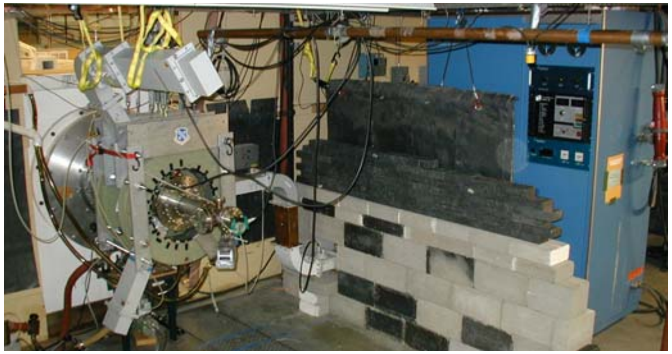

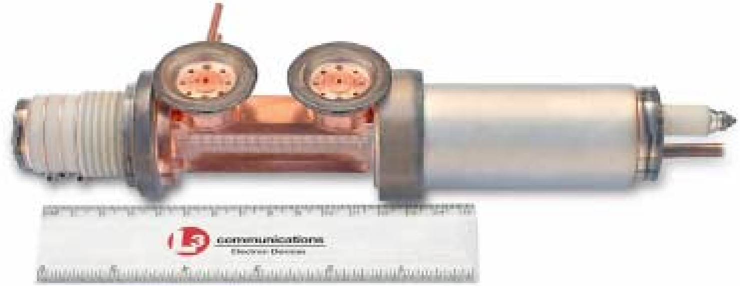

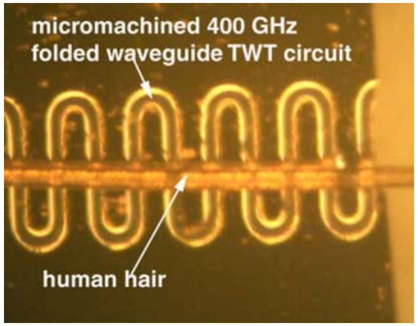

Plasma Physics Challenges of MM-to-THz and High Power Microwave Generation

John H. Booske

University of Wisconsin-Madison
Electrical and Computer Engineering

THE UNIVERSITY
of
WISCONSIN
MADISON

Credits

- *Hundreds* of colleagues and students (grad and undergrad)
- Particular recognition to the university, national laboratory and industrial colleagues and students working collaboratively with and within consortia
  - MURI-99 “Innovative Microwave Vacuum Electronics”
  - MURI-04 “Nanophysics of HPM Cathodes and RF Breakdown”
  - and on various funded and unfunded projects in recent years…
- US-AFOSR, US-ARO, UW, NGC, L3-Comm,…
- Special thanks to APS-DPP Program Committee

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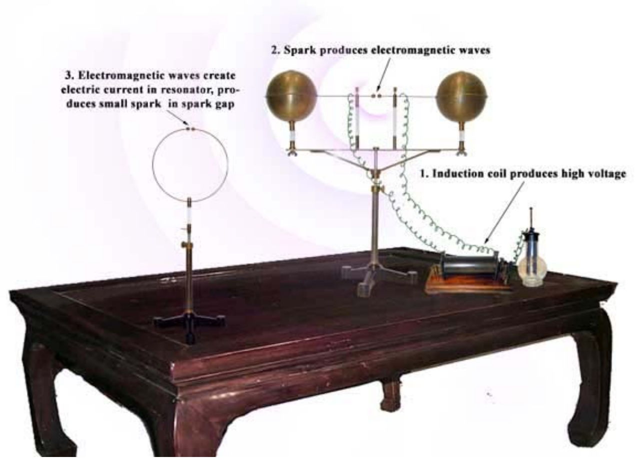
High Power Microwave Generation

- 1885-1889: Heinrich Hertz, generation and study of radio waves, confirming Maxwell's theory
- 1917: Tesla proposed radio wave radar
- 1920-1940: US, UK, France, Germany developed radar for ship & aircraft navigation and enemy plane detection
- RF radar: gave UK edge in Battle of Britain
- Microwave radar using UK-invented, US-improved (MIT Rad Lab) and US-manufactured ***high power magnetrons*** enabled efficient airborne radar to detect U-boat periscopes, anti-aircraft gun defenses, UK radar jammers, and provided air superiority to UK in WWII.
- Post-war surpluses of magnetron and receiver hardware enabled basic research in microwave spectroscopy, atmospheric science, radar, maser, and radio astronomy
- Since WWII, continued advances in microwave generator power and frequency have driven a large fraction of the advances in defense, commercial industry, and science



H. Hertz, Karlsrühe Polytechnic, ~ 1890

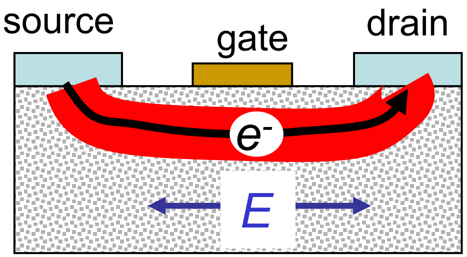
Boot & Randall magnetron, UK, 1939

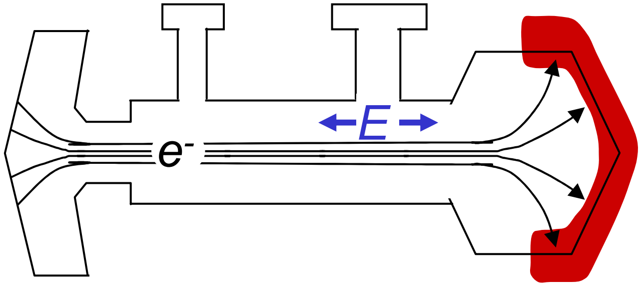
High Power Microwave Applications (using VEDs)

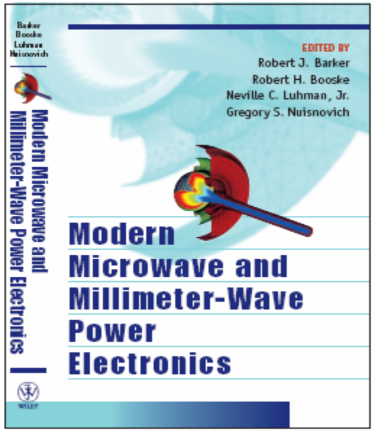
Civilian infrastructure and consumer markets	Broadcast media transmission (TV, radio) Satellite communications Cellular (wireless) communications Radar, e.g.: Air traffic control, Weather, Maritime Global Positioning System Domestic microwave cooking
Military	Radar: Search, Guidance, Track, Missile-seeker, Weather, Test Electronic Counter Measures (ECM) High Power Microwave (HPM) Electronic Attack
Scientific	Plasma heating and fusion energy research Charged particle accelerators Atmospheric radar Radio astronomy Medical/Biomedical Spectroscopy Deep space communications Materials Processing research Ground Penetrating Radar
Industrial	Testing and instrumentation Materials processing Industrial plasmas, especially for semiconductor manufacture

Vacuum vs Solid State Microwave Power Electronics

- Both convert kinetic energy (electron stream) to electromagnetic fields energy
  - Solid state electronic devices: electron stream and fields in solid semiconductor
  - Vacuum electronic devices: electron stream and fields in vacuum
- When high power density is needed, the advantages of vacuum outweigh vacuum packaging challenge and high voltage requirements
  - Managing and removing waste heat
  - Breakdown limits






Barker
Booske
Luhman
Nuisnovich

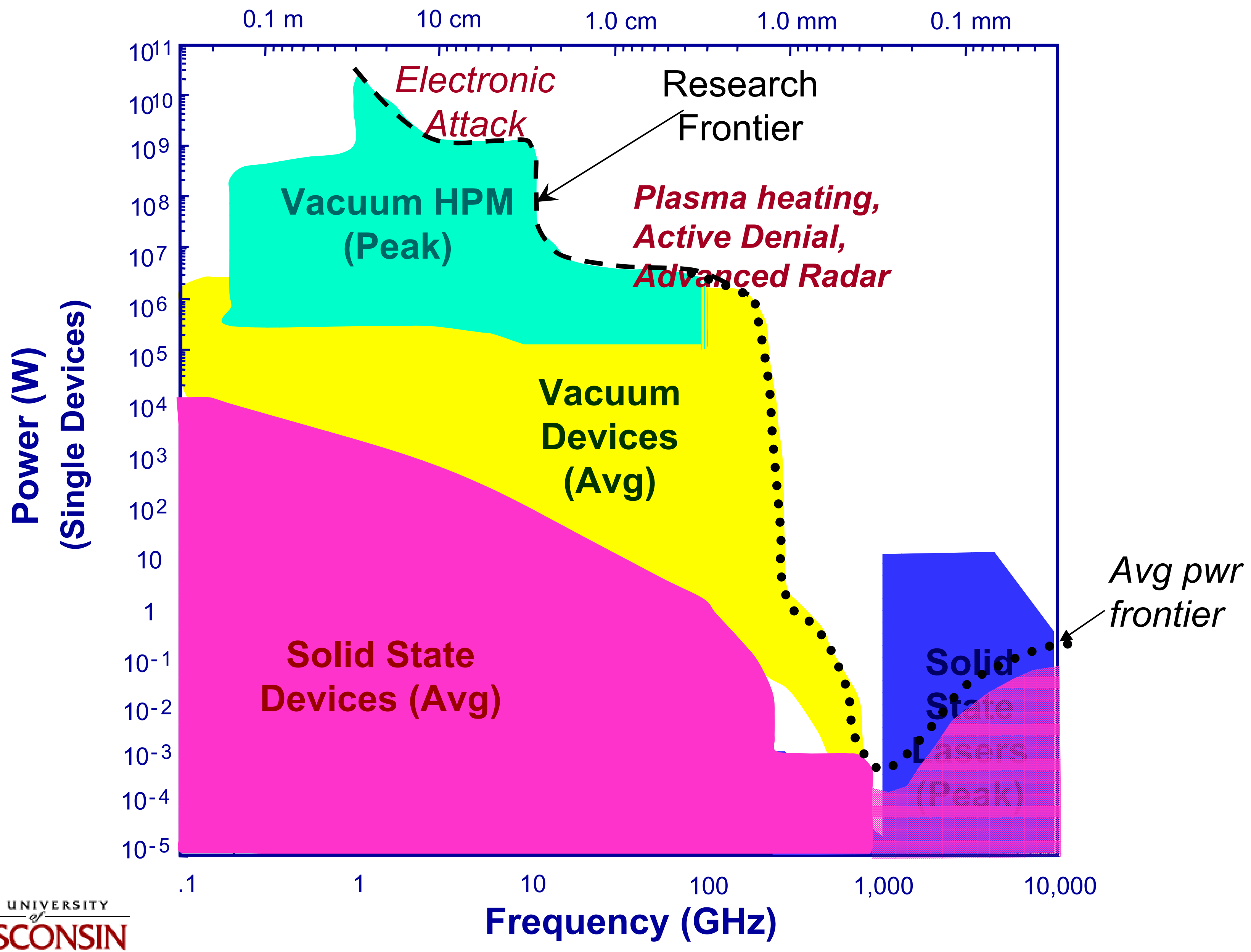
Modern Microwave and Millimeter-Wave Power Electronics

EDITED BY
Robert J. Barker
Robert H. Booske
Neville C. Luhman, Jr.
Gregory S. Nuisnovich

Modern Microwave and Millimeter-Wave Power Electronics

WILEY

See Chapter 1, “Modern Microwave and Millimeter-Wave Power Electronics,” Eds. Barker, Booske, Luhmann, Nusinovich (IEEE/Wiley, 2005).


0.1 m
10 cm
1.0 cm
1.0 mm
0.1 mm
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
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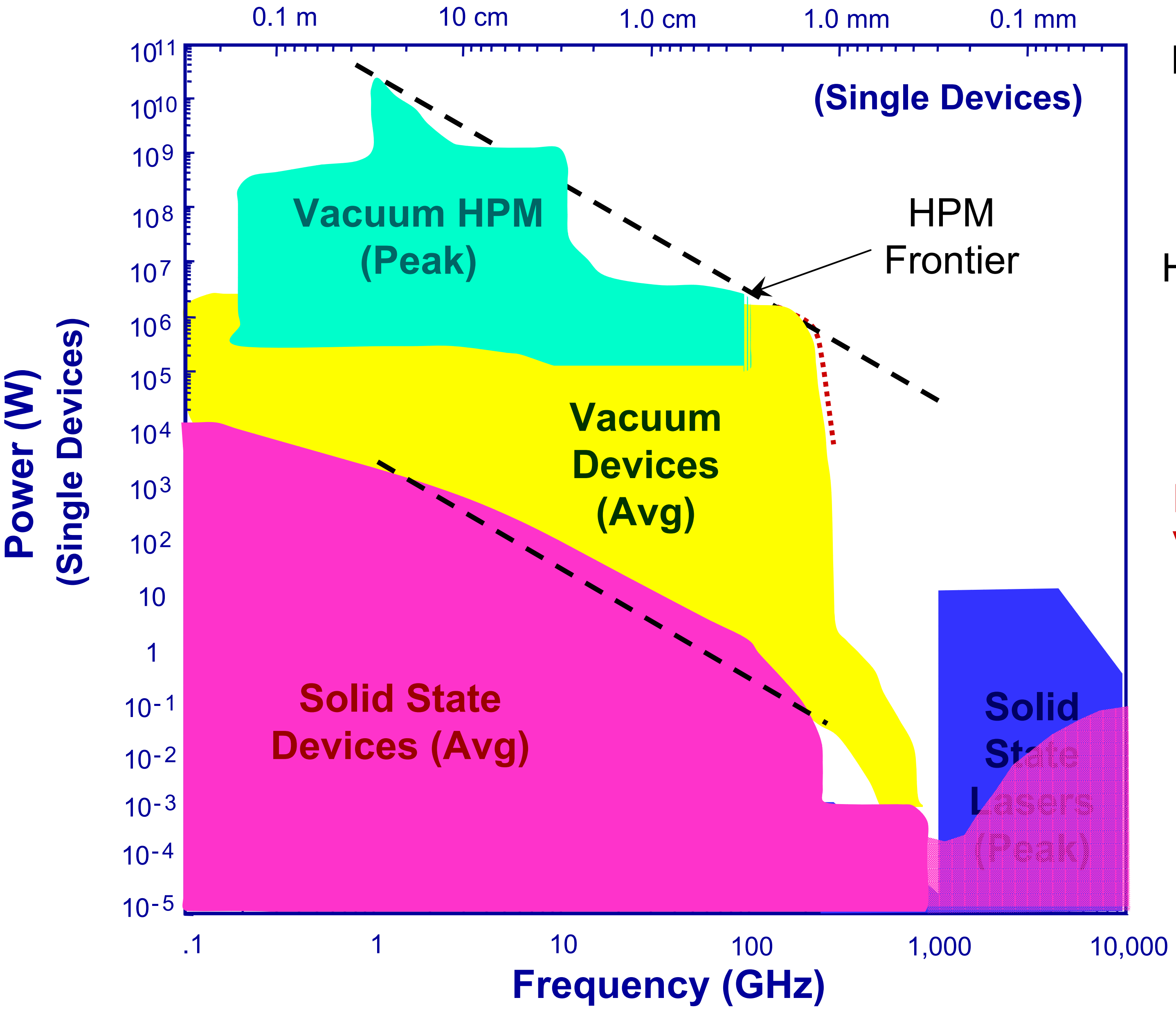
10^{5}
10^{4}
10^{3}
10^{2}
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
Power (W)
(Single Devices)
Electronic
Attack
Research
Frontier
Plasma heating,
Active Denial,
Advanced Radar
Vacuum HPM
(Peak)
Vacuum
Devices
(Avg)
Solid State
Devices (Avg)
Solid
State
Lasers
(Peak)
Avg pwr
frontier
.1
1
10
100
1,000
10,000
Frequency (GHz)



High power limit for Solid State $\propto 1/f^2$

and

HPM frontier $P \propto 1/f^2$

…*BUT* …

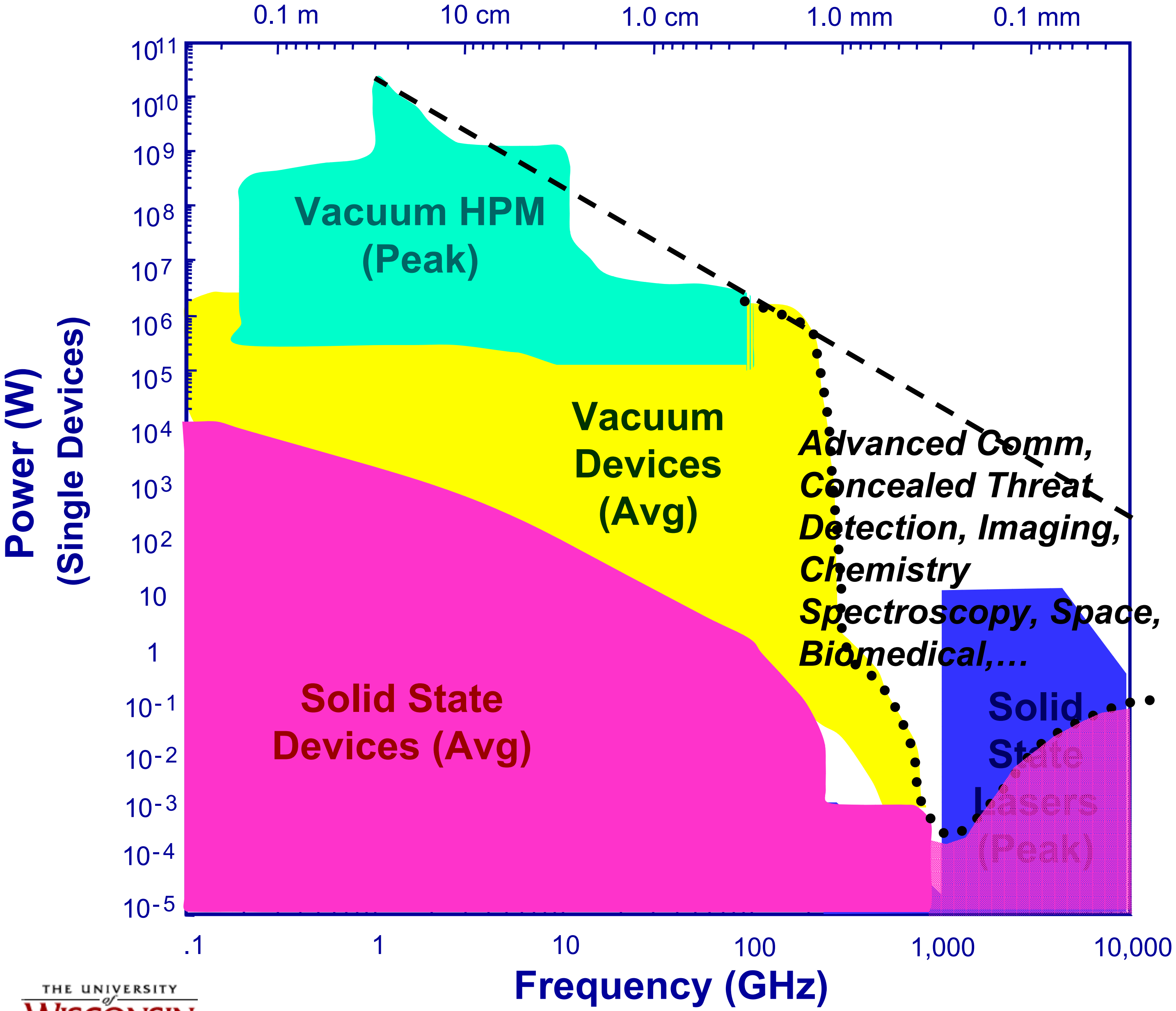
For $f > 100$ GHz VEDs frontier

$\langle P \rangle \not\propto 1/f^2$

* *note: does not include peak power from FELs above 100 GHz*

The "THz" regime"

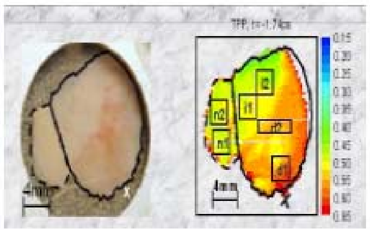
(THz and subTHz)



Security

Jeff. Lab

Medical



TeraView

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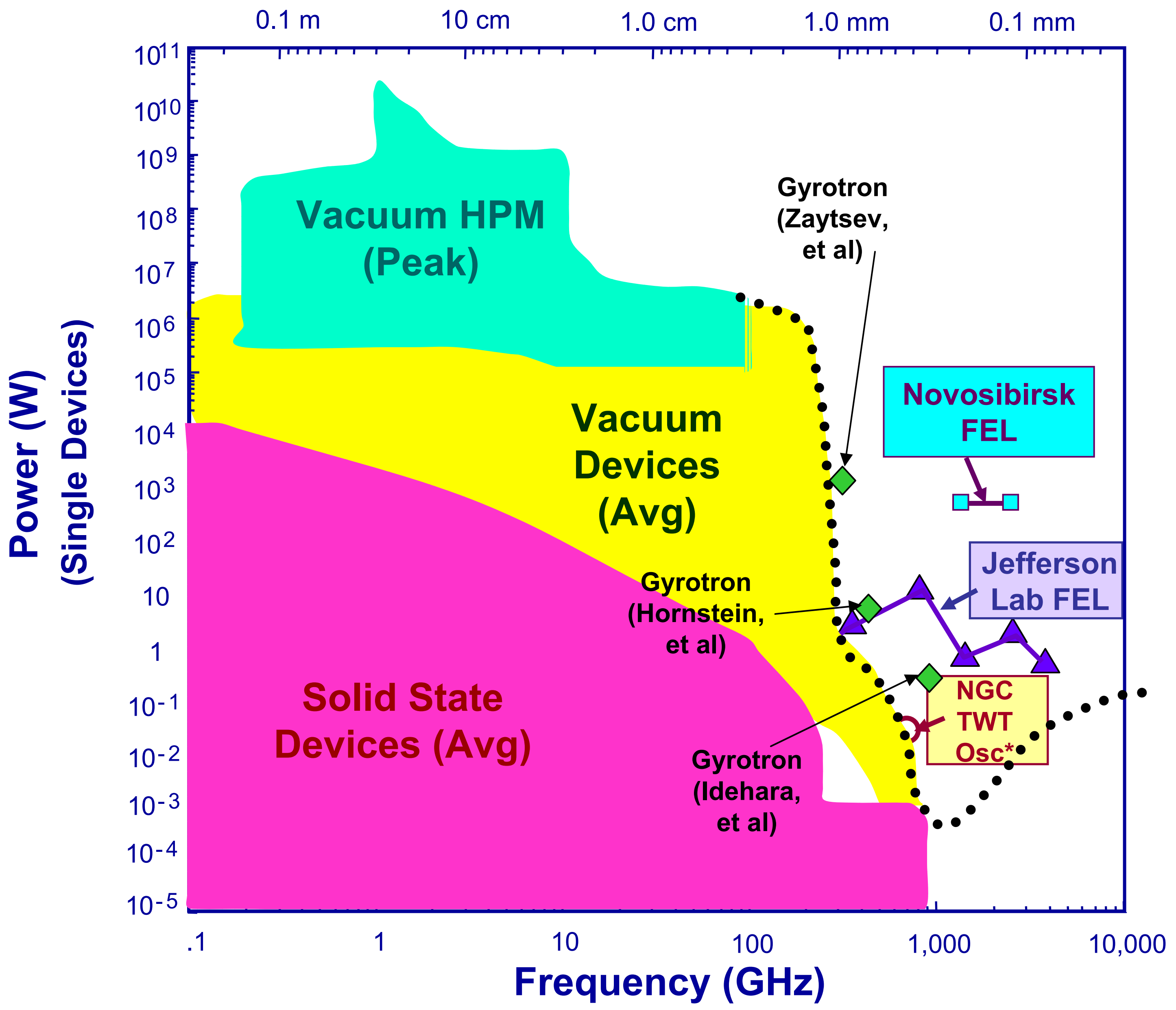
Recent vacuum electronic device breakthroughs towards filling the THz gap



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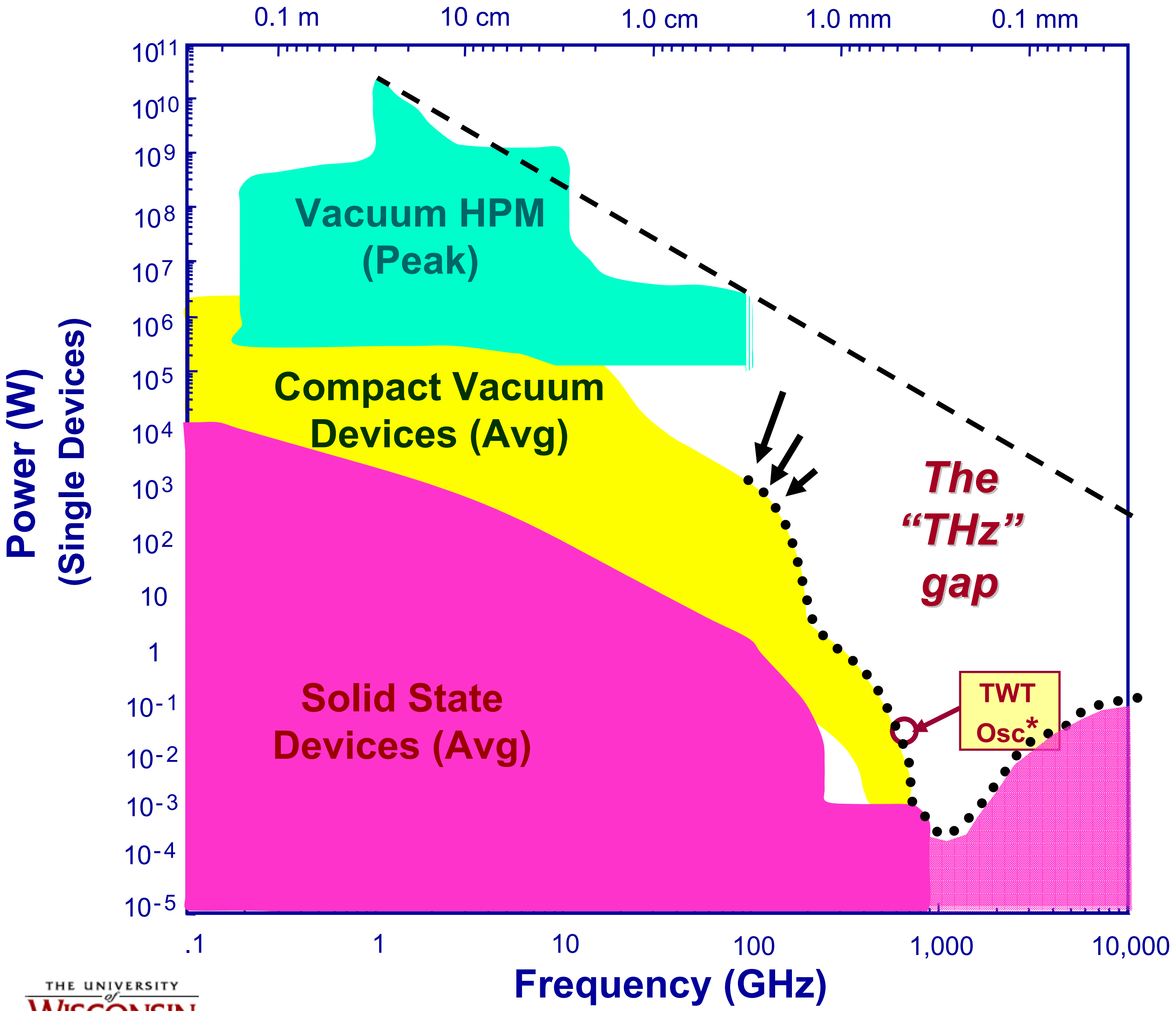
** note: does not include peak power from FELs above 100 GHz*



Modified edge of the frontier, given that many THz applications require *compact* and *mobile* sources with *high average power*

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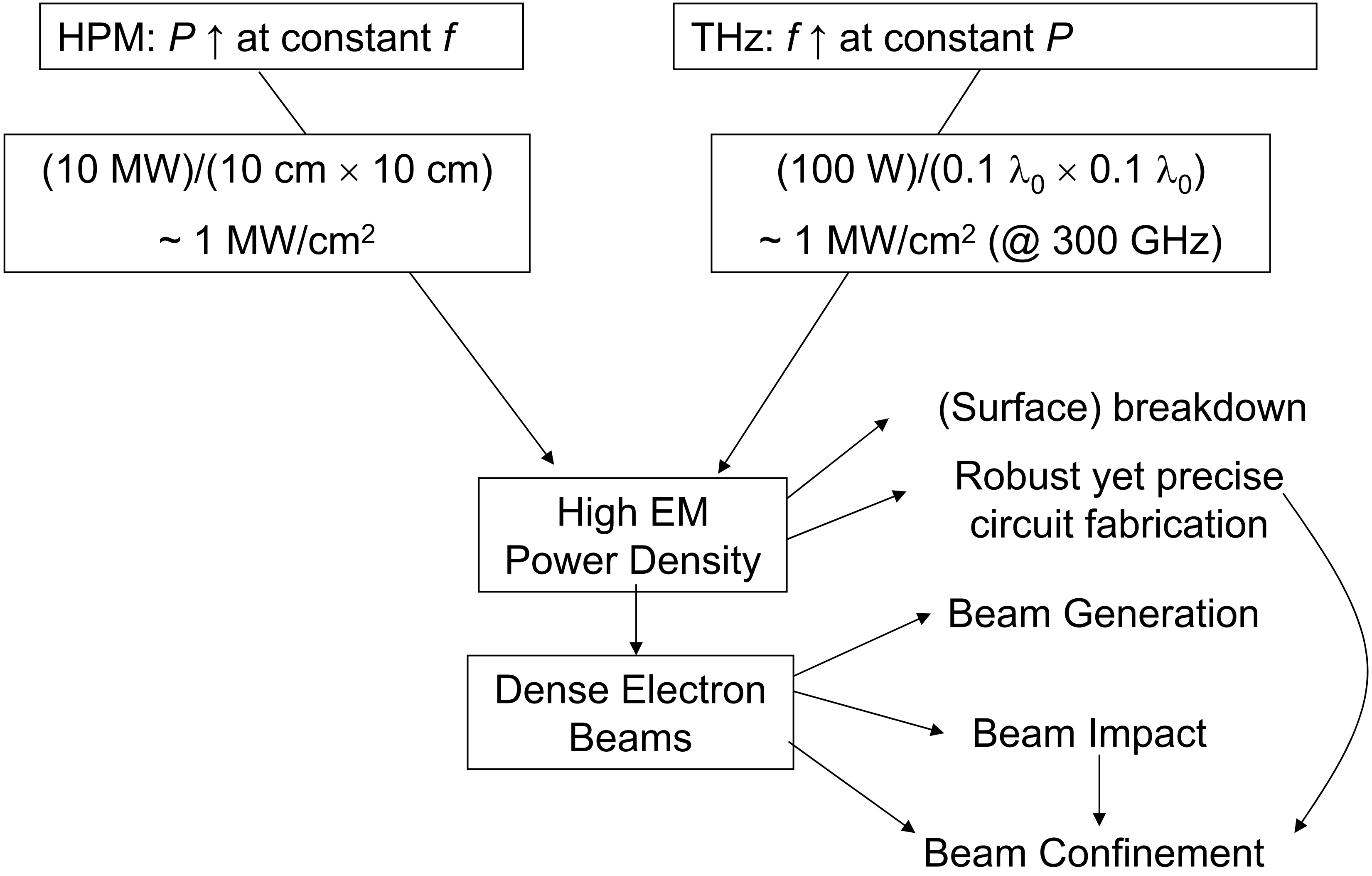
High Power Research Frontier

- Apparently two frontiers
  - Constant Pf^2 limit of HPM (1-100 GHz)
  - mmwave-to-THz, or "THz" gap (100 – 1000 GHz)
- Not so separate as they might seem: they share common "plasma physics" and related challenges of high power density:
  - Dense electron beams
  - Maximizing RF power density

Scaling



HPM: P ↑ at constant f

THz: f ↑ at constant P

(10 MW)/(10 cm × 10 cm)

~ 1 MW/cm^2

(100 W)/($0.1\ \lambda_0 \times 0.1\ \lambda_0$)

~ 1 MW/cm^2 (@ 300 GHz)

High EM Power Density

Dense Electron Beams

(Surface) breakdown

Robust yet precise circuit fabrication

Beam Generation

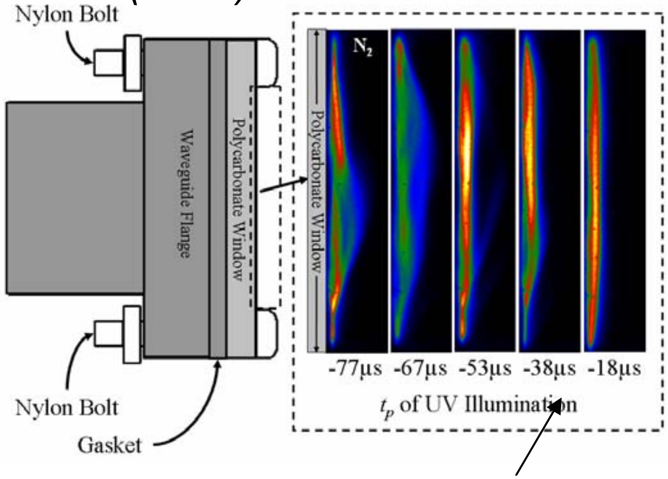
Beam Impact

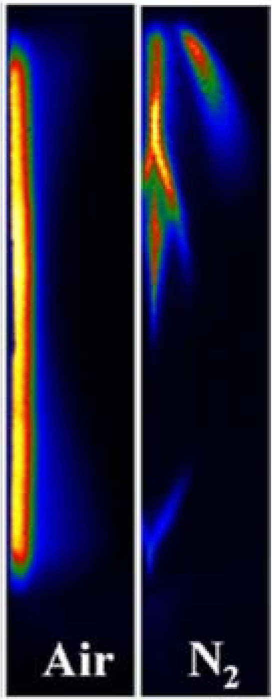
Beam Confinement

High Power Density: RF Breakdown

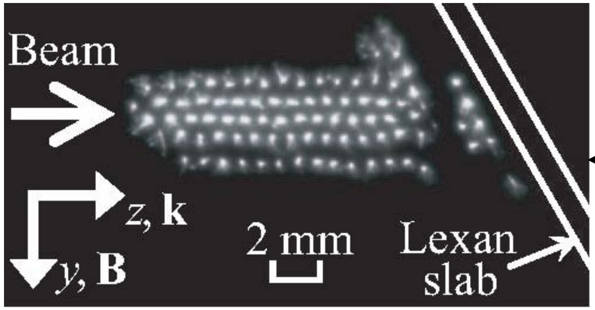
- Inside the vacuum device
  - Arcing damage
  - Interrupted operation
- Outside the vacuum
  - Reflected radiation
- Intense *E* fields
- Experiments
  - $E = f(p, \tau)$
  - Surface & *UV* effects at < 10 GHz and < 300 torr (TTU)
  - No *UV* or surface effects at 110 GHz, 760 torr but filamentation dominant (MIT)
  - *E* ~ 20-30 kV/cm @ 760 torr (AFRL, MIT, UW, 1 GHz – UV laser)

*Neuber, et al, Phys. Plasmas, **14**, 057102 (2007)*





2.85 GHz
TTU

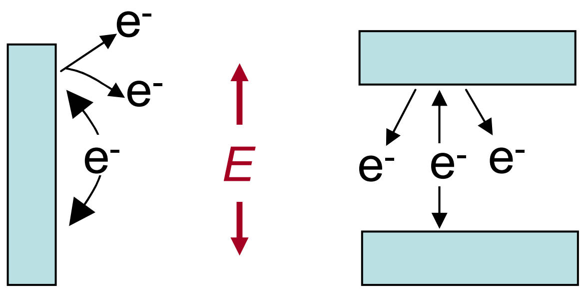


110 GHz
MIT

Hidaka, et al, Phys. Rev. Lett., in review (2007)

See also Poster TP8 42, Hidaka, et al, Thurs AM

RF Breakdown: Theoretical Understanding



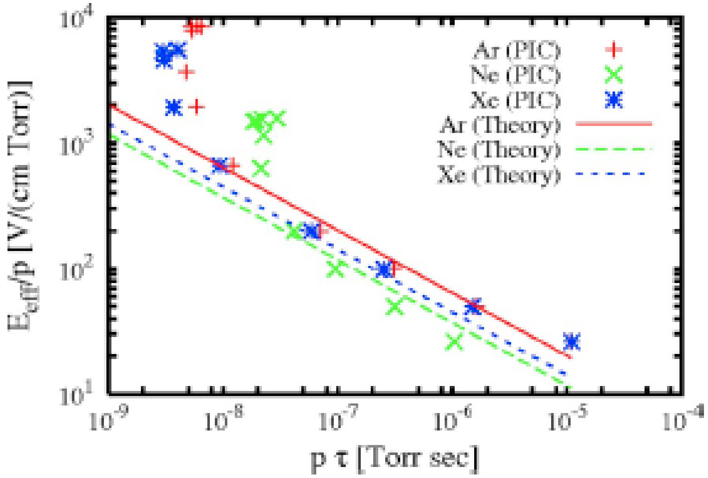
- Vacuum
  - Surface breakdown via multipactor

$$\tau_{transit} = 2m\,\mathrm{v}_0/eE_0 = T/2 \qquad \& \; \gamma(W_i) > 1$$

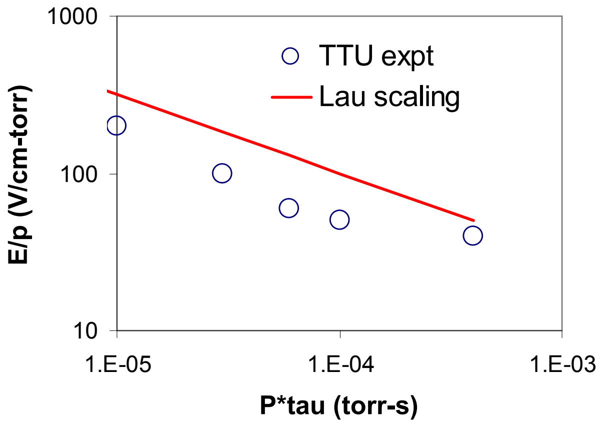
or field emission

$$E > \sim 10^8 \text{ V/m}$$

  - Primarily accelerator cavities
- High Pressure
  - Avalanche gas breakdown via avalanche ionization



$$E_{eff}[\mathrm{V/cm}] \approx K\sqrt{\frac{p(\mathrm{torr})}{\tau(\mathrm{s})}} \qquad \begin{cases} K \sim 0.05, \text{noble gases} \\ \mathrm{K} \sim 1, \text{air} \end{cases}$$



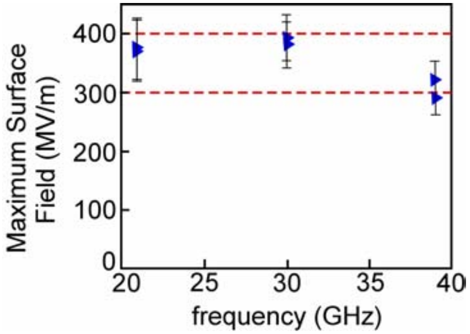
Lau, Verboncoeur, Kim, Appl. Phys. Lett. ***89****, 261501 (2006)*

See also, Oral Talk NO7, Wed morning, Nam, et al.

Frequency scaling

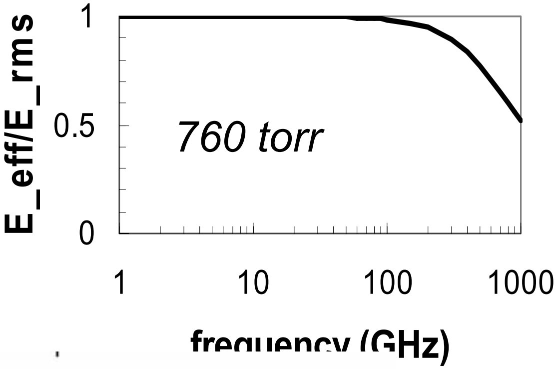
- Vacuum Breakdown

Braun, et al, PRL, vol 90, 224801 (2003)



- Air Breakdown

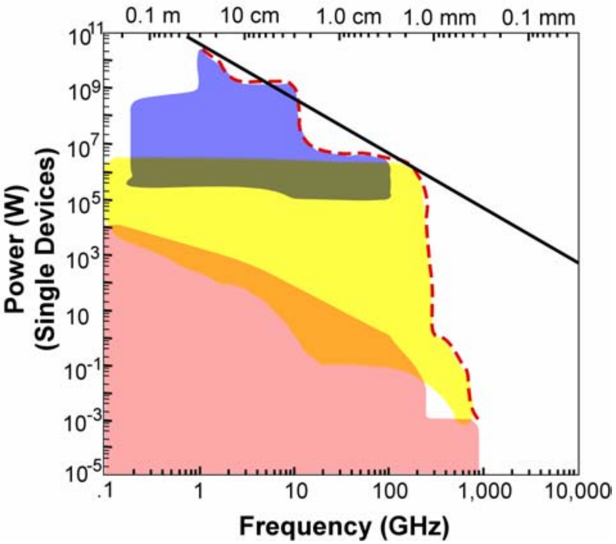
$$E_{eff} \approx \frac{E_0/\sqrt{2}}{\sqrt{1+\left(\omega/\nu_{\text{coll}}\right)^2}} \sim 20-30\,\text{kV/cm}$$



- Conclusions:
  - *E* for breakdown is ~ constant with frequency, or…

$$E_{BD} \sim \sqrt{Pf^2}$$

  - Breakdown a limiting phenomenon for f < ~100 GHz
  - Breakdown is not the limiting issue for f > ~100 GHz



High Power Density: THz Circuit Fabrication

- Limiting phenomenon: circuit sizes required for compact generators at $f > 100$ GHz
  - $r_{\text{circuit/tunnel}} \sim 0.1\lambda_0$ and $r_{\text{beam}} \sim r_{\text{ckt}}/2$

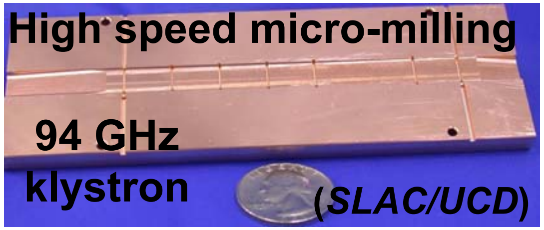
- For "as-designed" performance, need dimensional errors < ~ 3%

  [Pengvanich, et al, IEEE TED (to be published, 2008)]

  See also, Poster TP8 39, Pengvanich, Thursday, AM

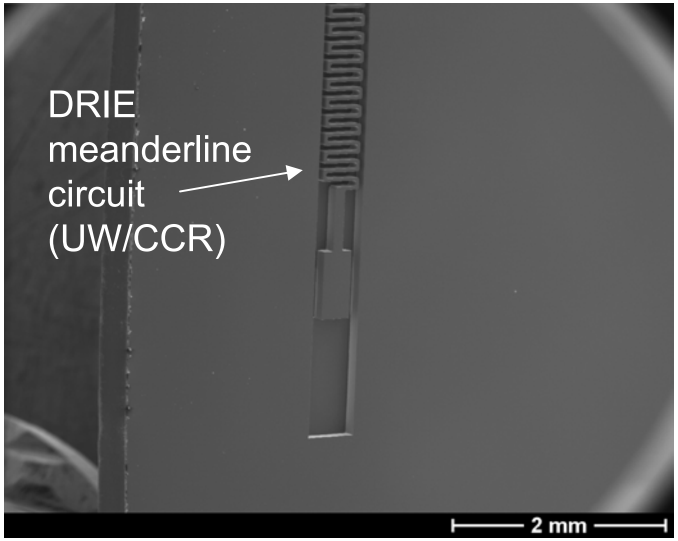
- How to make and assemble such precise circuits with high yield?
- Recent, intensive efforts to adapt MEMS microfabrication techniques to high frequency VEDs
  - 3D, mechanically and thermally robust
  - Many approaches under investigation
    - High speed micro-milling
    - Micro-EDM
    - Laser micromachining
    - Deep Reactive Ion Etching of Si (both circuits and molds)
    - Xray LIGA
    - UV LIGA

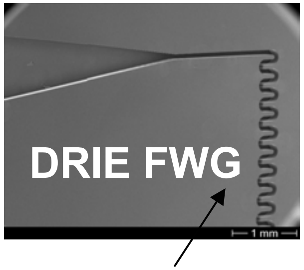
Microfab Circuit Examples


High speed micro-milling

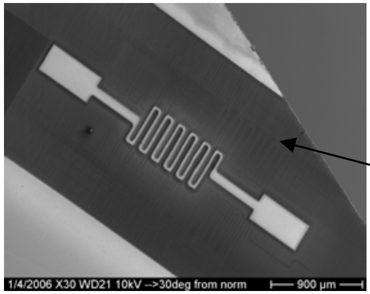
94 GHz klystron

(SLAC/UCD)


DRIE meanderline circuit (UW/CCR)


DRIE FWG

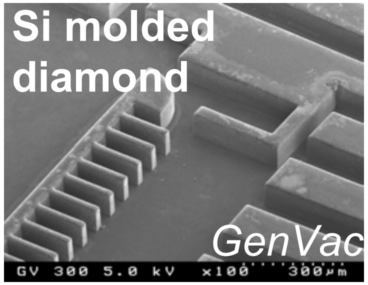
UW's DRIE FWGs in Si used by NGC for 670 GHz THz TWT oscillator



Laser micromachined meanderline circuit (UW/CCR)


FWG made by xray LIGA (SNU)

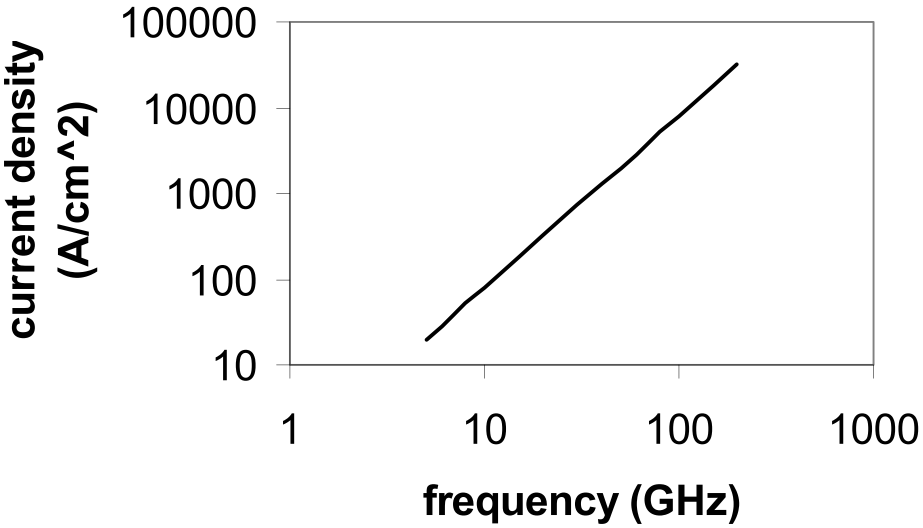
- Emerging "front-runners"
  - Micro EDM (< 10 µm wire diameter)
  - Deep Reactive Ion Etching of Si

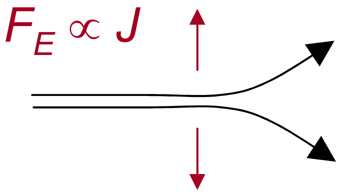

Si molded diamond

GenVac

Small Circuits + High Power = Dense Beams

- Reference device: 5 GHz, 100 W TWT amplifier
  - 2.5 kV, 0.2 A, 20 A/cm^2, $r_{ckt} \sim 0.02\lambda_0$ for compact high gain & efficiency
- Scale to 200 GHz at constant voltage…λ decreases by 40 X





Magnetic field focusing:

$$\omega_c^2 \geq 2\omega_p^2$$

or

$$B[\mathrm{kG}] \geq 1.5\frac{\sqrt{J\left[\left(\mathrm{A/cm}^2\right)\right]}}{\left(V[\mathrm{volts}]\right)^{1/4}}$$

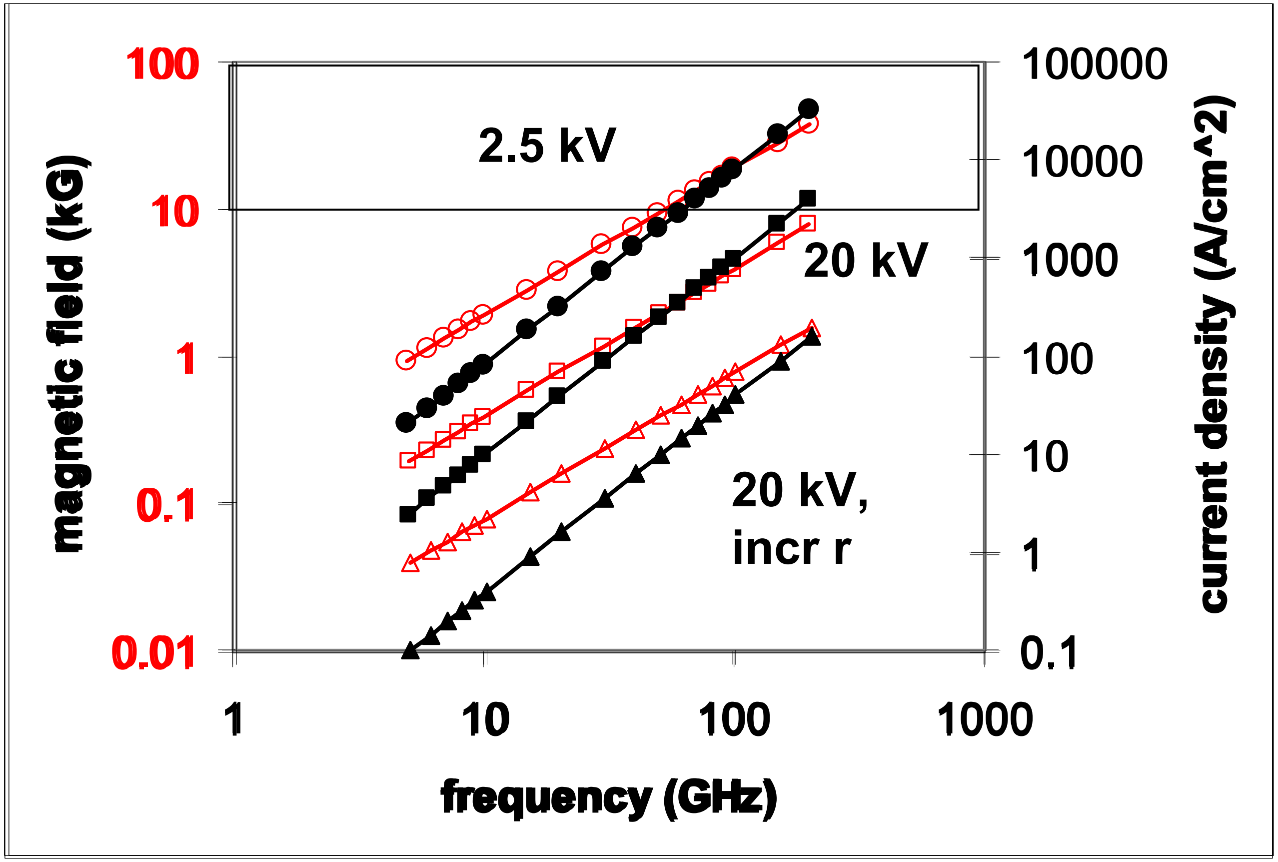
Scaling Challenges and Options

- Scale 5 GHz, 100 W TWT amplifier to 200 GHz
  - 2.5 kV, 0.2 A, 20 A/cm^2, $r_{ckt} \sim 0.02\lambda_0$ for compact high gain & efficiency
- $B_{max} \sim 10$ kG

Constant V

V → 20 kV

r ↑ 5 X



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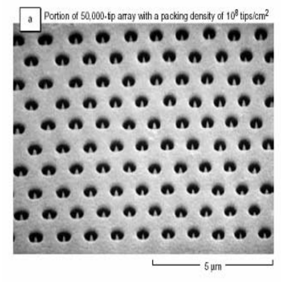
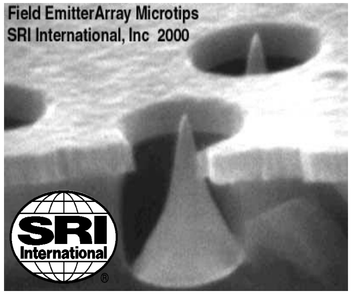
Recent High-J Cathode results

Field Emission-DC

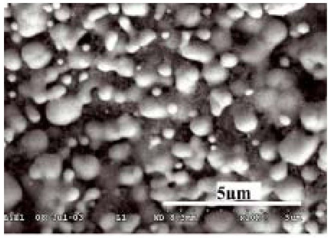
Gated Mo-tip field emitter array

(650 A/cm^2)



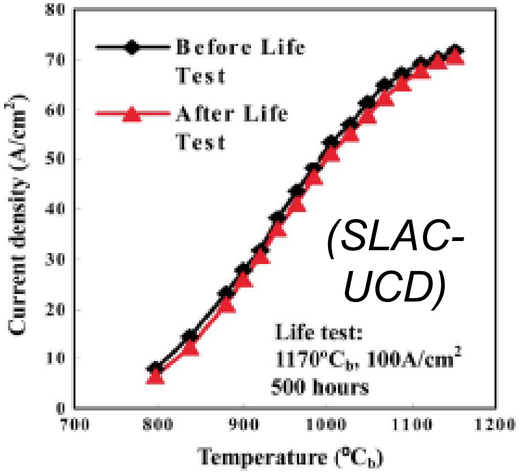


Thermionic Emission



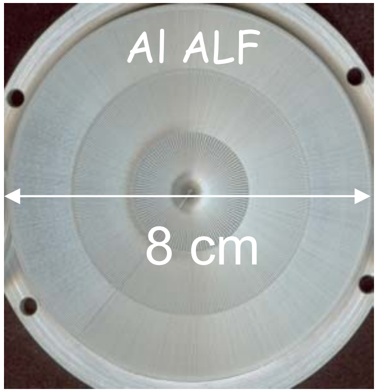
Scandate nanoparticles in porous Ba-doped W matrix

(BVERI)



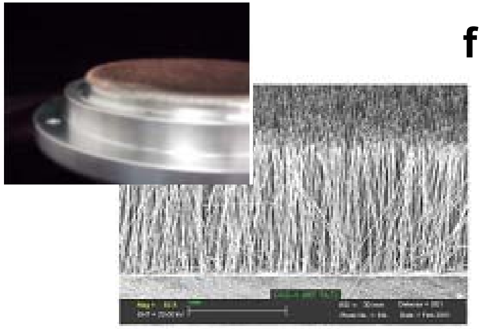
(SLAC-UCD)

Field Emission-pulsed



Laser-micro-textured aluminum cathode (UMich)

Sandia Natl Lab
80,000 A @ 4 MV (1.6 kA/cm^2)

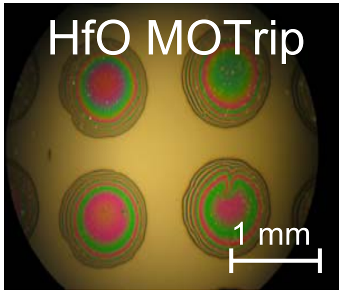


Csi-coated graphite fiber (AFRL-Kirtland)

> 10X reduction in E$_{turnon}$ due to CsI

10^6 shots

Up to 1 kA/cm^2



Metal oxide Triple Point cathode (UMich)

Gain extra ~ 80 A/cm^2

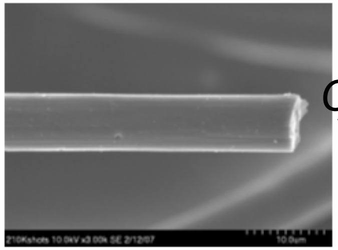
Posters TP8 36, 37
Thurs AM

Advancing cathode physics: Minimizing $E_{turn\text{-}on}$

Vlahos, Morgan, Booske
APL **91**, 144102 (2007)

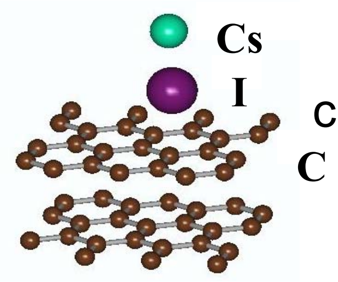
CsI treatment reduces $E_{turn\text{-}on}$ by 10-20X

Hi-res SEM →



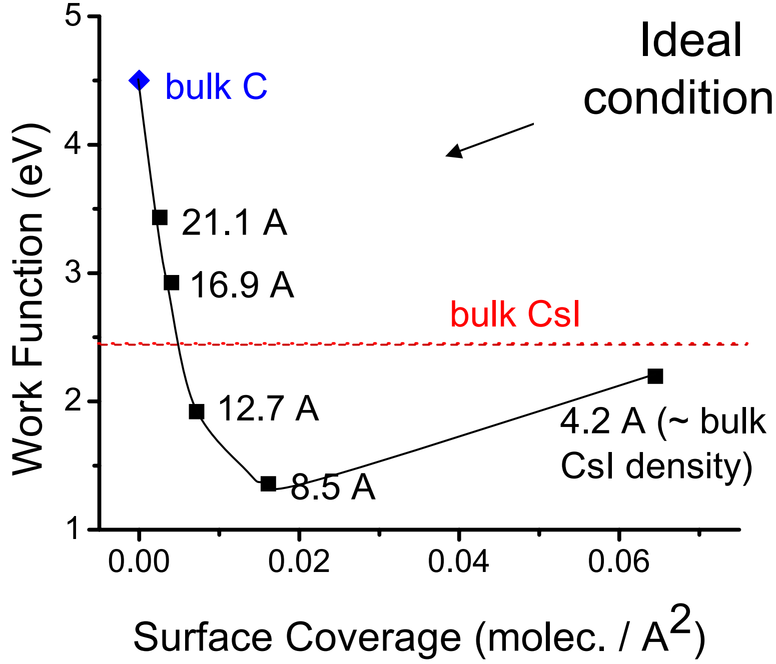
200K Shots

CsI thin film →

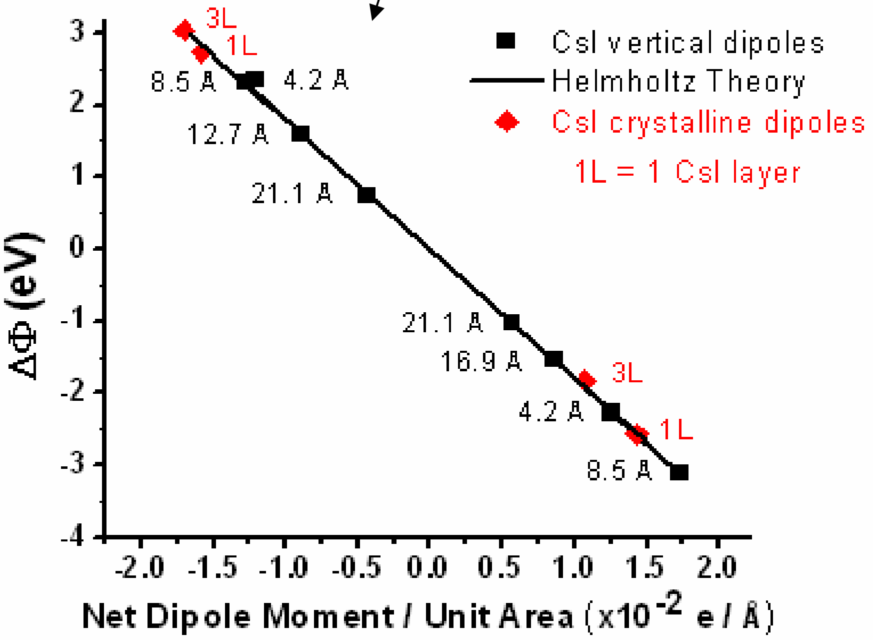


Ab initio computational modeling (V.A.S.P.)

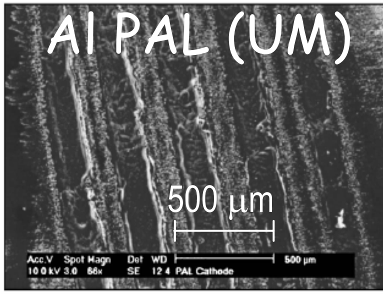
Why it works



Ideal conditions

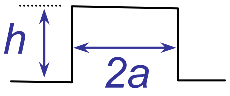


Advancing cathode physics: understanding field enhancement



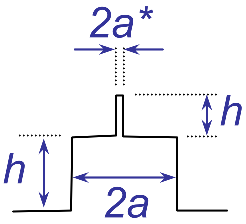
- Experimental studies [X.He, et al, Conf Proc IEEE IVNC, 2007] indicate that β~ 9-10 experimentally with ridges like these, when β~ 3 according to E-static calcs
- Recently derived the vacuum field enhancement factor for knife edge using conformal mapping*

$$\boxed{\beta\big|_{h>>a} \cong \sqrt{\frac{\pi}{4}} \times \sqrt{\frac{h}{a}} \propto \sqrt{\frac{h}{a}}}$$



- Asked question: what if decorated by small “invisible” features? What is net field enhancement?
- Derived result again for rectangular ridges (knife edges)

$$\boxed{\beta^*\big|_{h>>a>>h^*>>a^*} \cong \sqrt{\frac{\pi}{4}\frac{h}{a}} \times \sqrt{\frac{\pi}{4}\frac{h^*}{a^*}}}$$



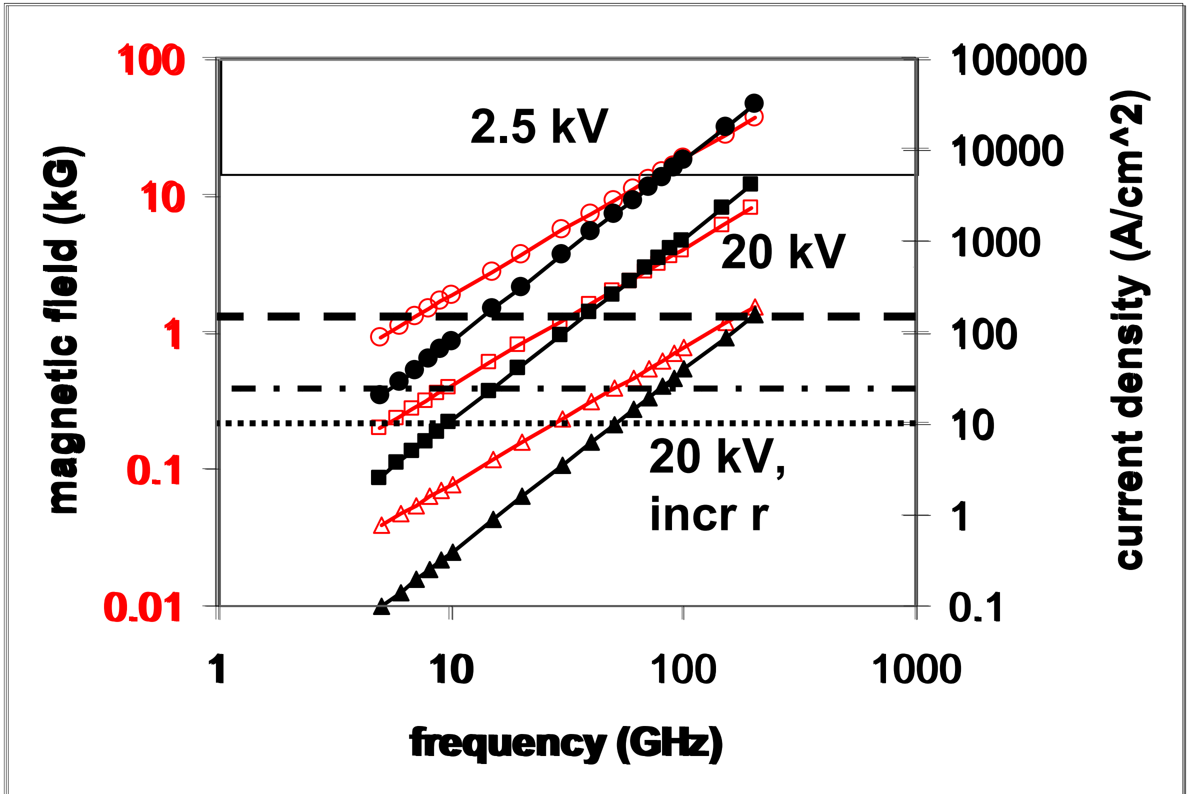
- Effect is not additive or dominated by one feature…effect is *multiplicative*
- Confirms and proves conjecture by Schottky [(Z. Physik **14**, 63,(1923)]

* Miller, Lau, and Booske, APL **91**, 074105. (2007)

See also, Poster TP8 38, Thursday AM

DC Dense Beam Cathode Summary

- Generating dense beams, i.e., cathodes
- Maximum cathode emission
  - Field emission—laboratory < 650 A/cm^2
  - Thermionic—short life (~ 100s hrs) < 150 A/cm^2
  - Field emission—device < 20 A/cm^2
  - Thermionic—long-life (1000s hrs) < 10 A/cm^2



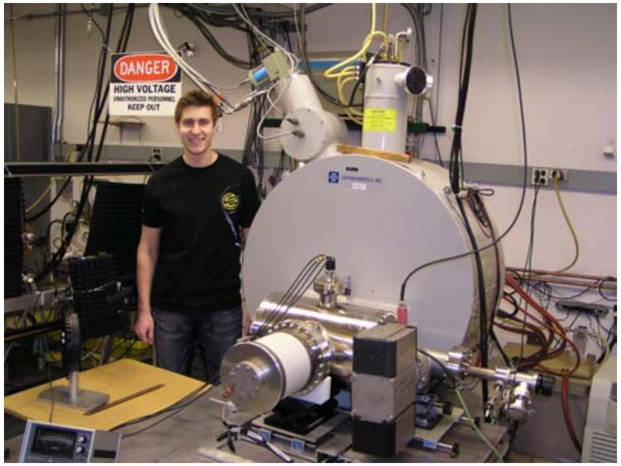
Advancing cathode physics: emission uniformity

- Mode competition and efficiency of vacuum electron devices are affected by the uniformity of electron beam
- High power mmwave gyrotron cathode emission is *not* uniform
- Two theories, both implicating mechanical machining and fabrication

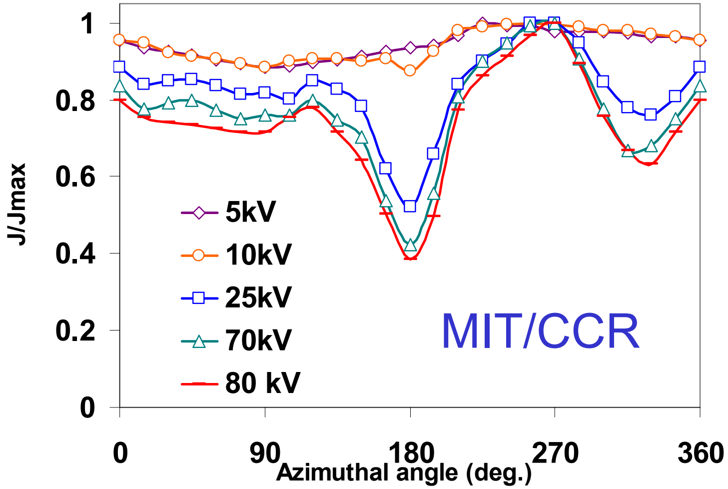
Anderson et. al , IEEE-TED 52, p. 825, 2005

Jensen, Lau, Jordan, APL **88** 164105 (2006)

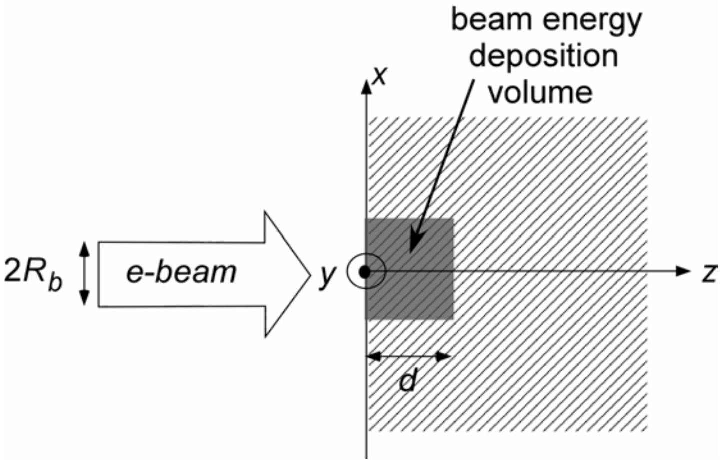
- Measurements at CCR underway with new cathodes made with new diamond cutting and Ba impregnation processes



110 GHz, 1.5 MW gyrotron (MIT)



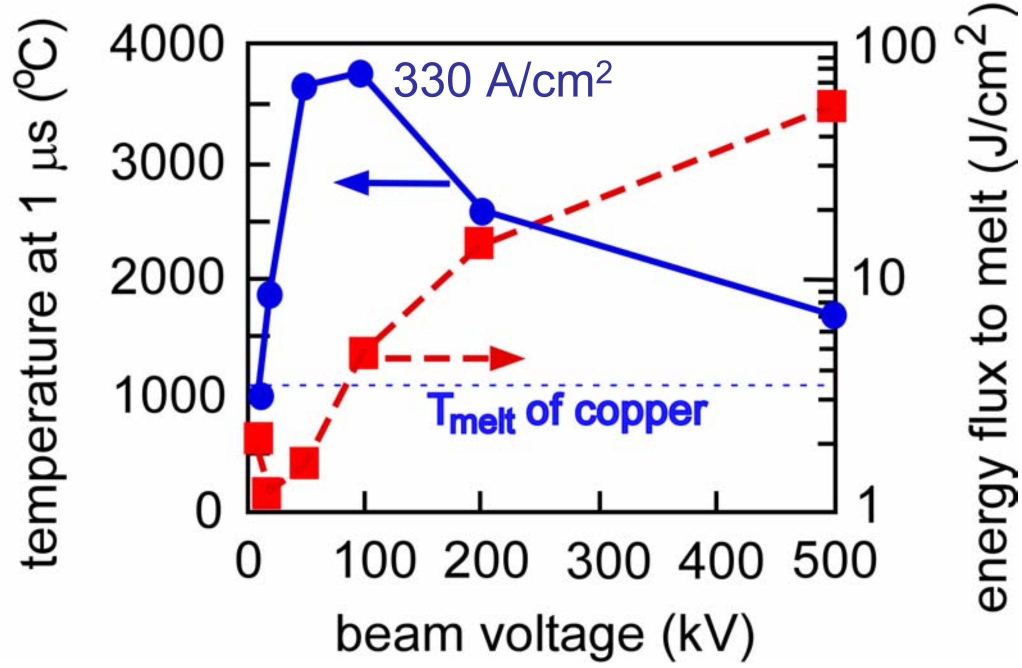
Dense beam impact physics



$$T(0,0,0,t)=\frac{V_bJ_b}{d\rho c}\int_0^t d\tau\left[\mathrm{erf}\left(\sqrt{\frac{t_r}{4\tau}}\right)\right]^2\mathrm{erf}\left(\sqrt{\frac{t_z}{4\tau}}\right),$$

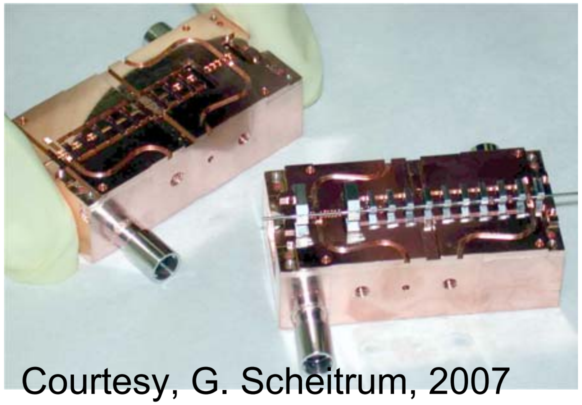
$$t_r=\frac{R_b^2}{D}\quad,\ t_z=\frac{d^2}{D}$$

(assume square cross section beam for easy math)

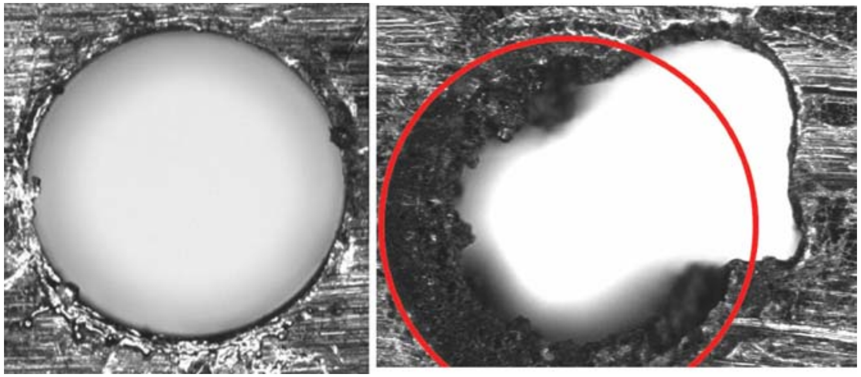


Beam Impact: experimental illustration

- SLAC *Klystrino*: 94 GHz, 1 kW klystron
  - G. Scheitrum, et al, *IEEE I.V.E.C. Conf Digest* (2002)
- 110 kV, 2.4 A, 0.25 mm radius
- Magnetic focusing design had small error near output (quadrupole leakage fields)
- Beam interception at exit of circuit
  - ~ 1 mm^2 impact area
  - ~ 1 MW/cm^2
  - t ~ 5 μs
  - Exceeded single pulse damage threshold
- *3D Electron optics and magnetic design codes are better now*
- Superior approaches currently being pursued (…more shortly)



Courtesy, G. Scheitrum, 2007



Additional Challenge: *at high frequencies, space charge not the magnetic focusing limit*

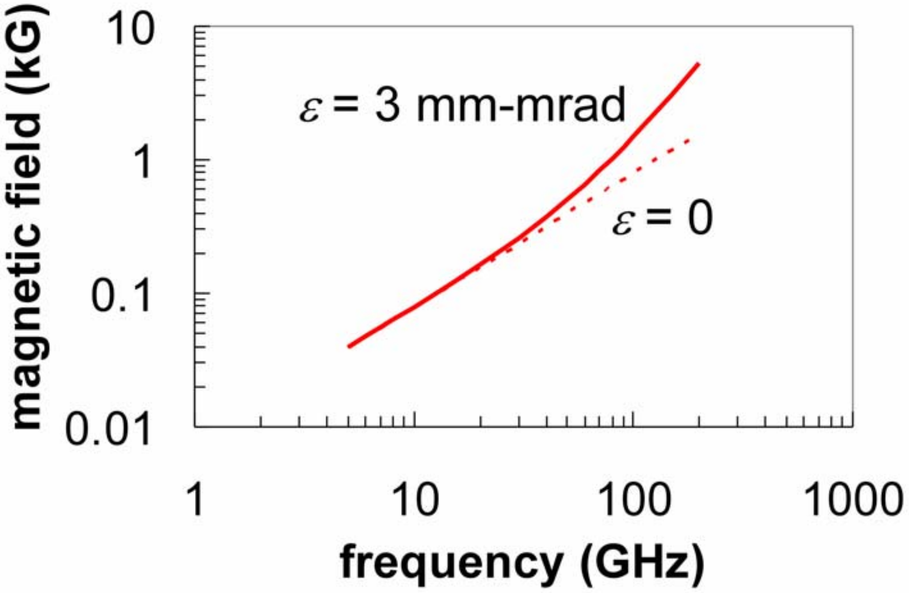
- Electrons have random transverse velocities
- Magnetic field must confine *both* space charge and transverse "pressure gradient" defocusing forces (*emittance*)
- Typical well-designed VED beam has ε ~ 3 mm-mrad
  - Edge emission
    - J.M. Finn, et al, IEEE T.P.S. **16**, 281 (1988)
  - Roughness
    - Y.Y. Lau, J.A.P. **61**, 36 (1987)
- Scaled 100 W, TWT with 20 kV and max radius
  - $kT_\perp$ ~ 5-10 eV @ 200 GHz
  - Single-gate FEAs, $kT_\perp$ ~ 10 eV

$$\omega_c^2 \geq 2\omega_p^2 + \left(\frac{2u_0}{a^2}\right)^2 \varepsilon^2$$

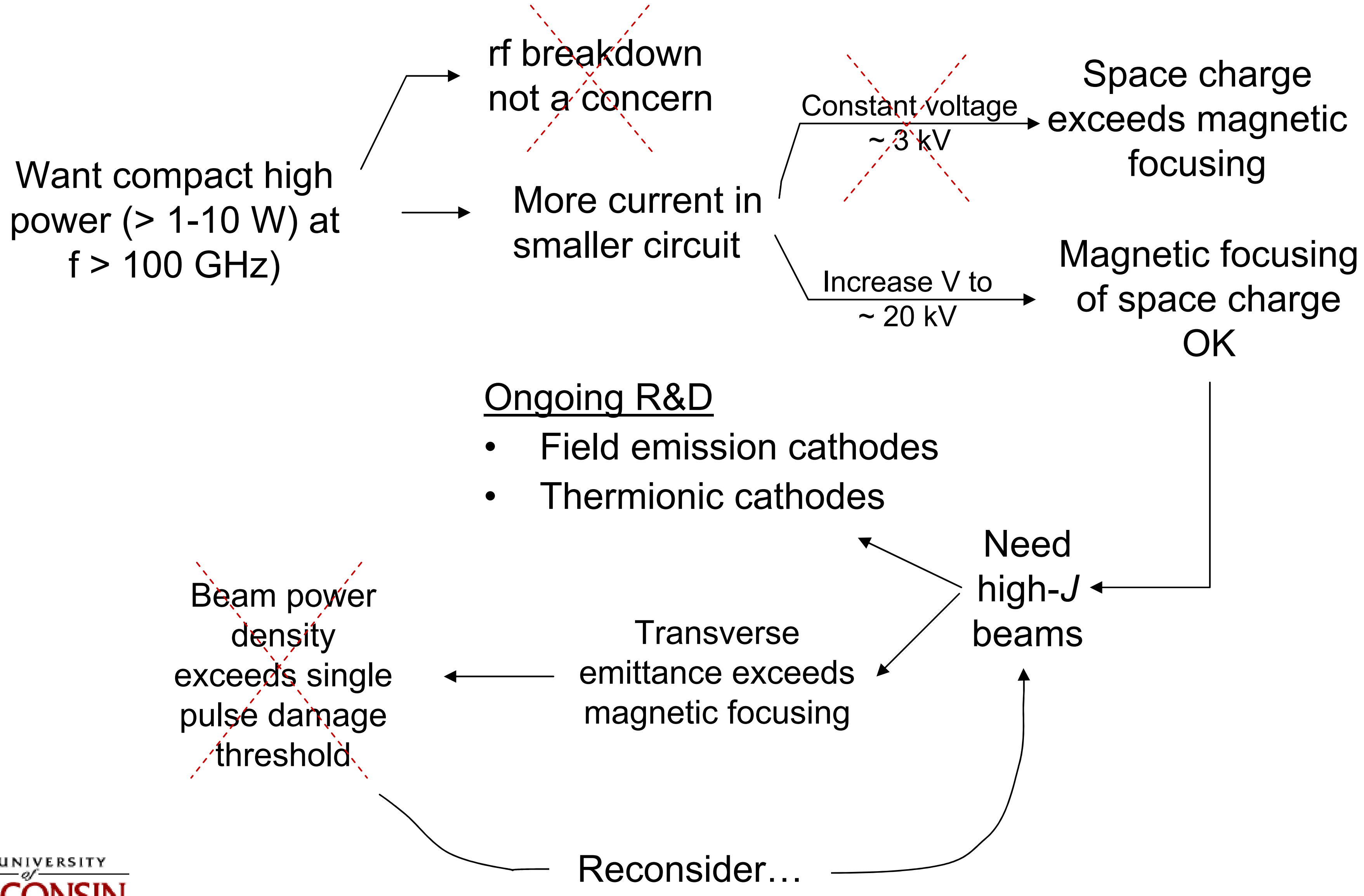
or

$$\omega_c^2 \geq 2\omega_p^2 + \frac{8kT_\perp}{ma^2}$$

J.D. Lawson, The Physics of Charged Particle Beams (Oxford, 1977)



Recap: higher compact THz power



Want compact high power (> 1-10 W) at f > 100 GHz)

~~rf breakdown not a concern~~

More current in smaller circuit

~~Constant voltage ~ 3 kV~~

Space charge exceeds magnetic focusing

Increase V to ~ 20 kV

Magnetic focusing of space charge OK

Need high-*J* beams

<u>Ongoing R&D</u>

- Field emission cathodes
- Thermionic cathodes

Transverse emittance exceeds magnetic focusing

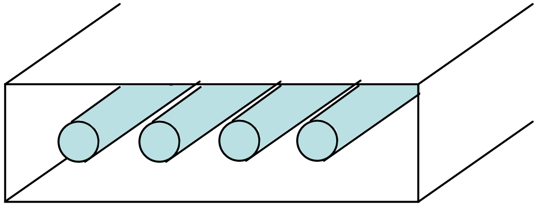
~~Beam power density exceeds single pulse damage threshold~~

Reconsider…

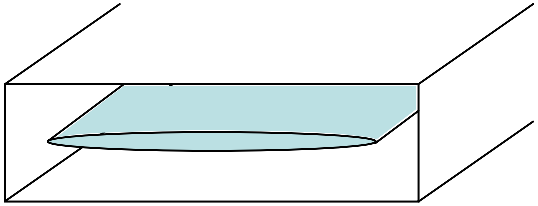
Alternative: Distributed Beams

- Objective: high beam *current* in small (high frequency) “circuits”
- Reduce current density by spreading out beam in one dimension, but leave other dimension small
- Options

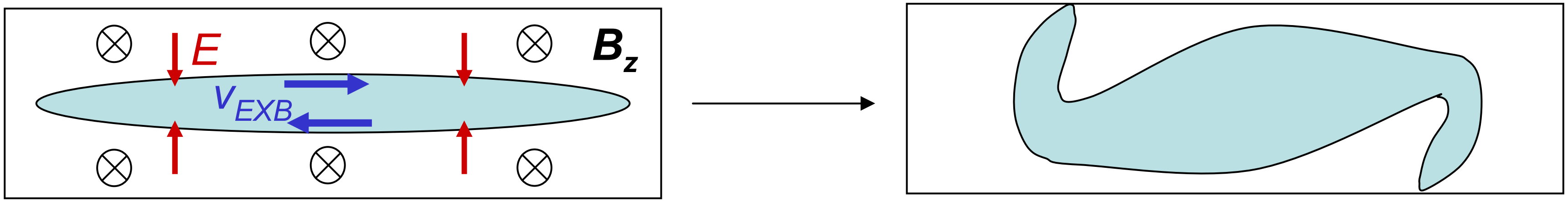
Multibeams



Sheet Beams

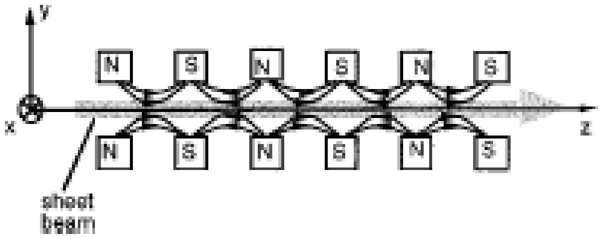


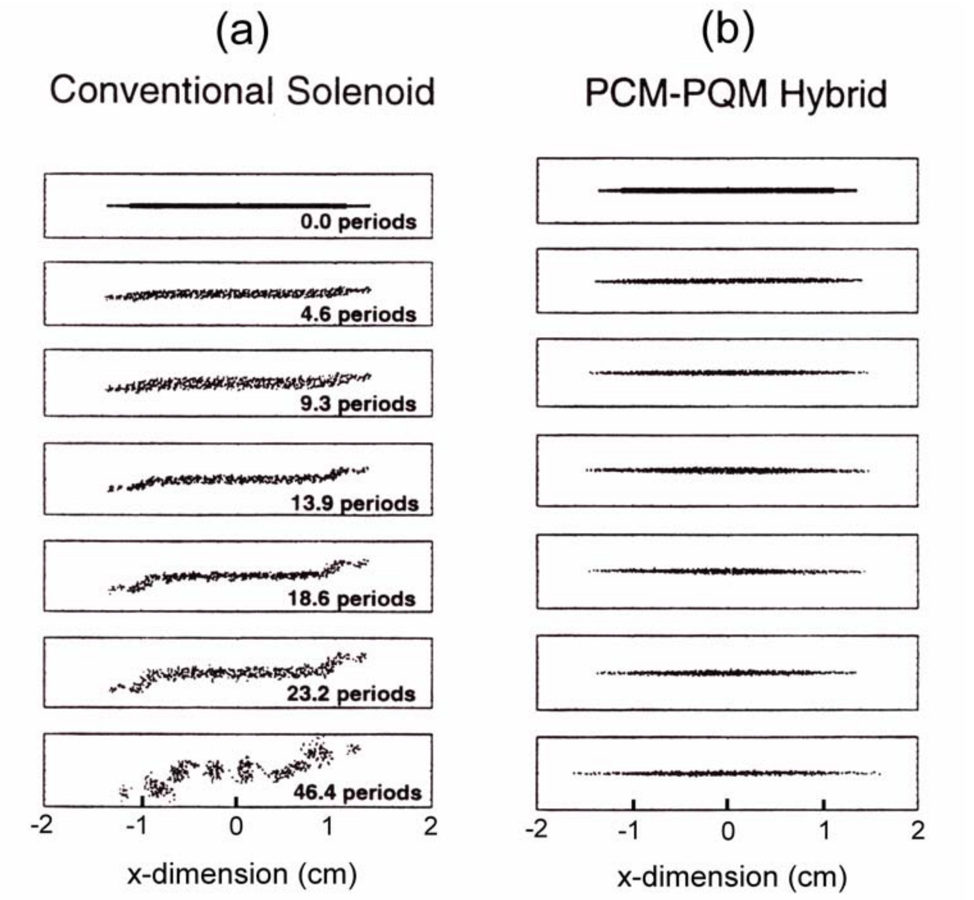
- New challenge: stable beam focusing…



Magnetic focusing of distributed beams

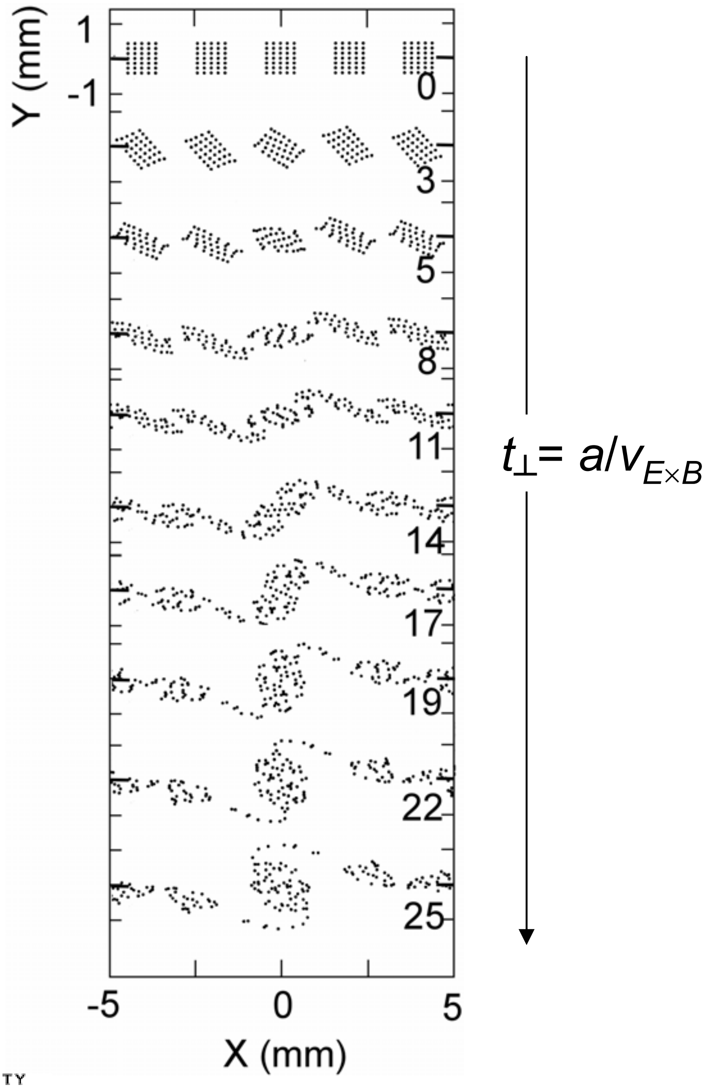
Basten and Booske,
J.Appl.Phys., **85**, 6313
(1999)





- Or…use wiggler focusing (Booske, et al., J.A.P., **64**, 6 (1988)
- Or…use solenoid focusing for *short* distances
- *How short?*...subject for additional research
- Scaling, $t_\perp \propto \dfrac{a}{v_{E\times B}} \sim a\dfrac{B}{E} \sim a\dfrac{\omega_c}{\omega_p^2}$
- High *B*, low beam density

Multibeams face similar issues



$t_\perp = a/v_{E\times B}$

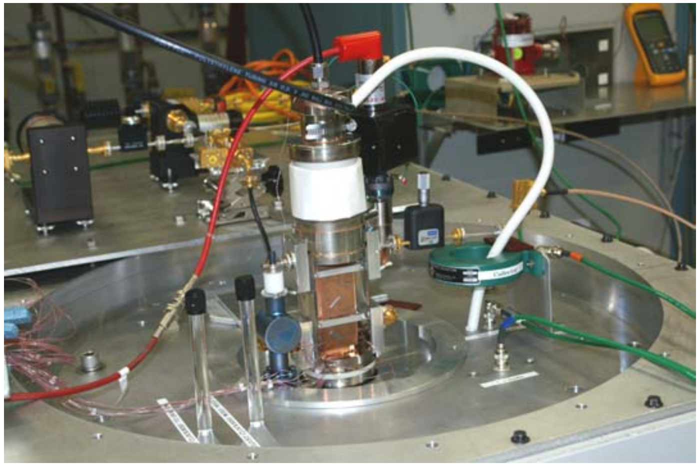
- “Smearing” distance, $z_s \leq u_0 t_\perp$.
- For 10 A/cm^2 and 20 kV,

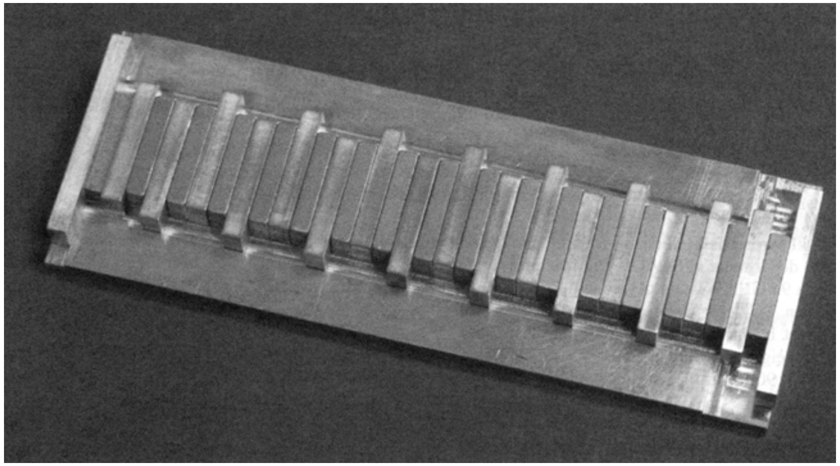
$$z_s\ (\text{cm}) \leq \sim 125/f(\text{GHz})$$

(thickness grows more slowly)

Illustrative successful application of sheet beam approach

- SLAC 94 GHz 1 kW sheet beam klystron
  - 74 kV, 3.6 A,
  - 1.1 kG offset PCM focusing
- > 90% transmission, no circuit damage
  - power density below single pulse damage threshold
  - G. Scheitrum, et al, IEEE IVEC Conf. Proc. (2006)
- Also,
  - LANL: Carlsten, et al, PRSTAB **8**, 062002 (2005)
  - NRL: Cooke, et al, 2006 IEEE I.V.E.C, 487-488.





THE UNIVERSITY of WISCONSIN MADISON

Recap

Want compact high power (> 1-10 W) at f > 100 GHz)

More current in smaller circuit

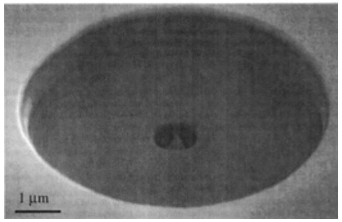
Distributed beams to get below single pulse damage threshold

For f > 200 GHz, transverse emittance exceeds magnetic focusing

Need lower transverse emittance beams!

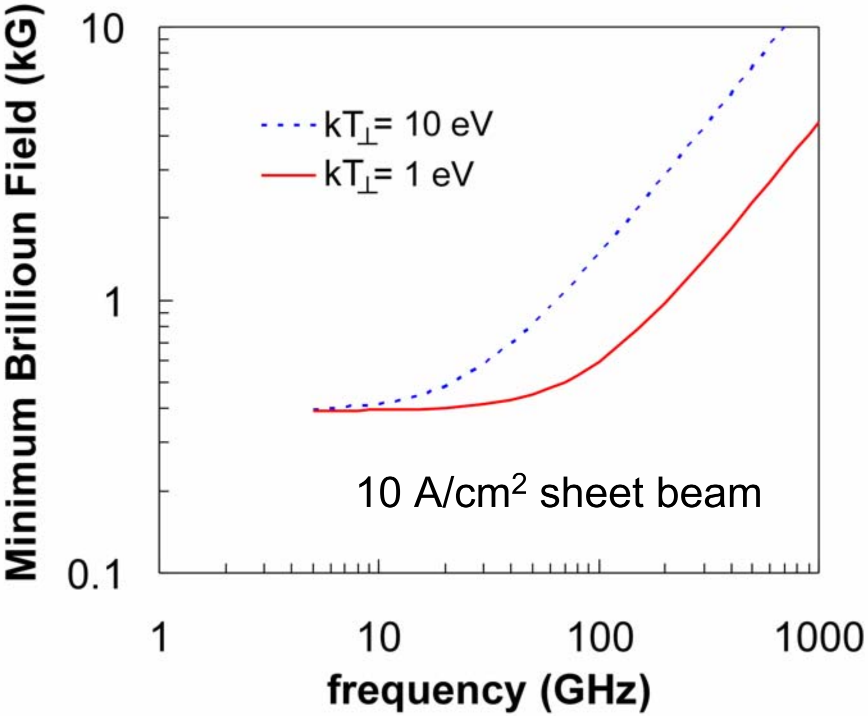
Reducing transverse beam emittance

- Beam cooling
  - Carlsten and Bishofberger, New J. Phys. **8**, 286 (2006).
  - Only for elliptical beams and requires extra magnetic optics
  - 10X reduction in ε, $kT_\perp$
- Advanced FEA cathodes with integral focus electrode, $kT_\perp \leq 1$ eV



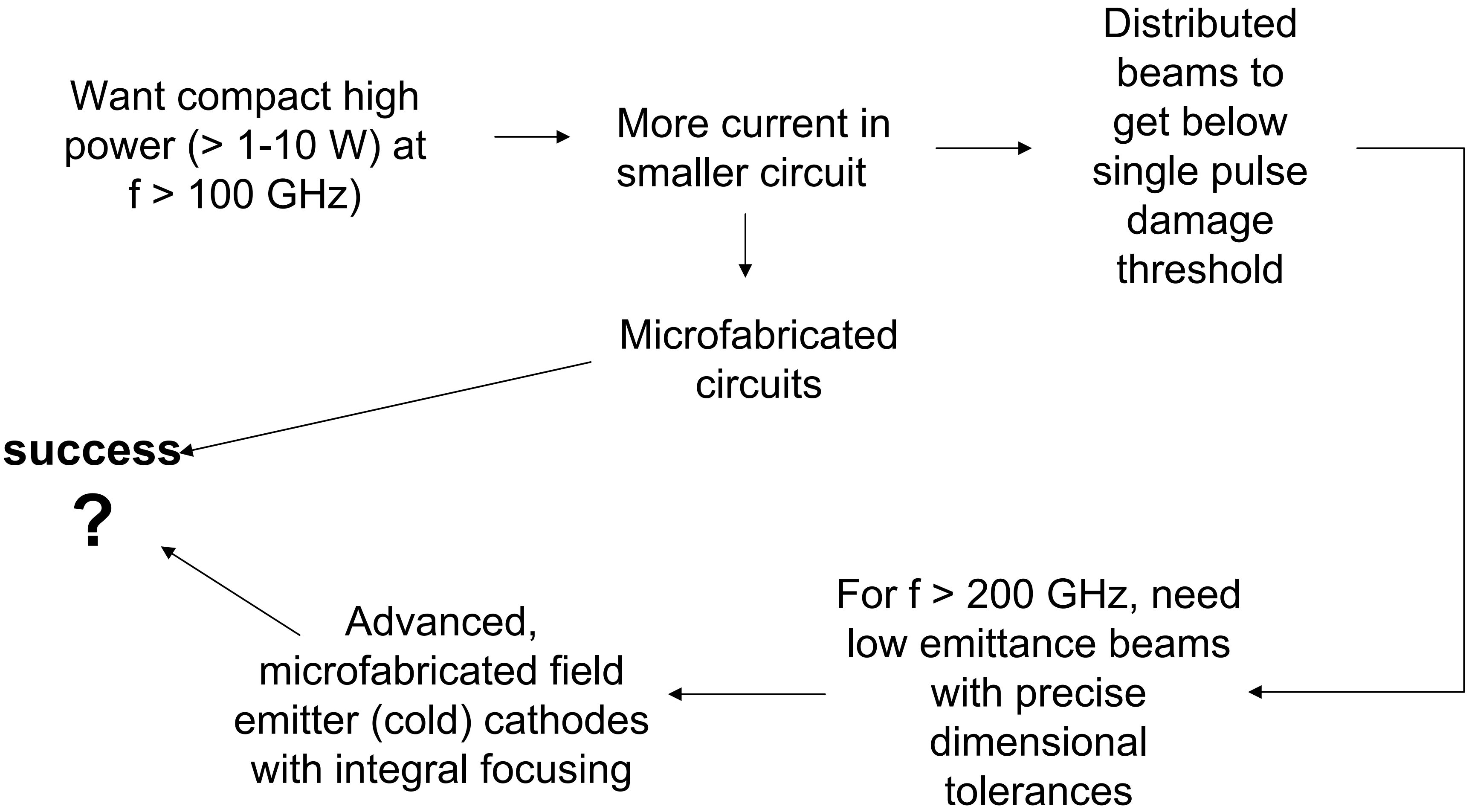
C.M. Tang, et al *JVST B* **14**, 3455 (1996)

C.A. Spindt, et al, in *Vacuum Microelectronics* (Wiley, 2001)



- ***Meanwhile, dimensions above 200 GHz may well require microfabricated cathodes (i.e., FEAs) to reliably achieve precise dimension and alignment tolerances.***

Recap



Want compact high power (> 1-10 W) at f > 100 GHz)

More current in smaller circuit

Distributed beams to get below single pulse damage threshold

Microfabricated circuits

For f > 200 GHz, need low emittance beams with precise dimensional tolerances

Advanced, microfabricated field emitter (cold) cathodes with integral focusing

success ?

What's left to do?

- Low emittance, uniform emission, high current density, *long-life*, distributed beam cathodes and "matching optics"
  - $kT_{\perp} < 1$ eV
  - $J \sim 10$ A/cm^2
- Advanced, quantitative, experimentally benchmarked studies of sheet and/or multibeam confinement and transport
  - Solenoidal fields
  - PCM/PPM fields
- Establish knowledge of best microfabrication approaches and microfabricated circuit performance
  - Precision-aligned assembly
  - Circuit attenuation, input/output coupling, vacuum packaging and windows
- Studies of electromagnetic mode control with overmoded distributed beam, high power circuits
  - Sheet beam & multibeam circuits
  - RF wall losses
- *Amplifiers*

Simulation tools

- How we’ve arrived here…
  - 3D EM models (steady state and time-dependent)
  - 3D steady state electron optics (trajectory) codes
  - 3D PIC codes for time-dependent particles + EM fields
  - 3D thermo-mechanical models
  - Ab Initio surface physics models
- Persistent, aggressive, detailed benchmarking against experiments
- Persistent institutional and individual leadership and investment
  - U.S. Naval Research Laboratory
  - U.S. Air Force Office of Scientific Research/AFRL
  - …and many more…

[Ch. 10, in *Modern Microwave and Millimeter-Wave Power Electronics* (IEEE/Wiley, 2005)]

[Ch. 11, in *High Power Microwave Sources and Technologies*, Eds. Barker, Schamiloglu (IEEE, 2001)]

Summary

- Vacuum electronic devices offer significant potential for applications in the (mmwave-to)-THz regime (~ 100 - 1000 GHz) that need compact high power
  - Advanced communications and radar
  - Concealed threat detection
  - Imaging…
- What will it take to push back the frontier?
  - High power densities
  - High current electron beams
- Common requirements and similar challenges with HPM (< 100 GHz)
  - Electronic attack
  - RF accelerators

Recent Breakthroughs

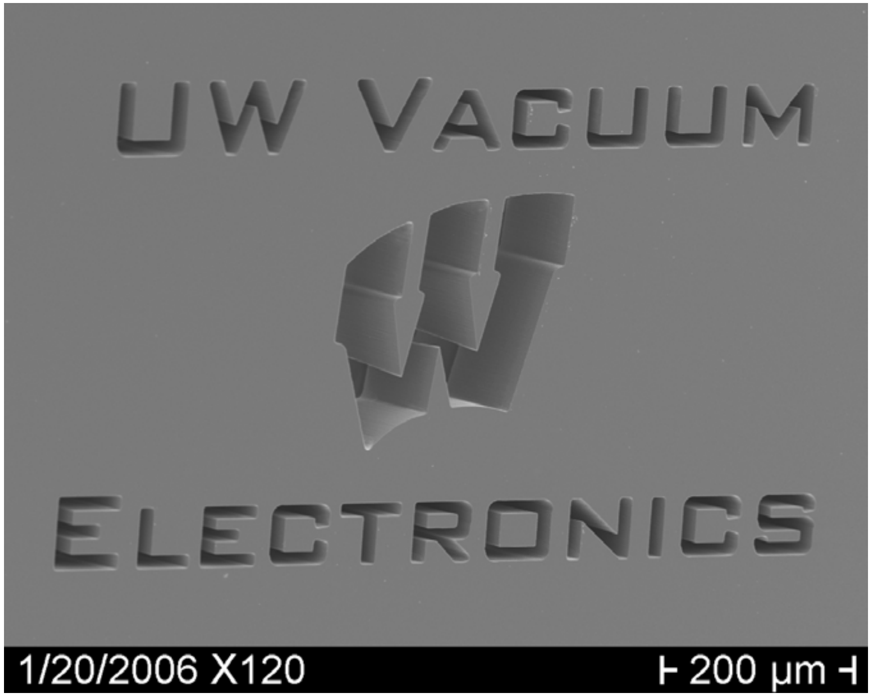
- Fabrication and engineering of miniature circuits
- Understanding rf breakdown
- New cathodes
- Understanding cathode emission physics

Challenges at the Frontier

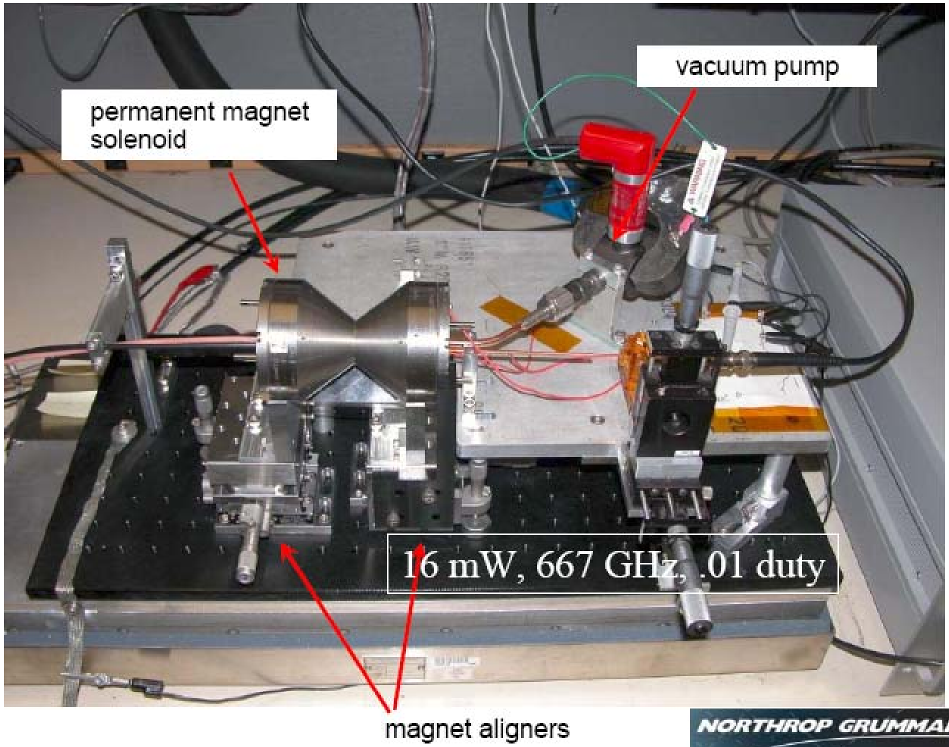
- High EM power density
    - HPM: delayed rf breakdown in air and vacuum
    - THz: mechanically and thermally robust miniature structures
- High current electron beams
  - Cathodes
    - HPM and THz: Long life and uniform emission
    - THz: Low emittance beams
  - Beam impact and collection
    - HPM: anode plasmas
    - HPM and THz: SEE physics, thermal engineering, materials choices
  - Beam confinement
    - THz: Transport & magnetic focusing physics for distributed beams
    - THz: Cathode and device engineering for precision alignment

…In other words…

…there's still a lot of fun to be had!



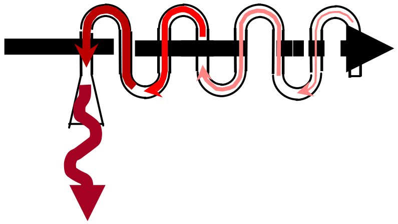
THz TWT oscillator



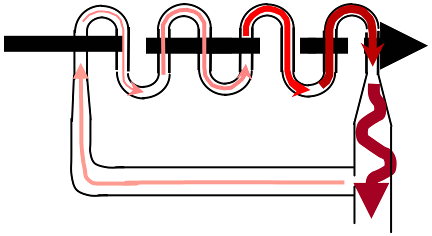
NORTHROP GRUMMAN

- TWT amplifier with regenerative feedback
- Precision microfabricated circuit
- DRIE Si folded waveguide circuit
- *0.3% rf efficiency! (> 10× higher than BWOs)
- Tucek, et al, Conf Proc. IEEE IVEC 2007 (Kitakyushu, Japan)

<u>BWO</u>



<u>Regenerative TWT Oscillator</u>



Bhattacharjee, Booske, vanderWeide, et al, IEEE T.P.S. **32**, 1002 (2004)

State of art in compact mmwave dense beam focusing

CPI Canada

3 kW peak

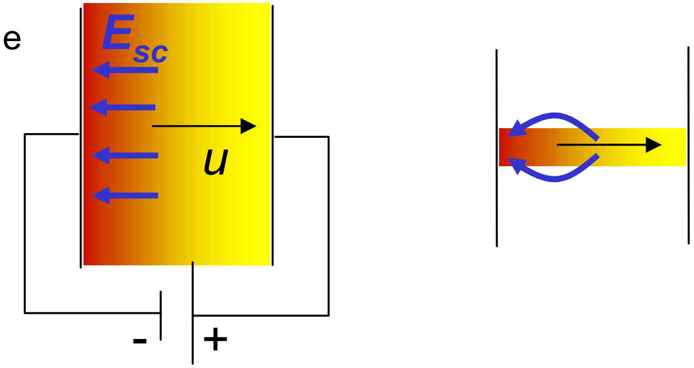
94 GHz EIK

- I ~ 0.6 A
- $J_{cathode}$ = 10 A/cm^2
- J_{beam} ~ 700 – 800 A/cm^2
- V ~ 16 kV
- ~ 1-10 MW/cm^2 (beam power density)

Advancing cathode physics: understanding differences in J_{max}

- Child-Langmuir law relates J to V_{anode}

$$J\left[\mathrm{A/cm^2}\right] = \rho u = 2.33\times10^{-6}\,\frac{V^{3/2}}{d^2}$$

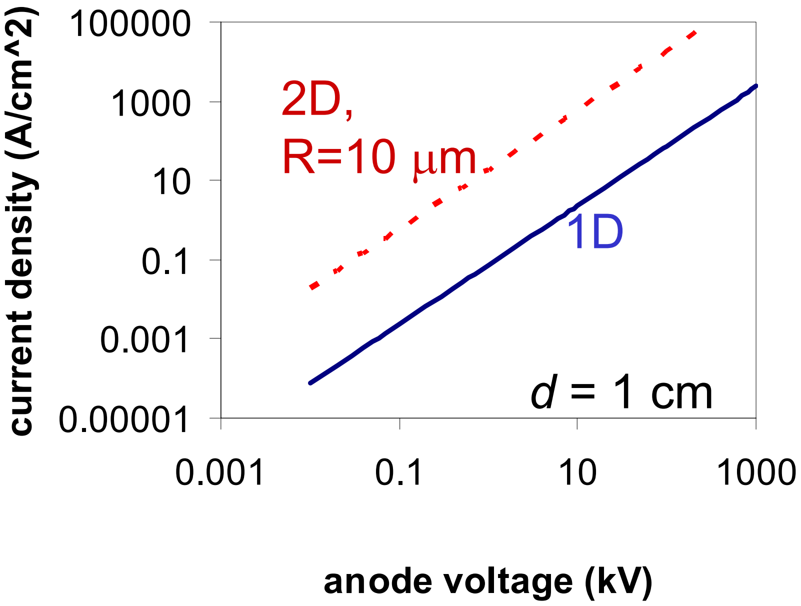


- 1000 A/cm² requires
  - Large (!) anode voltage to extract electrons from cathode
    - OK with short pulse HPM applications
    - Arcing with DC or long-pulse applications
  - Small area cathodes (low currents not useful for high power)

Y.Y. Lau, *PRL* **87**, 278301 (2001)

$$\frac{J_{CL}(2\mathrm{D})}{J_{CL}(1\mathrm{D})} \approx 1 + \frac{d}{4R}$$

Also, poster TP8 40, Ragan-Kelley, Verboncoeur



  - Explains 650 A/cm² FEA result