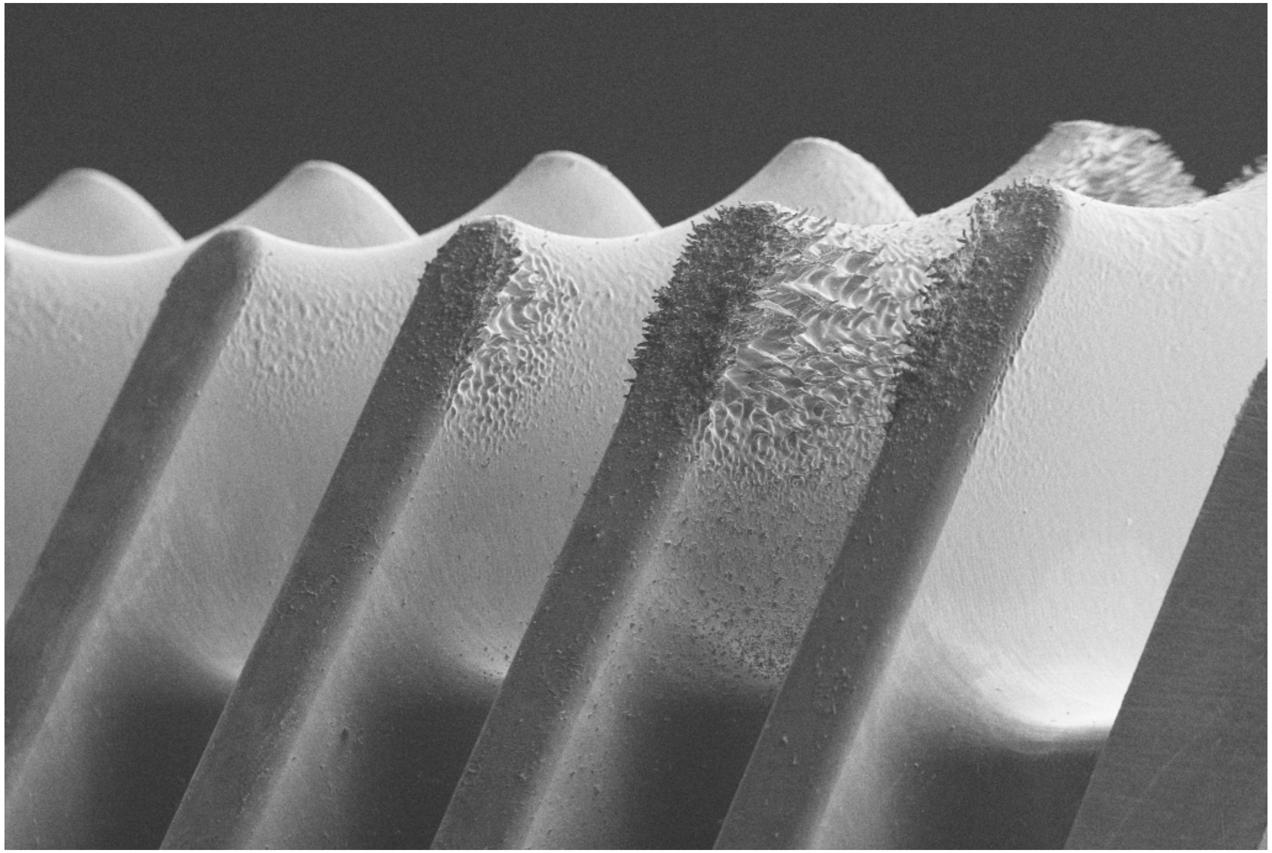
High-gradient rf constraints



W. Wuensch

X-band workshop

18-6-2007

Goal of this presentation

Motivate our effort and introduce our ideas on how to quantifying achievable gradient as a function of structure geometry

$$E_{acc}(\text{geometry})$$

It's not certain how simple this function can be, but we have something that works rather well.

The initial presentation is phenomenological but based on data which is often hard to compare. I try my best…

We also have an idea of how to proceed further which has a much stronger physical explanation (which is what I would really like to talk about) but it isn't mature yet.

Motivation

Both accelerating structures and PETS in CLIC will be running very near their performance limits in CLIC.

It is clear from experiments that the geometry of structures has a strong influence on the achievable gradient.

We expect that there is also a geometrical dependence of the PETS power capability.

A specific issue : while waiting for experimental data from the 2BTS we need to have a criterion for how many accelerating structures a PETS can feed.

The geometry has a strong influence on the beam through wakefields.

In order to systematically design and optimize a linac, it is necessary to quantify the achievable gradient as a function of geometry, to match our capability to determine wakefields as a function of geometry.

Motivation, continued

The rf constraints are a clear summary of our understanding of breakdown. We only really do science when we make quantitative predictions (OK that's a little bit strong…).

The constraints should ultimately be consistent with available data to the extent that the data can be compared.

For the courageous, deviations from the constraints can then be used to show other dependencies such as surface preparation or whatever even when structures don't have the same geometry.

It looks like we get something simple that is rather accurate.

Here they are

Surface Electric Field: $E_s < 380$ MV/m

Pulsed surface heating: $\Delta T < 56°C$

Power density:

$$\left(\frac{P}{1MW}\right)\left(\frac{1mm}{C}\right)\left(\frac{f}{12GHz}\right)\left(\frac{\tau}{70ns}\right)^{1/3} < 18$$

P is power, C is circumference of the first iris, τ is the pulse length.

Throughout this discussion there are two considerations:

What we consider to be a limit

The value which has been chosen

I will order the presentation historically because it will be easier,

1. Pulsed surface heating
2. Surface electric field
3. Power flow limit

Then a little bit on new directions…

Pulsed surface heating

Problem:

The surfaces exposed to high pulsed RF (Radio Frequency) currents are subjected to cyclic thermal stresses possibly resulting in surface break up by fatigue.

Fatigue performance of the cavity material has a direct influence on the achievable gradient of the machine.

Aim:

To find a material for the CLIC accelerating cavities, which can sustain the highest gradient during the 20 years of CLIC operation.

Challenge:

No material data exist in the literature for the CLIC parameter range.
Required number of cycles is 2.33×10^{10}.

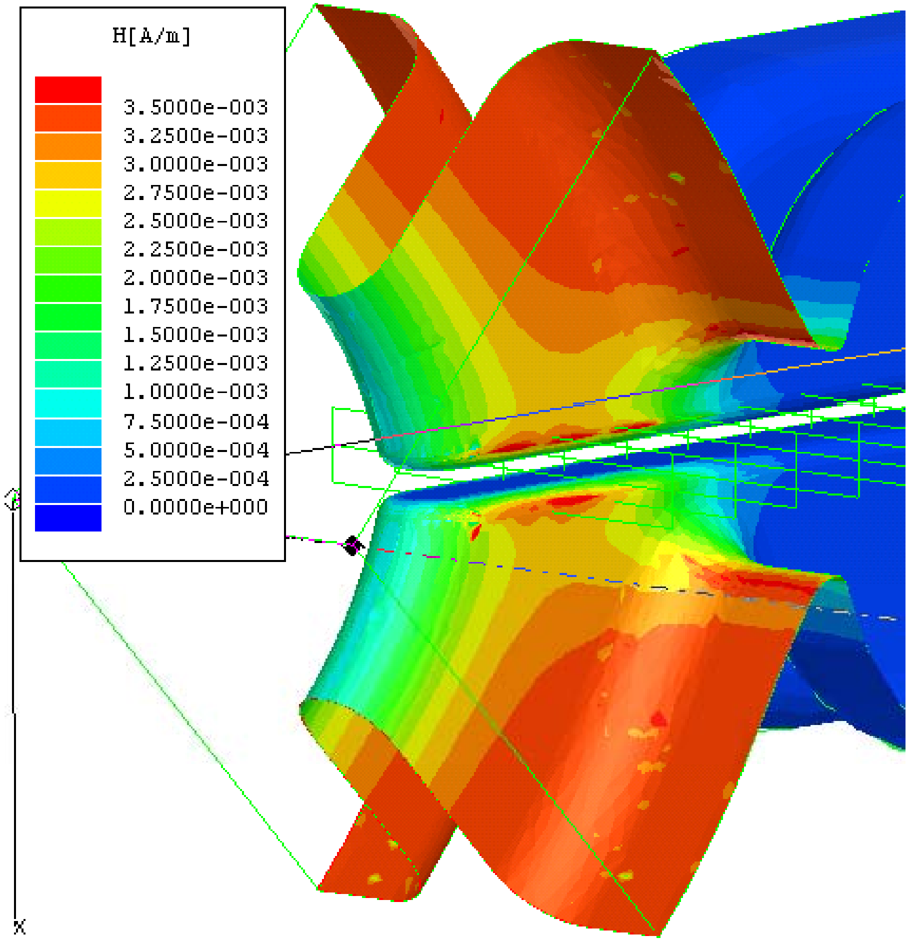
Methods:

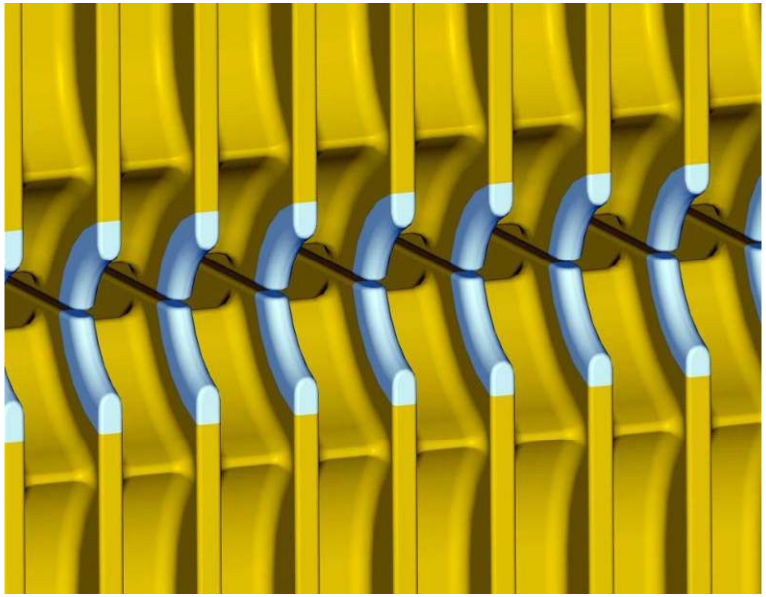
Ultrasonic fatigue test setup is used to study the high cycle fatigue. CLIC lifetime can be achieved in 20 days.

Pulsed laser test setup is used to study the thermal fatigue phenomena at low number of cycles range.

RF fatigue test setup, in collaboration with SLAC, California, is used to make few experiments in real conditions to validate the ultrasound and laser data.

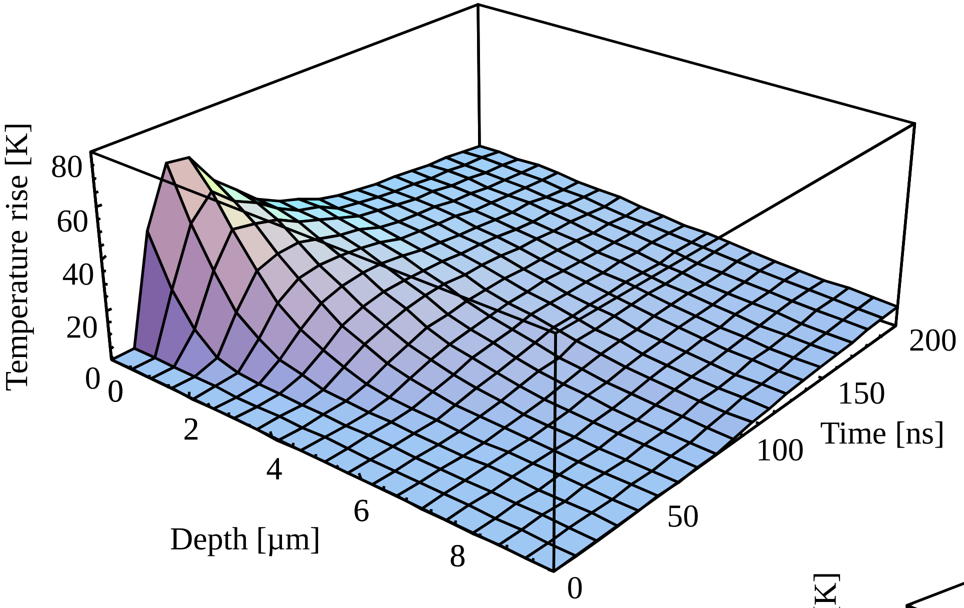
Surface magnetic field causes pulsed surface heating



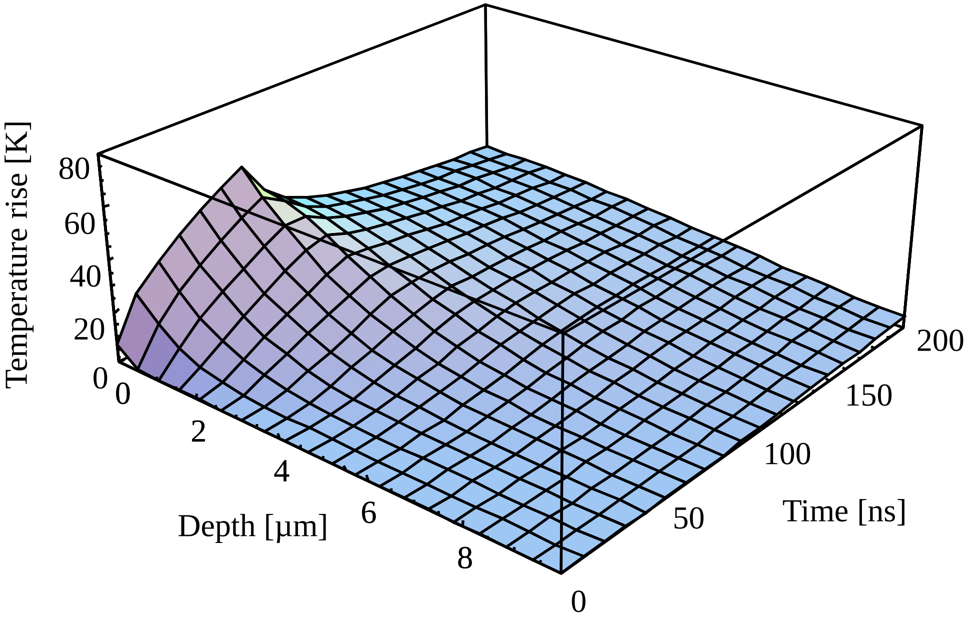


Comparison of heating profiles

← Laser pulse



RF pulse ↓



The pulse shapes correspond.
In particular the temperature profile at the peak is very similar, and results in similar stress level.

$$\sigma = \frac{\Delta T * E * \lambda}{(1-\nu)}$$

Can be solved analytically

Roughening of the surface, US testing


G. Arnau Izquierdo TS/MME


76 mm Dumbbell Sonotrode
Vue 3D zone affectee

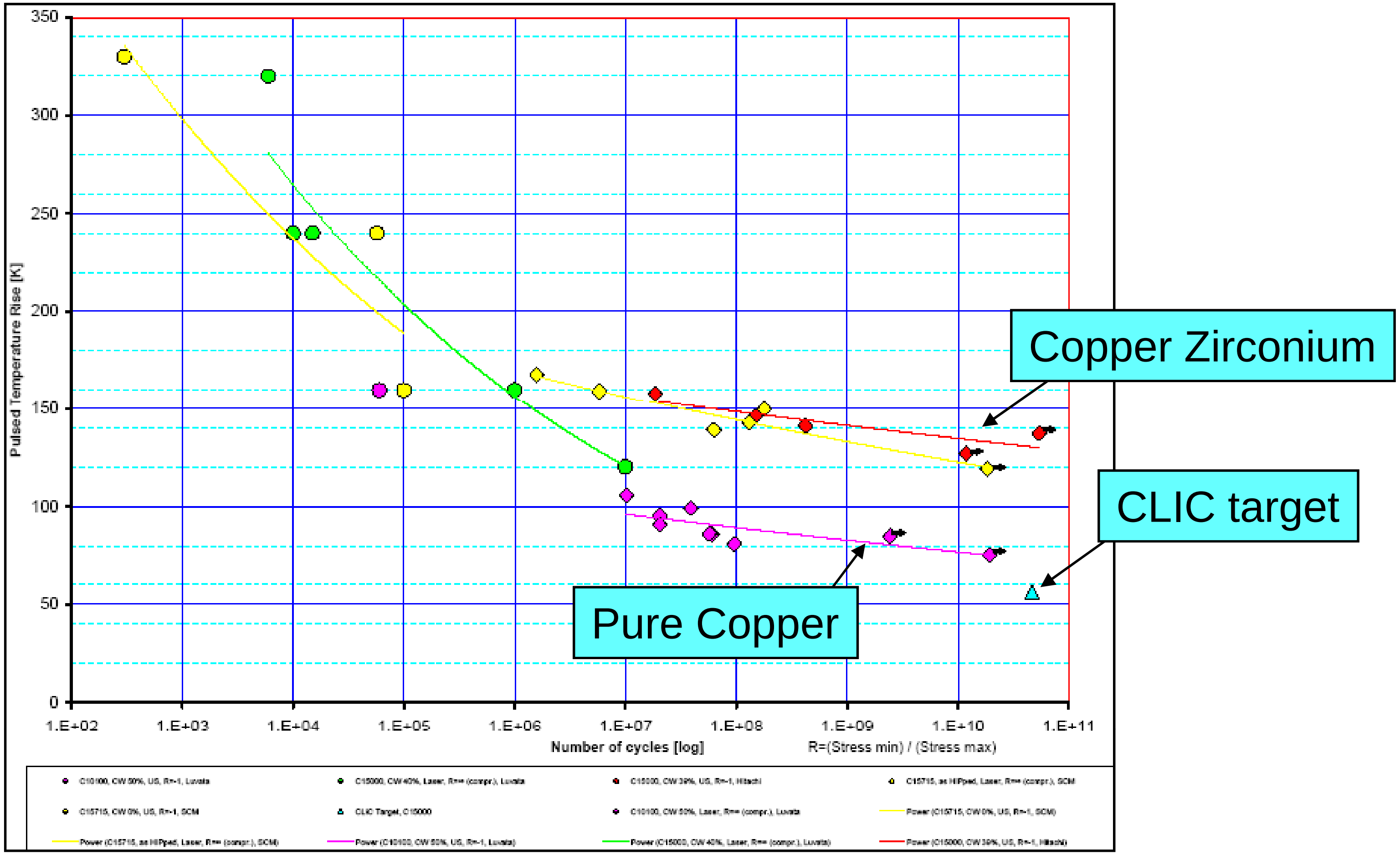
A. Cherif TS/MME

CLIC fatigue studies

Based on Ultrasonic and Laser tests, currently the best candidate is Copper Zirconium (C15000).

Current data suggest, that it will sustain the CLIC target gradient.

RF fatigue experiments at SLAC this summer will validate the data!



Copper Zirconium

CLIC target

Pure Copper

Peak surface electric field - rather straight forward idea

	Cu [MV/m]	Mo [MV/m]	Pulse length, breakdown rate
Dc spark	200	400	2 s, conditioning
CERN X-band	326		150 ns, conditioning
30 GHz 2π/3	253	308	70 ns, conditioning
CTF3 PETS	116		50 ns, conditioning

Already this data alone is inconsistent.

Add in observations by C. Adolphsen about X-band data that lower vg structures tolerate higher surface electric fields, indicates that the peak surface electric field is not a fundamental quantity.

Trying to sort out the apparent inconsistencies has directly lead a power limit and eventually to a power density like limit.

We however have kept a surface electric field constraint to keep the designs from drifting too far from existing data.

The limit of E_s<320 MV/m was chosen under the assumption we would use Mo – needs to be revaluated for the next round of optimization.

Now what appears to be the limiting most structures…

General observations for

$$\frac{P}{C} f\tau^{1/3} < const$$

- The power flow in a structure is proportional to the circumference of the smallest aperture.
- The result is that larger a/λ structures support lower surface fields
- But frequency scaled geometry structures give constant gradient
- Standard measured pulse length dependence.
- Inspired by ablation limit argument communicated to me by V. Dolgashev. This is where the τ to the something comes from.

Let’s see how it stands up by looking at data,

30 GHz data taken at the conditioning limit

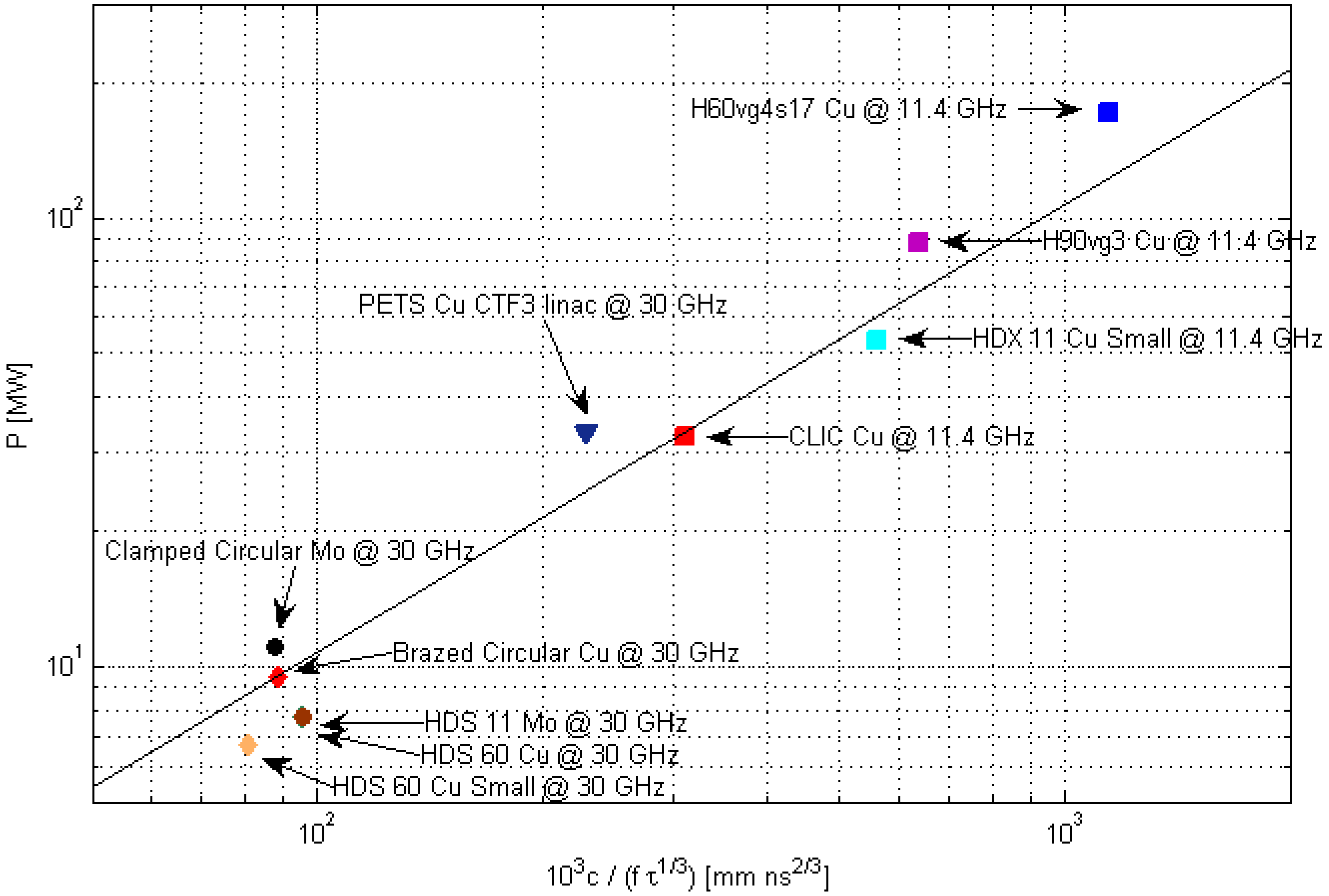
	f **[GHz]**	**V_g/c**	**E_{acc}** **[MeV/m]**	**E_{surf}** **[MeV/m]**	**P** **[MW]**	**τ** **[ns]**	**2a** **[mm]**	$\frac{P\tau^{1/3}}{C}$
Accelerating circular	30	0.047	116	253	34	70	3.5	13
CTF2 PETS	30	0.5			240	16	16	12
CTF3 PETS	30	0.40	30	116	100	50	9	13

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

	f **[GHz]**	V_g/c	E_{surf} **[MeV/m]**	P **[MW]**	τ **[ns]**	a **[mm]**	$\frac{P\tau^{1/3}}{2a}$
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

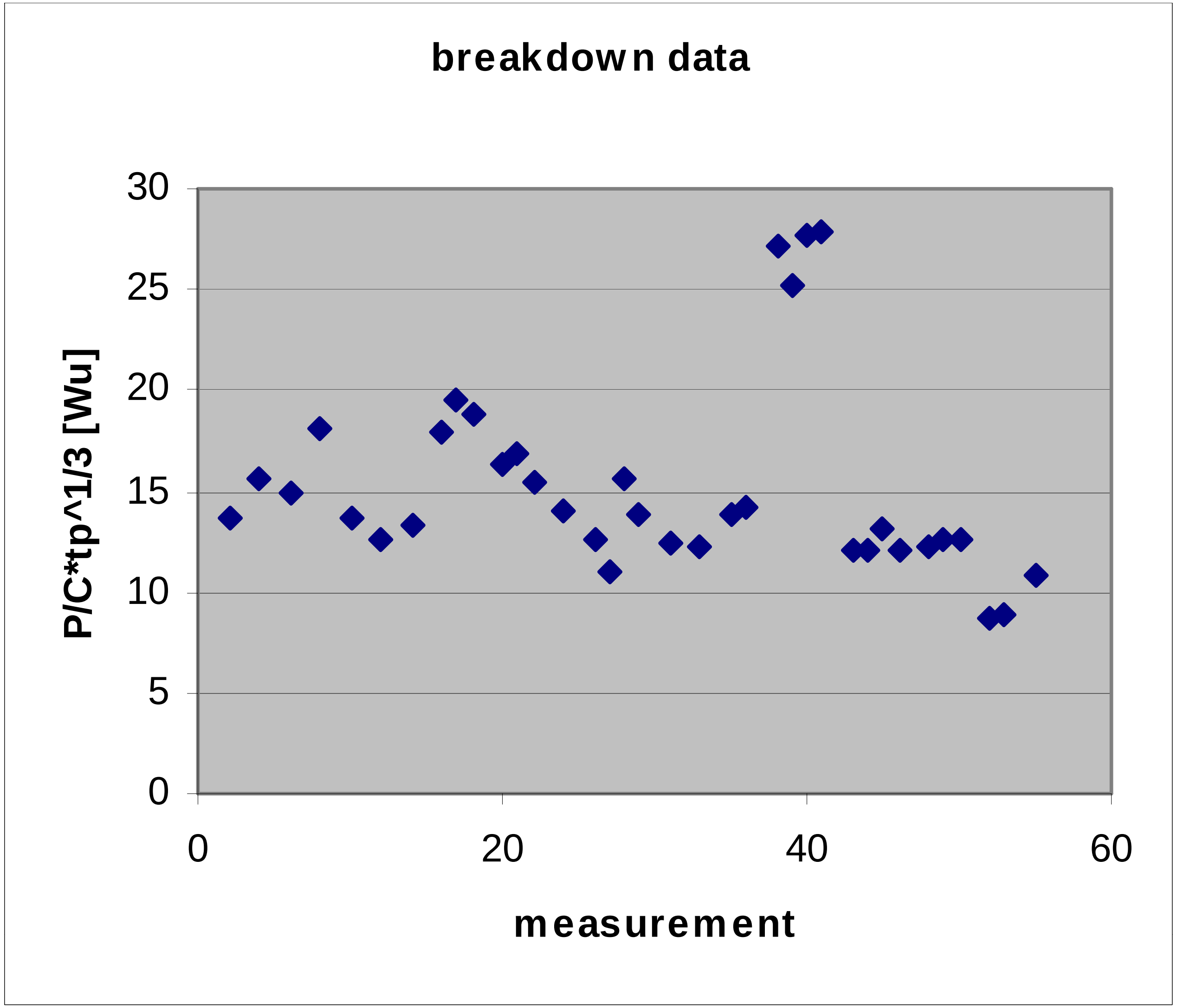
Agreement excellent! But waveguides have a different mode so do not compare absolute value of P/C to accelerating structures.

The big picture



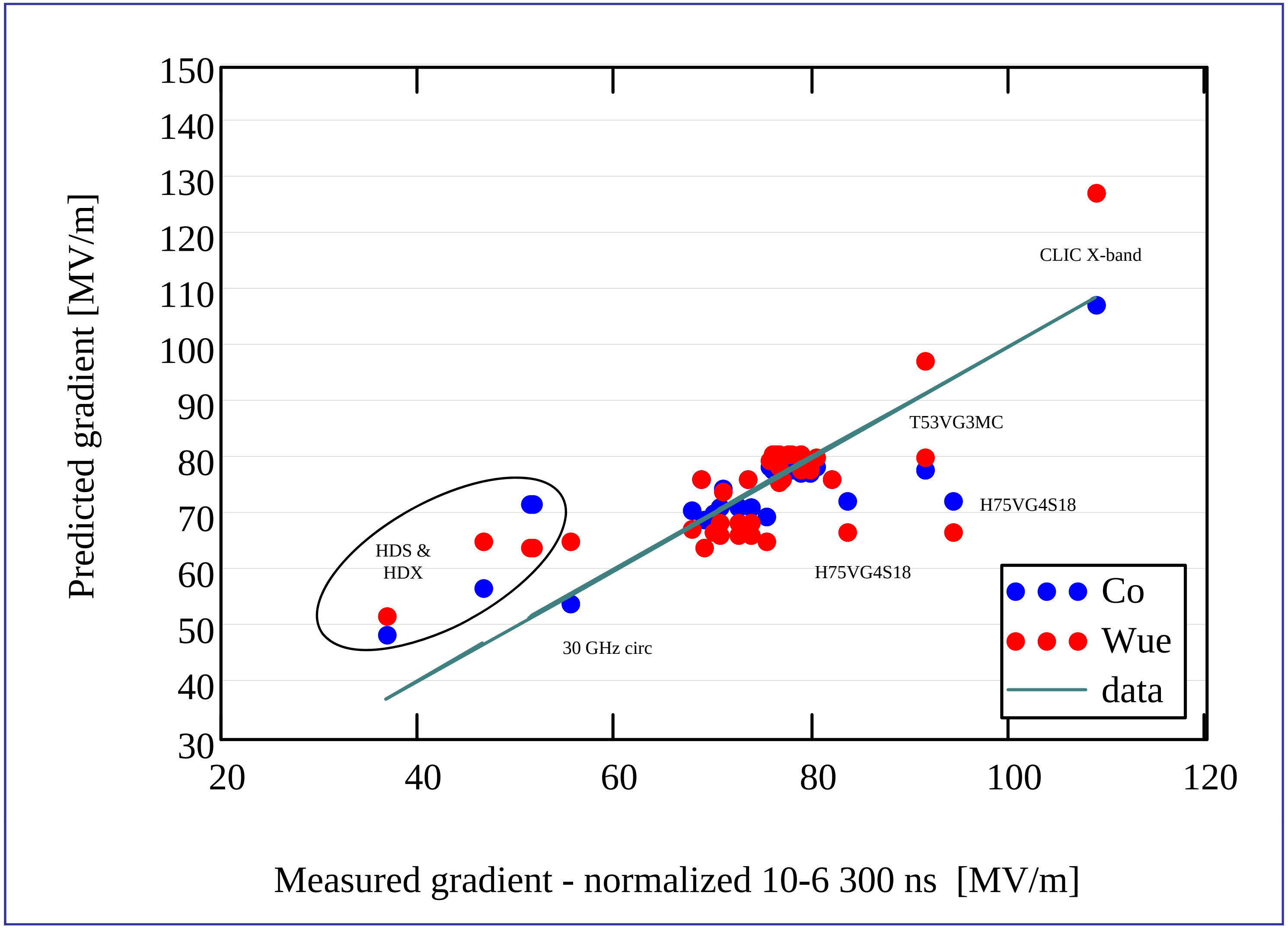
Data at 10-3 breakdown rate

X-band data

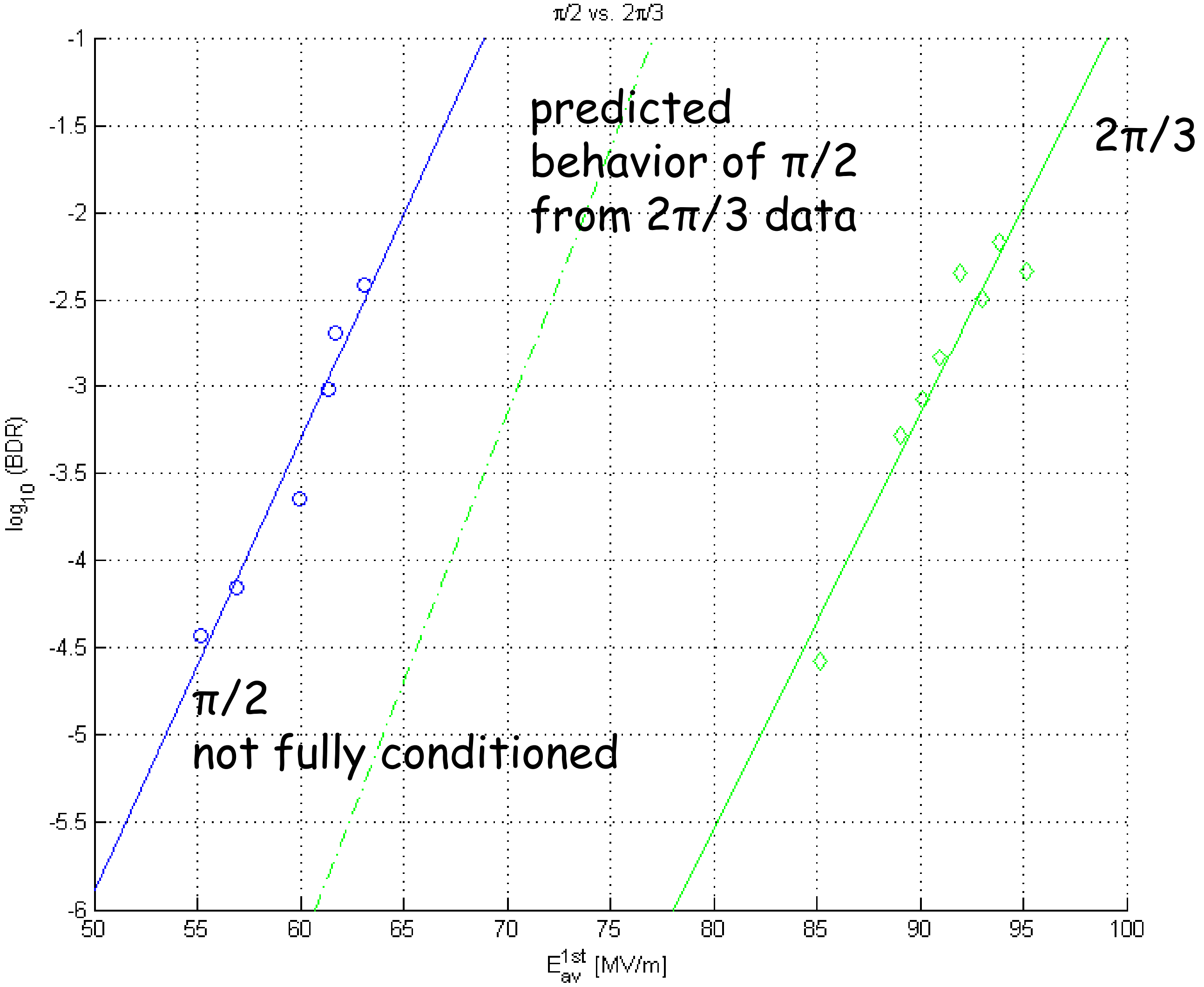


This where our choice of 18 wue for the optimization comes from

X-band data in another form



Direct comparison in experiment underway in CTF3



30 GHz copper 2π/3 and π/2, same fabrication, same couplers, same E_{acc}/E_s

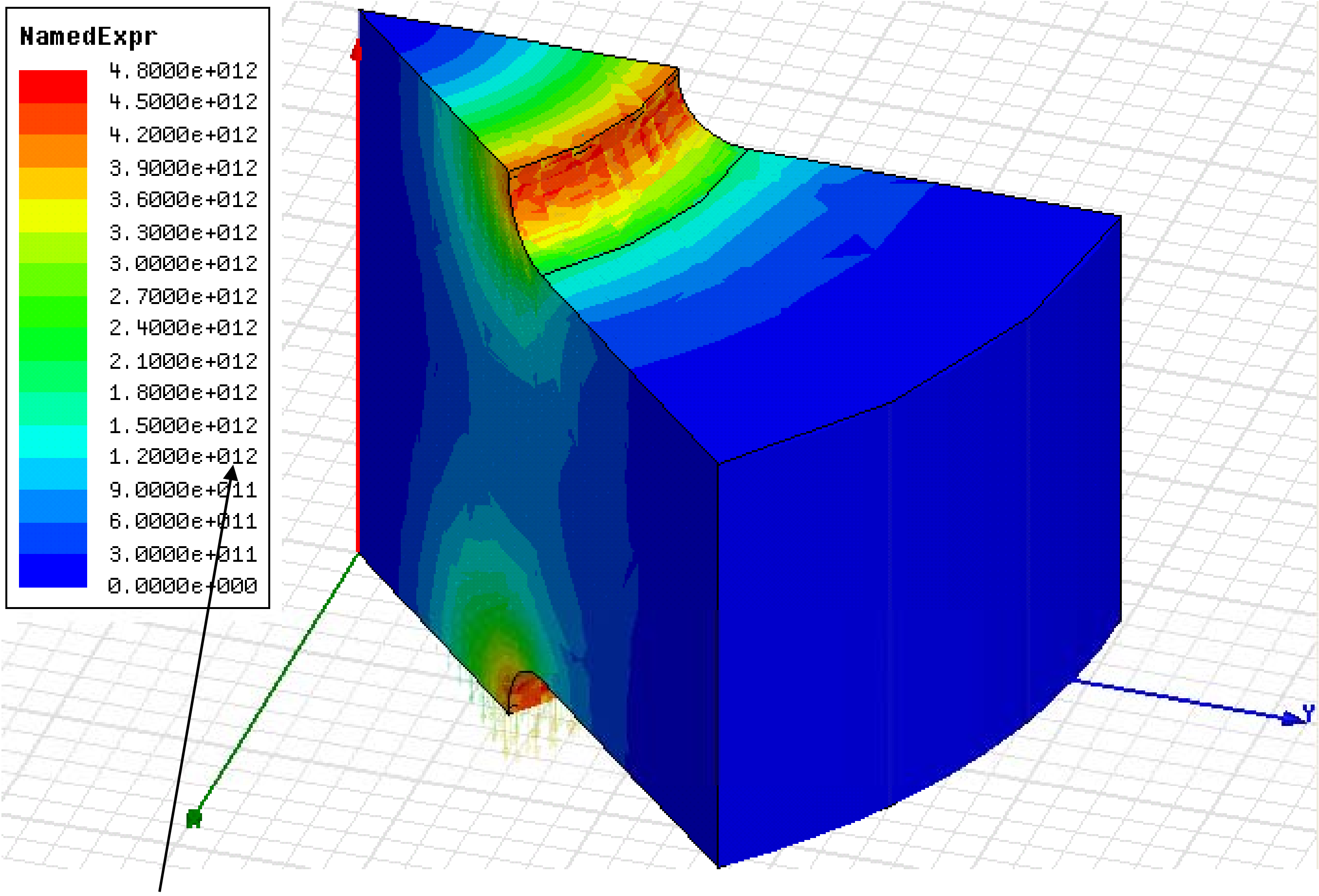
Next steps

P/C works reasonably well and we have used it extensively in our optimization.

Weaknesses: Frequency scaling is put in by hand. Physical arguments made from ablation limit but seems also to work well at low breakdown rates.

Find field quantity which scales like P/C and then extract physical meaning in breakdown trigger mechanism…

Power density available Cu 2π/3 at 90 MV/m, 20 MW, 70 ns, 10^{-3}



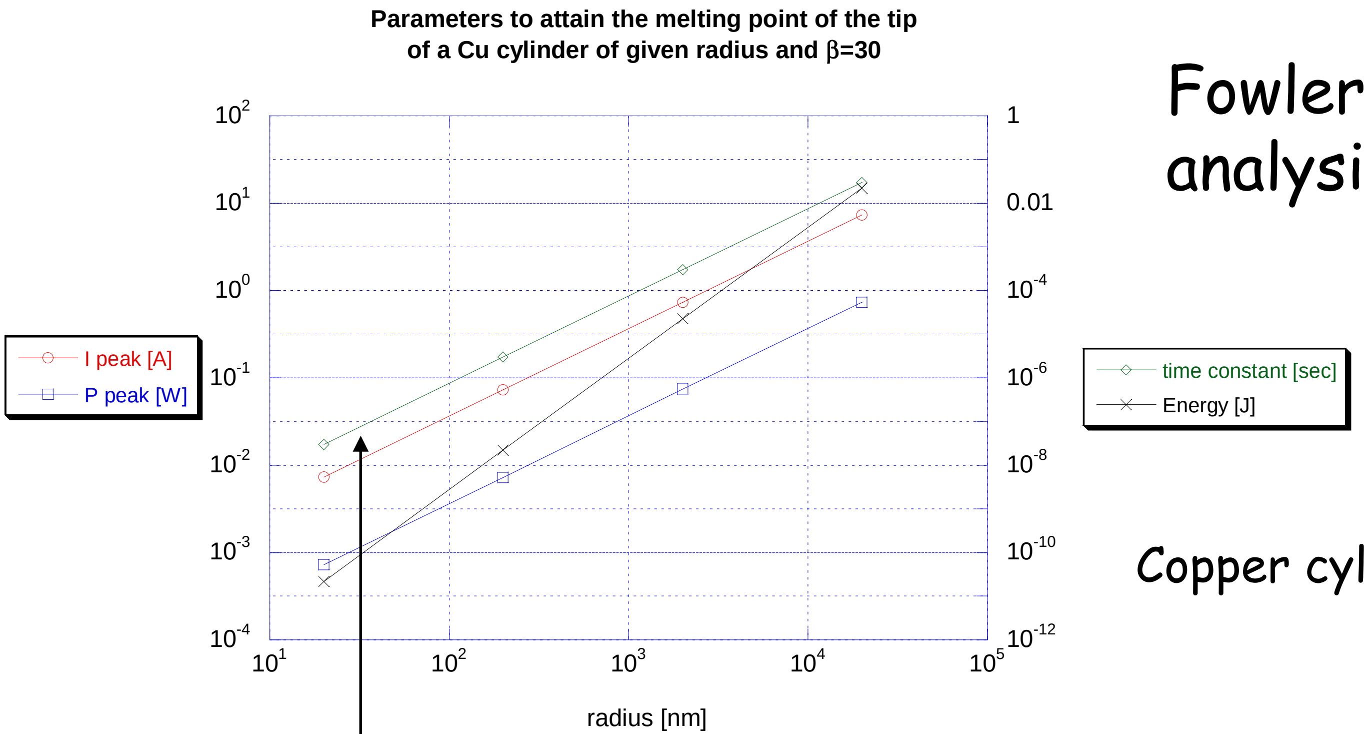
μW/nm²

Alexej

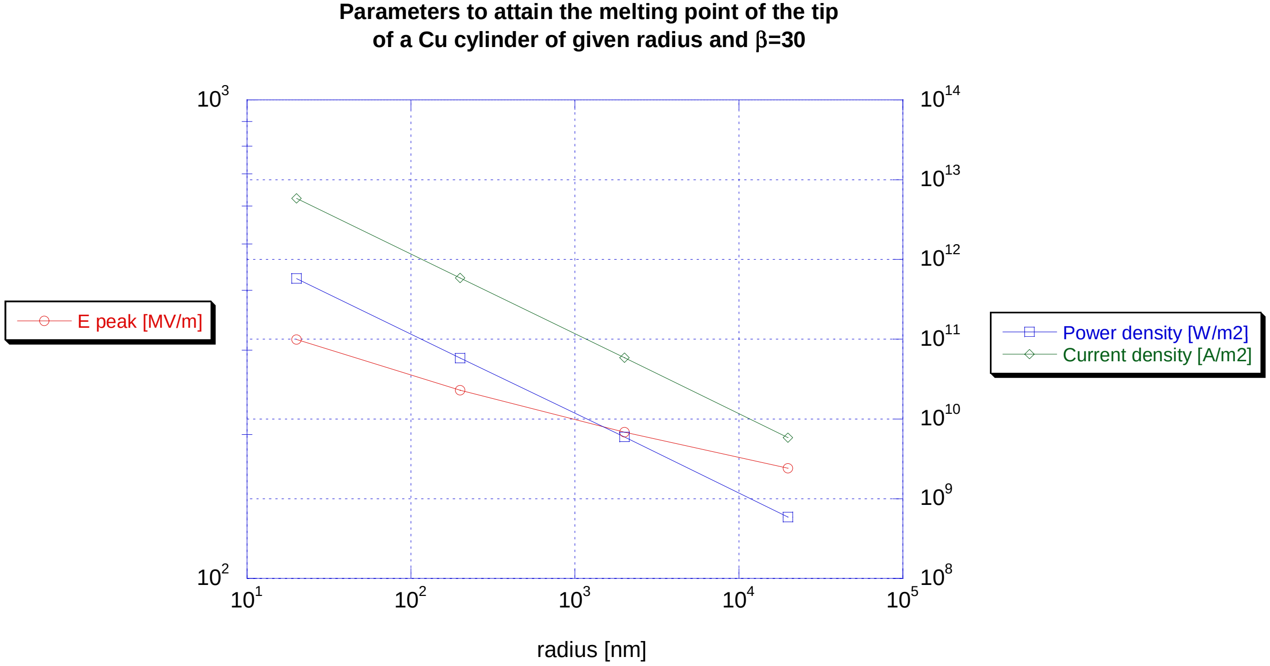
Fowler Nordheim analysis by Sergio

Copper cylinders, beta = 30

Power density required for triggering breakdown


Parameters to attain the melting point of the tip of a Cu cylinder of given radius and β=30

100 ns


Parameters to attain the melting point of the tip of a Cu cylinder of given radius and β=30

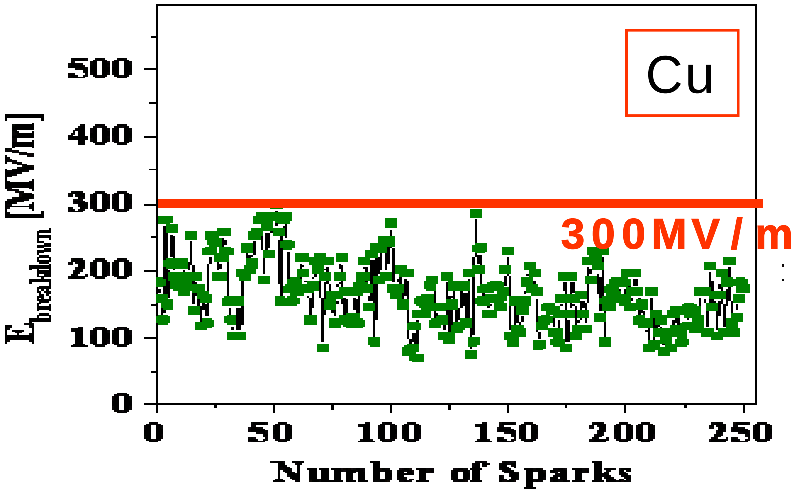
1-4 μW/nm^2 available and .2 μW/nm^2 needed is a remarkable agreement.

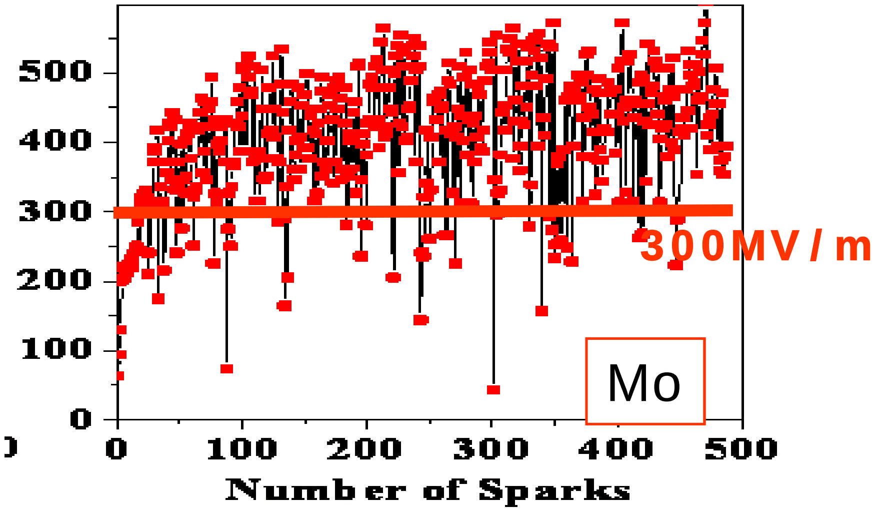
A local power flow is necessary to support even the breakdown trigger mechanism.

And very generally, this shows how a power limit is relevant at low breakdown rates (initial explanations evoked ablation limits etc.)

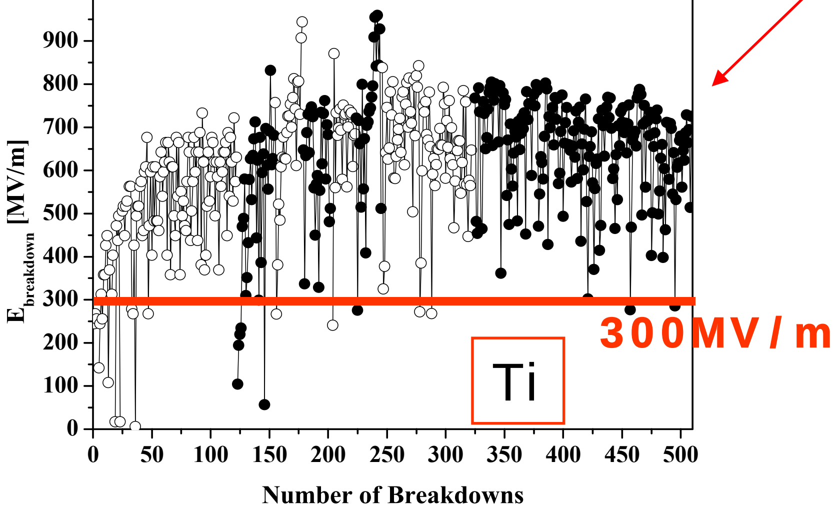
More insight into the coupling of rf to the emission sites is work under way.

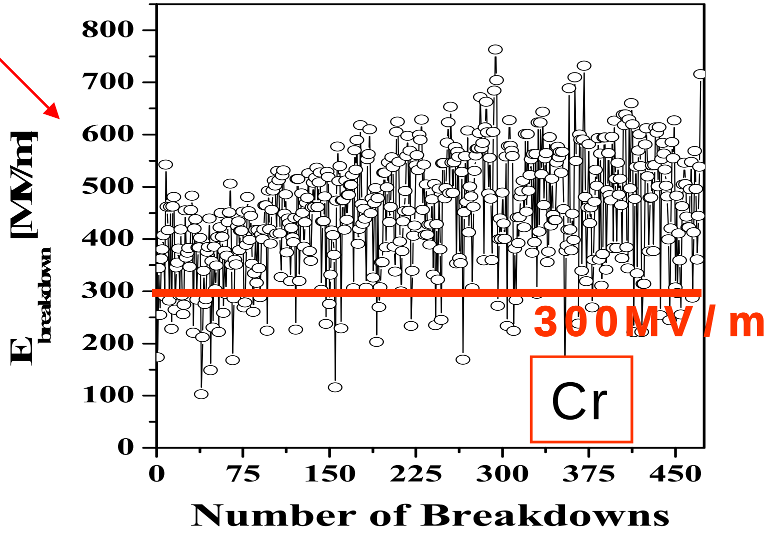
Tests on various materials



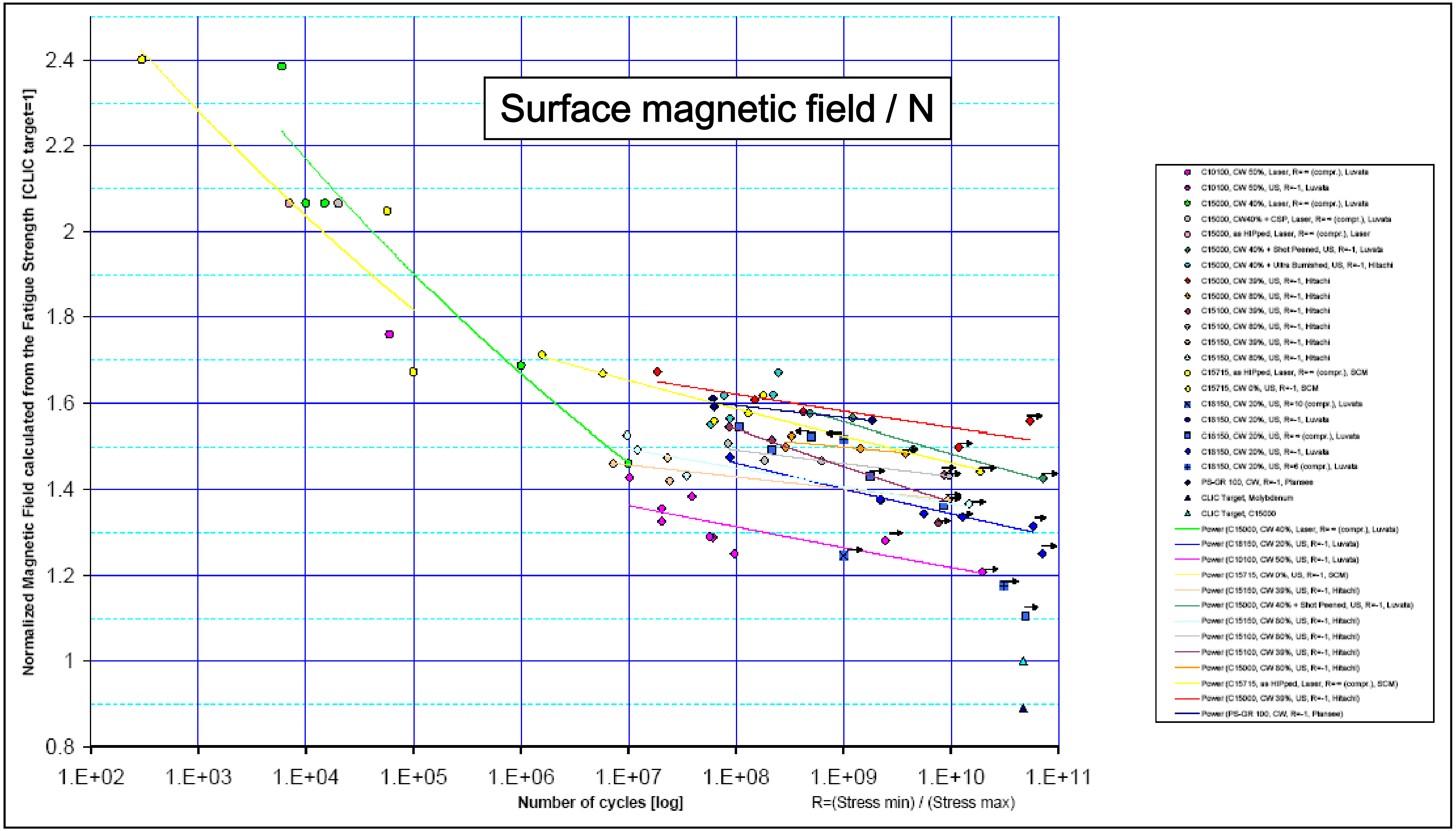


Good, but ...Strong erosion of the surface upon breakdown



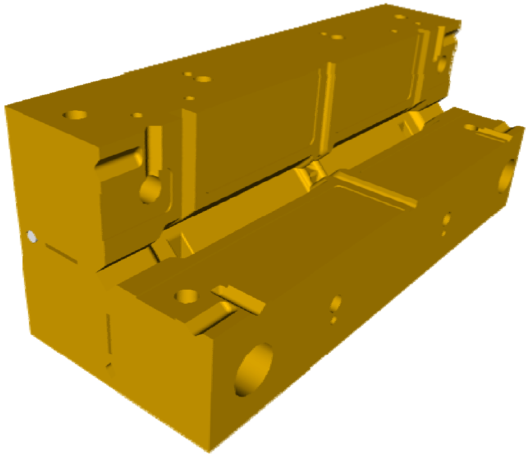


Up-to-date Ultrasonic & Laser fatigue test results

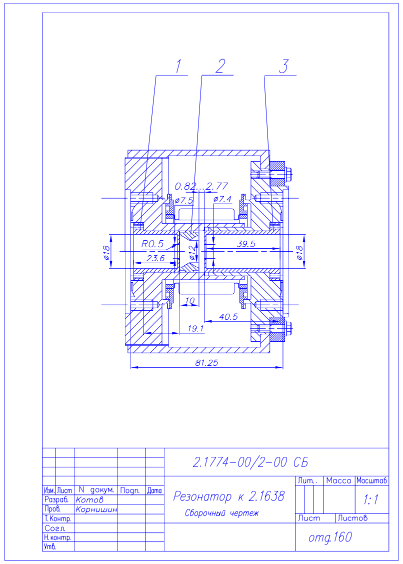


Planned RF Fatigue Tests

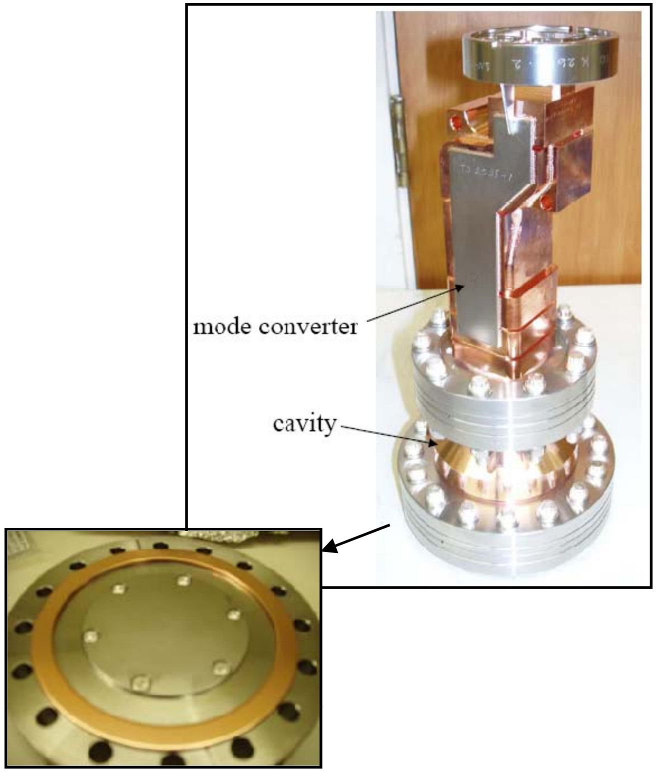
30 GHz pulsed heating cavity, CERN



30 GHz pulsed heating cavity, Dubna



11.4 GHz pulsed heating cavity, SLAC



S. Tantawi, SLAC