Traveling wave breakdown limit scaling
and
Some thoughts on the mechanism which gives the breakdown rate

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My personal view of the main theoretical questions

- How does a breakdown start? Trigger mechanism. Two main ideas – electron emission and tensile strength. J. Norem's team simulates the latter. Both ideas predict βE limit of material, but β is never derived.

- What are the breakdown dynamics? rf/plasma interaction. V. Dolgashev simulates breakdown and rf. P. Wilson has elaborate theory based on plasma spots. Predicts ordering of materials for ultimate gradient and gives pulse length dependence. S. Doebert and T. Ramsvik also have made material orderings.

- How do structure parameters enter into it? Surface field limits are commonly considered. W. Wuensch has theory with a power flow limit which predicts gradient relationship between different types of structures made of the same material. V. Dolgashev has simulated rectangular waveguides.

- What gives the breakdown rate and apparent material dependence? W. Wuensch has proposal that breakdown sites are subject to cyclical tensile stress and fatigue.

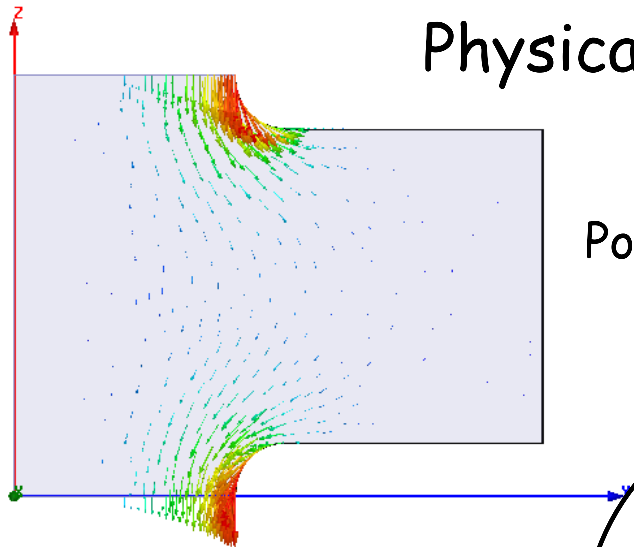
- What is conditioning and how best to do it? How does effect of breakdown affect breakdown trigger?

The case for a material dependent rf-breakdown limit scaling of

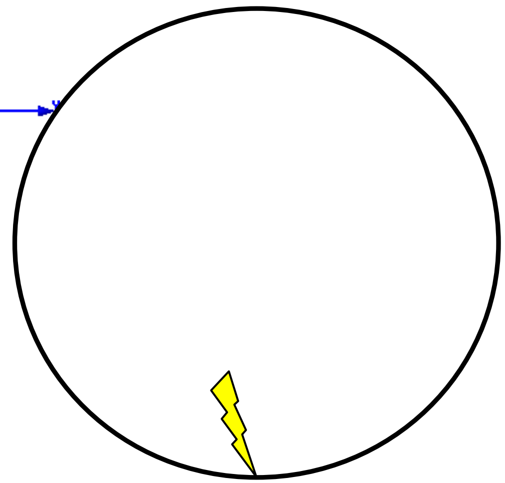
$$\frac{P\tau^{\alpha}}{C}$$

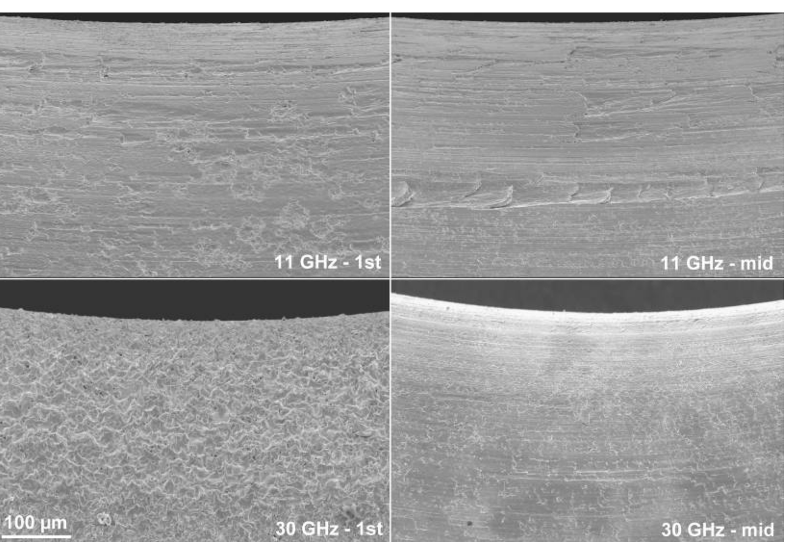
- P is power flow,
- τ is pulse length,
- C is the smallest structure circumference
- α is empirically determined with values around 1/2 (Mo) to 1/3 (Cu).

Physical arguments



Poynting vector





- Power flows in a thin layer above structure irises.
- Melted spots left by breakdown are small compared to the iris circumference as are images of light.
- Energy to melt spot small compared to total pulse energy.
- Melted spots evolve into damage.
- Power density available to feed discharge above spot of fixed transverse dimension is *P/C.*
- Surface field only needs to be high enough to *initiate* breakdown.
- Above a certain threshold the effect of the breakdown on the surface geometry is greater than on the field holding capability – material dependent saturation.

General observations

- Discharge is a fixed-sized small antenna that can only couple to a small fraction of the incoming power/energy.
- Inspired by ablation limit argument communicated to me by V. Dolgashev. This is where the τ to the something comes from.
- Consistent with the observation at X-band that lower v_g structures tolerate higher surface electric fields (C. Adolphsen).
- Basic difference with v_g reasoning is that power fed into a breakdown is given by a geometrical argument rather than an impedance matching argument.
- Circumference argument also makes a prediction about frequency dependence.

Let's see how it stands up,

30 GHz data taken at the conditioning limit

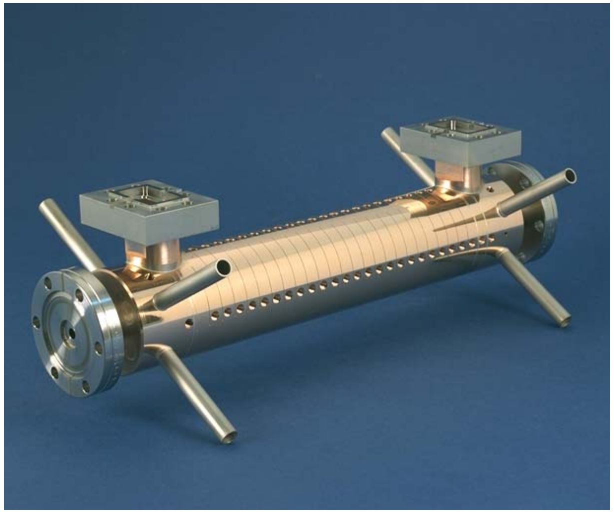
	f [GHz]	V_g/c	E_{acc} [MeV/m]	E_{surf} [MeV/m]	P [MW]	τ [ns]	$2a$ [mm]	$\frac{P\tau^{1/3}}{C}$
Accelerating circular	30	0.047	116	253	34	70	3.5	13
CTF2 PETS	30	0.5			240	16	16	12
CTF3 PETS	30	0.40	30	116	100	50	9	13

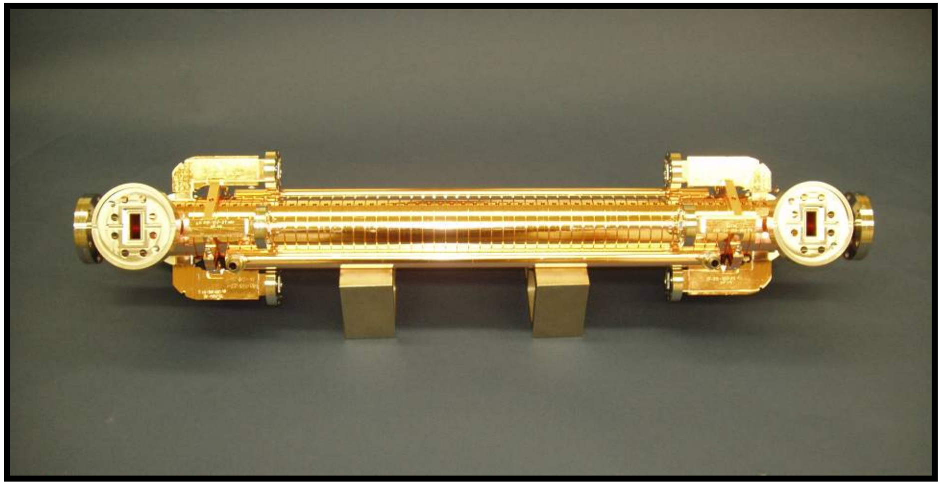
Analysis of waveguide data from experiment of V. Dolgashev and S. Tantawi

	f **[GHz]**	V_g/c	E_{surf} **[MeV/m]**	***P*** **[MW]**	**τ** **[ns]**	***a*** **[mm]**	$\frac{P\tau^{1/3}}{C}$
WR-90	11.424	0.82	60	56	750	22.9	11.2
Reduced width	11.424	0.18	45	32	750	13.3	10.8

X-band accelerating structure data

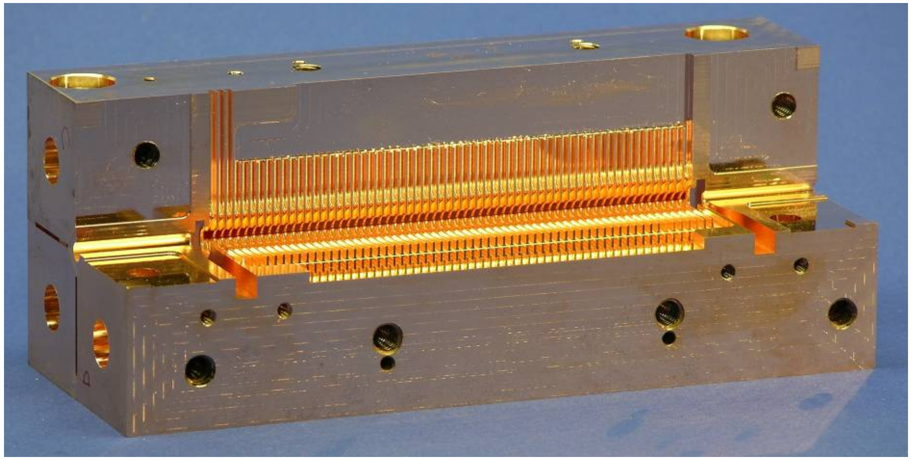
	f [GHz]	V_g/c	E_{acc} [MeV/m]	E_{surf} [MeV/m]	P [MW]	τ [ns]	$2a$ [mm]	$\frac{P\tau^{1/3}}{C}$
CERN X-band	11.424	0.011	153	326	69	150	6	19
NLC	11.424	0.045	72	152	140	100	11.4	18





HDS60 at 10^{-3} breakdown rate and 70 ns

	f [GHz]	V_g/c	E_{acc} [MeV/m]	E_{surf} [MeV/m]	P [MW]	τ [ns]	$2a$ [mm]	$\frac{P\tau^{1/3}}{C}$
HDS60	30	0.08	61	108	16	70	3.8	5.6
HDS60 reversed	30	0.051	75	124	13	70	3.2	5.4



…and then some significant differences emerge

	f [GHz]	V_g/c	E_{acc} [MeV/m]	E_{surf} [MeV/m]	P [MW]	τ [ns]	$2a$ [mm]	$\frac{P\tau^{1/3}}{C}$
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Acceler-ating	30	0.047	116	253	34	70	3.5	13
CTF2 PETS	30	0.5			240	16	16	12
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f dependence?

iris thickness?

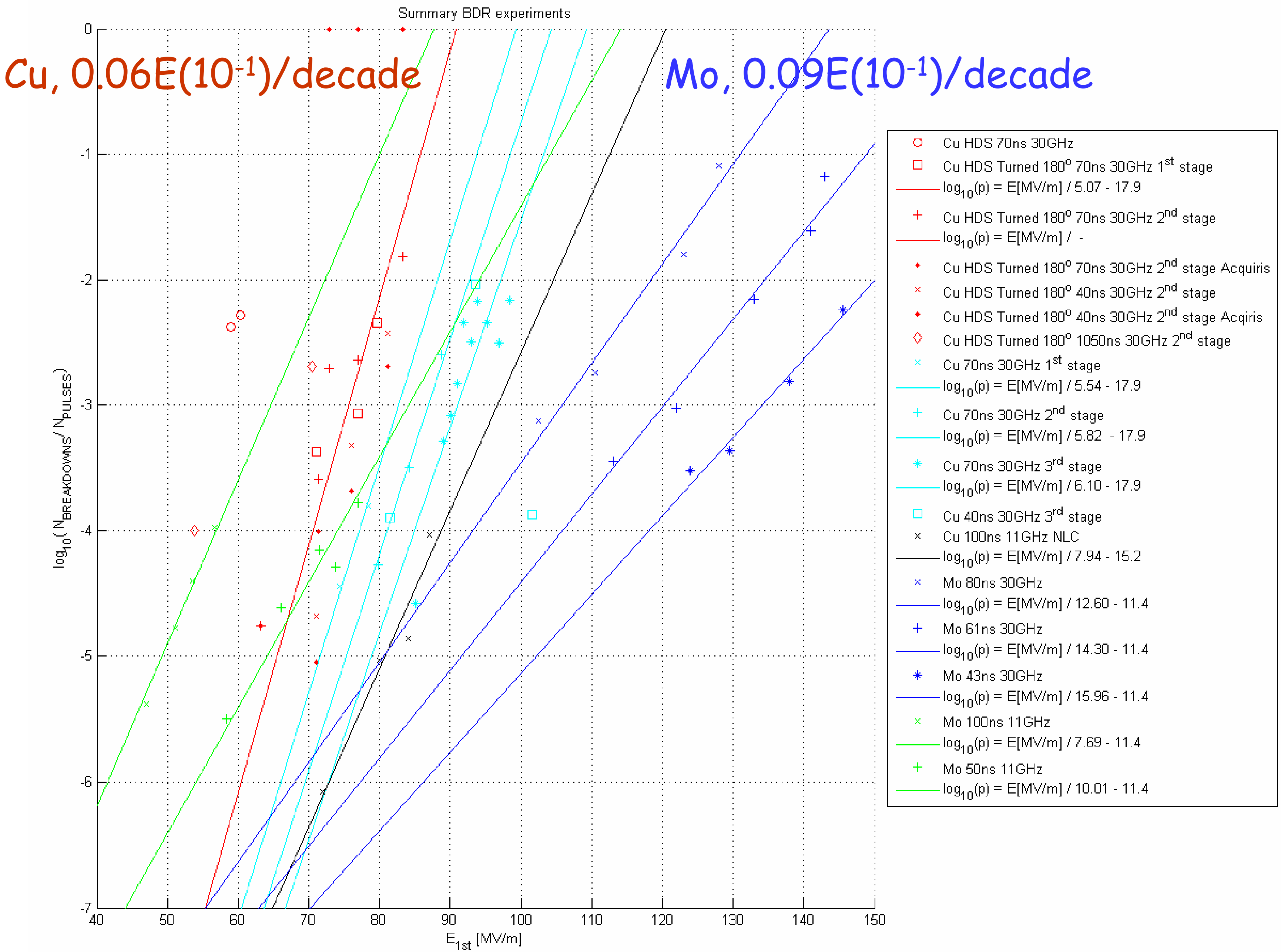
Circular and HDS60
10^{-3} breakdown rate and 70 ns

	f [GHz]	V_g/c	E_{acc} [MeV/m]	E_{surf} [MeV/m]	P [MW]	τ [ns]	$2a$ [mm]	$\frac{P\tau^{1/3}}{C}$
circular	30	0.047	90.3	198	20	70	3.5	7.3
HDS60	30	0.08	61	108	16	70	3.8	5.6
HDS60 reversed	30	0.051	75	124	13	70	3.2	5.4

Where could the difference come from?

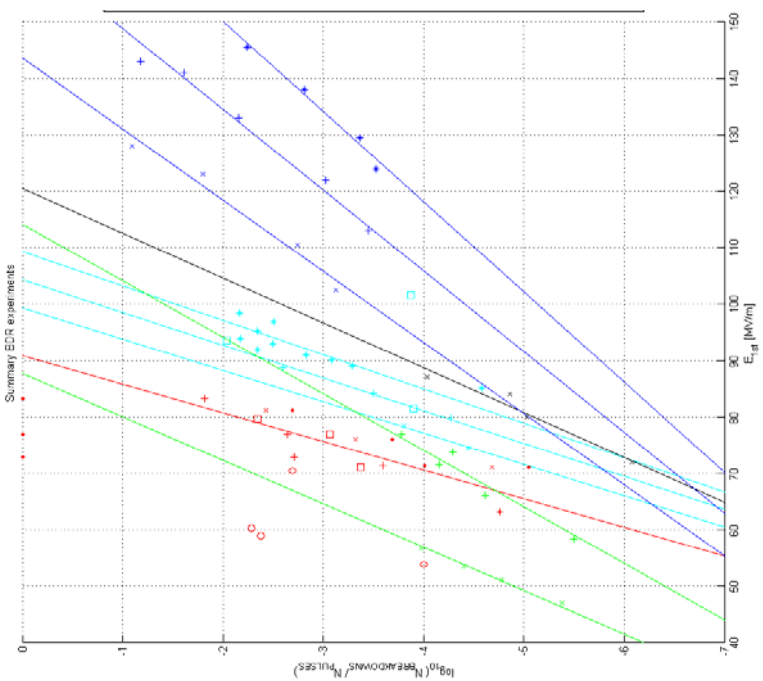
- HDS power flow concentration
- Iris thickness, circular 0.85 and HDS 0.55
- phase advance
- structure preparation

Breakdown probability: observed material dependence of slope

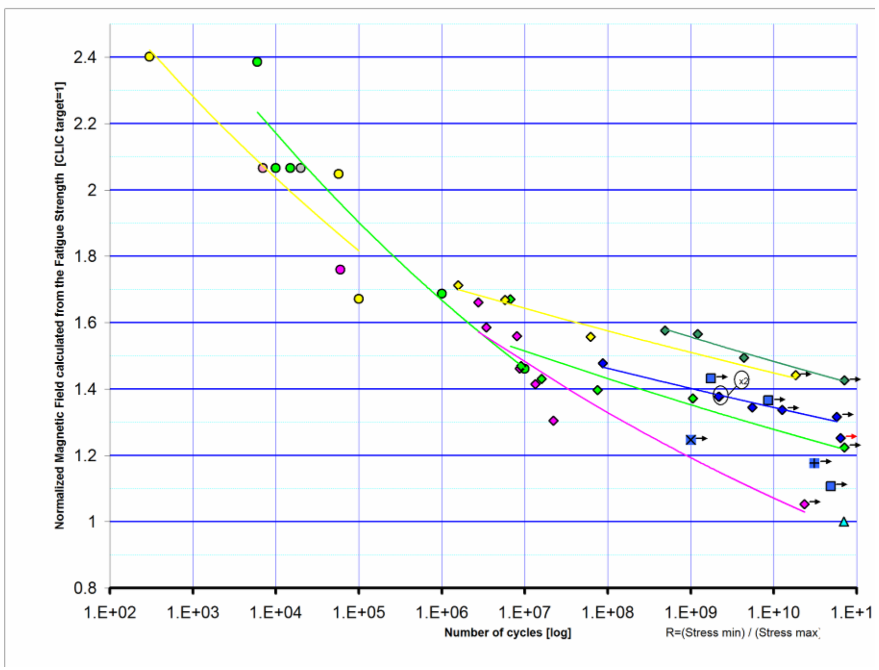


Breakdown rate and fatigue

Breakdown triggers involve induced stress: tensile strength and heating (D. Schulte).
Induced stress goes down with field, so fatigue S/N curve gives breakdown probability .
Alloying could then give strong influence, if properties survive breakdown.
Mo sonotrodes are under test, S. Heikkinen. We will see if behavior is reproduced.



rotated breakdown probability



Laser and ultrasonic fatigue data