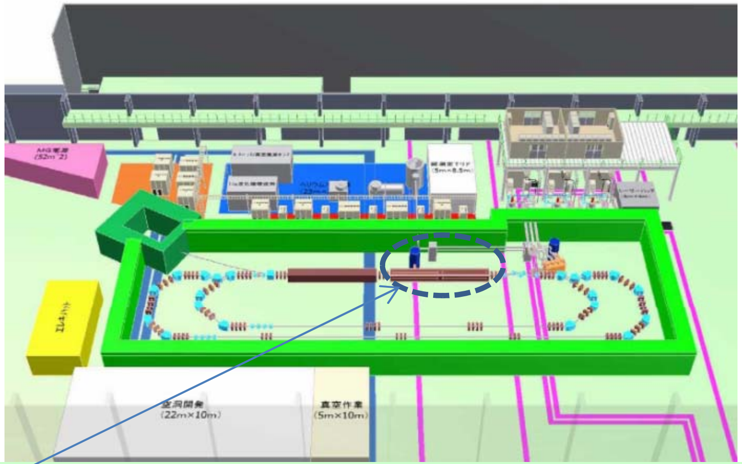
Input coupler development for KEK ERL main linac

Hiroshi Sakai, Takaaki Furuya, Masato Sato, Kenji Shinoe,
Kensei Umemori, Kazuhiro Enami(KEK),
Masaru Sawamura (JAEA), Enrico Cenni (Sokendai)

Compact ERL(cERL) @KEK

Contents

- Design of input coupler for ERL main linac
- High power test at test stand
- compact ERL(cERL) cryomodule test
- Summary

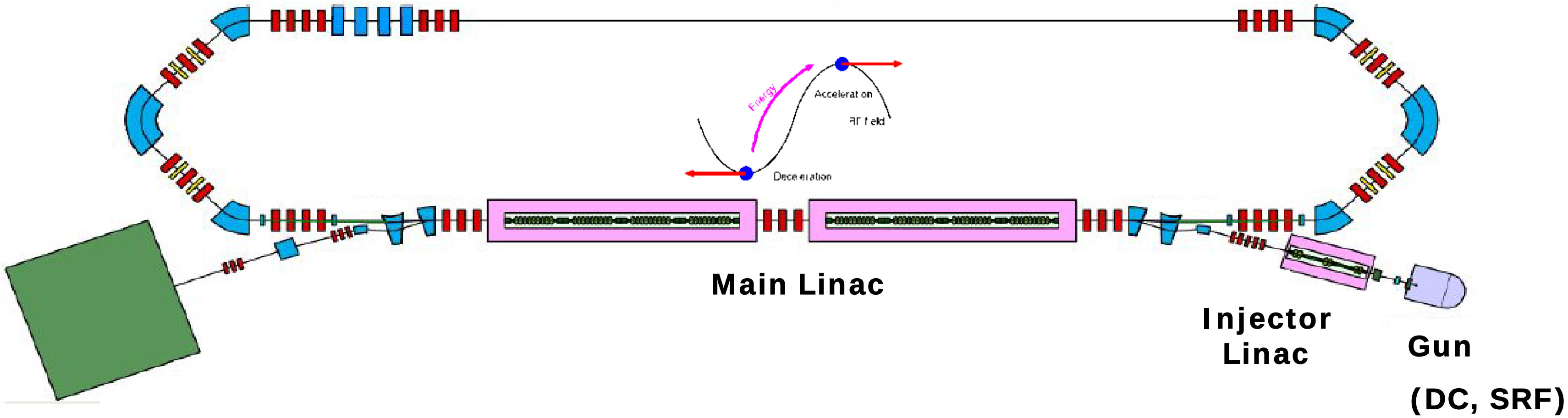


Injector beam commissioning start on 2013 spring

TTC CW SRF workshop @Cornell Univ. (2013.June.12-June.14)

Coupler requirements & properties for CW-ERL main linac

ERL design based on compact ERL (cERL)



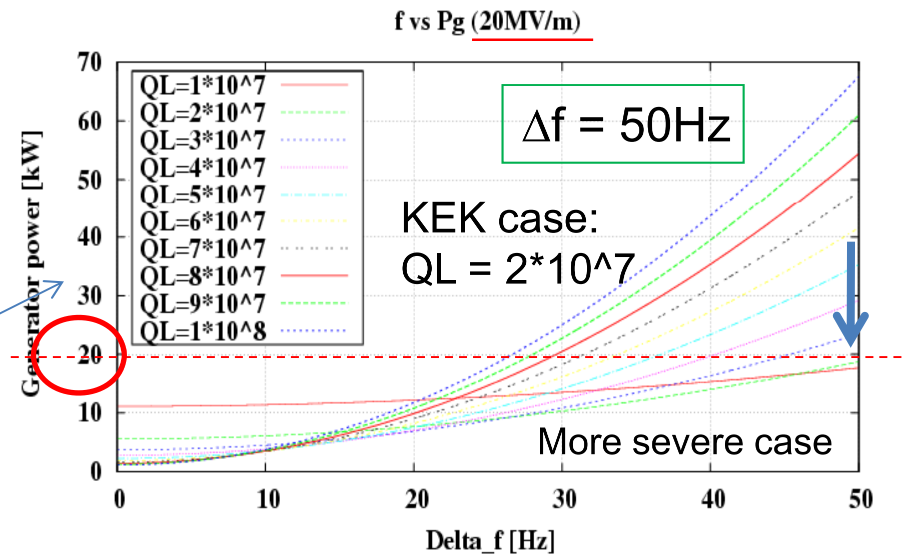
Main linac case (compared with injector)

--Low RF power thanks to Energy Recover
weak coupling (Qext = 1*10^7 – 1*10^8)
which depend on microphonics effect
basically 5-20kW will be needed.

--Reliabilties are another important points
due to fabricate large number of couplers.

$$P_g = \frac{V_c^2}{4(R/Q)Q_L}\left(1+4Q_L^2\left(\frac{\Delta f}{f}\right)^2\right)$$

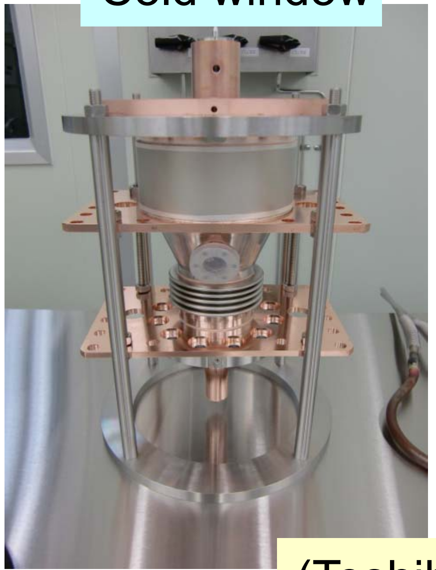
Calculation of ΔF vs Pg with different QL



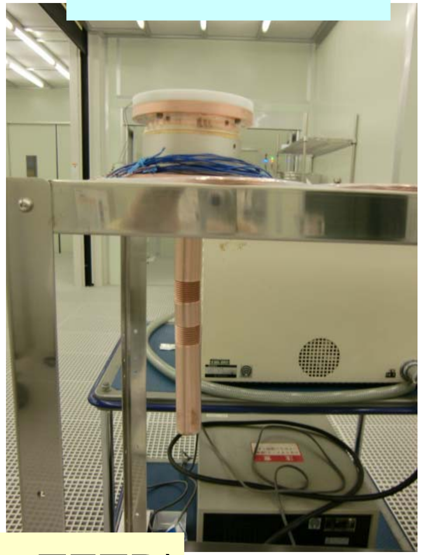
Basic parameters & design of input coupler for main linac at KEK

- Basic parameters
  - frequency : **CW, 1.3GHz**
  - Accelerating gradient : **Max 20MV/m (First)**
  - input power : **max 20kW** , standing wave (Δf=50Hz)
  - loaded Q(Q_L) : **(1-4) * 10^7 (variable coupling)**
- Points (modified from STF-BL coupler for CW)
  - Forced N2 gas cooling of inner conductor
  - Impedance from 50Ω to 60Ω
  - 99.7% purity of ceramic window are used.
  - make variable and add cold bellows

Cold window

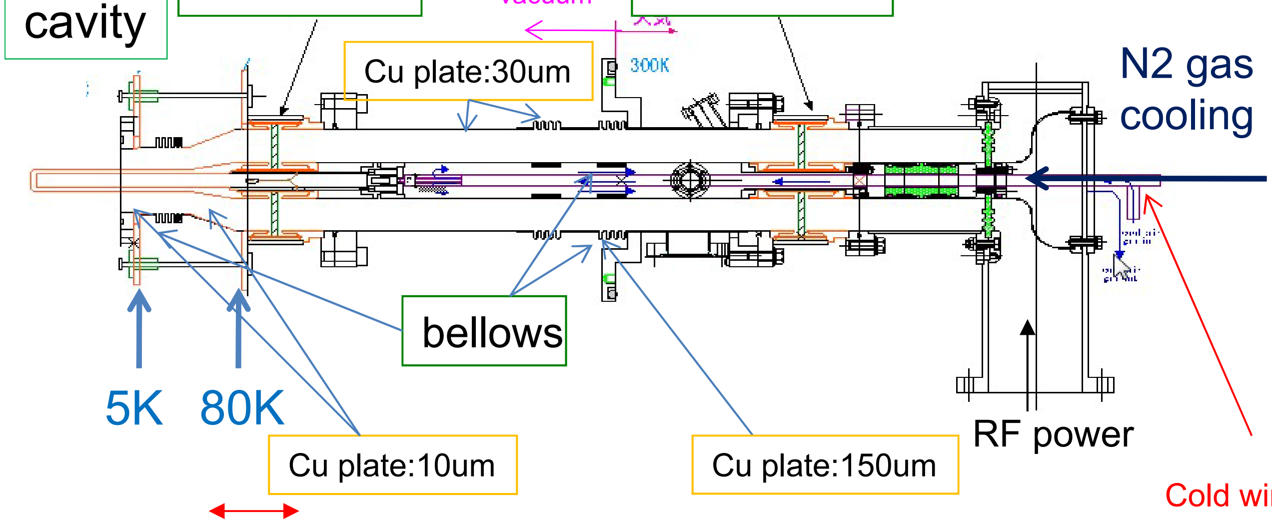


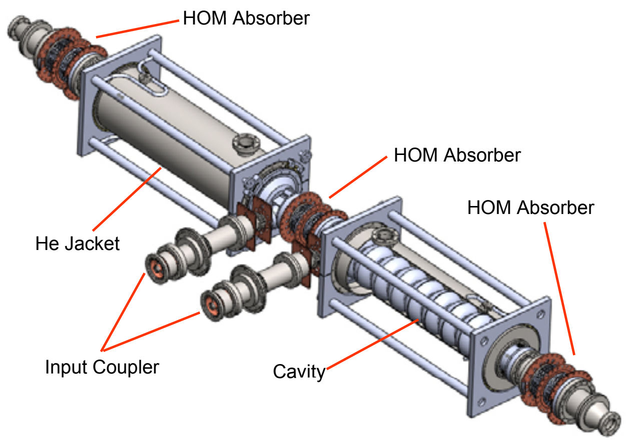
Warm window



(Toshiba TETD)

Basic design





Coaxial disk type ceramic window was used

Input coupler heat load (per cavity) (calculation)

10kW+10kW(=20kW) standing wave Dynamic loss

Dynamic loss	2K	5K	80K	300K
Inner conductor	-	-	14.7W	6.8W (forced gas cool)
Outer conductor	-	0.79W	1.3W	2.1W
Total	-	0.79W	16.0W	8.9W

20kW+20kW(=40kW) standing wave Dynamic loss

Dynamic loss	2K	5K	80K	300K
Inner conductor	-	-	29.4W	13.7W(forced gas cool)
Outer conductor	-	1.55W	2.5W	4.1W
Total	-	1.55W	31.9W	17.8W

Ceramic window heat <1W

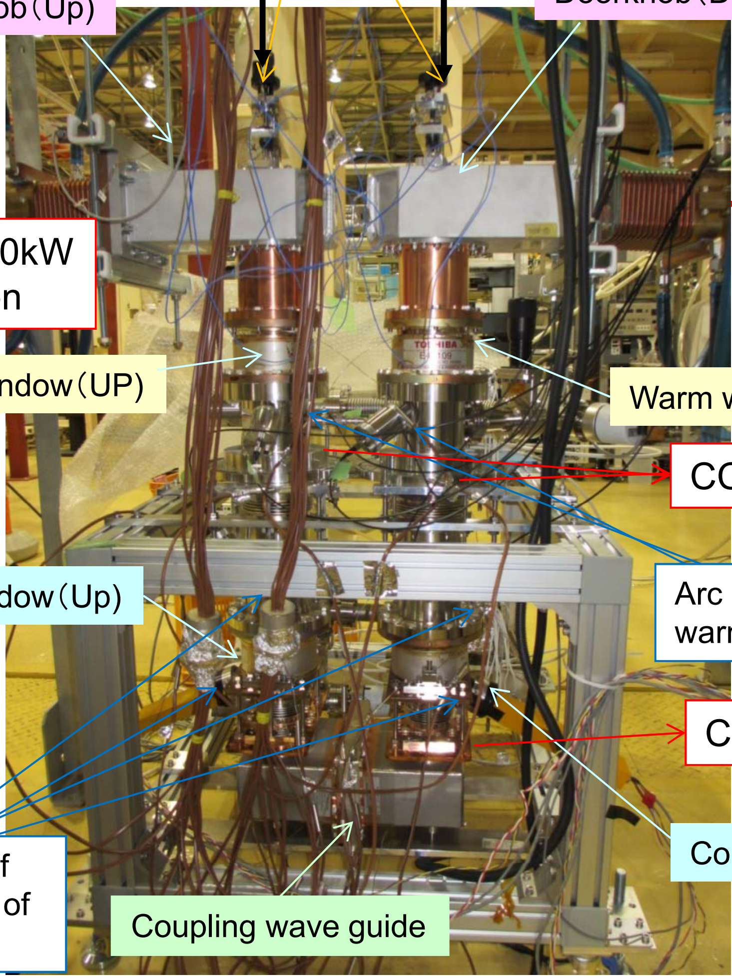
(Static loss)

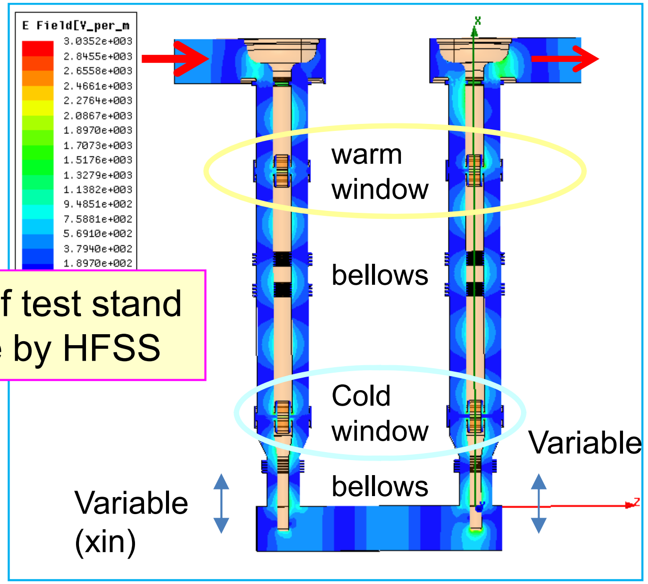
calc	5K→2K	80K→5K	300K→80K
Static loss Qc	< 0.3W (depend on sealing)	1.6W	(inner conductor) 5.5W (outer conductor)10W Total = 15.5W

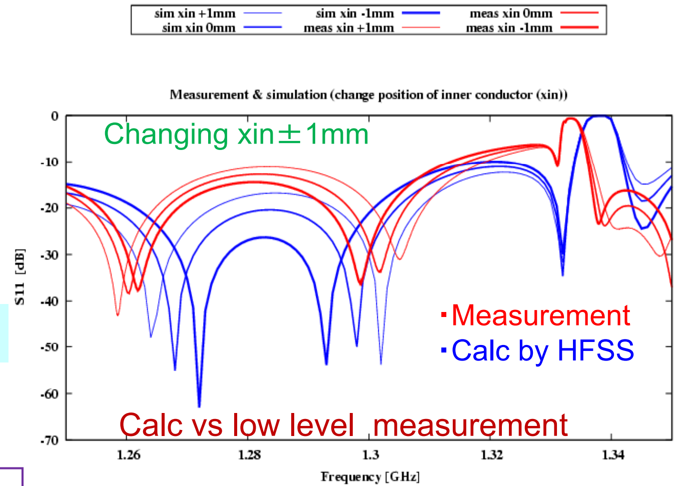
Come from N2 gas cooling

Coupler test stand for cERL cryomodule

Setup







Aim

Assembly work on class 4 clean room and bake 150degree for 24h

Processing coupler before assembly: SW 20kW -> TW 80kW (1/2 duty)

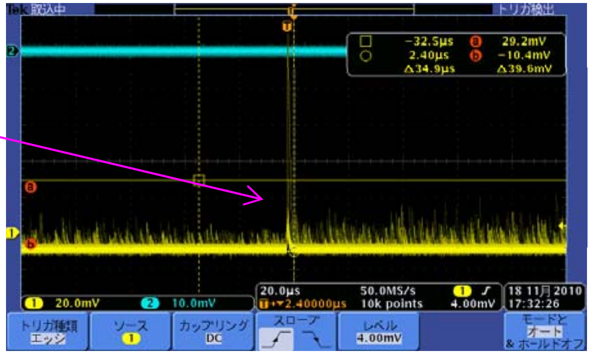
- 1.3GHz CW 300kW klystron used → Try TW 100kW to get mergin for CW
- arc sensor using fiber was tested for cryomodule power fast ITL < 10 us

S11 parameters measured and these measurements were also agree well with calc of HFSS.
→ set S11 < -25dB

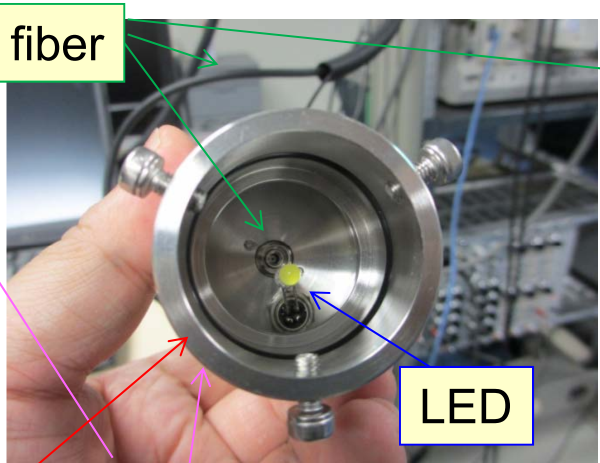
Fiber Arc sensor and its logic

Interlock from sudden discharge of ceramic for cERL beam operation (<10us required)
・fast arc sensor by using fiber and PMT
→ allow less than 1us response

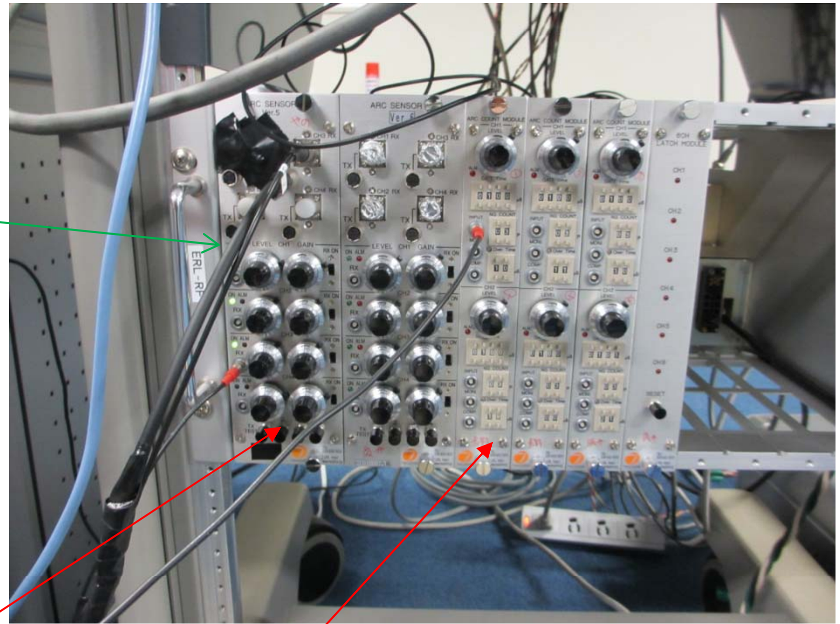
Typical fiber arc sensor signal from light (pulse width less than 1us)



Cold window



Fiber arc sensor



Fiber arc sensor → Arc sensor module (PMT) → Arc decision module (FPGA) → Machine protection module (FPGA)

Set sensor faced each window and detect light

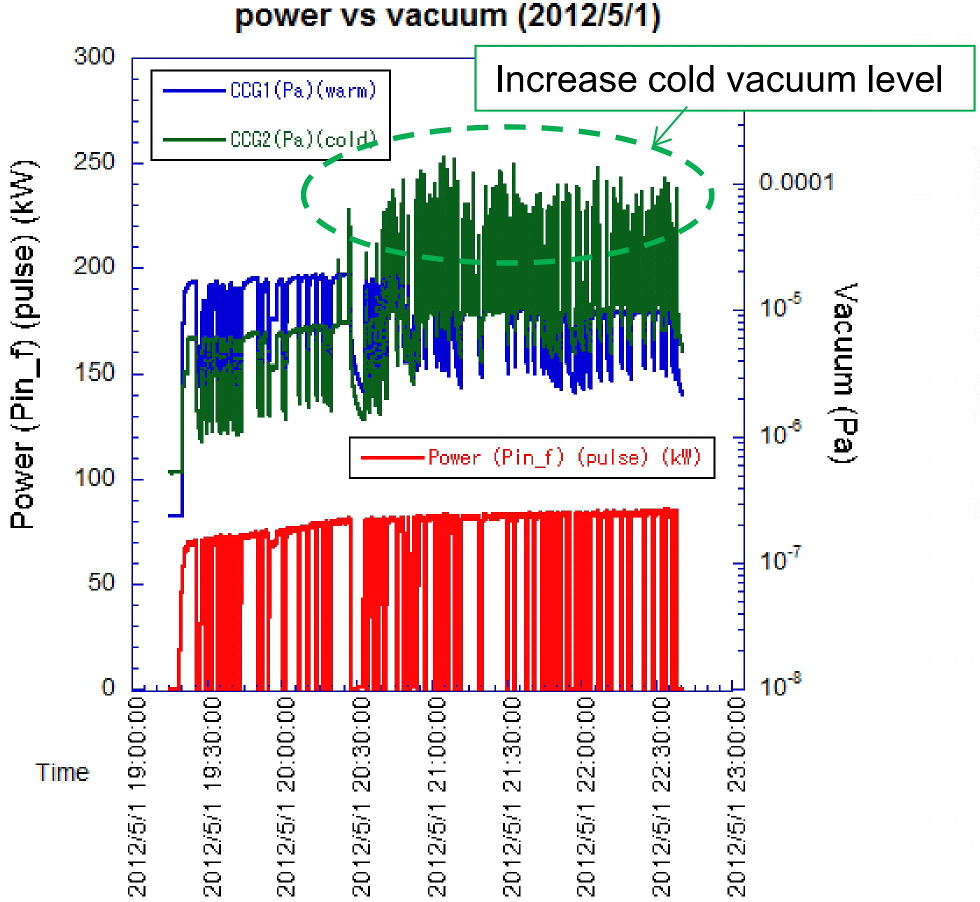
If Pulse height increase the finite threshold, make TTL pulse with same width

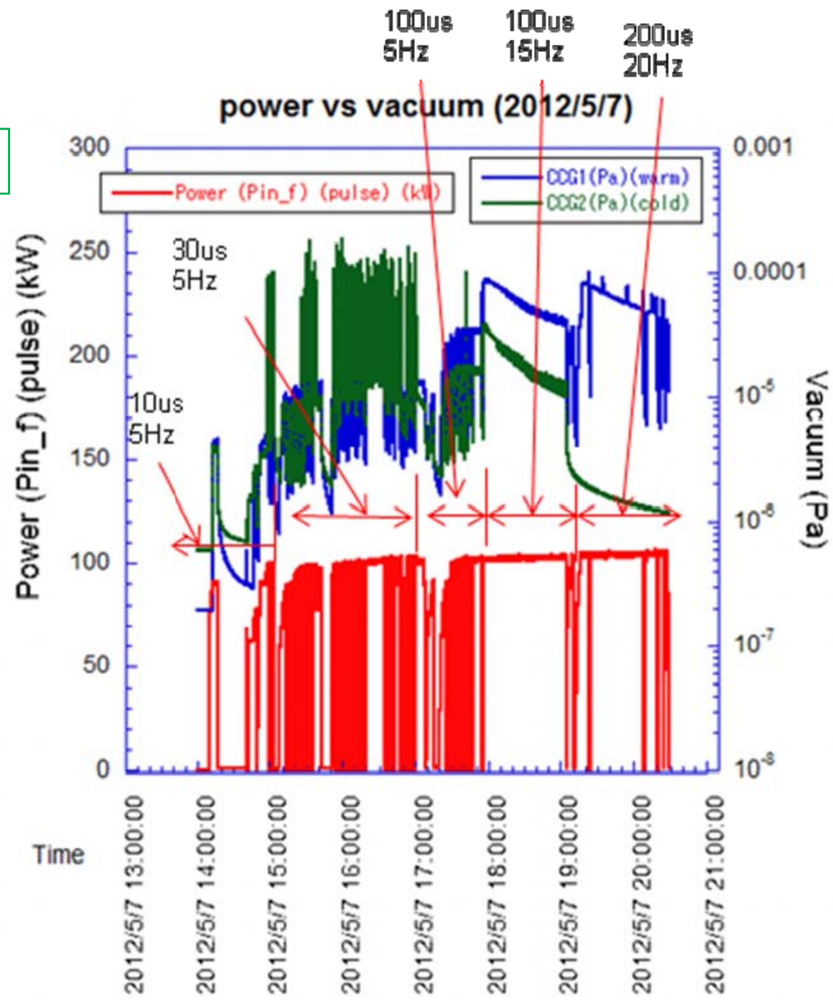
If count TTL pulse > N or >9us→ TTL out (against cosmic ray event)

Latch TTL pulse and RF off (< 10us)

Power test results with pulse processing (10us →200us)

Typical processing of 10us 5Hz (70kW→85kW)



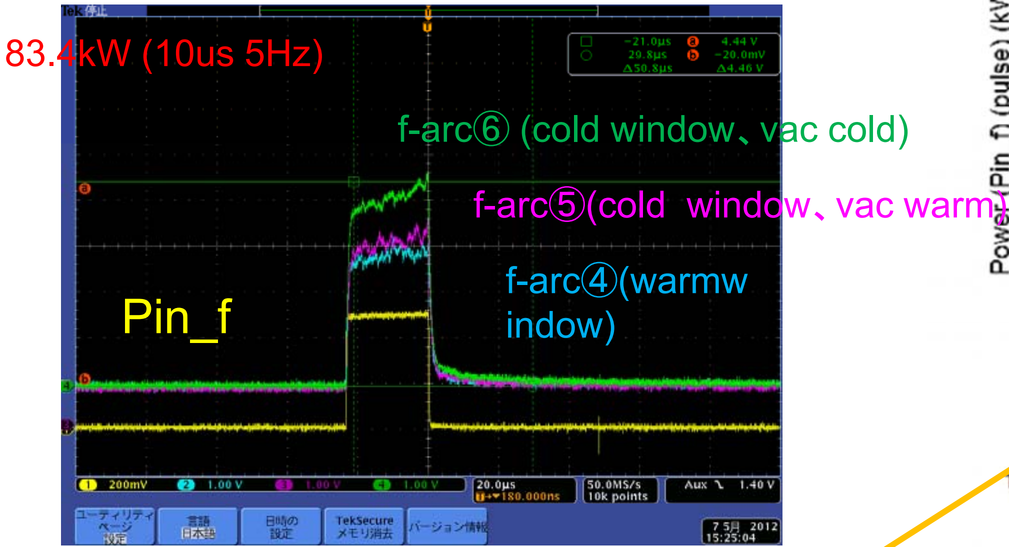


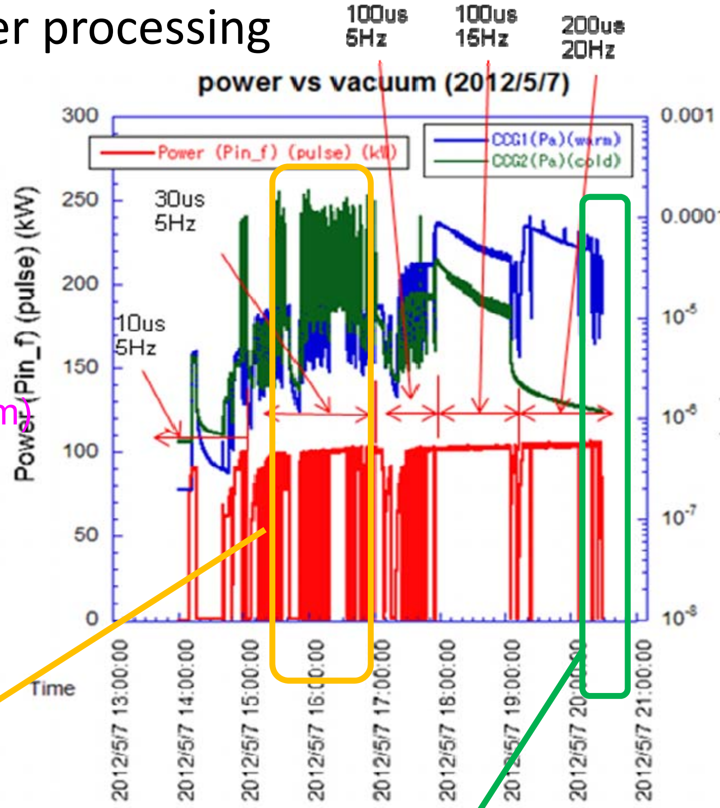
Start pulse processing with 10us width. On 27kW, vacuum was increased but processing level was gradually increased until 80kW with 6kW/h and many arc signal ITL. From 80kW to 100kW , sudden vacuum increase of cold window led the processing speed decreased to 2.5kW/h; processing level was slowly increased with many vacuum ITL (>1*10^-4Pa). Finally reached the 100kW with 10us width .

Next we lengthen pulse width 30us → 100us → 200us Continuing the processing and lengthen the pulse width suddenly vacuum level was better and finally we reached 105kW with 200us of 20Hz and no ITL was detected with arc and vacuum. → OK.TW 100kW pulse processing → continue lengthening

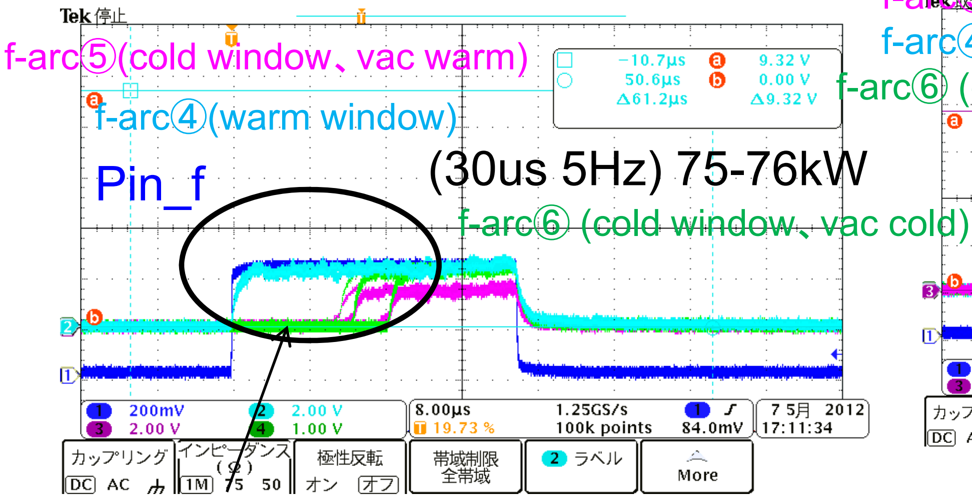
Detailed response of arc sensor signal under processing

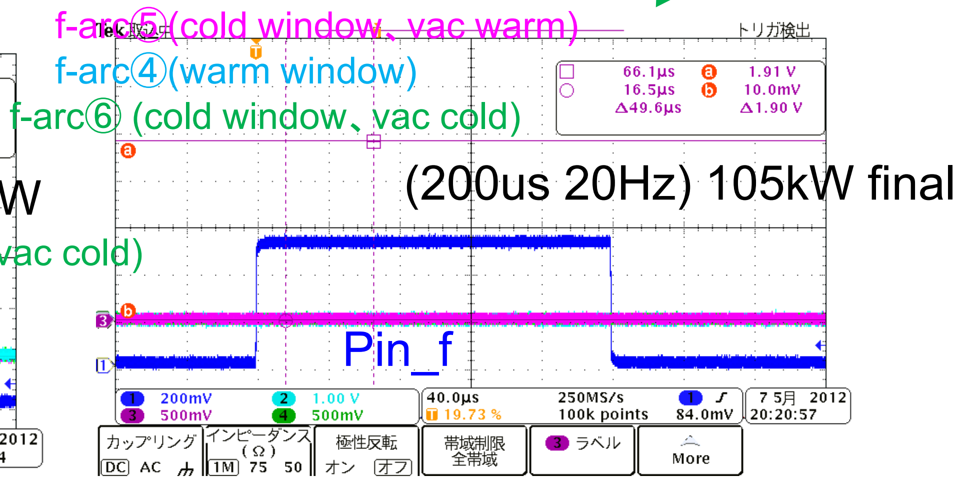
During processing with 10us, we see the arc signal event with ITL and gradually decreased this pulse this pulse height.





After processing with short pulse and apply long pulse





Arc signal was delayed if processing down with short pulse

If processing was done, we detected no arc signal

Processing time of coupler test stand

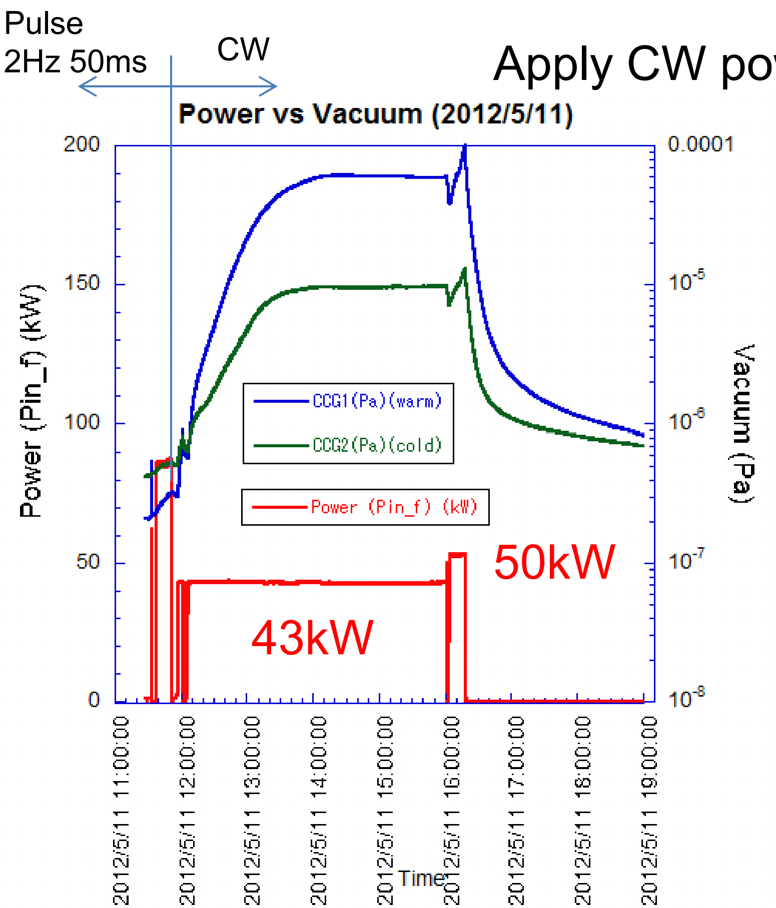
- Pulse processing
  - 10us 5Hz--20Hz (->100kW) (21h 40min)
  - 30us 5Hz (->100kW) (2h 10min)
  - 100us 5Hz (15Hz) (->102kW) (1h 50min)
  - 200us 10Hz (20Hz) (->105kW) (1h 20min)
  - 500us 20Hz (->102kW) (1h 7min)
  - 2ms 5Hz (100kW) (1h 11min)
  - 10ms 5Hz (95kW) (1h 7min)
  - 50ms 2Hz (92kW) (1h 4min)
  - 200ms 1Hz (88kW) (1h 5min)
  - 1s 0.5Hz (85kW) (1h 25min)
- CW (43kW) (4hours)

Power increase with processing and finally get no vacuum increase and arc event

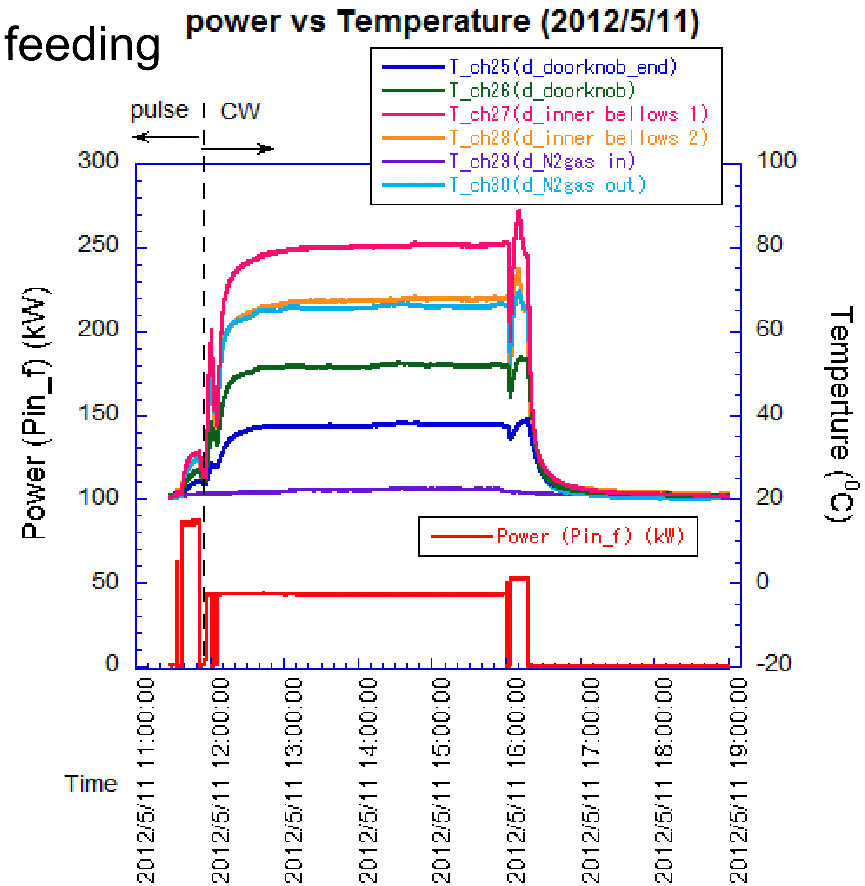
Search the stable field level of no ITL event for 1hour by lengthen the pulse width . 85kW of 1s pulse width of 0.5Hz (duty 50%) achieved.

Total pulse processing time (from 10us to 1s 0.5Hz) =**34hours**

Final results of coupler power test



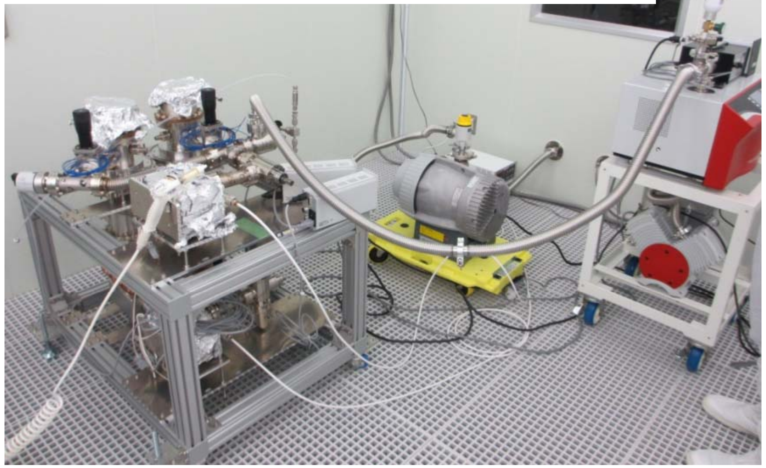
Apply CW power feeding



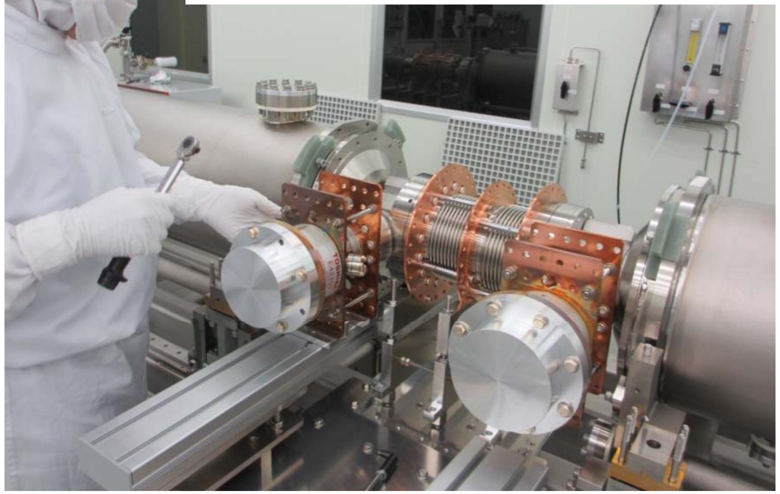
- RF power up to 105kW (pulse) (200us 20Hz)
  and done < 80kW TW processing with long pulse (1s 5Hz)
  43kW(CW) -> same as 20kW SW heat load
- Keep 43kW CW, 4hours → 50kW increased the vacuum after 20min due to the lack of outer cooling fan ability.
- Highest Temp: bellows of inner conductor (ΔT~60degree, OK)
  with N2 gas cooling of 120l/min

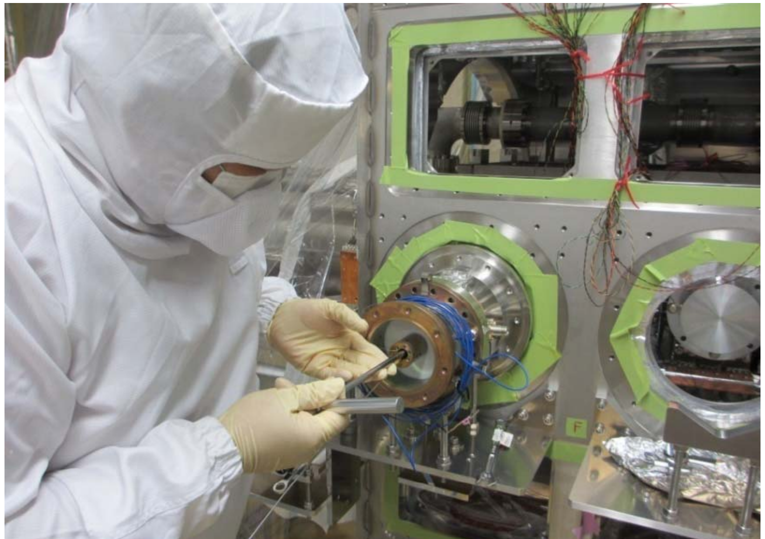
Module assembly of input coupler for cERL main linac

Leak check (no leak) & keep test stand in vacuum in clean room

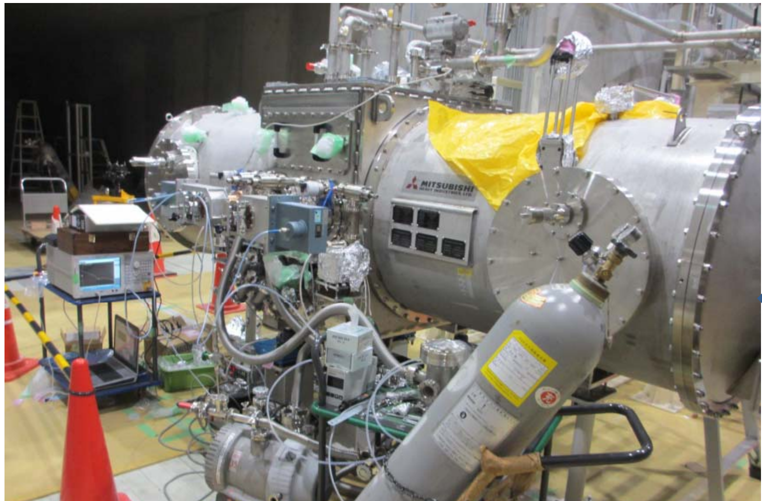


Connection of input coupler cold window in clean room (class 4)



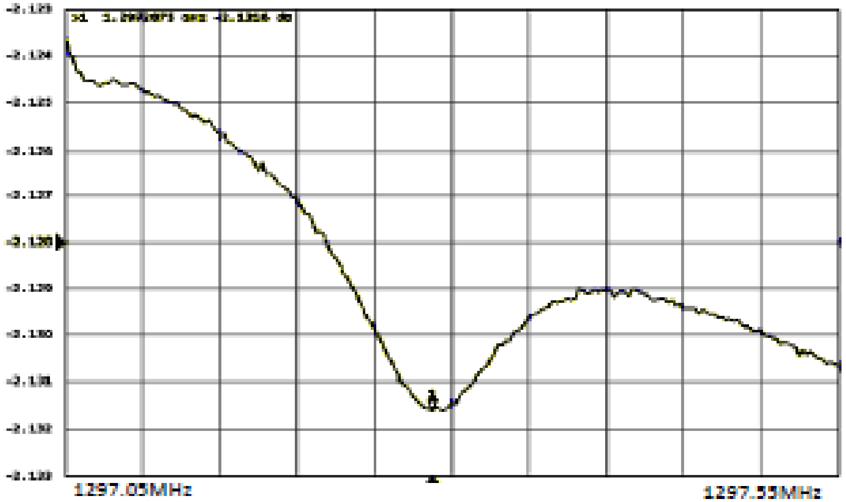


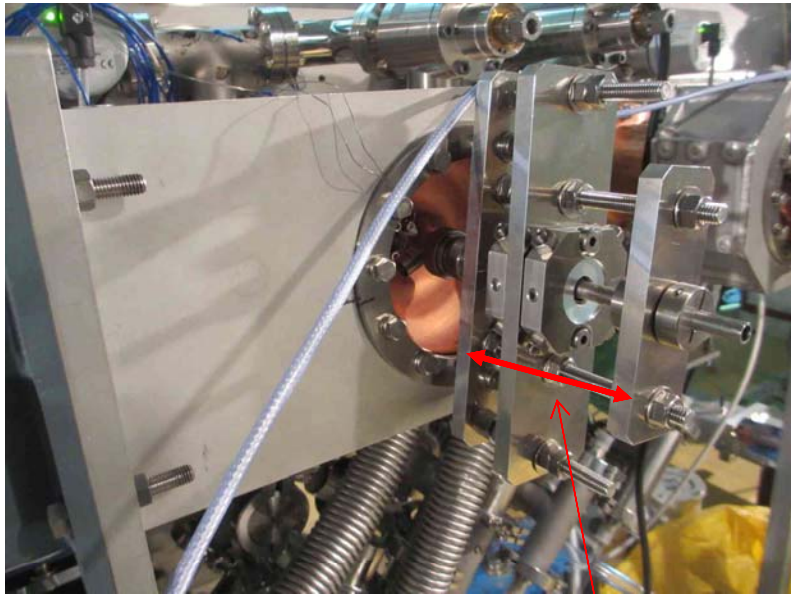
Connection of input coupler warm window in clean boose



Doorknob , inner rod, arc sensor & RF cable wereequipped

QL optimization & measurement



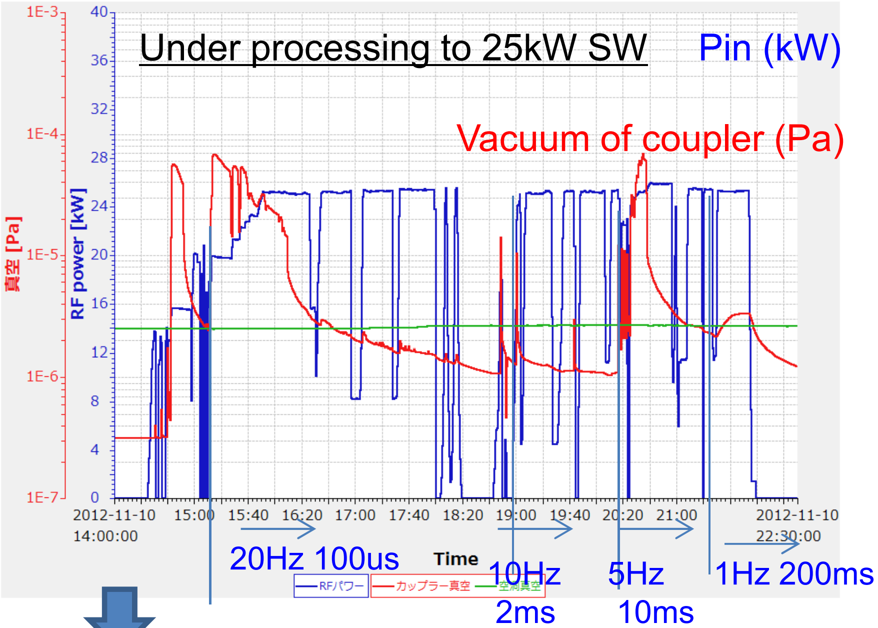


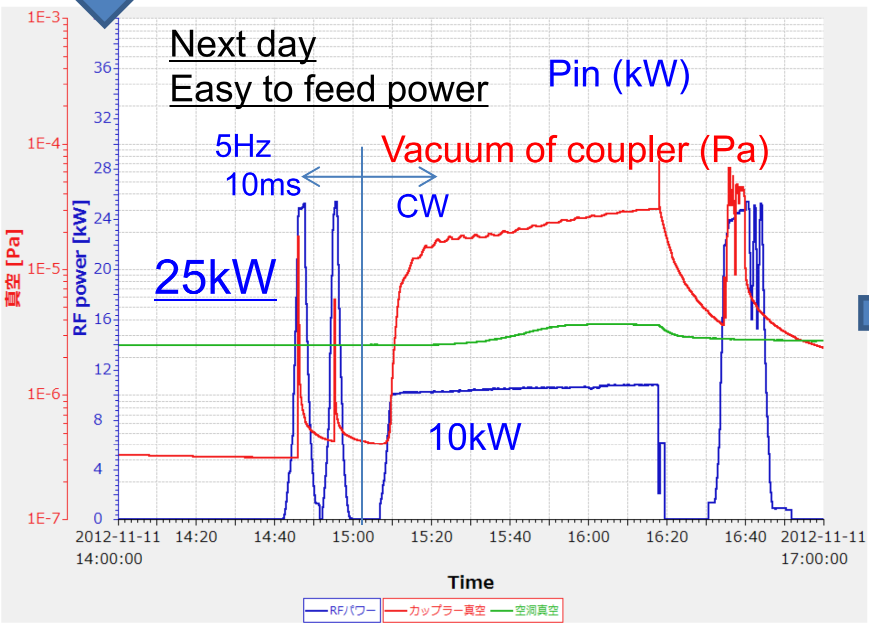
±5mm variable

- Input coupler has variable mechanism for Qext tuning.
- Measured Qext followed design values.
  - $1.5 \sim 5.3 \times 10^7$ for upper (#4 cavity)
  - $8.7 \times 10^6 \sim 3.3 \times 10^7$ for lower (#3 cavity)
  - design: $1 \sim 4 \times 10^7$

Coupler aging of each cavities of cyromodule & power test

Aging history after module assembly
(at room temperature)

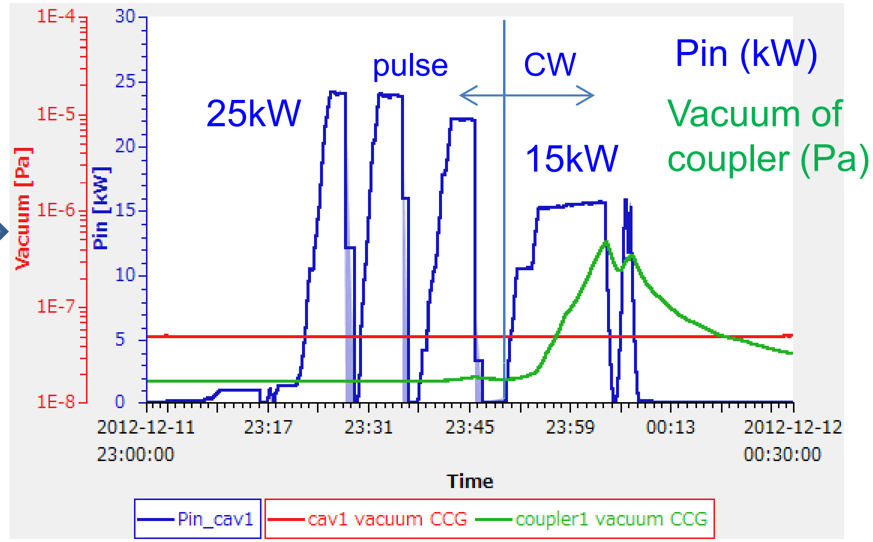




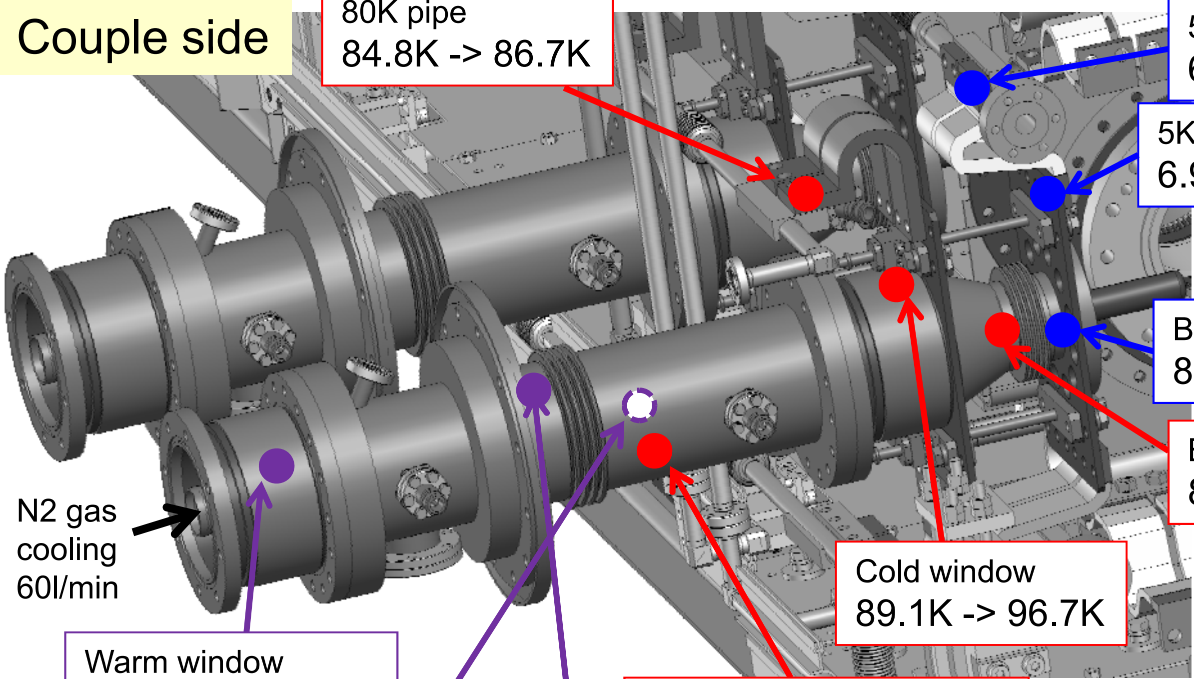
- After assembly, first we start aging at room temperature, 8 hours was needed for processing again in cryomodule.
- After finish processing, we did not meet the continuous electron activity under warm and 2K condition.
- Aging up to 15kW with CW detune condition @ 2K. Thanks to the processing of room temperature, aging time is much small (< less then 10min).
- Finally in high power test, power fed into 4.5kW with on resonance with QL=1.5*10^7
- Microphonics is Δf = 7Hz of pk-pk
- Vacuum level is less than 1*10^-6 Pa.

Coupler works well in cryomodule

Aging history (at 2K condition) detune



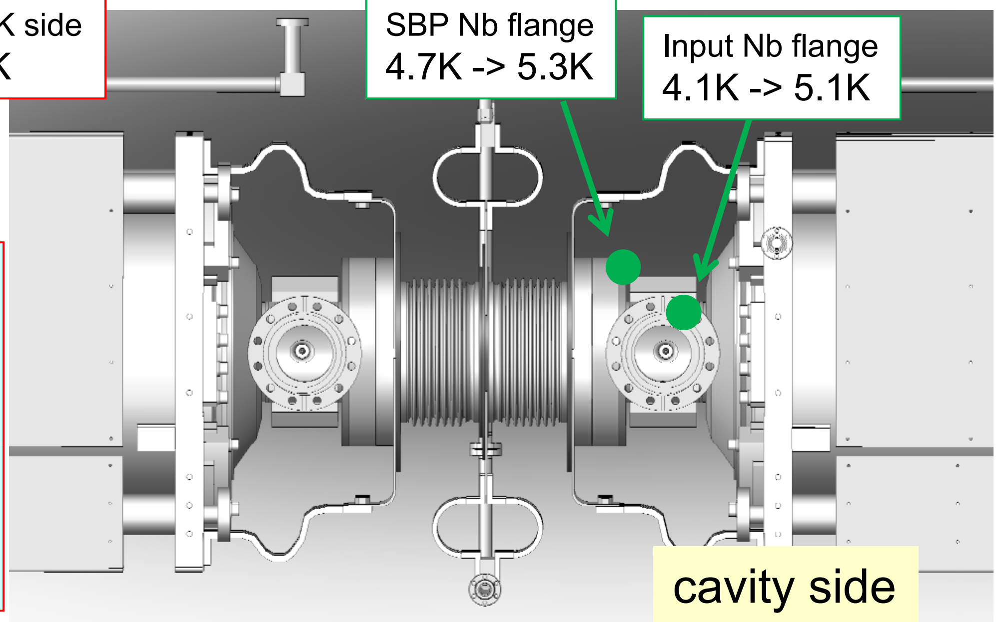
Temperature rises of input coupler under high power test in cryomodule



Plot upper side cavity
- Detune condition
- 15kW CW power
- standing wave

(before nopower
→ after 15kW power)

We note temperature of coupler on resonance with 5kW was less than these measurements results



Results of temperature measurements

- No significant temperature rise was observed. → **works well**
- 80K thermal anchor works well. Temperature of 5K thermal anchor increased. Come from some other heat load to 5K ?
- Bellows of cold part and warm part isolate temperature rise come from higher temperature as expected.
- N2 gas cooling also works well to suppress the temperature rise of inner conductor. ΔT = 38K when cooled by 60l/min flow

Summary

- We fabricated two input couplers for cERL main linac cryomodule, especially to meet CW high power feeding of 20kW standing wave.
- High power test at coupler test stand for cERL
  - 1.3GHz 300kW klystron used for more than 80kW traveling wave (=20kW SW)
  - we reached 105kW(20Hz,200us) under pulse processing.
  - Total pulse processing time is 34 hours.
  - 43kW CW power with traveling wave also feed and can keep for 4hours
  - Fiber arc sensor works effectively for ITL within 10us and see processing.
- cERL cryomodule test
  - QL of both couplers also met the design values of (1-4)*10^7.
  - processing were also applied up to 25kW with 0.2s pulse width within a half day.
  - Thanks to the processing of room temperature again, aging time is much small for cryomodule test of 2K condition (< less then 10min) up to 15kW SW on detune condition.
  - Finally we can keep 14MV with 4.5kW power feeding in high power test of QL=1.5*10^7
  - Michrophonics of Δf=7Hz of pk-pk. This is much smaller than expected.
  - No significant temperature rise was observed under 15kW power feeding.

These input couplers worked well in cERL main linac cryomodule

(Open) Issues for coupler

- How to suppress the heat leak to 2K or lower temperature？
  – Optimum Copper plating (thickness (-10um)) can reduce heat load. It'll be a technical issue to make thin plating.
  – Bellows (with cu plating) can separate the thermal heat load source. But temperature increase if dynamic loss is high.
  – Inner conductor cooling is necessary even if power decreased below 5kW CW power.
- How much will be expected on microphinics？
  – I think 50Hz overestimated for safety. Now Δf=7Hz of pk-pk for our cryomodule. Maybe 20Hz-30Hz is desiable ? But this depend on the cryomodule design.
- Is Cold window needed to prevent the sudden ceramic broken for main linac and to absorb the heat load at 80K ? → I think yes.
- Not only power ITL but also fast sensor (like arc sensor and/or electron sensor) (< a few us) is needed on coupler to beam, when the recovery condition break by sudden trip of coupler.
- Optimum & fast coupler conditioning

backup

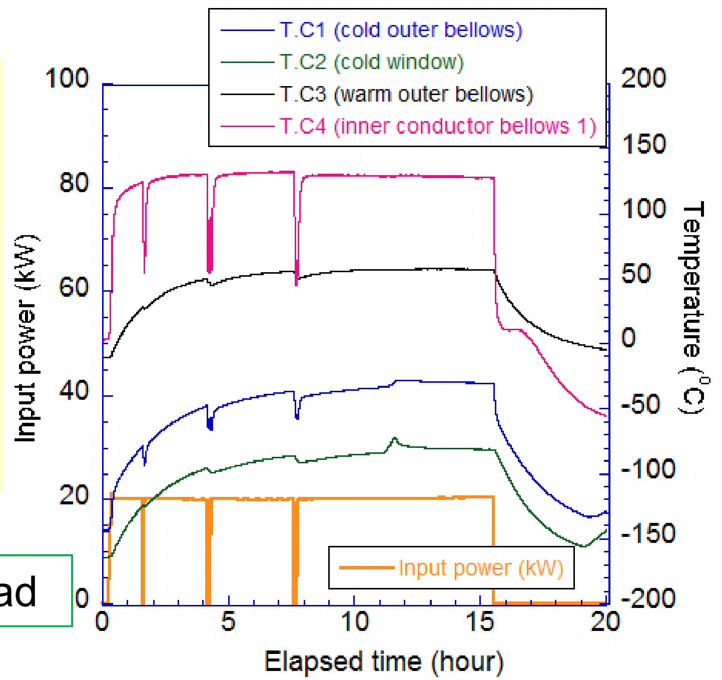
KEK-ERL main linac coupler high power test by prototype coupler (v1) with LN2 cooling

- **High power test of prototype of input coupler under liquid Nitrogen cooling with vacuum insulator**
  Add pulse processing for 8hours, (easy to process)
  Finally achieve 25kW power feeding with standing wave.

  Can keep 20kW power for 16hours with standing wave.
  Temperature of inner conductor is 120 °C.
  Temperature rise of cold bellows is 100K

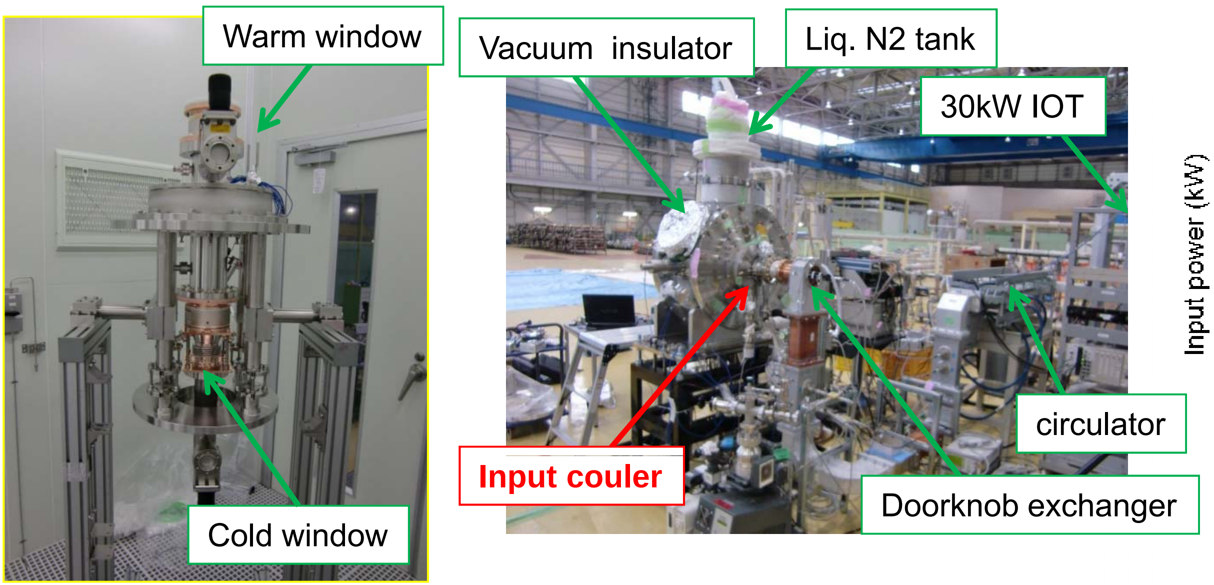
works well especially on the view point of the RF and heat load

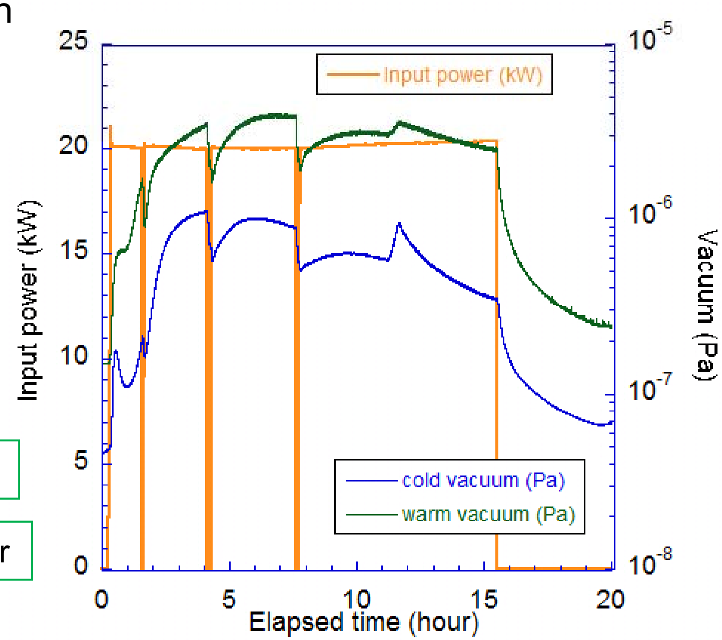
Results of keeping 20kW



Prototype of input coupler

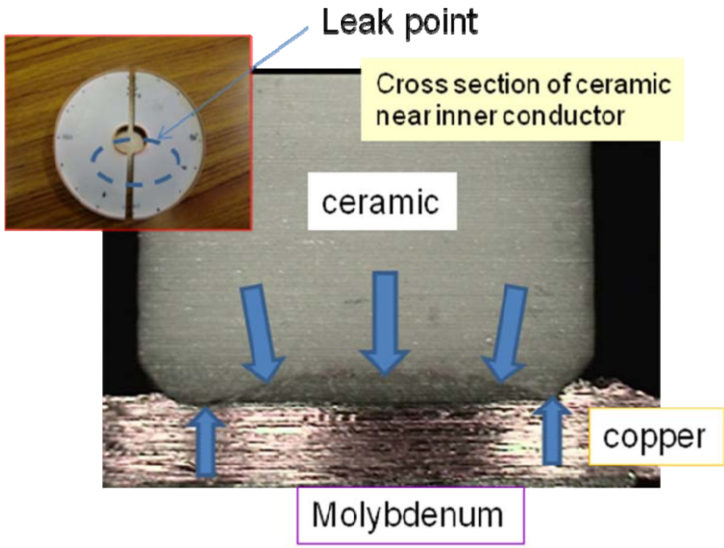
High power test setup with liquid Nitrogen





Sudden power down is mainly caused by noise of arc

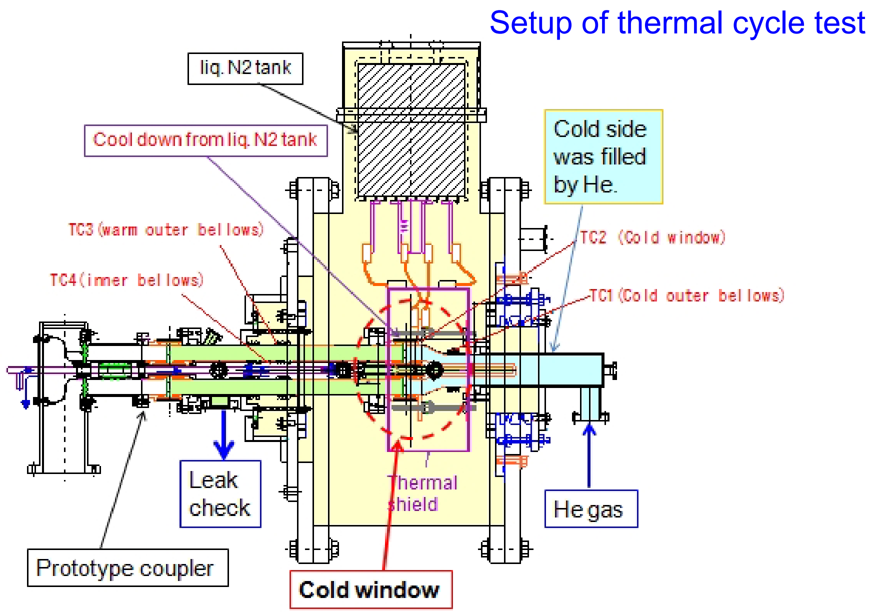
Thermal cycle tests of cold window of prototype coupler (v1)

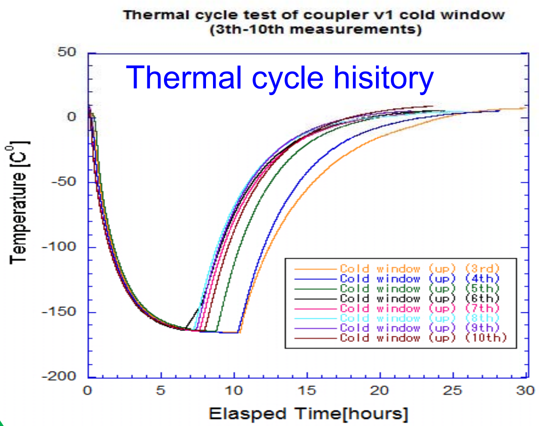


After 5th thrmal cycle test between 80K and 300K, old ceramic was broken

Changing point	Old Cold window	New Cold window (coupler v1)
Ceramic thickness	6.2mm	5.4mm
Cu thickness of inner conductor	1mm	0.8mm
Mo thickness	100%	200%
Max stress	100%	76%

Modify brazing condition to prototype cold window



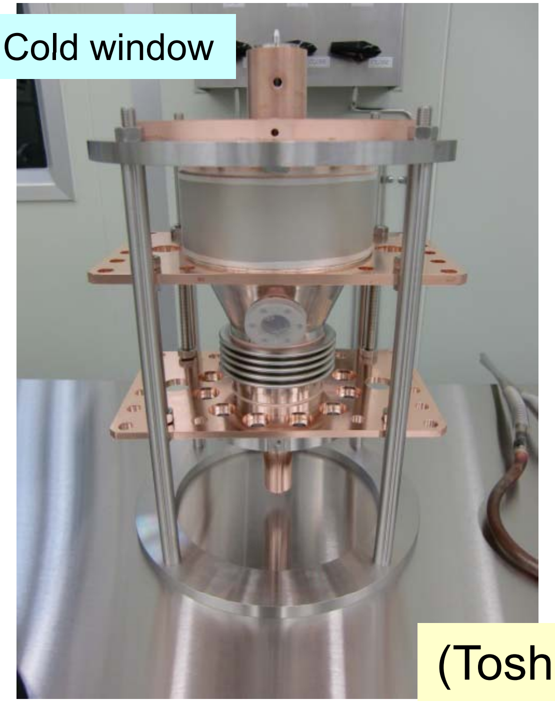


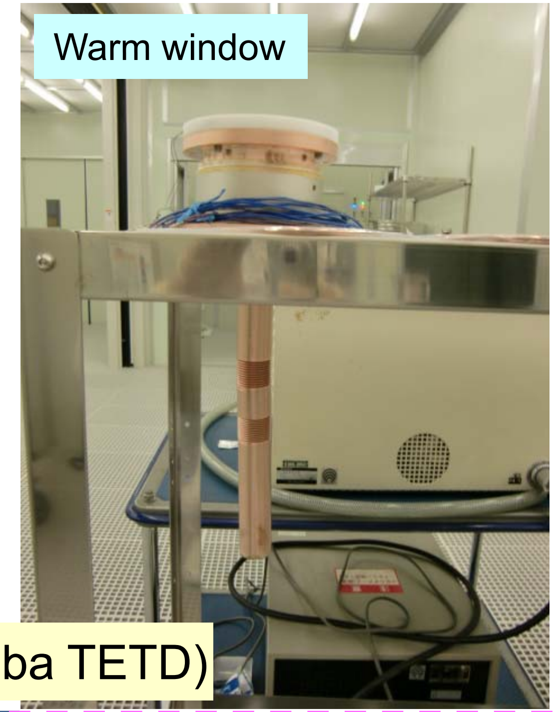
We applied the thermal cycle test by using LN2 cooling high power test stand as shown above. After 10 thermal cycle, no leak and crack was observed.

10 thermal cycle test is OK.
→ decide to fabricate two input coupler for cERL cryomodule

H.Sakai or M.Sato et al, Proc. of 15-th SRF, Chicago (2011)

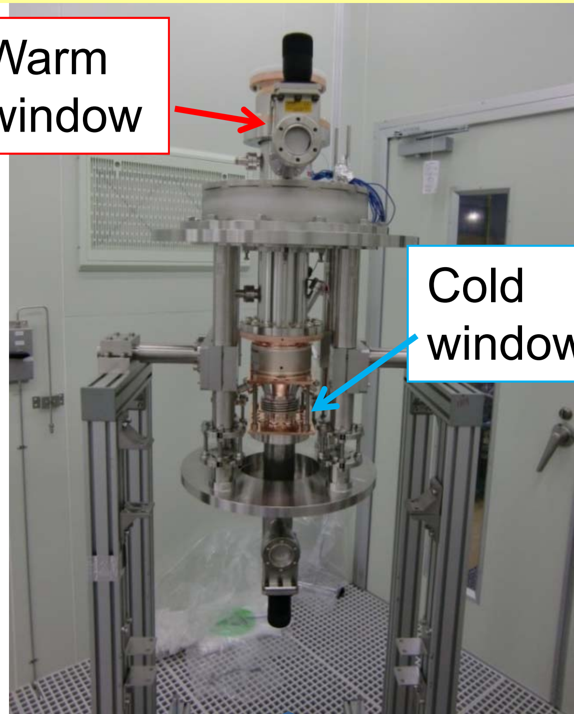
Prototype of input coupler (v1) & assembly in clean room for high power test



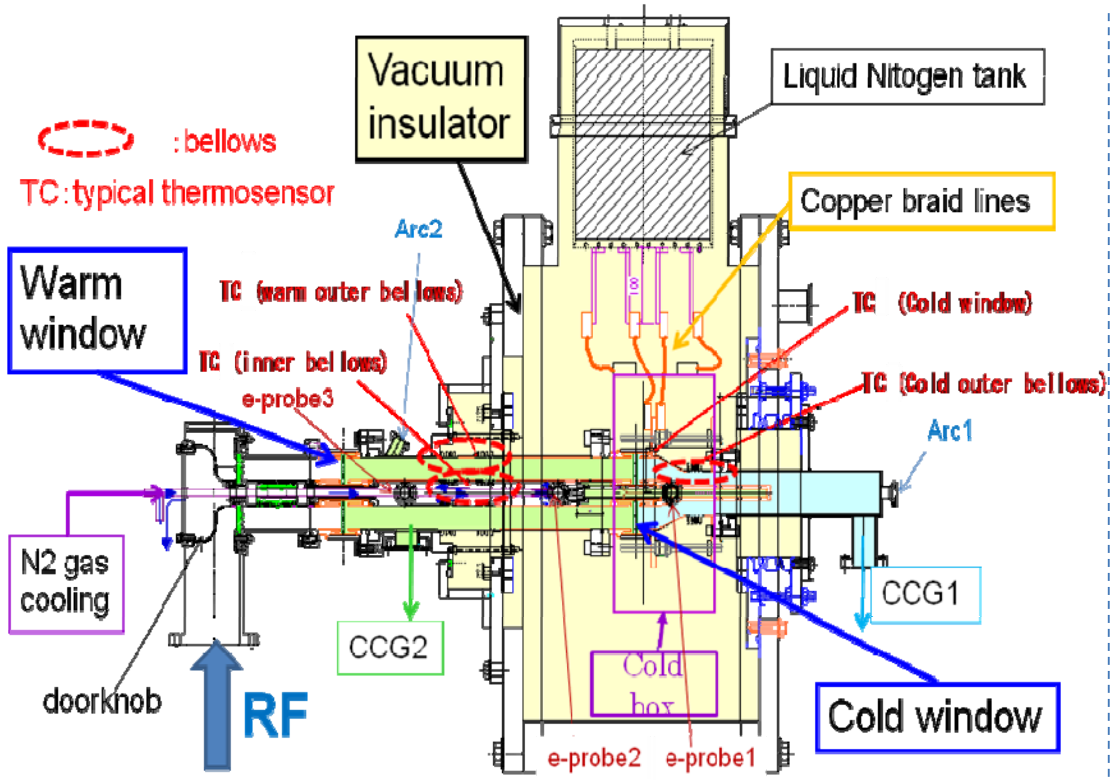


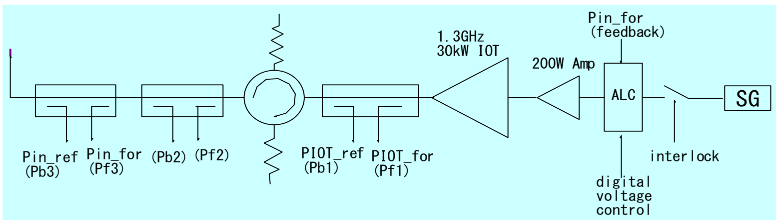
(Toshiba TETD)

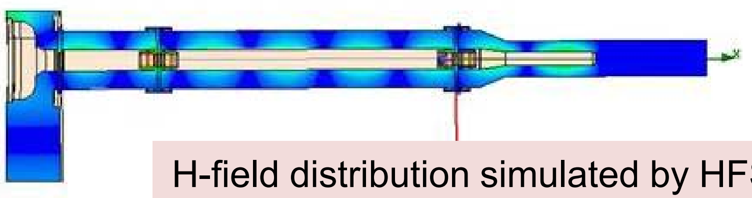
Prototype of input coupler



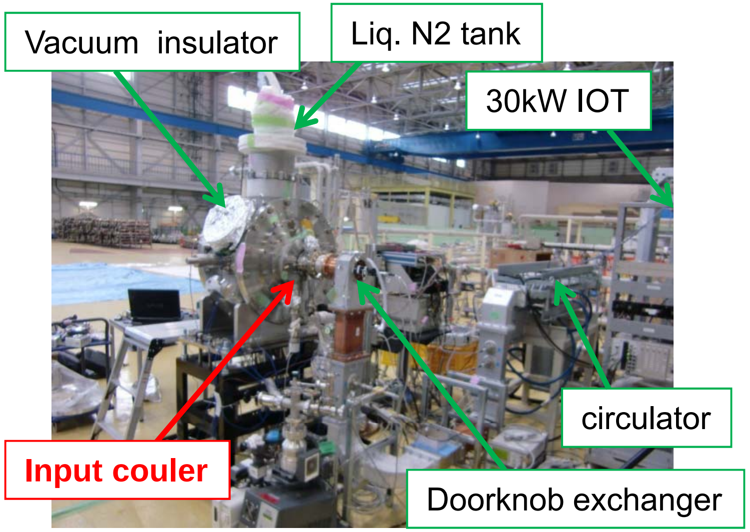
KEK-ERL main linac coupler high power test with liquid Nitrogen





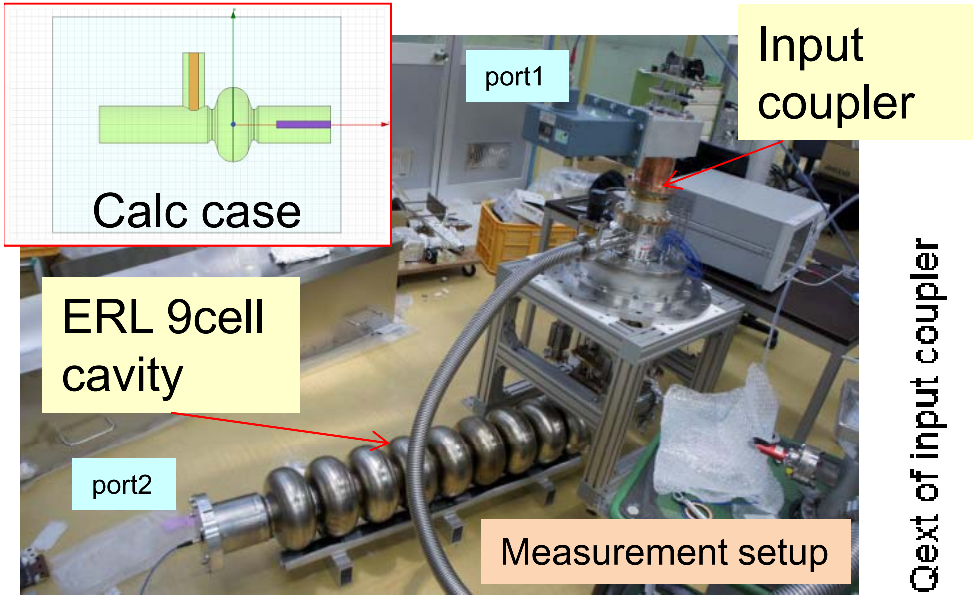


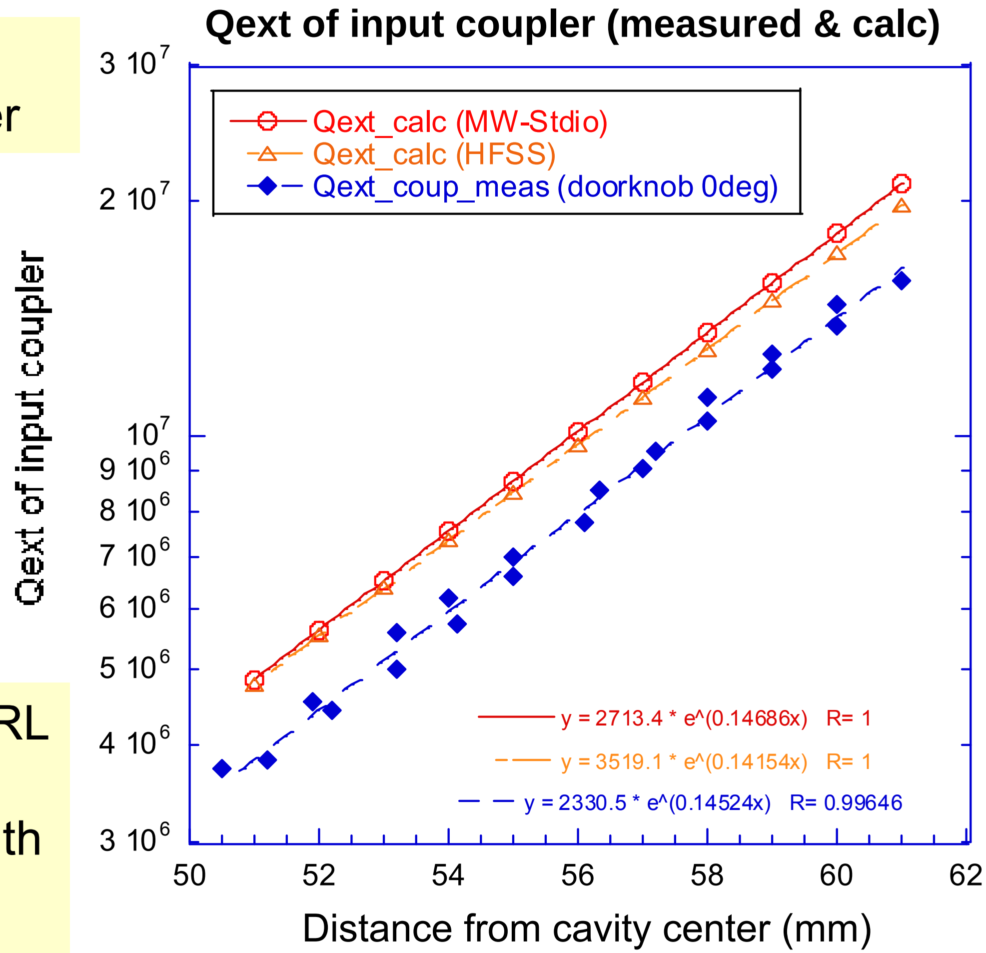
H-field distribution simulated by HFSS



- **High power test of prototype of input coupler under liquid Nitrogen cooling with vacuum insulator to know the real temperature rises under vacuum insulation as same as the cryomodule by feeding the high power .**
- To simulate the same standing wave condition of cryomodule, Bellows and ceramic windows were set not to stand the peak field in high power test.

Coupling measurements





・Connecting the input coupler to 9cell ERL cavity, we measure the coupling directly.
・Slope of Qext change with coupler length agree well with calculation with +-5mm.
・However, the measured value of Qext with doorknob exchanger is 1.3 times higher than calculation

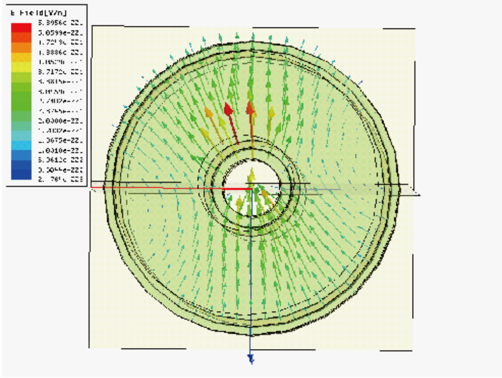
⇓

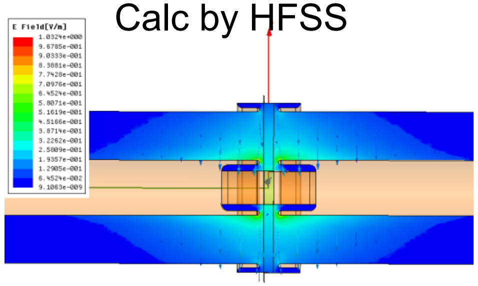
Change the length of 2mm short for cryomodule from measurement results.

Qext coupler	5.0*10^6	2.0*10^7
Meas 0deg (doorknob)	52.83mm	62.38mm
Calc (MW-Stdio)	51.20mm	60.64mm
Calc (HFSS)	51.09mm	60.88mm

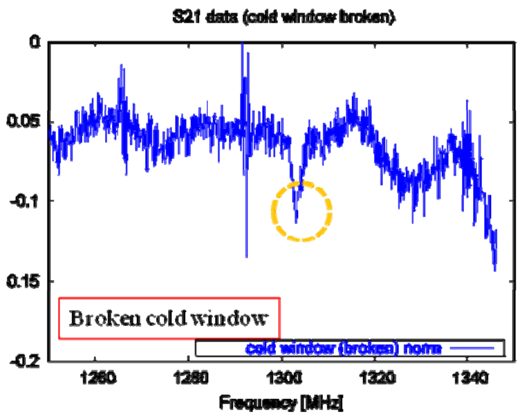
Cautions and learn from previous ceramic window test for ERL about disk ceramic with choke

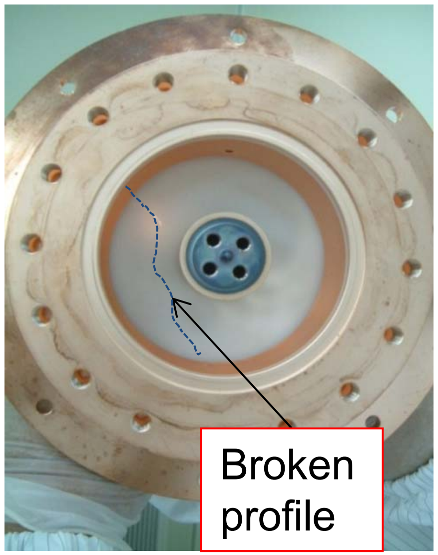
When modify the impedance or diameter from original





TE mode stands inside



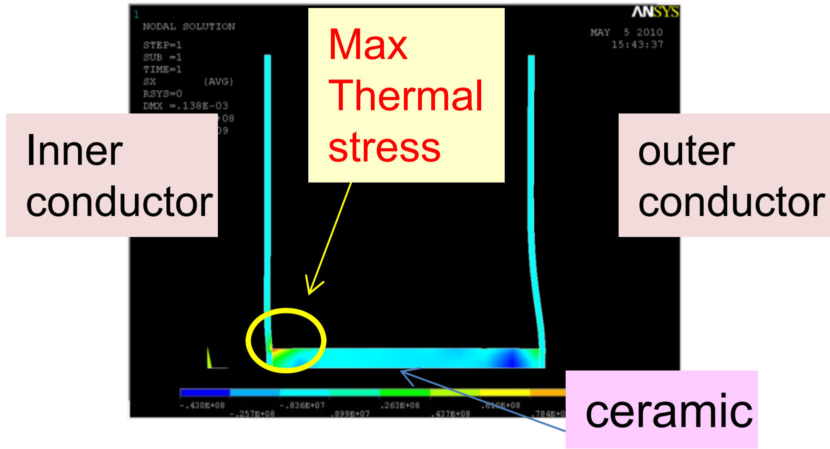


By changing the thickness of window, peak was shifted.

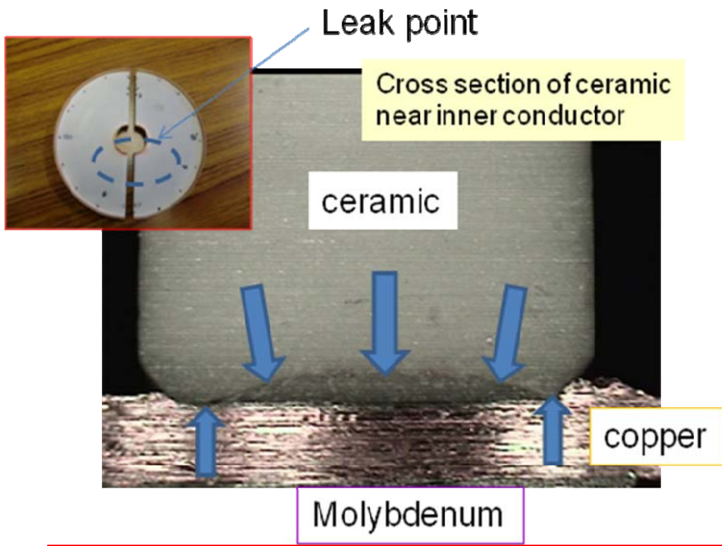
Please calculate not only S-parameter but also eigenmode of disk ceramic itself.

H.Sakai et al., Proc. of 14-th SRF Workshop, Berlin, p684-688, (2009)
K.Umemori et al., Proc. of IPAC10, Kyoto , p2959-2961, (2010)

Caution for using to cold window



After 5th thrmal cycle test between 80K and 300K, old ceramic was broken



modify the blazing conditions → 10 thermal cycle is OK now.

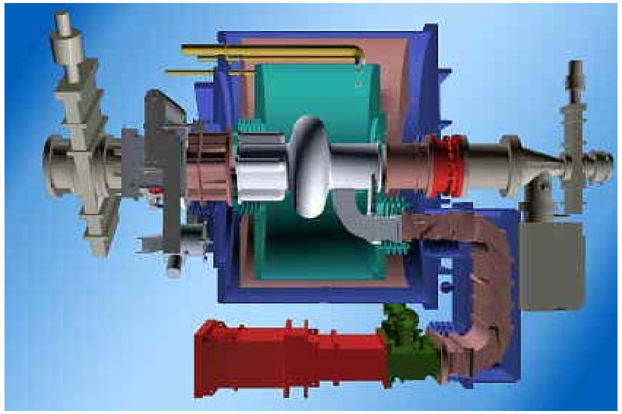
H.Sakai or M.Sato et al, Proc. of 15-th SRF, Chicago (2011)

Coupler choices for ERL

Waveguide

- Lower surface electric field
- higher thermal radiation
- No easy tuning

CESR waveguide
- >250kW
- 500 MHz
- WG Bend shields cold window from beam.



JLAB (CEBAF, JLAB-FEL)

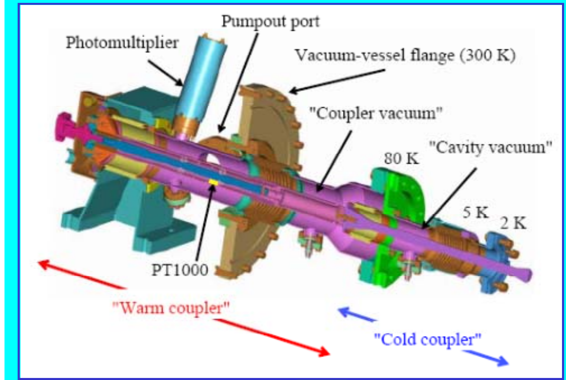
Coaxial

- Smaller heat leak
- Easier to make variable
- Easier to handle multipacting

●Cylinder ceramic (TTF type)

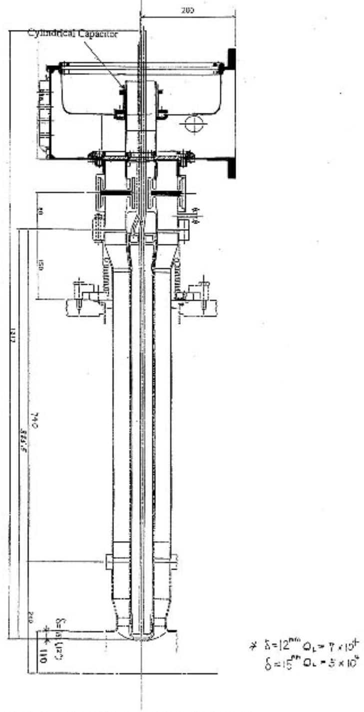
TTF-III
- 1.3GHz
- 2 Windows
- Adjustable Qext

KEKB coupler
- >400kW(operation)
- 509MHz
- Disk ceramic with choke



Cornell, Daresbury,HZB

●Disk ceramic (TRISTAN type)



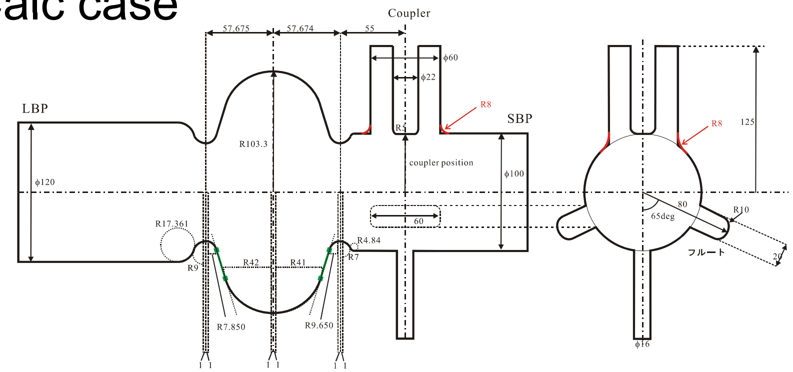
KEK, BNL (SNS), HZB

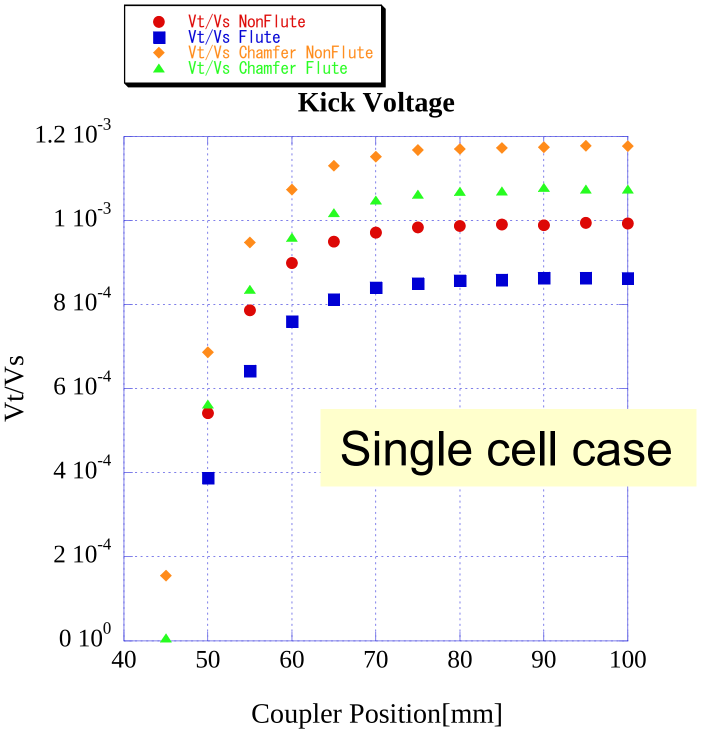
This coaxial disk ceramic window is reliably operated at KEKB applying up to CW 400kW with 1A beam current and STF with high peak power more than 1MW. at 1.3GHz. This is our choice.

Coupler kick & cancelation

By T. Muto

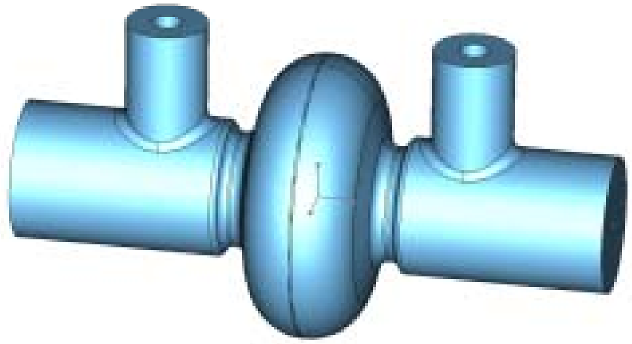
Calc case

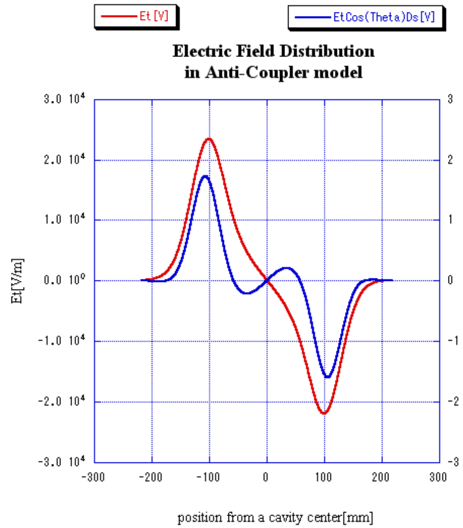


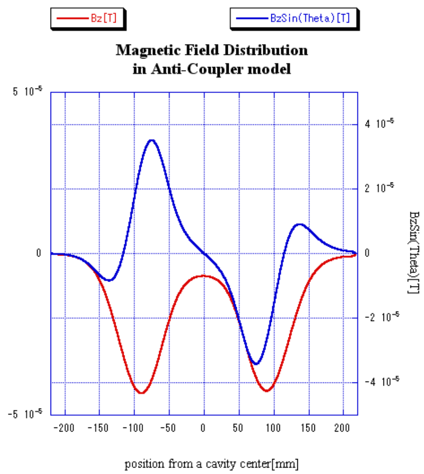


Single cell case

9cell case : Vt/Vs ~ 1*10^-4







E-field

Blue: beam

H-field

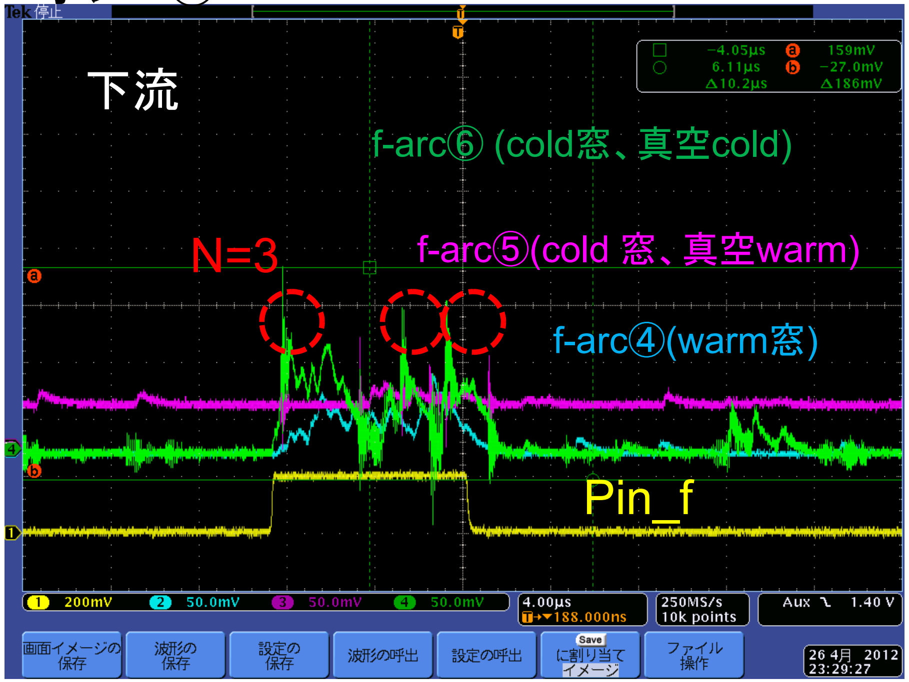
Blue: beam

Coupler kick will canceled with setting symmetry with optimum length

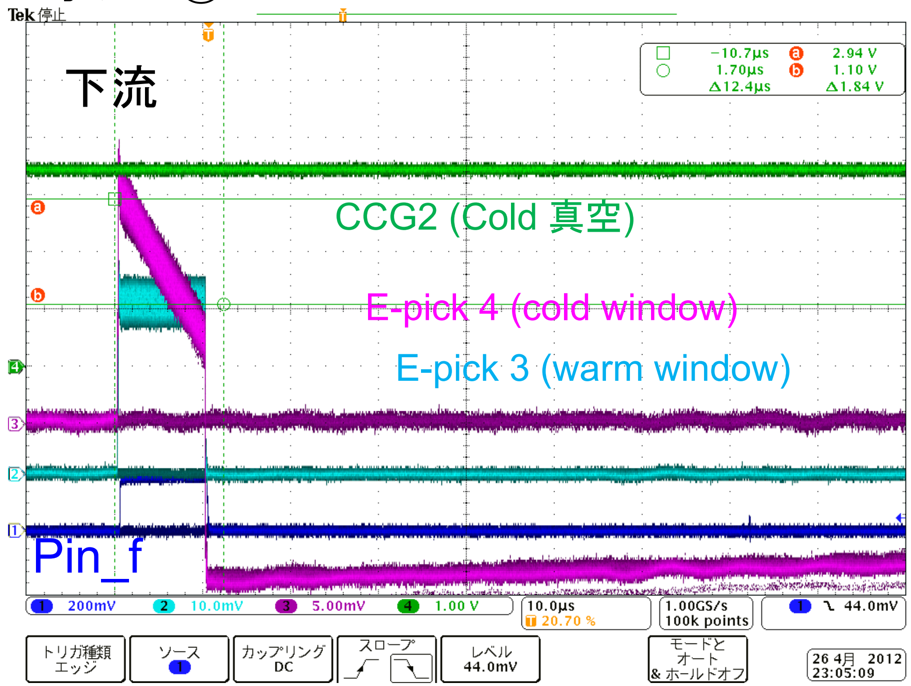
Typical data of fiber arc and e-pick after interlock (2012/4/26)

Pin_f = 23kW

オシロ③’



オシロ⑤



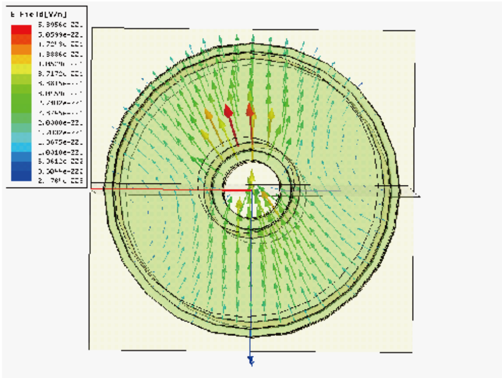
F-arc ⑤、⑥が反応、そのさいに⑤と関係するe-pick 4も信号が大きくなる。
もちろん、これに応じて真空も前々ページのように増大。（warm,Cold両方とも）

Fiberでarc interlockがかかった時は1us以下でpowerは落ちる。
ちなみにMPS moduleのこの時の設定は0.24usのdelay

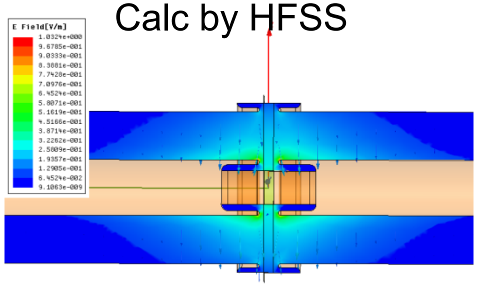
⇒ Interlockとしては十分

Cautions about disk ceramic with choke (about TRISTAN type coupler)

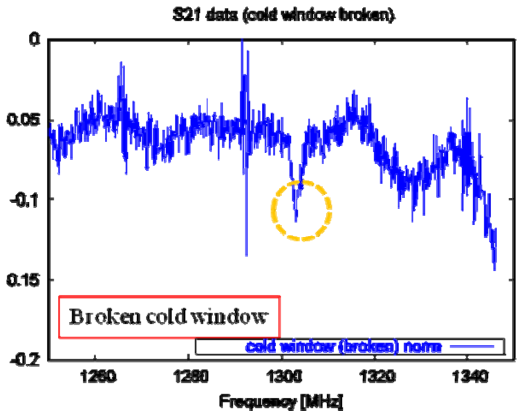
When modify the impedance or diameter from original

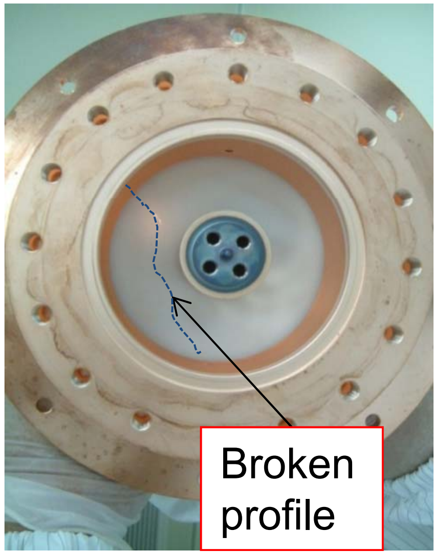


Calc by HFSS



TE mode stands inside

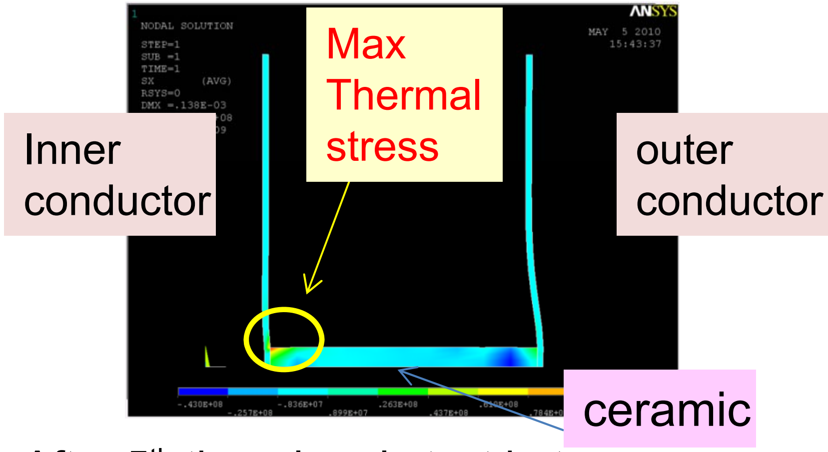




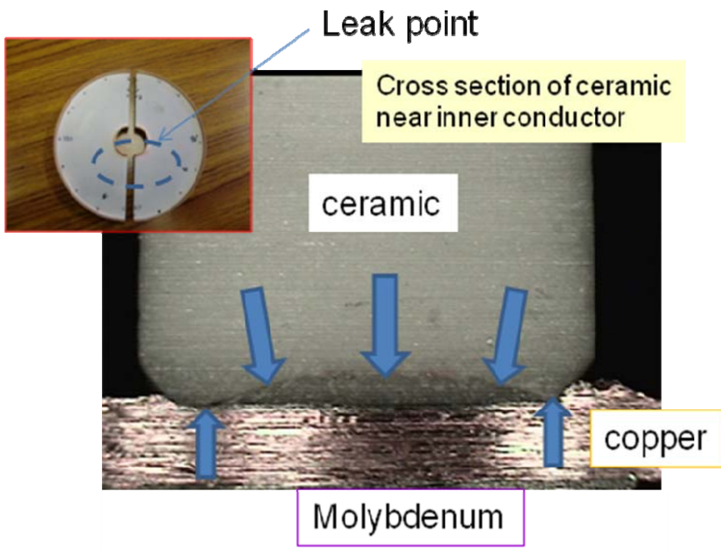
By changing the thickness of window, peak was shifted.

Please calculate not only S-parameter but also eigenmode of disk ceramic itself.

By using for cold window



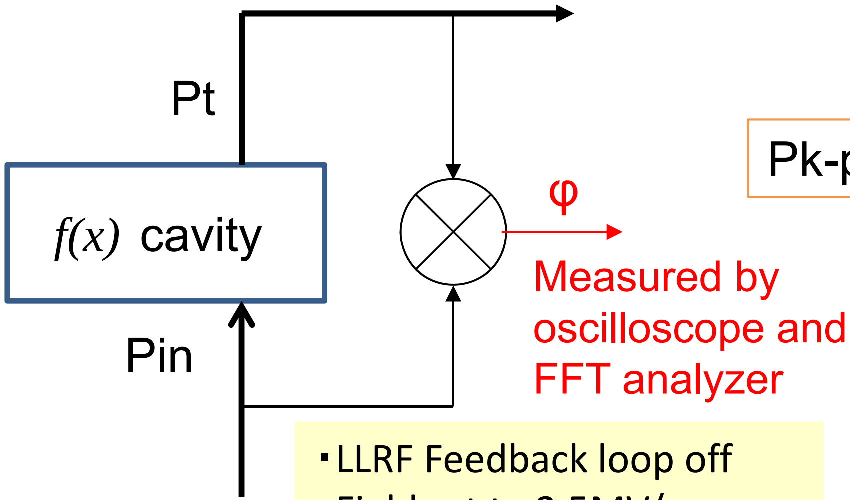
After 5th thrmal cycle test between 80K and 300K, ceramic was broken

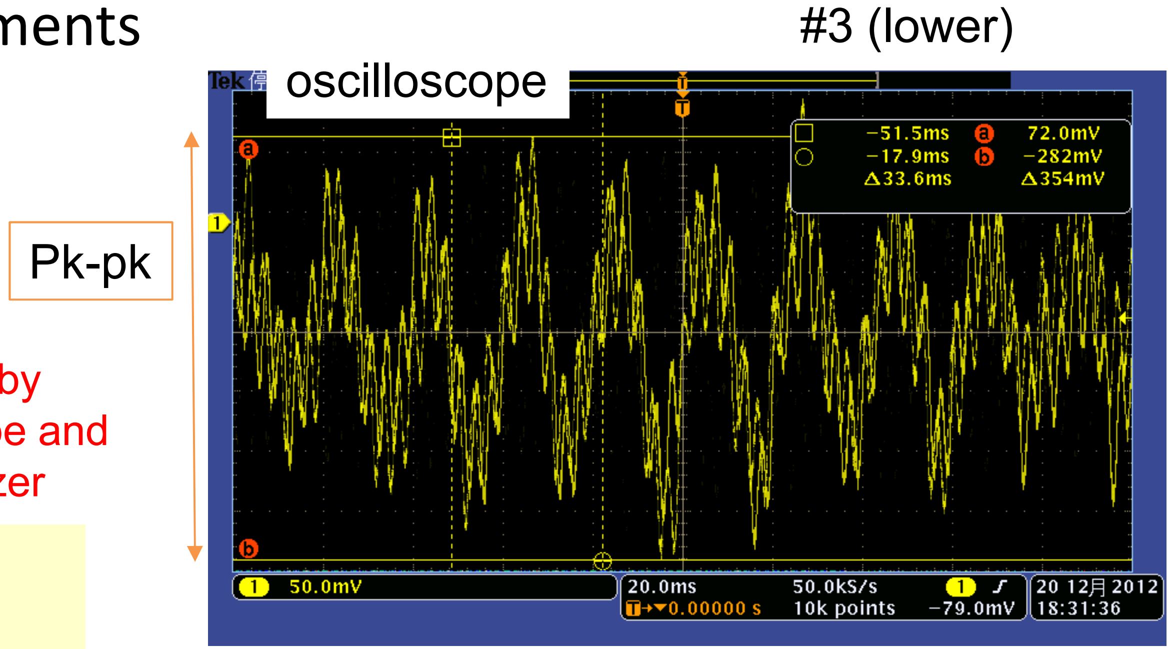


modify the blazing of conditions

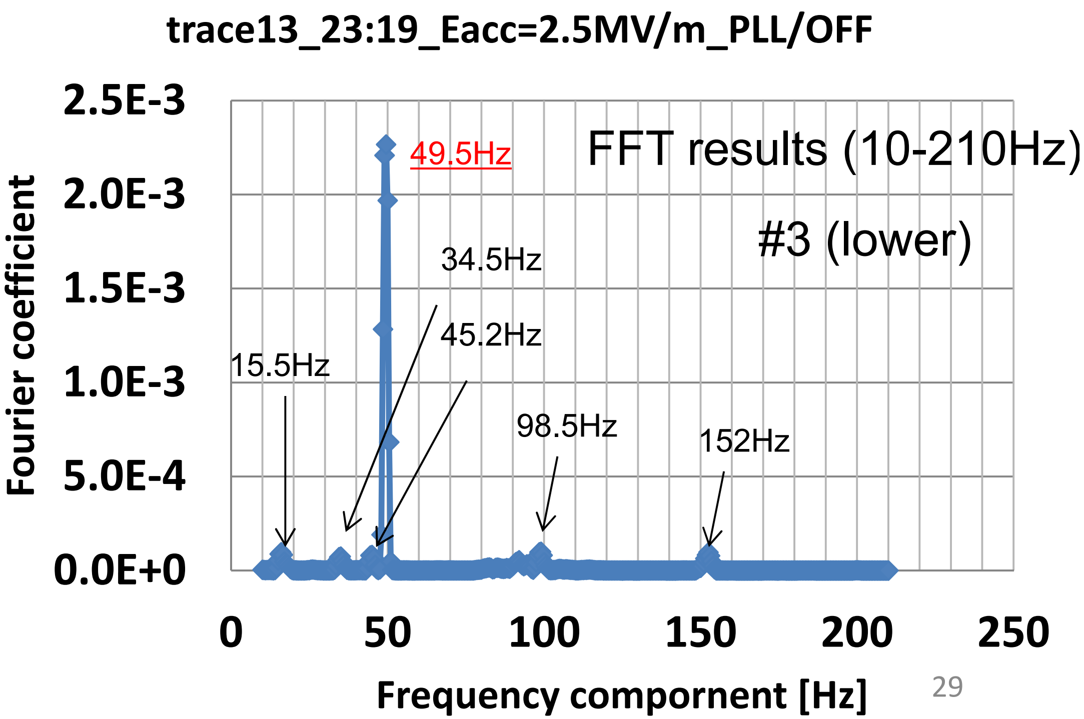
→ 10 thermal cycle is OK now.

2K microphonics measurements





- LLRF Feedback loop off
- Field set to 2.5MV/m
- Measured by #3 cavity



- Pk-pk = 7Hz by oscilloscope. It allow us to increase the QL higher than several *10^7 → lower power
- Main peak was observed at 49.5Hz (not 50Hz of electrical noise) by FFT analyzer ,which was not come from cavity resonance frequency.
- It might come from backbone and/or 5K flame resonance frequency??

We need to continue measuring michrophinics on next cERL operation