*SeminarIndustriali 2018 - THz per Applicazioni Scientifiche e Trasferimento Tecnologico*
*Laboratori Nazionali di Frascati - April 10th, 2018*

# Generation of advanced THz sources for compact accelerators and innovative diagnostics

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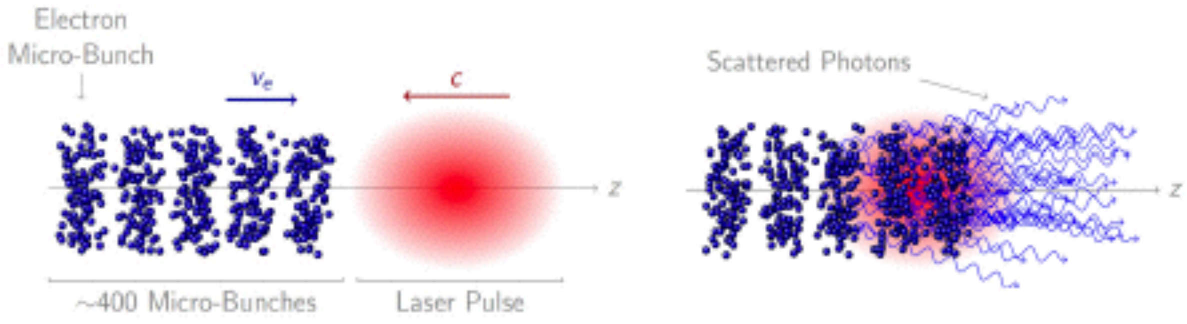
# Motivation

- Towards more compact facilities preserving the electron beam quality to drive high brilliance photon sources
  - Novel acceleration concepts
    - plasma/THz based
  - Innovative diagnostics devices
    - e.g. THz driven deflector
  - Compact applications
    - Radiators such as electromagnetic undulators



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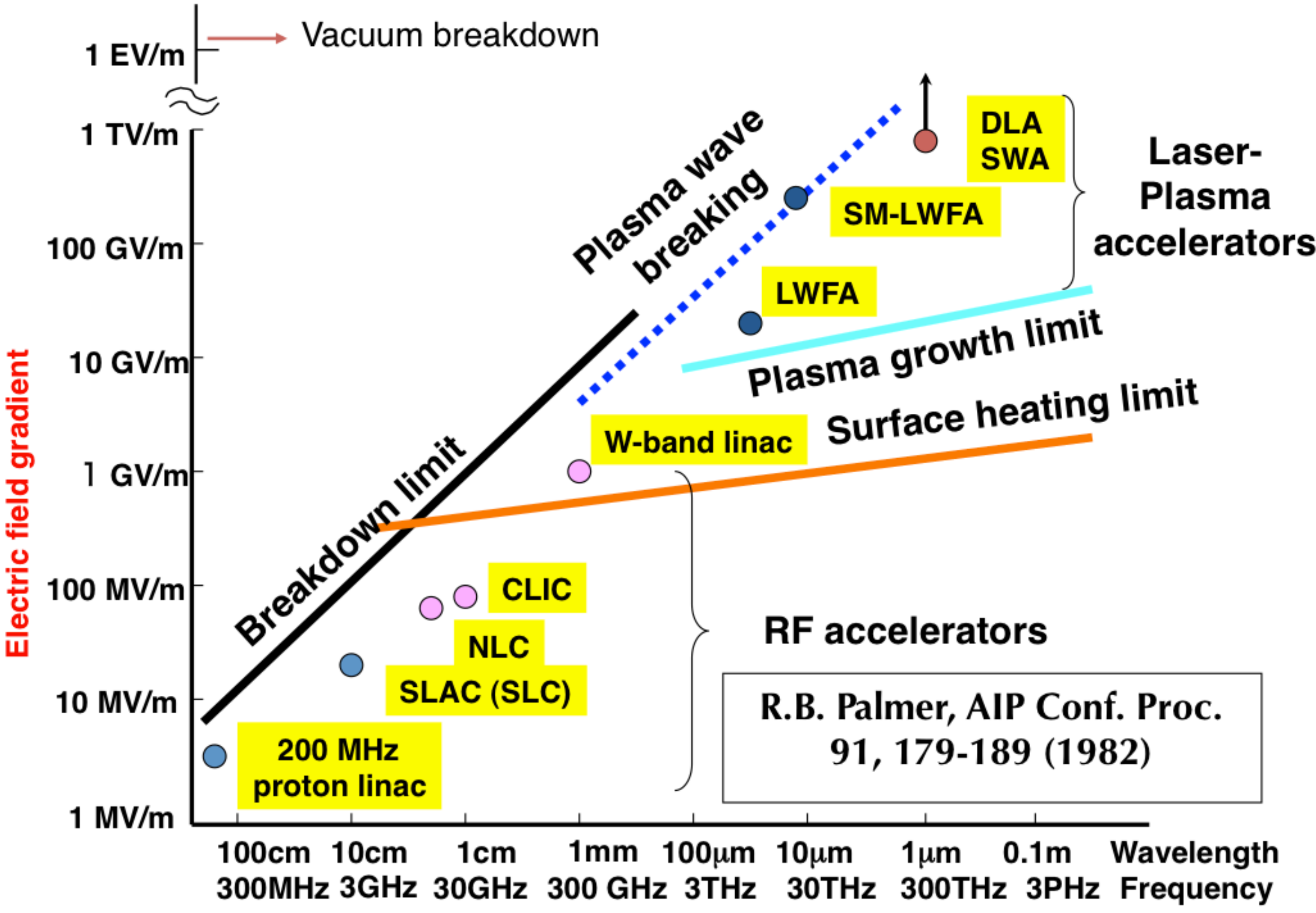
# State-of-the-Art Technology

- **Ultra-high gradients** require structures to sustain high fields
  - Plasma-based accelerators: ~10-100 GV/m
    - Limited by the *wave breaking field*

$$\boxed{\underset{[\mathrm{V/m}]}{E} \sim E_0 = m_e c\omega_p/e \simeq 96\sqrt{n_0[\mathrm{cm}^{-3}]}}$$

- Increase the accelerating field, i.e. increase RF frequency
  - RF metallic structures reached a **practical limit**
    - Gradient limited by *material breakdown*
      - X-band: ~100 MV/m



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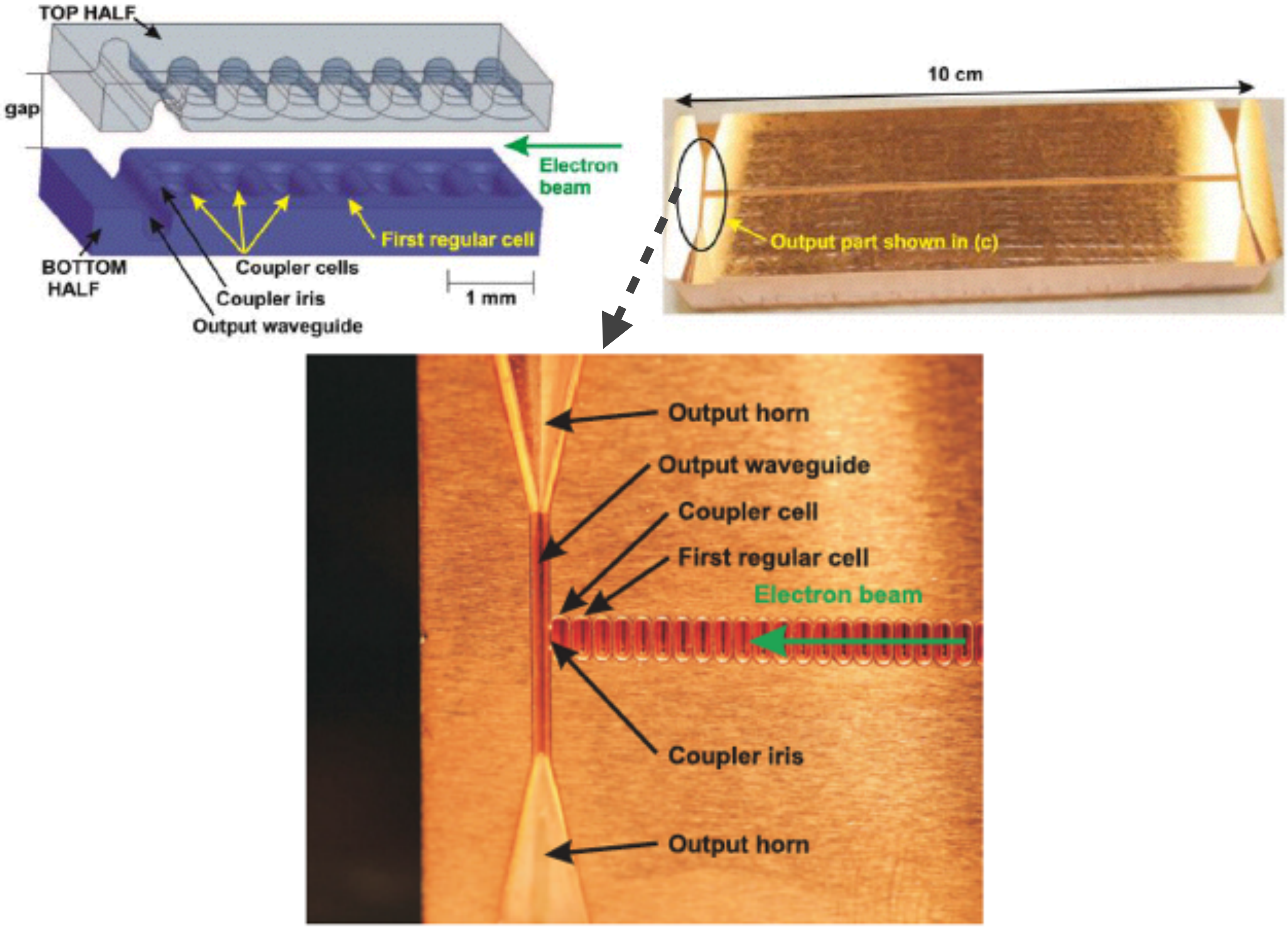
# State-of-the-Art Technology

**200 GHz traveling wave Cu-Ag structure**:
0.3 GV/m accelerating fields
with **peak surface fields** of **1.5 GV/m** and 2.4 ns



**M. D. Forno, et al. PRAB. 19, 011301 (2016).**

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# THz Acceleration

- **High-gradient accelerators** are attractive due to reduced size and improved electron beam quality
  - Increasing operational frequency
    - **higher breakdown fields** $E_s \propto \frac{f^{1/2}}{\tau^{1/4}}$
  - reduced pulse energy to achieve the same electric field in the cavity
    - stored energy $E_p \sim \lambda^{-3}$
    - **reduced pulse heating** $\Delta T \propto \frac{E_p}{A_{surface}} \propto \frac{V_{cavity}}{A_{surface}} \propto \lambda$

**=> High repetition rate operation becomes possible**

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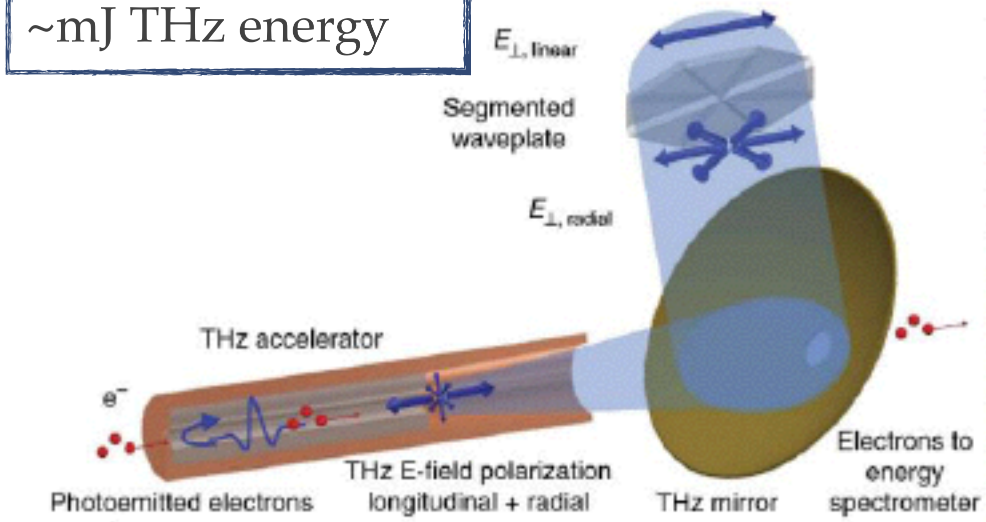
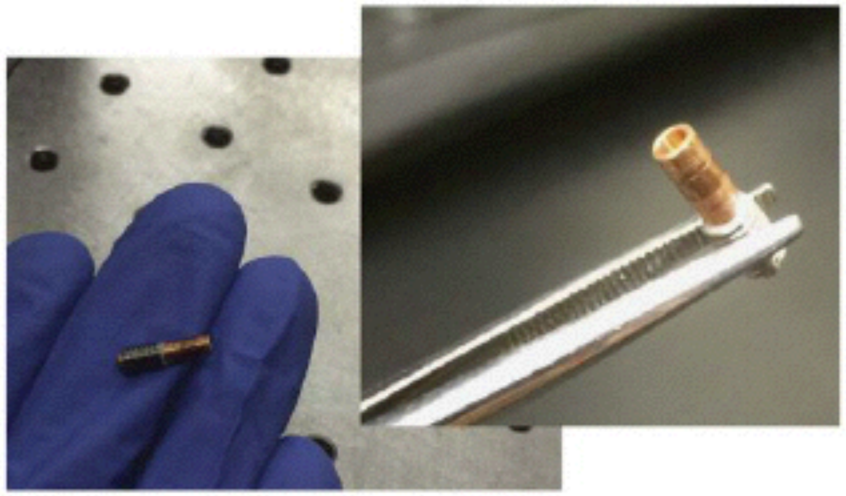
# First Proof-of-Principle Experiment

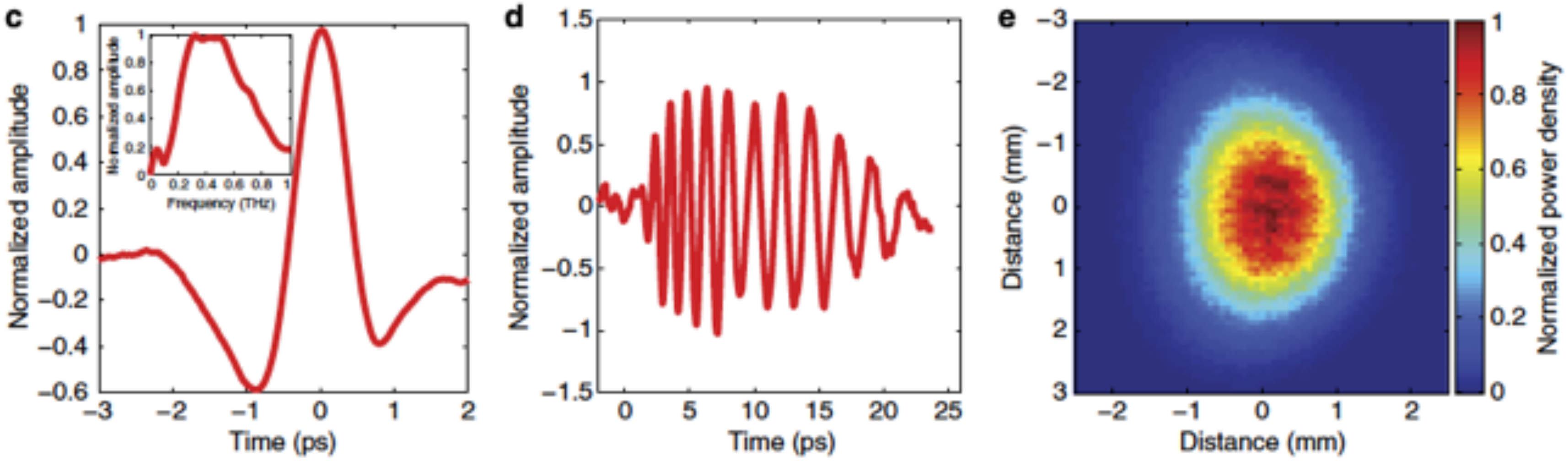
**Interesting THz range**

1 - 10 pC
0.1 - 1 THz
(0.3 THz ~ 1 mm)
~mJ THz energy

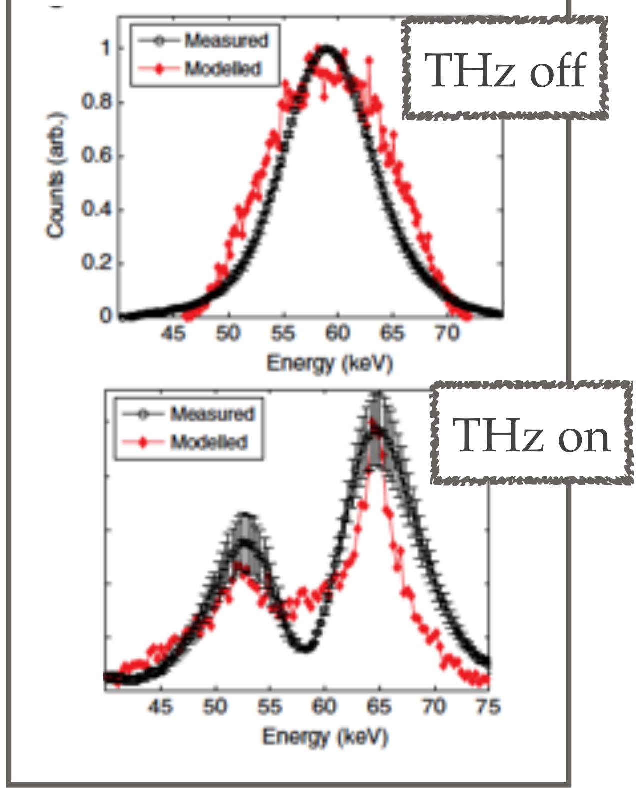
- Linearly to radially polarized THz pulses coupling into the THz waveguide
- The THz pulse is reflected at the end of the waveguide to co-propagate with the electron bunch
- The electron bunch is accelerated by the longitudinal electric field of the co-propagating THz pulse







**Demonstration of THz acceleration**



E. A. Nanni et al., Nature Comm. | 6:8486 | DOI: 10.1038/ncomms9486

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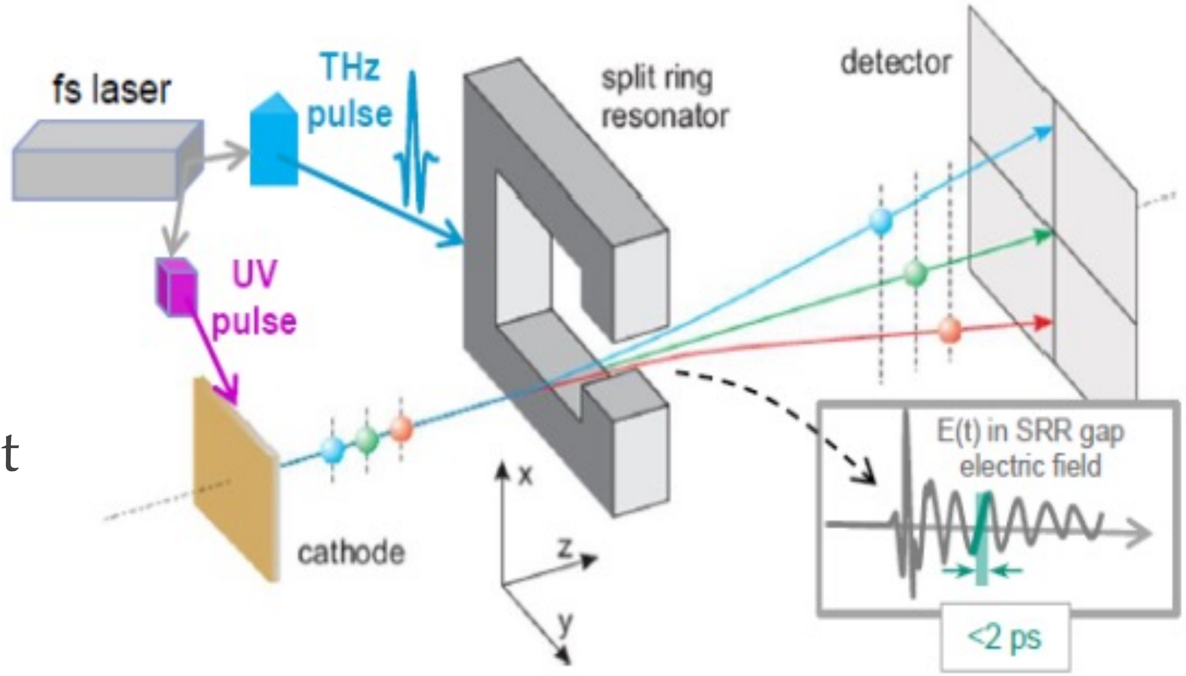
# THz Diagnostics

- **Streak camera-like** with the **streaking field being replaced by intense single cycle THz pulses focused to** a so-called **split-ring resonator**

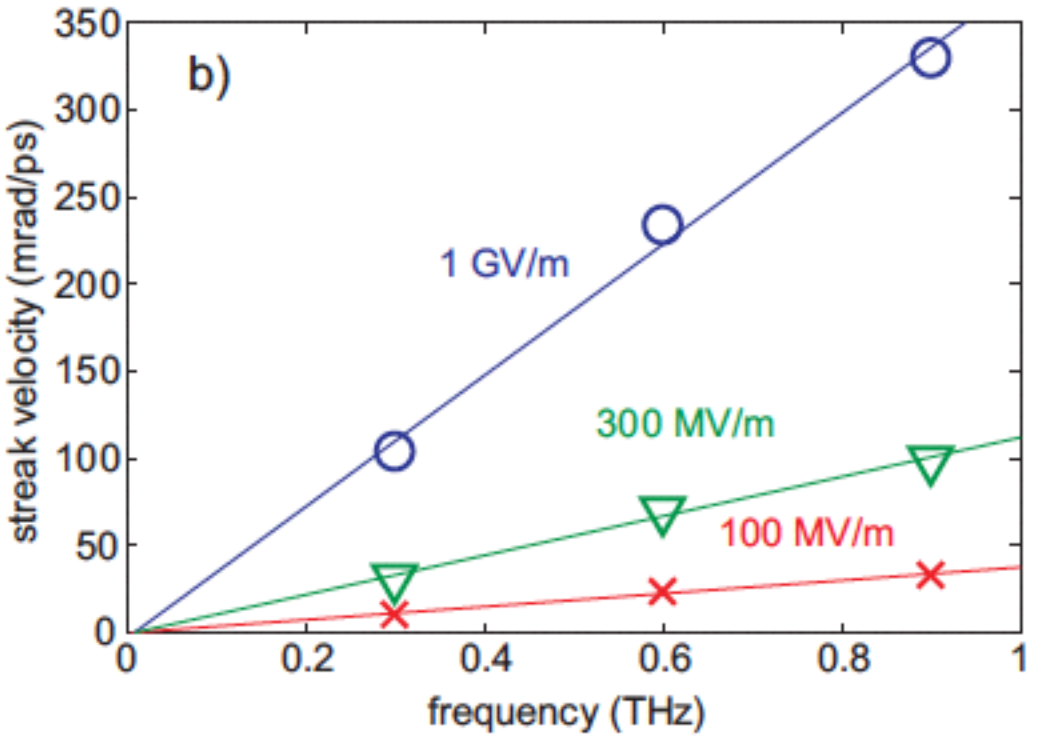
- **Resonantly absorbed THz radiation** => current flow in the ring resulting in an accumulation of charge carriers across the gap region

- Capacitive charging => **in-gap enhancement of the electric field** depending on the gap geometry



J. Fabianska, G Kassier & T. Feurer, *Scientific Reports* **4**, 5645, 2014

Gap area = 10 $\mu$m x 10 $\mu$m
resonance frequency = 0.3 THz → GV/m level
field enhancement is ~ 100



**Achievable temporal resolution** $\Delta t = \frac{\sigma_0}{v_{s,\vartheta}} \sim fs$

un-streak beam size, angular streak velocity

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# THz Sources

- The **THz frequency range** is a **unique area of source development** where **either conventional electron beam-driven** RF sources or **optically-driven sources** may be used
- Additional development of THz sources with narrow bandwidths to maximize coupling and interaction efficiency is needed
  - laser driven
    - optical rectification + tilted pulse front
  - linac driven
    - modern two-beam acceleration

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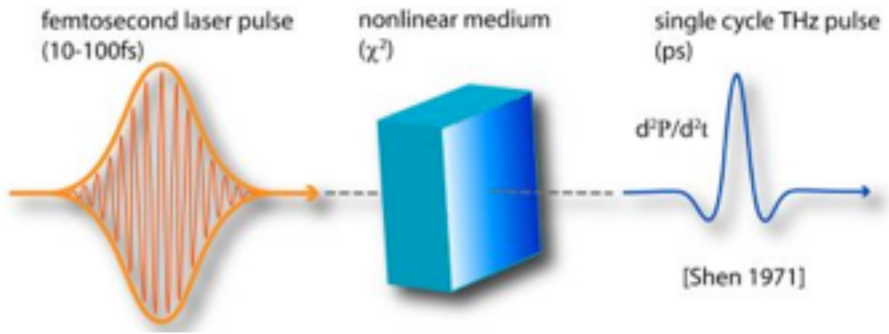
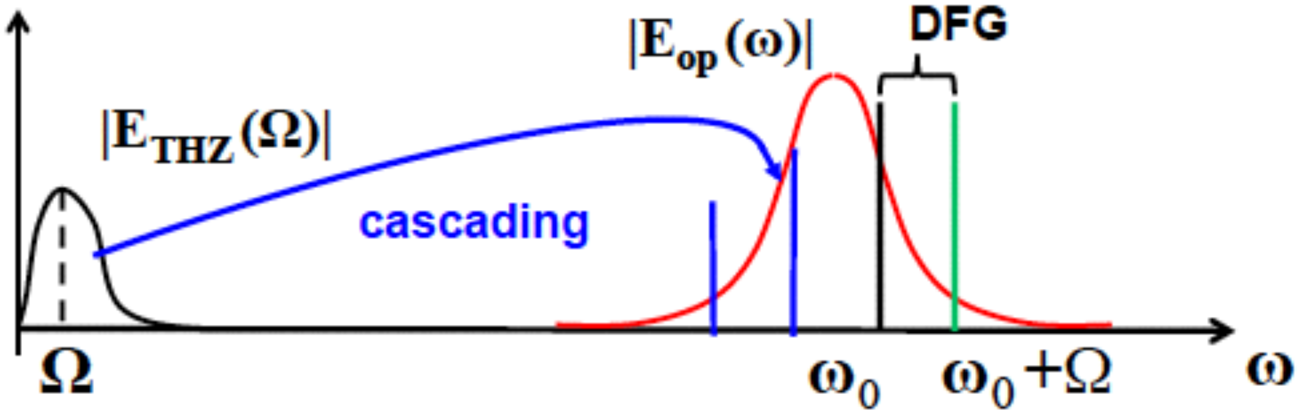
# Laser driven THz Sources

- The broad band IR pulse generates THz radiation via intra-pulse difference frequency generation (DFG), called optical rectification
- Optical rectification is a second order nonlinear process in which a nonlinear polarization is generated by the incoming laser field, mediated by the second order nonlinear susceptibility
- Most efficient method: ~1% energy conversion efficiency*, ~mJ THz pulse energy**



[Shen 1971]



- **Intra-pulse difference frequency generation**
- **THz bandwidth proportional to optical pulse bandwidth**
- **Must satisfy phase-matching condition**

$$\vec{k}(\omega+\Omega)-\vec{k}(\omega)=\vec{k}(\Omega)$$

**Lithium Niobate**

$$\boxed{n_g(\omega)=2, \quad n_p(\Omega)=5}$$

* S. W. Huang et al., Opt. Lett. 38(5), 796-798 (2013)
** C. Vicario, Opt. Lett. 10.1364/OL.99.09999 (2014)
** J. A. Fulop et al., Opt. Express 22(17), 20155-20163 (2014)

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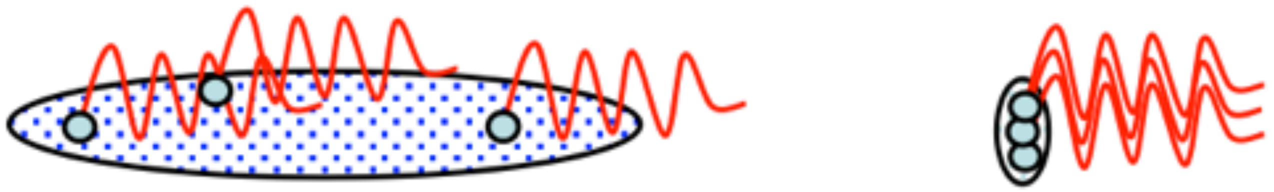
# Electron beam based THz source

## Broad band

- **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**

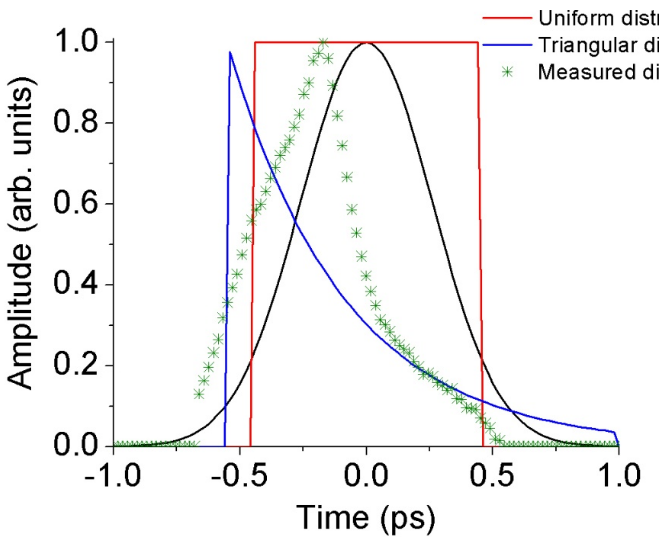


Coherent emission

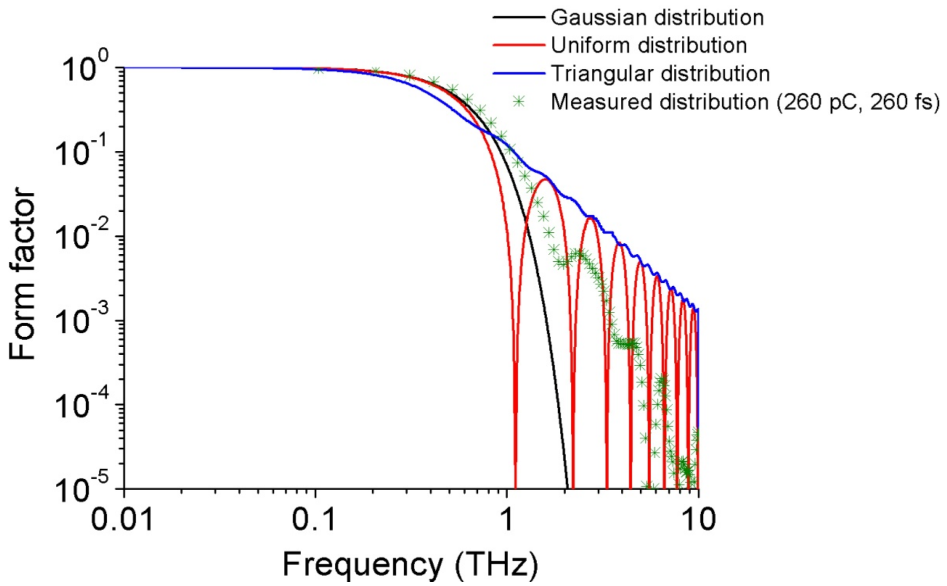
$\propto N^2$

- 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**



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

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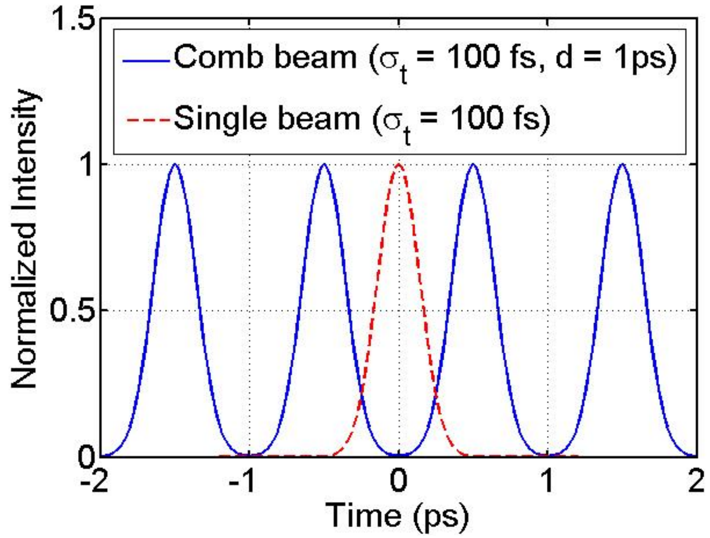
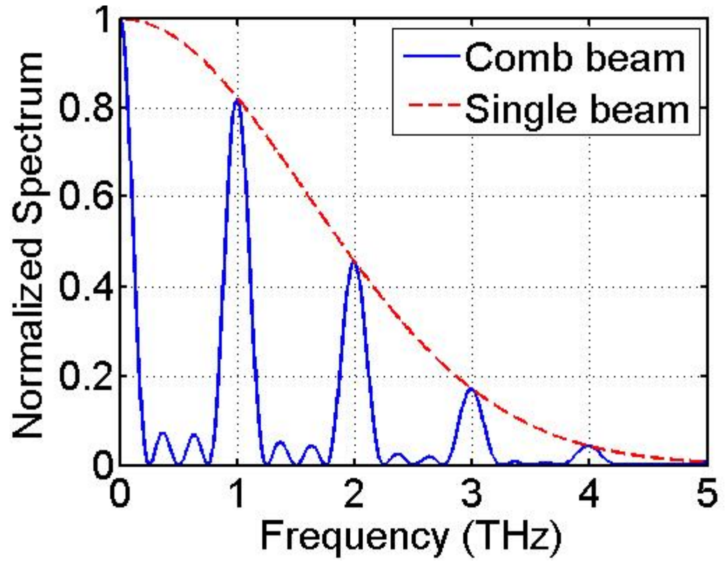
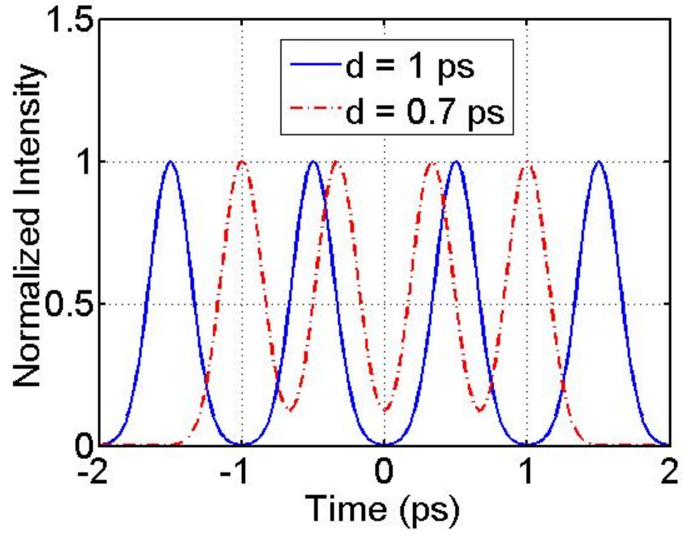
# Electron beam based THz source

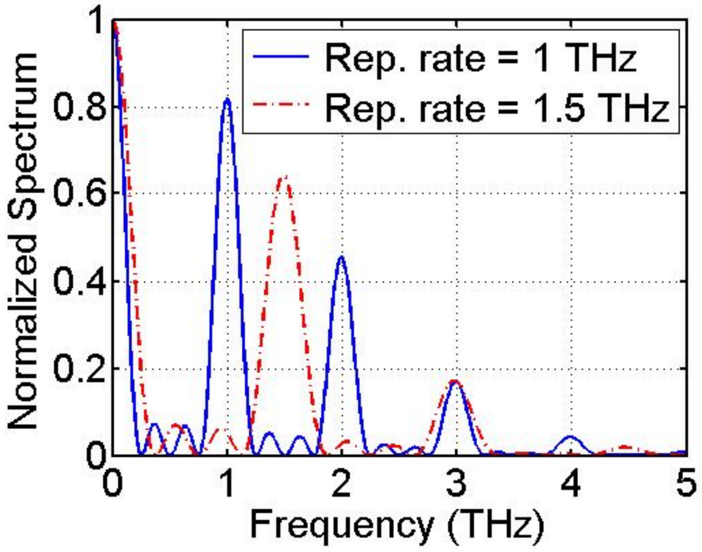
## Narrow band

- If a **longitudinally modulated beam**, i.e. a ***comb* beam**, interacts with an aluminum target, being the emission instantaneous, the bunch structure is frozen during the emission process
- If the width of the micro-pulses that constitutes the comb is reduced, the single pulse spectrum becomes larger, and **more harmonics of the micro-pulse repetition frequency appears** in the comb spectrum
- By **changing the time separation** between micro-pulses, **emission occurs at different THz frequencies**









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

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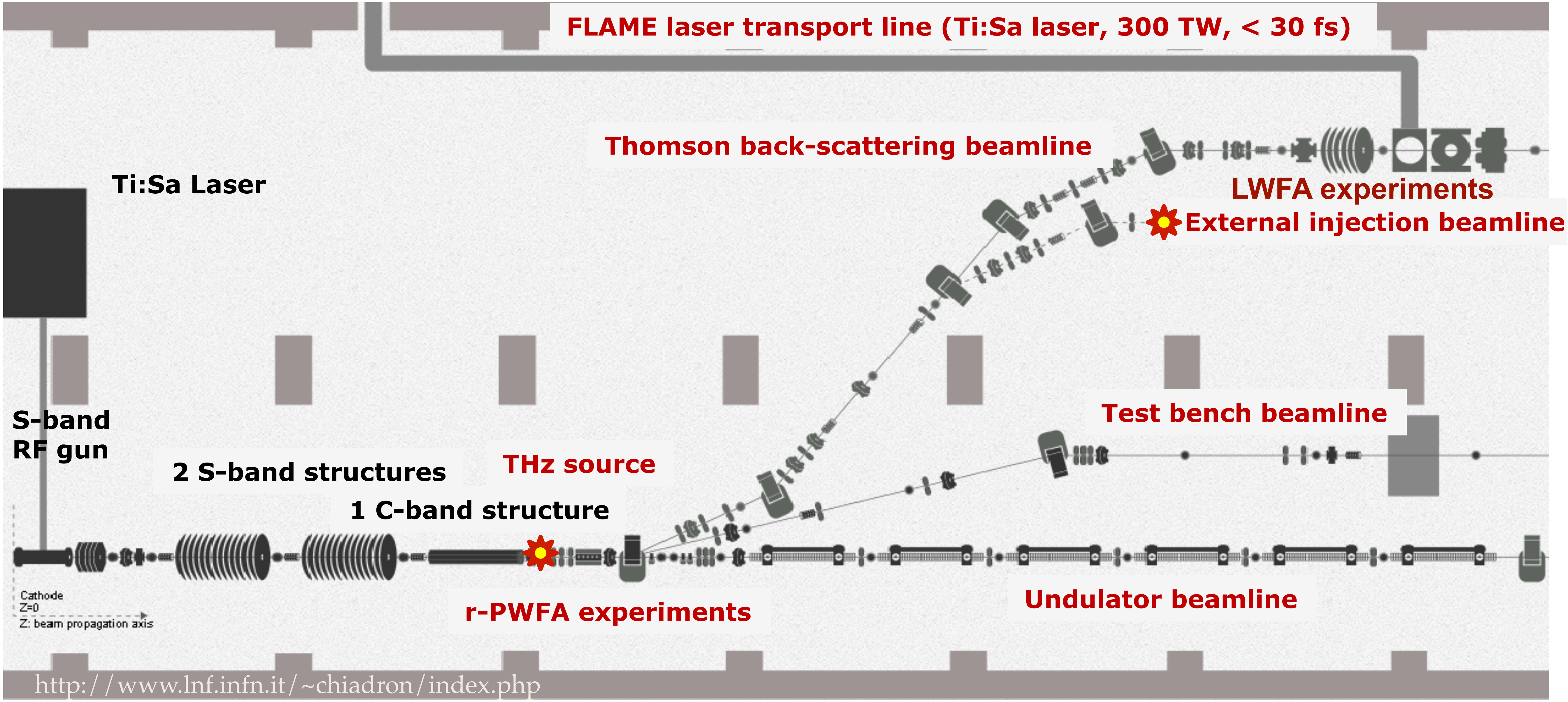
# SPARC_LAB Test Facility

Sources for Plasma Accelerators and Radiation Compton with Lasers And Beams



http://www.lnf.infn.it/~chiadron/index.php

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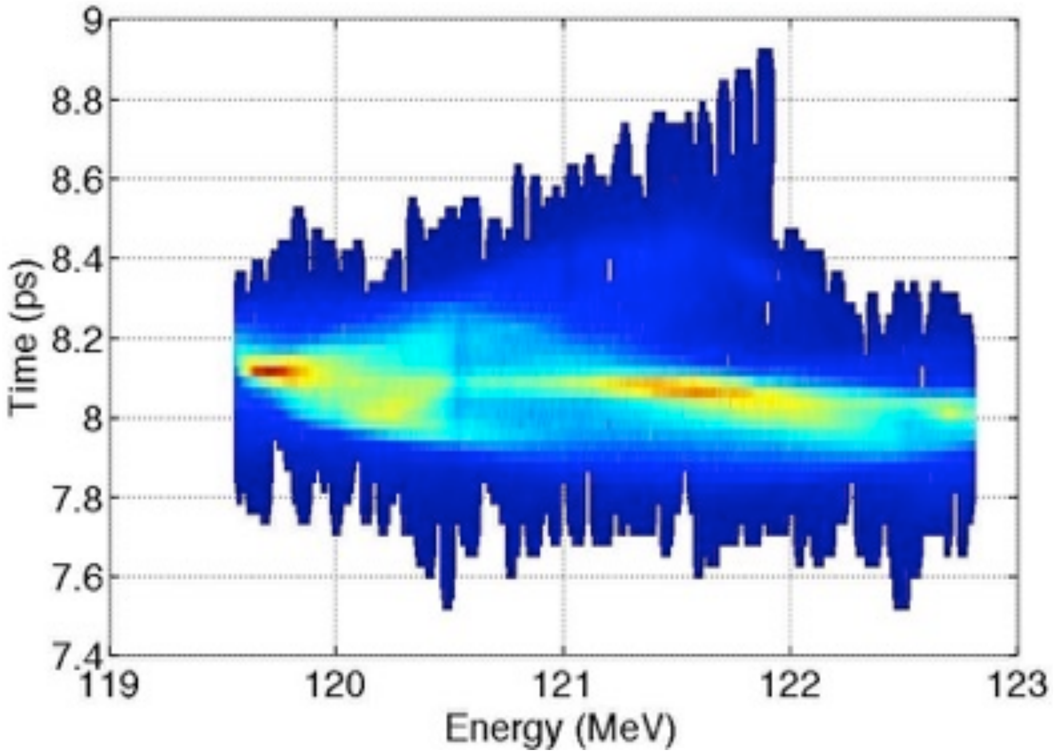
# Broad band THz Source

- High peak **broad band** THz source from sub-ps single bunches by means of CTR

## Electron Beam



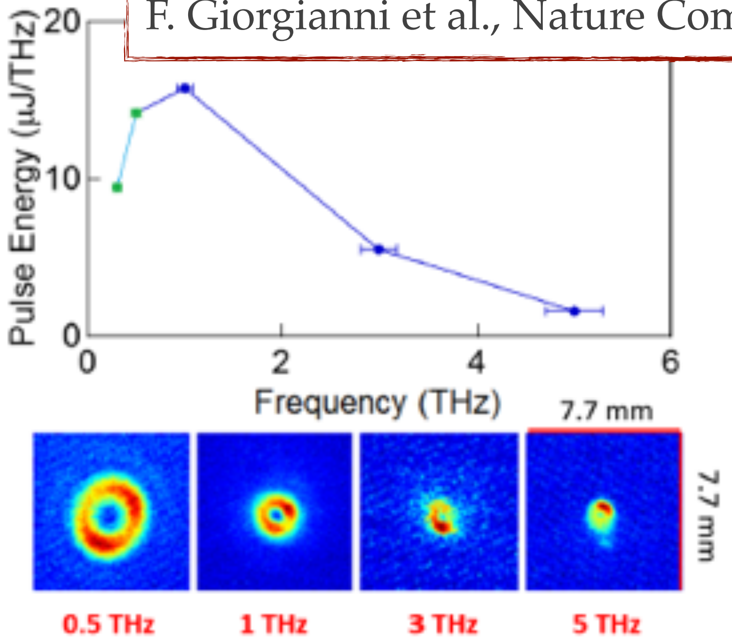
| | |
|---|---|
| **E (MeV)** | 121 (0.03) |
| **$\Delta E/E$ (%)** | 0.7 |
| **$\sigma_t$ (fs)** | 100(10) |
| **Q (pC)** | 600(25) |

E. Chiadroni et al., Appl. Phys. Lett. **102**, 094101 (2013)
F. Giorgianni et al., Nature Communications **7**:11421 (2016)

## THz radiation

| 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



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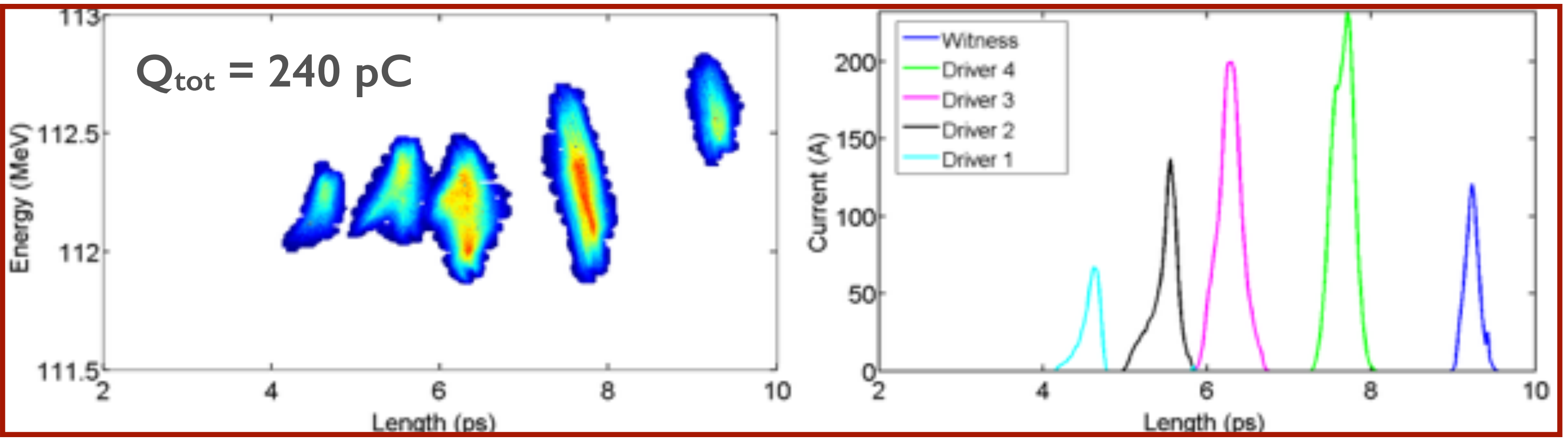
# Narrow band and Tunable THz Source

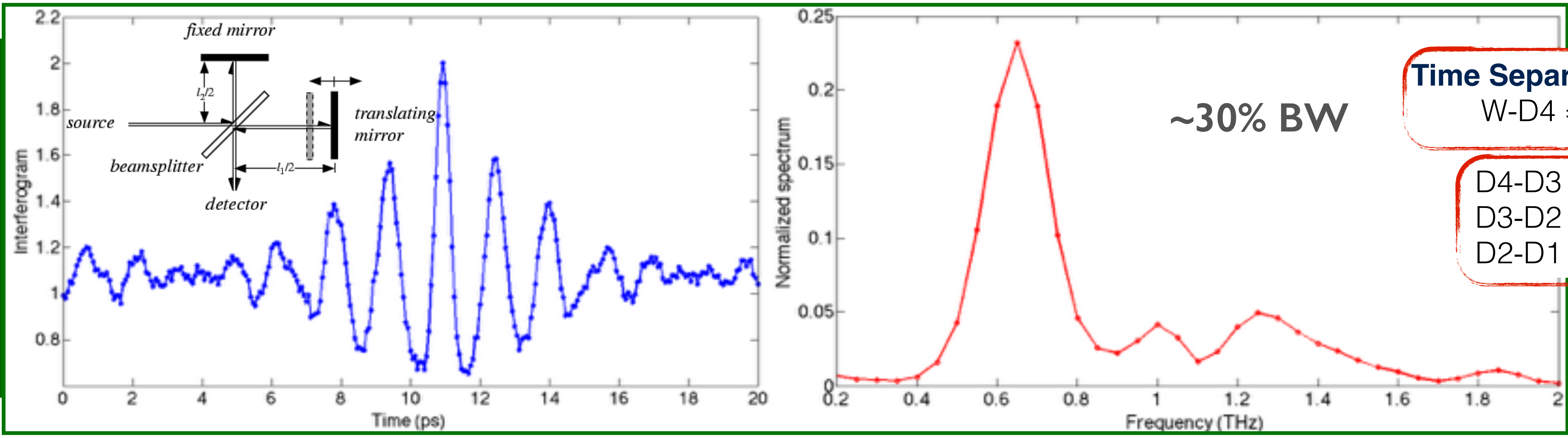
- **Tunable narrow band** THz source from Coherent Transition Radiation (CTR)

**Electron Beam**



| | Beam Energy (MeV) | Energy spread (%) | Bunch duration (ps) | Charge (pC) |
|---|---|---|---|---|
| **Witness Beam** | 112.58(0.03) | 0.084(0.003) | <0.088(0.001) | 24.04(0.28) |
| **Driver 4** | 112.28(0.03) | 0.159(0.003) | 0.042(0.001) | 74.91(0.46) |
| **Driver 3** | 112.17(0.03) | 0.112(0.003) | 0.092(0.001) | 69.39(0.36) |
| **Driver 2** | 112.26(0.02) | 0.087(0.003) | 0.113(0.001) | 36.34(0.20) |
| **Driver 1** | 112.20(0.02) | 0.045(0.004) | <0.100(0.024) | 36.34(0.20) |

**THz radiation**



**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. Chiadroni et al., Rev. Sci. Instrum. **84**, 022703 (2013)
F. Giorgianni et al., Appl. Sci. **6**, 2 (2016)

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# Achieved THz Parameters

| **Electron beam parameters** | Single bunch (VB mode: max compression) | 5-bunches per train (VB mode + laser comb) |
|---|---|---|
| Charge/bunch (pC) | 600 | 50 |
| Energy (MeV) | 120 | 110 |
| Bunch length (fs) | 100 | < 100 |
| Rep. Rate (Hz) | 10 | |

| **Radiation parameters** | SPARC (single bunch) | SPARC (5-bunches/train) |
|---|---|---|
| Energy per pulse (μJ) | 40 | ~1 (@ 1 THz) |
| Peak power (MW) | ~100 | ~10 (@ 1 THz) |
| Average power (μW) | ~100 | ~10 |
| Electric field (MV/cm) | 1.6 | $\sim 10^{-2}$ |
| Pulse duration (fs) | 100 | < 100 |
| Bandwidth | 0.3 – 5 THz | ~ 30% |

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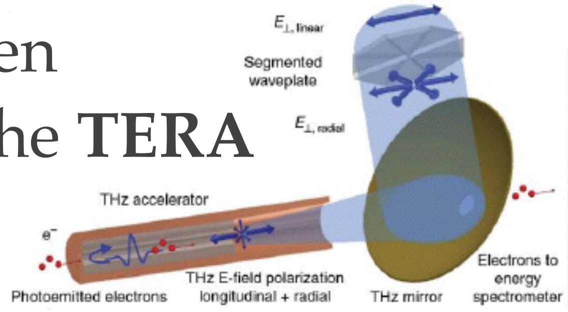
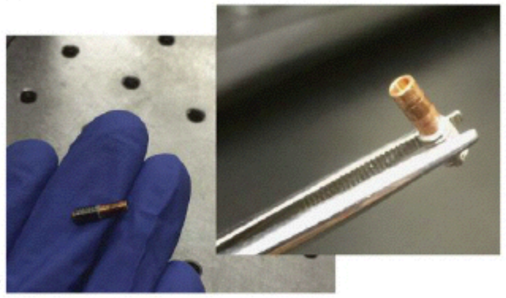
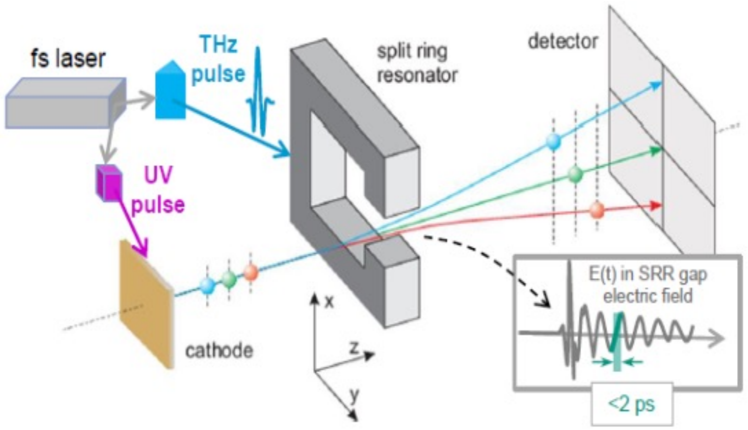
# Conclusions

- **THz acceleration**
    - The investigation and optimization of THz driven acceleration is in progress in the framework of the **TERA experiment** (funded by CSN5-INFN)





        - Preliminary studies on the most suitable material and geometry of the accelerating structure, based on the power, pulse length and bandwidth from the available THz sources



- **THz diagnostics**
    - Tests are planned at SPARC_LAB

- **Coherent THz radiation is currently produced and optimized at SPARC_LAB** through ultra-short relativistic beams
    - **Different THz emission regimes** by properly control electron bunch shaping, length, charge, therefore **by properly set photo-injectors parameters**