High Frequency Microwave Research for Advanced Accelerator Applications

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Outline

- **Motivation**
- Recent Progress
- Future Plans
- Centers of Excellence
- Conclusions

Motivation: Why High Frequency Microwaves?

High frequency microwaves can extend the energy reach of linear colliders

- **Advantages of High Frequency Microwaves:**
  - Accelerator size is reduced.
  - Energy stored in the accelerator structure decreases with frequency ω.
  - Higher gradient possible
    - Gradient limit due to dark current capture increases with ω.
    - What is the ultimate limit?
- **High Luminosity requires high average power sources**
  - Highest frequency considered for the near future is 100 GHz.
- **Issues of High Frequency Microwaves:**
  - Smaller structures hard to build
  - Microwave sources and components need development
  - Wakefields increase with frequency as ω^3

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- Motivation
- **Recent Progress at MIT**
  - **MIT 17 GHz Accelerator Laboratory**
  - **High Gradient Research at 17 GHz**
  - **Photonic Bandgap Structure Research**
- Other Recent Progress
- Future Plans
- Centers of Excellence
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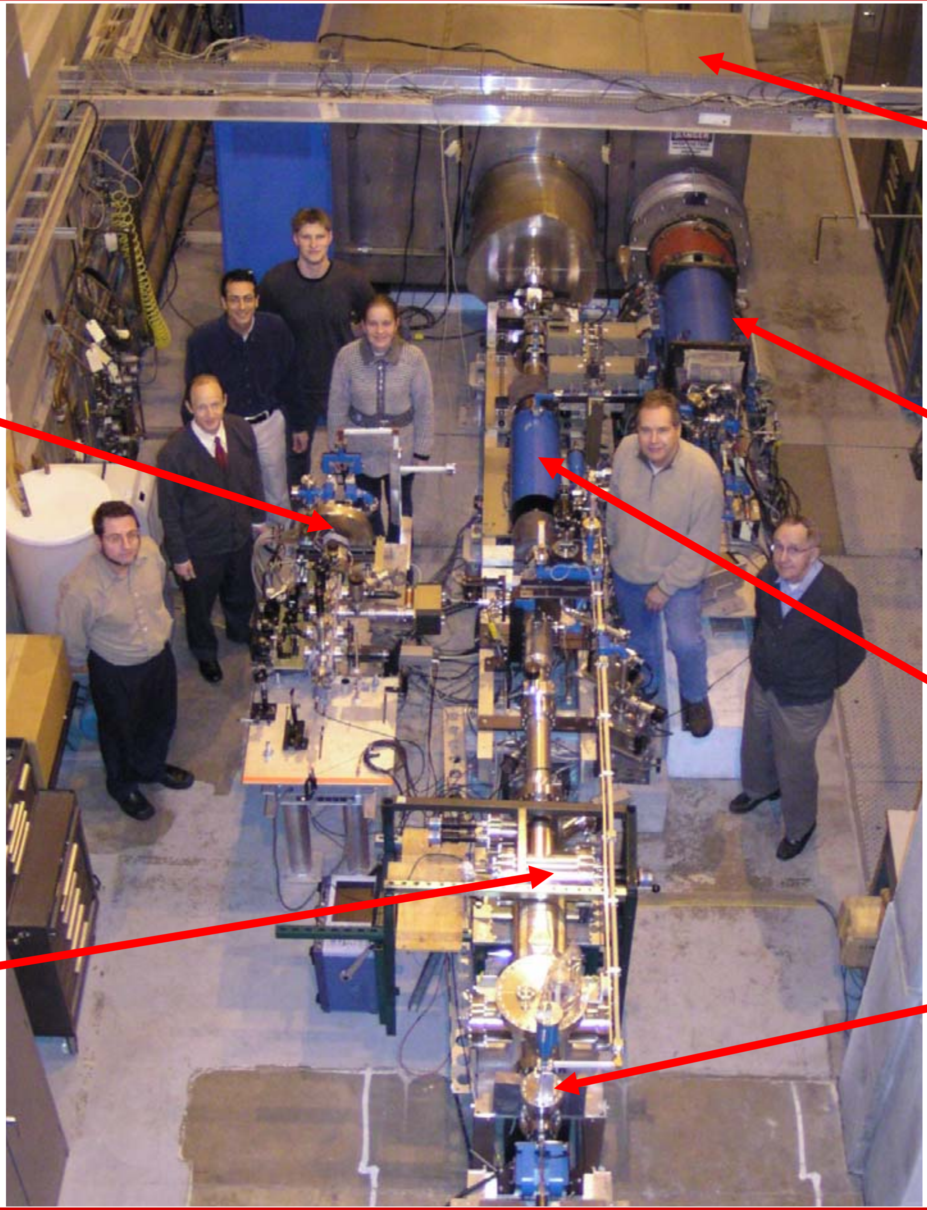
17 GHz Accelerator Laboratory at MIT



RF Break-down / RF Gun Test Stand

THz Smith-Purcell Expt.

Modulator
700 kV, 780A
1 μs flattop

Klystron 25 MW
@ 17.14 GHz

25 MeV Linac
0.5 m, 94 cells

Novel High Gradient Structure / Photonic Bandgap Test Stand

MIT 17 GHz 25 MeV Accelerator

- **Highest frequency stand-alone accelerator in the world.**
- **Can be (and is) operated by a single grad student.**
- **Research Program:**
  - **Investigation of Novel Structures with reduced wakefields**
  - **Diagnostics of femtosecond electron bunches**
  - **Studies of RF Breakdown**
  - **Demonstration of High Gradient Acceleration (> 50 MeV/m)**
  - **High gain (71 dB), 25 MW 17 GHz klystron**
- **Proposed activities as part of the US High Gradient Accelerator Collaboration**
- **Collaboration with Haimson Research Corp.**

MAJOR OPERATING PARAMETERS

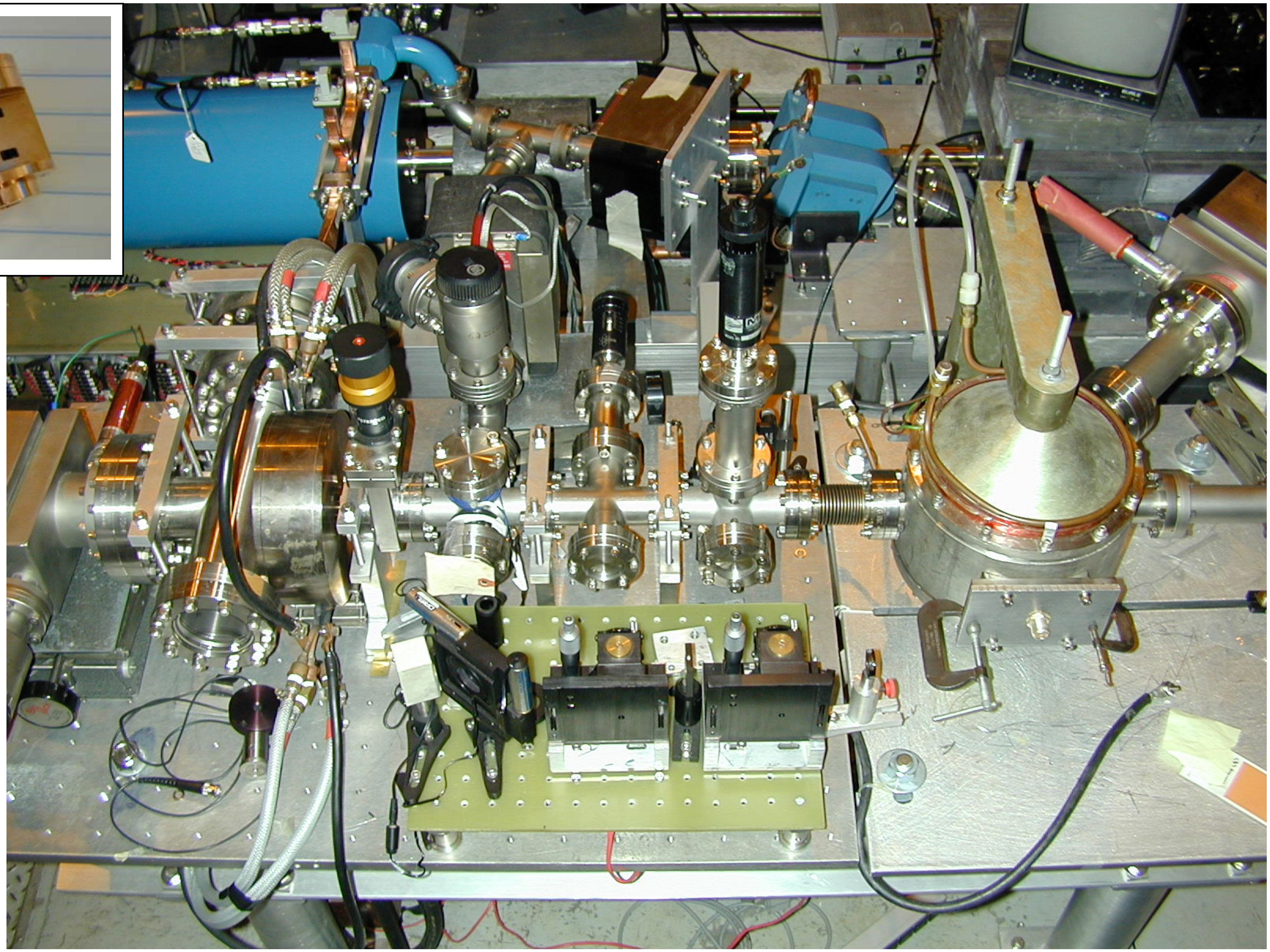
Haimson / MIT 17 GHz Accelerator

Parameter	Value
Klystron	25 MW, 17.14 GHz
Beam Energy	10-25 MeV
Average Current	0.2 A
Peak Current	80 A
Electrons/Bunch	10^8 (20 pC)
Emittance	2.5π mm-mrad
Beam Waist	1mm
Min. Bunch Length	60 μm (180 fs)

RF Breakdown / RF Gun Test Stand

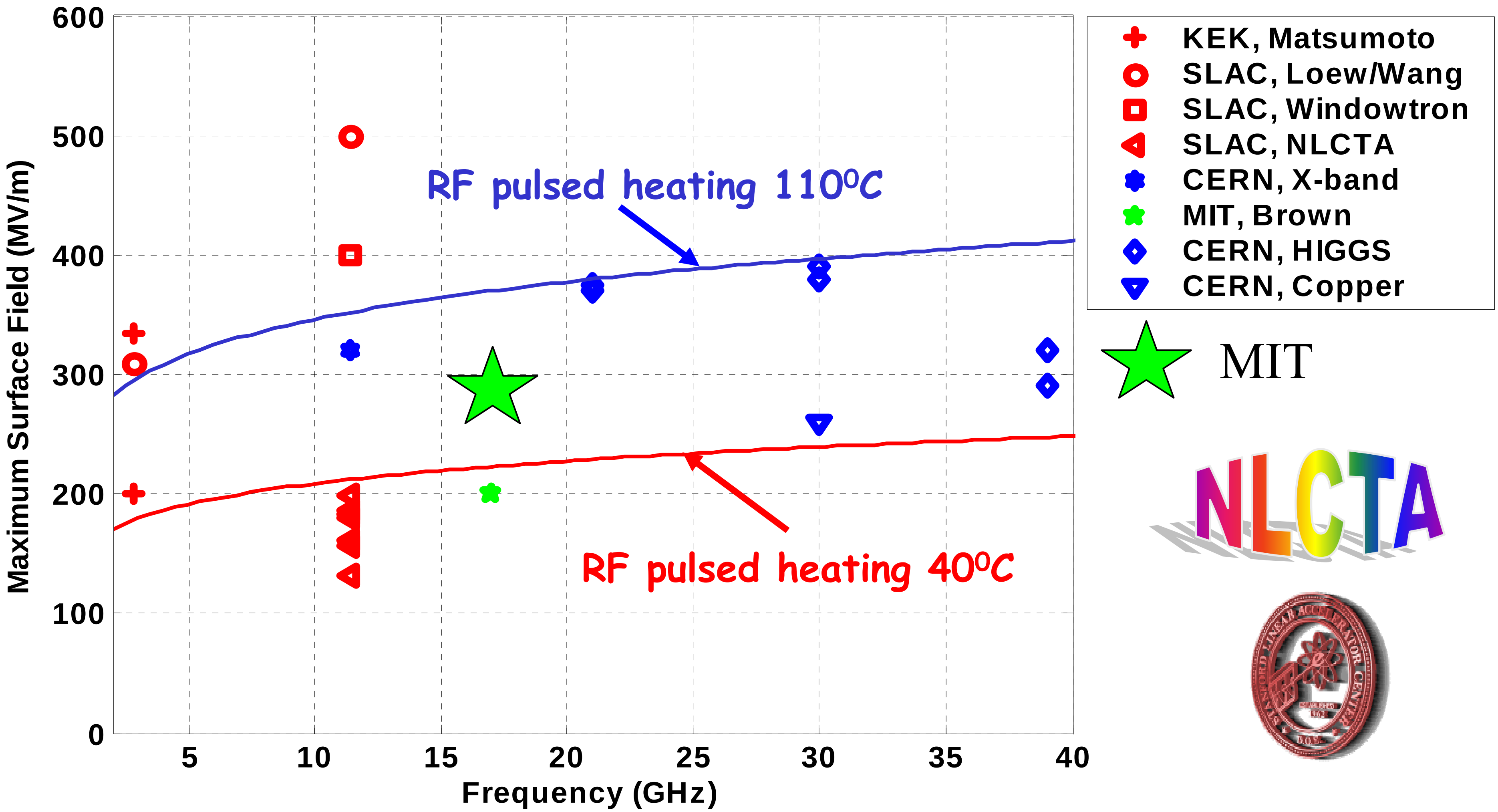
RF gun

- Useful for testing to 10 MW



MIT Breakdown Results vs. SLAC and CERN

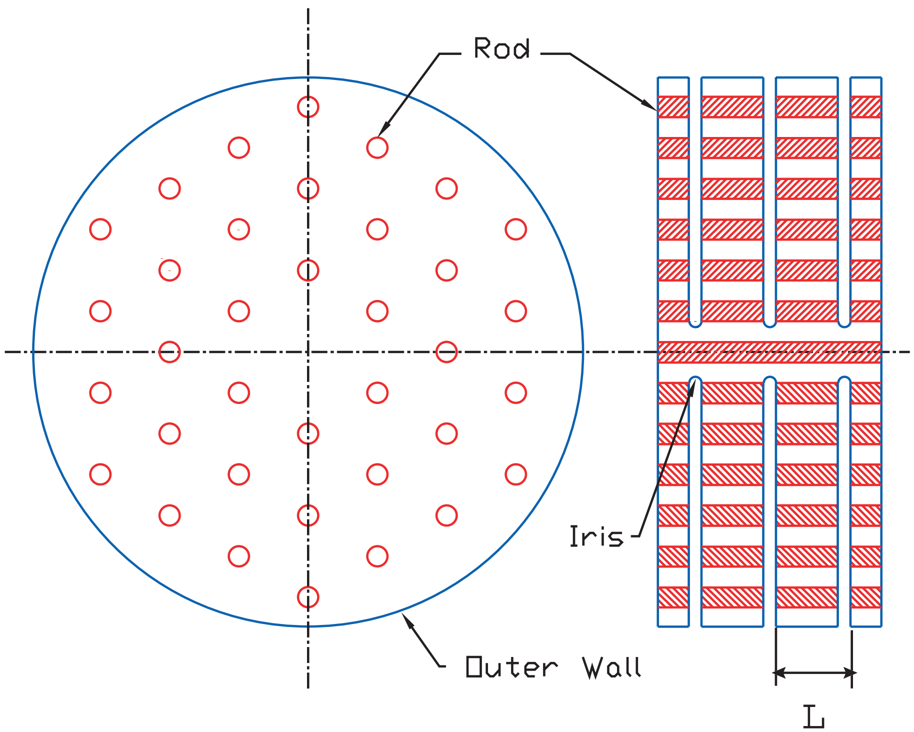
Adapted from Steffen Döbert, SLAC/CERN, Workshop, Argonne, 2003

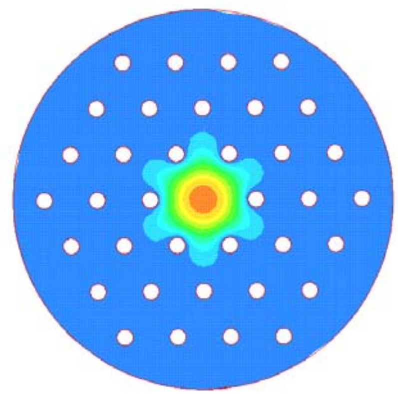


Ref.: W. Brown et al., PR-STAB, 2001

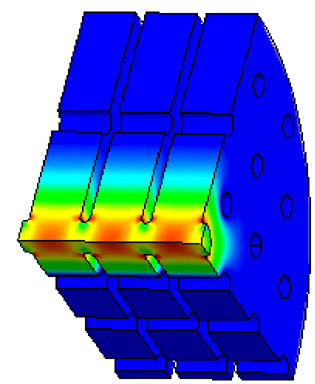
Motivation for Photonic Structure Research

- Wakefields increase with frequency as ω^3
- PBG (Photonic Bandgap) structure is effective for damping wakefields



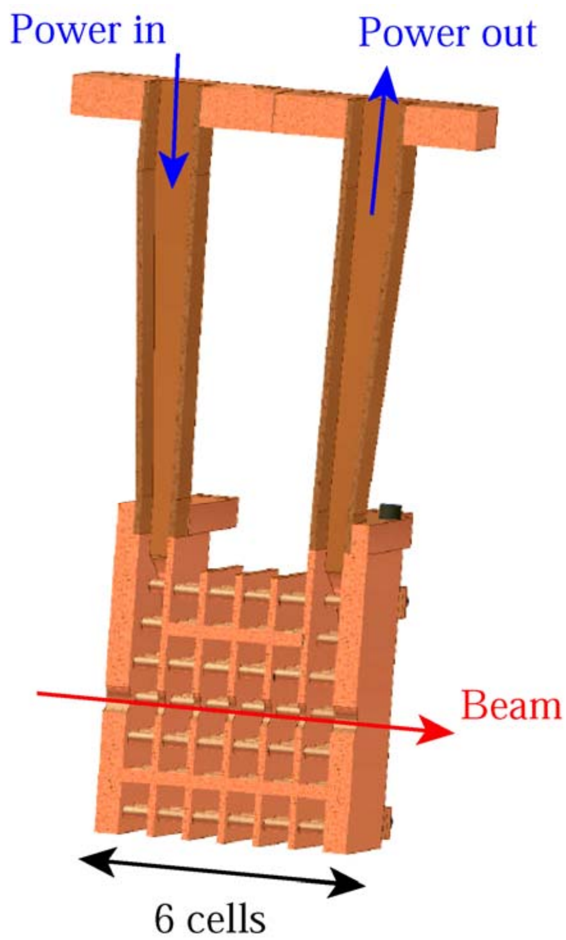


TM_{01}-like Mode of PBG Structure



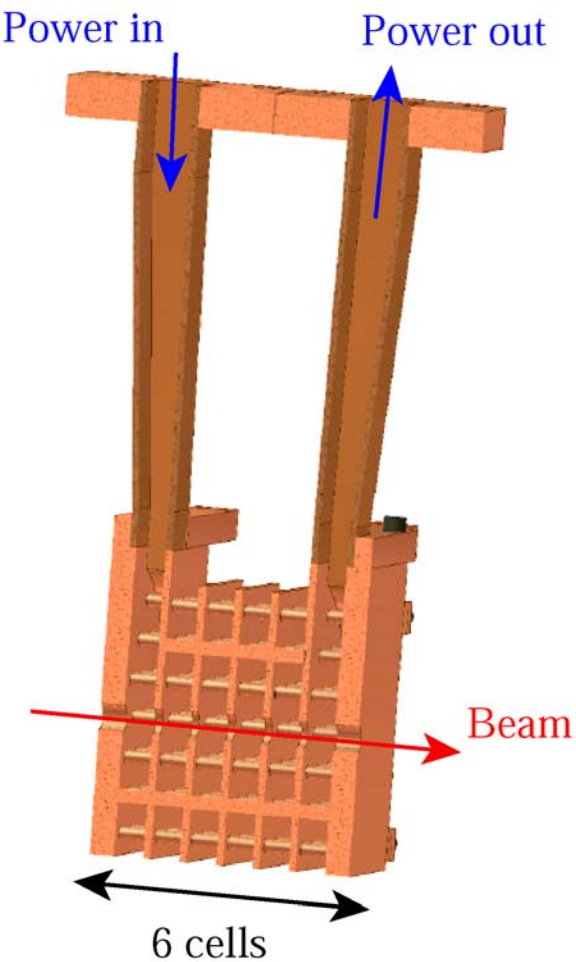
3D View Of Fields

Accelerator with PBG cells



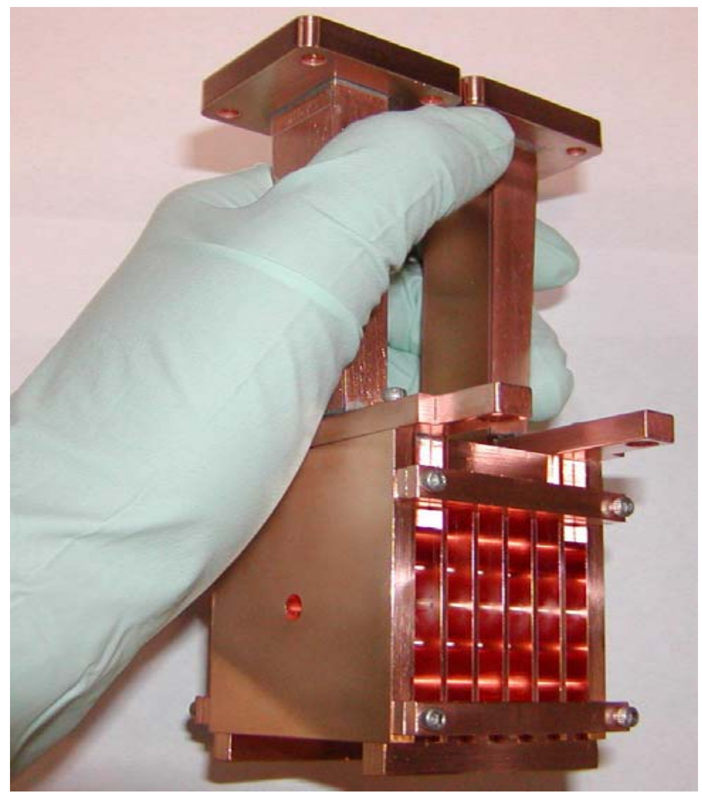
Frequency	17.140 GHz
Phase shift per cell	$2\pi/3$
Q_w	4188
r_s	98 MΩ /m
$[r_s/Q_w]$	23.4 kΩ /m
Group velocity	0.013c
Gradient	$25.2\sqrt{P[MW]}$ MV/m
Rod radius, *a*	1.08 mm
Lattice vector, *b*	6.97 mm
Iris radius	2.16 mm

Novel Accelerator Structure Test Stand

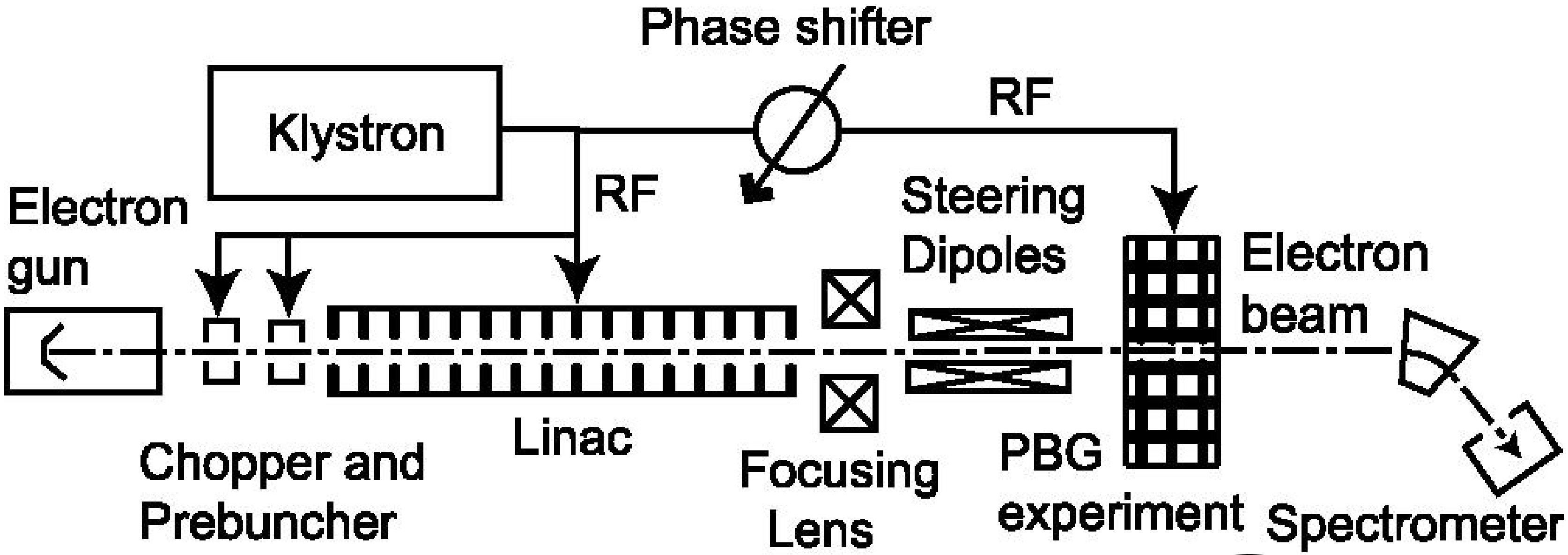


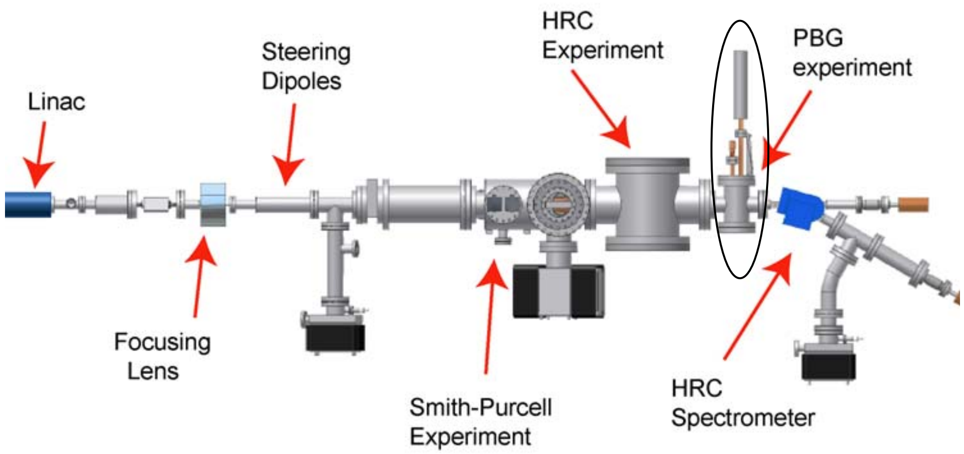
Six Cell Photonic Bandgap (PBG) Structure

- Design the structure
- Cold test the structure
- Hot test the PBG accelerator

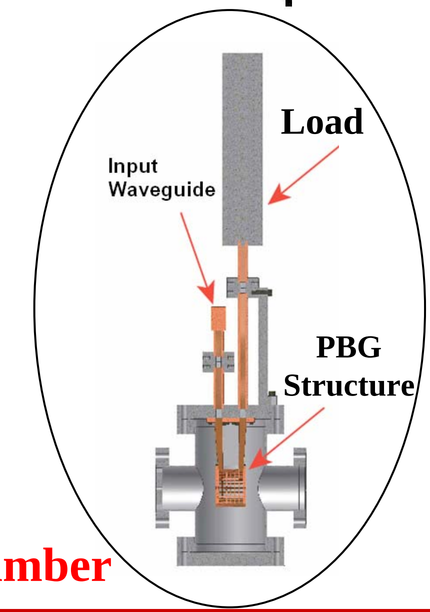


Experimental Schematic





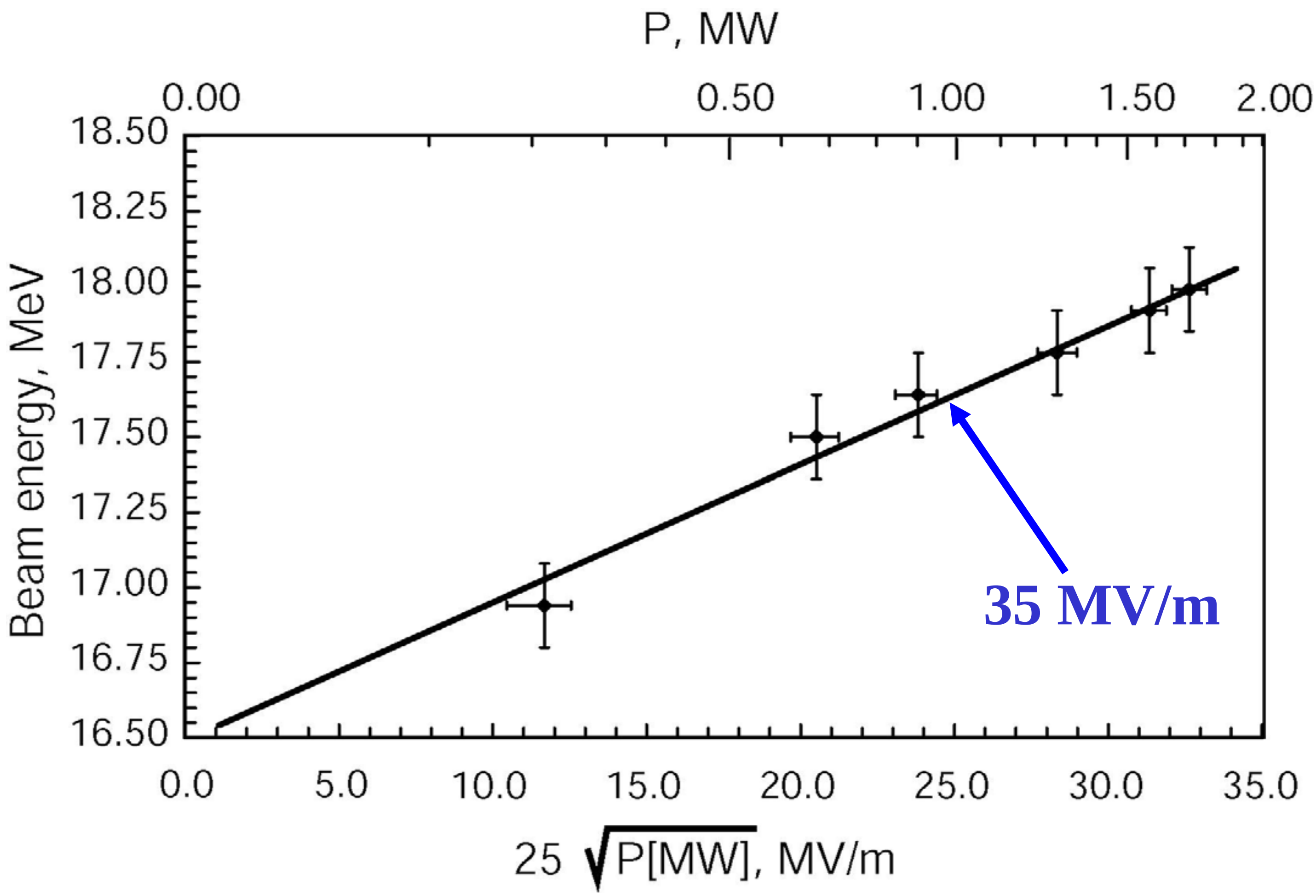
Beam Line



Test Chamber

Accelerator demonstration

- Beam energy increased with power as $P^{1/2}$, as expected.
- First successful PBG accelerator demonstration.



E. I. Smirnova et al., Physical Review Letters, 95, 074801 (2005).

2006 Outstanding Doctoral Thesis

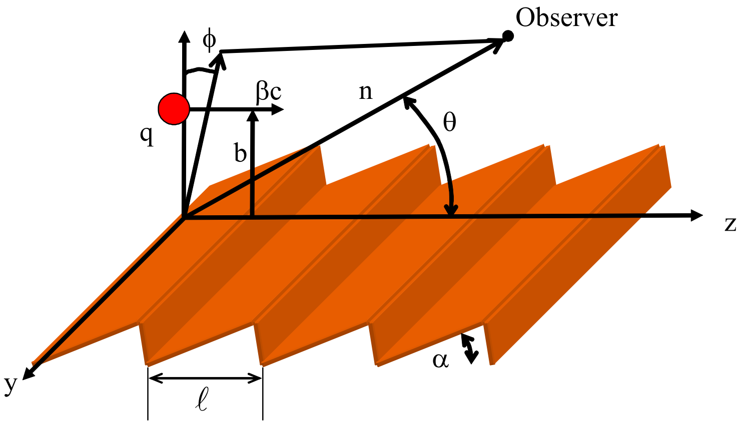
APS
2006 Outstanding
Doctoral Thesis
Research in Beam
Physics
to
Evgenya I. Smirnova
MIT

Dr. Smirnova is now at Los Alamos Natl. Lab

Citation:

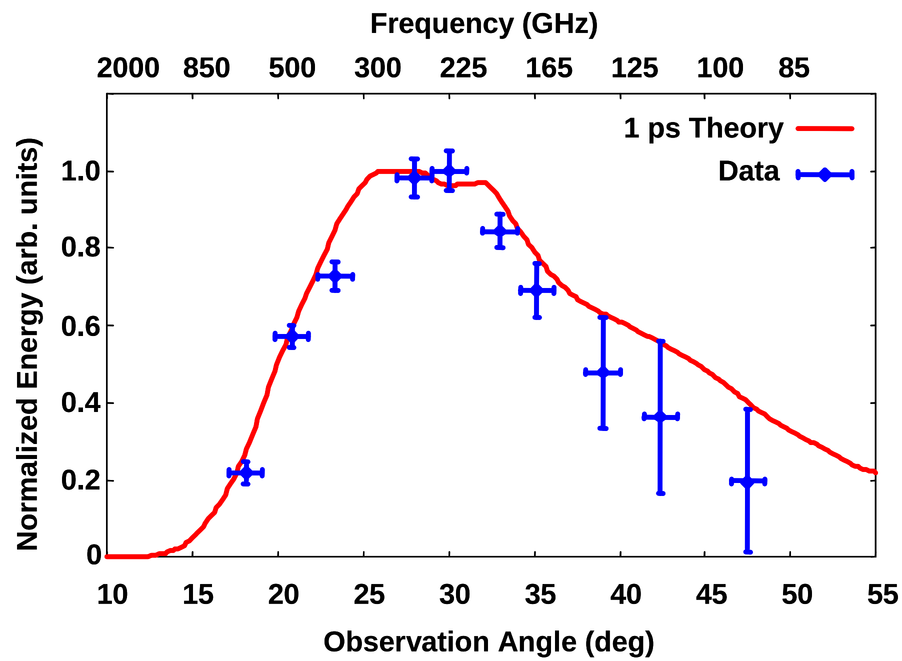
"For the design, fabrication and successful testing of a 17 GHz electron accelerator utilizing a photonic crystal structure."

Phase Locked THz Smith Purcell Radiation



Resonance condition:

$$\lambda_n = \frac{\ell}{n}\left(\frac{1}{\beta} - \cos\theta\right)$$



- Observation of Enhanced, Coherent Smith-Purcell Radiation at THz Freq.
- **Ph. D. thesis research of Mr. Stephen Korbly, graduated 2005**
- Published S. E. Korbly et al., Phys. Rev. Lett., **94,** 054803 (11 Feb. 2005).
- Dr. Korbly works for Passport Systems Inc. on accelerator R&D

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MMW Sources: 17 GHz Klystron

- A **71dB Gain High Efficiency Relativistic Klystron** using a High Current Linear Accelerator Traveling Wave Buncher Output Circuit
  - 17.14 GHz
  - 6 cavities
- High gain allows solid state driver.
- Testing will occur in Spring, 2006

Collector	89.9	A
Gun Volts	545	kV
P. RF Out	25.5	MW
Efficiency	51.9	%
P. Drive	1.8	W
Gain	71.5	dB

Haimson Research Corp.

MMW Sources: 34 GHz Magnicon

- **34 GHz Magnicon at Omega-P Inc.**
  - 34 GHZ, 45 MW PULSED MAGNICON, O.A. Nezhevenko et al., Omega-P, Inc.
  - Single frequency amplifier suitable for accelerator driver demonstrated.

Test Results	
Power, MW	**17**
Pulse duration, μsec	**0.25**
Repetition rate, Hz	**6**
Gain, dB	**54**
Beam voltage, kV	**450**
Beam current, A	**185**

High-power components providing pulse compression, transmission and input coupling to MMW accelerating structures are needed.

MMW Sources: 91 GHz GK

- 91 GHz Gyroklystron amplifier built by Calabazas Creek Research.
    - Power level of 10 MW
    - Efficiency > 40%
    - Gain of 55 dB
    - Frequency doubling option chosen

- Status: Completely built, waiting for testing at SLAC.

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US Collaboration (from Tantawi, 12/21/05)

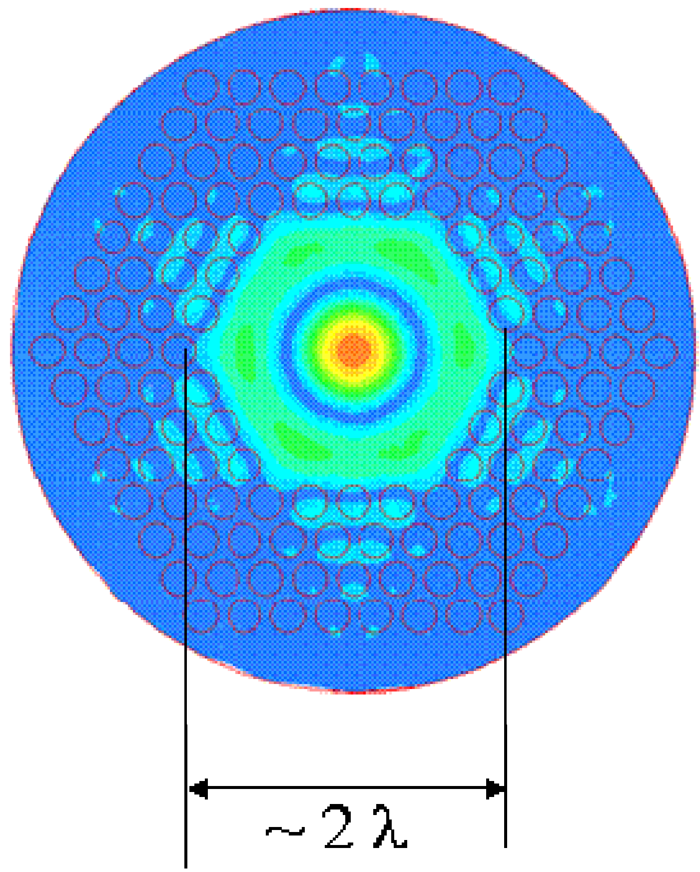
US Collaboration on High Gradient Research for a Multi-TeV Linear Collider

Motivation

- The ILC will reach ½ to 1 TeV cm energy.
- Advanced Accelerator research looking far beyond this, exploring laser and plasma acceleration
- Multi-TeV energy maybe to be reachable with extension of normal conducting high gradient technology.
- The CLIC Two-Beam approach offers a power source which is not so frequency specific—from 11-30 GHz at least.
- After extensive development, NLC achieved reliable 65 MV/m for collider-ready structures (achieved much higher gradients in selected tests!).
- Multi-TeV colliders need higher gradient—CERN specifications have been 150 MV/m loaded.
- This collaboration should aspire to build the bridge to span this gap.

Examples of Proposed MIT Novel Structure Research

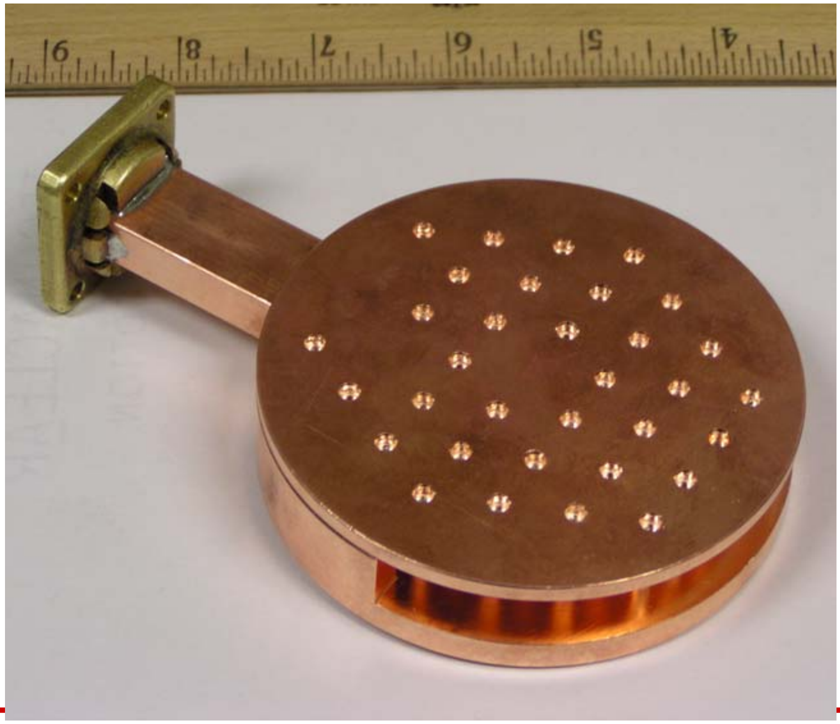
- Novel structures "outside of the box"
- MIT Examples:
  - Dielectric Photonic Bandgap Structures
  - High order mode accelerators
    - Shapiro et al., PAC03
  - Surface mode accelerators
    - Shapiro et al., PAC05
- New Ideas
  - Specific new proposals have been developed by MIT



TM_{02}–like mode

Example of Proposed MIT RF Breakdown Research

- Photonic bandgap structures to test breakdown
  - Easy to pump, access, change
  - High field on thin inner rods
  - No iris coupling, eliminates breakdown at the iris
  - Test of Cu, Mo, dielectrics, other materials



- **Brazed, High Q Photonic Bandgap Test Structure**

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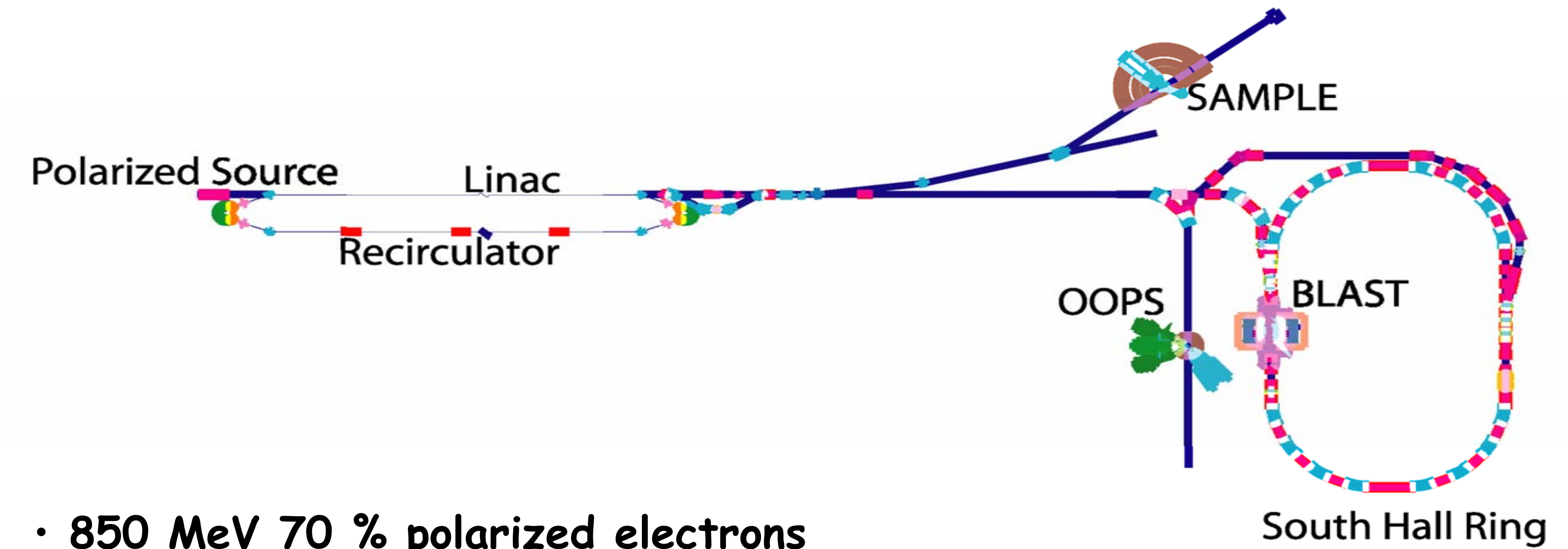
MIT-Bates Linear Accelerator Laboratory



- 850 MeV 70 % polarized electrons
- Stored current of 250 mA max. with 30 min. lifetime
- Accelerator complex refurbished in 1990s => reliable, efficient operation
- Over 130 Ph.D.s educated in nuclear physics at Bates over 30 years
- Phased out as nuclear physics user facility in 2005

MIT vision for Bates

Future vision of Bates as an interdisciplinary

Center for Accelerator Science and Technology (CAST)

- R&E Center (DOE/NP) to support research of NP faculty established in 2006
- MIT Physics educational initiative underway
- MIT has taken ownership of accelerator complex
- Proposal submitted to DOE/NP to carry out several accelerator experiments
- Proposal submitted to DOE/BES to develop Terahertz source
- Director of USPAS, W. Barletta, will take up residence at MIT in Spring 2006. Will explore possible use of Bates accelerator for USPAS.

Bates FY2006 Center Activities

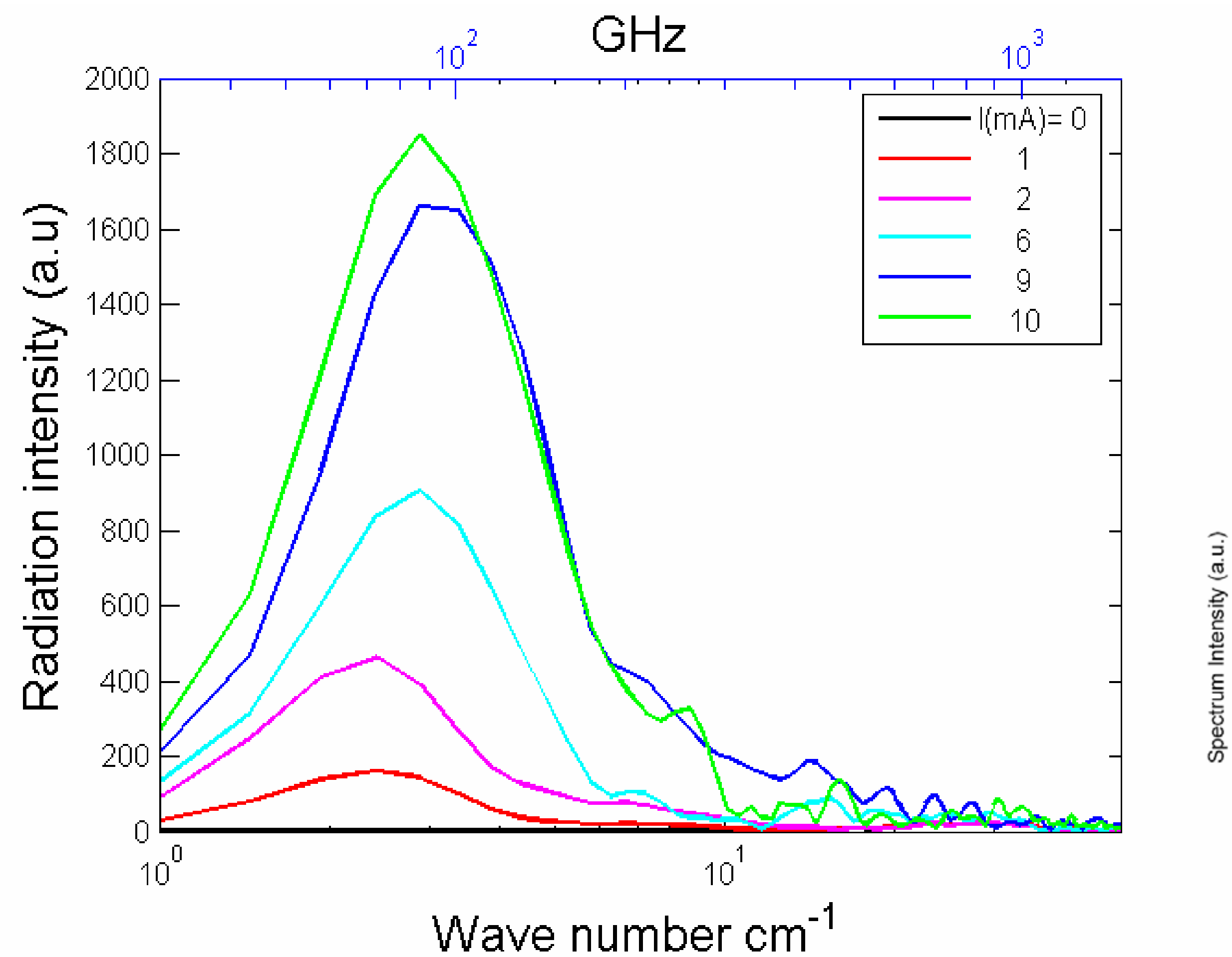
- Spectrometer/detector development **JLab, RHIC, SNO**
- Accelerator physics design **eRHIC, NSLS II, ELETTRA**
- Polarized source R&D **eRHIC, ILC**
- Optical stochastic cooling **RHIC, LHC**
- Terahertz source
- Cargo screener prototype development using ~ MeV accelerators - three projects funded and underway
- MIT Physics Department Junior Lab experiment using polarized electron source in development

Funded by DOE/NP, MIT, DHS, JLab and BNL.

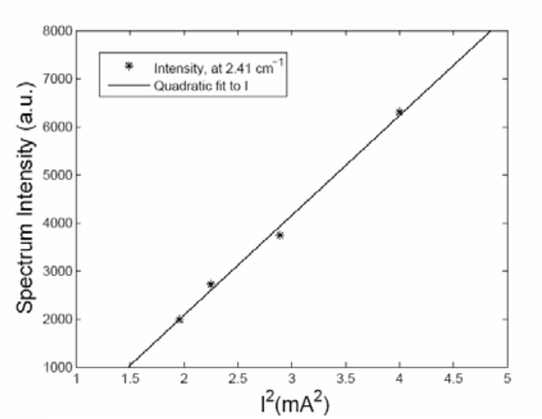
Terahertz source at Bates

- Electron storage rings can produce high average power in the Terahertz region using coherent synchrotron radiation; (demonstrated at BESSY, proposed at LBL)
- Development runs (in collaboration with BNL) in December 2004 and June 2005 produced coherent radiation measurement in the Terahertz region - see upcoming Phys. Rev. Lett.
- Three year R&D effort can transform Bates ring to an intense, coherent source of Terahertz radiation
- Wide range of applications in materials and biological science, medical imaging etc.
- Successful international workshop held in October 2005
- Proposal submitted to DOE/BES

Coherent Synchrotron Radiation from SHR June 6th, 2005



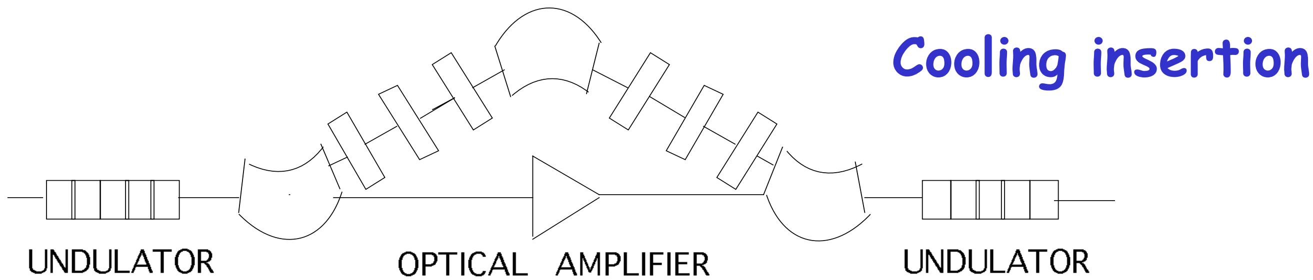
< 2mA, Intensity$\propto I^2$



First Demonstration of Optical Stochastic Cooling at SHR

- Low emittance hadron beams are essential for high luminosity collider operation: RHIC $\rightarrow$ eRHIC, LHC, etc.
- Cooling of the beam is essential to maximize luminosity
- Optical stochastic cooling (OSC) is a promising technique which has never been demonstrated
- A 200-300 MeV electron storage ring is ideal for a OSC demonstration
- MIT, Indiana Univ., BNL and LBL have submitted a proposal to mount an experiment to provide a first demonstration of OSC at the Bates SHR
- Capital equipment of order $1 million required

Bates OSC experiment



- Could locate in East straight section of the SHR: 10 meters available
- Requires sufficiently low electron energy such that the cooling time is shorter than the damping time
- MIT fast laser group of F. Kaertner will develop the optical amplifier
- Key experiment in demonstration of feasibility for RHIC: RHIC needs substantial development of optical amplifier
- Bates experiment would take three years and cost about $3 million
- Substantial aspects of the required capital equipment may be realized under the SBIR program

Operation of Bates accelerator

- Proposed activities using accelerator
  - optical stochastic cooling
  - Terahertz source development
  - educational instruction

  could be carried out with a run of about 2 months per year.
- Development of OSC could have major payoff for higher performance operation of RHIC
- This would cost about $ 1 million per year for manpower, accelerator maintenance and electricity.

Education

- Continue to have strong young MIT scientist (undergraduate, graduate student and post-doc) participation in accelerator physics activities at Bates
- Development of new MIT Physics Junior Lab experiment at Bates underway (P. Fisher, W. Franklin, and S. Steadman) using polarized electron source, funded by JLab
- Will work with W. Barletta and USPAS to utilize Bates accelerator: USPAS school scheduled for June 2006 at Waltham Westin
- Strong participation by MIT students in accelerator research activities – introduce them to large accelerator facilities, e.g. BNL and JLab

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Conclusions

- **High Frequency Microwave technology is the only practical way toward a multi-TeV, high luminosity linear collider in the next 30 years.**
- **MIT Program has achieved major milestones in**
  - High Frequency Microwave Accelerators
  - Millimeter Wave Sources
  - Critical Millimeter Wave Components
- **MIT Program is well aligned with goals of the US Collaboration on High Gradient Research**
  - Strong program will demonstrate major progress.
  - Excellence of proposed research.
  - Educational goals.
- **Bates is an ideal setting for a flexible, affordable Center of Excellence at a top research university**