Compact, e-beam based mm-and THz-wave light sources

S.G. Biedron, S.V. Milton (CSU) and G.P. Gallerano (ENEA)

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

Electrical & Computer
ENGINEERING

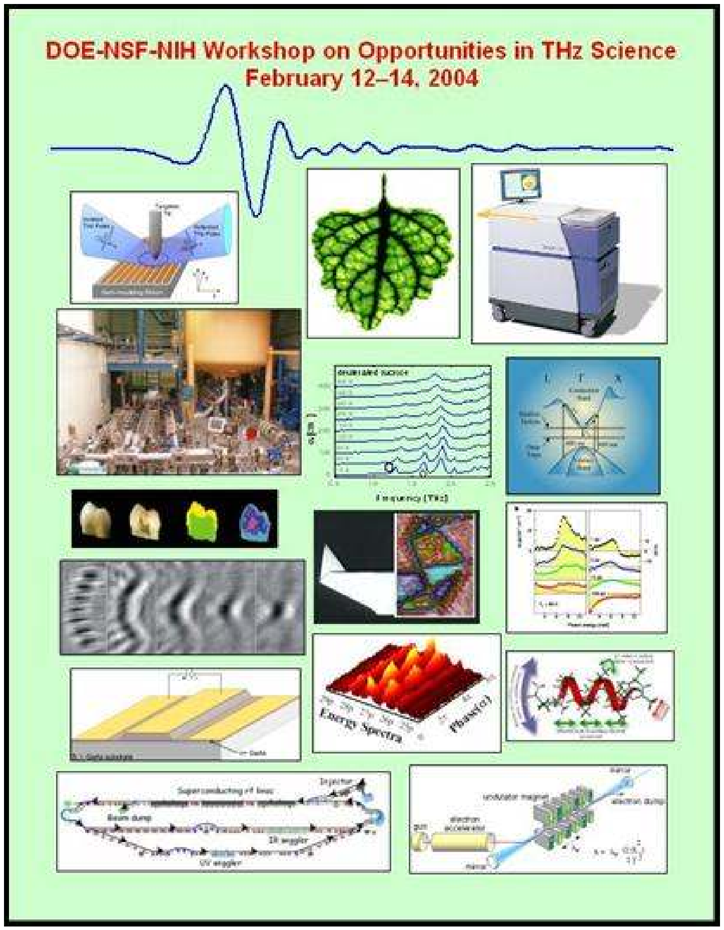
Colorado State University

Collaborators involved with the enclosed work

- CSU – S.G. Biedron, S.V. Milton and T. Burleson
- ENEA Frascati – G.P. Gallerano, A. Doria, E. Giovenale, G. Messina, and I. Panov Spassovsky
- Argonne – J. Noonan, M. Virgo, J. Schneider, L. Skubal, N. Gopalsami, Y. Li
- Naval Postgraduate School – J. Lewellen
- University of Twente – P.M.J. van der Slot

Funding Acknowledgements – Argonne LDRD, USDA, ONR, Italian government, EU, and Dutch Government.

Discussions about compact, high-power e-beam-based THz sources…a long history



And discussions about using THz for time-resolved experiments also has a long history…

"For example, one could envisage performing time-resolved X-ray diffraction experiments in a protein such as myoglobin which is known to have large scale sub-nanosecond dynamics which THz ps synchronous with the X-rays is used to drive specific collective modes of the protein." Page 59 of 2004 report of the DOE-NSF-NIH meeting "Opportunities in THz Science"

The genres of THz sources

- Solid state oscillators
- Gas and Quantum Cascade Lasers
- Laser driven emitters
- THz radiation from Free Electrons

"Free-electron" based sources

- Backward Wave Oscillators
- CW FEL (FEL Facilities)
- Synchrotron radiation sources
- Compact FELs
- Pre-bunched/pre-shaped electron beams/coherent radiators
- Transition radiation from fs-electron pulses
- Cerenkov-FELs
- Smith-Purcell radiation

What we did to shrink the size

- Pre-bunch the electron beam much like what is done in a klystron
  - Ballistic bunch compression gun (Argonne)
  - Gun and phase shifter combination (ENEA)
- Out-couple the radiation

SPIE Proceedings Vol. 3154, 1997; Phys Rev Lett 80, 2841 (1998)

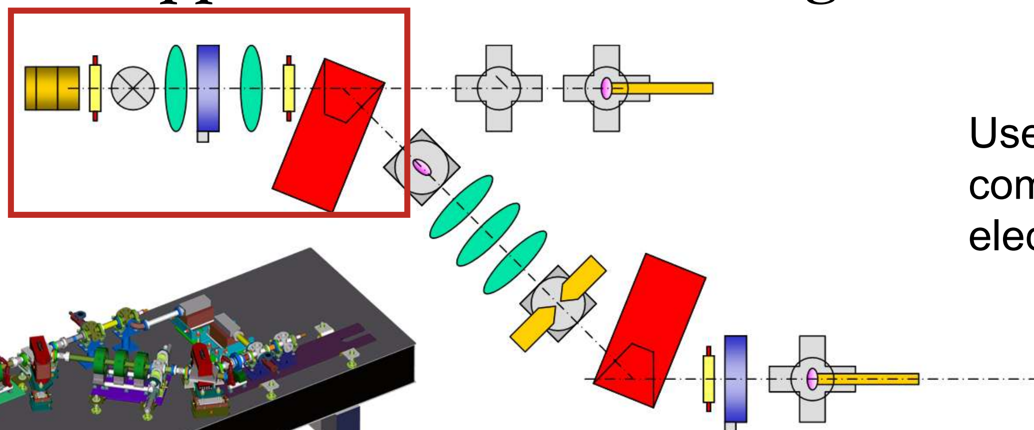
The Sources

- MAHPPS (Multi-Application Palletized High Power Photon Source) Prototype
- CATS (Compact Advanced THz Source)

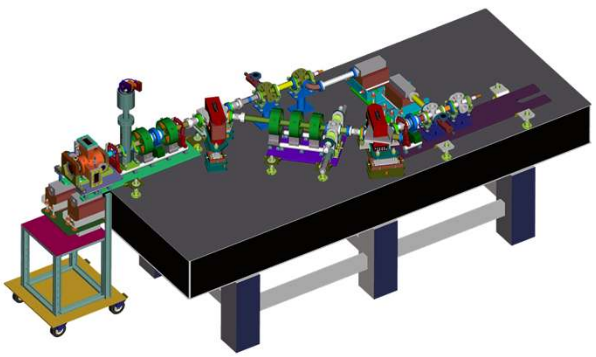
Details of both sources can be found in “Compact, High-Power Electron Beam Based Terahertz Sources, Proceedings of the IEEE, Vol. 95, No. 8, August 2007.

MAHPPS Prototype
(Multi-Application Palletized High Power Photon Source)

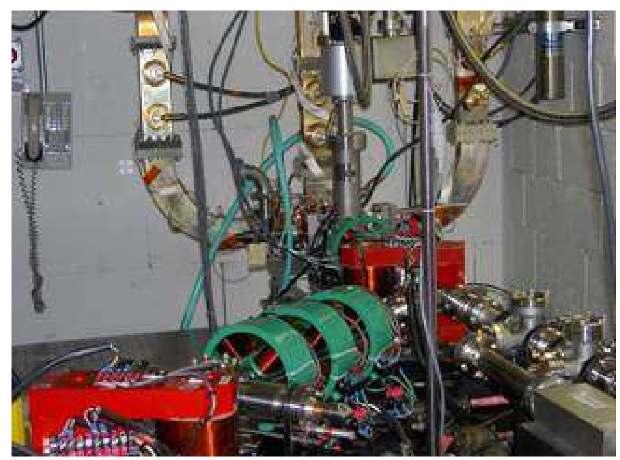
Primary System the rest is for diagnostics

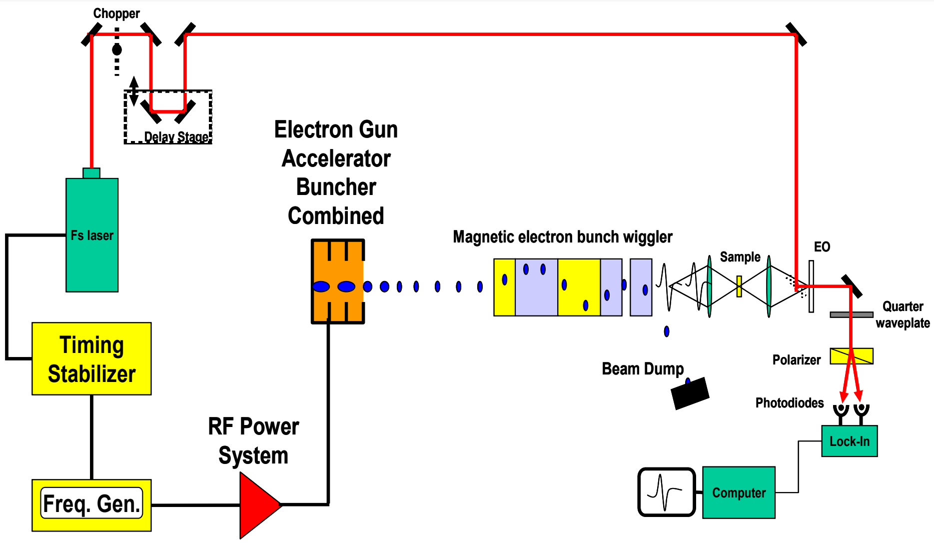


Uses ballistic bunch compression in an rf-driven electron gun system

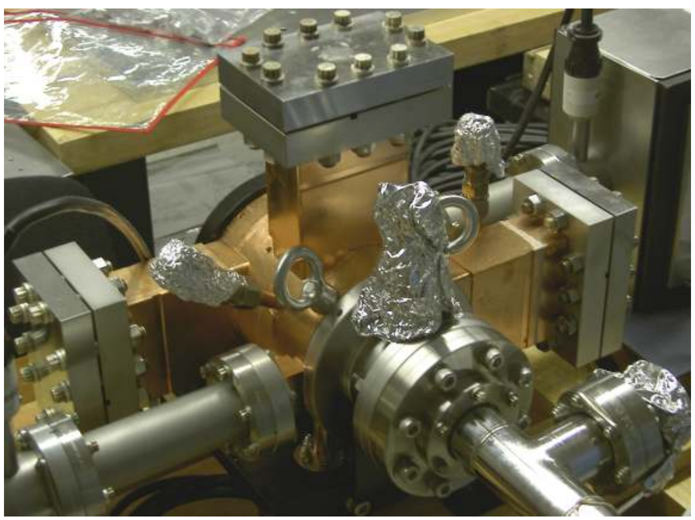


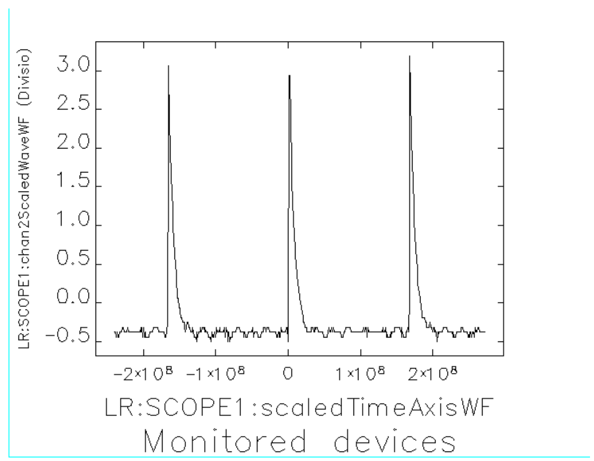
Standard optical table (gives scale)





With nearly 1 kA of peak current we **measured** half a MW of peak terahertz power (not compensating for losses through the system.)

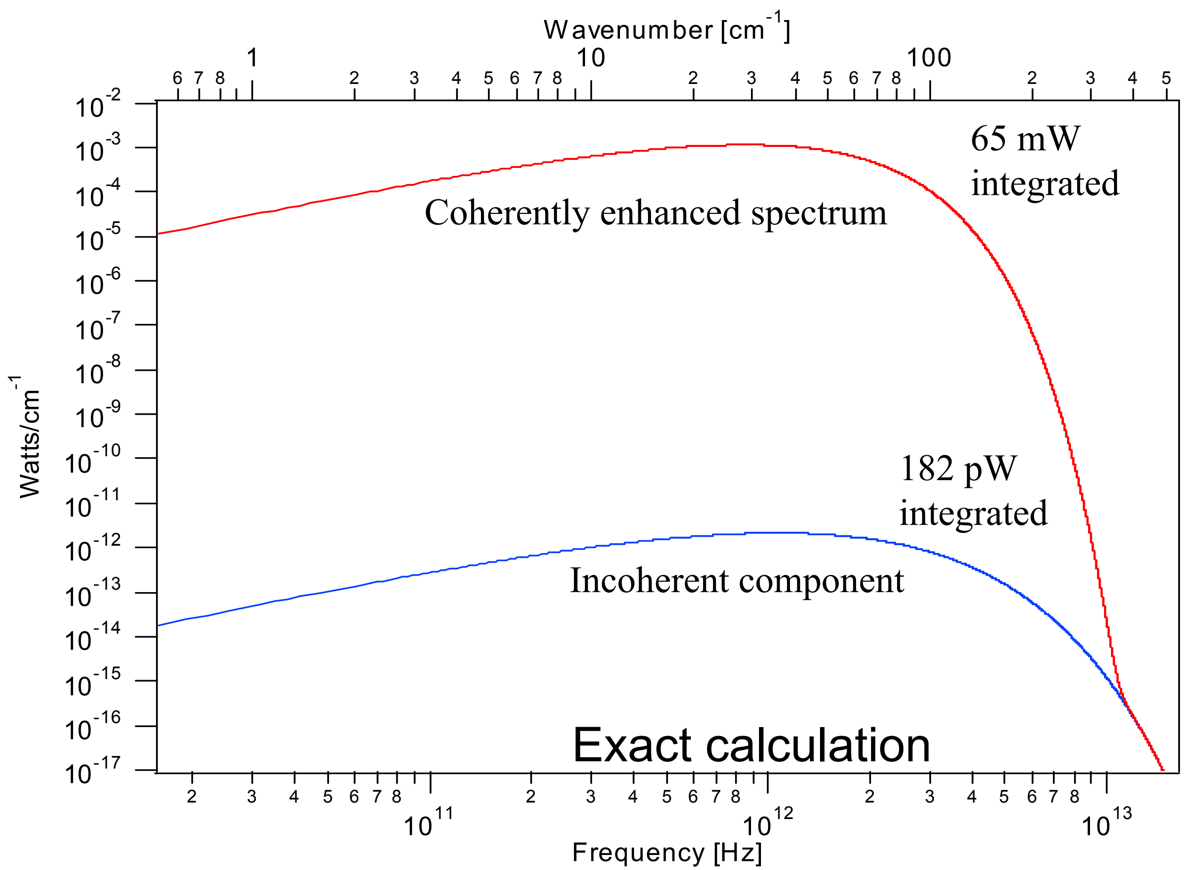




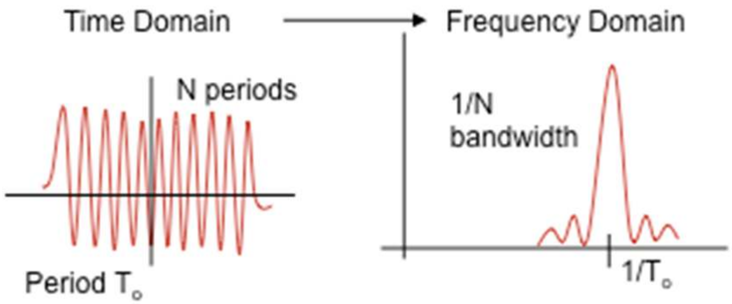
Terahertz signal (arbitrary units) versus time (ns).

Prototype Design

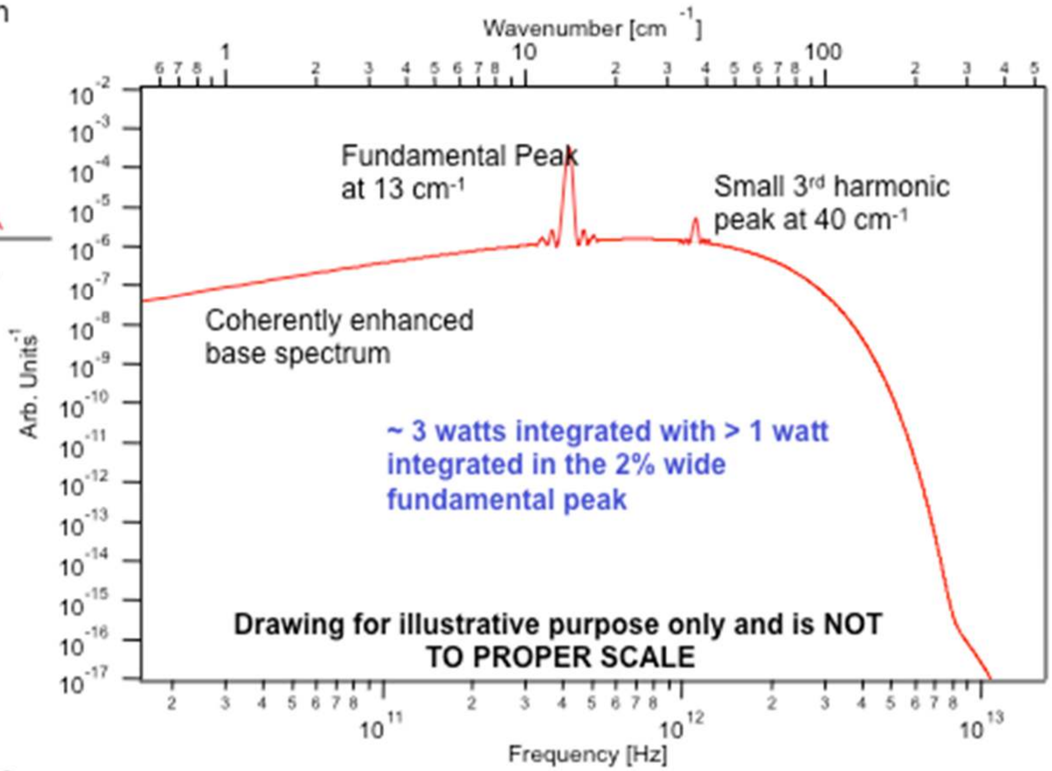
Beam distribution: gaussian (not entirely realistic, but represents the worse case) $\sigma_z = 50\mu m$
Charge per bunch: 100 pC
rf pulse duration: 2 μs
rf frequency: 2856 MHz
rf rep rate: 60 Hz
Beam energy: γ = 5 (~ 2.6 MeV)
Radius of curvature: 1 cm (~ 0.9 T field)



Prototype Design continued



- **Undulator Parameters**
  - *K* = 1
    - *Normalized B Field*
  - λ = 2.5 cm
  - N = 50 periods
- **Beam Parameters**
  - Same as earlier example



The fundamental peak central frequency can be easily changed by shifting the beam energy

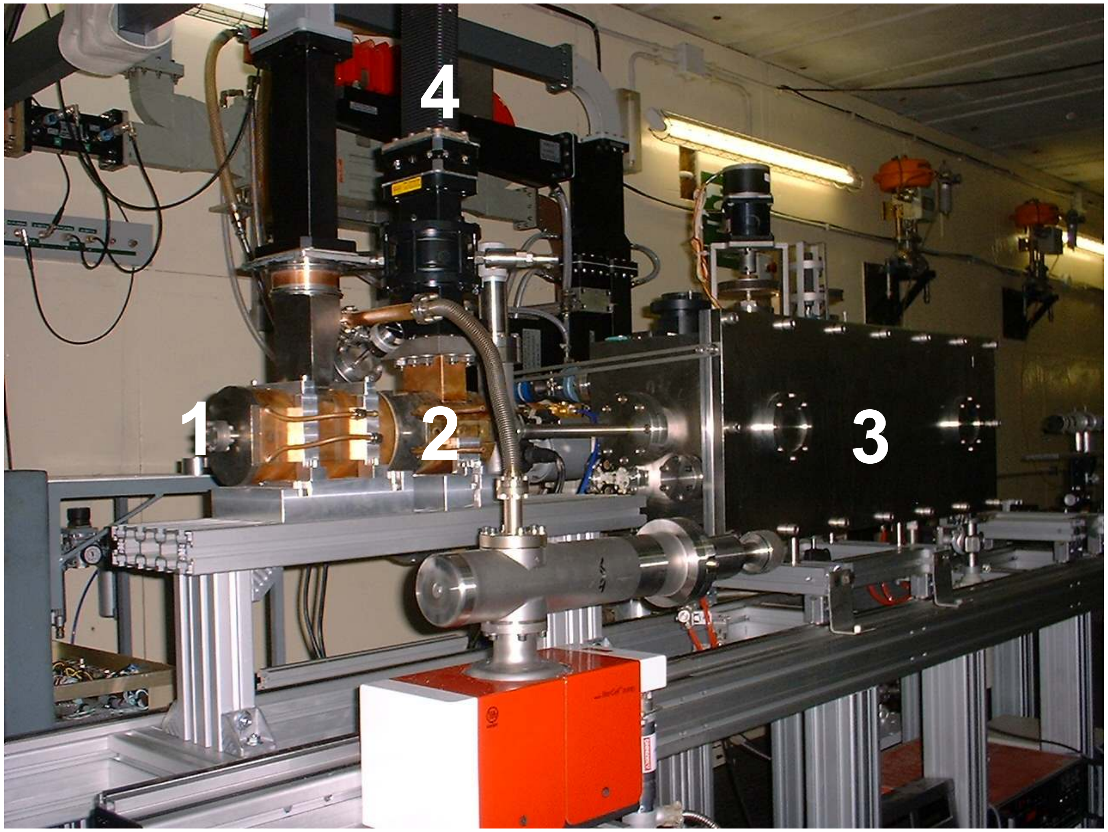
FEL CATS in ENEA Frascati
CATS (Compact Advanced THz Source)

Tunability between 450 and 800 μm (0.7 – 0.4 THz) has been achieved at a fixed value of the undulator gap (K=0.75)
with a rectangular waveguide of dimensions
a = 24 mm and b = 6 mm.

Output power: 1.5 kW @ 0.4 THz

10 μs pulse duration

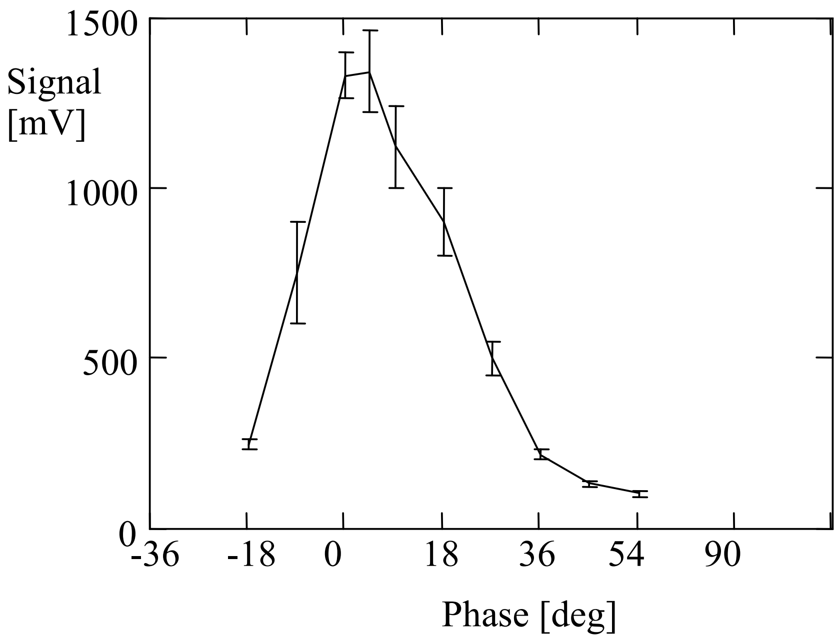
$E = 2 – 3$ MeV
$I_P = 5$ A
$\lambda_U = 2.5$ cm N=16



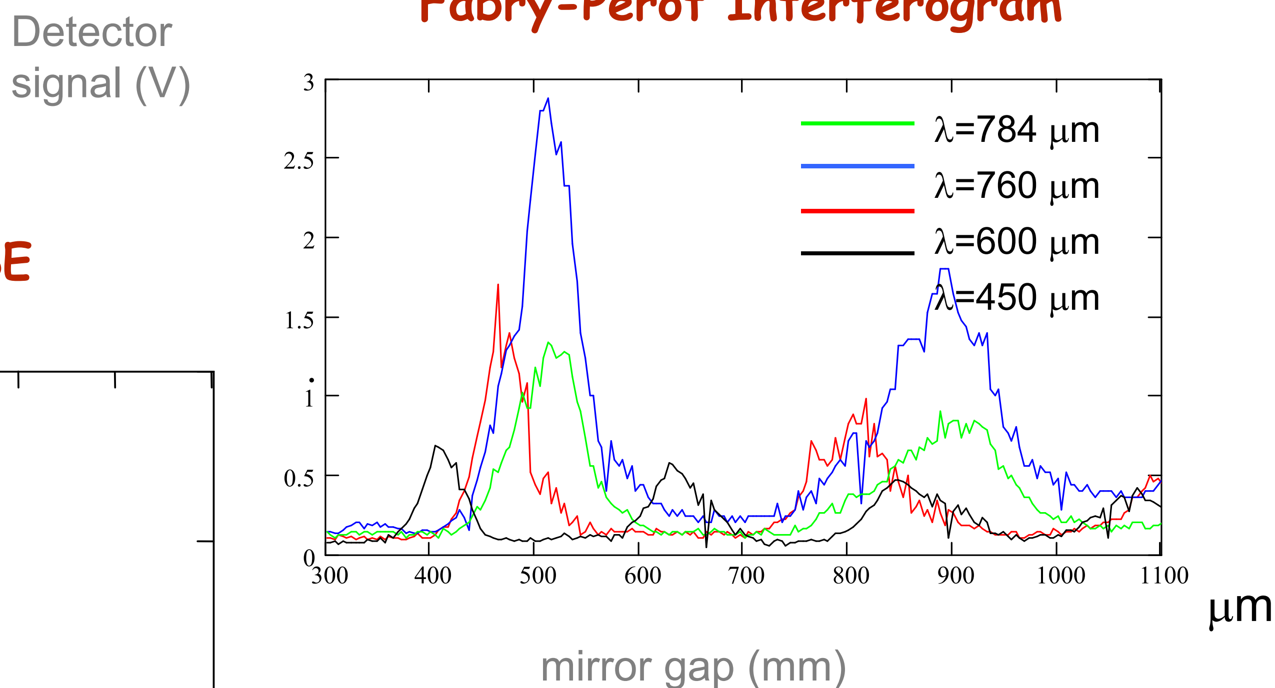
1: Linac - 2: PMD - 3: Vacuum chamber/undulator - 4: RF System

CATS' Tunability is obtained by varying amplitude and phase in the PMD

THz POWER vs.PMD PHASE

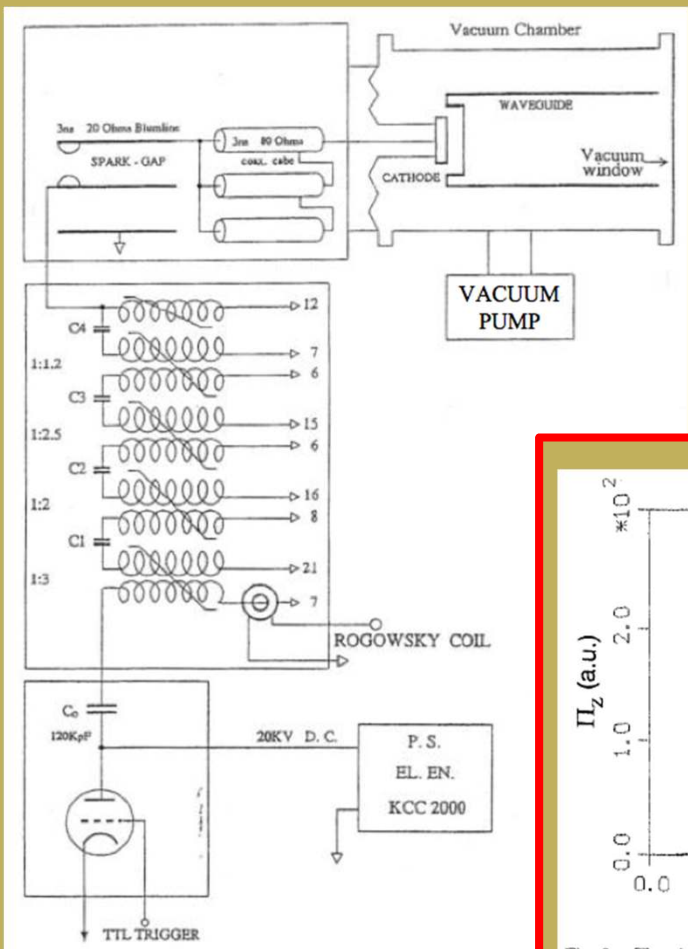


Fabry-Perot Interferogram



The PMD becomes an accelerating structure as the RF phase is varied.

High Current Pulser for THz Generation



Compact 1.5 MV, High-Current Pulser operated in a Virtual Cathode mode with waveguide. Generates ~ 100 MW output power during a few ns pulse.

I.G. Yovchev, I.P. Spassovsky, N.A. Nikolov, D.P. Dimotrov, G. Messina, P. Raimondi, J.J. Barroso, R.A. Correa, “Numerical simulation of High Power Virtual Cathode reflex Triode Driven by Repetitive Short Pulse Electron Gun”, IEEE Trans. On Plasma Science – 24, No.3 (1996) 1015-1022.

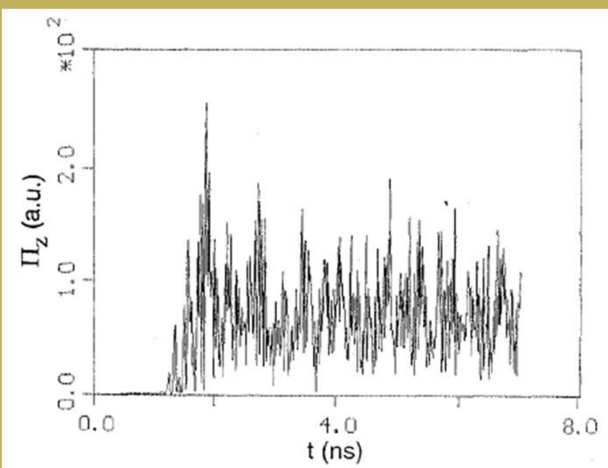


Fig. 3. Time history of the Poynting vector z-component in a point $r = 3.5$ cm, $z = 22$ cm.

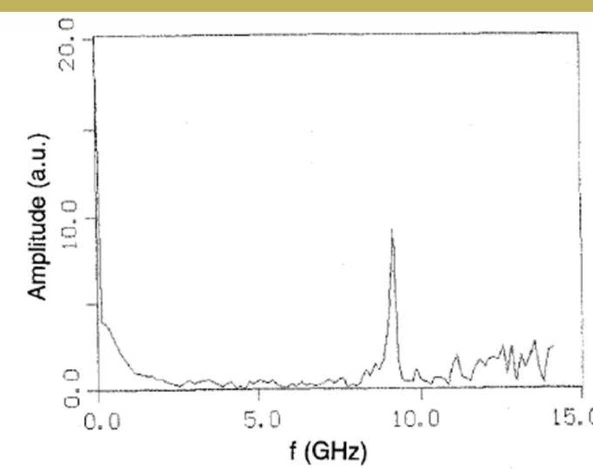


Fig. 5. Fourier transform of the beam current through the anode foil.

Summary

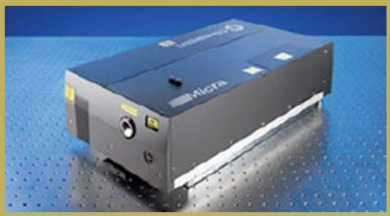
- High-power, THz sources (broadband or narrow-band) can be generated using pre-bunched electron beams that enable coherent radiators.
- These radiators are compact (small room or vehicle) WITH all the bells and whistles (peripherals).
- *We envision that such a THz system could be designed and engineered to be on a mobile device that could be used a different beamlines at synchrotron and FEL user facilities to further enable time-resolved research.*

Backups

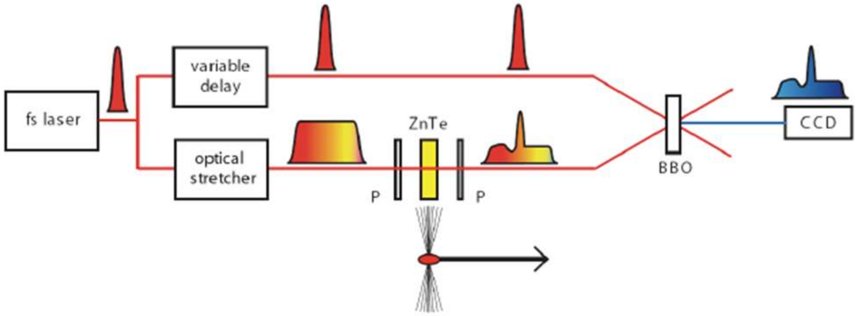
Build up of the CSU laser and accelerator sources

- CSU is building up laser-test and accelerator-test facilities
  - The laser-based facility will serve to develop electron beam diagnostics. We must generate THz to mimic the electron beam transition radiation to develop the diagnostics. The Ti-Saph system will arrive in January. (Coherent "Micra" mode-locked Ti:Saph oscillator at ~83 MHz.)
  - The accelerator-based system will be built up during CY 2012.

Laser source



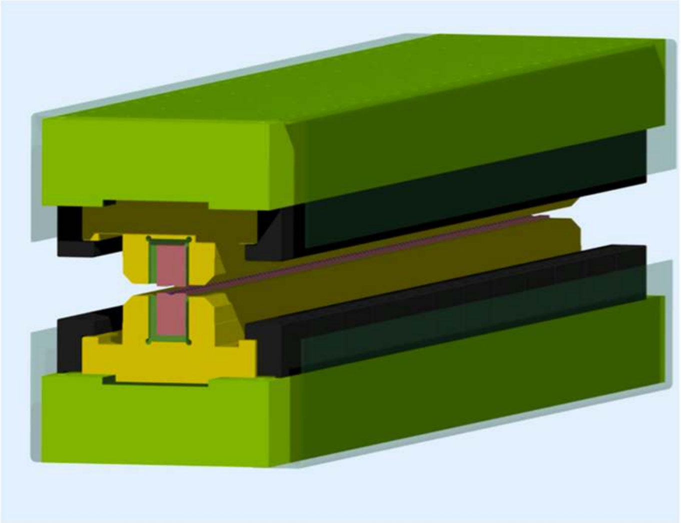
CSU Laser Lab – Coherent Ti:Saph – EOS and Photocathode driver



- Probe laser is optically stretched with time-wavelength correlation
- EO effect is imprinted on pulse
- Coincidence of stretched pulse and short pulse generates optical sum signal.
- Output angle is a function of sum signal frequency, creating an image.

Accelerator Source

Electron energy	E = 6 MeV (γ = 12.74)
repetition frequency	81.25 MHz
micropulse	25 ps
macropulse	18 μs
Undulator	
• wavelength	λ_w = 25 mm
• field	B = 0.67 T
• number of periods	N_w = 50
light transport	waveguide
resonator	waveguide (hole coupling)

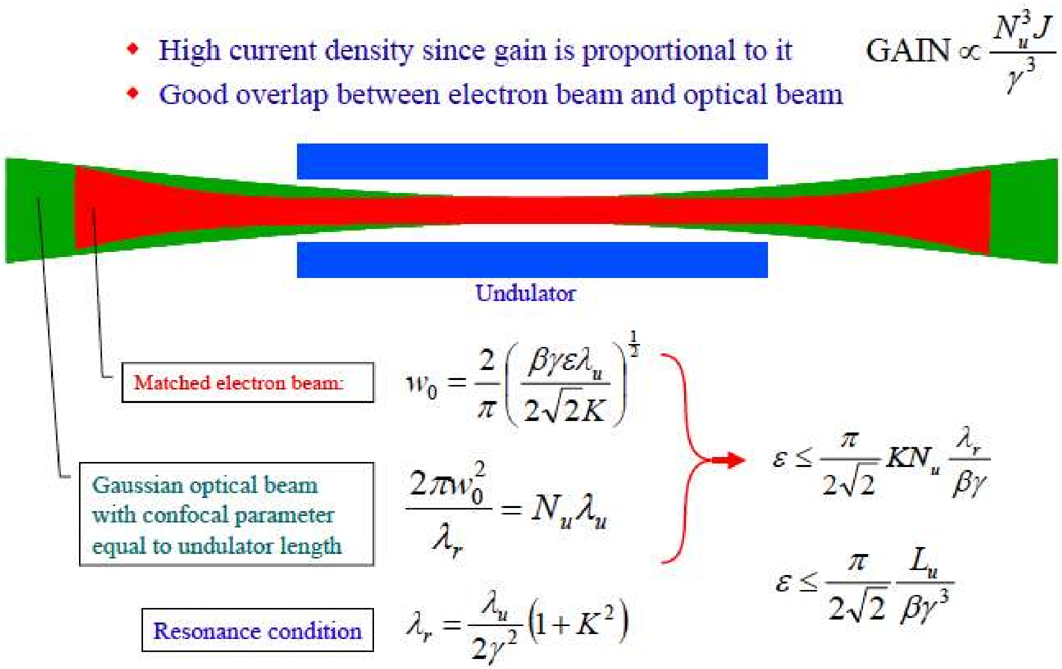


CSU Linear Accelerator

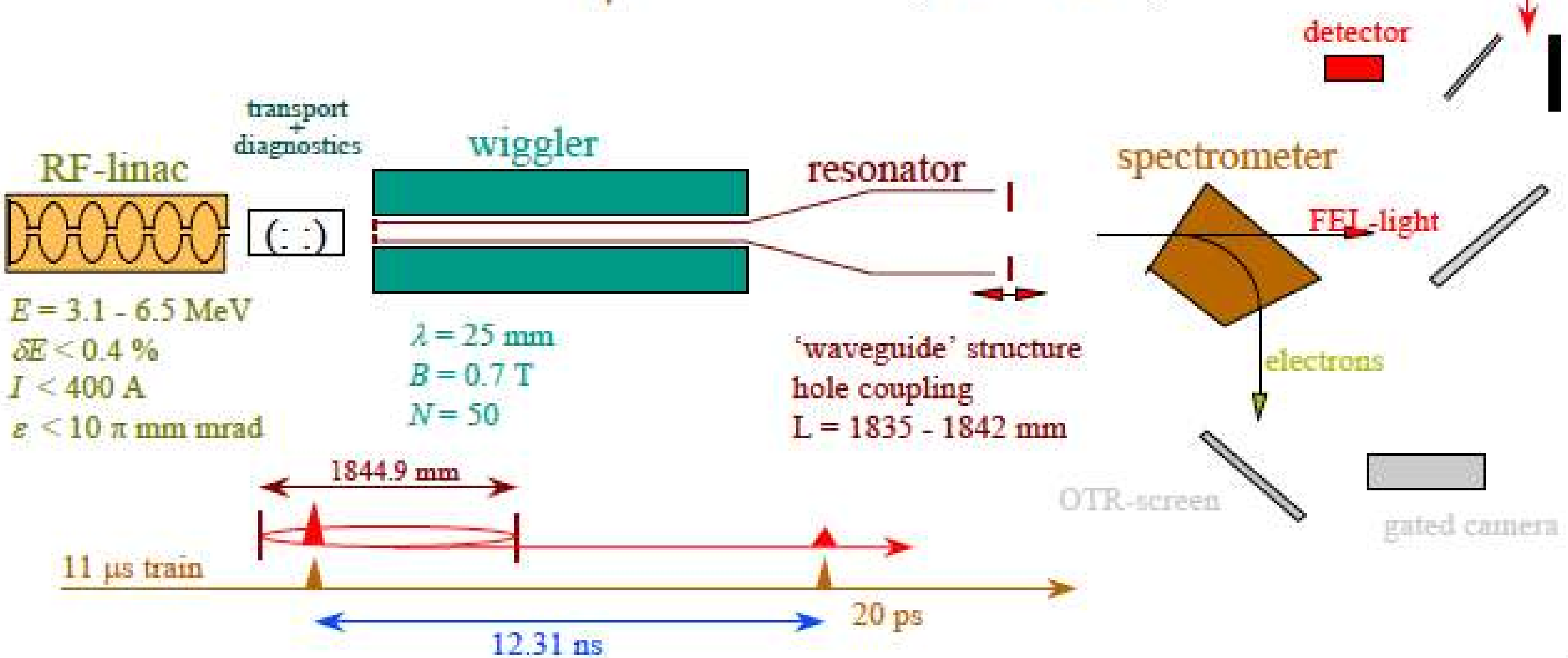
Design parameters	[mm]
Undulator wavelength	25
Half gap	4.0
Overhang of magnet	6.0
Half thickness of pole	2.00
Half thickness of magnet	4.25
Height of pole	40.0
Height of magnet	45.0
Half width of pole	15.0
Half width of magnet	21.0

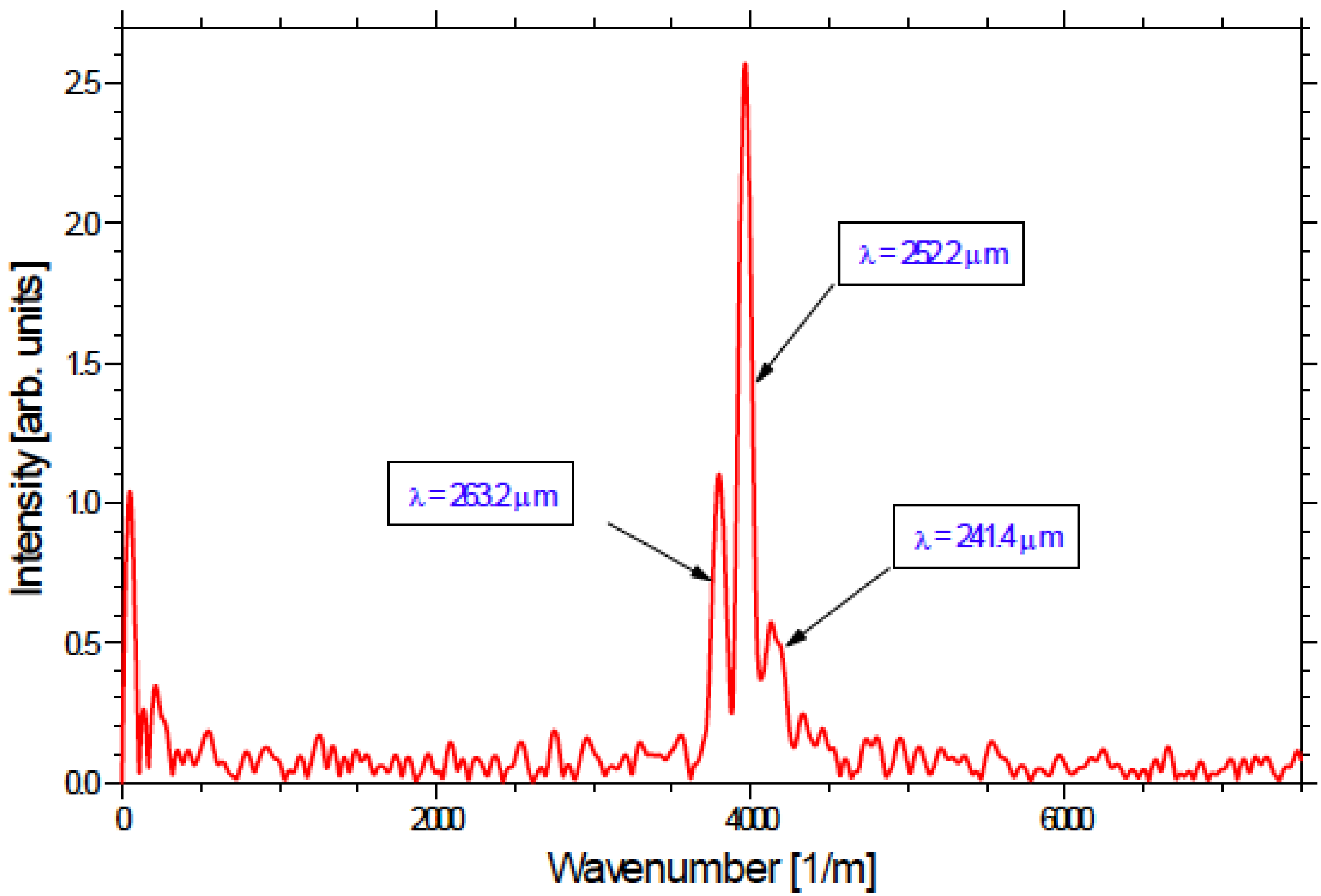
THz generation

- Tunable between 200-800 microns
- About 1 MW peak peak power from 900 MW available beam power (6 MeV, 150 A peak current)
- Average (80 MHz rep rate, 18 microsecond macropulse,25-ps micropulse)



$$\lambda_s = \frac{\lambda_w}{2\gamma^2}\left(1 + K^2\right)\left(\frac{v_{ph} - v_e}{c - v_e}\right)$$




λ = 252.2 μm
λ = 263.2 μm
λ = 241.4 μm
Intensity [arb. units]
Wavenumber [1/m]
0.0
0.5
1.0
1.5
2.0
2.5
0
2000
4000
6000