The CLIC accelerating structure development program

Tsinghua University
24-3-2010
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Outline

- Introduction
- Coupled rf design and linac optimization
- High-power test program
- Transverse wakefield suppression
- Fundamental breakdown and pulsed-surface-heating studies

Introduction:

The main challenges for accelerating structures for CLIC:

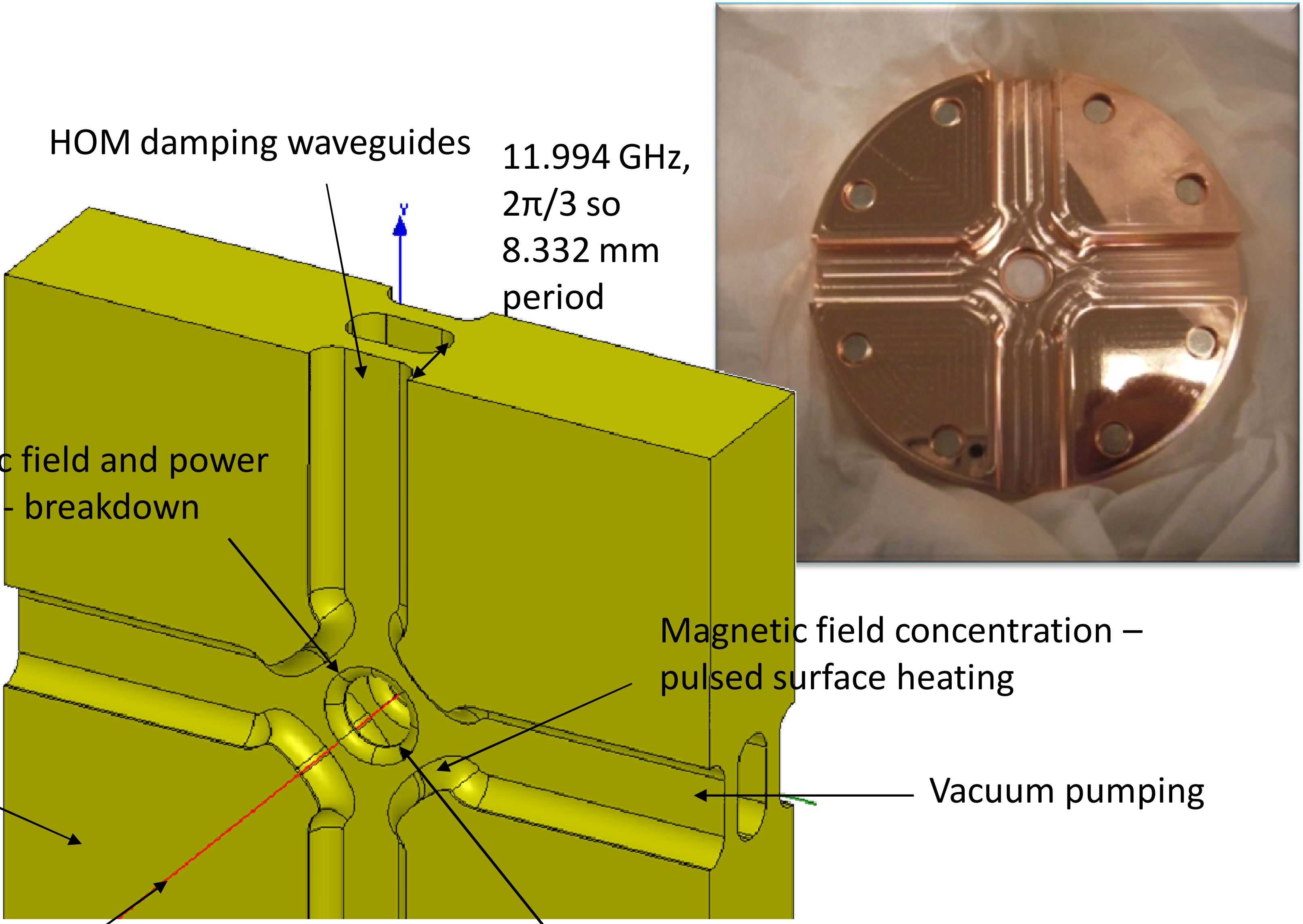
100 MV/m accelerating gradient with a breakdown rate of the order of 10^{-7}/pulse/m, pulse length of 250 ns. Performance is mainly limited by vacuum breakdown and pulsed surface heating. Need strong coupling to the beam to remain efficient which in turn gives,

Demanding beam dynamics requirements - low short-range transverse wakefields and strong long-range wakefield suppression. Both complicate getting a high gradient. Requires micron assembly and alignment tolerances.

I will not cover our PETS, decelerating structure, program today.

Coupled rf design and linac optimization

Baseline accelerating structure features



HOM damping waveguides

11.994 GHz,
2π/3 so
8.332 mm
period

Alignment

High electric field and power
flow region - breakdown

Magnetic field concentration –
pulsed surface heating

Cooling

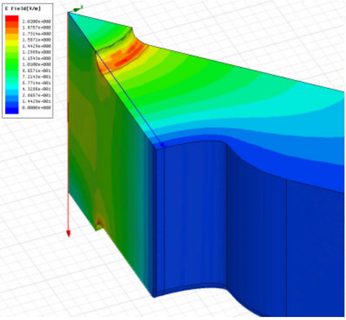
Vacuum pumping

Short range wakefields

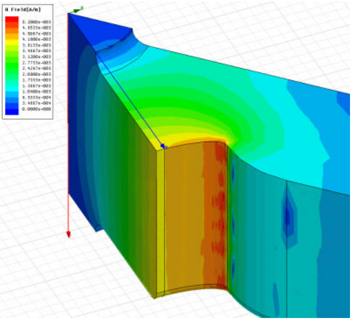
Beam and rf

Accelerating structure features

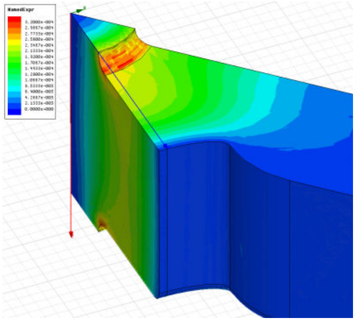
E_s/E_a

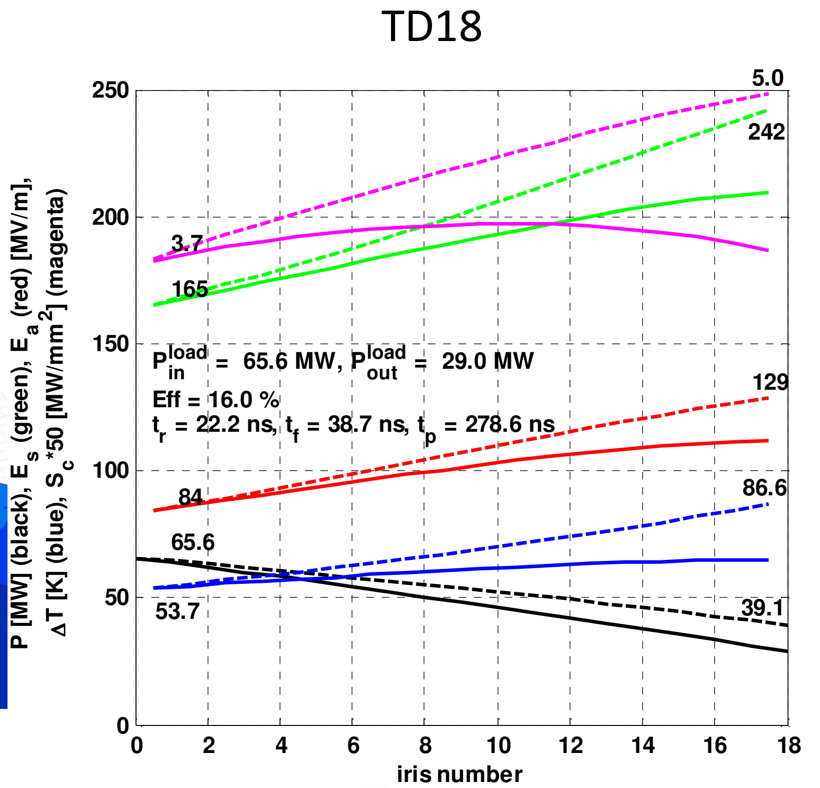


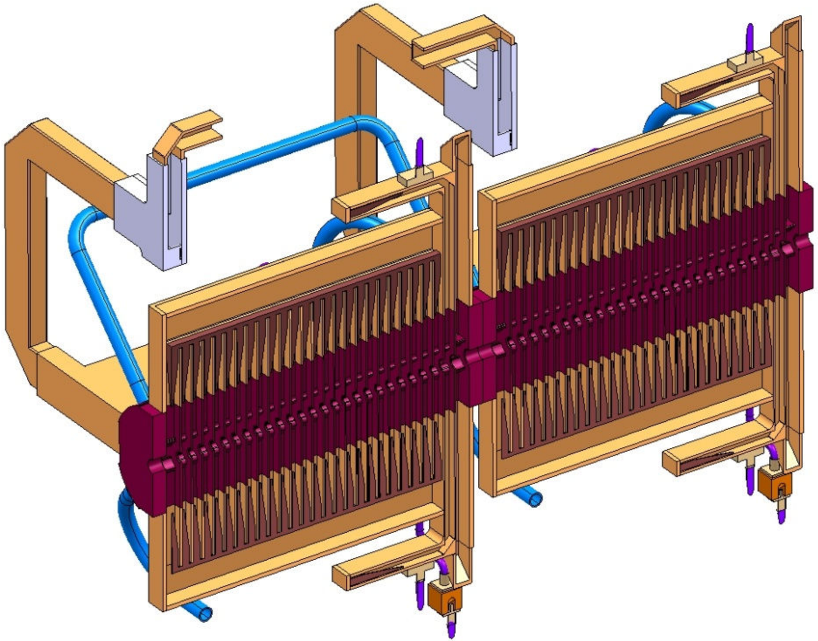
H_s/E_a



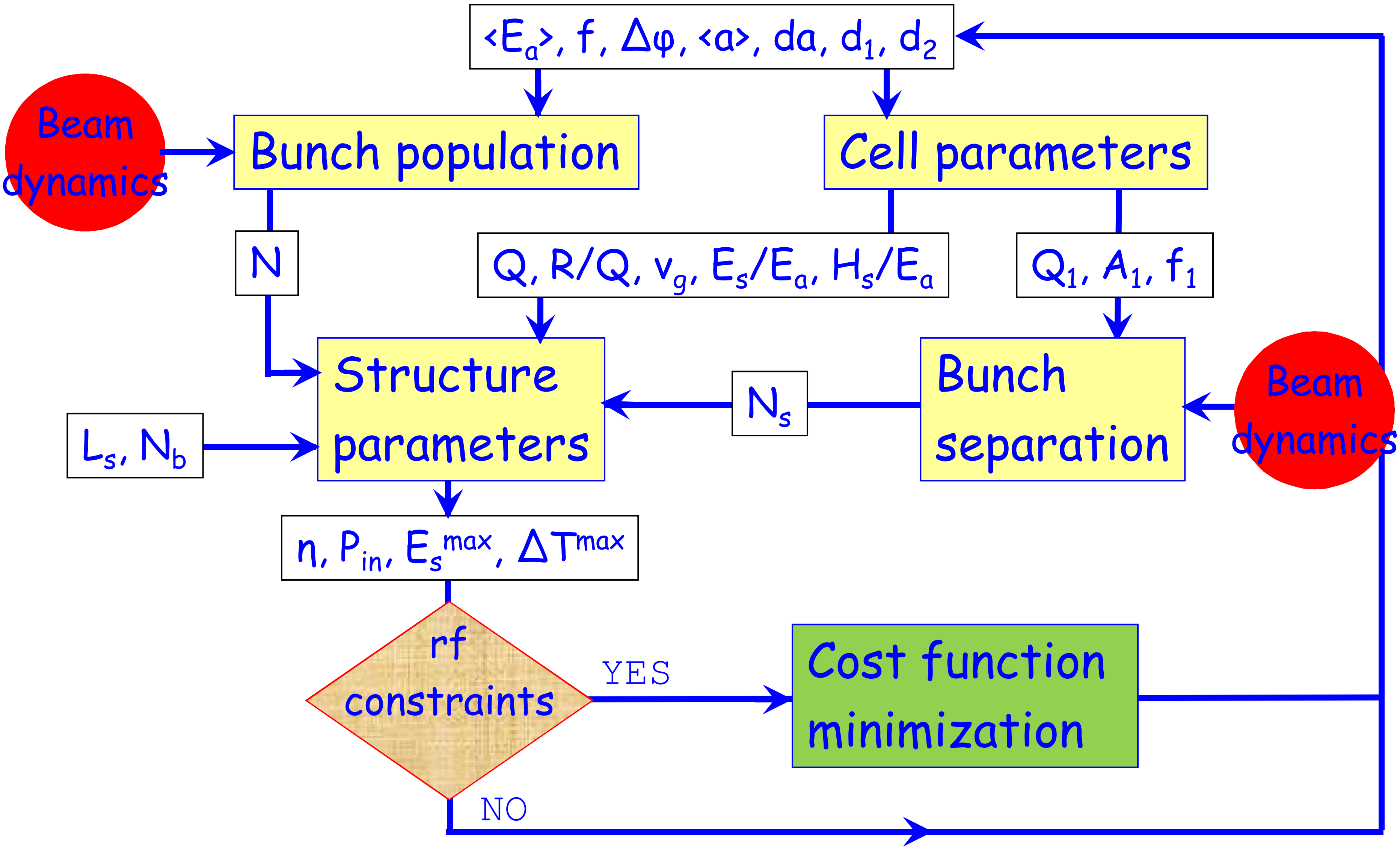
S_c/E_a^2







Optimization procedure



$\langle E_a\rangle$, f, $\Delta\varphi$, $\langle a\rangle$, da, d_1, d_2

Beam dynamics

Bunch population

Cell parameters

N

Q, R/Q, v_g, E_s/E_a, H_s/E_a

Q_1, A_1, f_1

Structure parameters

N_s

Bunch separation

Beam dynamics

L_s, N_b

η, P_{in}, E_s^{max}, ΔT^{max}

rf constraints

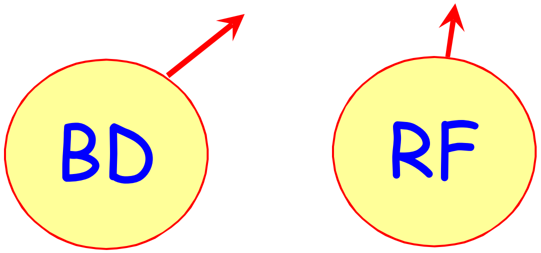
YES

Cost function minimization

NO

Beam dynamics input

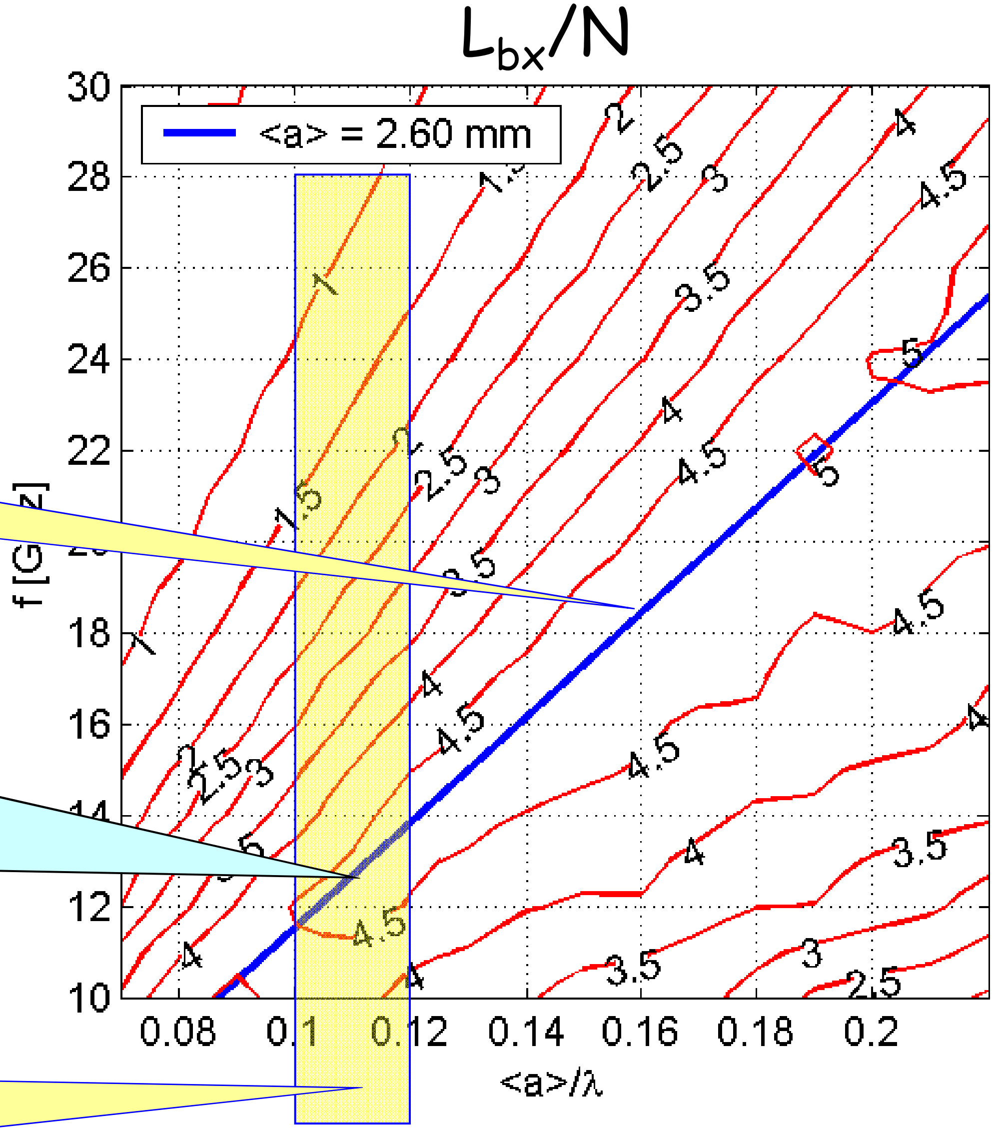
$$\mathrm{FoM} = L_{bx}/N \cdot \eta$$



BD optimum aperture:
<a> = 2.6 mm

Why X-band ?
Crossing gives
optimum frequency

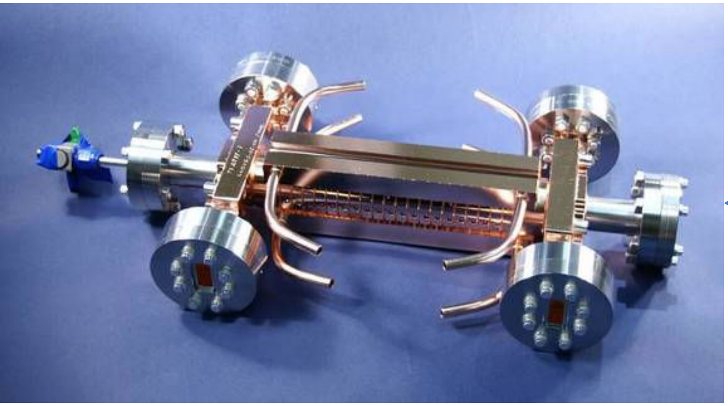
High-power RF optimum aperture: <a>/λ = 0.1 ÷ 0.12



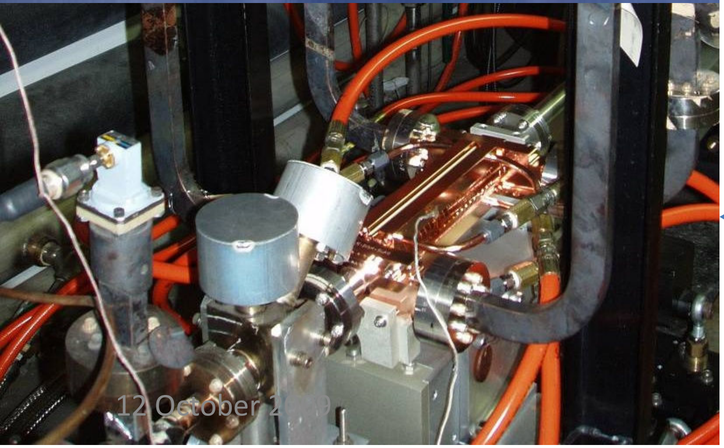
High-power test program

CERN/KEK/SLAC high-power test structures

T18 - undamped

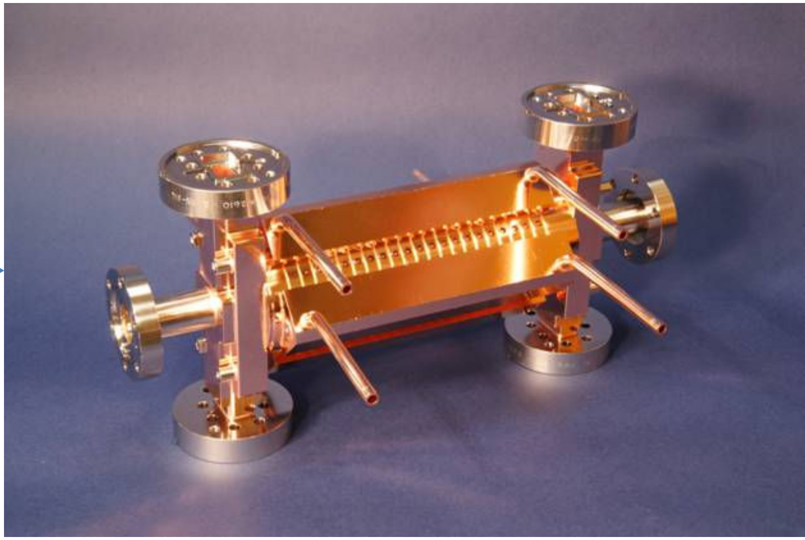


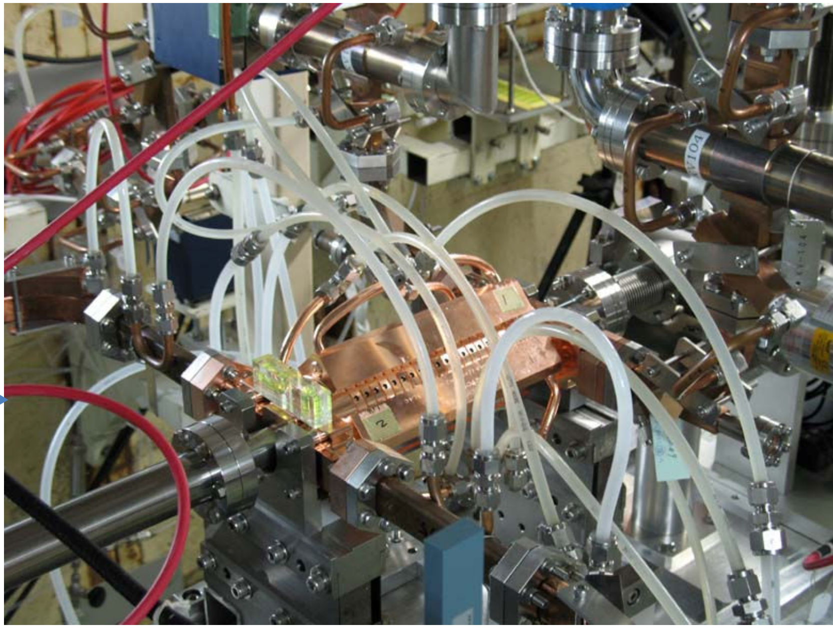
Done



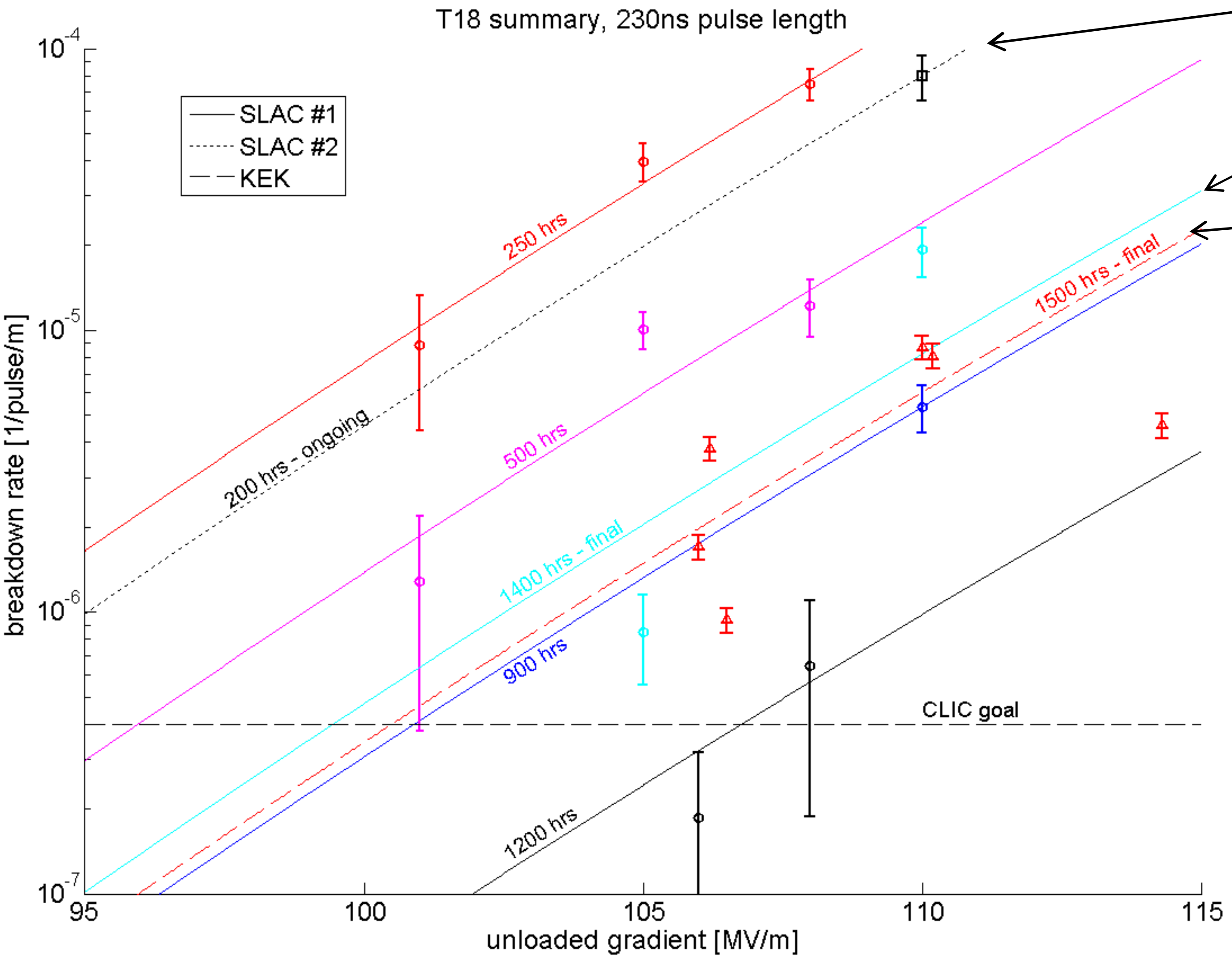
Under test

TD18 - damped





CERN/KEK/SLAC T18 structure tests



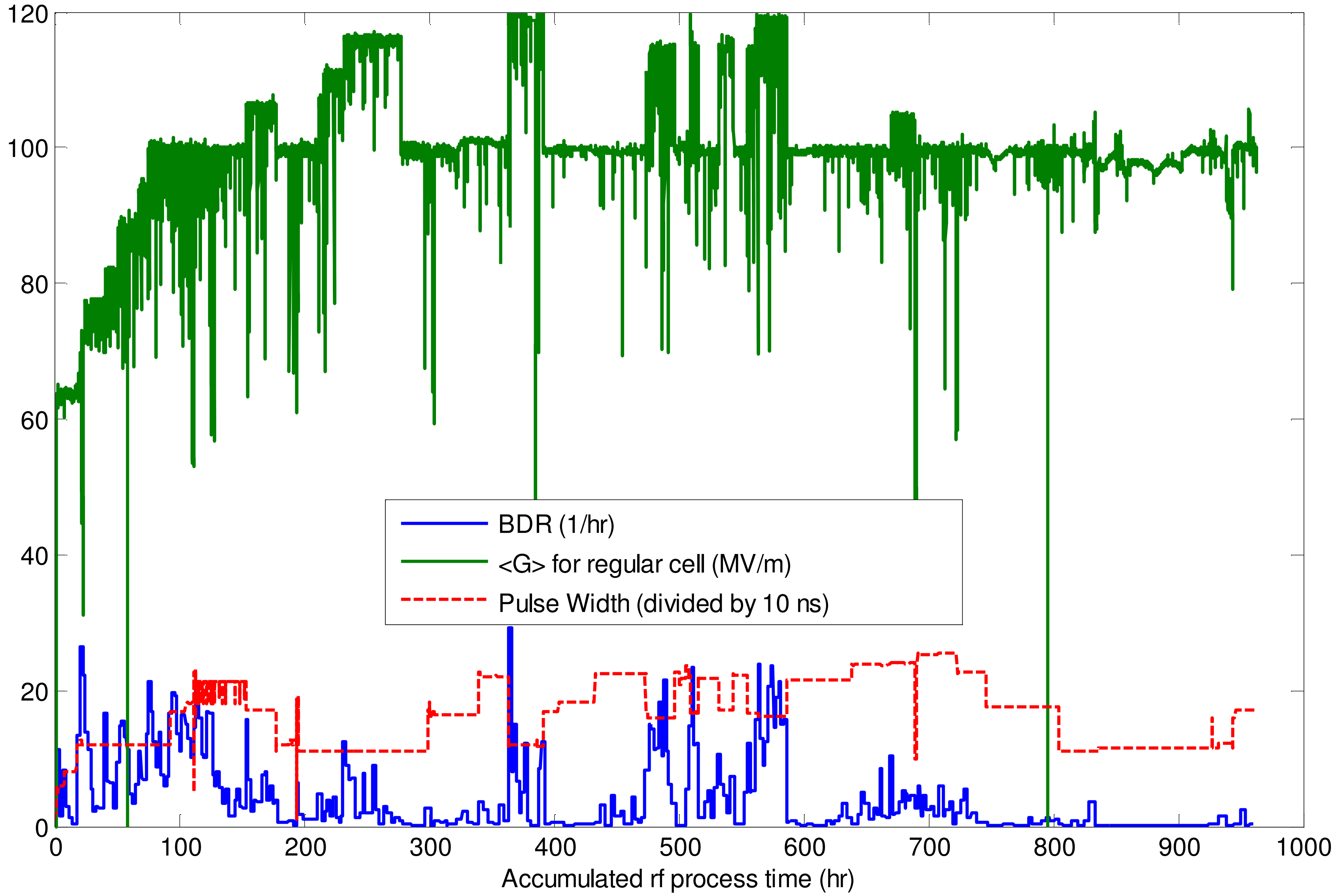
SLAC 2

SLAC 1

KEK

Lines are $E^{30}/BDR=const$

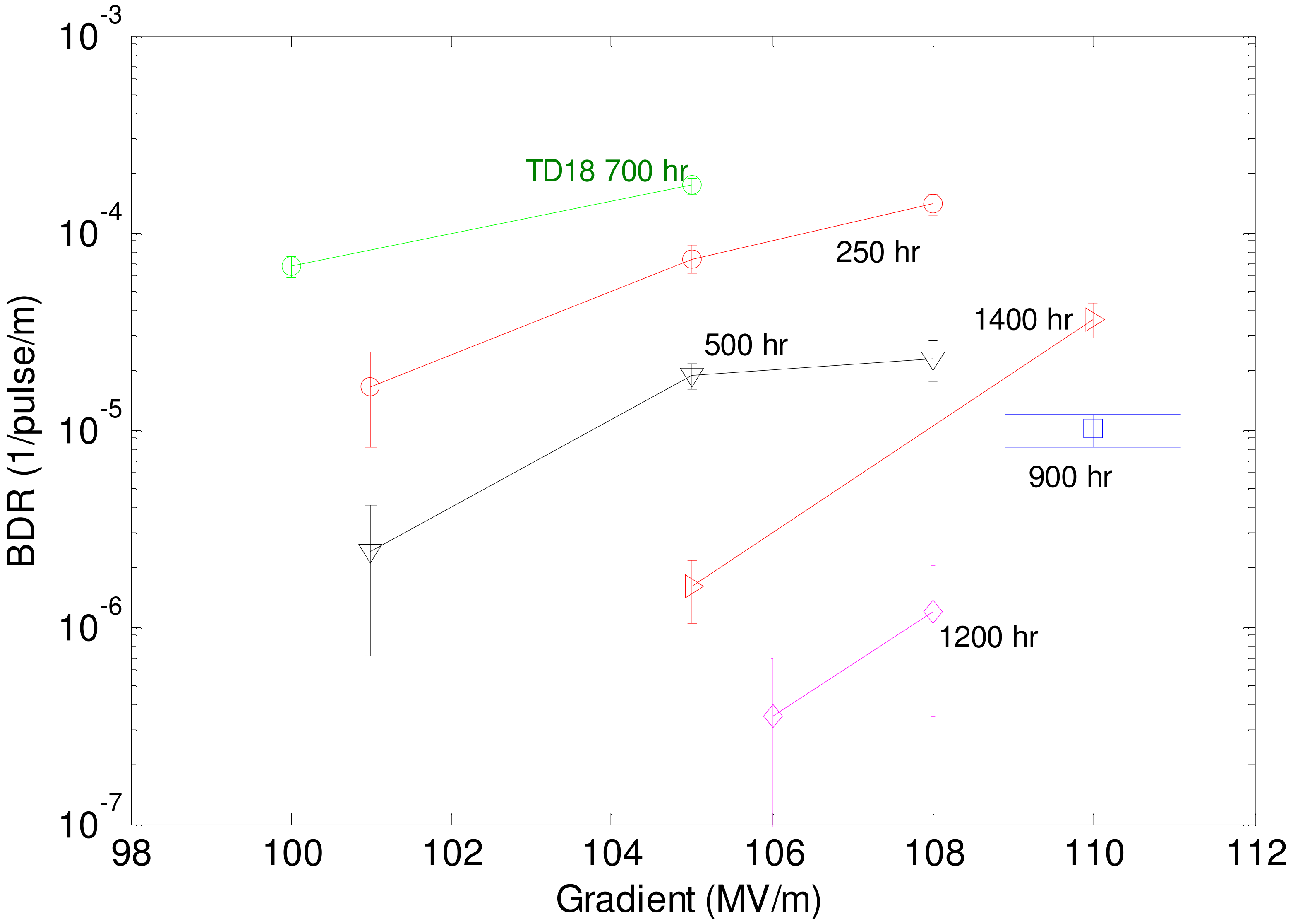
High Power Test begin at 12/03/2009 15:00



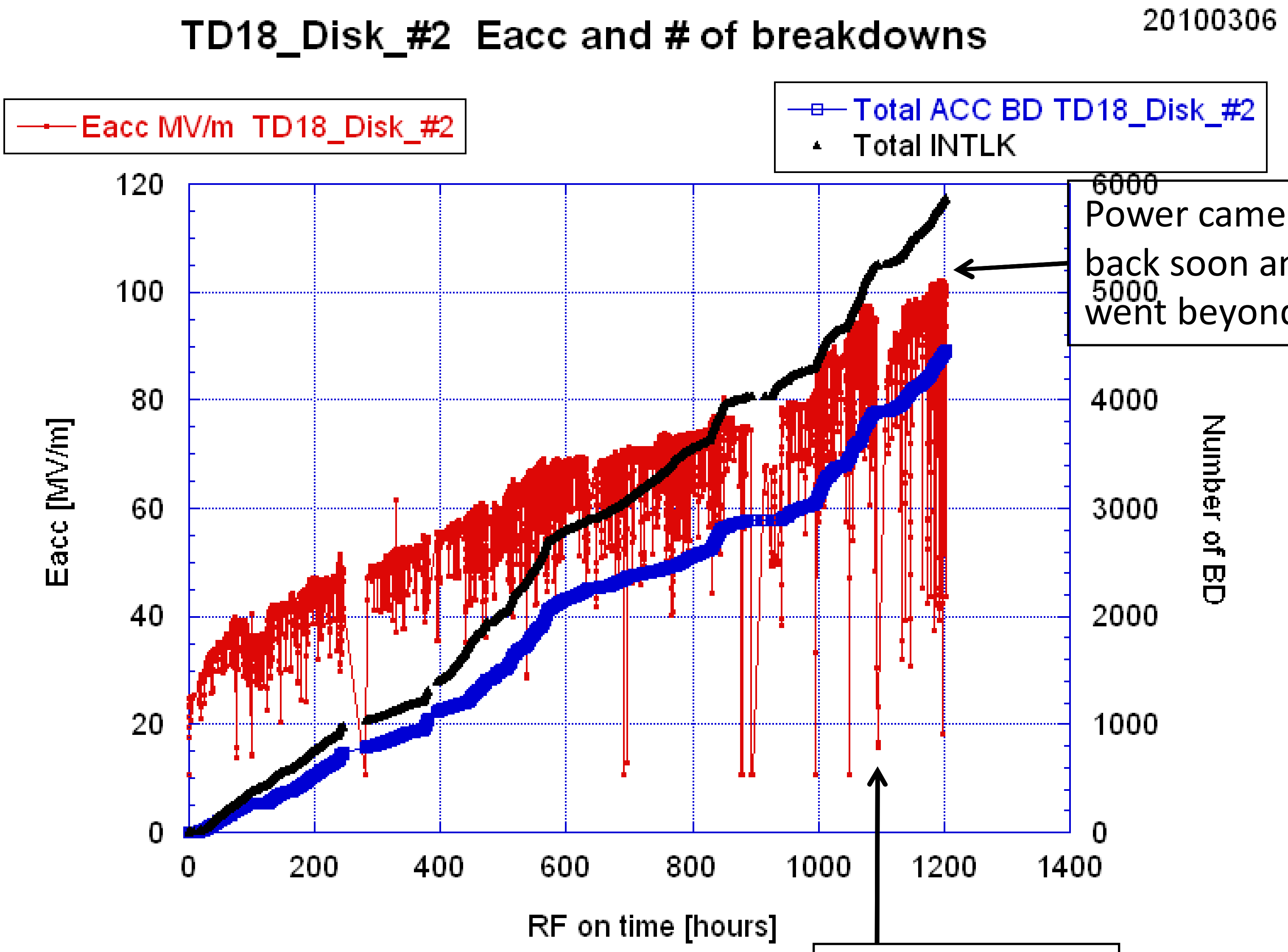
TD-18

Faya Wang, SLAC

RF Process Results Comparison with T18_SLAC1



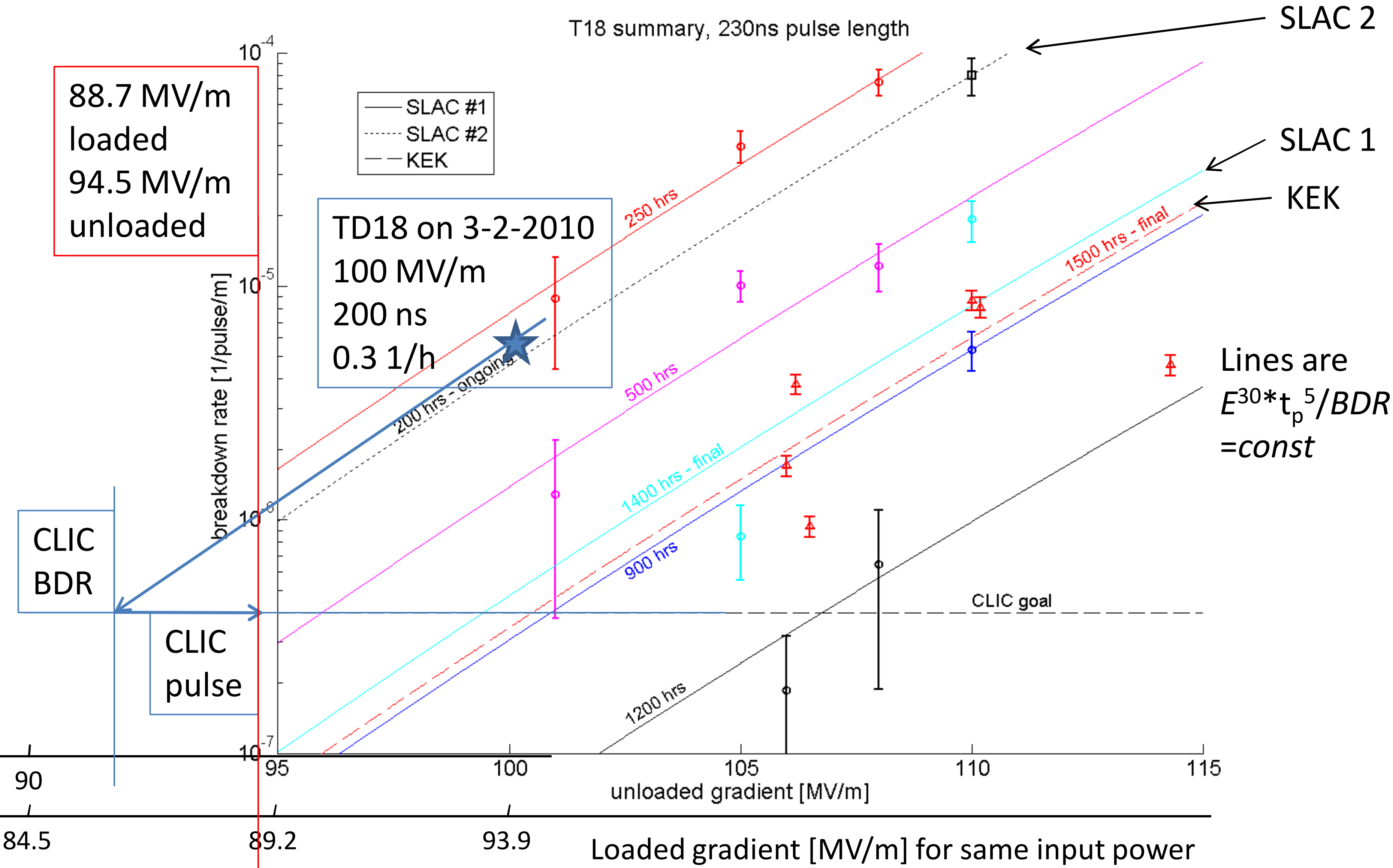
Pulse width 230ns, Green line for TD18, Others for T18



Power came back soon and went beyond.

Change of Left-arm RF load.

CERN/KEK/SLAC T18/TD18 structure tests



SLAC 2

SLAC 1

KEK

88.7 MV/m
loaded
94.5 MV/m
unloaded

TD18 on 3-2-2010
100 MV/m
200 ns
0.3 1/h

CLIC
BDR

CLIC
pulse

Lines are
$E^{30}*t_p^{5}/BDR$
=*const*

Accelerating structure development core program

Adopt NLC/JLC technology

Structure for 100 MV/m using high-power scaling laws – T18

Two successful tests, third underway, have shown that **100 MV/m, 240 ns, 10^{-6} to 10^{-7} range is feasible.**

Add damping features – TD18

Successful start of one test already shows damping features do not significantly affect performance. **Damped structures at 100 MV/m are feasible.**

CLIC nominal structure with better rf design for higher efficiency – TD24 (and T24 to be systematic)

Predicted equivalent performance from high-power limits but more efficient. Needs verification, tests in spring.

Verification of features such as SiC loads, compact coupler, wakefield monitor

Mechanical design underway (tricky).

Fine tuning of design, optimization of process, medium series production and testing

Accelerating structure critical issues and programs 2

Long range wakefield damping of the order of two orders of magnitude in six fundamental cycles.

- Simulations using a number of different techniques and programs
- Experimental program including a test in ASSET and indirect wakefield monitor tests.
- Baseline heavy damping. Alternatives are slotted quadrants, DDS (Manchester) and Choke mode (Tsinghua)

From CLIC advisory committee meeting of 2-2-2010

Micron precision manufacture, assembly and integration

- Dedicated manufacturing study
- Subsystem (cooling, vacuum, support) design
- Wakefield monitor development
- Dedicated cost studies are underway
- Other X-band and high gradient applications like TERA, X-FEL to gain experience and spread expertise.

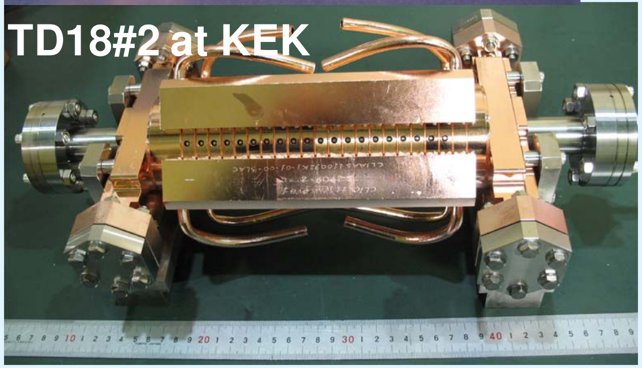
Dynamic Vacuum

- Work program is now being established. Goal is direct measurement, we will likely need a combination of measurement and simulation.

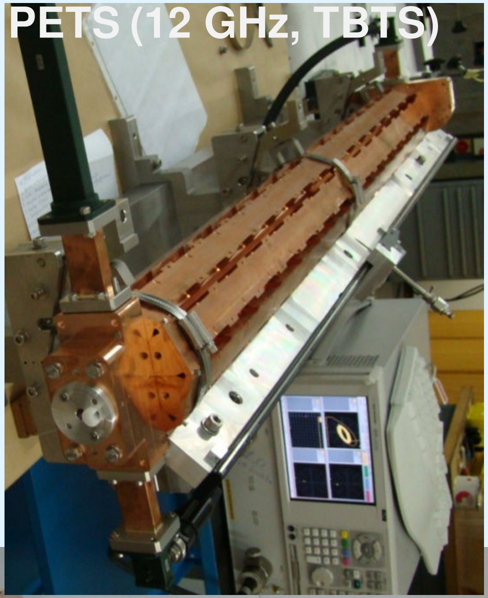
Manufacturing

Introduction


TD18#3 at SLAC

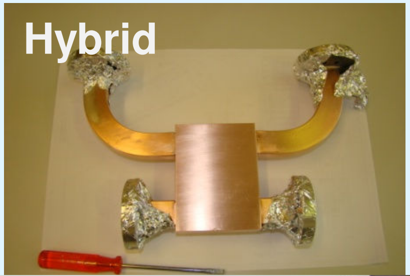

TD18#2 at KEK


TD24#2 at CERN (12 GHz)


PETS (12 GHz, TBTS)


PETS (11.4 GHz, test at SLAC)


High-power dry load


Hybrid


Variable high power splitter

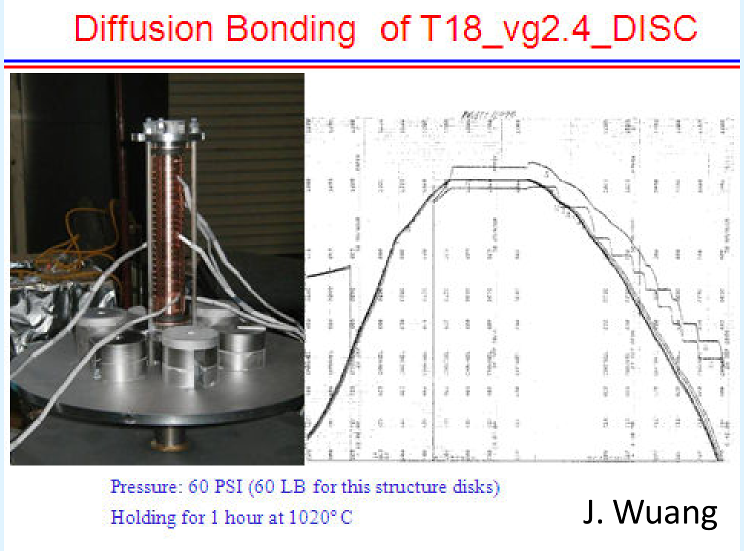
Baseline procedure

Diamond machining (sealed structures)

Cleaning with light etch

H2 diffusion bonding/brazing at ~ 1000 ˚C

Vacuum baking 650 ˚C > 10 days



Diffusion Bonding of T18_vg2.4_DISC

Pressure: 60 PSI (60 LB for this structure disks)

Holding for 1 hour at 1020° C

J. Wuang

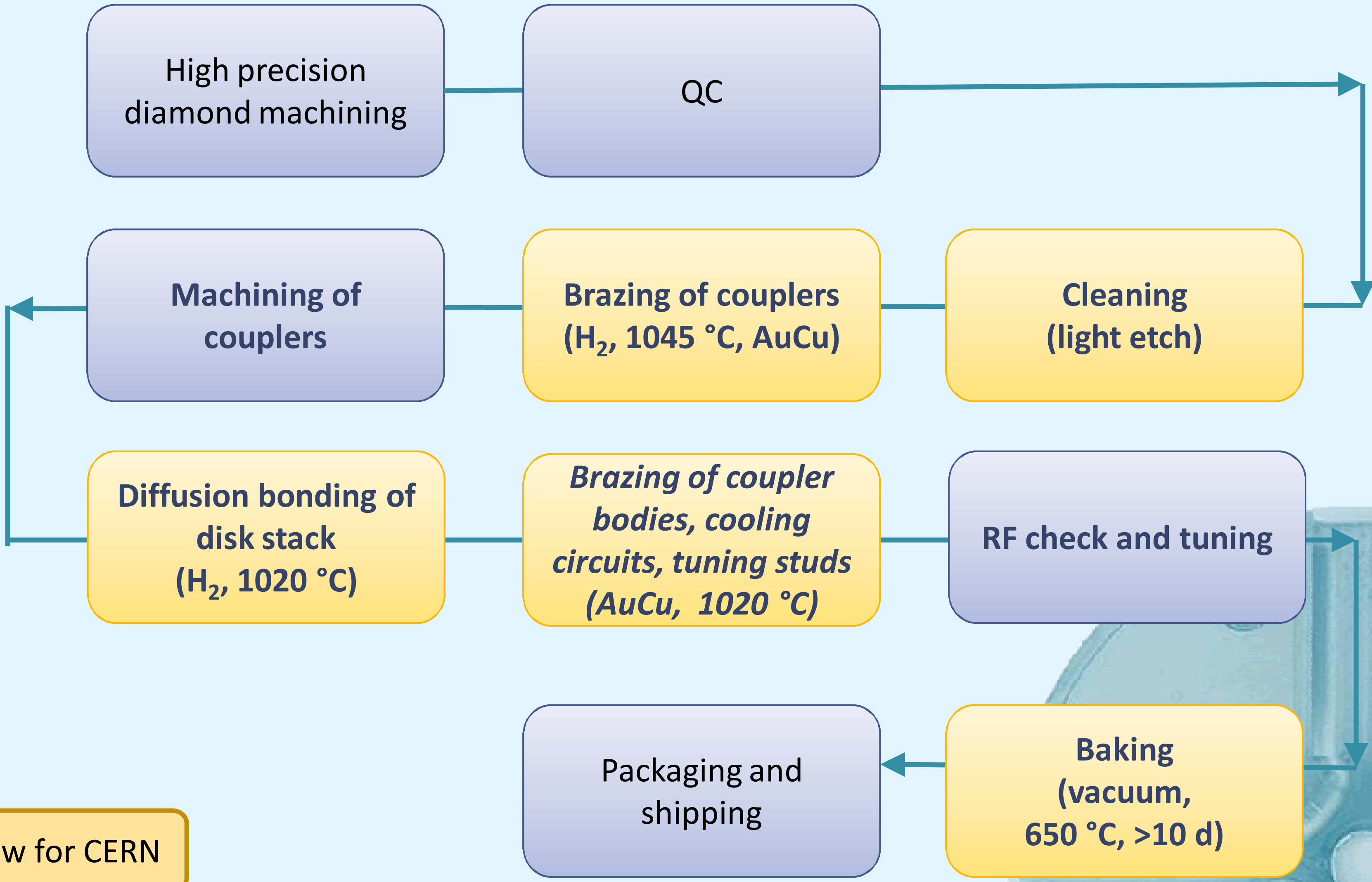
Vacuum Baking of T18_vg2.4_DISC

650° C

10 days

J. Wuang

Baseline manufacturing flow



High precision diamond machining

QC

Cleaning (light etch)

Brazing of couplers (H_2, 1045 °C, AuCu)

Machining of couplers

Diffusion bonding of disk stack (H_2, 1020 °C)

Brazing of coupler bodies, cooling circuits, tuning studs (AuCu, 1020 °C)

RF check and tuning

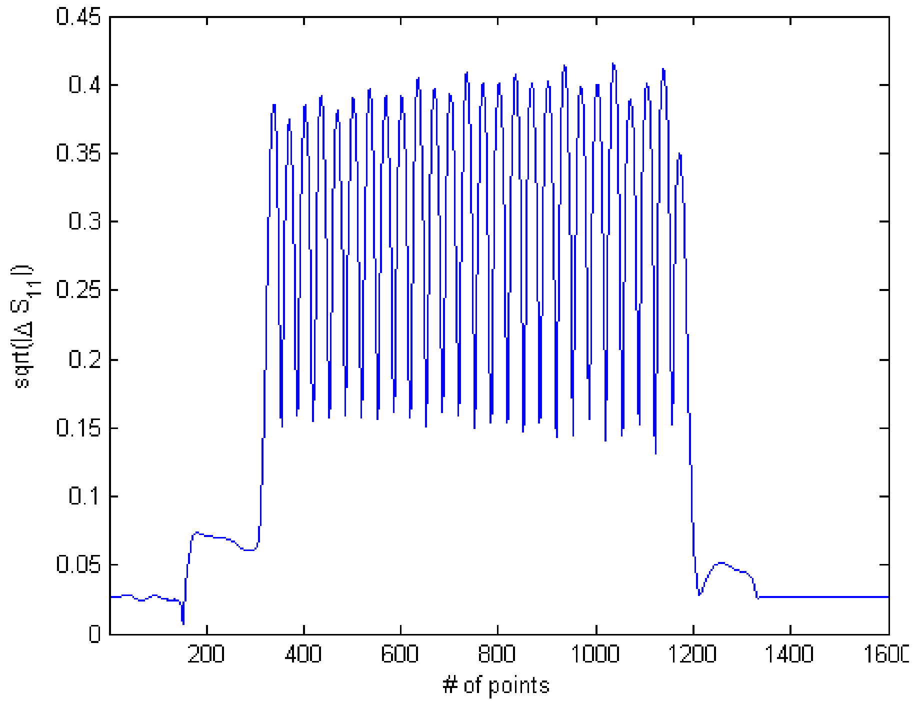
Baking (vacuum, 650 °C, >10 d)

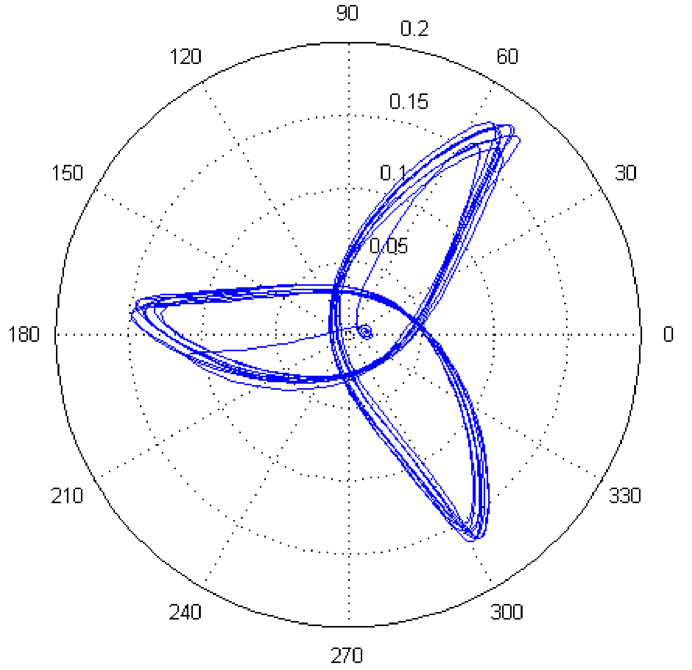
Packaging and shipping

New for CERN

G. Riddone, 5th CLIC-ACE, 02/02/2010

rf tuning TD24

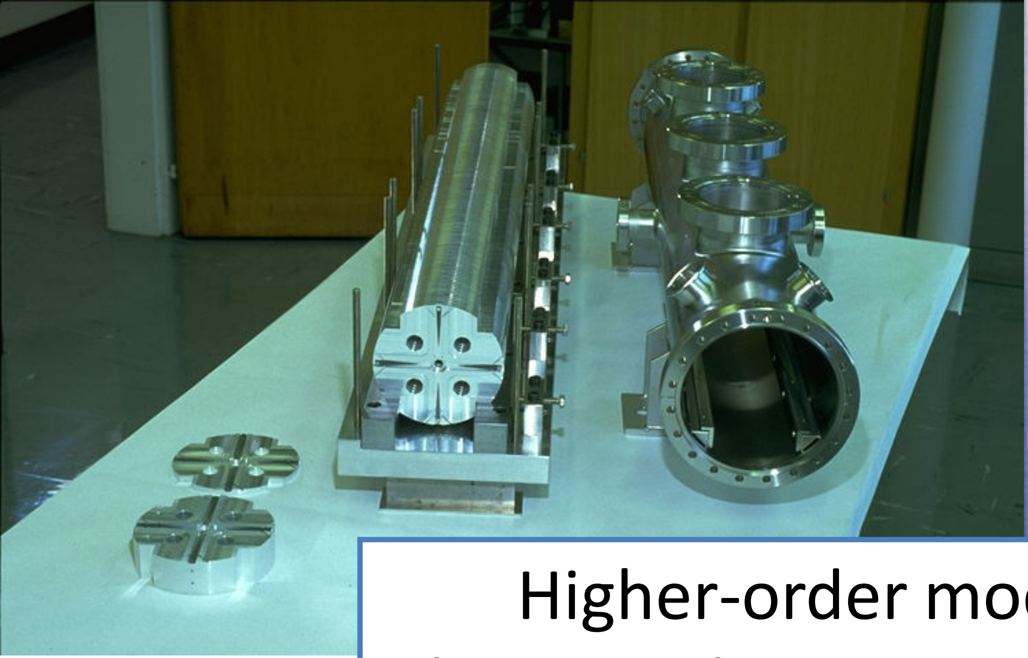


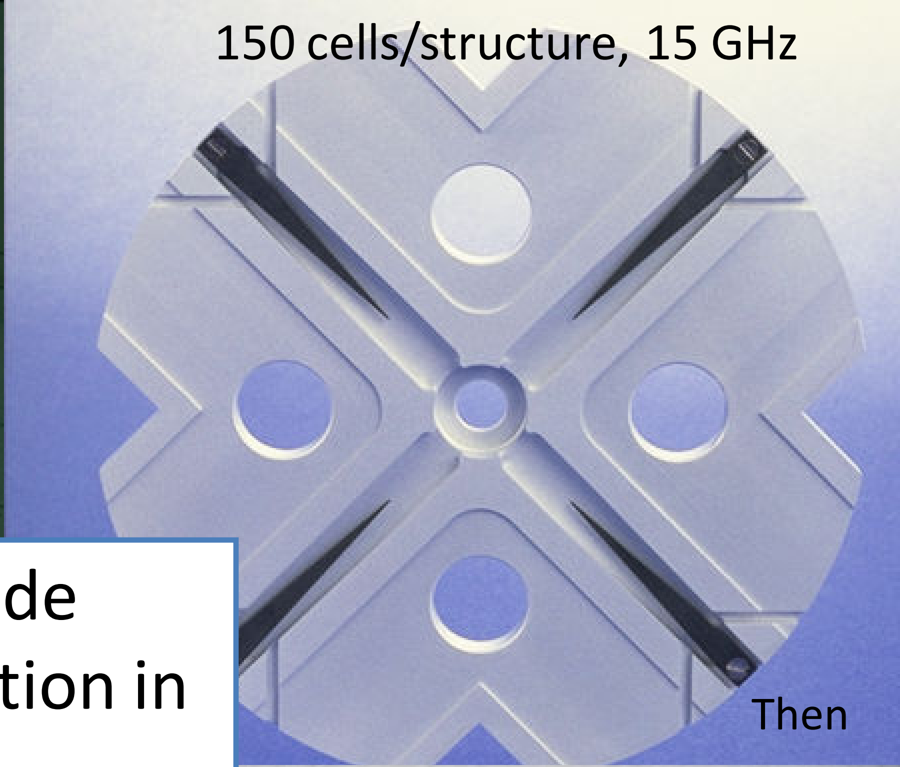


Jiaru Shi

Transverse wakefield suppression

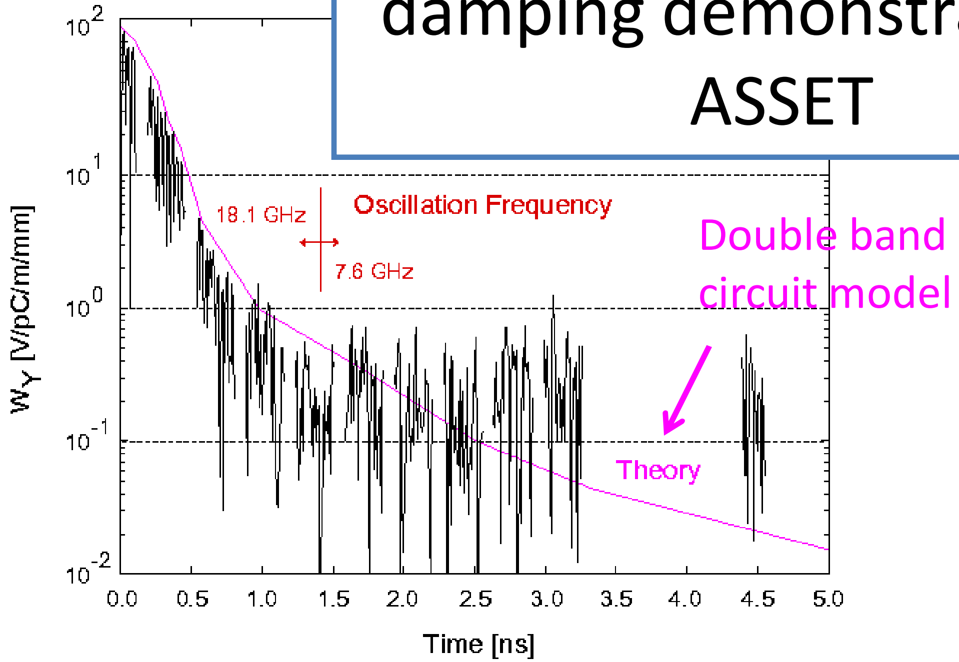
Higher-order mode damping demonstration in ASSET





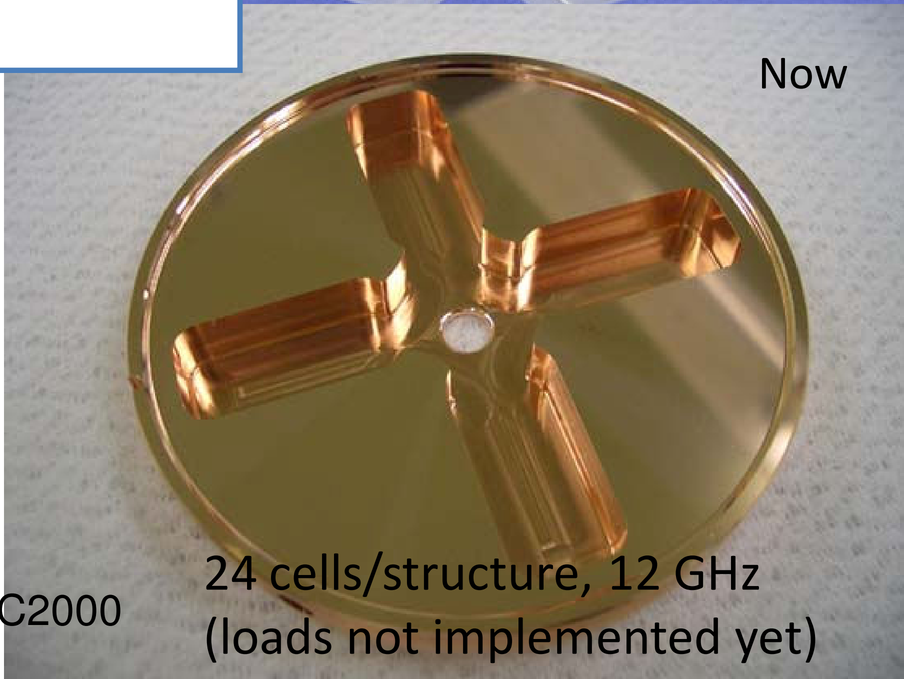
150 cells/structure, 15 GHz

Then



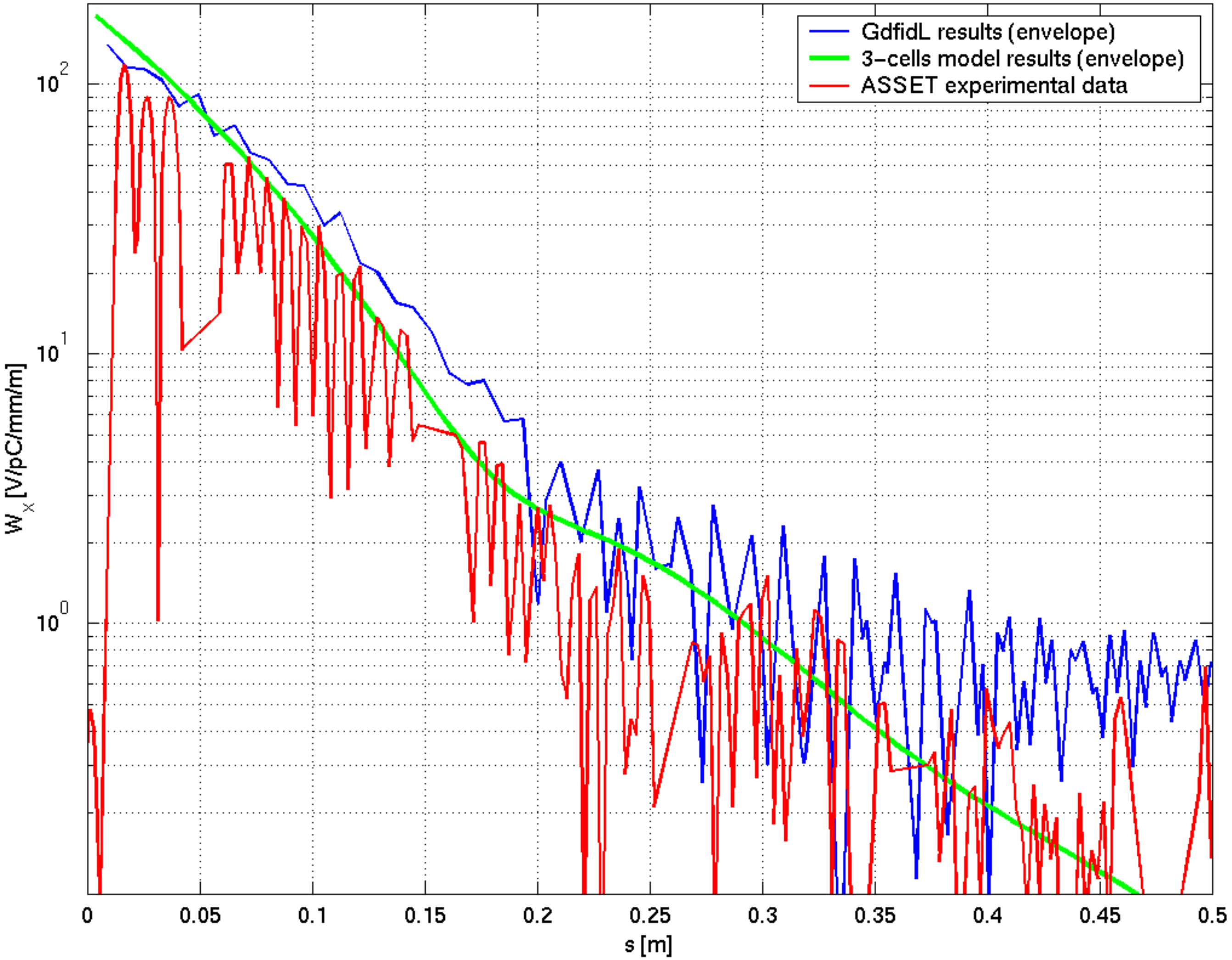
An Asset Test of the CLIC Accelerating Structure, PAC2000

Now

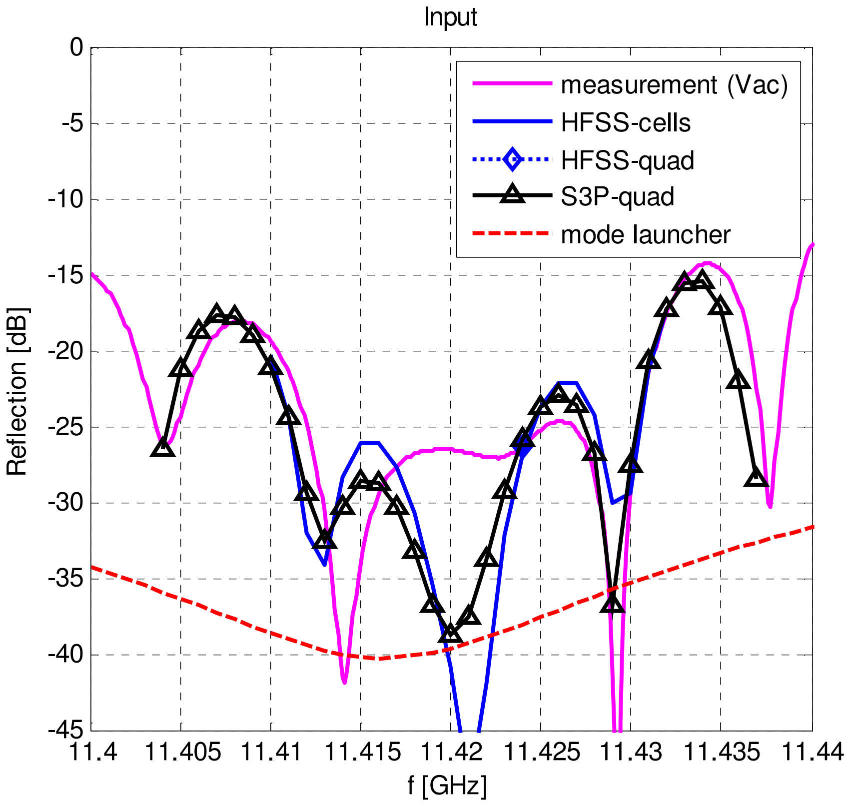


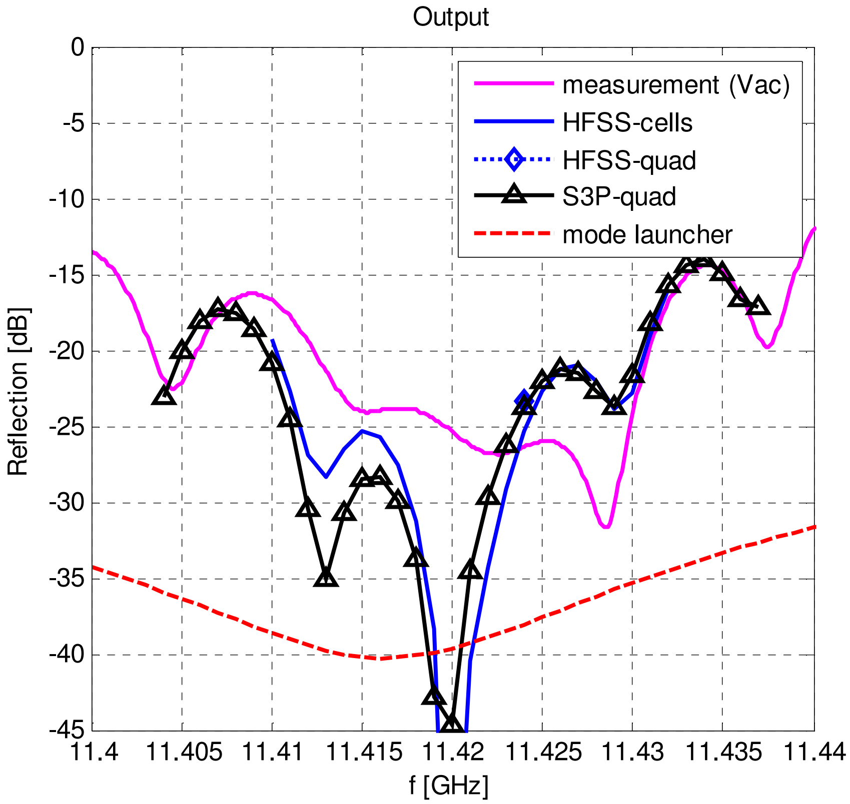
24 cells/structure, 12 GHz
(loads not implemented yet)

Full length TDS results comparison



Reflection: comparison





There is very small (~1MHz) or no difference in frequency between simulations and the air corrected measurements

Our computational capability is constantly being refined and benchmarked.

Fundamental breakdown and pulsed surface heating studies

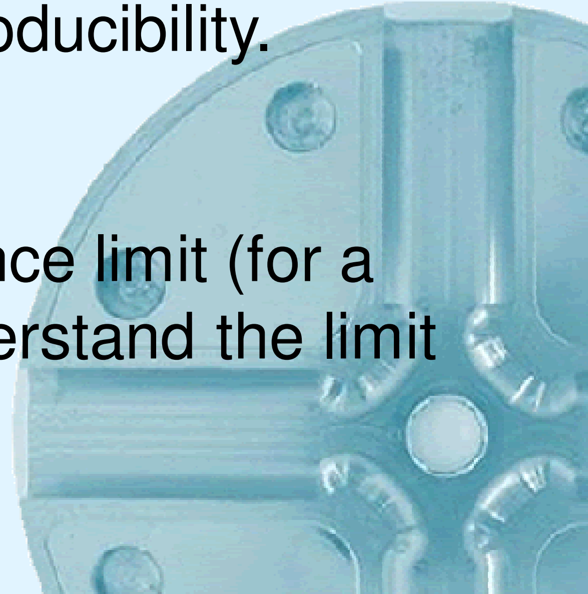
High-power rf theory and simulation effort

Over the past couple of decades computational tools have developed to the point that we can now accurately design complex, 3-D and even multi-moded rf structures.

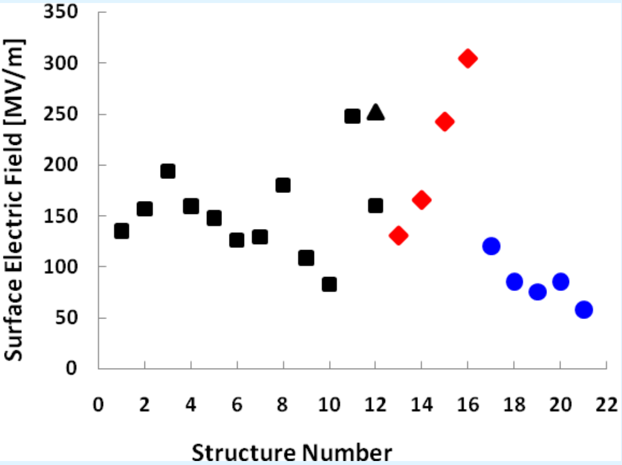
The ability to predict high-power performance has lagged behind:

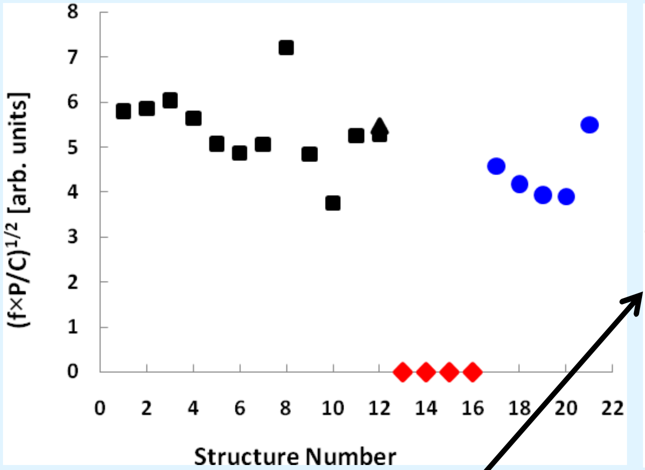
- A lot depends on preparation. But NLC/JLC made enormous progress in improving performance and reproducibility.
- The phenomena are extremely complex.

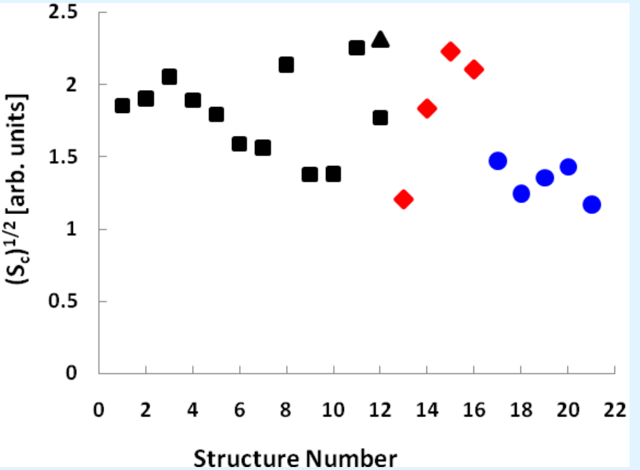
CLIC aims to run very close to the performance limit (for a given breakdown rate) so we had better understand the limit pretty well.



S_c: high-power design parameter





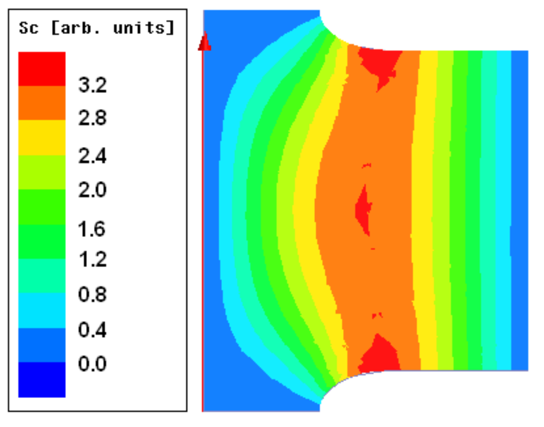


X-band and 30 GHz, pulses of the order of 100 ns.

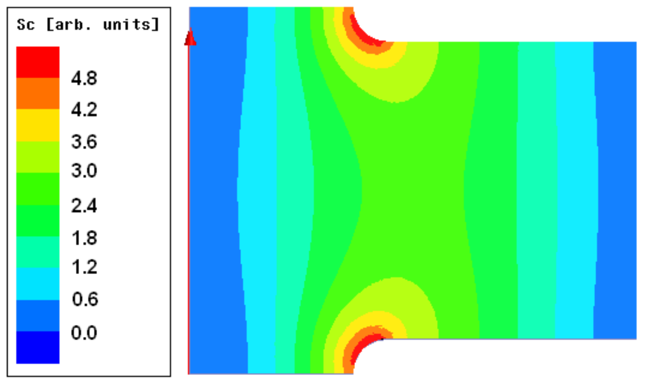
Travelling and standing wave

Related to the complex Poynting vector:

$$S_c = \Re\left\{\overline{S}\right\} + g_c \cdot \Im\left\{\overline{S}\right\}$$

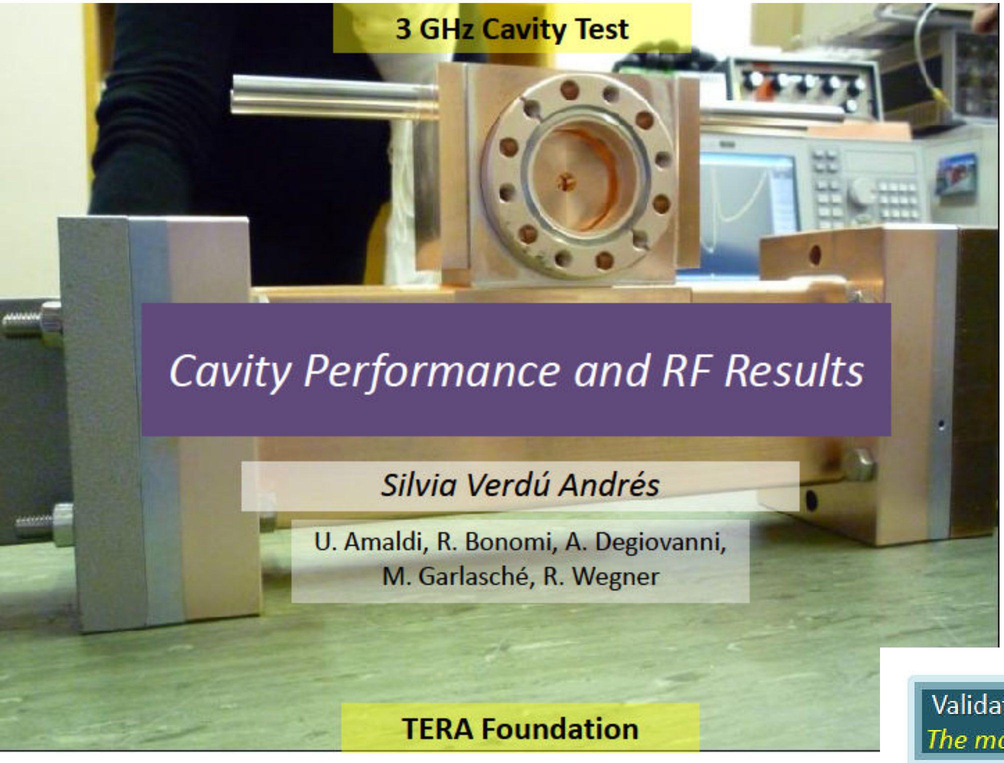


Travelling wave



Standing wave

W. Wuensch



3 GHz Cavity Test

Cavity Performance and RF Results

Silvia Verdú Andrés

U. Amaldi, R. Bonomi, A. Degiovanni,
M. Garlasché, R. Wegner

TERA Foundation

Do our high-gradient limits extend all the way down to S-band and microsecond pulses?

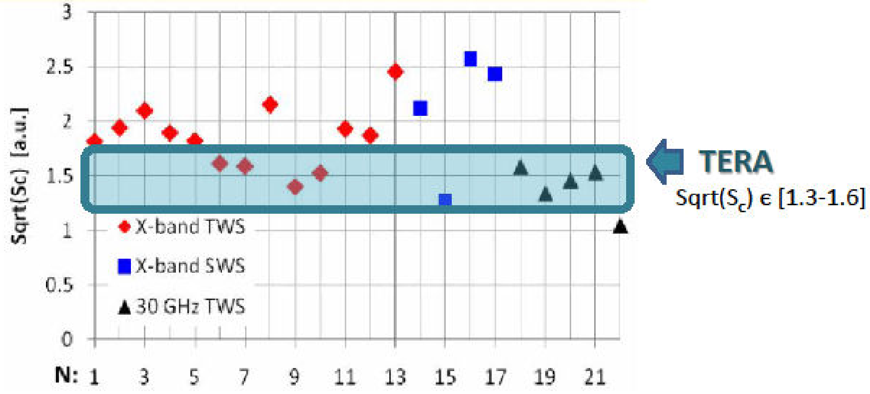
PRELIMINARY RESULTS!

Validation of CLIC observations:
The modified Poynting vector as a RF constraint to high gradient performance

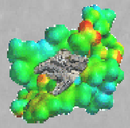
The square root of S_C has been scaled to t_{pulse} =**200 ns** and BDR=**10^{-6} bbp/m**

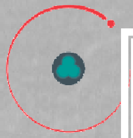
$$\sqrt{S_C^{equiv}} = \sqrt{S_C} \cdot \left(\frac{t_{pulse}}{t_{pulse}^{ref}}\right)^{\frac{1}{6}} \cdot \left(\frac{BDR^{ref}}{BDR}\right)^{\frac{1}{30}}$$

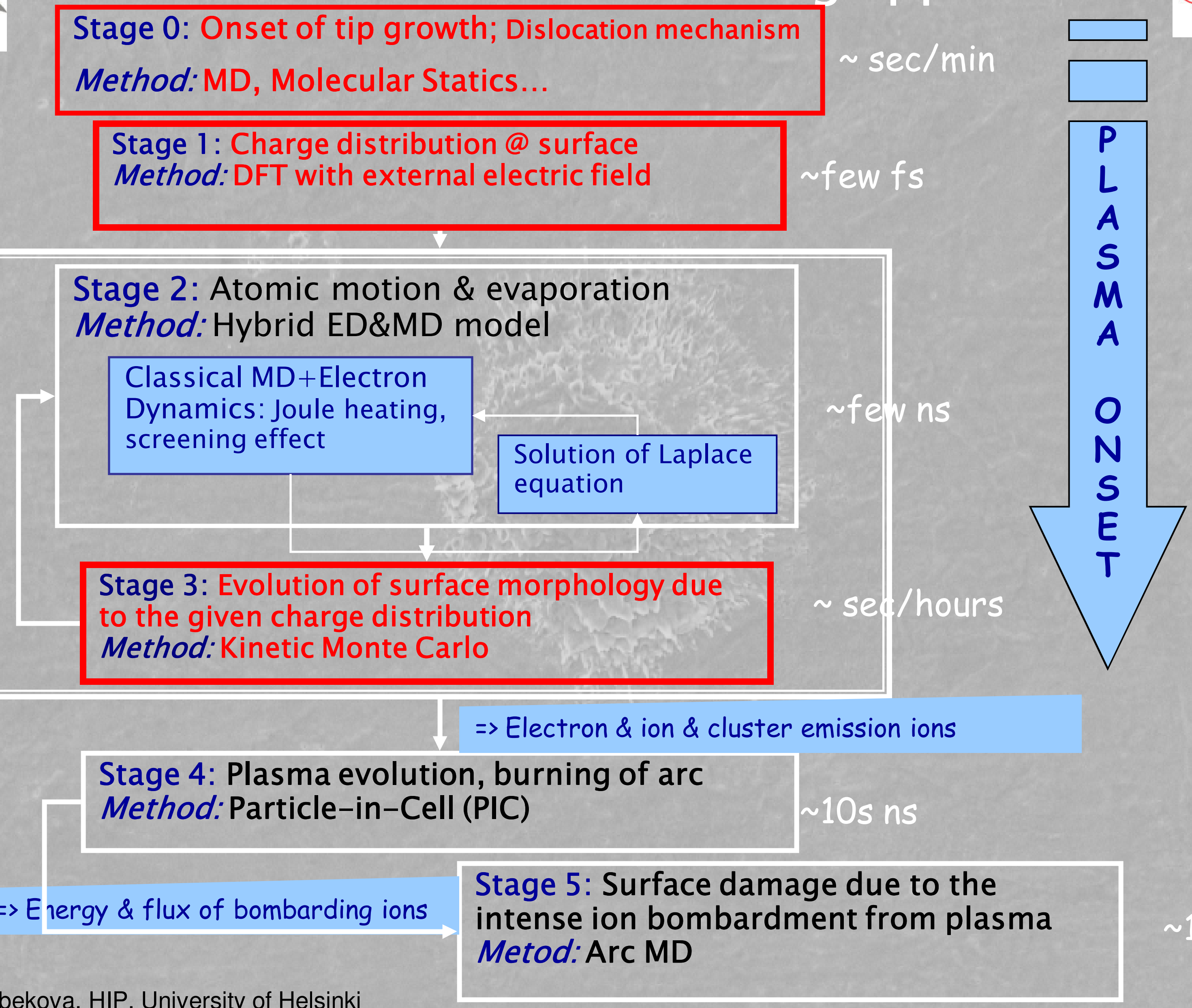
"A New Local Field Quantity Describing the High Gradient Limit of Accelerating Structures",
A.Grudiev et al., Phys.Rev.ST Accel. Beams (2009) 102001



Electrical Breakdown in multiscale modeling approach







Stage 0: Onset of tip growth; Dislocation mechanism

Method: MD, Molecular Statics…

~ sec/min

Stage 1: Charge distribution @ surface

Method: DFT with external electric field

~few fs

Stage 2: Atomic motion & evaporation

Method: Hybrid ED&MD model

Classical MD+Electron Dynamics: Joule heating, screening effect

Solution of Laplace equation

~few ns

Stage 3: Evolution of surface morphology due to the given charge distribution

Method: Kinetic Monte Carlo

~ sec/hours

=> Electron & ion & cluster emission ions

Stage 4: Plasma evolution, burning of arc

Method: Particle-in-Cell (PIC)

~10s ns

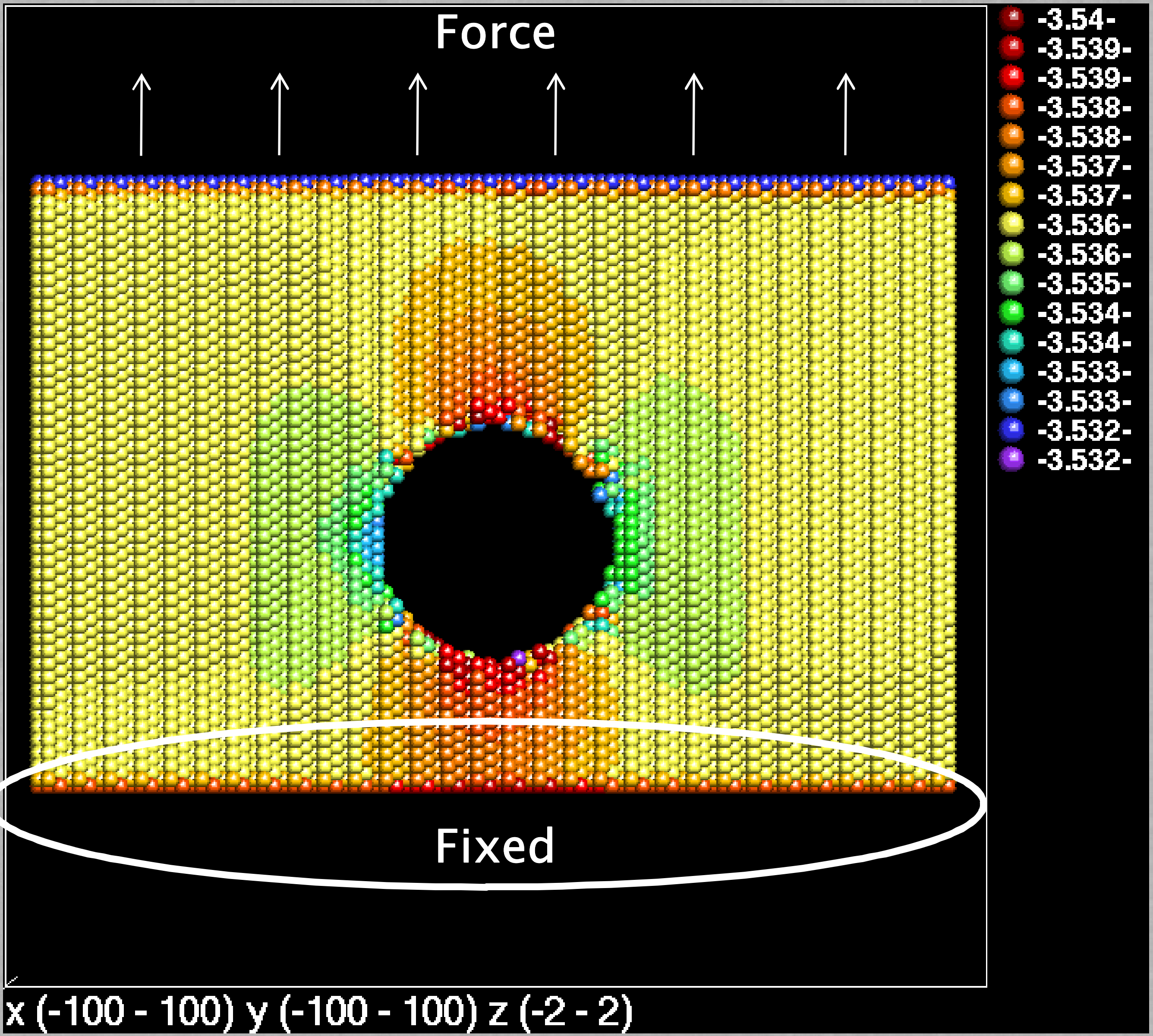
=> Energy & flux of bombarding ions

Stage 5: Surface damage due to the intense ion bombardment from plasma

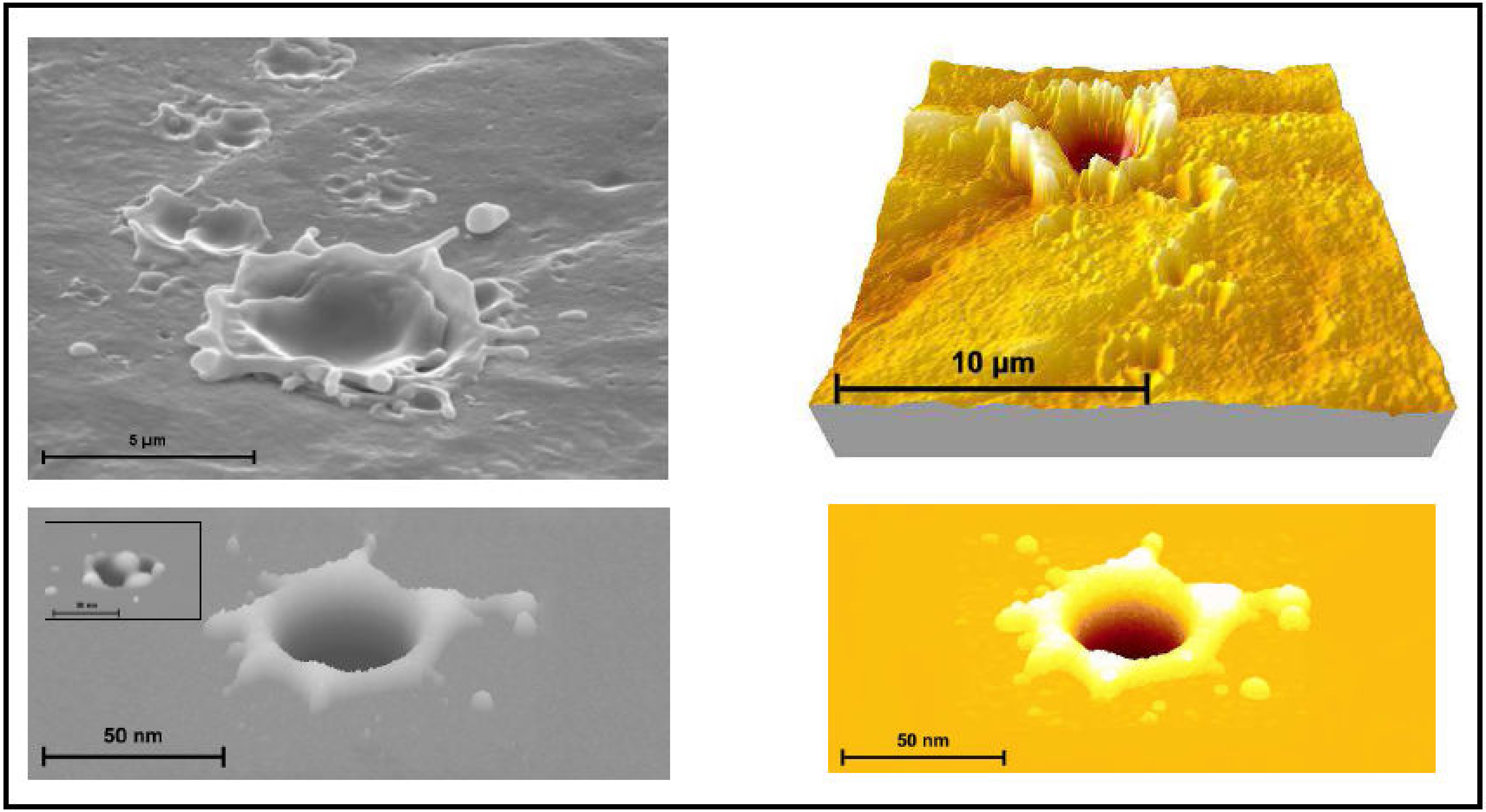
Metod: Arc MD

~100s ns

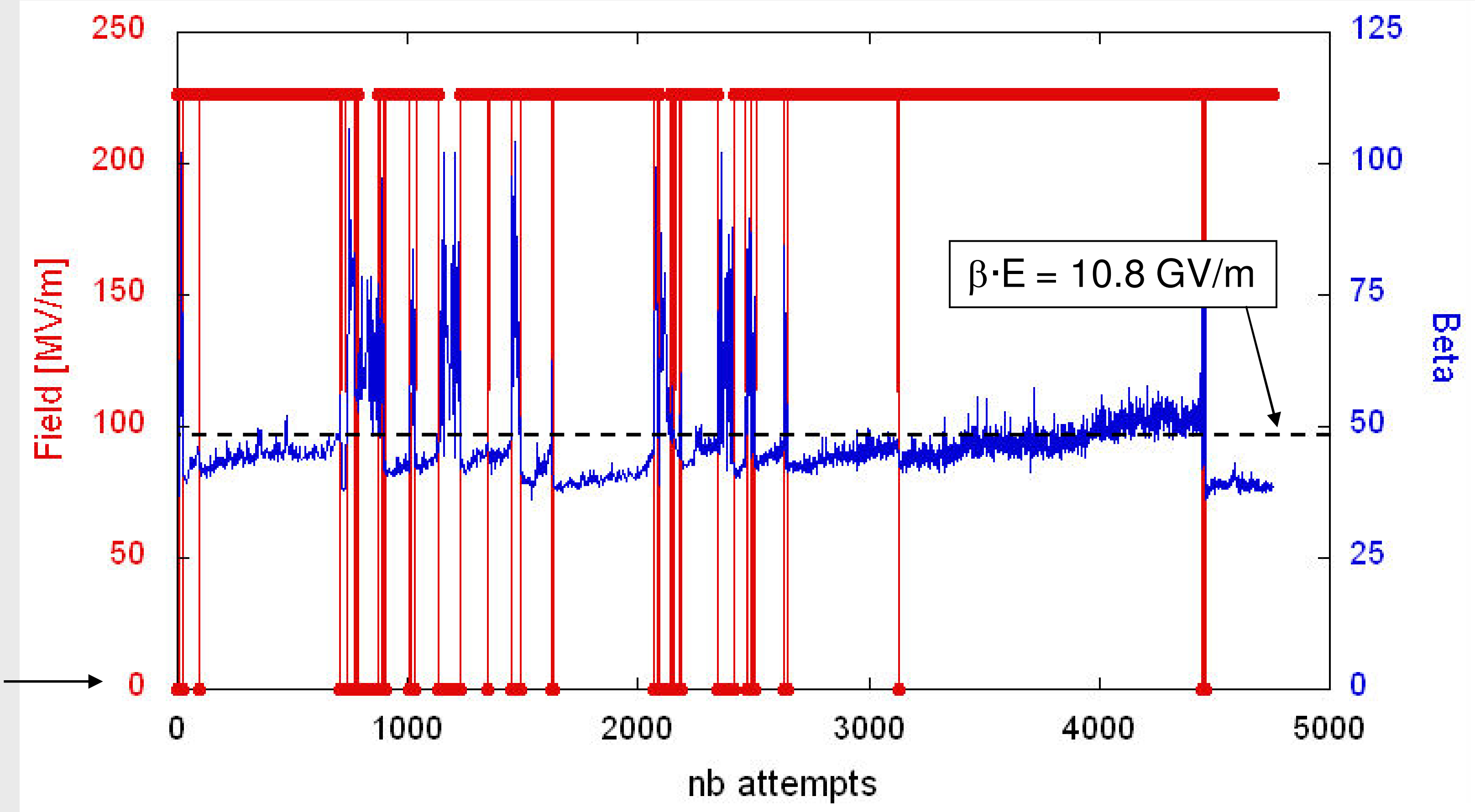
Voids as dislocation sources



Plasma-surface interaction.
Crater formation.



Evolution of β during BDR measurements (Cu)



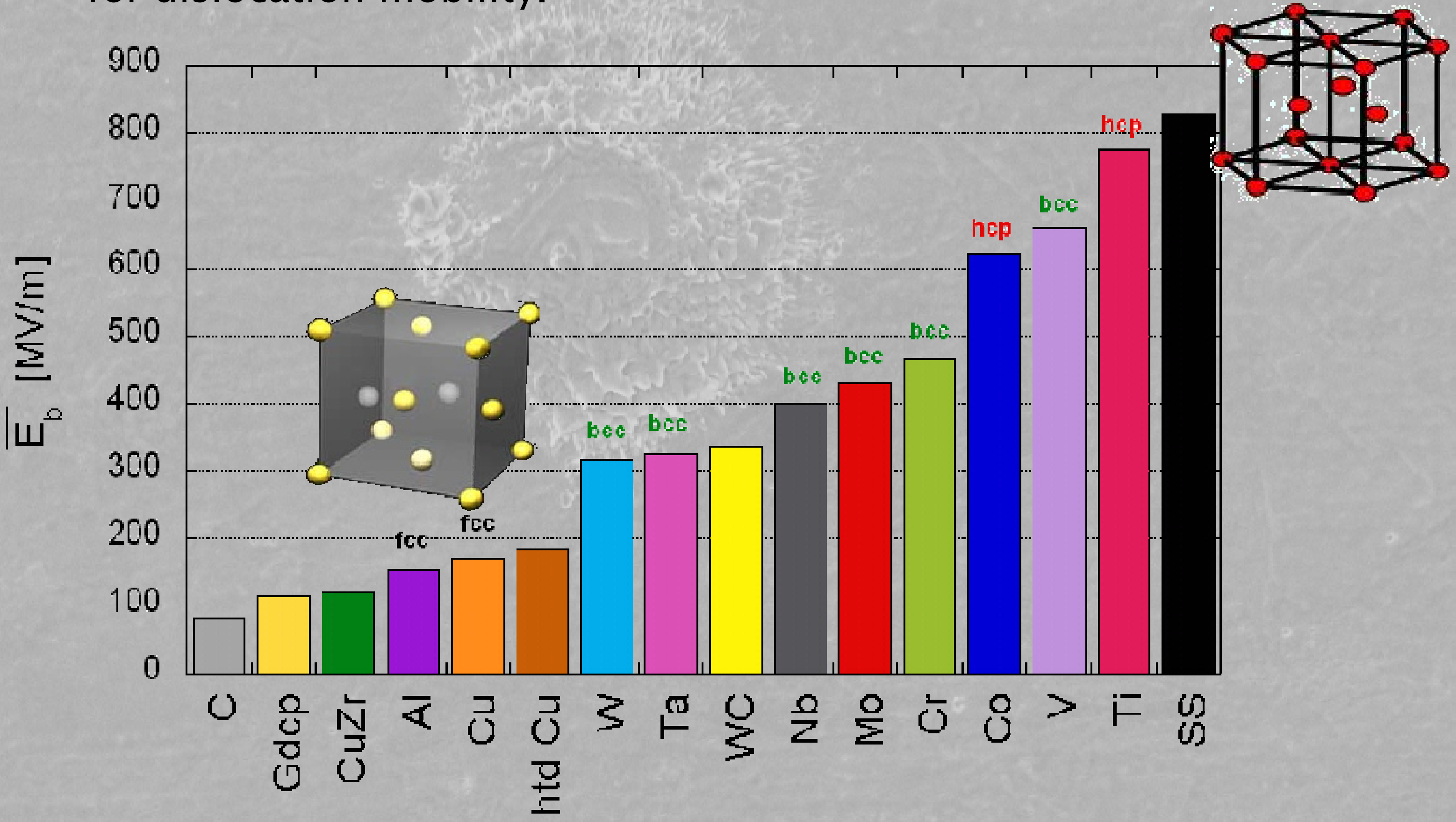
spark →

- breakdown as soon as $\beta > 48$ (↔ $\beta \cdot 225$ MV/m > 10.8 GV/m)
- consecutive breakdowns as long as $\beta > \beta_{threshold}$

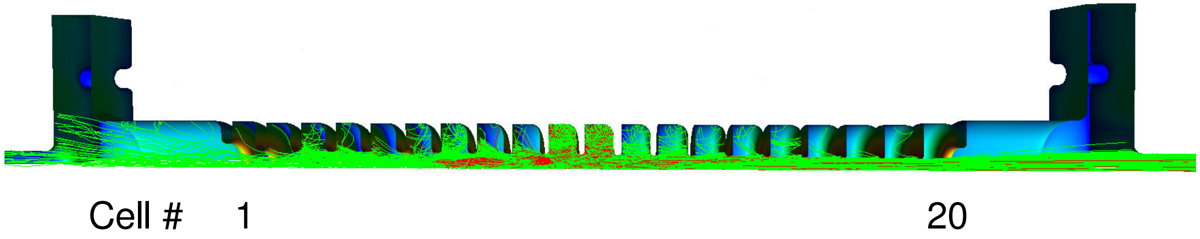
→ length and occurence of breakdown clusters ↔ evolution of β

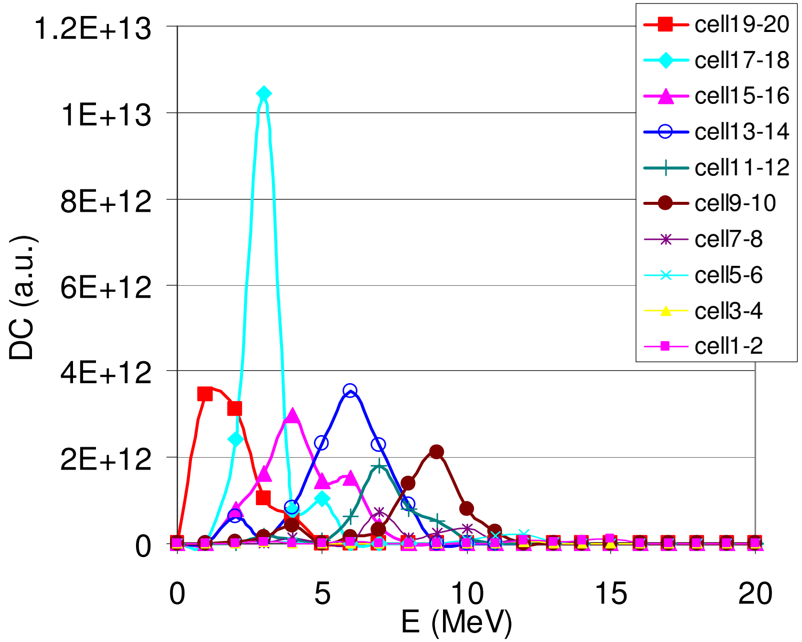
Recent experiment at CERN: CLIC-note

- The dislocation motion is strongly bound to the atomic structure of metals. In FCC (face-centered cubic) the dislocation are the most mobile and HCP (hexagonal close-packed) are the hardest for dislocation mobility.



Energy of Captured Dark Current vs Location





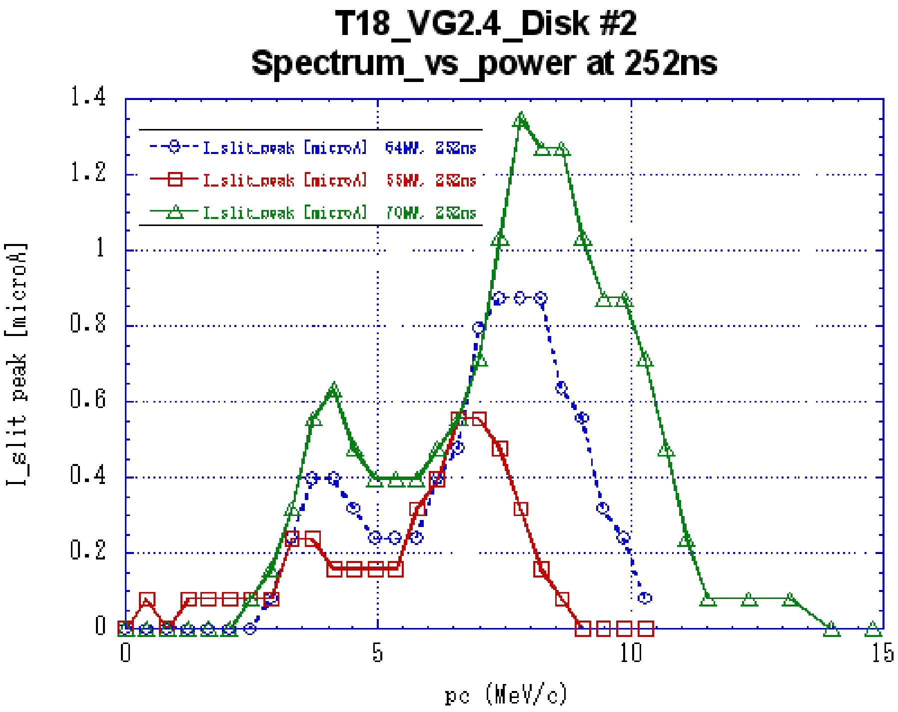
Simulation

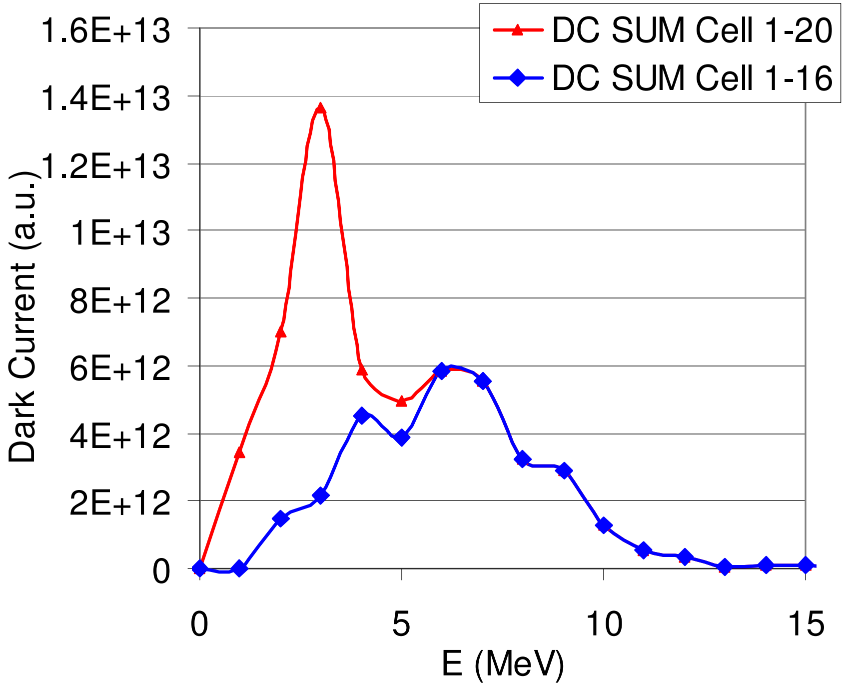
Electron energy as function of emission location.

- Eacc=97MV/m.
- Higher cell number indicates downstream location

Electrons emitted upstream are accelerated to higher energy (monitored at output end).

Dark Current Spectrum Comparison





Measured dark current energy spectrum at downstream (need to scale by 1/(pc)

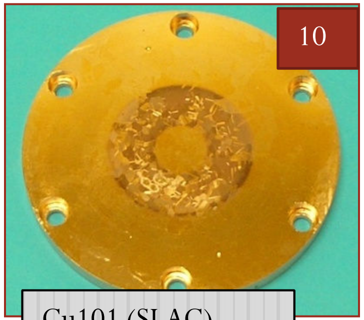
Spectrum from Track3P simulation, 97MV/m gradient.

"Certain" collimation of beampipe on dark current is considered in simulation data. More detailed analysis Needed.

Hardness Test Value

Lisa Laurent, SLAC

Pulse Heating Samples (CLIC09)


10

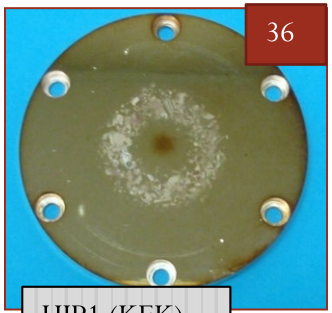
Cu101 (SLAC)


19

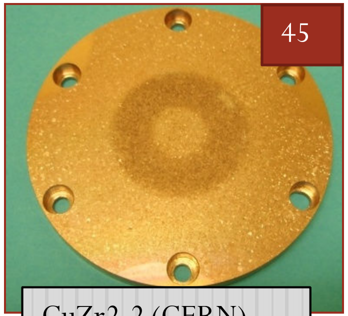
KEK3 (KEK)


33

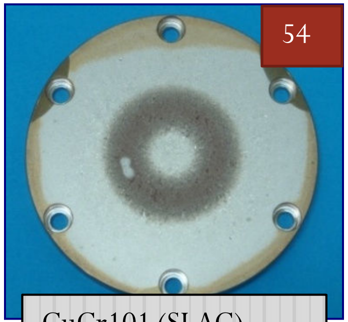
HIP2 (KEK)


36

HIP1 (KEK)


45

CuZr2-2 (CERN)


54

CuCr101 (SLAC)


??

Single Crys Cu (KEK)


62

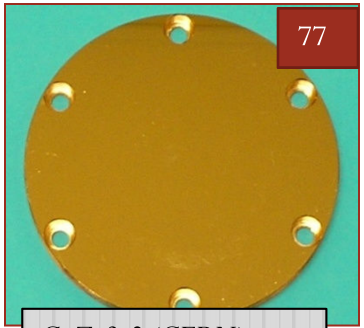
E-Dep. Cu (KEK)


64

AgPCu (KEK)


75

Glidcop4-2 (CERN)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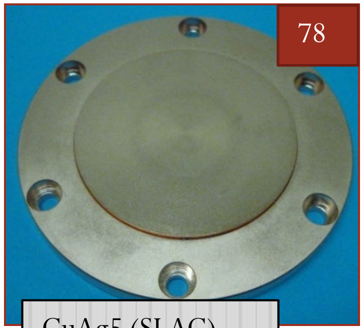
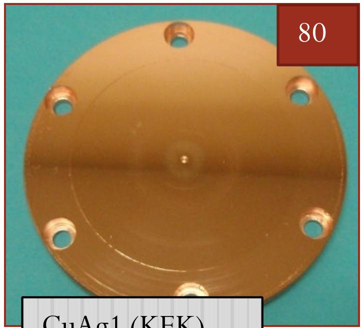
CuZr3-2 (CERN)


78

CuAg5 (SLAC)


80

CuAg1 (KEK)

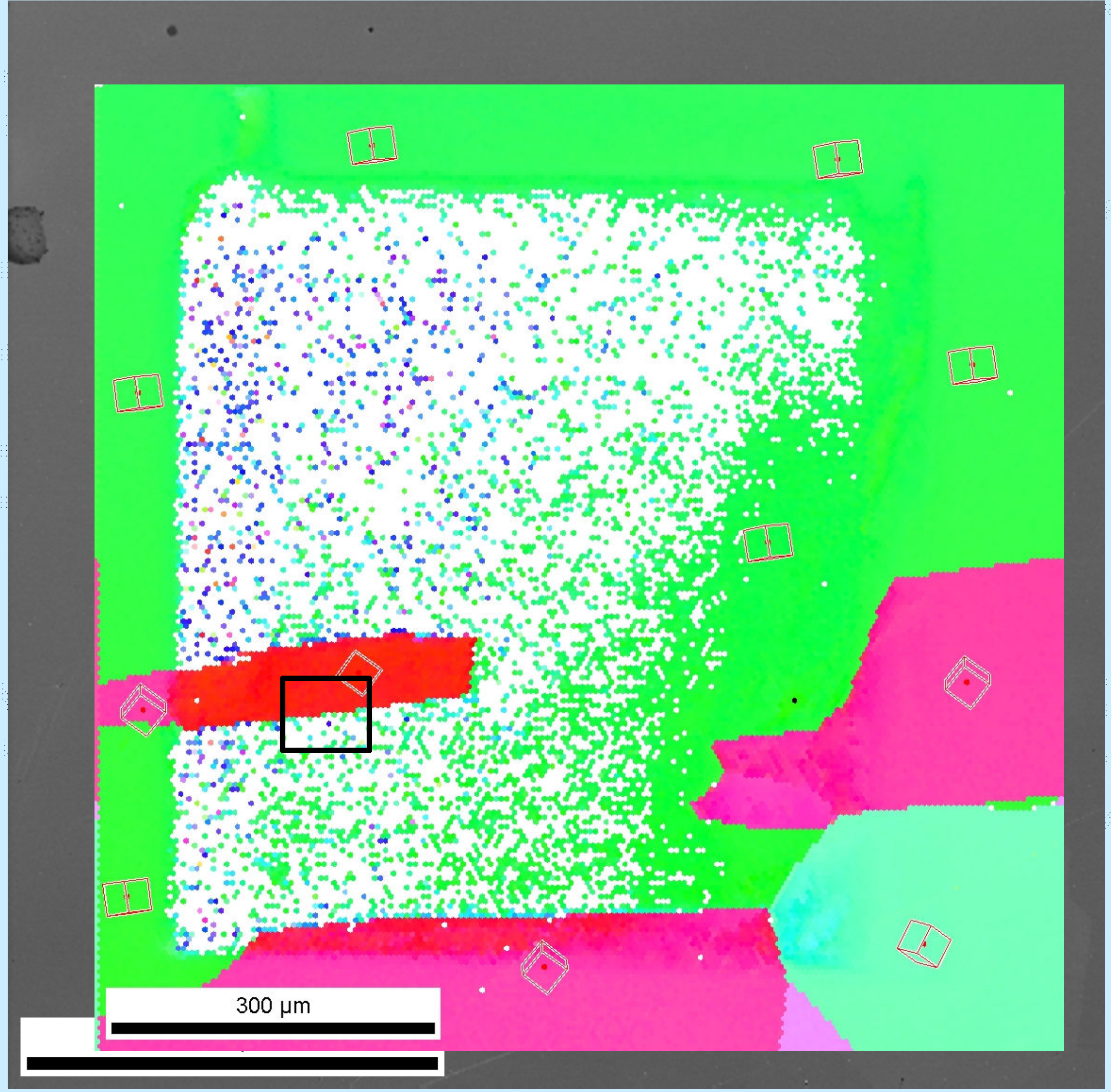

83

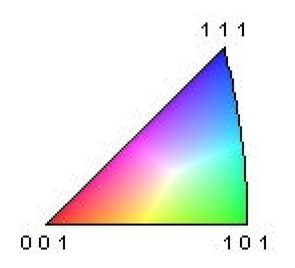
CuCr102 (SLAC)

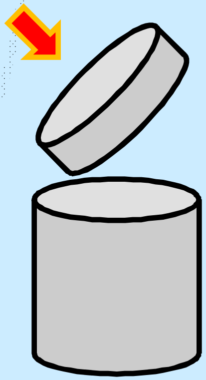

85

Glidcop4-1 (CERN)

C10100_2h@1000_EP_45°Probe3_C1







C10100_2h@1000_EP_45°Probe3_C1