

# KEK activities on CLIC X-band Accelerating Structures

Tsinghua Univ., March 24

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- Basic idea behind KEK X-band R&D
- History of X-band developments at KEK
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- Basic studies related to breakdown
- Expansion of our collaboration

# Areas of concern for KEK X-band R&D

- LC before ITRP and extension to LC-related study with CLIC
- X-band Application
- Basic technology for high energy accelerator
- Scientific understanding of processing and breakdowns

# History of X-band developments at KEK

- Early 1990: High precision machining + diffusion bonding
  - Establishment of fabrication technology → 1.3m DS
- Late 1990: realized discharge problem
  - Reduce group velocity, shorter str.
- By 2004 ITRP: 60cm HDDS
  - Eacc established 50~65MV/m
  - HOM suppression: HDDS weak damping + detuning
- 2007~: CLIC → X-band & higher gradient
  - collaboration CERN+SLAC+KEK
  - 30cm TW acc structure

# Relevant accelerator structures

Stage	Unit	JLC-X	GLC	CLIC-C	CLIC-G
Year		1996	2004	2007	2010
ECM	TeV	1	1	3	3
Structure	Type	DS	HDDS	CG / HDS	HDS
Length	m	1.3	0.6	0.2	0.3
$E_{acc}$	MV/m	73 / 60	65 / 50	120 / 100	120 / 100
$P_{IN}$	MW	130	57	65	64
$\langle a / \lambda \rangle$		0.2~0.14	0.2 ~ 0.15	0.15~0.08	0.12~0.09
$V_g/c$	%	10 ~ 2	4.5~0.8	2.4~0.7	1.7~0.8
$\Delta T$	$^{\circ}C$		< 19	71	53

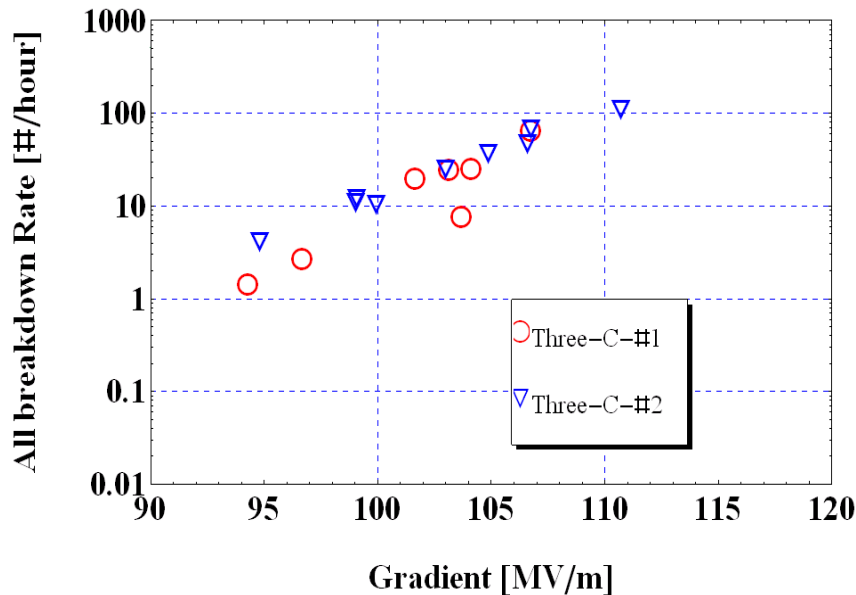
# Some typical experiments in mind

- High gradient characteristics only reflects the material choice!?
  - After processing
  - After number of breakdowns
  - After saturation
- Is this true?
  - Not electric field but magnetic field is the key?
  - Surface treatment is not the issue?
  - Hard/soft may or may not be the issue?

# Single-cell SW high gradient test at SLAC

ultra clean condition vs  
normal surface processing conditions.

Surface treatment is  
not the issue??

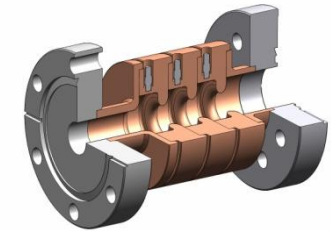
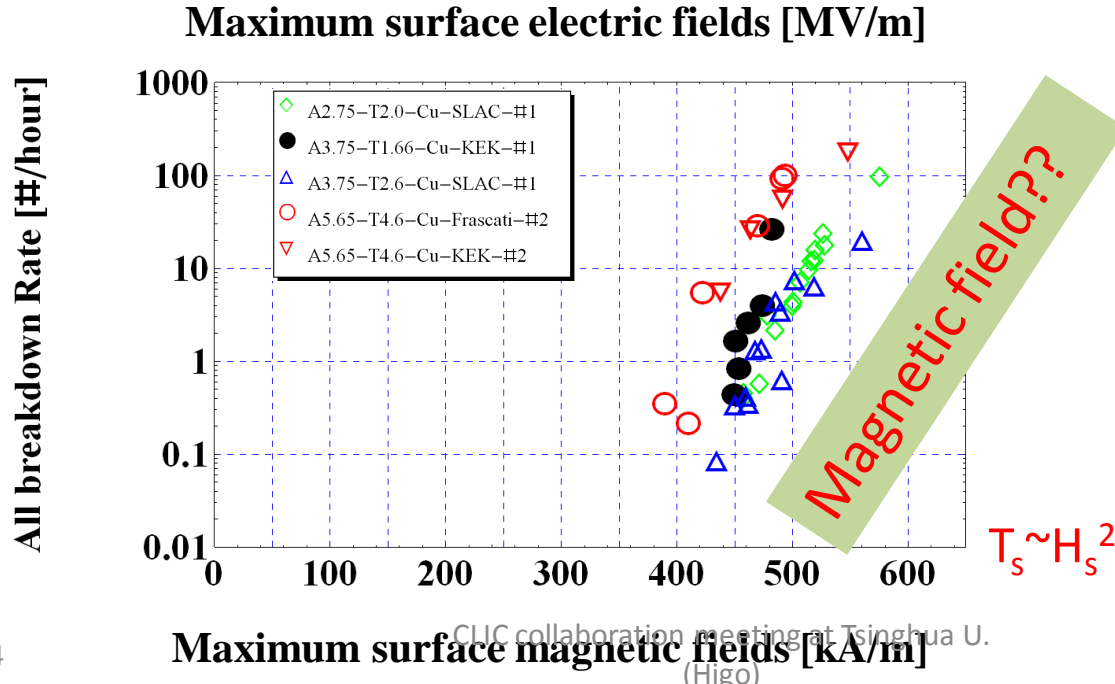
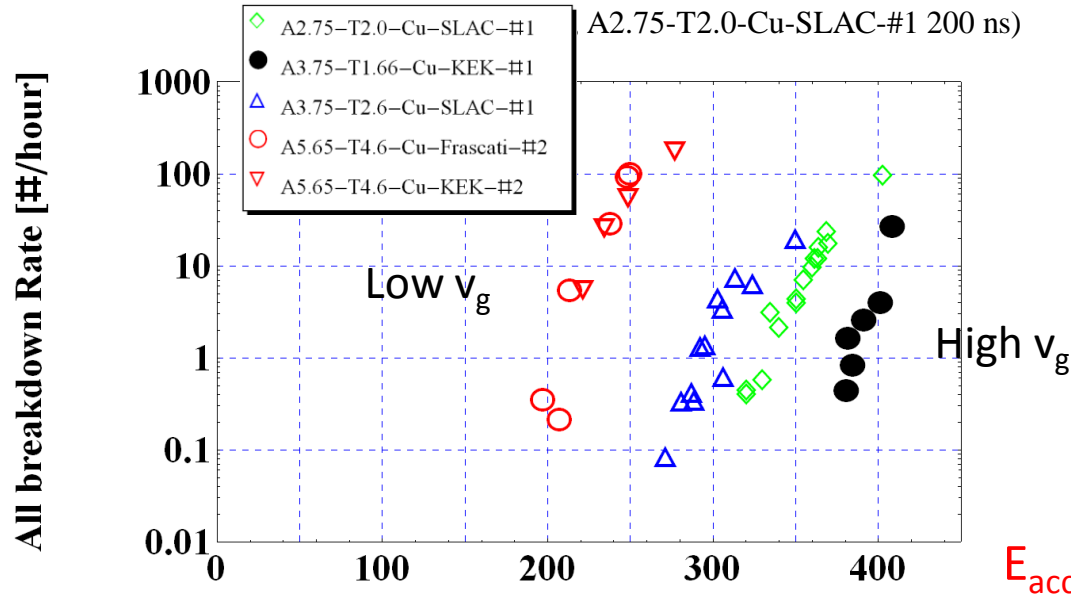


The near perfect surface processing affected only the processing time. The second structure processed to maximum gradient in few minutes vs few hours for the normally processed structure.

But we are curious how the processing proceeds and how high we can obtain without serious damage.

# Surface fields for 5 different single cell structures, *shaped* pulse

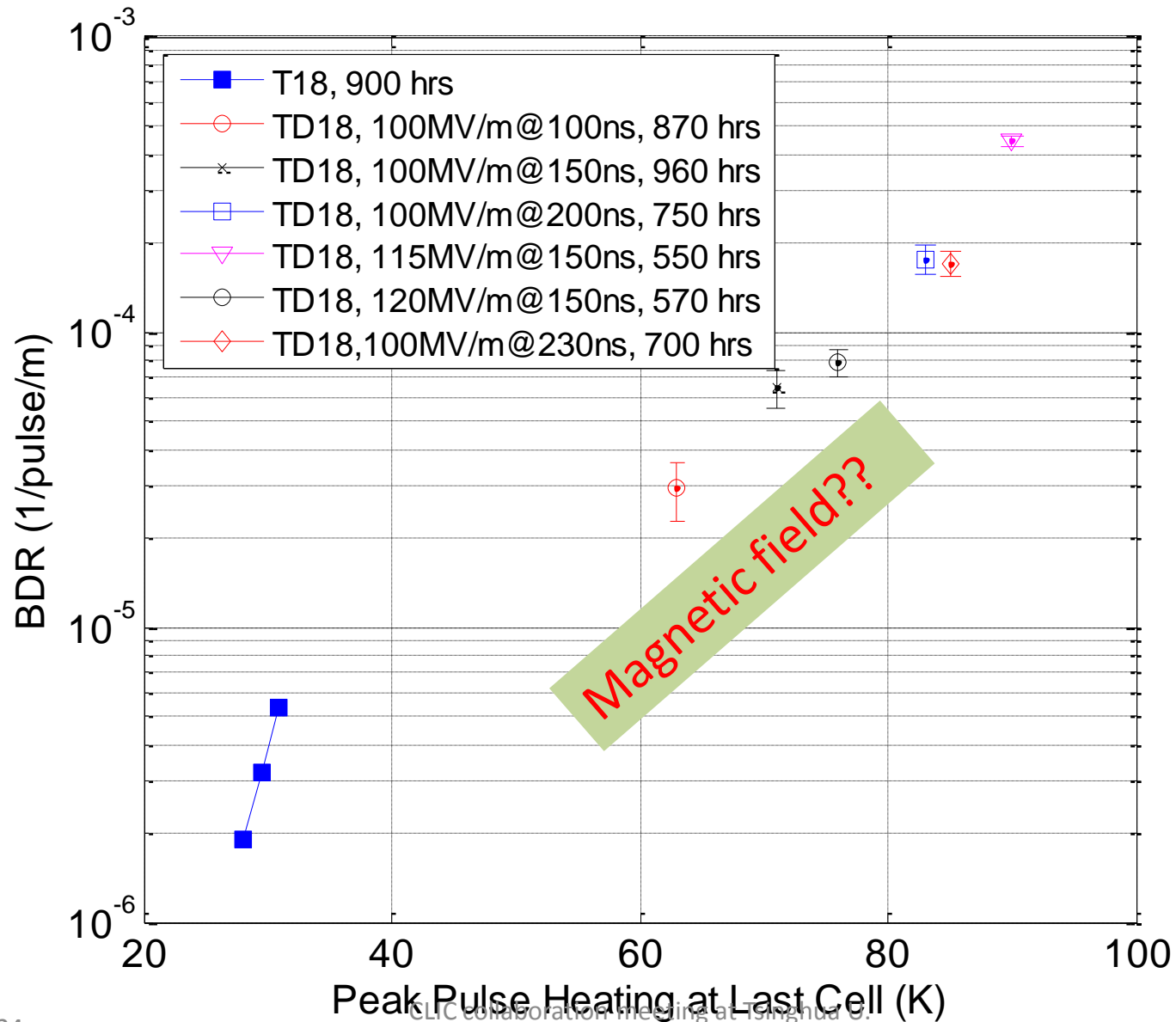
(flat part: A5.65-T4.6-KEK-#1- 150 ns, A5.65-T4.6-Frascati-#2- 150 ns, A3.75-T2.6-Cu-SLAC-#1: 150 ns, A3.75-T1.66-Cu-KEK-



For the same BDR  
 Different shape  
 → Different  $E_{acc}$   
 but  
 Very similar  $H_s$



# BDR Pulse Heating Dependence

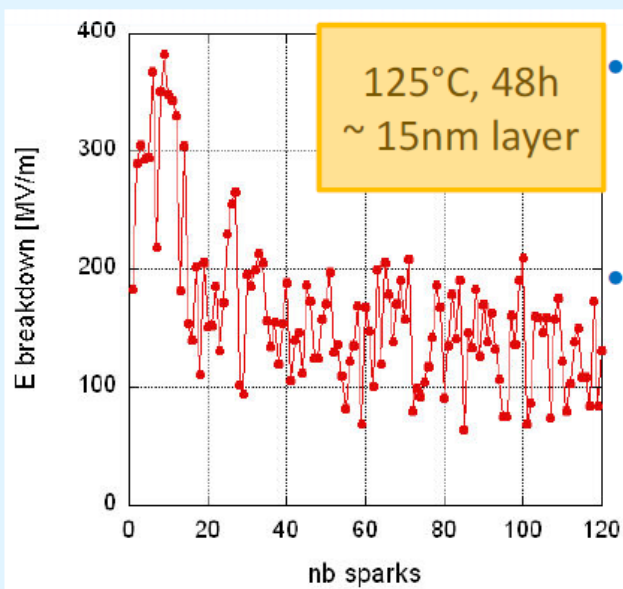




# The oxide layer of Cu

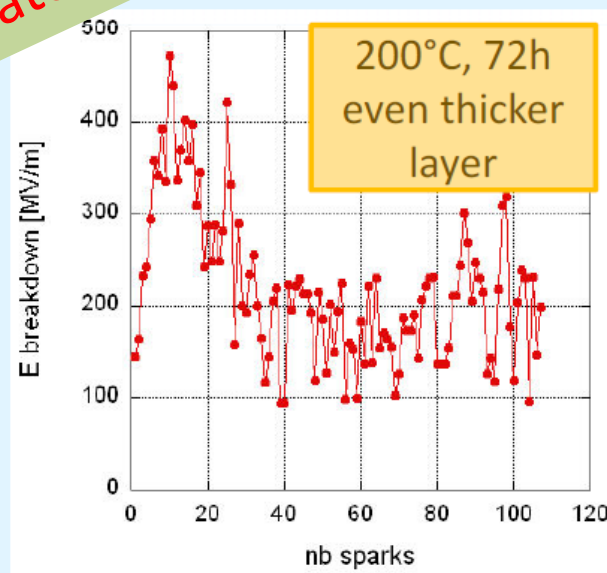
- An oxide layer has been grown on Cu. It was thicker than the natural oxide layer.
- Higher initial  $E_{BRD}$  and conductivity.
- Has also a different  $E_{LOC}$  as the natural oxide layer, oxidised Cu material?

After saturation, or after number of breakdowns, surface property is lost and totally determined by the material?



• During conditioning,  $E_{BRD} = 350-500$  MV/m in both cases

• This lasts only for 15-20 sparks (left case) or 20-40 sparks (right case)



# General idea behind our study

- Take these experimental results in mind.
- Before reaching this saturated regime, there should be a place to play with the surface condition or crystal structure.
- Can we stay in this regime for high gradient?
- How to proceed through this regime to saturation?
- Inevitable to go beyond this regime for high gradient?
- Want to study the performance from this view point.
- Then we understand and conclude in which regime we play for the linear collider.
- One of the key issues for our studies is devoted to this point, in addition to pursuing higher and higher gradient.

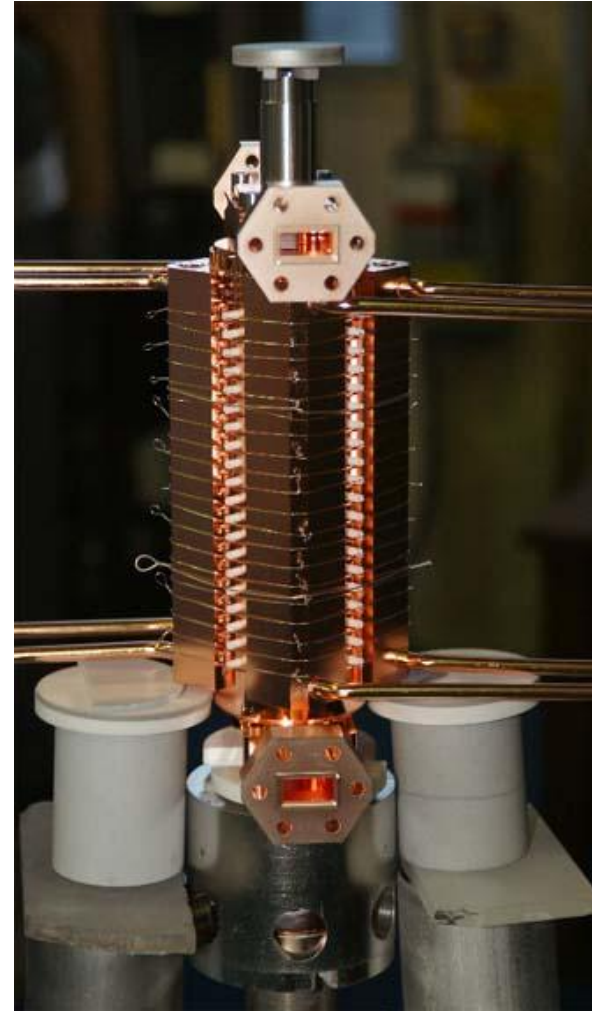
# Preparation of accelerator structures

- Technology established as of GLC/NLC era
  - KEK precision machining of parts
  - SLAC assembly
  - Now further study is ongoing with SLAC and CERN to improve in future
- Fabrication flow
  - Precision machining
  - Chemical polish
  - Diffusion bonding and brazing in hydrogen furnace
  - Baking in vacuum at 650C

# Fabrication of damped structures



KEK fabricated all parts.



SLAC made assembly.

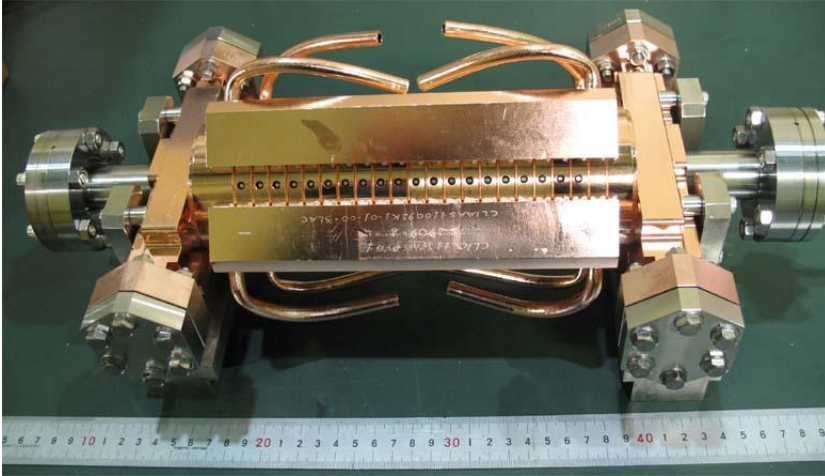
# Vacuum Baking of T18\_vg2.4\_DISC



**650° C**  
**10 days**  
**at SLAC**

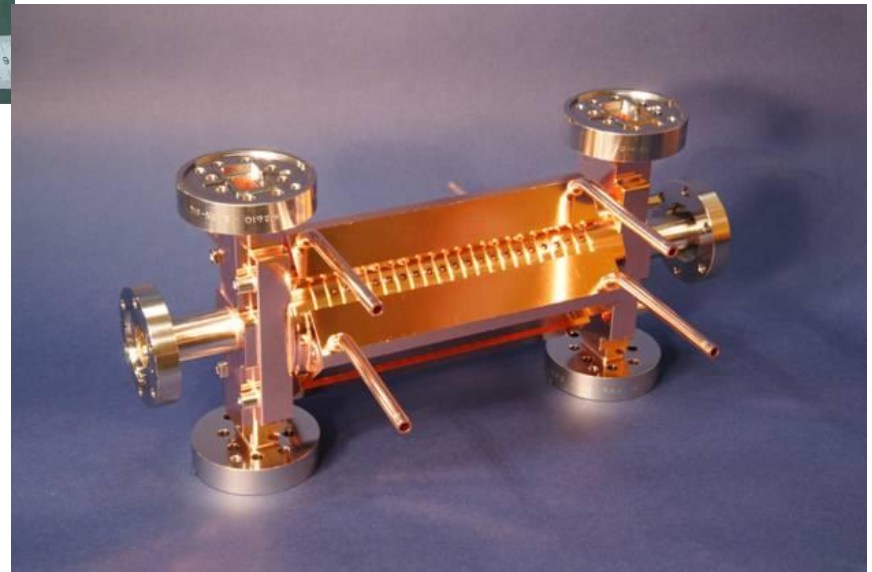
# TD18 first pair #2(KEK) & #3(SLAC)

Design = CLIC-C



#2 being tested at KEK  
Nextef

#3 being tested at  
SLAC NLCTA

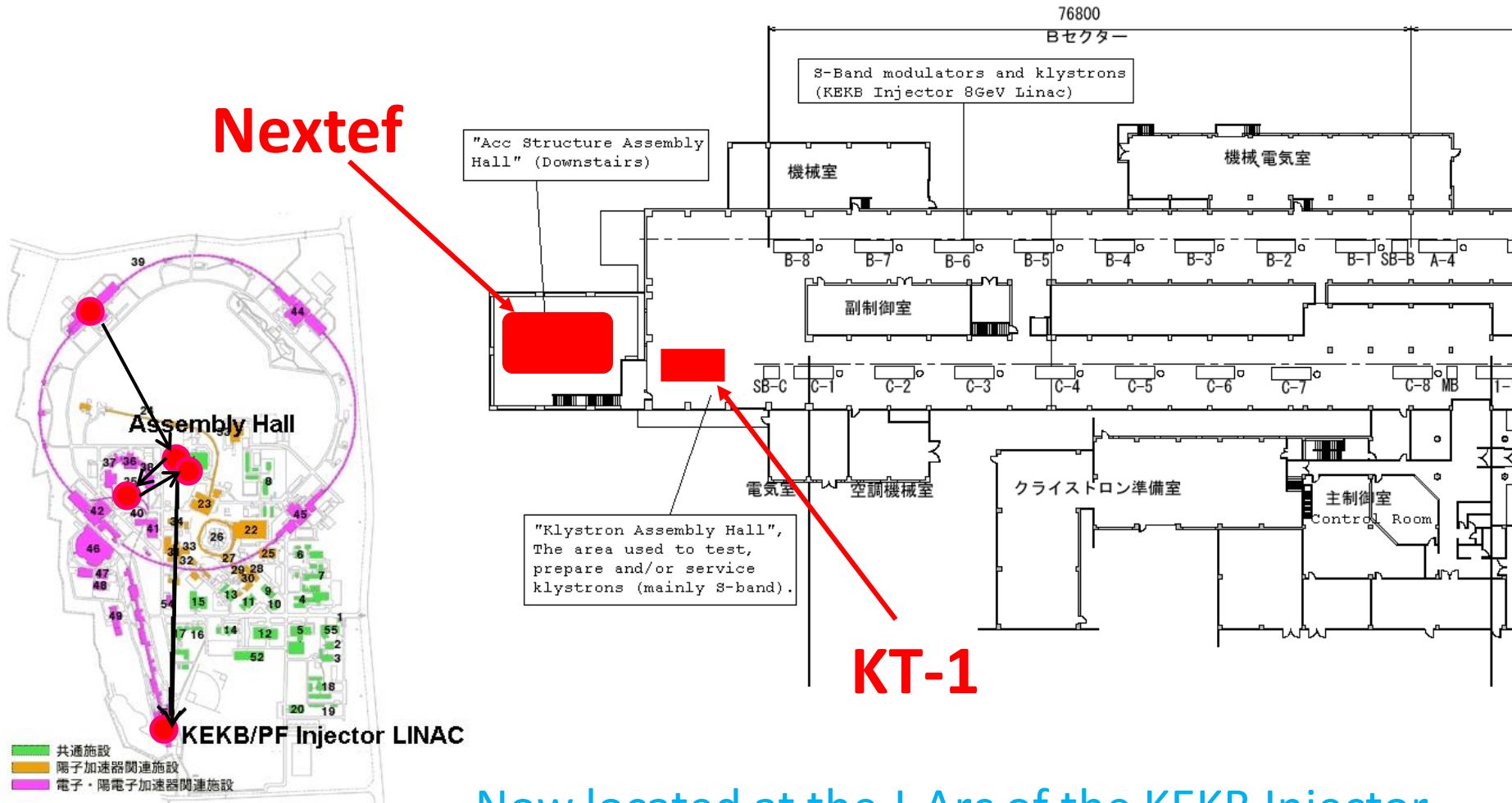


# Structure test philosophy

- Evaluate at more than one laboratory
  - Independent evaluation
  - Equivalent to “S0” idea for ILC
  - Obtain statistical info and cross checking
- Requirement for facility
  - Long-term operation
  - 100MW or more power for over 100MV/m level
- Actual facilities
  - SLAC NLCTA with pulse compression
  - KEK Nextef with two klystrons
  - CERN 12GHz being developed
  - The comparison of three independent studies is a healthy condition, which should be kept.



# Test facilities of KEK

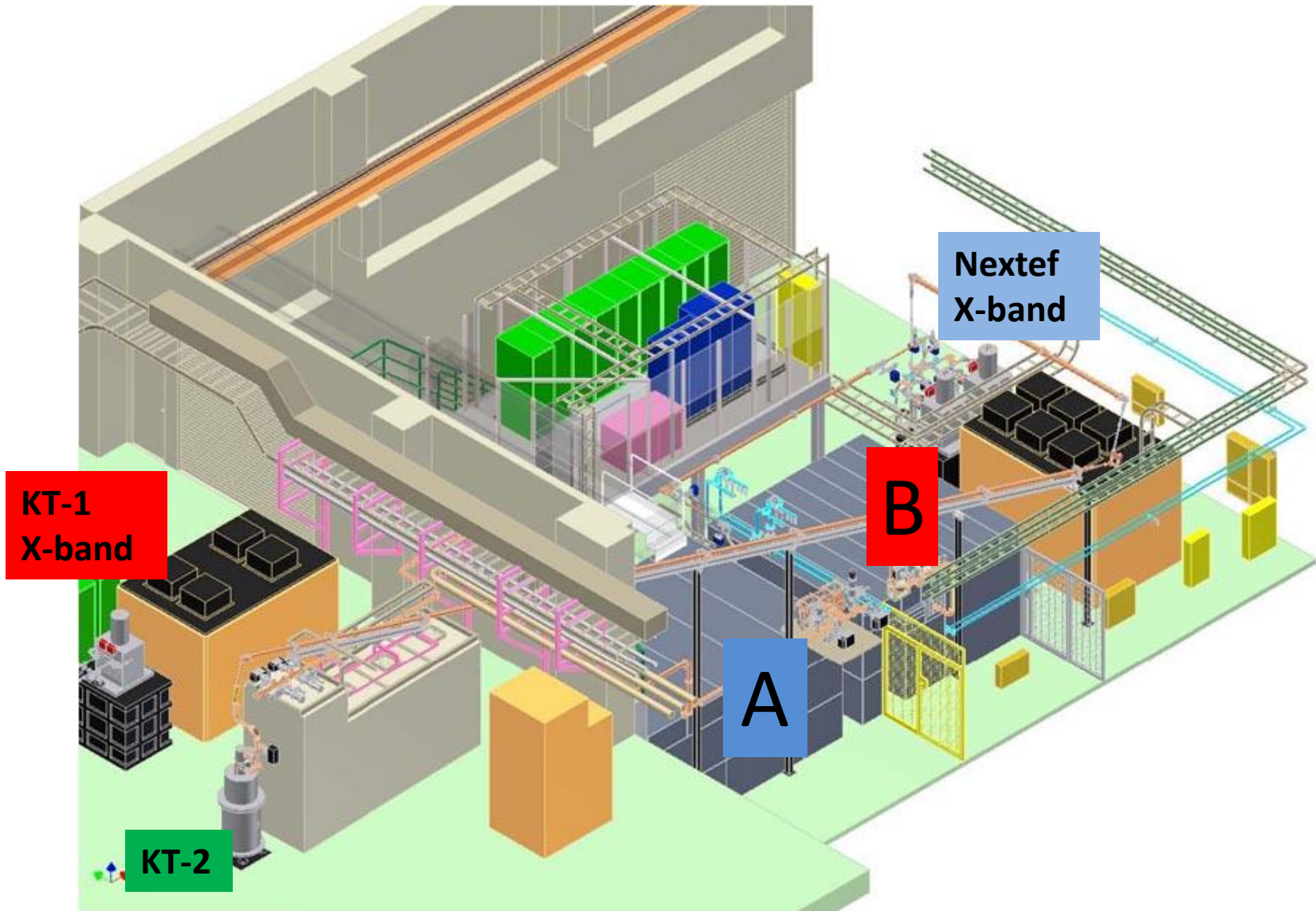


Now located at the J-Arc of the KEKB Injector

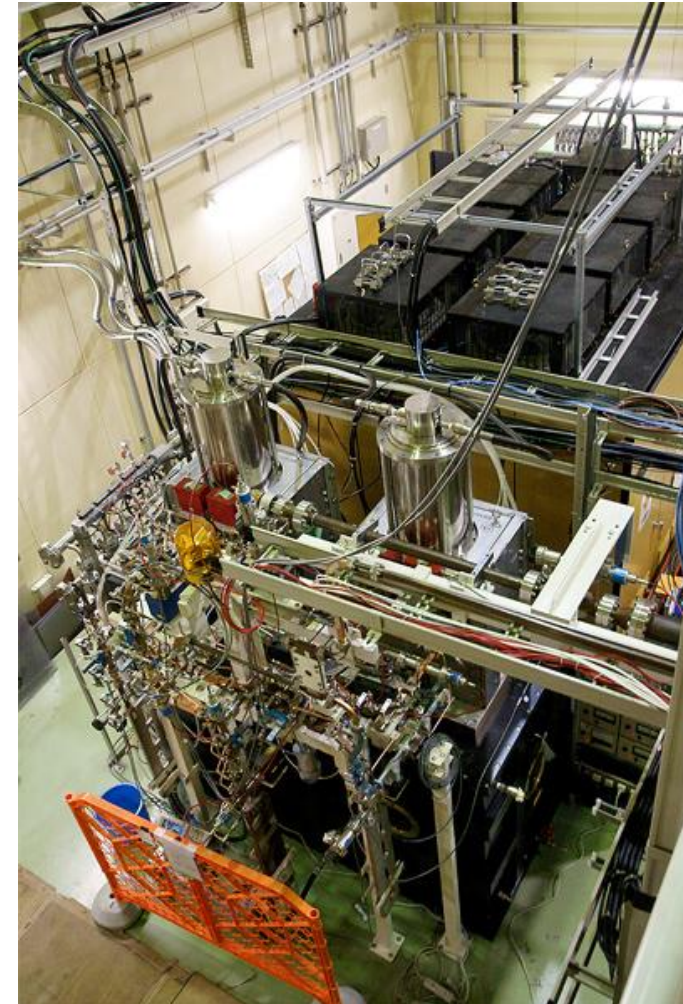
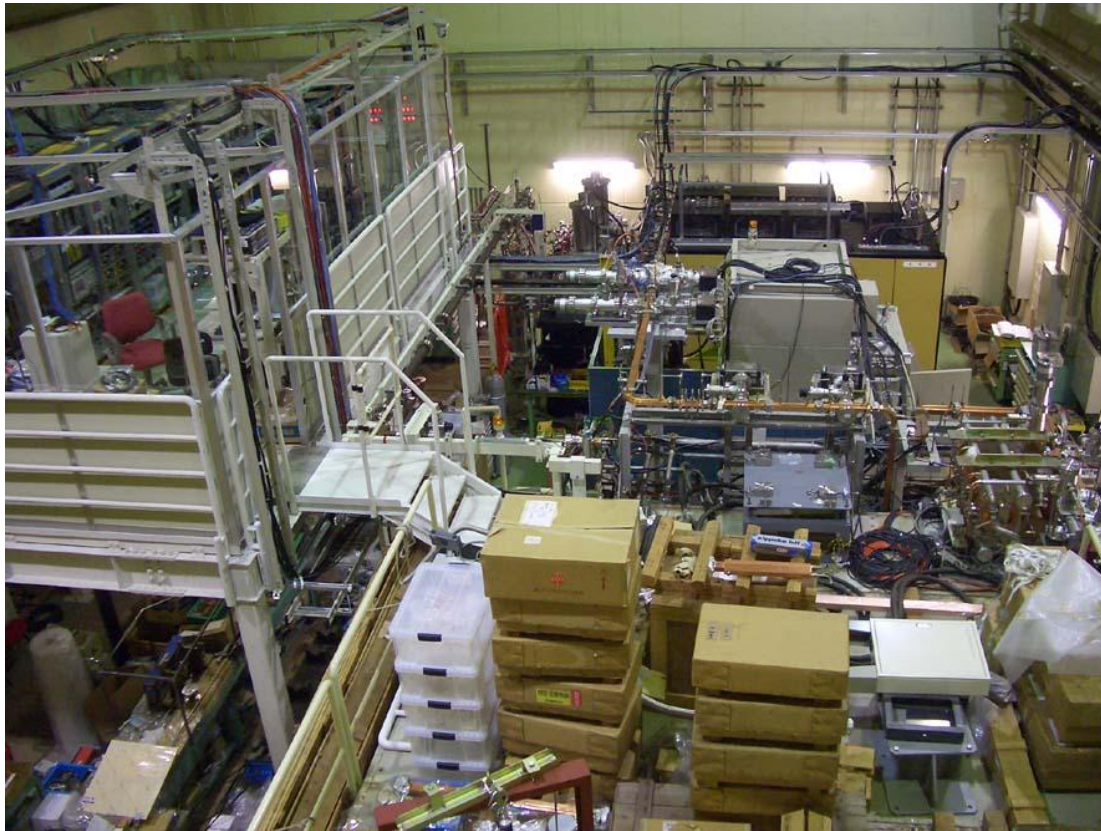
# KEK test facilities

- Nextef
  - Shield-A being used for structure tests
  - Shield-B being prepared for basic studies, taking power from KT-1
- KT-1
  - One PPM klystron
  - High gradient study with narrow waveguide
  - High power study on components
  - Feed shield B

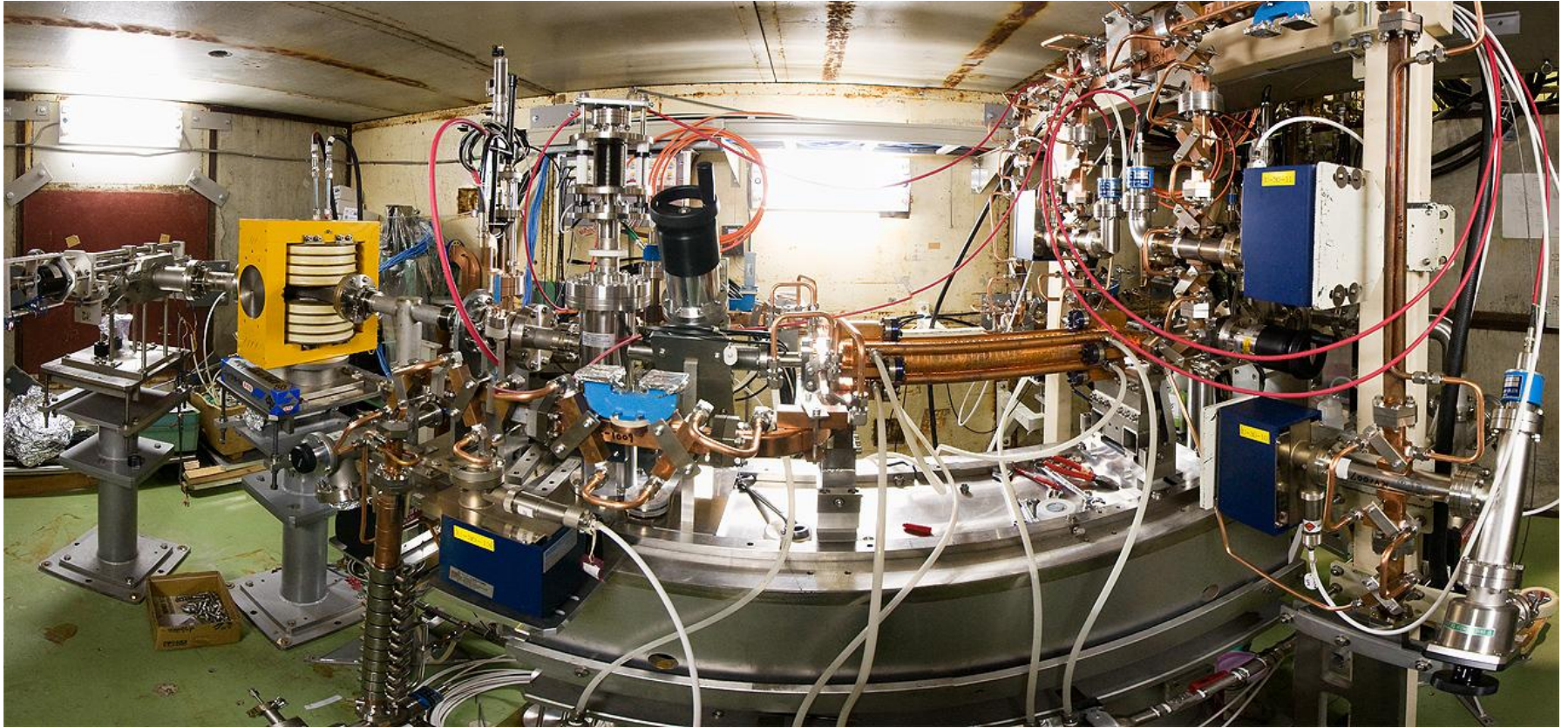
# KEK: Nextef Configuration



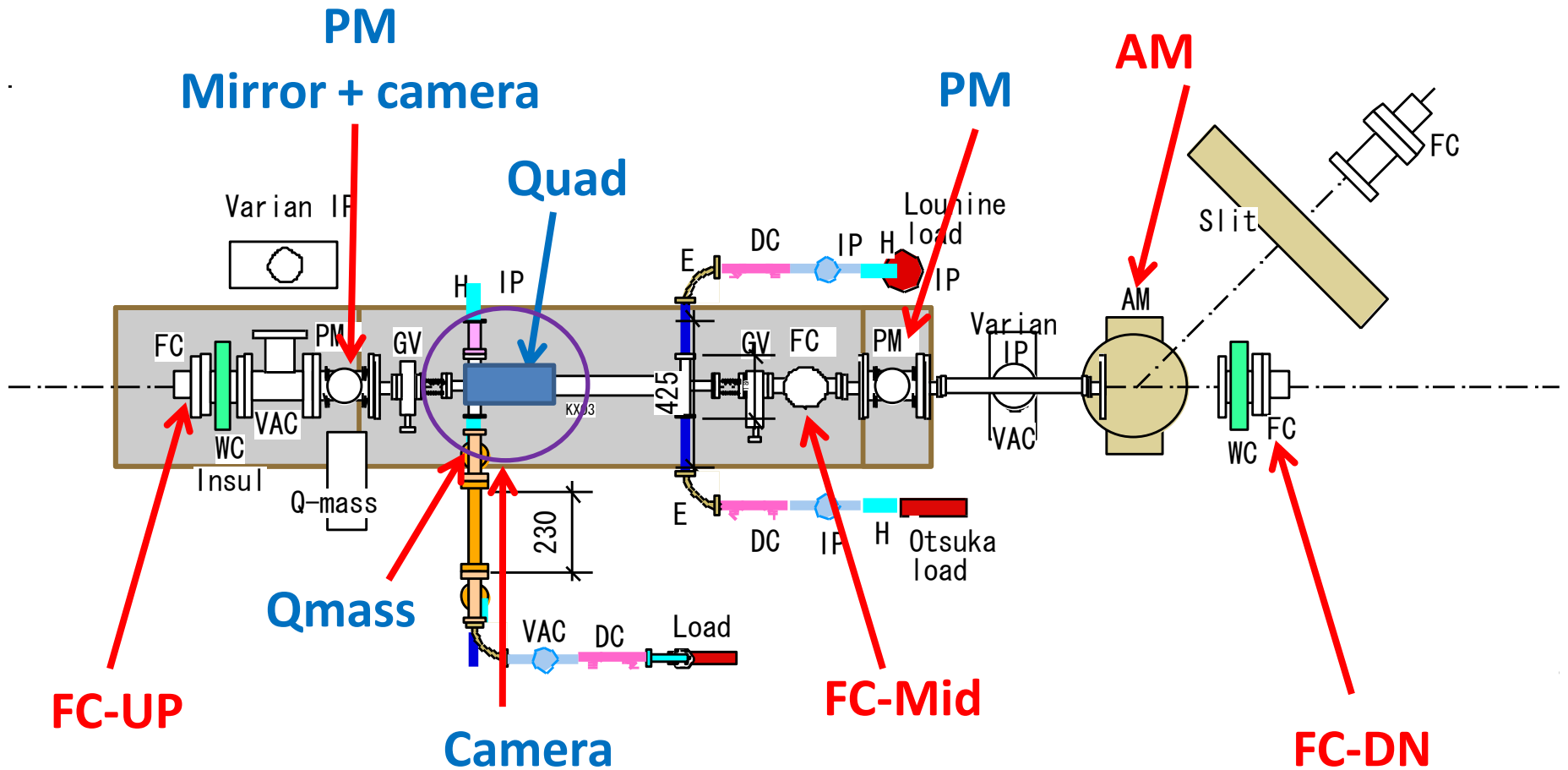
# Nextef operation since 2007



# Nextef inside shield room



# Monitors and components in shield-A



# High gradient test of three structures

- Disk-based un-damped
  - T18\_Disk Oct. 2008~June 2009
  - 4000hr, 9 months
- Quad-based heavily damped
  - TD18\_Quad\_#5 Sep. 2009~Nov. 2009
  - 1000hr, 3 months
- Disk-based heavily damped
  - TD18\_Disk\_#2 Dec. 2009~
  - 1200hr, 4 month+

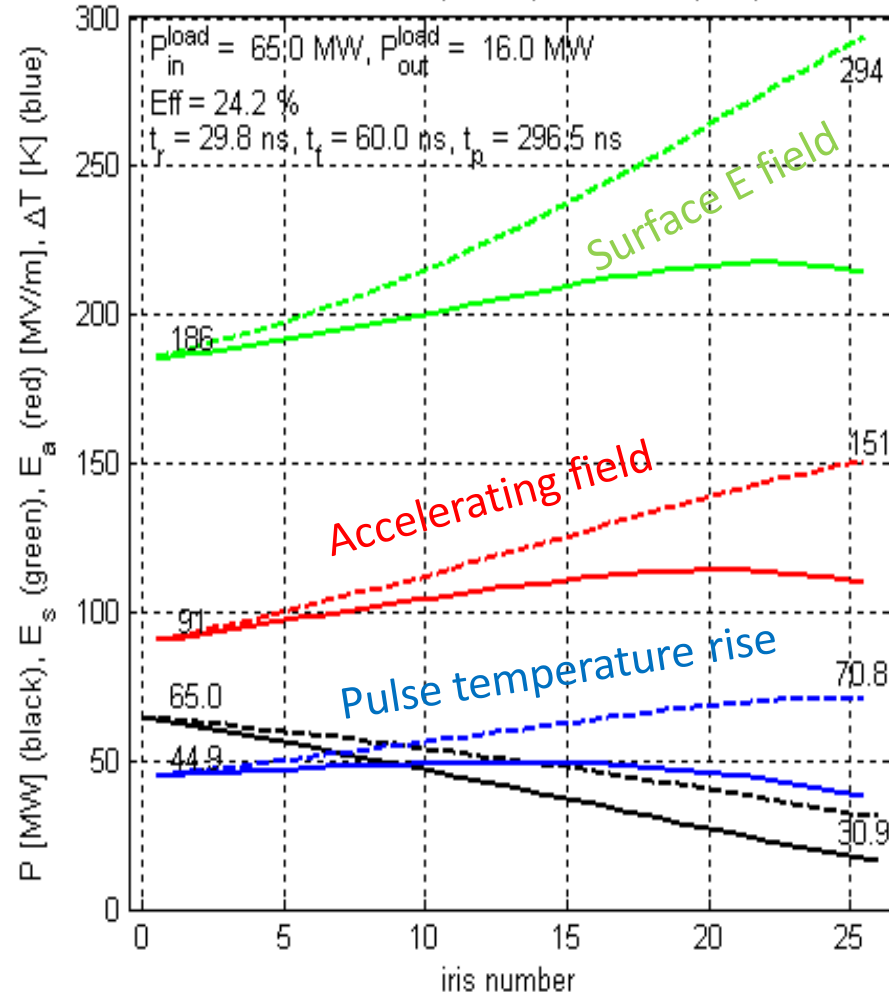
# T18\_Disk\_#2

- Aim
  - Electric gradient: possibility to realize 100MV/m within tolerable breakdown rate
- Design geometry
  - No damping slots
  - Big increase of gradient toward downstream
  - No big pulse heating temperature rise



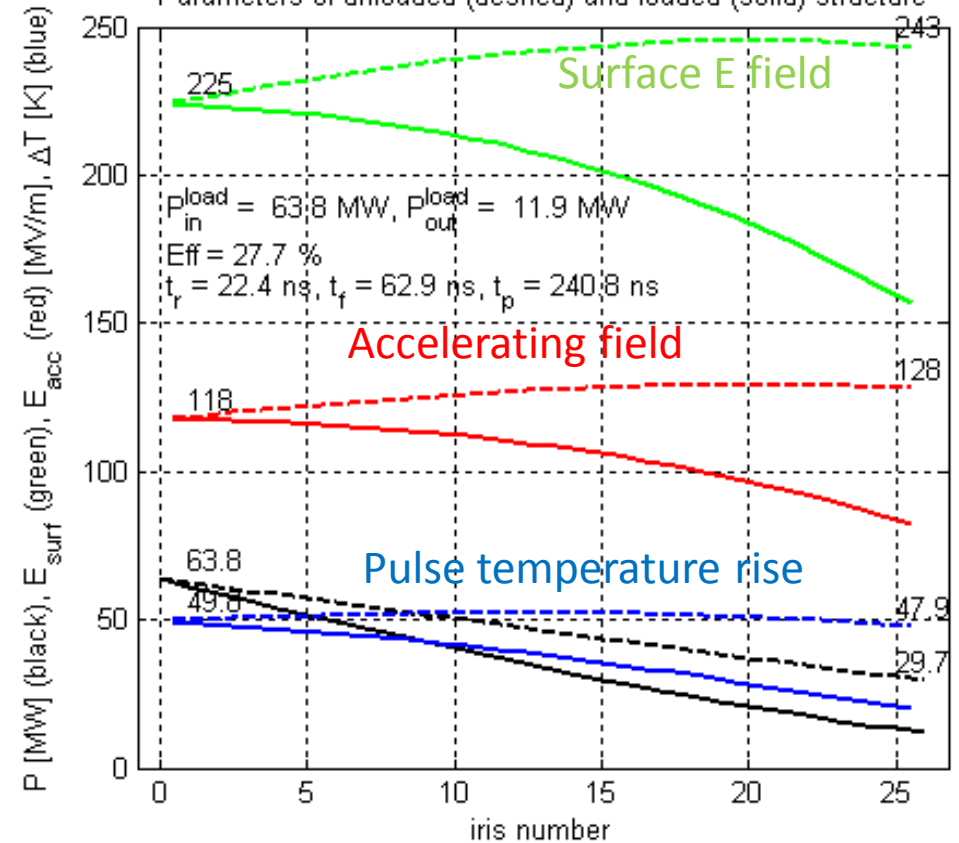
## CLIC Test: CLIC\_C (T18 tested)

Parameters of unloaded (dashed) and loaded (solid) structure

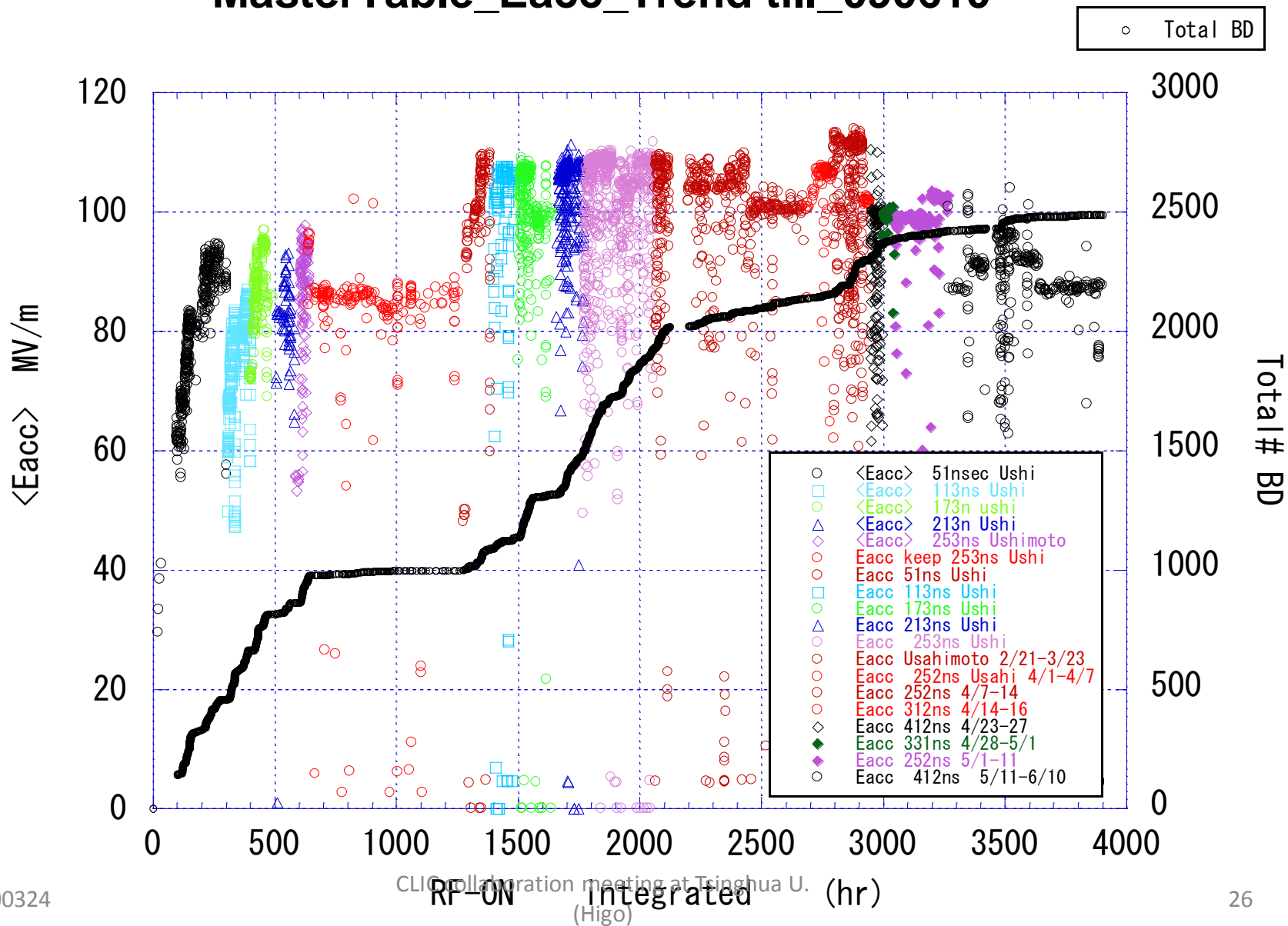


## CLIC Nominal: CLIC\_G (T24 being tested in 2010)

Parameters of unloaded (dashed) and loaded (solid) structure

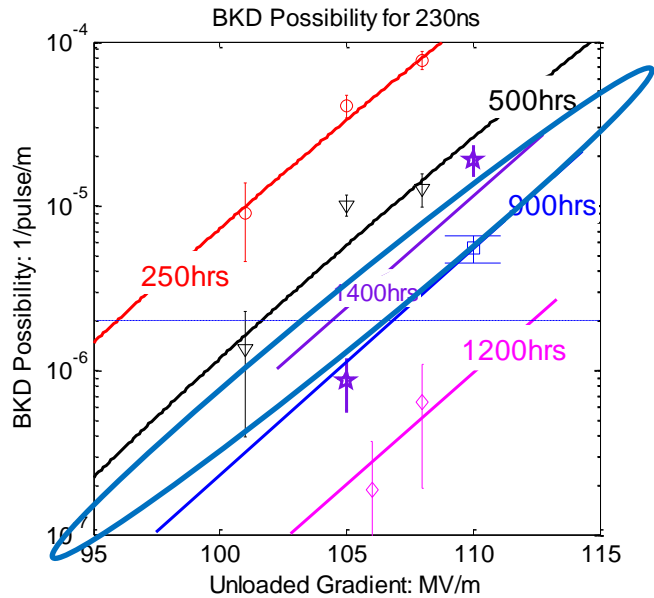
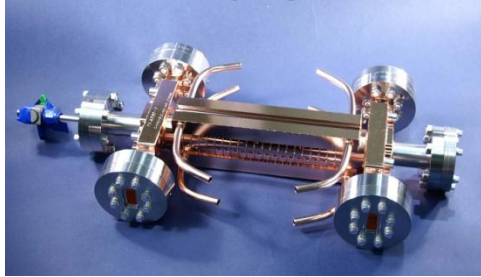


## MasterTable\_Eacc\_Trend till\_090610

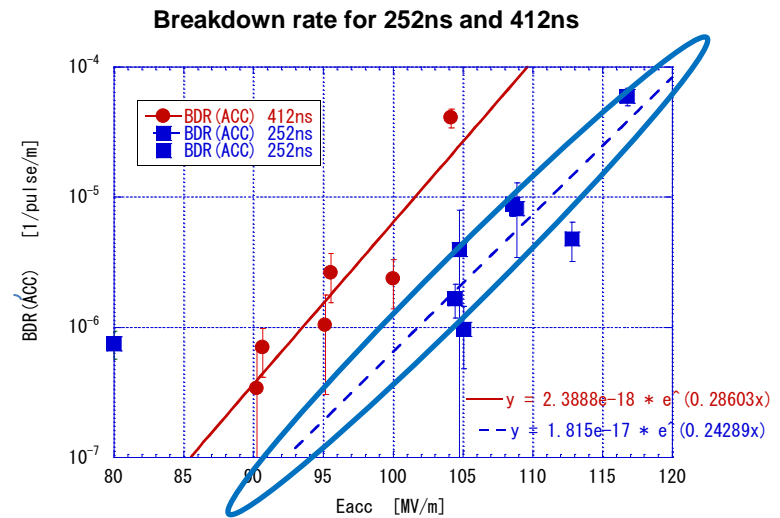
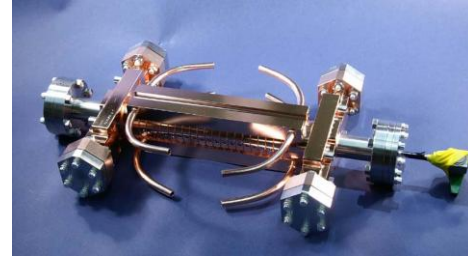


# Establishment of experiments to quantitatively compare

## #1 SLACで試験



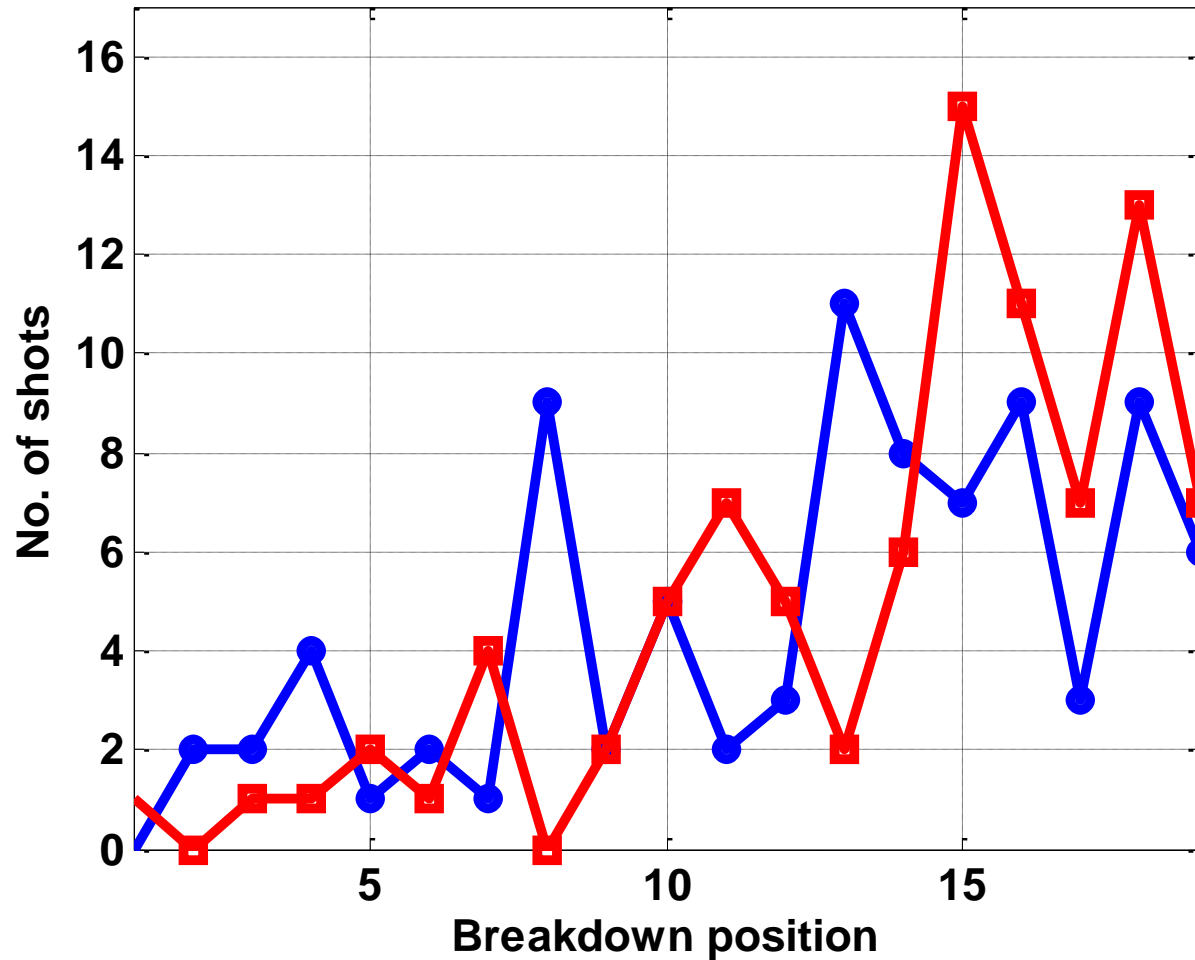
## #2 KEKで試験



C. Adolphsen, US-  
HG@ANL, 2009

Roughly the same breakdown rates were observed for a pair of structures.  
Will pursue the same comparison again for the second pair.

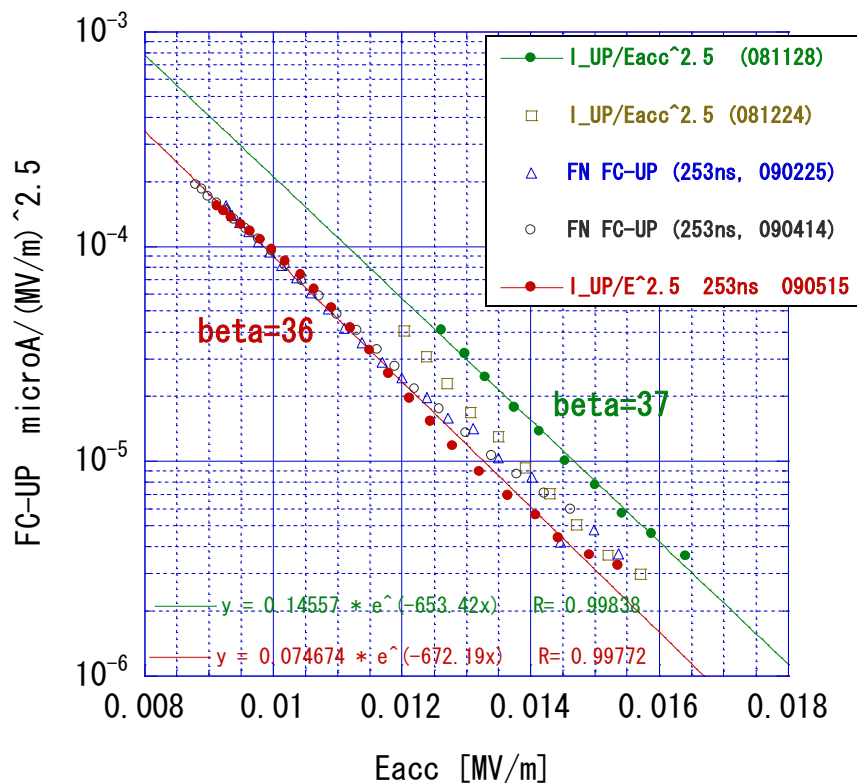
## Breakdown position for 205 ns data



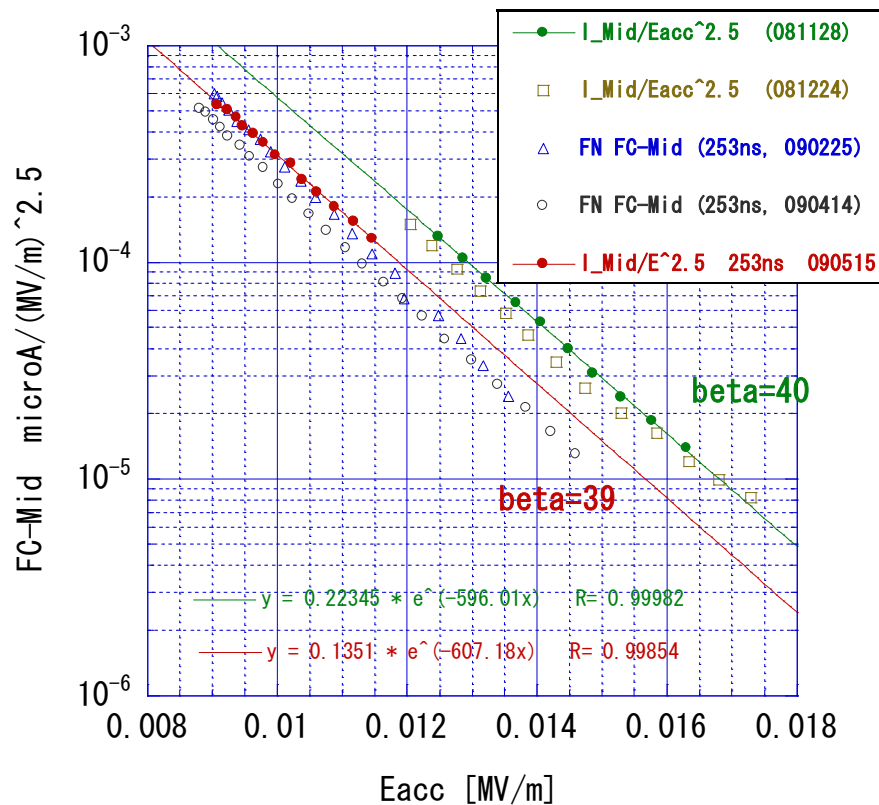
Red real cell timing, blue linear cell timing, 205 ns data

# Dark current evolution 252nsec

T18\_#2 Dark Current evolution  
081128-081224-090224-090414-090515



T18\_#2 Dark Current evolution  
081128-081224-090224-090414-090515

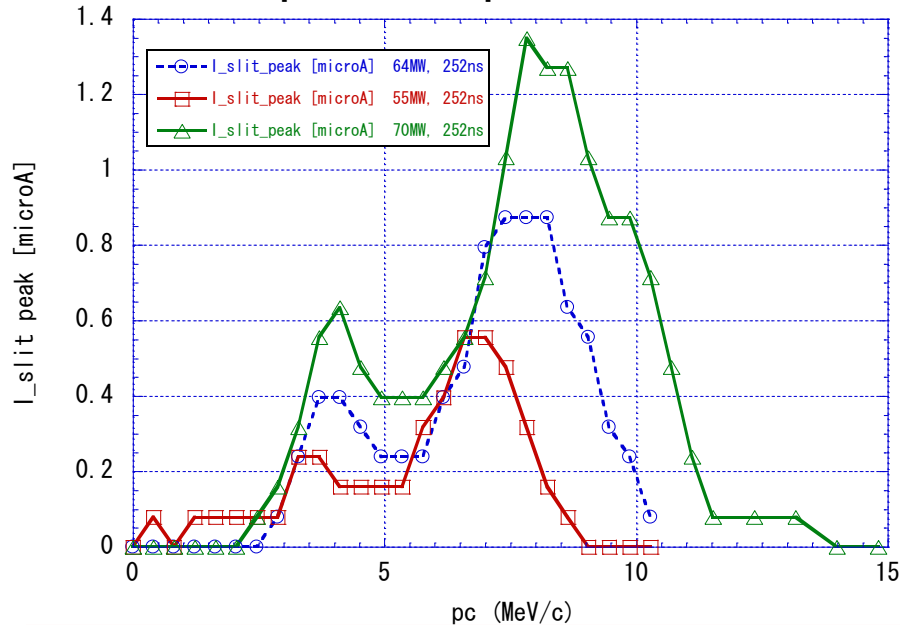


Measured at RF ON 700 – 1200 – 2100 – 3000 – 3400 hours  
Decreasing amount, no big change in shape nor slope (beta).

# Dark current spectra in June

Dependence on power

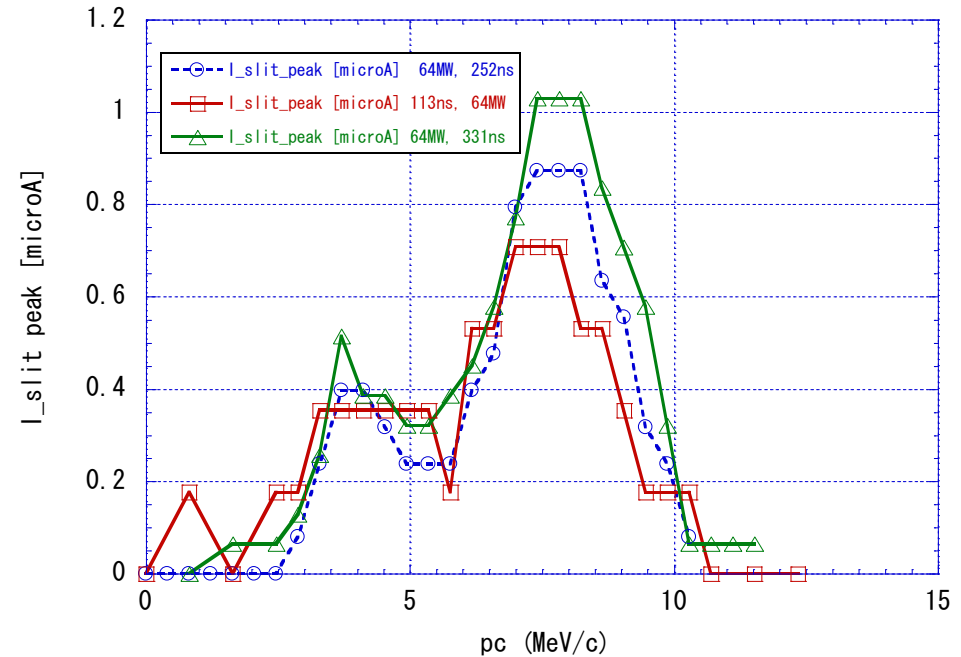
T18\_VG2.4\_Disk #2  
Spectrum\_vs\_power at 252ns



Dependence on width

T18\_VG2.4\_Disk #2  
Spectrum\_vs\_Width at 64MW

090618



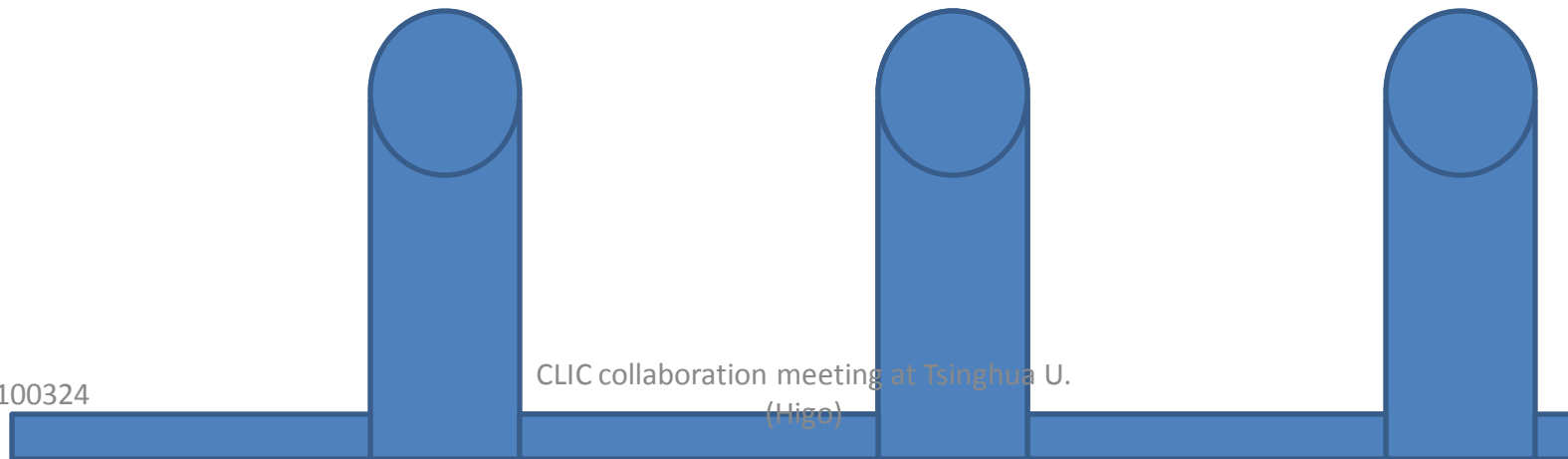
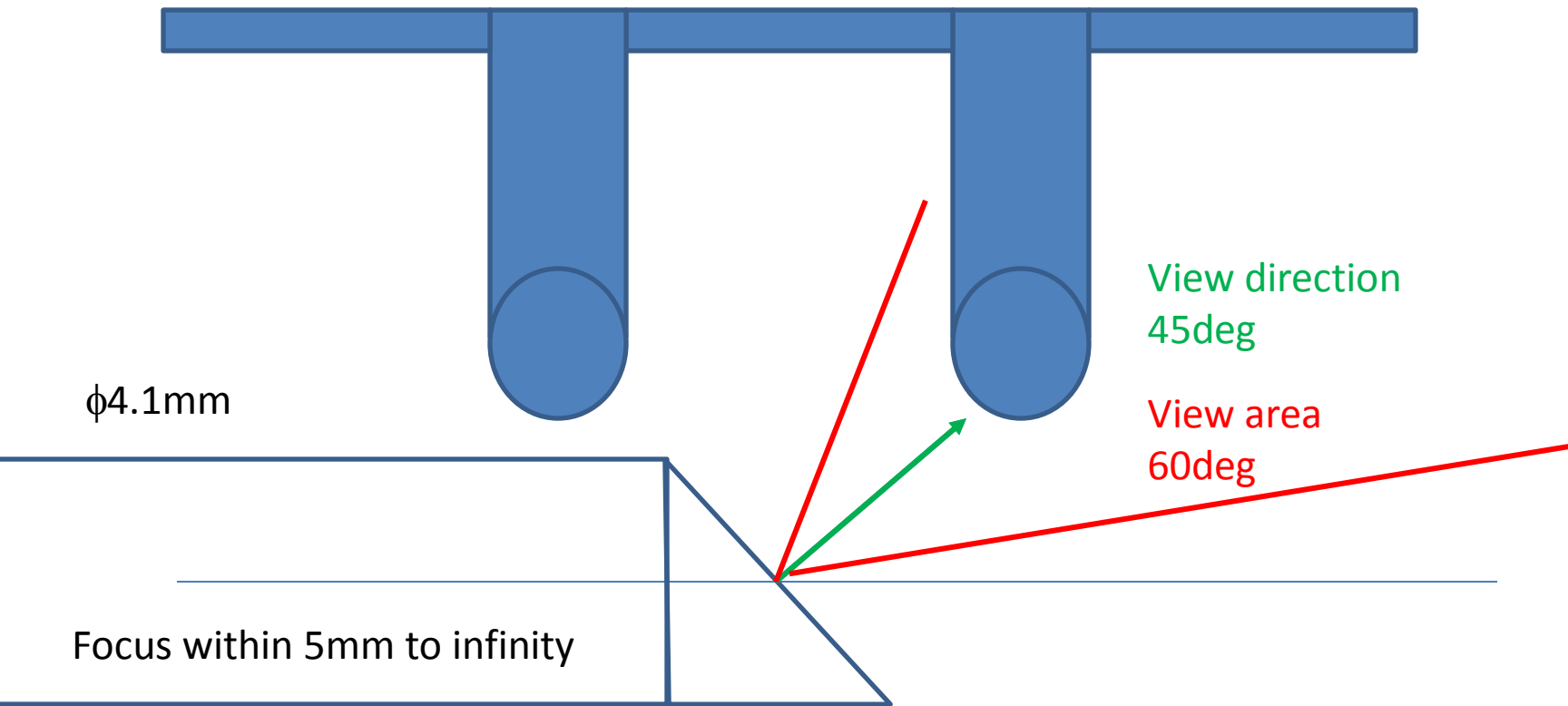
Actual field of analyzer magnet was checked.

The formula used up to now  $pc[\text{MeV/m}] = 1.646 \times I [\text{A}] = 8.23 \times \text{Ref. Volt. [V]}$  was confirmed.

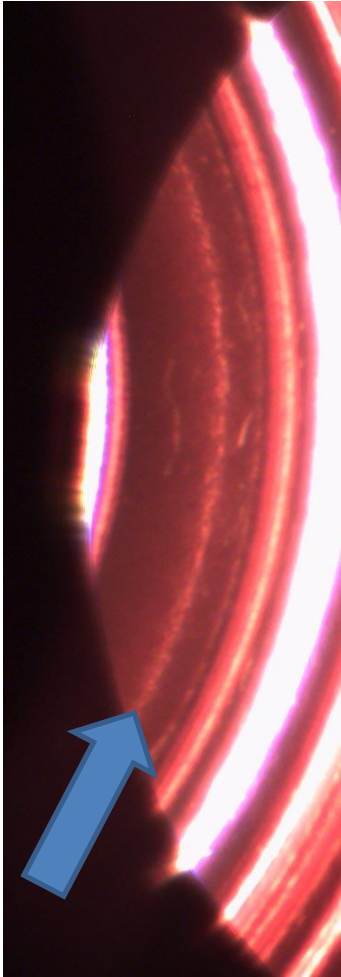
Two peaks appear and higher for higher momentum one.

Less than  $\frac{1}{2}$  of full acceleration.

Little exists below 2.5MeV/m.

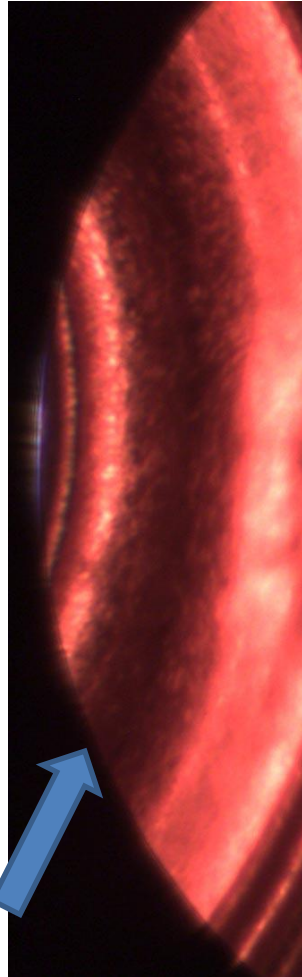


# Optical inspection upstream and downstream

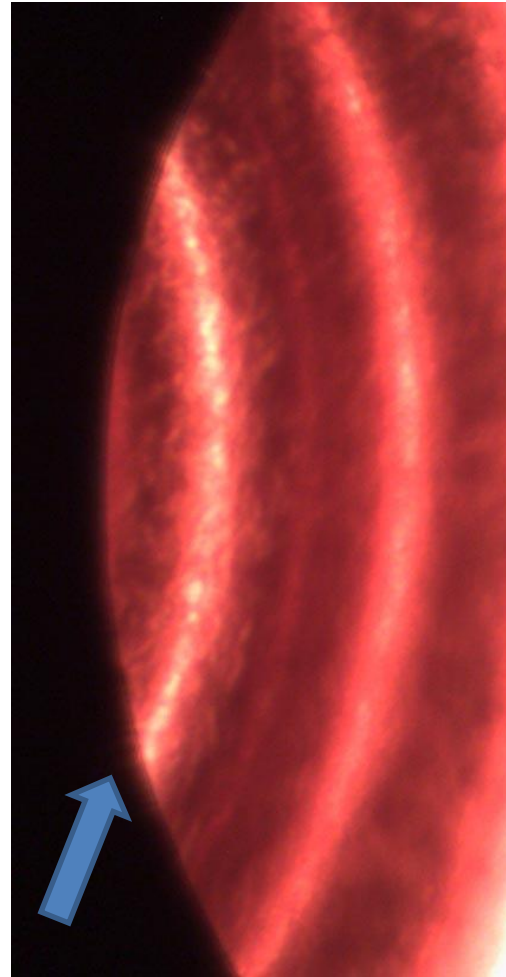


Insertion 82.7mm  
Iris #1 at match cell

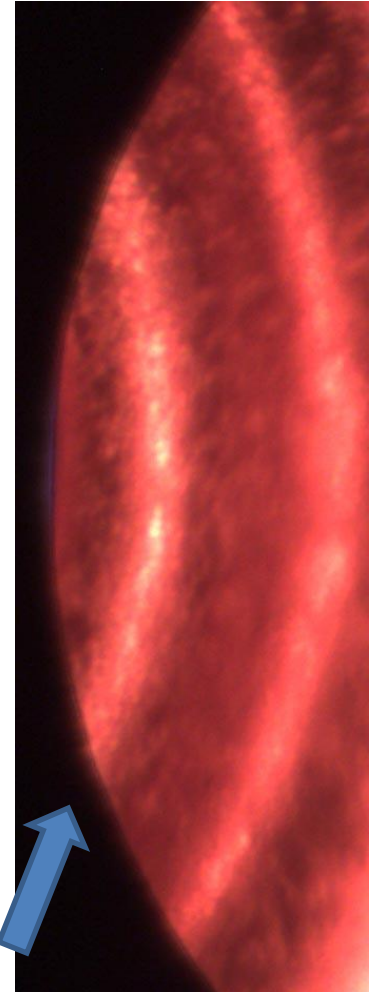
20100324



Insertion 98.0mm  
Iris #2 at first  
regular cell



252.2mm Iris #19  
Down side iris of last  
regular cell



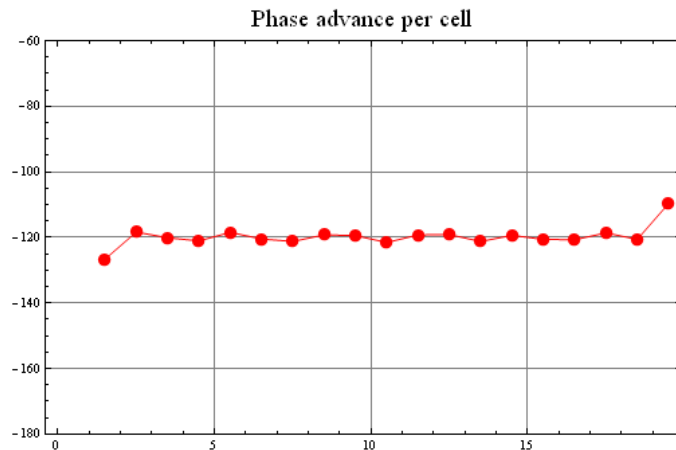
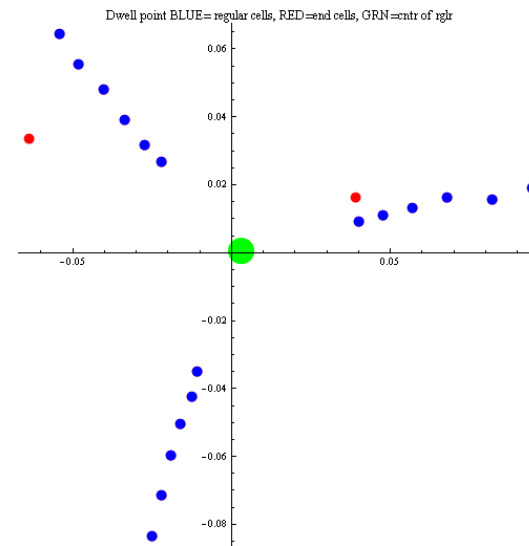
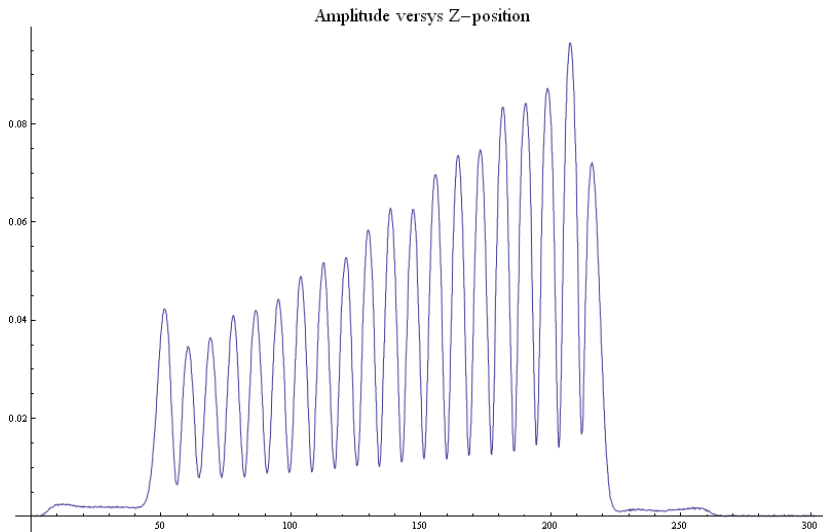
261.3mm  
Last regular cell iris #20



# Optical inspection result and future

- No significant variation as cell position was observed
  - Though more breakdowns happened downstream end estimated from RF pulse shape
- Need to inspect with better spacial resolution
  - Change to better bore scope or adjust focal plane?
  - Should be inspected by SEM

# As of completion, meas. By J. Lewandowski



11.42128MHz@119.754deg/cell

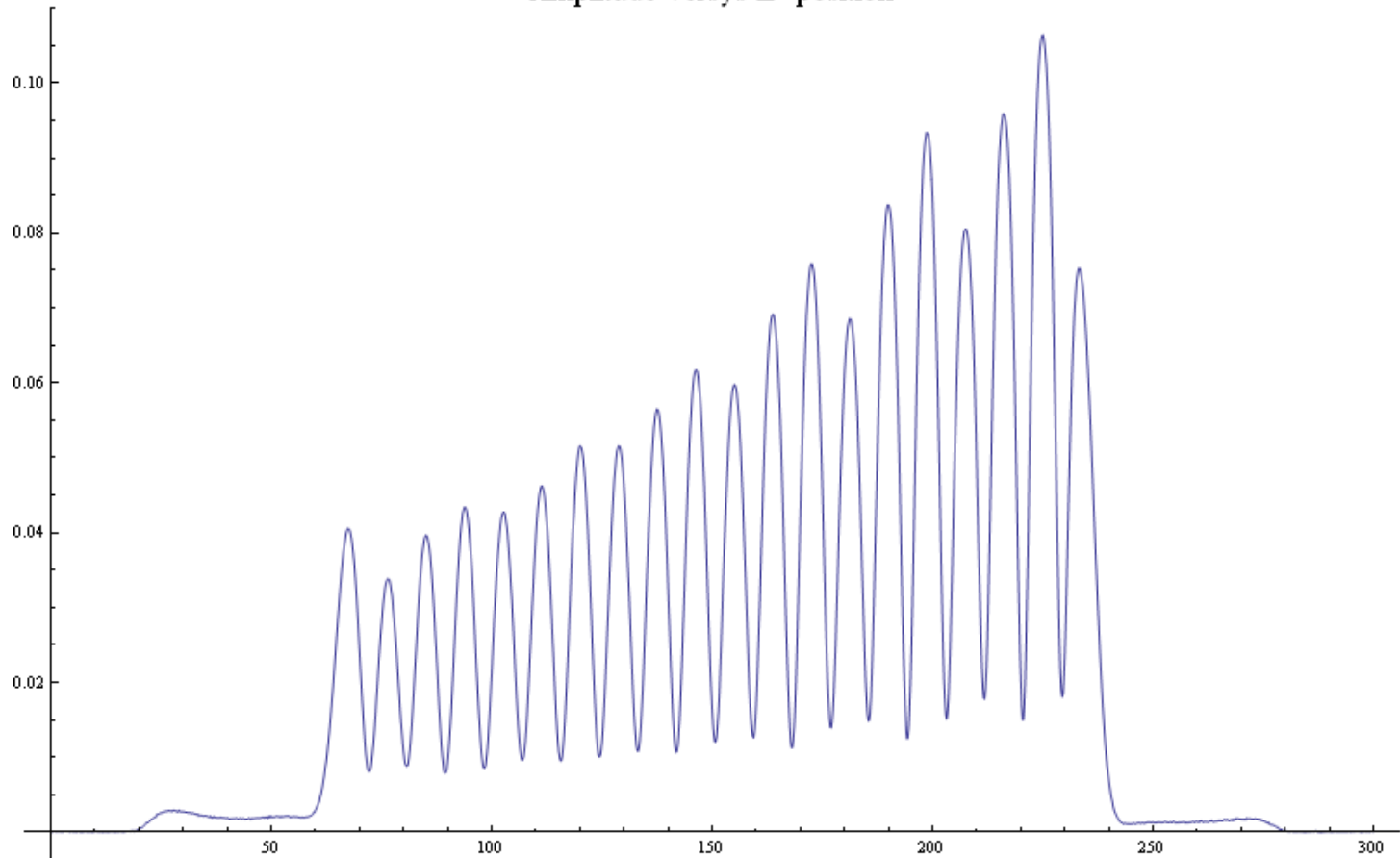
at 22.3degC

11.4233MHz at 30C in VAC

→ -0.7MHz than nominal

# Bead pull amplitude plot 11422MHz after high gradient test

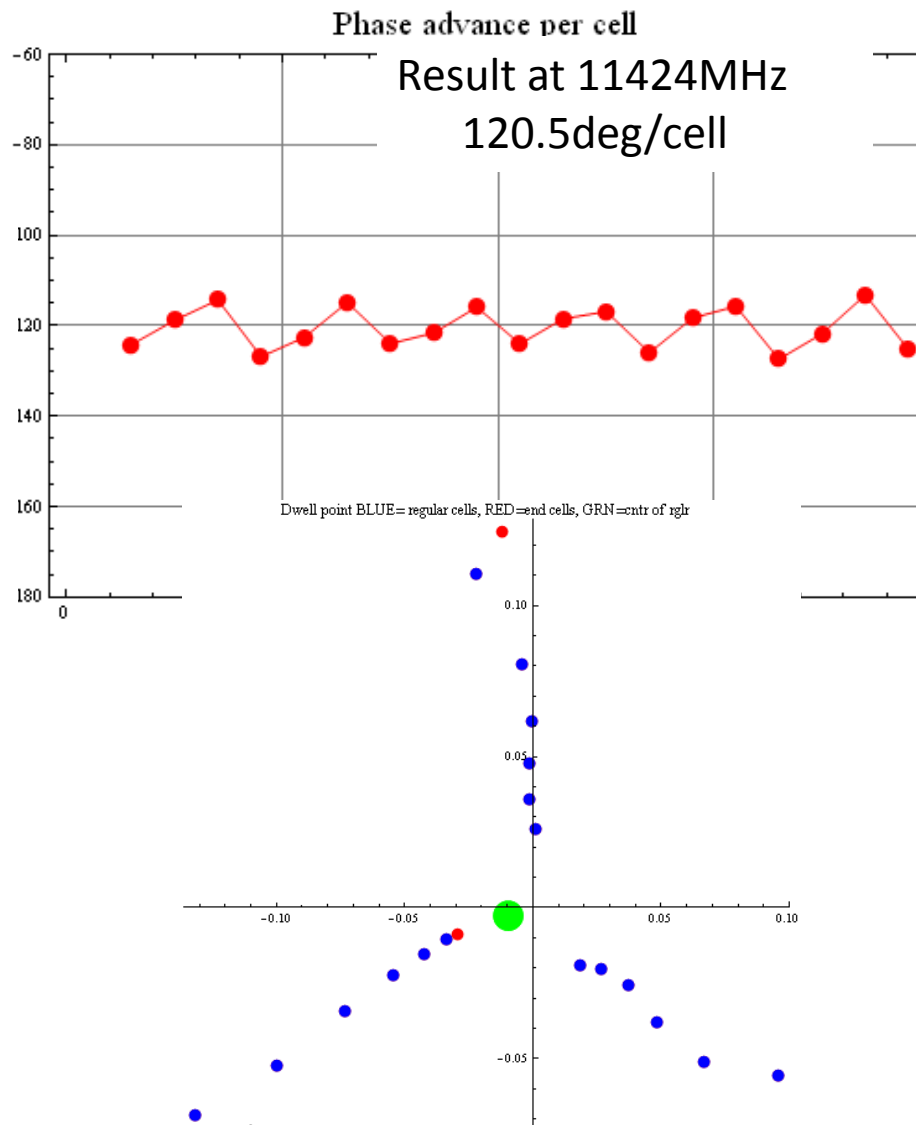
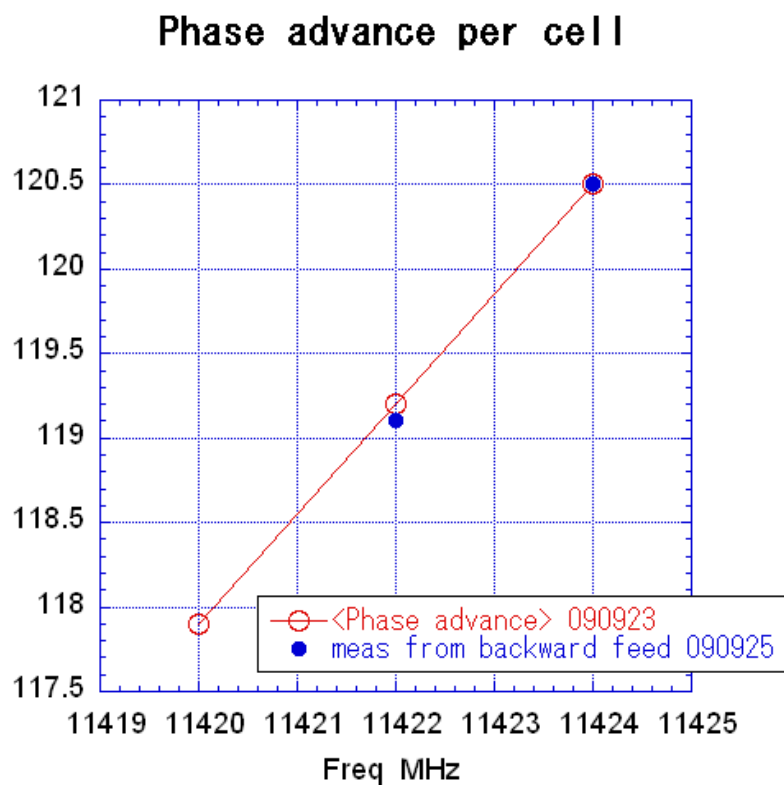
Amplitude versus Z-position



Input side

Output side

# Phase and frequency after high gradient test



# RF change due to high gradient test

- RF evaluated after high gradient test for 4000 hours with 2500 breakdowns in 800M pulses.
  - Input matching was kept.
  - Output matching changed by  $\Gamma=0.05$  level.
  - Average frequency increased by  $1.1+0.7=+1.8\text{MHz}$ .
  - Field ripple  $\pm 4.4\%$  appeared near output end.
- Above change in RF performance was observed.
  - Need to confirm carefully with SLAC data.
  - If this is due to the actual structure change, not tolerable.  $\rightarrow$  Need the number of breakdowns be limited until reaching operation.

# T18\_Disk summary

- 100MV/m was proven to be feasible
- Similar breakdown rate between SLAC and KEK
- Breakdown rate decreased as processing proceed
- Breakdown probability is higher in downstream cells
- Dark current can be fit with modified FN formula
- Dark current decreases as processing proceeds
- No big change in field enhancement value
- Dark current dominates in low energy region, from a few down-stream cells
- RF property seems changed due to the processing
- Long-term operational stability should be proven

# TD18\_Quad\_#5

- Aim
  - Study the structure split in longitudinal plane
  - Taste the one with 50 micron radius at the edge
- Design geometry
  - Large damping aperture
  - Big increase of gradient toward downstream
  - Big pulse heating temperature rise at the damping port opening

# KEK's version: 50 micron chamfer

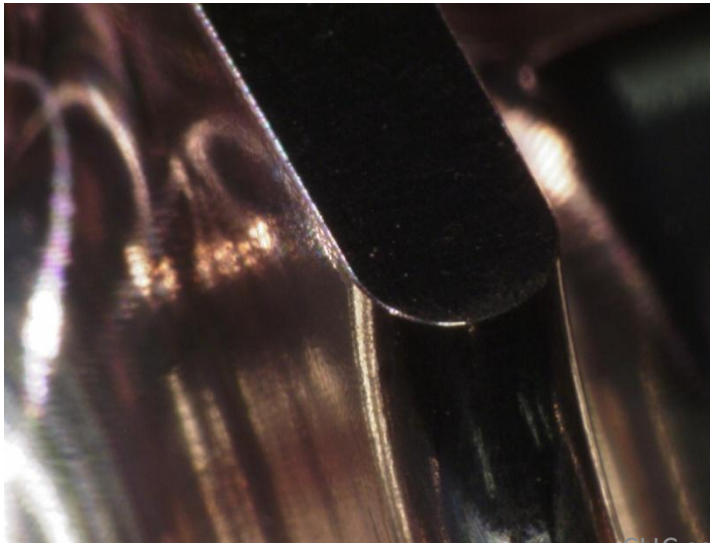


Made of **CuZr** without heat treatment.

**50 micron rounding**: shape with **angles and bumps**.

**Reference planes** were formed by milling in a **few micron level** without re-chucking for shaping cells.

**Assembly** was done within **ten micron level**.

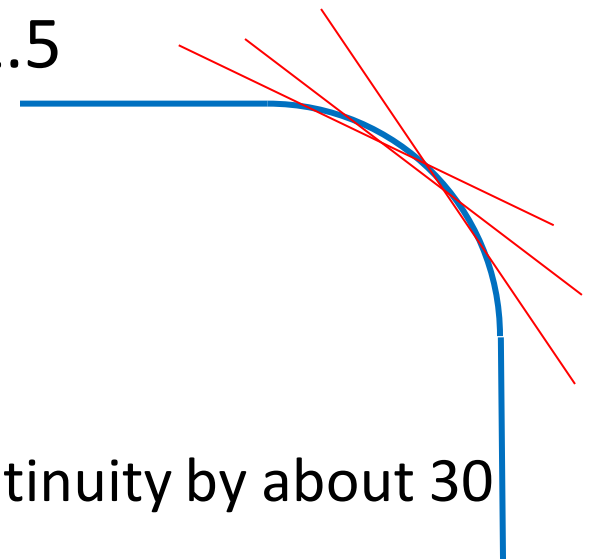




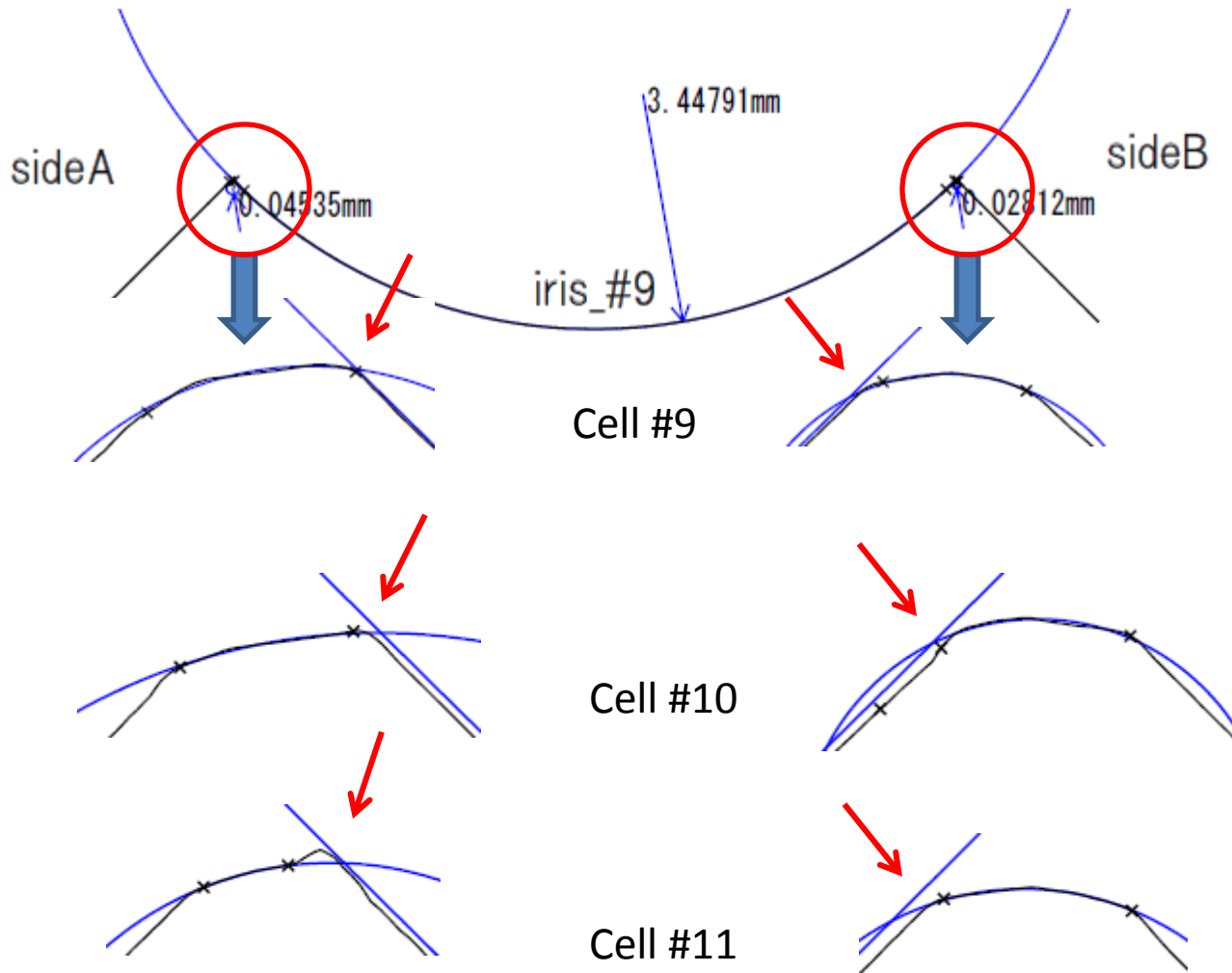
# Possible cause of high dark current

## Field enhancement due to round chamfer

- Simulation of field enhancement
  - 1.4 ~ 1.6 at radius
  - with  $\text{gap} < \text{radius}/5$ ,  $\text{step} < \text{radius}/2.5$
- Only a few tool passes
  - to shape 50 micron radius
  - with radius tool of 2mm
    - If three passed  $\rightarrow$  tangential discontinuity by about 30 degree
    - Can be relaxed by such as EP in future



# Detailed shape at R0.05 chamfer



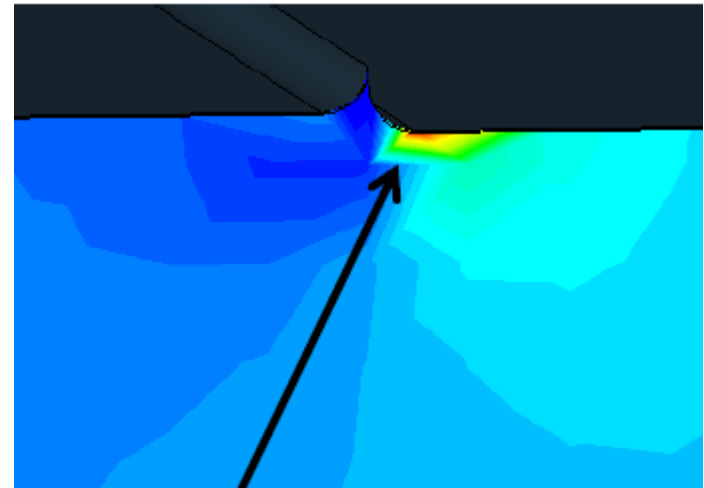
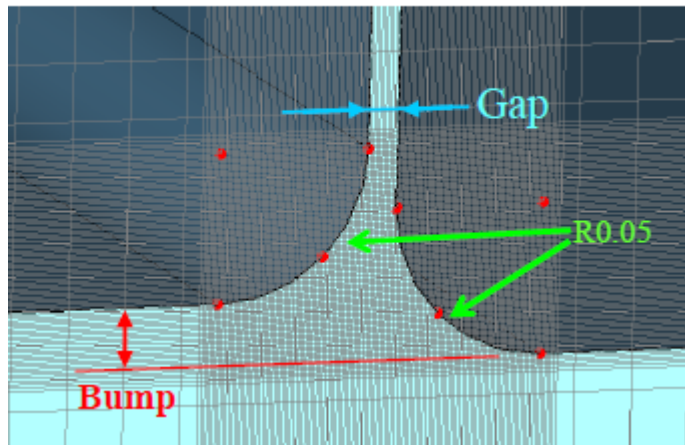
Only 2~3 tool passes over  $R0.05$  90deg rounding.

Not tangential connection from smooth surface. 30-40 degree edge emerges.

Sharp edges or bumps exist at the rim.

# Electric field enhancement in a shallow channel with round chamfer

Calculation done by T. Abe by CST MS. Waveguide field.



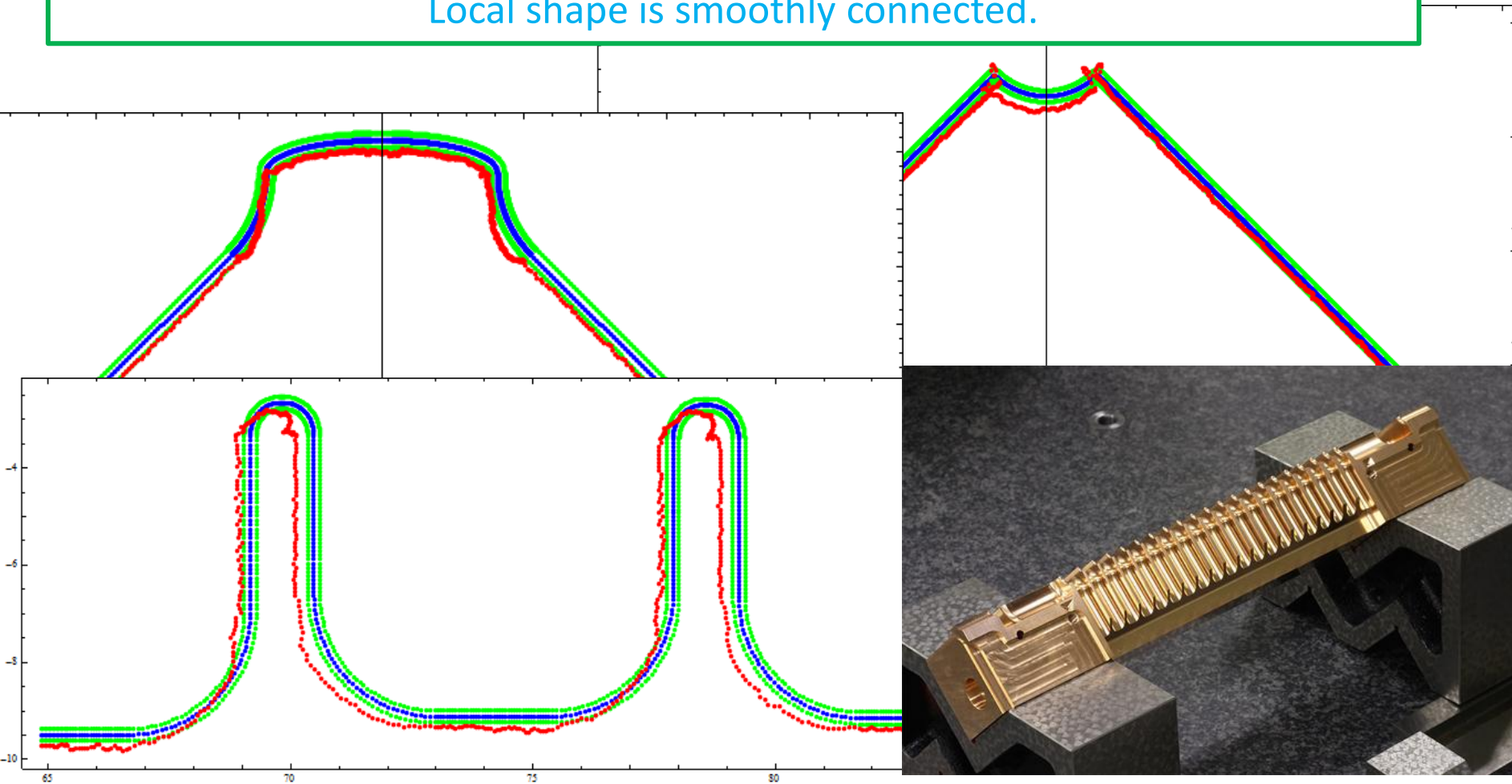
Gap (micron)	Bump (micron)	$E_{max} / E_{nominal}$
0	0	1.39
0	20	1.57
10	20	1.58

# Production of quadrant Q1-1

Green lines are  $\pm 2.5$  microns.

Followings shows worst part out of four measured areas along the axis.

Local shape is smoothly connected.

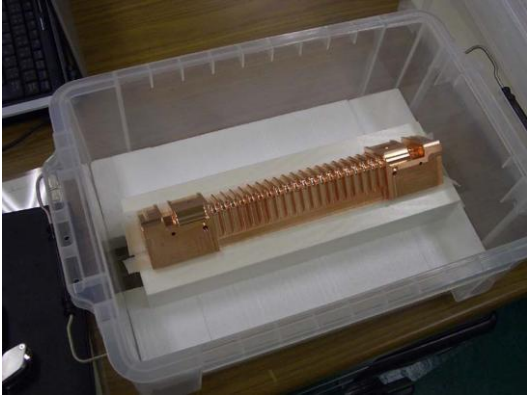


# Surface: No etching

## No high-temperature heat treatment

- Alcohol bath
  - with ultra-sonic vibration for 5 minutes.
- Acetone bath twice
  - with ultra-sonic vibration for 5 minutes.
- Nitrogen blow
- Storage in a deccicator
  - Initially filled with nitrogen gas.
  - Storage for more than a month.

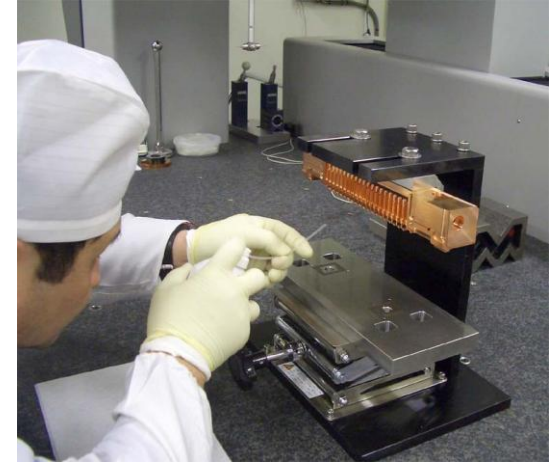
# Assembly



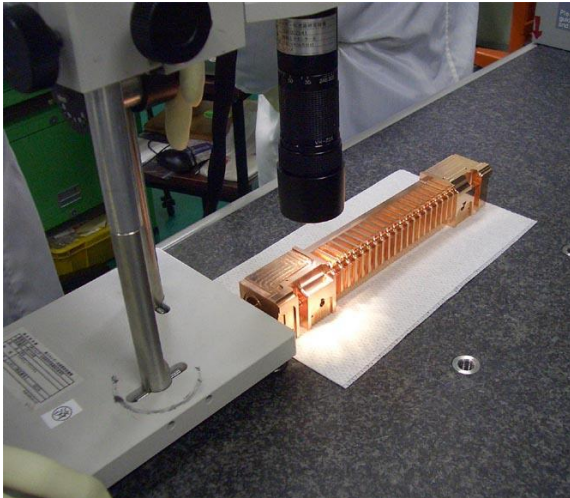
Carry and storage



First hanging



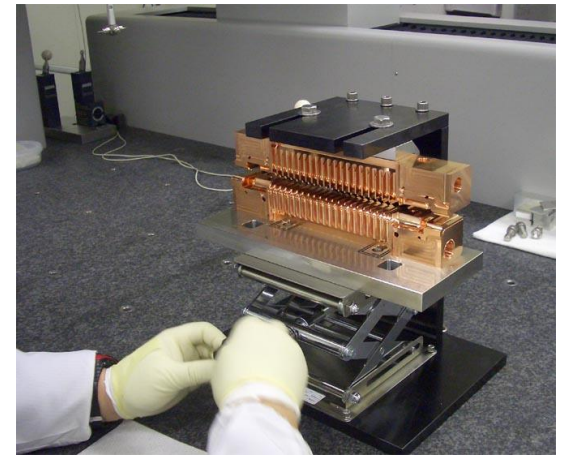
Prepare next quad approach



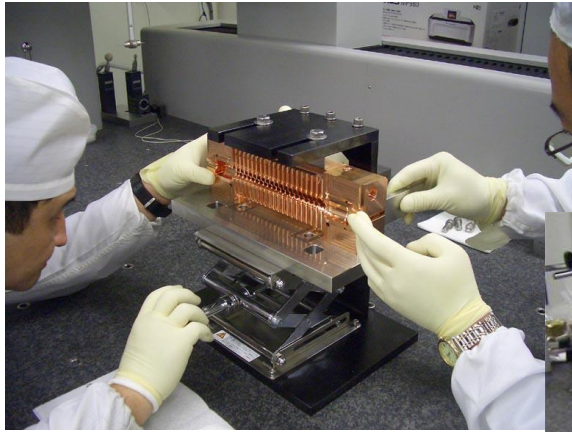
Edge inspection



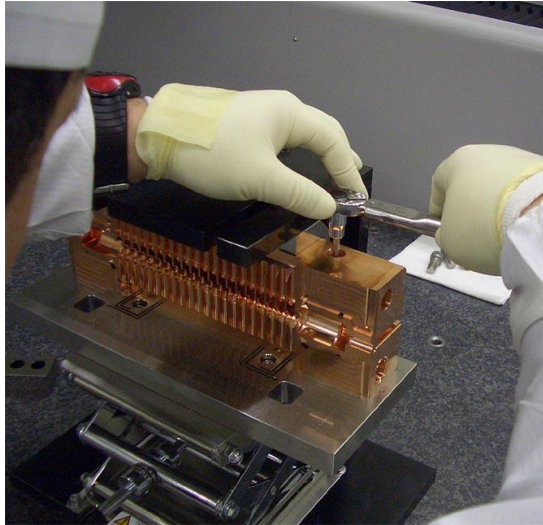
Check ball diameter



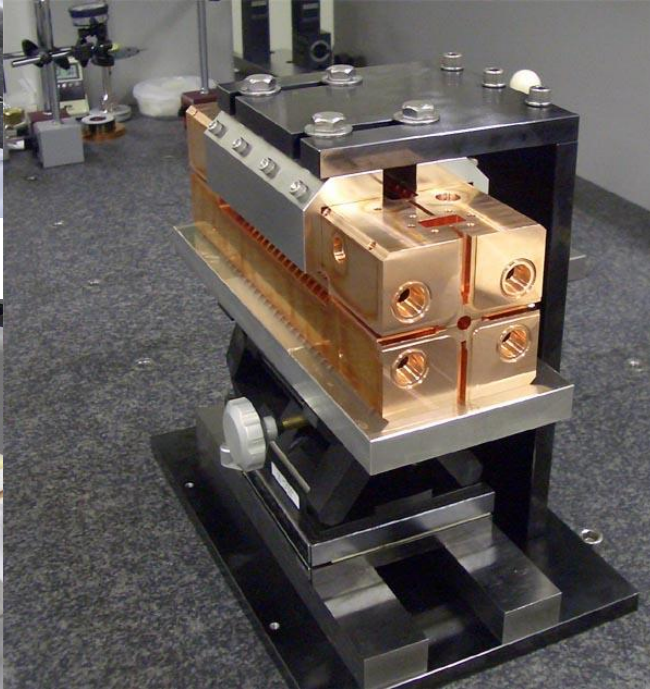
Second hanging



Fine adjustment



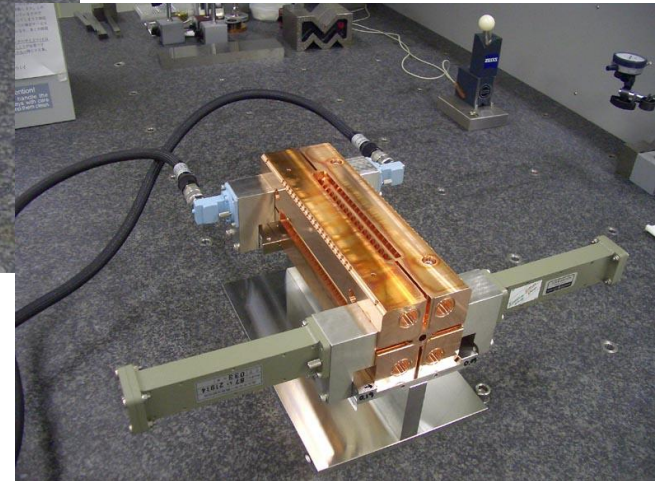
Fixing by bolt



Completion of stack



Alignment checking



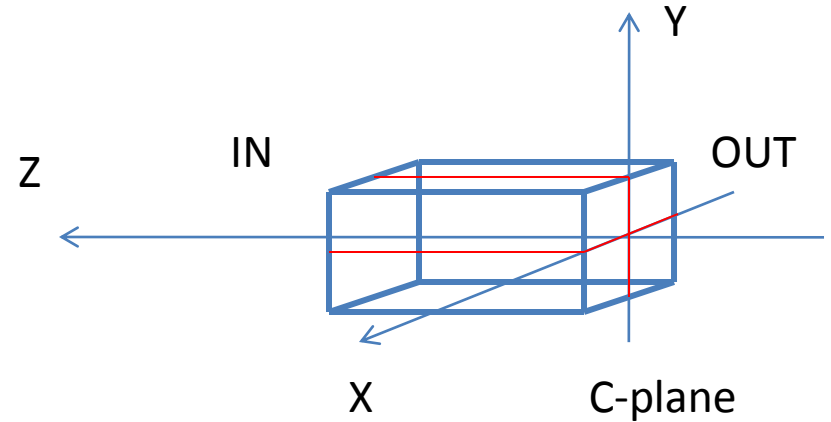
RF setup

Manual adjustment before final pressing, without ball and groove mechanism. Misalignment: within ten microns.

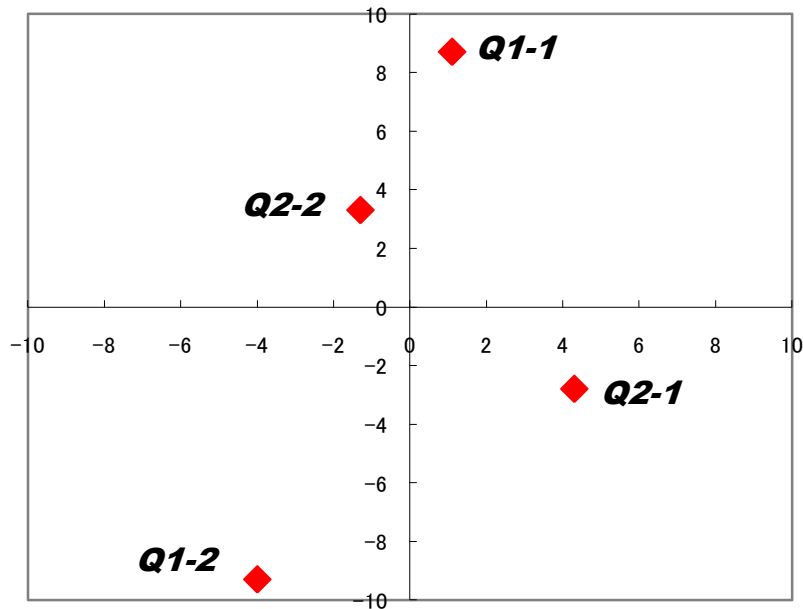
Reproducibility: a few microns. CLIC collaboration meeting at Tsinghua U.

# Final alignment

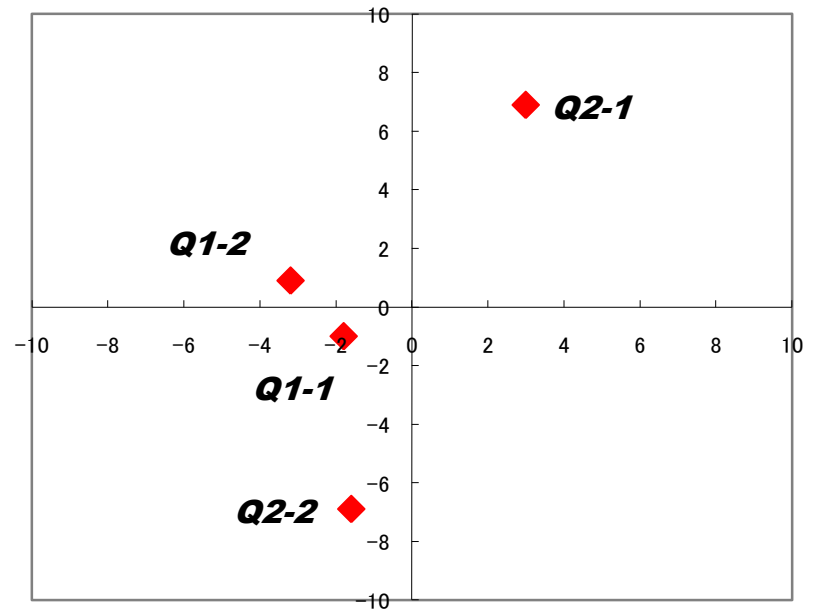
Misalignment of each quadrant  
w.r.t. the average of four quadrants  
(units are in micron)



Input side

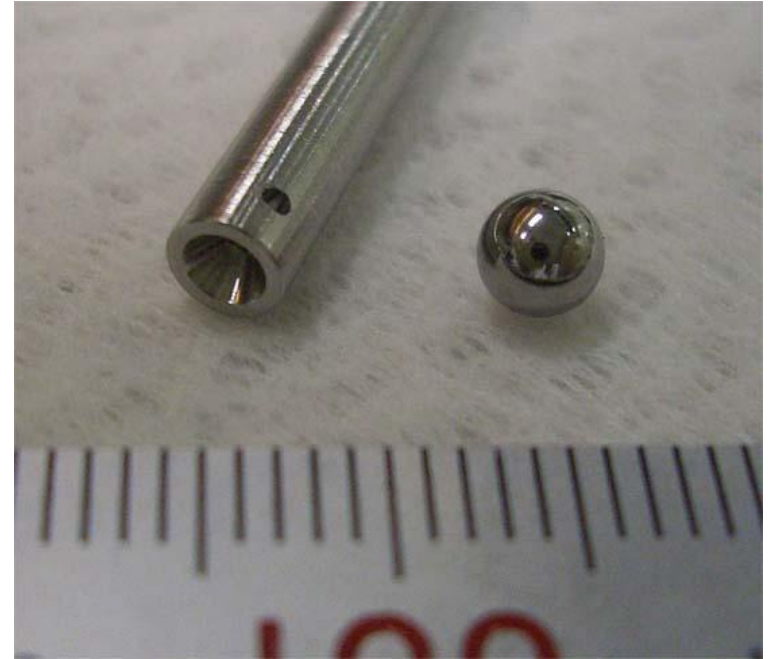
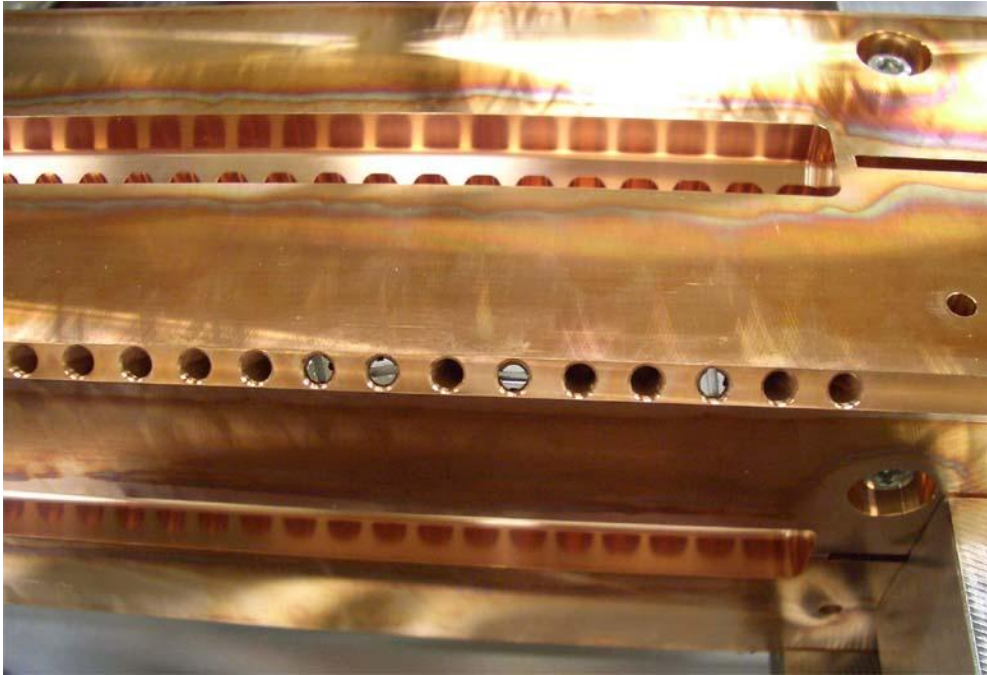


Output side (C-plane)



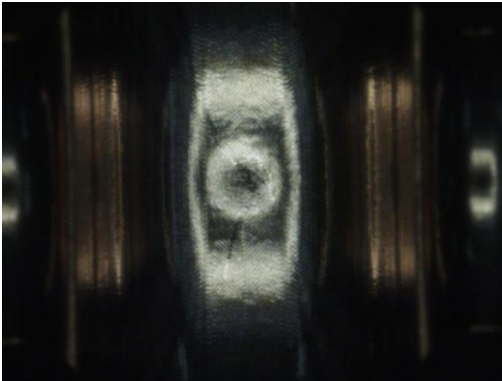


# Elastic tuning with a ball being kept push

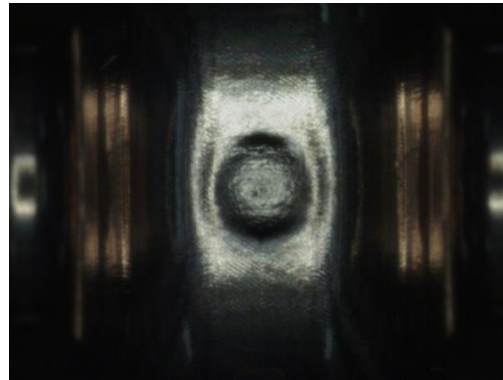


4mm stainless ball pushed by minus watch driver.  
Pushing by turning with Higo's hand full force.  
Elastic deformation kept, meaning that the tuning pins  
are kept pushing the balls.

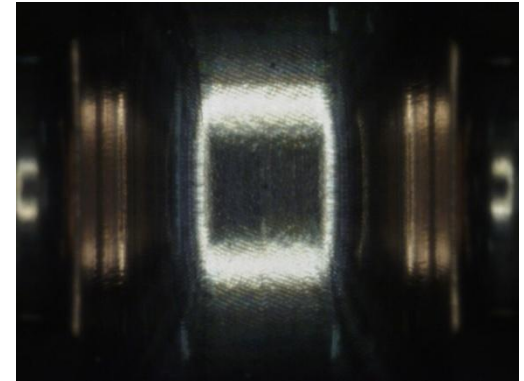
# Notice: Deformed cavity wall



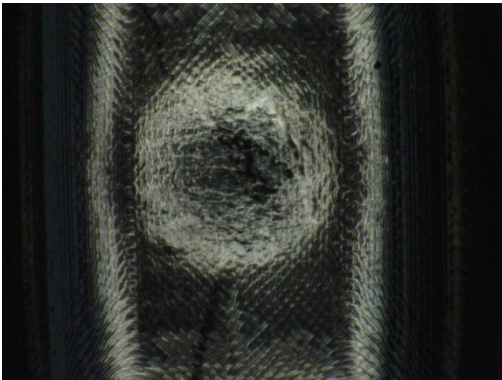
Cell 3( × 35)



Cell 8( × 35)

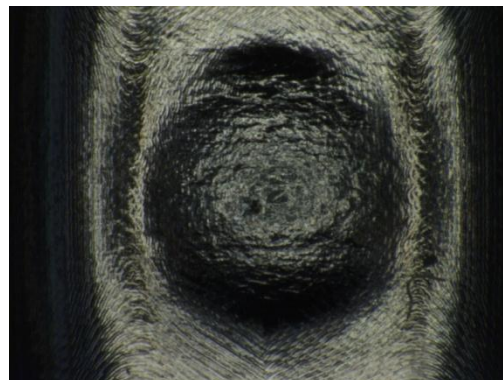


Cell 10( × 35)



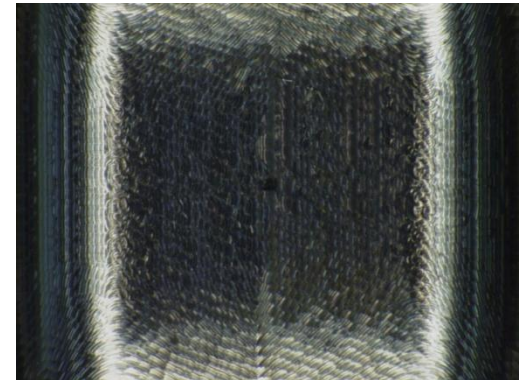
Cell 3( × 100)

Cell3 deformation: 0.053mm



Cell 8( × 100)

Cell8 deformation: 0.167mm

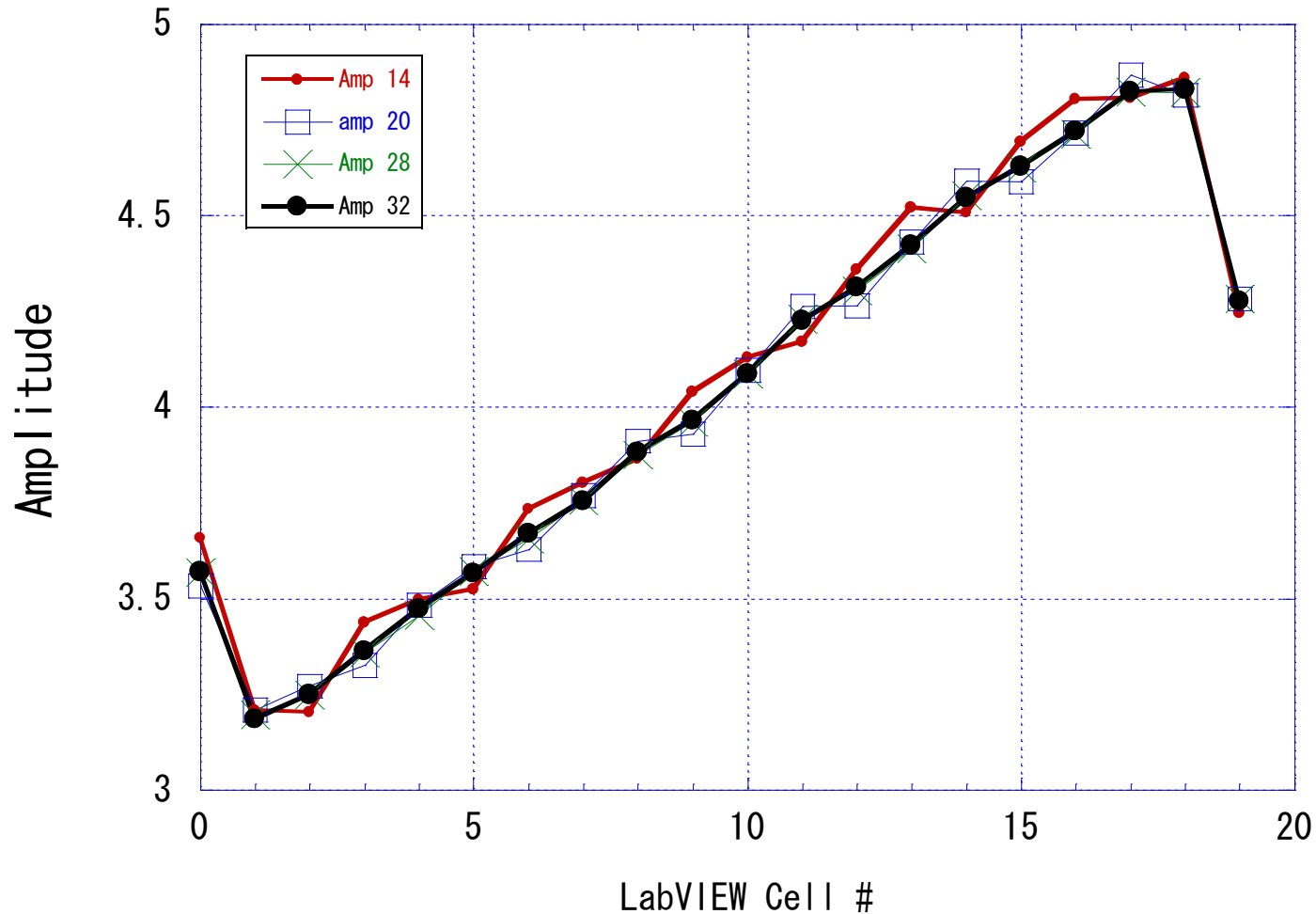


Cell 10( × 100)

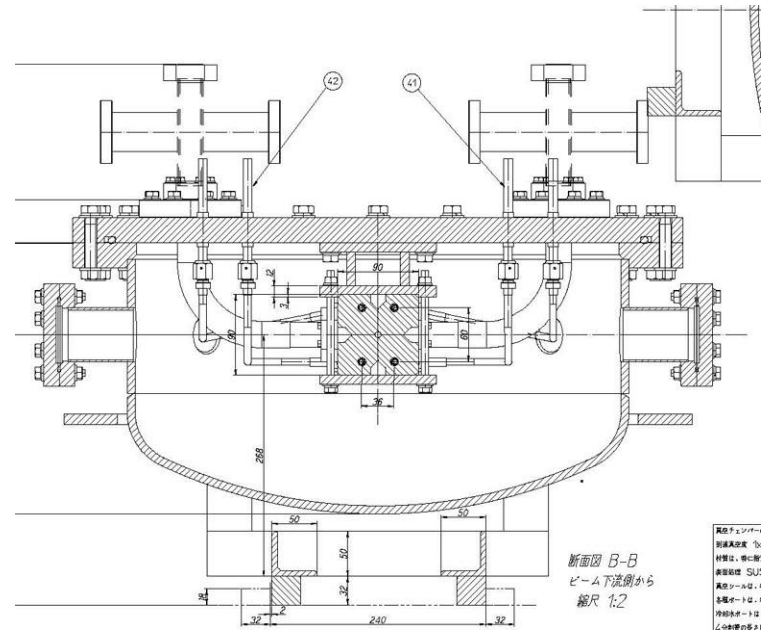
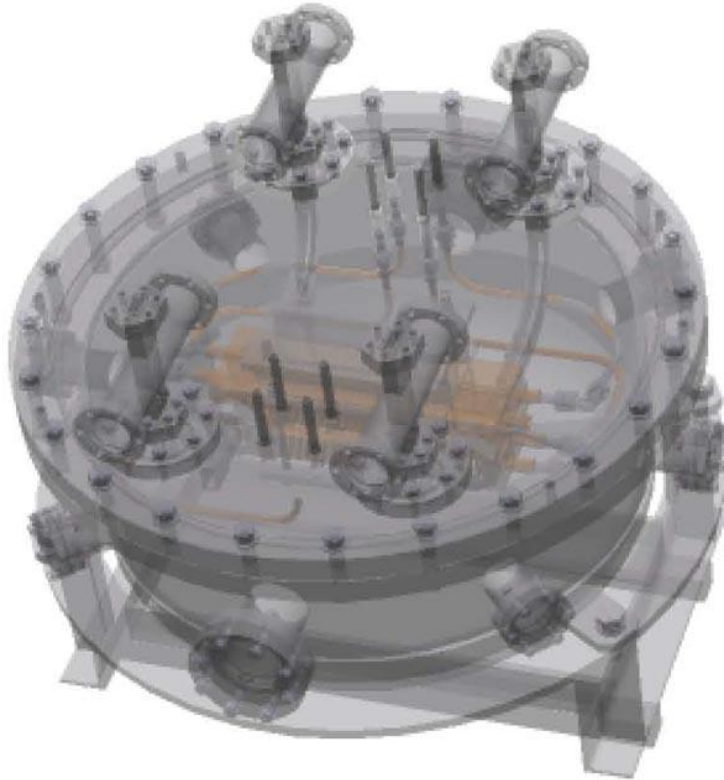
Cell10 no tuning

# Field smoothness after tuning good.

Raw amplitude of bead pull measurement  
bead pull # 14-20-28-32



# Vacuum chamber design



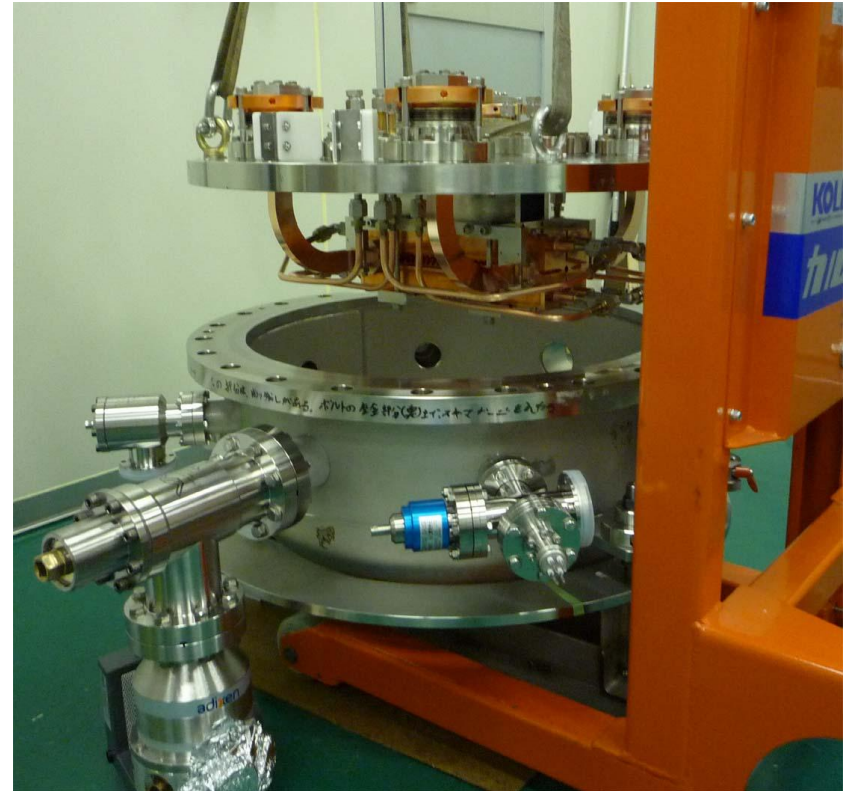
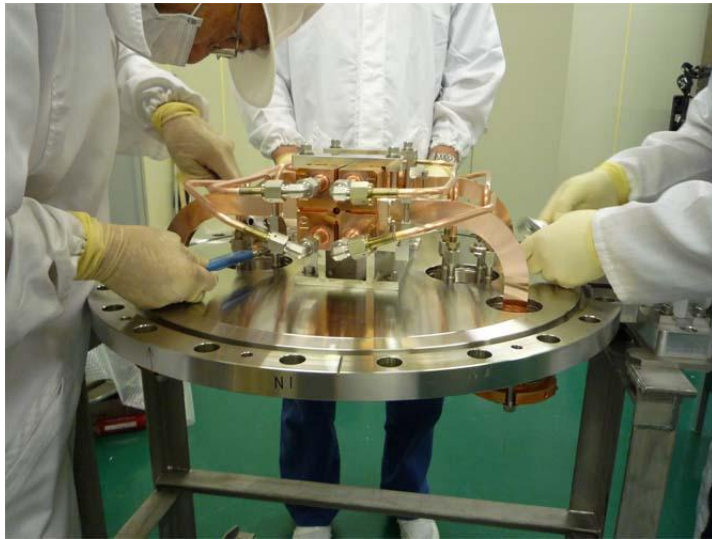
U-tight seal (round metal gasket)

VCR connector for cooling water connection

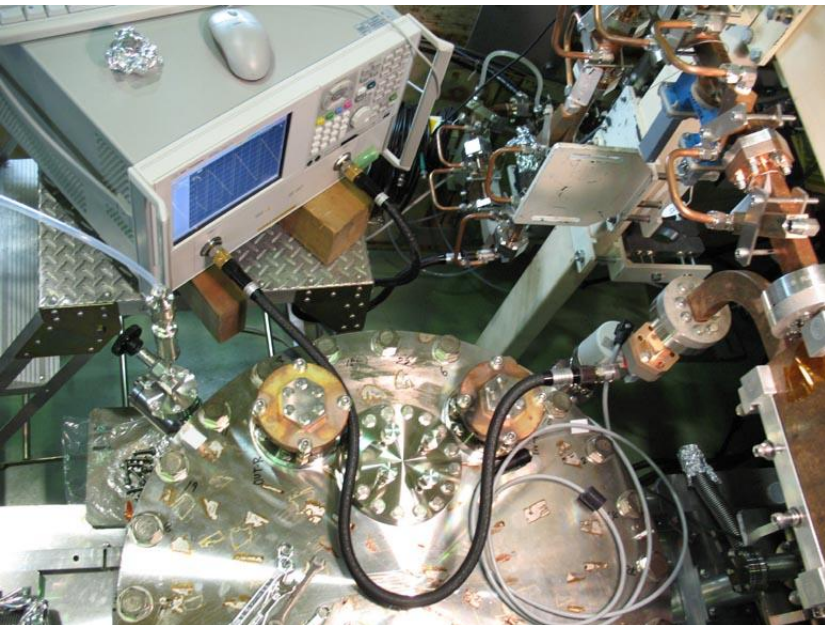
Thin H-bend being vac sealed with bellows

Vac evacuation from CF114 mounted on chamber with IP 70l/s and from WR90 at just 0.5m from structure

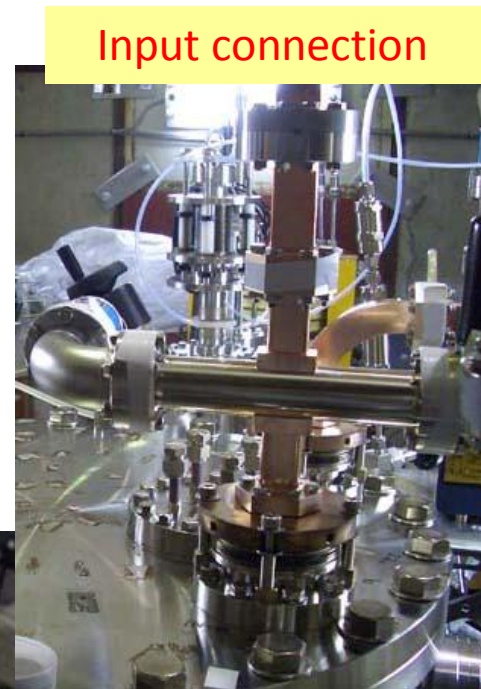
# Installation into chamber



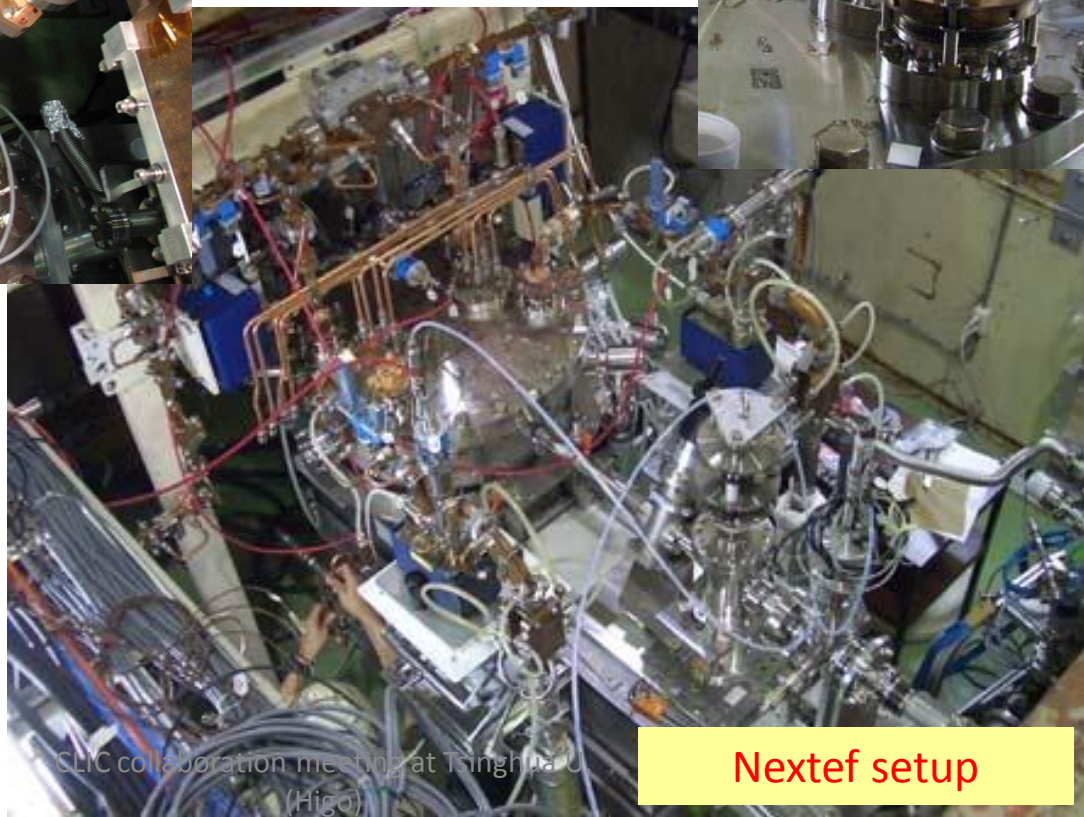
# Installed into Nextef



3dB phase check

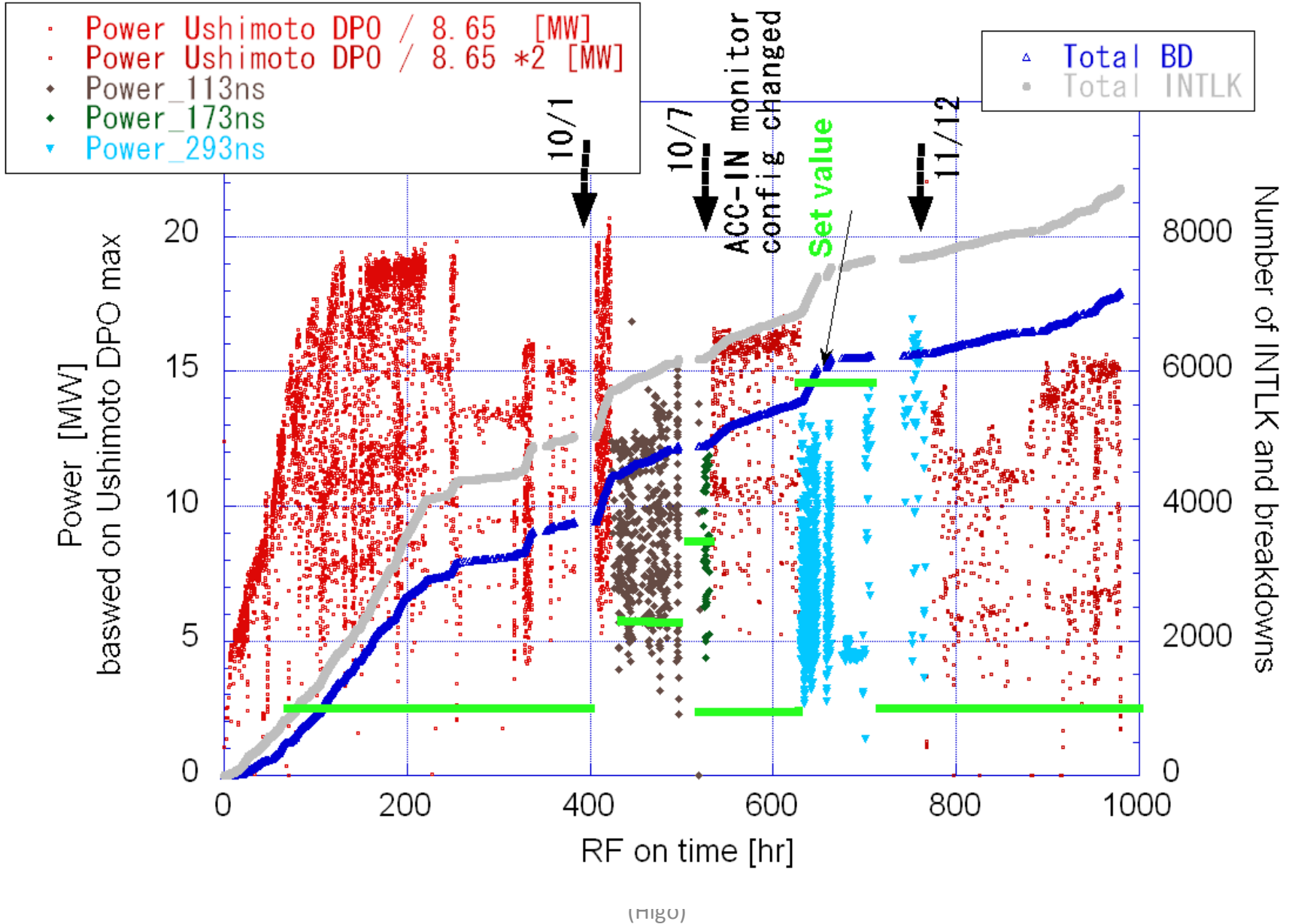


Input connection



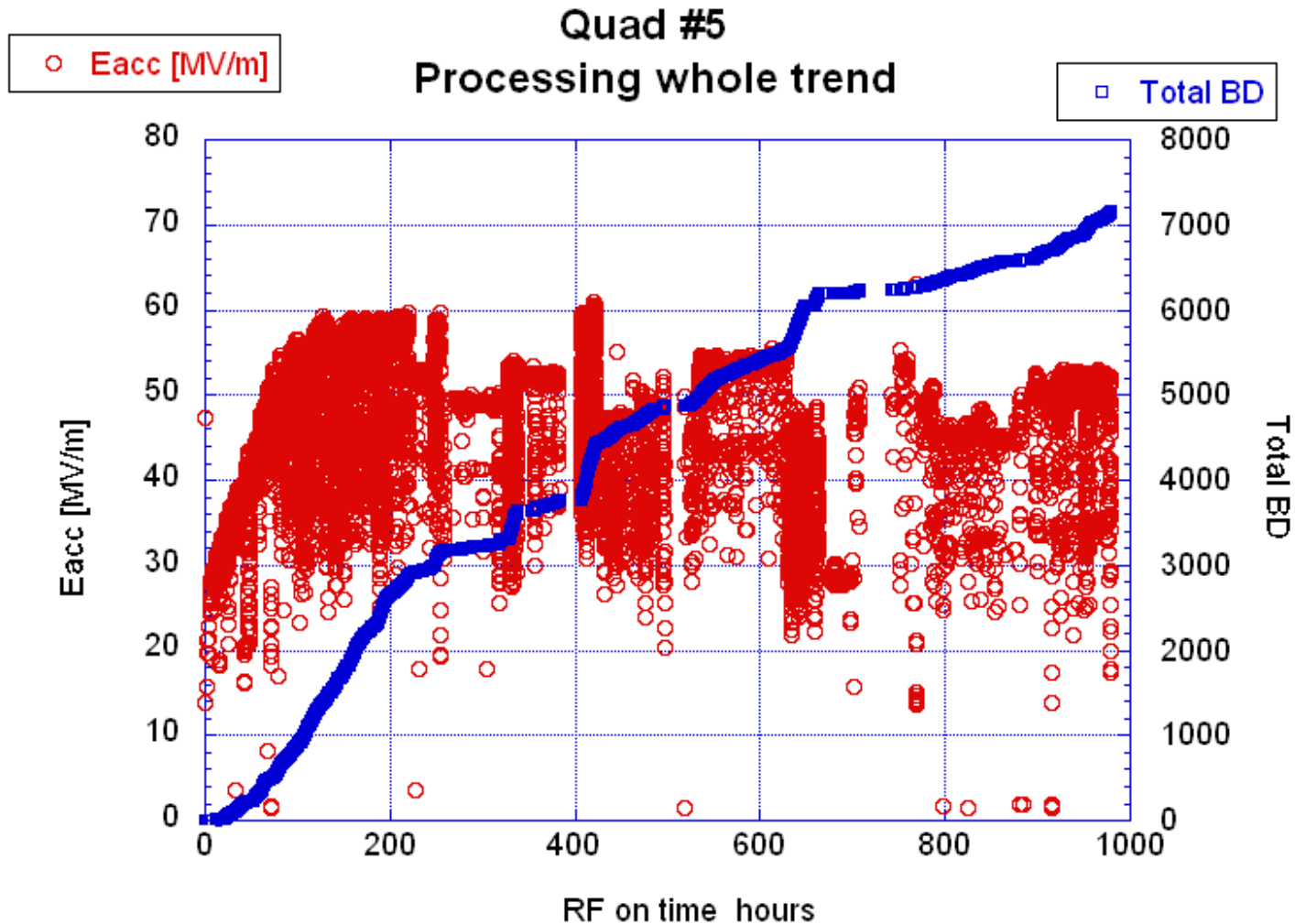
Nextef setup

# Quad #5 Whole Processing



# Gradient limited at 50~60MV/m

50nsec

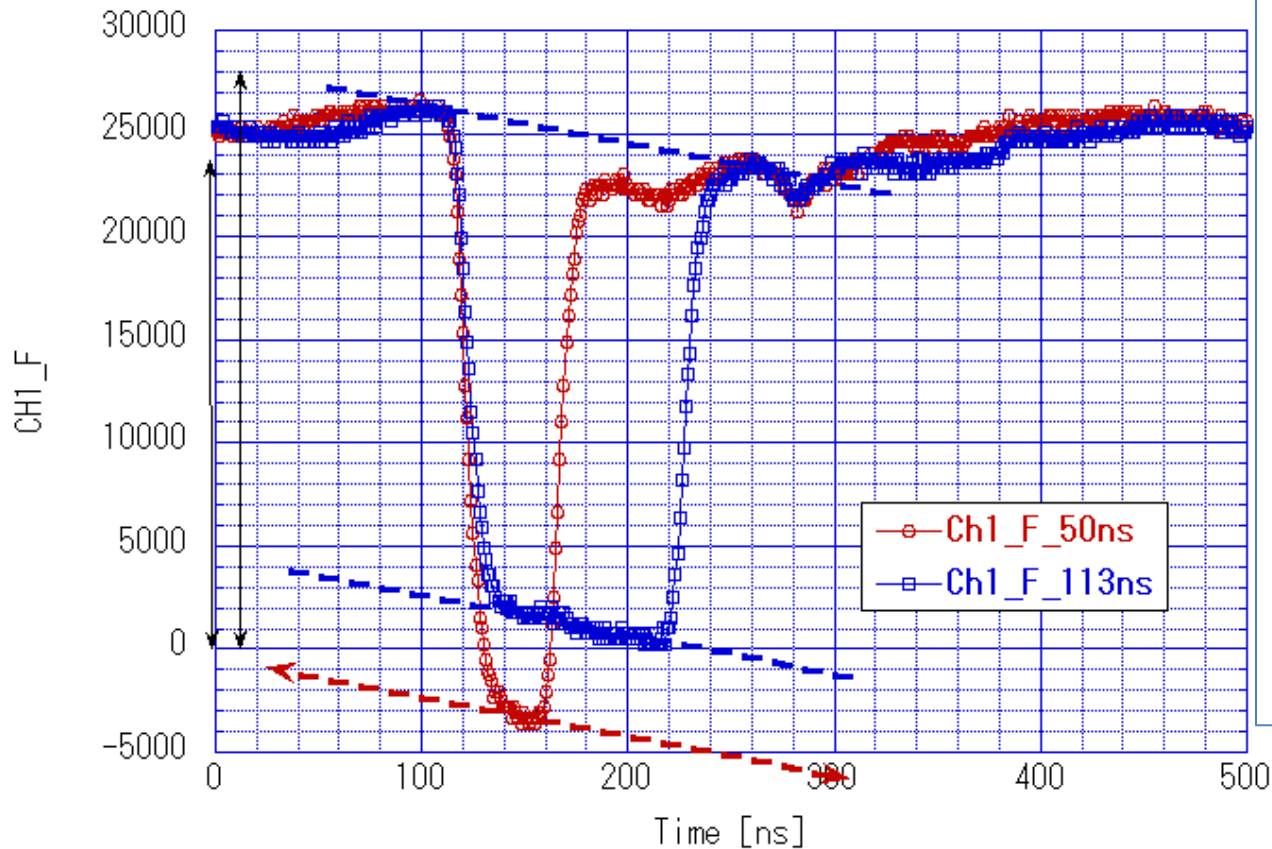




# ACC-IN pulse at hard limit

Run4\_090926\_050209\_1 51ns

Run11\_091004\_19244 113ns



Tp(ns)

51 113

Power (MW)

19 14

Ea (MV/m)

59 50

Sqrt(Tp)\*Power

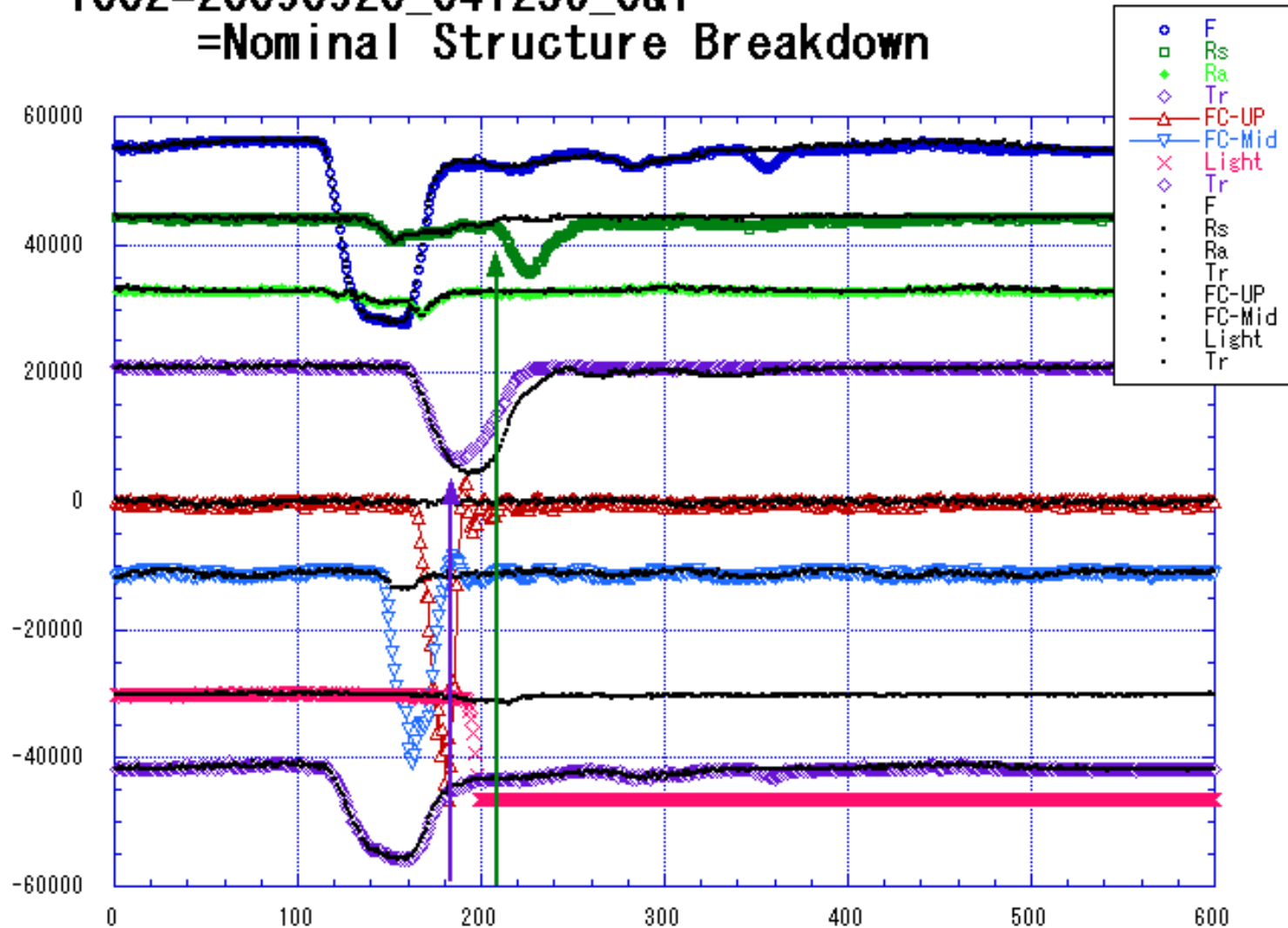
135 147

# Vacuum characteristics

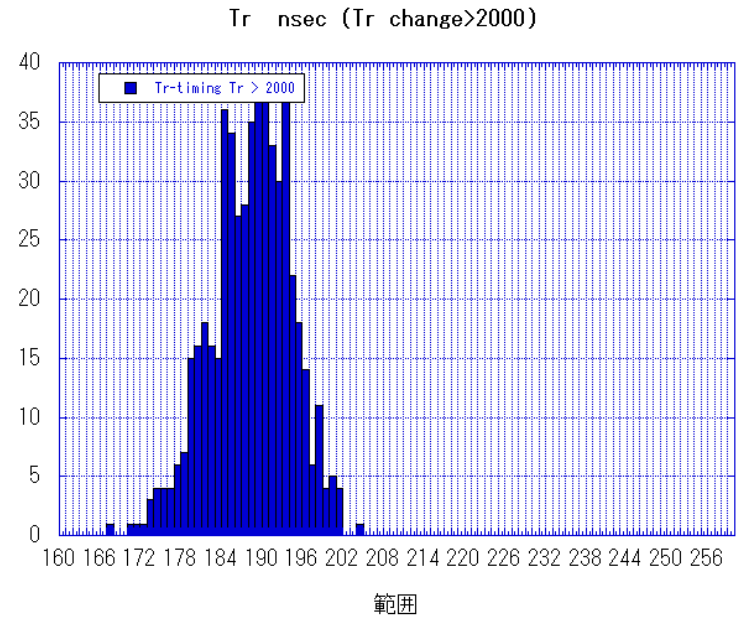
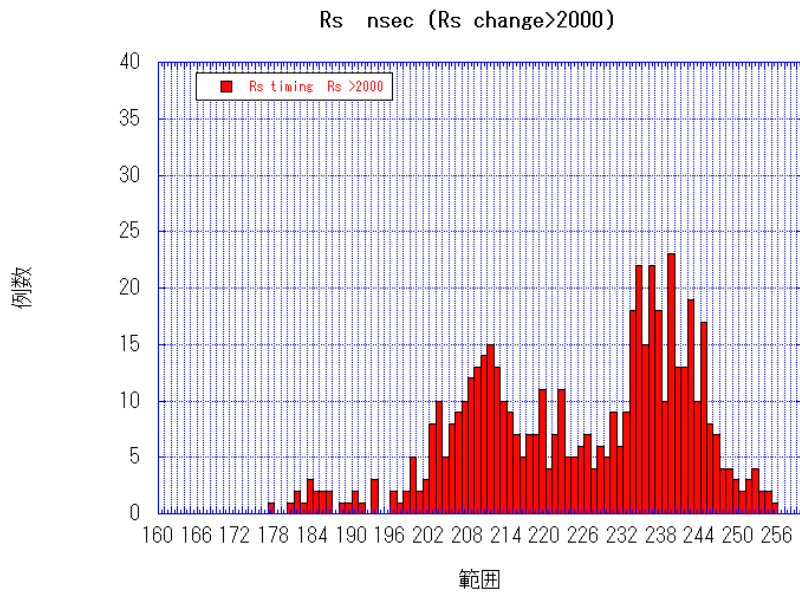
- Vacuum total pressure
  - Base pressure at  $<10^{-6}\text{Pa}$
  - Typically processing  $<10^{-5}\text{Pa}$
  - Increases every time at few to 5MW range if **after RF-OFF** for more than several hours
- Mass spectrum
  - **M=2, 28 and 44** increase with RF-ON, but **not M=18**
    - Especially when reaching power limit
  - **M=2 becomes dominant** residual gas after an hour or so run
  - M=27 and 28 change in a similar manner as time, **indicating hydrocarbon-origin** surface contamination

# Breakdown pulse analysis

1002=20090920\_041256\_0&1  
 =Nominal Structure Breakdown

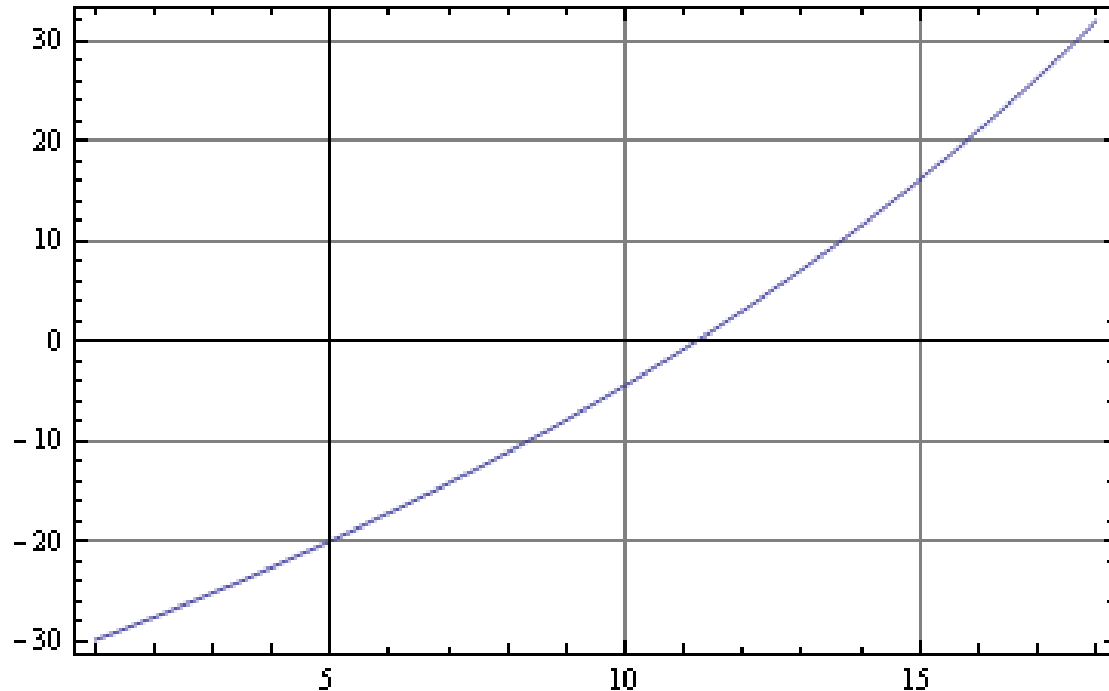


# Timing distribution for change > 2000



# T18 structure Function $F[z]$

time difference for the BD info to reach both ends



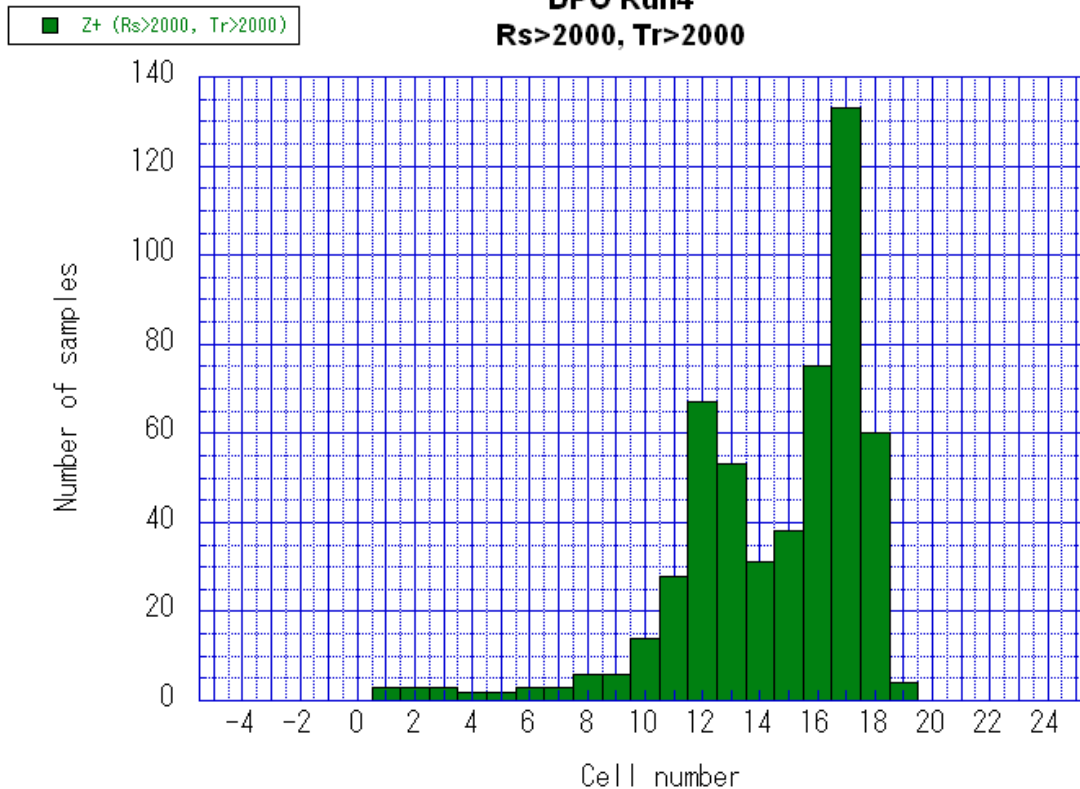
Use time difference  $R_s(\text{rise}) - T_r(\text{fall})$  to calculate BD position.  
Function  $F(z)$  is calculated from design  $v_g(z)$ .

# Breakdown cell distribution >2000

50ns higher target run

090930 analysis

Quad #5 BD cell distribution  
DPO Run4  
Rs>2000, Tr>2000



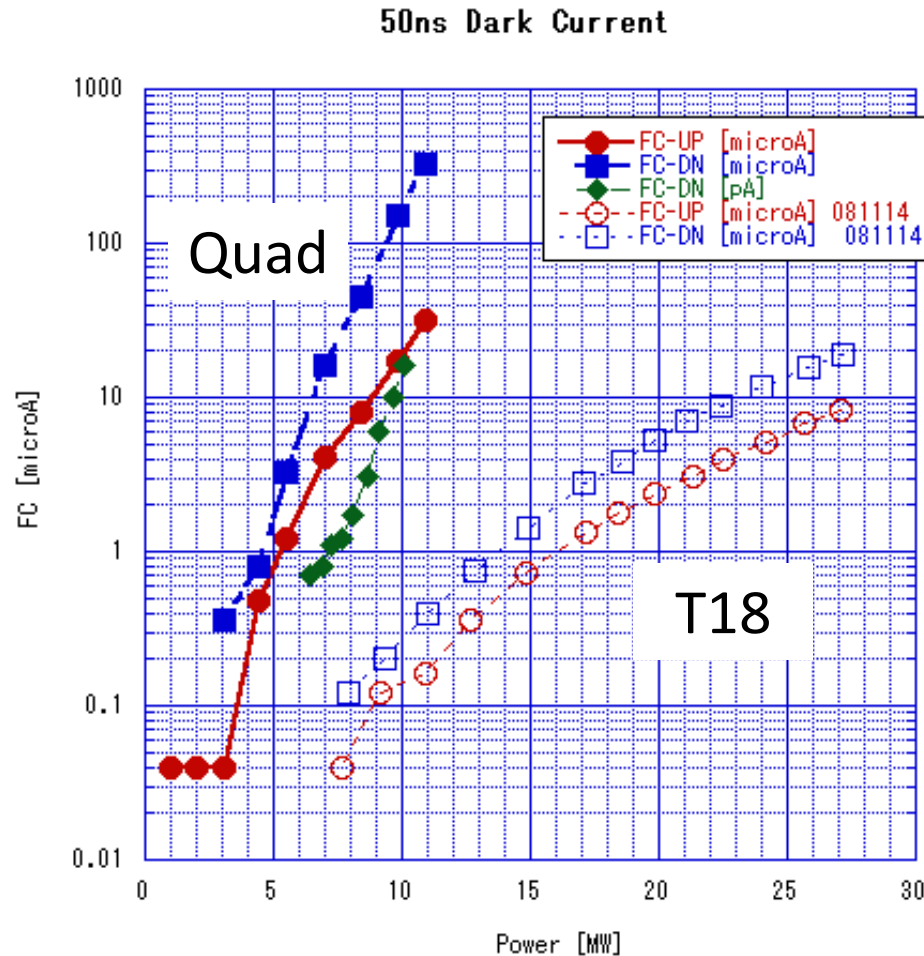
Mostly  
downstream half.

Simply increasing  
toward output  
end.

Indication of BD  
following some  
field gradient.

534 events were analyzed out of 1919 INTLK.

# Quad dark current much larger than T18

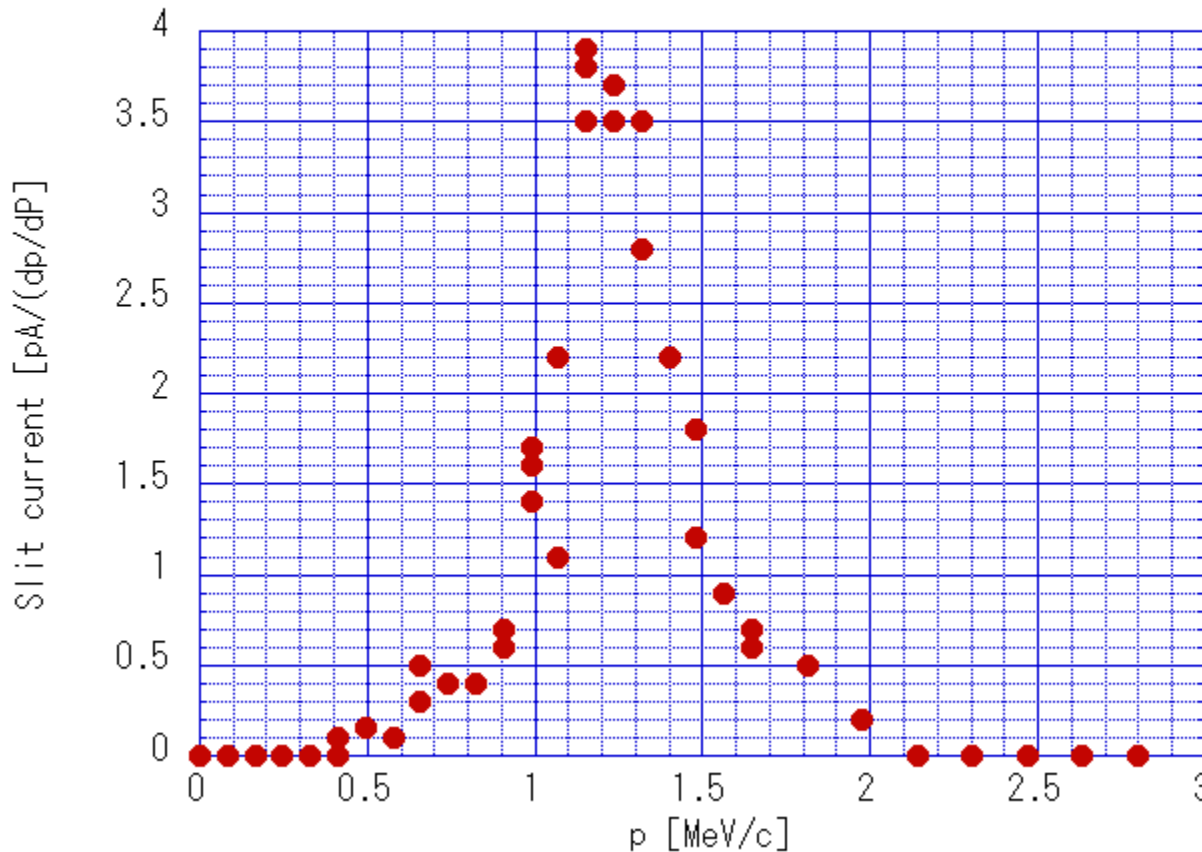


(Note: Power is just the value in the control program panel. Read 12MW as 19MW, though relative comparison between quad and T18\_disk is OK without this.)

# Spectrum peak at very low energy

090926

Quad #5 Dark current spectrum  
50ns, 19MW



T18\_Disk  
Peaks at 8MeV/c  
and 4MeV/c with  
108MV/m

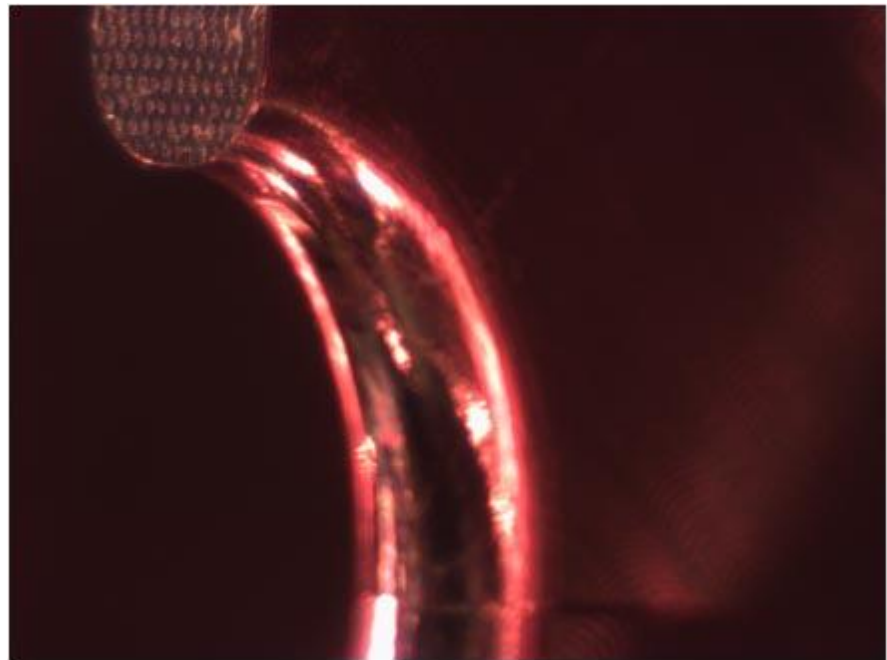
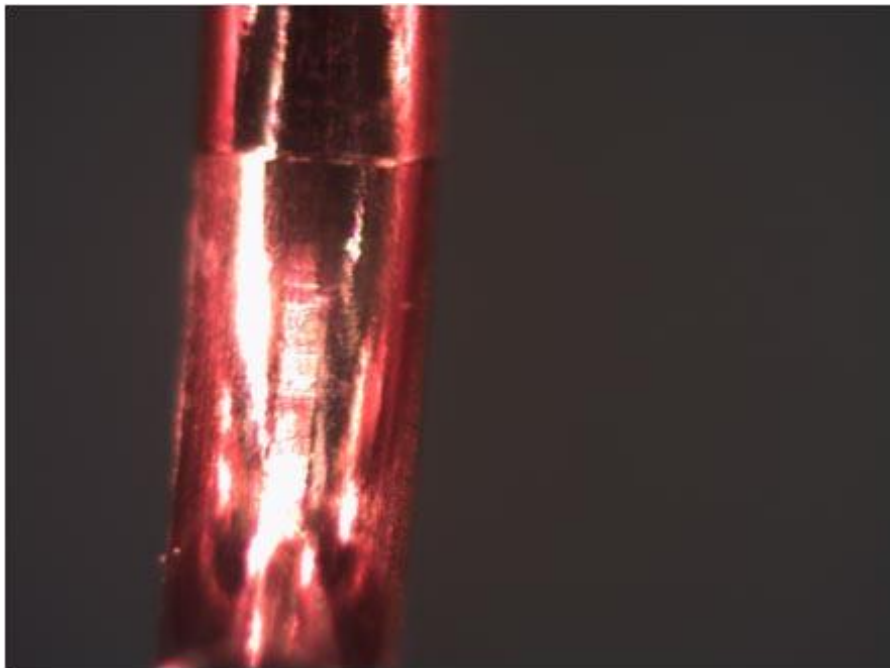
Present quad  
Peak at 1.2MeV/c  
(=0.8MeV)  
with 19MW →  
59MV/m

It seems only the last cell or +1 contributes mostly.

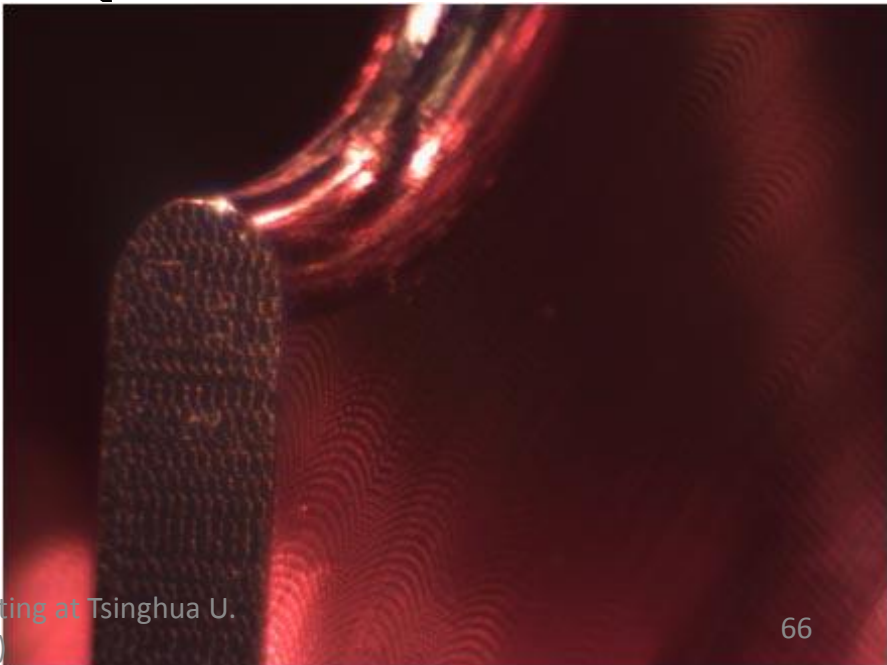
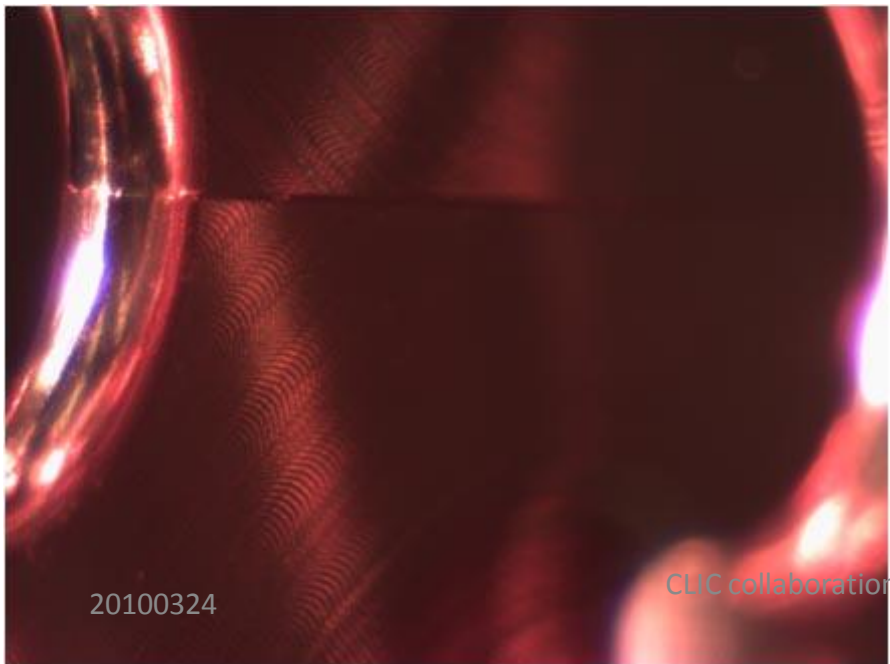


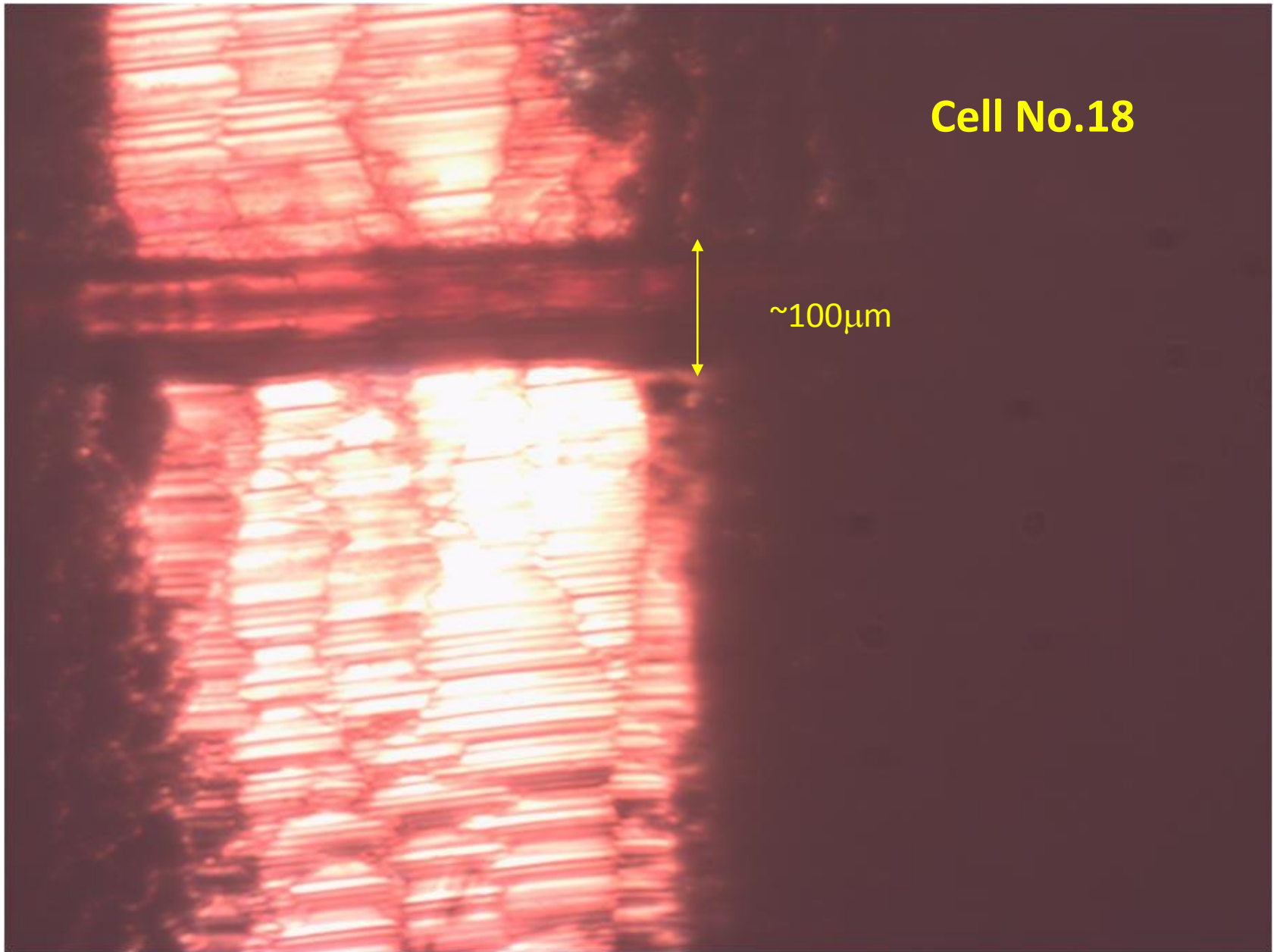
# Inspection with long-distance microscope after finishing high gradient test





**No.18 Q2-2 to match Q1-1**





Cell No.18

~100 $\mu$ m

# Surface inspection summary

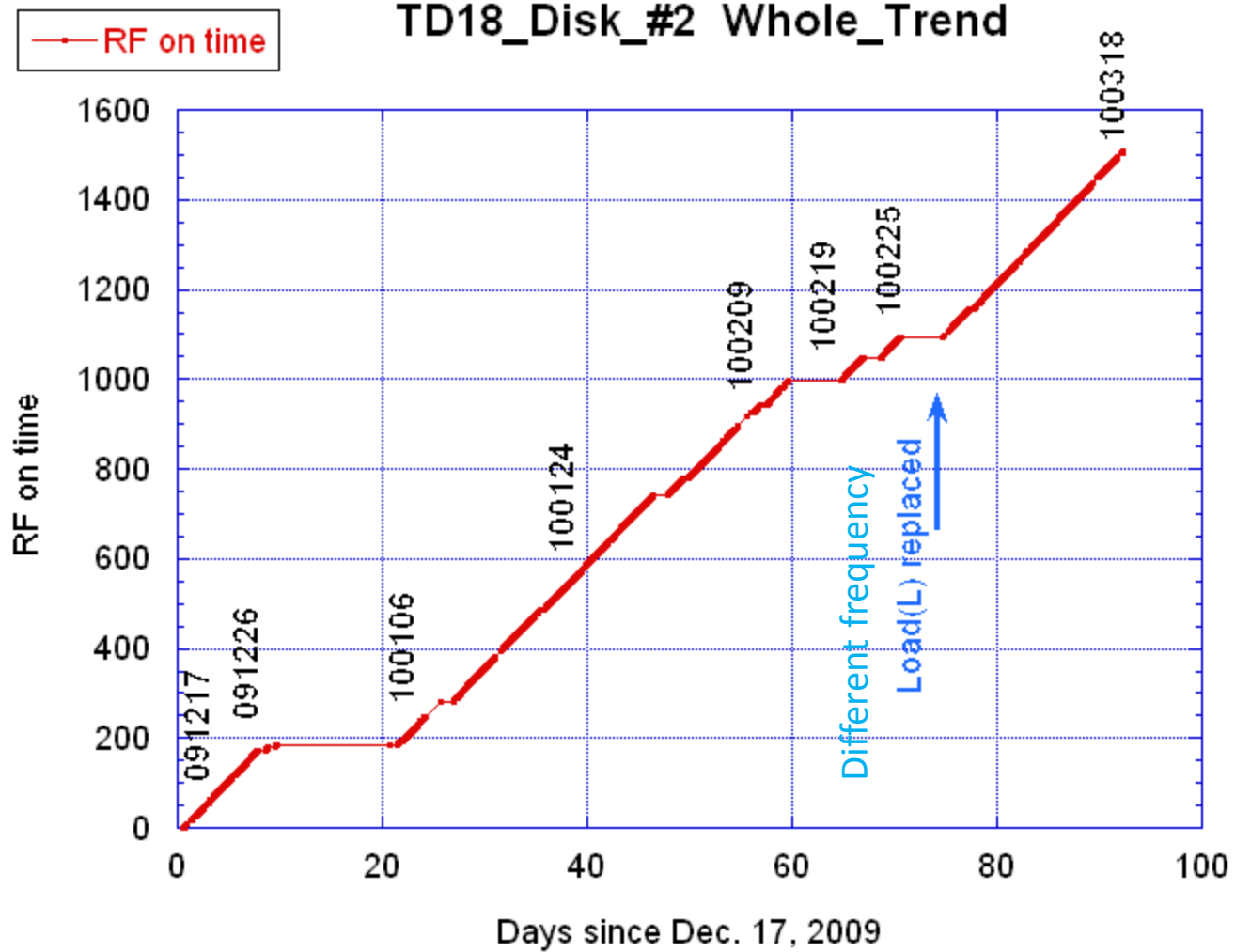
- Optical inspection with long-distance focus microscope
- Still not easy to see the arcing spots
- Will go to SEM
  - though only the center of the rod can be observed in a Japanese company in April
- Will go to CERN SEM for full inspection

# TD18\_Quad summary

- Very slow processing
- Hard ceiling in processing gradient
  - 60MV/m @ 50ns, 50MV/m @ 113ns
- No further progress with EP (SLAC)
- Gas trapping at mating surfaces?
- Discharge due to edge? → arc is not only at the edge
- We do not understand why these longitudinal split ones are not well in high gradient performance
- Still worthwhile to study because of the estimated cheapness in mass production
- Probably reasonable to test with CD10-type setup

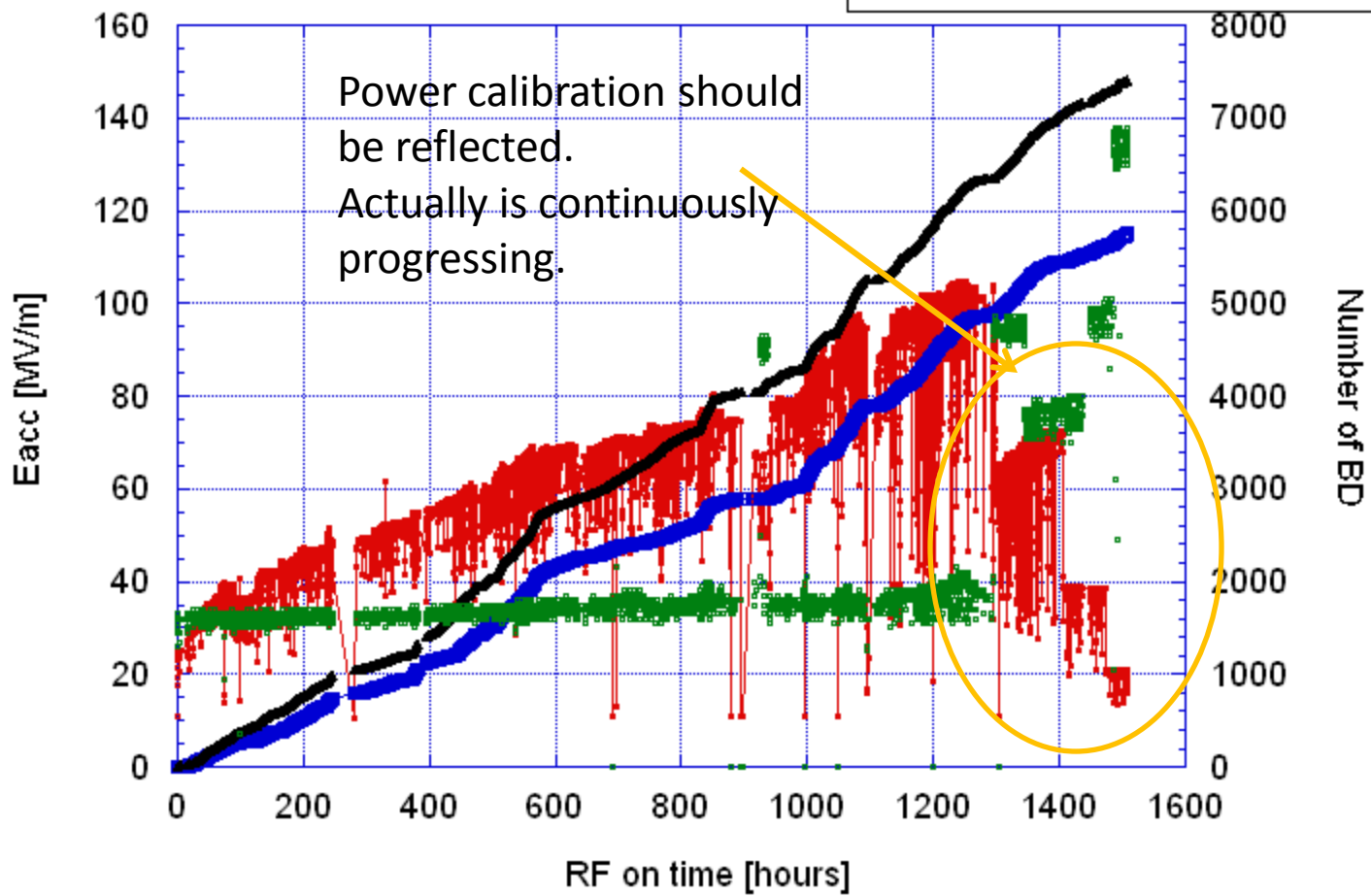
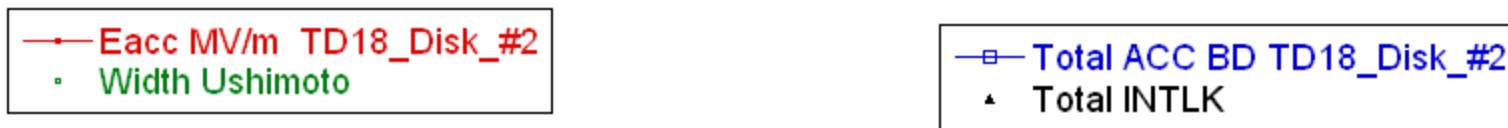
# TD18\_Disk\_#2

- Aim: Prove heavily damped structure
  - Electric gradient: possibility to realize 100MV/m
- Design geometry
  - Heavy damping slots with wide opening
  - Big increase of gradient toward downstream
  - Big pulse heating temperature rise at the damping port opening
  - No longitudinal cut but disk-based as T18 structures
- Fabrication in practice
  - Milling surface in many places
  - CP and VAC baking are the same as T18



# TD18\_Disk\_#2 Eacc, Pulse width and # of breakdowns

20100318

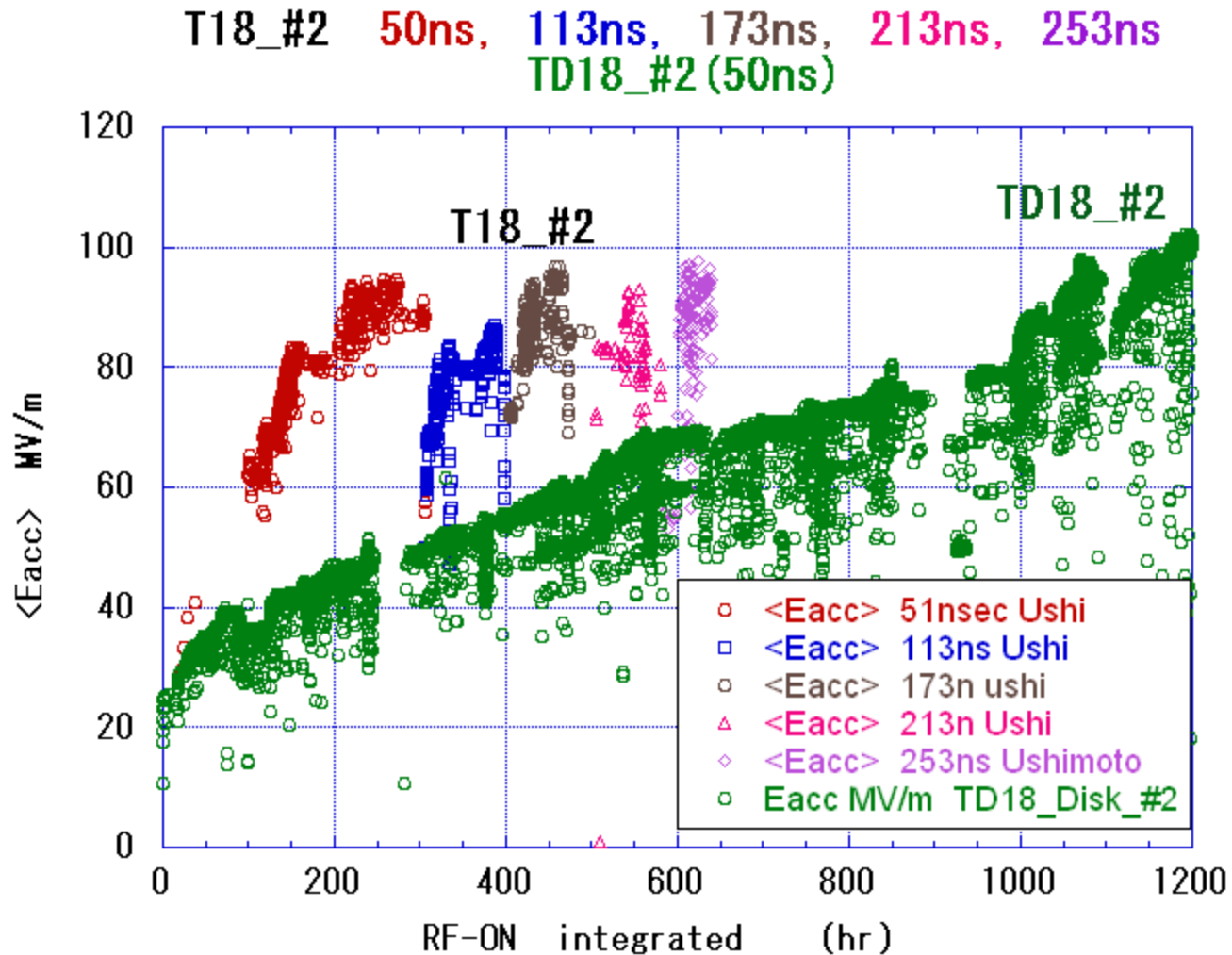


51ns → 112ns → 91ns → 112ns → 152ns

CLIC collaboration meeting at Tsinghua U.  
(Higo)



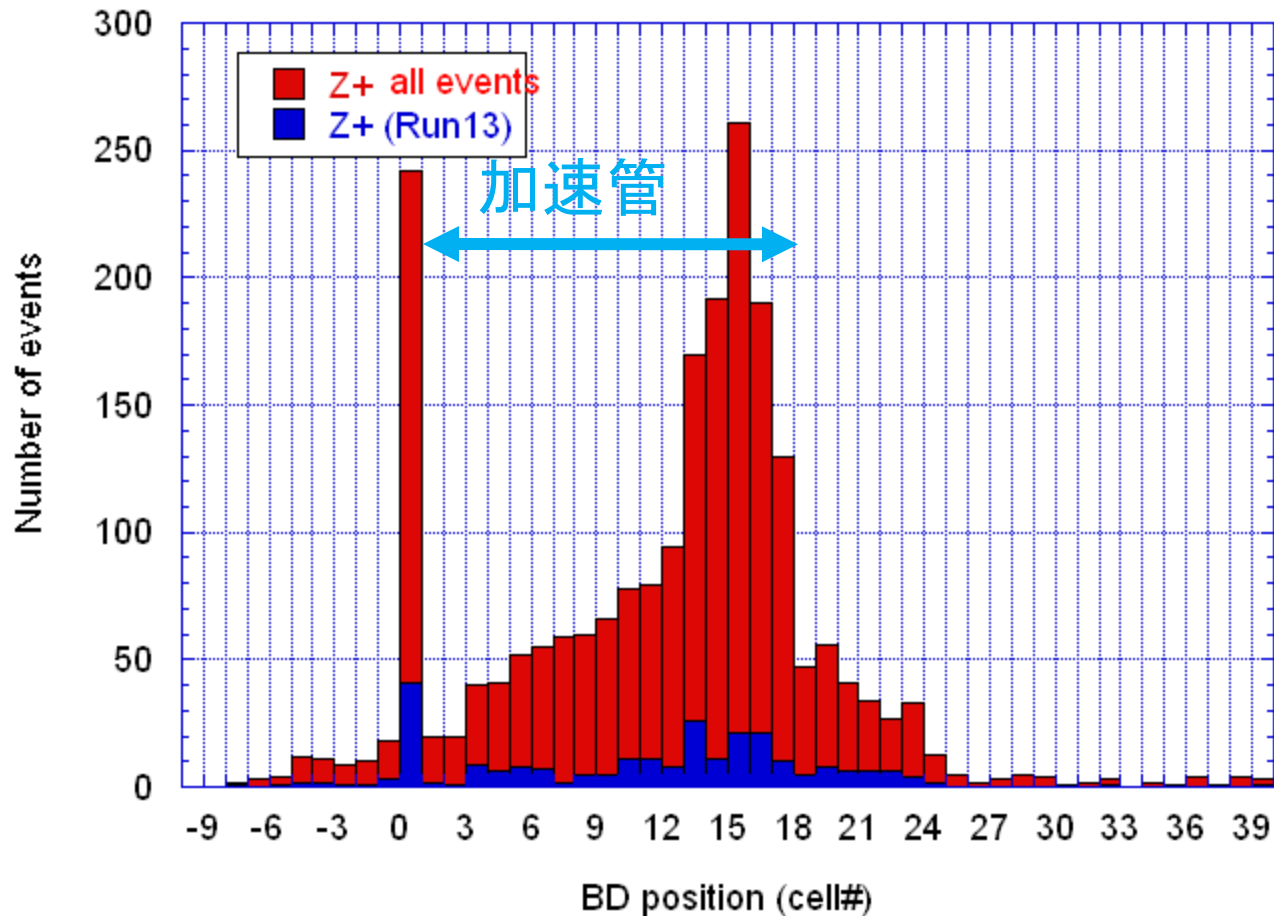
# Disk-based: un-damp vs heavy damp

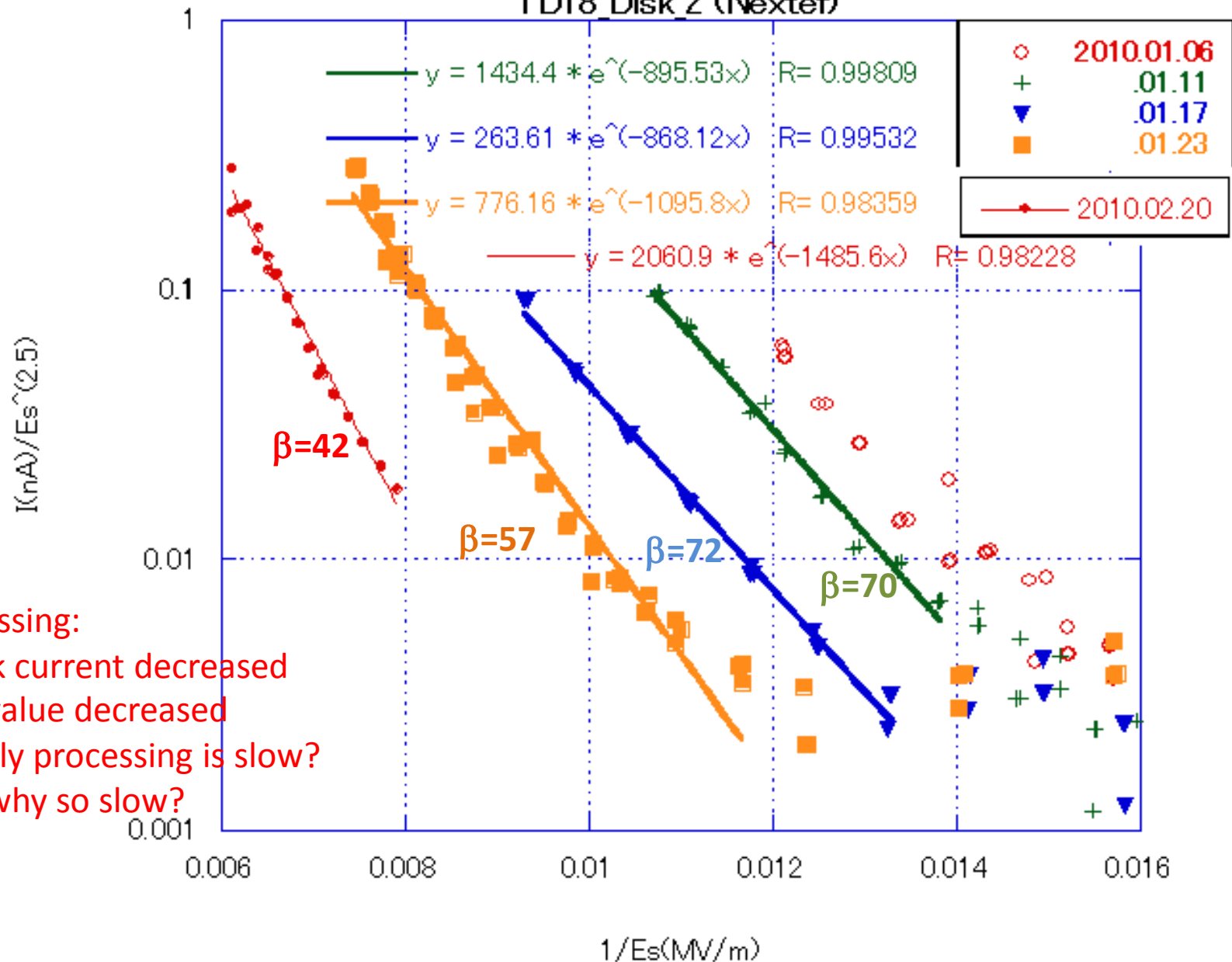


# Breakdowns localized at downstream

20100221

TD18\_Disk #2 Breakdown position  
all events till 100221 during run\_13

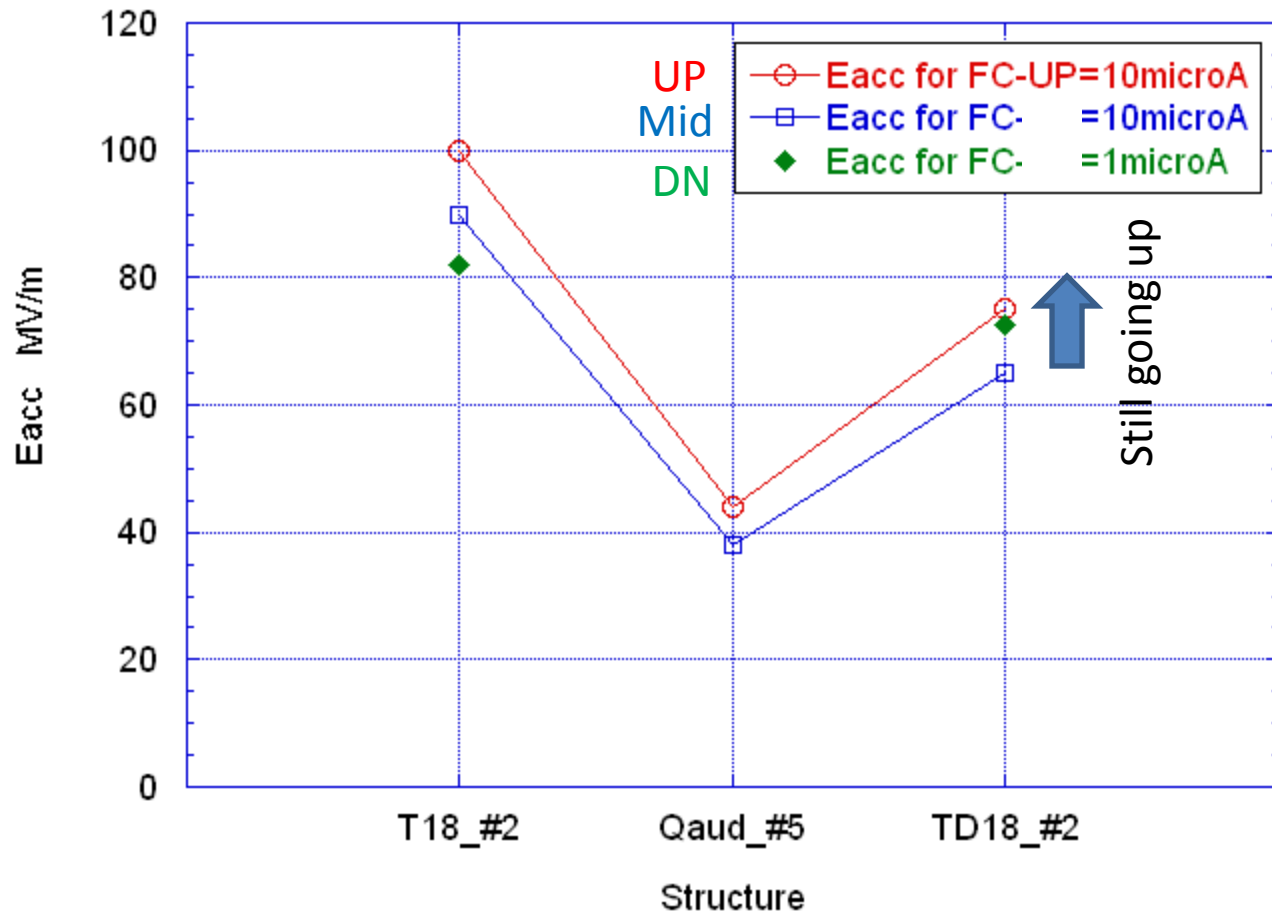




Processing:  
 Dark current decreased  
 $\beta$ -value decreased  
 only processing is slow?  
 why so slow?

## Eacc at some dark current level

FC-UP=10microA, FC-Mid=10microA, FC-DN=1microA



# TD18\_Disk\_#2 test in practice

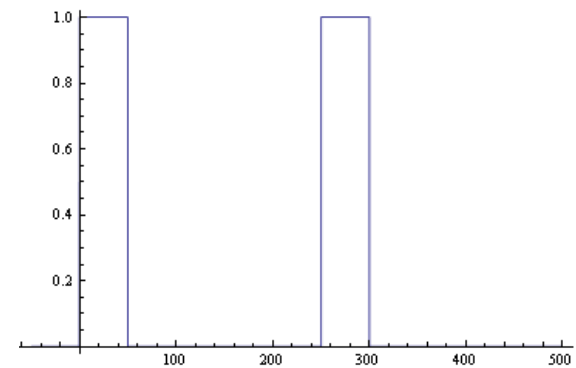
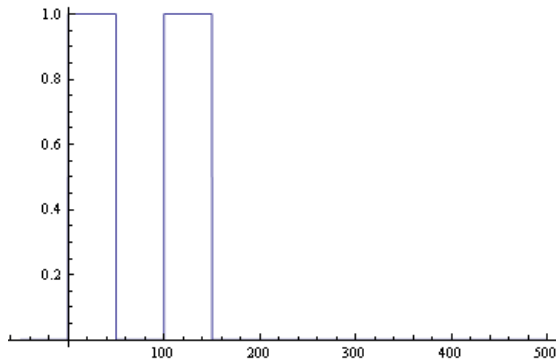
- Replacing load(L)
  - Acc str BD originated from the BD from the load line disappeared.
- Processing at 50 nsec
  - Reached 100MV/m after 1200hrs with 6000 breakdowns.
  - Still slow processing speed
- Pulse width increased up to 152nsec
  - Roughly the same power level as that of 51ns was reached without difficulty
  - It means 100MV/m level was achieved at longer pulse.
- Power was calibrated with the present setup
  - Peak power meter was used as a reference
  - Kly comb. (S+N) and ACC-IN power were calibrated.

# TD18\_Disk summary

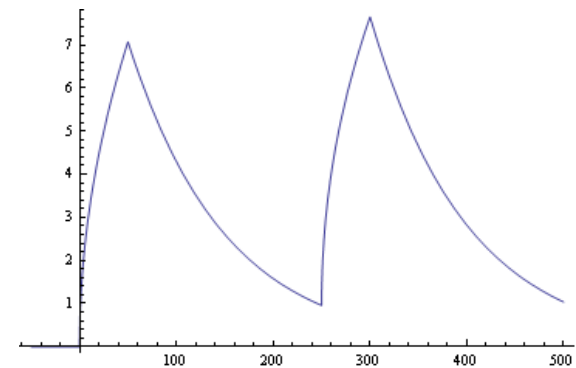
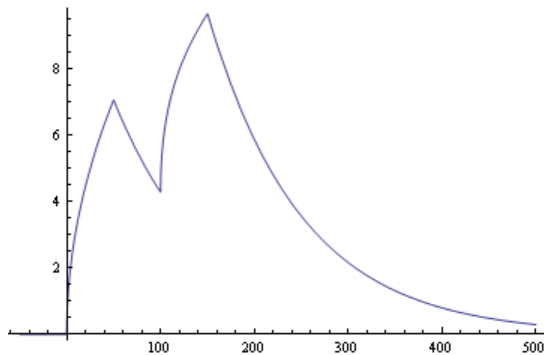
- The processing speed is very slow comparing to that of T18\_Disk\_#2 or SLAC for TD18\_#3.
  - Difference in trip criteria?
  - Difference in acc structure itself?
  - Difference in processing protocol?
  - Need quantitative comparison in detail
- Dark current level reached the similar level to that of T18\_Disk\_#2.
- Even though the processing seems still proceeding, it may be stopped sometime not very far away but after trying some experimental important studies.

# Possible tests with RF shaping

RF pulse



Temperature



More breakdown in the second pulse?  
Same dark current for both?

Almost independent?  
Twice processing speed?

# TD18\_Disk test idea in near future

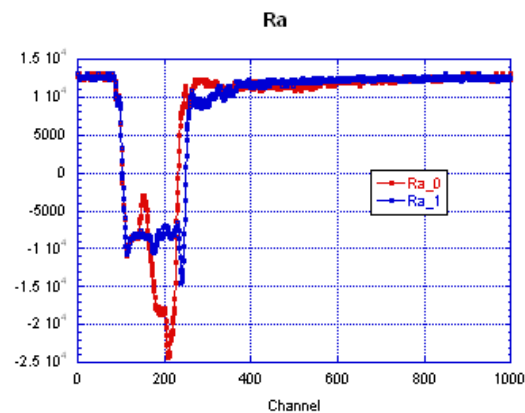
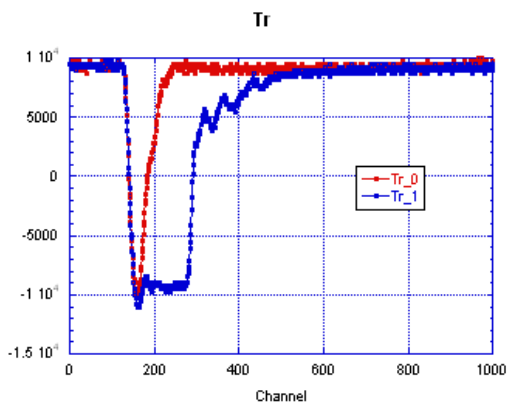
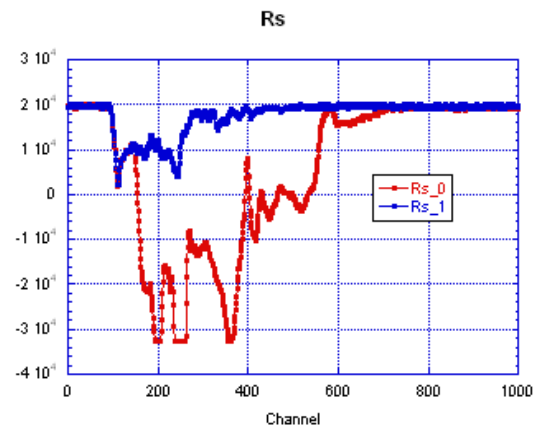
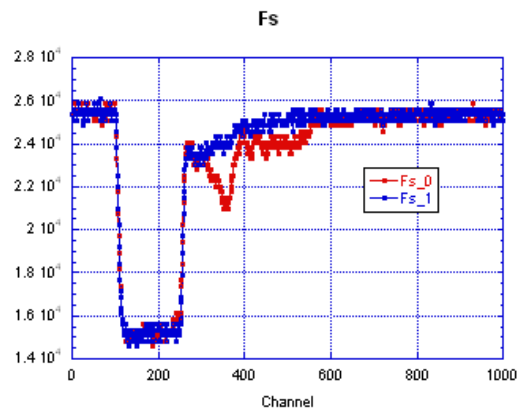
- Evaluate performance with a longer pulse width
- Study with such as two-pulse operation
- Check dark current evolution to the final saturation
- Finish and go next test



# Improvement in Nextef studies

- Much room for anyone to help us

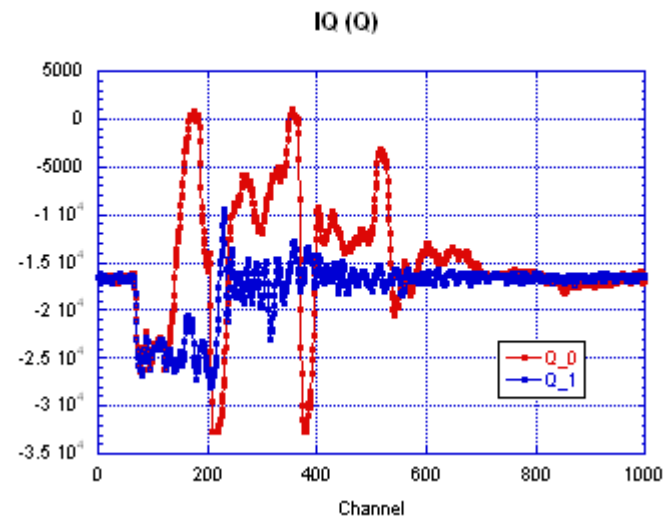
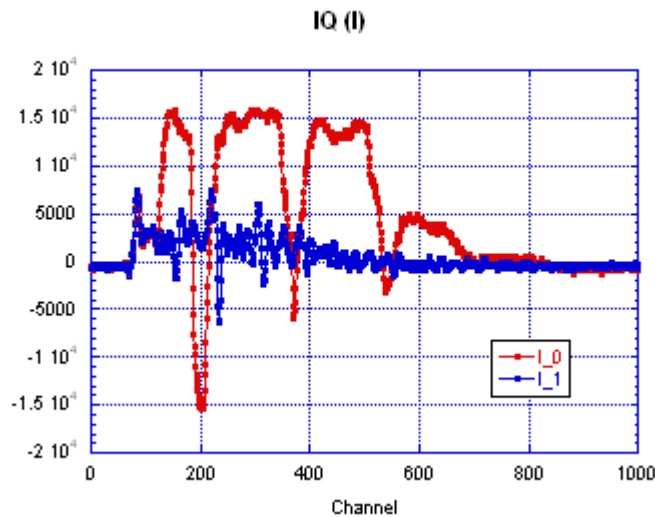
# Evaluation of missing energy to be implemented



Pulse analysis, such as missing energy evaluation is still to be established. Good manpower is needed.

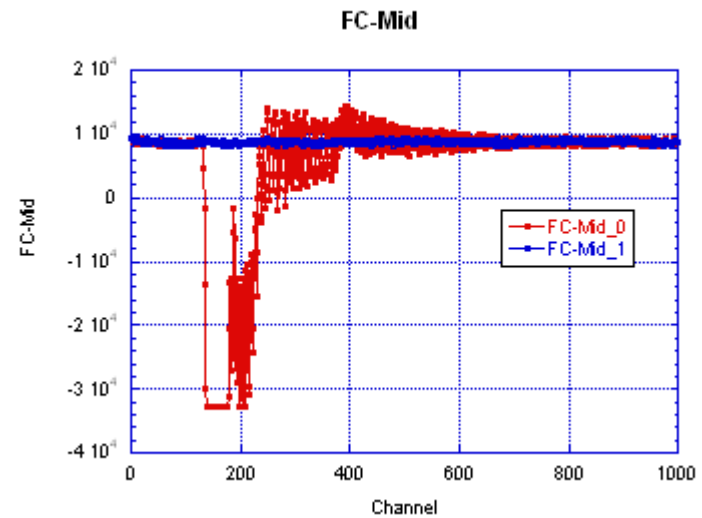
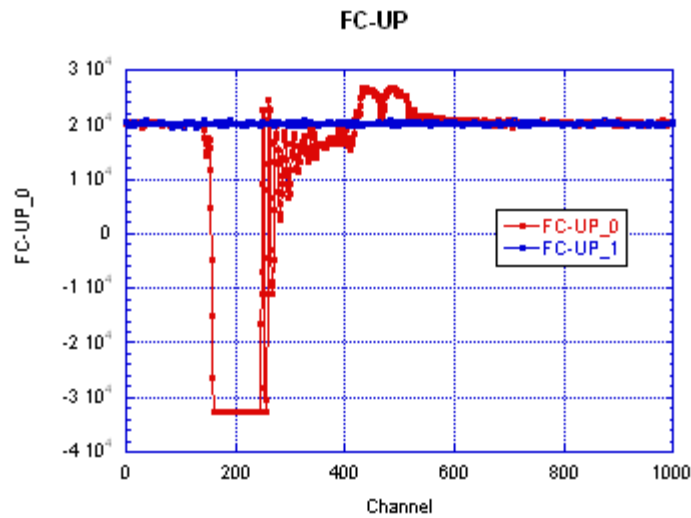
# Rs Phase measurement to be established

## BD pulse with IQ



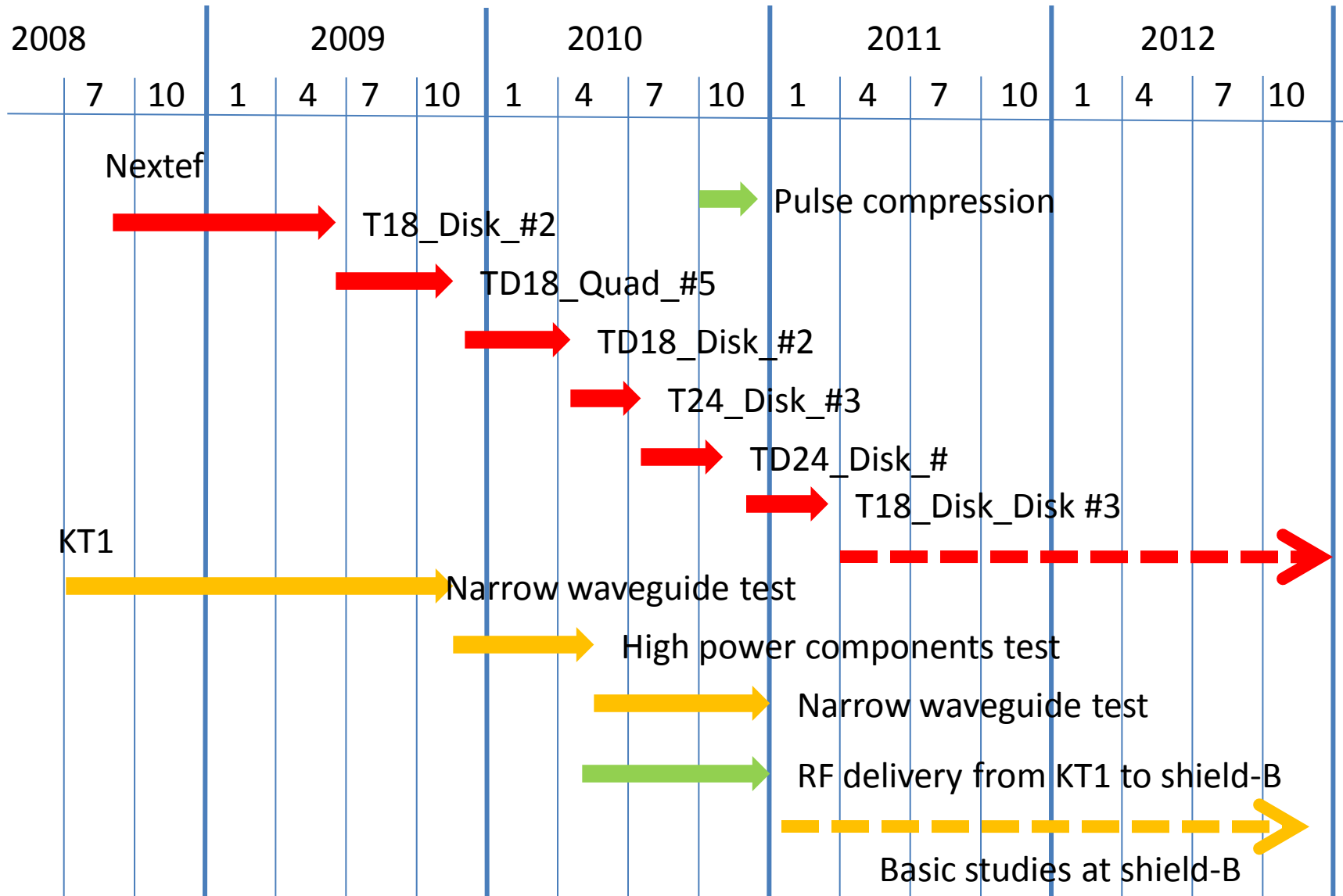
Pulse analysis is still to be established. Good manpower is needed.

# FC-UP and FC-Mid

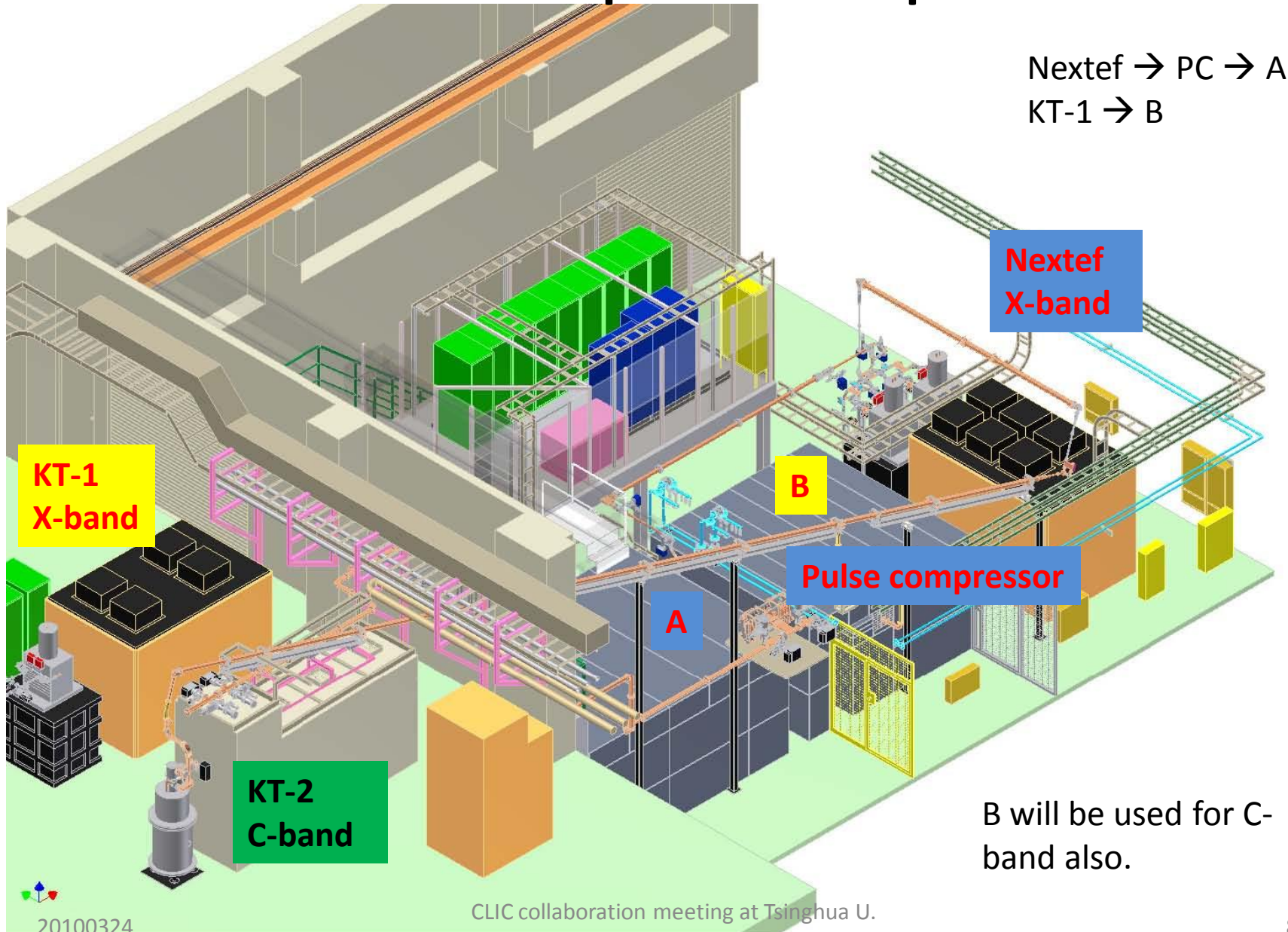


Relation to RF can be better analyzed?

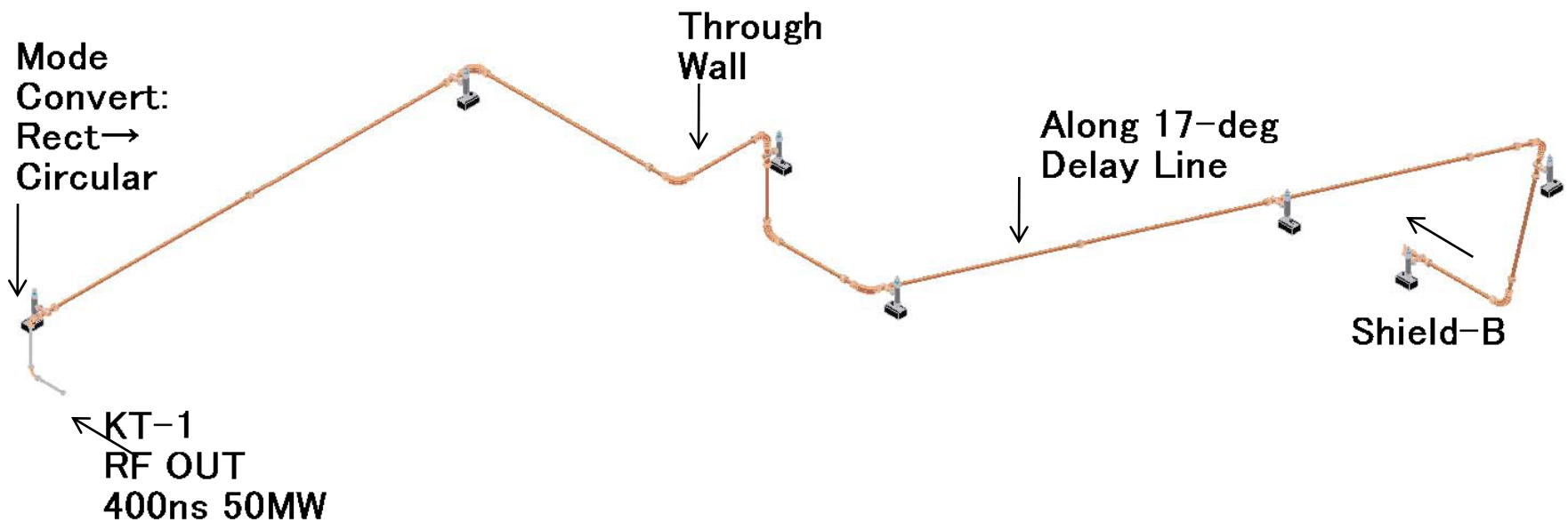
# KEK operation plan Nextef & KT1



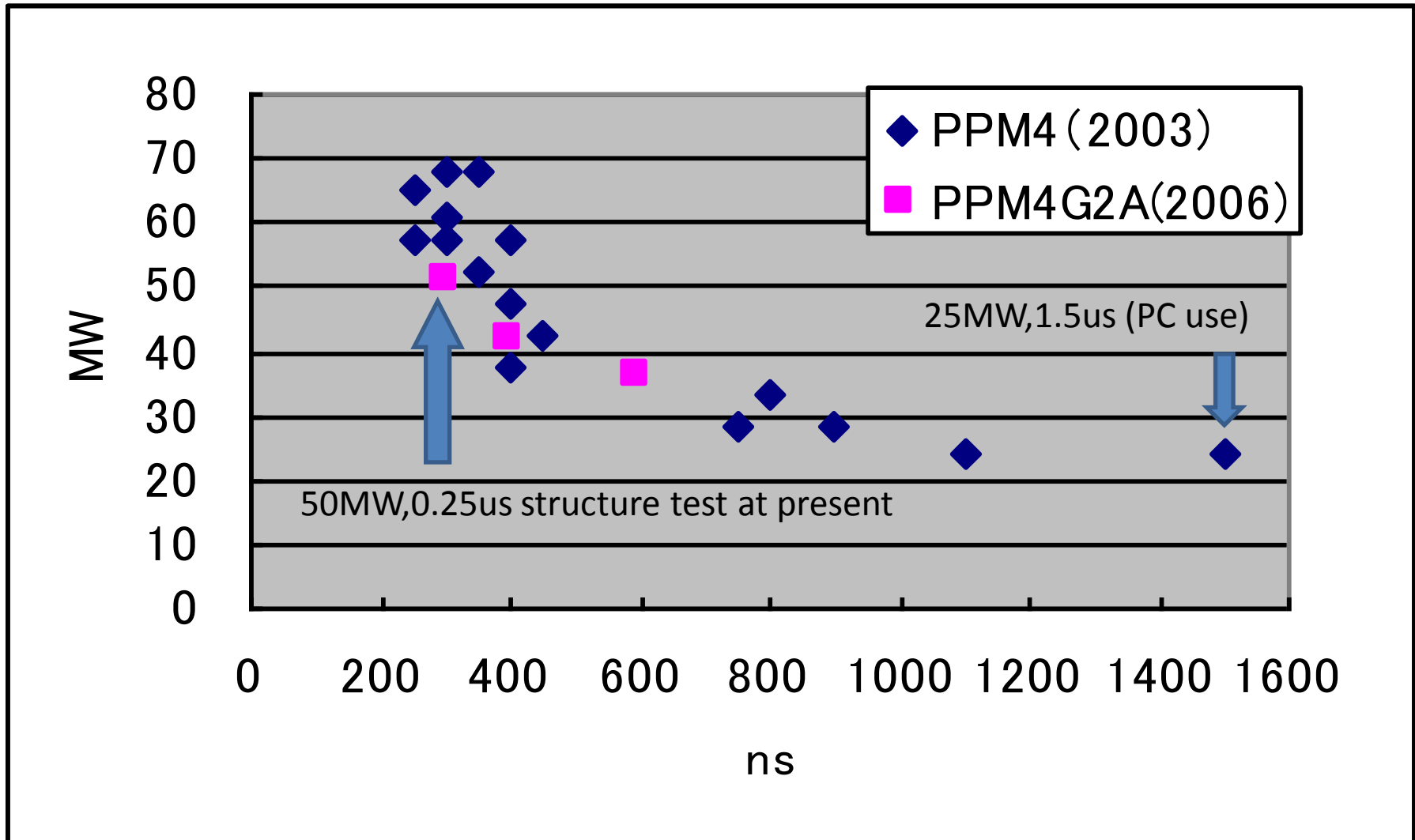
# Nextef expansion plan



# Configuration of the Power Line from KT-1 to shield-B



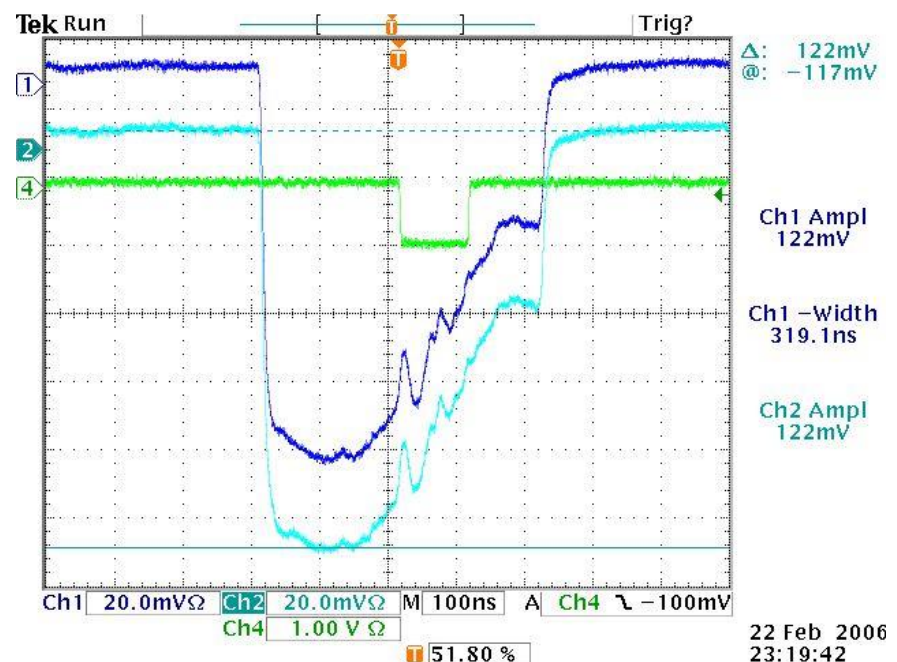
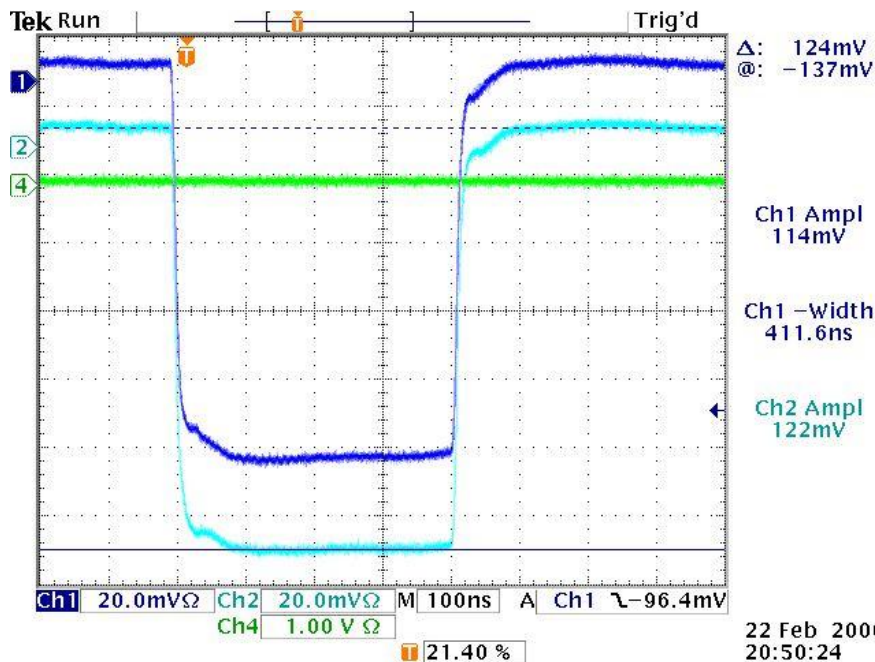
# PPM klystron output power limit





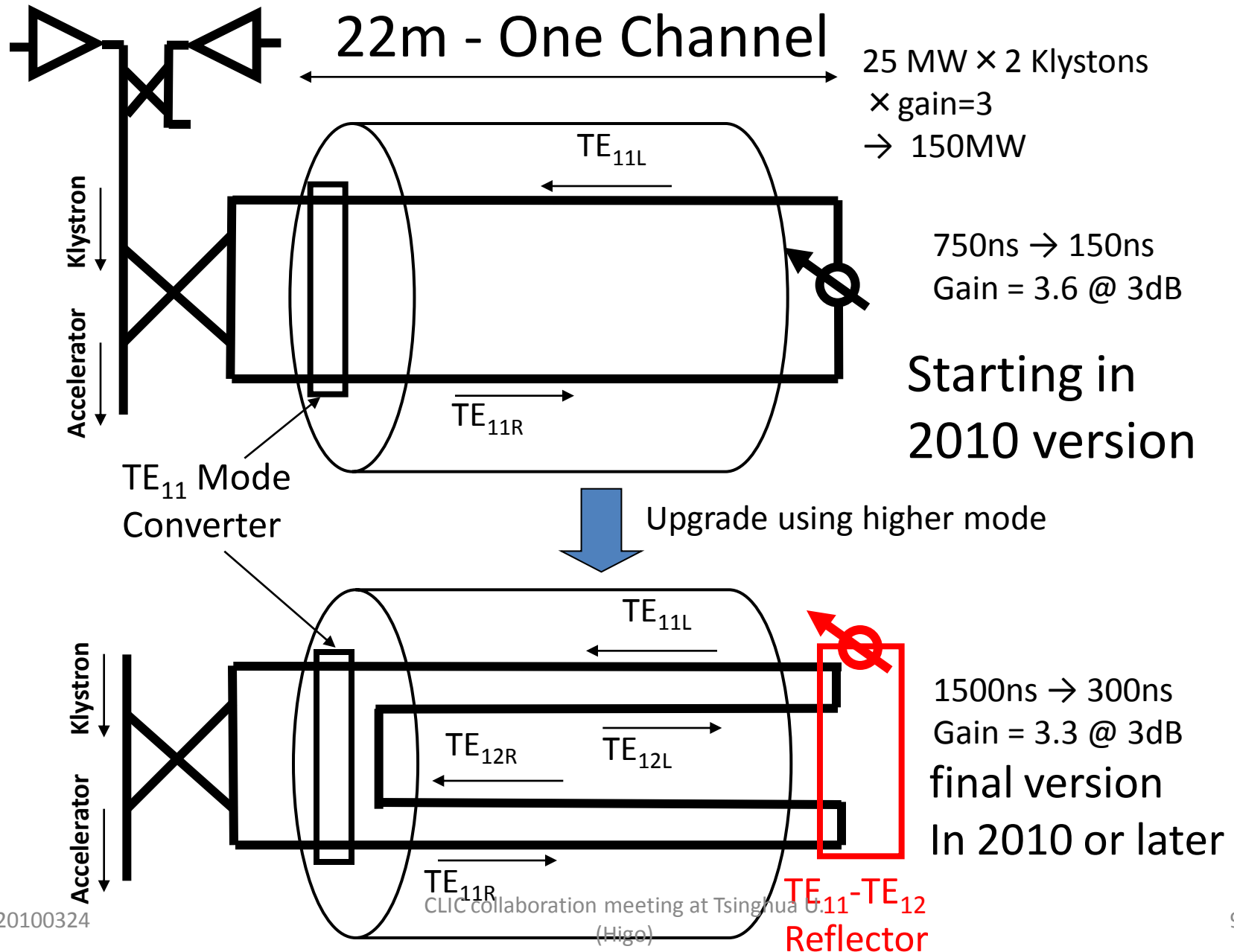
# PPMクライストロンの運転限界

The availability of ppm klystron depends on the required RF quality. Empirically we have known that RF pulses were often broken when the product of the pulse width and peak power is large.



Example of RF Pulse Waveforms:  
Normal(Left) and Pulse Shortening (Right).

# Pulse Compressor (circular TE11 / TE21) proposed by M. Yoshida.

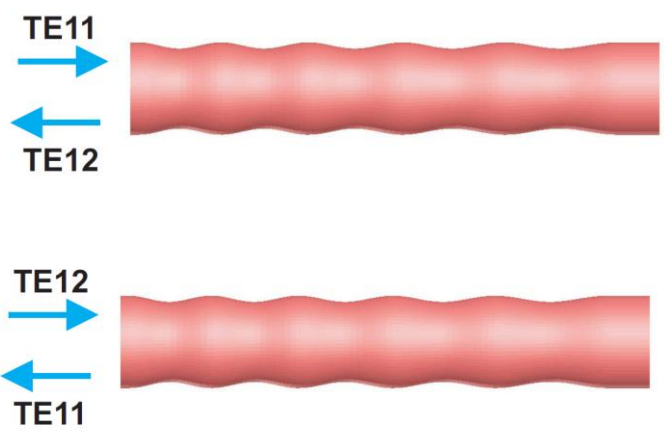
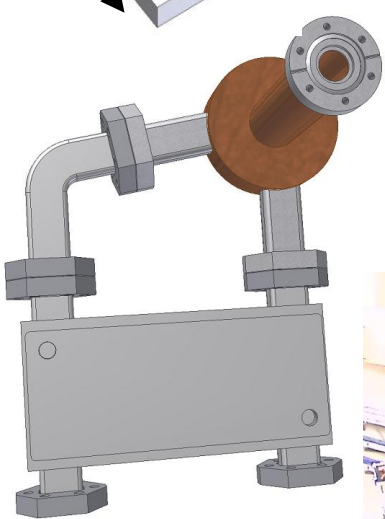
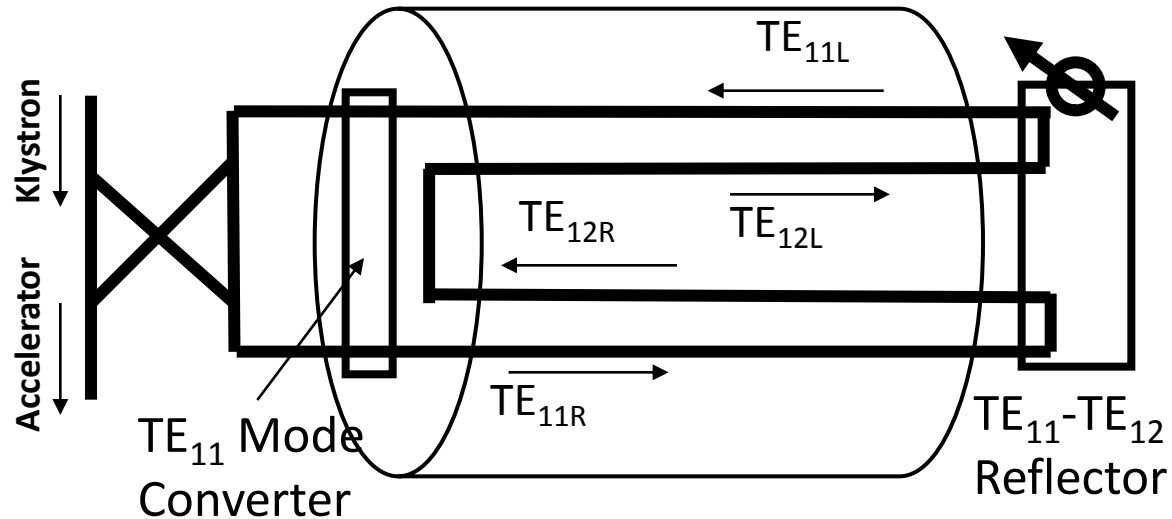
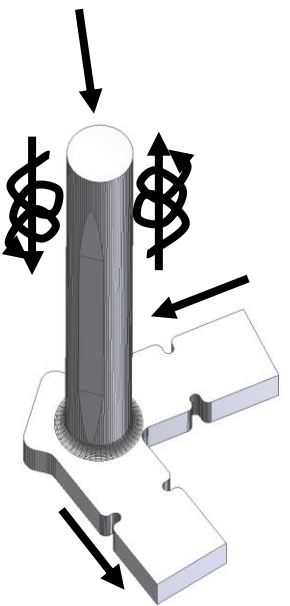


# パルス圧縮器の構成

(Traveling Wave Delay Line Pulse Compressor)

モード変換器

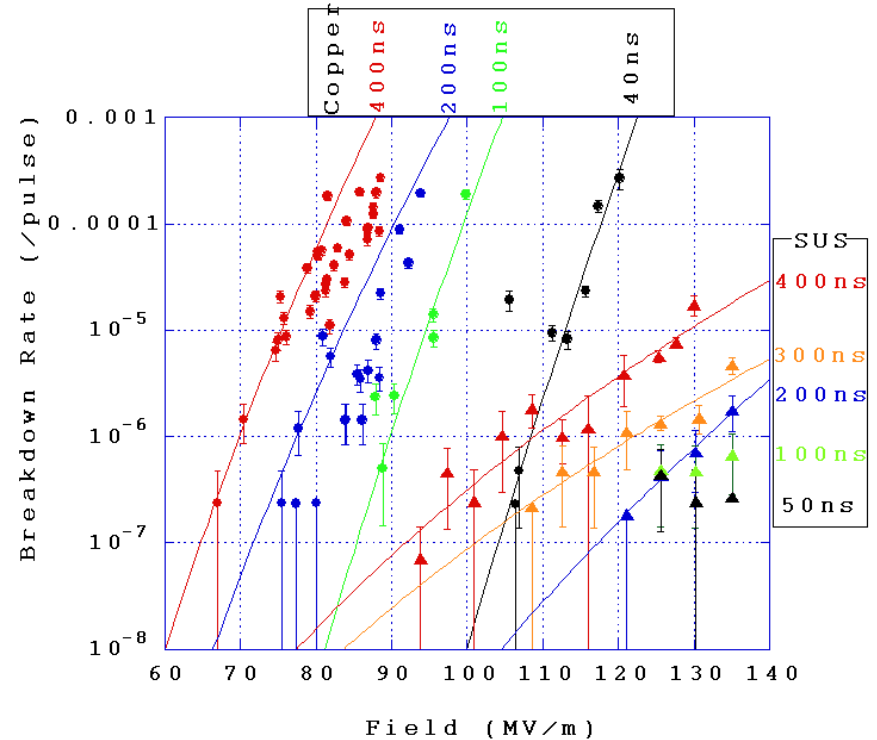
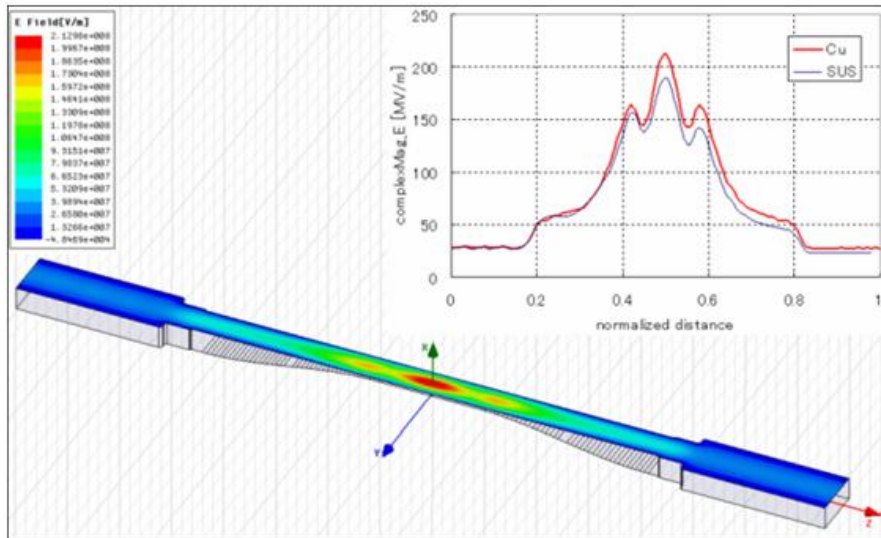
by Kazakov



# Some area on basic high gradient studies with KT-1

- Narrow waveguide
  - FE microscope and/or DC-HV breakdown
  - C10/CD10 TW small setup
  - Single-cell setup as SLAC
- 
- These themes are to be prioritized through discussion among us

# High gradient study with narrow waveguide at KEK

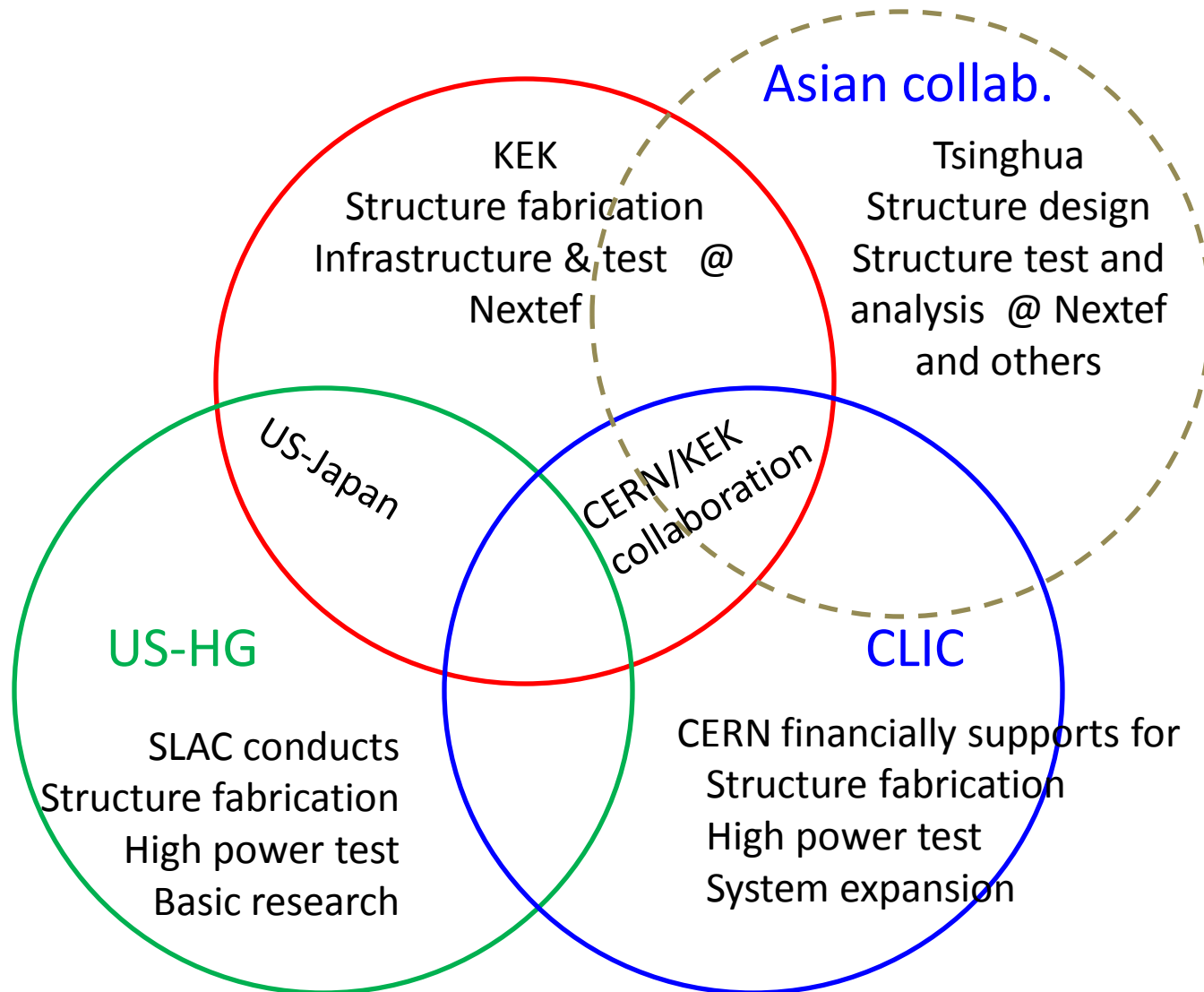


Materials are compared with breakdown rates.  
Copper BDR  $\gg$  Stainless-steel BDR  
We may try molybdenum next.

# Establish a shield-B for basic studies

- We keep collaborating with **SLAC single-cell SW** activities
- But also we establish **Shield-B connecting to KT-1** in 2010
- Shield-B is originally used for **C-band** but we can use it for **X-band**. X-band can coexist with C-band or it may be used for multi-frequency experiment in future.

# X-band collaboration



# Conclusion

- Nextef will run fully dedicated for the feasibility study of CLIC 100MV/m
- Nextef will boost peak power and high power stability by introducing pulse compression system in 2010
- We try to construct a test area in addition for key studies in a simpler configuration
- From these tests and design efforts, we want to confirm the feasible design as of NOW.
- Let us effectively collaborate among us, especially expanding in Asian collaboration for KEK to contribute