# Discussion on critical issues for testing:
## breakdown identification, preparation for test, processing protocol, etc.

4th Annual X-band Structure Collaboration Meeting

May 3, 2010

T. Higo (KEK)

# The purpose and way of this timeslot

- I want the present discussion to focus on the high gradient performance evaluation of main linac accelerator structures for CLIC.
- I picked up some view graphs so that you are triggered to present comments and discussions.
- To do items 1—10 appeared here are those we think needed for KEK activities, but also common to all this community.

# To do

1. Summarize the present processing early stage
2. Get BDR from medium field level
3. Take BRD values carefully in statistical manner in mind
4. Evaluate the evolution of BDR
5. Try to correlate BDR with other observed results
6. Measure dark current to monitor processing
7. Evaluate for whole life of accelerator structure
8. Do more with post-mortem by SEM
9. Do tests with simple geometries
10. Work hard to conclude present-day feasibility description

# For completing feasibility study

- Requirement for CLIC
- Requirement for linear collider
- Requirement for other applications

- Following discussions are for LC especially CLIC
- Items needed for feasibility judgment

- Is it enough with evaluation items of on-going high gradient tests?
- Let us consider what we need and what we can.

# What are needed to evaluate for judging the feasibility

- Fabrication and preparation until feeding power
  - Required processes, associated time and cost, .....
- Performance in processing without beam
  - Processing speed
  - Ultimate reach of $E_{acc}$ field
  - Breakdown rate vs $E_{acc}$
  - Evolution of breakdown rate
  - Breakdown rate vs pulse width/shape
  - Dark current
  - Damage during processing
- Performance with beam
- Deterioration due to long-term operation

# We have started a series of tests on 11.4GHz prototype structures

| | T18_#1 | T18_#2 | T18_#3 | T18_#4 | TD18_#1 | TD18_#2 |
|---|---|---|---|---|---|---|
| Cell make | KEK | KEK | KEK | KEK | KEK | KEK |
| Bonding | SLAC | SLAC | SLAC | SLAC | SLAC | SLAC |
| Test | SLAC, done | KEK, done | SLAC, done | KEK, future | SLAC, in test | KEK, in test |

We have also tested two quadrant type structures.

Let us take these examples in mind and optimize our tests in near future including 12GHz structures.

# Basic studies with simple setup are ongoing

| Single-cell | C10/CD10 | Waveguide | DC spark | Pulse heating |
|---|---|---|---|---|
| SLAC | SLAC | SLAC / KEK | CERN | SLAC |
| SW | TW | TW | DC | SW |
| On-going | On-going | Sleeping | On-going | On-going |

These also are already on-going and let us extend these to complement the tests with prototype structures and help understand physics behind the results.

# Background
# Accelerator design in mind

- How high can / should the gradient be?
  - CLIC sets 100MV/m for 3TeV
  - We should ask ourselves whether it can be realized and when?
  - For a certain timing of the project, we should declare the practical value.
  - Should it be 100? Can it be lower or higher?
- Tolerable breakdown rate?
  - During processing?
  - Through the accelerator life?
- What HOM performance is required?
  - Big interrelation between pulse heating and damping geometry

# Key technical issues should be understood

## in fabrication and preparation until feeding power

- Do we need diamond turning?
- Do we need high temperature vacuum treatment of material?
- Do we need hydrogen high temperature process?
- Do we need vacuum baking at 650C for a week?

- All these should be confirmed with dedicated tests to understood in their mechanisms to confirm.
- This can be accomplished by the systematic basic tests in addition to a series of prototype structure tests.

# What can/should we learn from processing without beam?

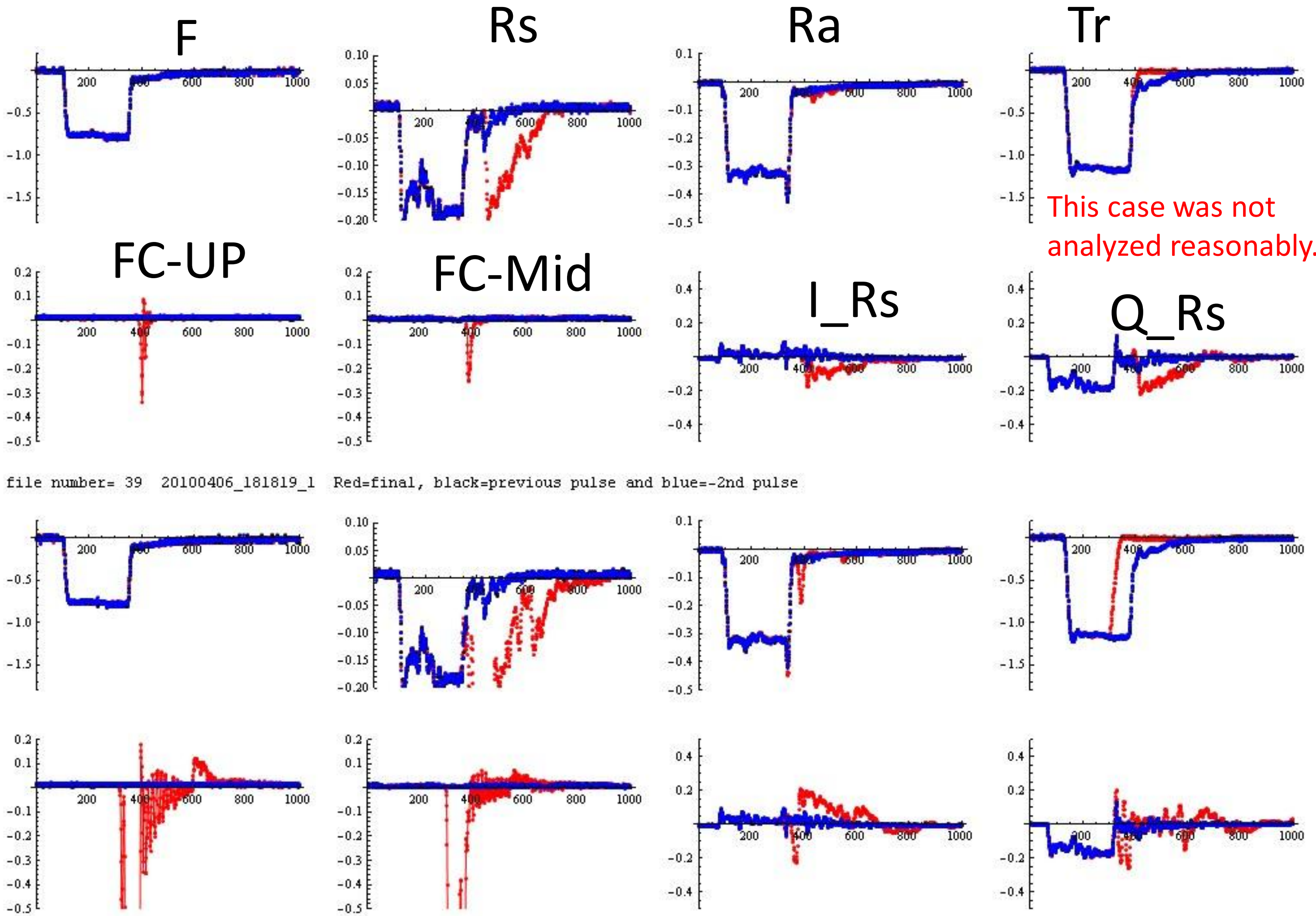
- Higher field toward downstream
  - Especially in T18/TD18
- What is RF processing? Why do we need it?
  - Improvement or deterioration?
  - Inevitable process?
  - Can it be replaced by careful preparation?
- Breakdowns are inevitable? Tolerable amount?
  - Tolerable number of breakdowns
  - Tolerable breakdown size
- What determines the processing speed?
  - Ramping speed for recovery from fault
    - Waiting time
    - Recovery path (width, power, others ....)

# Difference in processing speed exists

- Processing speed
  - One of the important characteristics
  - Compare it w.r.t. time or #BD?
  - We should compare among experiments
- Breakdown identification is related
  - Related to how to identify breakdowns
    - Missing energy (SLAC), current flush (KEK)
    - RF reflection, RF transmission
    - Need to critically compare, but not yet done fully
- Processing protocol is also related
  - Speed and path of recovery from BD

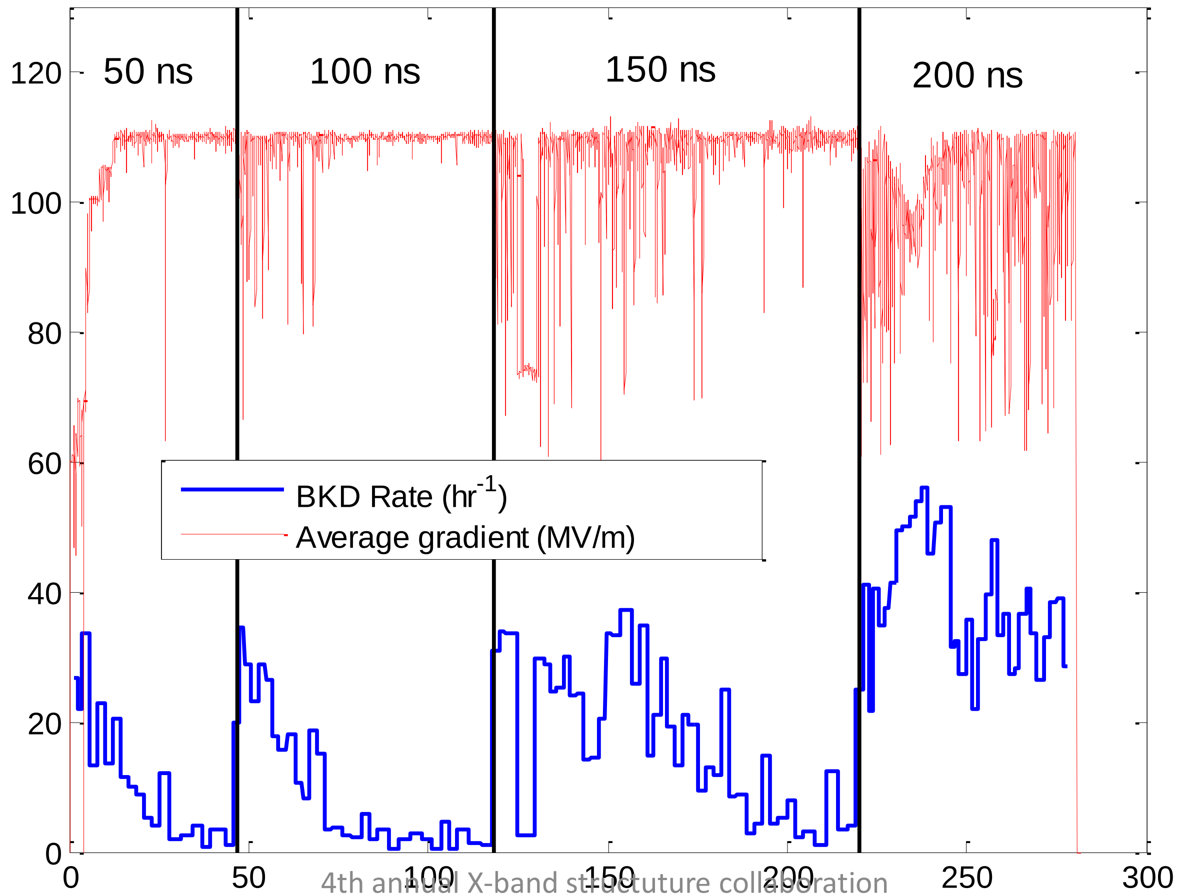
# TD18_#2 test at KEK

## Some pulse:  Run34  #38 and #39



# Second T18 Structure Tested at SLAC

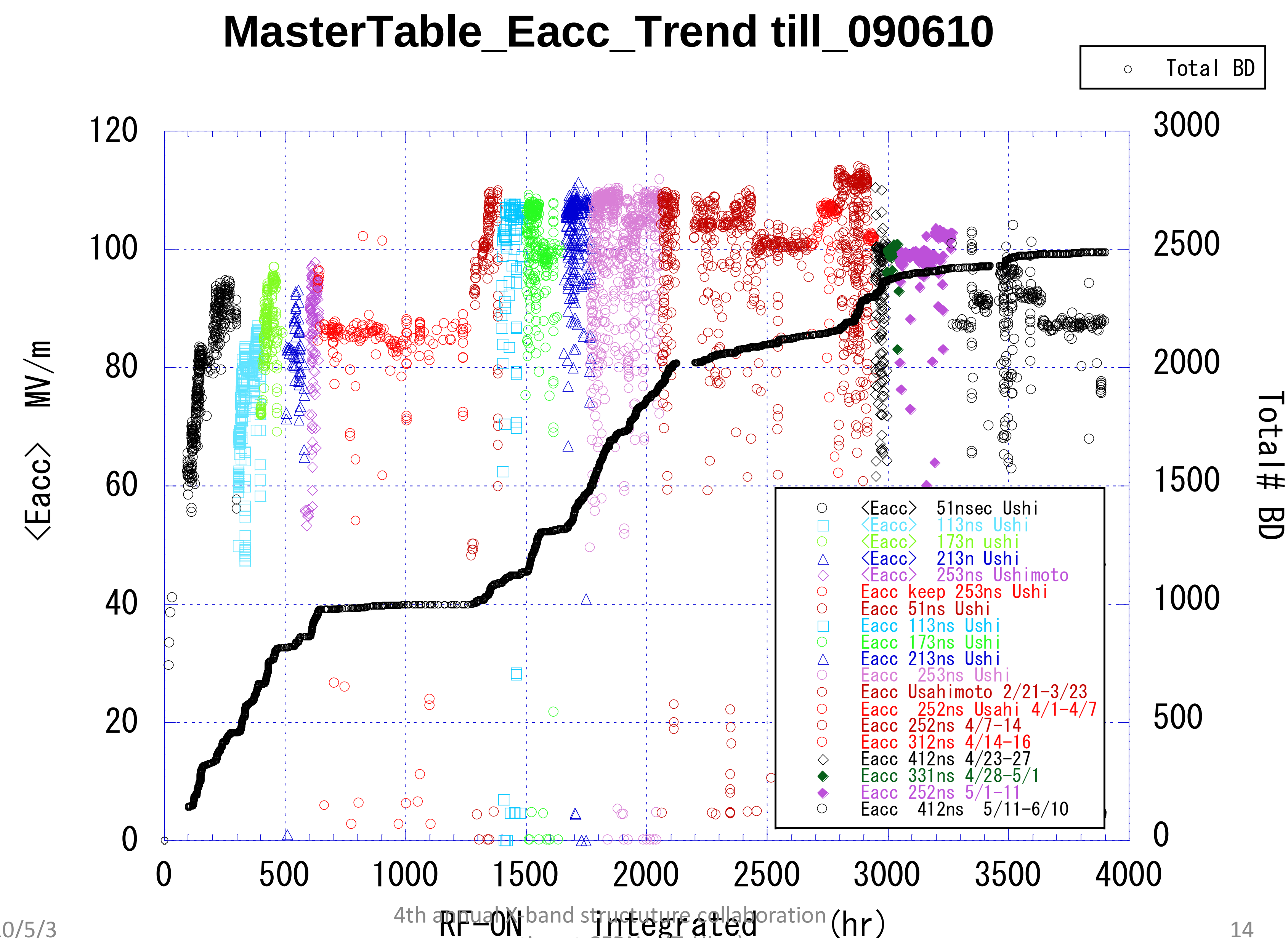
This time, processed structure by progressively lengthening the pulse at constant gradient (110 MV/m)



# Whole history of processing of T18_VG2.4_Disk #2

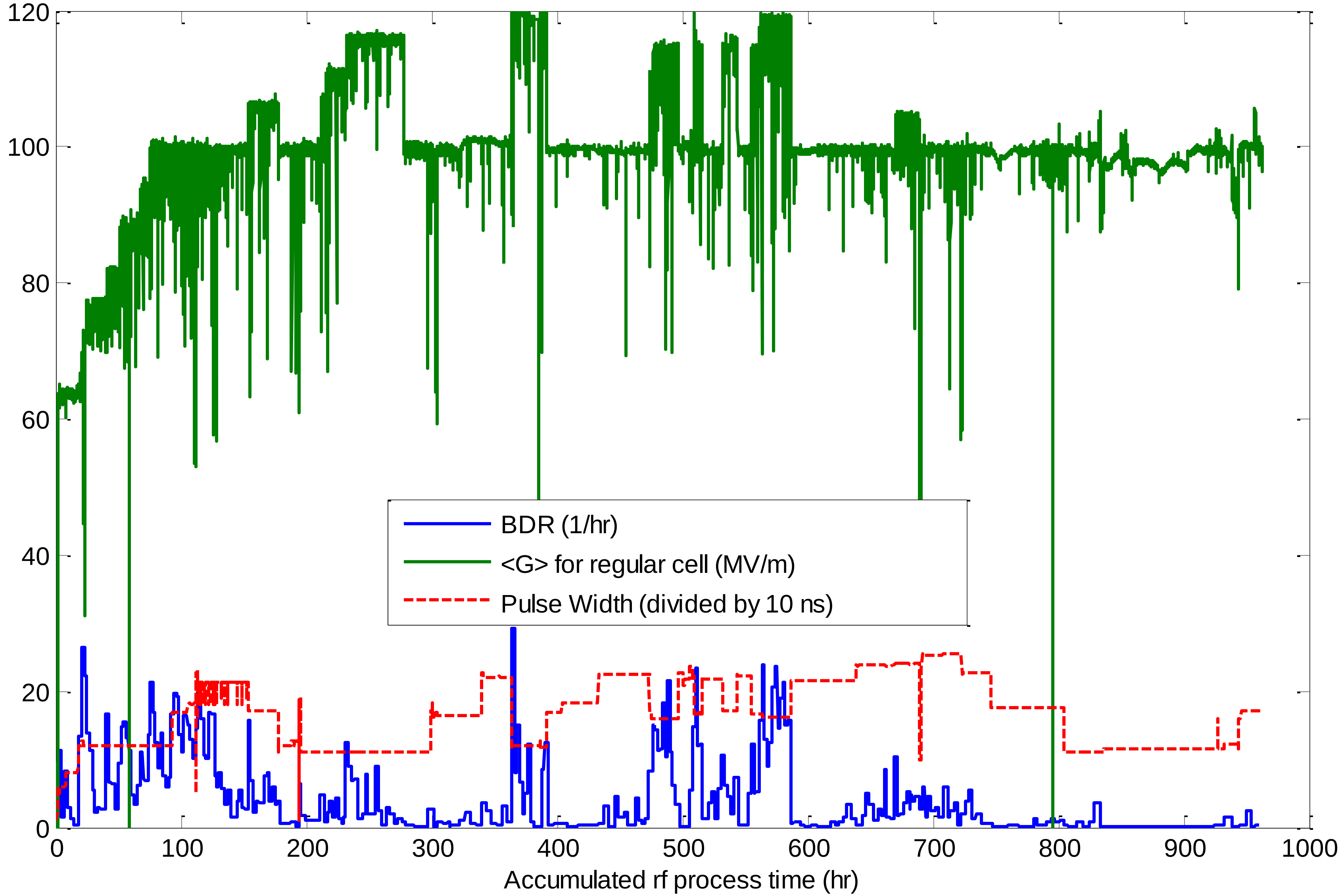
T18_#2, T. Higo

090610

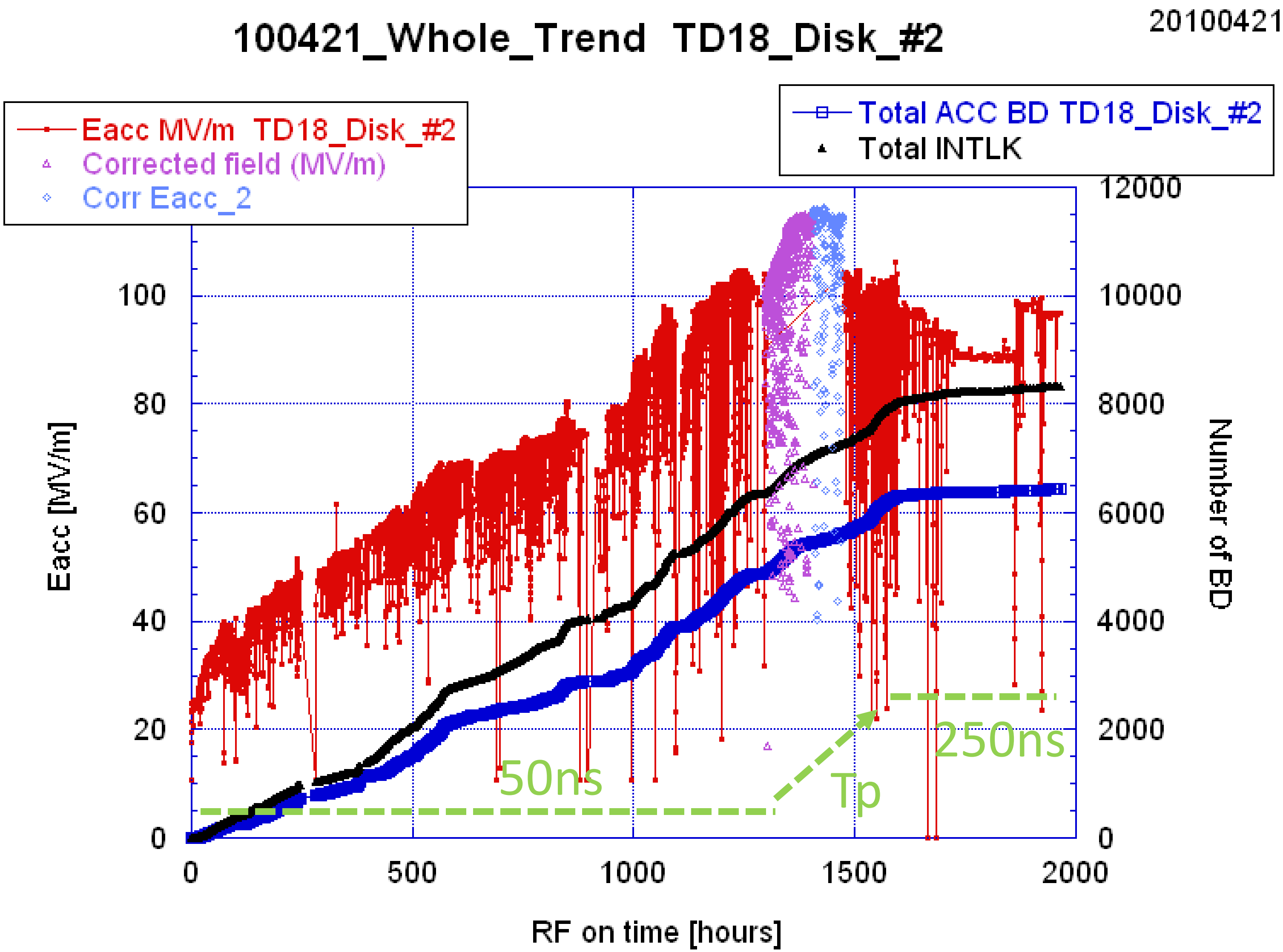


TD18_#3 Faya Wang, 10 March 2010

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



TD18_#2, S. Matsumoto, in this meeting



# To do -1

- These are some of recent examples.
- Let us summarize such processing characteristics
- And try to identify the driving source of difference
  - The way of processing or the structure itself?

# We have done a series of tests on prototype structures

| | T18_#1 | T18_#2 | T18_#3 | T18_#4 | TD18_#1 | TD18_#2 | TD18_#3 | Quad_#? | Quad_#5 |
|---|---|---|---|---|---|---|---|---|---|
| Type | Disk | Disk | Disk | Disk | Disk | Disk | Disk | Quad | Quad |
| Make | KEK/SLAC | KEK/SLAC | KEK/SLAC | KEK/SLAC | CERN | KEK/SLAC | KEK/SLAC | CERN | KEK |
| Material | OFC | OFC | OFC | OFC | OFC | OFC | OFC | OFC | CuZr |
| Test | SLAC | KEK | SLAC | KEK | SLAC | KEK | SLAC | SLAC | KEK |
| Status | Done | | Doen | to be tested | Done | under test | Done | Done | Done |
| #BD till goal | | 2000 | 280 * | | | 1500 | 80 | | |
| Hrs till goal | | 4000 | 3300 # | | | 6000 | 800? | | |
| Trip source | ME | FC | ME | | ME | FC | ME | ME | FC |
| | | | | | | | | | |
| | | | | | | | | | |
| Total number of BD | | 4000 | | | | >2000 $ | | | |
| | | | | | | | | | |
| | | | | | | | | | |
| | | | | | | | | | |
| | | | | | | | | | |
| | | | | | | | | | |

*Till reaching 200ns
#Before next width, stay before BDR<1/hr
$On-going
ME Missing energy
FC Faraday cup current burst
Goal 100MV/m with >230ns

Should compare these processing-related values in a systematical manner.

# Let us think
# What drives the processing?

- Number of breakdowns?
  - Surface processing through breakdowns
- RF processing time?
  - Field emission makes surface modification?
- Higher gradient or longer pulse operation?
  - Through higher dark current?
- Introduction of other perturbation?
  - Hot spot?

# Is the present processing protocol the best?

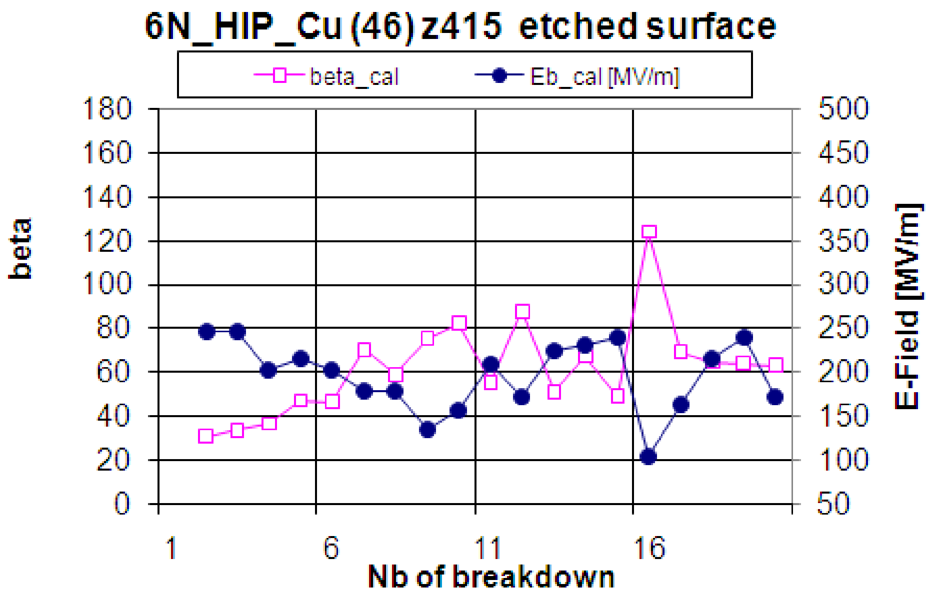
- Any difference in its final performance
  - depending on the different protocol?
- Difference in such as
  - Peak power ramping speed during recovery
  - Width reduction and re-widening (SLAC)?
- Can we propose a processing in actual LC?
  - Any difference from what we do now?

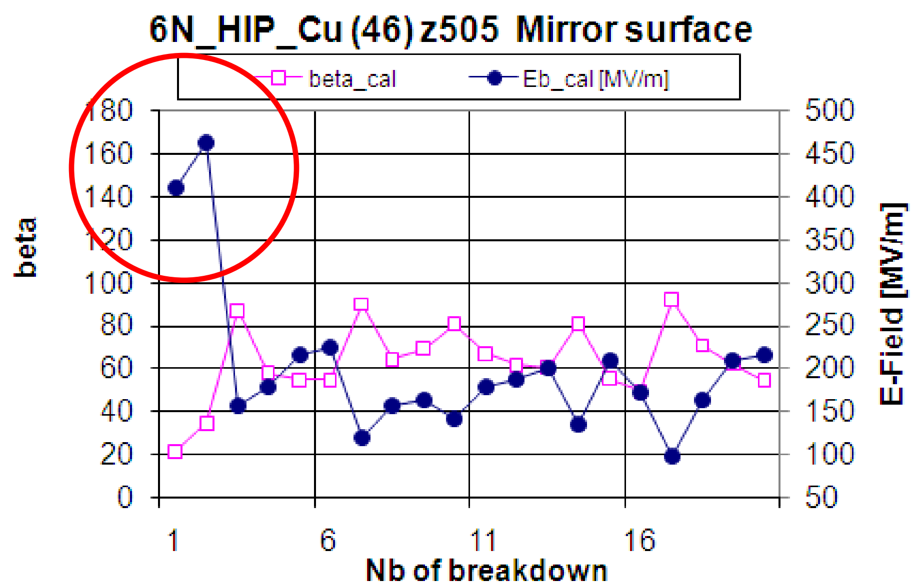
# How to define the ultimate field reach and operation level

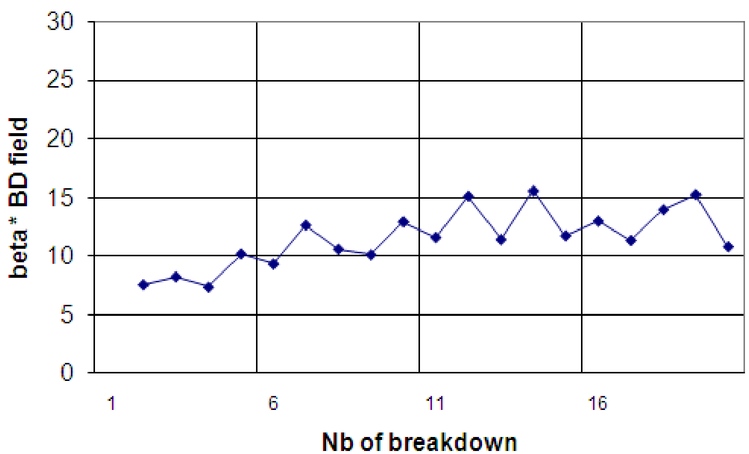
- A significant deterioration may starts above some level in pulse energy or in peak power
  - Very stable operation may be possible before suffering from many breakdowns
  - For example, see an experiment in DC spark test in next page
- Where should we stop further processing?
  - In case we can live within the level.
- Should we evaluate the performance step by step from lower field level?
  - See a simple schematic in peak power ramping and BDR evaluation

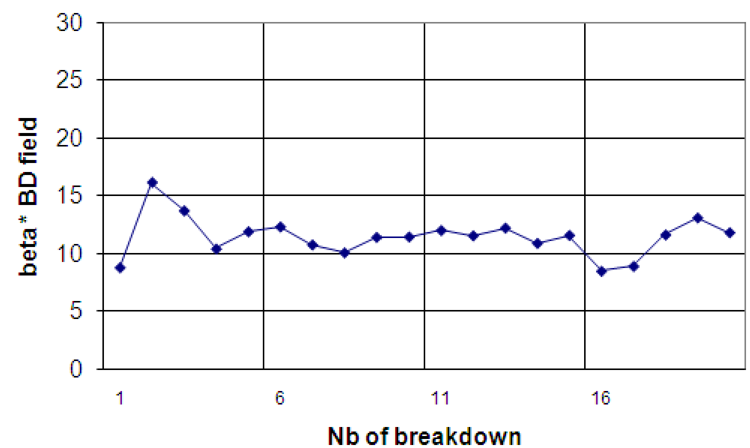
# Etched vs. Mirror surface

K. Yokoyama, private communication



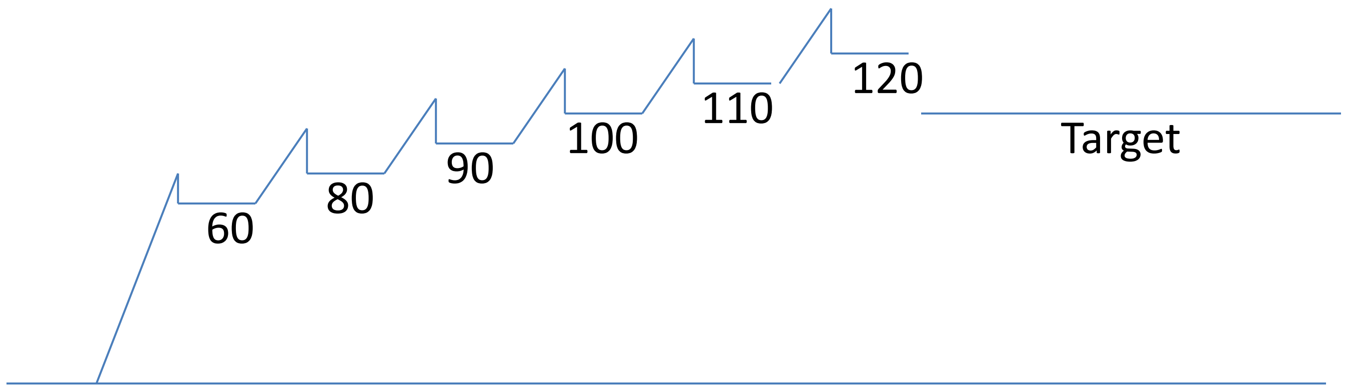




- It seems to take longer time until saturation.
- The first BD field is low.

- β and BD field seems to be stable at the beginning.
- The first BD field is very high (~ 450 MV/m)

# Should confirm lower level operation




Evaluate lower level operation

without (before) severe damage

in peak power or in pulse energy ??

to confirm the robust and well-established level

Then go higher to evaluate at the nominal value

with trying to detect when the deterioration starts

# To do -2

- Taking these consideration,

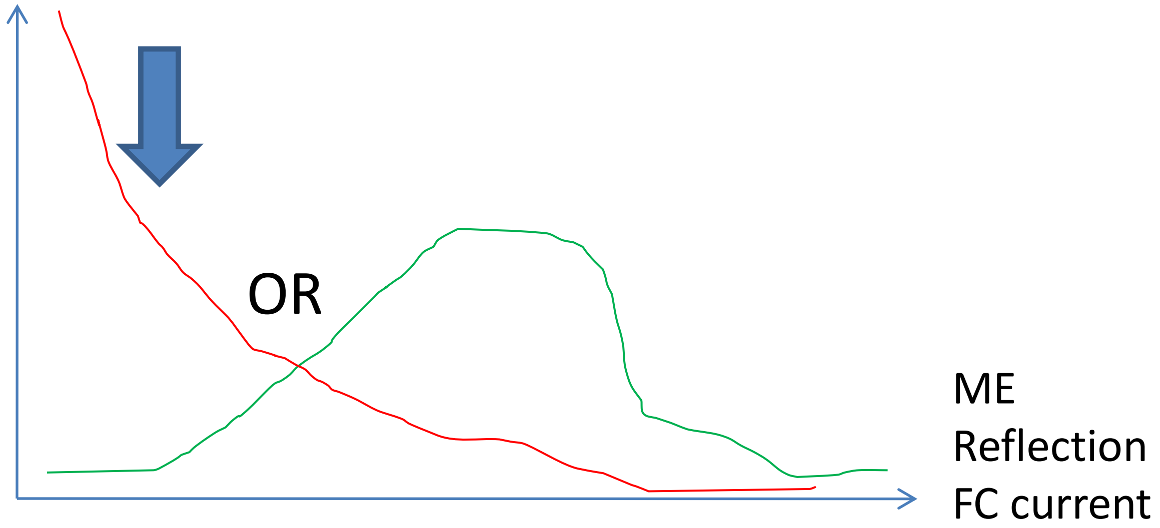
- Let us evaluate the BDR evaluation before reaching to the goal of 100MV/m
- Try to find the point over which deterioration starts (and possible the reason/mechanism)

# Breakdown rate evaluation

- BD identification is needed
- It changes in time
- BD behaves in a statistical manner
- …..

# BD identification and threshold setting

In missing energy (SLAC) or current flush (KEK), or ??



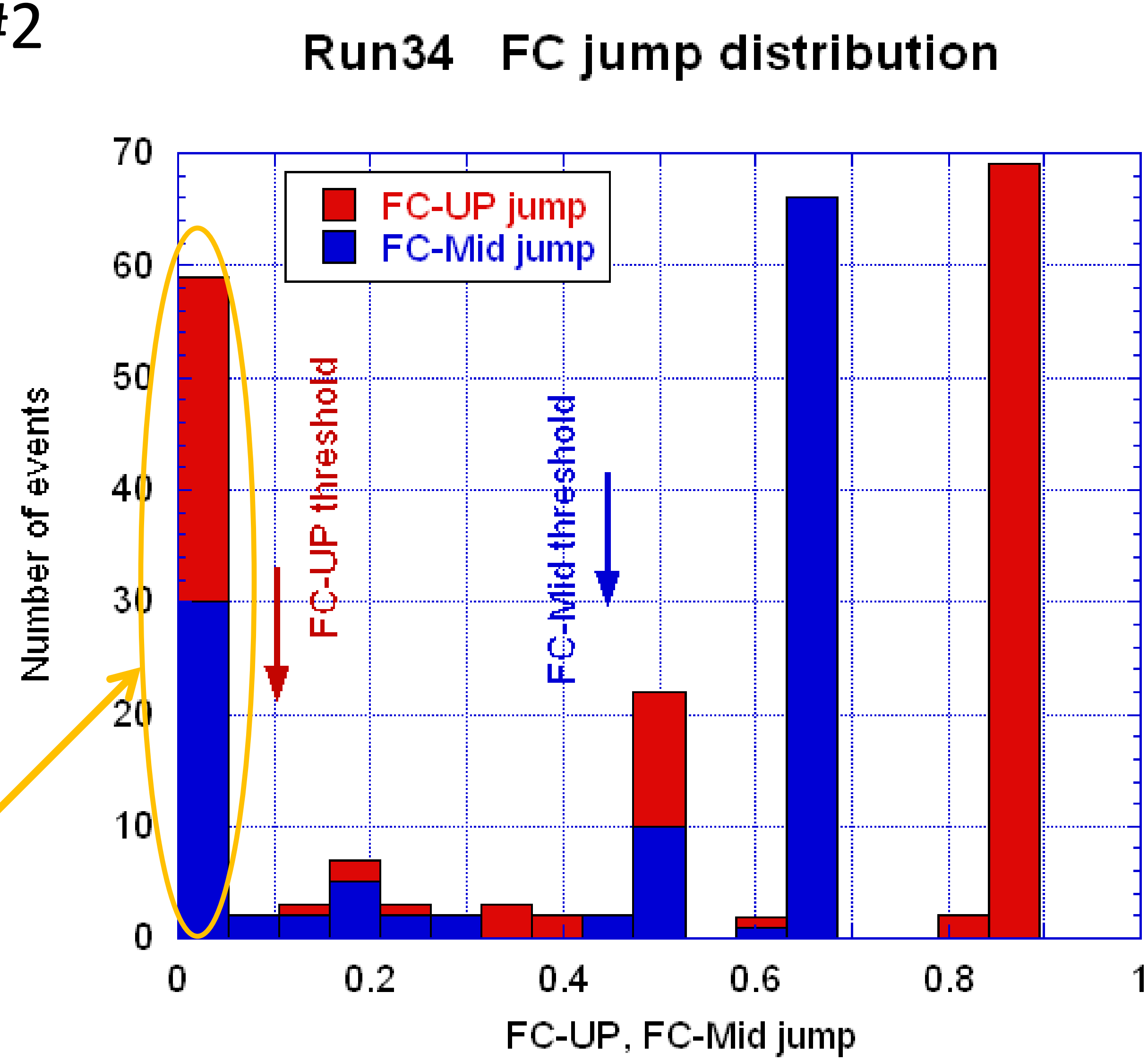

We should confirm the distribution and the threshold position.

Do we have clear experimental evidence?

Do we have information below threshold?

Do we have any deterioration below threshold?

# TD18_Disk_#2




Almost all confirmed to be spurious

# To do -3

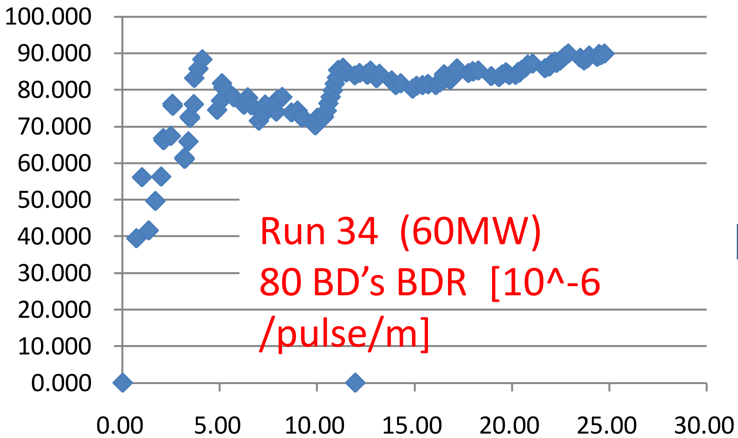
- Let us evaluate the present situation of how we identify breakdowns in a quantitative manner

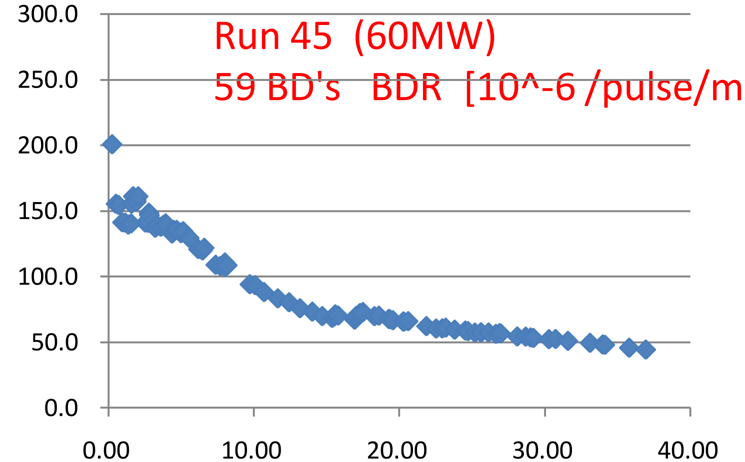
# Deduction of breakdown rate

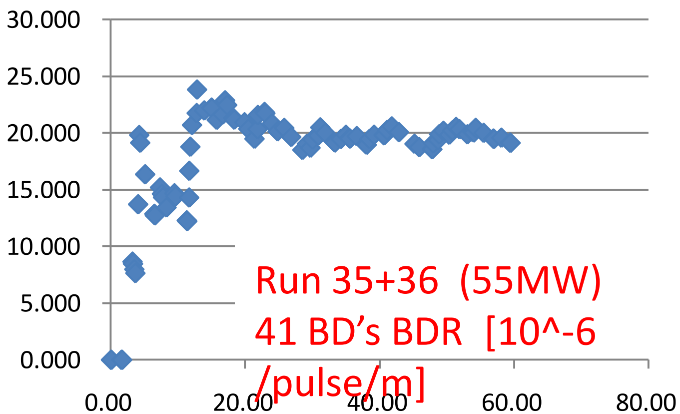
- = #BD/period?
- We should be careful when to read the BDR values.
  - Breakdowns appear in an irregular manner in time.
  - Some breakdown triggers following breakdowns in very short time intervals.
  - Are the BDR values well saturated in a statistical view point?
  - In a smaller value case, the error is large due to limited time to count many BD's.
- Evaluation period long enough?
  - Even not, we should extract data. Just be careful to read and use these data points.

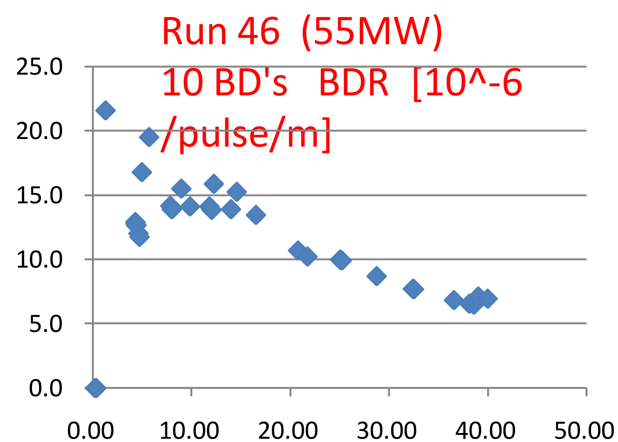
# Breakdown rate measurements at 252ns

1st meas. 2nd meas.

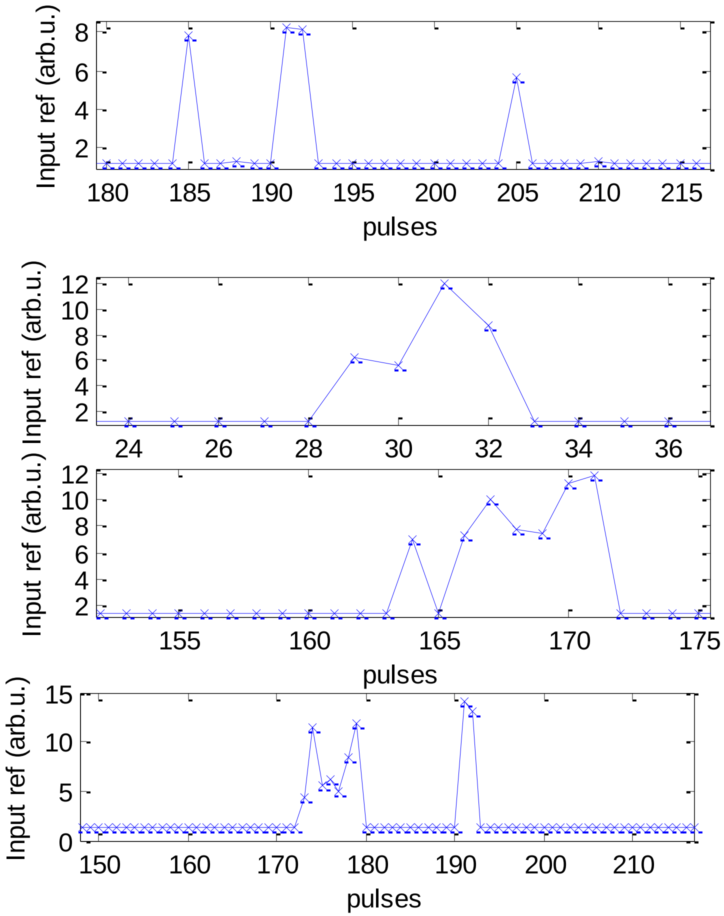


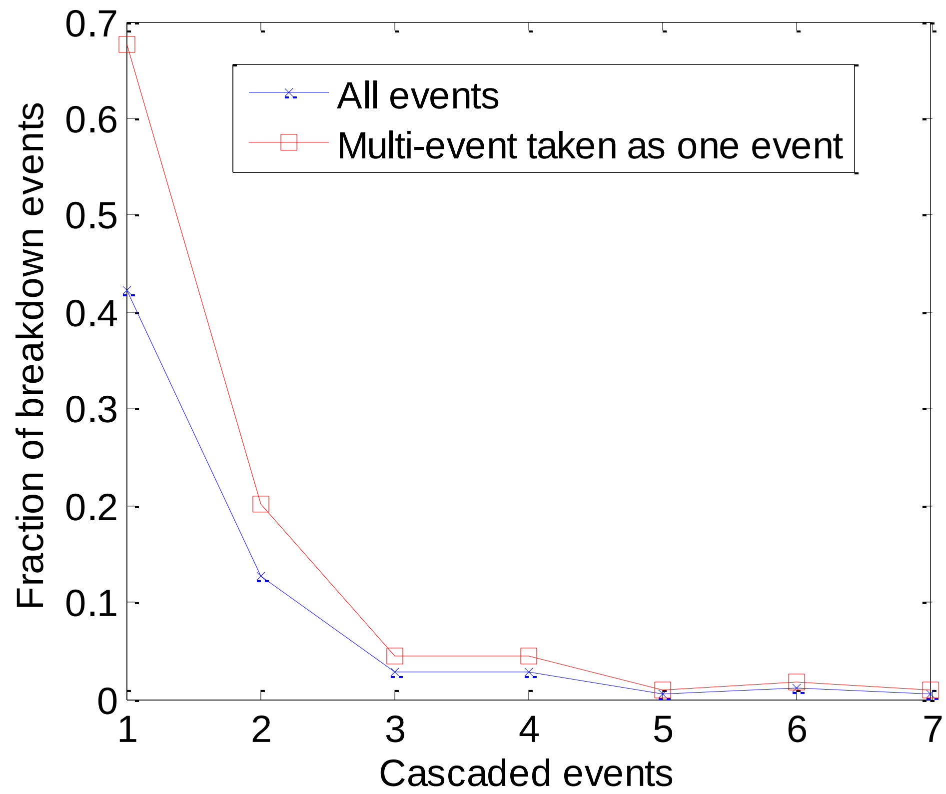



# Cascaded BDR Test at 100 MV/m @ 200ns



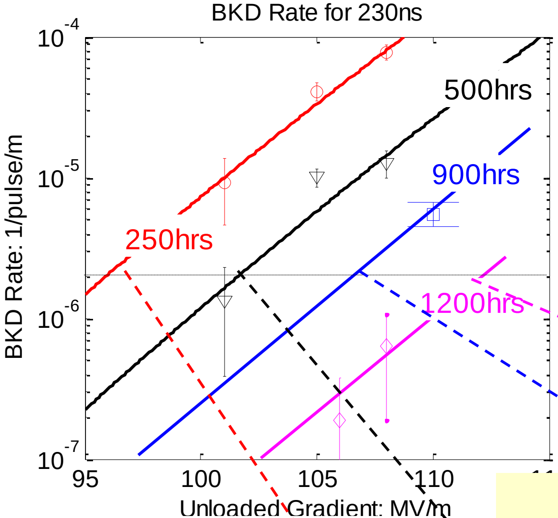

33 hrs for the total test.

| Type | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| Events | 77 | 23 | 5 | 5 | 1 | 2 | 1 |

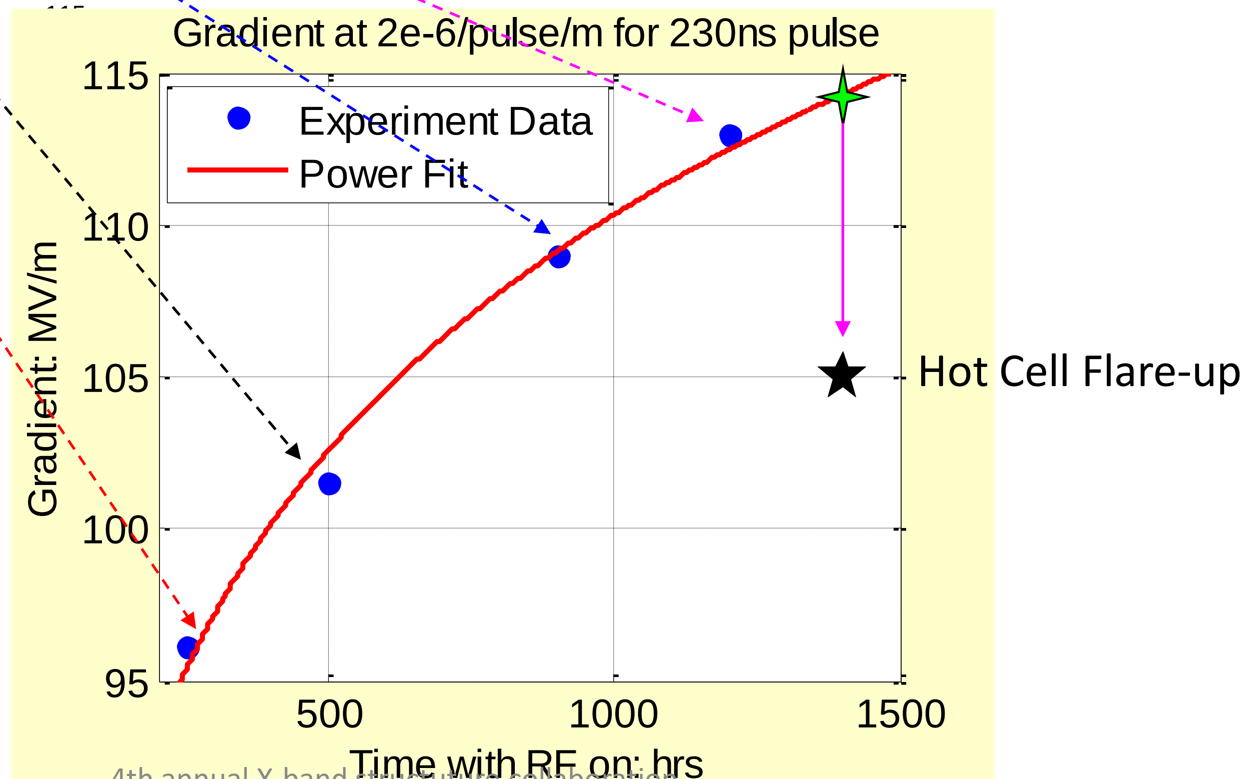
# Actual evolution of breakdown frequency

- Should evaluate the evolution in time
  - Keep decreasing?
  - Gets saturated? When? Why?
  - Any unexpected increase happens?
- Total number of breakdowns in life
  - should be expected from above information
- Speedup the evaluation
  - Evaluation at higher level may suffer from onset of severe deterioration?
  - But we do not have any practical way to get precise data. What to do?

# First T18 Structure Tested at SLAC

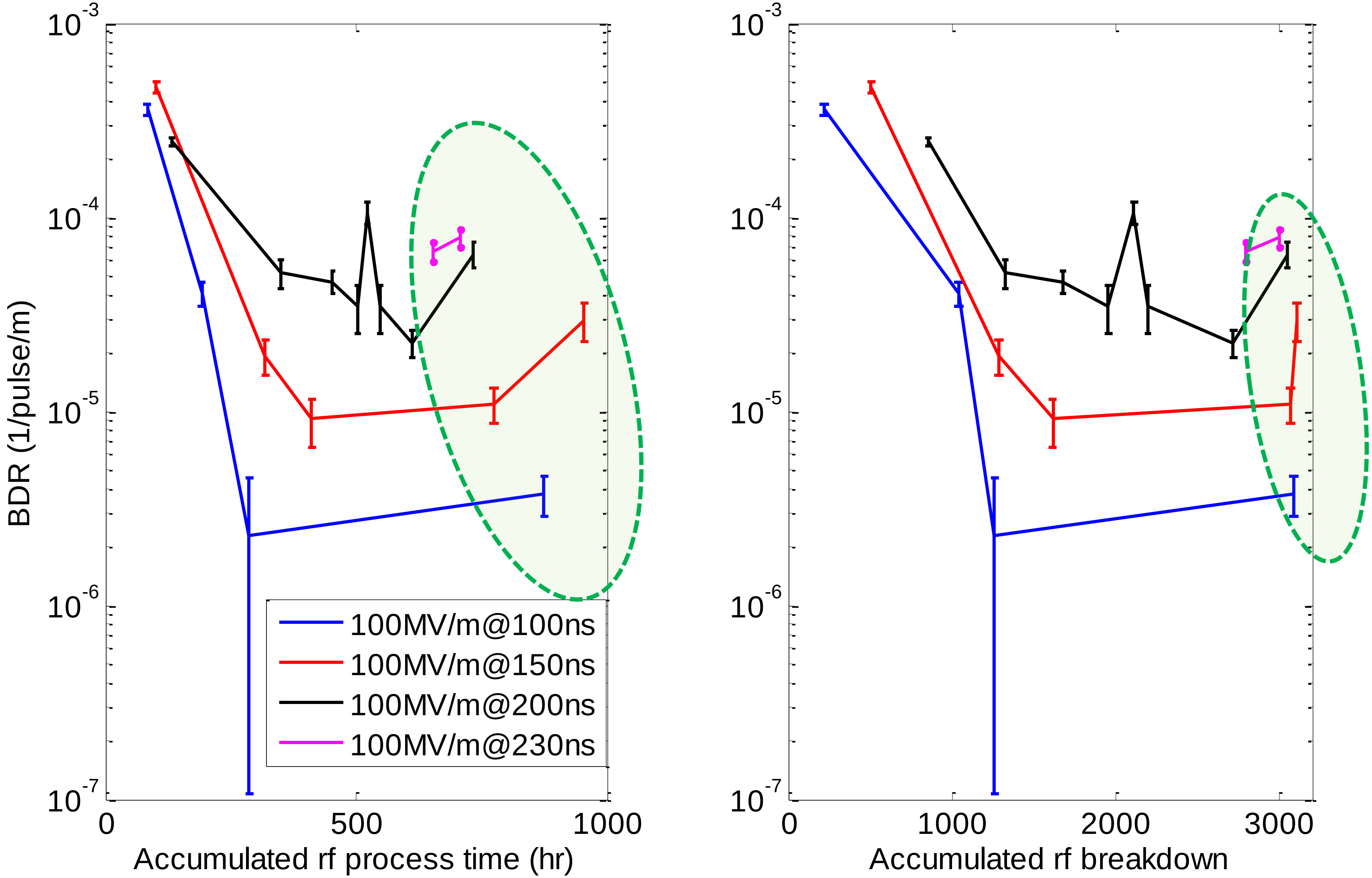



Gradient Increase Over Time at a Constant Breakdown Rate

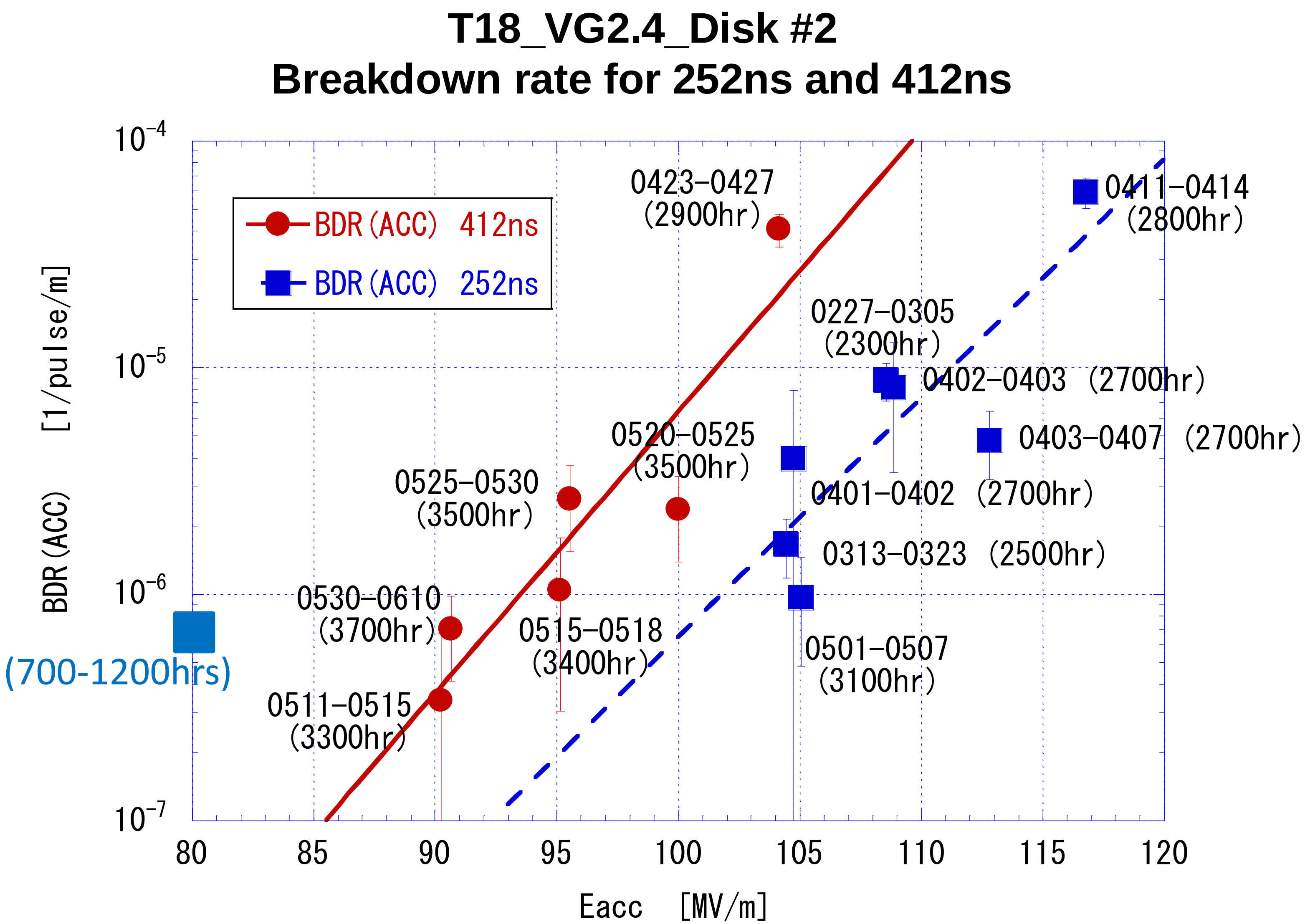


TD18_#3 Faya Wang, 10 March 2010

# BDR evolution with rf process



# Breakdown rate



# To do -4

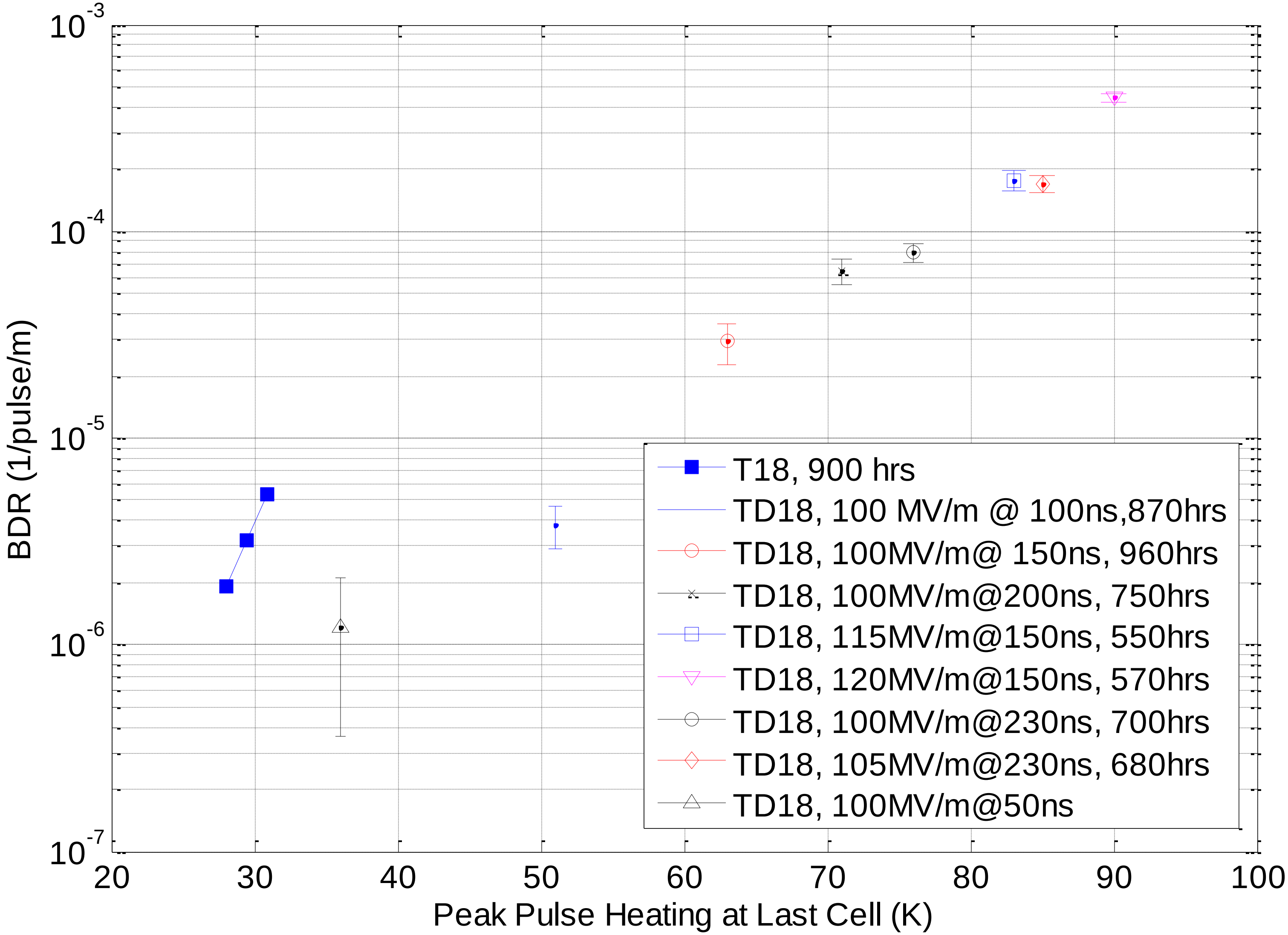
- Let us evaluate the evolution of breakdown rate
- Try to see whether it keeps decreasing or gets saturated or it deteriorate from some point?
- It needs long period operation, rather than tasting too many structures quickly. (I admit though that the latter is effective in some purpose.)

# Breakdown rate vs pulse width/shape

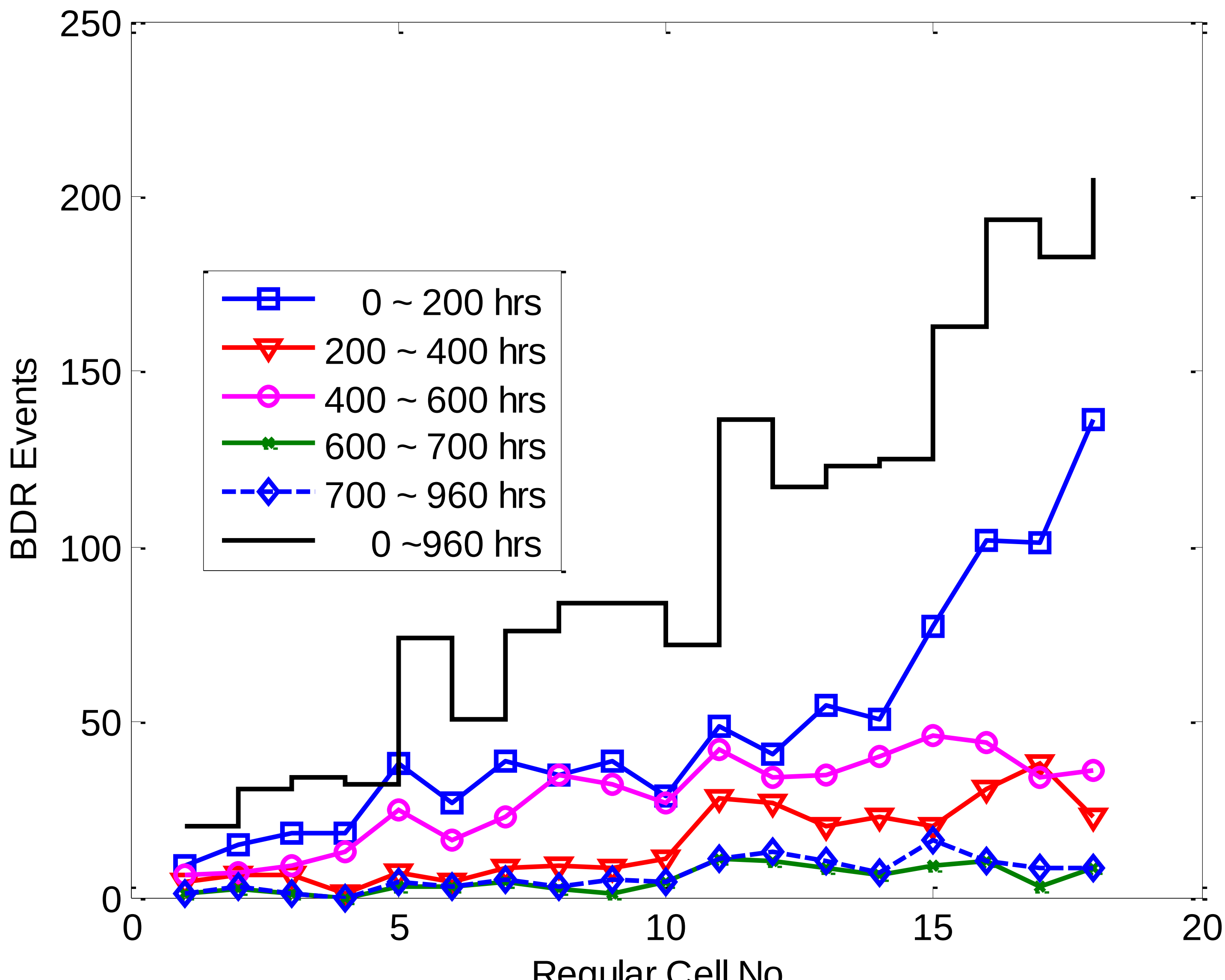
- Evaluation as function of
  - Pulse heating temperature rise
  - Any other thought?
- These trials are important
  - for understanding the mechanism of trigger of BD
- Results are consistent or understandable?
  - With other observations?
    - Breakdown location?
    - Breakdown timing in pulse
      - Period of irradiation with RF before BD

TD18_#3 Faya Wang, 17 March 2010

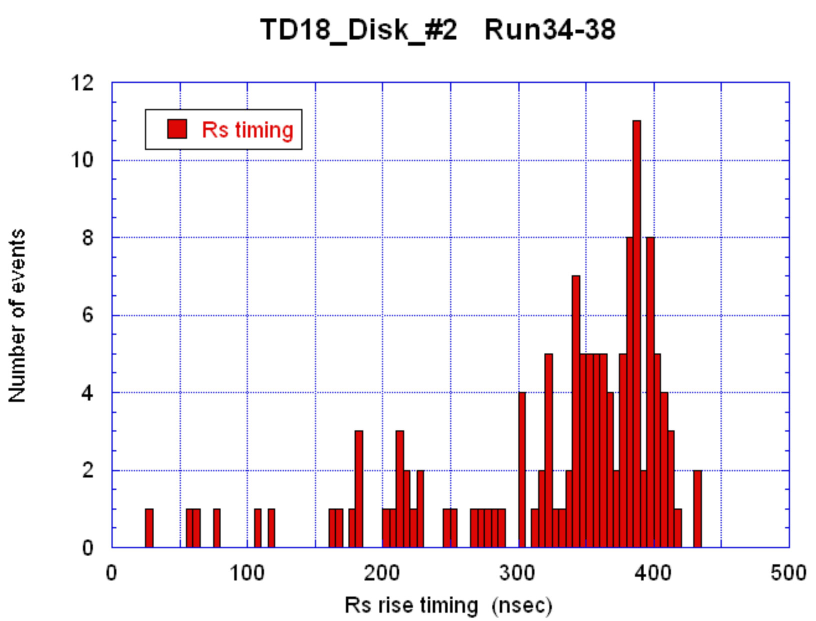
# BDR Pulse Heating Dependence

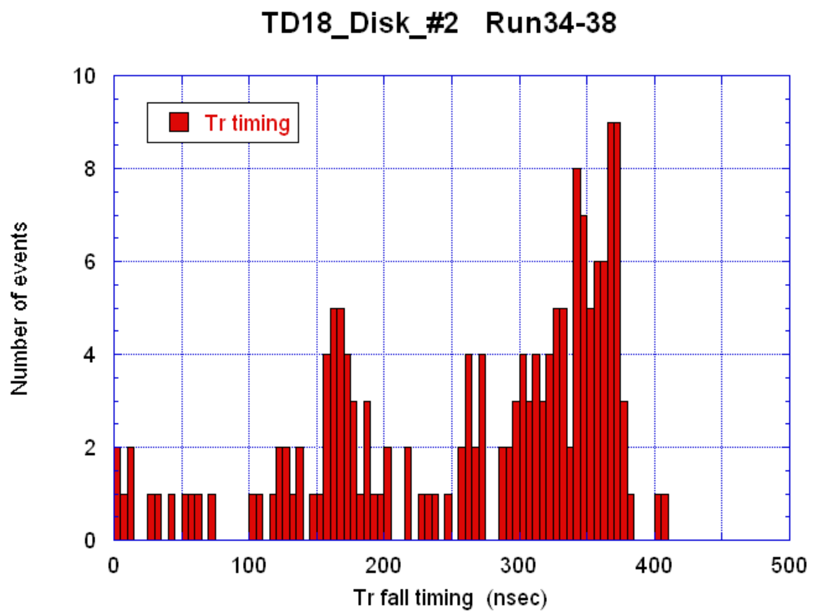


# Breakdown distribution at different stage



# Timing statistics for Rs rise and Tr fall



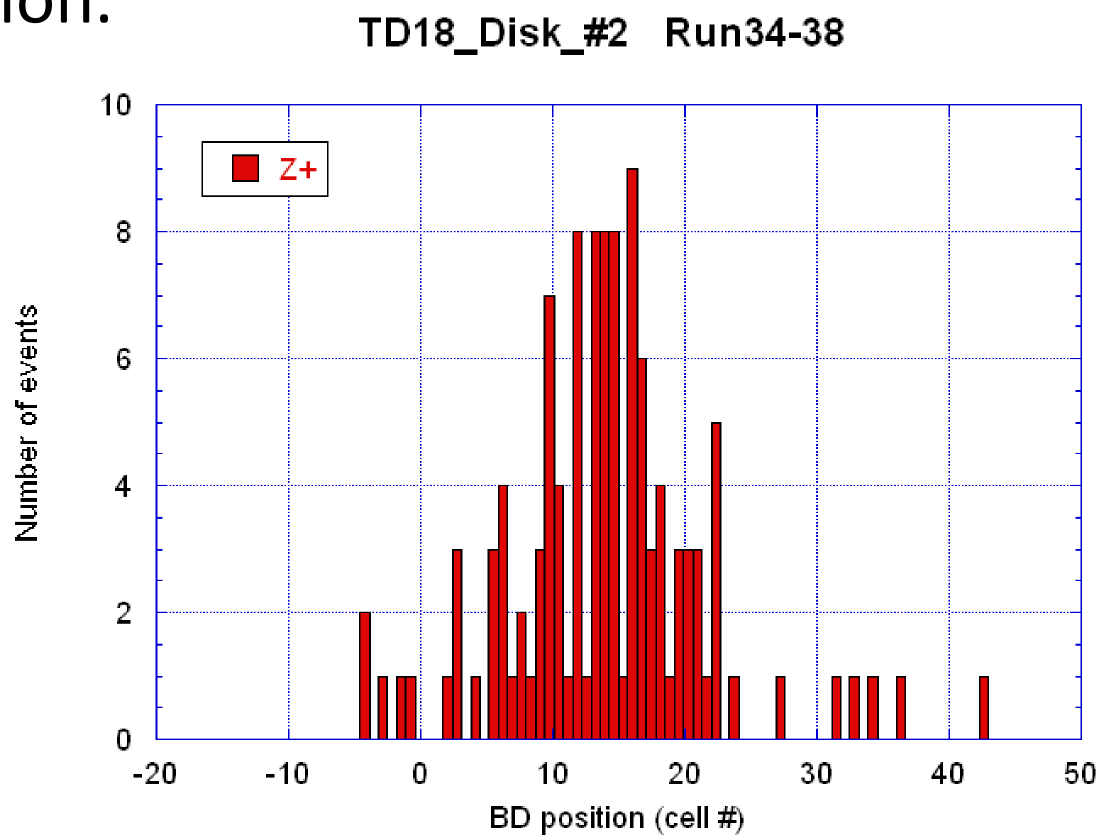




Rs: 100—350ns for 252nsec pulse
Most of Rs change sit around 360+-50nsec

This Tr reflects the information of irradiation period before BD

Tr: 150—400ns for 252nsec pulse
Most frequent when approaching to the end, from 300 to 370ns.
There is a small bump at 170 nsec, at the beginning of pulse.

# BD location.




Should revise the resolution of the analysis of BD location

# To do -5

- Try to correlate the BDR to other observables
  - Such as pulse heating
  - Pulse width and pulse shape
  - Breakdown location
  - Breakdown timing
- To understand the trigger mechanism to drive breakdowns

# Pulse-to-pulse stable dark current

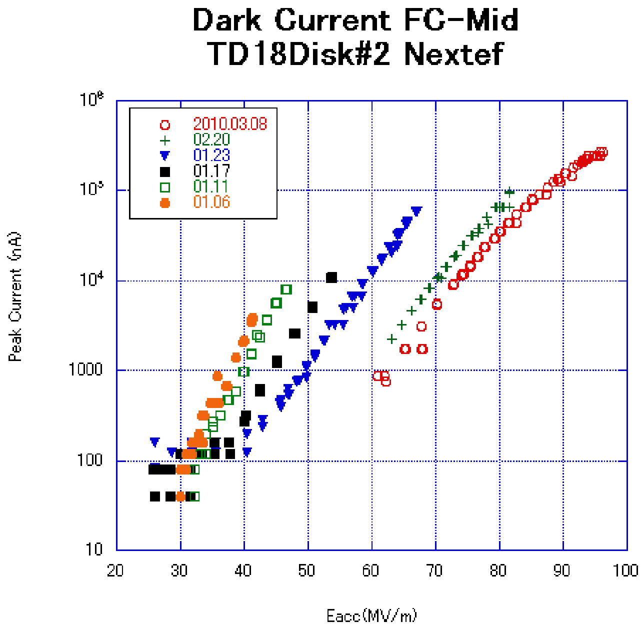
- Important to measure the evolution?
  - Amount of FE current
  - Beta values in FN
  - Decrease and saturation, or jump up?
  - Can be one of the measures of processing?
- Energy spectrum
  - To understand the FE position information
  - Possible relation to trigger of BD

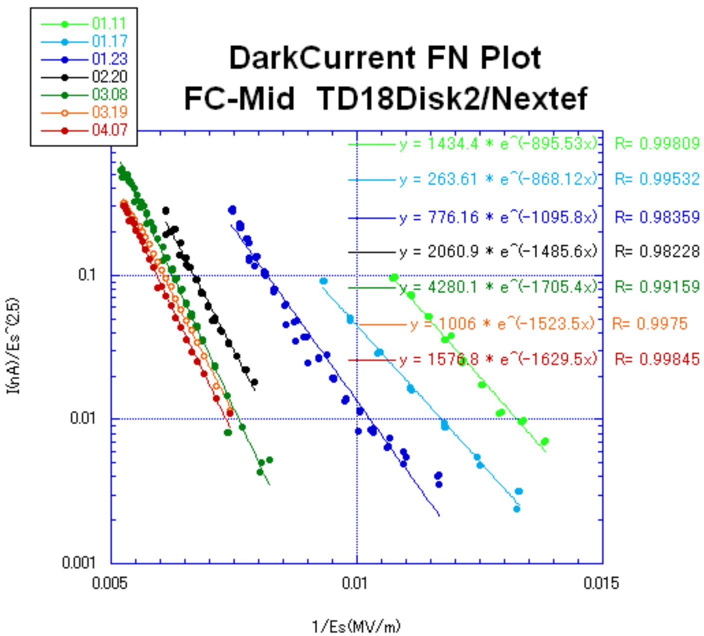
TD18_#2, S. Matsumoto, in this meeting

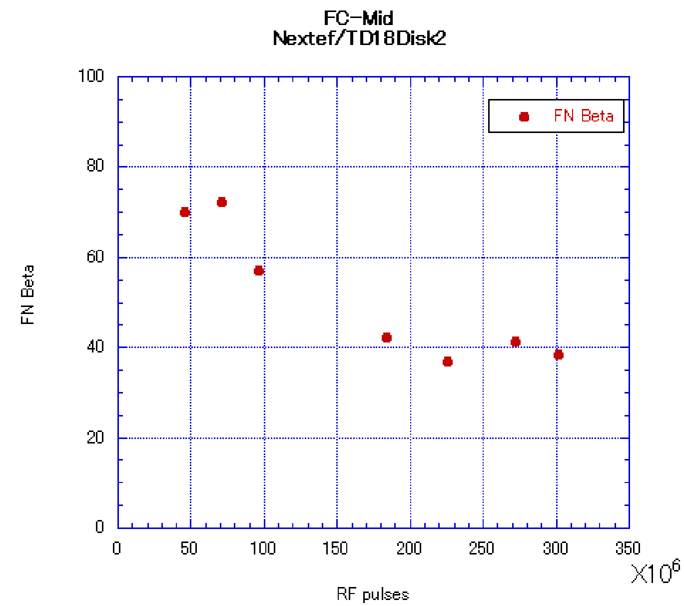
# TD18_#2

# Dark current evolution

## especially at early stage of processing



# To do -6

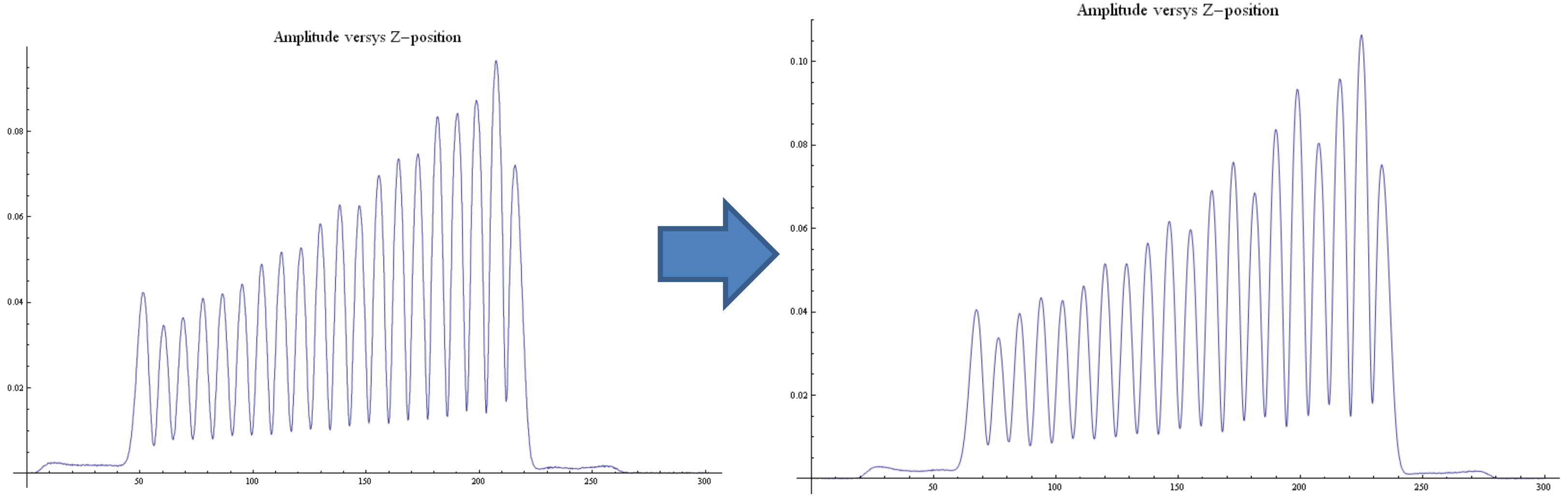
- Dark current should be observed as processing proceeds
- Try to find relation between stable FE current and reached high gradient performance

- To get relation between dark current to processing.
- This information may give us a way to monitor processing.

# Damage during processing or in operation

- Deterioration are observed
  - Cell frequency change
    - Especially non-uniform change: not easy to compensate
  - Breakdown pits and rough surface profile
    - Larger field enhancement?
    - Cleaner surface?
    - Hard surface due to rapid cooling?
  - Triggers to the following breakdowns
- Degree of deterioration should be evaluated
  - Easily subject to the systematic error in measurement
  - Well-established setup should be used

# T18_Disk_#2 Bead pull amplitude plot before and after high power test




1. Some Eacc smoothness was deteriorated.
2. Average frequency increased by 1.1MHz after 4000 hours processing with 2500 breakdowns in total.
3. 1MHz → ~40degrees/structure

Should carefully measure to evaluate the effect.

# Performance with beam

- Field profile along structure changes
  - Especially on T18 or TD18
  - Long-term stability is to be determined with beam
- Evaluation is needed with/without beam
  - On BDR
  - On BD location

# Long-term operation

- We should confirm the life-time stability
  - The stability against practically long-enough operation at nominal field
- How to do it?
  - Design a structure with the same Es and Hs distribution without beam as those with beam and test it without beam
  - Let us operate for full 2 months (1500hrs)
    - At 10% higher field to gain x10 BDR
    - To simulate 2 years operation to estimate 10 year run
    - We can also get evolution information if exists
  - Finally should inspect RF characteristics and proceed SEM inspection

# To do -7

- Evaluate possible damage on structure due to processing
- Design a structure with nominal loaded Ea distribution without beam
- Estimate the stability over lifetime range

- To estimate the life time history of accelerator structure.

# SEM inspection after high gradient test

- Postmortem inspection
  - Optical seems not enough, though non-destructive
  - SEM seems most powerful, though destructive for other than quad
- What should we evaluate
  - Any foreign objects? Try to find possible source!
  - Surface deterioration?
    - On high electric field area
    - On high magnetic field area
- We should cut and see with SEM on the structures
  - T18_Disk_#1, #2, TD18_Disk_#2, #3?
  - Unless we have clear idea for another experimental plan

# To do -8

- Let us proceed post-mortem inspection by SEM on most of the tested structures unless we have clear idea what to be tested in future
- Try to correlate this inspection to the obtained high gradient performance

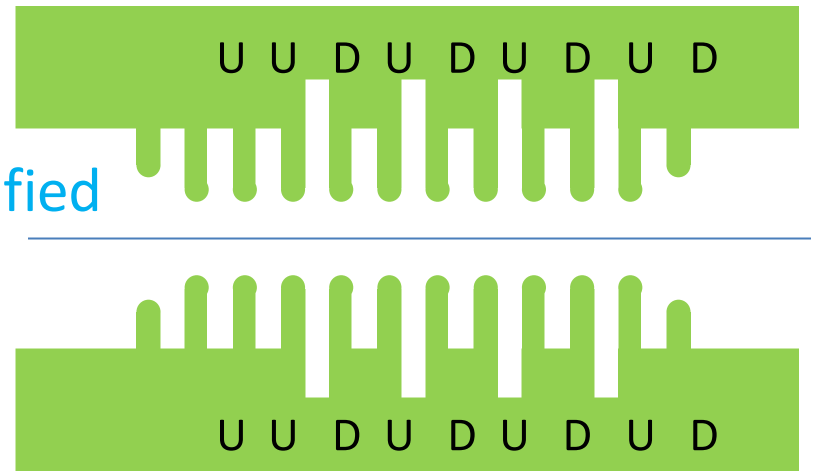
- To convert a dead body into birth of another life!

# Simple-geometry studies are needed for understanding the results on prototype structures

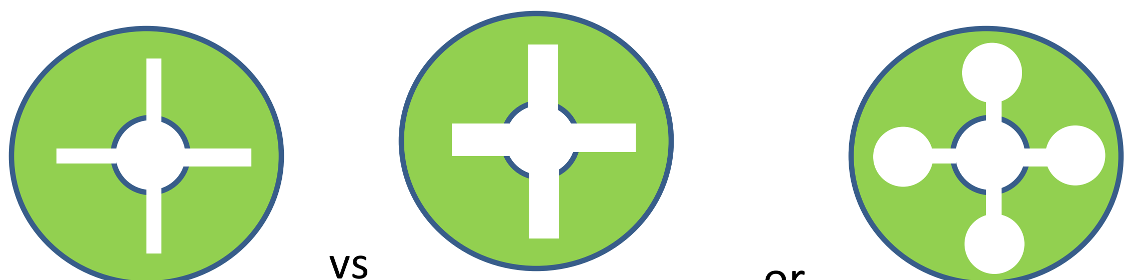
- Single-cell SW breakdown study
  - Performance taken from moderate field level (~80?)
    - Milled cell
    - LG cell
    - Quad
    - Heavy damping
    - Etc.
- Modified C10/CD10 in 10 cell setup
  - SW needed?
  - TW

# Evaluation of effect of damping port

C10-modified




SW or TW in C10-modified



Med. Heavy damp

vs

Heavy damp

or

DDS

# To do -9

- Let us plan a series of high gradient test with simple geometries from moderate field level
- Try to correlate the results to the performance observed in full-size prototype structures

- This should serve us with not only the understanding of the intrinsic limit but also some hints to go another direction to further higher gradient.

# In summary:
# My conclusion with deferring to discussion

- Essential evaluation measure is still
  - BDR and early processing characteristics
- More information is needed to judge feasibility
  - Dependence on pulse shape
  - Evolution and estimated change in lifetime scale
  - Effect of beam loading
  - Long-term stability
- Simple-geometry studies must to be done
  - In parallel to understand the mechanism and physics
  - Single-cell or several to 10 cell setup
  - SW and TW
- Study at the moderate field level should be done
  - before addressing higher and target operation level

# X-band strategy to take now

- We need to show the feasible level based on now.
- Characterize the structures of present-day design (TD24) in low-60?, medium-80, goal-100, and higher-110 gradient levels.
- Conclude by ourselves the present-day feasibility of accelerator structures based on copper material.
- Show to outside world the feasibility at each field level.
  - Established level + level to be confirmed in near future, …..
- Then after, explore further developments including other design and other material or surface treatments.

# Last to do -10

- Work hard with enjoying finding physics
  - Not only in a systematically well-organized manner for CLIC
  - But also with various different view points to understand the physics behind

- This is to conclude the feasibility
  - Of present-day established level
  - And judgment on 100MV/m
  - And possible idea to higher gradient