Nanosecond rf-Power Switch for Gyrotron-Driven Millimeter-Wave Accelerators*

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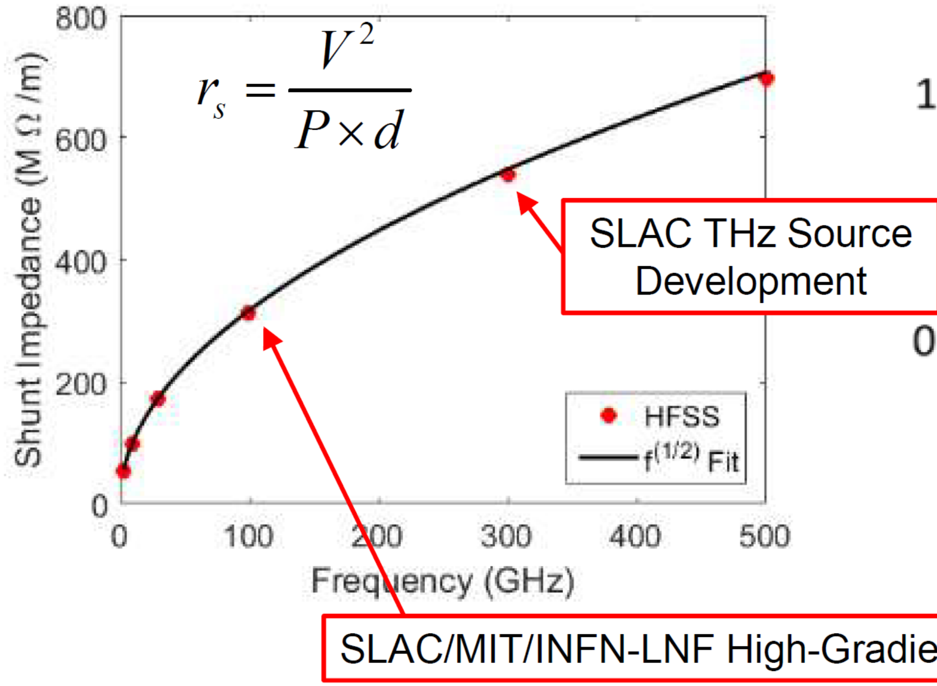
Outline

- **Motivation**
- **Nanosecond RF-power switch development**
- **High resolution spectrometer development**

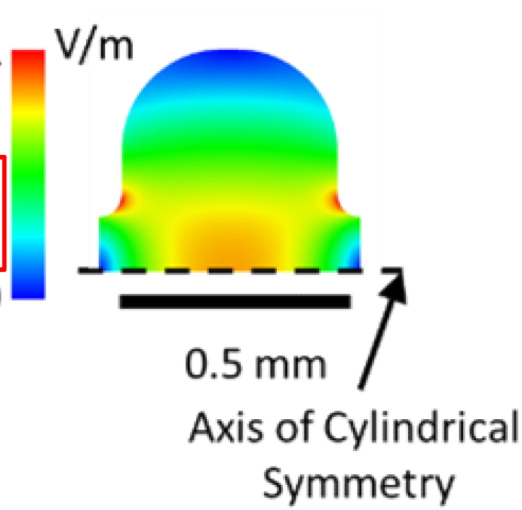
THz Accelerating Structures

- Advantages of operating at THz frequencies
  - Shunt impedance increases as $f^{1/2}$
    - For the structures with a similar shape
  - RF breakdown rate is lower for the same EM-field amplitudes at higher frequencies

Shunt Impedance for TM_{01} π-mode Structures

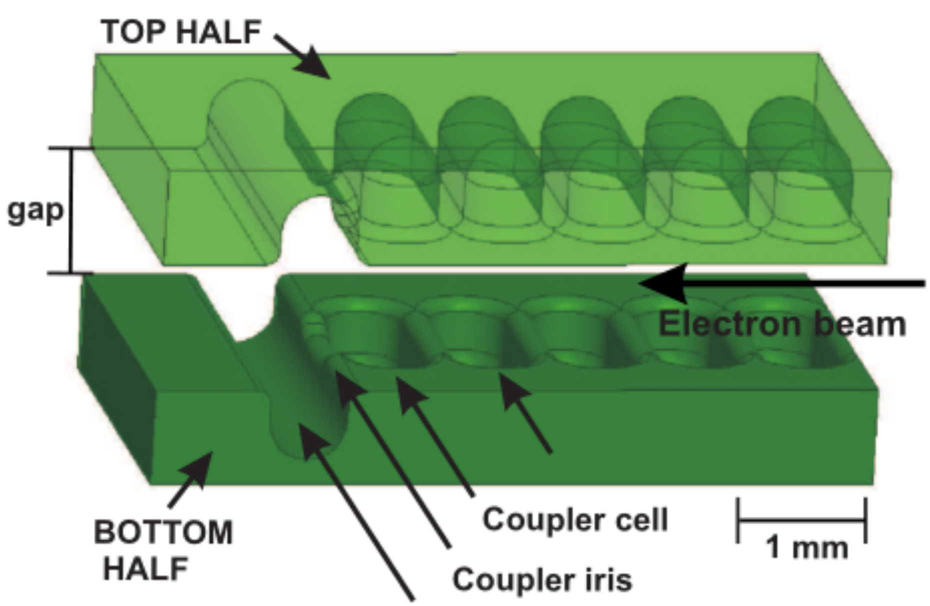


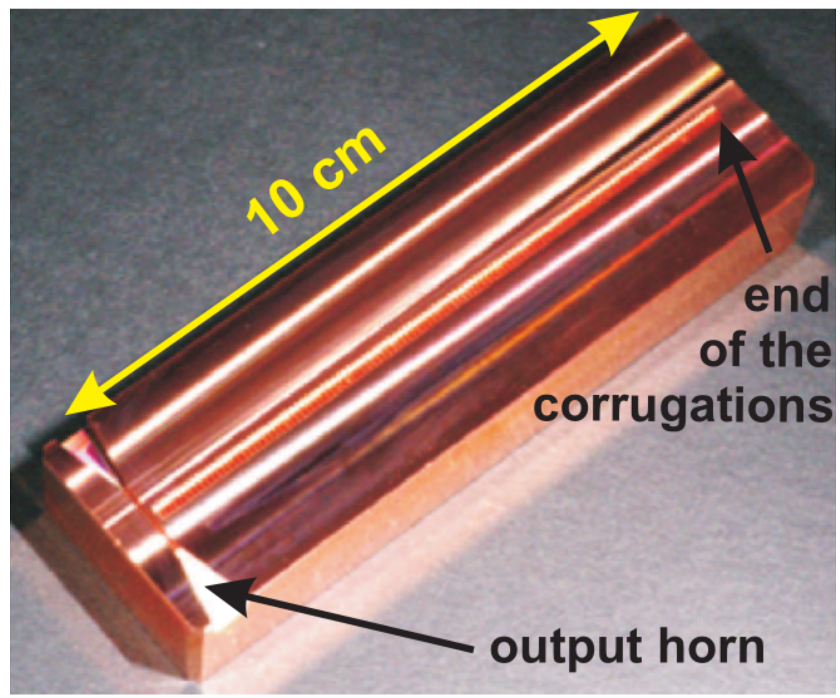
~300 GHz Structure



SLAC 100 GHz 200 MV/m Structure*

- The structure is open, made of two separate metal blocks
- The two halves are placed together, with a gap between, forming an open accelerating structure
- The structure was excited by the FACET ultra-relativistic electron bunch





* More details in M. Dal Forno et al., Phys. Rev. Accel. Beams 19, 051302, 2016; M. Dal Forno et al., Phys. Rev. Accel. Beams 19, 011301, 2016; M. Dal Forno et al., Phys. Rev. Accel. Beams 19, 111301, 2016; M. Dal Forno et al., Nucl. Instrum. Methods Phys. Res A 864, 12 (2017); M. Dal Forno et al., Phys. Rev. Accel. Beams 23, 09131, 2018;

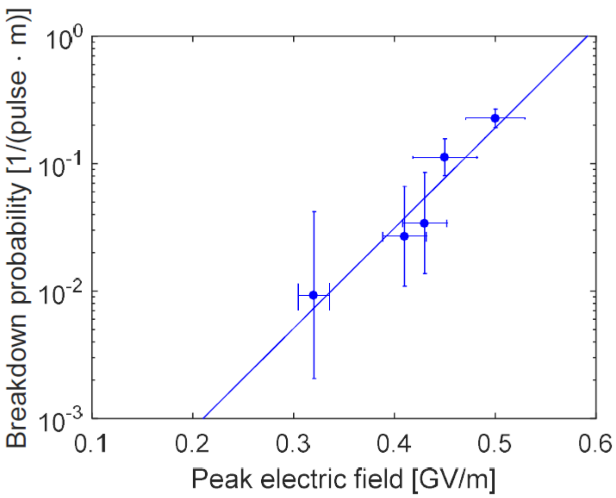
RF Breakdowns tests at FACET

- RF breakdowns limit the accelerating gradient
- Breakdown rate scales with peak fields and pulse length

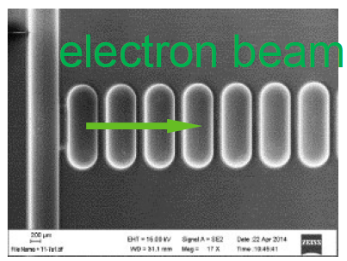
$$\Delta T = \frac{{H_{max}}^2 \sqrt{t_{pulse}}}{\sigma\delta\sqrt{\pi\rho' c_\varepsilon k}} \qquad \frac{{E_{max}}^{30} {t_{pulse}}^5}{BDR} = \text{const}$$

- For 200 MV/m structures @ 100 GHz, the pulse length should be limited to <10 ns

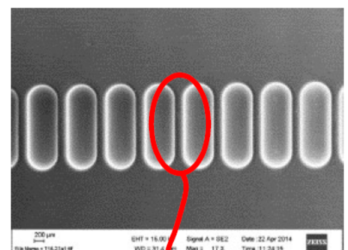
Breakdown rate measurements: travelling wave Cu-Ag 100 GHz structure (Nov 2015)



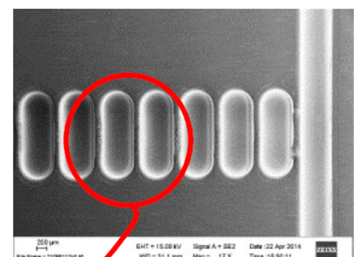
Observation of Damage: travelling wave Cu 100 GHz structure



Input coupler, cells 1-7, no damage

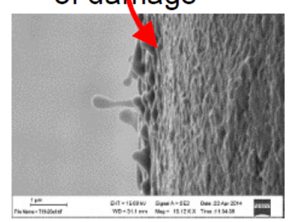


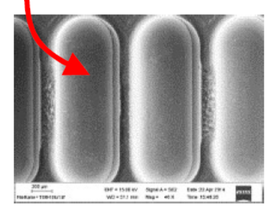
Cells 16-23, fist signs of damage



Output coupler, massive breakdown damage

Acc. gradient 0.3 GV/m
E_{peak} 0.64 GV/m
Pulse Length ~2.3 ns

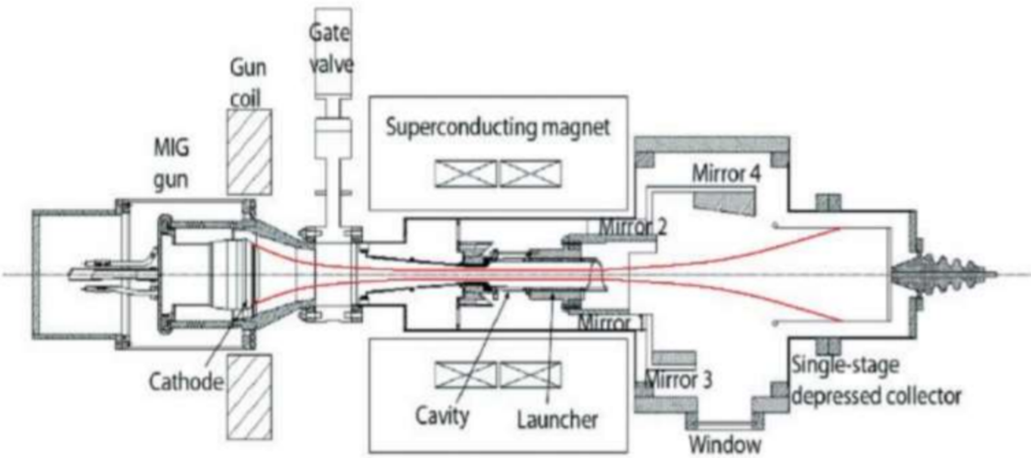




* More details in M. Dal Forno et al., AIP Conference Proceedings 1812, 060011 (2017)

External Power Source

- RF sources limited in mm-wave range
- MIT 1 MW gyrotron oscillator at 110 GHz with up to 3 μs pulses and frequency tunability



* More details in Tax, David S., et al. IEEE Transactions on Plasma Science 41.4 (2013): 862-871.

RadiaBeam role:

1. To develop a switch to reduce the input pulse duration to 1-10 ns level
2. To develop a spectrometer for RFBD detection

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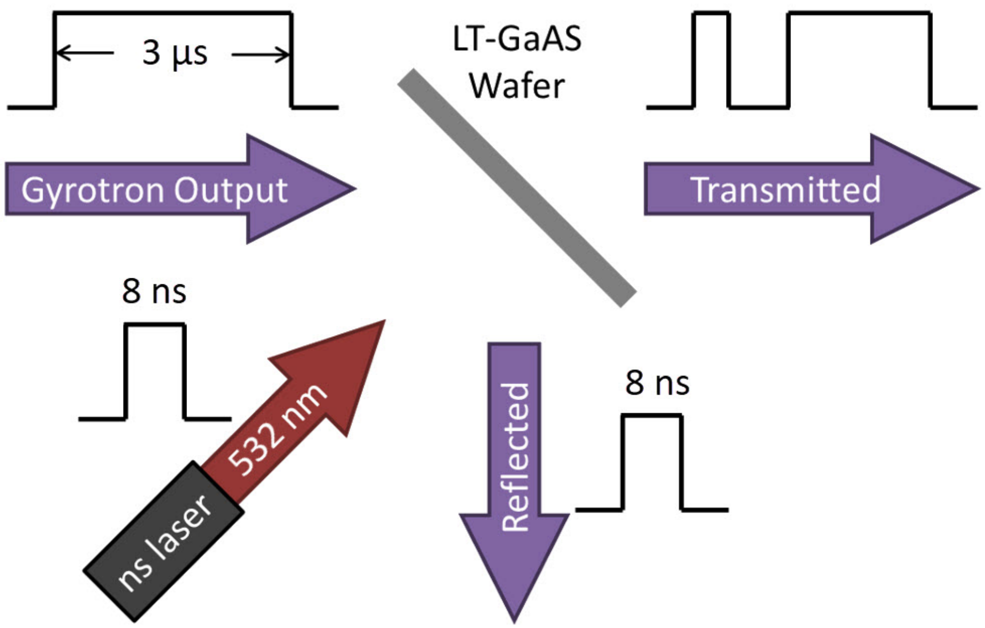
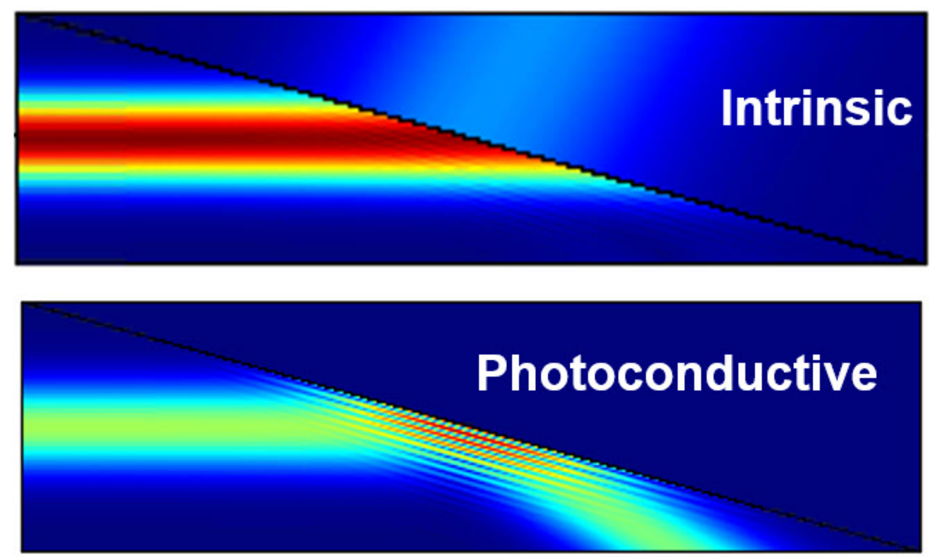
Laser-gated THz Switch

- In order to selectively shorten the long pulse generated by the gyrotron, it is possible to implement light-controlled semiconductor shutters via the photoconductive effect



Brewster angle ~ 74 degrees

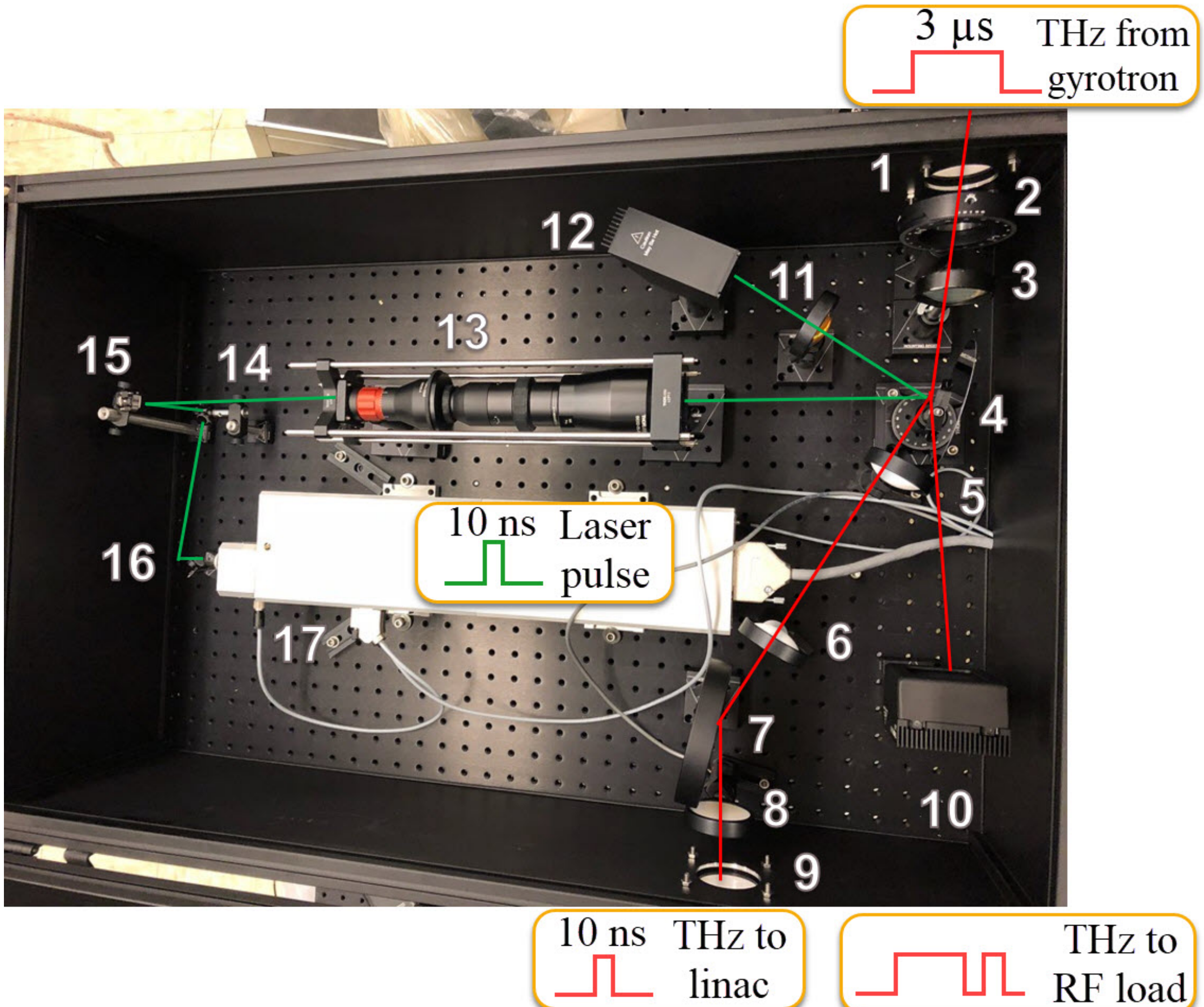


- Drude-Lorentz model analysis indicated 90% threshold for the power reflection coefficient with 532-nm laser at intensity levels of 800 W/cm^2 for Si and by 2 kW/cm^2 for GaAs.

* More details in S. Kutsaev et al., Phys. Rev. Appied 11, 034052 (2019)

THz Switch Design

- THz Switch assembly was developed at RadiaBeam and installed at MIT Plasma Science and Fusion Center (PSFC)



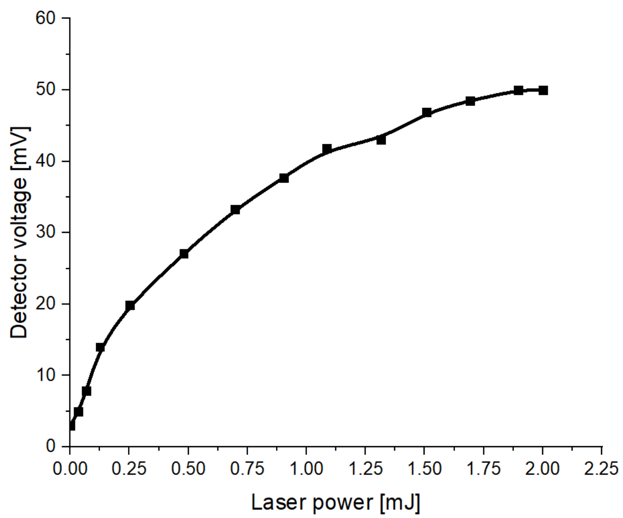
1. Input THz window
2. Polarizer
3. THz lens no. 1
4. Wafer
5. THz lens no. 2
6. THz lens no. 3
7. Mirror
8. THz lens no. 4
9. Output THz window
10. THz load
11. Optical lens
12. Laser dump
13. Beam expander
14. Alignment mirror no. 1
15. Alignment mirror no. 2
16. Alignment mirror no. 3
17. 532 nm laser

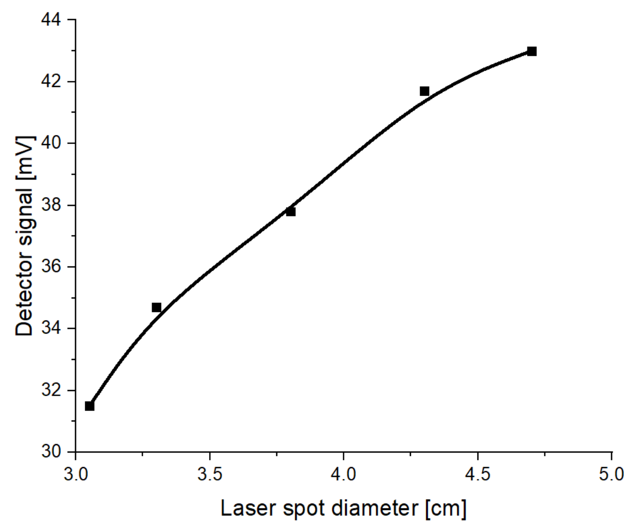
Switch Characterization

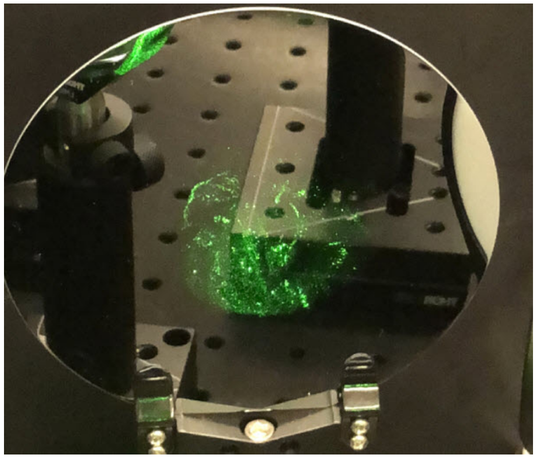
- We measured the losses inside the switch components

Location	Schottky, mV	transmission, %
Power source	220	n/a
Input window	209	95%
Polarizer	182	82%
Lens 1	210	95%
Wafer (Cu)	135	61%
Output window (Si)	50	22%
Output window (Cu)	72	32%

- Transmitted signal as a function of laser parameters
  - Power after expander = 2 mJ



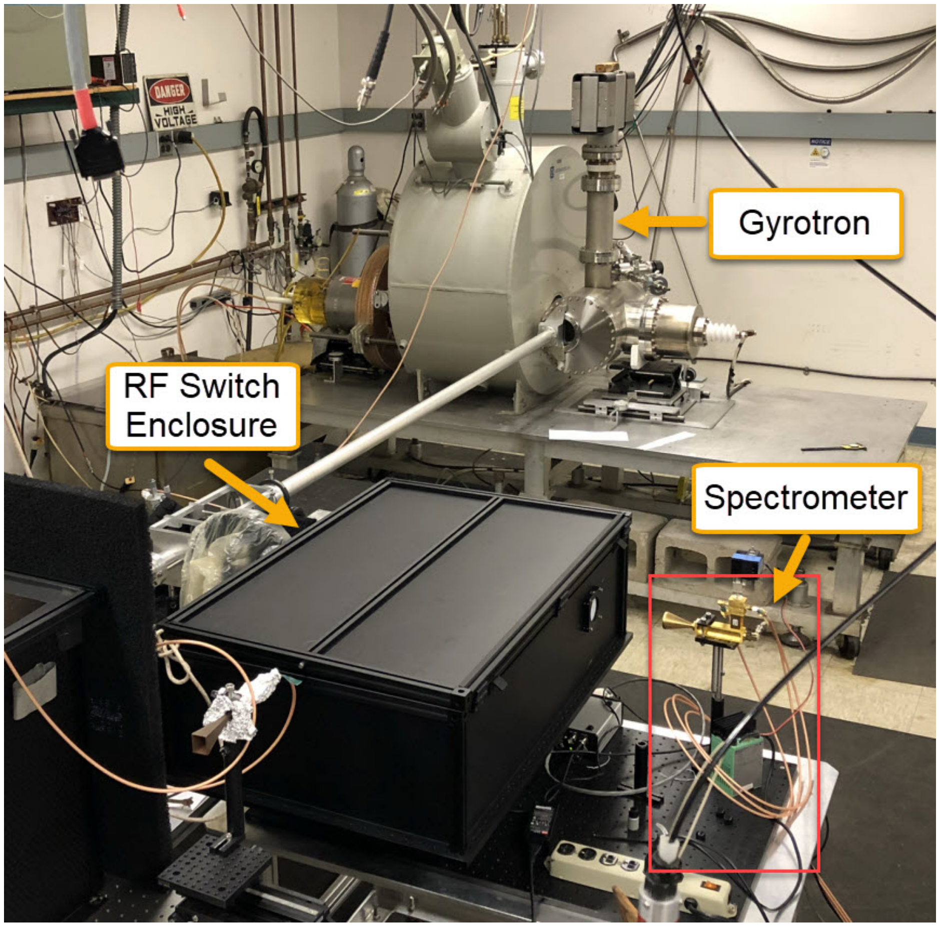


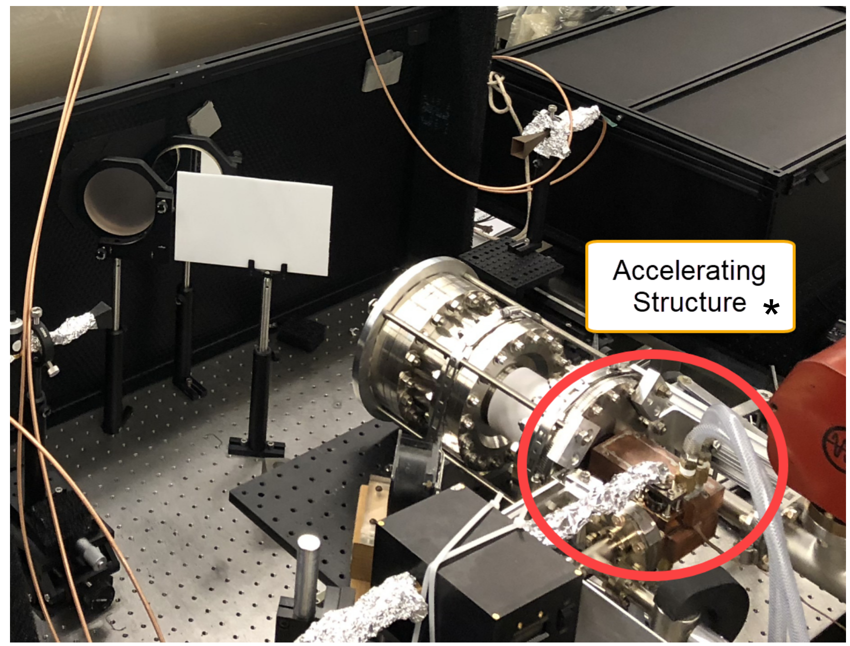


Non- uniform beam density

Experimental Setup

- The spectrometer was installed at MIT to experimentally define its power and time characteristics

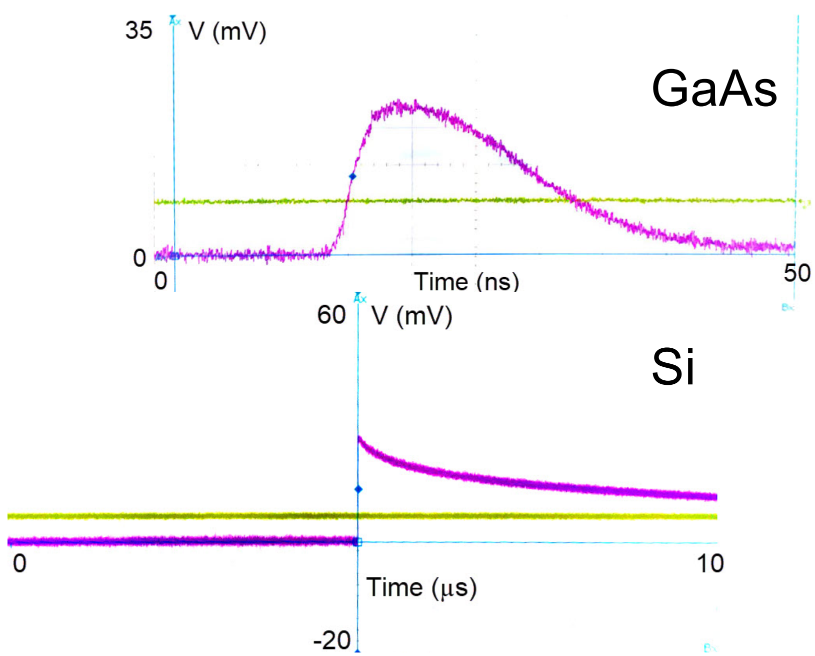


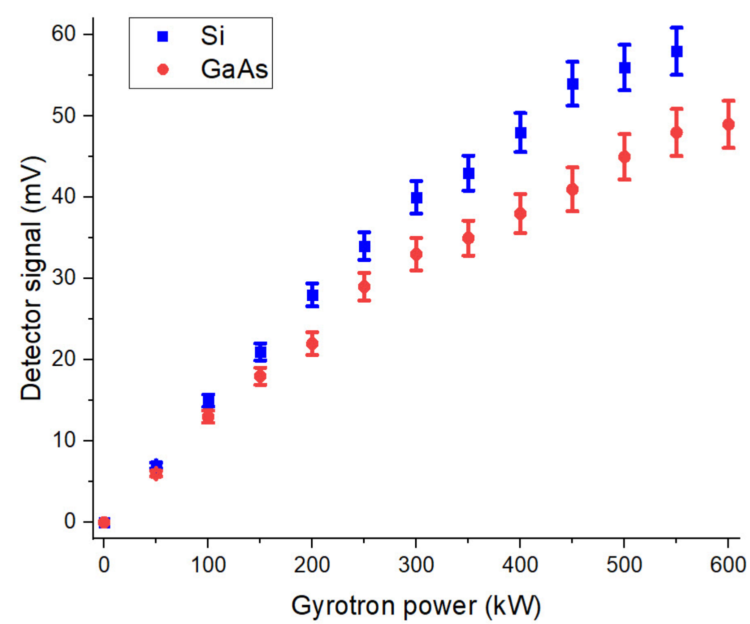


* More details in E. Nanni et al. in Proceedings of 9th International Particle Accelerator Conference, Vancouver, Canada, (2018), p. 1224.

Switch Tests with Gyrotron

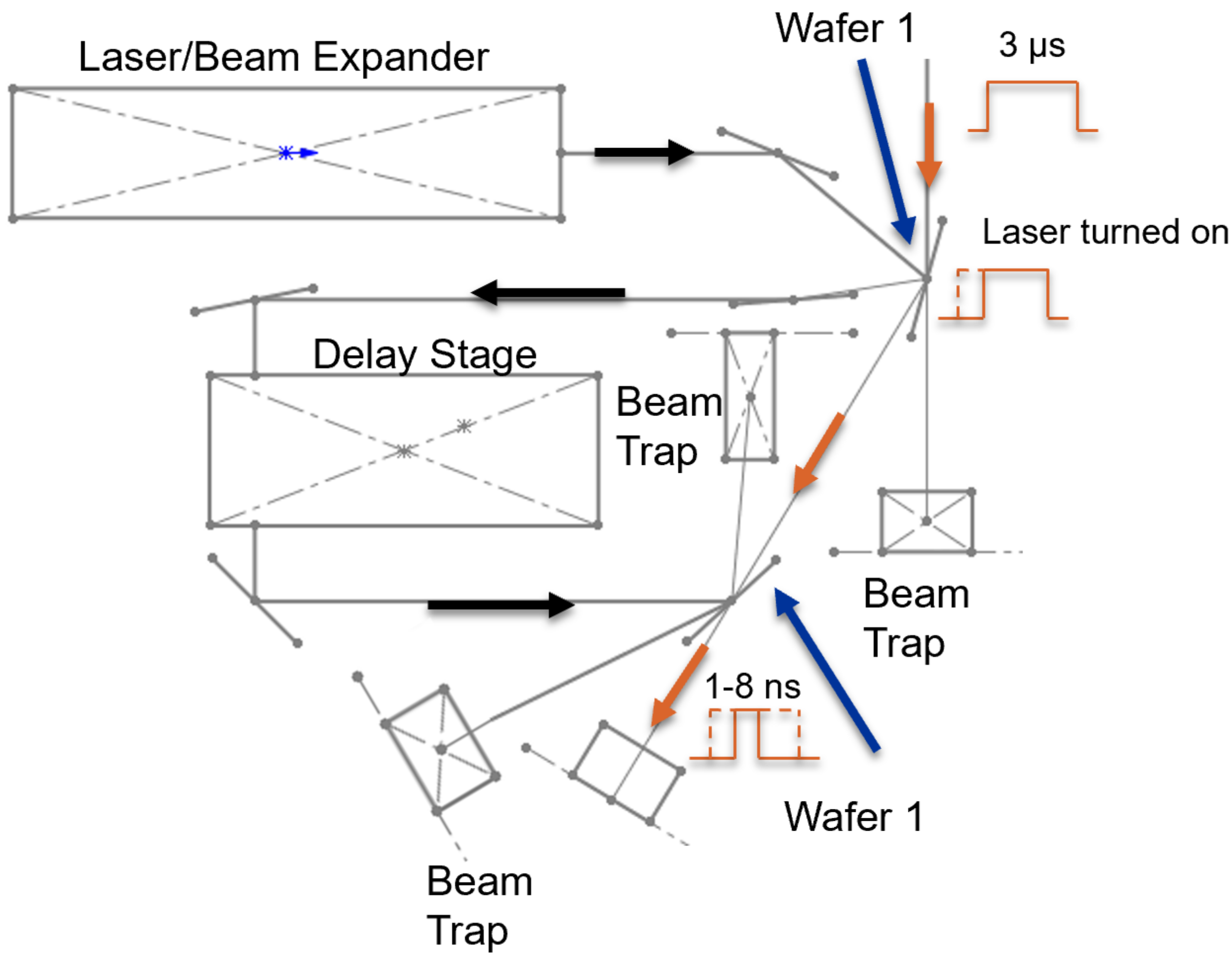
- We increased the power from 0 to 600 kW (max available) and measured the signal with the Schottky detector
  - This power will produce an accelerating gradient above 200 MV/m in a SLAC *W*-band accelerating structure
  - The FWHM of the GaAs reflecting mode is about 12–15 ns, while the FWHM of the silicon is about 6 μs,
  - The rise time of both wafers is about 3 ns.





Variable Pulse Width

- Two silicon wafers (long decay time) will be turned on with an adjustable delay time to vary the pulse length



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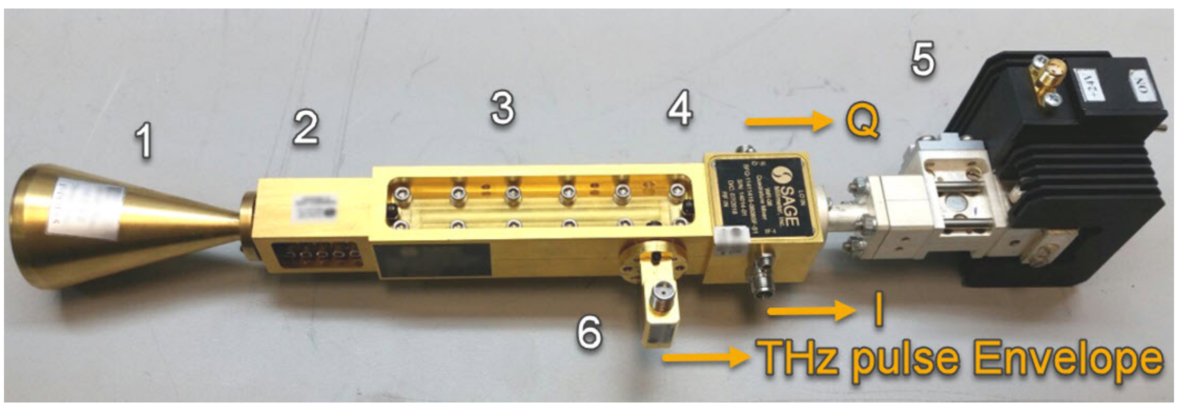
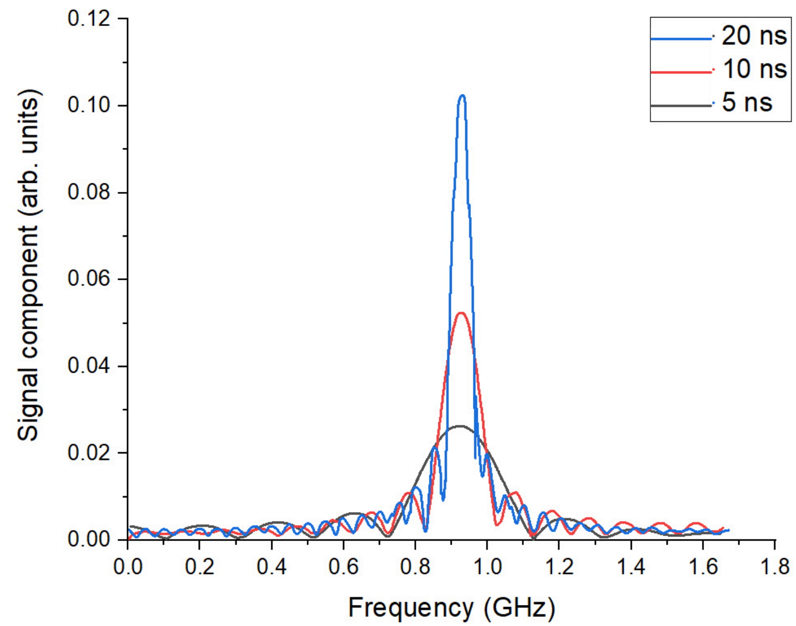
Single-Shot Spectrometer

- With a heterodyne approach, it is possible to down-convert the frequency from 110 GHz to 1 GHz range, digitize and apply FFT decomposition
  - The frequency range is defined as Sampling rate / 2
  - The frequency resolution as 1/Pulse length
- IQ modulation is needed to detect if the signal frequency is lower or higher than LO

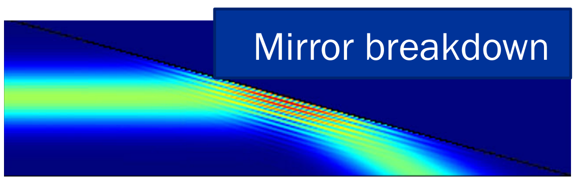


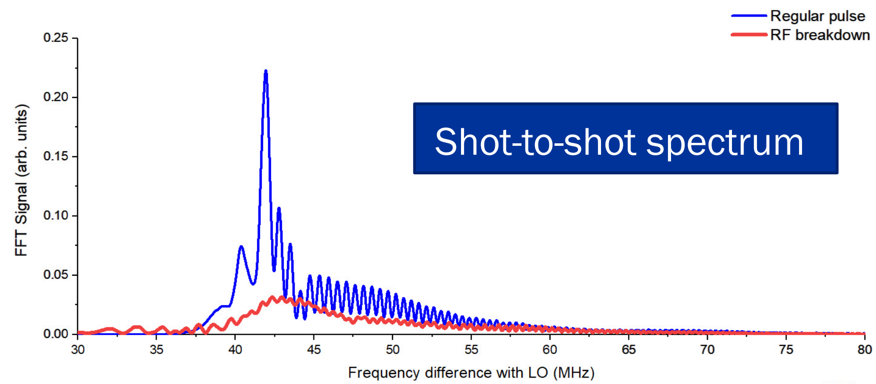
1 – 30-dB horn antenna, 2 – Band-pass filter, 3 – Directional coupler, 4 – IQ-mixer, 5 – Local oscillator, 6 – Schottky amplitude detector.

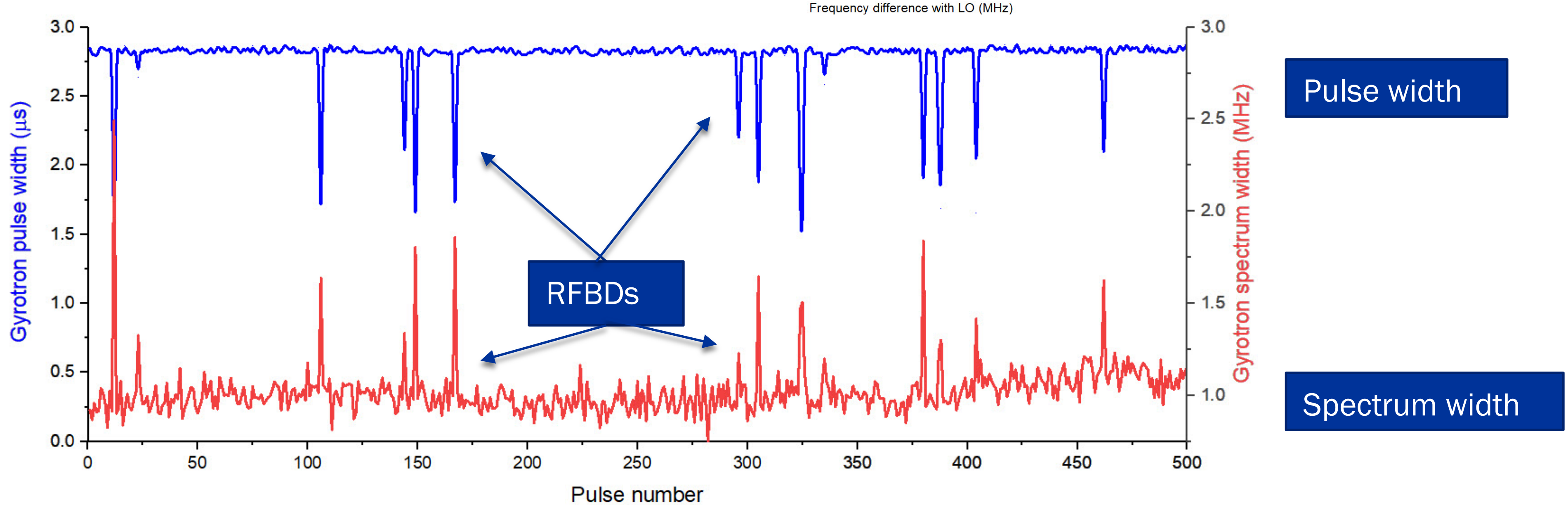


Breakdown Studies

- We have done real-time shot-to-shot measurements over the 10 minutes
  - Pulse width, frequency bandwidth and shot-to-shot spectra are measured

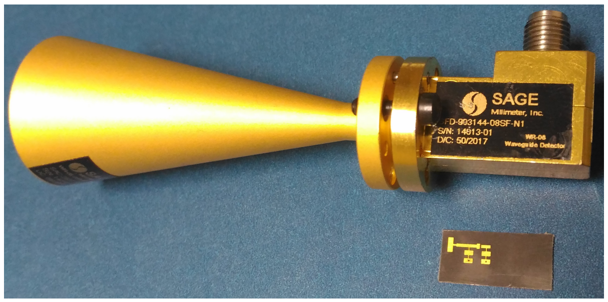


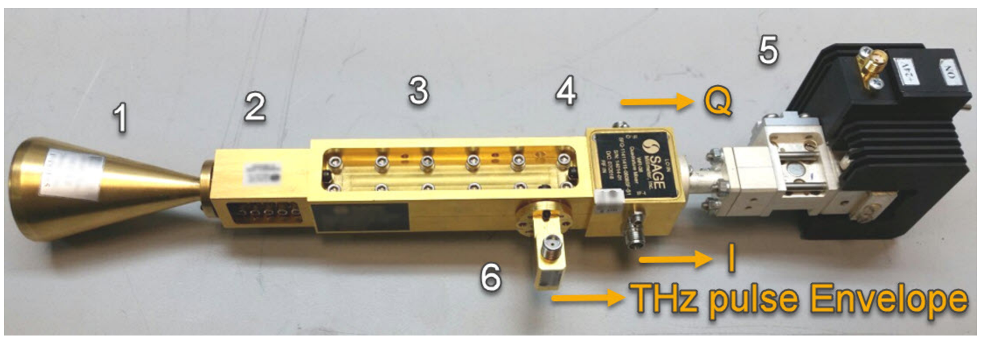


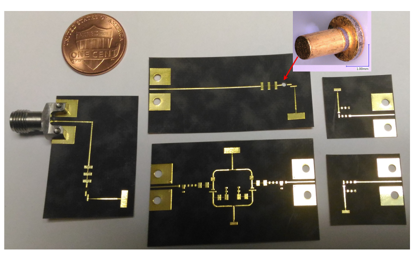


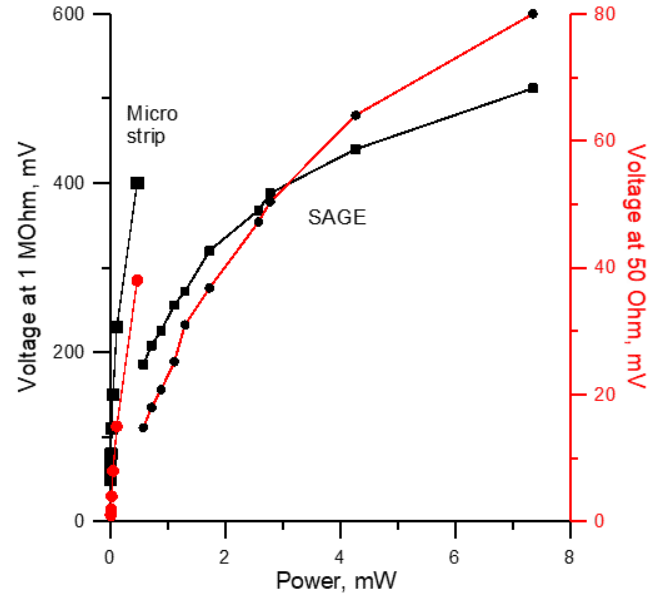
Spectrometer Upgrade

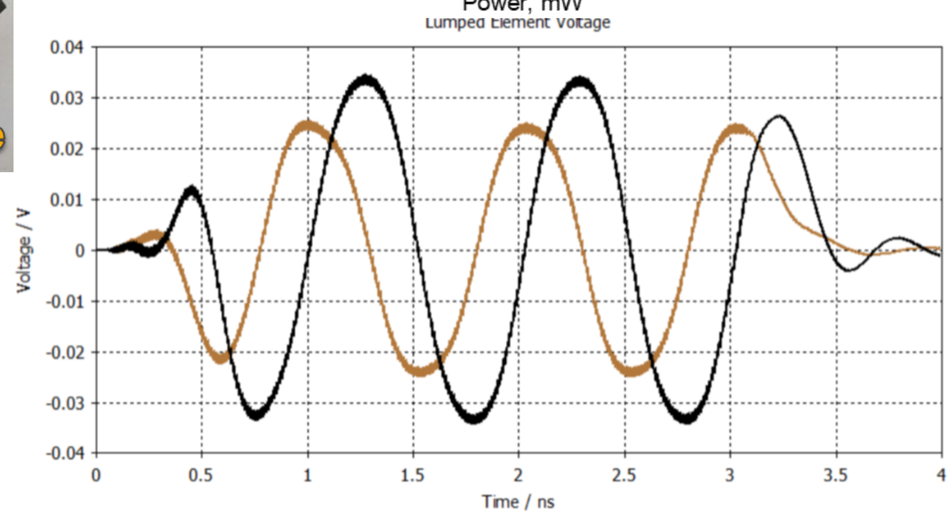
- We will replaced SAGE components with a PCB board with a RadiaBeam-build f/2 source based on anti-parallel diode pair











Next steps

- Complete the development of the 2-wafer variable pulse length switch
- Test, debug and install PCB-based heterodyne downconverter
- Develop real time inexpensive and compact DAQ system (so far we've been reliant on 12 GHz scope for signal readout..)
- Finally, characterize the breakdown dynamics of SLAC structure at MIT

Project Team

- RadiaBeam Systems, LLC
  - Sergey V Kutsaev, Alexander Smirnov, Bryce Jacobson, Marcos Ruelas, Joshua Condori, Dmitriy Shchegolkov, Alex Murokh
- SLAC National Accelerator Laboratory
  - Emilio Nanni, Valery Dolgashev, Massimo Dal Forno
- MIT
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