清華大學
Tsinghua University

Development of Normal-Conducting High-Gradient Accelerating Structures

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2018/9/18

on behalf of the team and collaboration

the 29th Linear Accelerator Conference, LINAC2018, Beijing, China

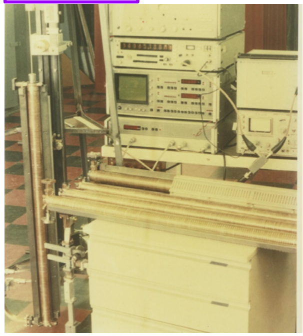
Outline

- Introduction
- Development and test of Traveling-Wave Prototype at Tsinghua
- Design and fabrication of Choke-mode structures
- High-gradient performance of Choke-mode structures
- Summary

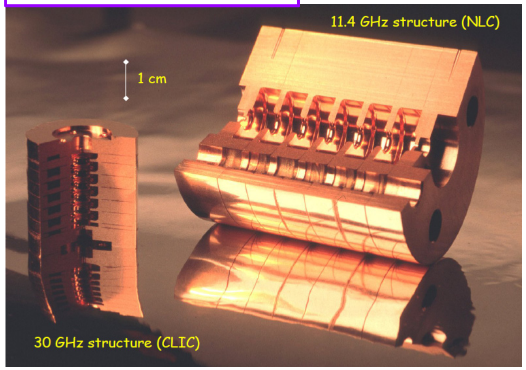
X-band high-gradient accelerating technology

- Dates back to the VLEPP project in 1970s
- Shape optimization
  - lower group velocity, optimize surface field
- Fabrication technology
  - halves structure, quadrant structure, precise machining and alignment
- 100 MV/m accelerating gradient

VLEPP

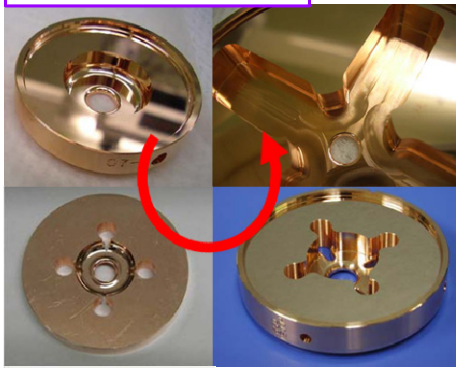


Compact structure



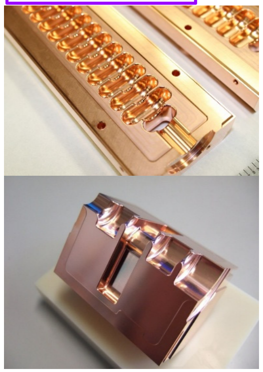
T. Higo, Proceedings of LINAC2010

Shape optimization



V. Dolgashev, Proceedings of CLIC workshop2017

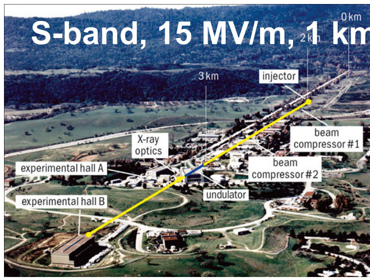
Fabrication



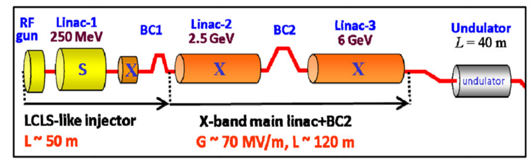
T. Abe, Proceedings of PASJ2017

High-gradient accelerator application (1/2)

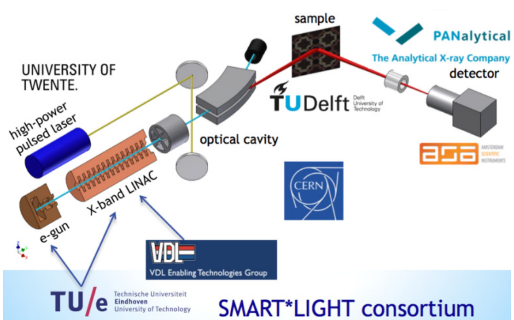
- Compact XFEL

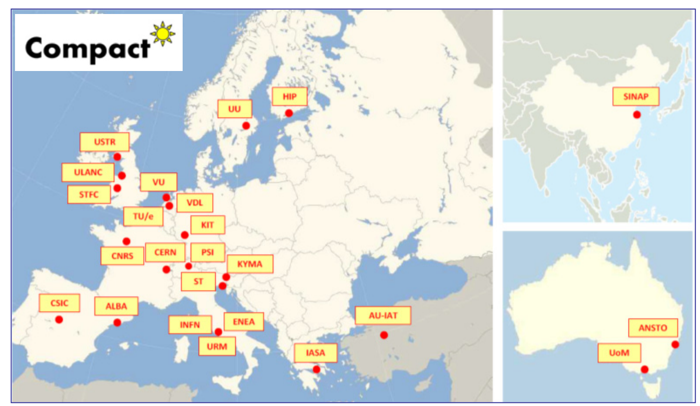


X-band, 70 MV/m, ~100 m



- Small light source, industrial and medical accelerators
  - Compact Light
  - X-band Thomson Scattering Source



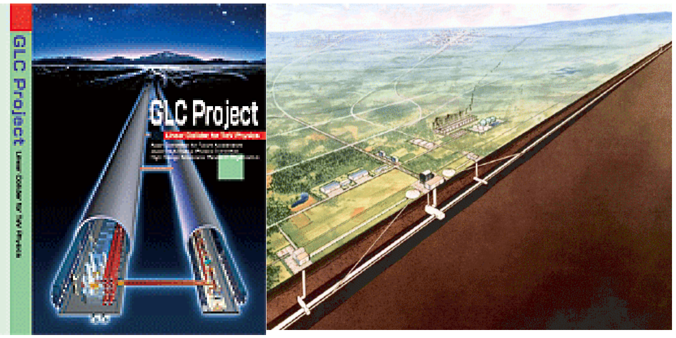


C. Adolphsen et al., Proceedings of LINAC2010
W. Fang et al., Proceedings of LINAC2014
U. Amaldi et al., NIMA 620, 563, 2010
H. Tanaka et al., Nat. Photon 6, 540, 2011
M.J. Boland et al., Proceedings of IPAC2014
J. Shi, Proceedings of HG2017
G. D'Auria, Proceedings of HG2017

High-gradient accelerator application (2/2)

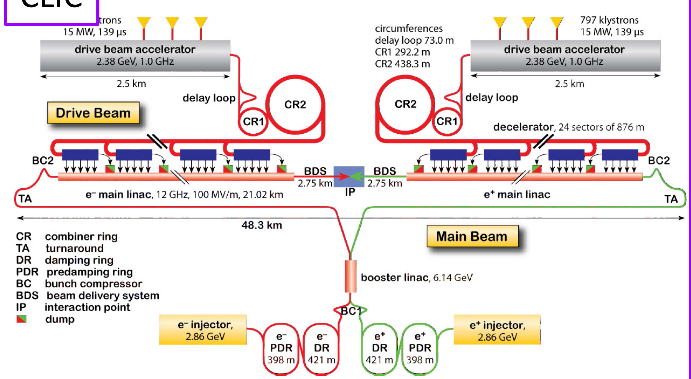
- Linear colliders based on X-band technology

GLC



NLC

CLIC



Project	VLEPP	NLC	GLC	CLIC
Main institute	BINP	SLAC	KEK	CERN
Frequency [GHz]	6 / 14	11.4	11.4	30 / 12
Gradient [MV/m]	100	50	50	150 / 100
Power source	Kly	Kly	Kly	Two-beam
Structure length [m]	1	1.8 / 0.6	1.3 / 0.6	0.2~0.3

T. Higo, Proceedings of LINAC2010
A. Faus-Golfe, Proceedings of HG2017

CLIC-study at CERN, X-band high-gradient activity worldwide

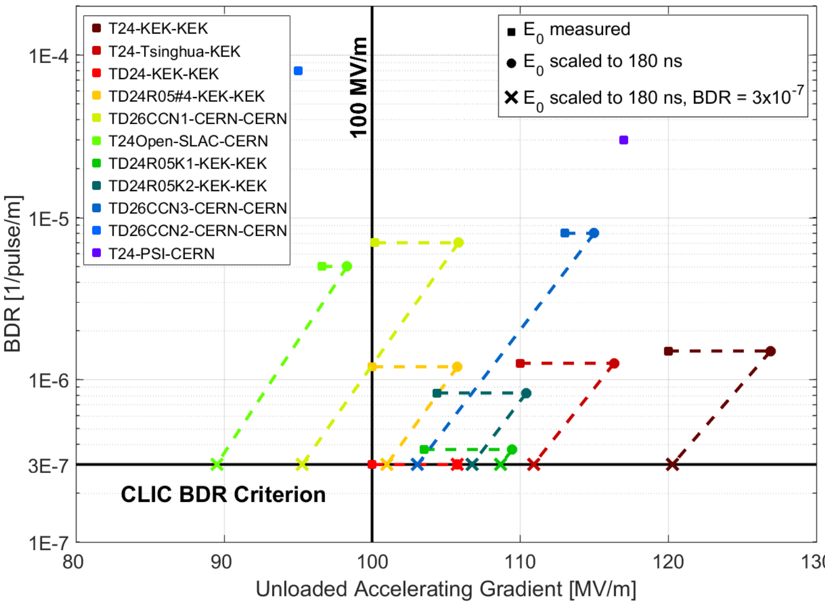
- **Structure flow**
- **→ Design**

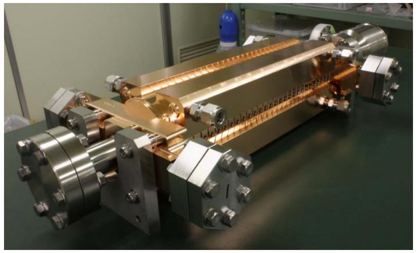
→ Fabrication (machining, brazing, tuning…)

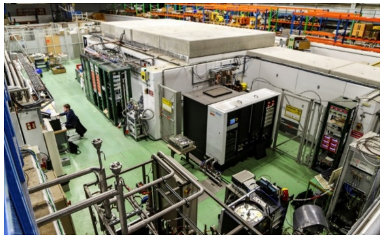
→ High power test (at different stations)

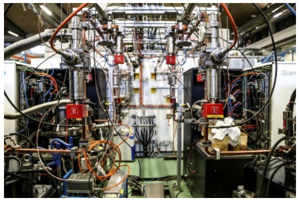
→ Analysis

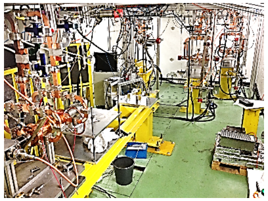
- **Achieved 100 MV/m gradient**











[1] Philip Burrows, CLIC workshop 2018

Tsinghua Activity, and Collaborators from KEK

- Tsinghua University
  - Join CLIC-study collaboration in 2009
  - To develop high-gradient X-band structures at Tsinghua, with choke-mode damping
  - Jiaru Shi, Hao Zha, Xiaowei Wu, Ping Wang, Maomao Peng, Huaibi Chen, et al.

- KEK collabration
  - Linac shift leaders and Mitsubishi operators
  - Karube, Kawabata, Asai from CarrierCom
  - Matsui, et al from PlusWork
  - Tetsuo Abe, Toshikazu Takatomi, Shuji Matsumoto, Yoshio Arakida, Toshiyasu Higo

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- Introduction
- Development and test of Traveling-Wave Prototype at Tsinghua
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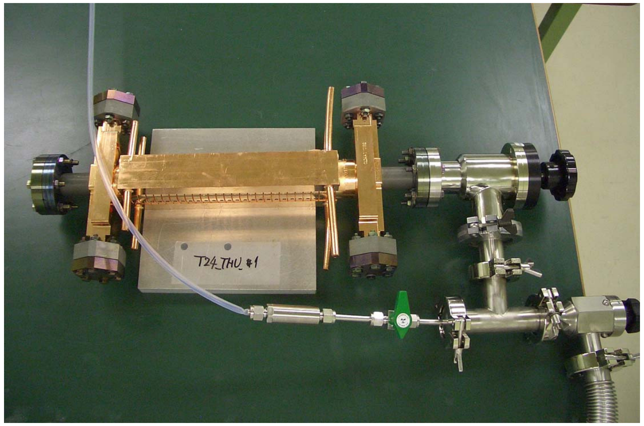
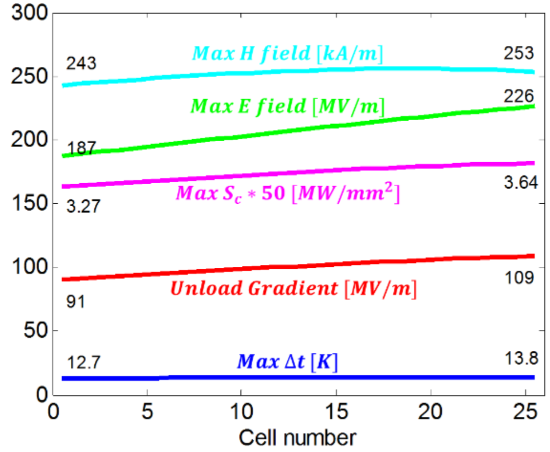
Traveling-wave structure prototype: T24_THU_#1

- Traveling-wave structure made by Tsinghua: T24_THU_#1
  - X-band high-gradient accelerating structure
  - constant gradient 24 cell
  - CLIC-G RF design
- Frequency: 11.424 GHz
- Unloaded gradient: 100 MV/m @ input power of 42.4 MW

T24_THU_#1

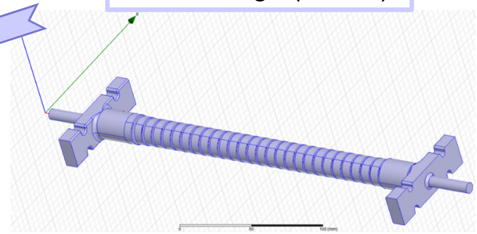


RF parameters@ 100 MV/m



Fabrication and test flow of T24_THU_#1

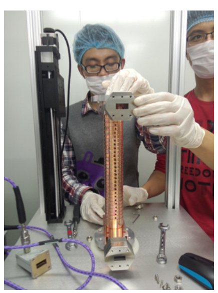
CLIC design (CERN)

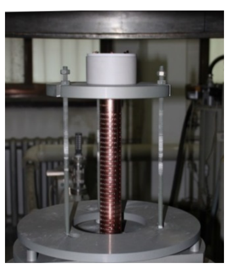


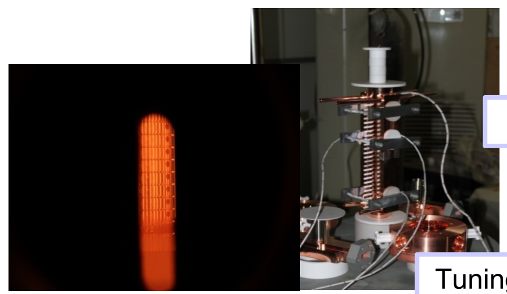
Disk fabrication (VDL)

Cleaning & etching (Tsinghua Univ.)

RF measurement (Tsinghua Univ.)

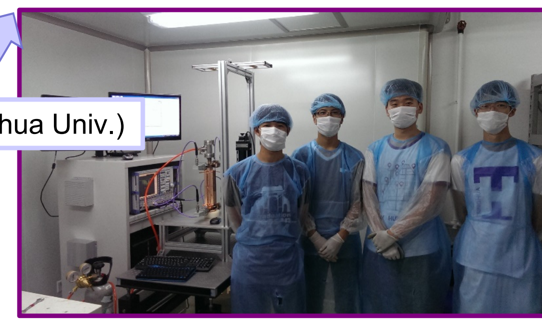






Diffusion bonding & brazing (Tsinghua Univ.)

Tuning (Tsinghua Univ.)

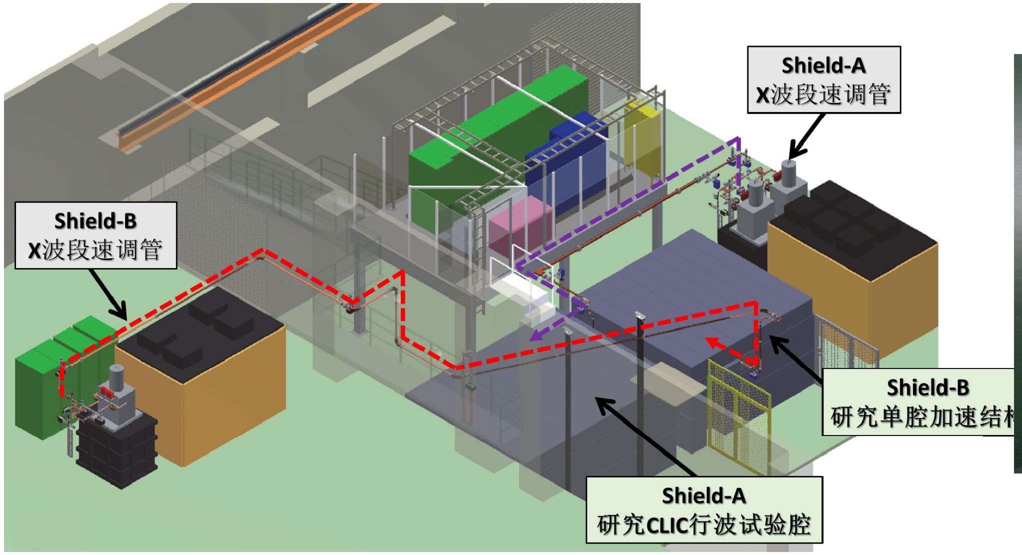


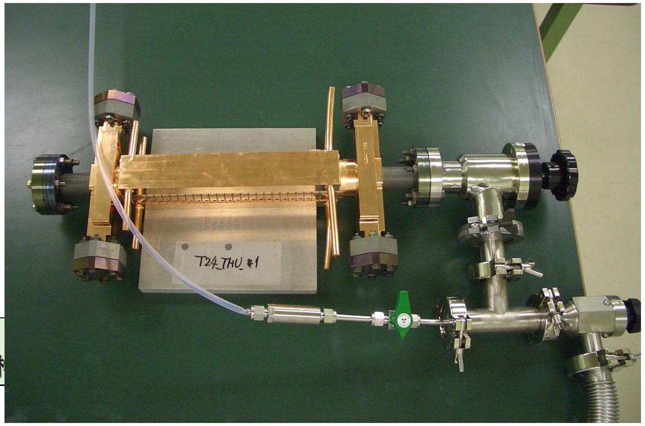
Baking (Tsinghua Univ.)

High-gradient test (Nextef-KEK)

High-gradient test stand

- High-gradient test was conducted in Nextef at KEK (New X-band Test Facility)
- Frequency: 11.424 GHz
- Repetition rate: 50 Hz
- Shield-A, traveling-wave structure test stand, max power of 100 MW
- Shield-B, standing-wave structure test stand, max power of 33 MW

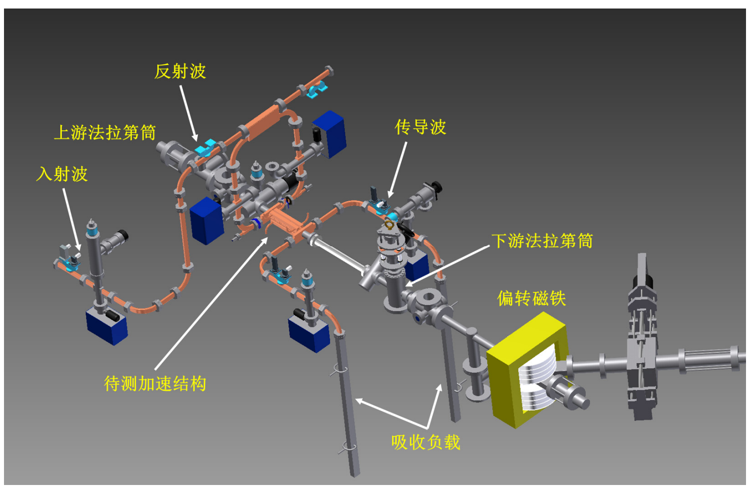




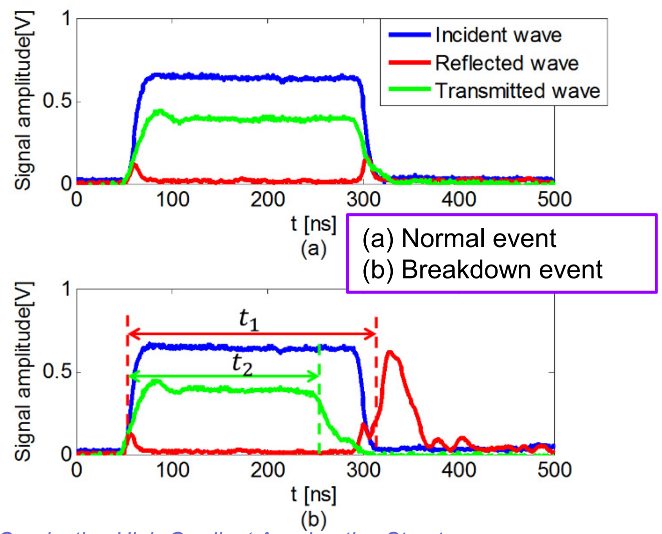
Shield-A setup & signal acquisition

- High-gradient test of traveling-wave structure was conducted in Shield-A of Nextef
- Incident, reflected and transmitted signals were collected by directional couplers
- Field emission current measured by upstream and downstream faraday cups
- Microwave and current signals were used for breakdown detection

Shield-A setup

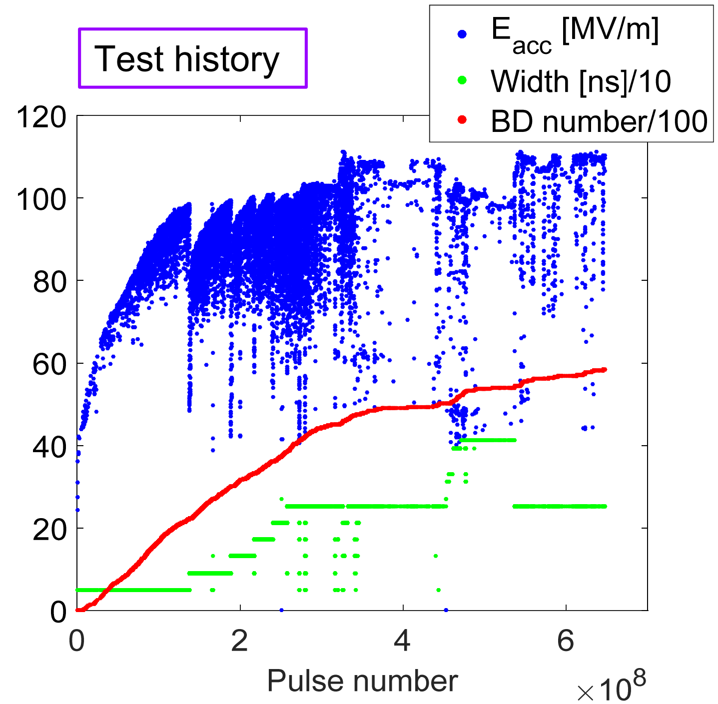


Signals

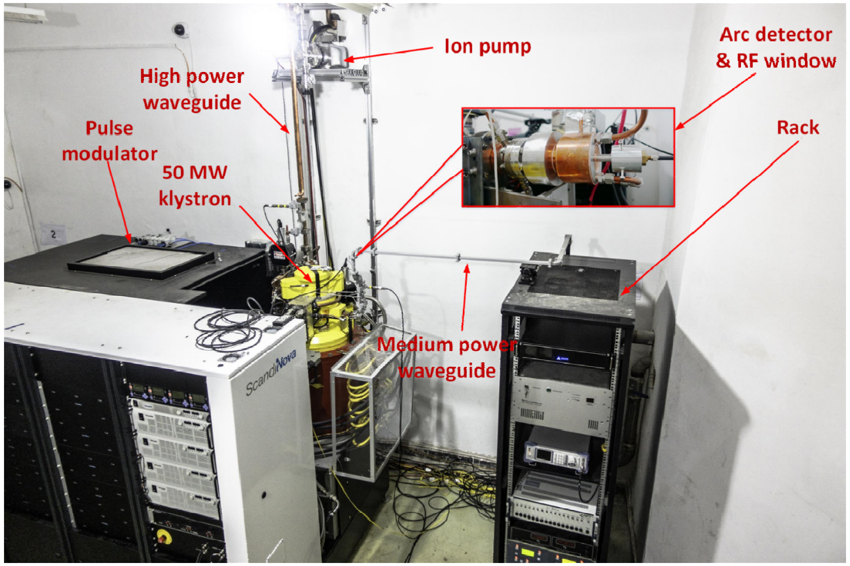


High-gradient test result (1/3)

- Increase power and pulse width during the test
  - stop next pulse when breakdown occurs and reduce the power
  - input the power after several tens of seconds
- 3,600 h RF-on time
  - 6.47×10^8 RF pulses
- Good high-gradient performance was observed
  - reached 110.2 MV/m @ 1.26×10^{-6} bpp, 252 ns
- Validated Tsinghua X-band high-gradient technology

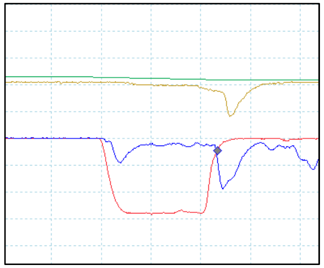


Tsinghua X-band high-power Test Stand (THUNIX)



CPI VKX-8311 Klystron
ScandiNova Modulator

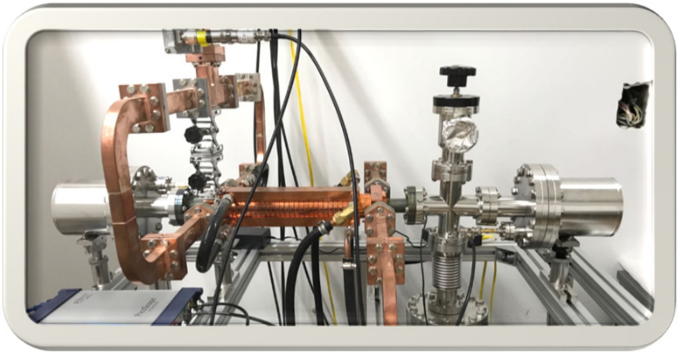
>50MW @11.424GHz
40Hz rep. rate
1.5 μs flattop

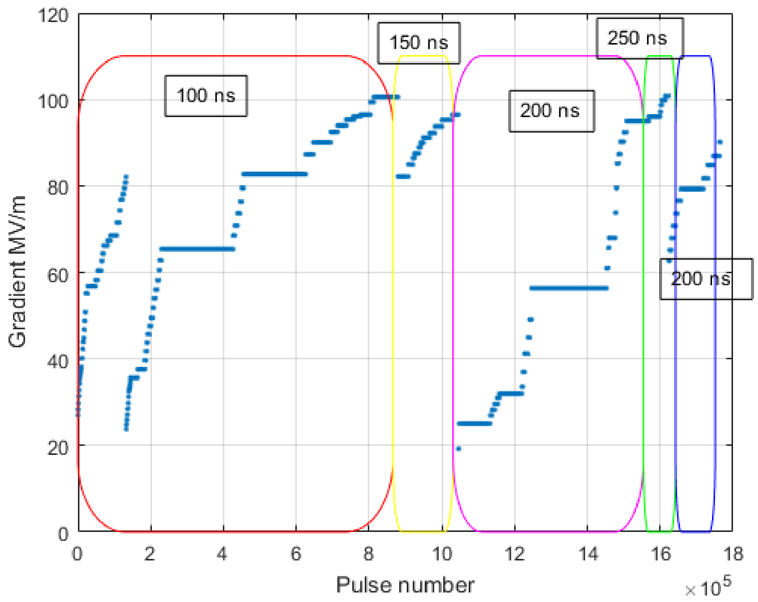


Home made
RF components

T24_THU#1 Reload

- Back from KEK in 2017.
  - Vacuum sealed
- Installed in June 2018 (1 week, open air)
- ~40 Hours Run in September
  - Most 10Hz, later 40Hz
- Reaches 100MV/m 200ns after 40 hours!





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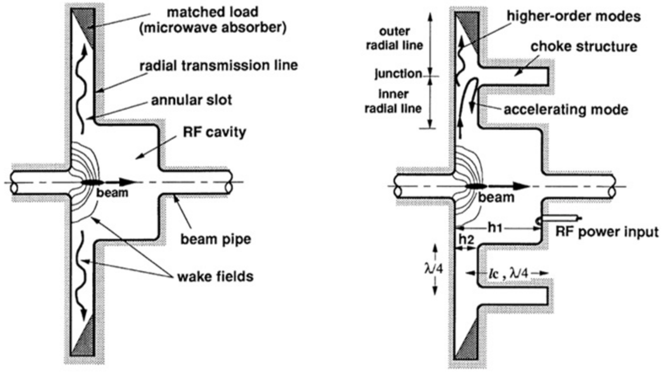
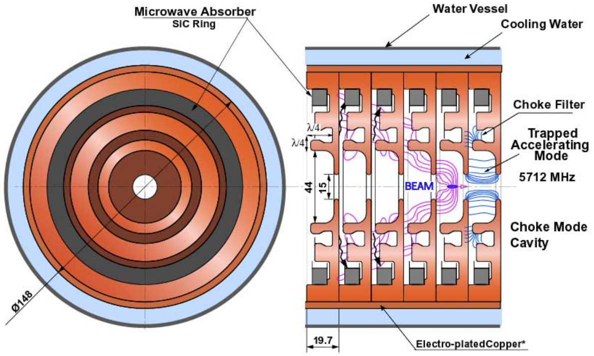
Choke-mode structure

- Proposed by T. Shintake in 1992
  - HOM absorbed in the end of the radial line
  - λ/4 choke reflects the fundamental mode
- Applied in Spring-8 and SACLA XFEL
  - working at C-band (5.712 GHz)
  - gradient around 35-40 MV/m
- Alternative choice for CLIC main linac

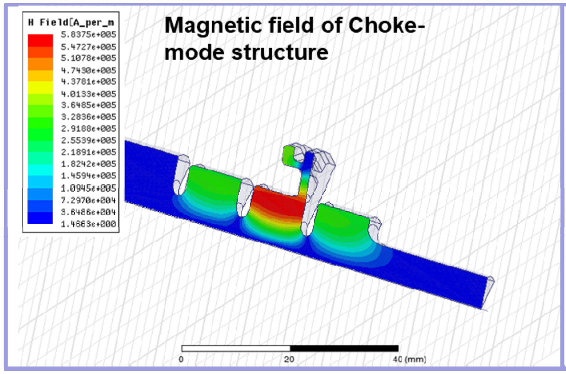


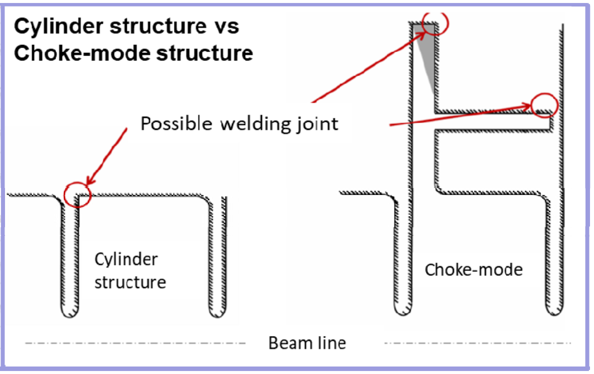


T. Shintake, Japanese J.Appl.Phys.31:L1567-L1570 (1992)
R. M. Jones, Phys. Rev. ST Accel. Beams 12, 104801, 2009.
http://www-xfel.spring8.or.jp

Why Choke-mode structure?

- Circular symmetric, easy fabrication
- Low surface magnetic field, low pulse heating, possible low breakdown rate
- Low magnetic field at the welding joint





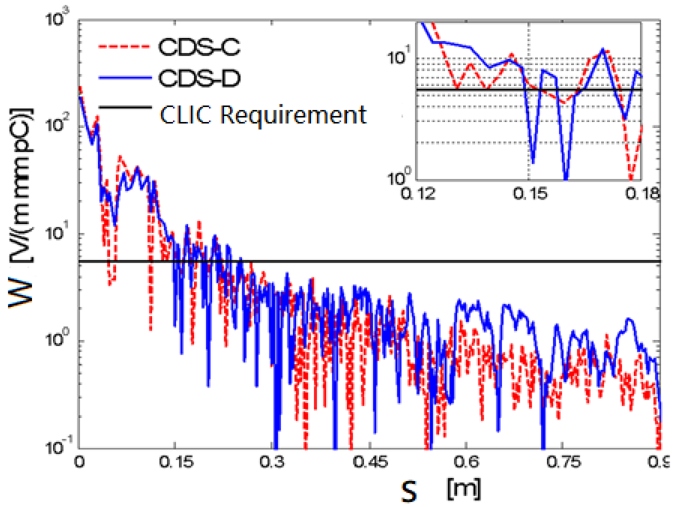
Hao.Zha, ph.D thesis

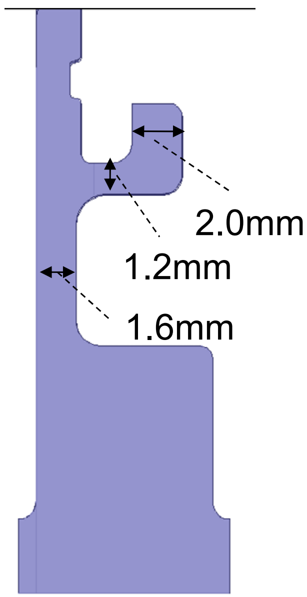
To compare:
Waveguide damping

REF: CLIC-Study

X-band Choke-mode damped structure for CLIC main linac (design)

- In 2013, design of the CLIC Choke-mode damped structure
- $W_\perp$ (0.15m)~4 V/pC/m/mm meets the requirement
- Comparable to the baseline design, waveguide damping



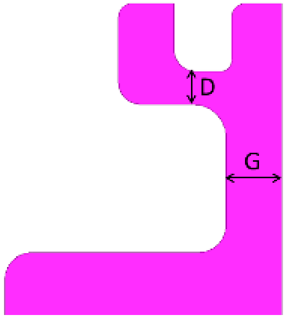


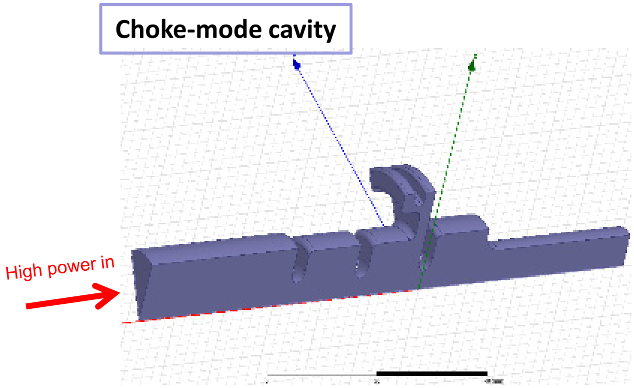
High-gradient performance of X-band choke is still unknown

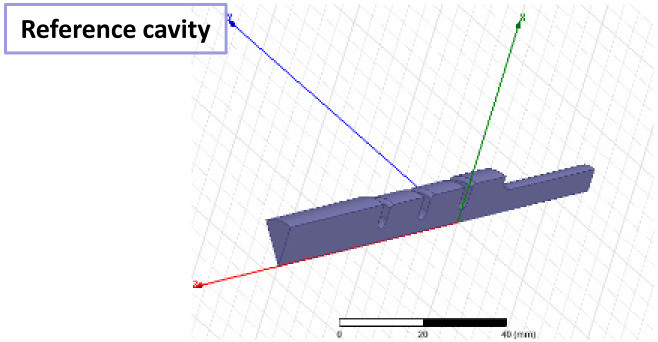
Hao.Zha, ph.D thesis

Design of Choke-mode cavities

- High-gradient performance
  - of different choke dimensions
- Six single-cell standing-wave (SW) structures, at 11.424 GHz
  - THU-CHK-#1~ THU-CHK-#5 (different choke dimensions)
  - THU-REF (single-cell structure without choke)







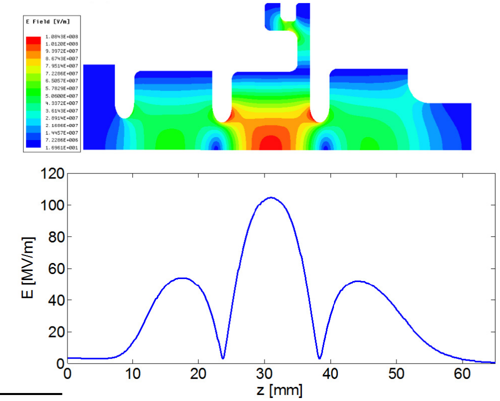
Cavity tuning

Tune the full structure

- Work at π-mode, 11.424 GHz
- Critical coupling

Modify choke dimension to change the choke field

Choke-mode structure E field



RF parameters

THU-	R_E	R_p [MV/(m $\sqrt{\text{MW}}$)]	Q_0	E_{choke}/E_{surf}
REF	2.05	130	9010	1
CHK-#1	2.10	109	7519	0.76
CHK-#2	2.05	104	7247	0.92
CHK-#3	2.04	110	8006	0.73
CHK-#4	2.06	112	8210	0.69
CHK-#5	2.05	103	7864	0.84

$$R_E = \frac{E_{surf}}{E_{acc}}$$

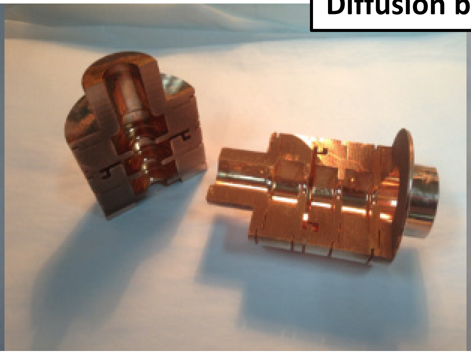
$$R_p = \frac{E_{surf}\ [\text{MV/m}]}{\sqrt{P_{loss}\ [\text{MW}]}}$$

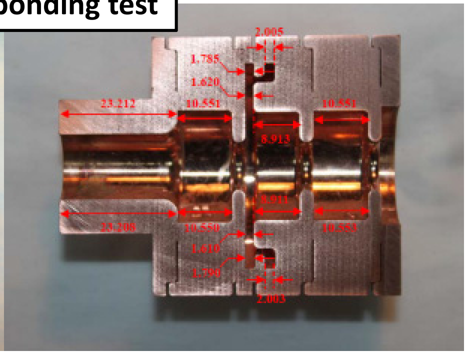
Fabrication

- Cell manufacture and diffusion bonding at Tsinghua University
- A diffusion bonding test of choke-mode cavity was done to check the quality as contact areas of each choke-mode structure disks are not consistent vertically
- Good results were seen after cutting the test structure

Choke-mode cavity cell

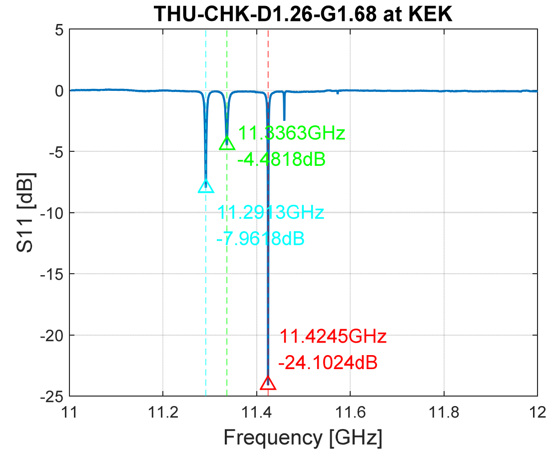
Diffusion bonding test

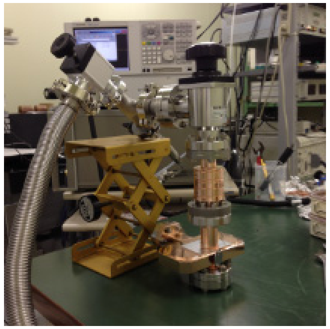


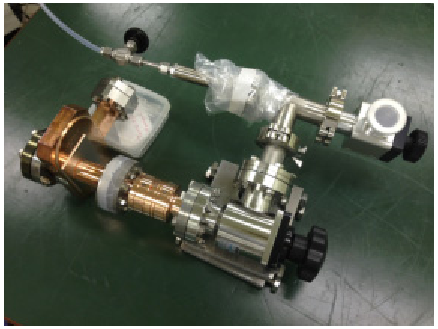


Low power RF measurements

- Bench test, tuning, and baking were done in Tsinghua
- Structures shipped to KEK after being closed by vacuum valves to keep vacuum environment
- Frequency check at KEK kept consistent with the test results in Tsinghua University







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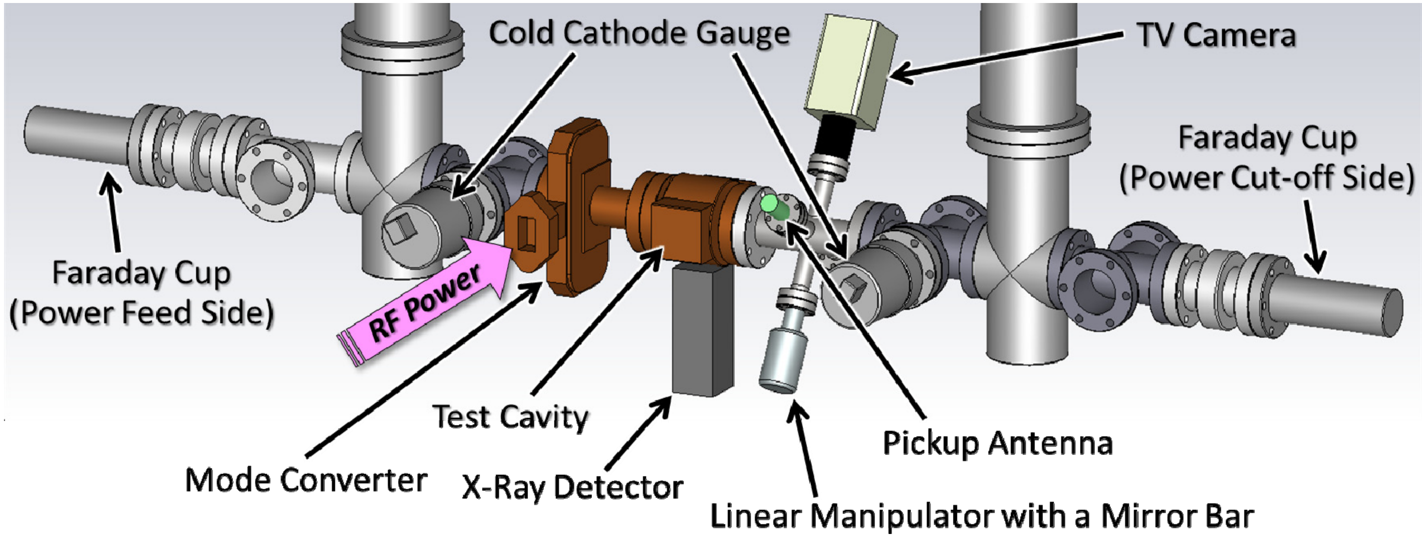
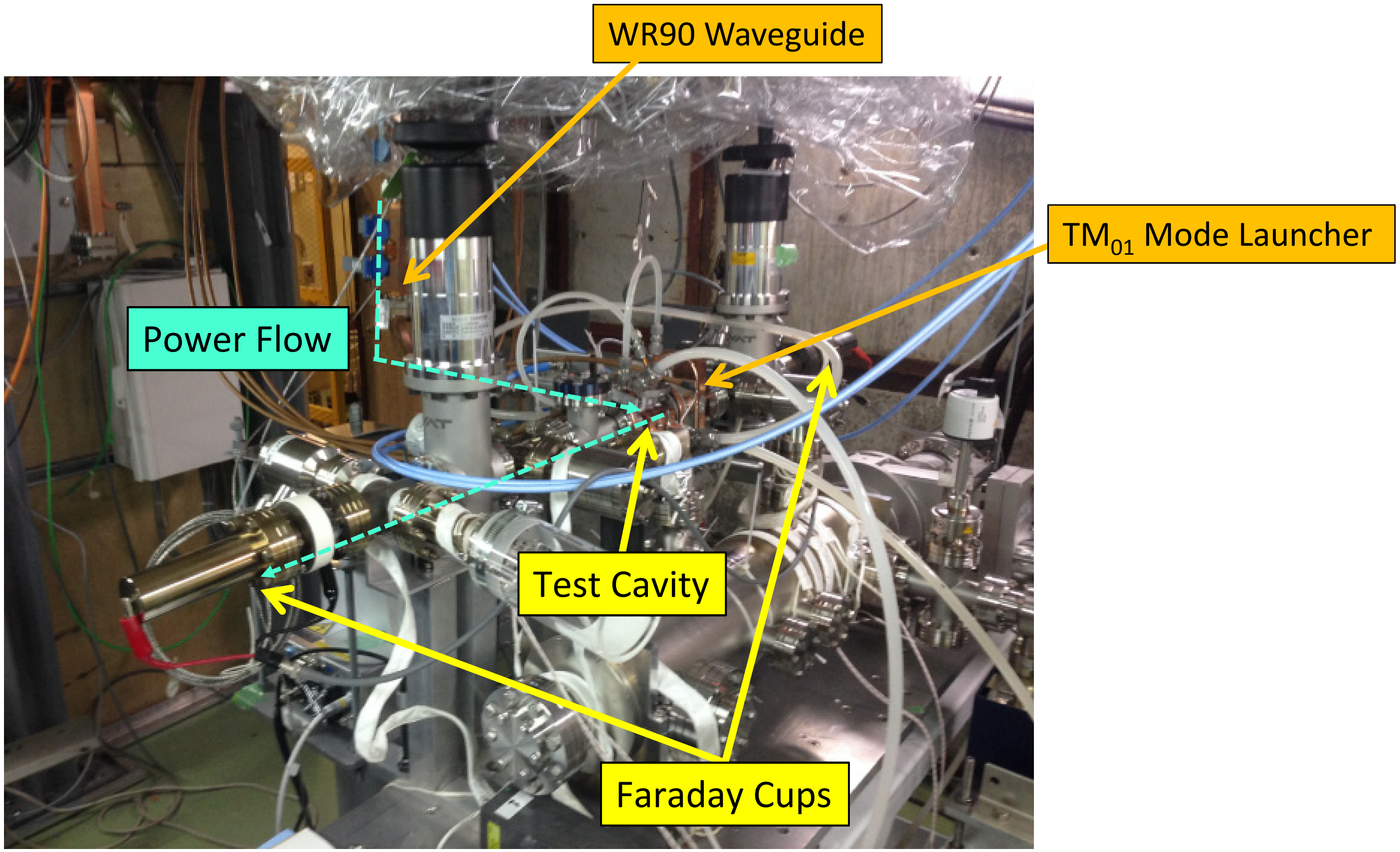
Shield-B setup

- High-gradient test carried out in Shield-B of Nextef
- Shield-B test stand
  - Incident and reflection waves collected by Directional Couplers
  - Dark current captured by Faraday Cups



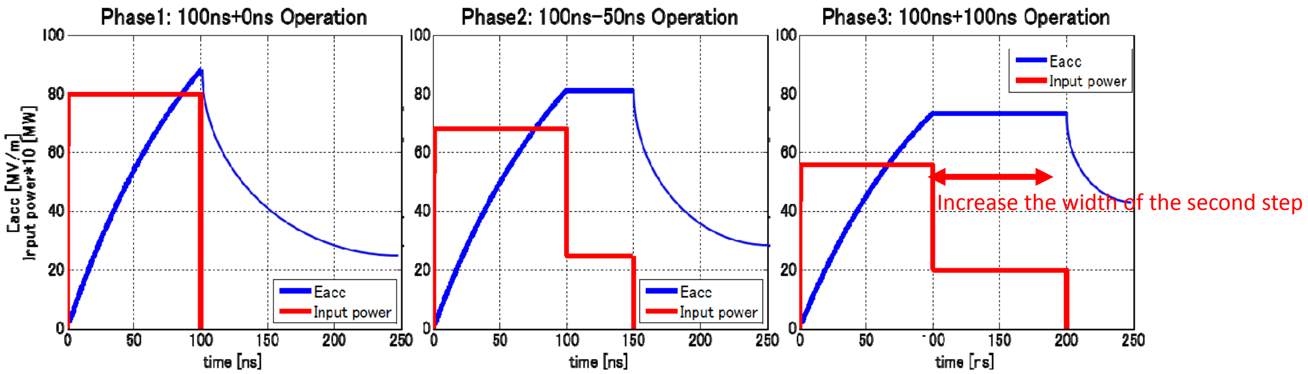
T. Abe et al., Proceedings of PASJ2016

Shield-B setup



RF pulse shaping

- Use double step input waveform
- Filling time around 100ns
- Keep the ratio of the two steps constant to make flat E field inside cavity
- Increase the width of the second step



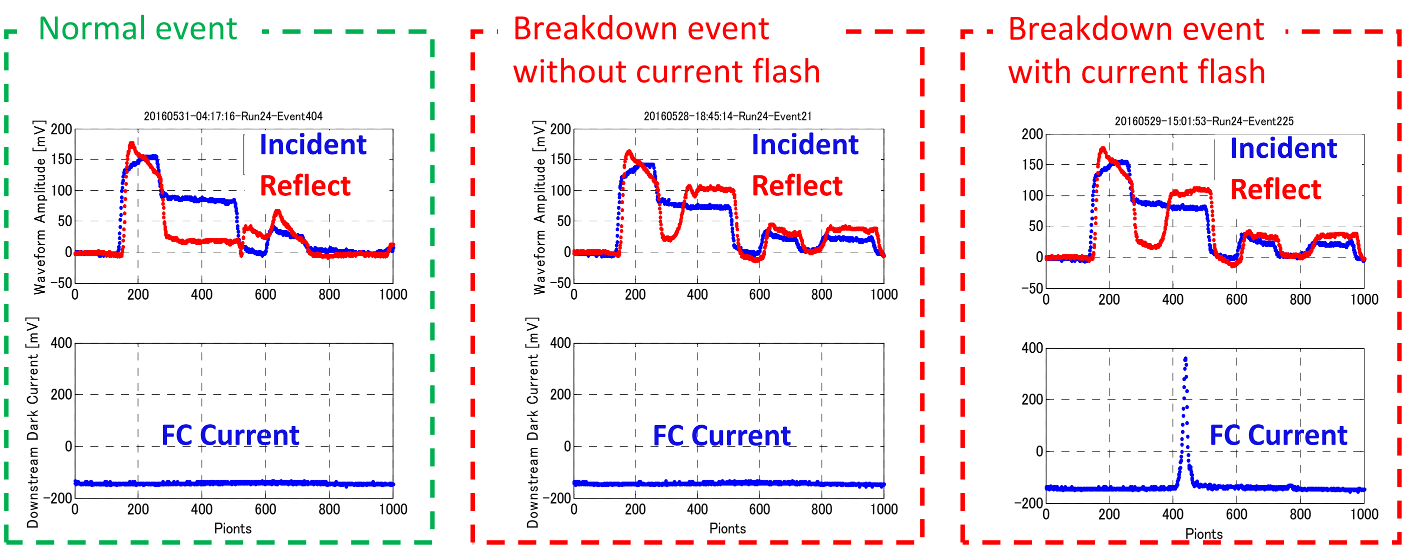
Typical breakdowns w or w/o current flash

Two types of breakdown events were observed

- Breakdown with current flash (CF-BD)→ speculated to be occur in the cylinder cavity
- Breakdown without current flash→ speculated to be occur in choke

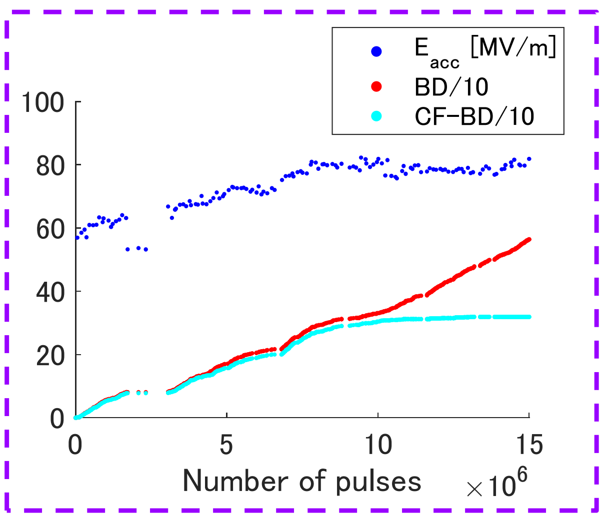
98.6% breakdown events were accompanied with current flash in THU-REF

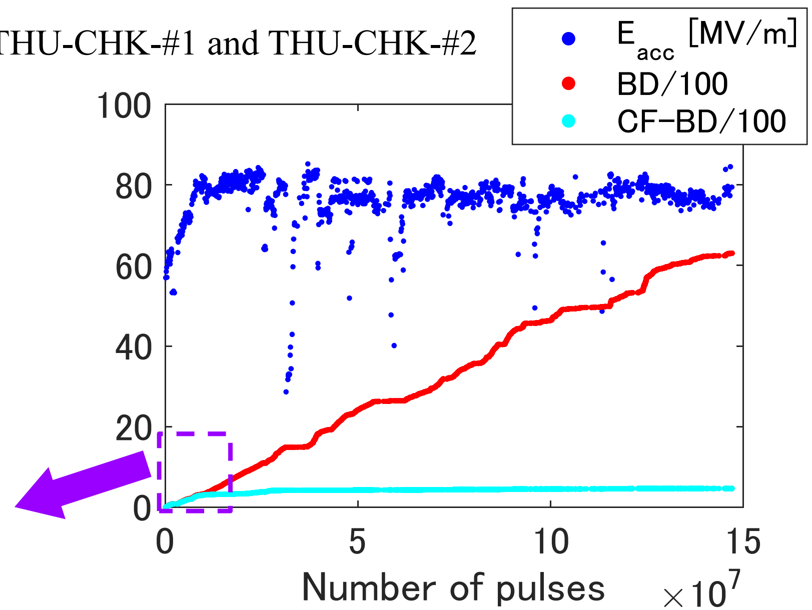
- Faraday Cup has good capture rate for the dark current



Two types of breakdowns

- Breakdowns were accompanied by the current flash into the Faraday cup during the initial ramping stage of THU-CHK-#1
- After initial ramping, few current flash breakdowns were observed in the detected events
- Same phenomenon was seen in THU-CHK-#1 and THU-CHK-#2

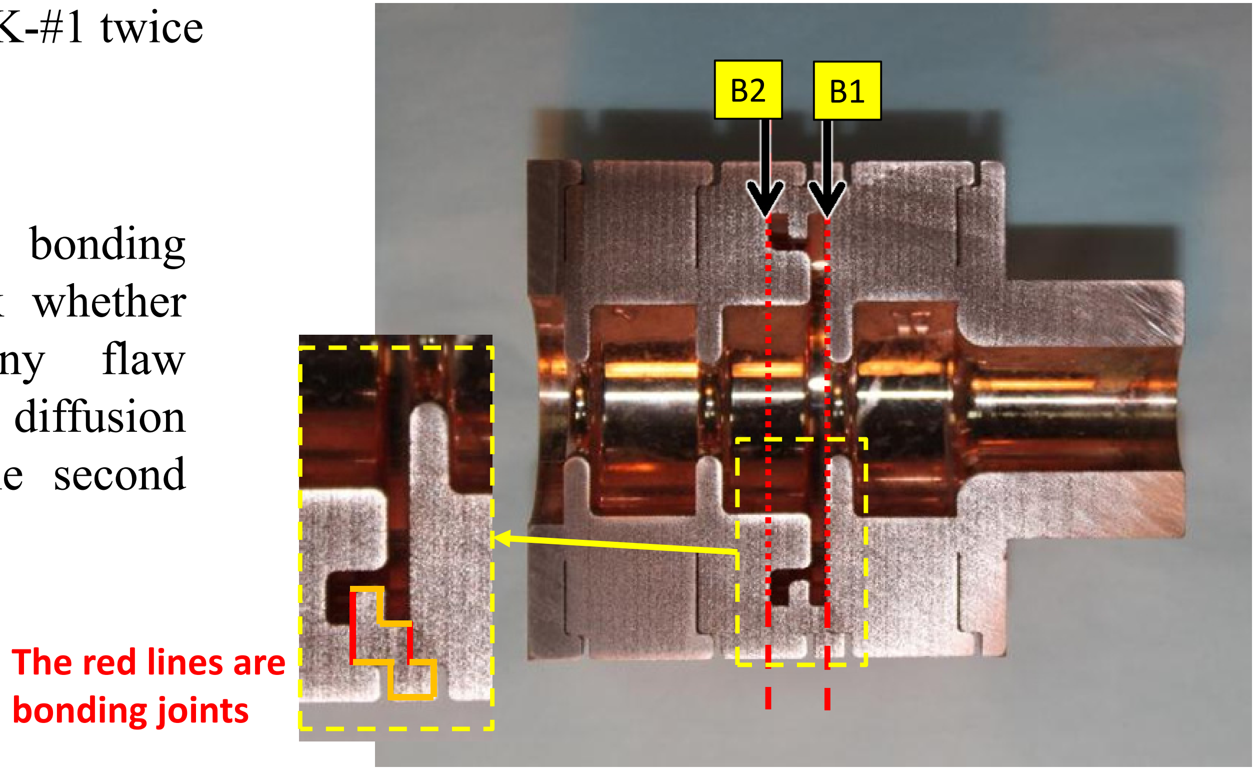




Postmortem of choke-mode structure

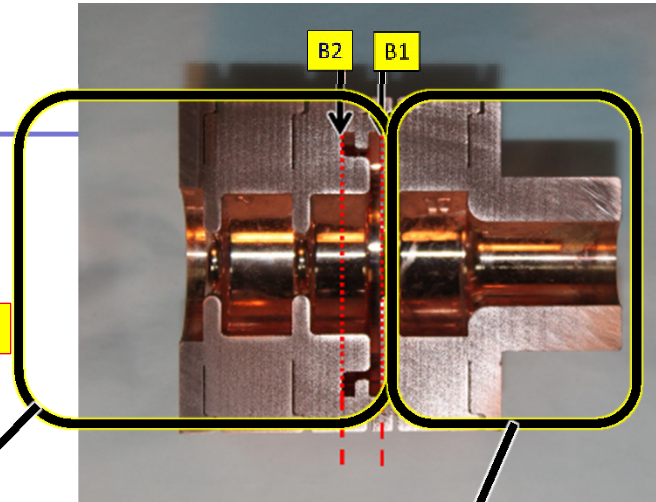
Cut THU-CHK-#1 twice (B1 and B2)

We kept the bonding joint to check whether there are any flaw during the diffusion bonding in the second cutting



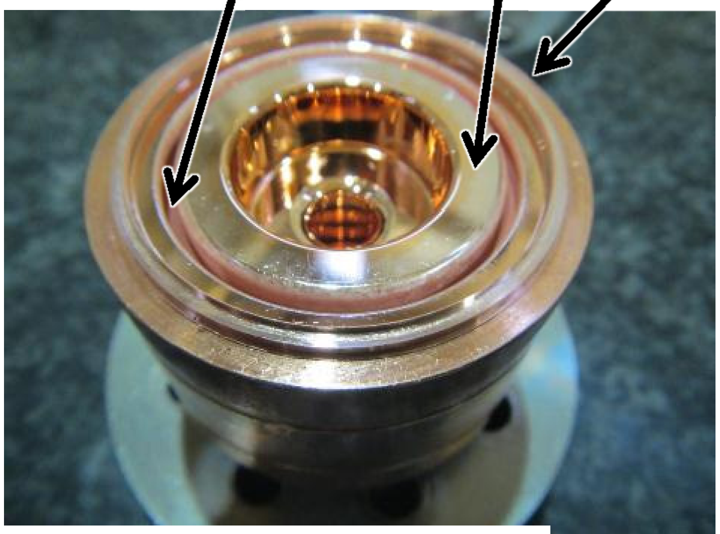
After the cutting

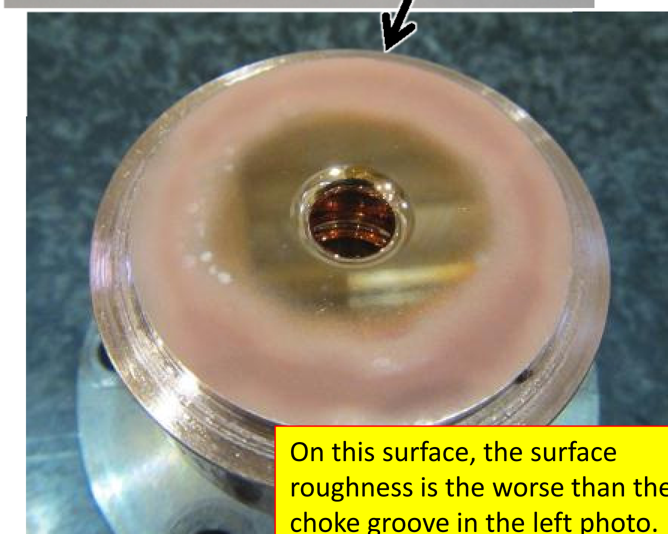
- The surfaces of the irises and cavity are very clean.
- KEYENCE VE-8800 was used to do the further inspections



This surface is also clean.

The surface of this choke groove seems to be very bad.



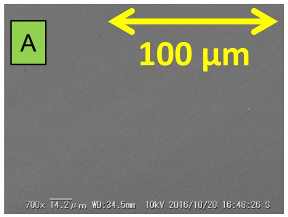


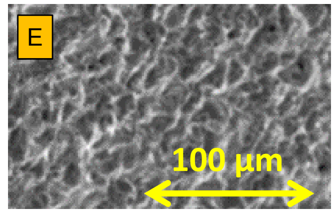
On this surface, the surface roughness is the worse than the choke groove in the left photo.

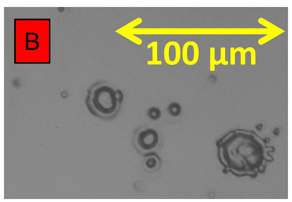
Modified from Abe's presentation

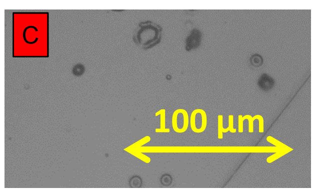
Inner surface observation results

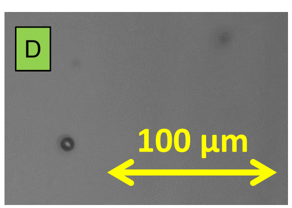
Conclusion:
Many breakdown spots at B、C
Copper sputtering at E、F、G
Choke was damaged
Iris area was clean

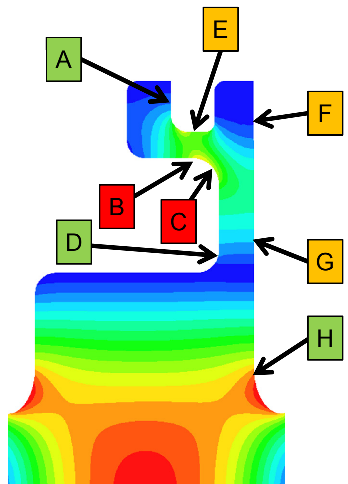




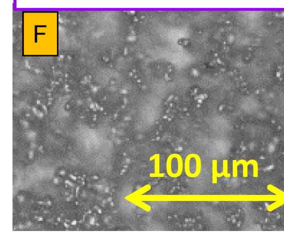


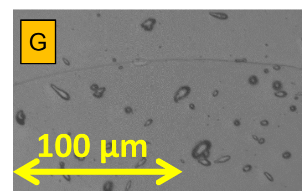


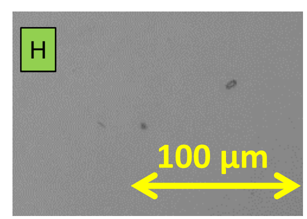




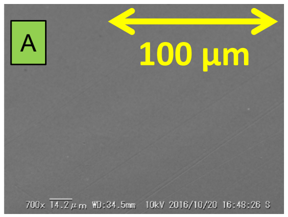
Choke E field

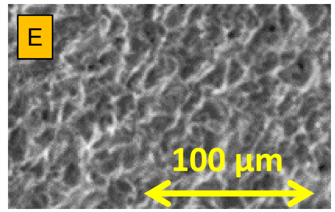


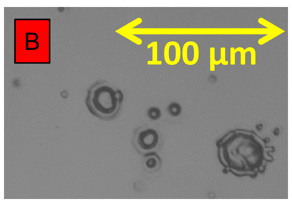


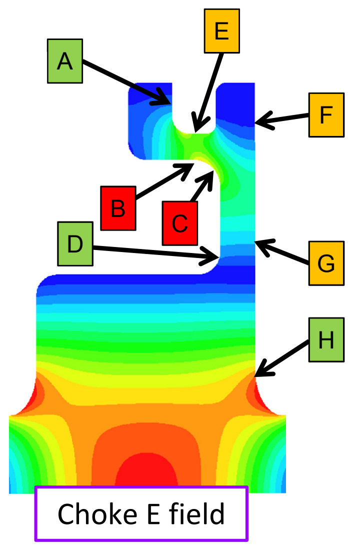


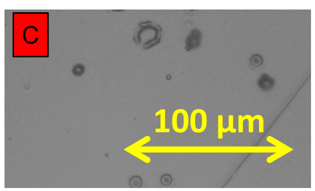
Inner surface observation results

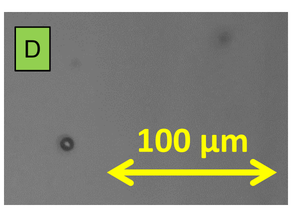




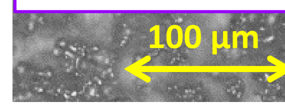


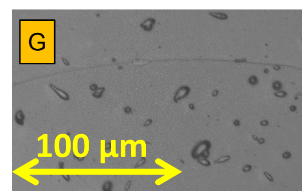


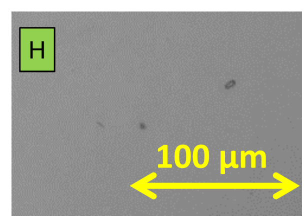




Conclusion:
Many breakdown spots at B、C
Copper sputtering at E、F、G
Choke was damaged
Iris area was clean
High-gradient performance limited by the breakdown events at choke area!

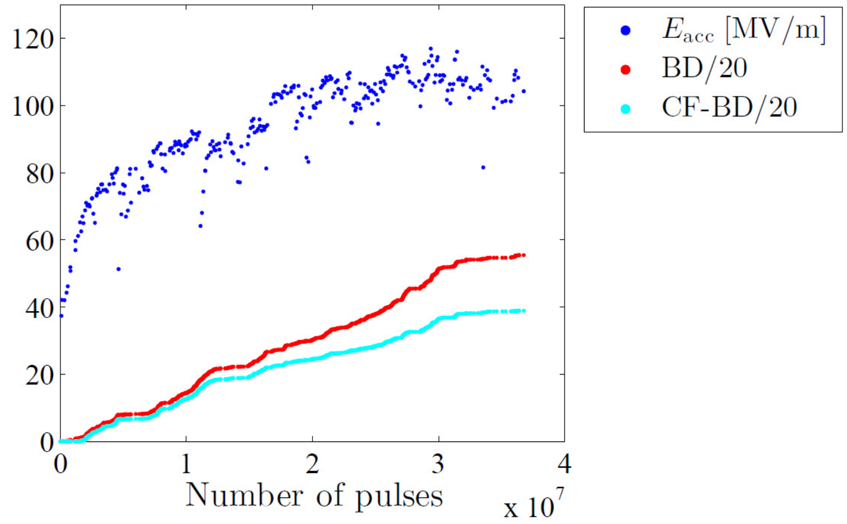




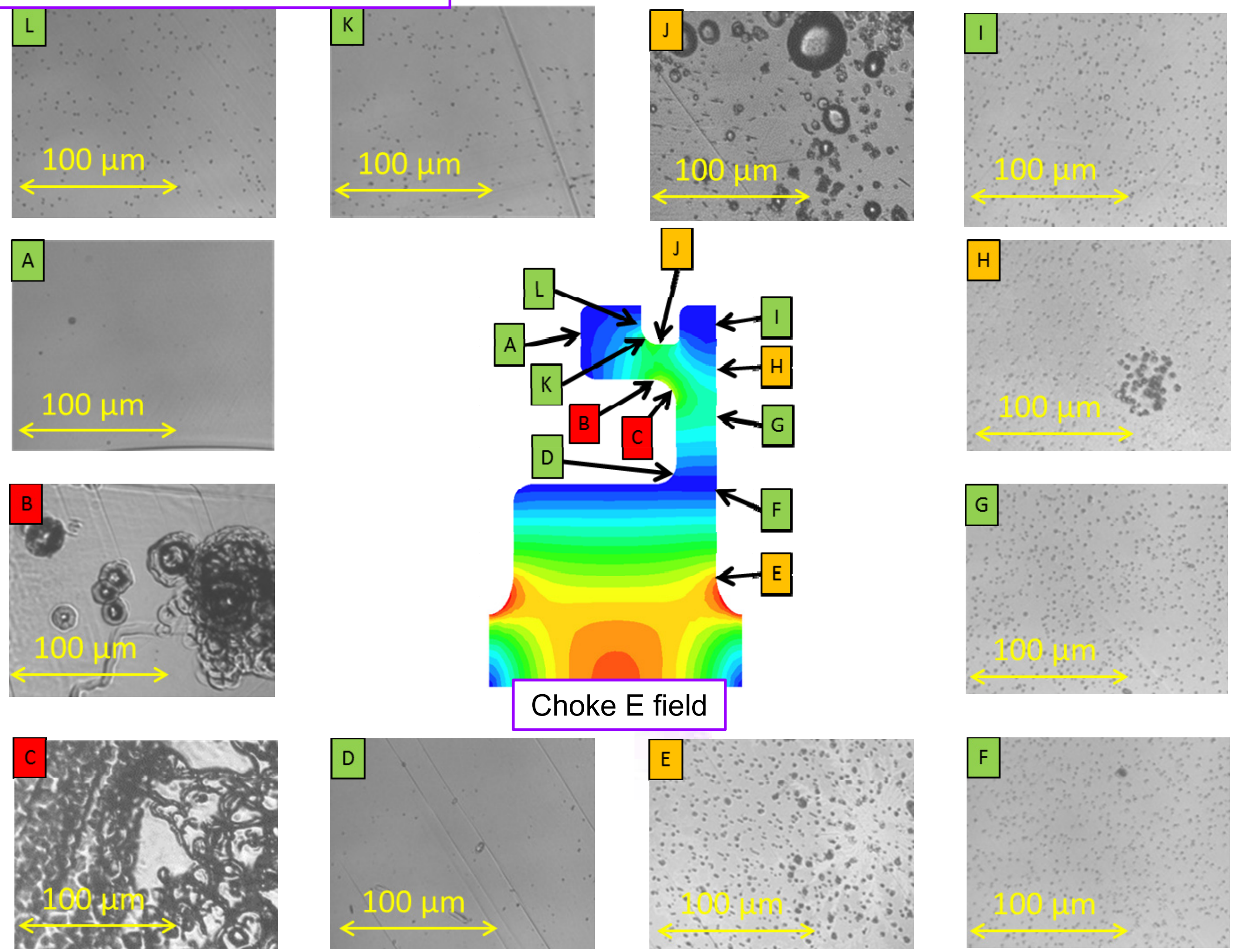


THU-CHK-#3 breakdown signals

- Breakdown events accompanied with current flash observed during the whole test
- Both of the two types occurred when gradient got saturated
- Same phenomenon was seen in THU-CHK-#4 and THU-CHK-#5

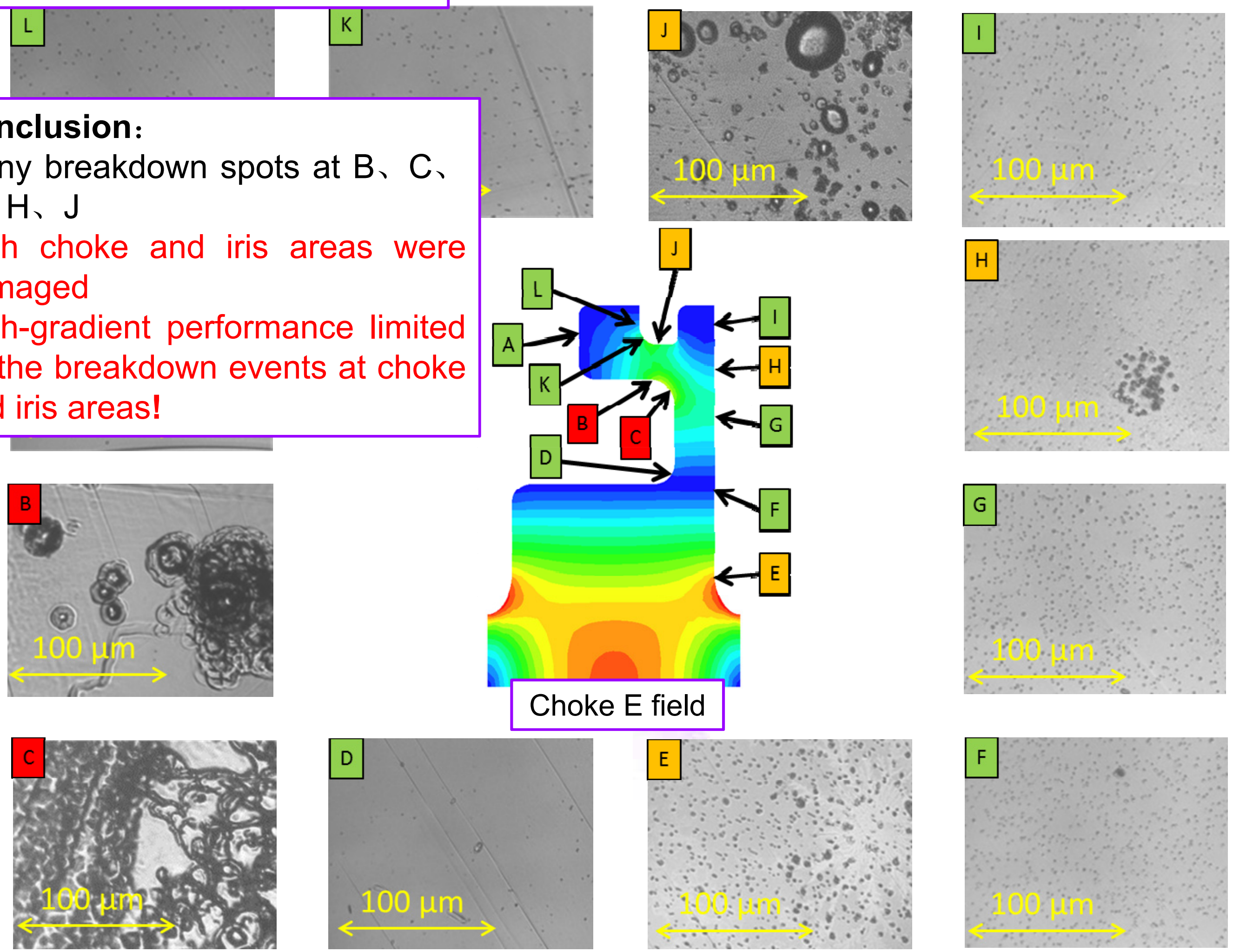


THU-CHK-#3 observation results



THU-CHK-#3 observation results

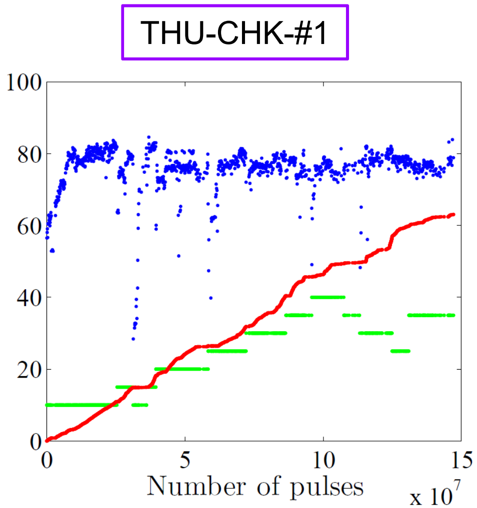
Conclusion:
Many breakdown spots at B、C、E、H、J
Both choke and iris areas were damaged
High-gradient performance limited by the breakdown events at choke and iris areas!

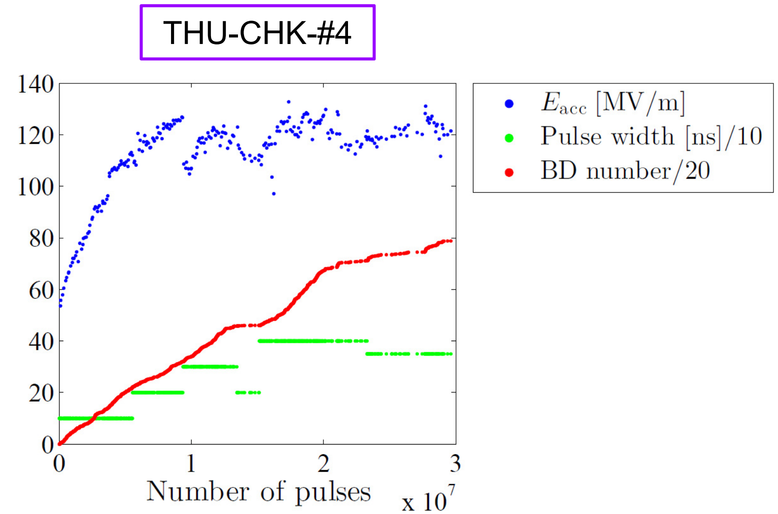


Choke E field

High-gradient history of Choke-mode structures

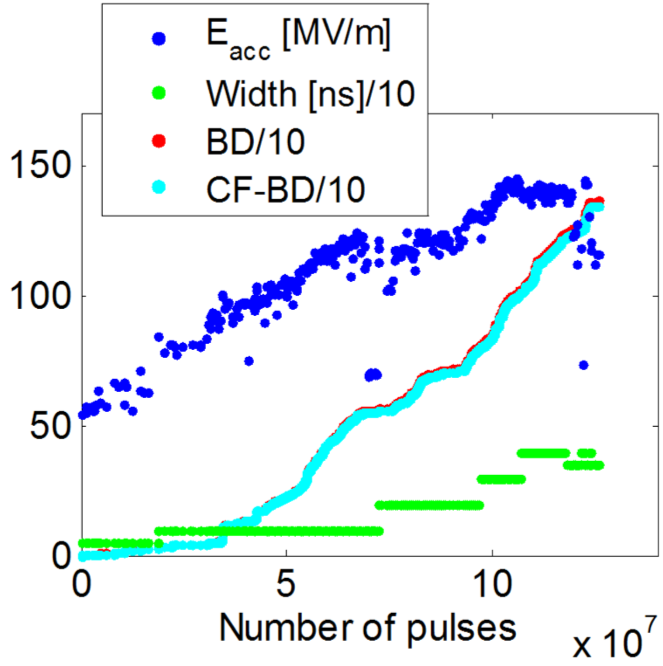
- THU-CHK-#1
  - Cannot ramp input power after 1.0×10^7 RF pulses, same as THU-CHK-#2
  - Max gradient reached 85 MV/m at longer pulse operation
- THU-CHK-#4
  - Fast ramping speed, same as THU-CHK-#3
  - Max gradient reached 131 MV/m at longer pulse operation





High-gradient history of THU-REF

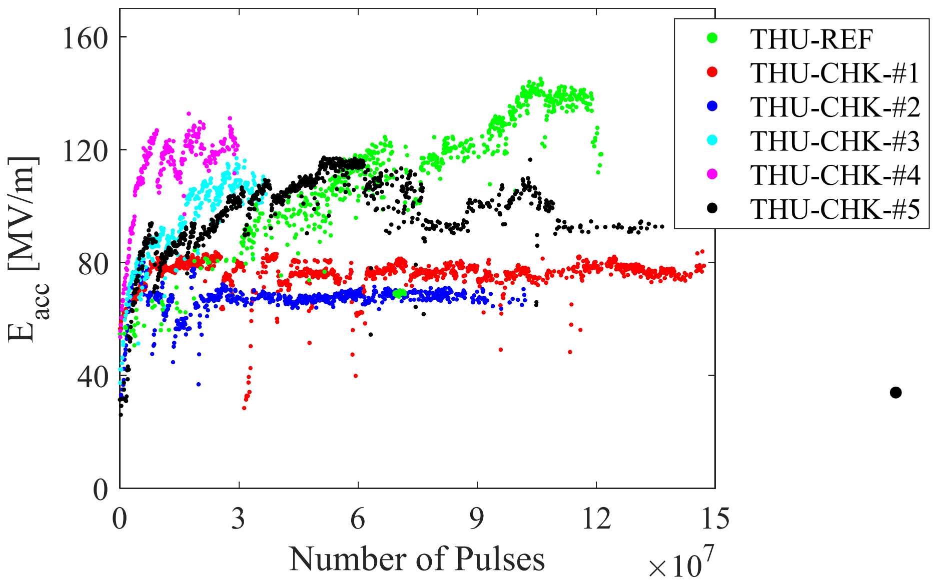
- Max gradient reached 145 MV/m: Validate Tsinghua X-band fabrication technology
- 98.6% breakdown events were accompanied with current flash



Comparison of single-cell structures

- Same max E_{choke} in THU-CHK-#1 and THU-CHK-#2
  - Breakdown in choke limits high-gradient performance

THU-CHK-	$E_{\text{acc}}{}^{\text{max}}$ [MV/m]	$E_{\text{choke}}{}^{\text{max}}$ [MV/m]	$\frac{E_{\text{choke}}}{E_{\text{surf}}}$
#1	85	134	0.76
#2	71	135	0.92
#3	117	175	0.73
#4	131	185	0.69
#5	118	200	0.84



- Fast ramping speed in THU-CHK-#4
  - Increase choke dimension can increase the E_{choke} and high-gradient performance

High-gradient performance evaluation of chokes

Study the relationship between Max normalized gradient and E_{choke}/E_{surf} and dimension D [mm] by applying the high-gradient test data of choke-mode structures

$$\frac{BDR}{{E_{acc}}^{30} \cdot \tau^5} = \text{constant}$$

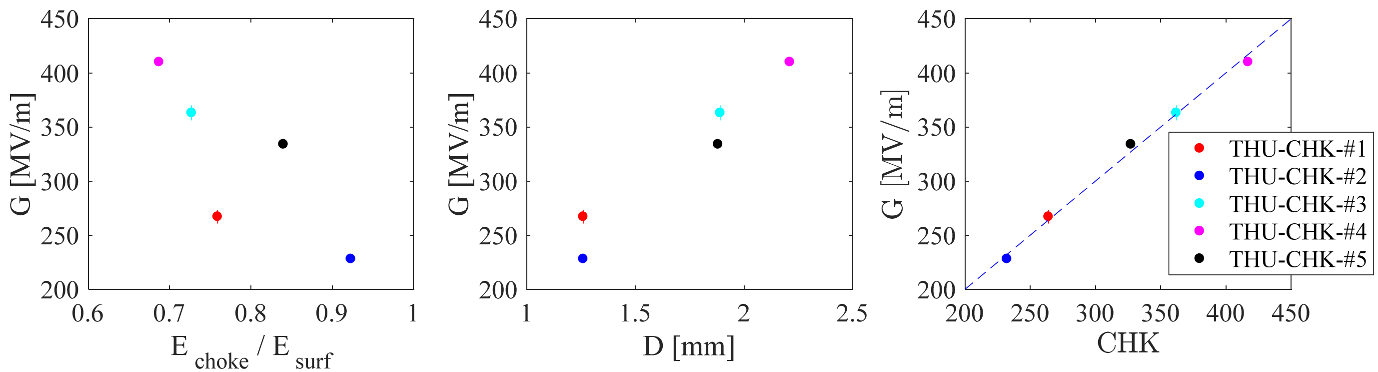
$$G = \frac{E_{acc} \cdot \tau^{1/6}}{BDR^{1/30}}$$

THU-CHK-	E_{choke}/E_{surf}	D [mm]	G [MV/m]
#1	0.76	1.26	267
#2	0.92	1.26	228
#3	0.73	1.89	363
#4	0.69	2.21	410
#5	0.84	1.88	330

$G = \text{constant} \times (E_{choke}/E_{surf})^{\alpha} \times (D)^{\beta}$
$\text{CHK} = 187 \times (E_{choke}/E_{surf})^{-0.70} \times (D)^{0.68}$

CHK can be used to guide choke design, evaluate high-gradient performance

Only determined by the geometry



Summary

- 100 MV/m X-band accelerating structure prototype developed and tested at Tsinghua University
  - worldwide activity of high-gradient normal conducting structures indicates that X-band technology is mature
  - Application in *compact* Inverse Compton source in Tsinghua TTX

- Series of single-cell SW structures were designed, fabricated, and tested
  - to study the high-gradient performance of choke-mode damped structure, for multiple-bunch operation
  - High-gradient as high as 130 MV/m was obtained, along with a 145 MV/m undamped reference structure
  - A new quantity was proposed to guide the design of high-gradient choke-mode structures, to couple the wake-field damping with high-gradient performance in the design stage

Thank you for attention!