KEK activities on CLIC X-band Accelerating Structures

Tsinghua Univ., March 24
T. Higo (KEK)

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- Basic idea behind KEK X-band R&D
- History of X-band developments at KEK
- Preparation of test structures
- Test facilities
- Test results of accelerating structures
- Expansion of Nextef facility
- 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
  - 30㎝ TW acc structure

Relevant accelerator structures

Stage	Unit	JLC-X	GLC	CLIC-C	CLIC-G
Year		1996	2004	2007	2010
E_{CM}	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
ΔT	℃		< 19	71	53

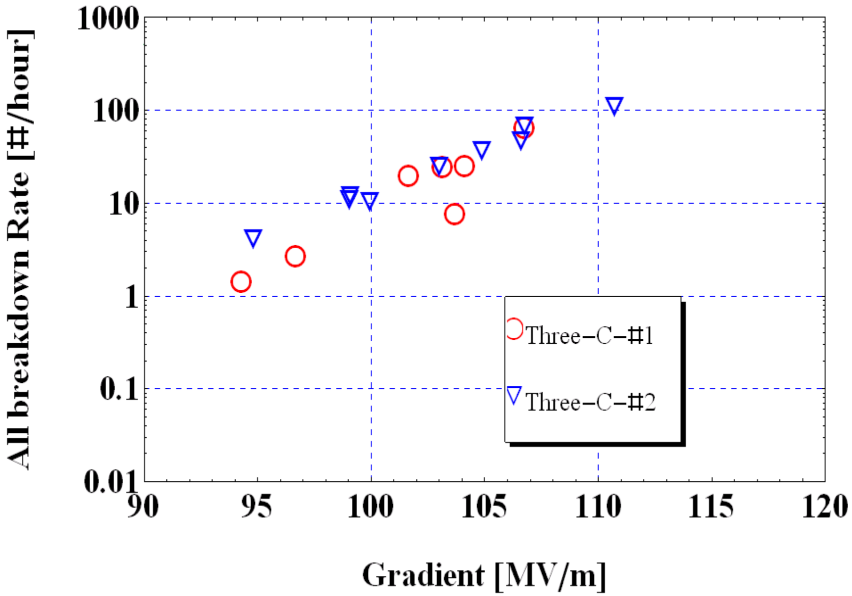
Some typical experiments in mind

- 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??

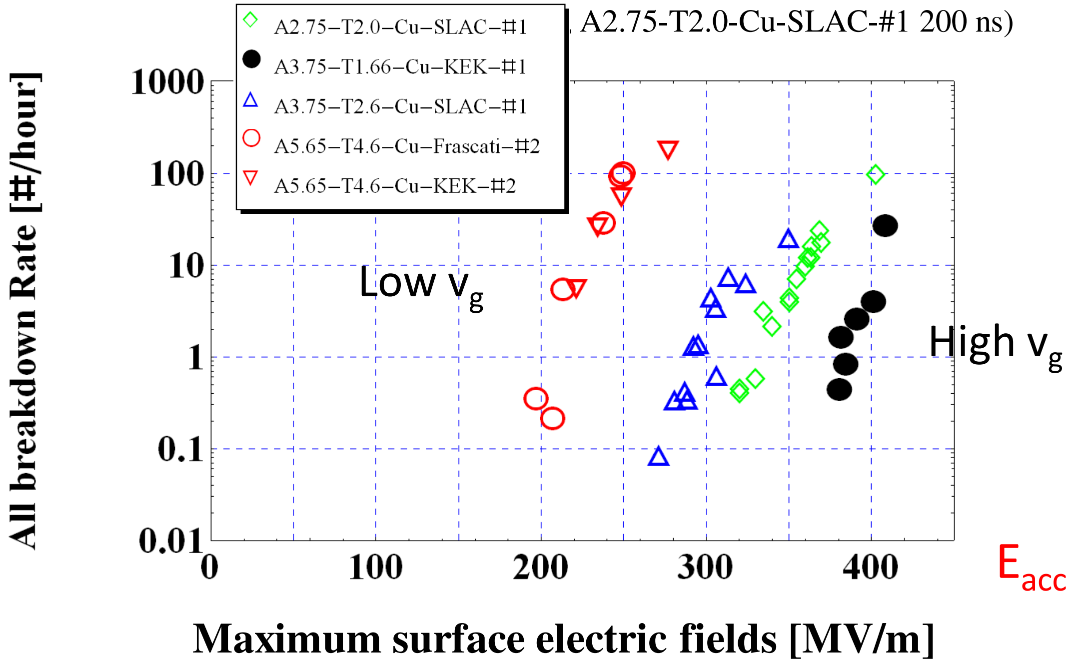


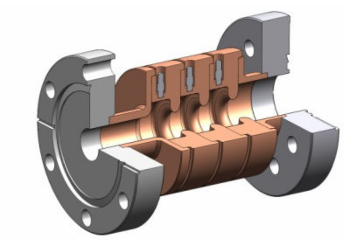
The near perfect surface processing affected only the processing time. The second structure processed to maximum gradient in few minutes vs few hours for the normally processed structure.

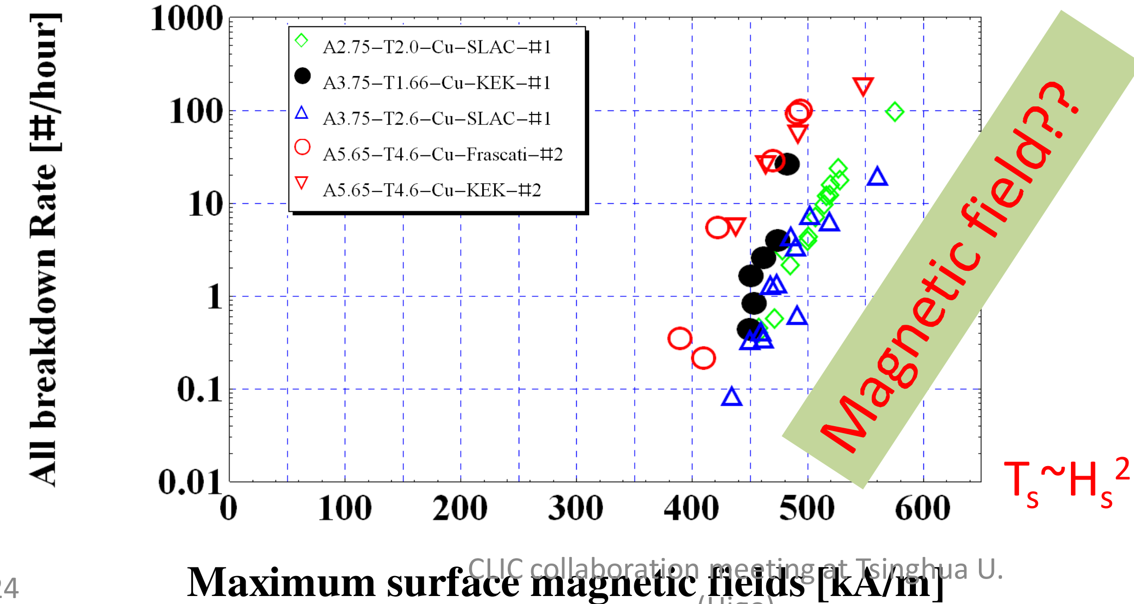
But we are curious how the processing proceeds and how high we can obtain without serious damage.

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-
, A2.75-T2.0-Cu-SLAC-#1 200 ns)







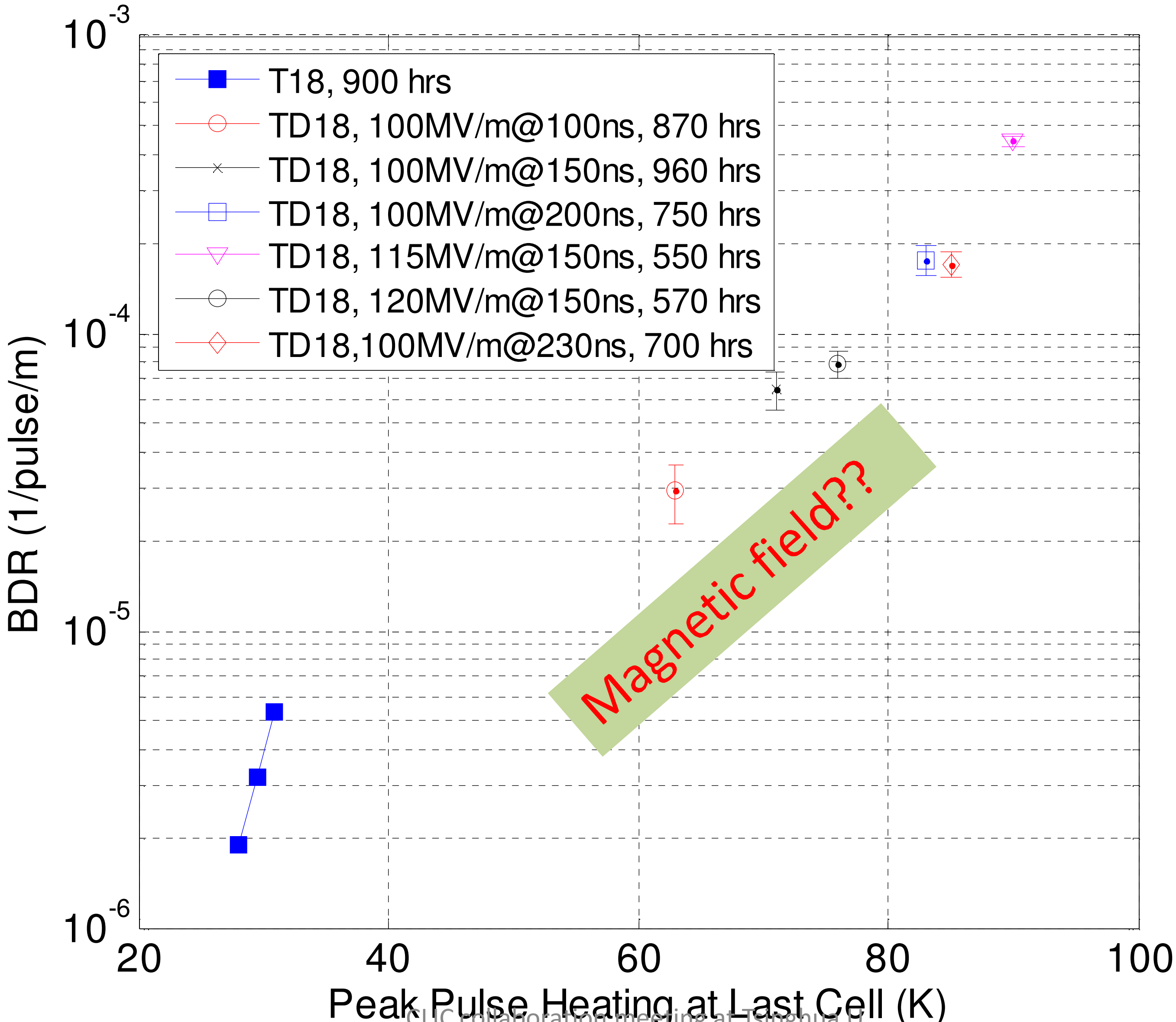
For the same BDR

Different shape
→Different Eacc

but
Very similar Hs

V.A. Dolgashev, 16 December 2008

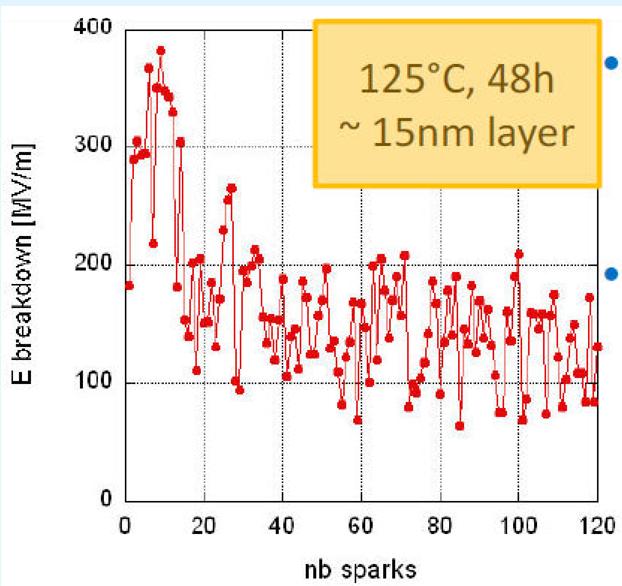
BDR Pulse Heating Dependence



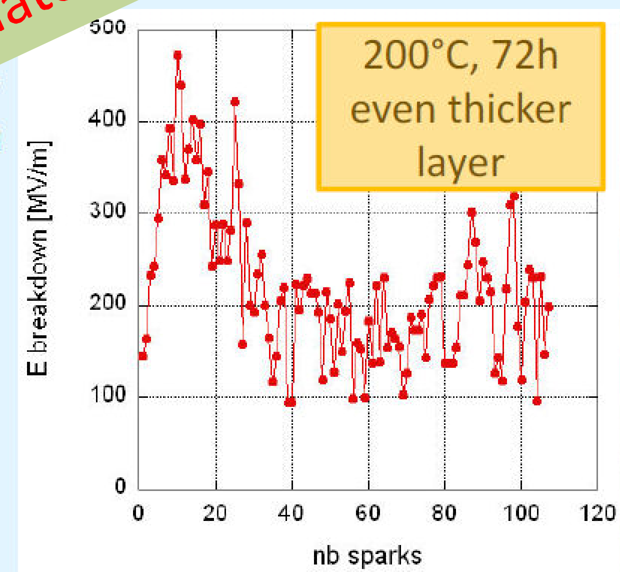
The oxide layer of Cu

- An oxide layer has been grov was thicker than the nat
  - Higher initial E_{BRD} and conc
  - Has also a different E_{LOC} as t oxidised Cu

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)



(Higo)

General idea behind our study

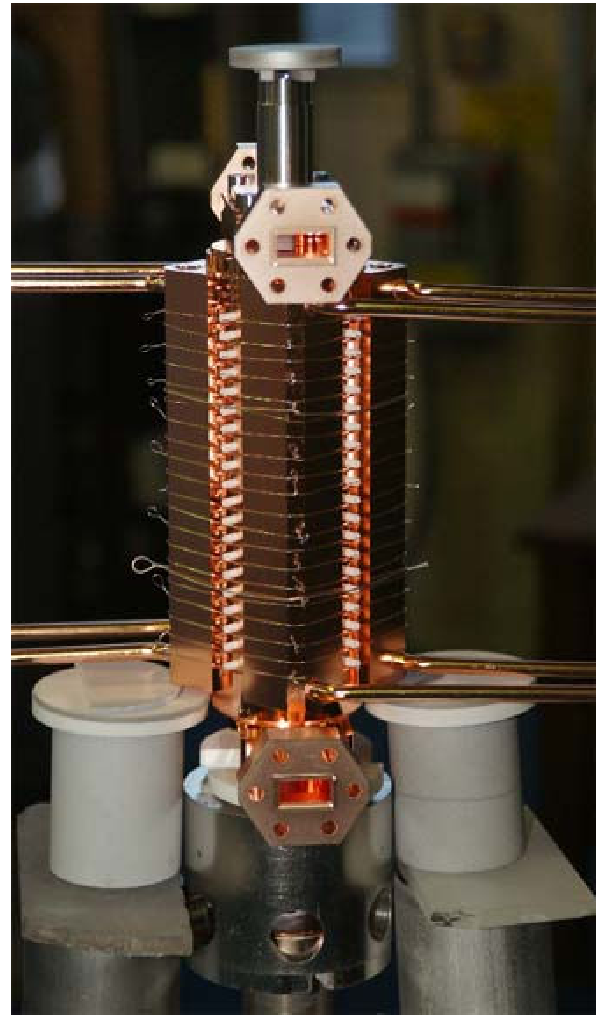
- Take these experimental results in mind.
- Before reaching this saturated regime, there should be a place to play with the surface condition or crystal structure.
- Can we stay in this regime for high gradient?
- How to proceed through this regime to saturation?
- Inevitable to go beyond this regime 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

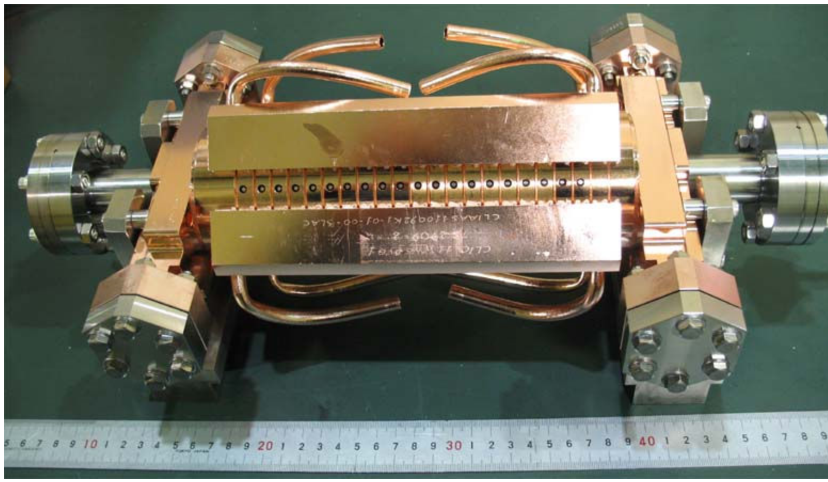
10 days

at SLAC

From Sami, Mar. 1

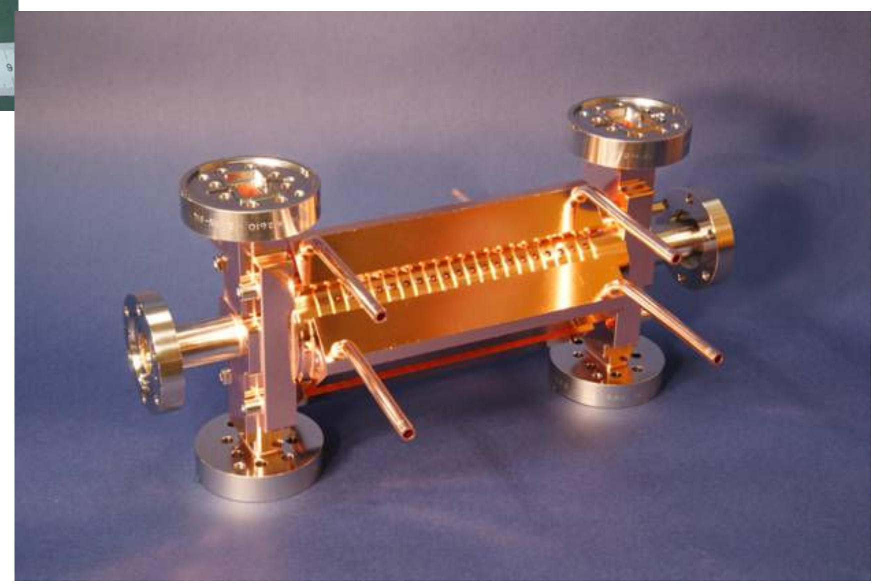
TD18 first pair #2(KEK) & #3(SLAC)

Design = CLIC-C



#2 being tested at KEK Nextef

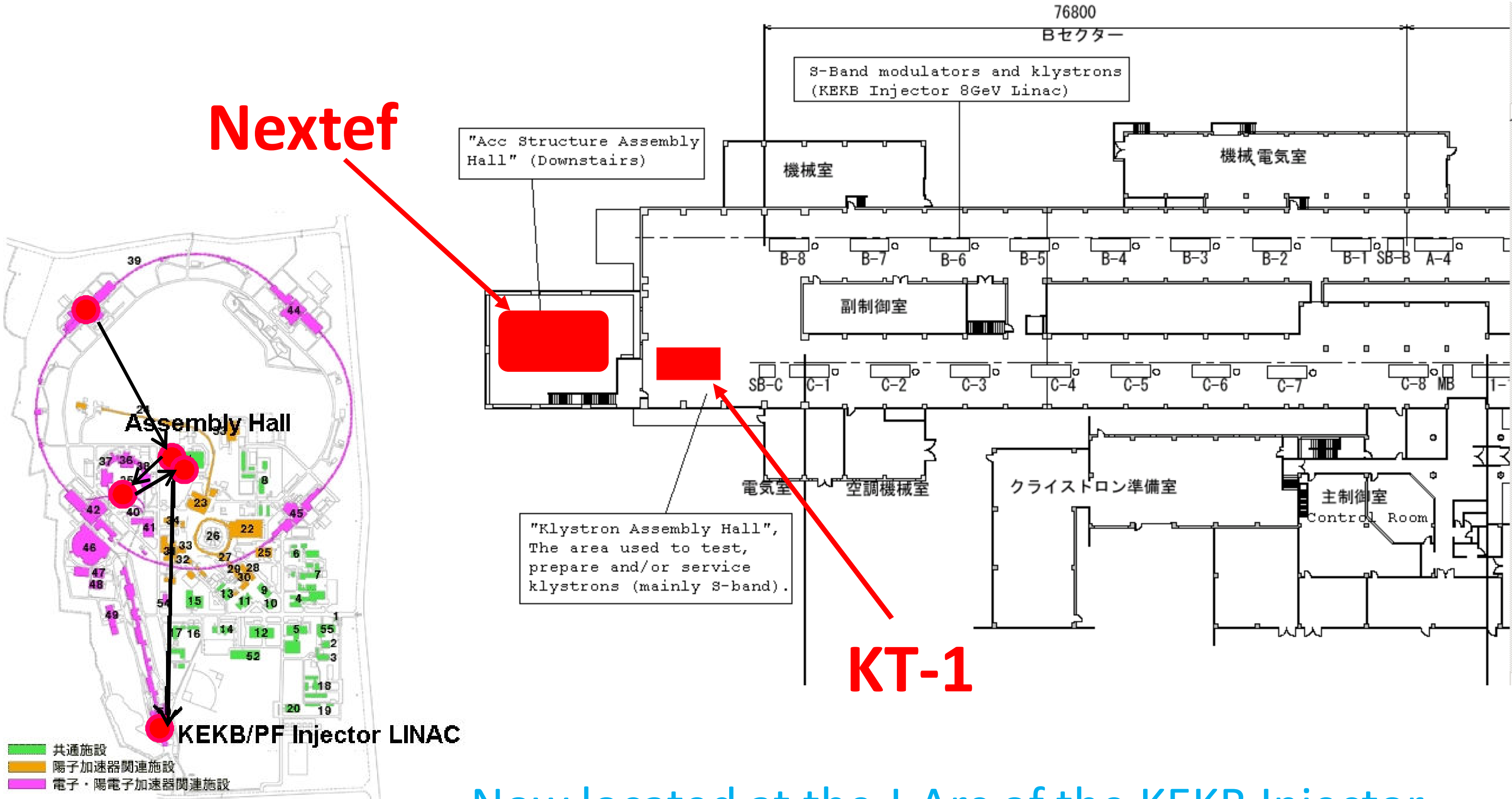
#3 being tested at SLAC NLCTA



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

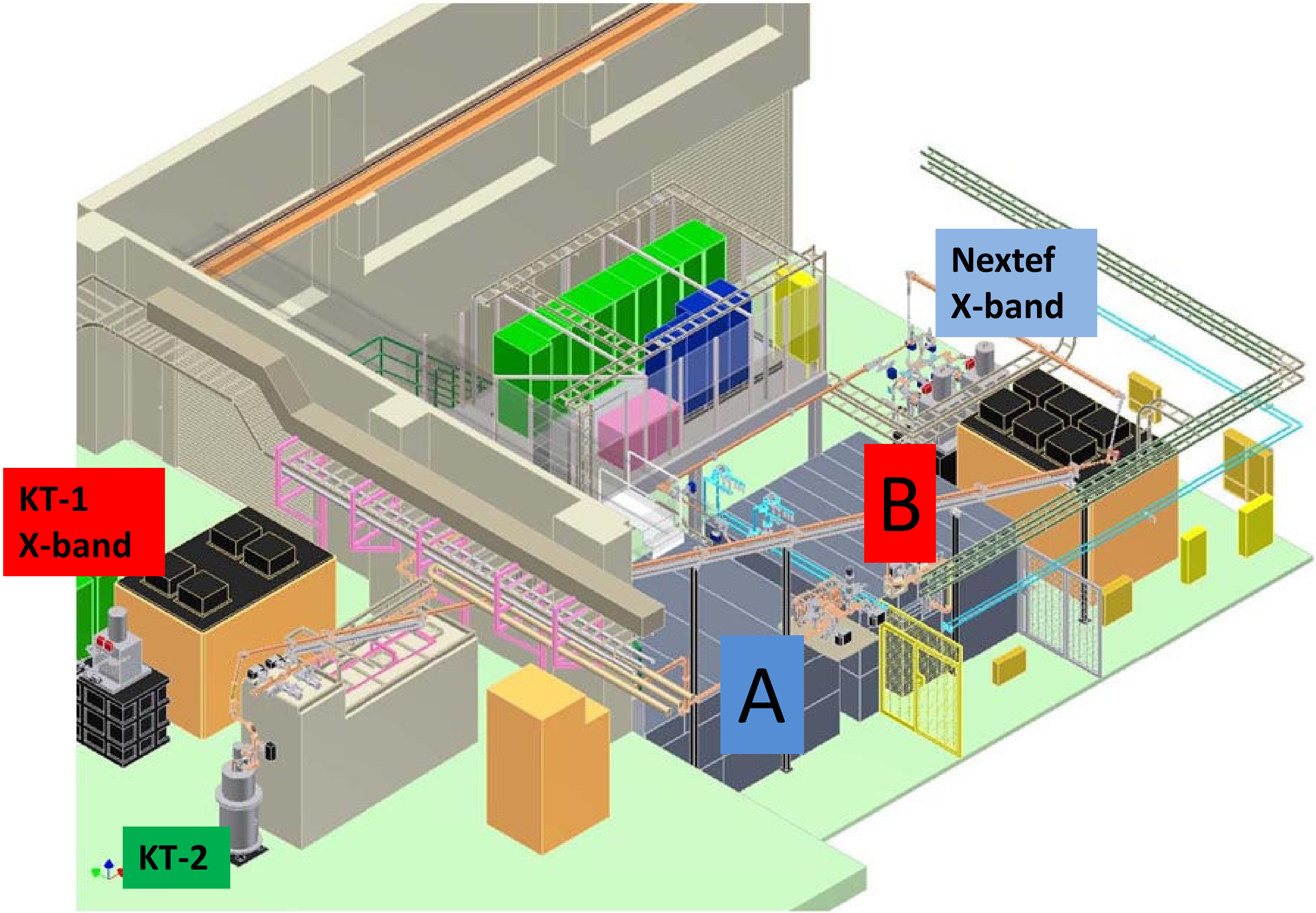


Now located at the J-Arc of the KEKB Injector

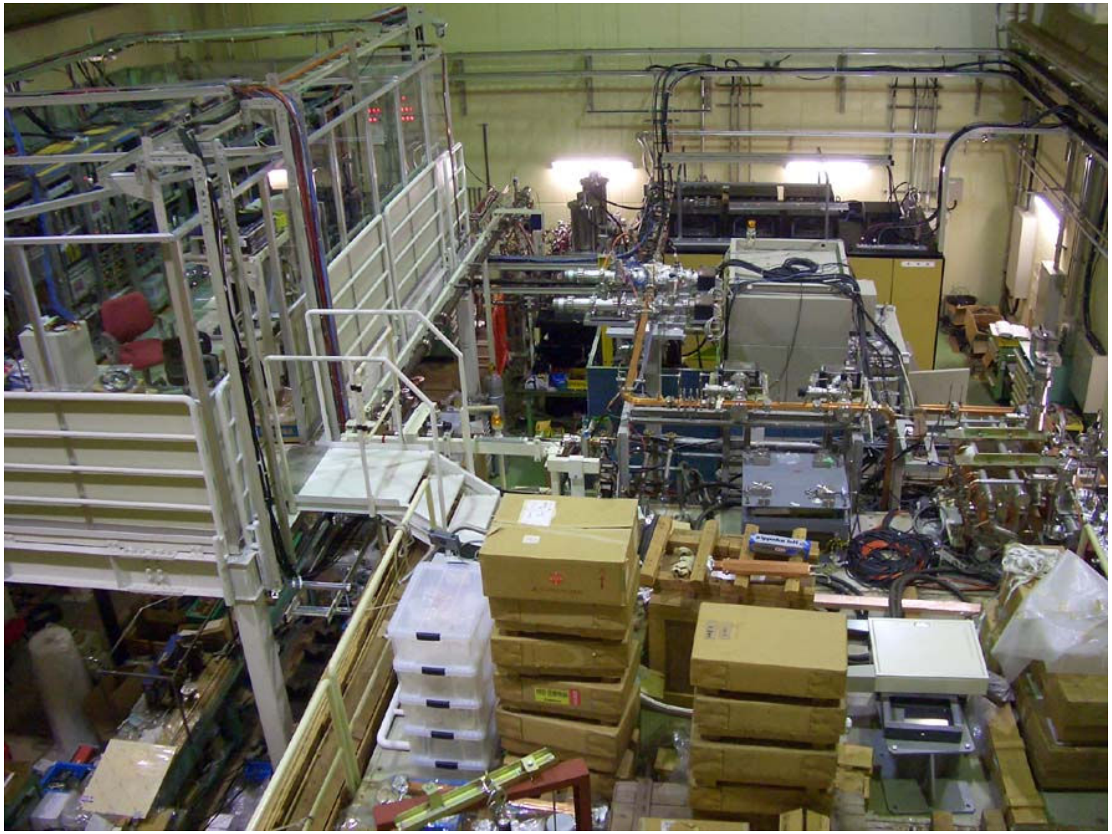
KEK test facilities

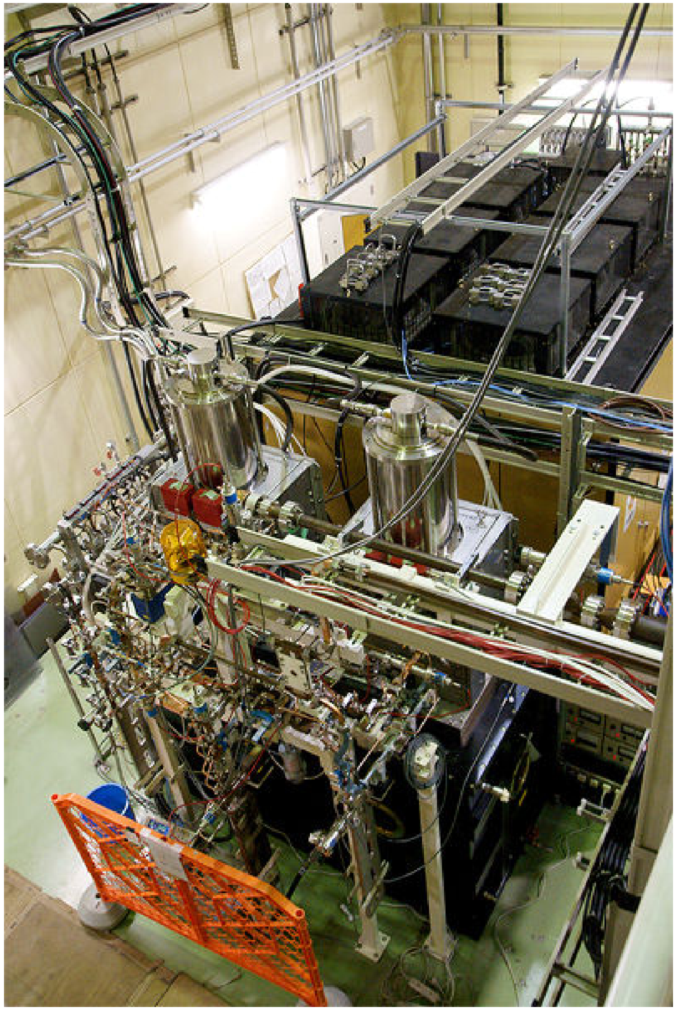
- Nextef
  - Shield-A being used for structure tests
  - Shield-B being prepared for basic studies, taking power from KT-1
- KT-1
  - One PPM klystron
  - High gradient study with narrow waveguide
  - High power study on components
  - Feed shield B

KEK: Nextef Configuration

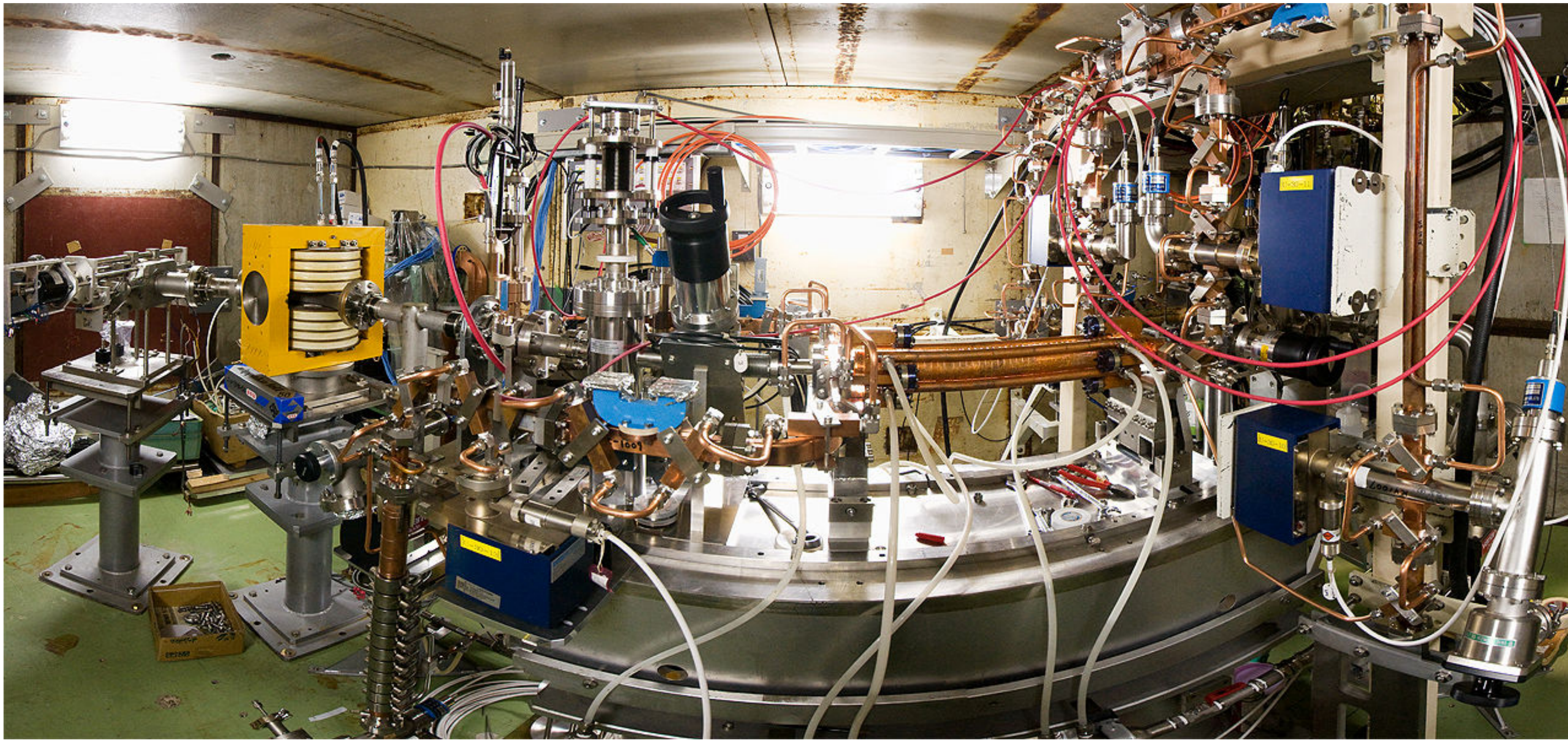


Nextef operation since 2007

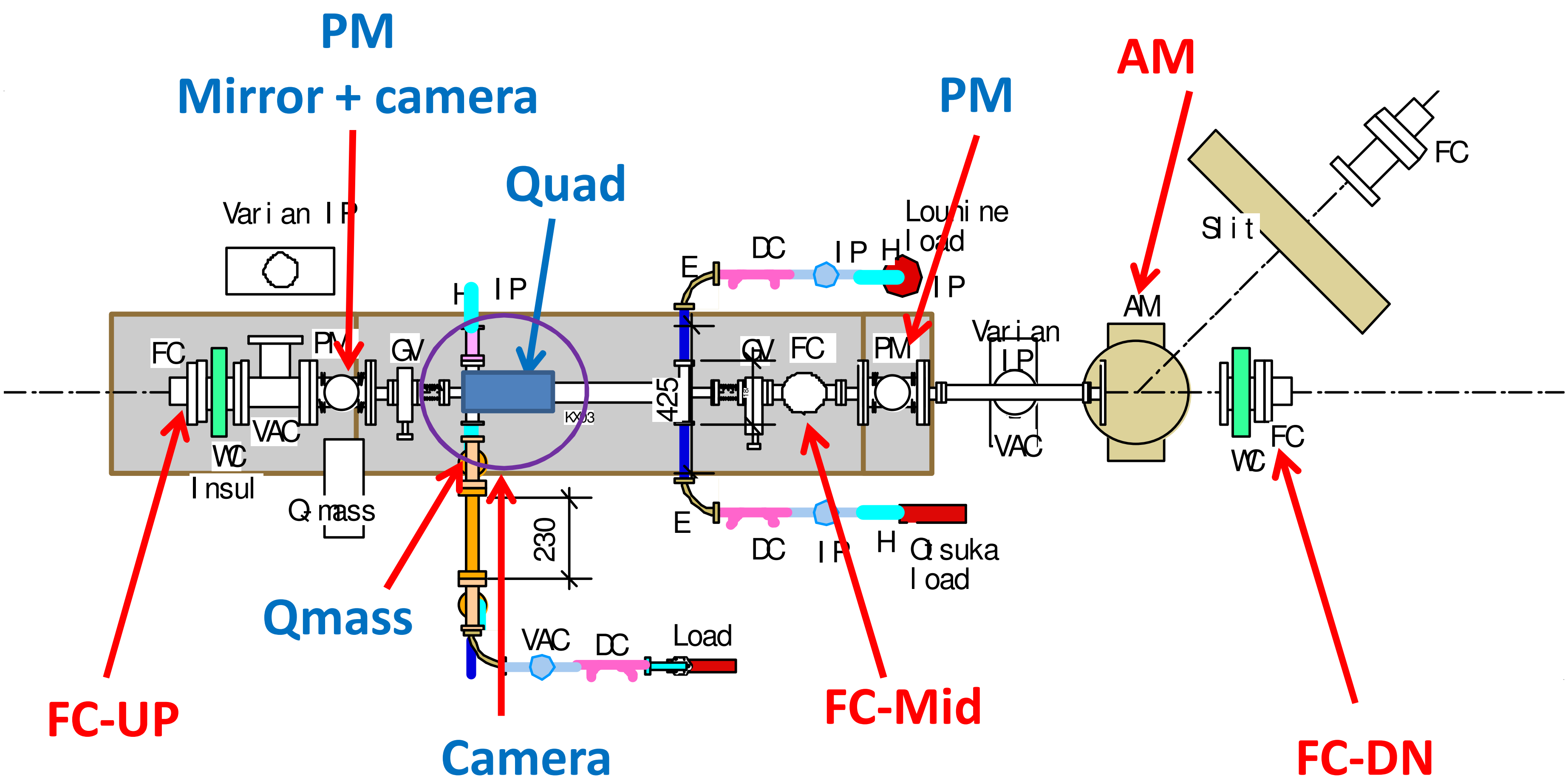




Nextef   inside shield room



Monitors and components in shield-A



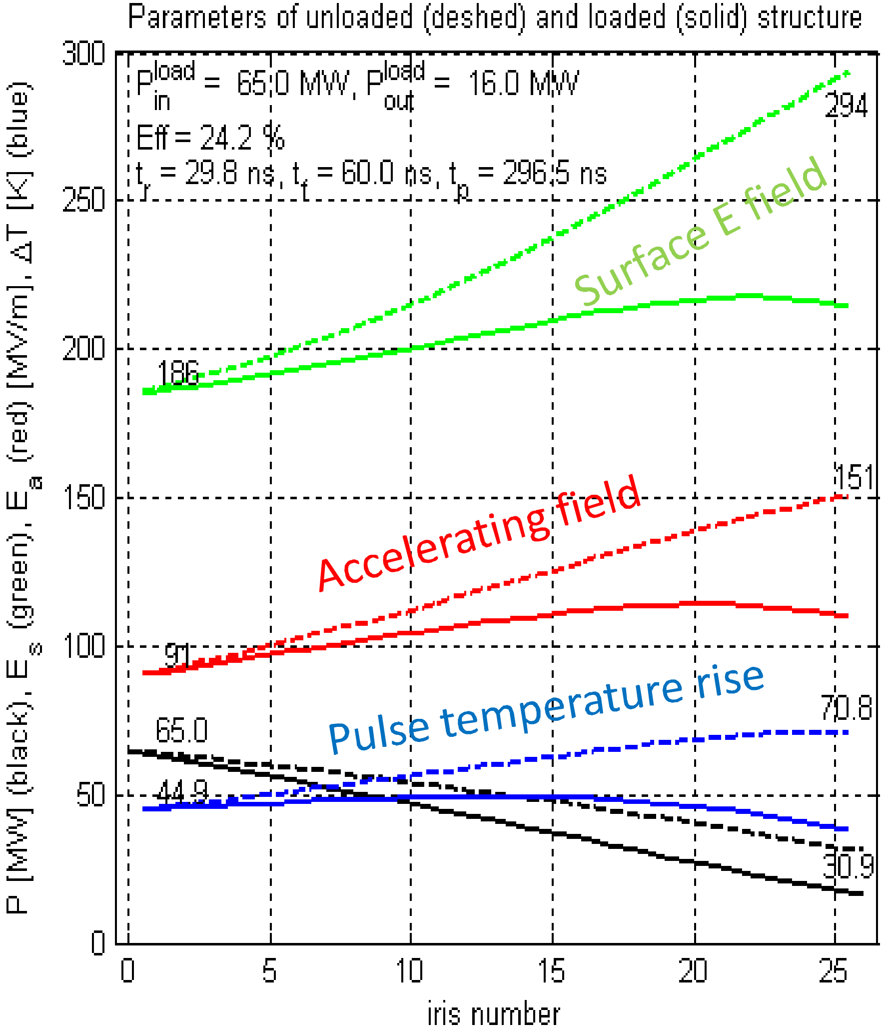
High gradient test of three structures

- 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+

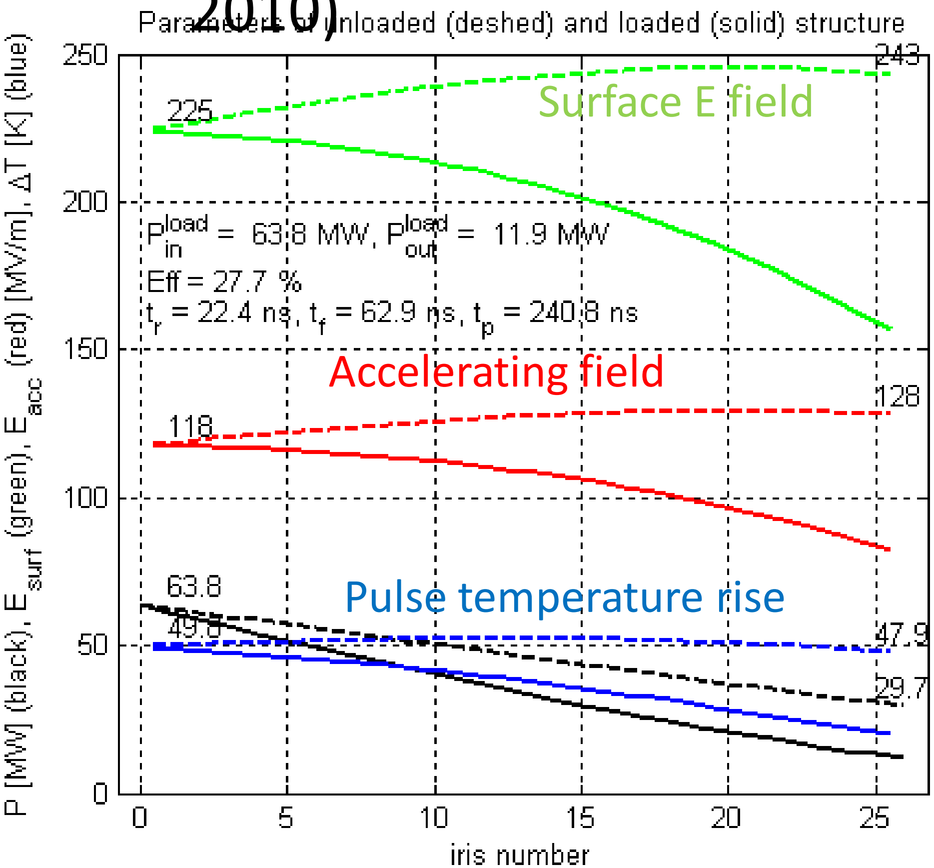
T18_Disk_#2

- 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)

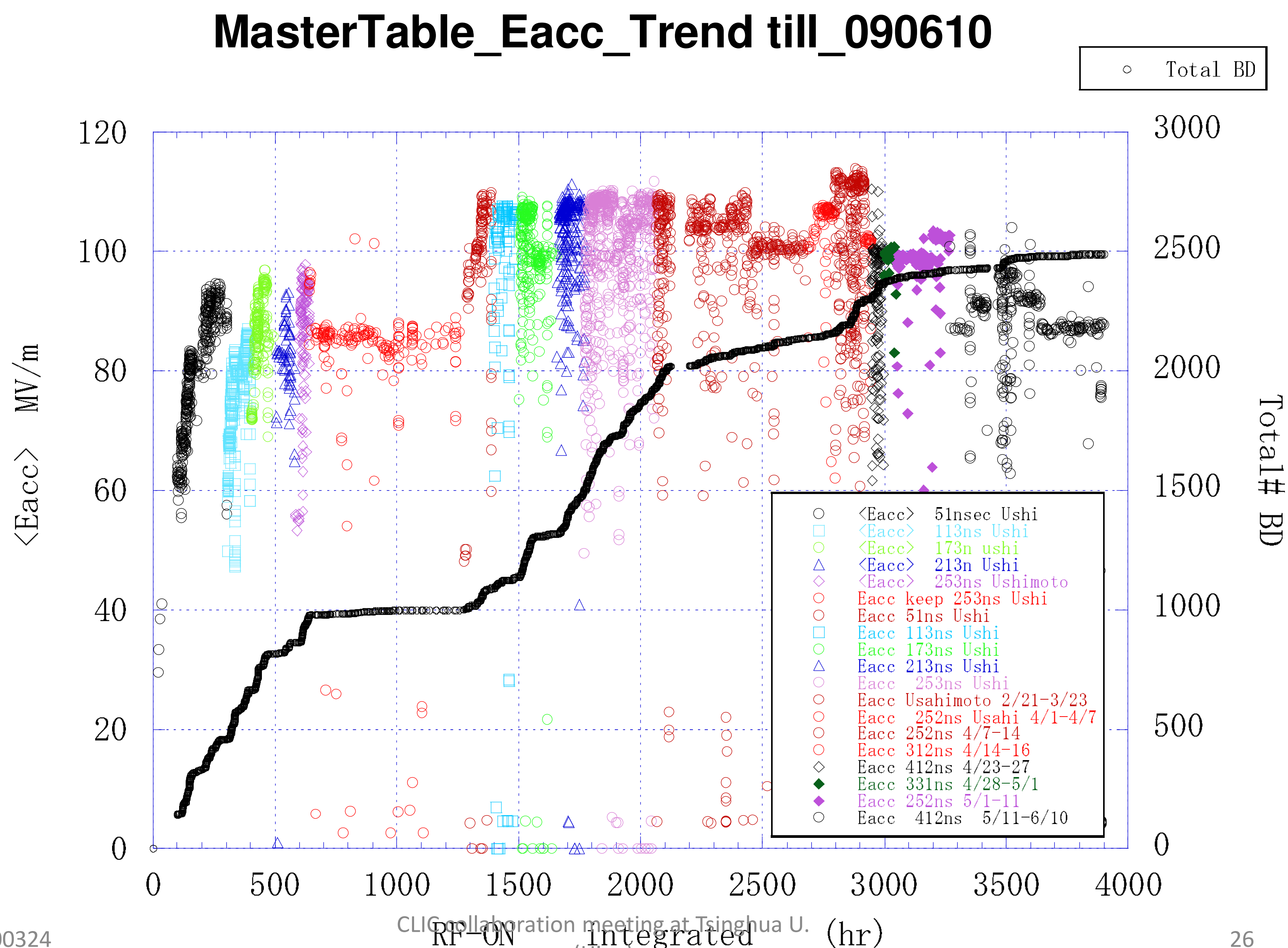


CLIC Nominal: CLIC_G (T24 being tested in 2010)



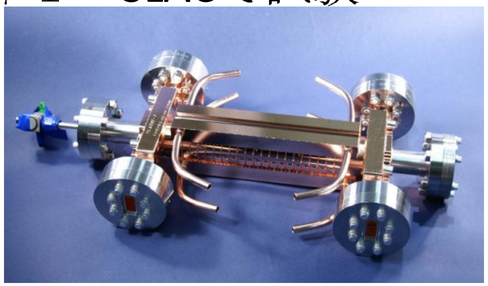
T18_Disk #2(KEK)

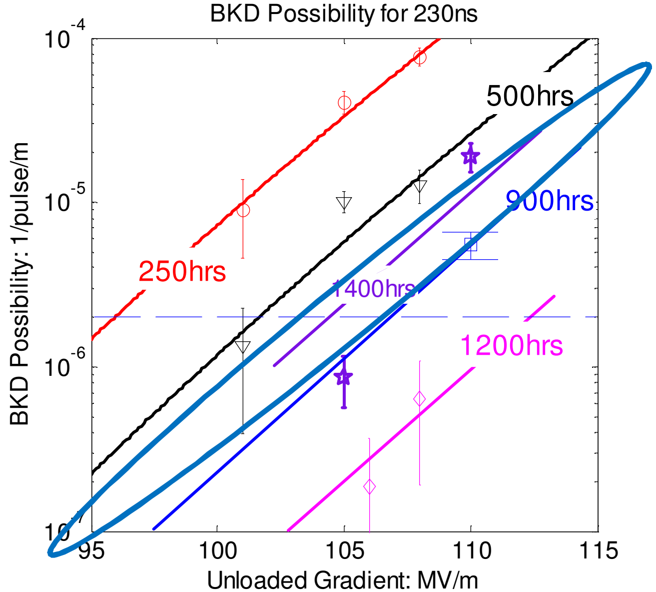
090610



Establishment of experiments to quantitatively compare

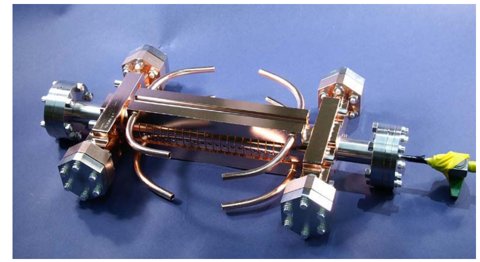
＃１　SLACで試験

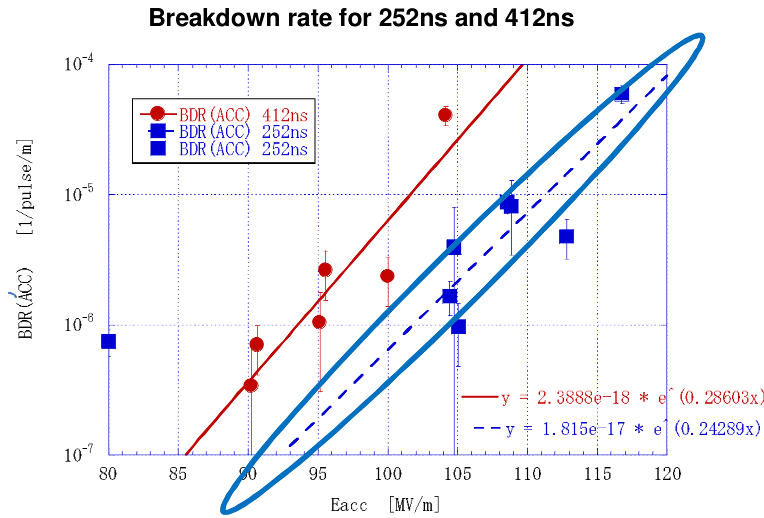




C. Adolphsen, US-HG@ANL, 2009

＃2　KEKで試験

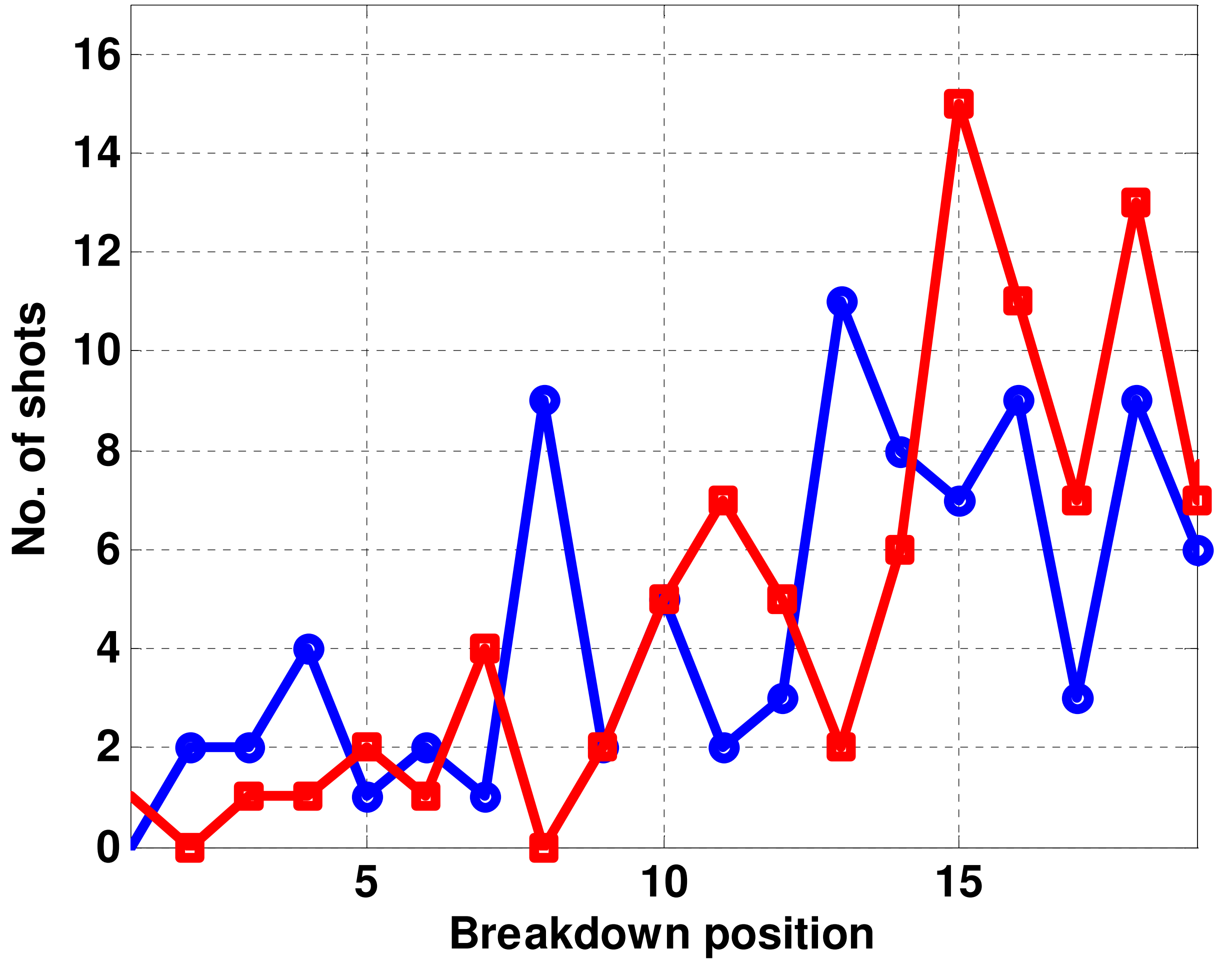




Roughly the same breakdown rates were observed for a pair of structures.
Will pursue the same comparison again for the second pair.

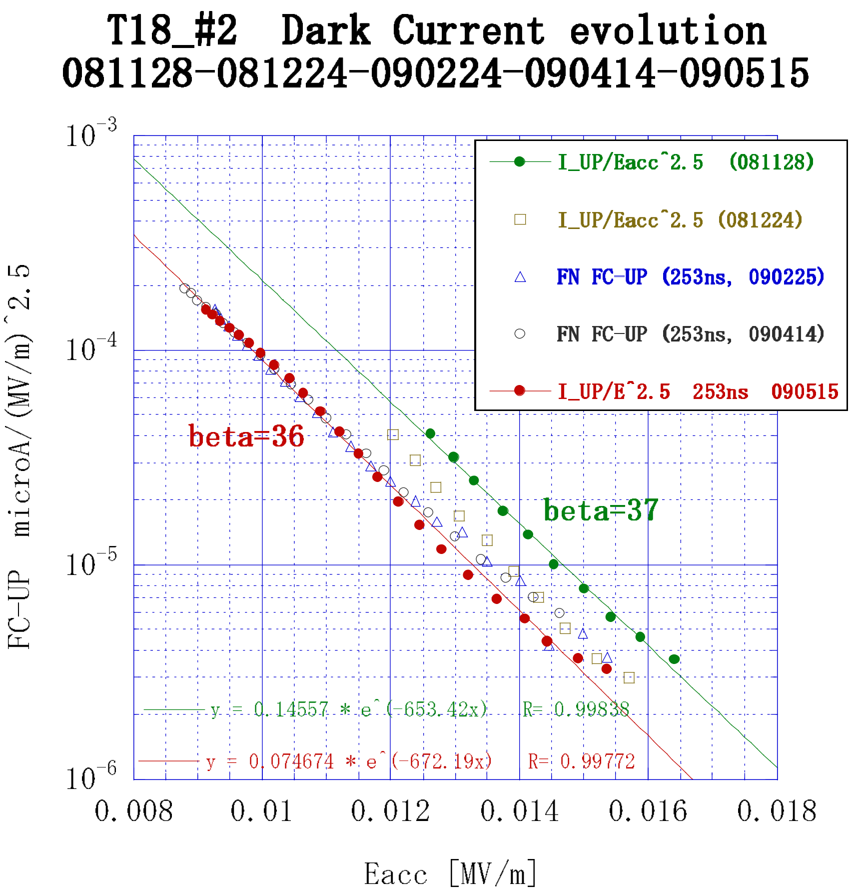
Steffen 090227

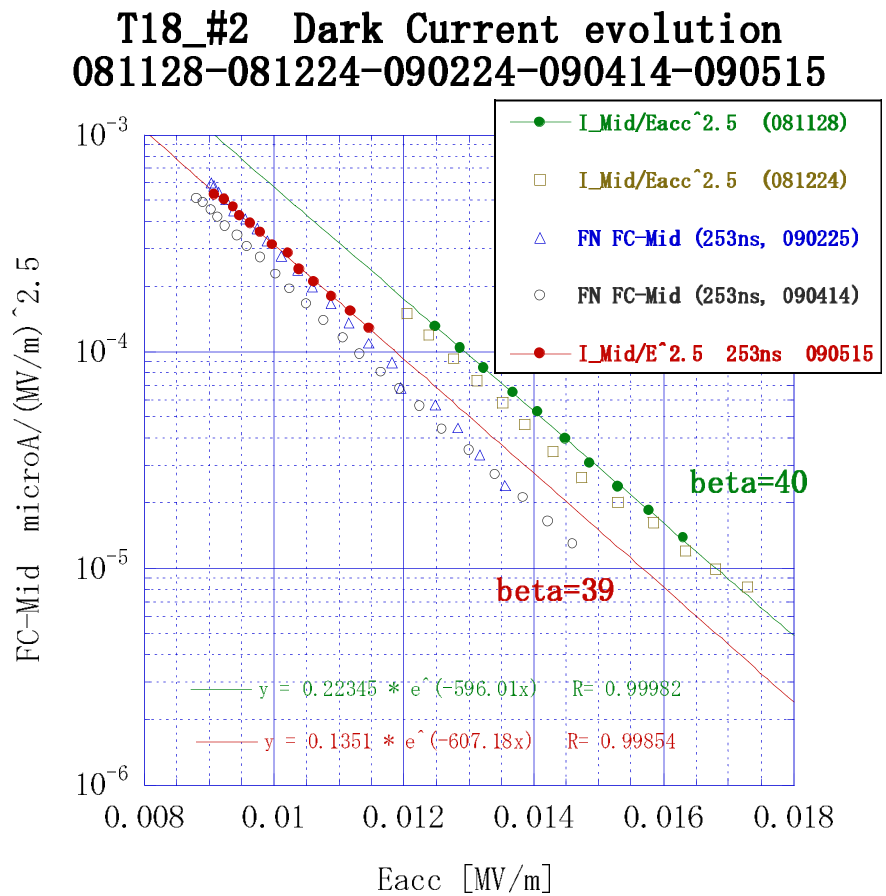
Breakdown position for 205 ns data



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

Dark current evolution 252nsec

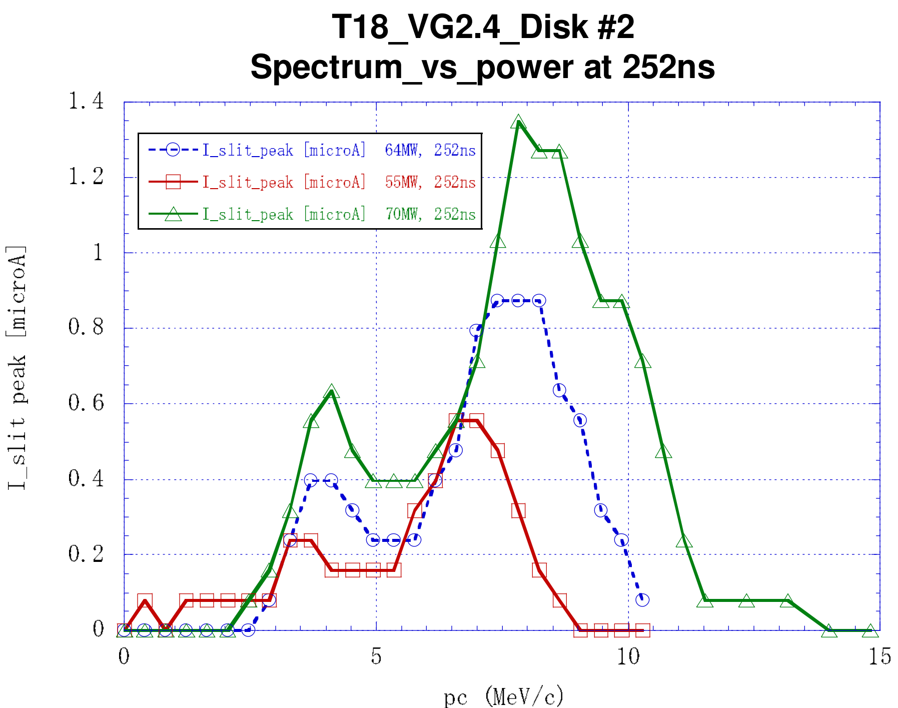




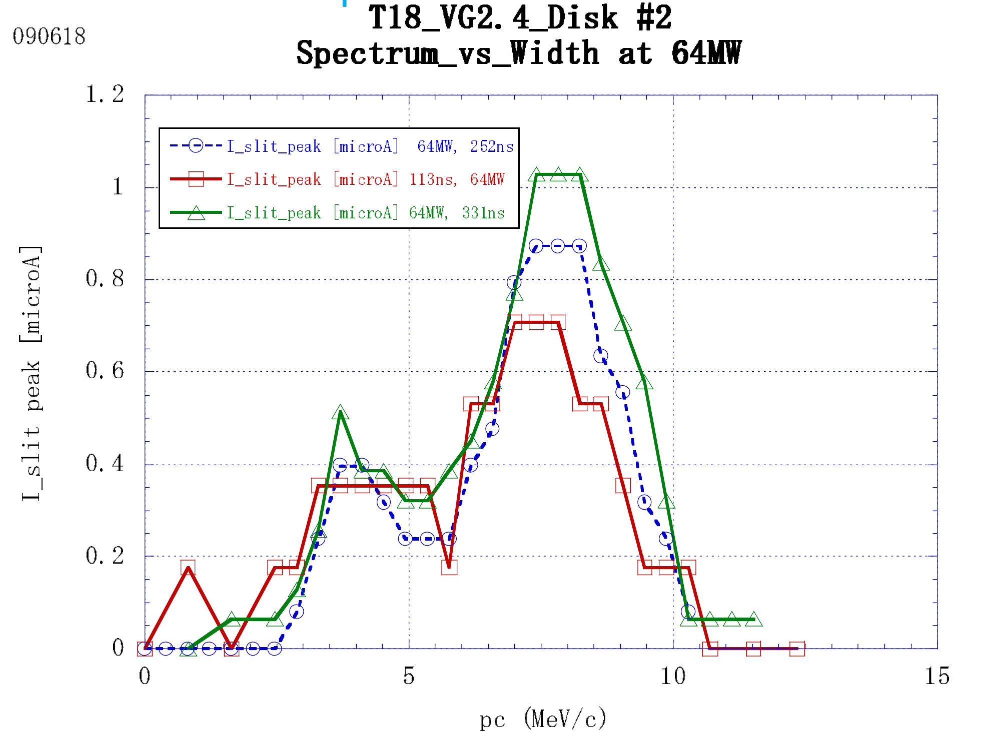
Measured at RF ON 700 – 1200 – 2100 – 3000 – 3400 hours
Decreasing amount, no big change in shape nor slope (beta).

Dark current spectra in June

Dependence on power



Dependence on width



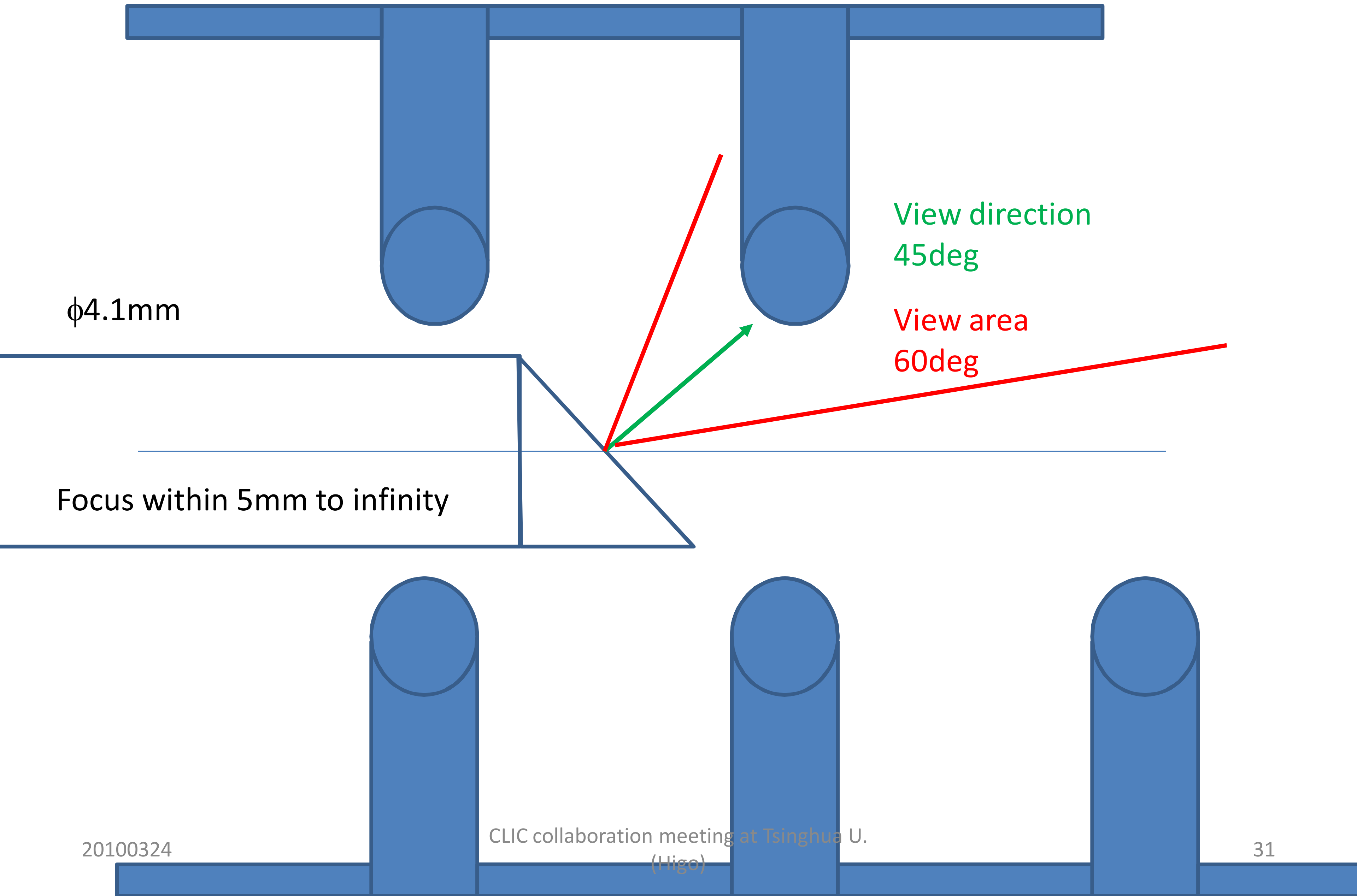
Actual field of analyzer magnet was checked.

The formula used up to now pc[MeV/m] = 1.646 x I [A] = 8.23xRef. Volt. [V] was confirmed.

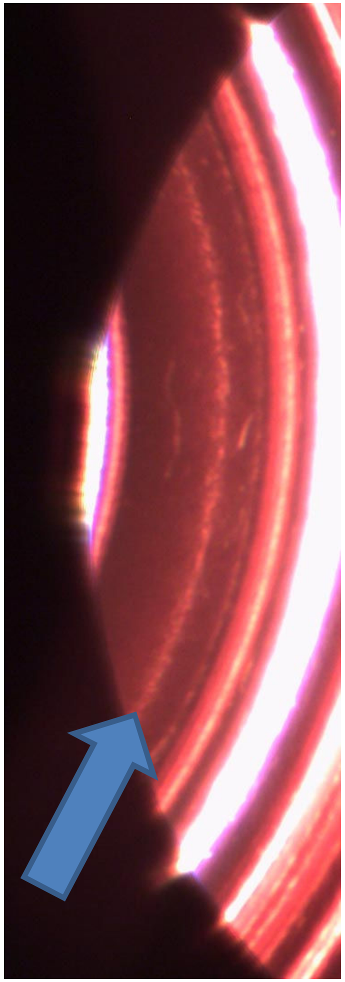
Two peaks appear and higher for higher momentum one.

Less than ½ of full acceleration.

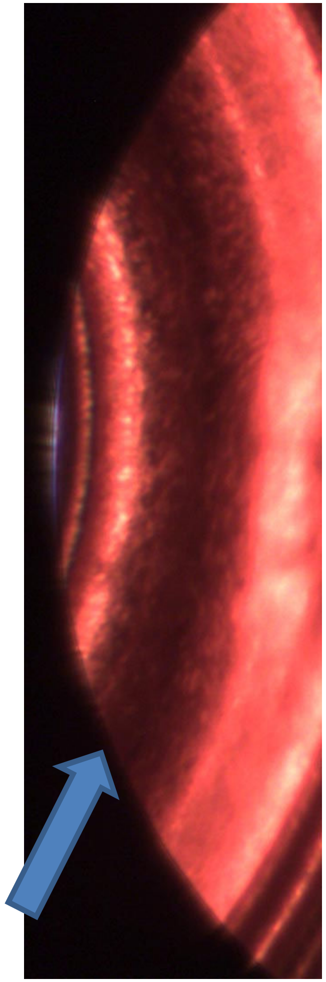
Little exists below 2.5MeV/m.


View direction
45deg
View area
60deg
ϕ4.1mm
Focus within 5mm to infinity

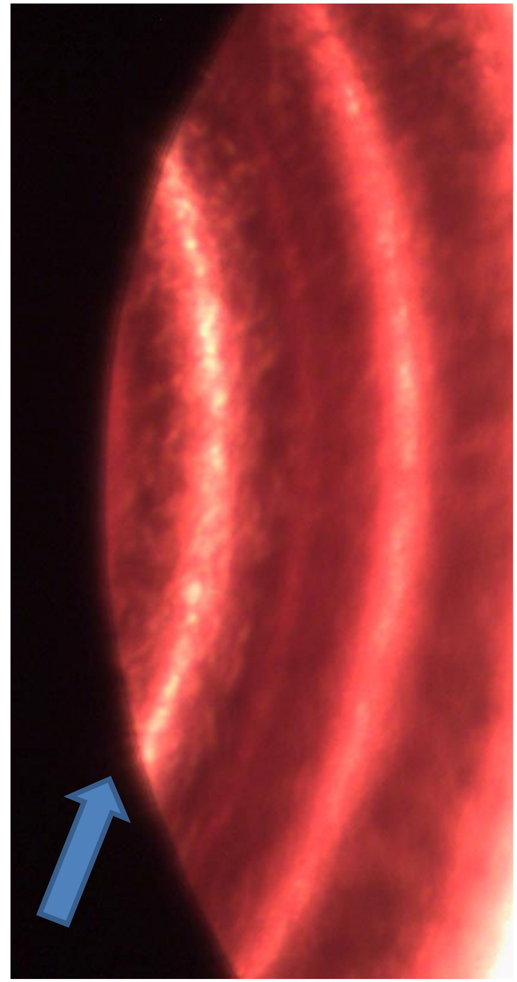
Optical inspection upstream and downstream



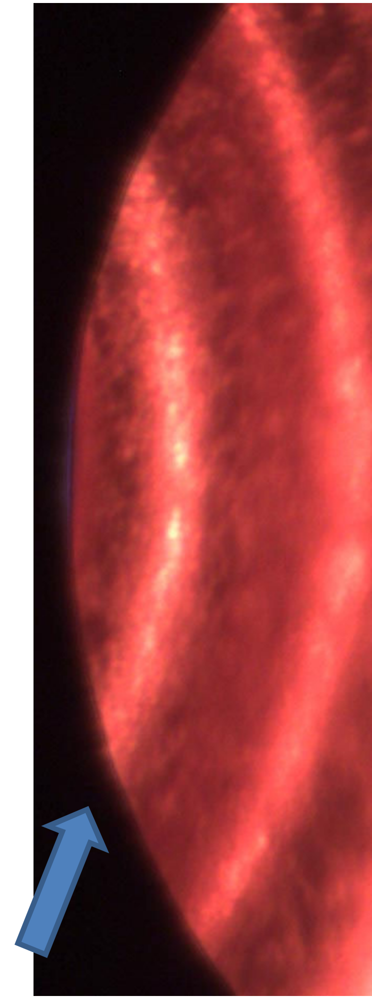
Insertion 82.7mm
Iris #1 at match cell



Insertion 98.0mm
Iris #2 at first regular cell



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

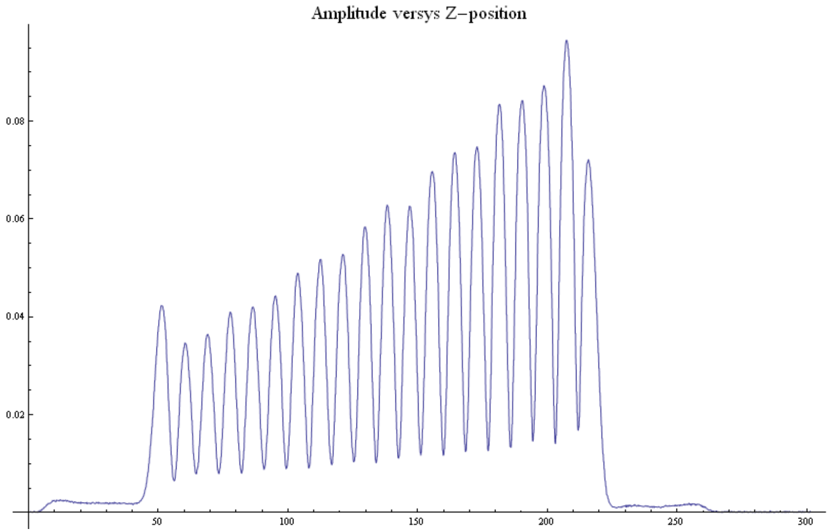


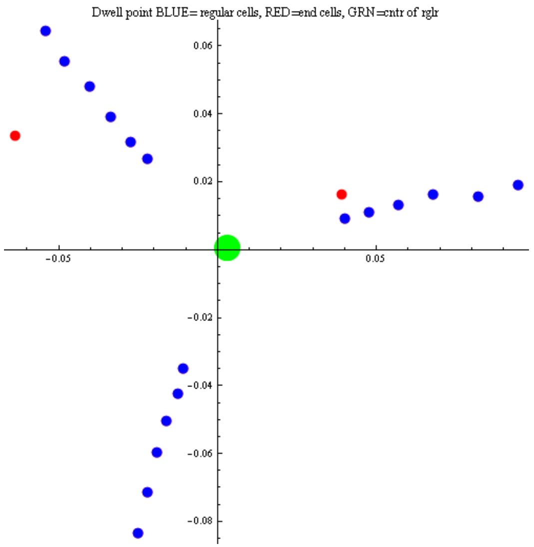
261.3mm
Last regular cell iris #20

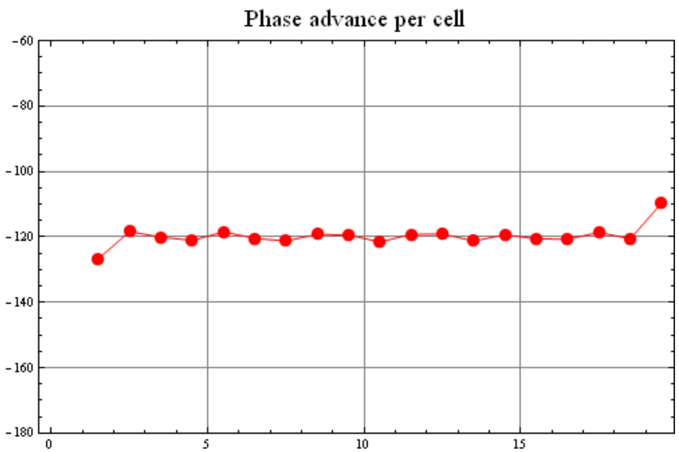
Optical inspection result and future

- 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

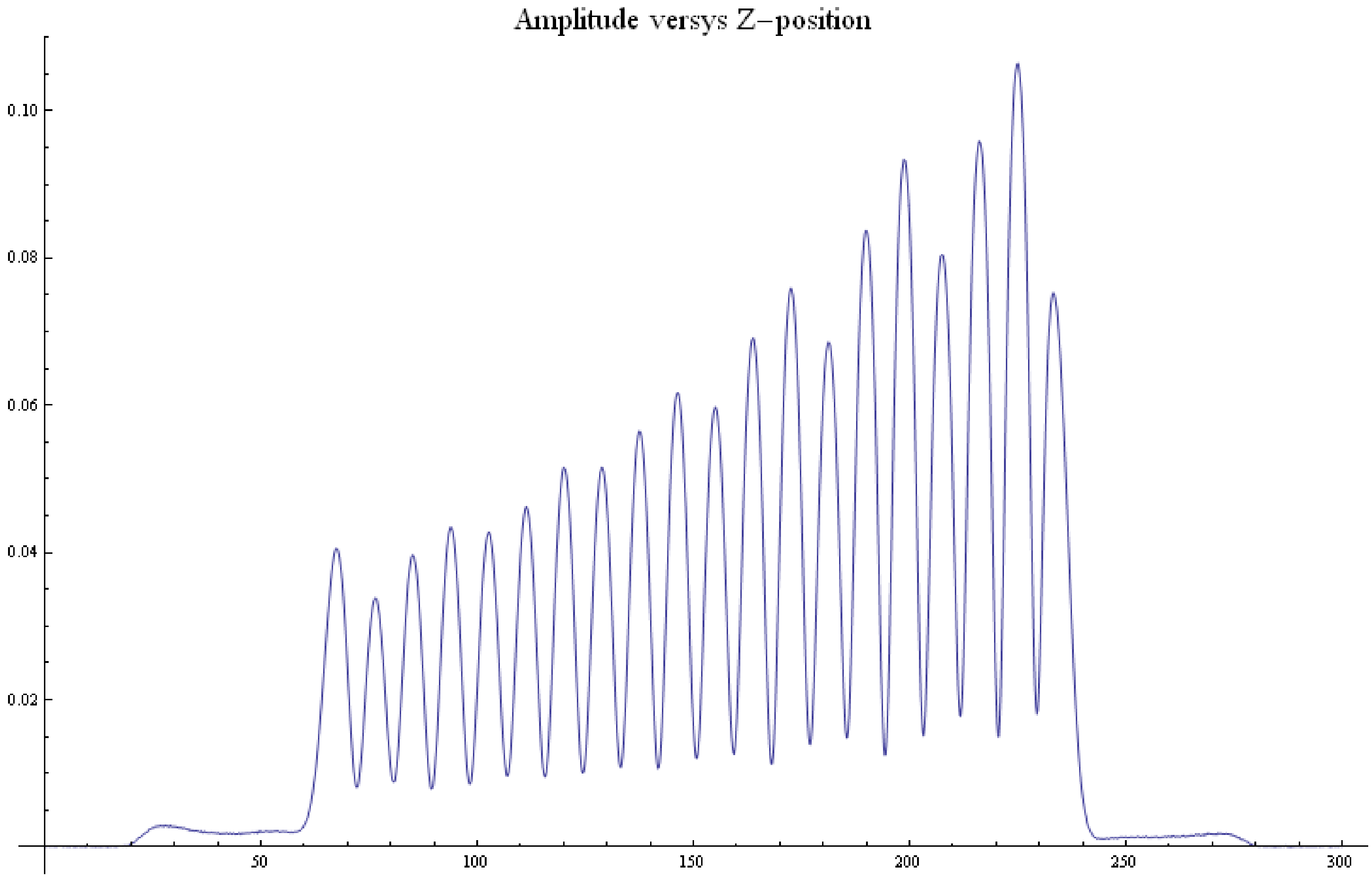






11.42128MHz@119.754deg/cell
at 22.3degC
11.4233MHz at 30C in VAC
→ -0.7MHz than nominal

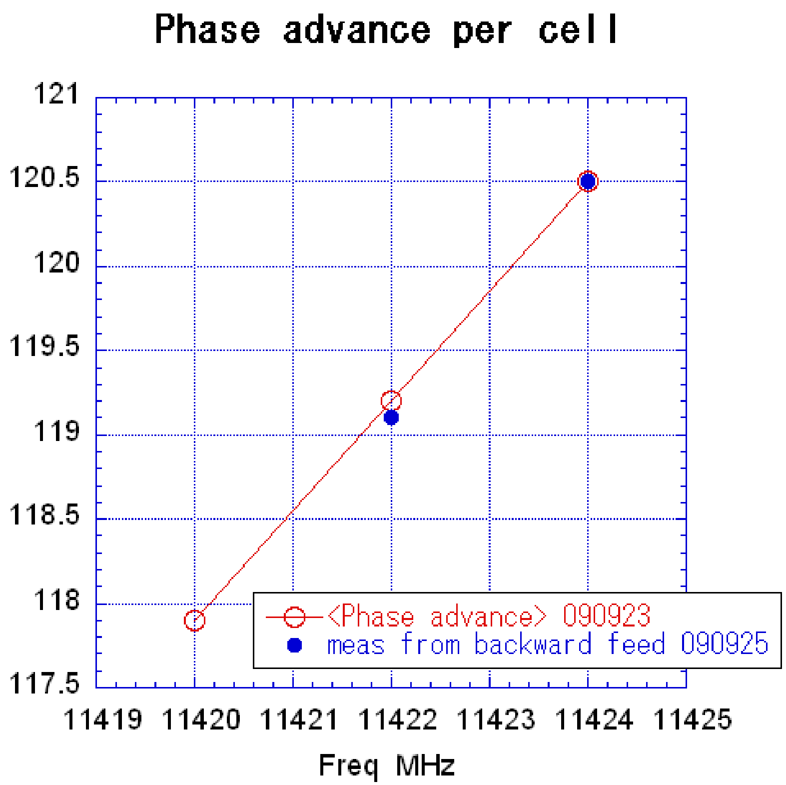
Bead pull amplitude plot 11422MHz after high gradient test

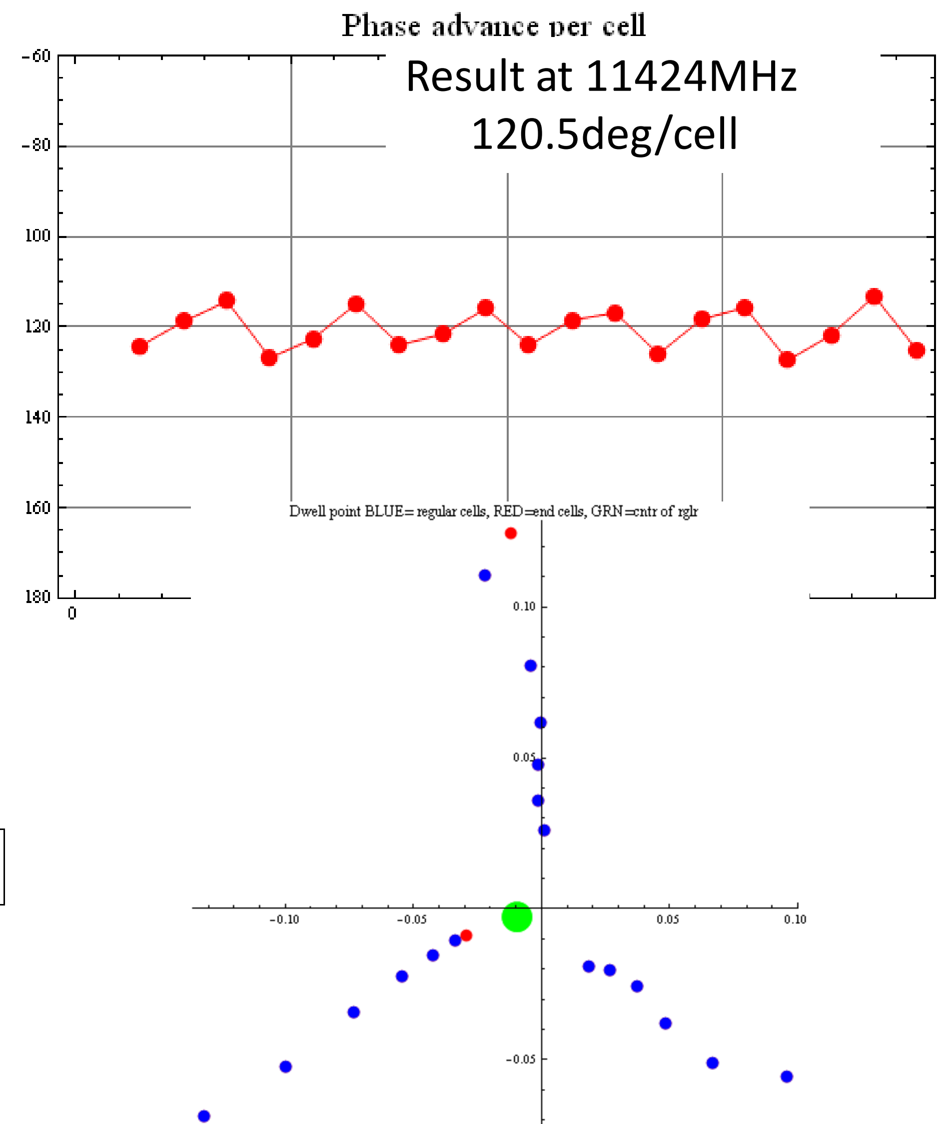


Input side

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 Γ=0.05 level.
  - Average frequency increased by 1.1+0.7=+1.8MHz.
  - Field ripple±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.→ Need the number of breakdowns be limited until reaching operation.

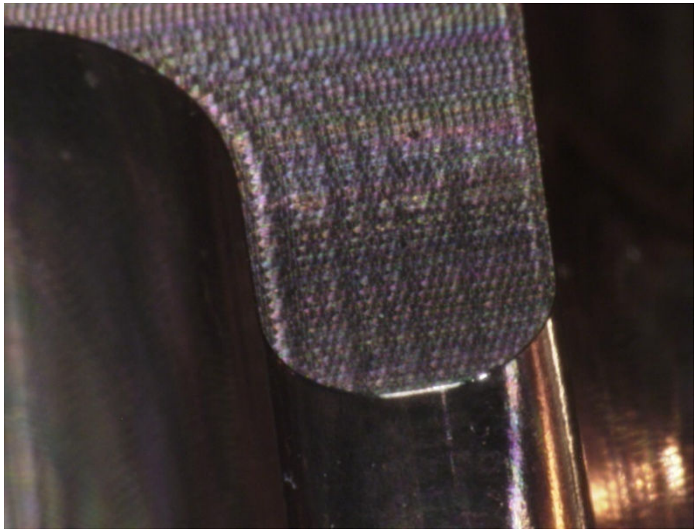
T18_Disk summary

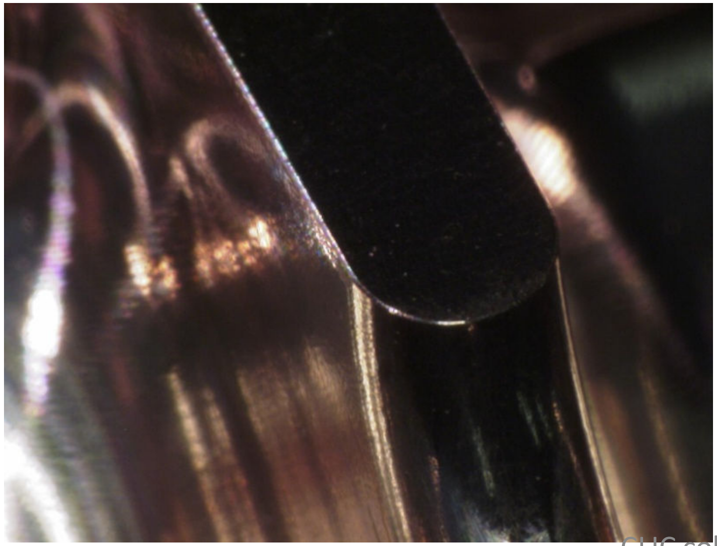
- 100MV/m was proven to be feasible
- Similar breakdown rate between SLAC and KEK
- Breakdown rate decreased as processing proceed
- Breakdown probability is higher in downstream cells
- Dark current can be fit with modified FN formula
- Dark current decreases as processing proceeds
- No big change in 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.

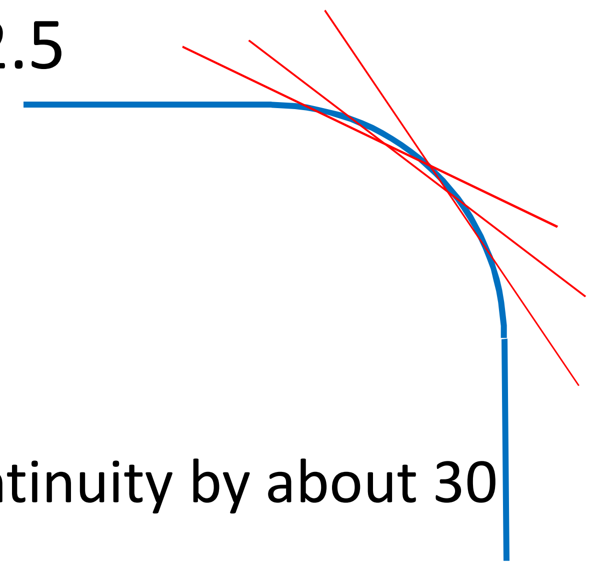
50 micron rounding: shape with angles and bumps.

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

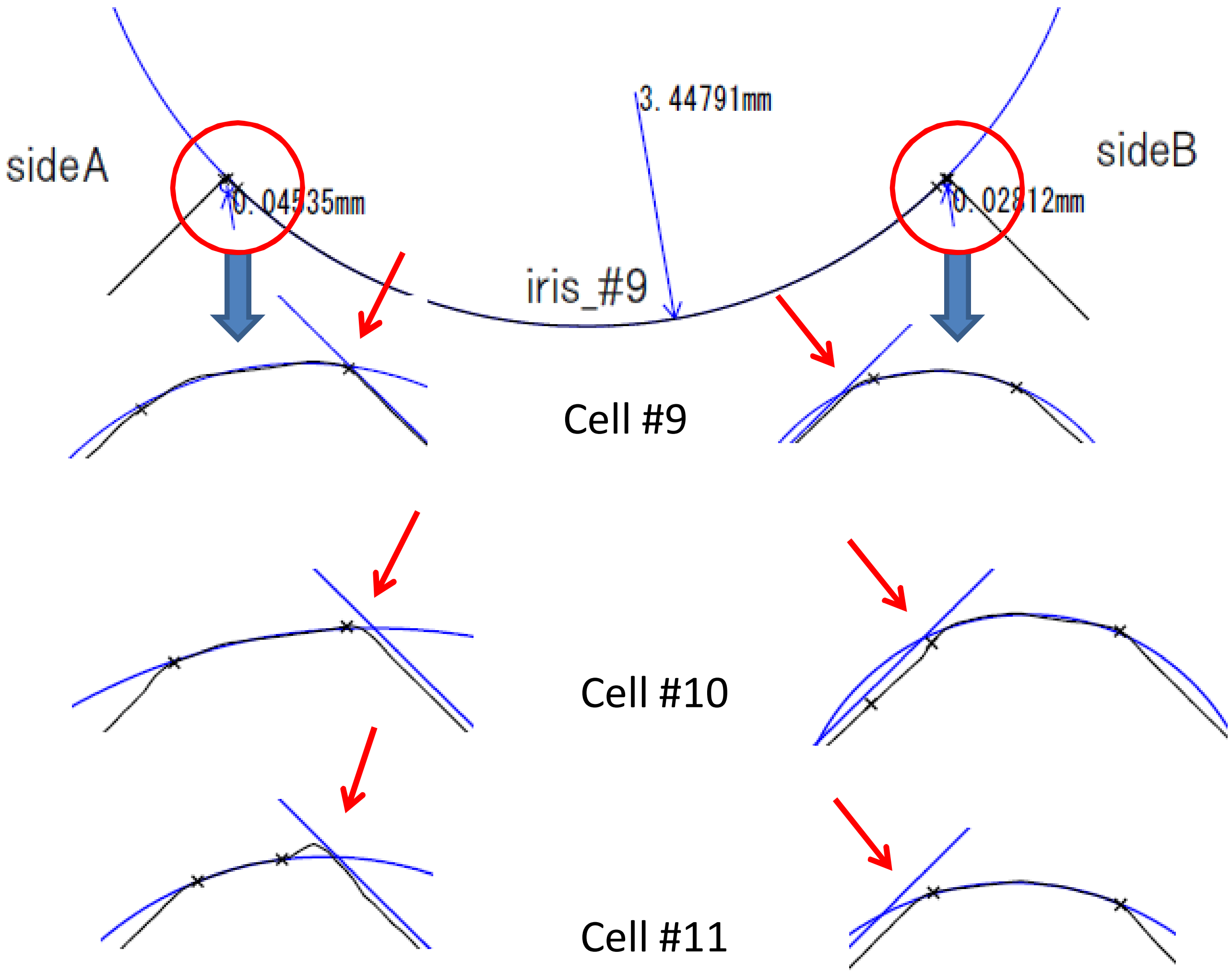
Assembly was done within ten micron level.

Possible cause of high dark current
Field enhancement due to round chamfer

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



Detailed shape at R0.05 chamfer



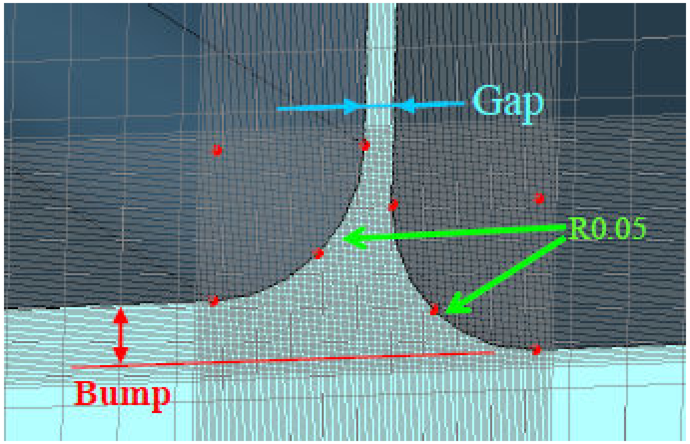
Only 2~3 tool passes over R0.05 90deg rounding.

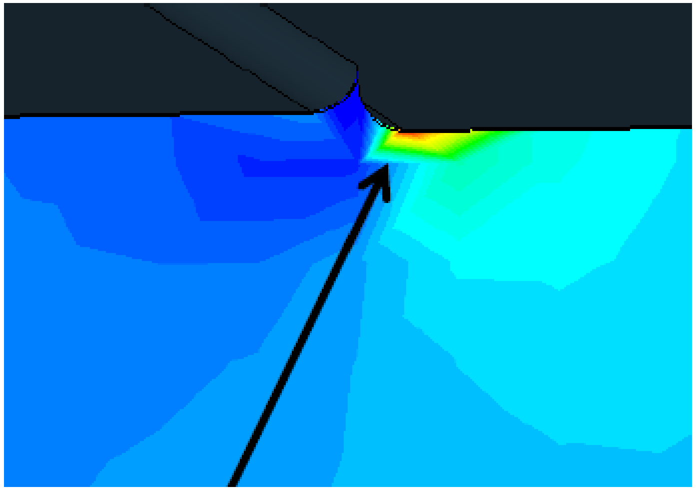
Not tangential connection from smooth surface. 30-40 degree edge emerges.

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.

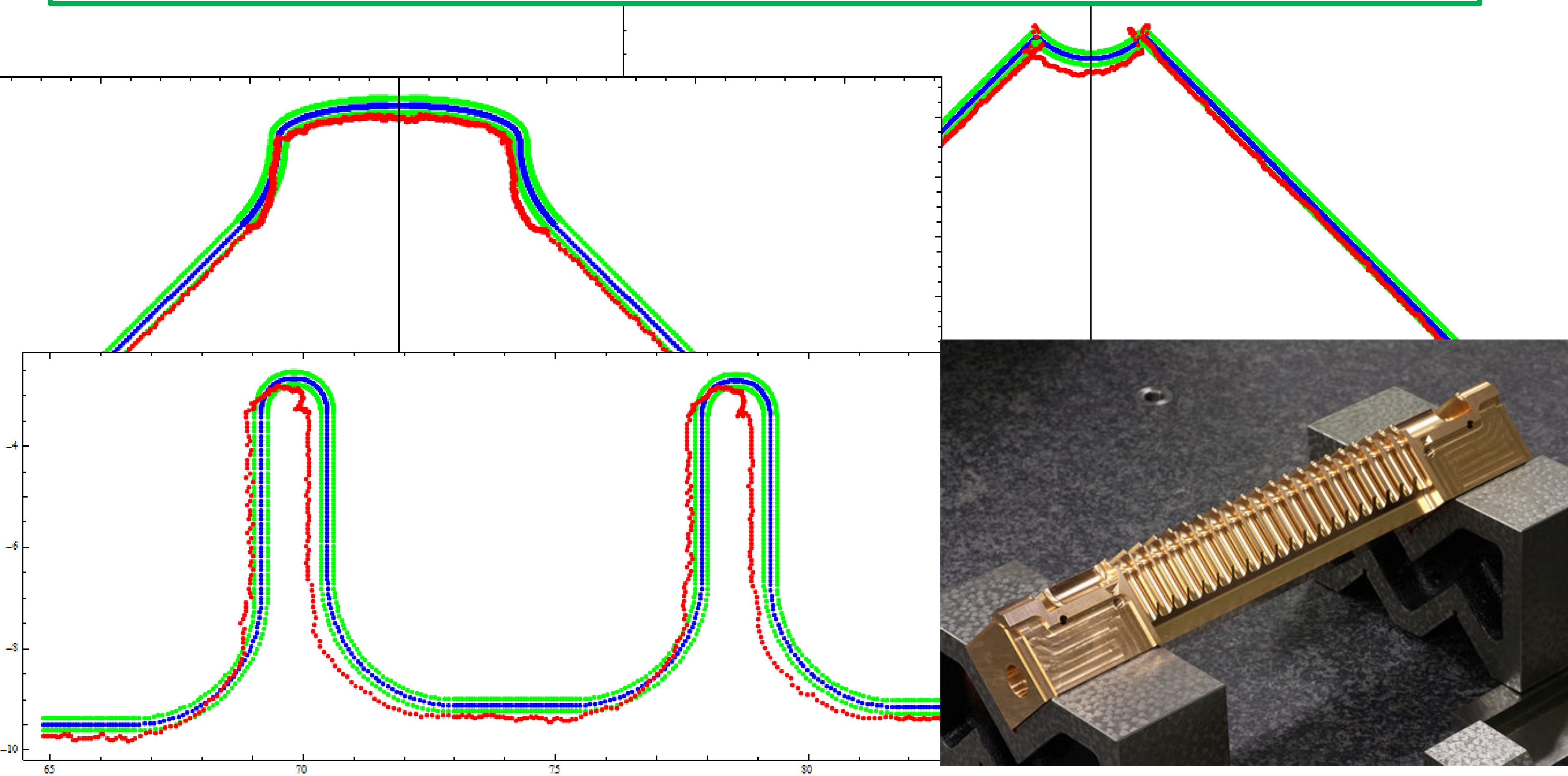




Gap (micron)	Bump (micron)	Emax / Enominal
0	0	1.39
0	20	1.57
10	20	1.58

Production of quadrant Q1-1

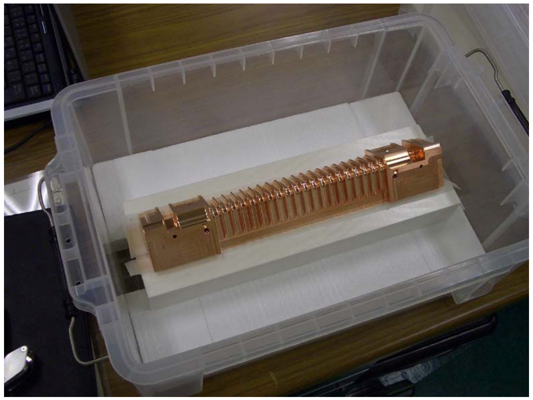
Green lines are ±2.5 microns.
Followings shows worst part out of four measured areas along the axis.
Local shape is smoothly connected.



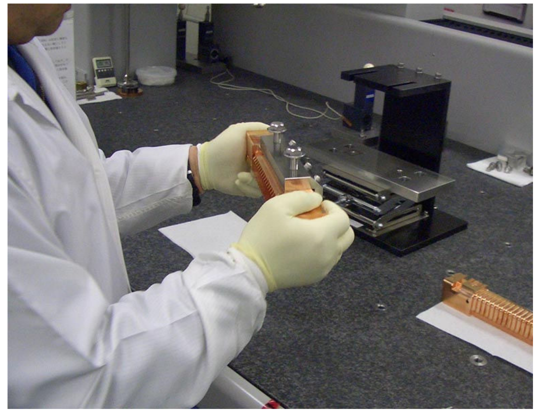
Surface: No etching
No high-temperature heat treatment

- 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.

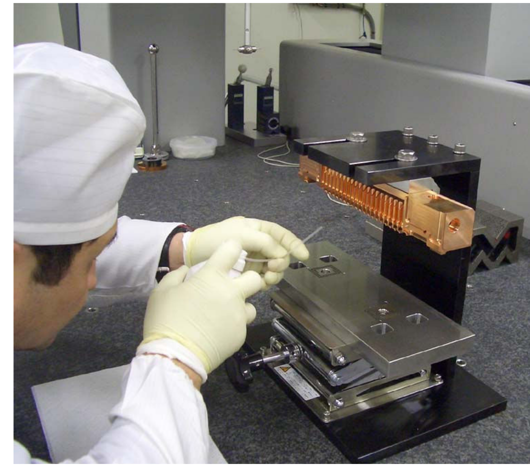
Assembly



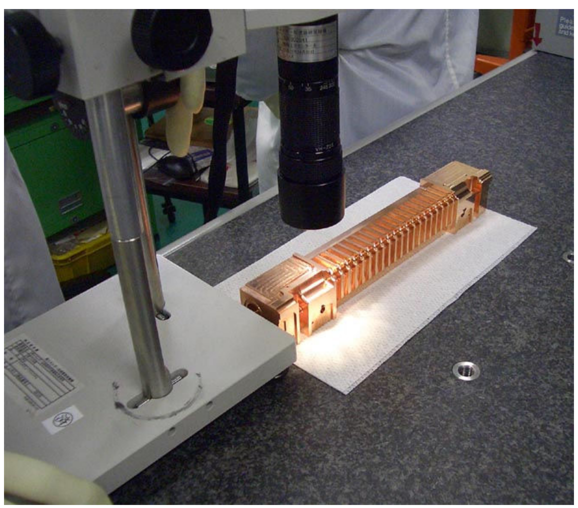
Carry and storage



First hanging

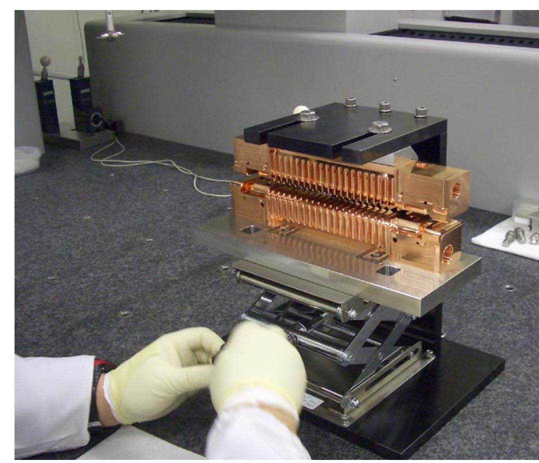


Prepare next quad approach

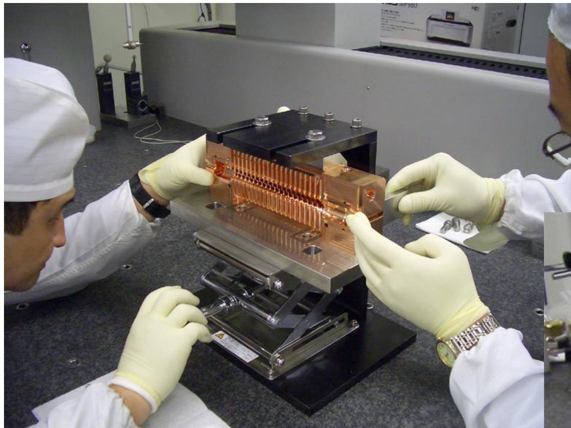


Edge inspection

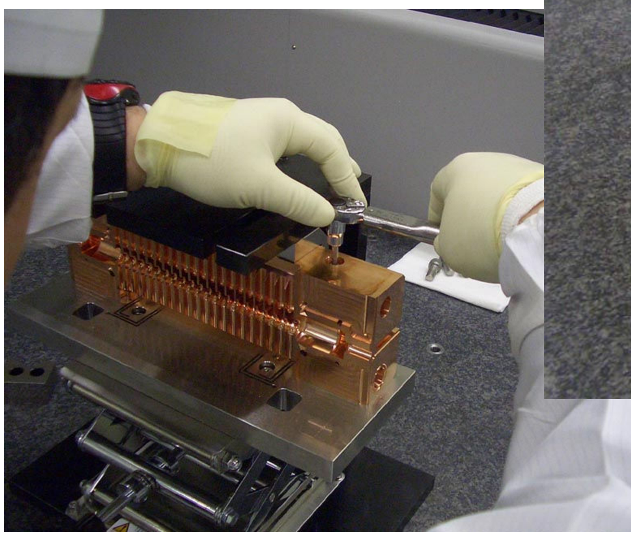
Check ball diameter



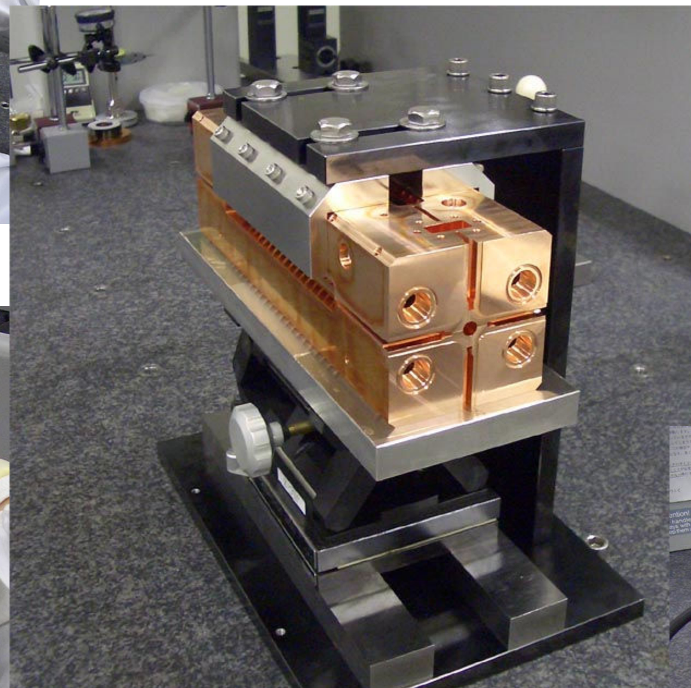
Second hanging



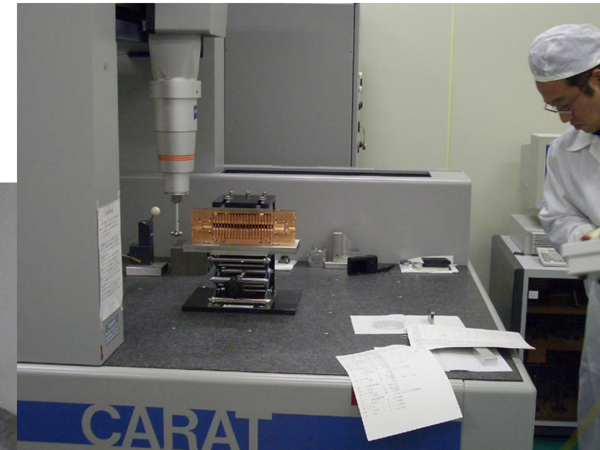
Fine adjustment



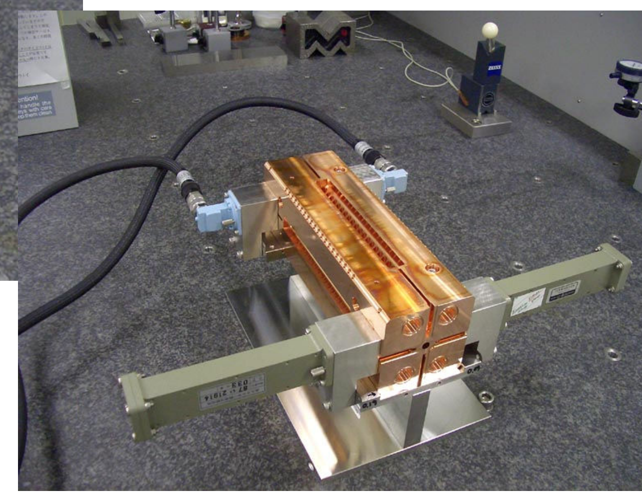
Fixing by bolt



Completion of stack



Alignment checking



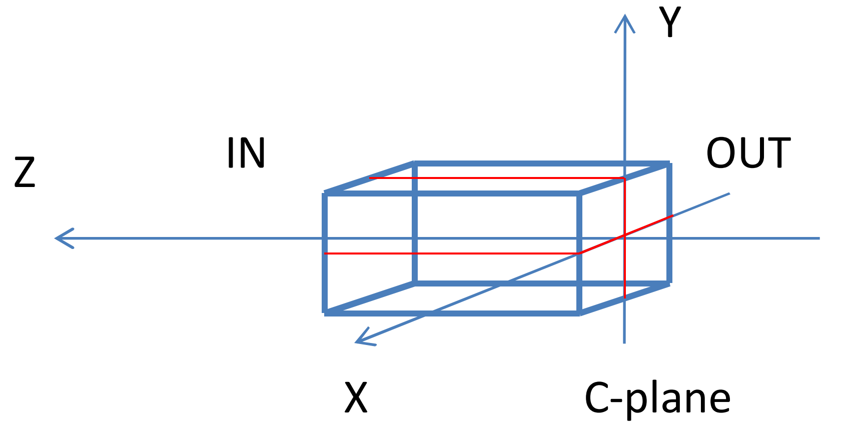
RF setup

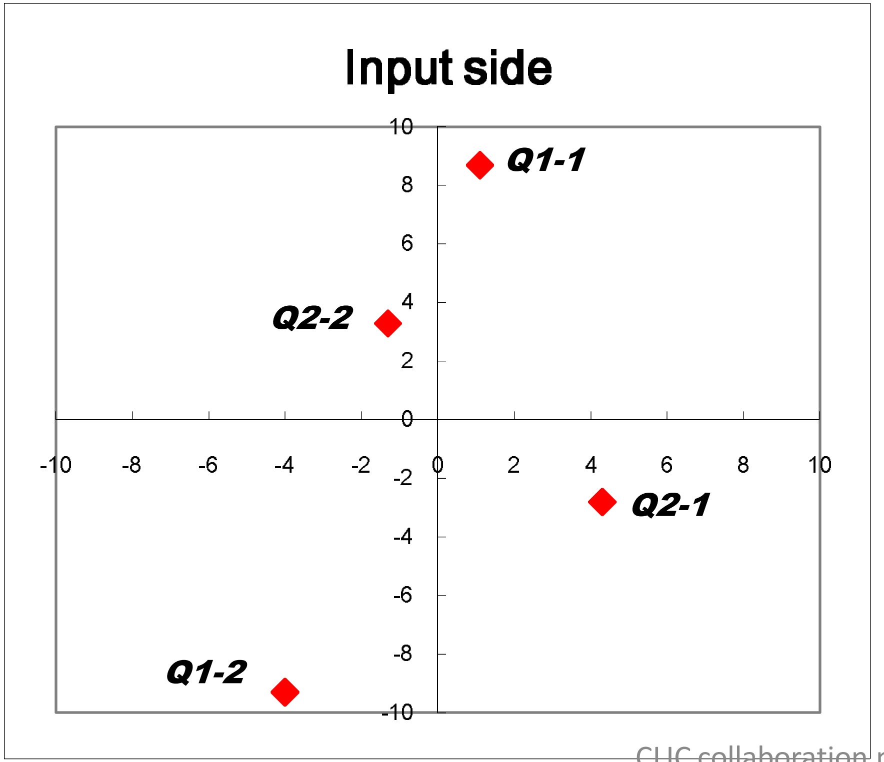
Manual adjustment before final pressing, without ball and groove mechanism. Misalignment: within ten microns.

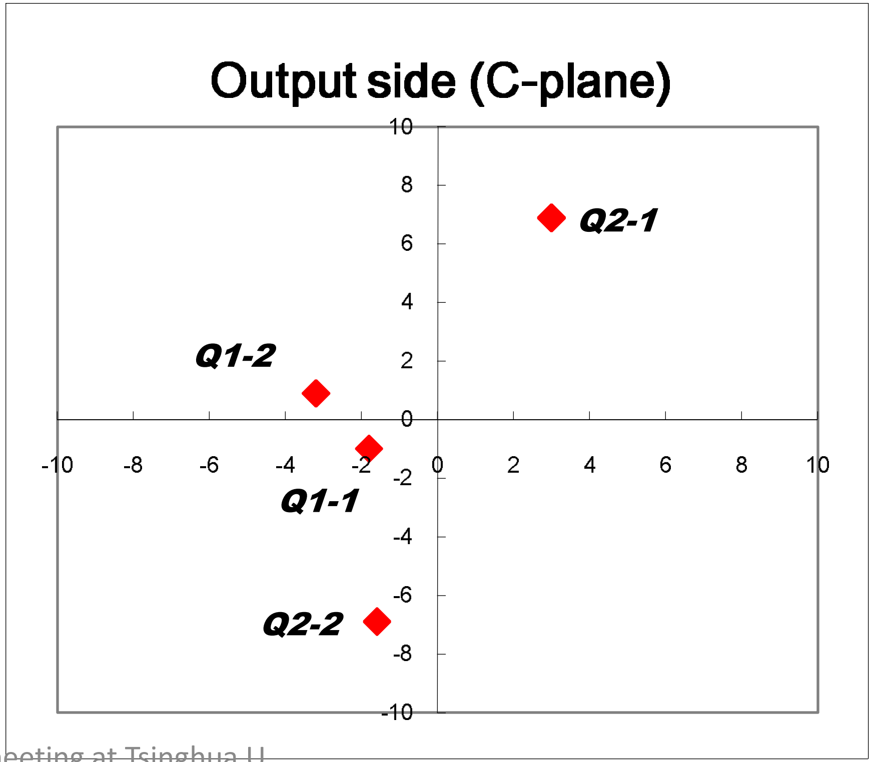
Reproducibility: a few microns.

Final alignment

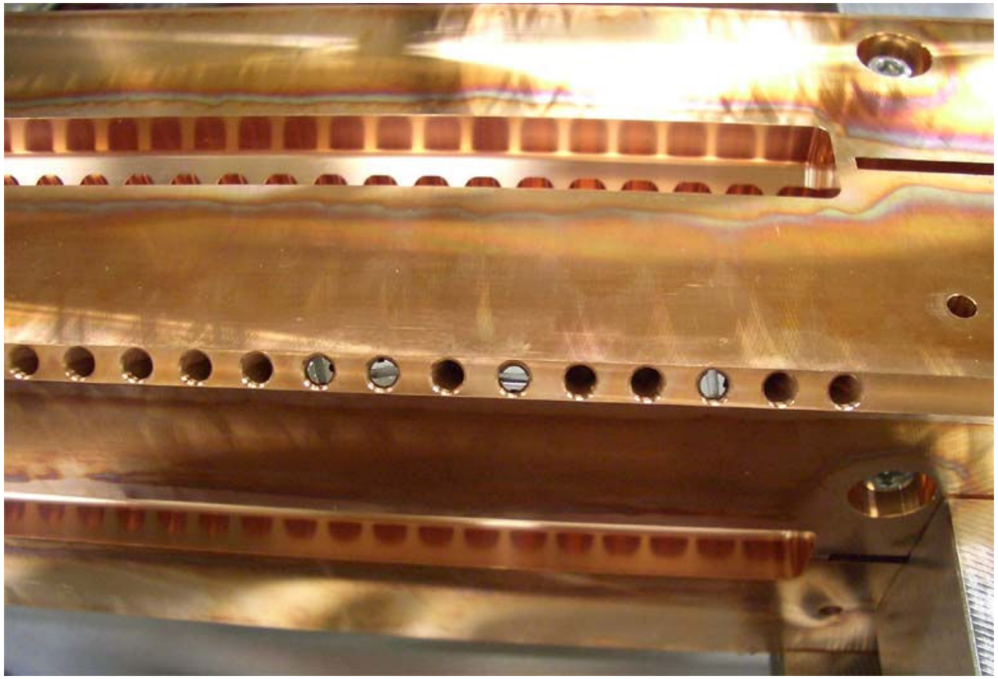
Misalignment of each quadrant
w.r.t. the average of four quadrants
(units are in micron)

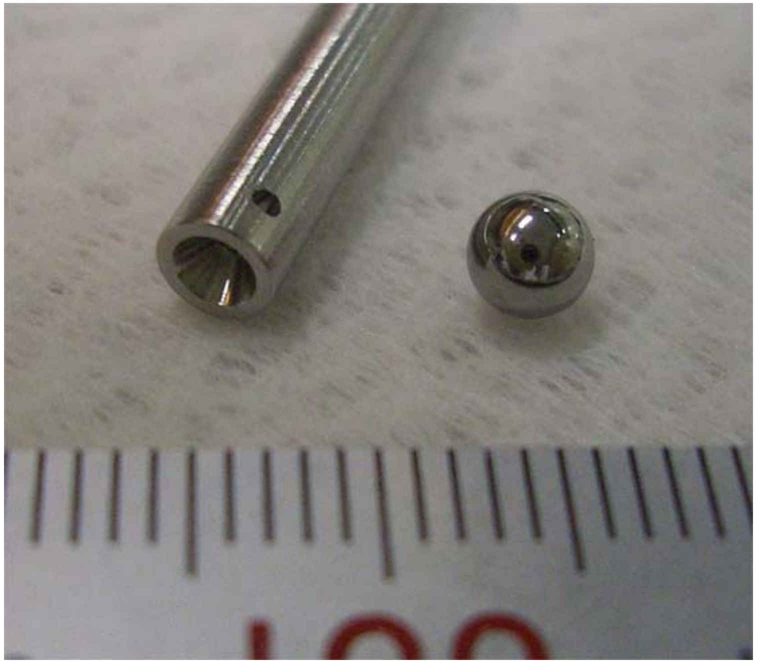






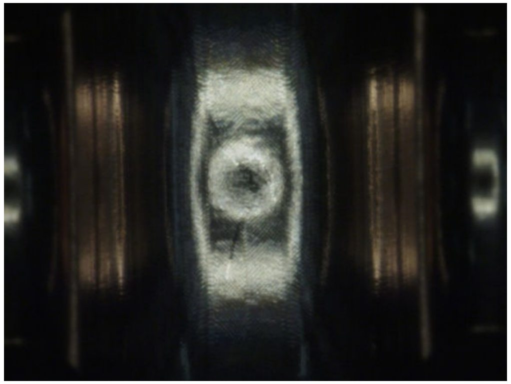
Elastic tuning with a ball being kept push



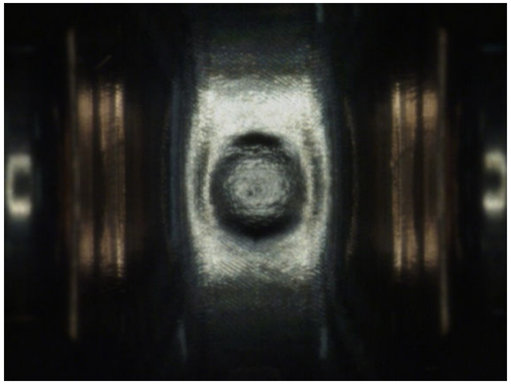


4mm stainless ball pushed by minus watch driver.
Pushing by turning with Higo's hand full force.
Elastic deformation kept, meaning that the tuning pins are kept pushing the balls.

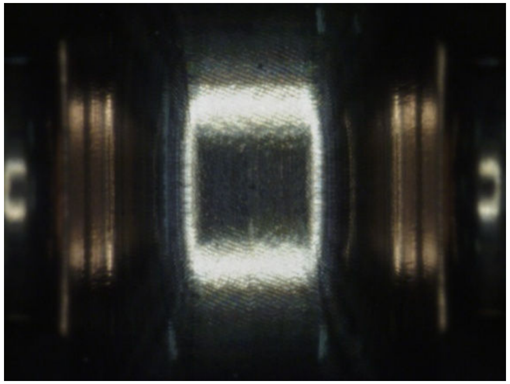
Notice: Deformed cavity wall



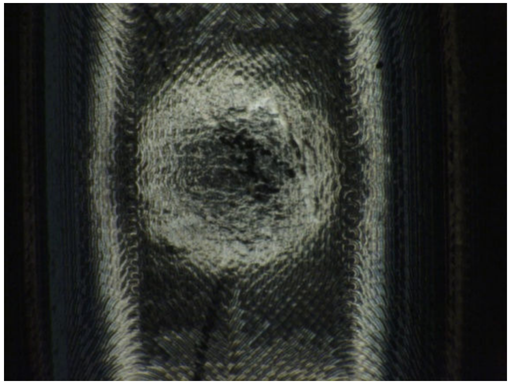
Cell 3(×35)



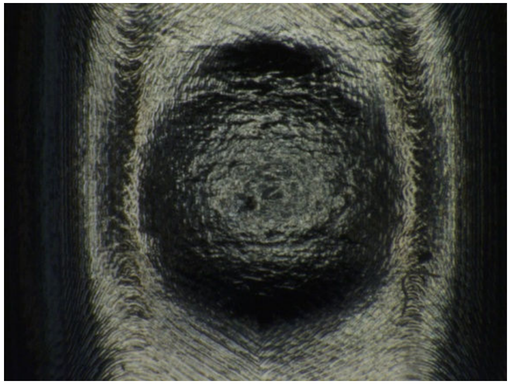
Cell 8(×35)



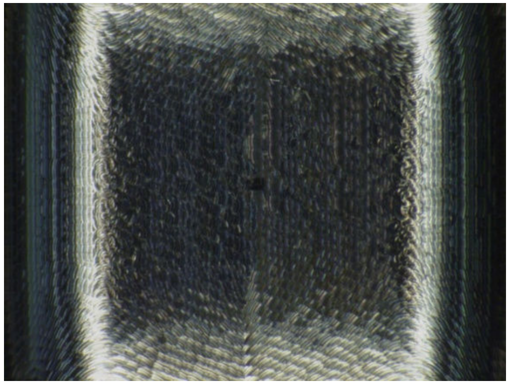
Cell 10(×35)



Cell 3(×100)



Cell 8(×100)



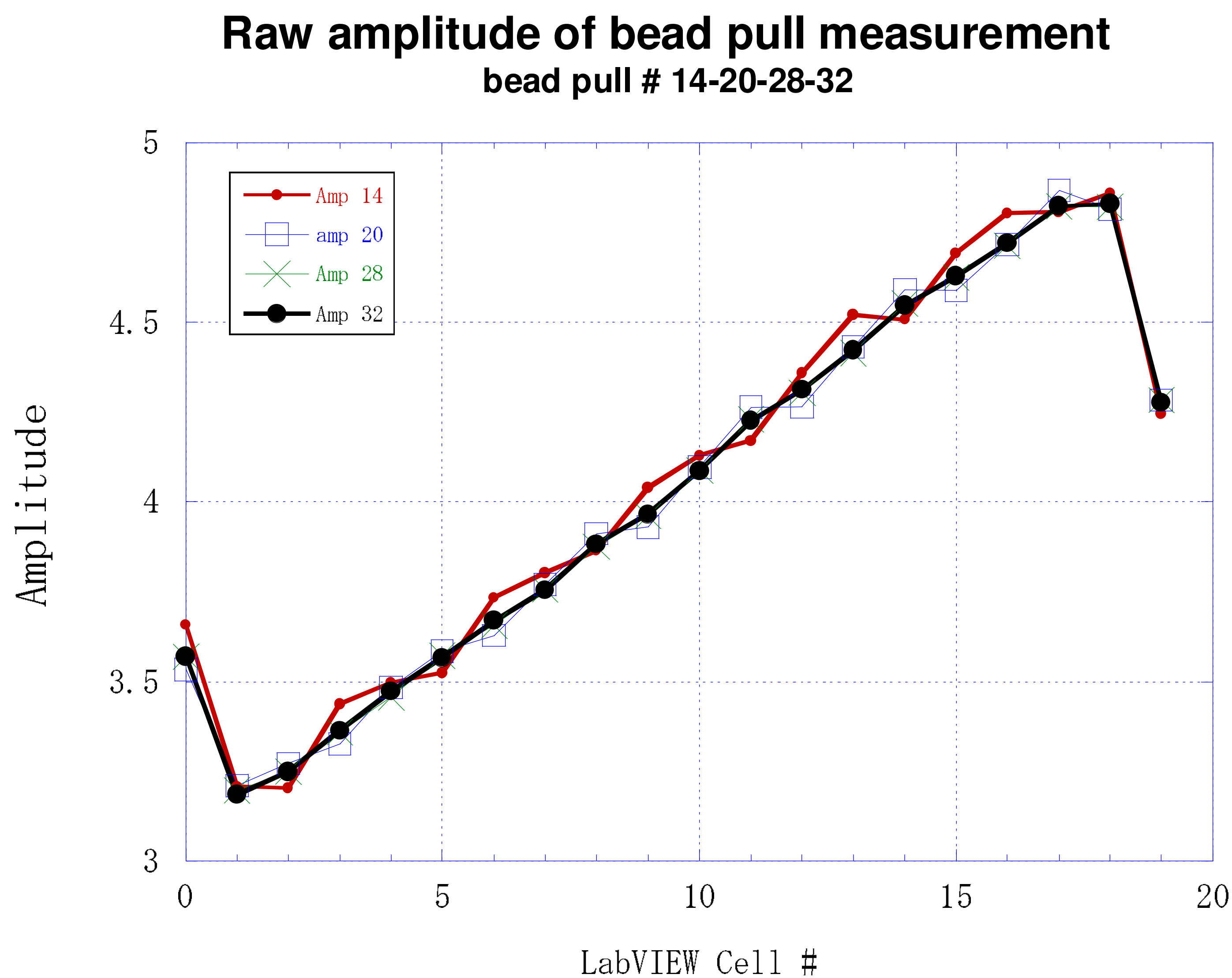
Cell 10(×100)

Cell3 deformation：0.053mm

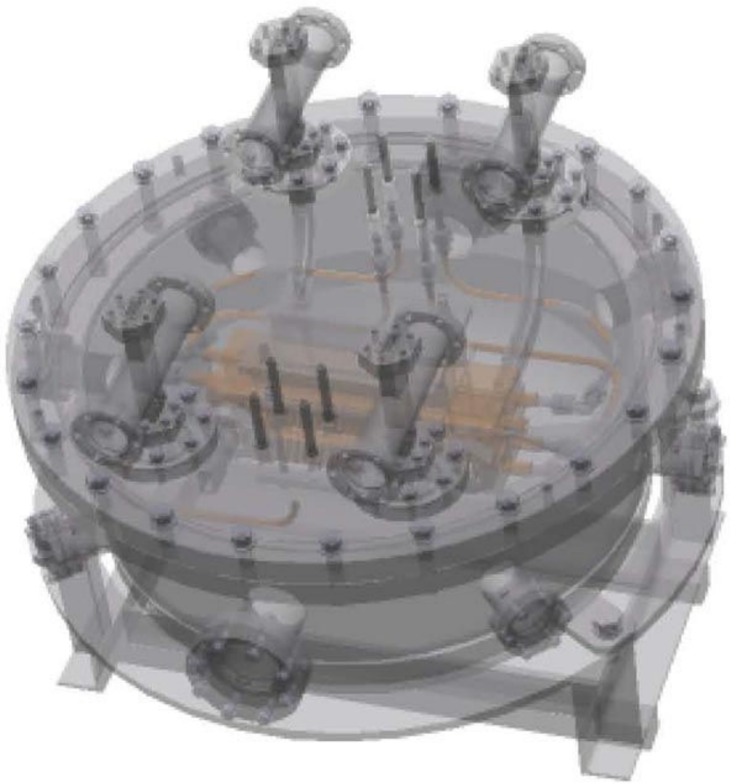
Cell8 deformation：0.167mm

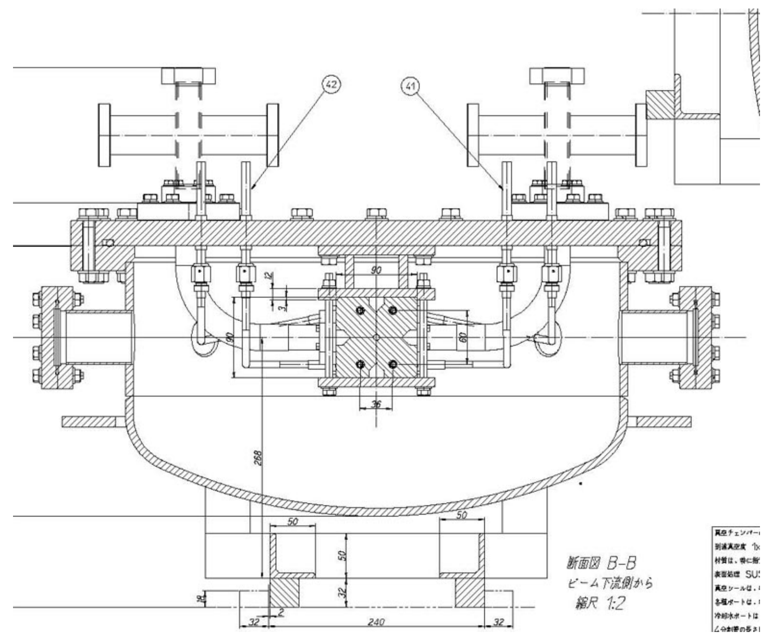
Cell10 no tuning

Field smoothness after tuning good.



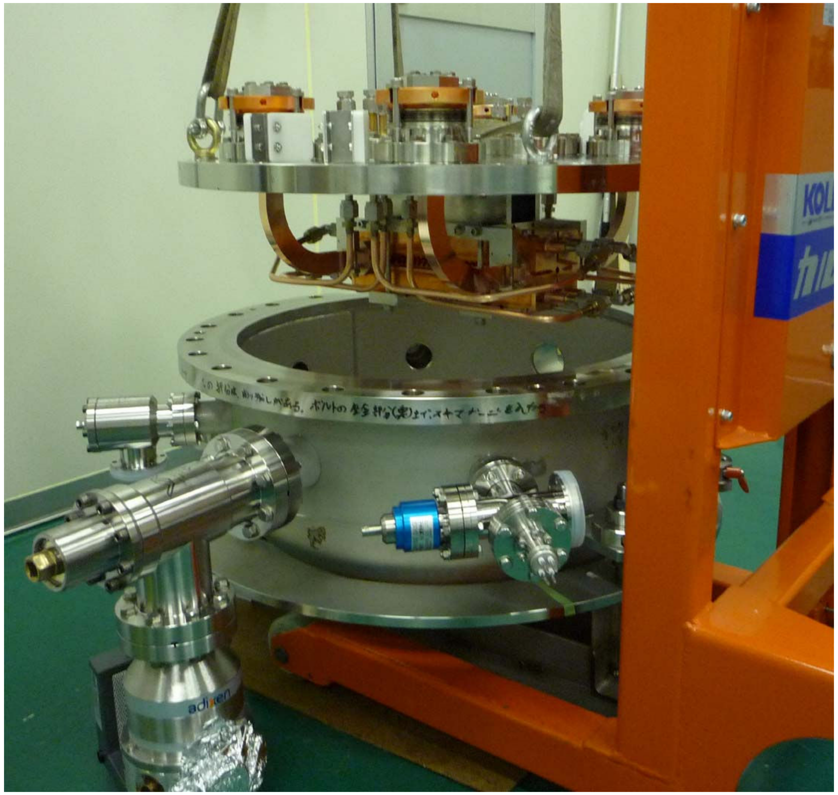
Vacuum chamber design

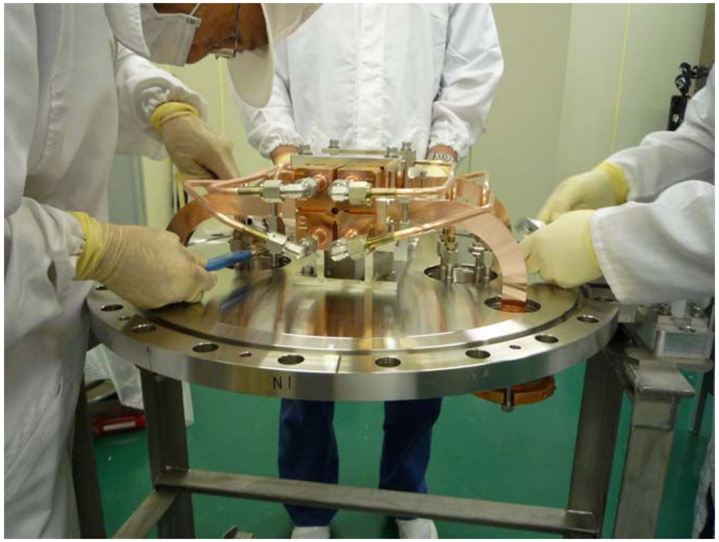




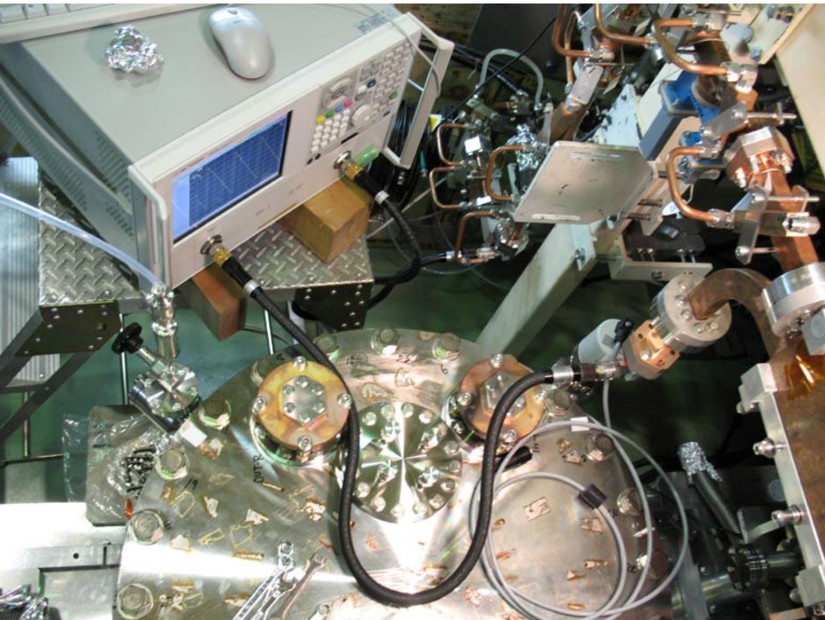
U-tight seal (round metal gasket)
VCR connector for cooling water connection
Thin H-bend being vac sealed with bellows
Vac evacuation from CF114 mounted on chamber with IP 70l/s and from WR90 at just 0.5m from structure

Installation into chamber

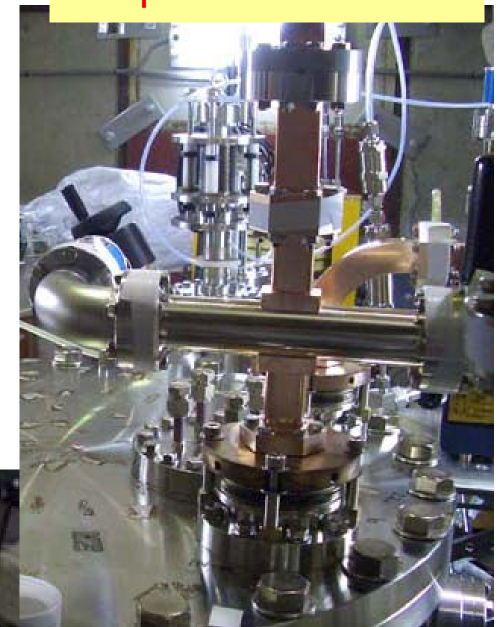




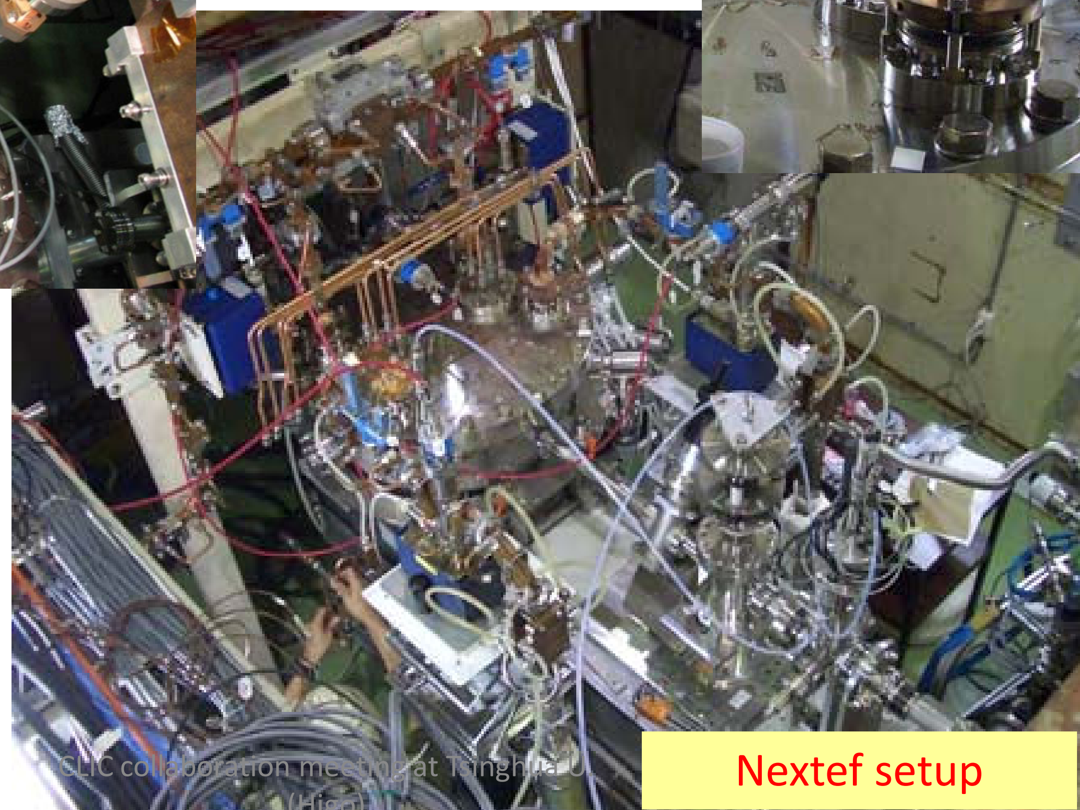
Installed into Nextef



3dB phase check



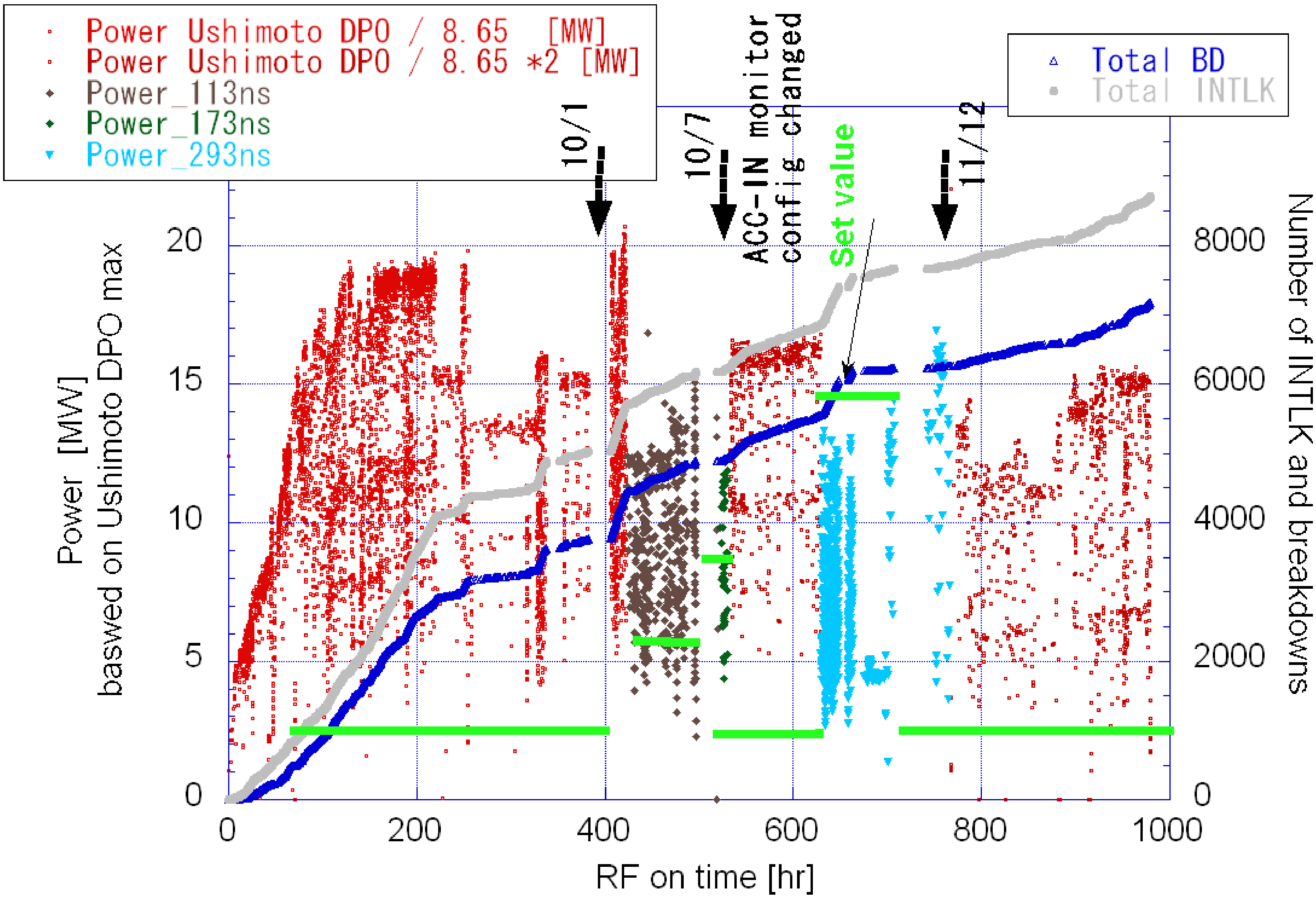
Input connection



Nextef setup

till 091203

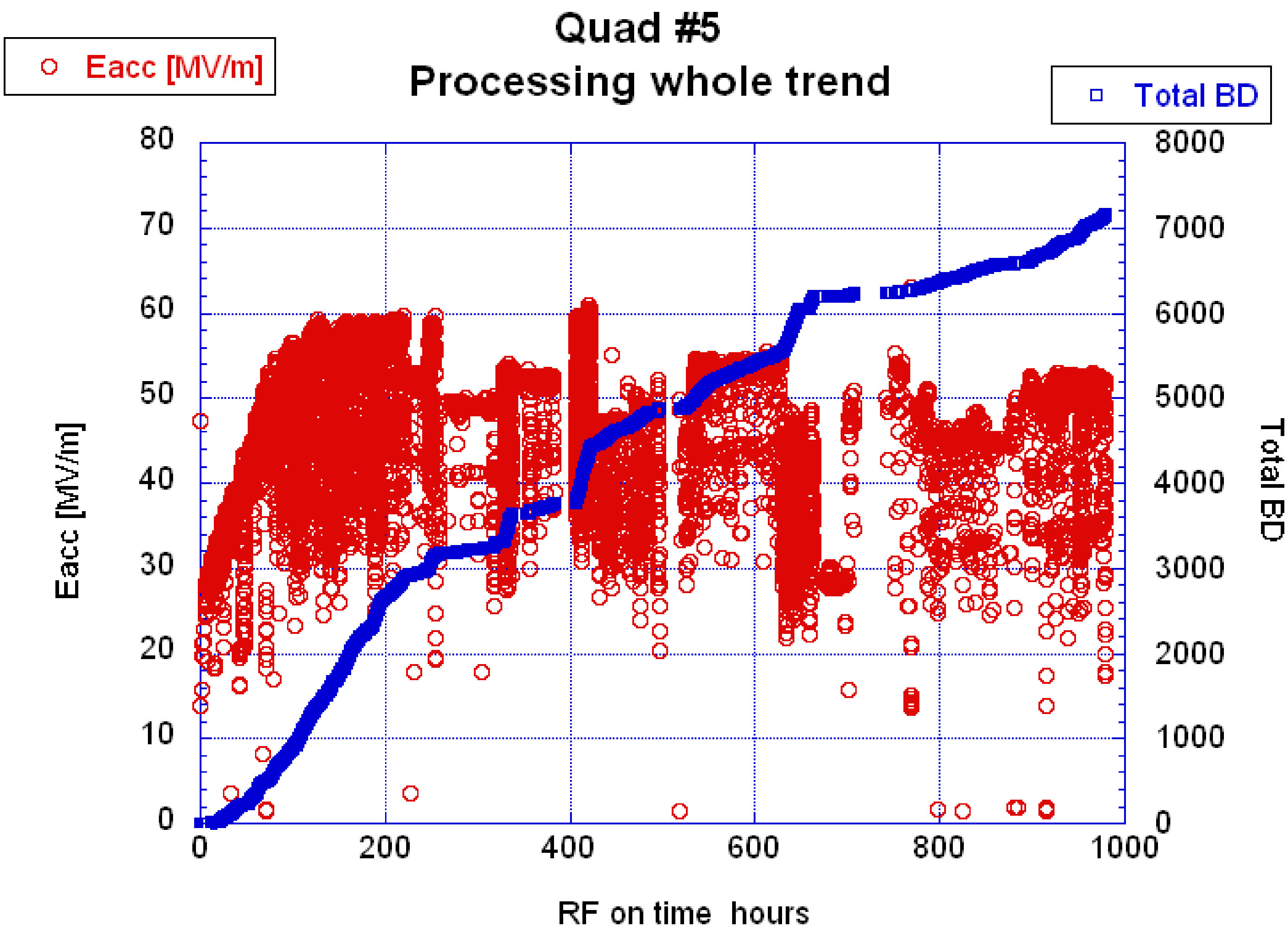
Quad #5 Whole Processing



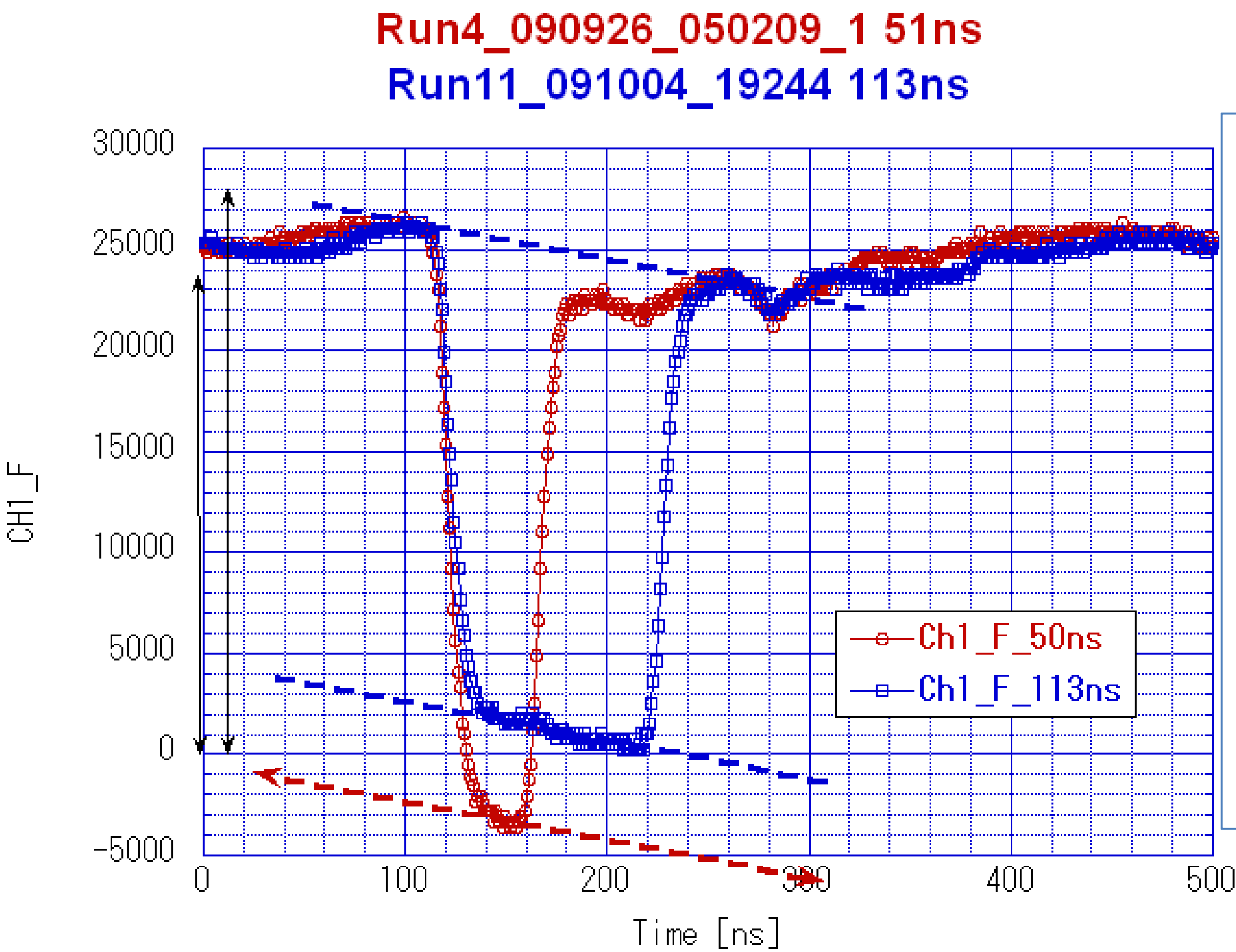
(Higo)

Gradient limited at 50~60MV/m

50nsec



ACC-IN pulse at hard limit



Tp(ns)
51 113

Power (MW)
19 14

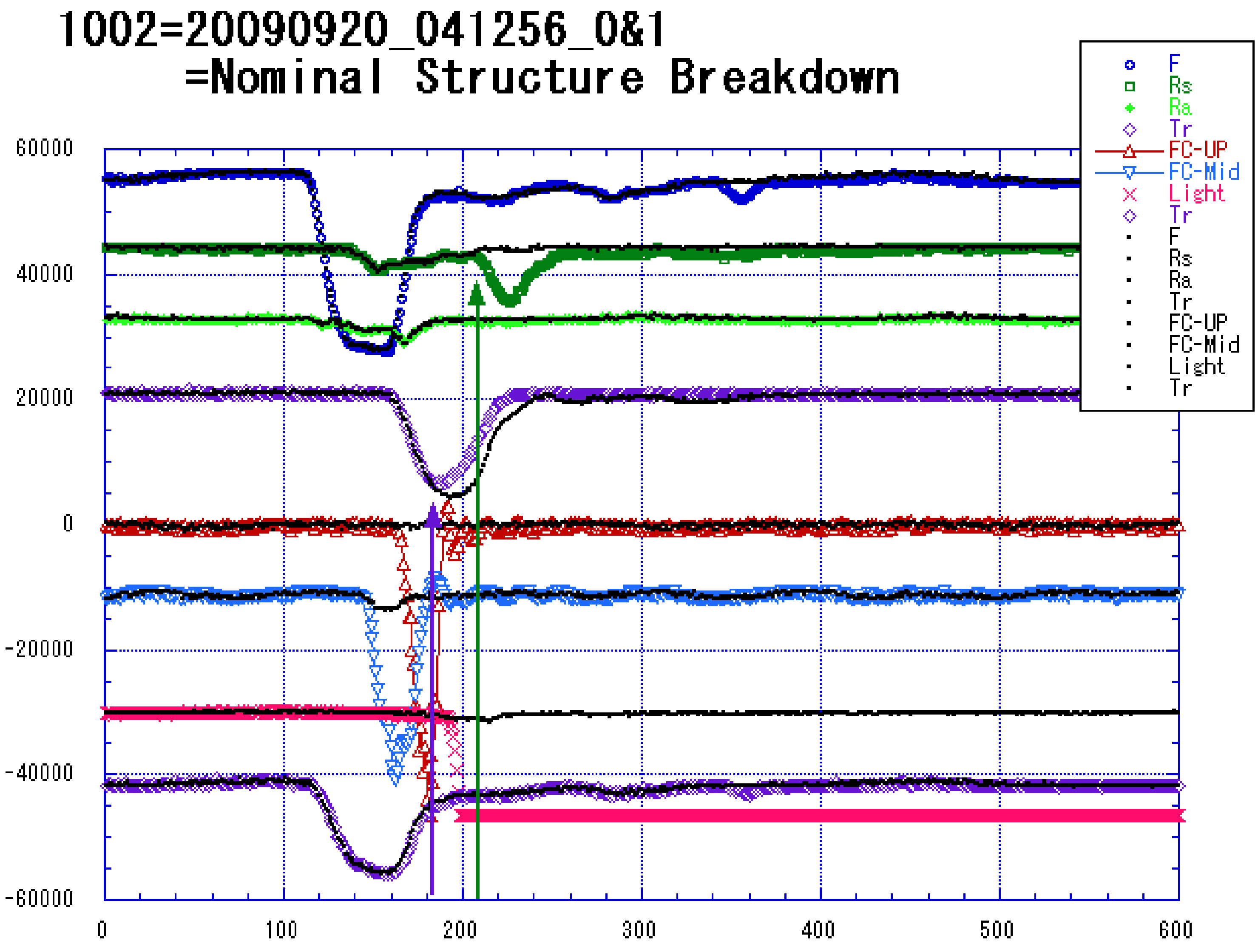
Ea (MV/m)
59 50

Sqrt(Tp)*Power
135 147

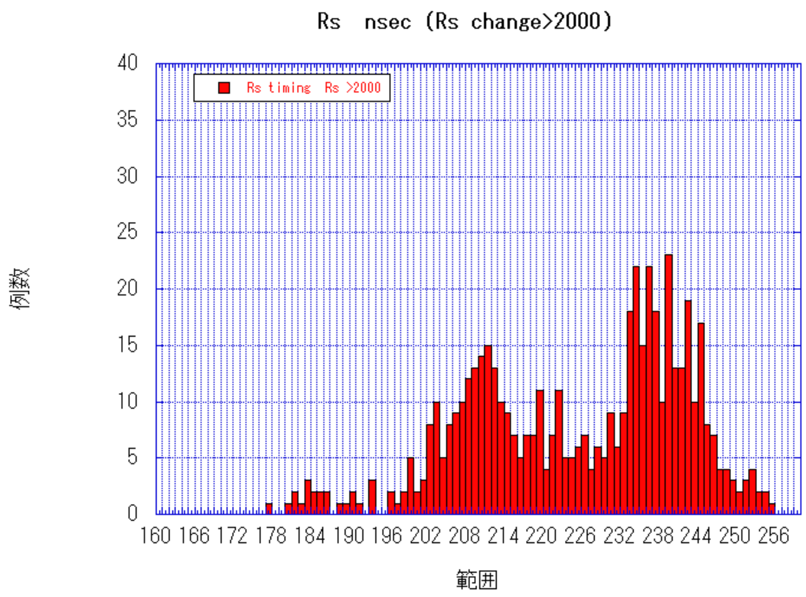
Vacuum characteristics

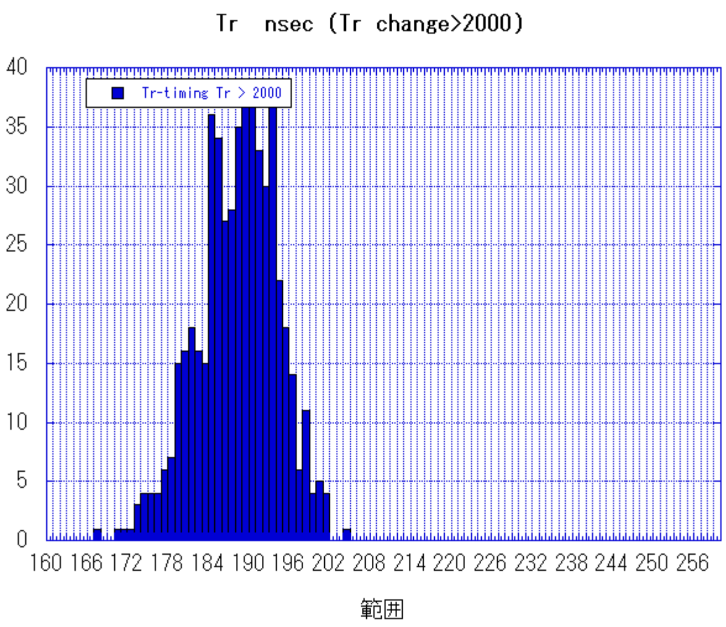
- Vacuum total pressure
  - Base pressure at $<10^{-6}$Pa
  - Typically processing $<10^{-5}$Pa
  - Increases every time at few to 5MW range if after RF-OFF for more than several hours
- Mass spectrum
  - M=2, 28 and 44 increase with RF-ON, but not M=18
    - Especially when reaching power limit
  - 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

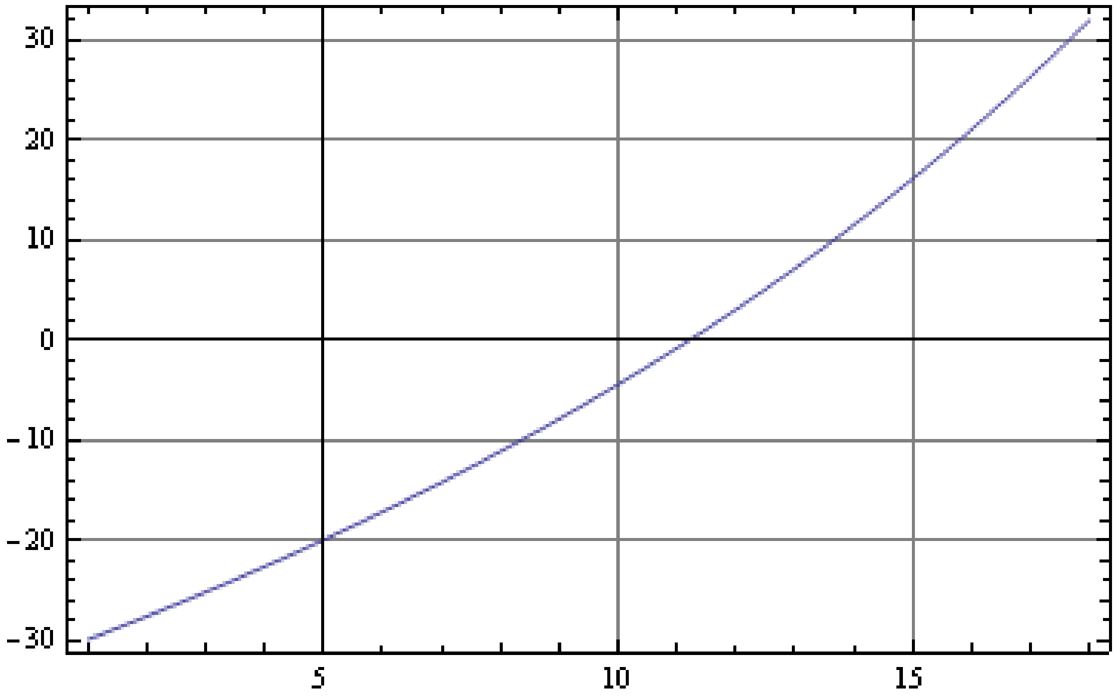


Timing distribution for change>2000





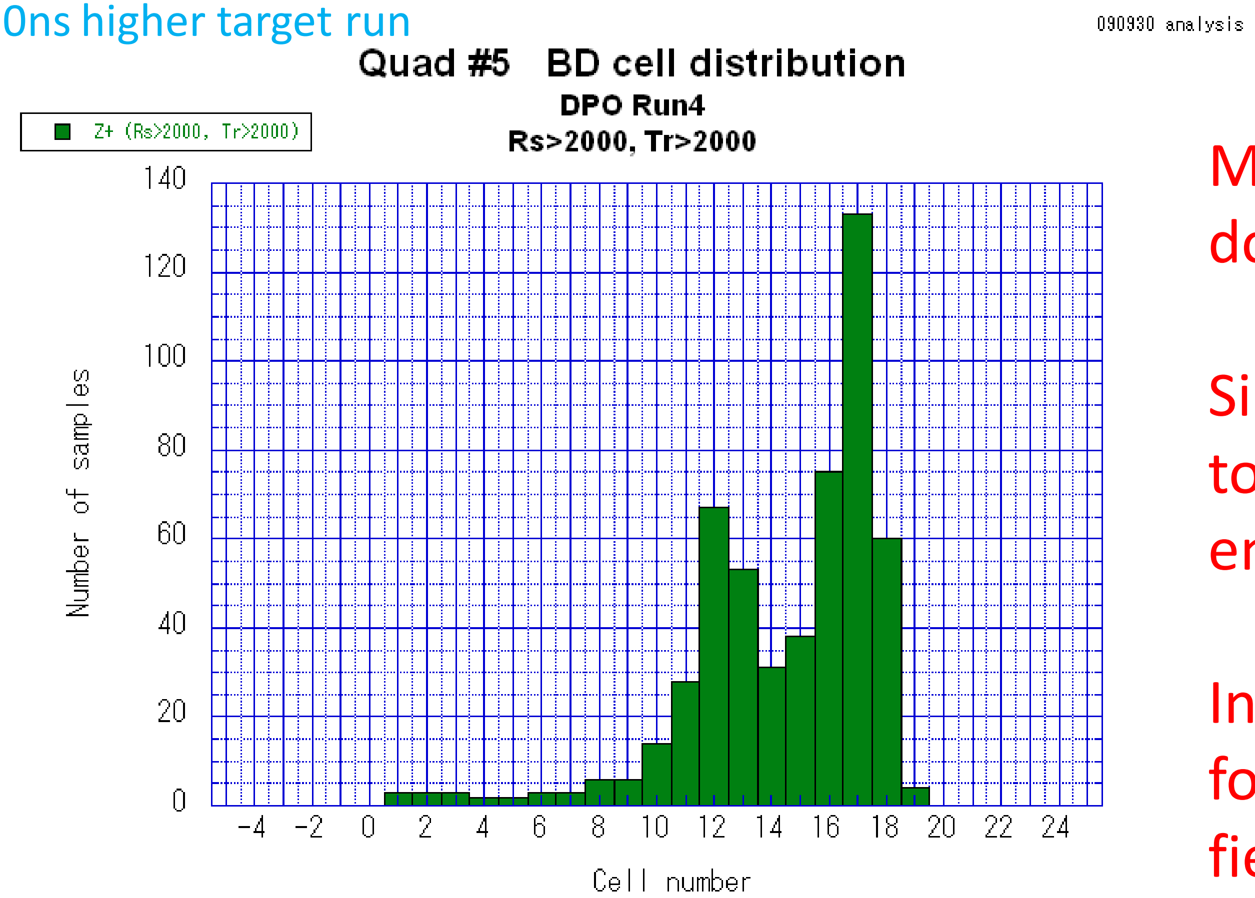
T18 structure Function F[z]
time difference for the BD info to reach both ends



Use time difference Rs(rise)-Tr(fall) to calculate BD position.
Function F(z) is calculated from design vg(z).

Breakdown cell distribution >2000

50ns higher target run



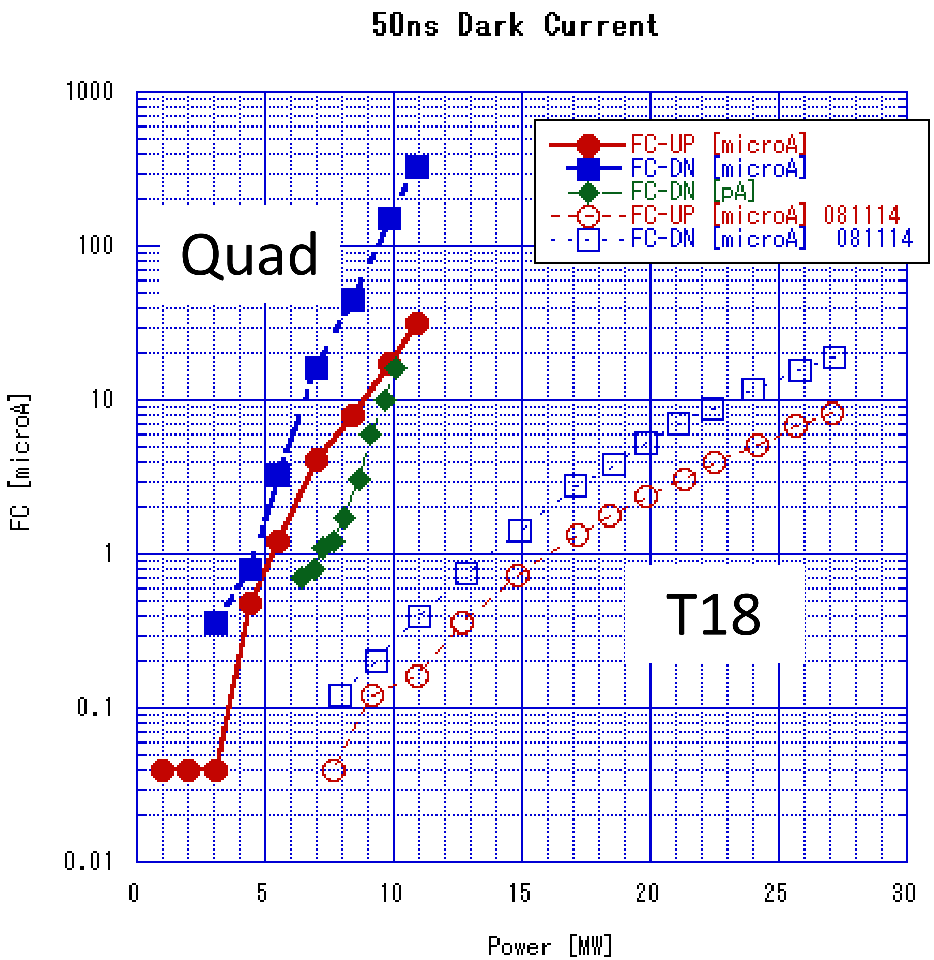
Mostly downstream half.

Simply increasing toward output end.

Indication of BD following some field gradient.

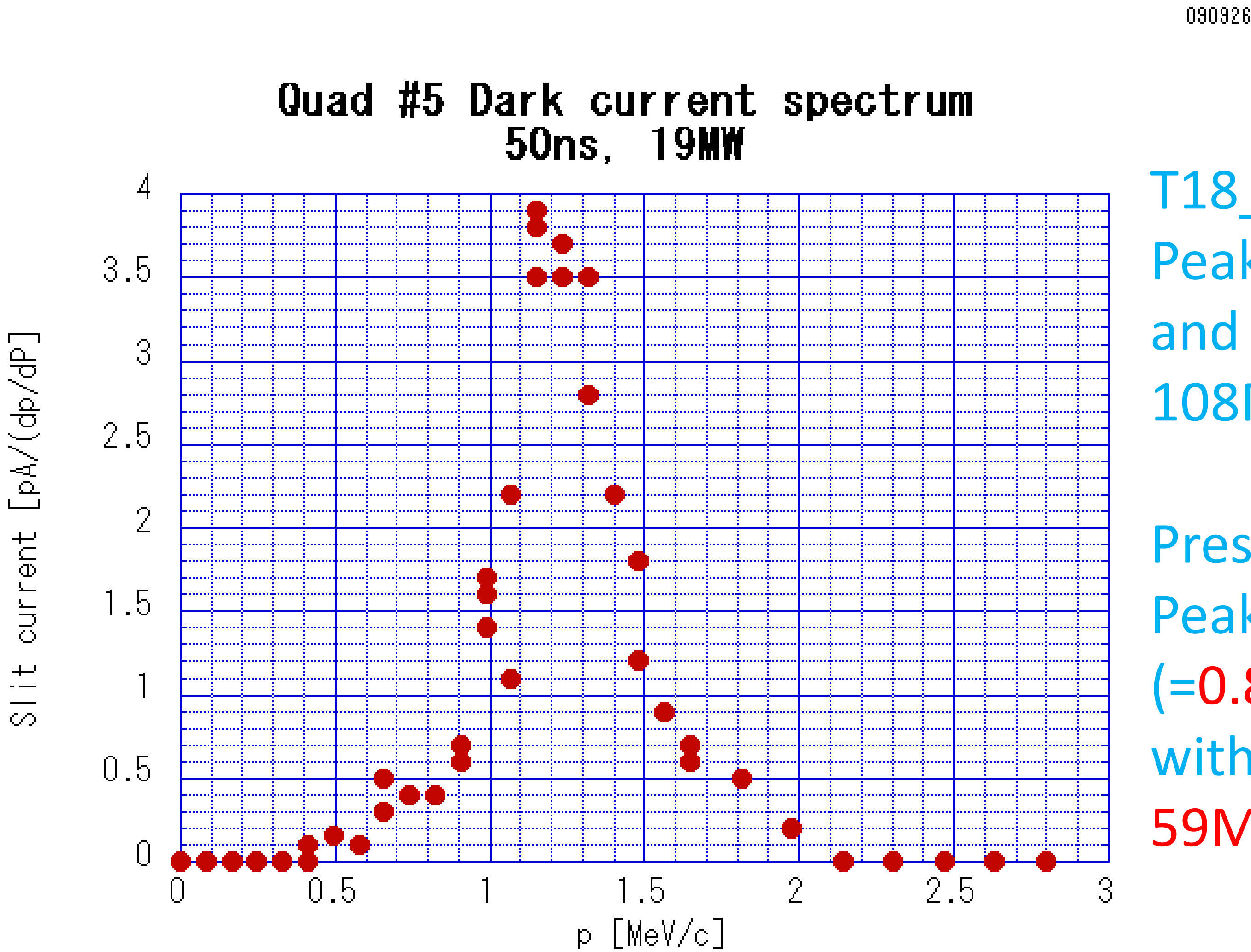
534 events were analyzed out of 1919 INTLK.

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

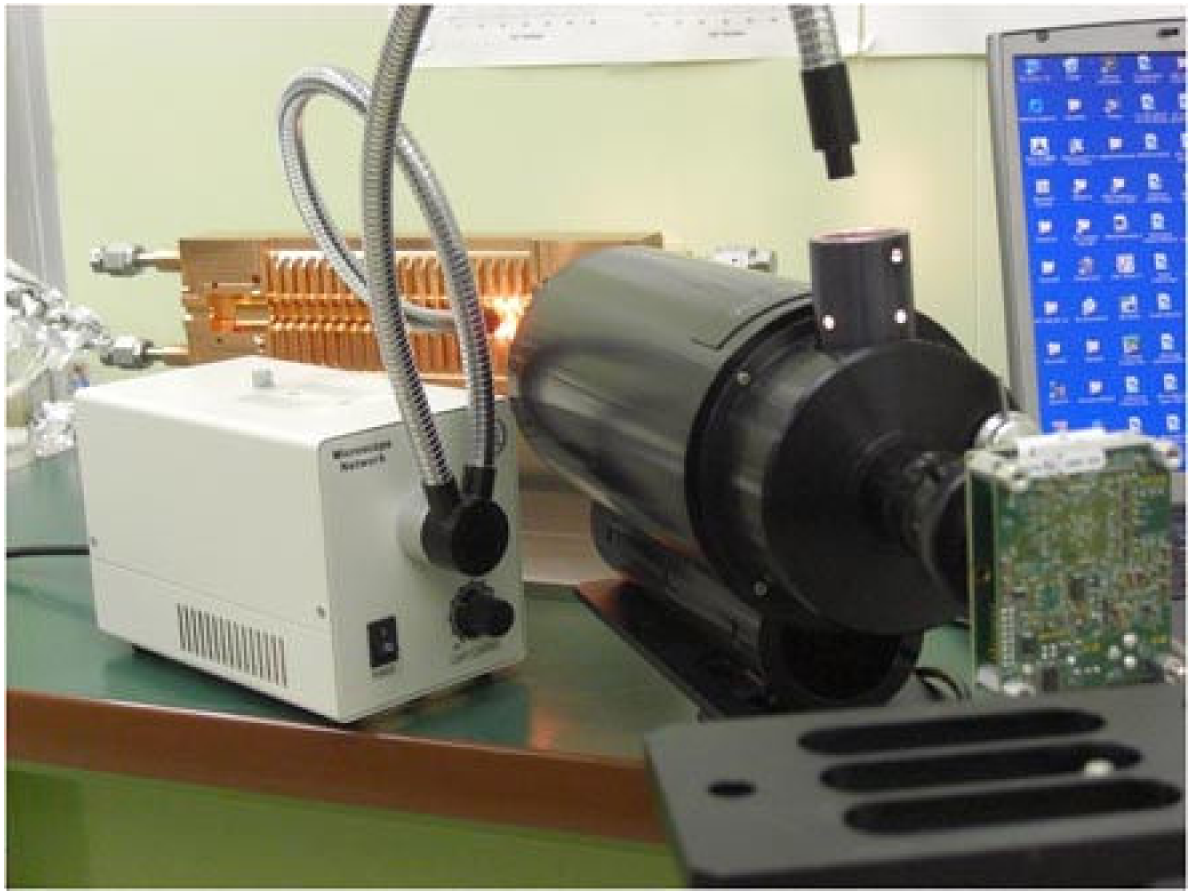


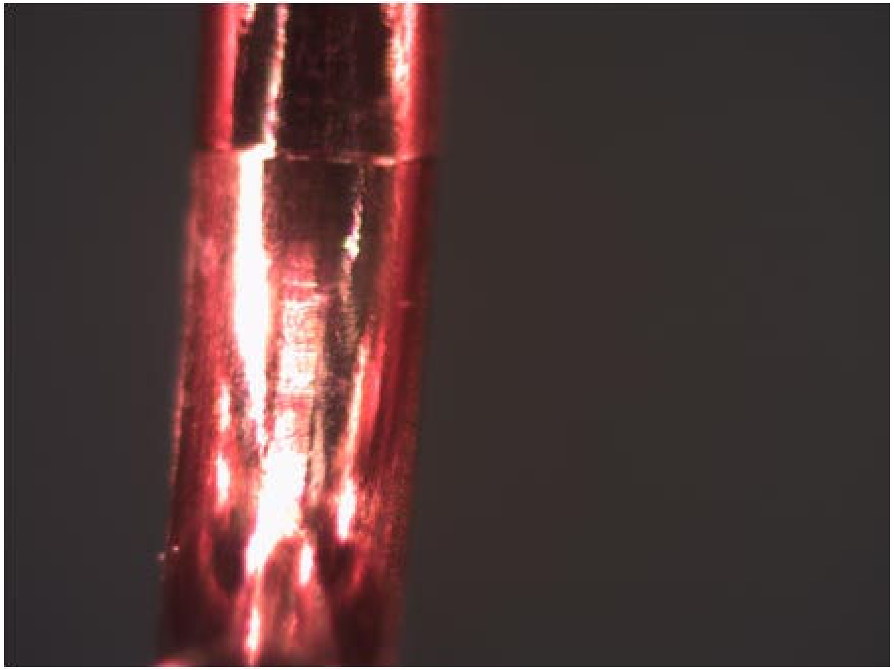
T18_Disk
Peaks at 8MeV/c and 4MeV/c with 108MV/m

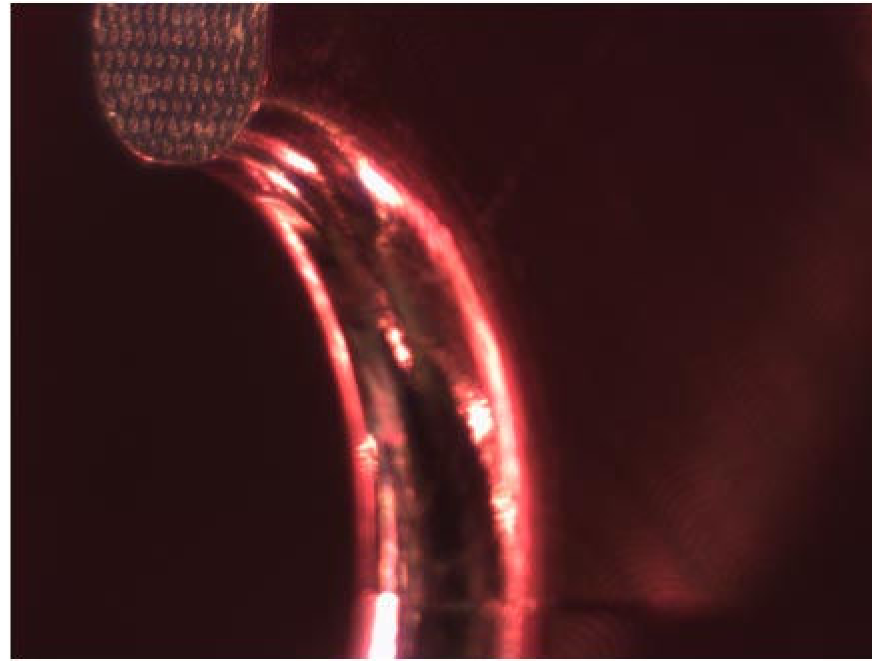
Present quad
Peak at 1.2MeV/c (=0.8MeV) with 19MW → 59MV/m

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

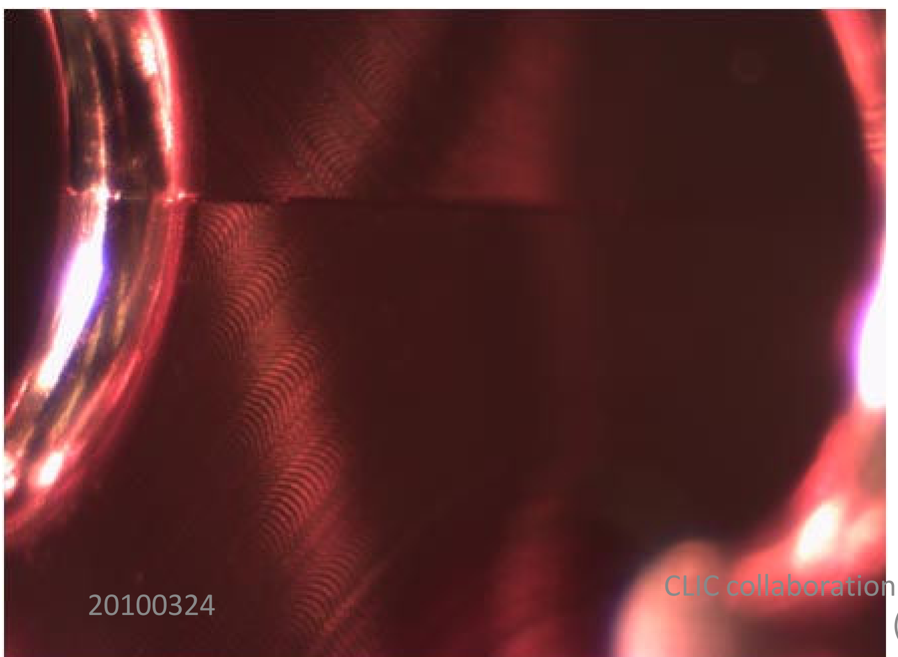
Inspection with long-distance microscope after finishing high gradient test

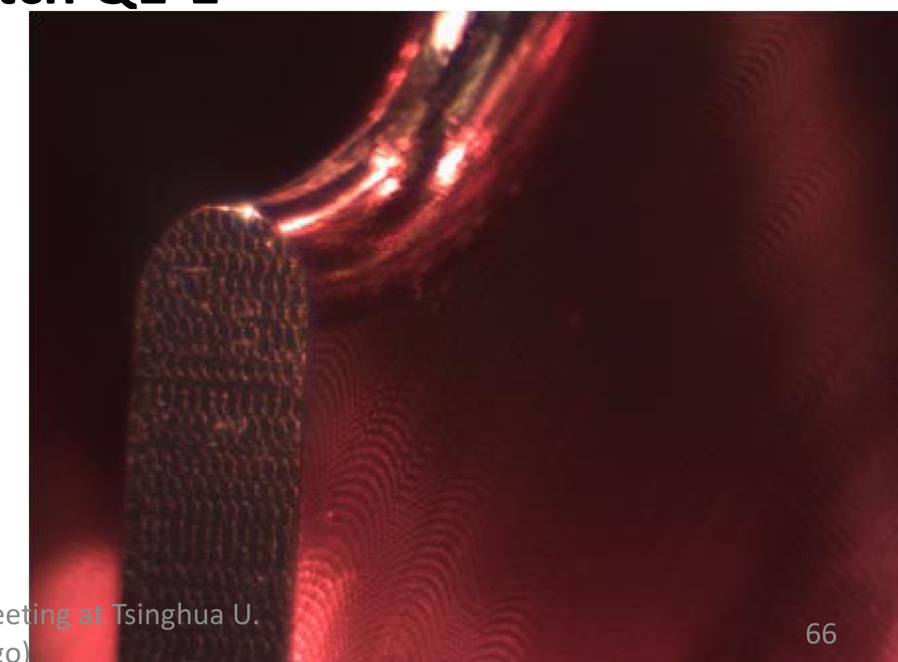


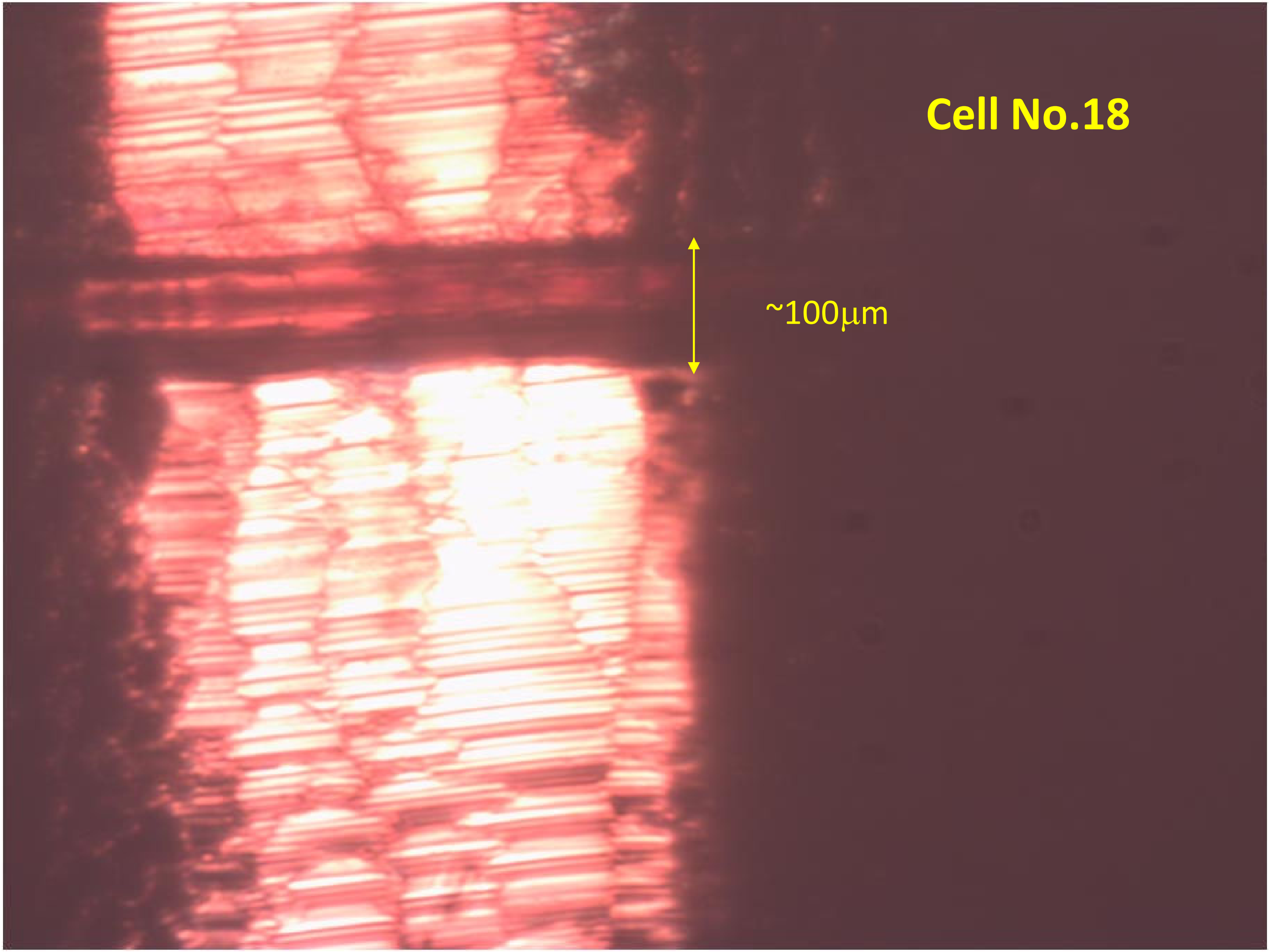




No.18 Q2-2 to match Q1-1






Cell No.18
~100μm

Surface inspection summary

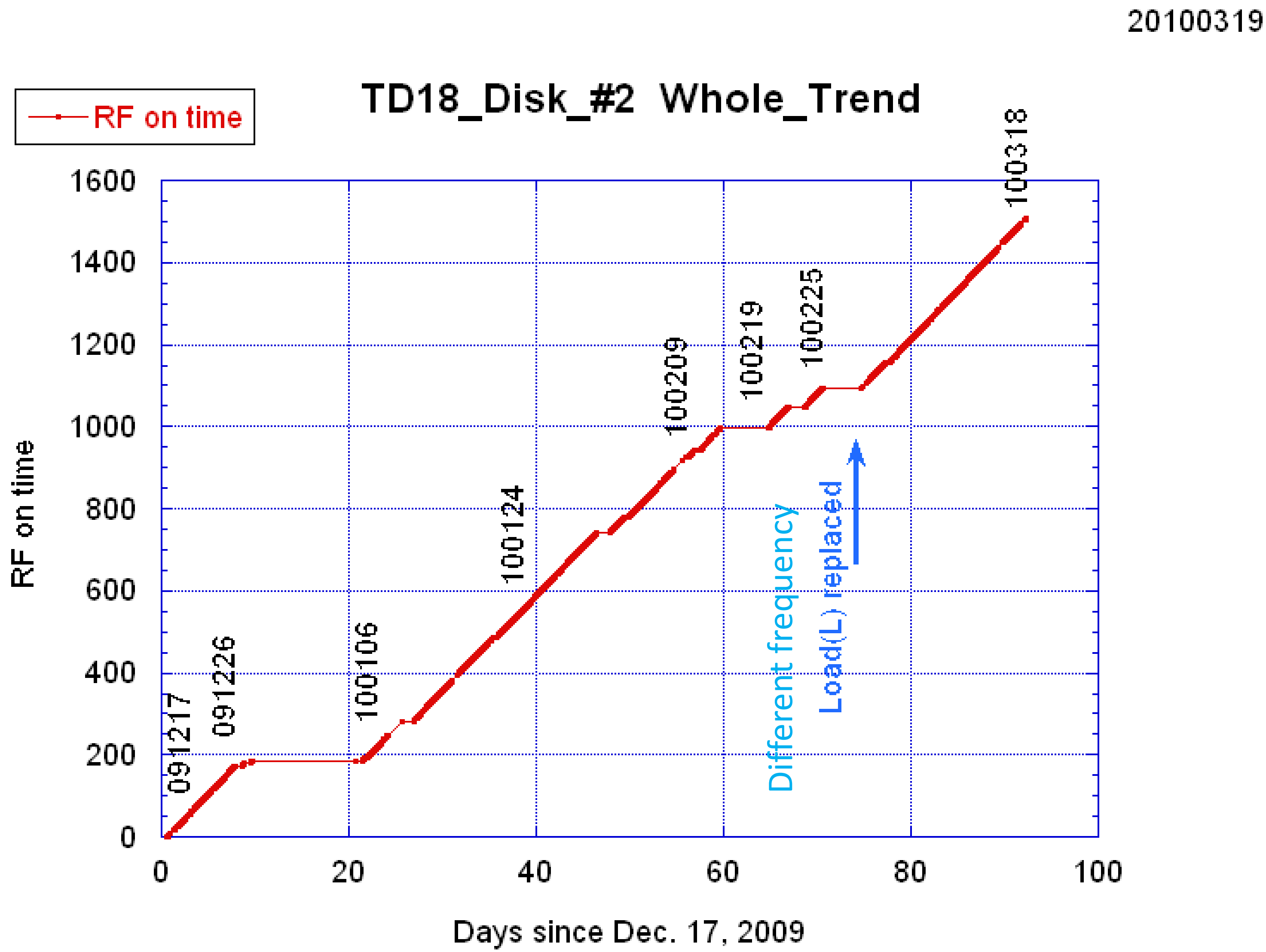
- Optical inspection with long-distance focus microscope
- Still not easy to see the arcing spots
- Will go to SEM
  - though only the center of the rod can be observed in a Japanese company in April
- Will go to CERN SEM for full inspection

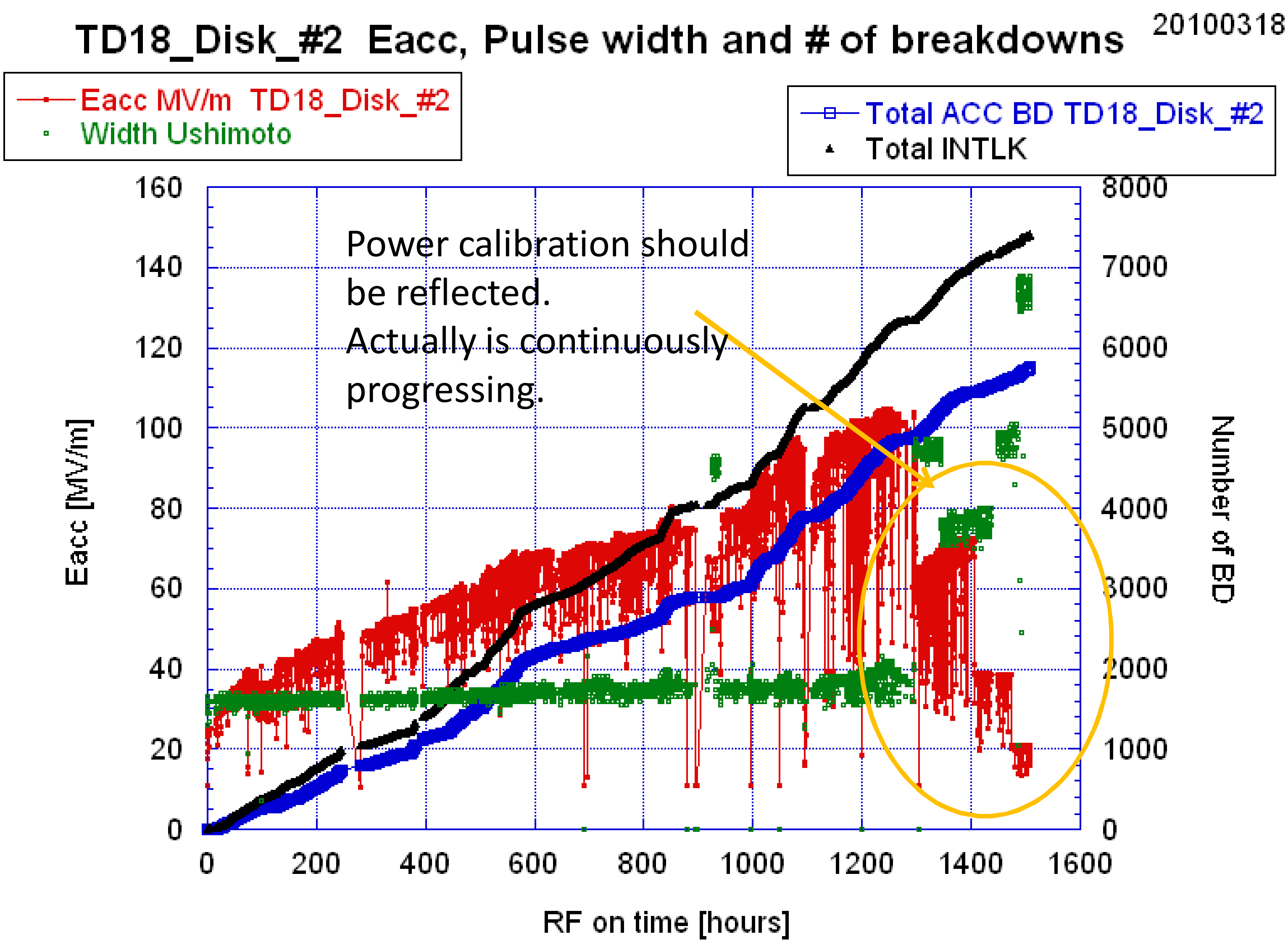
TD18_Quad summary

- 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

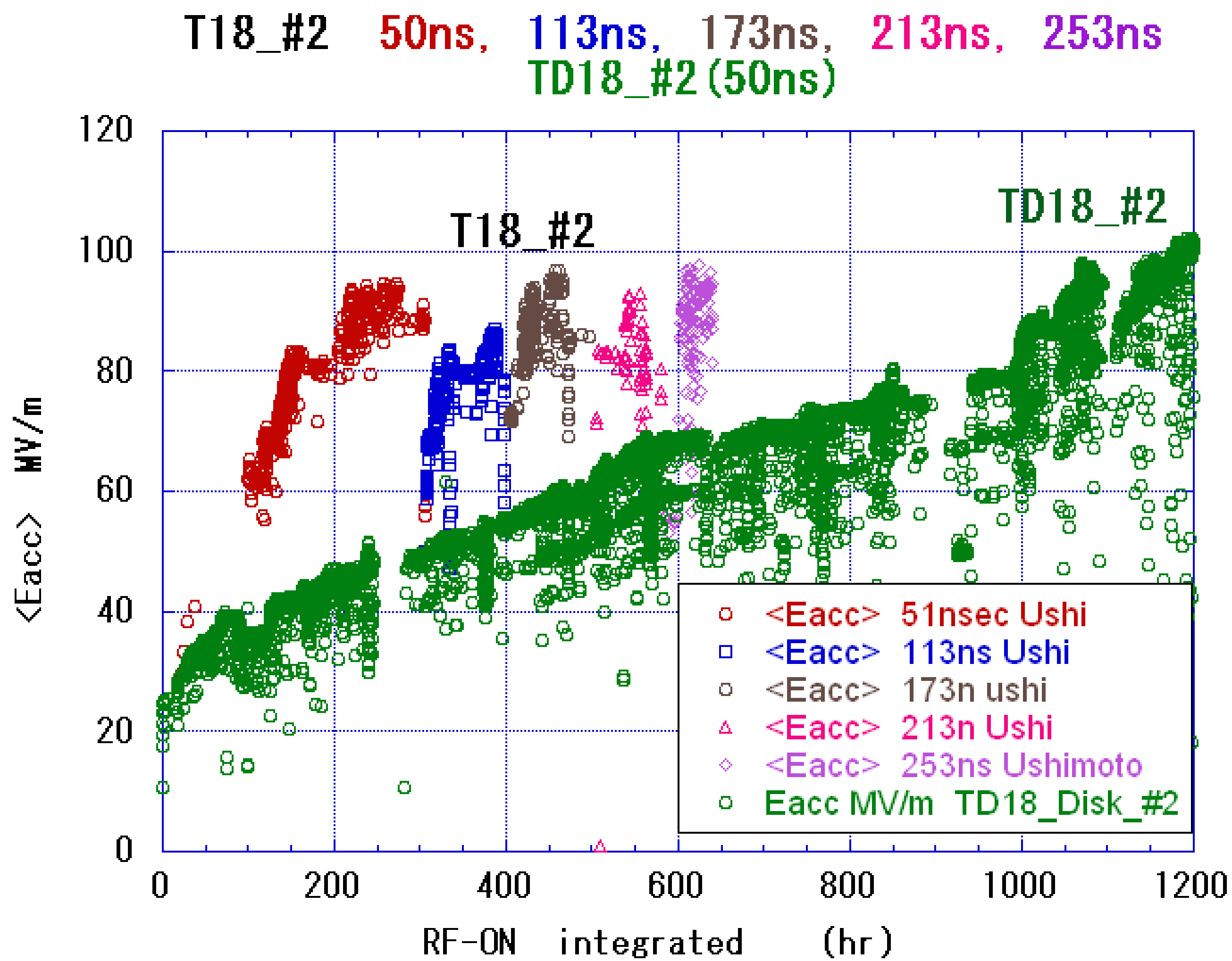
- Aim: Prove heavily damped structure
  - Electric gradient: possibility to realize 100MV/m
- Design geometry
  - Heavy damping slots with wide opening
  - Big increase of gradient toward downstream
  - Big pulse heating temperature rise at the damping port opening
  - No longitudinal cut but disk-based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


20100319
RF on time
TD18_Disk_#2 Whole_Trend
1600
1400
1200
1000
800
600
400
200
0
RF on time
0
20
40
60
80
100
Days since Dec. 17, 2009
091217
091226
100106
100124
100209
100219
100225
100318
Different frequency
Load(L) replaced

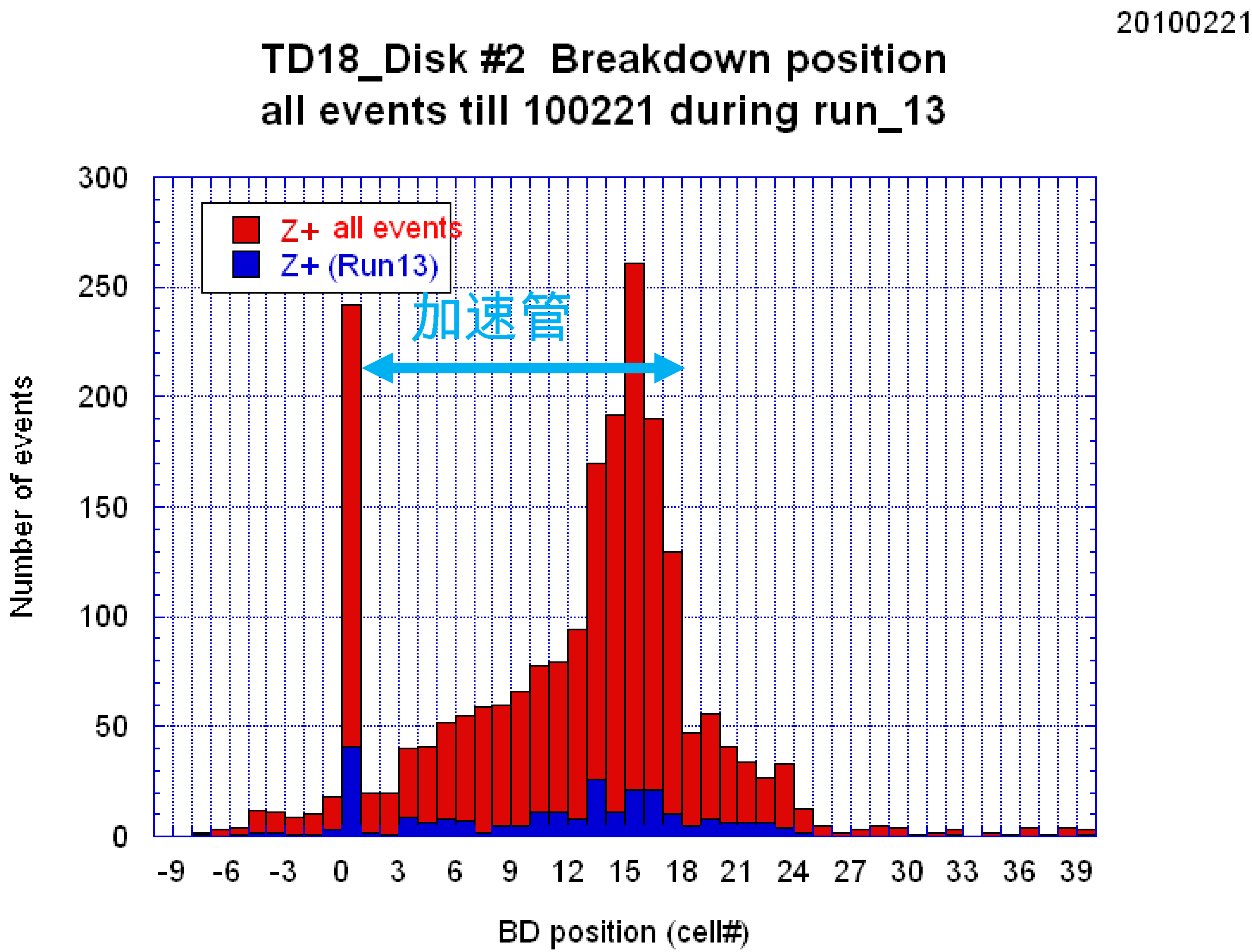


51ns → 112ns → 91ns → 112ns → 152ns

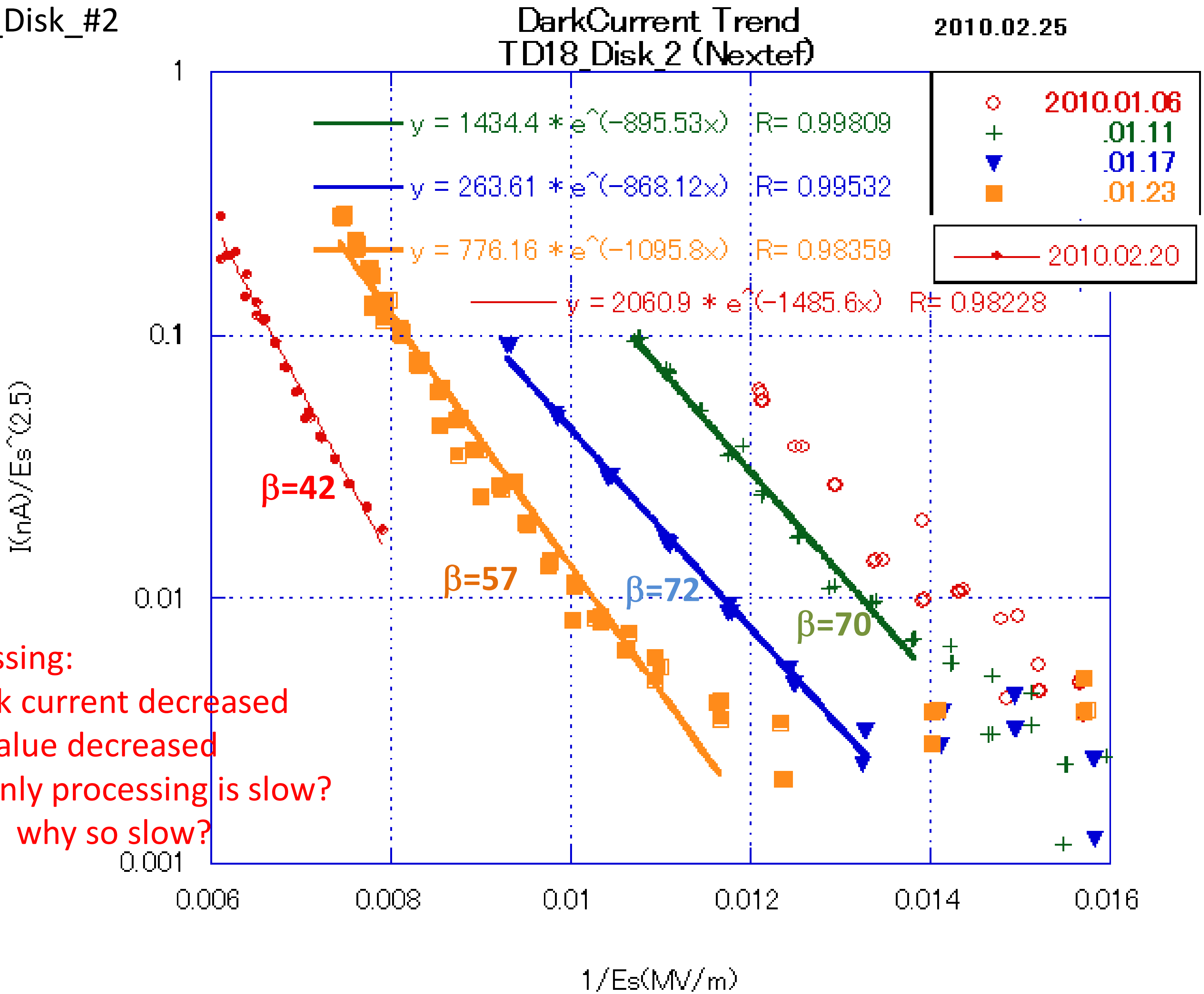
Disk-based: un-damp vs heavy damp



Breakdowns localized at downstream



TD18_Disk_#2



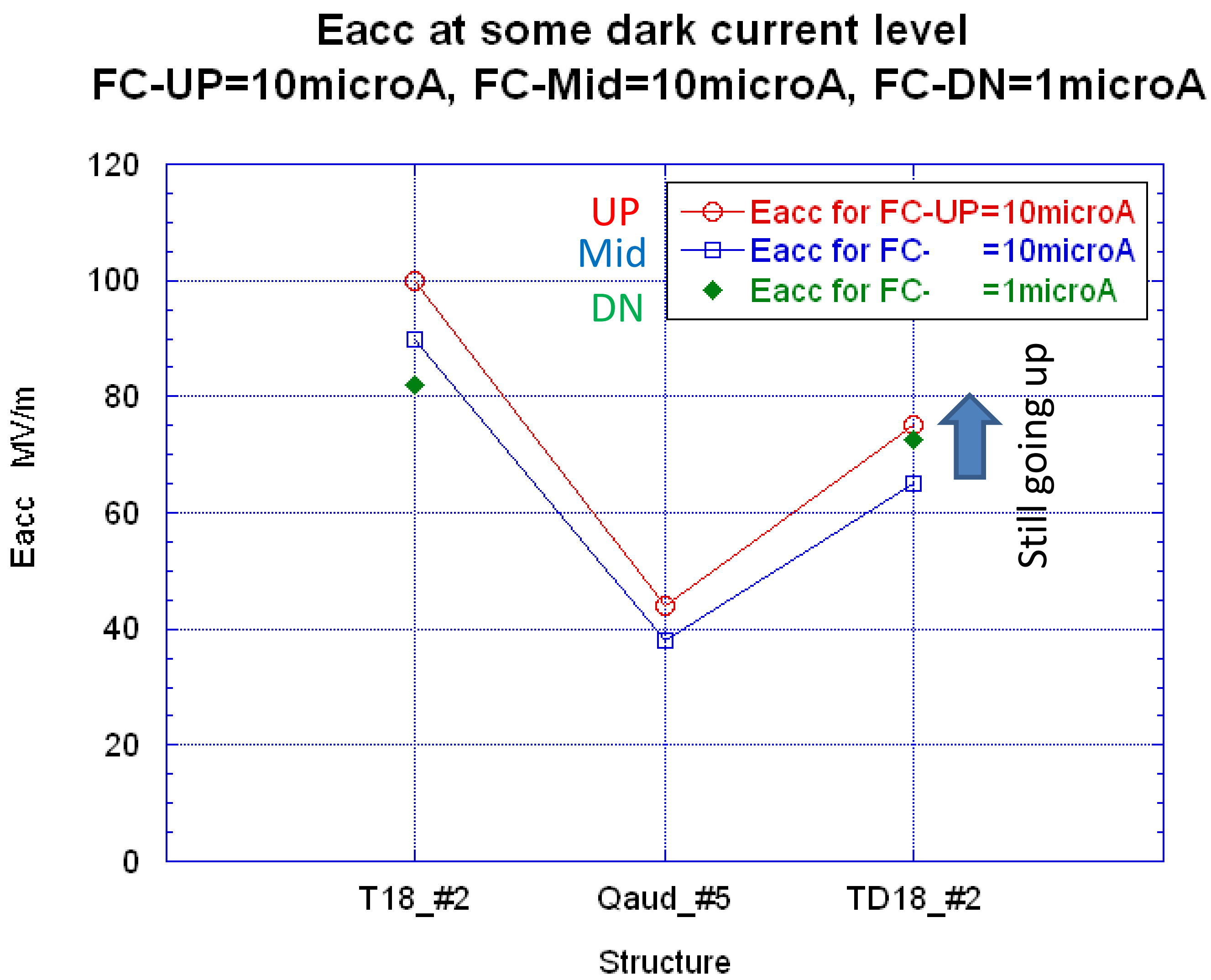
Processing:

Dark current decreased

β-value decreased

only processing is slow?

why so slow?


Eacc at some dark current level
FC-UP=10microA, FC-Mid=10microA, FC-DN=1microA
120
100
80
60
40
20
0
Eacc MV/m
UP
Mid
DN
Eacc for FC-UP=10microA
Eacc for FC- =10microA
Eacc for FC- =1microA
Still going up
T18_#2
Qaud_#5
TD18_#2
Structure

TD18_Disk_#2 test in practice

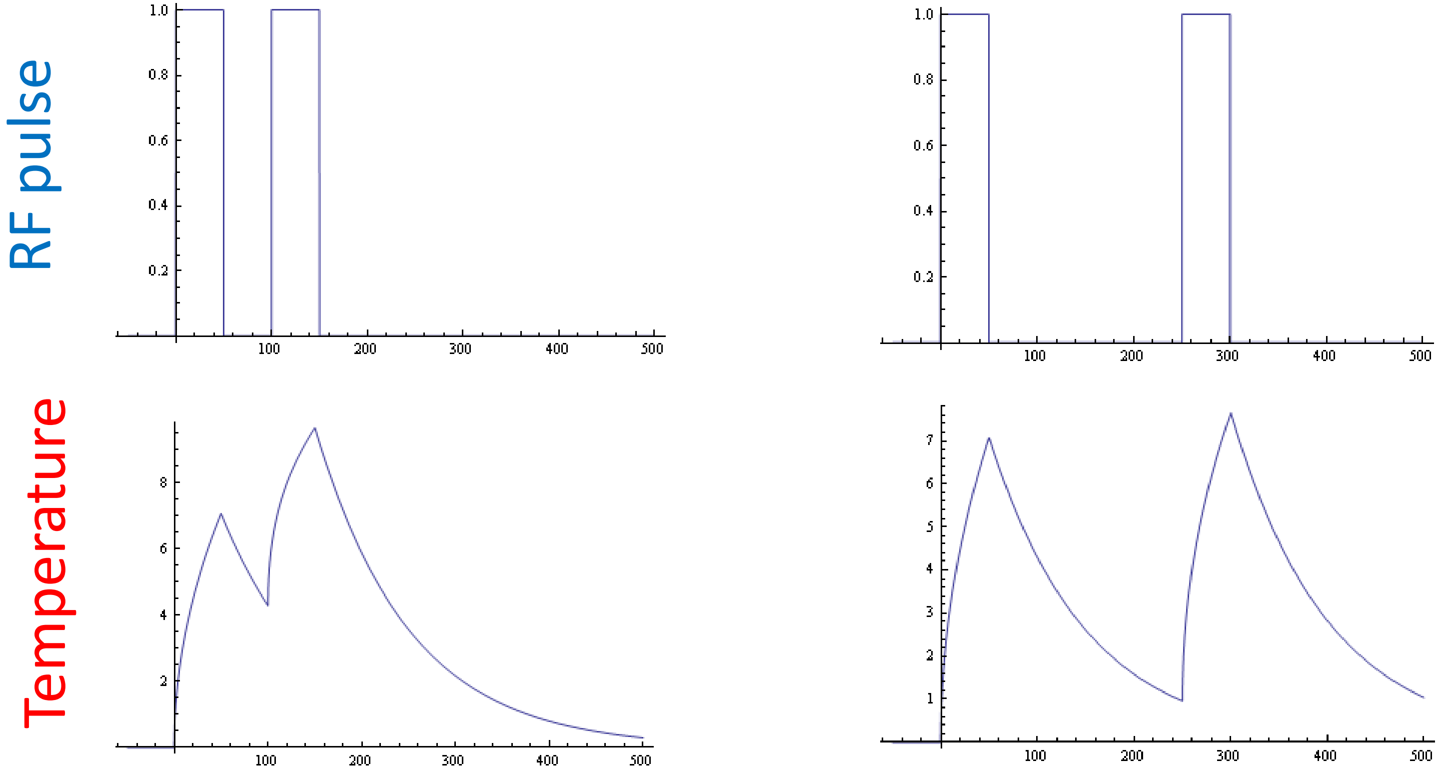
- Replacing load(L)
  - Acc str BD originated from the BD from the load line disappeared.
- Processing at 50 nsec
  - Reached 100MV/m after 1200hrs with 6000 breakdowns.
  - Still slow processing speed
- Pulse width increased up to 152nsec
  - Roughly the same power level as that of 51ns was reached 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



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

Almost independent?
Twice processing speed?

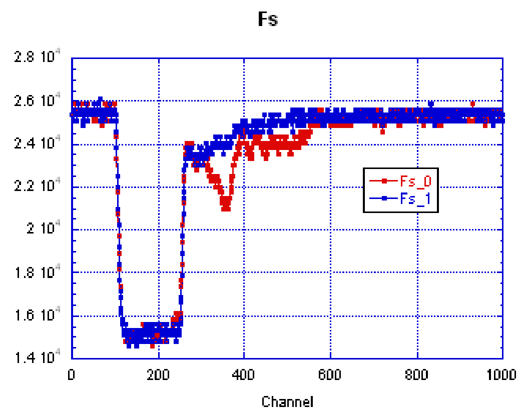
TD18_Disk test idea in near future

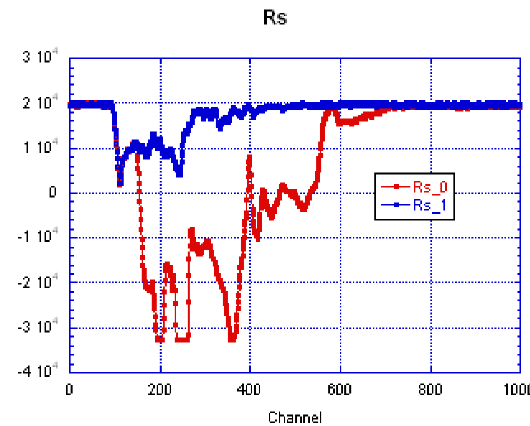
- Evaluate performance with a longer pulse width
- Study with such as two-pulse operation
- Check dark current evolution to the final saturation
- Finish and go next test

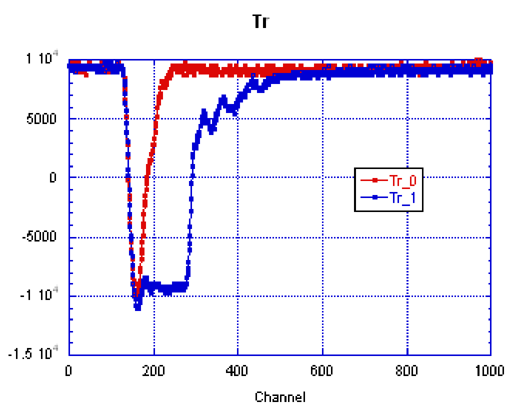
Improvement in Nextef studies

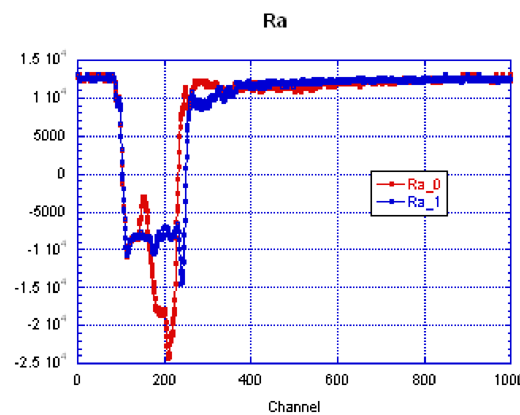
- Much room for anyone to help us

Evaluation of missing energy to be implemented



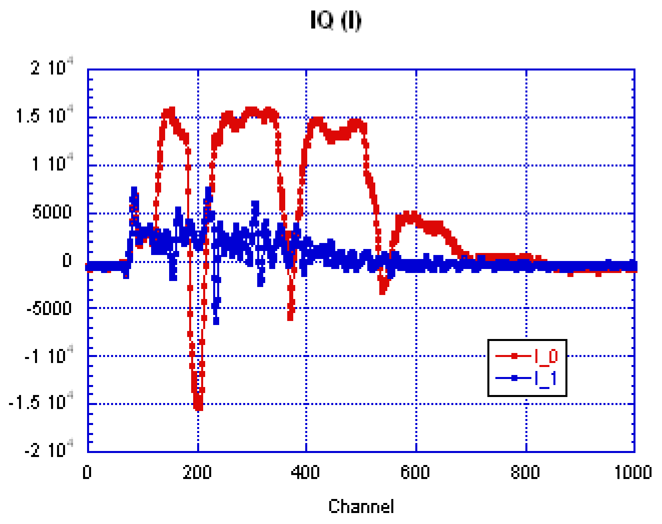


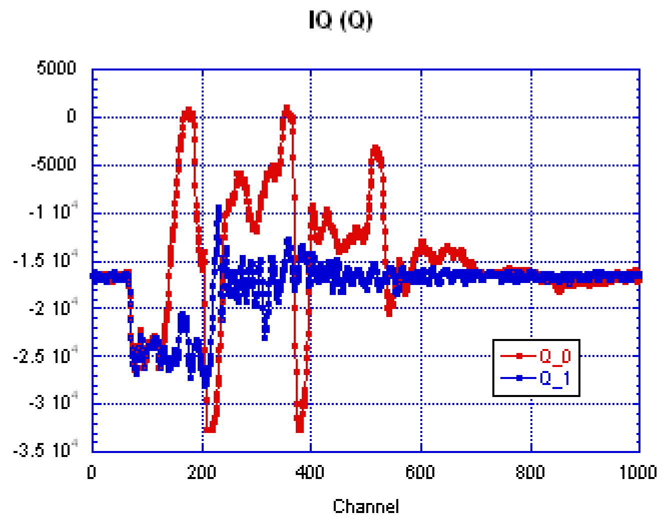




Pulse analysis, such as missing energy evaluation is still to be established. Good manpower is needed.

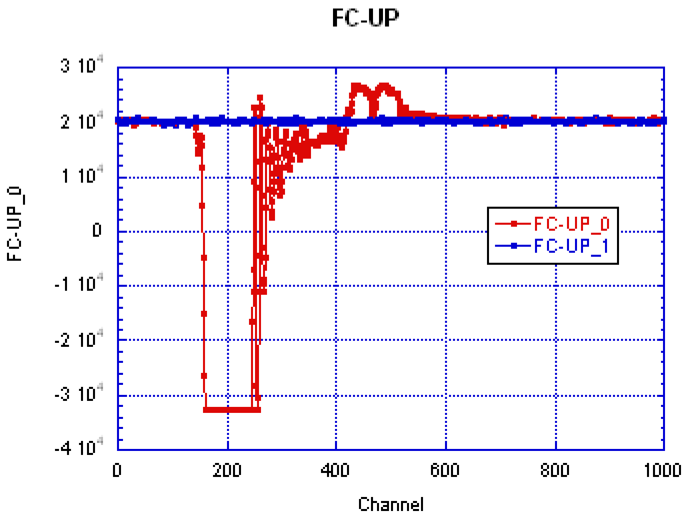
Rs Phase measurement to be established BD pulse with IQ

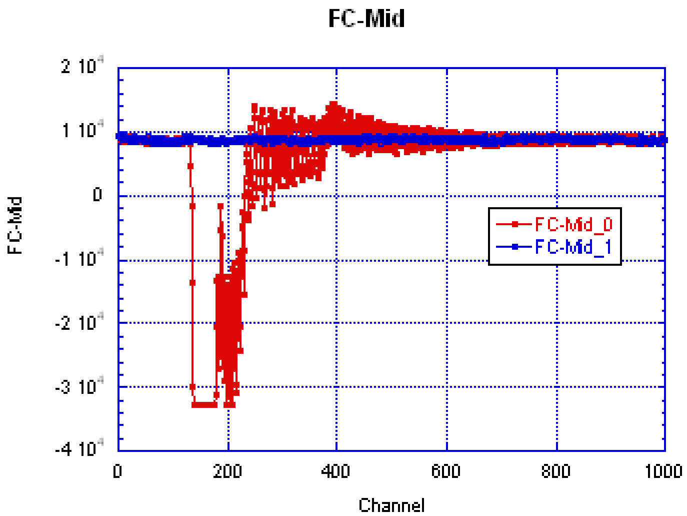




Pulse analysis is still to be established. Good manpower is needed.

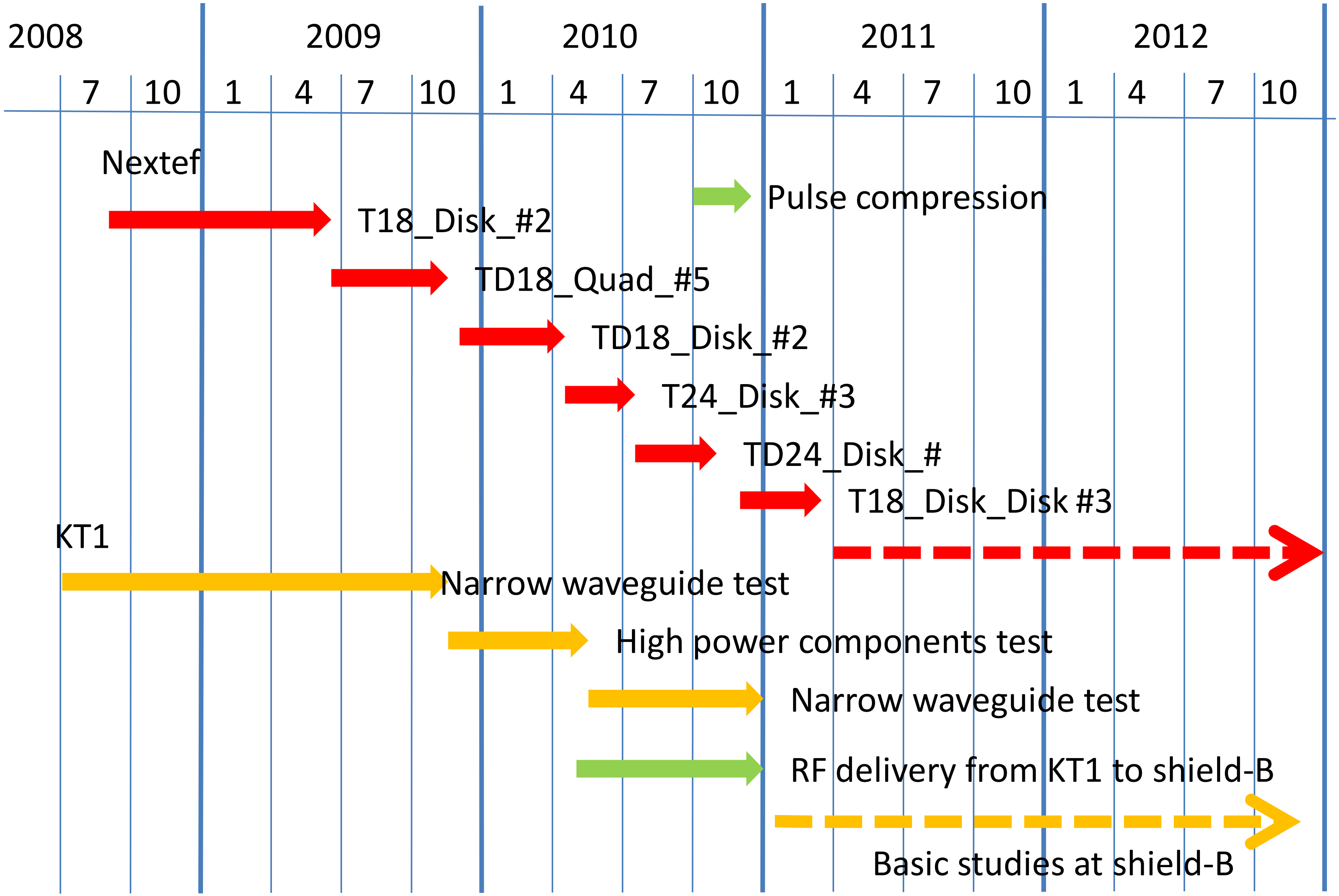
FC-UP and FC-Mid





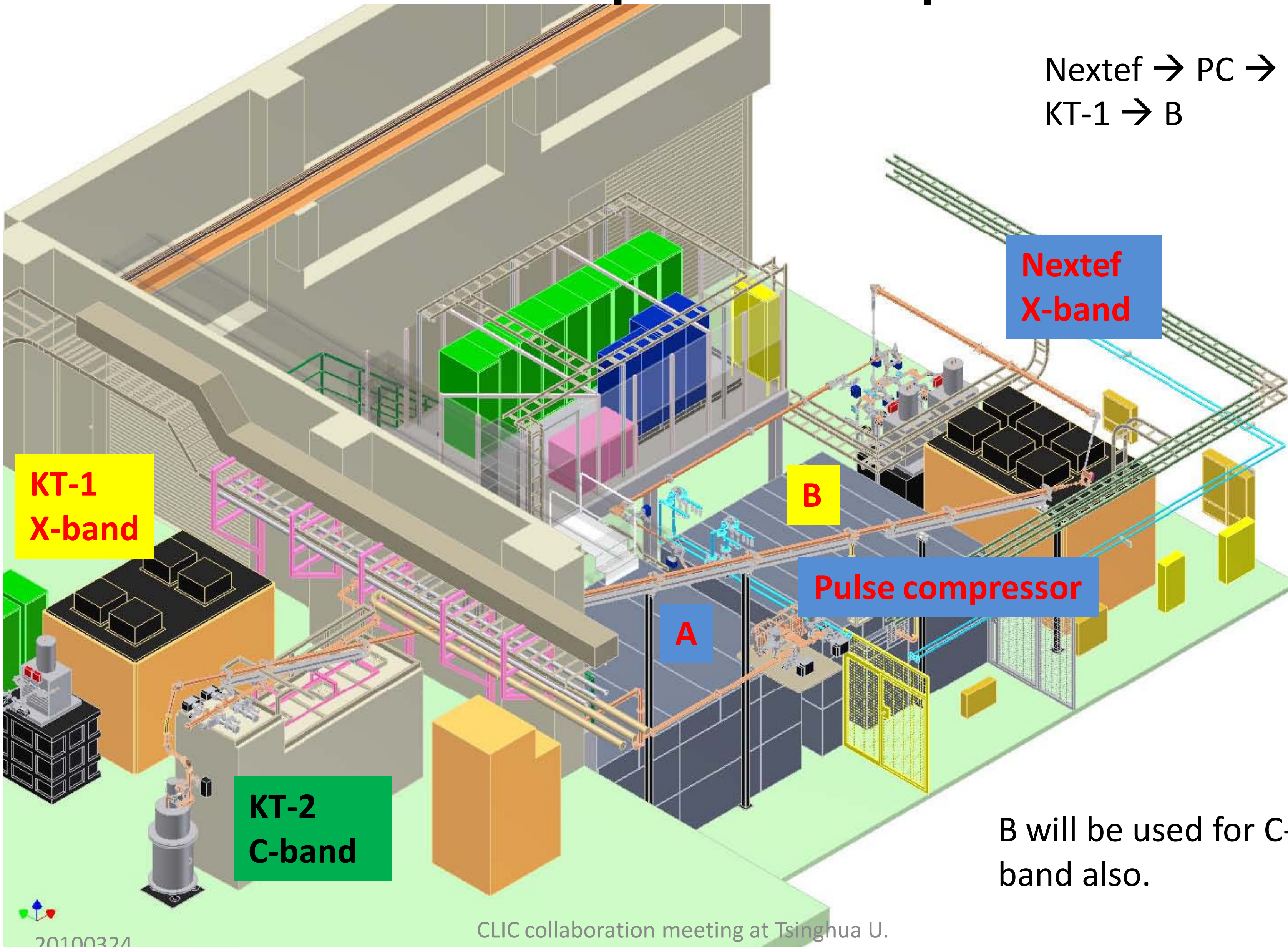
Relation to RF can be better analyzed?

KEK operation plan Nextef & KT1



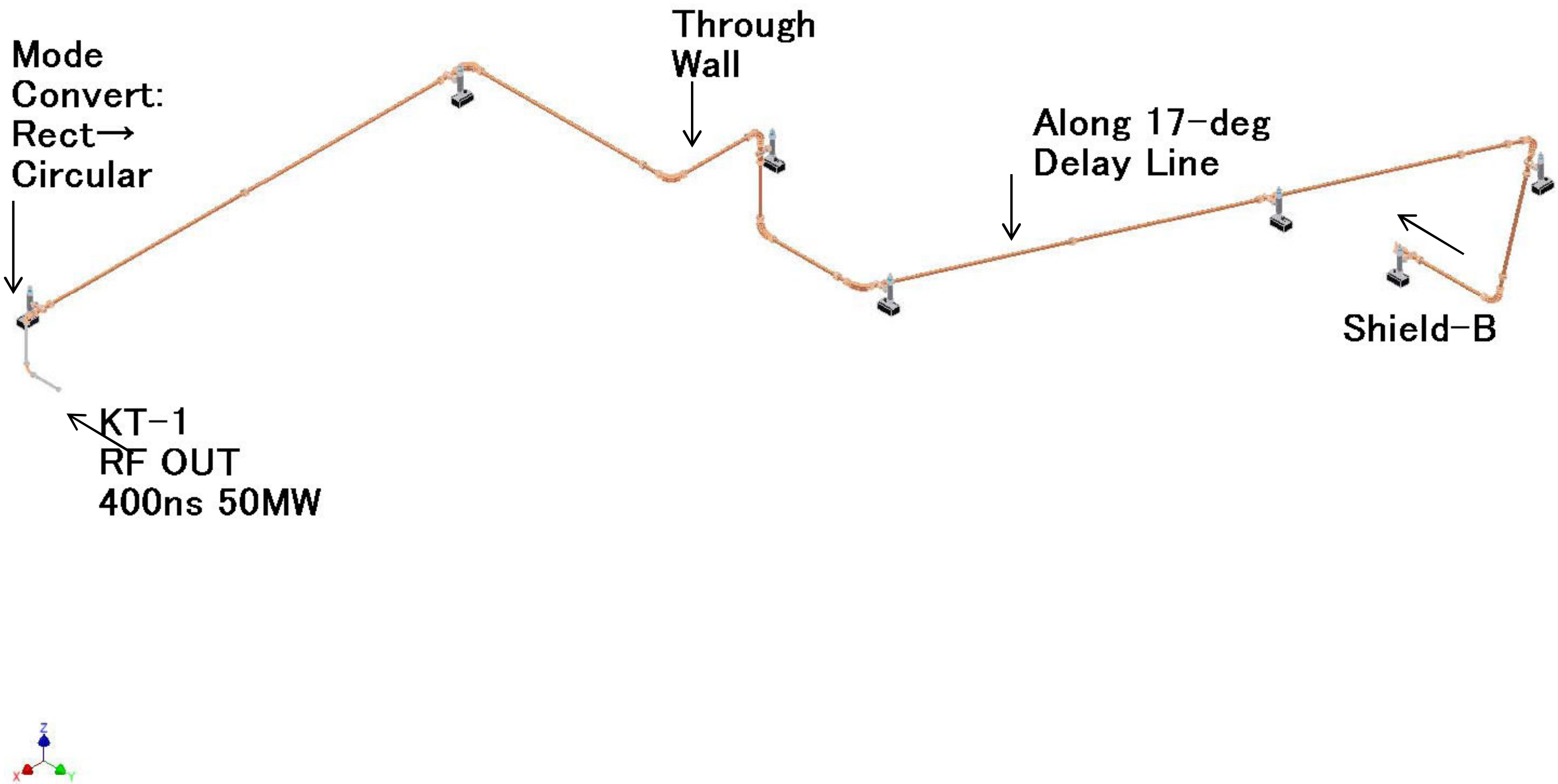
Nextef expansion plan

Nextef → PC → A
KT-1 → B

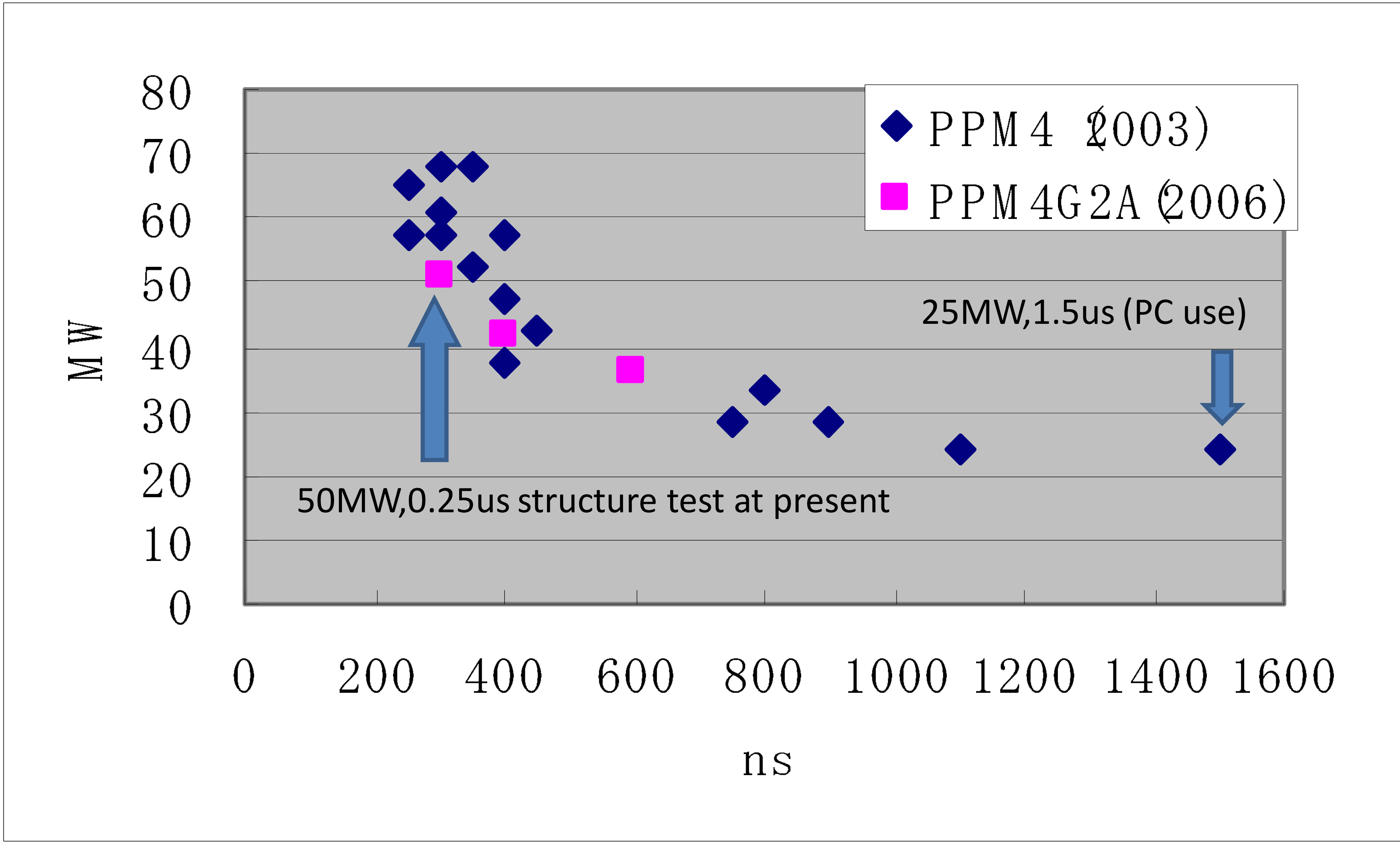


B will be used for C-band also.

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

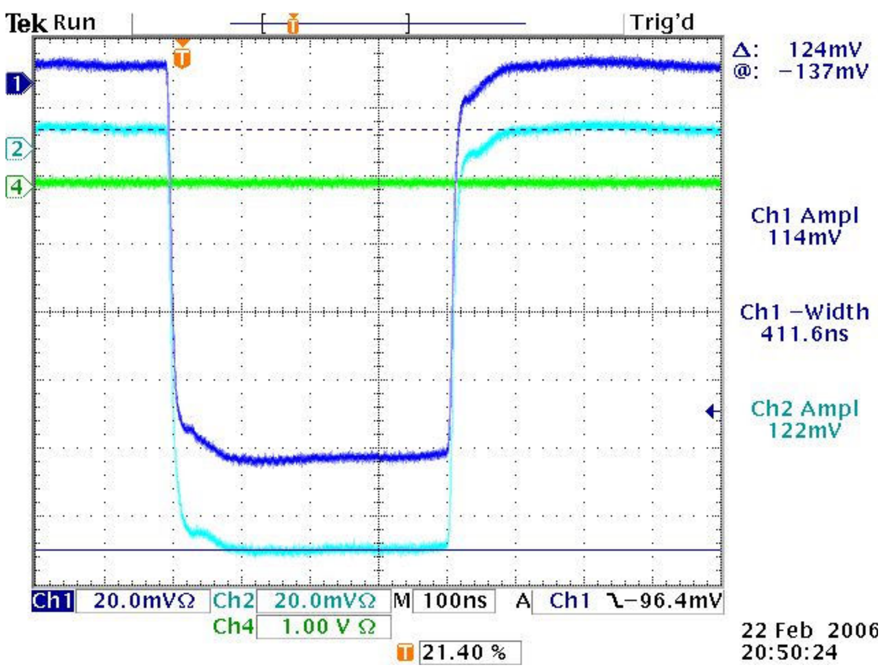


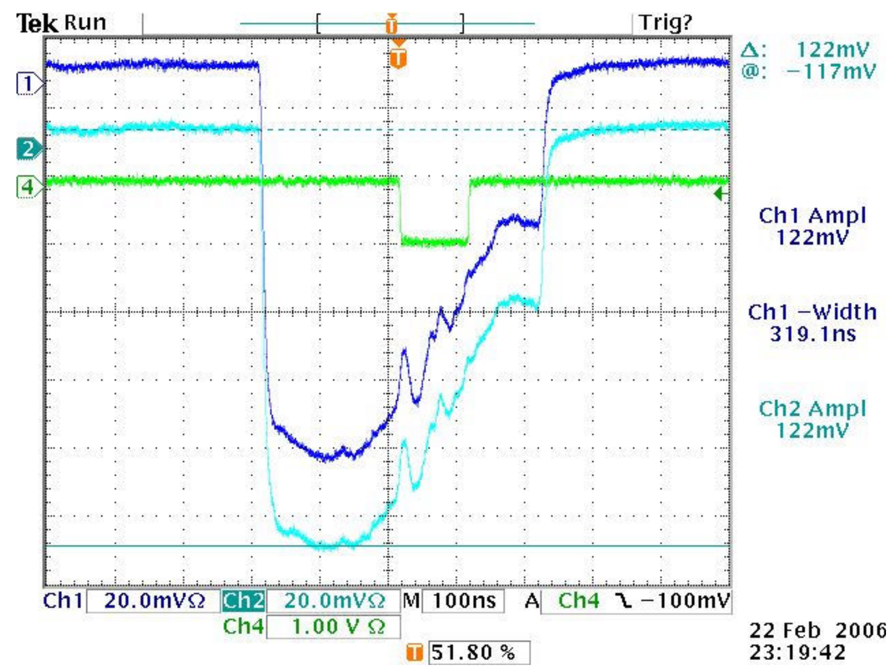
PPM klystron output power limit



PPMクライストロンの運転限界

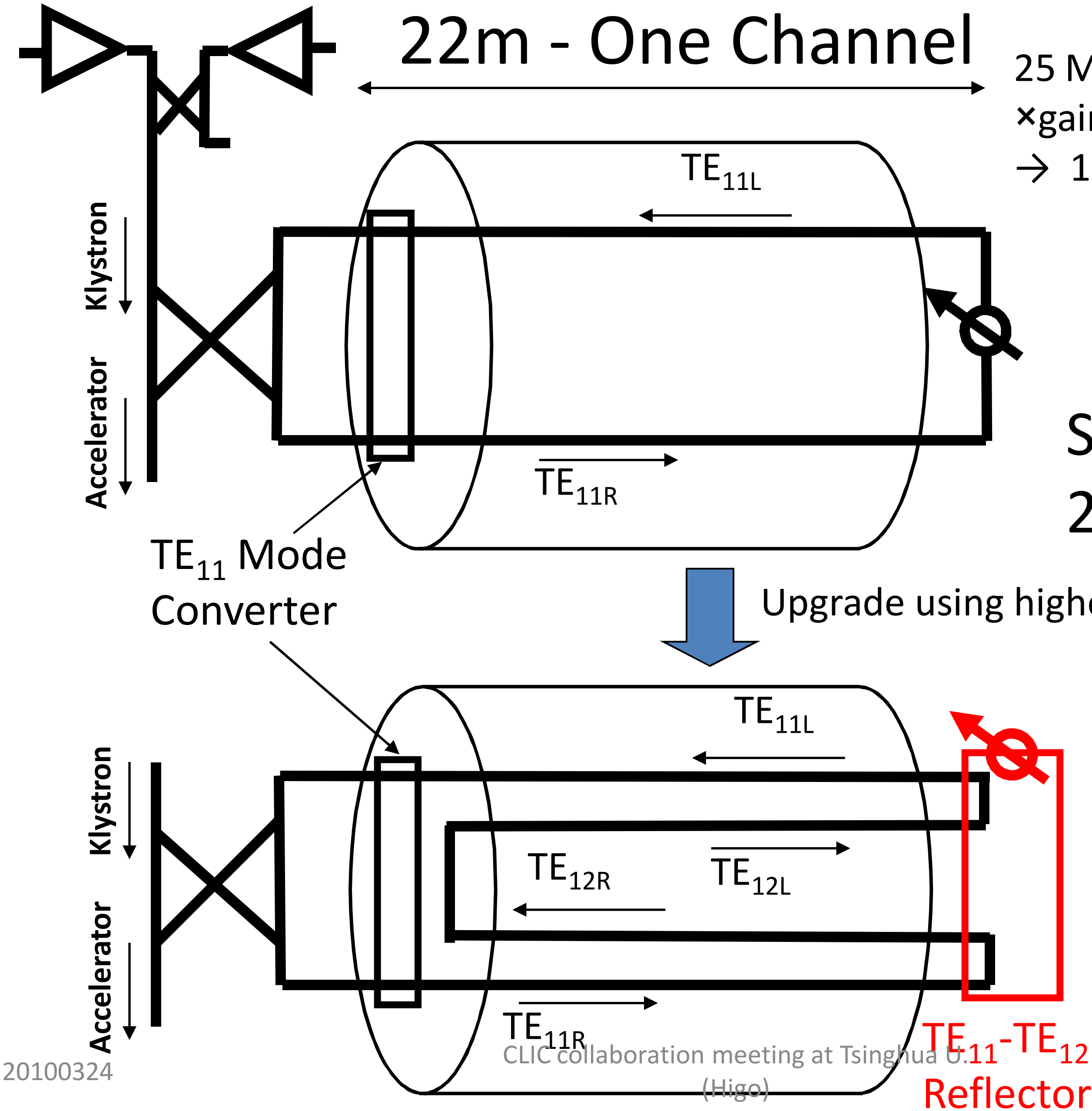
The availability of ppm klystron depends on the required RF quality. Empirically we have known that RF pulses were often broken when the product of the pulse width and peak power is large.





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

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



25 MW×2 Klystons
×gain=3
→ 150MW

750ns → 150ns
Gain = 3.6 @ 3dB

Starting in
2010 version

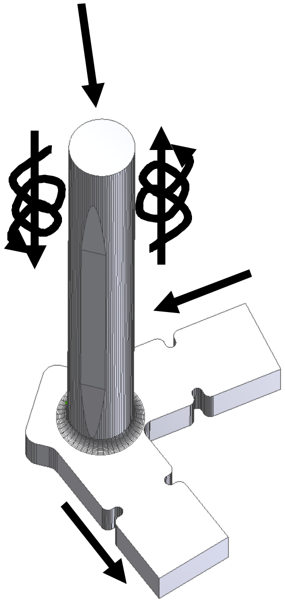
1500ns → 300ns
Gain = 3.3 @ 3dB
final version
In 2010 or later

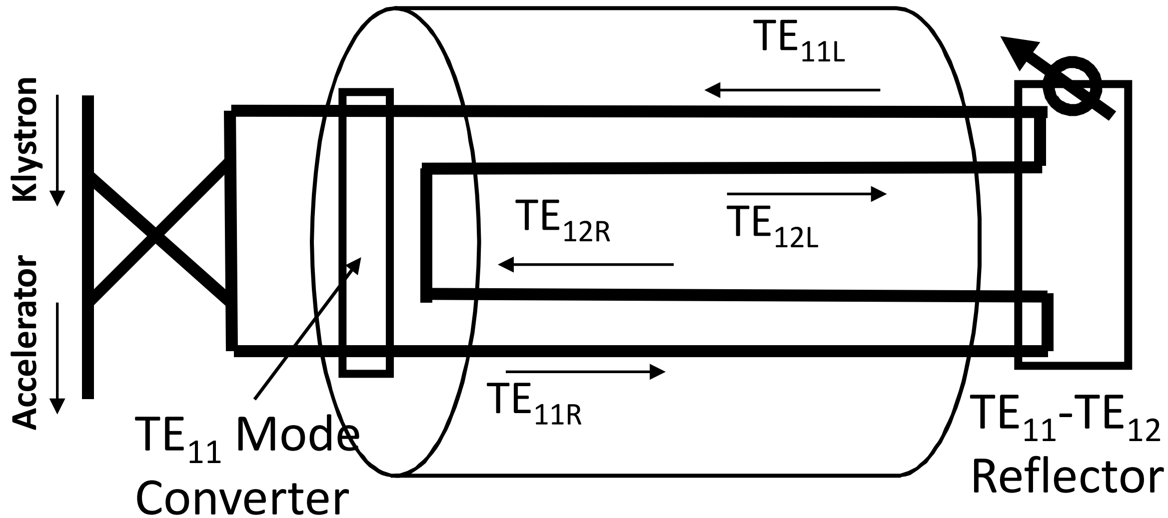
モード変換器

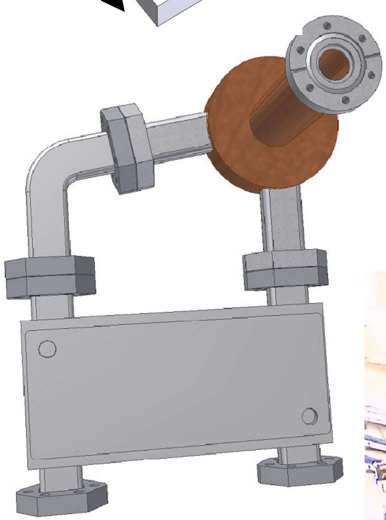
by Kazakov

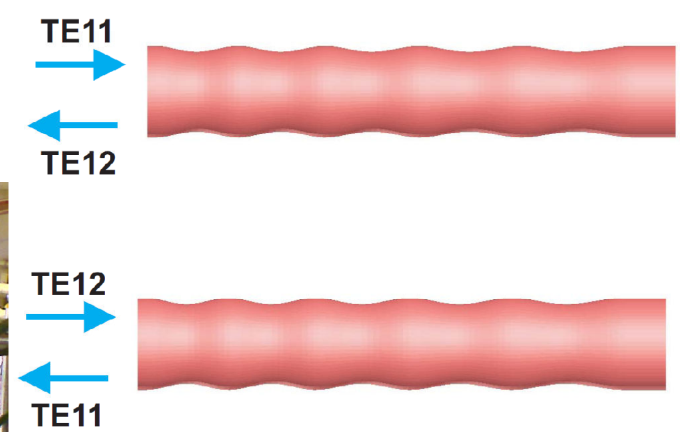
パルス圧縮器の構成

(Traveling Wave Delay Line Pulse Compressor)







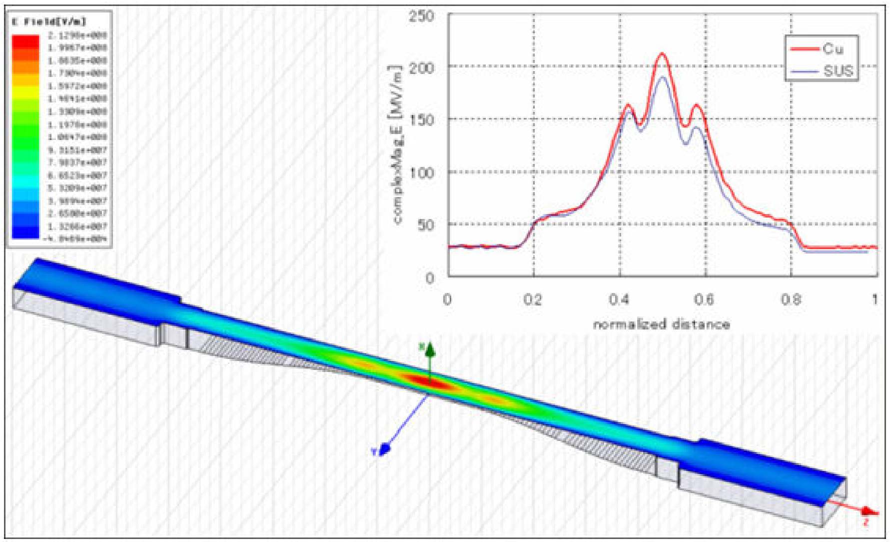


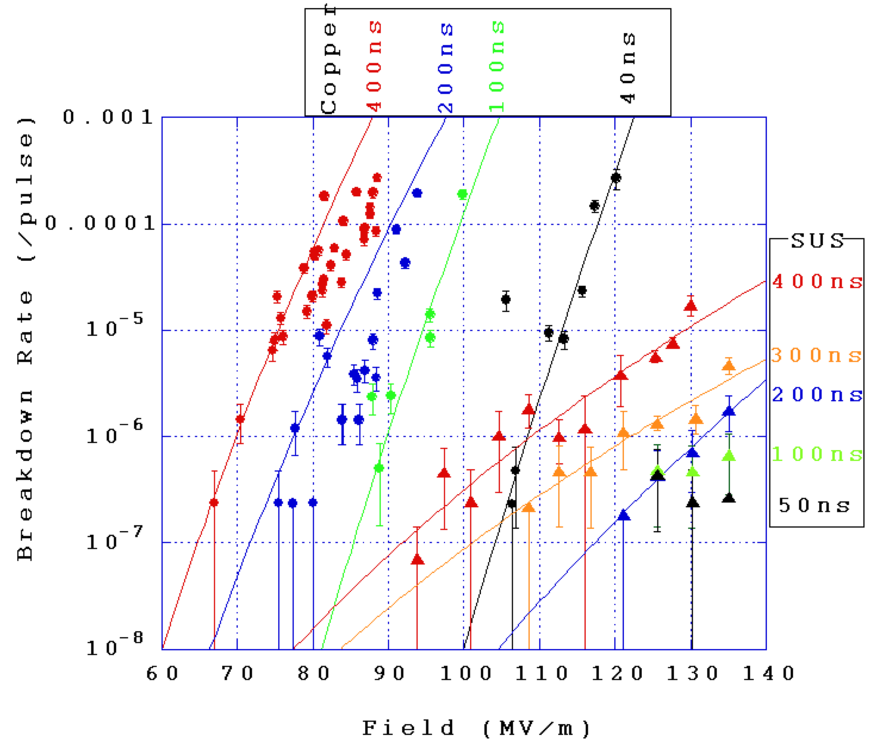
Some area on basic high gradient studies with KT-1

- 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.

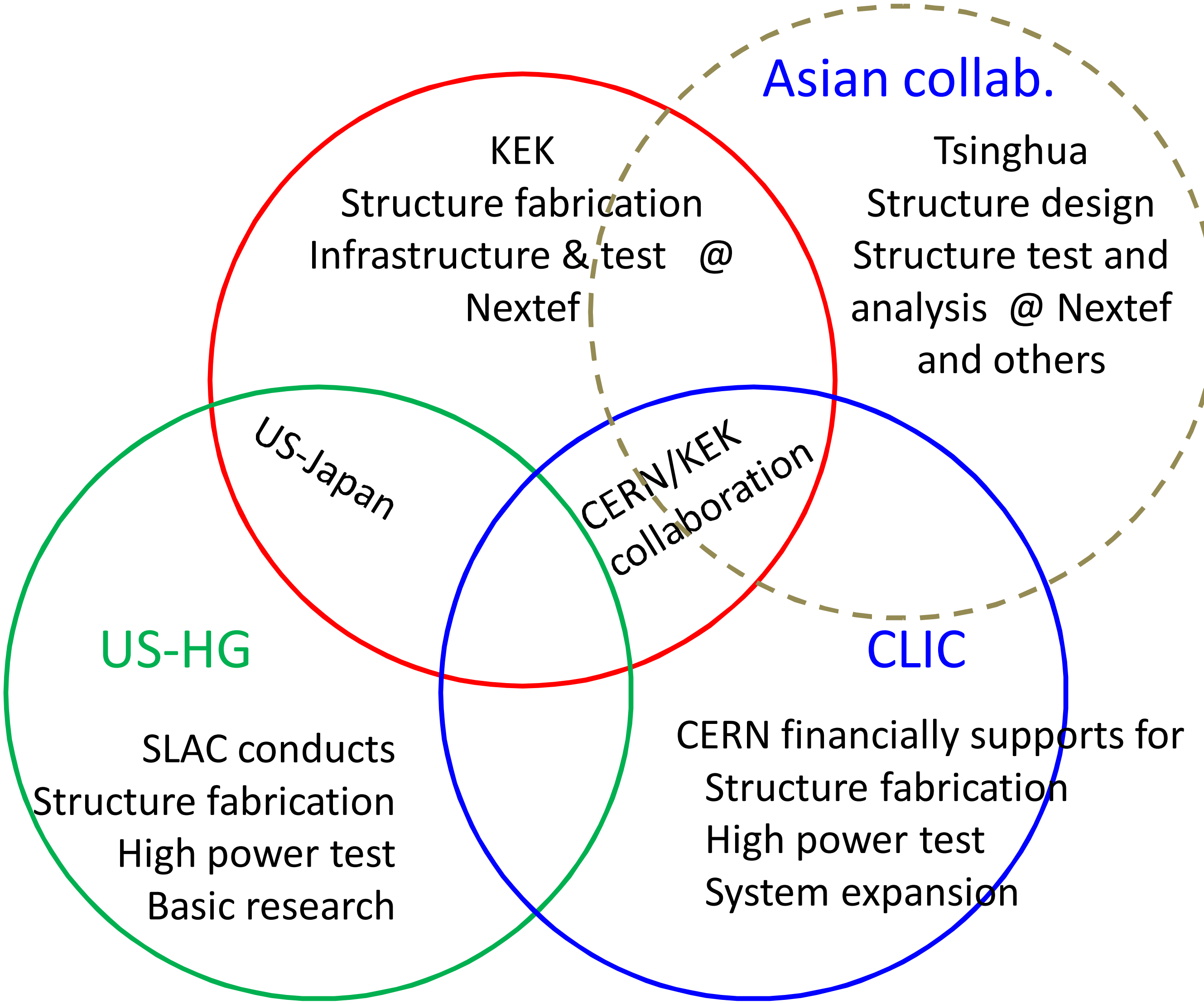
Copper BDR >> Stainless-steel BDR

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