CLIC Accelerating Structure R&D Introduction

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CLIC ACE

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Outline

- The three goals of the structure R&D program
- Introduction to CLIC accelerating structures
- Main technical challenges
- Overview of activities
- Specific topic: rf constraints

Goal one

Demonstrate the feasibility of 100 MV/m (equivalent loaded gradient) by 2010.

- with an appropriate pulse length, pulse shape and breakdown rate
- structure with all major features such as full length, higher order mode damping etc.
- would give a reasonable efficiency in CLIC (good rf to beam efficiency, low enough wakes for good beam dynamics)
- design, build, prepare and test lots of structures and test areas

Goal two

Design (and maintain design) of the nominal accelerating structure for the CLIC which,

- provides the basis for the study of the rest of the machine (so must anticipate developments)

- gives an optimized efficiency in CLIC

- should survive 10^{11} pulses (from predicted fatigue behavior based on specialized experiments)

- could be made to required tolerances, microns, in mass production after dedicated development

- would be part of a cost minimized CLIC when fully integrated in the machine

Goal three

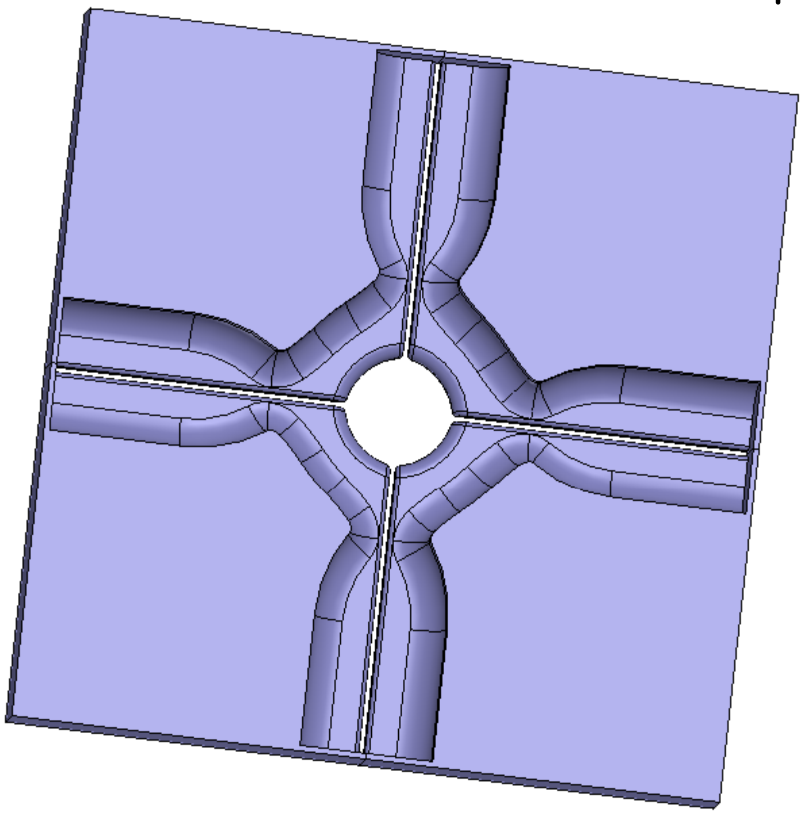
Investigate new ideas and technologies which would give higher performance.

- understand and quantify breakdown
- develop new rf designs (rf parameters, input couplers, damping mechanisms for example) with better high-power performance
- new materials
- new processing/cleaning/preparation
- improve tolerances

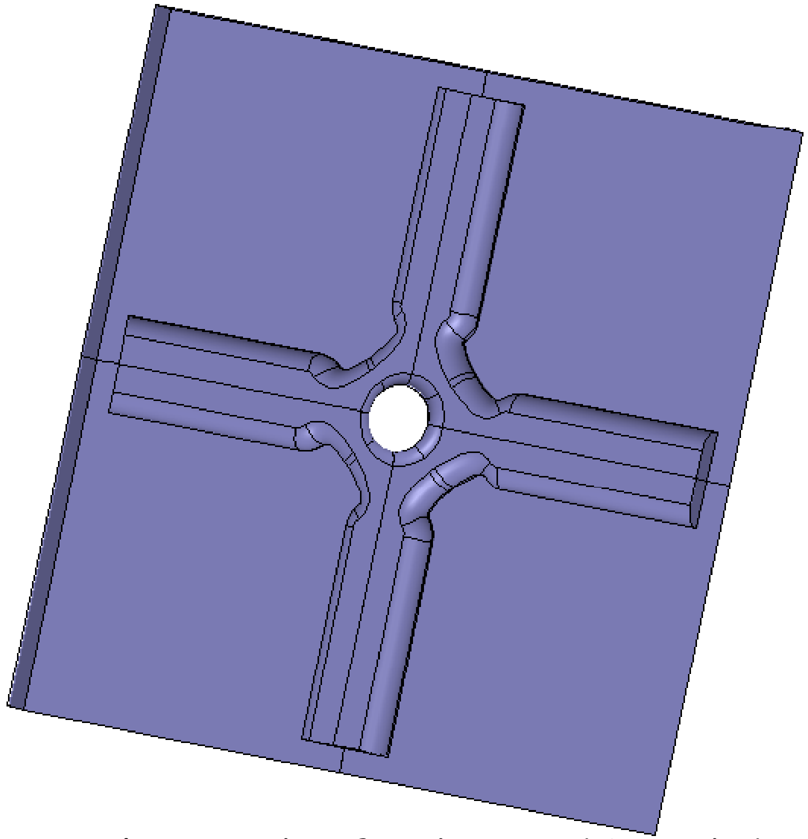
Introduction to CLIC accelerating structures

Traveling wave structure, heavy transverse mode damping, detuning

Two main types under consideration – Hybrid Damped Structure (HDS), Waveguide Damped Structure (WDS). Reevaluation of DDS and choke mode in pipeline.

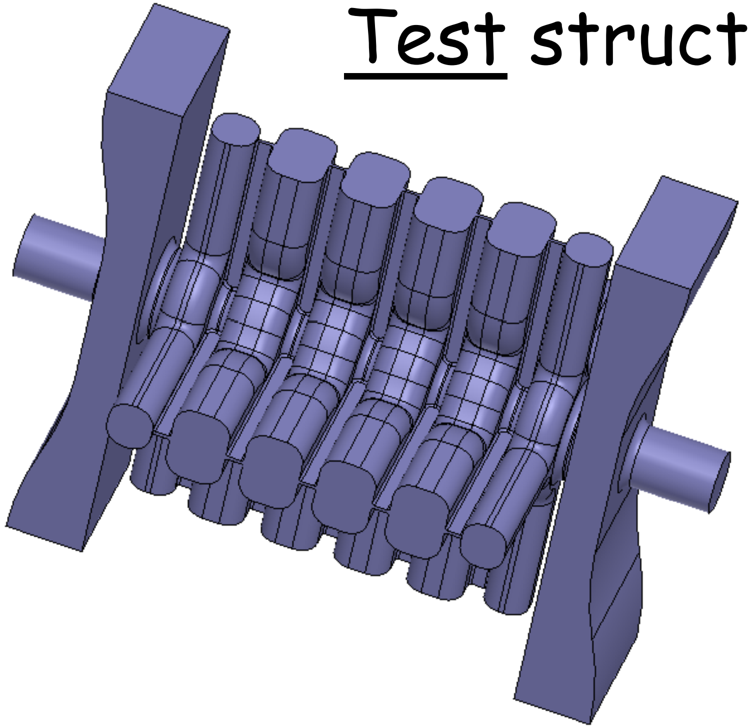


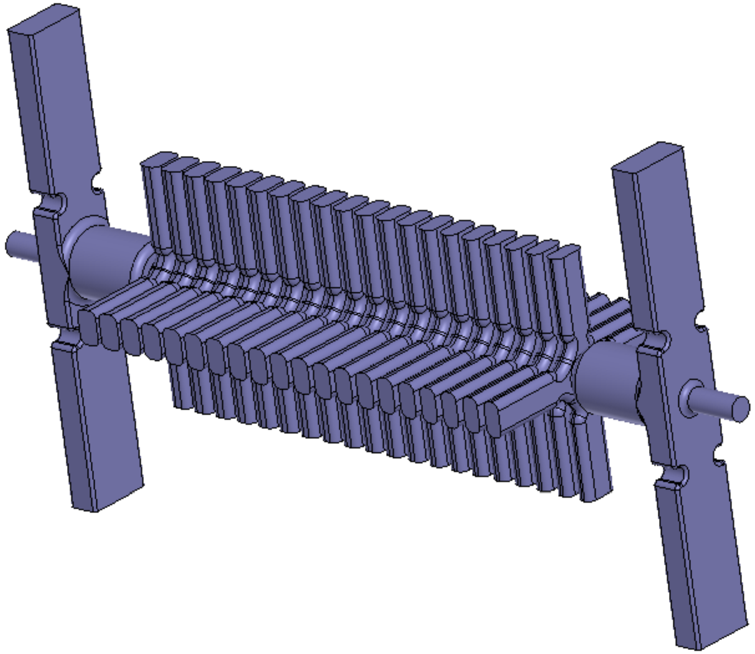
HDS: better for pulsed surface heating, quadrant assembly necessary

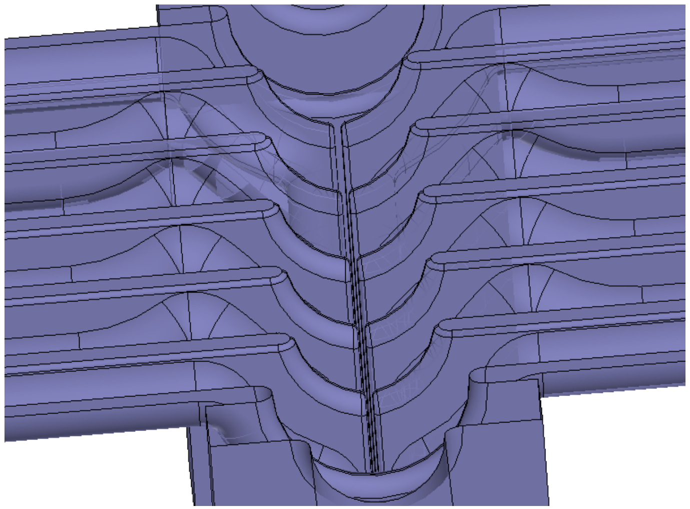


WDS: less risk of enhanced breakdown at iris, disk or quadrant assembly

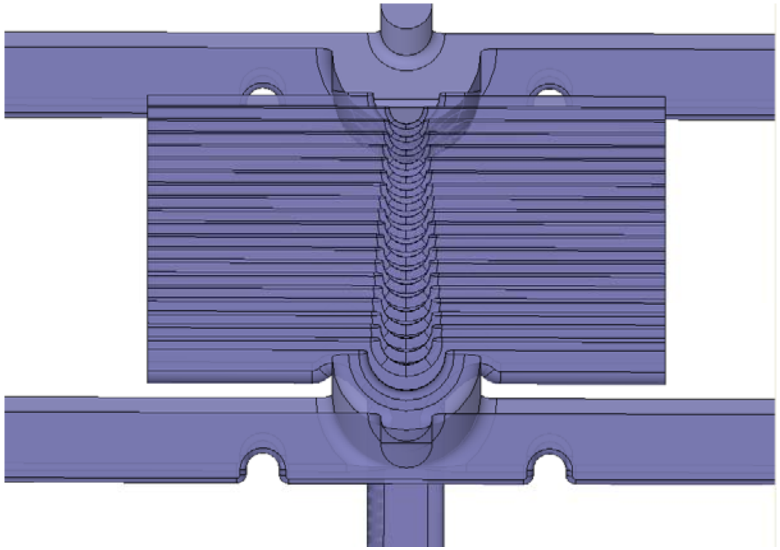
Test structures







HDS

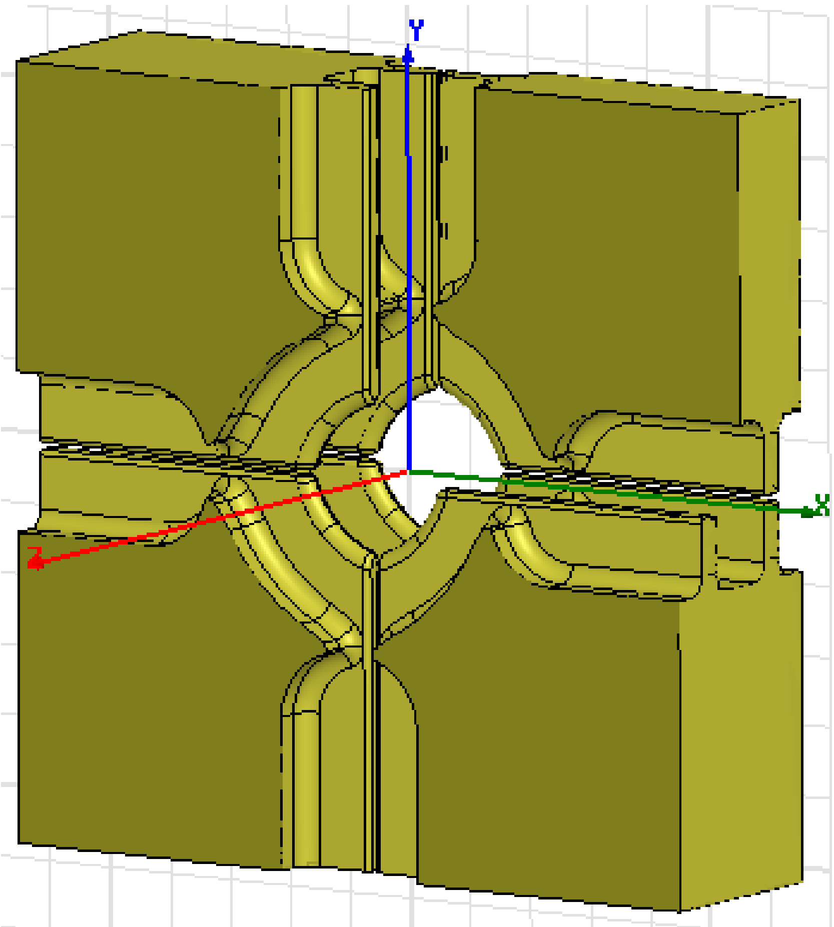


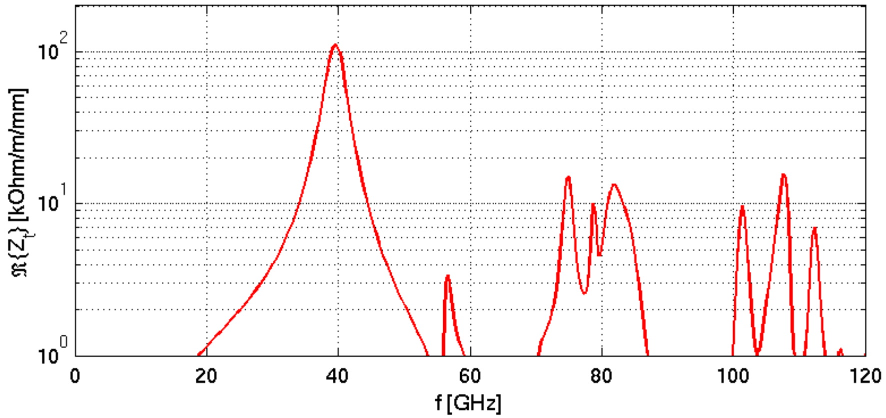
WDS

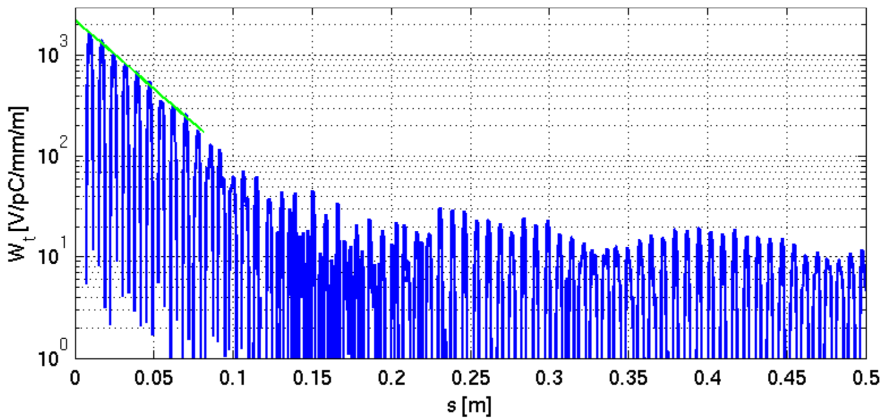
Hybrid Damped Structure (HDS)

Combination of slotted iris and radial waveguide (hybrid) damping

results in low Q-factor of the first dipole mode: ~ **10**



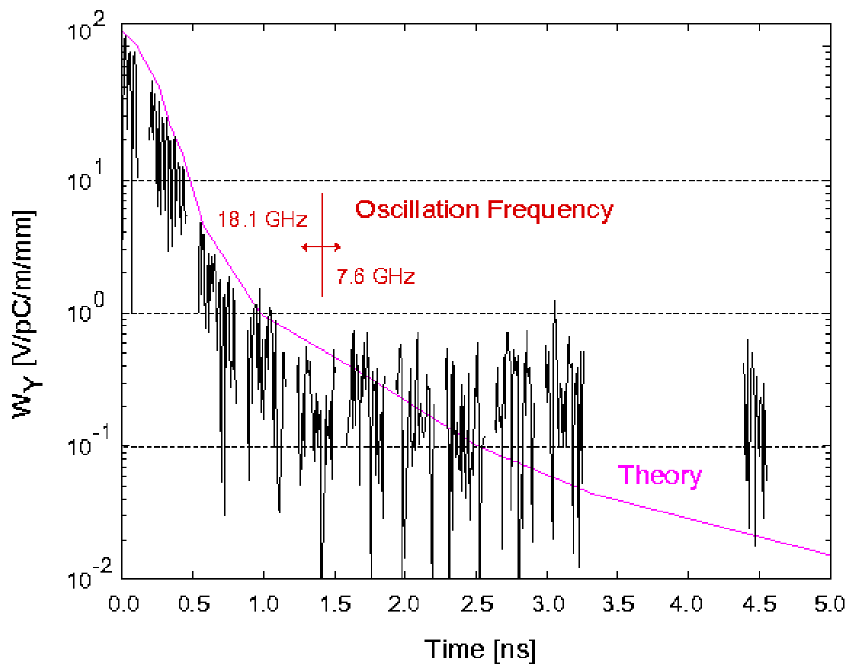


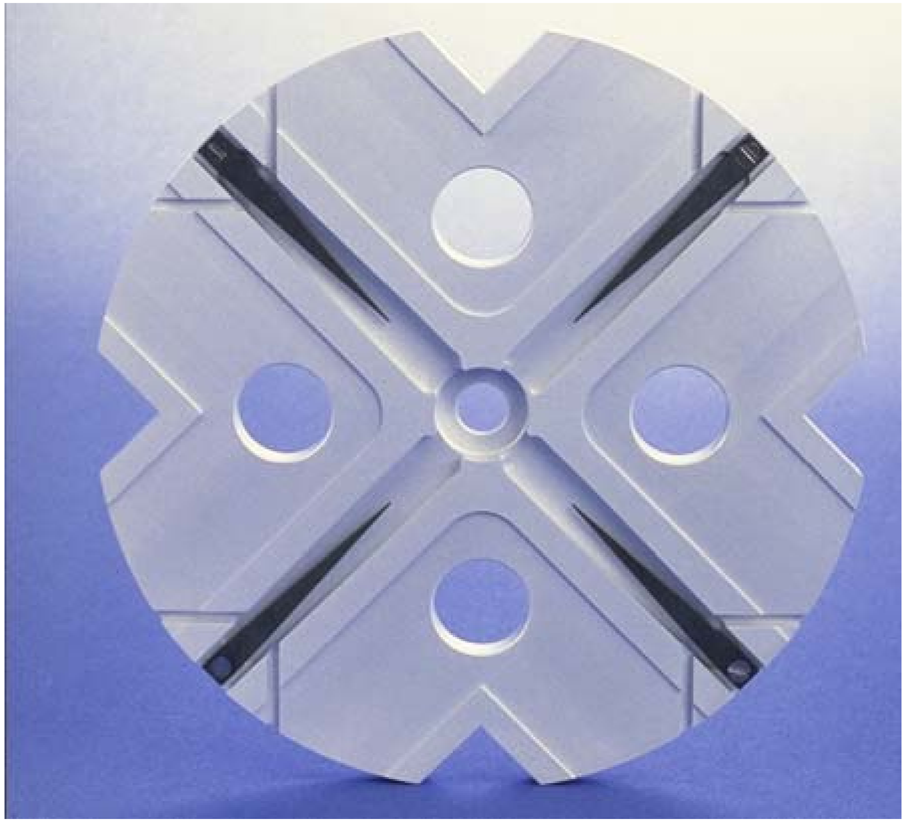


TDS design and modeling

•Strong damping, moderate detuning

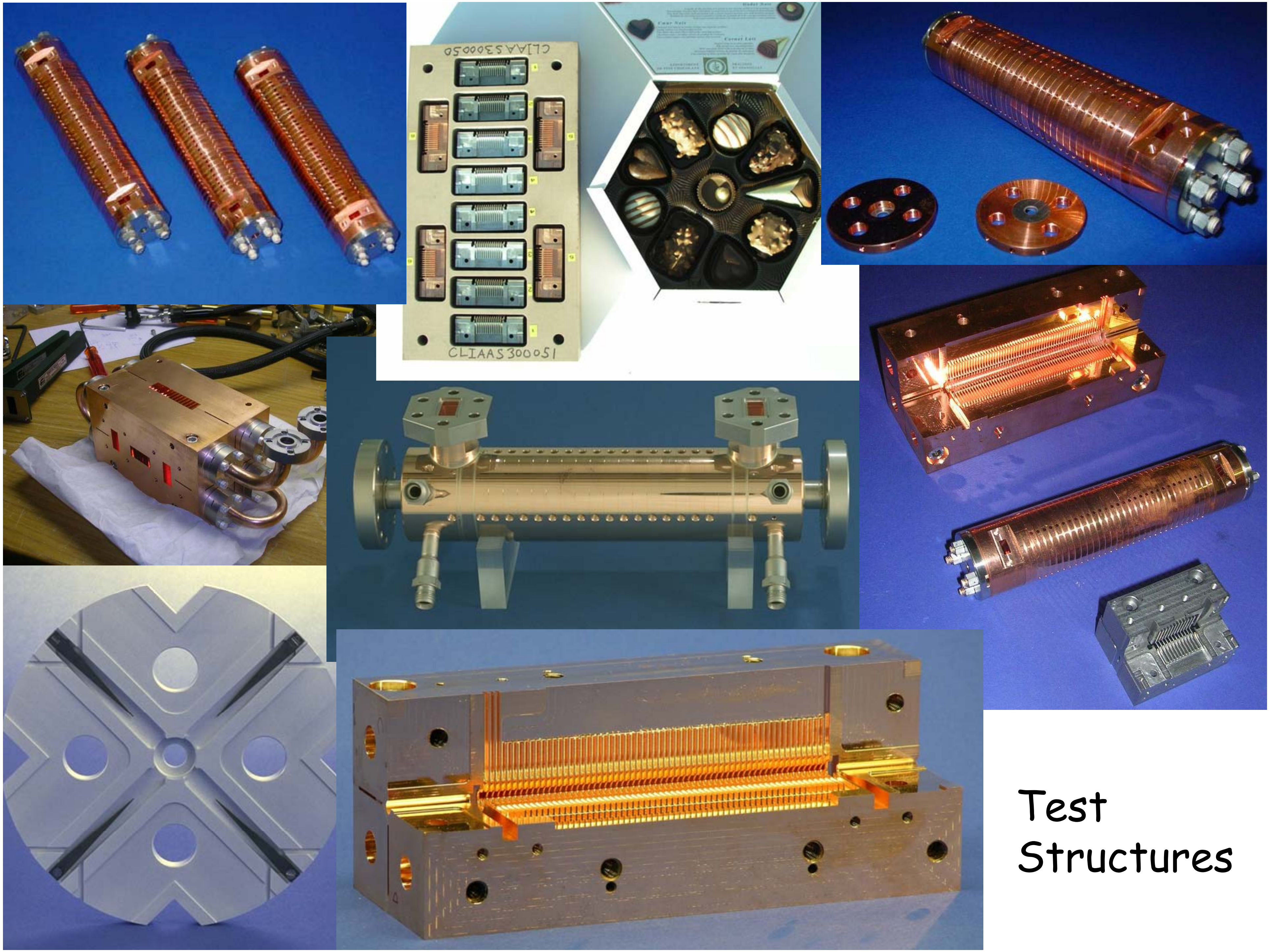
•Damping computed via double-band circuit model. Circuit elements determined from MAFIA frequency-domain calculations. Load modeled using HFSS.





ASSET demonstration of damping

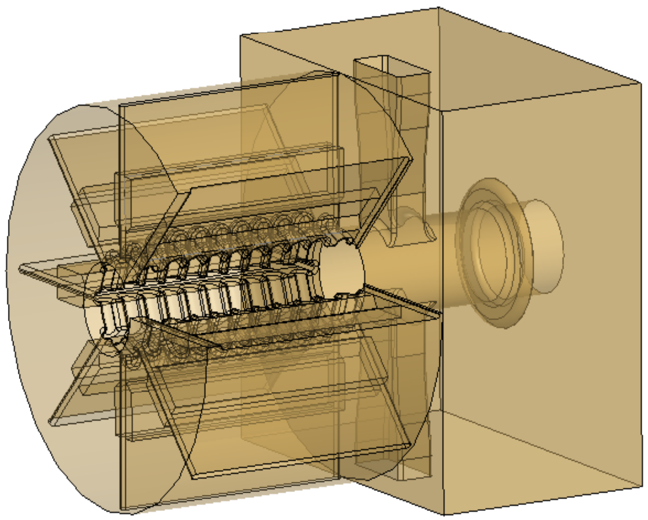
Long range wakefield benchmark

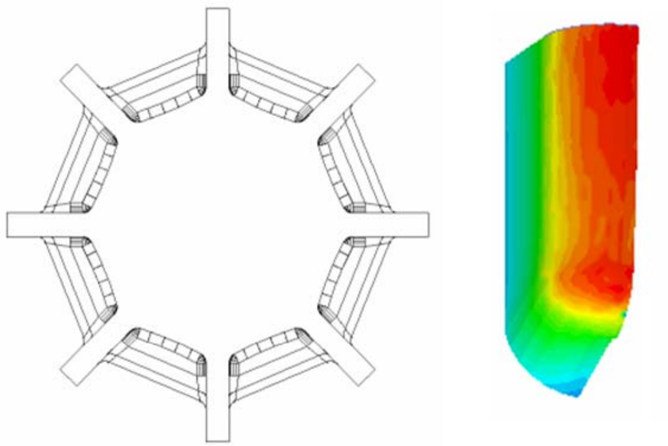


Test Structures

PETS

• The development program for power generating structures, PETS, is made in a close parallel to the accelerating structures.
• Many common rf concepts, computational techniques, fabrication but the over-moded, low gradient, high power high group velocity device has its own set of challenges.
• Many technological ideas used in the PETS are studied on the accelerating structures and will be carried over and will be checked experimentally when the 2BTS is available.
• The PETS as rf objects are not covered in detail in this ACE but Roberto will cover their integration in the drive beam decelerator.





Main technical challenges in accelerating structures

rf breakdown

pulsed surface heating

transverse wakefield damping

tolerances

cost

(dark current capture)

I will only discuss the first two subjects in any detail and make only a preparation for discussion of the other subjects

rf breakdown, short summary

Accelerating gradient is limited by breakdown (arcing, sparking),

- sets ultimate gradient of a structure.

- gives lower practical gradient for an acceptable breakdown rate. CLIC will have around 10^5 structures, spark acts on beam so our working estimate for breakdown rate is 10^{-6}. Breakdown rate is standard measurement in testing. Model for exponential behavior exists (I don't have time…). Kick was measured in NLCTA and will be measured again in the 2BTS.

- damages structure during conditioning when running above the operating (low breakdown rate) power and/or in accumulated breakdowns over lifetime of the machine (10^{-6}x10^{11} is still a lot of breakdowns). Investigation of new materials was initiated by this. Inspection of structures standard procedure.

rf breakdown, numbers

1. Low a/λ=0.12 X-band structure ran at 150 MV/m, 150 ns in 1994 but at high breakdown rate (values were not measured). Aperture was considered to be too small for use in a collider.
2. 30 GHz tests in CTF2 through 2001 showed high gradients (193 MV/m with Mo!) but at short pulse lengths (16 ns), high breakdown rates and with chewed up structures.
3. NLCA structures made 55 MV/m, 400 ns, 10^{-6}.
4. Strong evidence from first full year of full pulse length, correct breakdown rate 30 GHz testing in CTF3 that 150 MV/m is out of range for 2010.
5. Strong evidence from first full year of full pulse length 30 GHz testing in CTF3 that frequency scaling is either weak or flat.

There is more consistency here than first appears, rf constraints…

CLIC fatigue studies

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.

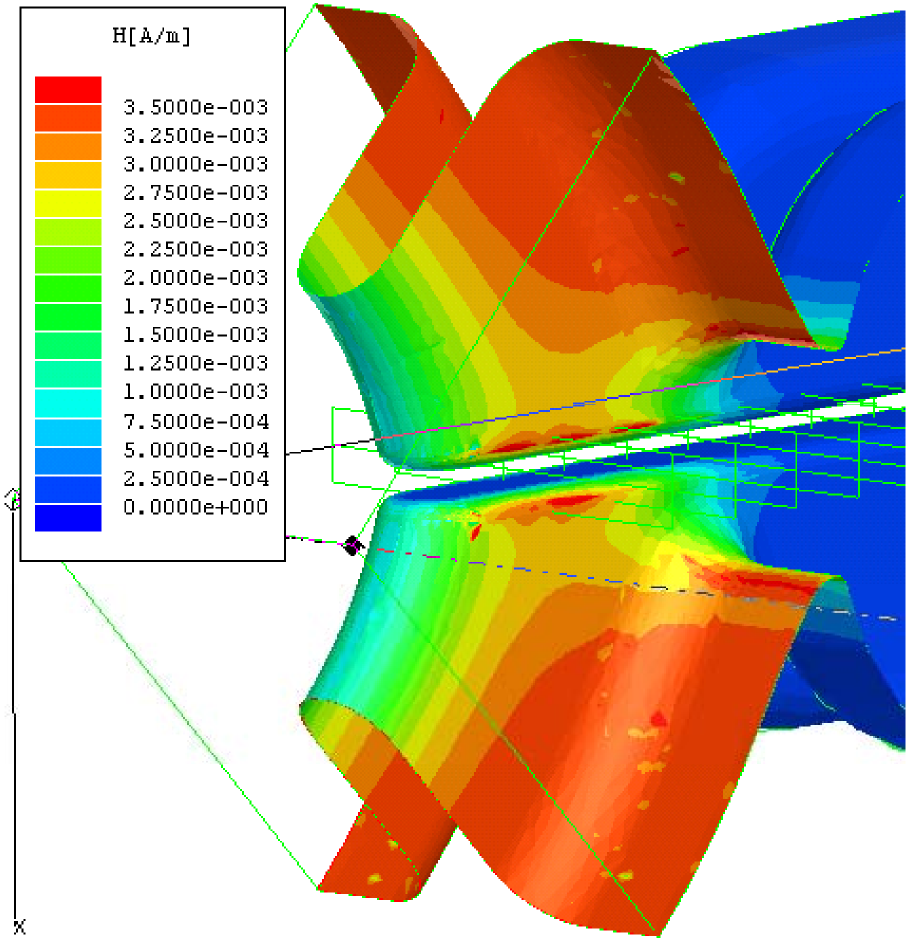
Challenge:
No material data exist in the literature for the CLIC parameter range.
Required number of cycles is 2.33×10^{10}.

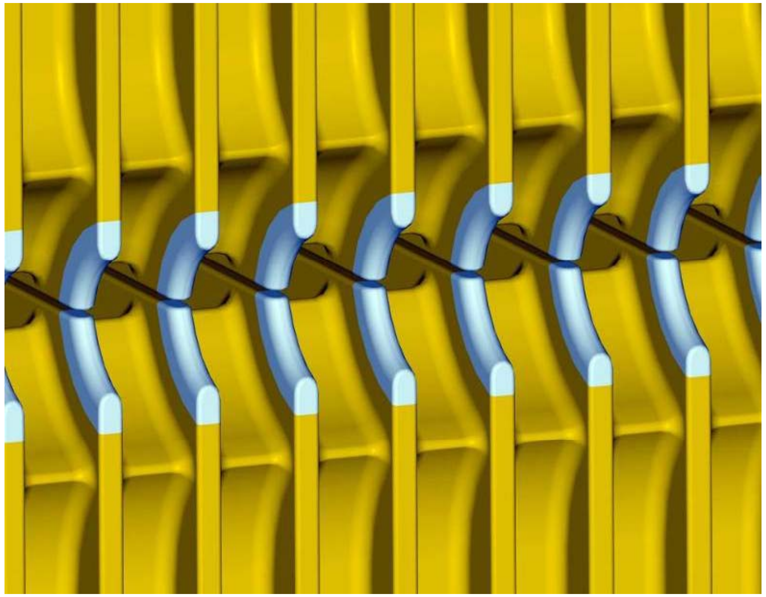
Methods:
Ultrasonic fatigue test setup is used to study the high cycle fatigue. CLIC lifetime can be achieved in 20 days.

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



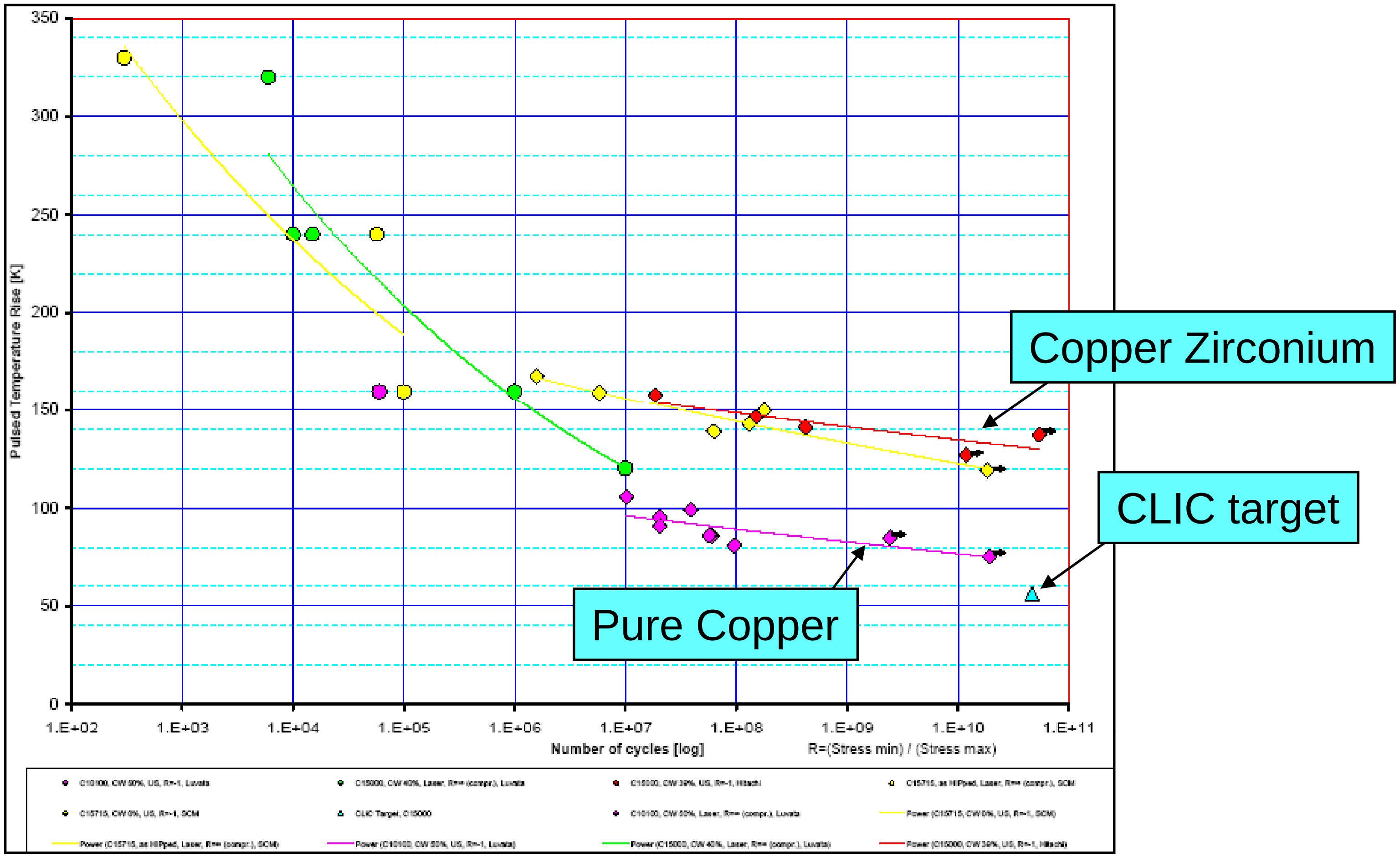


CLIC fatigue studies

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!



Optimization

Optimization procedure was developed to make a search for feasible parameters which takes into account high-power rf constraints, rf design, effect on beam and eventually cost (talks of myself, Alexej, Daniel and Hans).

Personal summary of outcome: 100 MV/m at X-band in copper is reachable assuming reasonable scalings of existing results. Demonstrating (as opposed to defending) this is GOAL 1.

The choice of parameters and the need for efficiency however leaves us with very demanding, few to ten micron, fabrication, alignment and measurement tolerances.

Now a simplified view of the main interplays which dominate our design,

Interplay 1

Geometries which give higher gradients are generally worse for beam dynamics (increased wakes, emittance growth and consequently lowered efficiency).

Directions,

- Quantify the relationship between structure geometry and gradient. Basic data from structures with different parameters analyzed, more data needed.

- Integrated rf design/beam dynamics/cost design loop.

- Improved mechanical tolerances and/or structure BPM performance!

- Better processing, materials etc.

Interplay 2

Features needed for higher order mode damping cause increased pulse surface heating and can give lowered gradient potential from rf breakdown

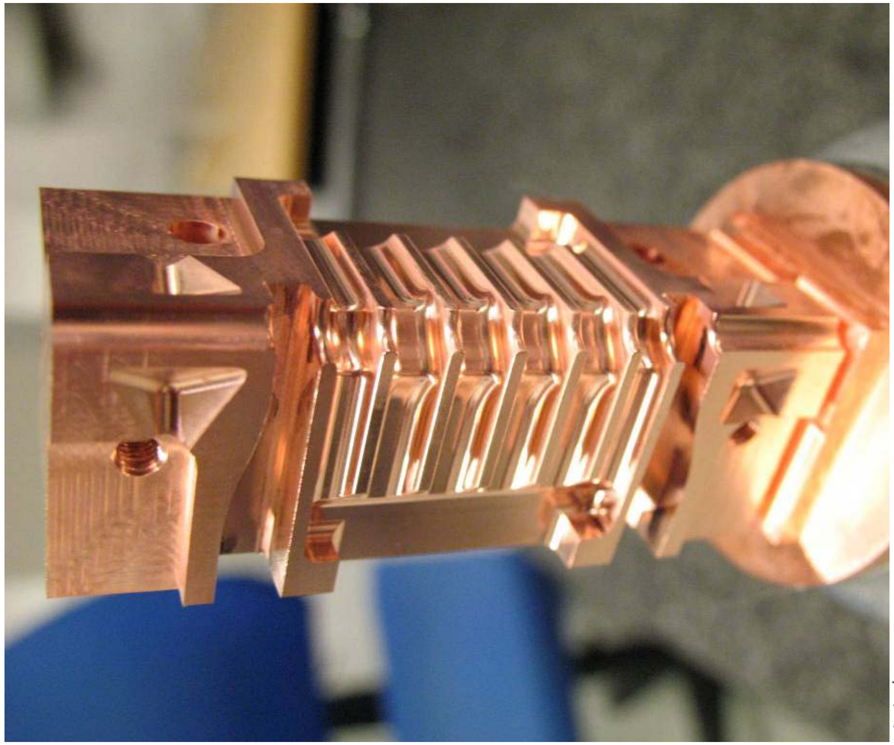
Directions,

- High power comparison of damping schemes (Slotted iris HDS, waveguide damped WDS, revisit DDS and choke mode)

- Quantify rf breakdown

- Integrated rf design/beam dynamics/cost design loop (I know I am repeating myself)

- Basic data on pulsed surface heating, raise potential through copper alloys, etc.

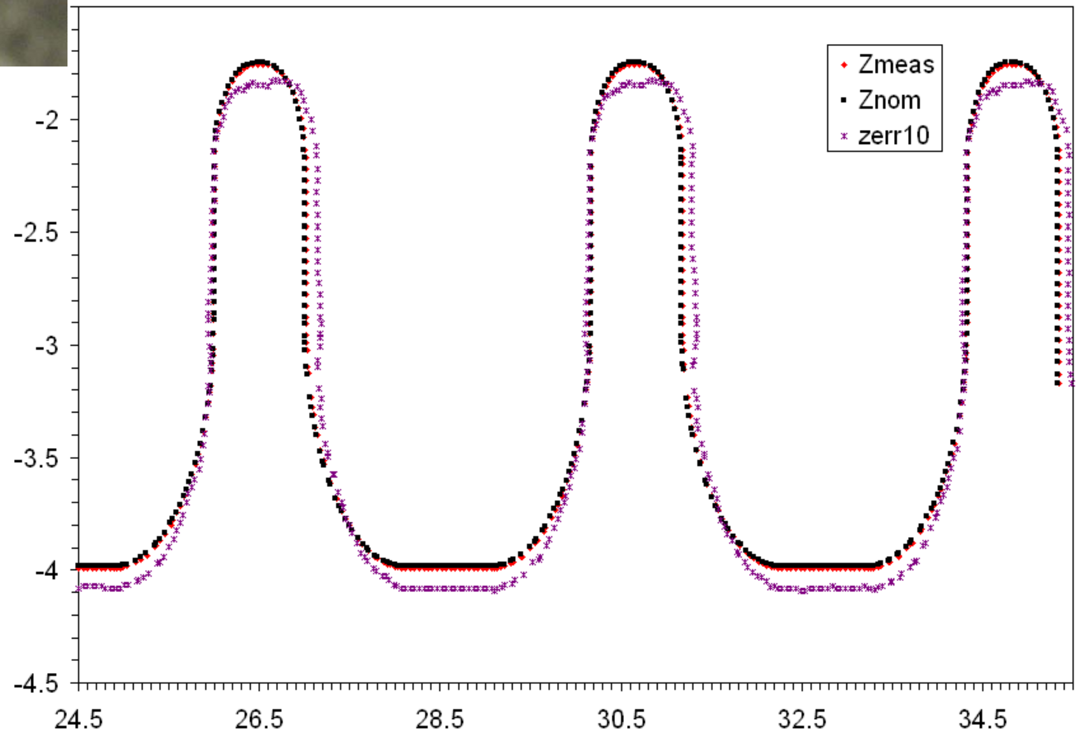


Achieved tolerances in 3-d milling

Result: Machine movement is accurate to better than a couple of μm (probably below measurement error).

Measurement and input of tool diameter into machining file gives dominant error. About 12-15 μm. Cut then fit calibration must be implemented.

error scale expanded by x10



This data is for a 30 GHz structure, expected improvement at X-band from larger tool.

Structure activities overview

- rf design, computation
- rf testing. Ongoing: 30 GHz testing in CTF3 and X-band testing at NLCTA. Future: 2BTS in CTF3, KEK, MYTUBE at CERN
- dc spark testing. Used to quantify preparation procedures and test new materials. Will be used to benchmark breakdown simulation work.
- Preparation technique studies. Heating, etching, rising etc.
- New materials for breakdown (this activity is regrouping after inconsistent results from Mo) and for pulsed surface heating. Bimetallics.
- Precision machining studies

Structure activities overview, continued

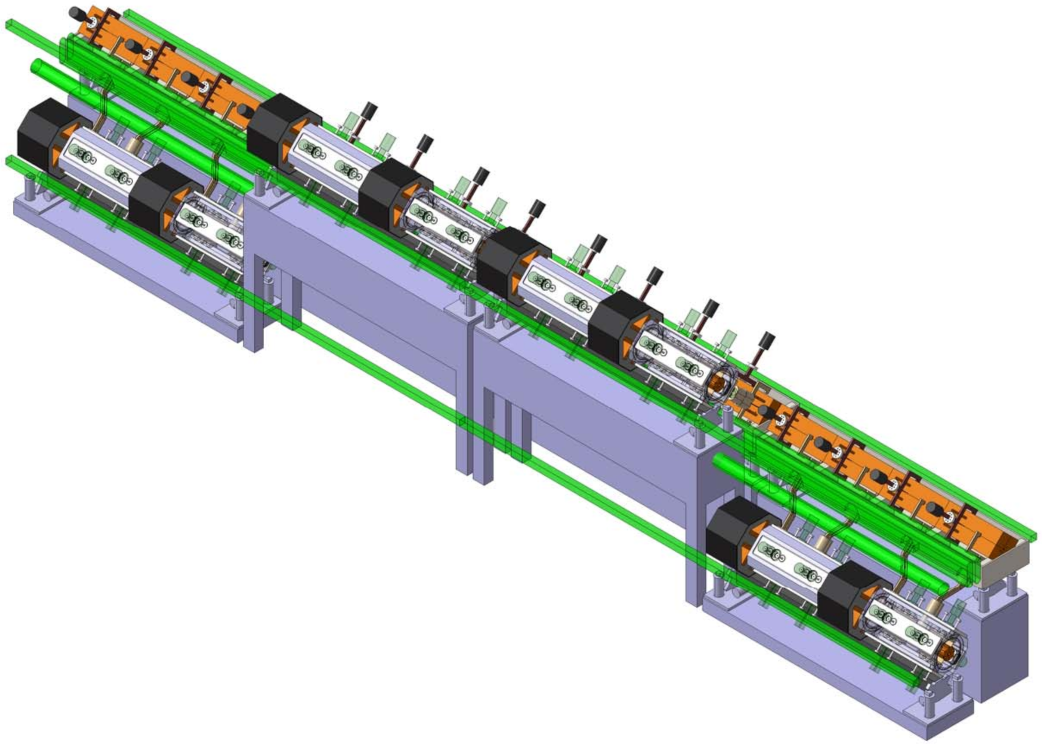
- Breakdown theory. Quantifying limits, trigger mechanisms, rf absorption, damage mechanisms.

- ultrasonic, pulsed laser and rf fatigue testing

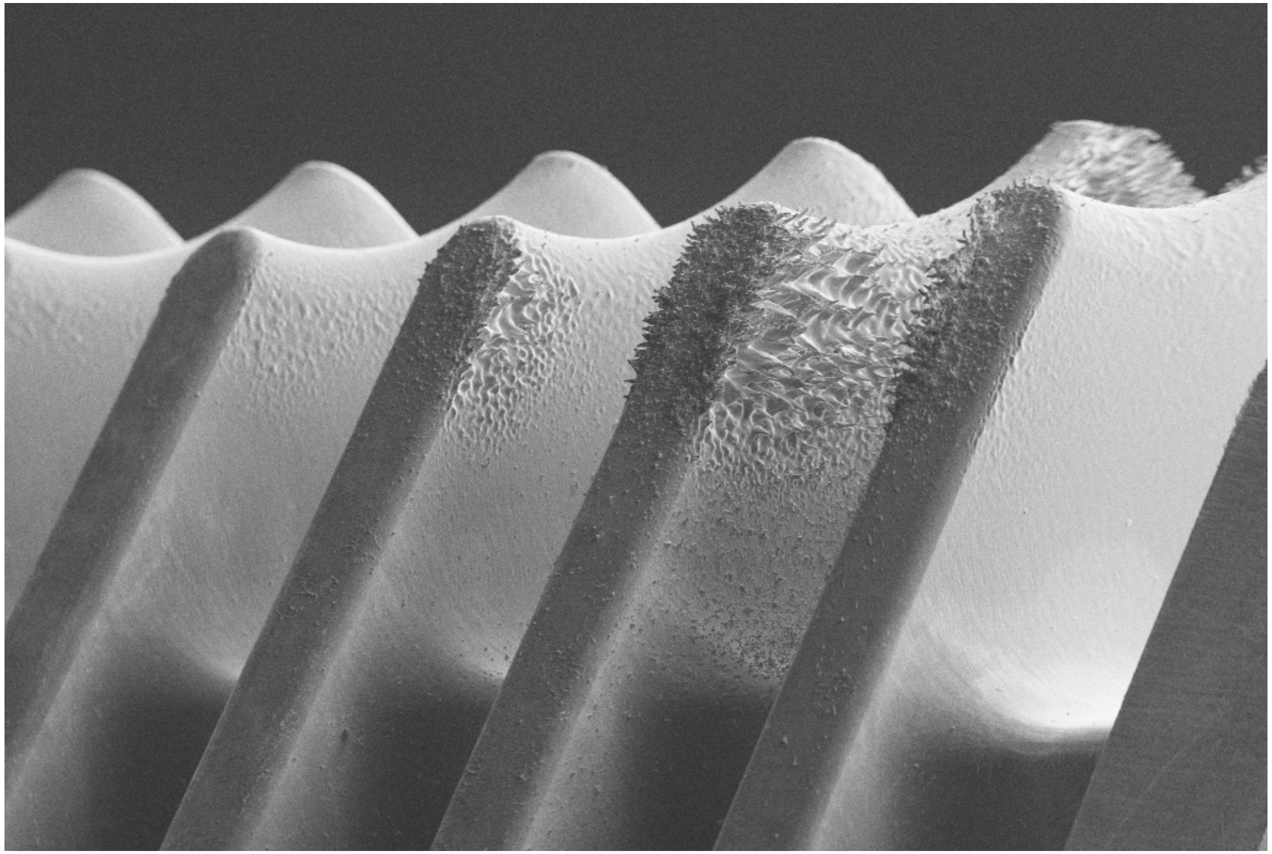
- Collaborations (ongoing and developing): BARC (India), Cockcroft Institute, Dubna, Finnish Industrial network, Frascati, HIP Finland, IAP Ukraine, KEK, Pakistan, Saclay, SLAC, Uppsala

And not to forget,

- rf components
- PETS
- module design



High-gradient rf constraints



Goal of this part of the 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 (mostly covered already)
2. Surface electric field
3. Power flow limit

Then a little bit on new directions…

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.

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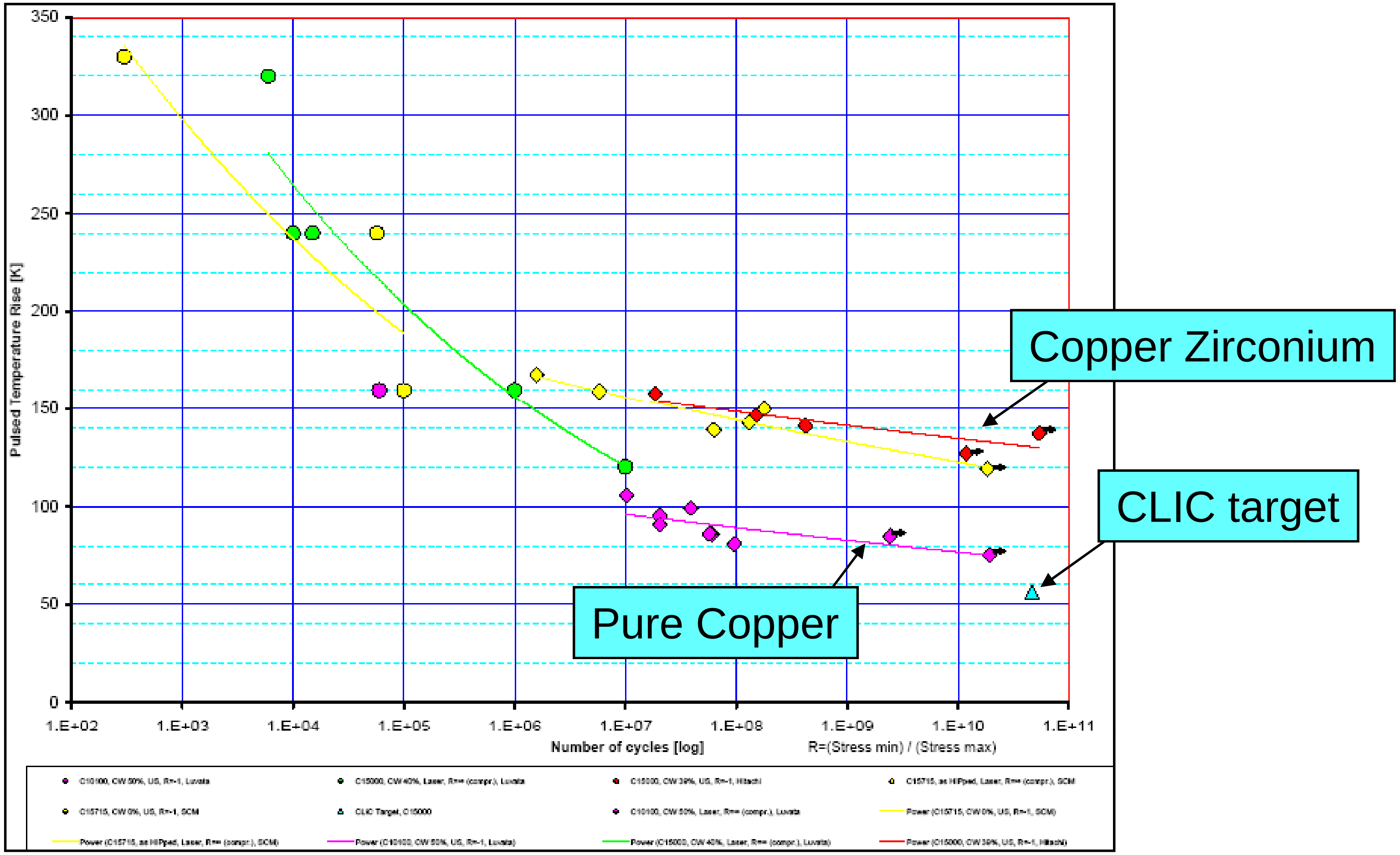


Peak surface electric field – rather straight forward idea

	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

same phase advance, iris thickness, machining and assembly

	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

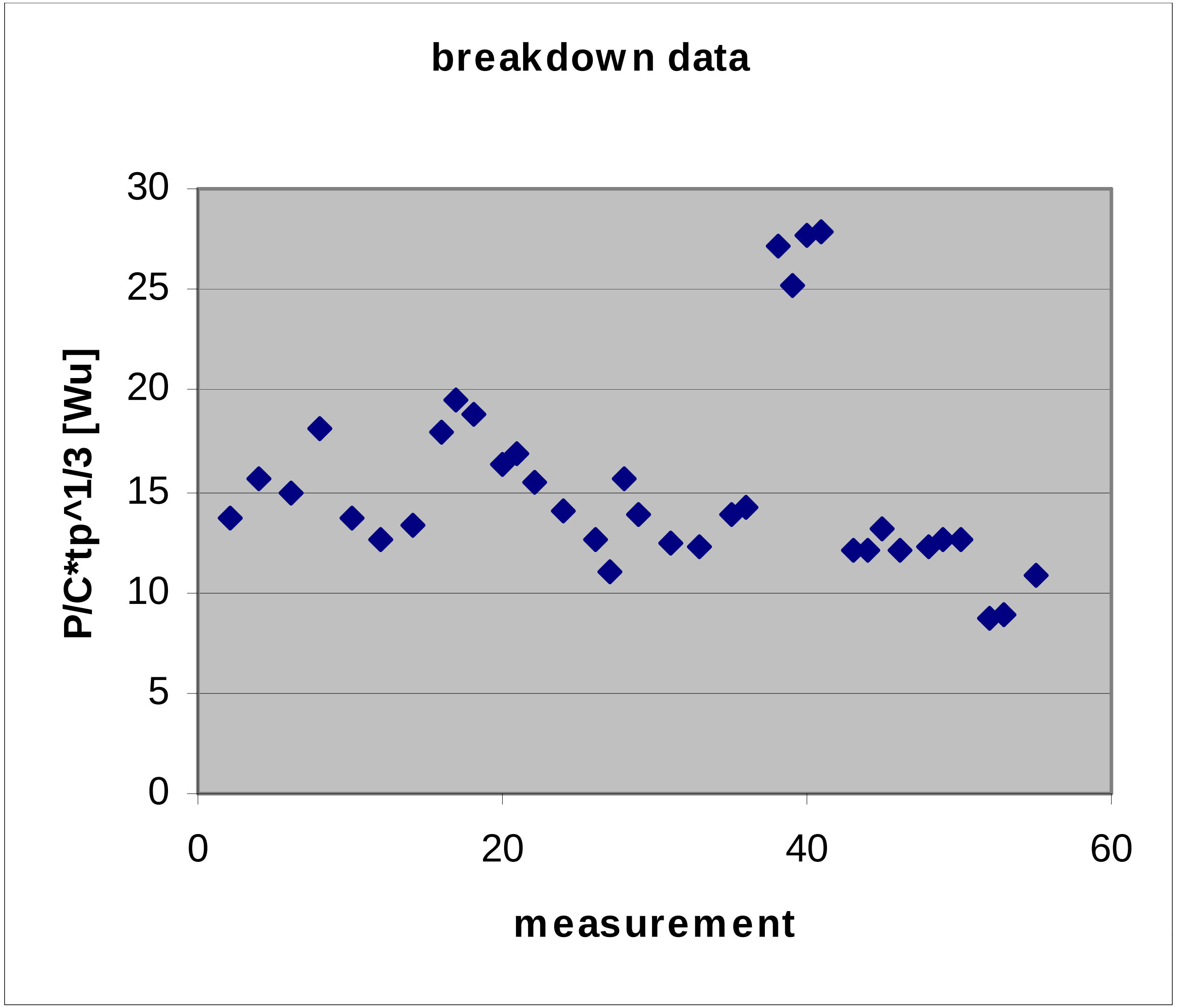
Analysis of waveguide data from clean experiment of V. Dolgashev and S. Tantawi

	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.

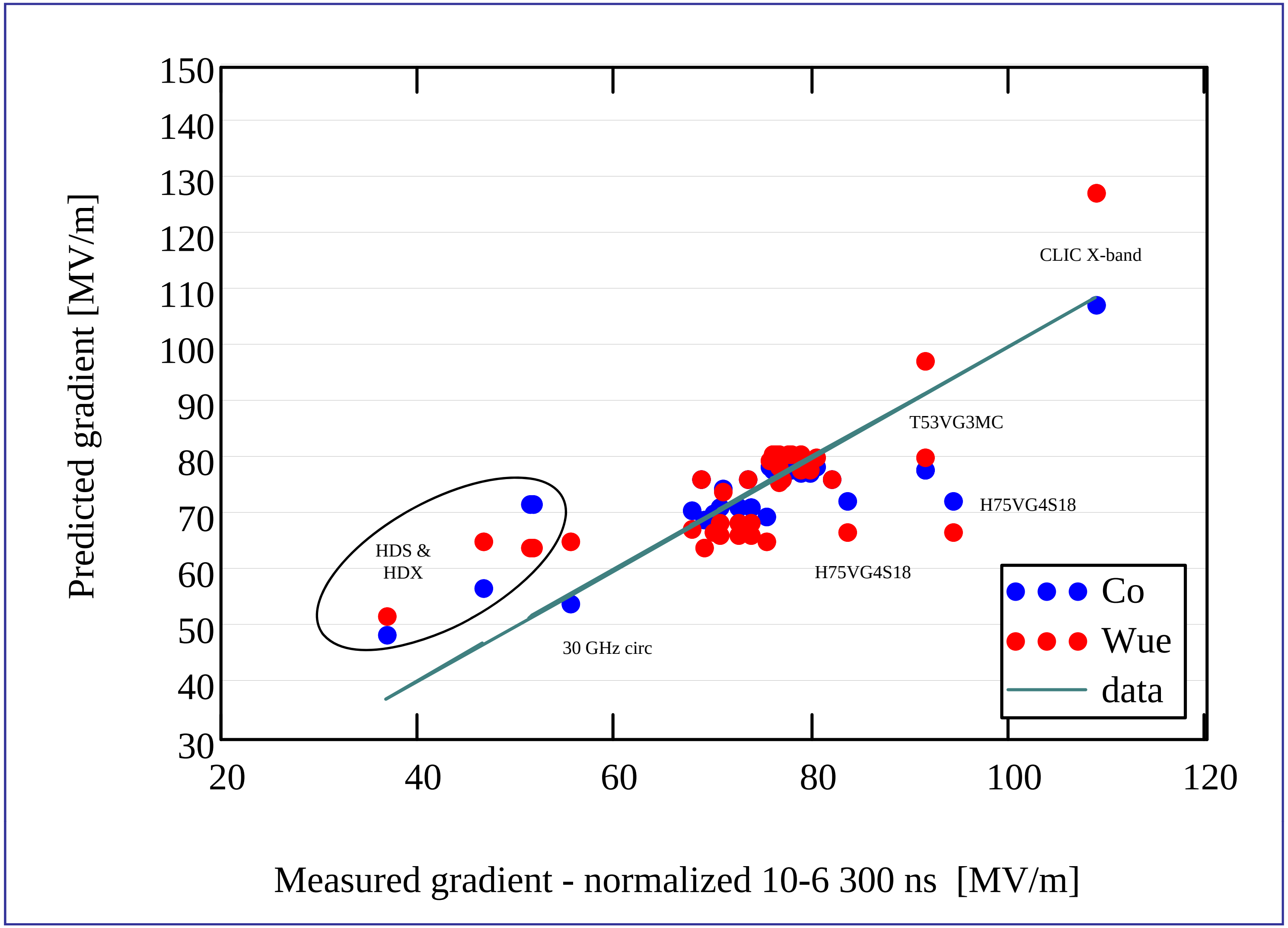
X-band data

Wide range of phase advance, couplers, machining, assembly

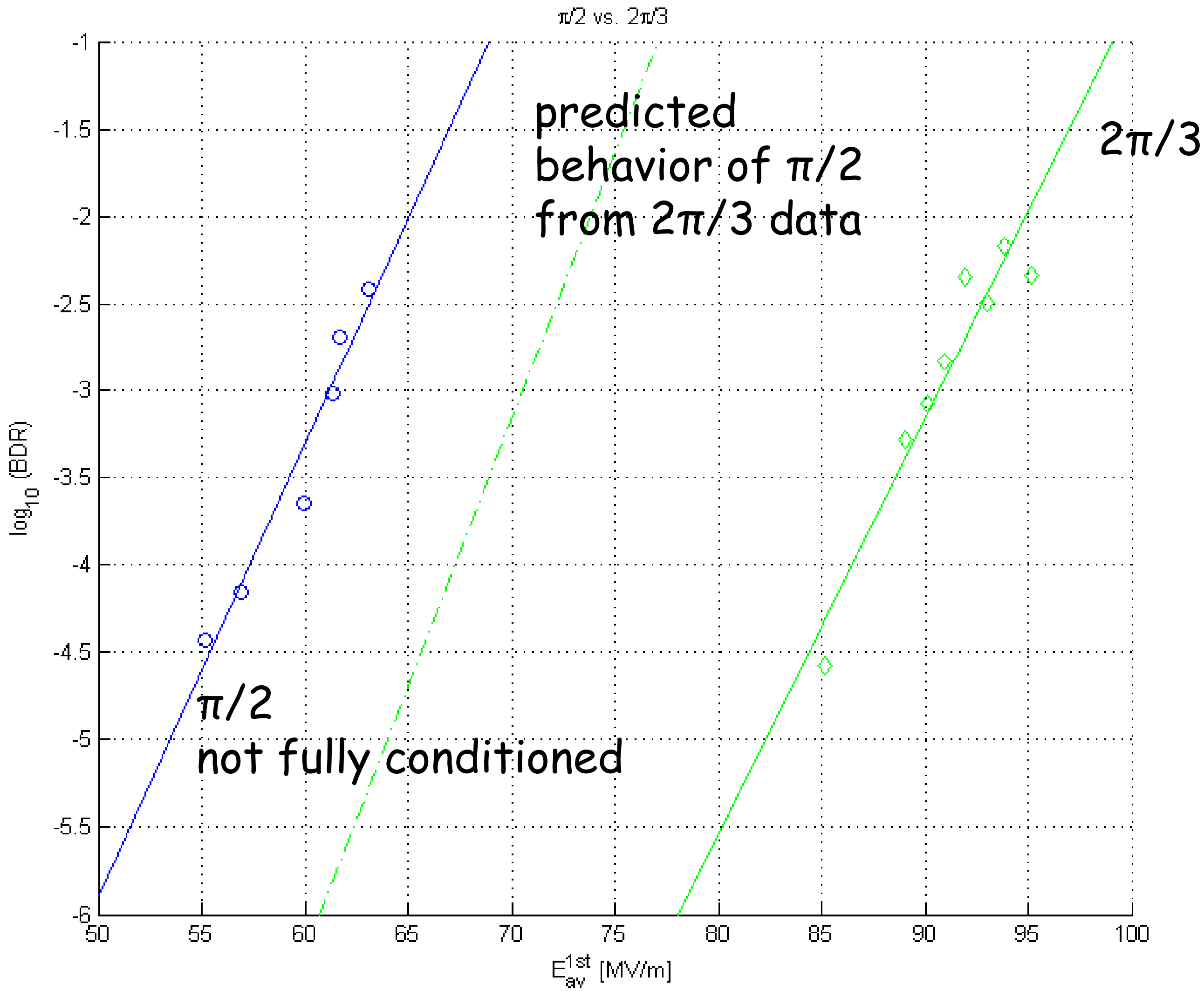


This where our choice of 18 wue for the optimization comes from

X-band data in another form



Direct comparison in experiment underway in CTF3



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

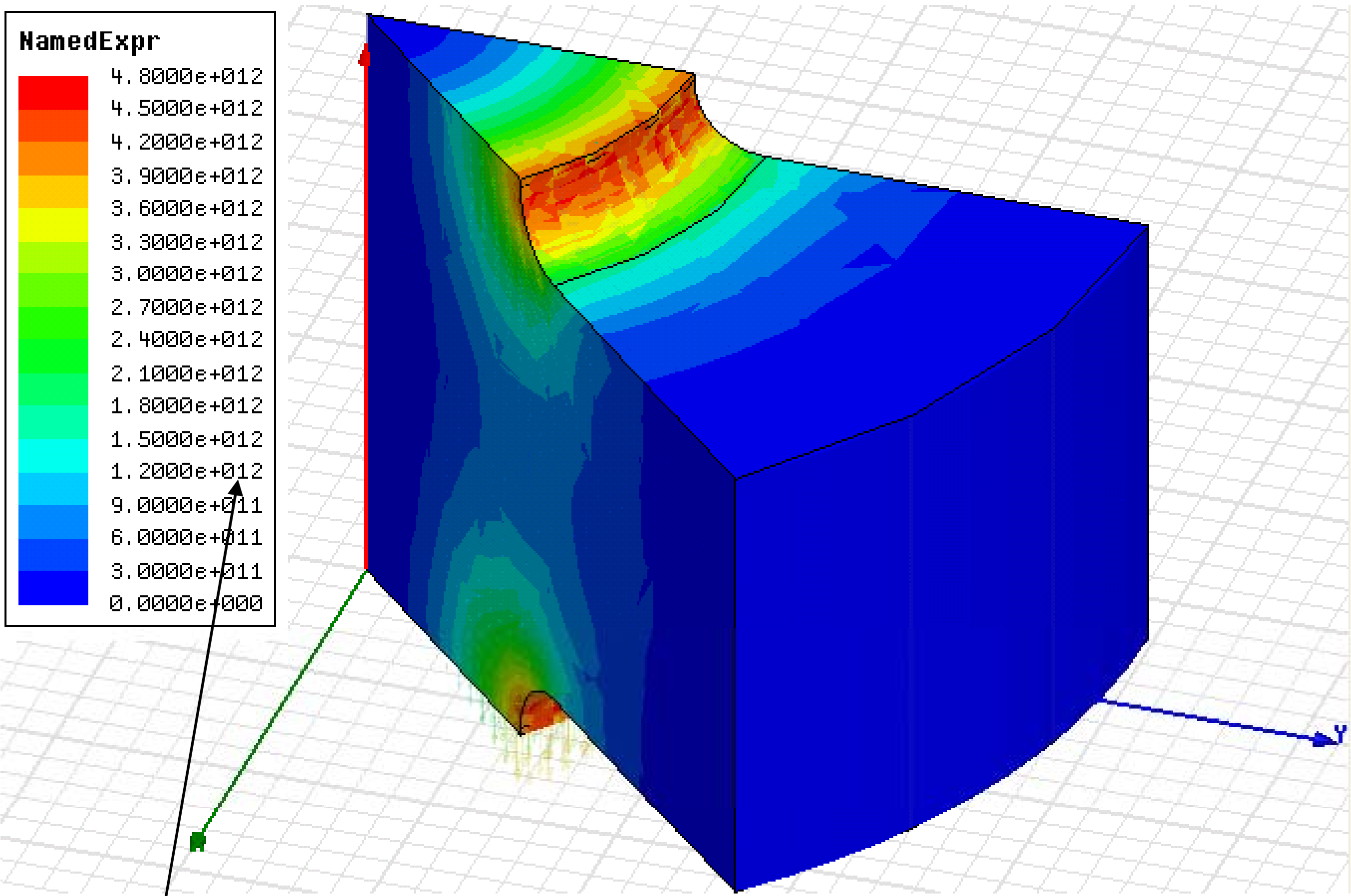
Next steps

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}



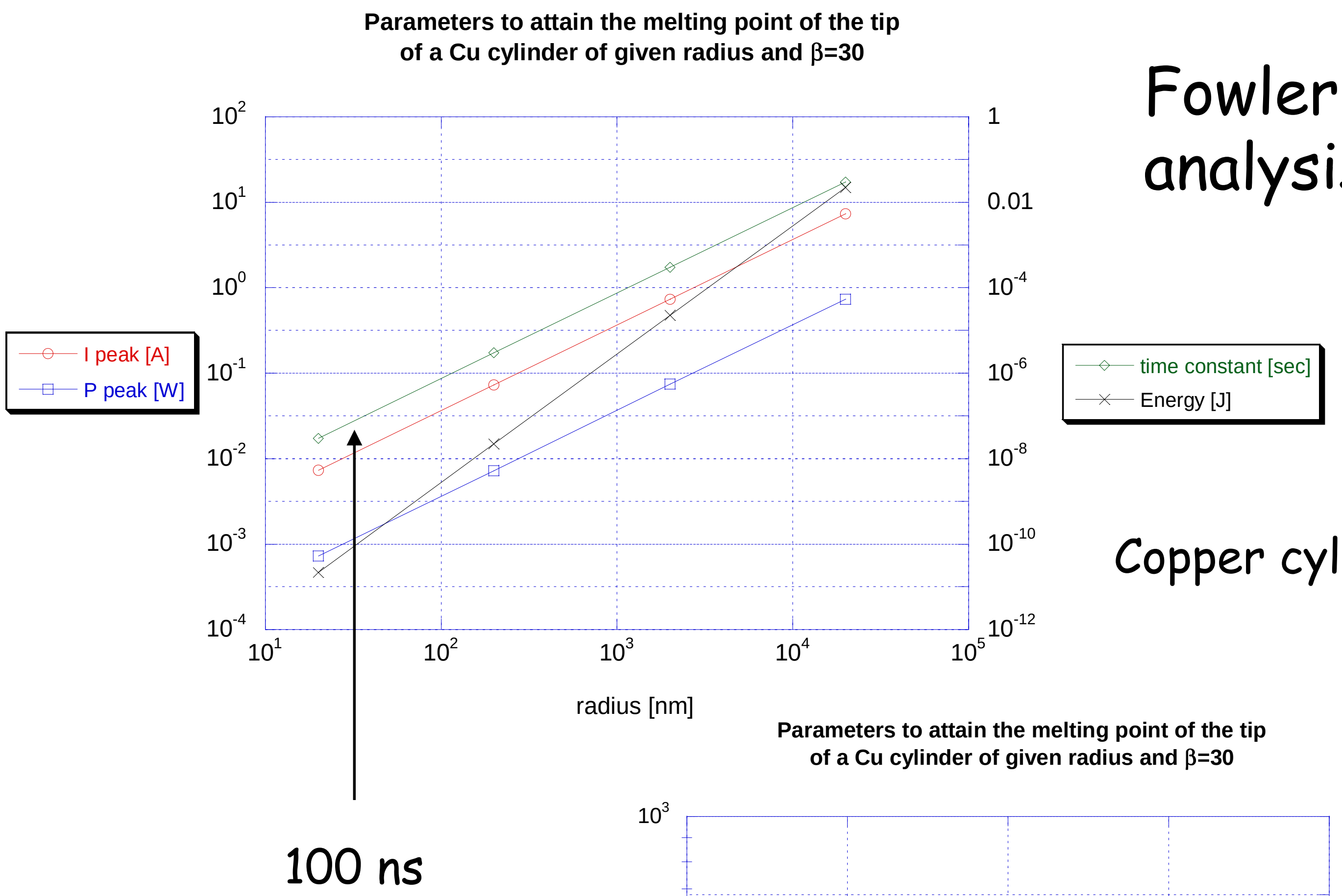
μW/nm²

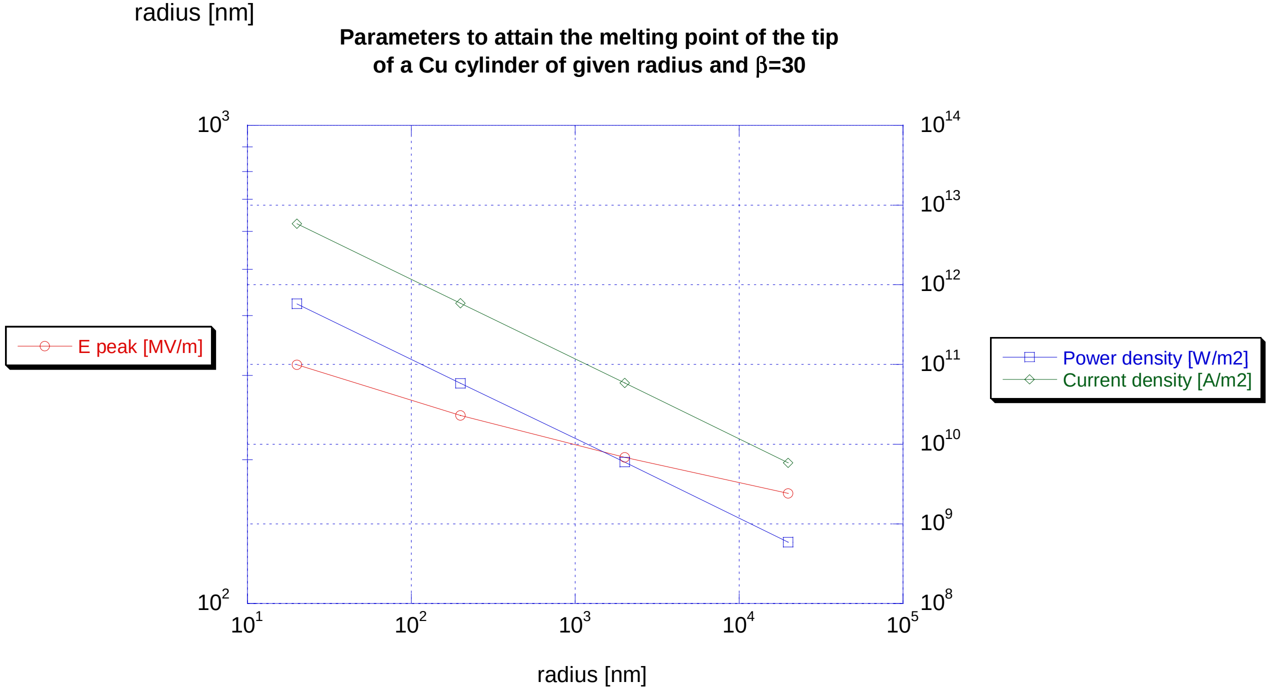
Alexej

Fowler Nordheim analysis by Sergio

Copper cylinders, beta = 30

Power density required for triggering breakdown





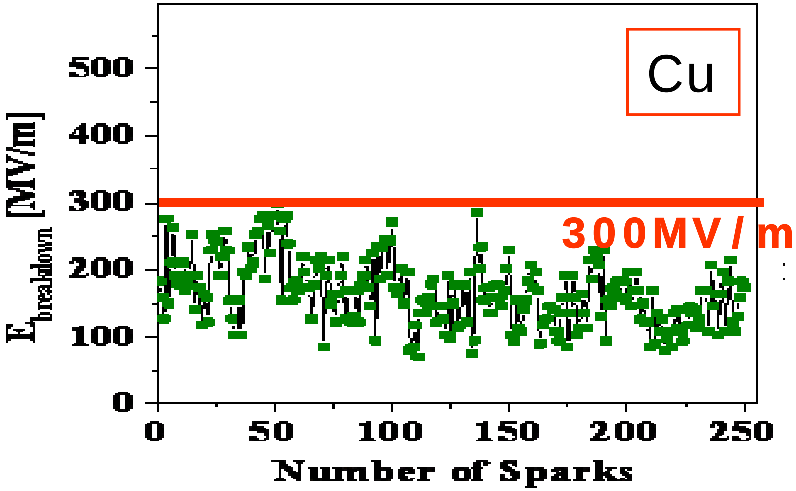
1-4 μW/nm^2 available and .2 μW/nm^2 needed is a remarkable agreement.

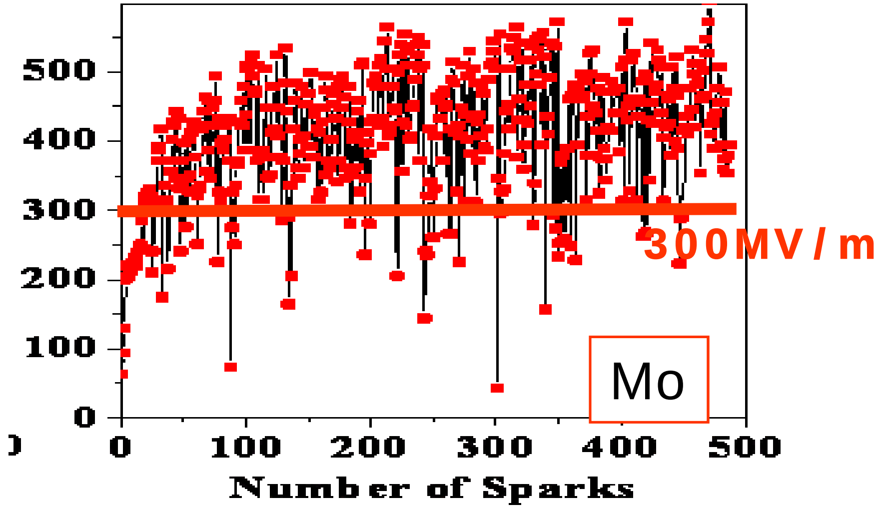
A local power flow is necessary to support even the breakdown trigger mechanism.

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

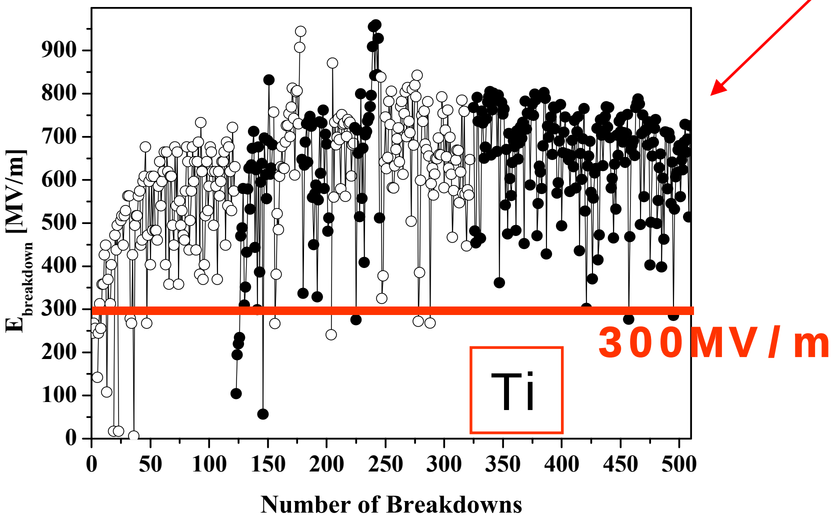
More insight into the coupling of rf to the emission sites is work under way.

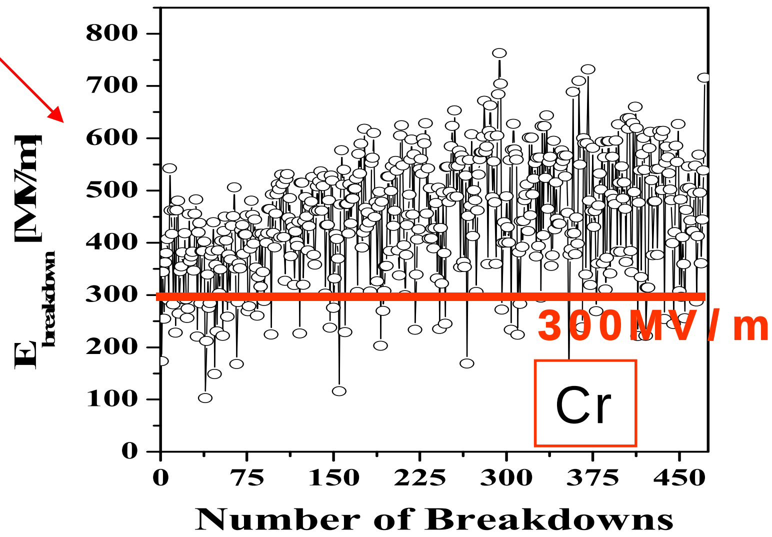
Tests on various materials



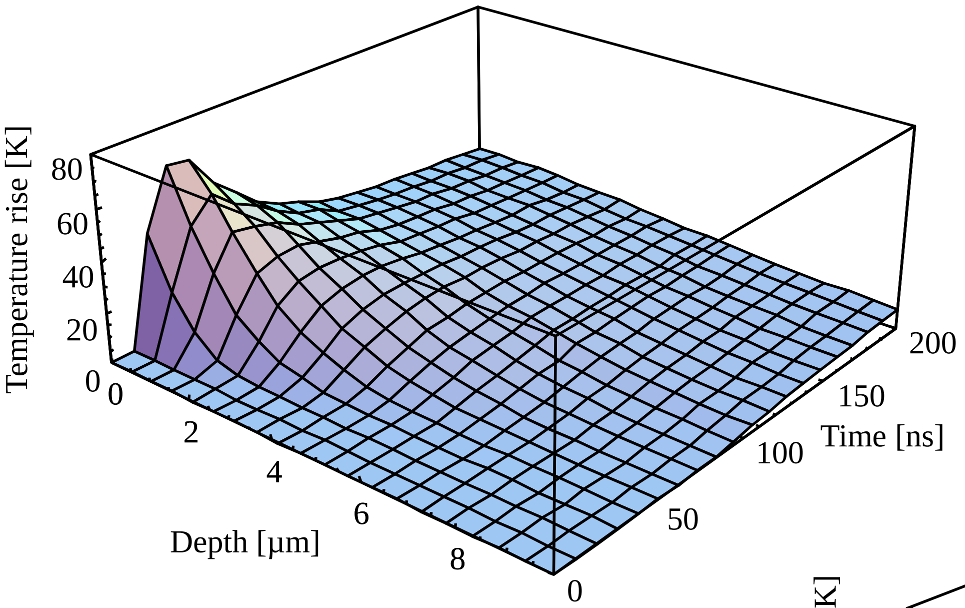


Good, but ...Strong erosion of the surface upon breakdown



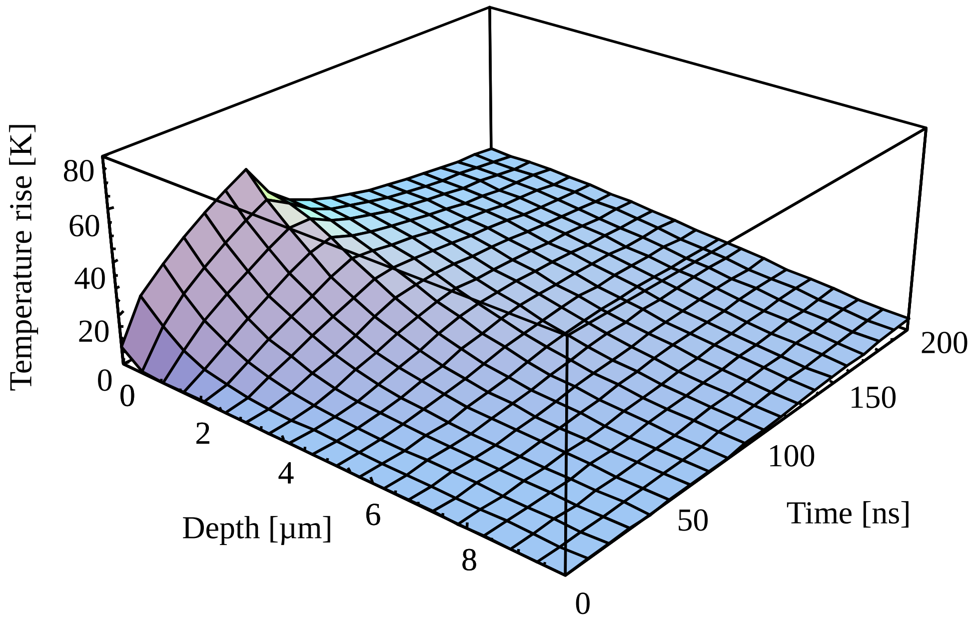


Comparison of heating profiles



← 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.

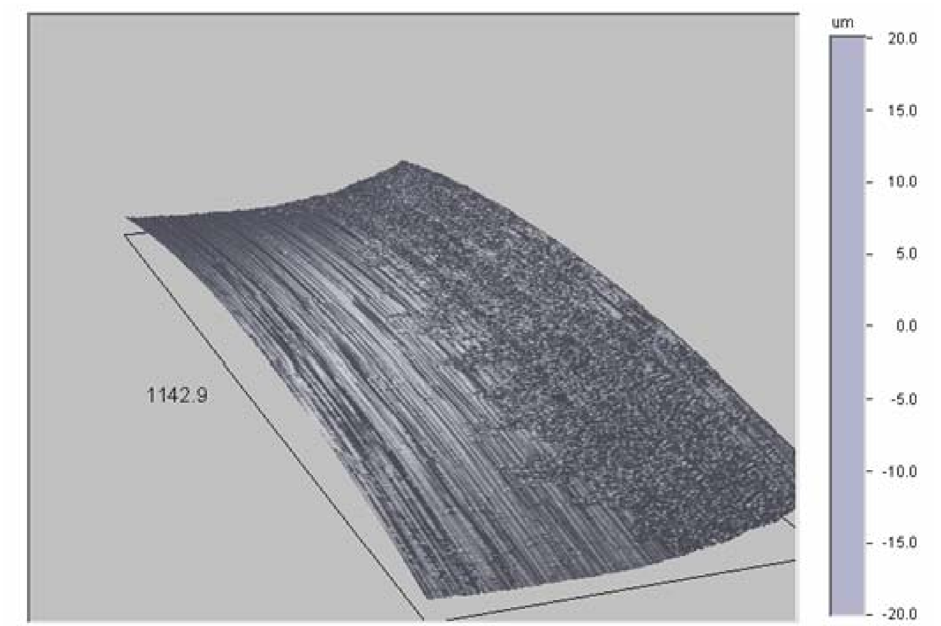
$$\sigma = \frac{\Delta T * E * \lambda}{(1-\nu)}$$

Can be solved analytically

Roughening of the surface, US testing

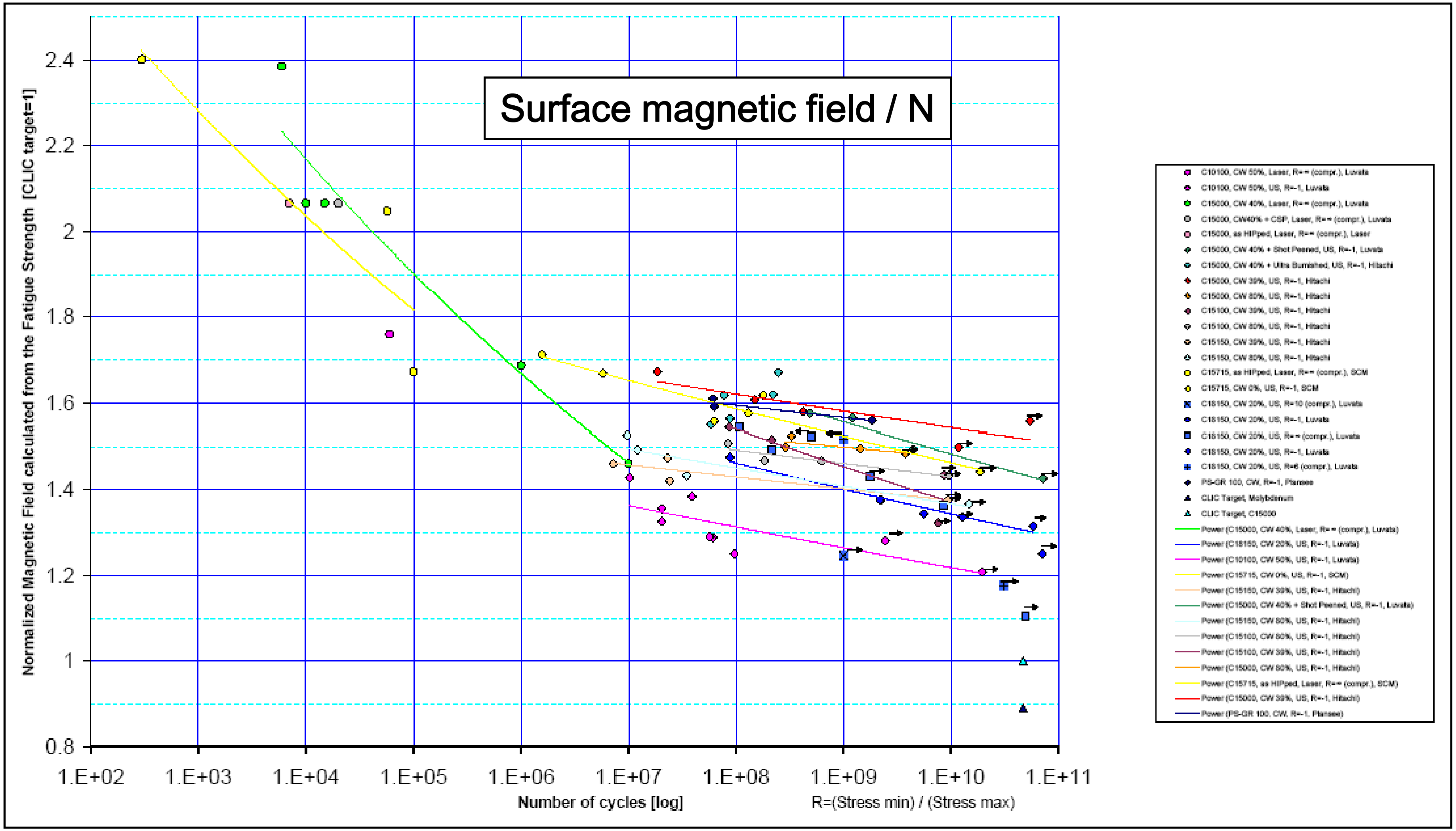
G. Arnau Izquierdo TS/MME

76 mm Dumbbell Sonotrode
Vue 3D zone affectee



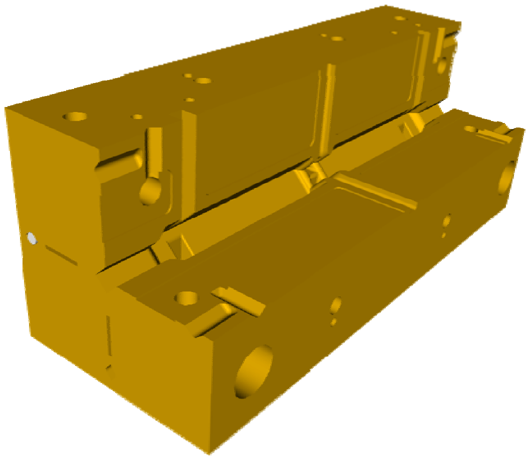
A. Cherif TS/MME

Up-to-date Ultrasonic & Laser fatigue test results

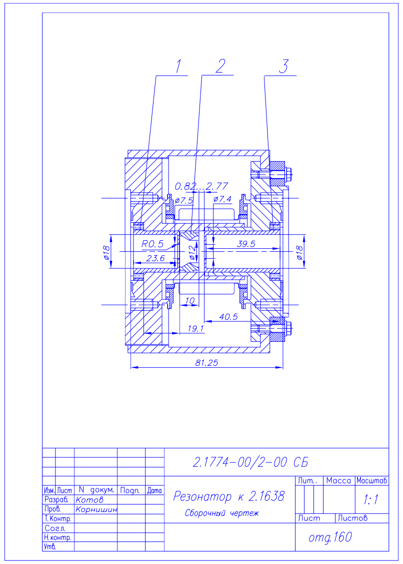


Planned RF Fatigue Tests

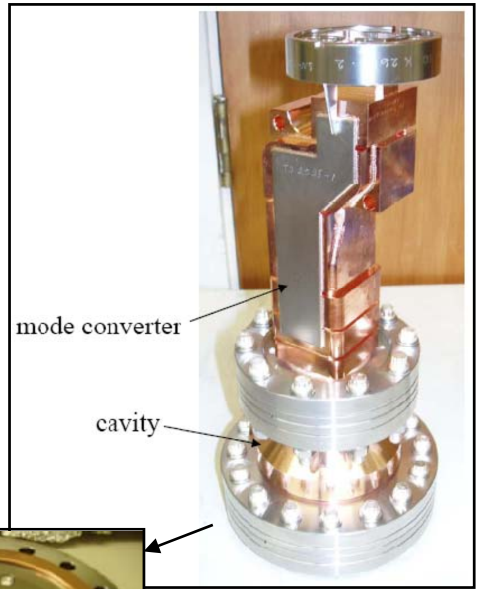
30 GHz pulsed heating cavity, CERN

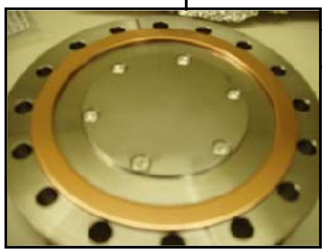


30 GHz pulsed heating cavity, Dubna



11.4 GHz pulsed heating cavity, SLAC





S. Tantawi, SLAC