Massachusetts Institute of Technology

Gyrotron-based High Gradient THz Accelerator Test Facility

Sudheer Jawla, Julian Picard, Jeremy Genoud,

Ivan Mastovsky, Michael Shapiro and Richard Temkin

Plasma Science and Fusion Center, MIT, Cambridge, USA-02139

Massachusetts Institute of Technology

Outline

- Motivation
- Experimental Setup
  - 1 MW 110 GHz Gyrotron
  - Nanosecond Timescale Pulse Generation
- High Gradient Accelerator structure Testing
- Future Developments

Outline

Massachusetts Institute of Technology

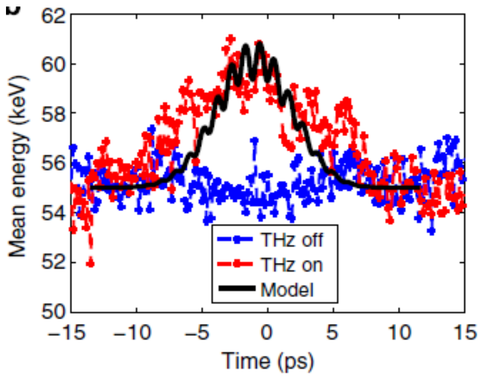
- Motivation
- Experimental Setup
  - 1 MW 110 GHz Gyrotron
  - Nanosecond Timescale Pulse Generation
- High Gradient Accelerator structure Testing
- Future Developments

Massachusetts Institute of Technology

Laser based THz Accelerators

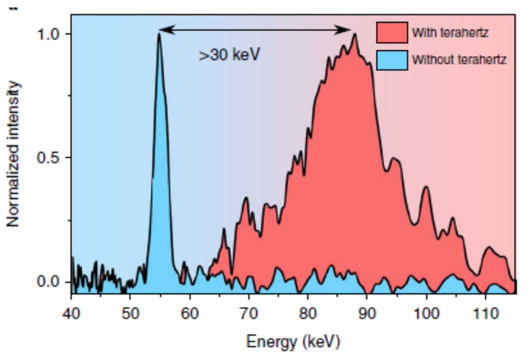
- GeV/m acceleration is achievable at THz frequencies
  - Shunt impedance $\propto f^{1/2}$, filling time $\propto f^{-3/2}$
- THz is generated by optical techniques using complex laser systems
- Pulse energy used in present experiments is limited to few tens of μJ

Nanni et al, Nat. Comm. 2015



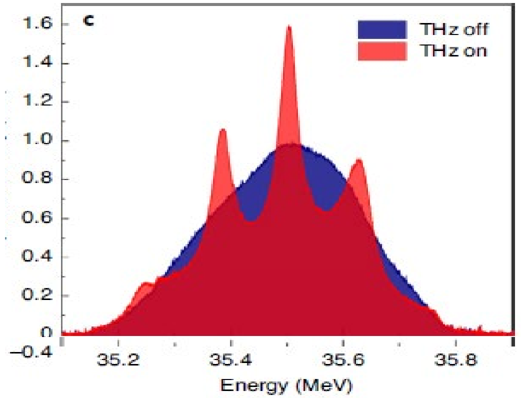
2.5MeV/m 0.45 THz, **10 μJ, 2.2 ps**
Pump: 1.5-mJ, 1.03 mm, 1 kHz

Zhang et al, Nat. Photonics, 2018



70MeV/m, 0.3 THz, **2 x 6 μJ**
Pump: 40 mJ, 1.1ps, 1.02 mm, 10 Hz

Hibberd et al, Nat. Photonics, 2020



2MeV/m, 0.4 THz, **2.1 μJ, 2 ps**

Other works use similar energy levels

Laser based THz Accelerators

- Higher gradient accelerators will require THz pulses at
  - Higher power
  - short timescales of *ps* to *ns* long
  - high repetition rates
- Difficult to achieve high pulse energy at high repetition rates using optical techniques
- Laser based THz pulse generation system has
  - Low wall plug efficiency << 1%
  - Cost per average power is high
- Very useful advance for specialized applications at low average power

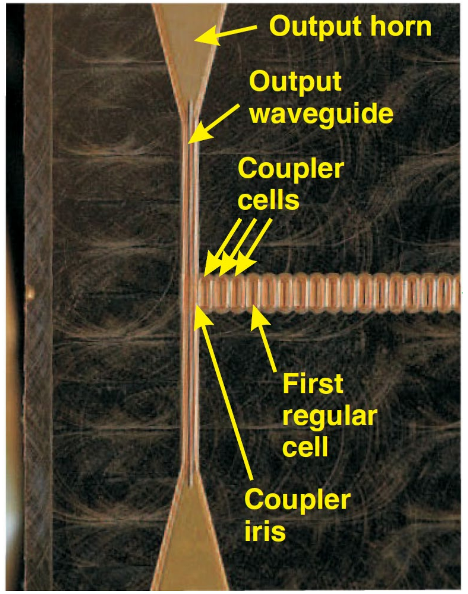
Massachusetts Institute of Technology

THz Wakefield Accelerators (FACET)

- Beam driven 200 GHz all metallic structure @ FACET
  - peak surface electric field 500 MV/m
  - rf pulse length of 0.3 ns
  - accelerating gradient of 56 MV/m
- RF fields excited by the FACET ultrarelativistic electron beam @20 GeV, 1 -15 Hz rep rate

- Beam driven system has
  - Very low wall plug efficiency
  - Cost per average power is very high
  - Breakdown performance is influenced by driving beam

Picture of the 200 GHz copper accelerating structure



Dal Forno, Massimo, et al. PRAB 19.1 (2016): 011301

Advantages of Gyrotron based Accelerator system

- Gyrotrons can produce very high average power
  - CW power up to 1 MW at frequencies to 250 GHz
  - Pulsed gyrotron up to 670 GHz
  - Modest beam power requirements < 100kV, < 50A
- High wall plug efficiency, typical 35%, >50% can be achieved
- Cost per average power relatively low
- Short pulses can be generated from an oscillator using a switch or directly in an amplifier
- THz power could be transported/distributed using low loss corrugated waveguides and quasi-optical systems

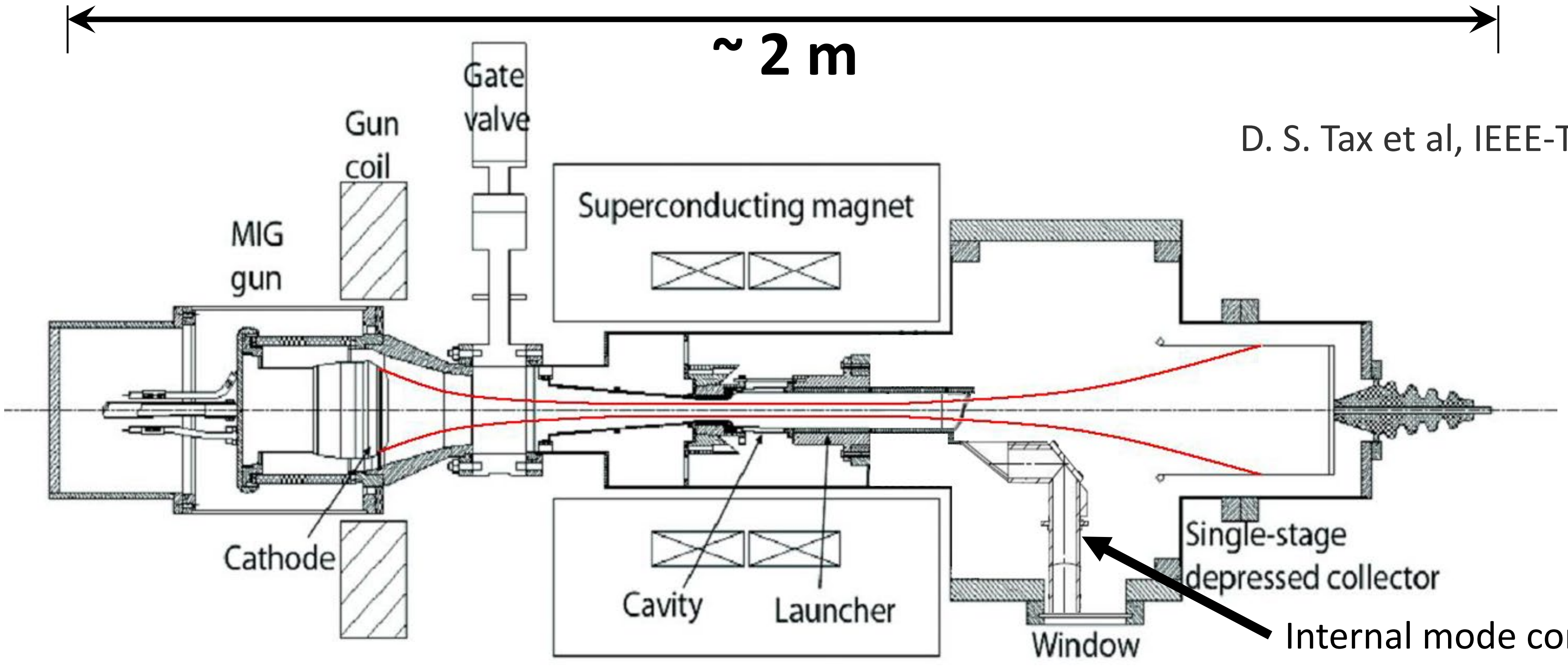
Outline

Massachusetts Institute of Technology

- Motivation
- Experimental Setup
  - 1 MW 110 GHz Gyrotron
  - Nanosecond Timescale Pulse Generation
- High Gradient Accelerator structure Testing
- Future Developments

Megawatt 110 GHz Gyrotron at MIT

Massachusetts Institute of Technology

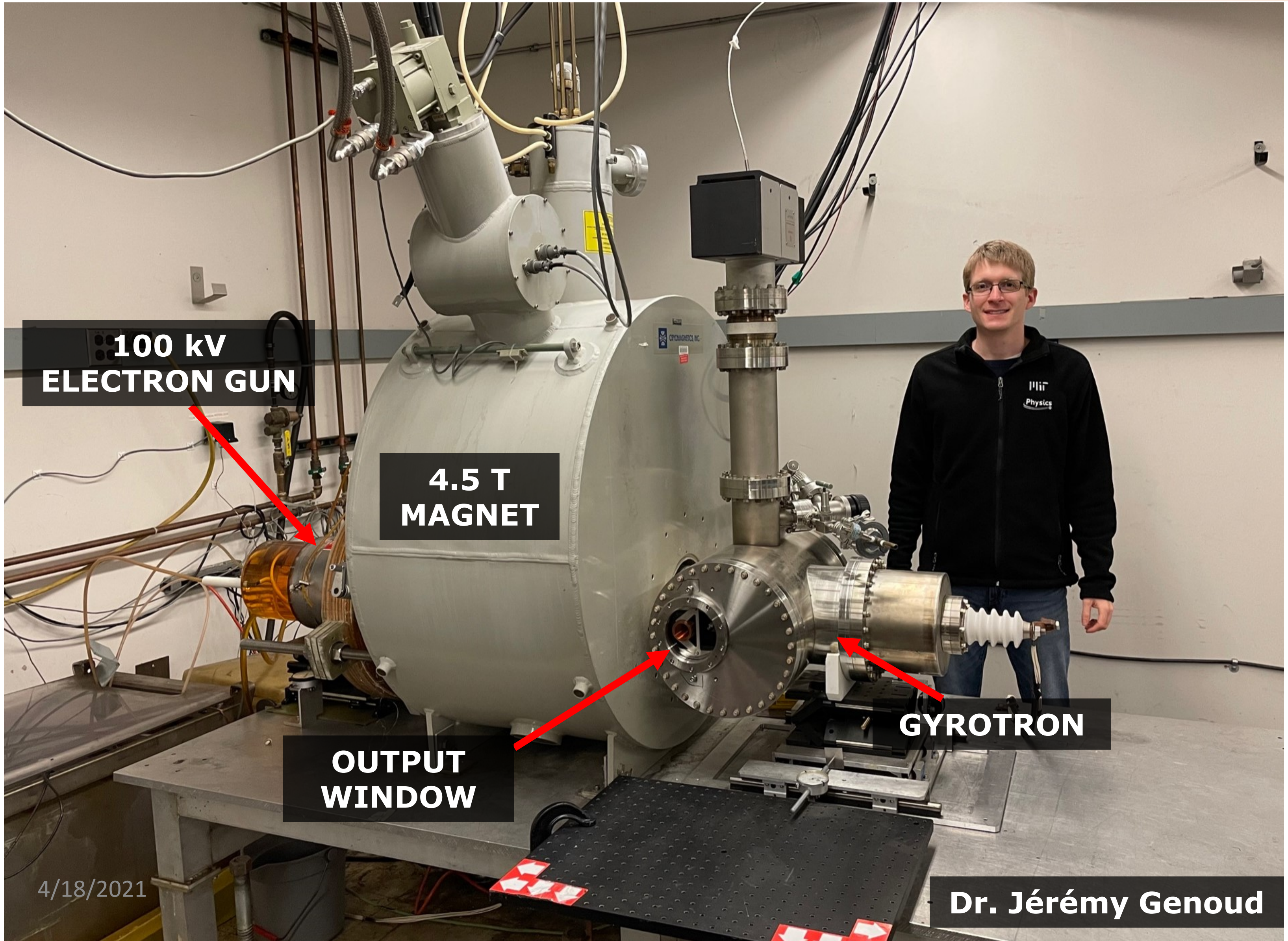


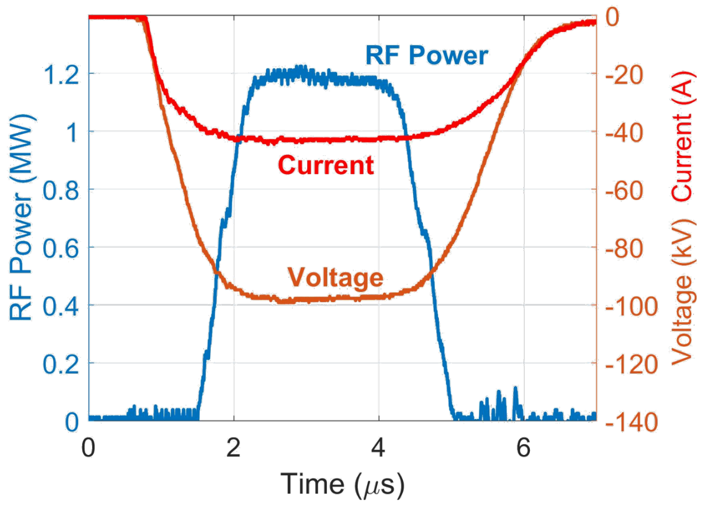
D. S. Tax et al, IEEE-TPS, 2014

J. Neilson, *et al.*, IEEE T-ED 2018

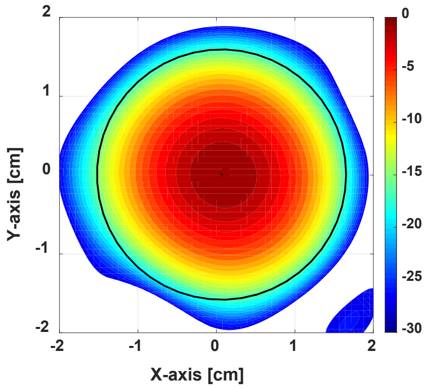
- Frequency = 110 GHz
- Power = 1.25 MW
- Voltage = 96 kV
- Current = 40 A
- Operating mode: $TE_{22,6}$
- Pulse length = 3 μs
- B = 4.4 T
- α= 1.4

Megawatt 110 GHz Gyrotron at MIT



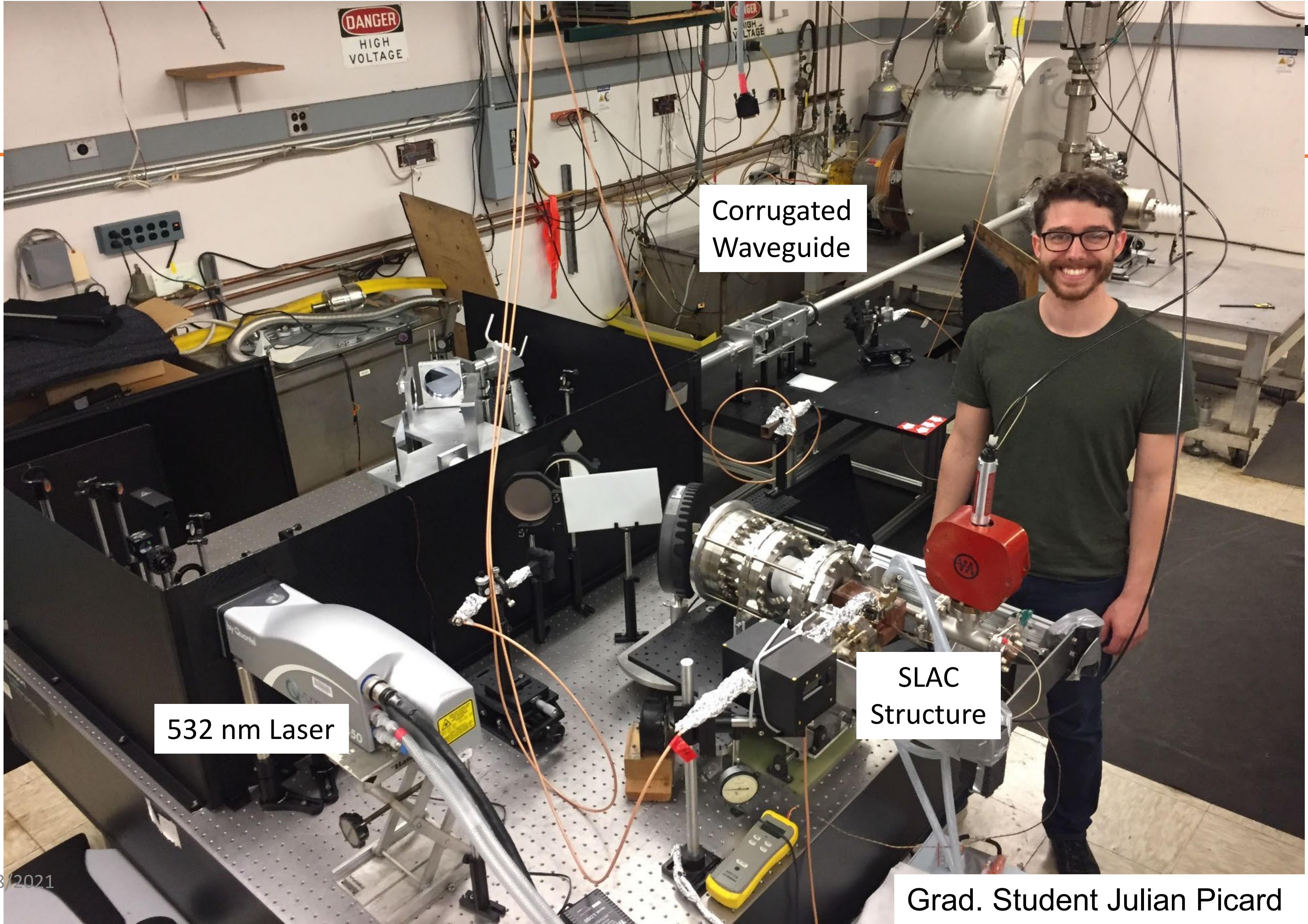


Corrugated Waveguide Output



97.5% HE_{11} mode

Massachusetts Institute of Technology



Outline

Massachusetts Institute of Technology

- Motivation
- Experimental Setup
  - 1 MW 110 GHz Gyrotron
  - Nanosecond Timescale Pulse Generation
- High Gradient Accelerator structure Testing
- Future Developments

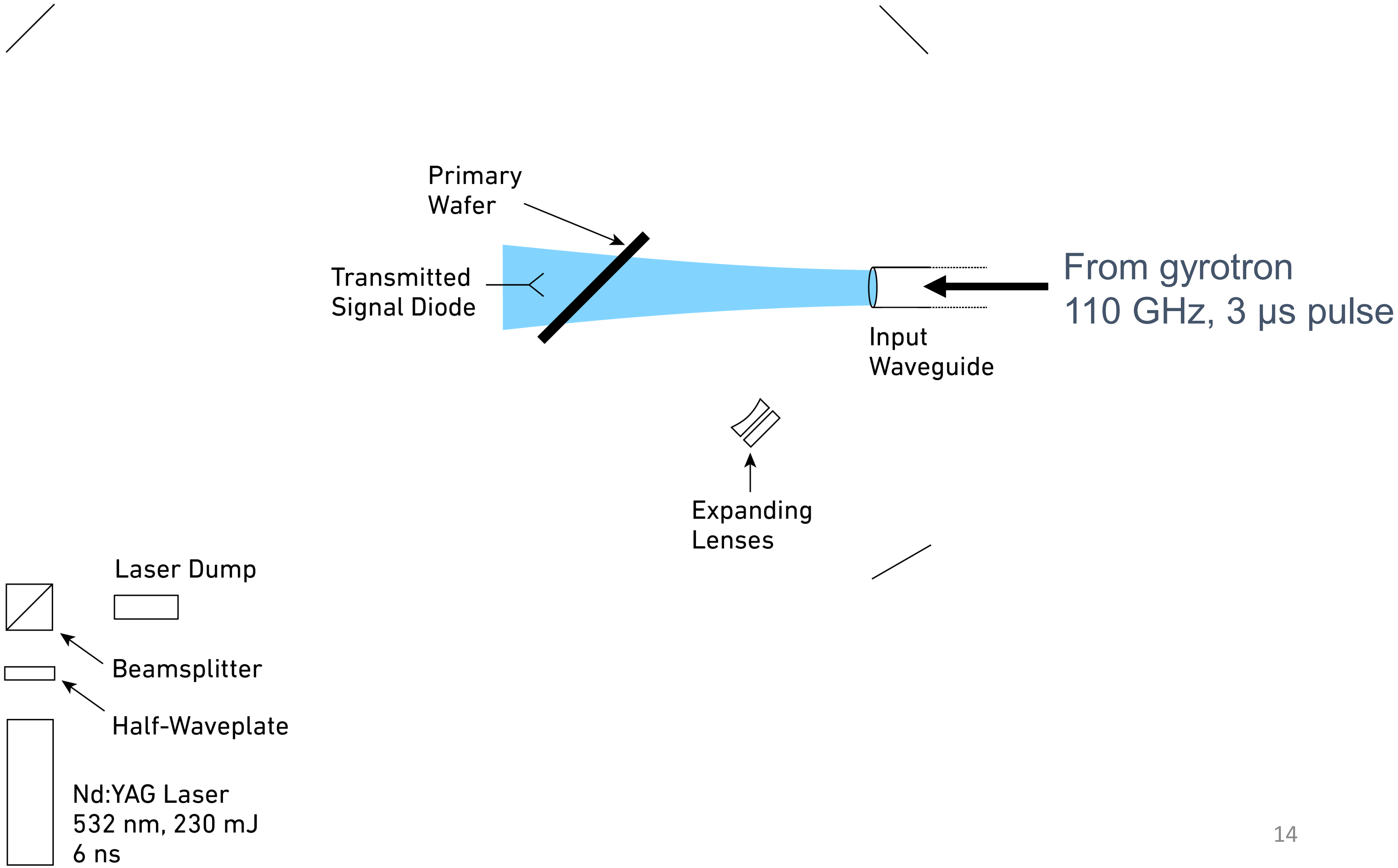
Laser-Driven Semiconductor Switch

Massachusetts Institute of Technology

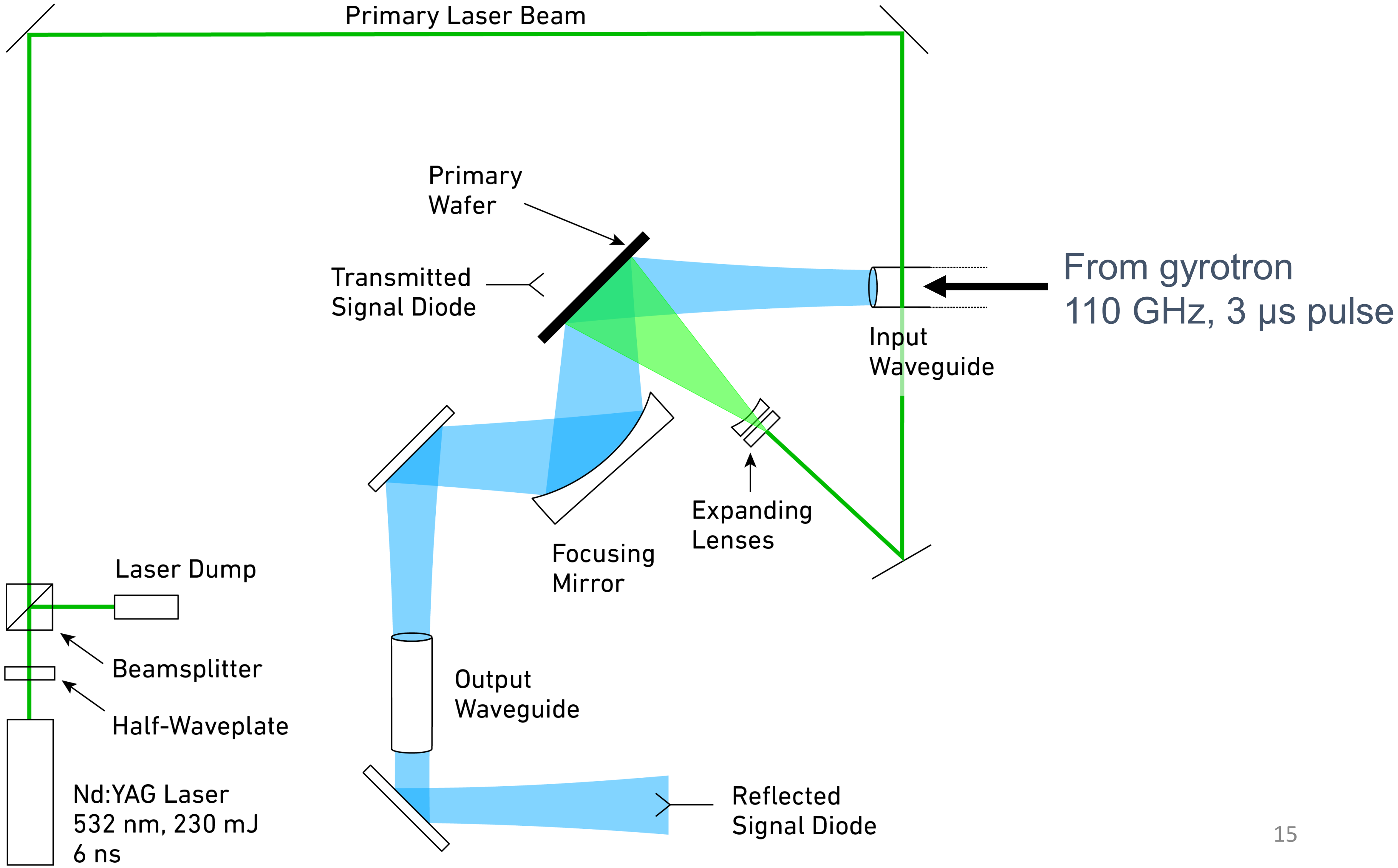
- Reflects RF from a CW or long-pulse source by inducing temporary reflectance in semiconductor wafer
- Reflectance induced with a laser where $E_{photon} > E_{bandgap}$ that generates an electron-hole plasma in the wafer
- Pioneering work done in the 1970s, behavior well characterized at low power levels
- Never previously demonstrated above kW power level.

Laser-Driven Semiconductor Switch

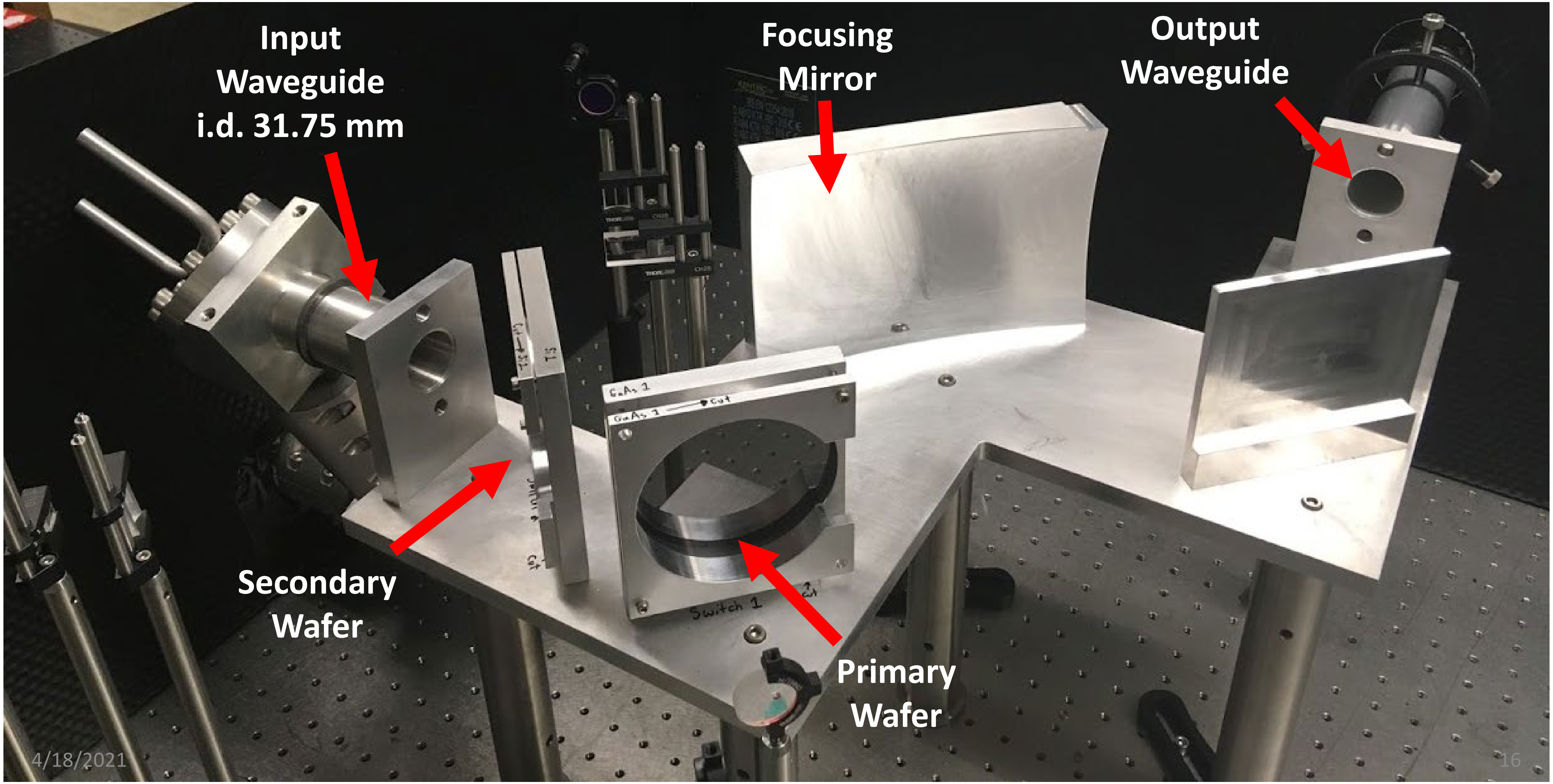
Massachusetts Institute of Technology



Laser-Driven Semiconductor Switch



Experimental Setup



Output Pulses

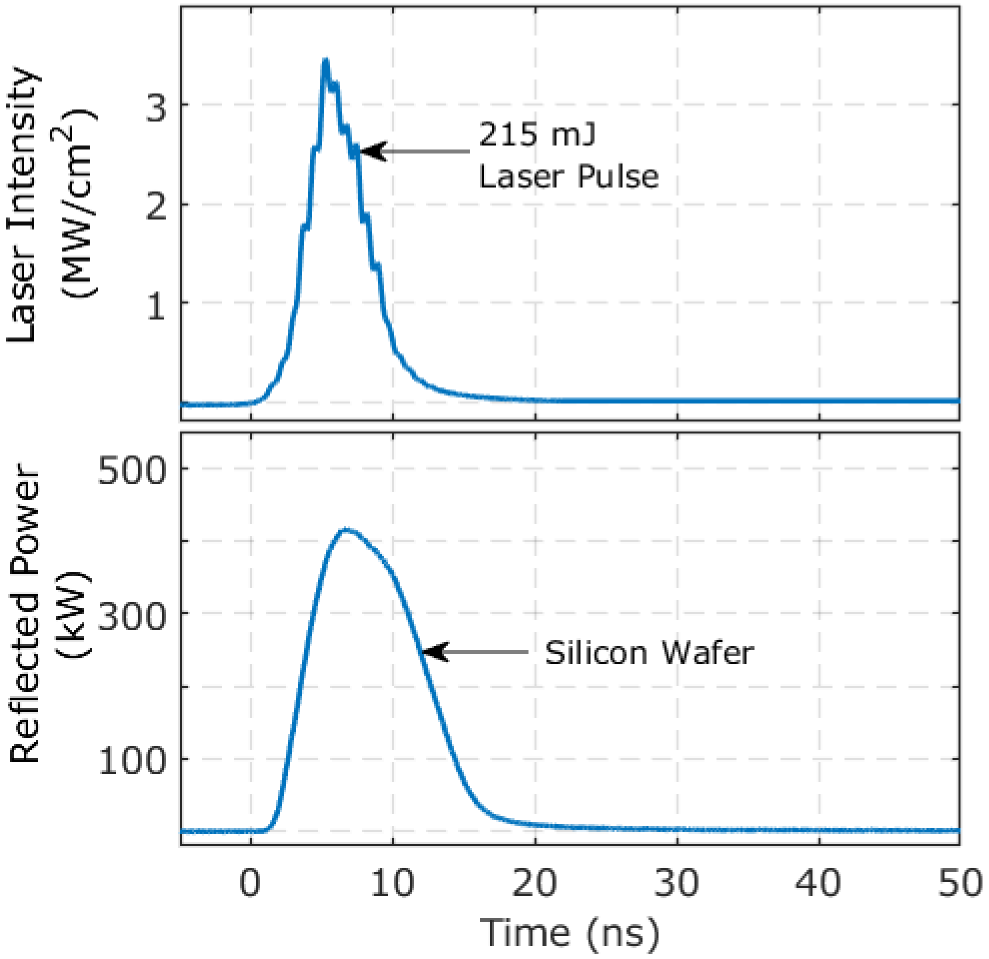
- Input laser pulse

  Laser: 215 mJ @ 6 ns

  peak intensity at wafer 3.5 MW/cm^2,

  energy density 15.3 mJ/cm^2

- Incident gyrotron pulse 525 kW @ 3 us
- Output pulse 410 kW @ 9 ns



Results published: Picard, et al., Appl. Phys. Lett., 2019

Outline

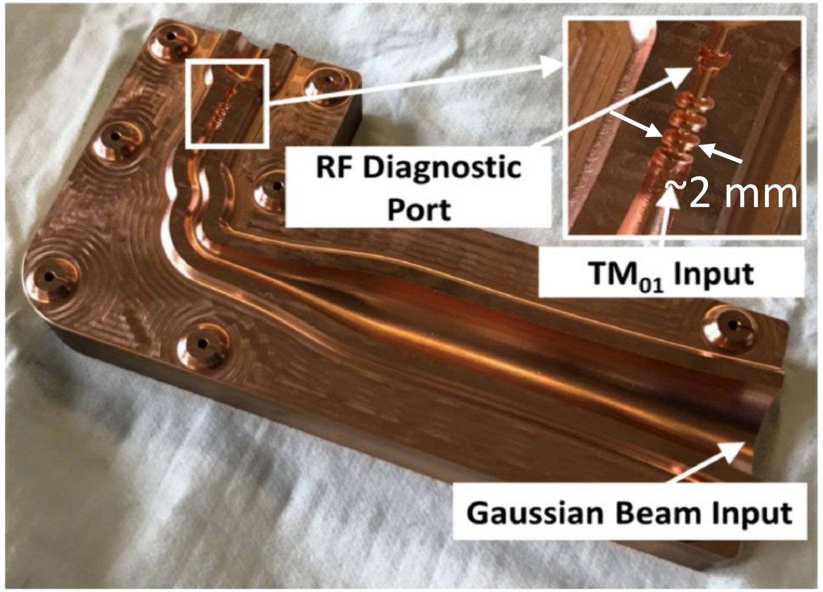
Massachusetts Institute of Technology

- Motivation
- Experimental Setup
  - 1 MW 110 GHz Gyrotron
  - Nanosecond Timescale Pulse Generation
- High Gradient Accelerator structure Testing
- Future Developments

SLAC Accelerator Structure Testing

Accelerating structure built by SLAC was tested

- Input gyrotron power @ 570 kW in 10 ns pulses
- Total number of pulses 1.5×10^5 @1Hz
- Accelerating gradient achieved 230 MV/m.
- Peak surface electric field 0.52 GV/m.
- More details in M. Othman's talk tomorrow
- Another SLAC structure will be tested soon



Picture from : E. Nanni, AAC Workshop 2018

Othman, et. al. Appl. Phys. Lett., 2020.

First demonstration of a HGA structure testing using a MW gyrotron at 110 GHz.

Outline

- Motivation
- Experimental Setup
  - 1 MW 110 GHz Gyrotron
  - Nanosecond Timescale Pulse Generation
- High Gradient Accelerator structure Testing
- **Future Developments**

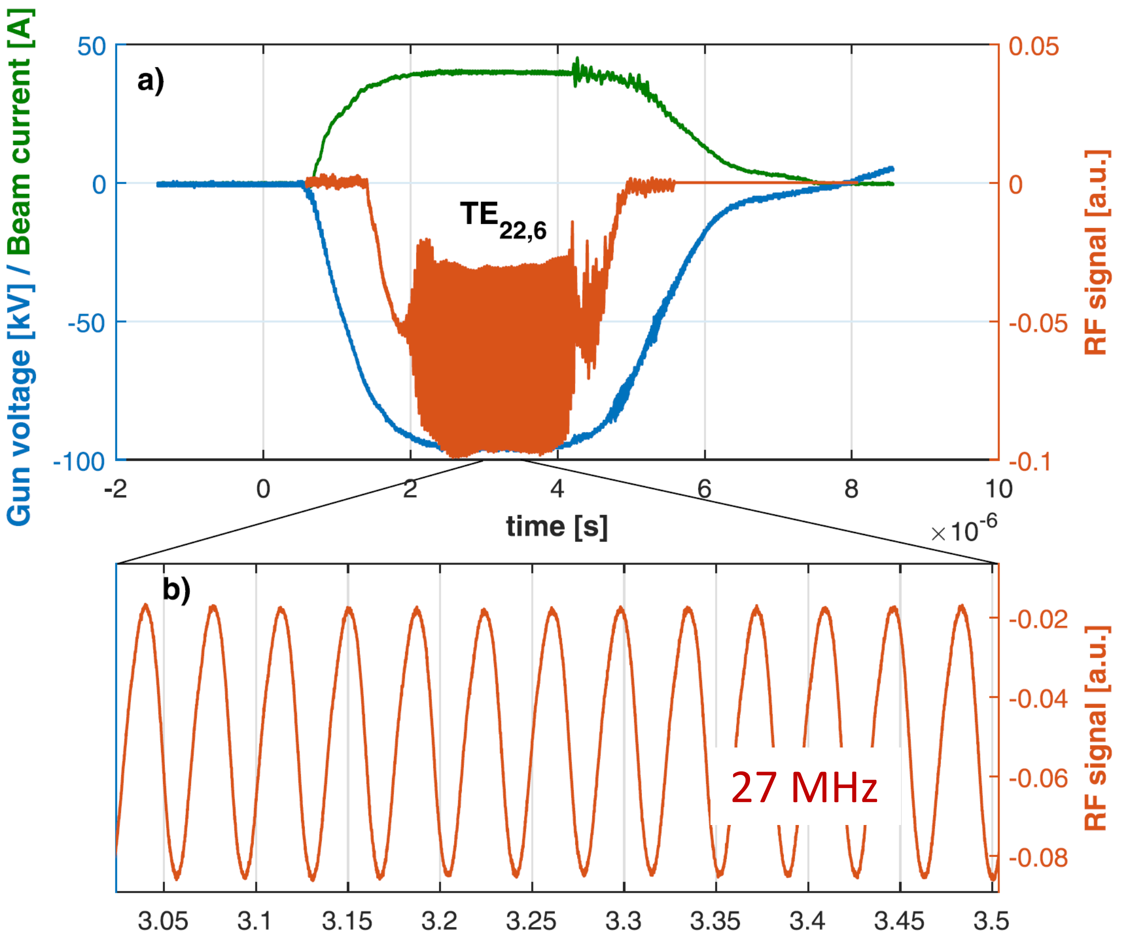
Future developments

- Gyrotron oscillators
  - High rep rate operation
  - Pulse compression
- Gyroamplifiers
  - Higher power
  - Phase manipulation

High rep rate operation by Self-modulation

- Gyrotron power can be modulated by reflection
- Stable operation in self-modulated regime
  - Controlled reflection @~ 21%
  - 27 MHz modulation -> 37 ns pulse
  - Output power 300 kW
- Operating mode $TE_{22,6}$ is maintained

Genoud, et. al, *Journal of Infrared, Millimeter, and Terahertz Waves*, Jan, 2021.

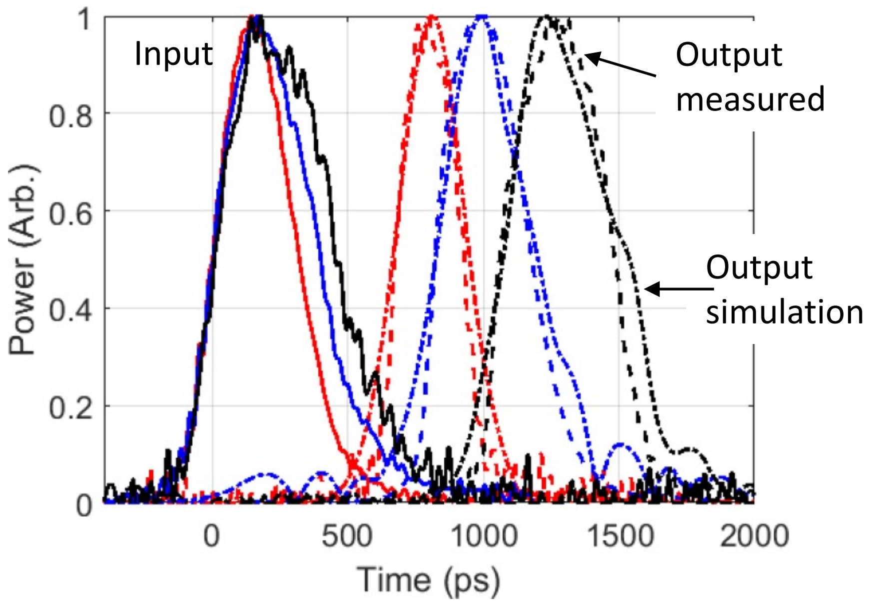


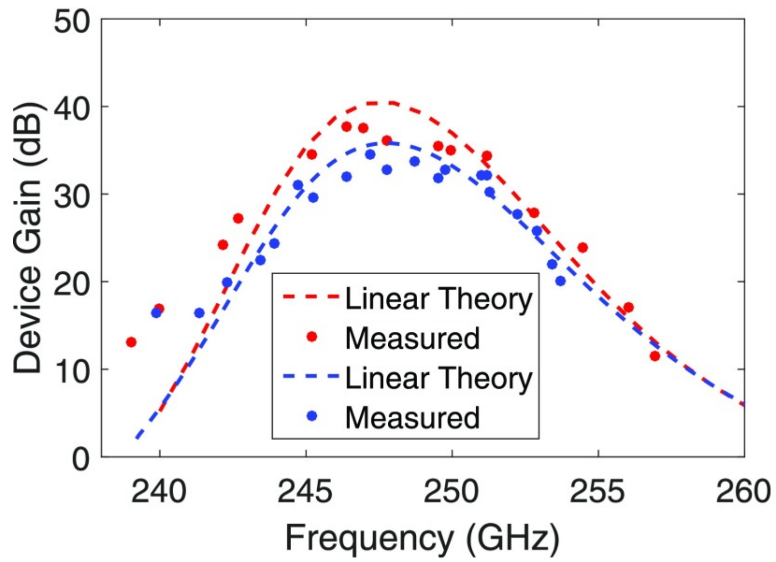
Gyroamplifier for Accelerators

Massachusetts Institute of Technology

Gyroamplifiers can directly produce ps pulses at 250 GHz

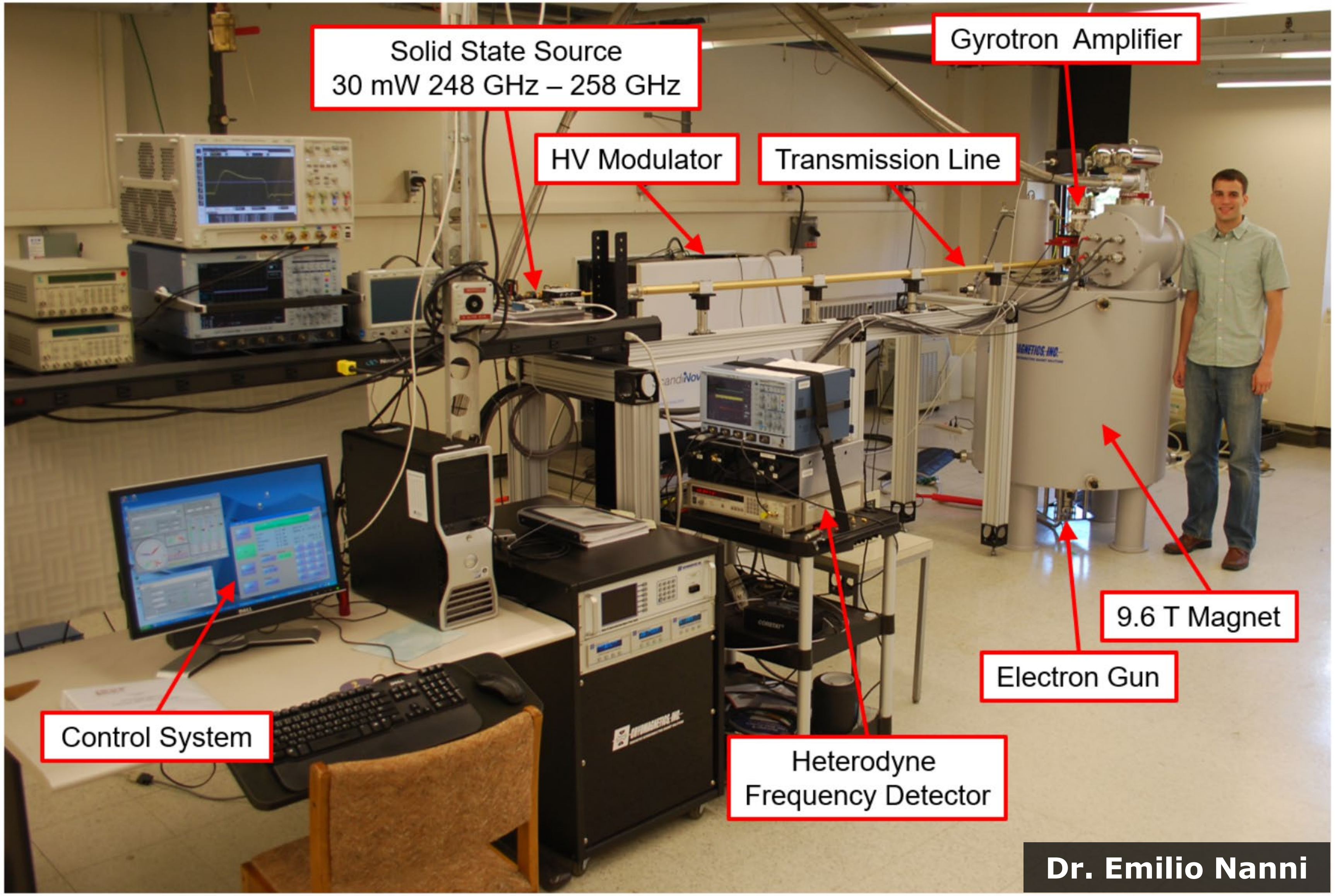
- 250 ps long pulse amplified without distortion
- 23 kV, 700 mA electron beam
- 40 dB device gain, 50 W peak power
- Limited by input drive power ~7 mW
- Higher power can be achieved by increasing the input drive power and optimized circuit





Nanni et. al. APL, 2017

Gyroamplifier for Accelerators



Summary

- Gyrotrons can produce ns pulses at high peak power.
- First demonstration of a gyrotron based THz Accelerator.
  - Second accelerator structure will be tested soon.
- Possible future developments
  - High rep rate operation
  - Pulse compression
  - Gyroamplifiers

A gyrotron based facility looks very promising for high gradient THz accelerators.

Acknowledgements

Massachusetts Institute of Technology

Collaborators

SLAC

U.S. DEPARTMENT OF ENERGY | Office of Science