Progress on CLIC rf structures

Outline

1. Accelerating structures
2. PETS (rf power generating structures)
3. Coupled rf system
4. Breakdown simulation
5. Outlook

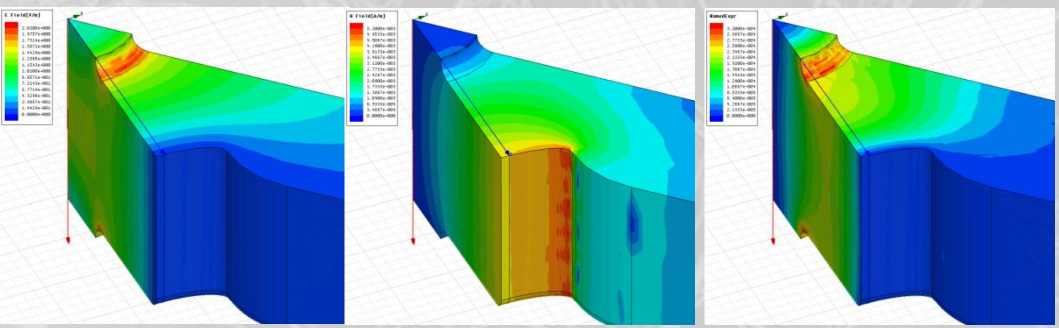
Accelerating structures – specifications

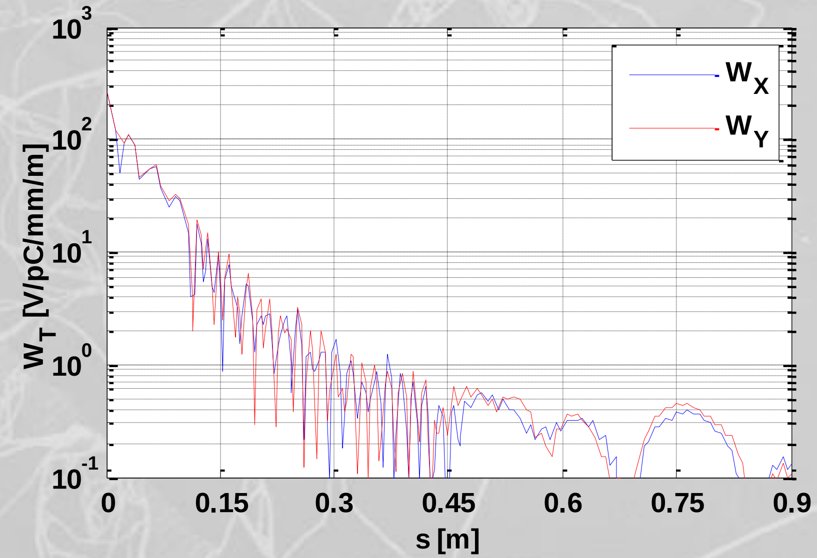
High-gradient:
1. 100 MV/m loaded gradient
2. 170 (flat top)/240 (full) ns pulse length
3. $<4\text{x}10^{-7}$ /pulse/m breakdown rate

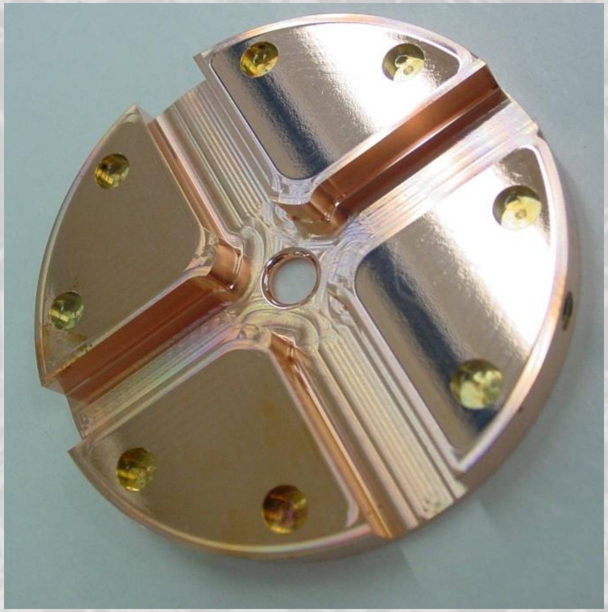
Beam dynamics:
1. 5.8 mm diameter minimum average aperture (short range transverse wake)
2. < 1 V/pC/mm/m long-range transverse wakefield at second bunch (approximately x50 suppression).

Accelerating structures – features

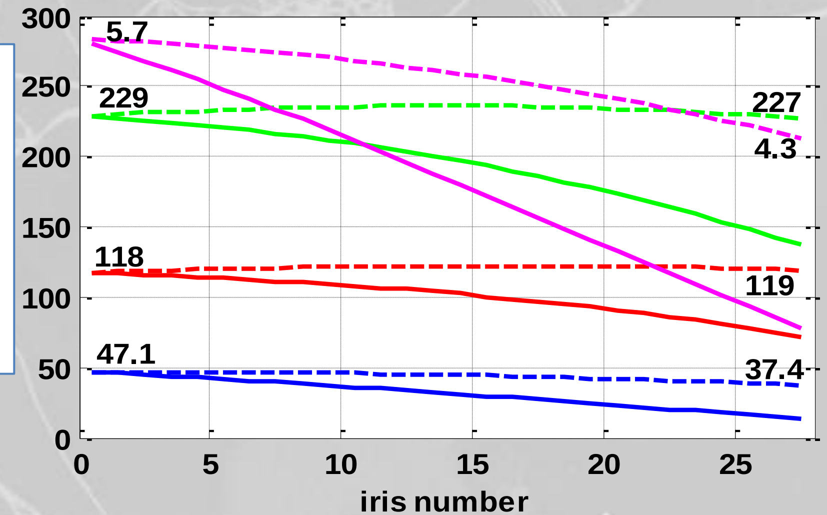
E_s/E_a H_s/E_a S_c/E_a^2





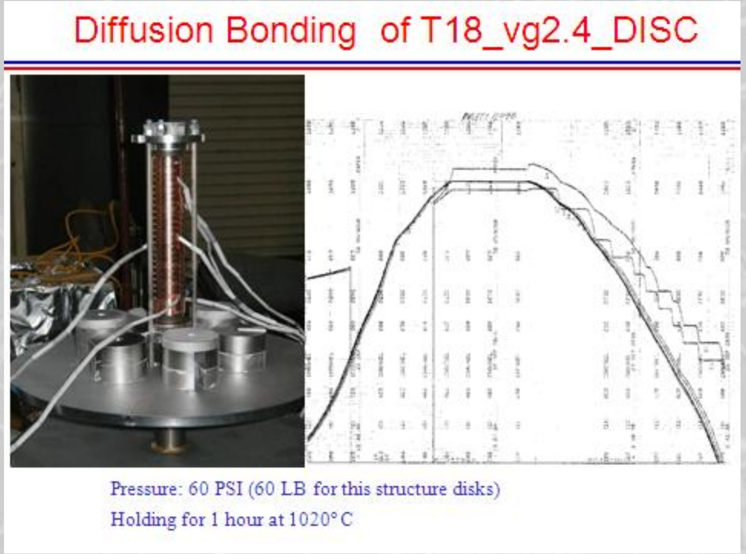


$S_c^{½}$ [MW/mm^2]
E_s max [MV/m]
E_{acc} [MV/m]
ΔT [°C]
dashed – unloaded
solid – loaded

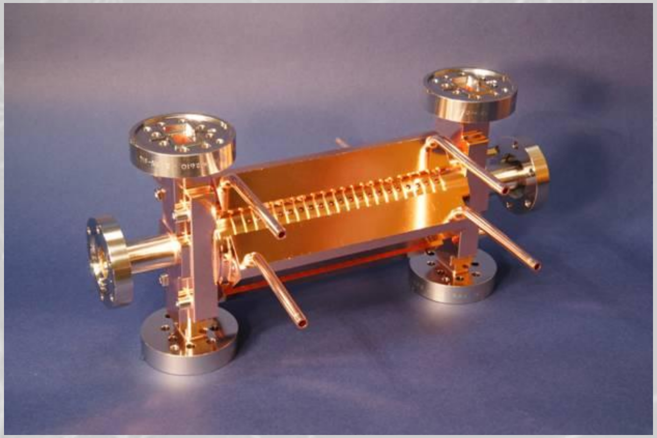


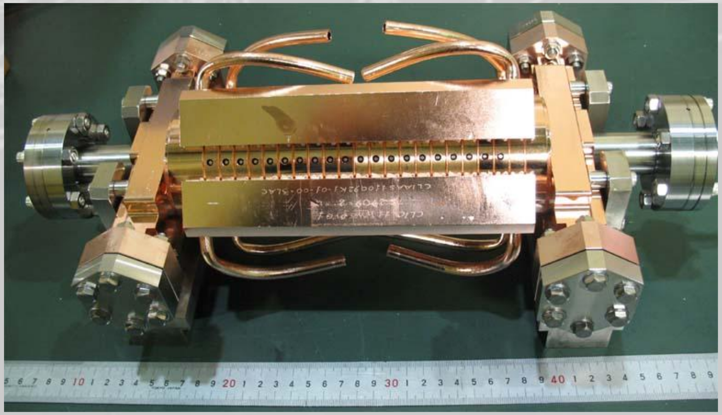
Accelerating structures – manufacture

Stacking disks



Temperature treatment for high-gradient





Structures ready for test

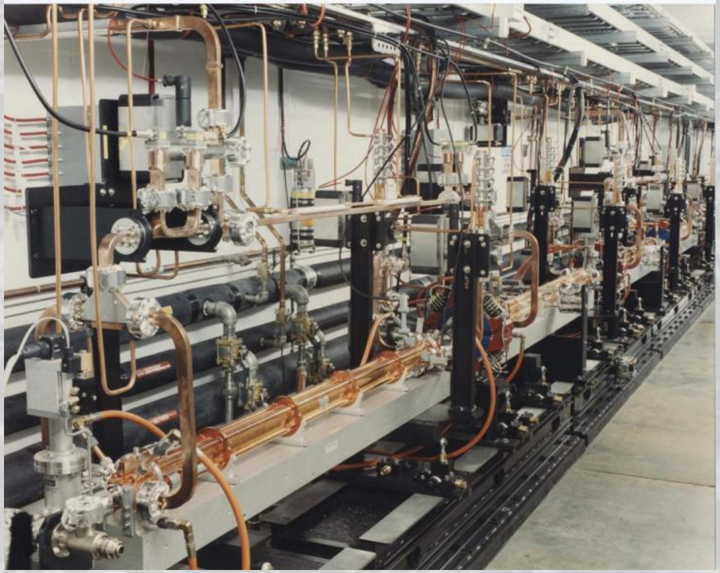
Preparation for high-gradients

Our baseline treatment for high-gradient was developed by the NLC/JLC program.

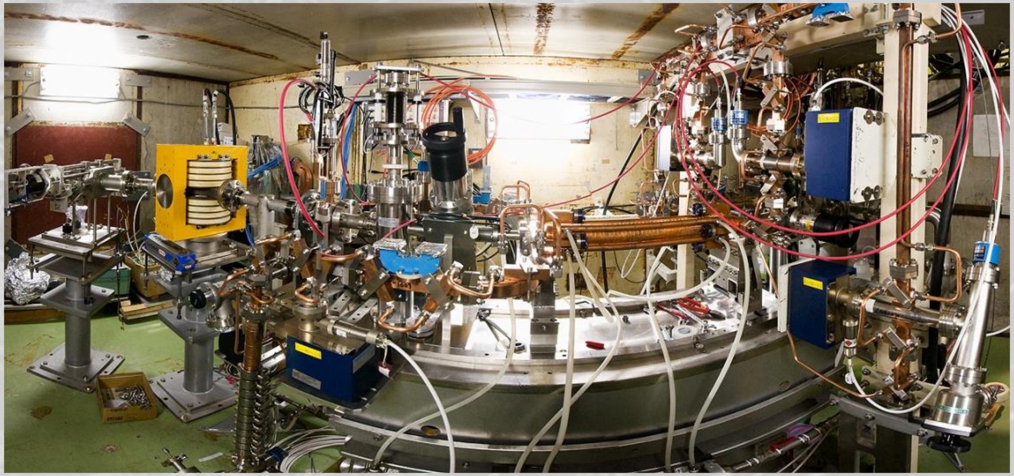
Our current understanding of *why exactly* it works is emerging from our ongoing breakdown physics study. Crystal dislocations appear to be the cause of our gradient limit (ok, there is still a debate!).

1. **Etching** –Etching occurs preferentially at dislocations due to lower local work function. This is particularly important for milled surfaces, which have significant induced stress and consequently high dislocation density. Also removes particles.
2. **1050 °C hydrogen fire**– Near melting point results in significant annealing. Relieves stresses and reduces dislocation density. Excellent removal of chemical contaminants.

Prototype accelerating structure test areas (klystron based)



NLCTA at SLAC



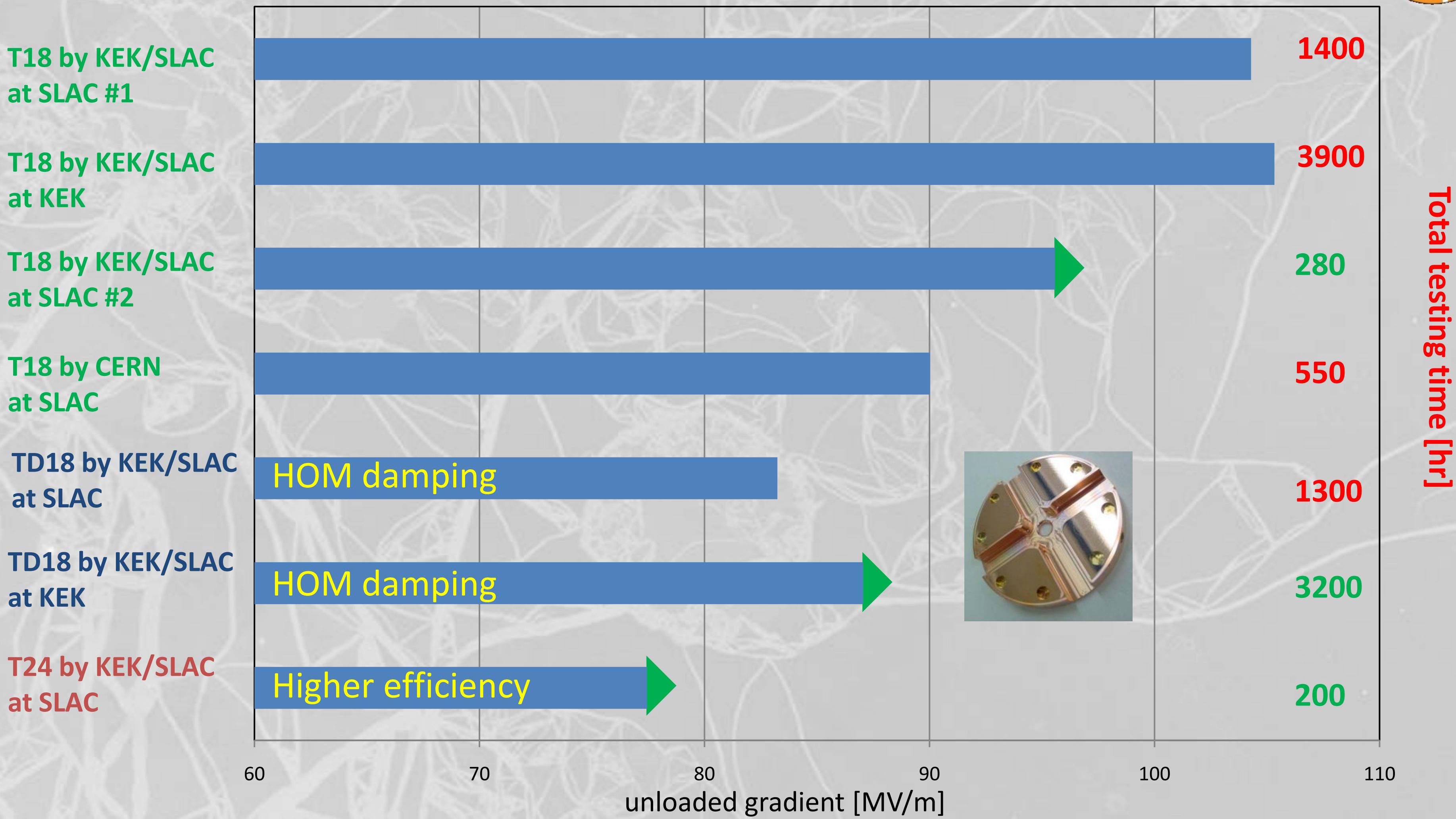
Nextef at KEK

Summary of CLIC accelerating structure test results

Structure type	Fabrication	Test location	Total testing time [hr]	Unloaded gradient [MV/m]	Flat top pulse length [ns]	Breakdown rate [1/pulse/meter]
T18	KEK/SLAC	SLAC	1400	105	230	1.6×10^{-6}
T18	KEK/SLAC	KEK	3900	102	252	8×10^{-7}
T18	KEK/SLAC	SLAC	280	110	230	7.7×10^{-5}
T18	CERN	SLAC	550	90	230	1.3×10^{-6}
TD18	KEK/SLAC	SLAC	1300	85 (a)	230	2.4×10^{-6}
				100 (b)	230	7.6×10^{-5}
TD18	KEK/SLAC	KEK	3200	87 (a)	252	2×10^{-6}
				102 (b)	252	1.4×10^{-5}
T24	KEK/SLAC	SLAC	200	92	200	9.8×10^{-5}
TD24	CERN	TBTS	<1 (0.8Hz)	55	≈ 100	$O(10^{-2})$

conditioning continues (a) BDR specification run (b) gradient specification run

Synthesis of accelerating structure test results scaled to CLIC breakdown rate

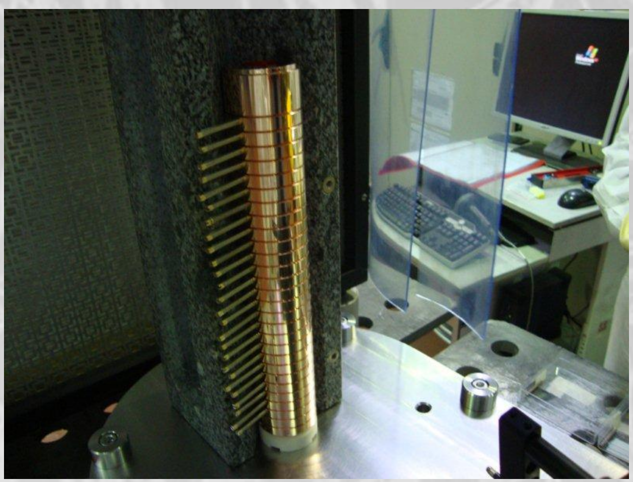


Scaling to CLIC conditions: Scaled from lowest measured BDR to $BDR=4*10^{-7}$ and τ=180 ns (CLIC flat-top is 170 ns), using standard $E^{29}\tau^{5}/BDR$=const. Correction to compensate for beam loading not included – expected to be less than about 7%.

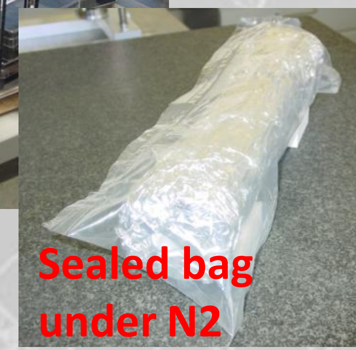
A new level of care for CERN-built structures

Individual inspection

Operation done under laminar flow



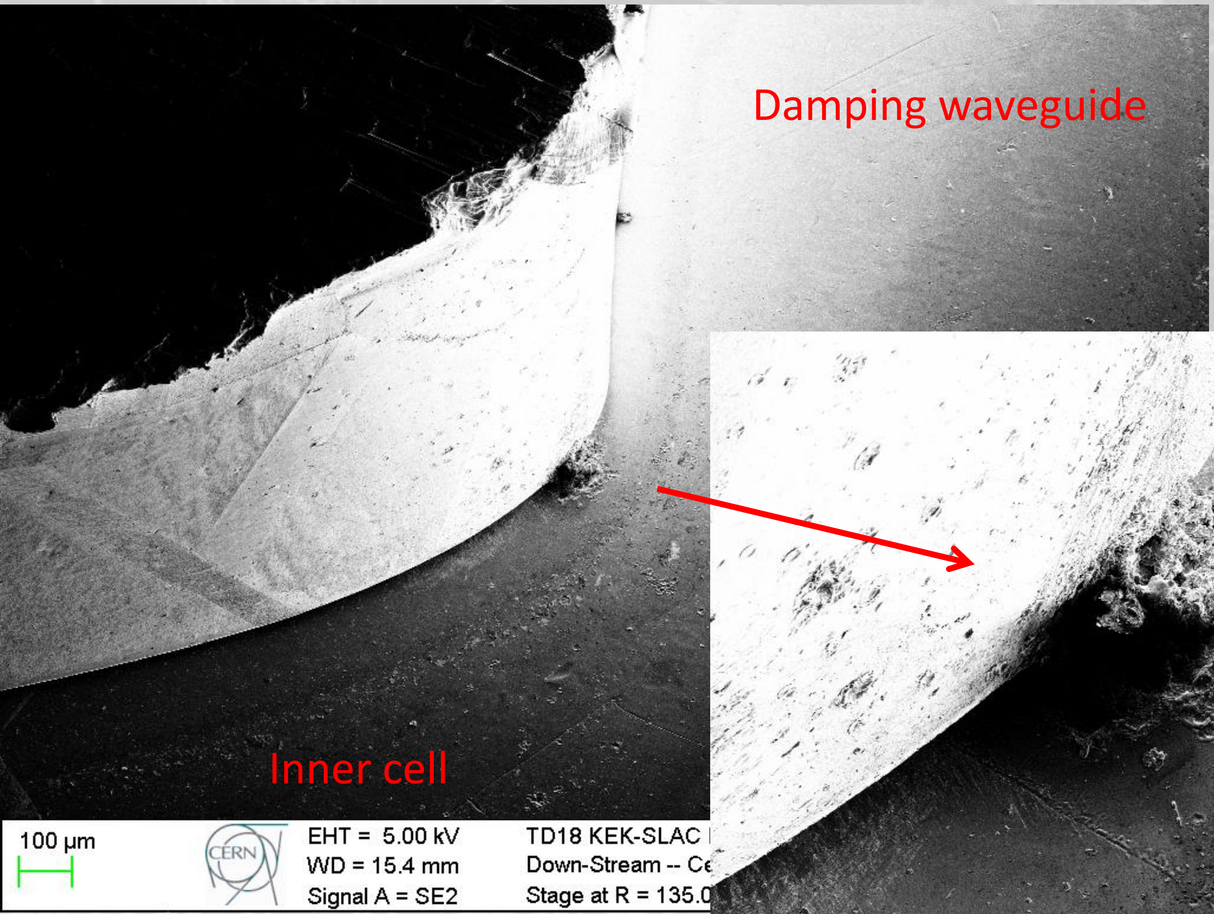
Boxes under N2



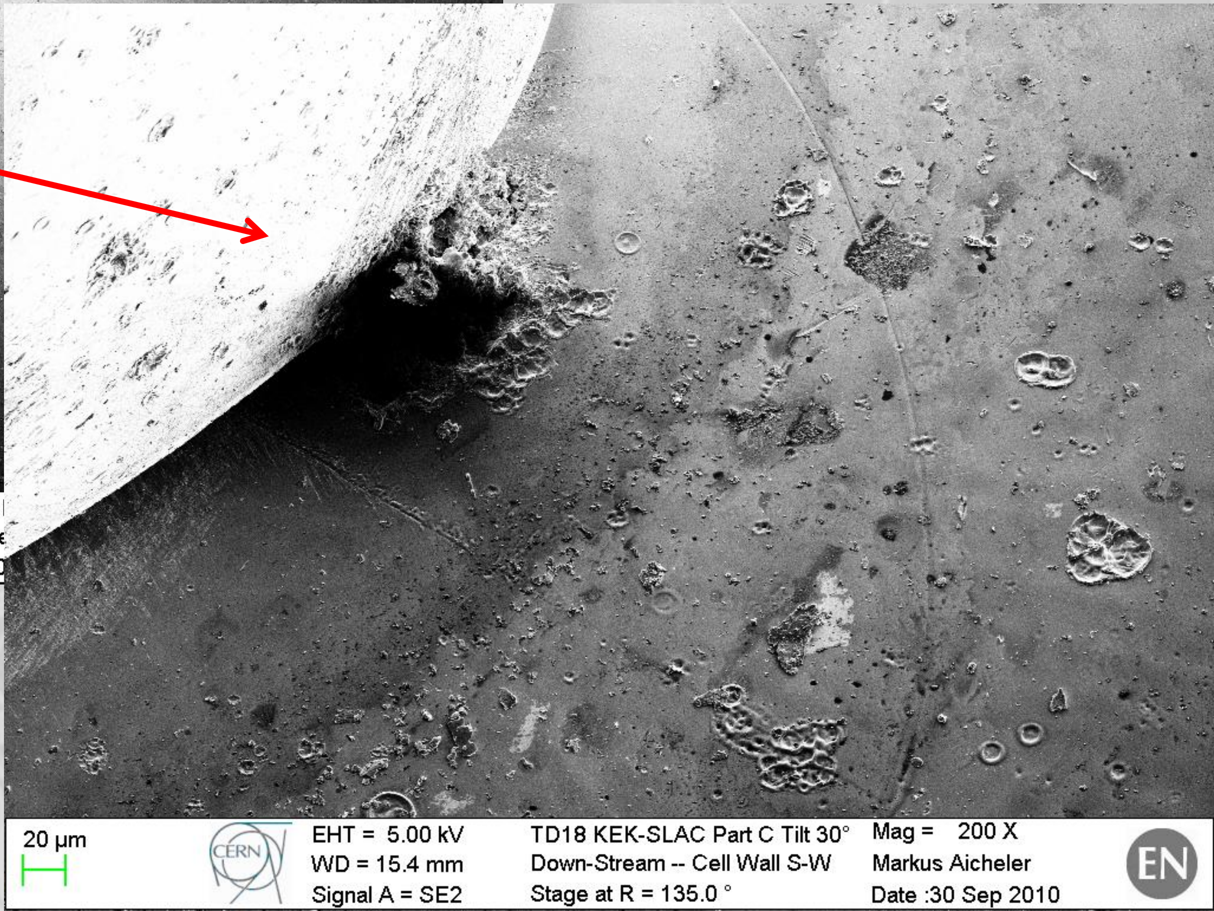
Sealed bag under N2

RF measurement

And now some very recent news!

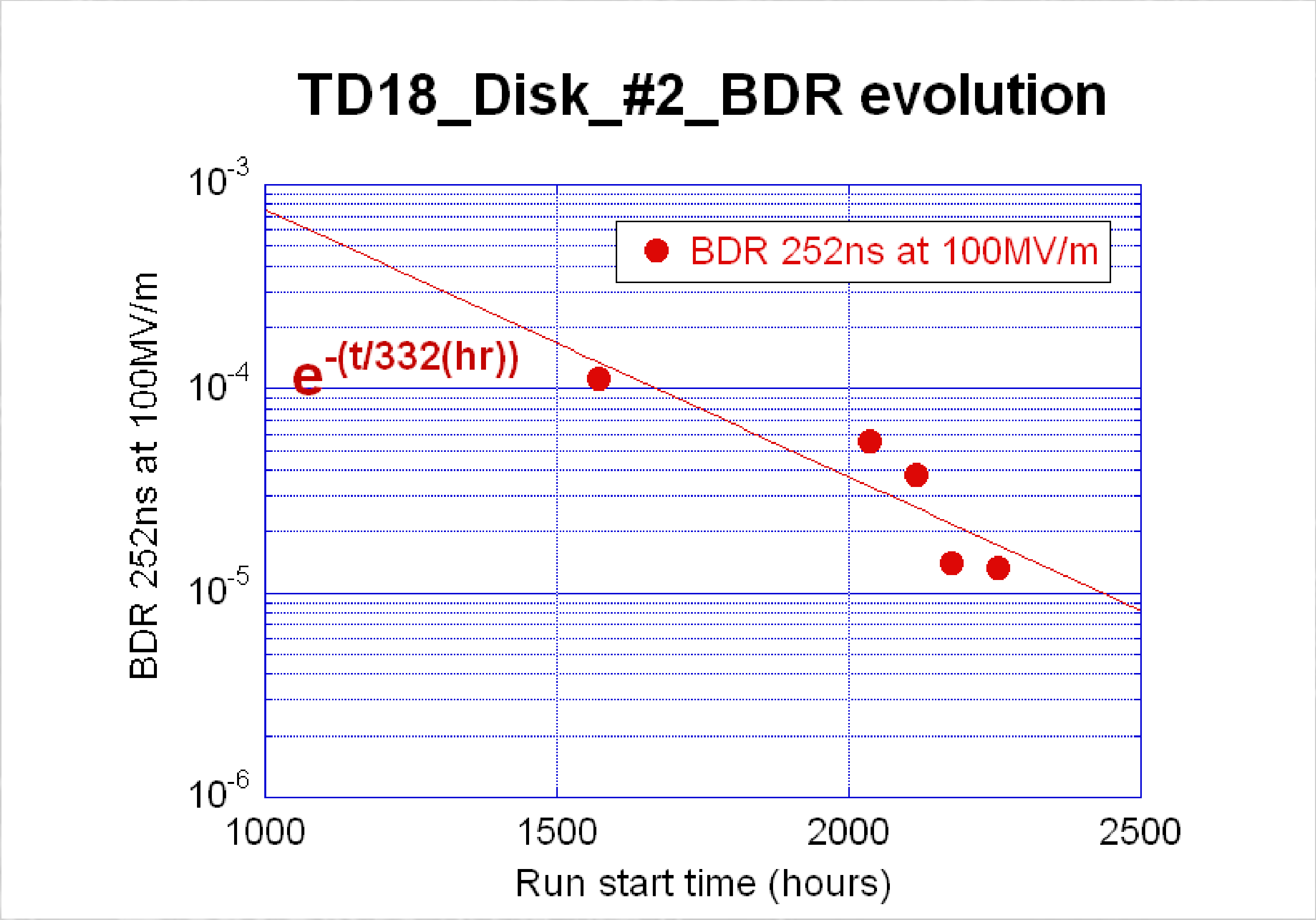


Points of enhanced breakdown rate in TD18 tested at SLAC probably identified.
Origin seems to be a combination incomplete bonding and high surface currents.



Study of origin of problem and corrective action underway.

Breakdown rate evolution with extended running



TD18 test at KEK

Accelerating structures – next steps

- Resolve issue of enhanced breakdown rate in damped structures
- Verify performance of nominal design (T24) structure
- Put the two together for TD24
- Add damping material (n.b. CTF3 drive beam linac has ≈ 2000 SiC loads plus PETS-test described below)
- Add compact coupler
- Statistics
    - Structure yield – roughly ¼ of structures are down on gradient by about 10-20% for baseline fabrication procedure. Now need to build and test a few tens of structures to work out bugs.
    - Low breakdown rate running – run below our BDR specification. 10^7 pulses takes 2.3 days…
    - Extended running – generally the structures improve with time but we have seen a hot iris develop once (first T18 at SLAC).

PETS – specifications

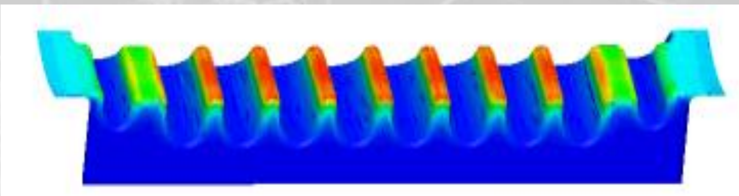
High-power:

1. 135 MW output power
2. 170 (flat top)/240 (full) ns pulse length
3. $<2\mathrm{x}10^{-7}$ 1/pulse/m breakdown rate

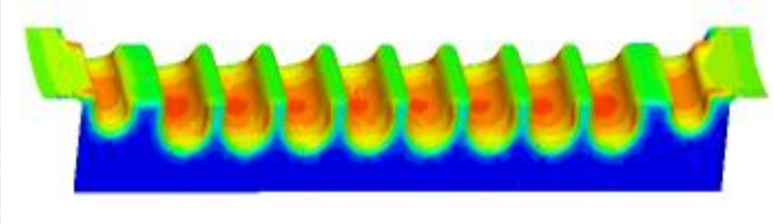
Beam dynamics:

1. Fundamental mode: gives 23 mm diameter aperture which corresponds to $a/\lambda=0.46$ and $v_g/c=0.49$ to give 2.2 kΩ/m, longitudinal impedance
2. Single bunch transverse wake: < 8 V/pC/mm/m
3. Long-range transverse wakefield with effective suppression of main HOMs by $Q_n(1-\beta_n)<8$ each

PETS – fundamental mode characteristics



Surface electric field



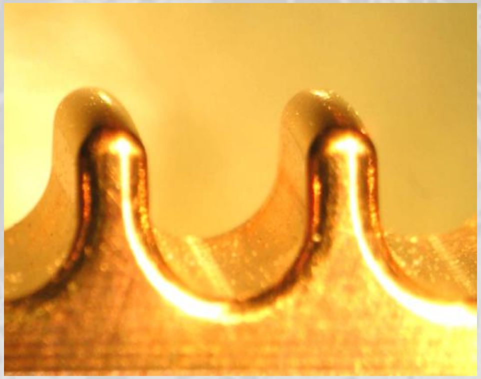
Surface magnetic field

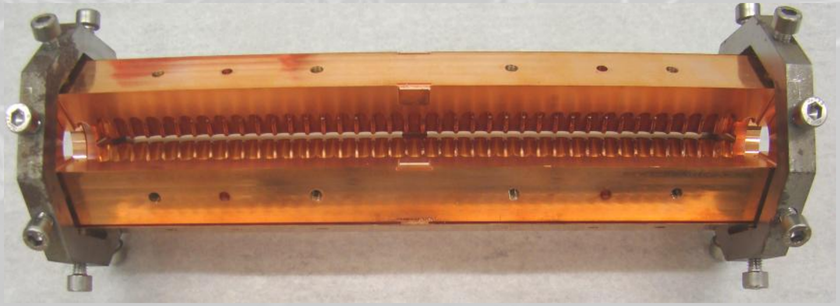
Beam-driven structure so power rises quadratically with current and length,

- 135 MW for 100 A beam
- 213 mm active length

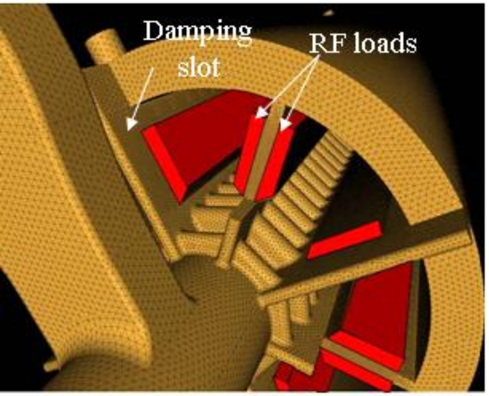
Maximum fields at output with values,

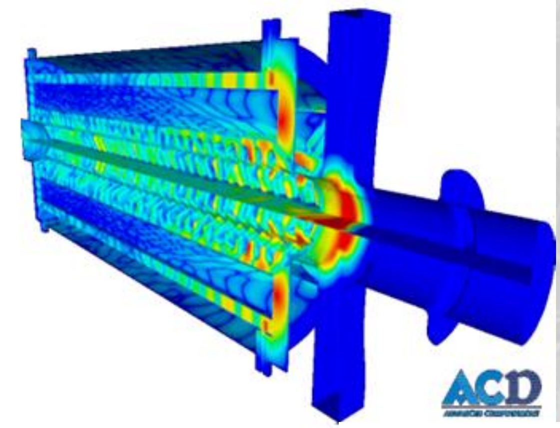
- E_{surf}=56 MV/m
- ΔT=1.8 (H_{surf}=0.08 MA/m)
- S_c=1.2 MW/mm^2





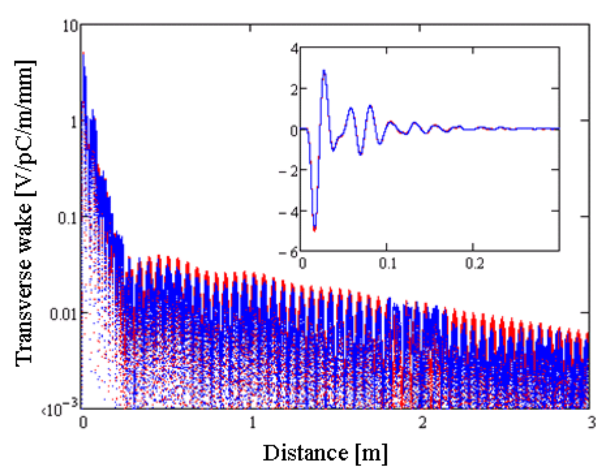
PETS – HOM suppression features

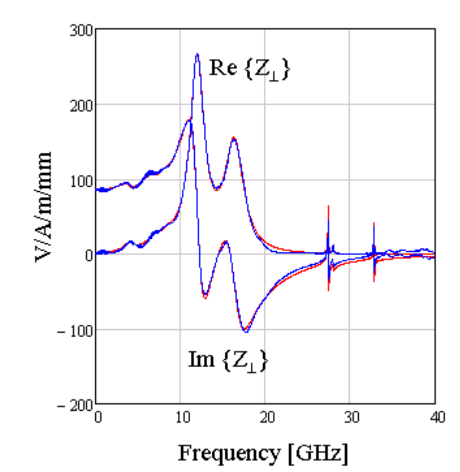


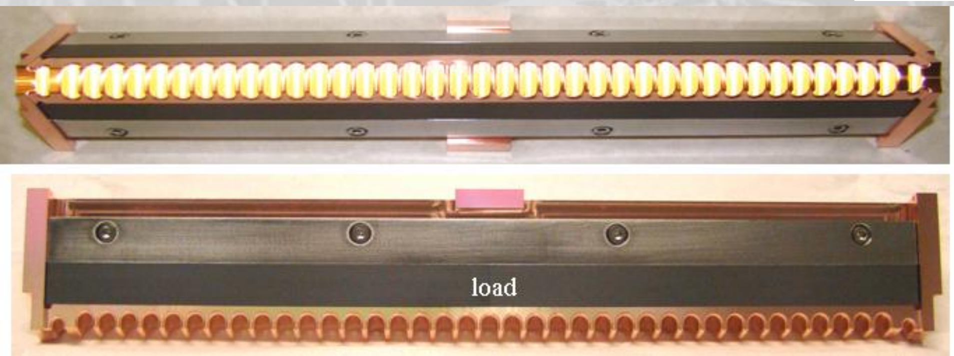


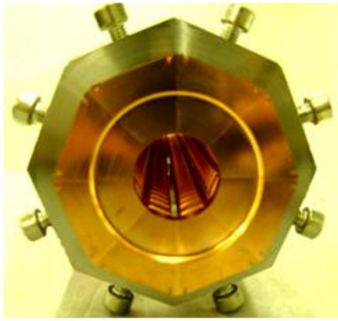
ACE3P analysis of HOM properties

GdfidL and ACE3P benchmarking with analysis of PETS HOM properties









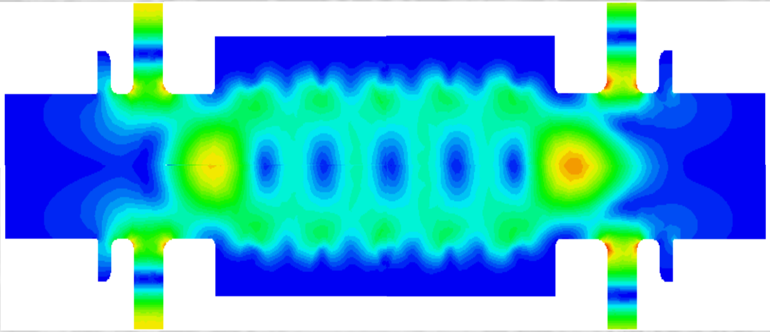
PETS for high-power testing
with SiC absorbers installed.

PETS – the high-power testing challenge

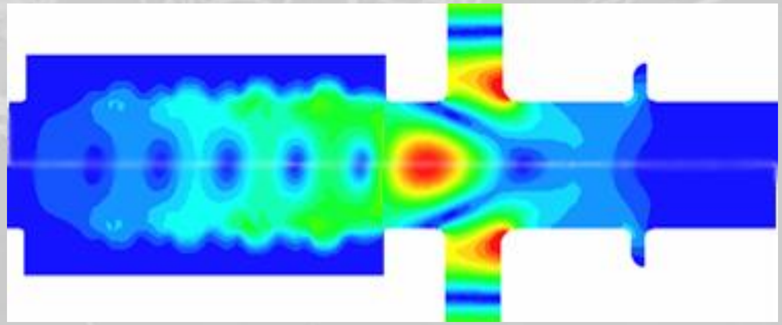
To high-power test the PETS in nominal conditions would require a 100 A driving beam.

“Waveguide” test with klystron/pulse compressor
- not many 135+ MW X-band power sources – ASTA at SLAC
- much harder to run, full fields at input

Beam-based tests with CTF3 4-30 A beam.
- 1000 mm long PETS
- Connect output to input – beam-driven rf resonant ring for lower, <10 A, current



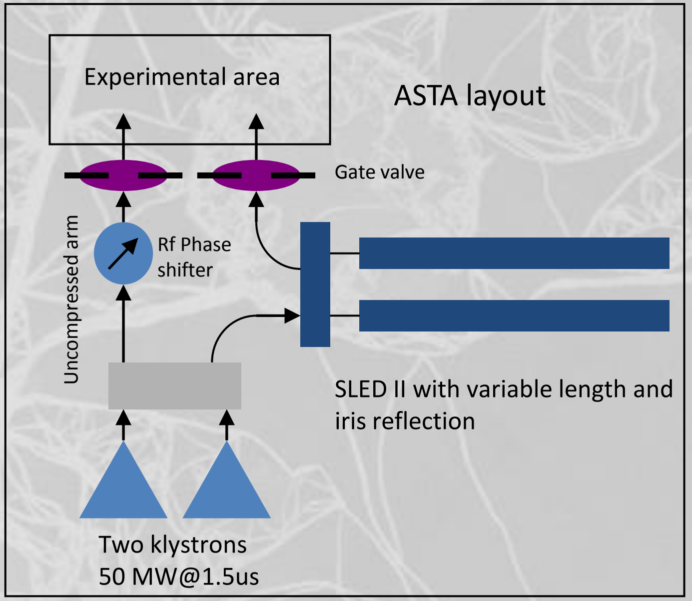
Fields in klystron and recirculation tests

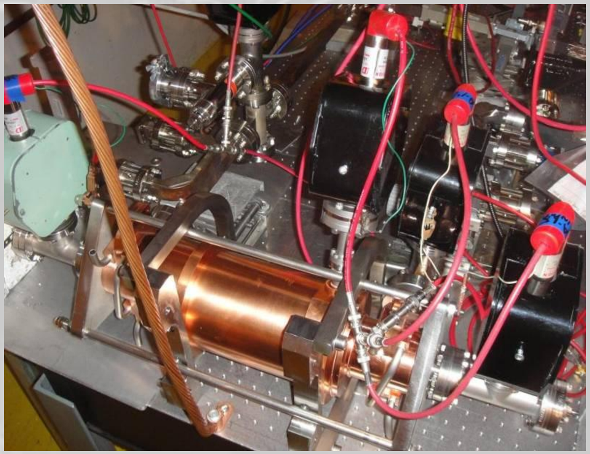


Fields in CLIC and CTF3 at high current

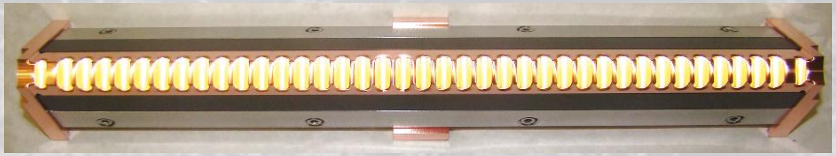
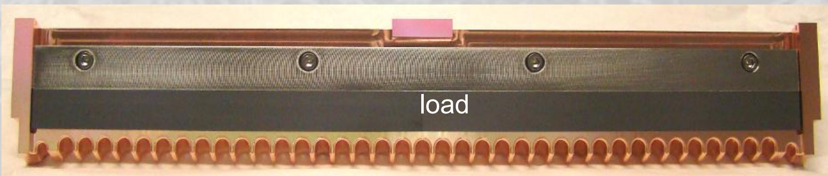
PETS testing in ASTA

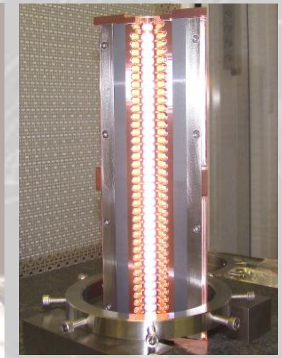
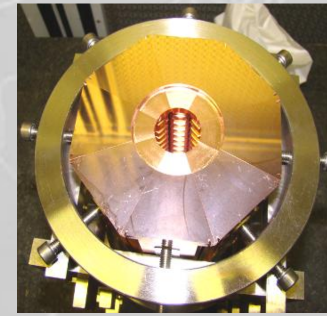
PETS waveguide-mode PETS testing is being done at ASTA in SLAC an impressive facility but testing a single object with 135+ MW power is very challenging. The results you will see are a mixture of conditioning of the PETS and ASTA…



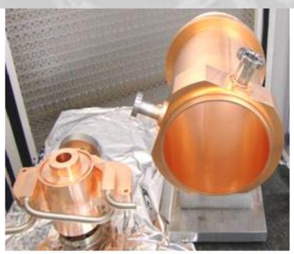
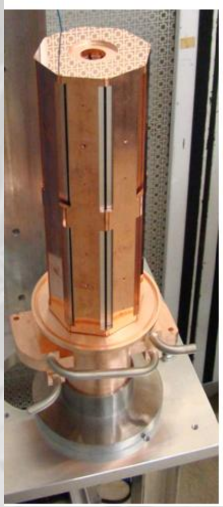


ASTA test PETS version with damping slots and **damping material (SiC)**

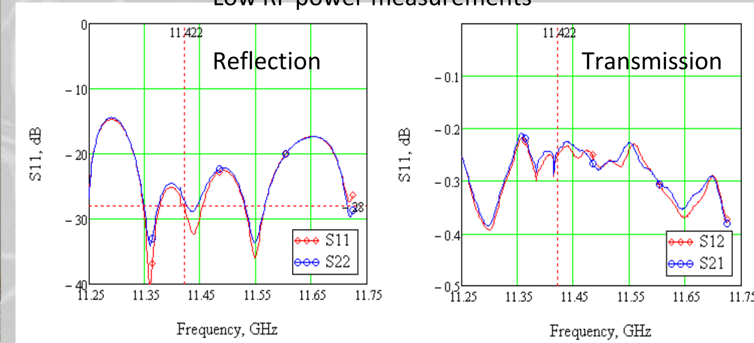



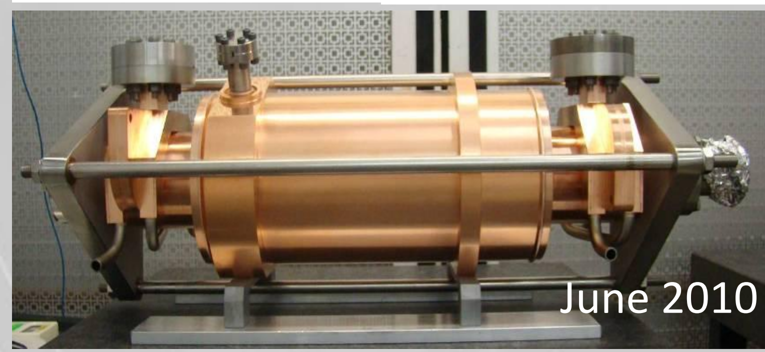




PETS preparation for the EB welding of the RF couplers and the mini-tank

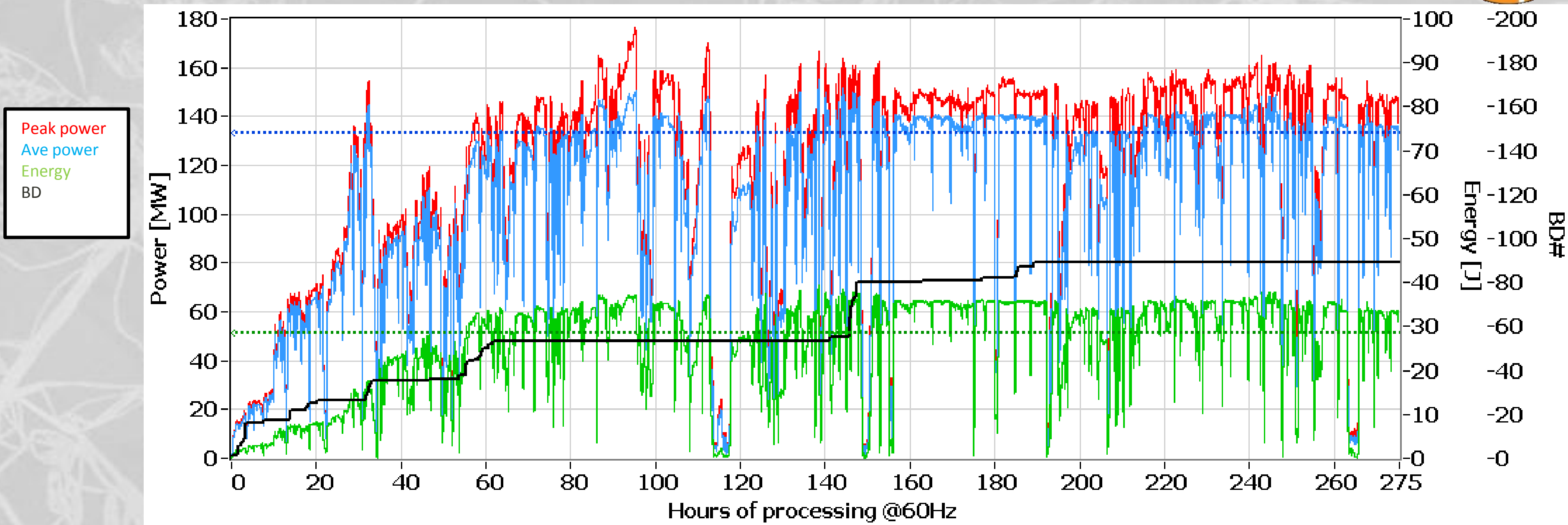




Low RF power measurements

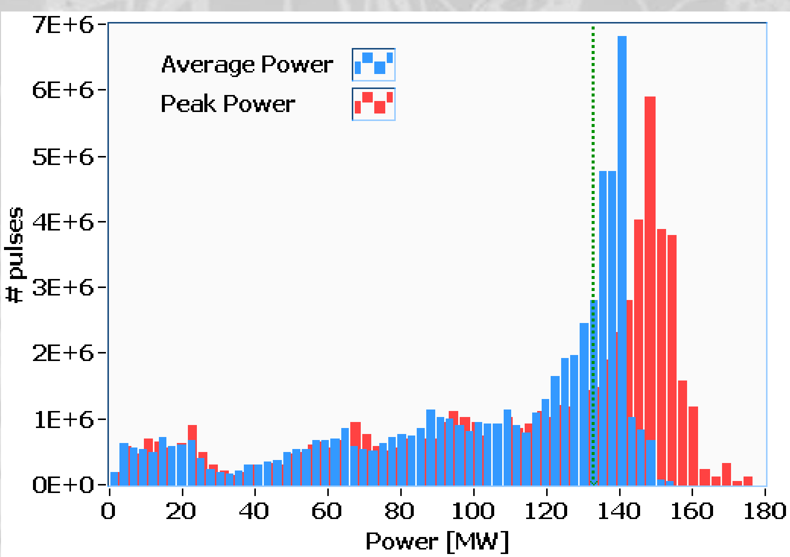




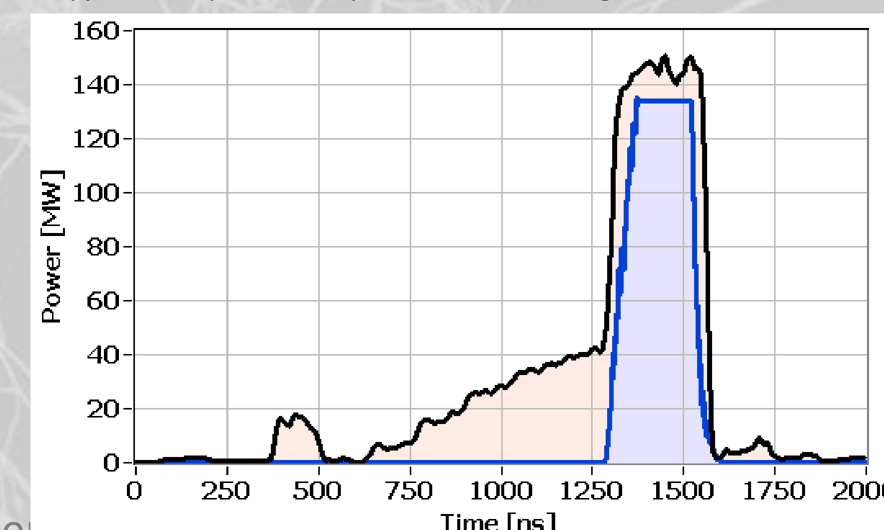
PETS conditioning and “nominal power” run



Average and peak power distributions

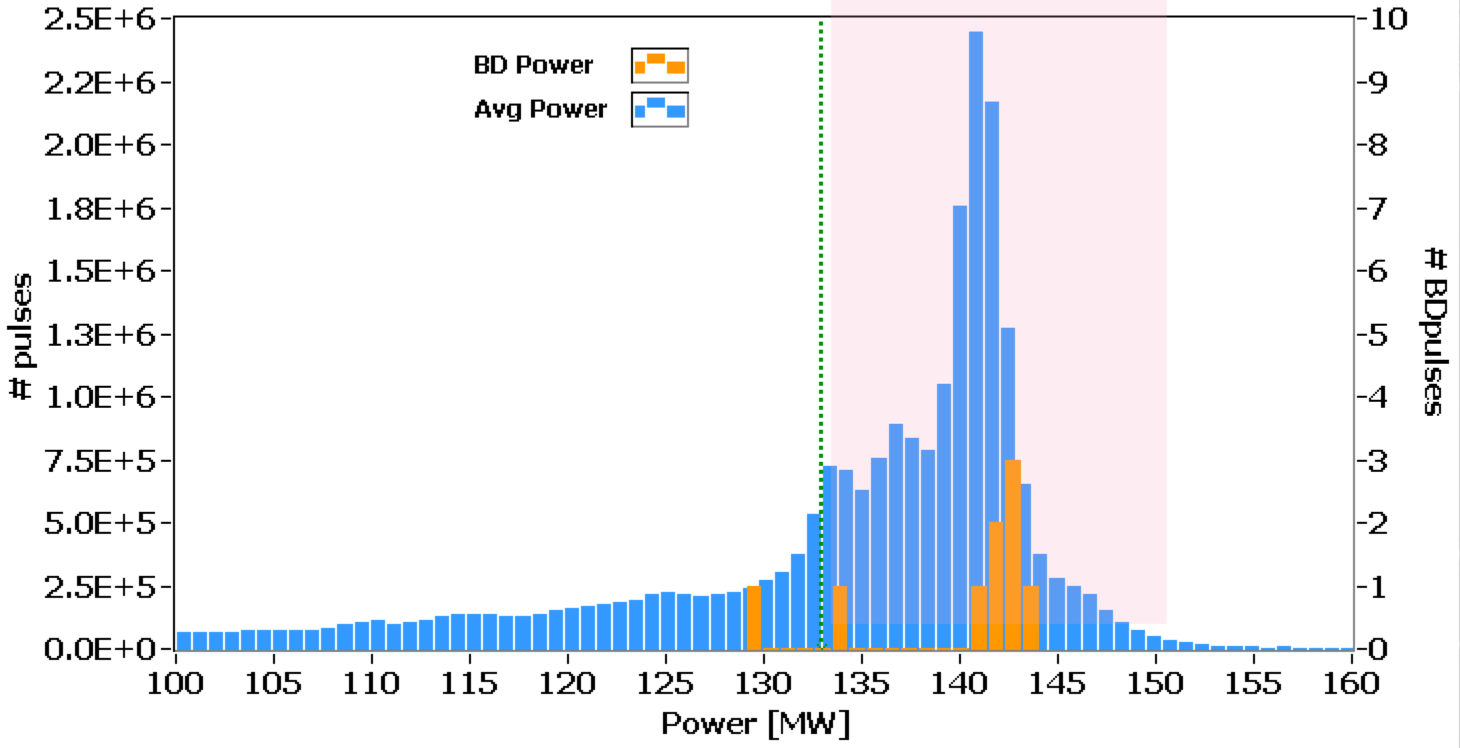


Typical RF pulse shape in ASTA during last 110 hours



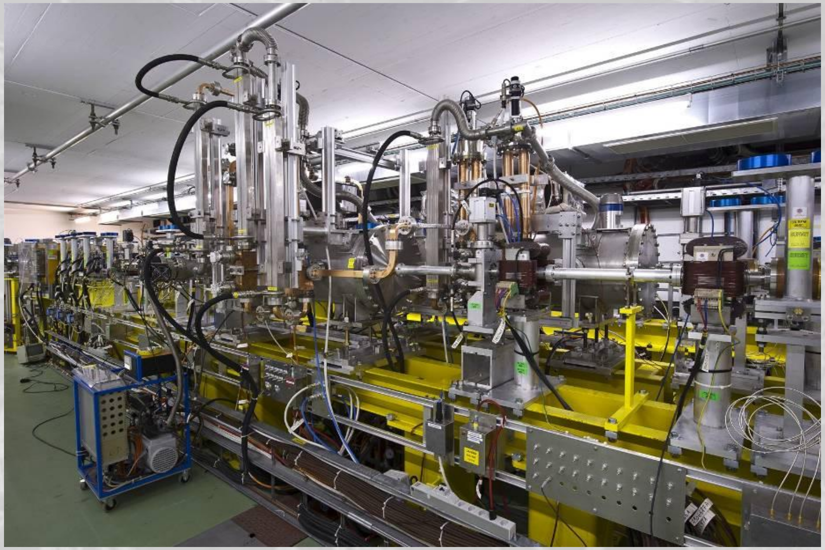
Extraction of PETS breakdown trip rate

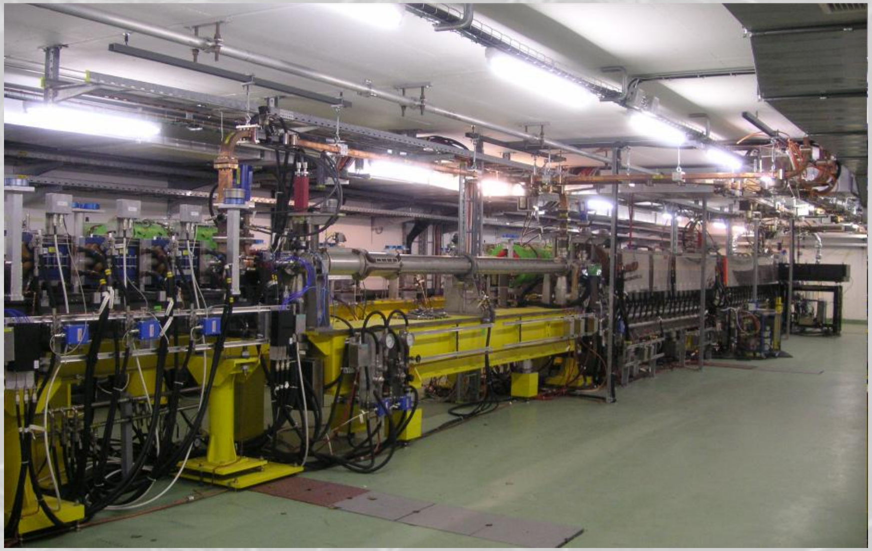
Part of the statistical distribution → 1.55×10^7 pulses

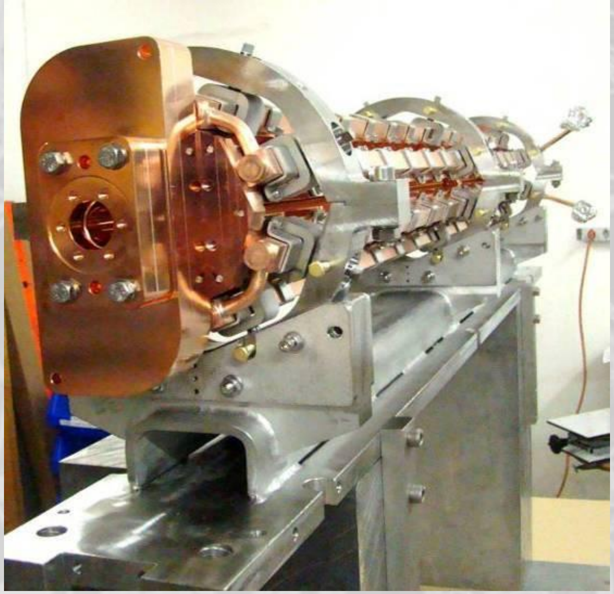


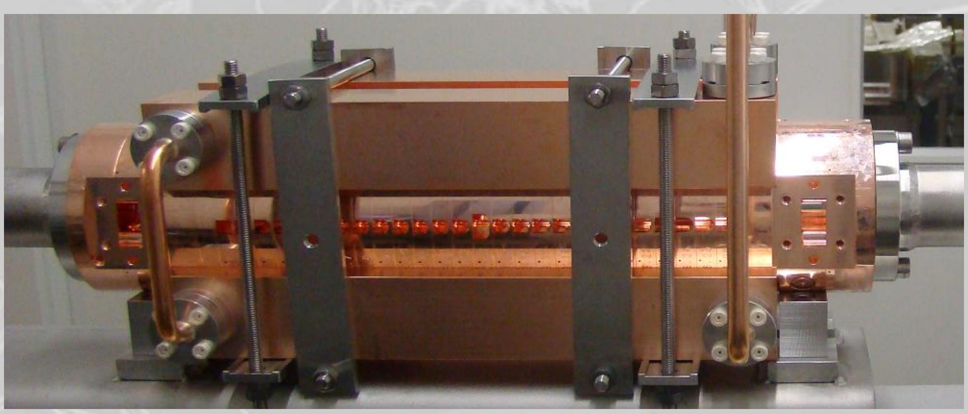
- 1.55×10^7 pulses were accumulated in a 125 hour run.
- 8 PETS breakdowns were identified giving a breakdown rate of **5.3×10^{-7}/pulse**.
- Most of the breakdowns were located in the upper tail of the distribution, which makes BDR estimate rather conservative.
- During the last 80 hours no breakdowns were registered giving a BDR **$<1.2 \times 10^{-7}$/pulse**.

TBTS and rf structures in CTF3

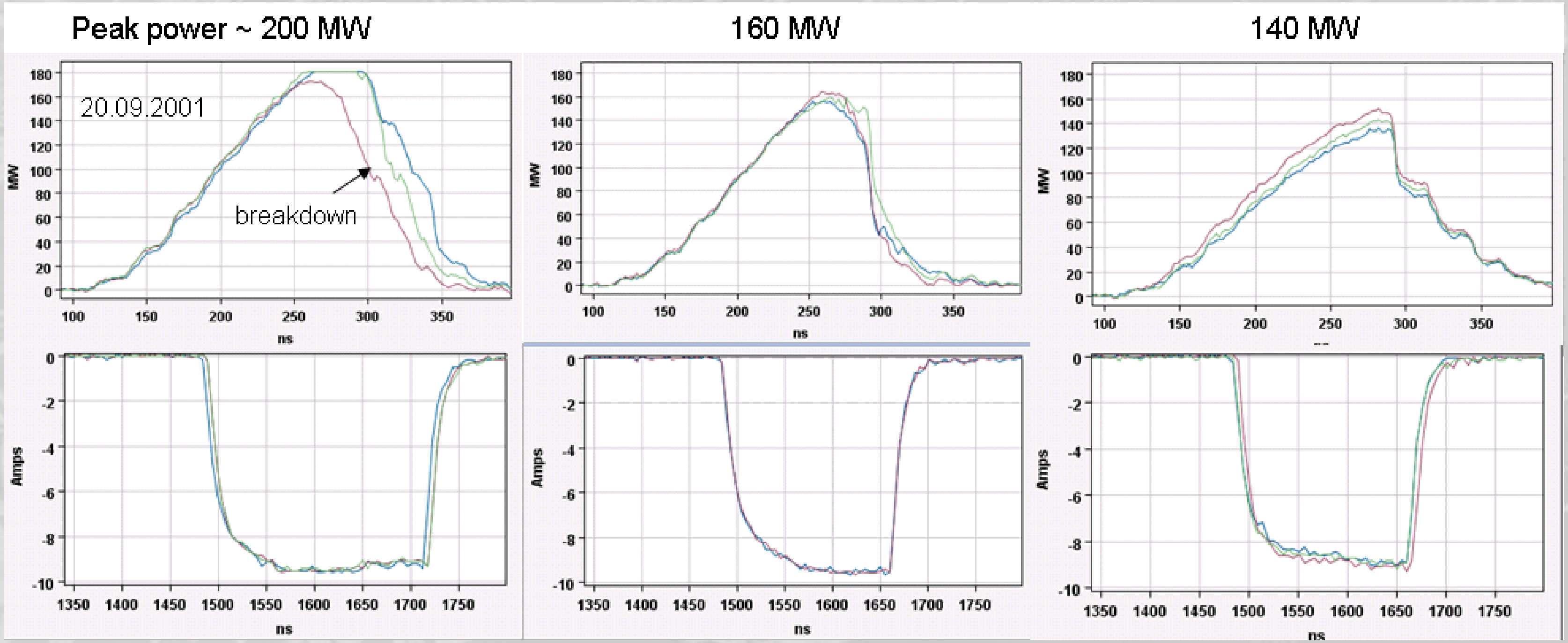






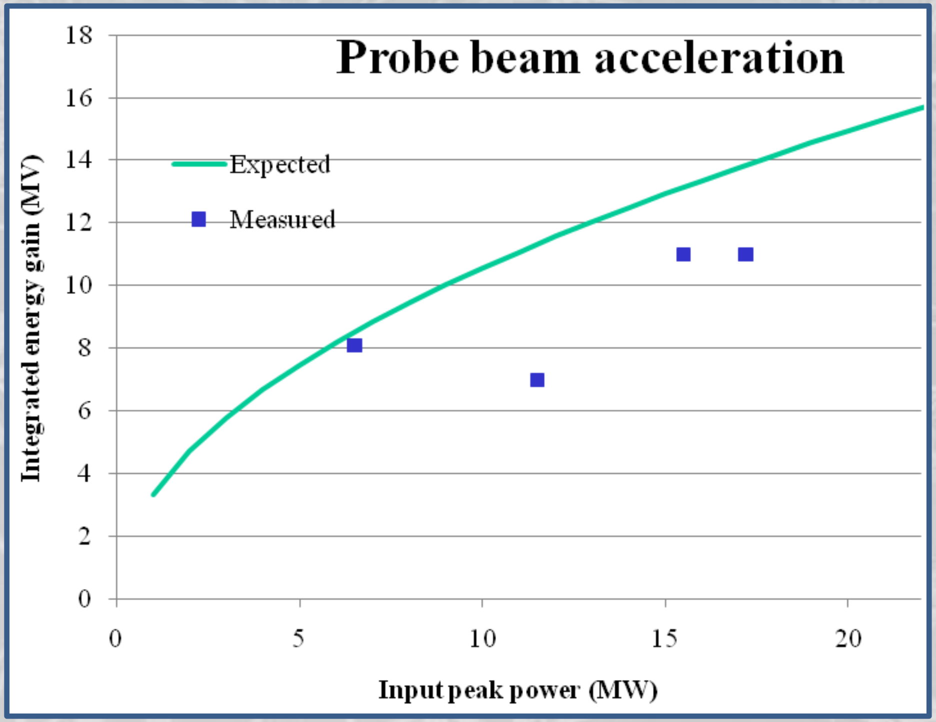


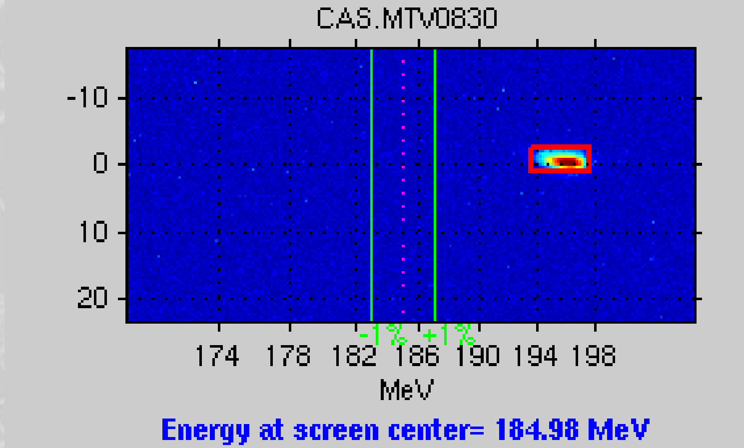
PETS power performance status



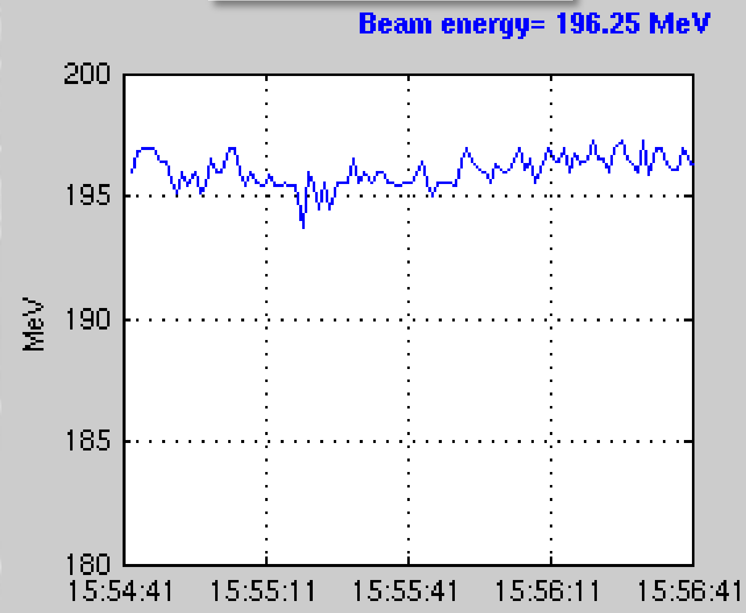
Power in recirculation mode after $3x10^5$ pulses (less than 2 hours to compare to 50/60 Hz repetition rate klystron test).

Coupled rf system with acceleration





Drive beam ON



Two-beam acceleration now starting at X-band (We used to do this all the time at 30 GHz).
Energy gain corresponds to 55 MV/m.

The new kid on the block

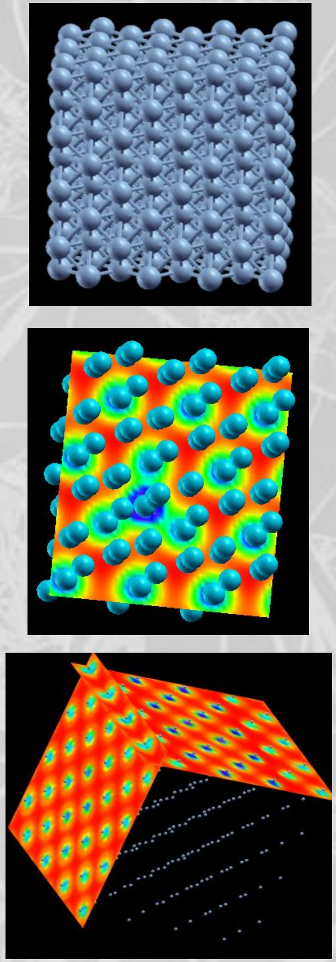
The SLAC-built 11.994 GHz klystron (XL-5) for the CLIC structure testing area is now at CERN!

This is an extraordinarily important event for CLIC.

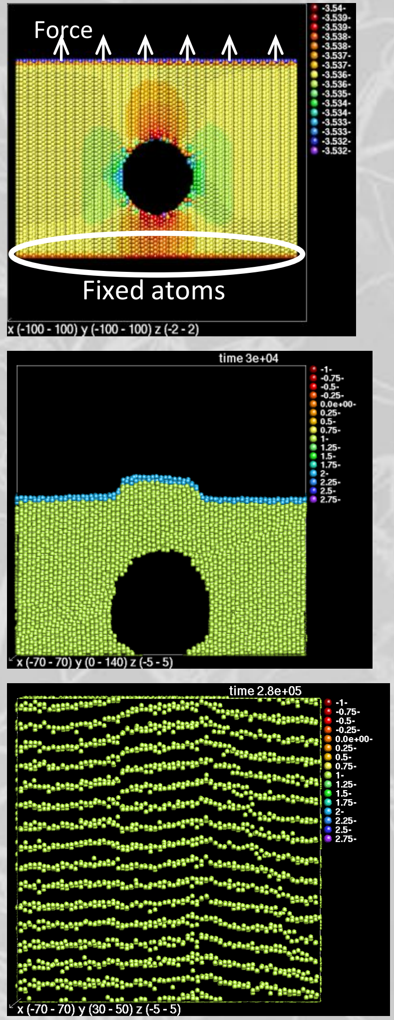
We clearly need more power sources to have the capacity to test the many tens of structures needed for the next stage of structure development.

The bar graph of accelerating structure performance on slide 8 needs to become a histogram.

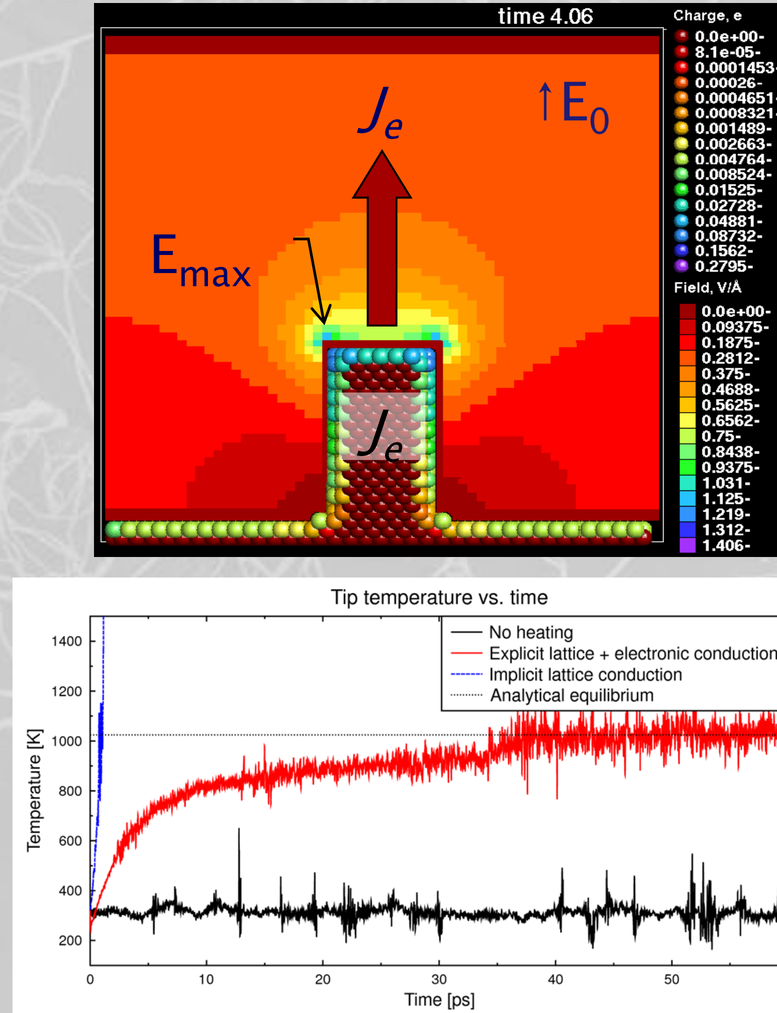
Multi-scale simulation of breakdown developed by the Helsinki Institute of Physics



1. Calculation of charge distribution in crystal

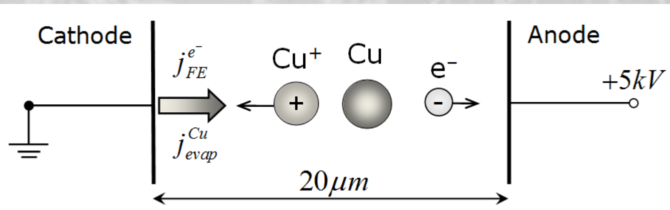


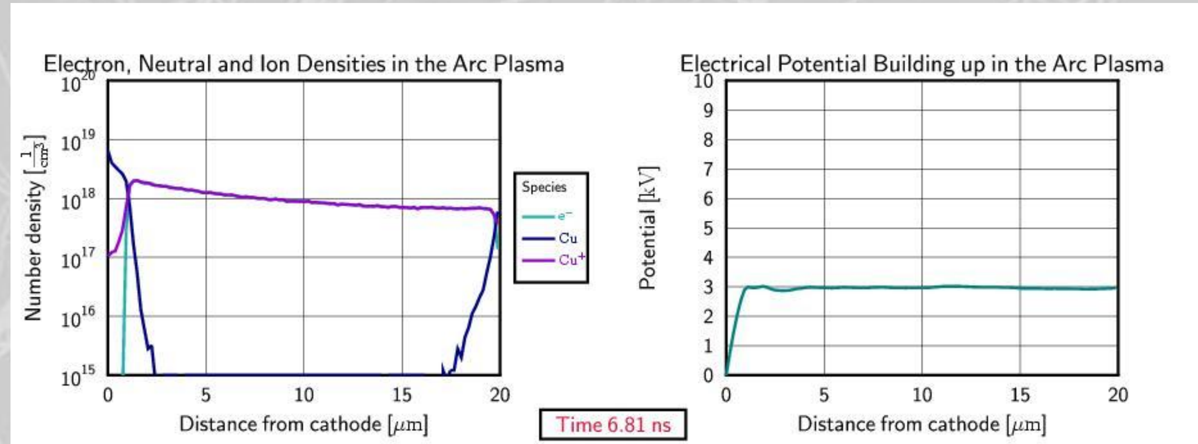
2. Emission site formation – breakdown rate



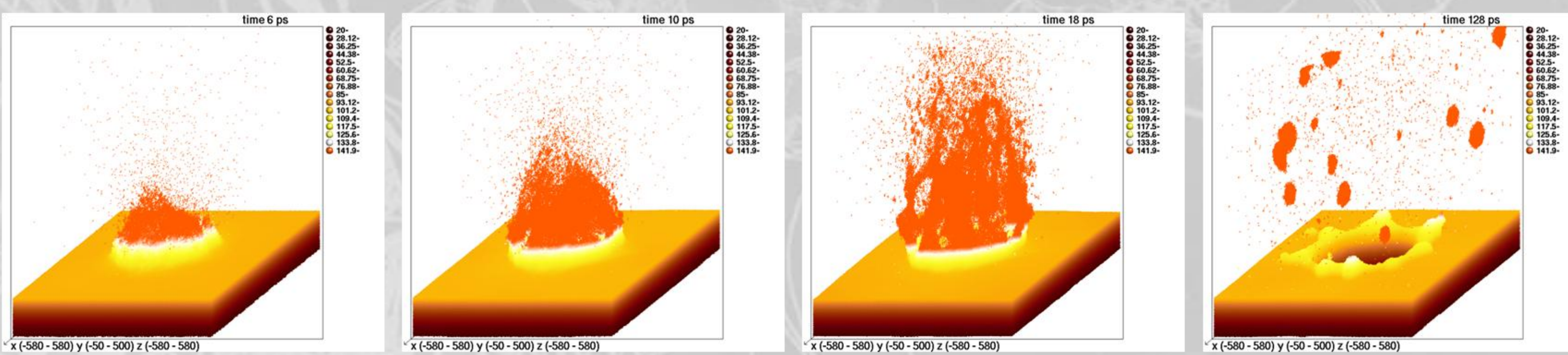
3. Field emission to breakdown trigger, including thermal effects

Multi-scale simulation of breakdown developed by the Helsinki Institute of Physics





4. Breakdown ignition and plasma formation



5. Surface damage mechanism

Outlook

- 0.1 GV/m acceleration looks feasible.
- 0.13 GW two-beam power production actually looks rather straightforward.
- Need to go from performance of individual structures to statistics.
- We start to understand what is going on rather well.

Acknowledgements

It has been my privilege to present highlights of scientific and technical work made by the combined effort of groups from roughly 35 institutes based in 17 countries – **my sincere thanks to all you**!

I hope that many of you will be able to attend working group 4 to discuss this work in greater detail and meet the people who are actually doing the work!

You are all also welcome to participate in our poster session on Wednesday afternoon.