAB Facility



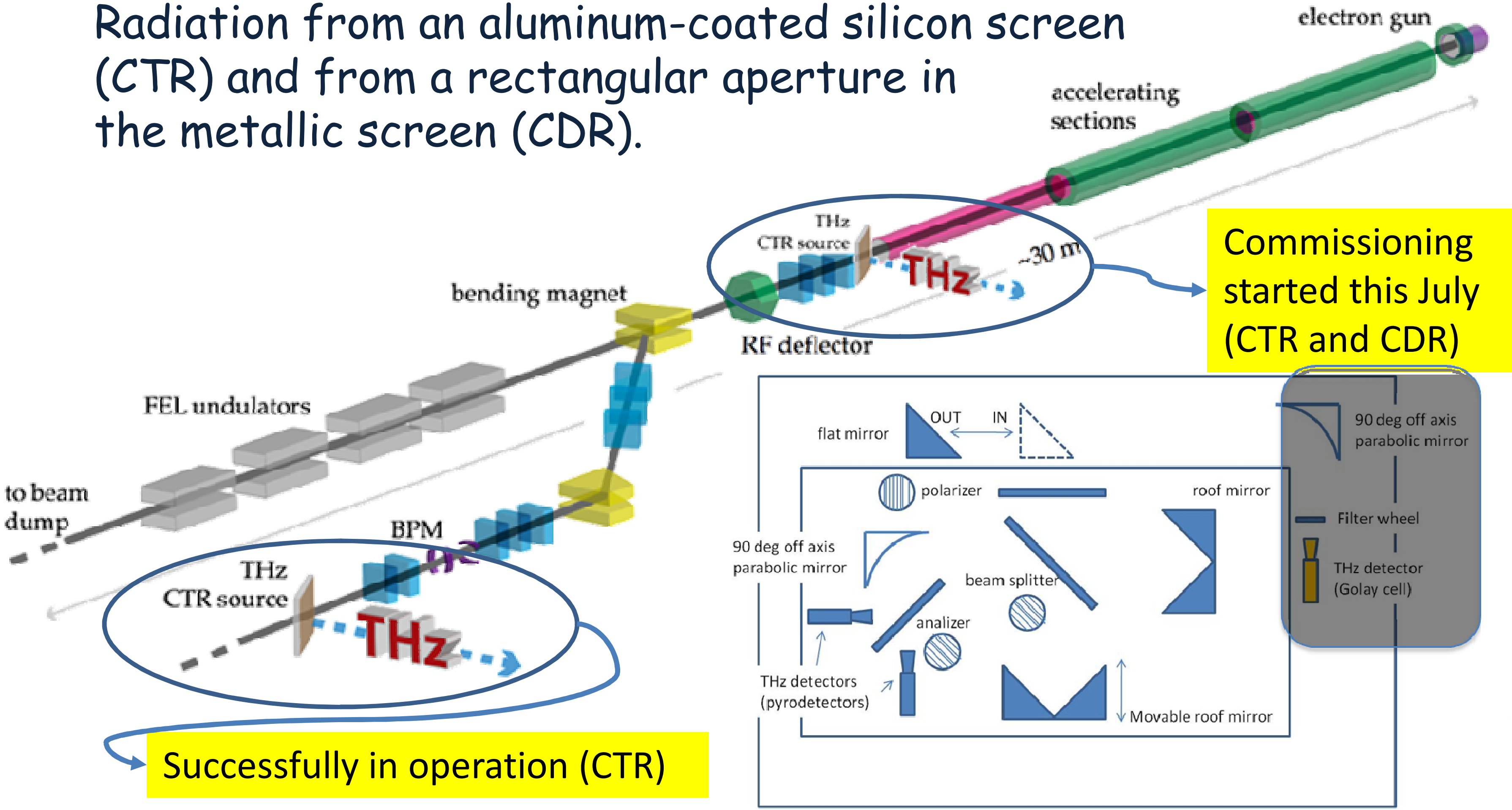
The SPARC Photo-injector



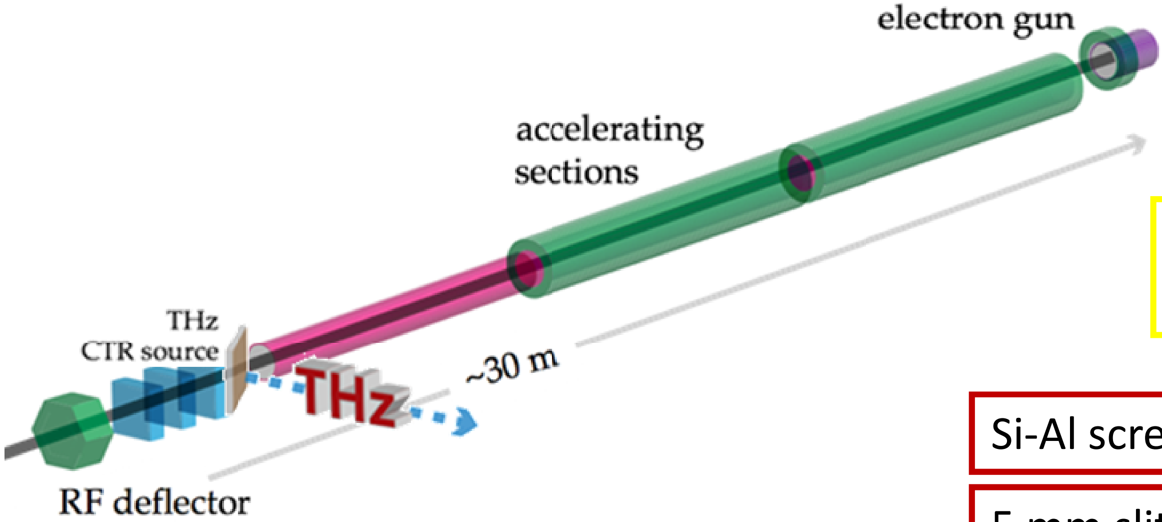
Beam energy	90 – 180 MeV	
Bunch charge	50 – 500 pC	
Rep. rate	10 Hz	
ε_n	< 2 mm-mrad	
σ_γ	0.05% - 1%	
Laser Pulse length	200 fs – 5 ps	(FWHM)

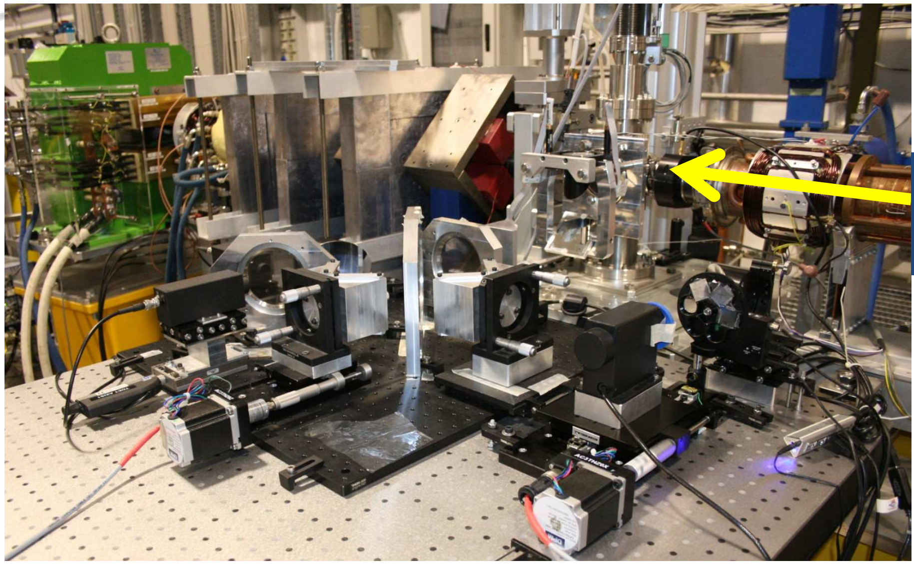
The SPARC_LAB THHz beam lines

- Linac-based source: The source is Coherent Radiation from an aluminum-coated silicon screen (CTR) and from a rectangular aperture in the metallic screen (CDR).



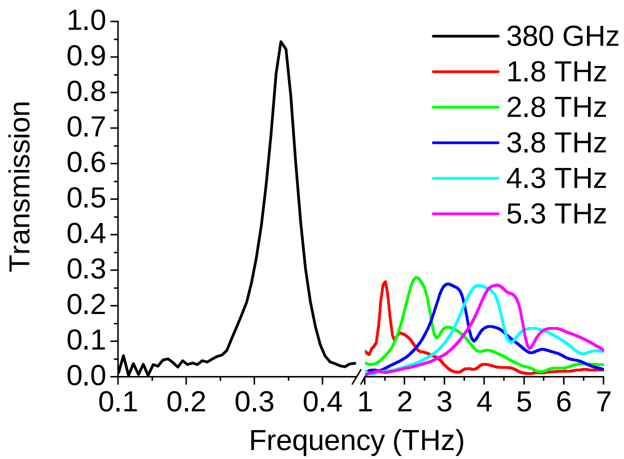
The New THz Beamline





Experimental Apparatus

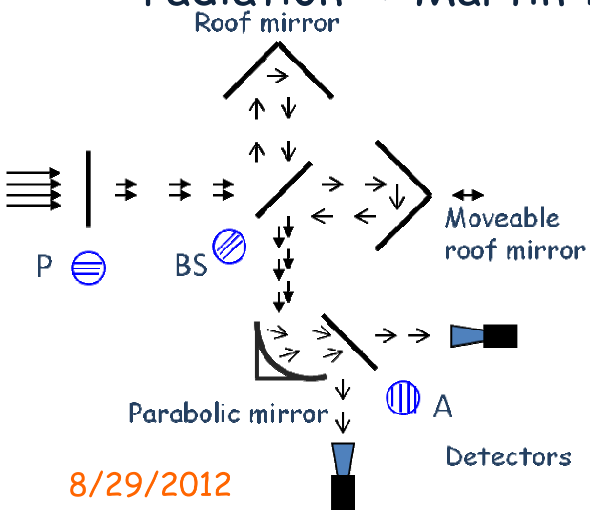
♫ Customized band-pass mesh filters



Golay cell detector

- o Operating spectral range: > 40 GHz
- o Active element: ø 6 mm
- o NEP@20 Hz ~ 10^{-10} W/Hz$^{0.5}$

♫ Frequency-domain technique based on the autocorrelation of coherent radiation => Martin-Pupplett interferometer



♫ BS splits polarizations

♫ Reflectivity coefficients depend on wires geometry

♫ Not-sensitive to correlated fluctuations due to instabilities in the e-beam

Pyroelectric detectors

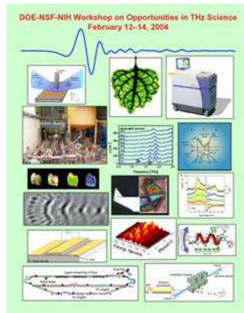
- o Operating spectral range: 0.1 – 3 THz
- o Active element: 2 mm x 3 mm
- o NEP@20 Hz ~ 10^{-8} W/Hz$^{0.5}$

Motivation

Coherent THz radiation from relativistic electron bunches

- as a powerful diagnostic of e-bunches that drive FELs, plasma-based accelerators
  - Non-intercepting radiation phenomena are preferred
- as a potential revolutionary source in different fields of science
  - Ultra-fast and non-linear phenomena
    - Peak Electric fields greater than 1-10 MV/cm
    - Intense single-cycle and multi-cycles THz radiation
  - THz pump-THz probe experiments
  - Molecular spectroscopy, imaging, etc.
    - Tunable THz radiation with narrow spectral bandwidth

http://science.energy.gov/~/media/bes/pdf/reports/files/thz_rpt.pdf



THE SPARC_LAB THz RADIATION

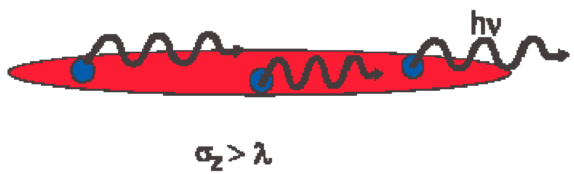
Coherent Radiation

The total radiation intensity emitted by a bunch of electrons is given by

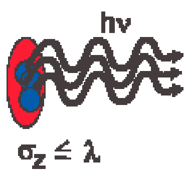
$$I_{tot}(\omega) = I_{sp}(\omega)\left[N + N(N-1)F(\omega)\right]$$

in which $I_{sp}(\omega)$ is the radiation intensity emitted by a single particle and $F(\omega)$ the bunch longitudinal form factor

$$F(\omega) = \left| \int dr_z S(r_z) e^{i\frac{\omega}{c} r_z} \right|^2$$



Long bunch emits incoherently



Short bunch emits coherently

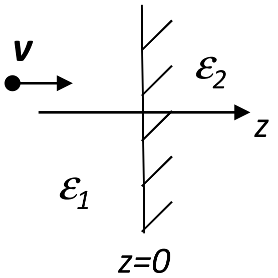
Coherent emission dominates on incoherent one at wavelengths equal or longer than the bunch length.

Measuring the coherent spectrum it is possible to reconstruct the bunch length and even its longitudinal structure.

Transition and Diffraction Radiation

The radiation results from the prompt change of the boundary conditions for the electromagnetic field carried by the particle in the first and second media.

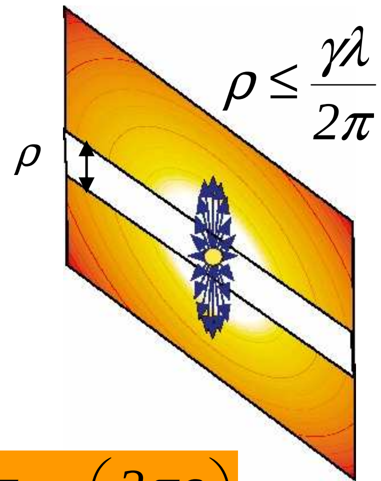
Transition Radiation



$$\frac{d^2 U_{sp}}{d\omega d\Omega} = \frac{e^2}{4\pi^3 \varepsilon_0 c} \frac{\beta^2 \sin^2(\vartheta)}{(1-\beta^2 \cos^2(\vartheta))^2}$$

- Ginzburg-Frank formula
  - infinite screen size (>> than $\gamma\lambda$)
  - infinitely thin
  - ideally flat
  - perfectly conducting material
  - far-field approximation

Diffraction Radiation

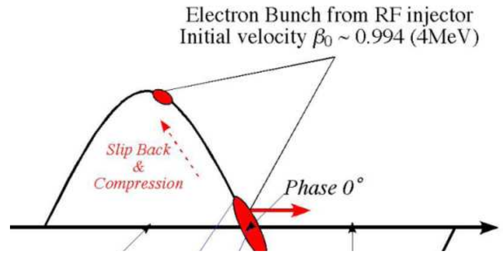


$$E_n(\lambda) \propto \frac{2\pi}{\gamma\lambda} K_1\left(\frac{2\pi\rho}{\gamma\lambda}\right)$$

Broad-band THz radiation

BROAD BAND
(150 GHz – 5 THz) with sub-ps high-brightness electron

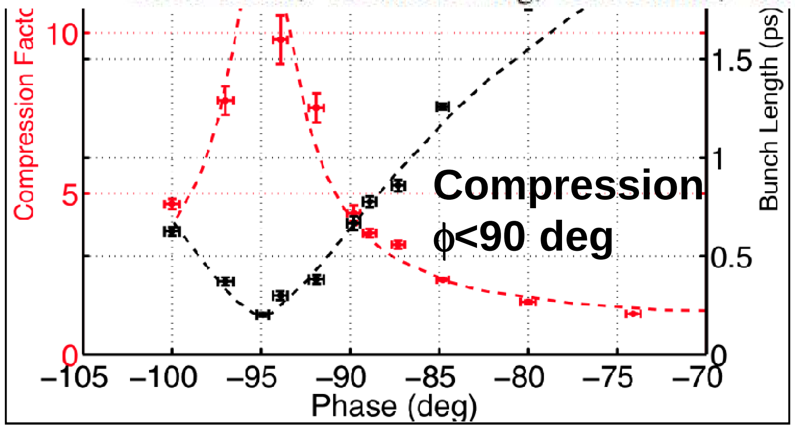
RF compression: VELOCITY

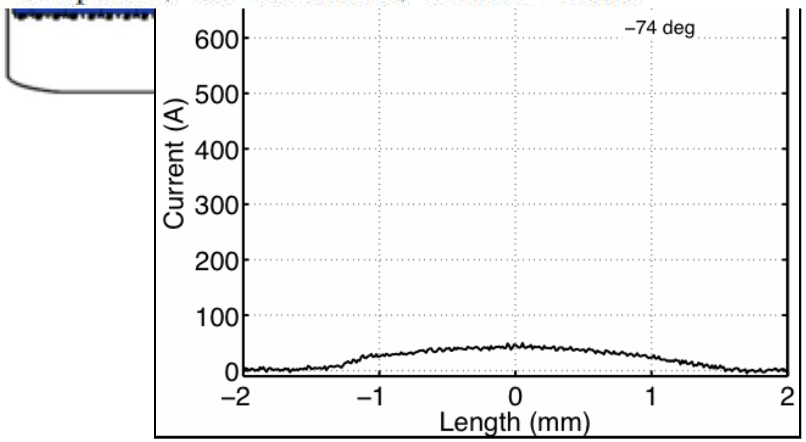


PRL 104, 054801 (2010) PHYSICAL REVIEW LETTERS week ending 5 FEBRUARY 2010

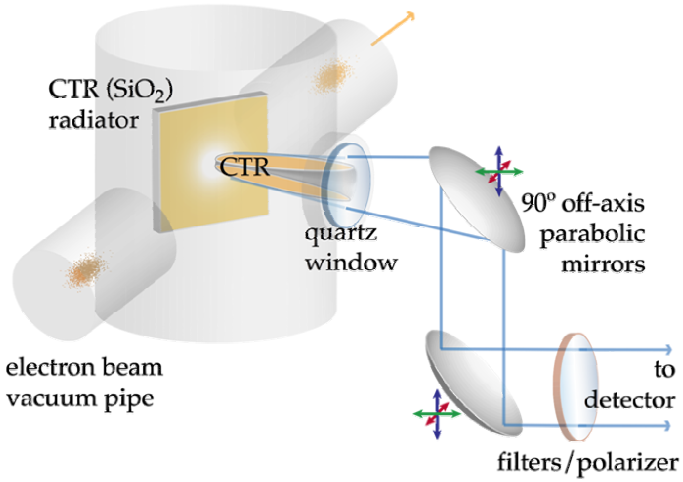
Experimental Demonstration of Emittance Compensation with Velocity Bunching

M. Ferrario,[1] D. Alesini,[1] A. Bacci,[3] M. Bellaveglia,[1] R. Boni,[1] M. Boscolo,[1] M. Castellano,[1] E. Chiadroni,[1] A. Cianchi,[2] L. Cultrera,[1] G. Di Pirro,[1] L. Ficcadenti,[1] D. Filippetto,[1] V. Fusco,[1] A. Gallo,[1] G. Gatti,[1] L. Giannessi,[4] M. Labat,[4] B. Marchetti,[2] C. Marrelli,[1] M. Migliorati,[1] A. Mostacci,[1] E. Pace,[1] L. Palumbo,[1] M. Quattromini,[4] C. Ronsivalle,[4] A. R. Rossi,[3] J. Rosenzweig,[5] L. Serafini,[3] M. Serluca,[6] B. Spataro,[1] C. Vaccarezza,[1] and C. Vicario[1]

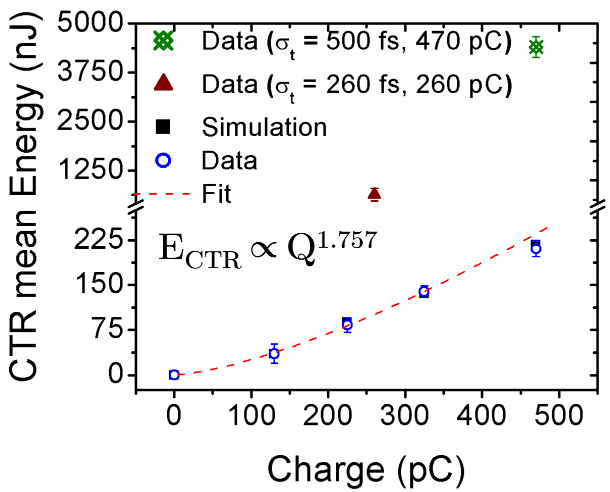


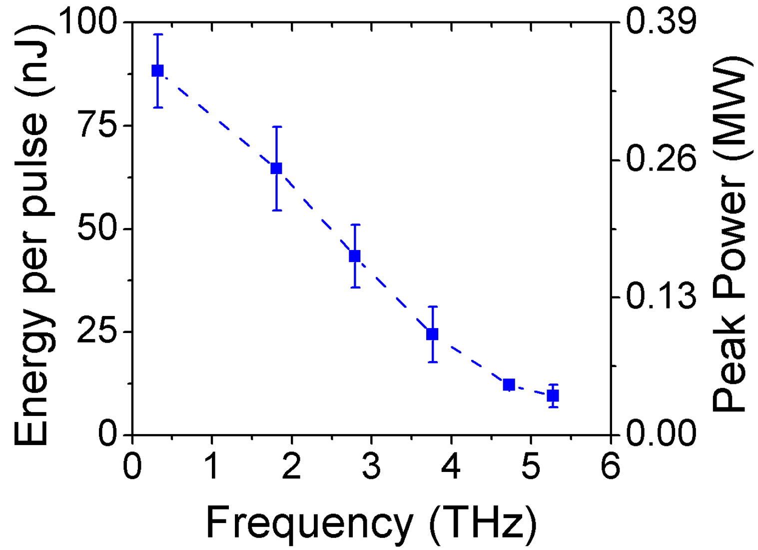


Broad-band THz radiation: Measurements

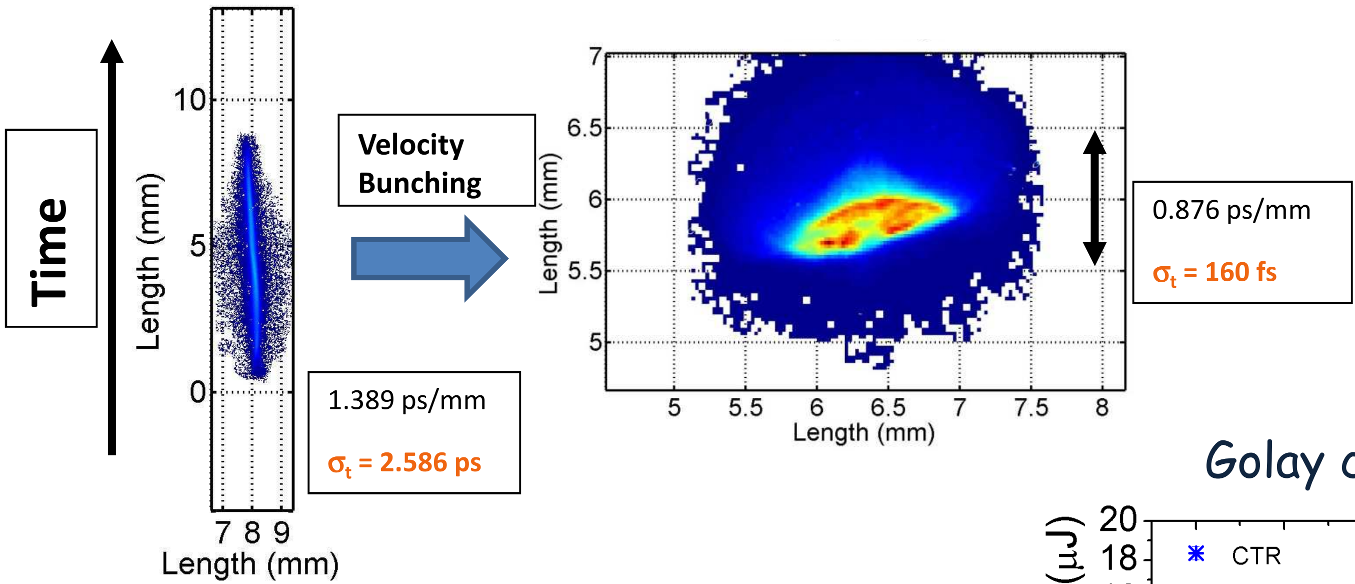


Electron beam parameters	
Energy (MeV)	100
Charge (pC)	260
RMS bunch length (fs)	260



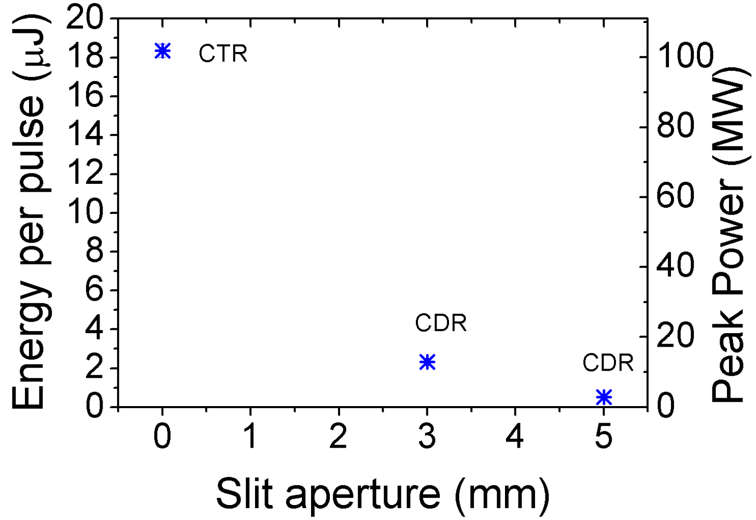


High energy *per* pulse THz radiation: Measurements



Electron beam parameters	
Energy (MeV)	120
Charge (pC)	300
# of electrons	$1.865*10^9$
RMS bunch length (fs)	160

Golay cell detector



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Narrow-band and Tunable THz Radiation

NARROW BAND

THz source with a longitudinally modulated beam, i.e. comb beam

- M. Ferrario. M. Boscolo et al., Int. J. of Mod. Phys. B, 2006 (Taipei 05 Workshop)

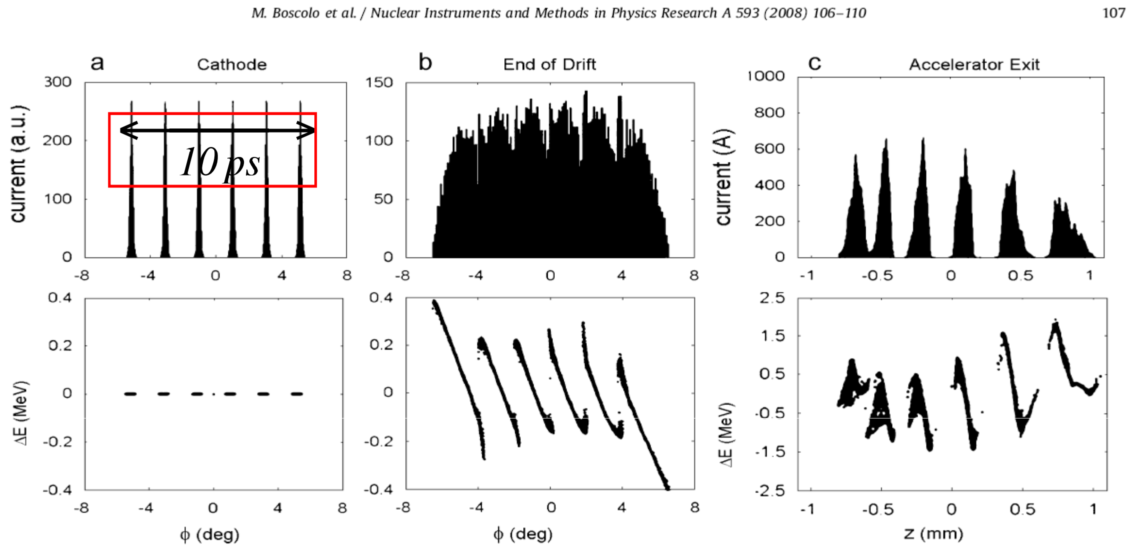
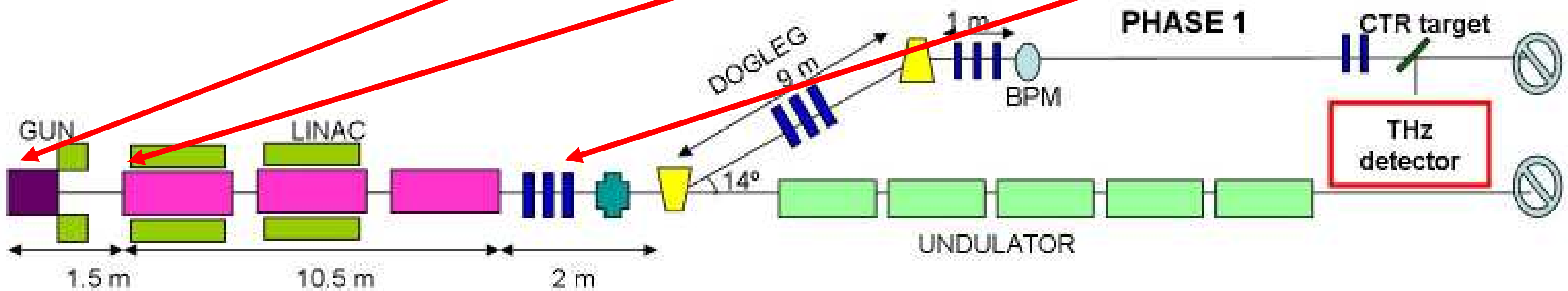
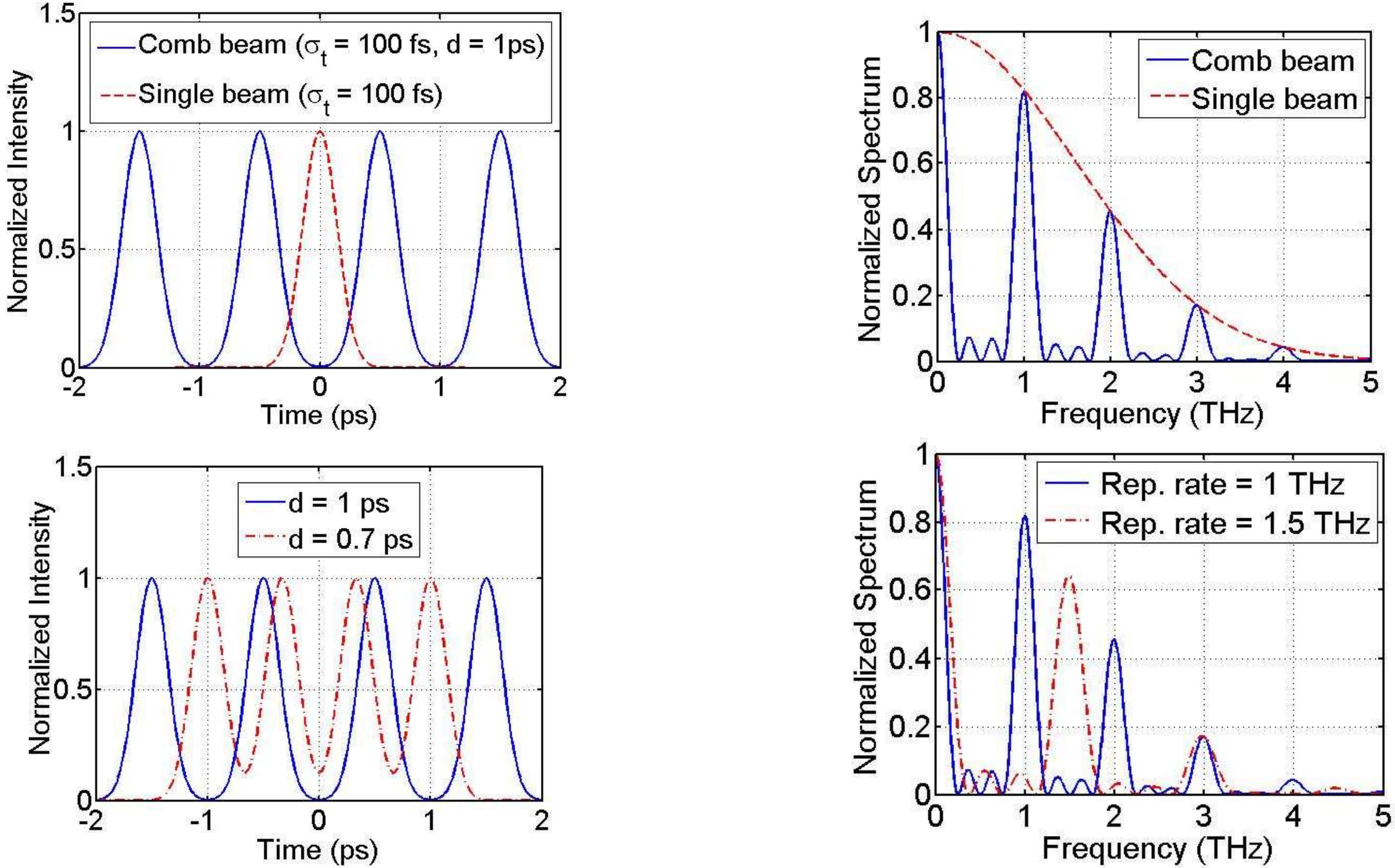


Fig. 1. Evolution of a six bunches electron beam train: the columns from left refer, respectively, to (a) the cathode, (b) the end of the drift at 150 cm and (c) the end of linac at 12 m far from cathode. The rows from top refer, respectively, to longitudinal profile and to energy modulation ΔE (MeV).



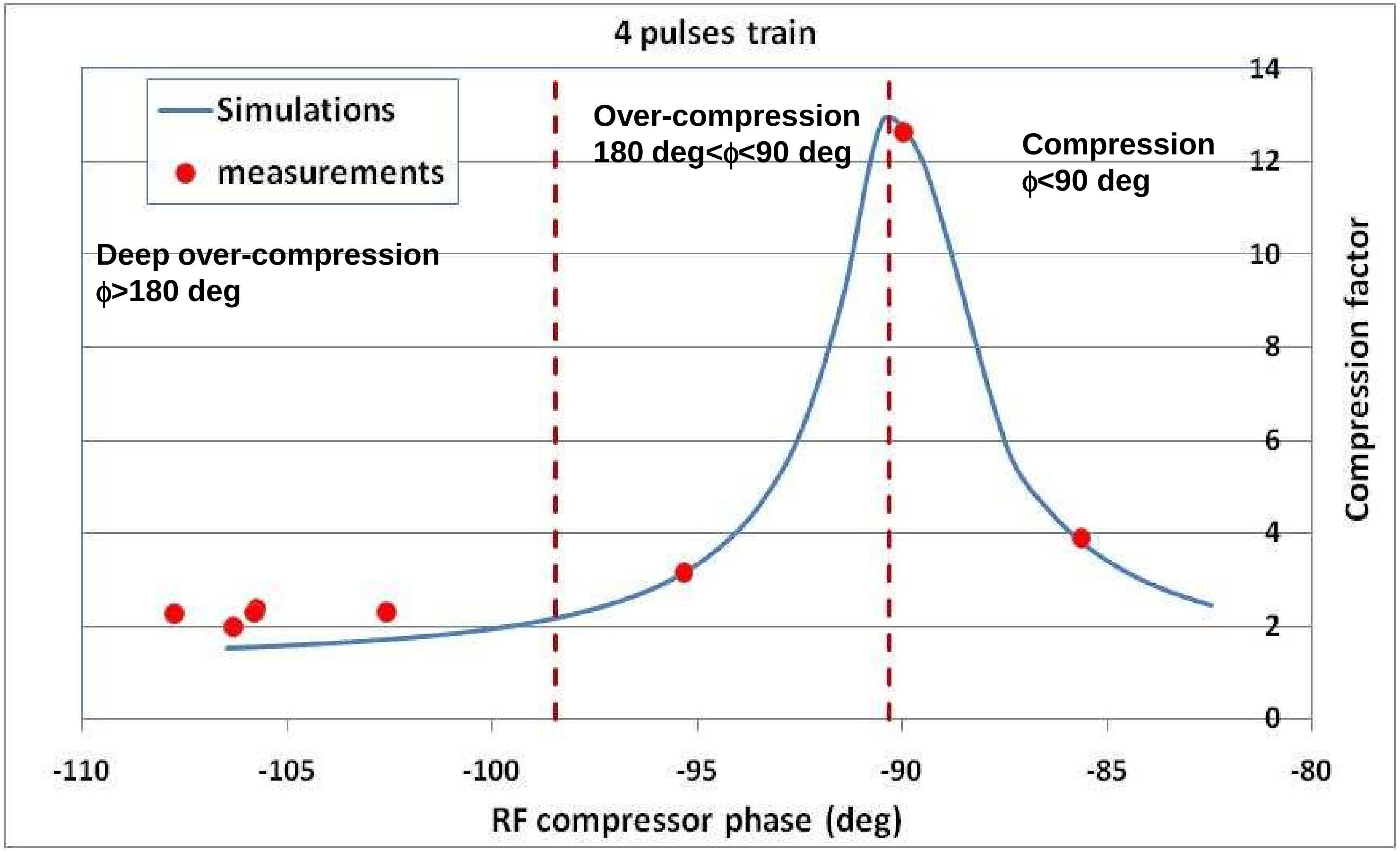
The RF compressor phases can be used as a selector of the number of pulses in the final train.

Narrow-band and Tunable THz Radiation



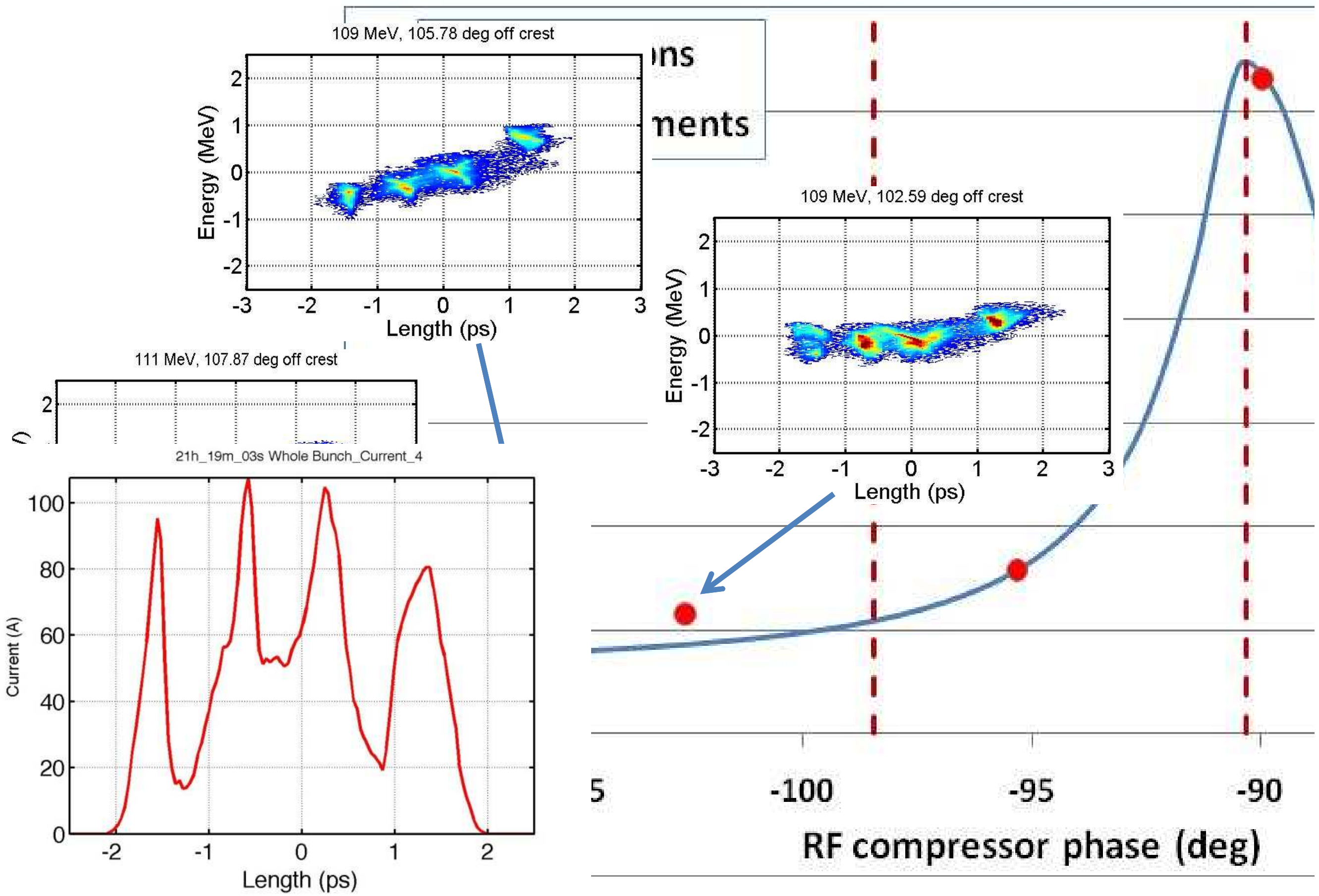
Pulse distance (i.e. THz frequency selection) VS Compression Phase

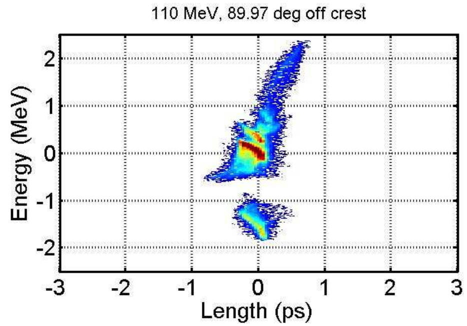
Compression curve of the whole bunch: ratio between the bunch length at the maximum energy with the bunch length for each injection phase in the first TW accelerating section



Pulse distance (i.e. THz frequency selection) VS Compression Phase

Deep over-compression
ϕ>180 deg



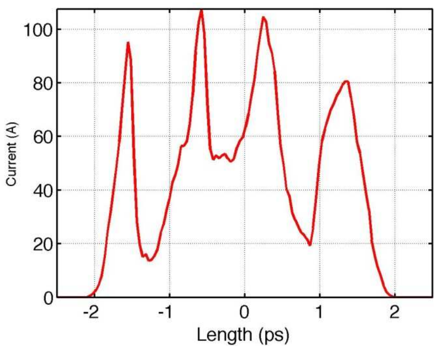


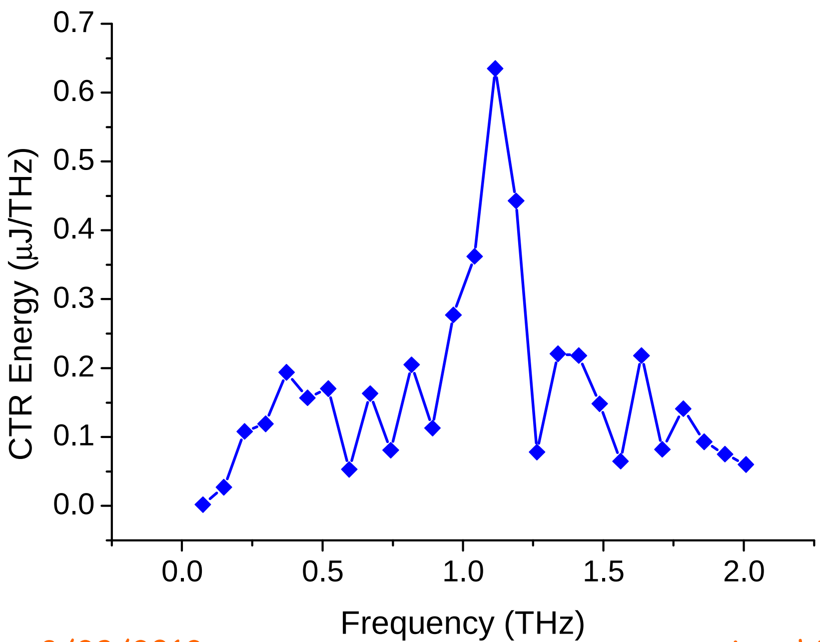
Measured Longitudinal Phase Space (LPS)

Electron beam parameters	
Energy (MeV)	110
Charge/bunch (pC)	50
RMS single bunch length (fs)	200

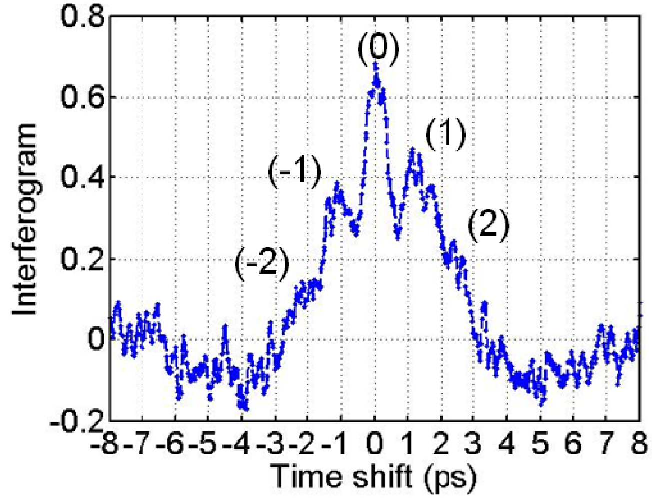
Narrow-band THz radiation: Measurements

Current profile as measured at the end of the linac





E. Chiadroni et al., J.Phys.Conf.Ser. **359,** 012018 (2012).



Assuming that the radius of the focused photon beam is r = 2 mm, since the retrieved CTR energy is 600 nJ (integrated up to 2 THz), the intensity of the whole CTR pulse (σ_t = 1 ps) is :

$$I_{CTR}[W/m^2] = \frac{E_{CTR}}{\pi r^2 (2.35\sigma_t)} \approx kW/cm^2$$

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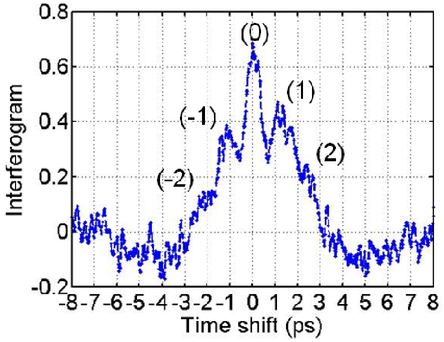
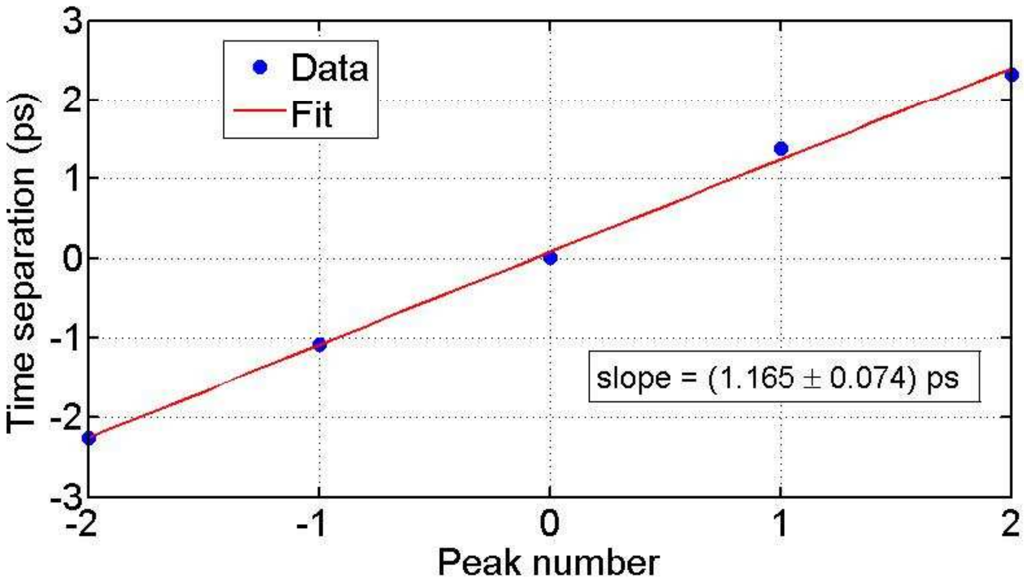
Longitudinal Diagnostics: 4-bunches per train

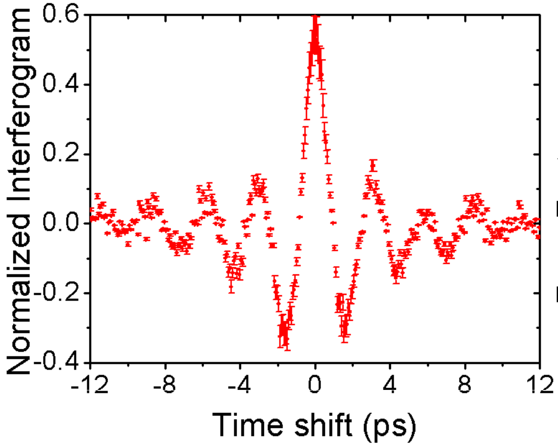


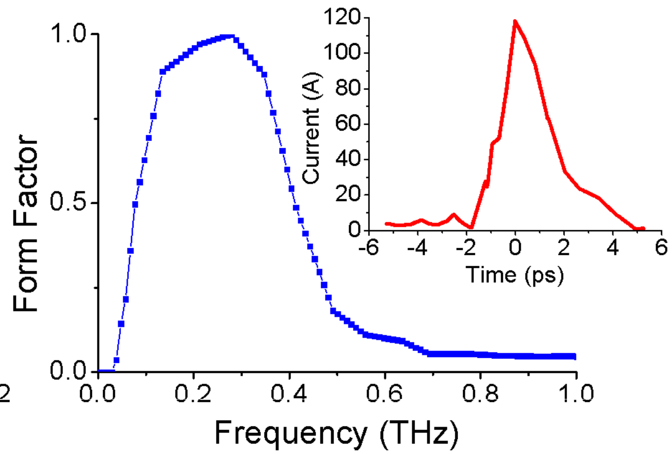
The slope corresponds to the bunch separation in the train.

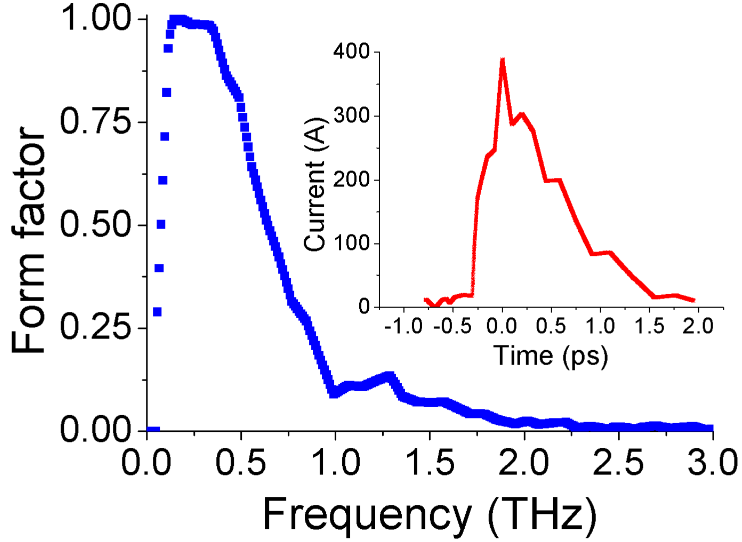


Longitudinal Diagnostics: Single Bunch

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







Electron beam parameters	
Energy (MeV)	120
Charge (pC)	300
RMS bunch length (ps)	0.45

Achieved THz Parameters

Electron beam parameters	Single bunch (VB mode: max compression)	4-bunches per train (VB mode + laser comb)
Charge/bunch (pC)	300	50
Energy (MeV)	130	100
Bunch length (fs)	170	200
Rep. Rate (Hz)	10	

Radiation parameters	SPARC (single bunch)	SPARC (4-bunches/train)
Energy per pulse (J)	$18\ 10^{-6}$	$0.6\ 10^{-6}$ (@ 1 THz)
Peak power (MW)	100	3 (@ 1 THz)
Average power (W)	$1.8\ 10^{-4}$	$6\ 10^{-6}$
Electric field (kV/cm)	> 100	> 10
Pulse duration (fs)	< 200	< 100
Bandwidth (%)	???	< 25

Conclusions

- SPARC_LAB is becoming a test bench for advanced high brightness beam applications (e.g. novel FEL schemes, coherent THz generation, x-ray radiation, PWFA and LWFA)
- Coherent THz radiation is currently produced and optimized at SPARC_LAB through ultra-short relativistic beams as both transition and diffraction radiation
- Different THz emission regimes have been achieved by properly control pulse shaping, length, charge and energy separation, therefore by properly set the photoinjector parameters
- In particular, the possibility of "high charge", tailored comb trains is interesting for high power, narrow band and tunable THz radiation
- Implement the optical setup for THz pump/probe studies
- Mission of SPARC_LAB is primarily to integrate and harmonize all the existing activities at the test-facility, coordinate commissioning, operation and upgrade of the experiments, stimulate research and development and submissions of proposals for experiments to be performed at the SPARC_LAB test-facility.

Acknowledgement

- **ALL OF YOU FOR THE ATTENTION**
- **SPARC TEAM**
  - M. Ferrario, M.P. Anania, M. Bellaveglia, M. Castellano, G. Di Pirro, G. Gatti, E. Pace, C. Vaccarezza (INFN/LNF)
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