The scaling of the traveling-wave rf breakdown limit

W. Wuensch
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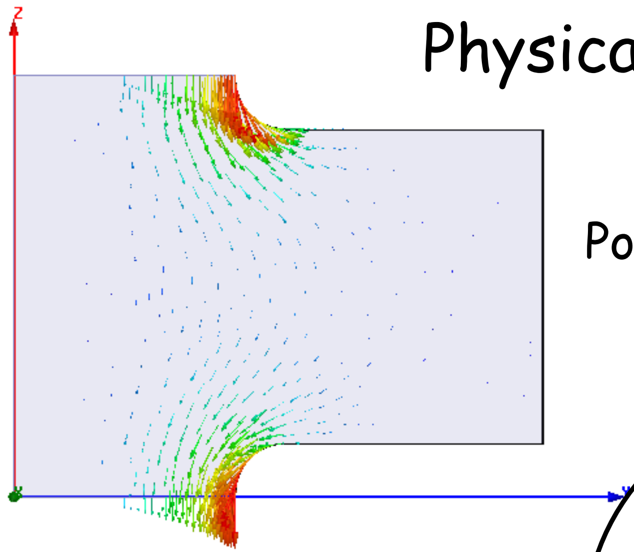
Objective: present the case for an rf-breakdown limit scaling of

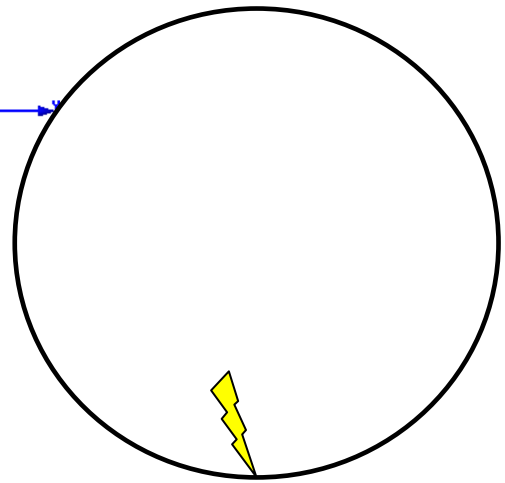
$$\frac{P\tau^{1/\alpha}}{C}$$

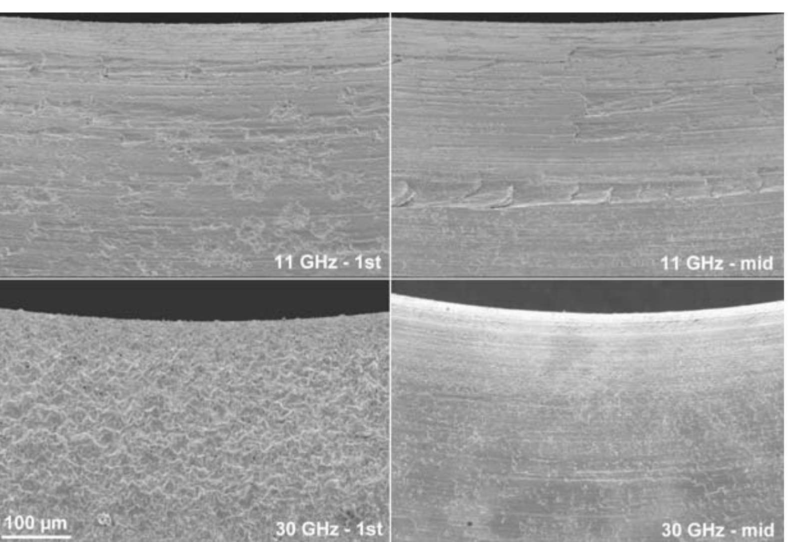
P is power flow, τ is pulse length, C is the structure circumference and α is around 1.5 (Mo) to 3 (Cu).

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.
- Motivating question: How many accelerating can be fed by a PETS?
- 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). Rigorous understanding on how diameters/surface fields/power flows interrelate is coming along…
- Basic difference with v_g reasoning is that power fed into a breakdown is given by a geometrical argument rather than an impedance argument.
- HOWEVER, circumference argument makes a prediction about frequency dependence.

Let’s see how it stands up,

Fixed frequency (30 GHz), variable geometry, fixed material (Cu), different pulse lengths (Argh!), all 'damaged'

	F [GHz]	V_g/c	E_{acc} [MeV/m]	E_{surf} [MeV/m]	P [MW]	T [ns]	D [mm]	$\frac{P\tau^{1/3}}{C}$
30 GHz Cu, CTF2	30	0.047	111	241	31	30	3.5	9
CTF2 PETS	30	0.500			240	16	16	12
CTF3 PETS	30	0.398	30	116	100	50	9	13

Variable frequency, variable geometry, fixed material (Cu), only 30 GHz 'damaged'

	F [GHz]	V_g/c	E_{acc} [MeV/m]	E_{surf} [MeV/m]	P [MW]	T [ns]	D [mm]	$\frac{P\tau^{1/3}}{C}$
NEPAL	3	0.008	50		61	1000	18	11
CERN X-band	11.424	0.011	153	326	69	150	6	20
NLC Conditioning limit	11.424	Around 0.05	75	Around 180	120	400	8.9	40
30 GHz Cu	30	0.047	111	241	31	30	3.5	9
CTF3 PETS	30	0.398	30	116	100	50	9	13

Variable frequency, fixed geometry, fixed material (W)

	F [GHz]	V_g/c	E_{acc} [MeV/m]	E_{surf} [MeV/m]	P [MW]	T [ns]	D [mm]	$\frac{P\tau^{2/3}}{C}$
W-iris	11.424	0.047	93	203	150	70	9.19	88
W-iris CTF2	30	0.047	151	329	57	16	3.5	33

Variable frequency, fixed geometry, fixed material (Mo), very different conditioning/surfaces

	F [GHz]	V_g/c	E_{acc} [MeV/m]	E_{surf} [MeV/m]	*P* [MW]	*T* [ns]	*D* [mm]	$\frac{P\tau^{2/3}}{C}$
Mo-iris	11.424	0.047	70	153	85	100	9.19	63
Mo-iris CTF2	30	0.047	192	420	93	16	3.5	54
Mo-iris CTF3	30	0.047	148	323	55	70	3.5	85

Waveguides/components

	F [GHz]	V_g/c	E_{acc} [MeV/m]	E_{surf} [MeV/m]	P [MW]	T [ns]	D [mm]	$\frac{P\tau^{1/3}}{C}$
NLC 4-pack	11.424				600	400	40	35
Our high-power	30				100	50	14.86	8
WR-90	11.424				100	1200	45.7*	23
WR-34	30	0.82			100	50	17.6*	21

*broad wall lengths

$\frac{P\tau^{1/\alpha}}{C}$ status

- To the pedantic (and perhaps correctly), the data does not allow a definitive statement on the validity of anything: damage, conditioning strategy variations, normal fluctuations, pulse length, clamping. It is however clear what we need to do and everything has been set into motion to get there. In the mean time we must do what we can or do nothing!
- Physically plausible.
- Quantitative prediction of surface electric field/power flow/pulse length/geometry.
- Fits 30 GHz data rather well.
- Allowable values seem to be higher at X-band – something is still missing from the full frequency scaling. Iris thickness?

So what are the today's best values for rf constraints (least to most controversial)?

- Pulsed surface heating: Unchanged at 540 MA/m and 70 ns with square root pulse length dependence.
- Peak surface electric field: Unchanged at 380 MV/m. Consistent with dc spark. Consistent with downstream cells in structures.
- Power flow - pulse energy: 50 MW, 70 ns downgraded by 36% (20% in field) to 32 MW, 70 ns for breakdown rate back-off. Assume damage problem is tolerable with a small back-off (threshold effect) offset by better conditioning. Assume compromise $P\,\tau^{\frac{1}{2}}$/circ for scaling work.

From away day

Alternative view on the Mo structure test – just take gradients

Achieved peak gradient: 140 MV/m, 70 ns
Typical ratio between peak and average beam loaded, 20%: 112 MV/m
Back-off for breakdown rate, 20%: 90 MV/m
Then lower again to increase group velocity…

Discussion since away day

We may want to consider allowing a higher limit at lower frequency.

Linearly connect X-band copper data to 30 GHz Mo data with a linearly varying pulse length dependence? Yuck.