# High Frequency Integrated Vacuum Electronics (HiFIVE) Industry Day Meeting

## Background, Program Objectives and Structure

Mark J. Rosker
Program Manager
24 July 2007

# Agenda

| | | |
|---|---|---|
| ***Introduction*** | | |
| 1300-1330 | Background, Program Objectives and Structure | Mark Rosker (DARPA) |
| ***Area of Interest I: Vacuum Electronic Circuit Elements*** | | |
| 1330-1350 | High Current Density, Long-Life Cathode | Dev Palmer (ARO) |
| 1350-1410 | High Aspect-Ratio Electron Beam<br>High Efficiency Interaction Structure | Baruch Levush (NRL) |
| 1410-1430 | BREAK | |
| 1430-1440 | High-Power MMIC Driver | Alfred Hung (ARL) |
| 1440-1455 | High-Efficiency Thermal Management | Jeff Calame (NRL) |
| ***Area of Interest II: Vacuum Electronic Circuit Design, Integration, and Demonstration*** | | |
| 1455-1515 | High Power Amplifier Design | Baruch Levush (NRL) |
| 1515-1530 | Circuit Integration<br>Circuit Demonstration | Jeff Calame (NRL) |
| 1530-1545 | BREAK | |
| ***Wrap-Up*** | | |
| 1545-1700 | Questions & Answers | Mark Rosker (DARPA) |

# DARPA Organization

**Director, Tony Tether**
**Deputy Director, Bob Leheny**

### Tactical Technology
Steve Welby
Steve Walker

- Air/Space/Land/Sea Platforms
- Unmanned Systems
- Space Operations
- Laser Systems
- Precision Strike

### Information Exploitation
Bob Tenney
Mark Davis

- Sensors
- Exploitation Systems
- Command & Control

### Strategic Technology
Dave Honey
Larry Stotts/Brian Pierce

- Space Sensors/Structures
- Strategic & Tactical Networks
- Information Assurance
- Underground Facility Detection & Characterization
- Chem/Bio Defense
- Maritime Operations

### Defense Sciences
Brett Giroir
Barbara McQuiston

- Physical Sciences
- Materials
- Biology
- Mathematics
- Human Effectiveness
- Bio Warfare Defense

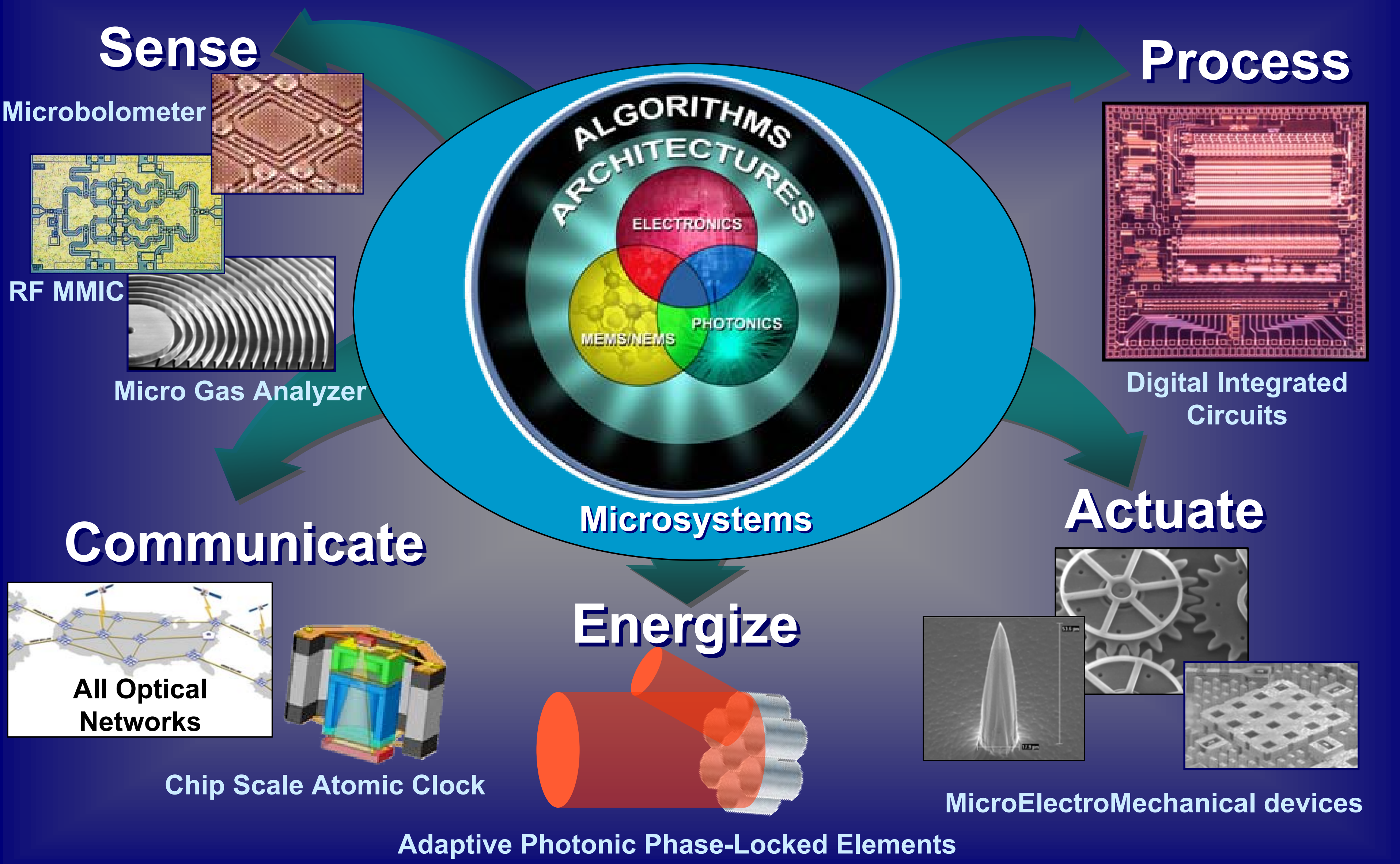
### Information Processing Technology
Charlie Holland
Charles Morefield

- Cognitive Systems
- High Productivity Computing Systems
- Language Translation

### Microsystems Technology
John Zolper
Dean Collins

- Electronics
- Photonics
- MEMS
- Algorithms
- Integrated Microsystems

# Microsystems Technology Office: Enabling Future Capability



# Welcome to HiFIVE

# Legal Disclaimer


**_The DARPA / MTO HiFIVE program is not associated with any children's magazine_**

# An Application Example: Something That Cannot be Done Today

**Question #1**

***Is there an optimal RF frequency for an all-weather tactical comm link?***

- "Optimal" = highest possible channel capacity
- Include antenna gain and atmosphere loss
- Assume RF components are available and performance (power, NF) is frequency invariant

**Insight #1**

***Yes. The "upper MMW" (i.e., 200 – 300 GHz)***

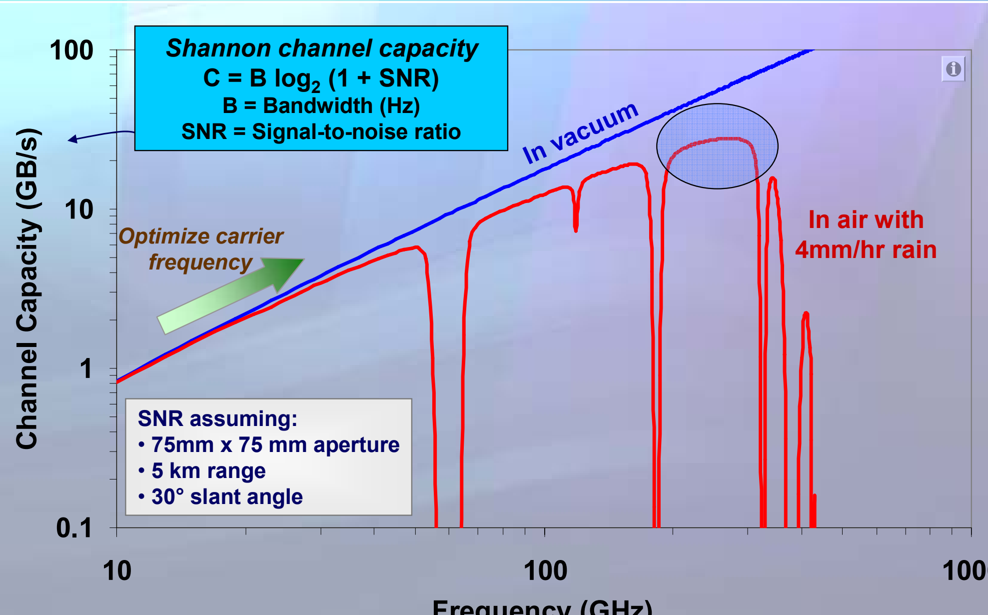
- Capacities can be comparable to SOA fibers!
- Even in relatively bad weather

***But such a link requires a high power amplifier that doesn't exist today***

**The Challenge**

***Can MTO make a "useable" power amplifier for the upper MMW?***

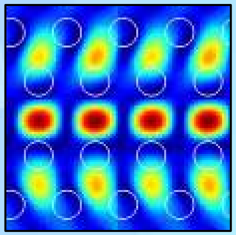
- High power
  - Many 10's of W, not just a few W
- High bandwidth
  - Many GHz, not MHz
- Compact
  - Similar MPM's used now for such platforms

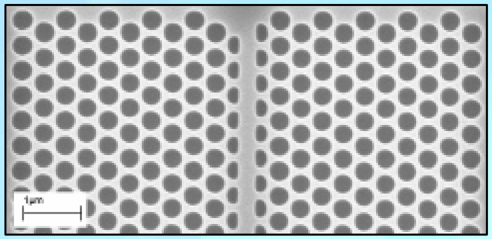


# A Technology-Driven Question

**Question #2**

## *Can the ideas of slow-light and EM (photonic) bandgap structures lead to RF device performance breakthroughs?*





*For optimal energy extraction, we must:*

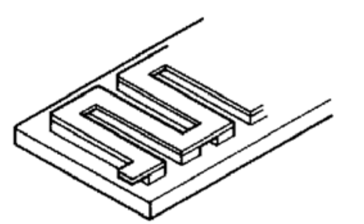
- Decrease the light (RF) wave velocity to increase the interaction time of the electron stream

$$V_{RF} \approx V_{electrons}$$

| | Solid-State | Vacuum Electronics |
|---|---|---|
| $V_{electrons}$ | low | high |
| Interaction Length | µm | mm |

**Insight #2**

## *We've been here before!*

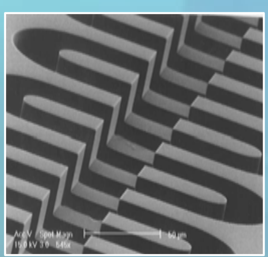


Dielectric-supported meander line

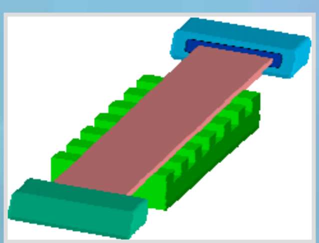
Vacuum electronics:
the *original* slow-wave device

## *…but new approaches are now available.*

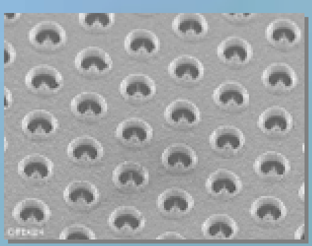
*Si micromachining for high-frequency slow-wave structures*



*High aspect ratio* electron beams for slow-light structures*



*Cold beams*

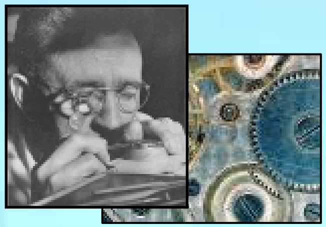


***Can we use these new ideas to solve the "upper MMW" PA challenge?***

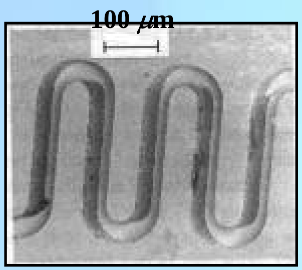
* Ratio of total width of beam(s) to thickness

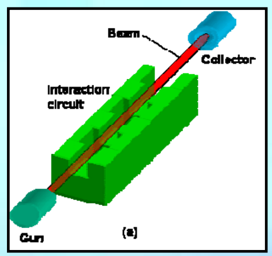
# Can we go… *Back to the Future?*


***Why didn't slow-wave vacuum electronics lead to a compact, high power-BW upper MMW power amplifier ?***



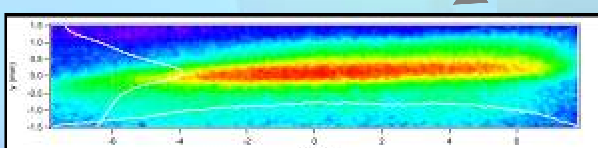
- **Couldn't build it:** Required slow-wave structure tolerances beyond conventional (wire EDM) machining
  → Better fabrication method

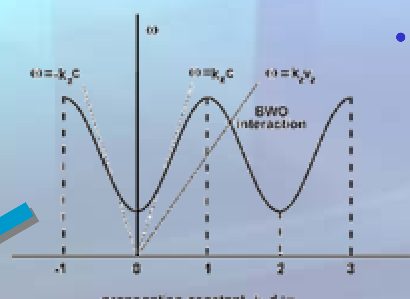


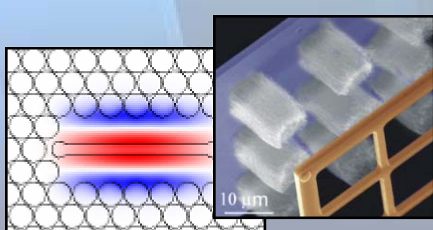

- **Couldn't extract enough power from it:** Power out from slow-wave structure scales ~ $Nf^{-8/3}$
  → High aspect ratio (N) e-beam*

* Ratio of total width of beam(s) to thickness






- **Couldn't keep velocity match:** Bandwidth limited by electron velocity spread, mode dispersion, and energy transfer
  → Beam cooling
  → Reduced mode dispersion
  → Tapering

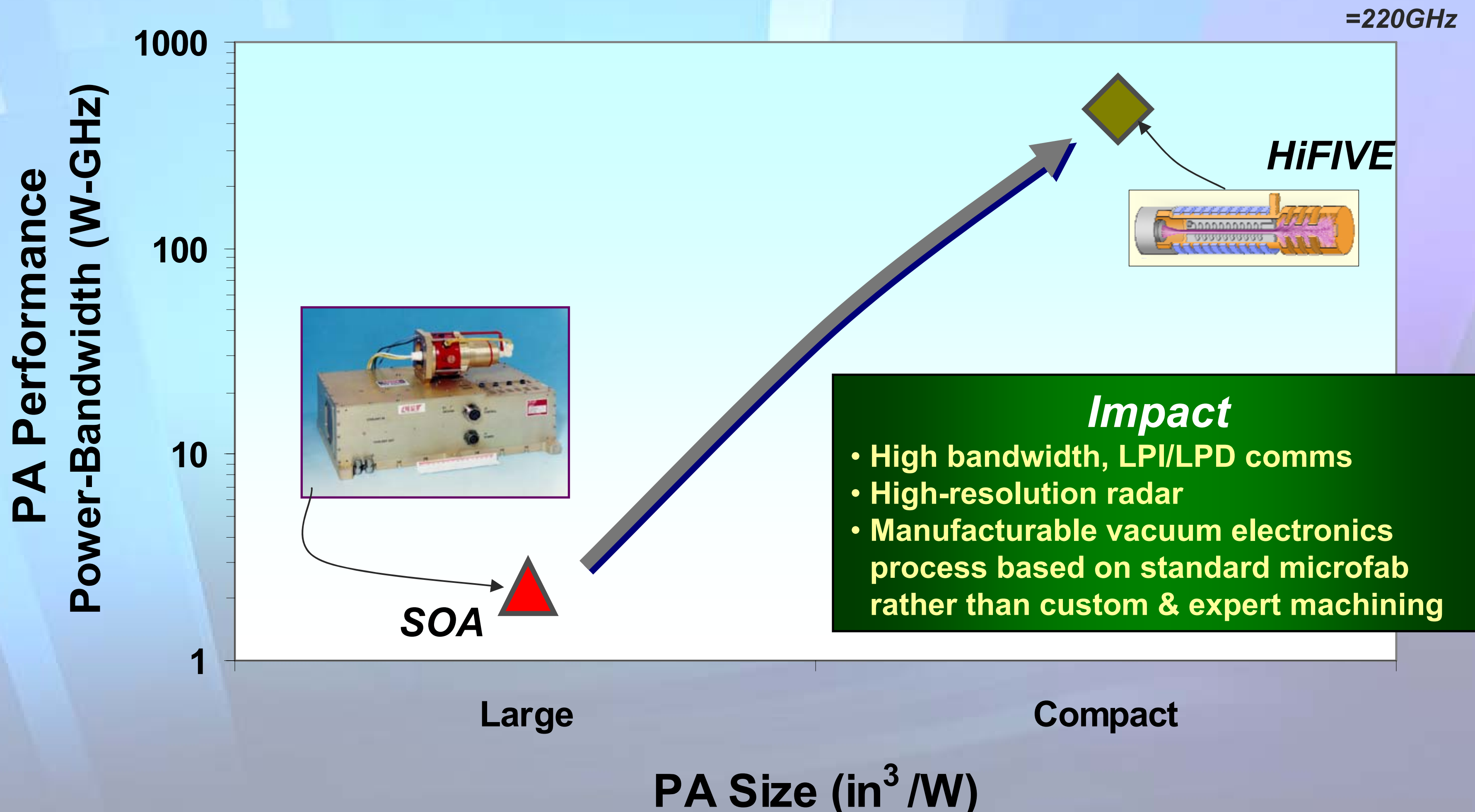



***Microfabrication technology is our time machine!***

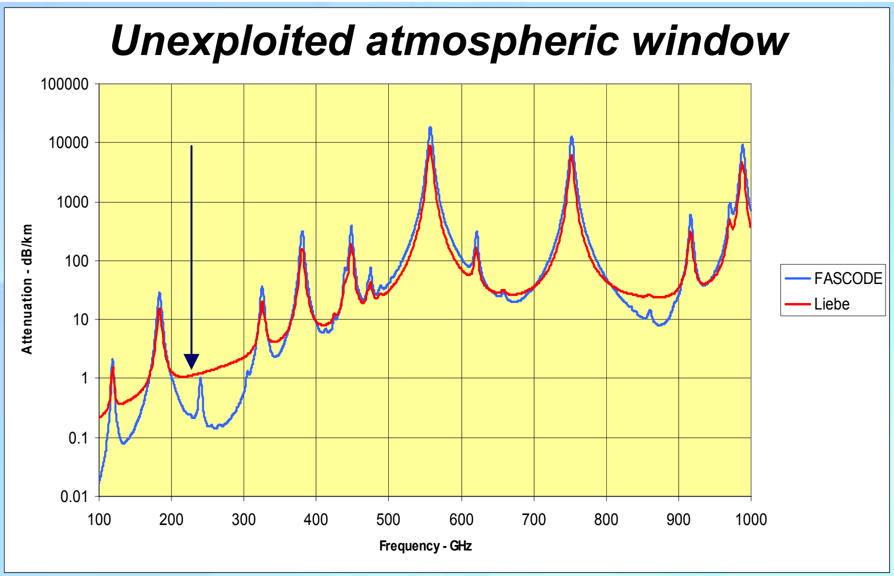
# High Frequency Integrated Vacuum Electronics (HiFIVE)

## *Program Objective*

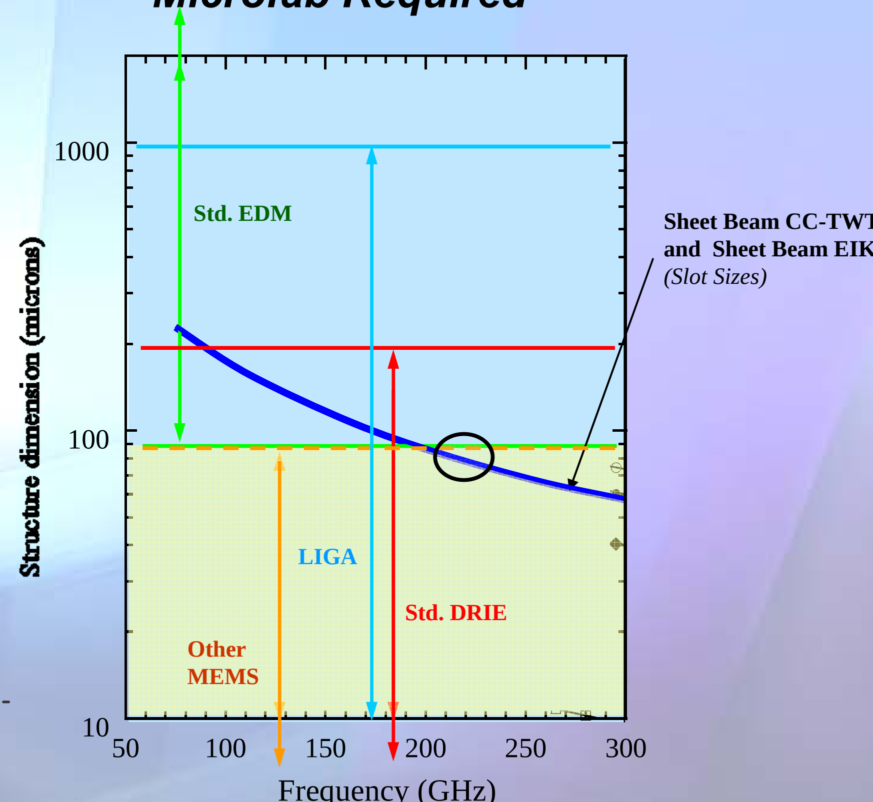
**Demonstrate a compact, high-bandwidth, high-power "upper millimeter-wave" amplifier**

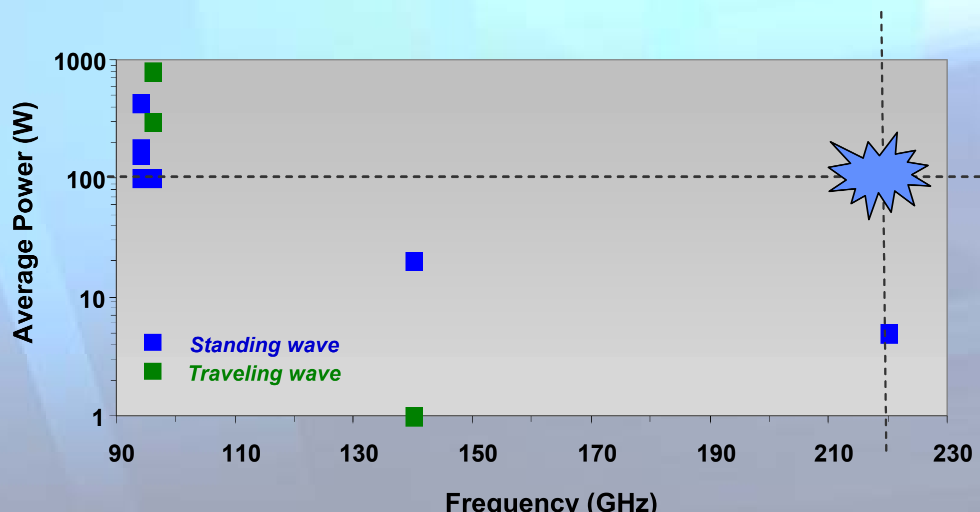


# Why 220GHz?



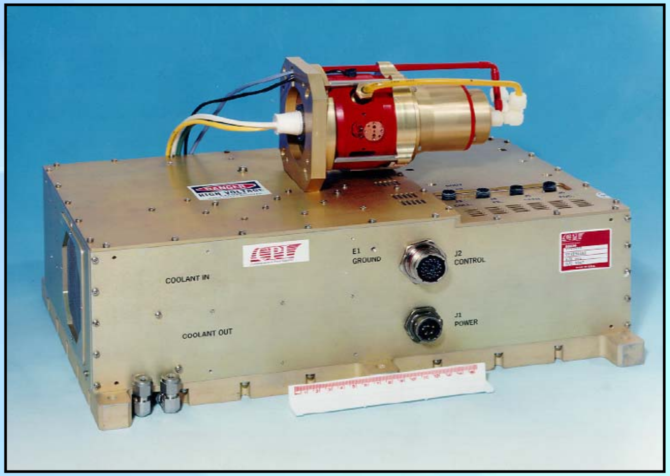

## *Microfab Required*



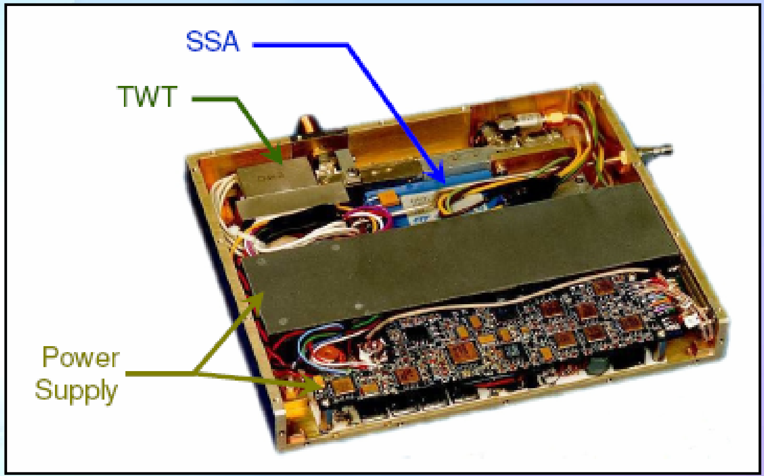



# What Is Compact?

*PA size can be dominated by the high voltage power supply*




*Substantial engineering has miniaturized & flight qualified HV power supplies to ~20kV*



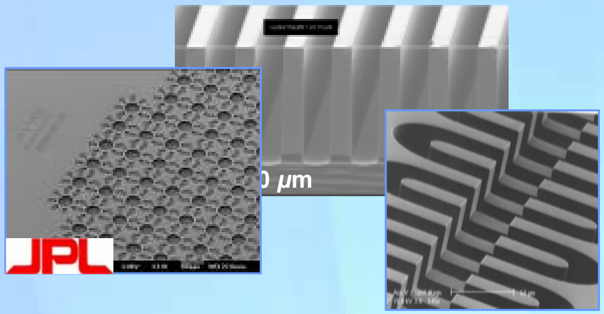

**Fixed upper limit on circuit magnetic field $B_{max}$ due to permanent magnet technology (~ 11 kG)**

**Practical upper limit on beam voltage ~ 20 kV**

***In HiFIVE, we expect V < 20kV and $B_{max}$ < 11kG***

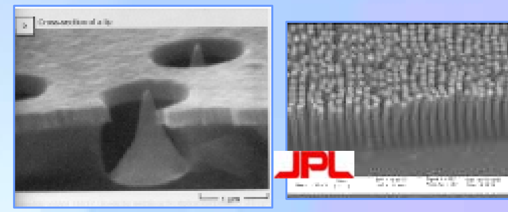
# Why Now?
# Some HiFIVE Enablers

## Micromachining Approaches Achieving Fine Surface Smoothness and High Aspect Ratio



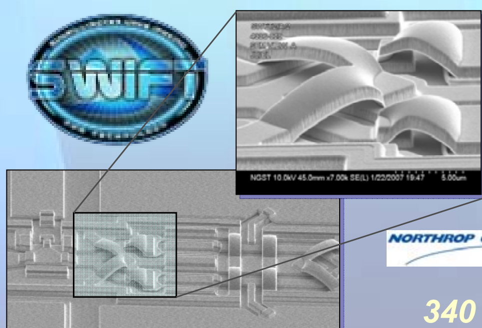
- *High precision machining of interaction structures*
- *Structures susceptible to outgassing adsorption*
- *Depth of structure difficult for many techniques*

## Novel Field Emitter Array Cathodes with Improved Current Density



- *Compact and efficient*
- *Very short lifetimes*
- *Further increase in current densities needed*

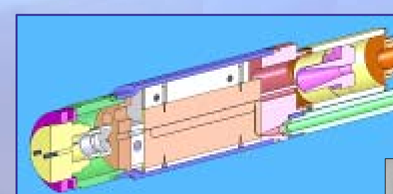
## High Frequency MMIC Process



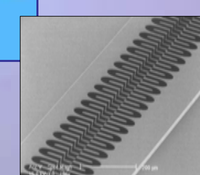
*340 GHz MMIC*

- *Frequency of operation now well beyond 220GHz*
- *Need to increase power*
- *Integrating the device is difficult (high loss)*

## THz Frequency TWTA Demo



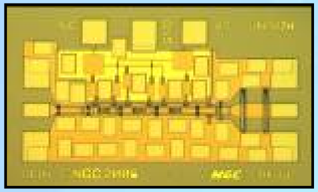
*1st THz frequency (0.65THz) vacuum device*



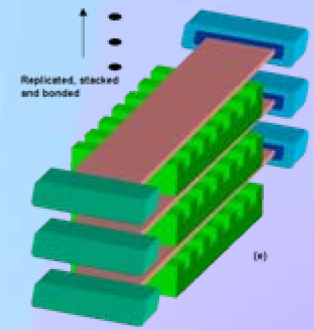
- *High precision machining at frequency*
- *Round beam*
- *Lower frequency structure more difficult*

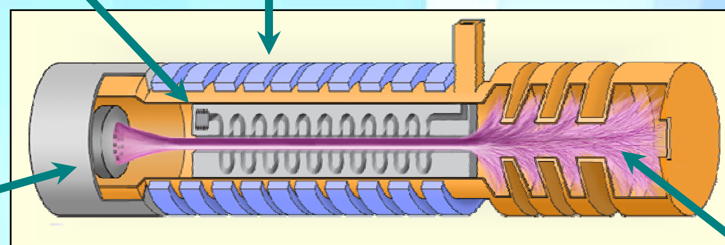
# Technical Challenges

### *High Power MMIC Driver*
- Accommodate relatively low VE gain at 220 GHz



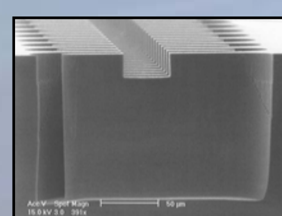
### *High Aspect-Ratio Devices*
- High efficiency interaction structures
- Single vs. multi-beam topologies
- Magnetic compression to achieve high aspect ratio beam (N~100)
- Mitigation of parasitic oscillations



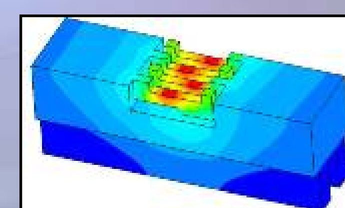



### *High Current Density, Long Life Cathodes*
- High unfocused current density (~100A/cm$^2$)
- Life > $10^3$ hrs

### *High Precision Micromachined Fabrication and Integration*
- Achieve required smoothness & aspect ratio
- Material/technology/process compatibility
- Heterogeneous integration
- Maintain high vacuum

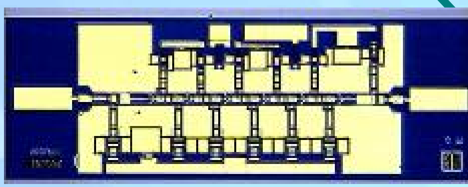


### *High Efficiency Thermal Management*
- Mode confinement / reduction of beam interception
- Aggressive thermal management (mat'ls and structures)

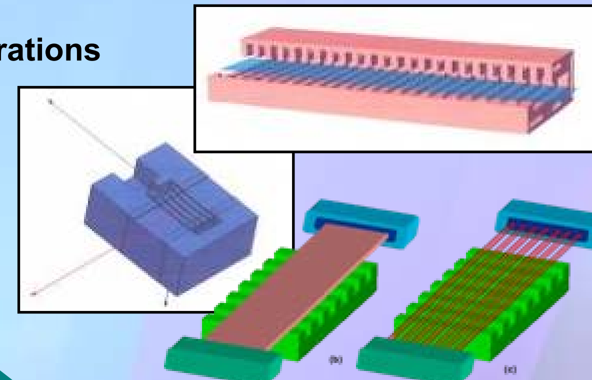


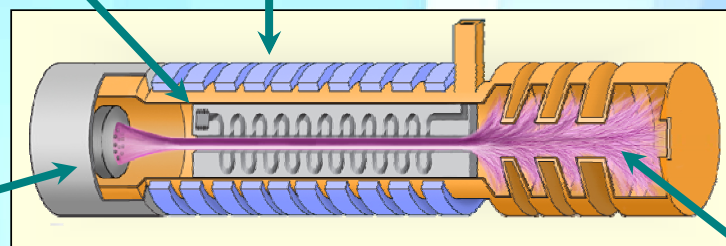
# Illustrative Technical Approaches

### *High Power MMIC Driver*
- InP HEMT or HBT MMIC

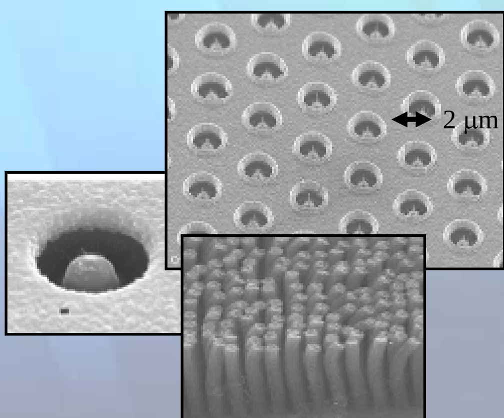


### *High Aspect-Ratio Devices*
- High efficiency interaction structures
- Sheet beam EIK
- Sheet beam coupled cavity traveling wave
- Helix
- Stacked multi-beam configurations

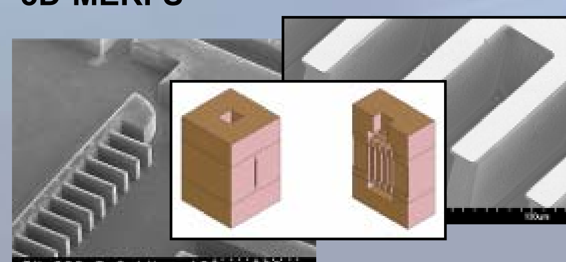




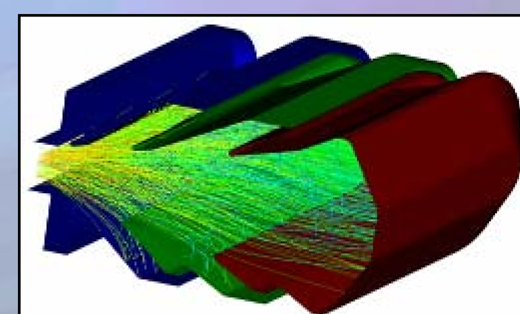
### *High Current Density, Long Life Cathodes*
- Field emitters (cold cathodes)
- Carbon nanotube bundles
- Scandates




### *High Precision Micromachined Fabrication and Integration*
- DRIE
- LIGA
- CVD diamond with metallization
- 3D-MERFS



### *High Efficiency Thermal Management*
- Multi-stage depressed collector
- Microchannel cooling



# Program Schedule

***Demonstrations***

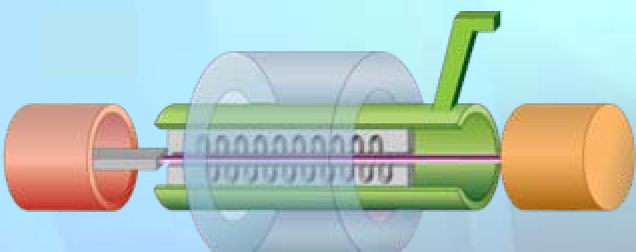
1. Beam stick: Demonstrate a high aspect ratio beam with required power and transport efficiency
2. Cold test: Validation of interaction structure design

***Critical Components***

## Phase I

Key challenges addressed:

- High-aspect ratio electron beam
- Interaction structure topology
- High current density cathode



***Demonstrations***

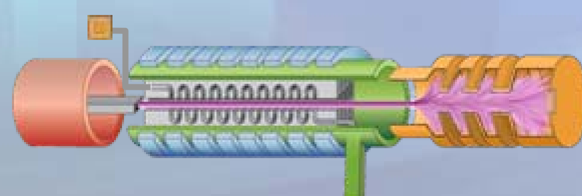
1. HPA demo: Demonstrate a high power-bandwidth product high power amplifier
2. Integrable cathode demo: long-life high current density cathode

***High Power Amplifier***

## Phase II

Key challenges addressed:

- High power driver
- High efficiency thermal management
- High current density cathode



***Objective Demonstration***

- Demonstrate an integrated high power amplifier with ultrahigh power-bandwidth product

***Fully-integrated High Power Amplifier***

## Phase III

Key challenges addressed:

- Heterogeneous Integration
- Maintain high vacuum

**Phase durations to be proposed by the bidders**

# Program Metrics

| Metric | Unit | SOA | Phase I | Phase II | Phase III |
|---|---|---|---|---|---|
| **Go/No Go Metrics** | | | | | |
| Beam voltage | kV | | 20 | | |
| Cathode current density (1) | A/cm² | 10 | 750 | | |
| Beam aspect ratio (2) | | 1 | 25 | | |
| Beam transport efficiency | % | | 95 | | |
| Center frequency accuracy | % | | $\pm 2$ | | |
| $P_{out}$ (3) | W | 5 (4) | | 50 | 50 |
| Bandwidth | GHz | 0.4 (4) | | 5 | 5 |
| Power-bandwidth product | W*GHz | 2 (4) | | 250 | 500 |
| Efficiency (5) | % | <1% | | 5% | 5% |
| Total current (6) | mA | 100 | | 250 (7) | 250 (8) |
| **Other Metrics** | | | | | |
| Spectral purity (9) | dBc | | | -50 | -50 |
| Driver output power (3) | mW | 50 (4) | | 50 | 50 |

(1) Measured in beam stick; pulsed
(2) Defined as sum of the width of all beams/thickness of beams
(3) Average power at 220GHz, measured external to device
(4) Projected performance at 220GHz; research device
(5) Total wallplug efficiency
(6) Measured at cathode surface, for 1000 hours life
(7) As a component
(8) Integrated into HPA
(9) Measured 250kHz from carrier

# Demonstrations

| Metric | Unit | Phase I | | Phase II | | Phase III | |
|---|---|---|---|---|---|---|---|
| | | Value | Demo | Value | Demo | Value | Demo |
| **Go/No-Go Metrics** | | | | | | | |
| Beam voltage | kV | 20 | 1A | | | | |
| Circuit current density [1] | $A/cm^2$ | 750 | 1A | | | | |
| Beam aspect-ratio [2] | | 25 | 1A | | | | |
| Beam transport efficiency | % | 95 | 1A | | | | |
| Center frequency accuracy | % | ±2 | 1B | | | | |
| $P_{out}$ [3] | W | | | 50 | 2A | 50 | 3 |
| Bandwidth | GHz | | | 5 | 2A | 5 | 3 |
| Power-bandwidth product | W*GHz | | | 250 | 2A | 500 | 3 |
| Efficiency [4] | % | | | 5% | 2A | 5% | 3 |
| Total current [5] | mA | | | 250 [6] | 2B | 250 [7] | 3 |
| **Additional Metrics** | | | | | | | |
| Spectral purity [8] | dBc | | | -50 | 2A | -50 | 3 |
| Driver output power [3] | mW | | | 50 | 2A | 50 | 3 |

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# Advanced Studies

*"The HiFIVE program has two Technical Areas of Interest. Bidders are requested to address both technical areas of interest in a comprehensive manner. However, highly innovative advanced studies in one or more of these technical areas by individual investigator or small groups may also be considered. A bidder who is proposing such an advanced study should clearly identify it as such, should present its (limited) objectives and metrics (see below), and should explain the relevance of the work to the overall program goals..."*

## More Likely to Be of Interest

- Efforts that could improve the likelihood that the integrated ("main") performers will be successful, by (for example)…
  - Providing a useful new tool (e.g., design) beyond what it already available
  - Providing a needed capability (e.g., test) beyond what it already available
  - Mitigating downstream risks (e.g., in a future Phase)
  - → There should exist a path by which technology will transition to the main performers
- Efforts that could extend the technology developed by the main performers by (for example)…
  - Facilitating transition
  - Solving "adjacent" challenges
  - → There should be a clear explanation of how

## Less Likely to Be of Interest

- Efforts that attempt to solve a subset of the same technical challenges the main performers are simultaneously addressing ("Provide a partial solution to the problem")
- Proposals that may merely "improve" the choice of demonstration circuits

***A proposal with metrics and/or demo circuits that are mainly the same as those described in the BAA probably isn't an advanced study***

# Some BAA Excepts

- *A <u>team approach</u> is strongly encouraged.*
- *Each phase will culminate in specified demonstration(s) that will serve to validate that the goals of that phase have been achieved and that the performer has met the GNG metrics.*
- *Offerors should describe, in detail, within their proposal how they plan to evaluate the demonstration circuits to validate that they have met the GNG requirements.*
- *Table 1 shows the minimal set of GNG metric values which must be achieved by the conclusion of each phase. Offerors may, at their option, propose a more ambitious and/or detailed set of GNG metrics.*
- *The primary deliverables for the HiFIVE program will be the experimental demonstrations described in Section 3 above…The performer should deliver the demonstration devices (or copies thereof) along with a description of the test equipment and test procedures necessary to enable the Government to conduct independent test and evaluation.*
- *Proposers must define a realistic schedule and budget that meets the milestone and deliverable requirements.*

# Some Important Dates

| | |
|---|---|
| • Proposal abstract due | 22 Aug 2007 |
| • Feedback from DARPA | 24 Sep 2007* |
| • Full proposal due | 23 Oct 2007 |

* Approx.

***Discussion with the DARPA PM are allowed & encouraged***

# Agenda

### *Introduction*

| | | |
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| 1300-1330 | Background, Program Objectives and Structure | Mark Rosker (DARPA) |

### *Area of Interest I: Vacuum Electronic Circuit Elements*

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### *Wrap-Up*

| | | |
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| 1545-1700 | Questions & Answers | Mark Rosker (DARPA) |