Longitudinally-Split Side-Coupled High-Shunt-Impedance C-band Structure Fabricated in Two Halves

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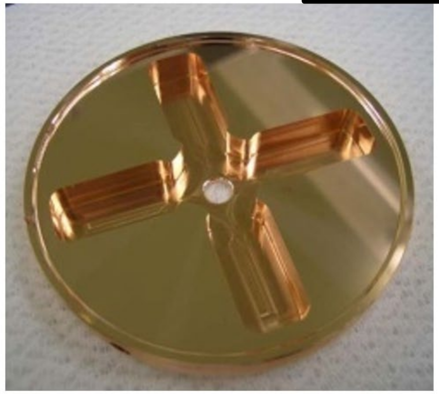
in collaboration with Mitsubishi Heavy Industries Machinery Systems, Ltd.

The 2024 International Workshop on Future Linear Colliders (LCWS2024)

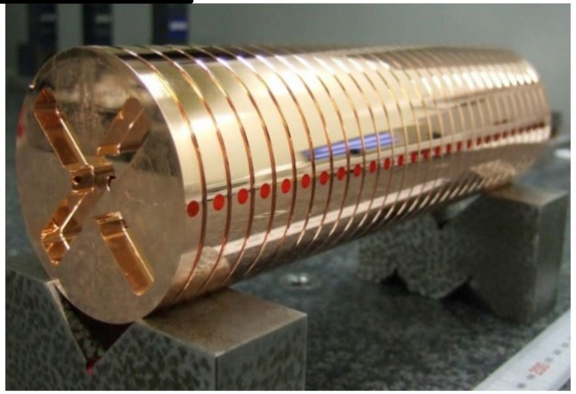
on July 10th, 2024 at the University of Tokyo, Japan

Two “*Orthogonal*” Fabrication Methods

Disk-type



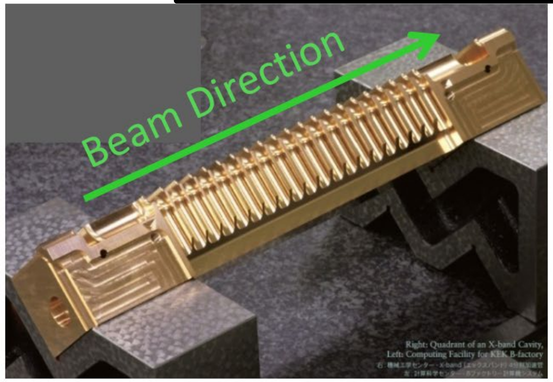
A damped disk



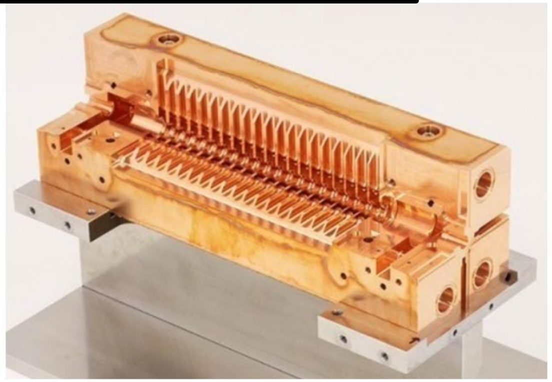
Disks stacked and bonded

- Advantages
  - ✓ Machining by turning for main parts
  - ✓ Very smooth surface (Ra < 100 nm) easily achieved
- Disadvantages
  - ✓ **Many parts** of dozen of disks to be made by ultraprecision machining
    - → Followed by delicate stack and bonding
  - ✓ Great care needed to be taken
  - ✓ **Surface currents due to the accelerating mode flow across many disk-to-disk junctions.**

Longitudinally-split type



A Quadrant



Three Quadrants

- Advantages
  - ✓ **Only two or four parts** to be made by simple machining with (five-axes) milling machines
  - ✓ Simple assembly process
    - → Possibility of significant cost reduction
  - ✓ **Surface currents due to the accelerating mode do not flow across any bonding junction.**
- Disadvantages
  - ✓ Not very smooth surface (Ra > 100 nm)
  - ✓ **Possible virtual leak from halves or quadrants junctions**
    - → **Solved in our improved version**
  - ✓ **Field enhancements at the edges of halves or quadrants**
    - → **Partially solved in our improved version**

DESIGN IMPROVEMENT

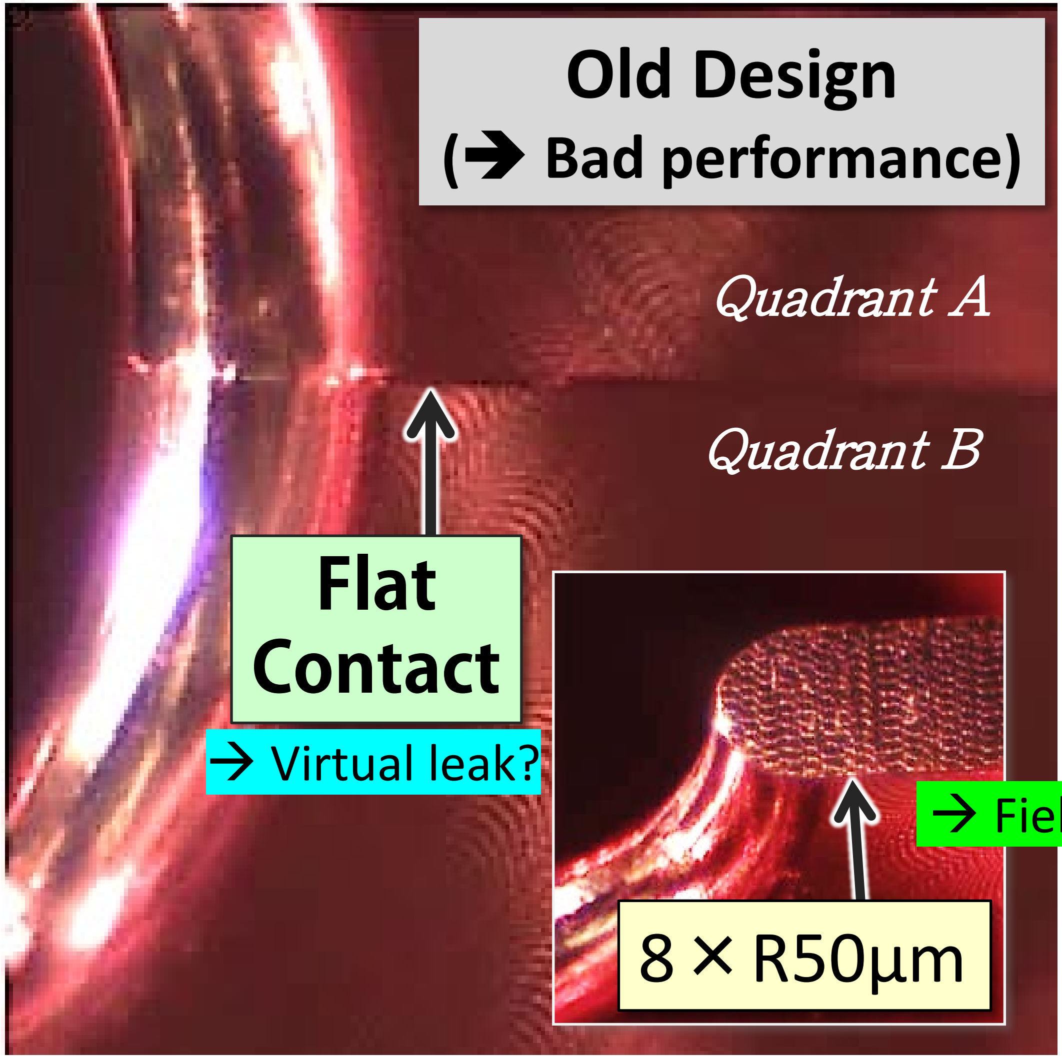
to
- ✓ Avoid virtual leak
- ✓ Suppress the field enhancement

The chamfer radius and small-gap size were optimized based on simulation to minimize

A) Field enhancement at the corner of the quadrants (→ +25%)

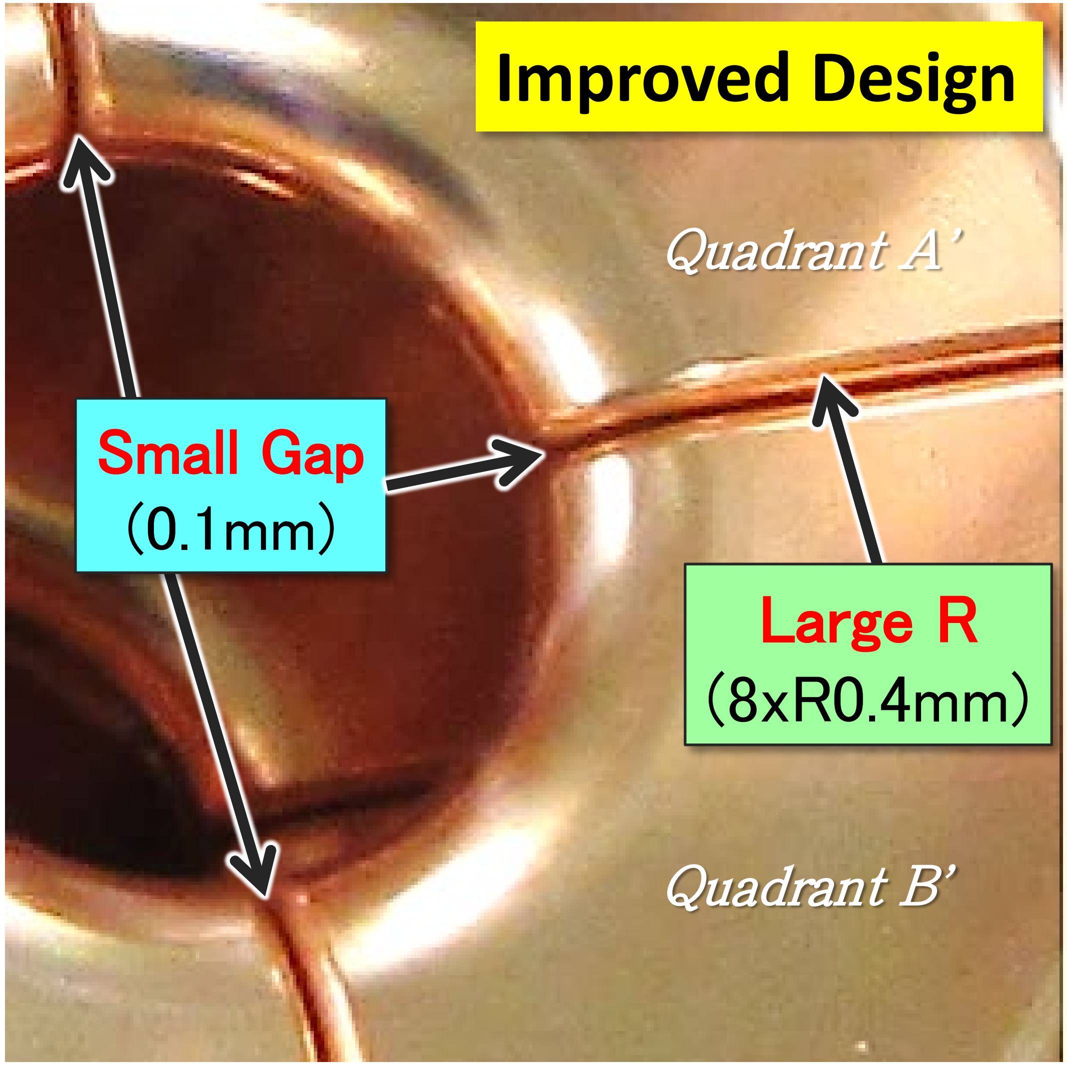
B) Deterioration of the shunt impedance (→ -2%)

For details, see T. Abe *et al.*, "Fabrication of Quadrant-Type X-Band Single-Cell Structure used for High Gradient Tests," presented at the 11th Annual Meeting of Particle Accelerator Society of Japan (2014), Paper ID: SUP042.

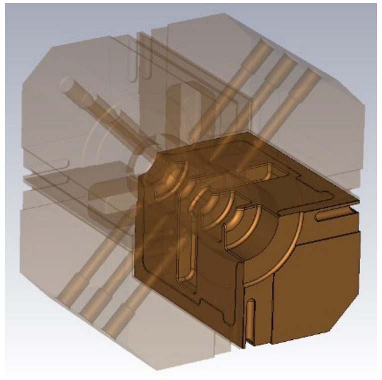


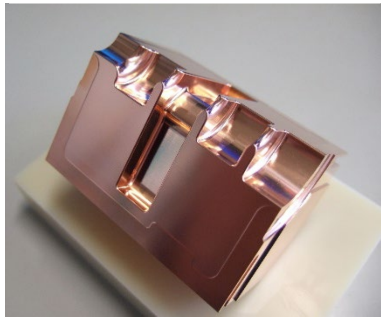
← Photo of the iris →

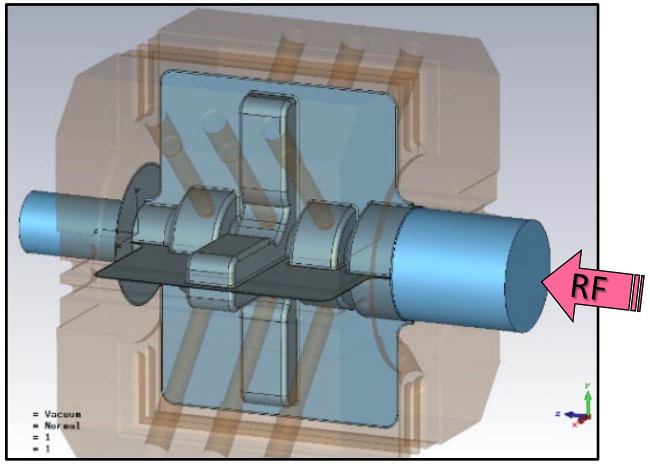
→ Field enhancement



Demonstration of the High-Gradient Performance for an X-band (11.4 GHz) single-cell Standing-Wave cavity (2017)

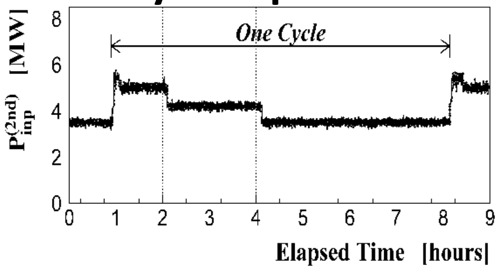




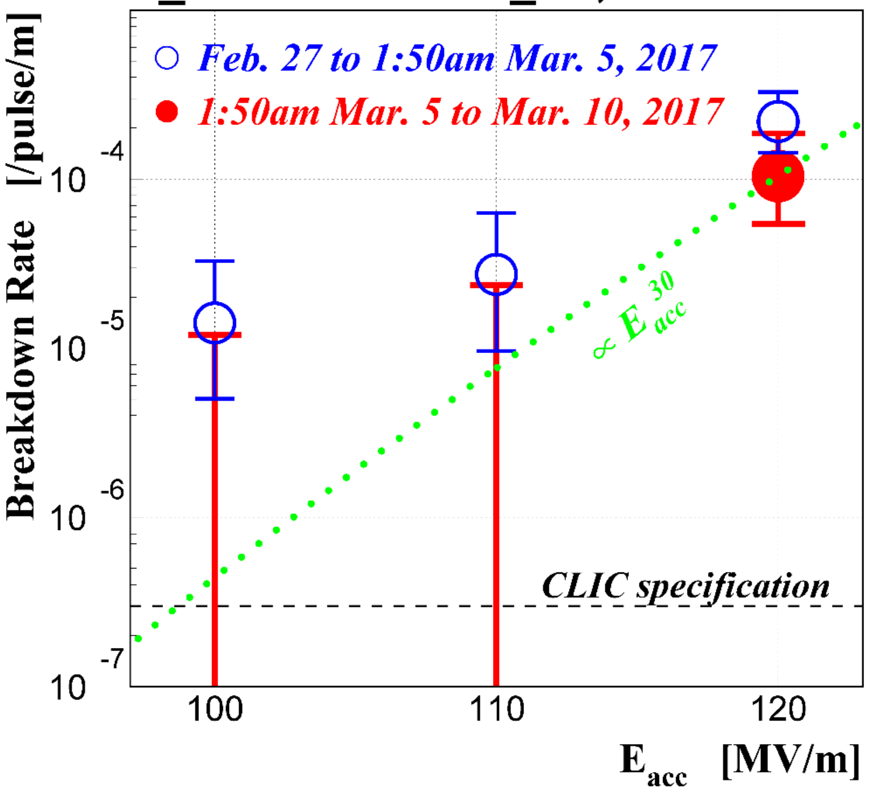


[T. Abe *et al.*, "*High-Gradient Test Results on a Quadrant-Type X-Band Single-Cell Structure,*" presented at the 14th Annual Meeting of Particle Accelerator Society of Japan (2017), PaperID: WEP039.]

Cycle Operation



Breakdown-rate meas. after RF conditioning performed at KEK / **Nextef1** / Shield-B



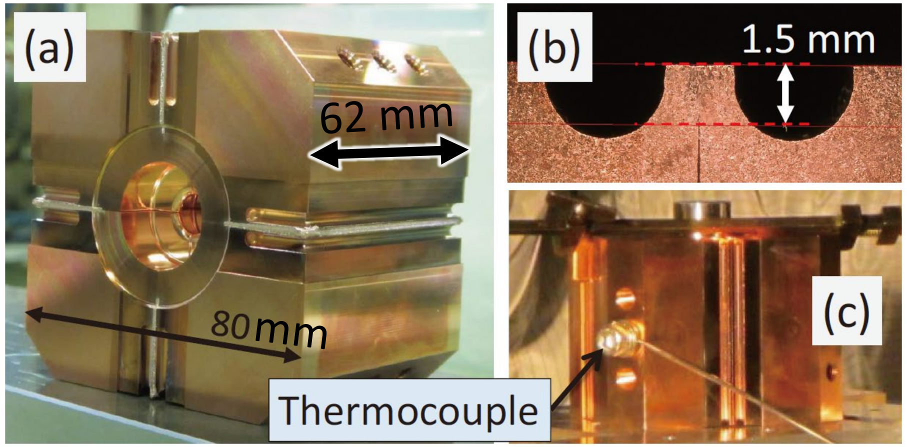
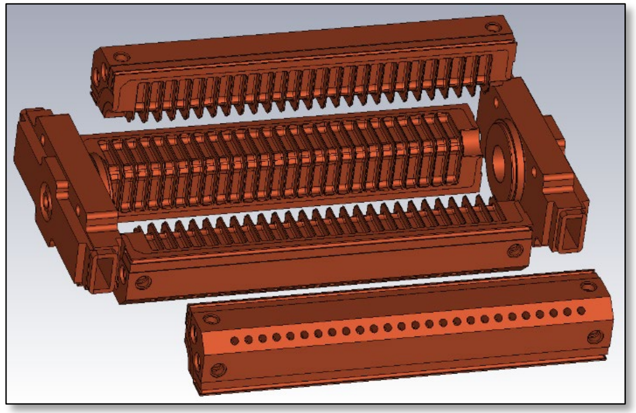


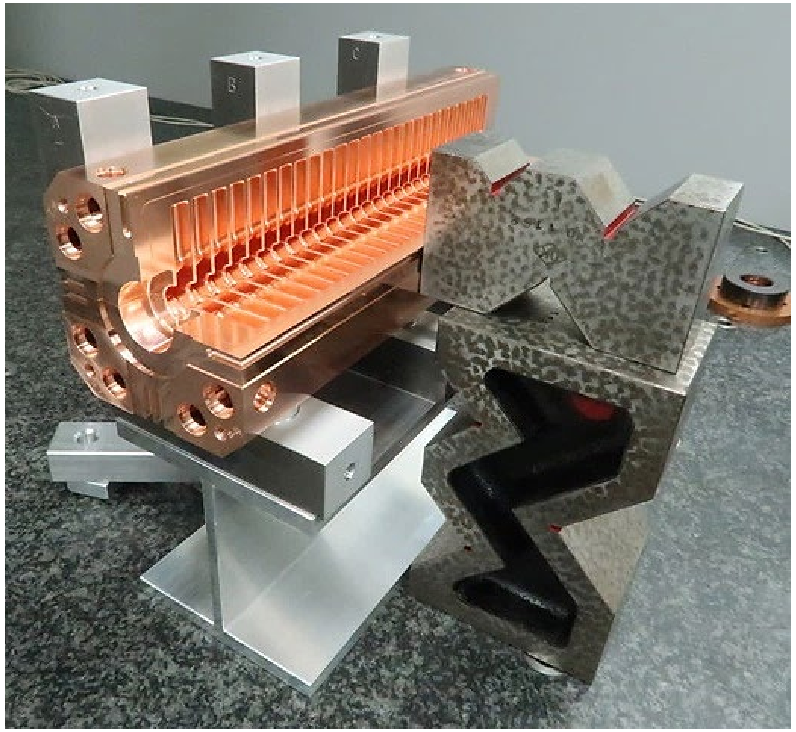
Figure 12: EBW of the quadrants. (a) After the EBW. (b) Welding penetration depth for the EBW conditions described in [13]. (c) A thermocouple is attached.

Good high-gradient performance demonstrated!

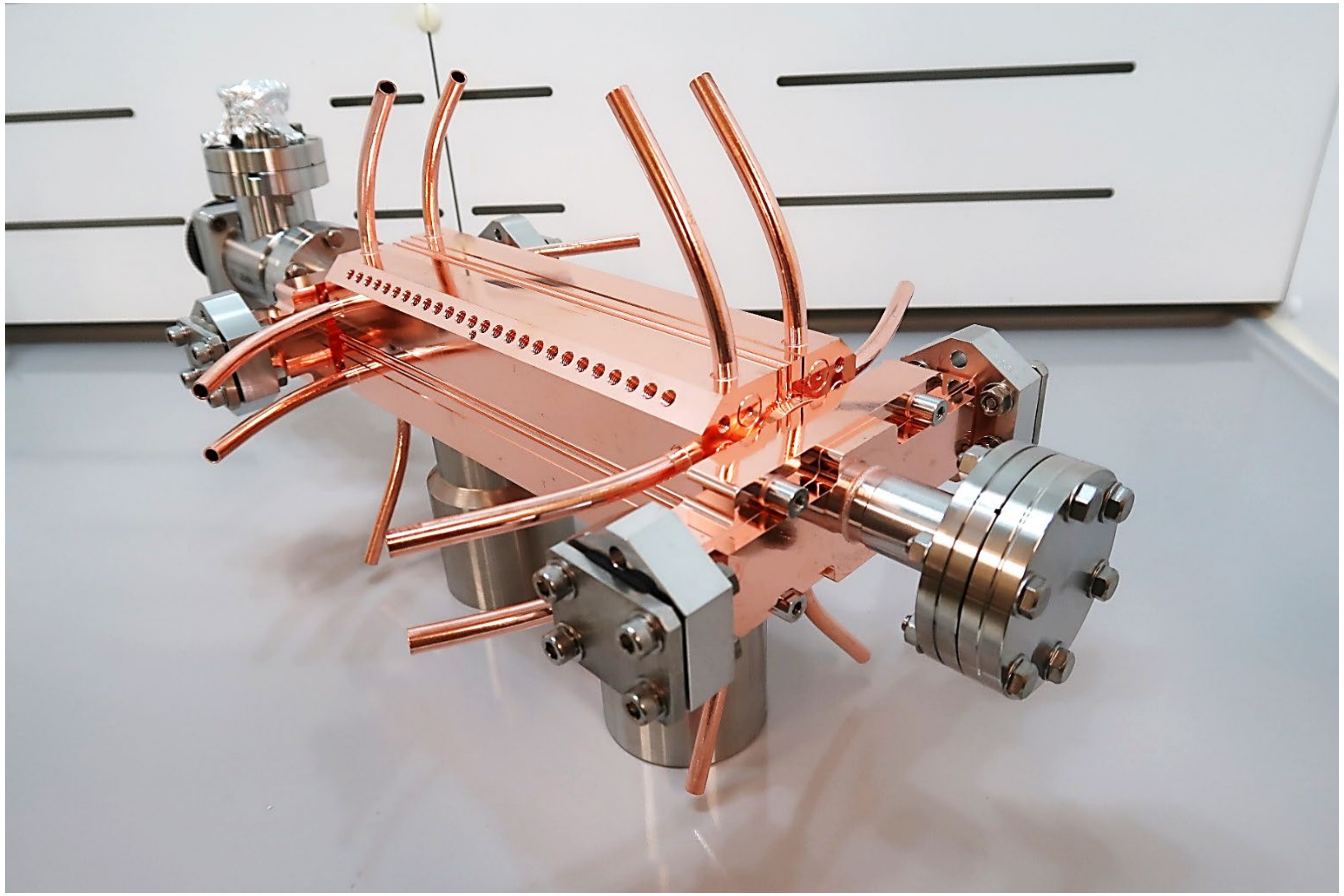
Full-scale CLIC prototype fabricated in four quadrants

(11.4 GHz; traveling wave)





TD24R10_QUAD-R04G01_K1



- ✓ The fabrication completed
- ✓ But high-gradient testing not yet performed due to the big fire at Nextef1

Application to Compact Medical Linac (C-band: 5.71 GHz)

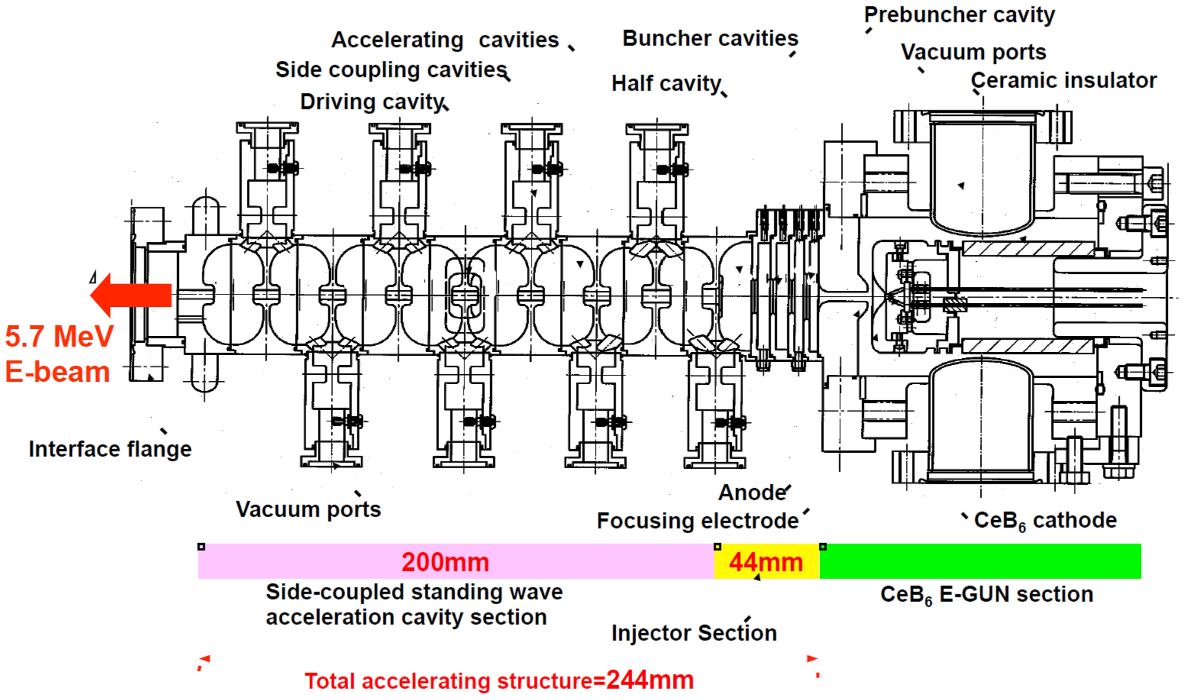
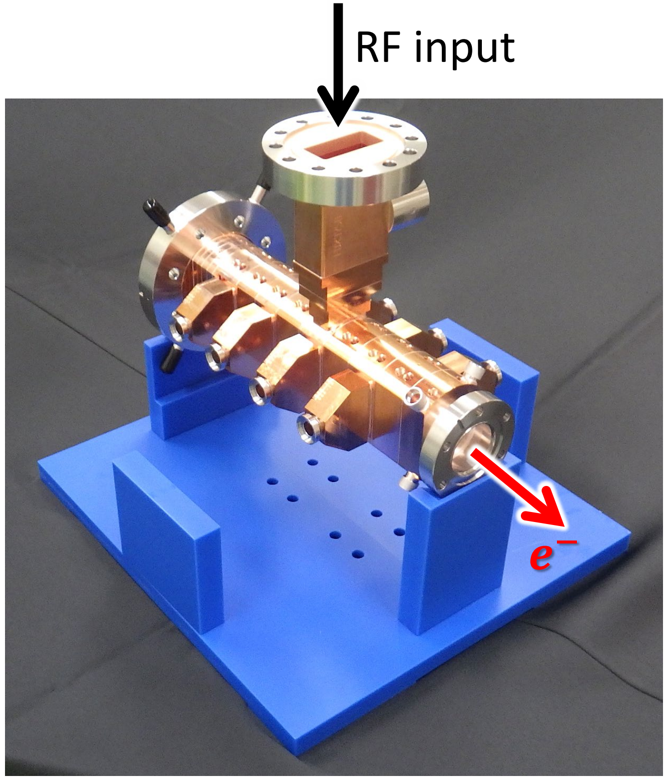


図 4.5　加速管の全体構成図

Extracted from Yuichiro KAMINO's text in OHO'24 seminar (in Japanese):
http://accwww2.kek.jp/oho/oho12/oho12_txt/9%20kamino_mhi%2020120820.pdf

- ✓ Input coupling : 1.4 – 2.0
- ✓ Input RF power: ~3 MW
- ✓ Beam energy: ~6 MeV
- ✓ Beam current (peak): > 75mA
- ✓ Beam diameter: 1.5 – 2.0 mm

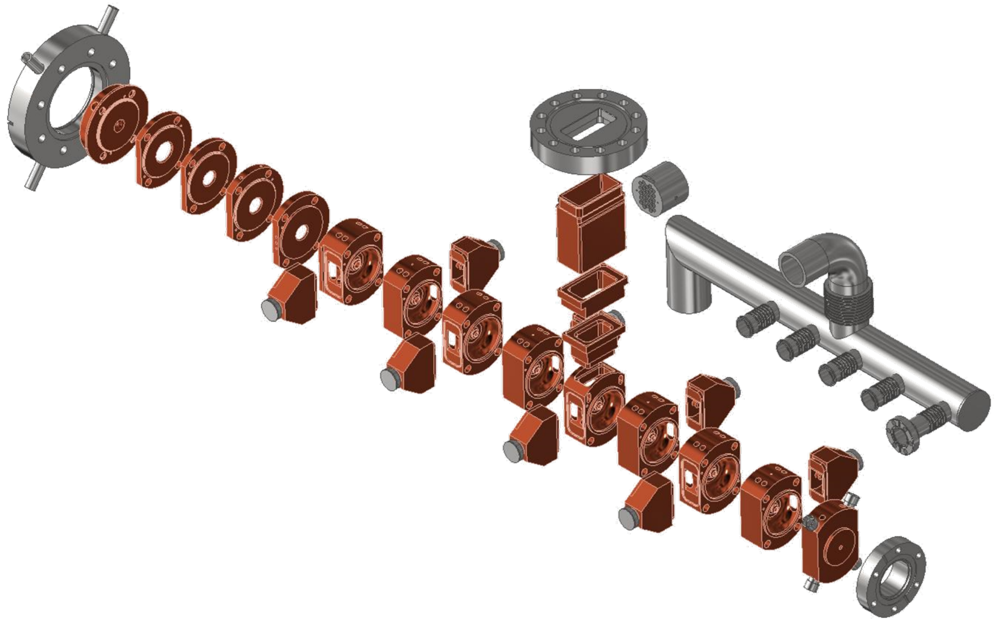


- **Side-coupled standing-wave structure**
- **To be installed in a gantry**

Apart from the side-coupled structure,
the longitudinally-split type should be promising for normal-conducting linear colliders.

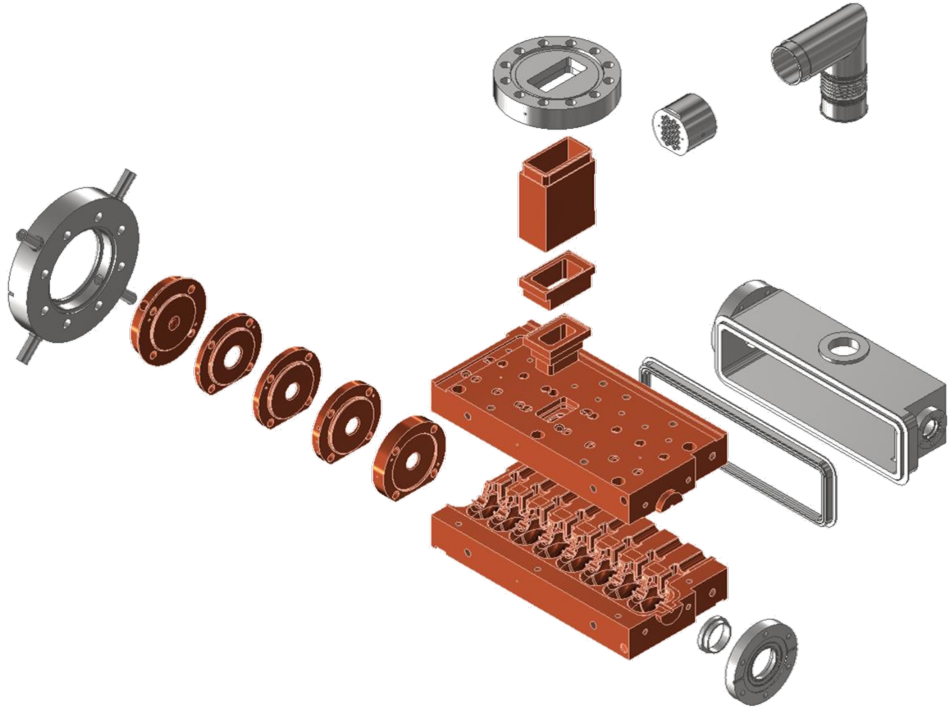
Conventional-versus-New

Conventional disk type structure consisting of 59 parts



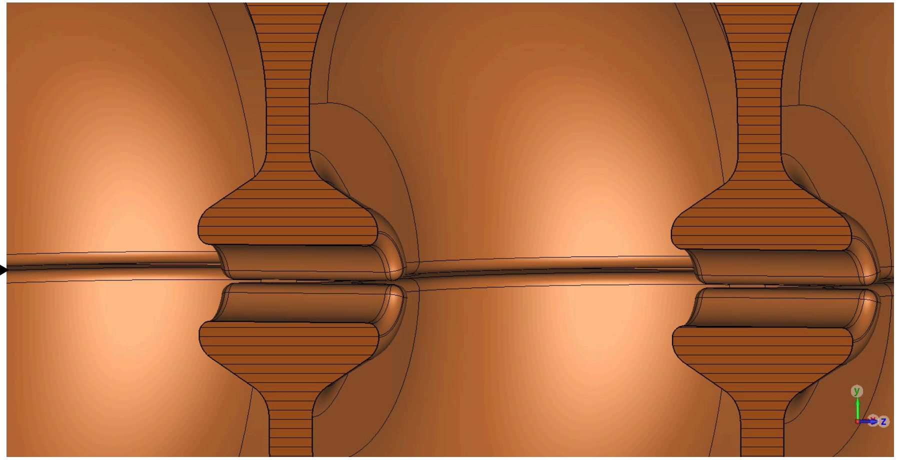
Brazed into one through two steps

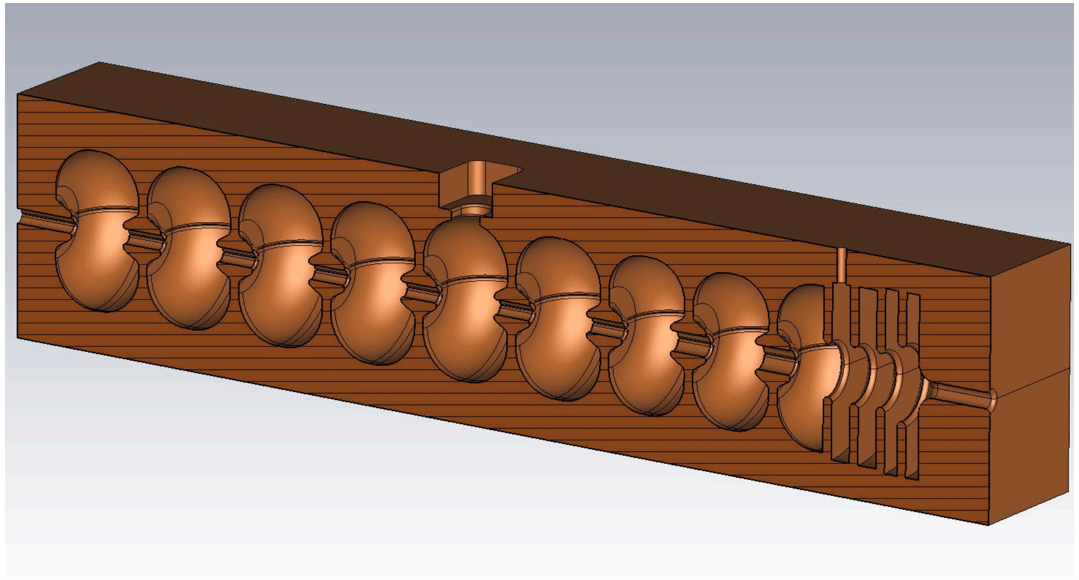
Longitudinally-split type structure consisting of 25 parts

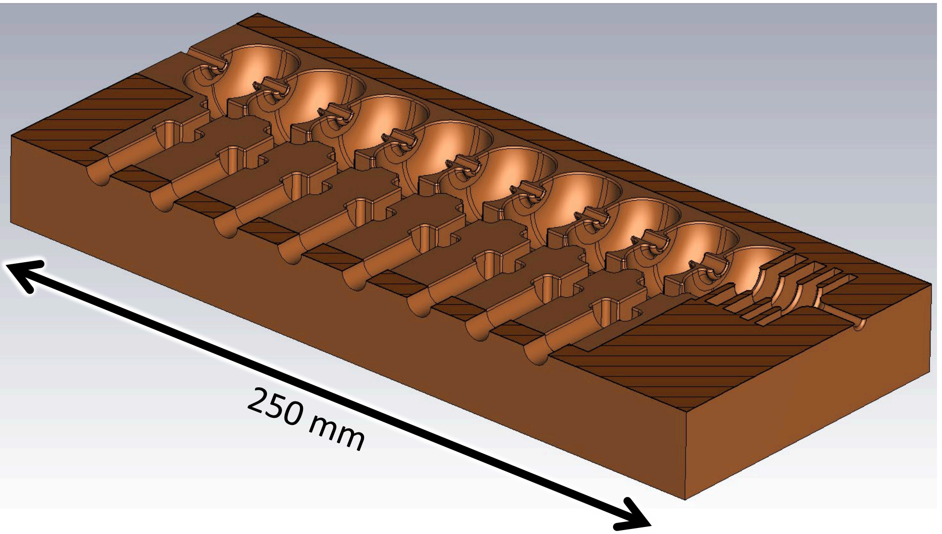


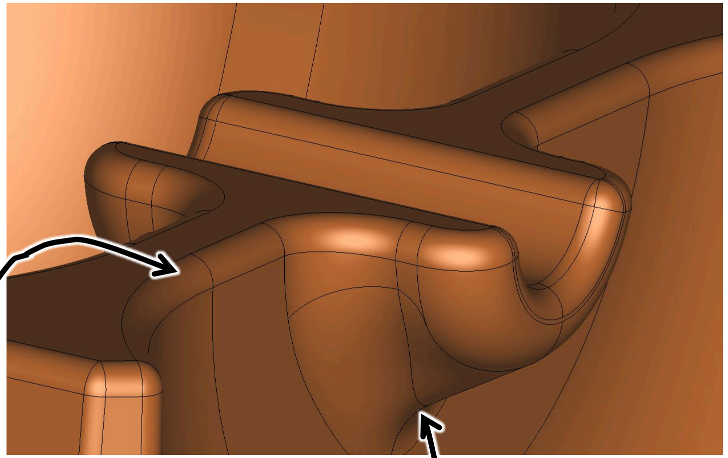
To be brazed into one in a single step

New design features









PATPEND
(PCT/JP2023/023388)

- ✓ Small gap (0.1 mm)
- ✓ Large round chamber (R0.6mm)
- ✓ Nose cones with:
  - ➢ Long protuberance for high shunt impedances
  - ➢ “Skirt” for cost-effective machining
    - → Final machining easily possible with a single milling tool
    - → Tiny deterioration in Rsh (< 0.1%)
- ✓ Coupling cavities to one side for material saving

Comparison with the earlier development

Our structure

For β=1 cells

$$\frac{R_{sh}}{L} = \sim 140\ \mathrm{M\Omega/m}$$

at 5.7 GHz (C-band)

$$\frac{R_{sh}}{L} = \sim 180\ \mathrm{M\Omega/m}$$

at 9.3 GHz (X-band)

Higher shunt impedance!

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ACCELERATORS OF CHARGED PARTICLES FOR NUCLEAR TECHNOLOGIES

Electron Accelerator for Replacement of Radioactive Sources in Insect Sterilization Facilities

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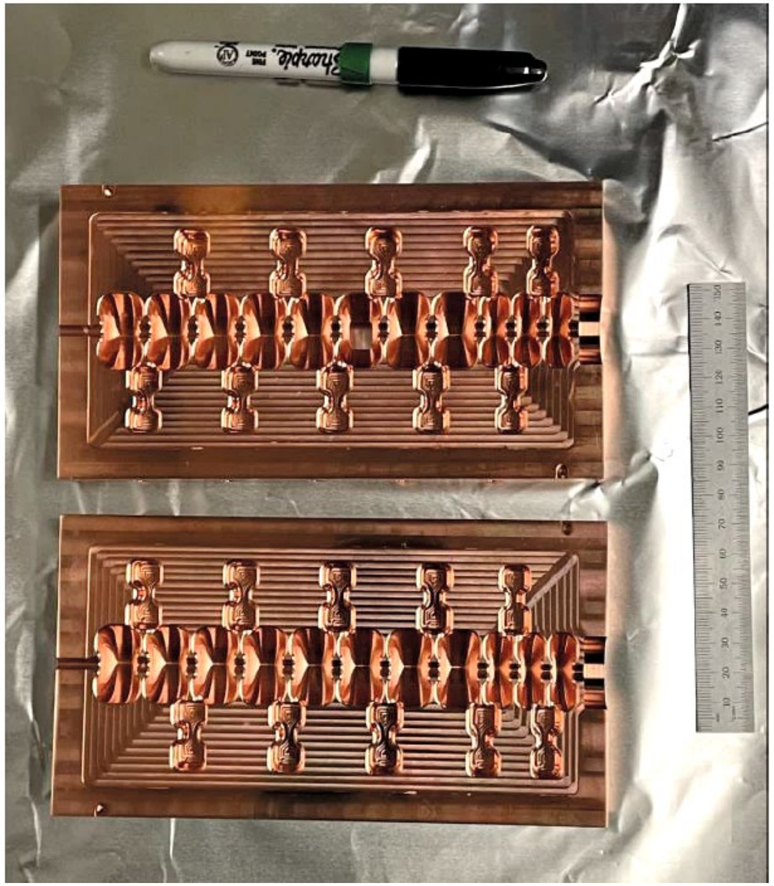


For β=1 cells

$$\frac{R_{sh}}{L} = 124.3\ \mathrm{M\Omega/m}$$

at 9.3 GHz (X-band)

High-power test of a single-cell test cavity

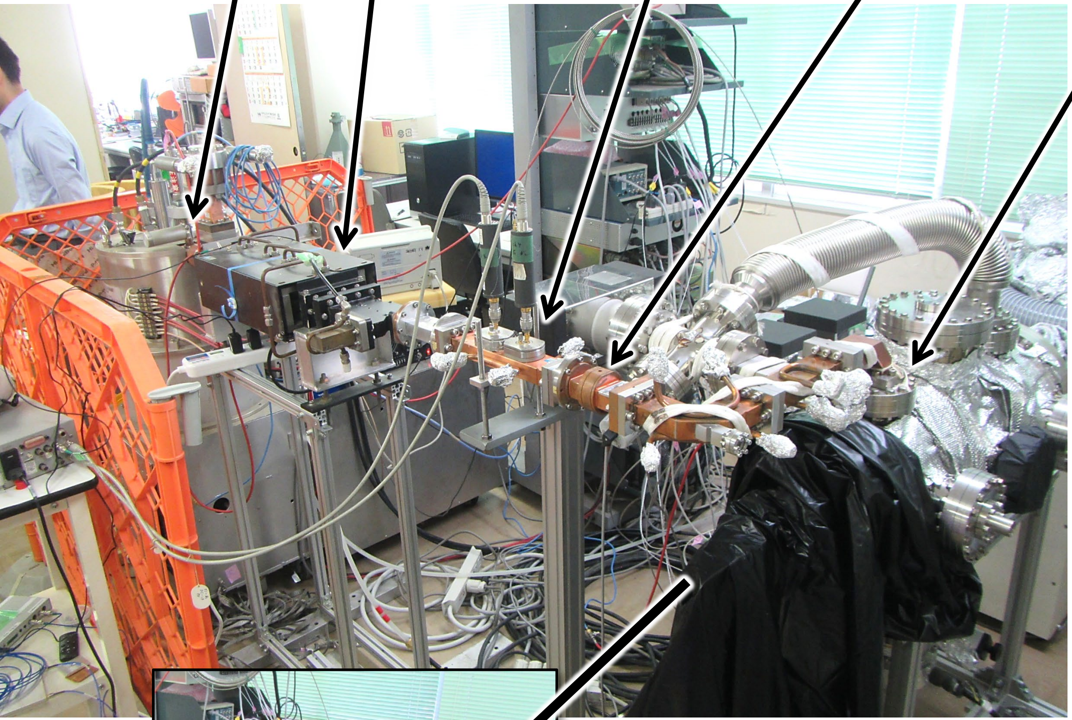
150 kW (max) C-band klystron
(4 µs, 40 Hz)

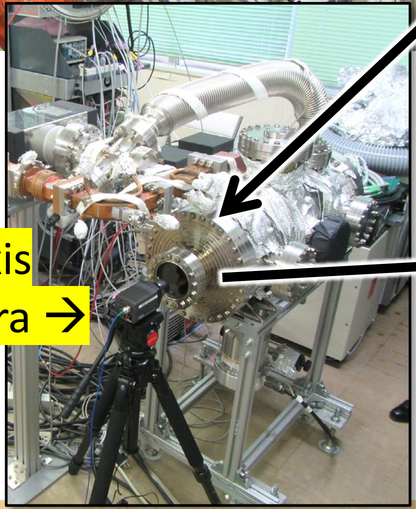
Circulator

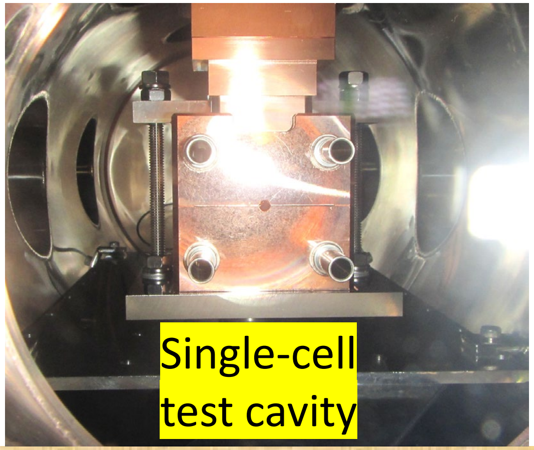
Directional coupler

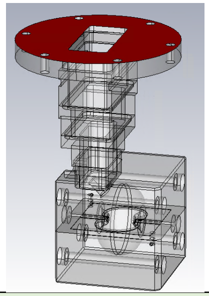
RF window

Vacuum chamber

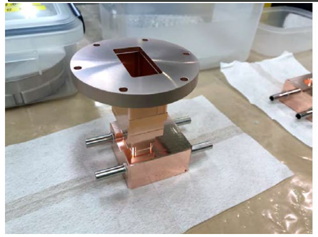


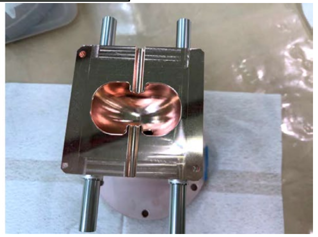






- ✓ Ra ≈ 0.6 µm
- ✓ Q_0(meas)/Q_0(sim) = 99.9%
- ✓ Profile accuracy: ~20 µm

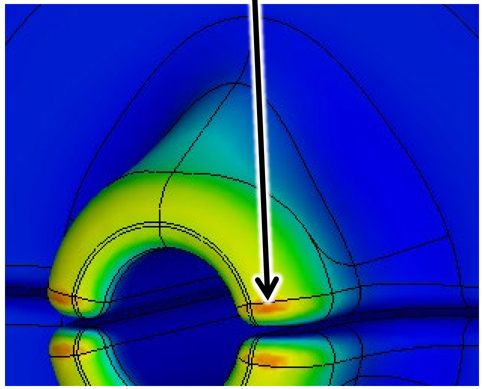


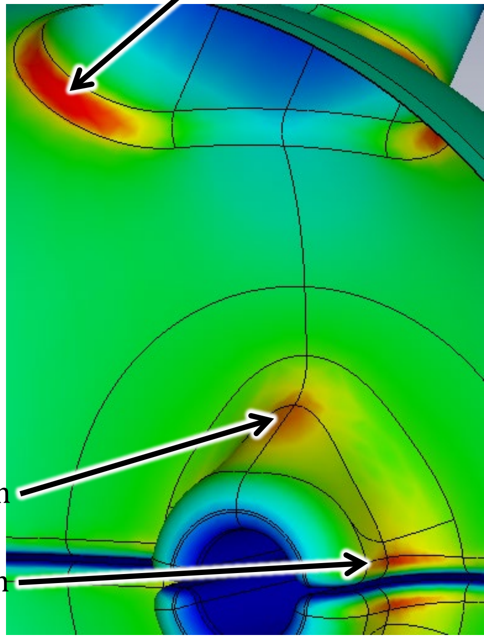


Surface field at $P_{inp} = 150$ kW
($E_{acc} = \sim 30$ MV/m)

$E_{surf}^{(max)} = \sim 170$ MV/m

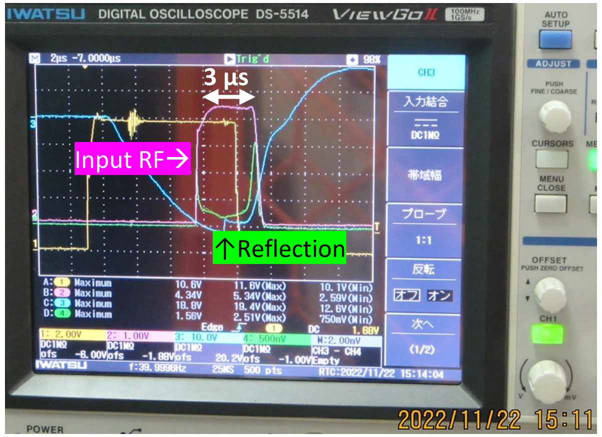
$H_{surf}^{(max)} = \sim 140$ kA/m



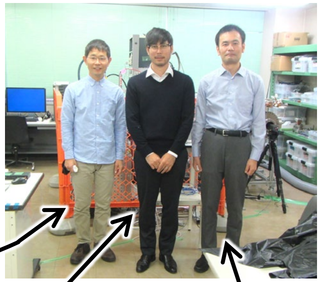


$H_{surf} = \sim 120$ kA/m

$H_{surf} = \sim 130$ kA/m

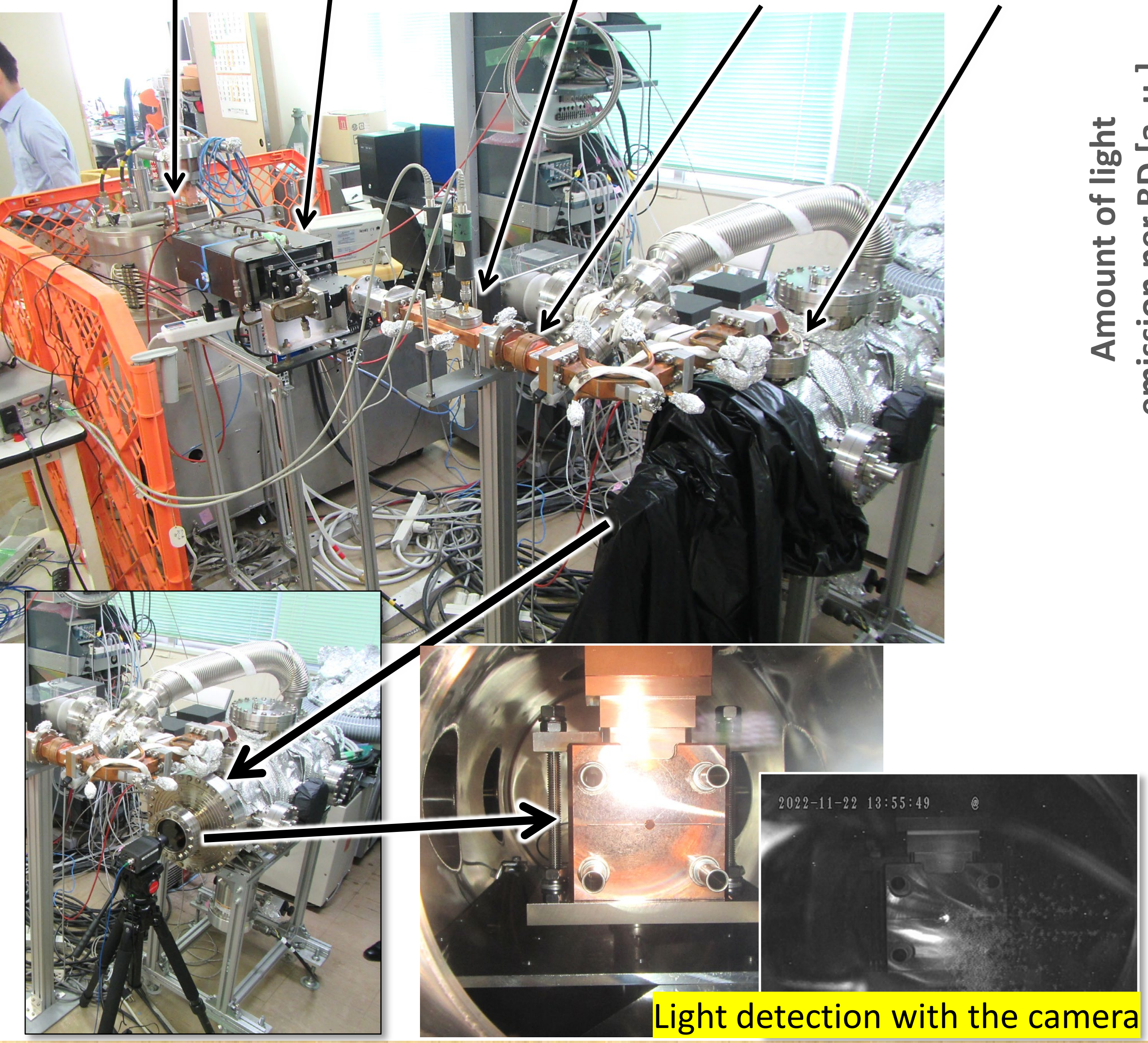


Core members of the development team

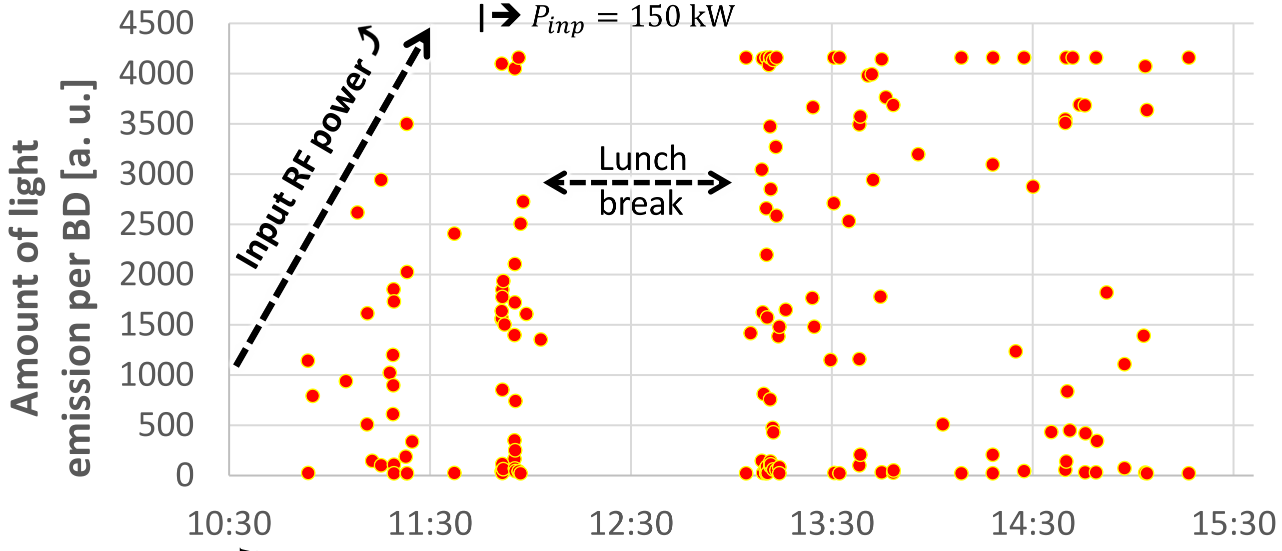


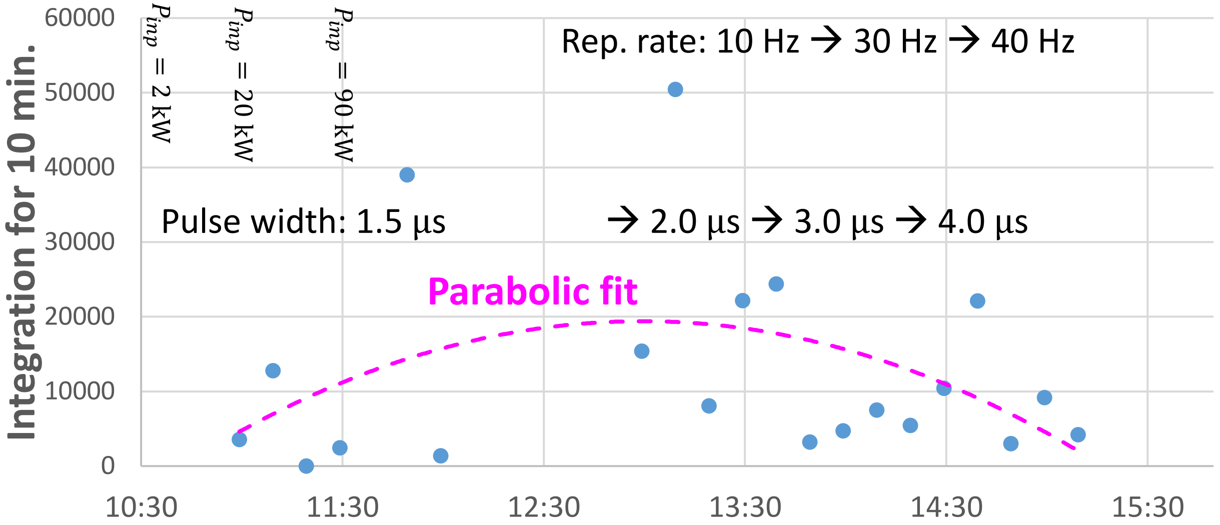
Masashi KIMURA , Nobuyuki SHIGEOKA (MHI-MS)

High-power test result of the single-cell test cavity



One-day high-power RF conditioning history

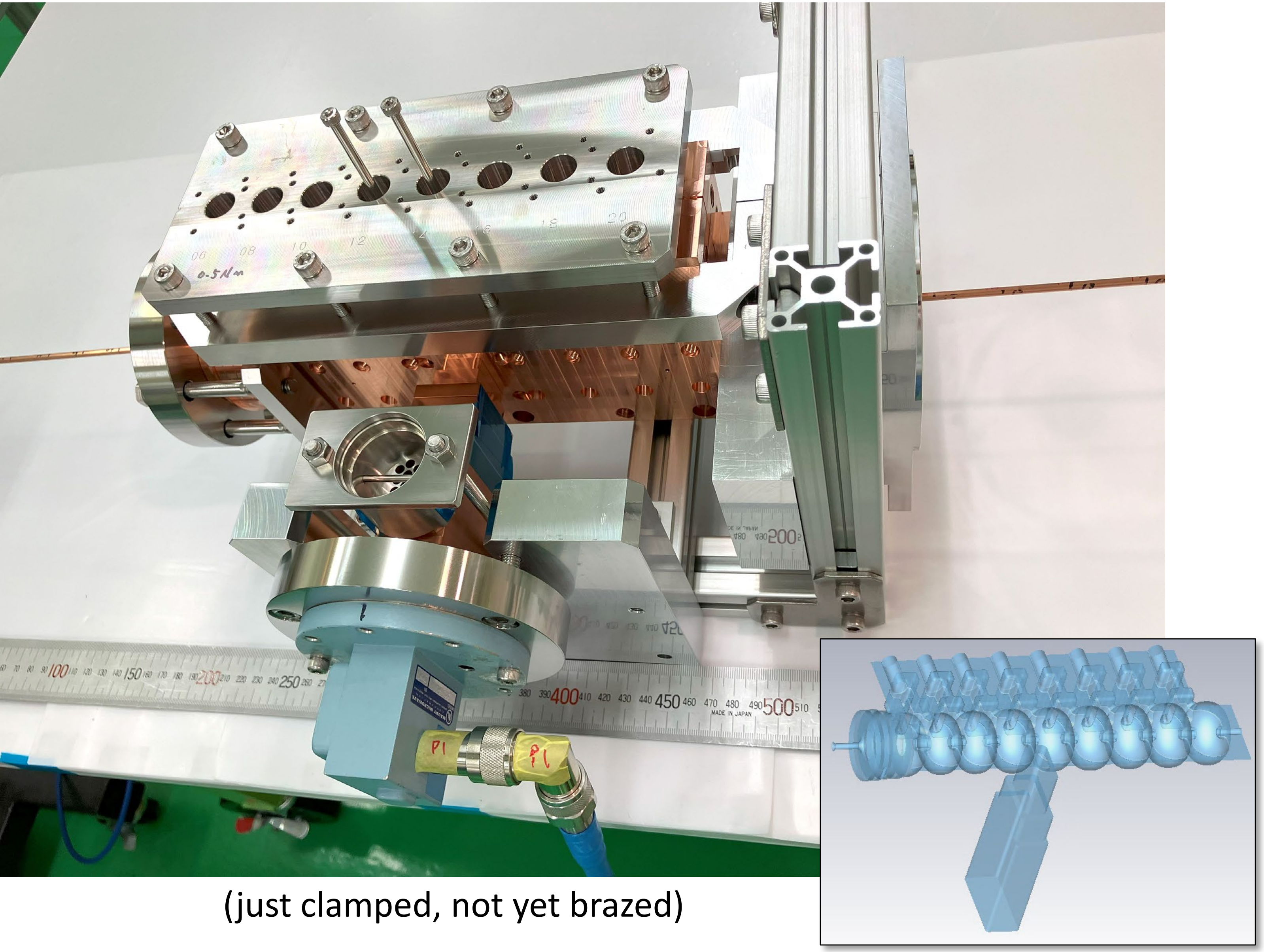




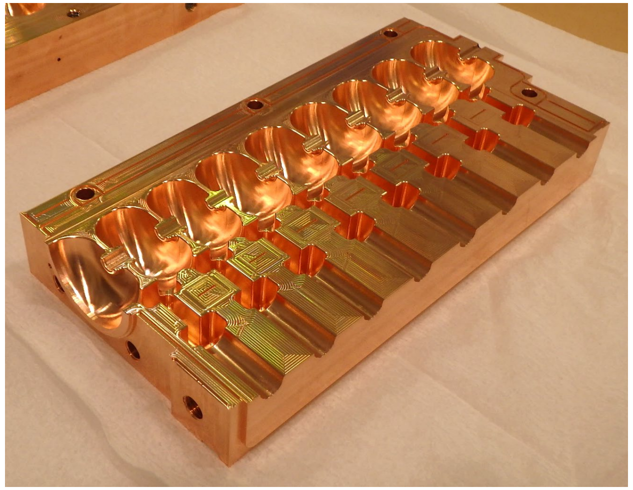
The average amount of light emissions at BDs decreased even though with higher rep. rates and longer pulse widths

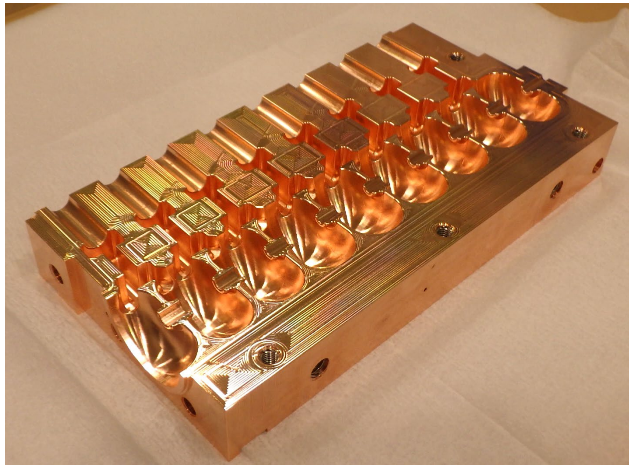
→ Good conditioning effect seen in a day!

Fabrication of a full-scale prototype (2024)



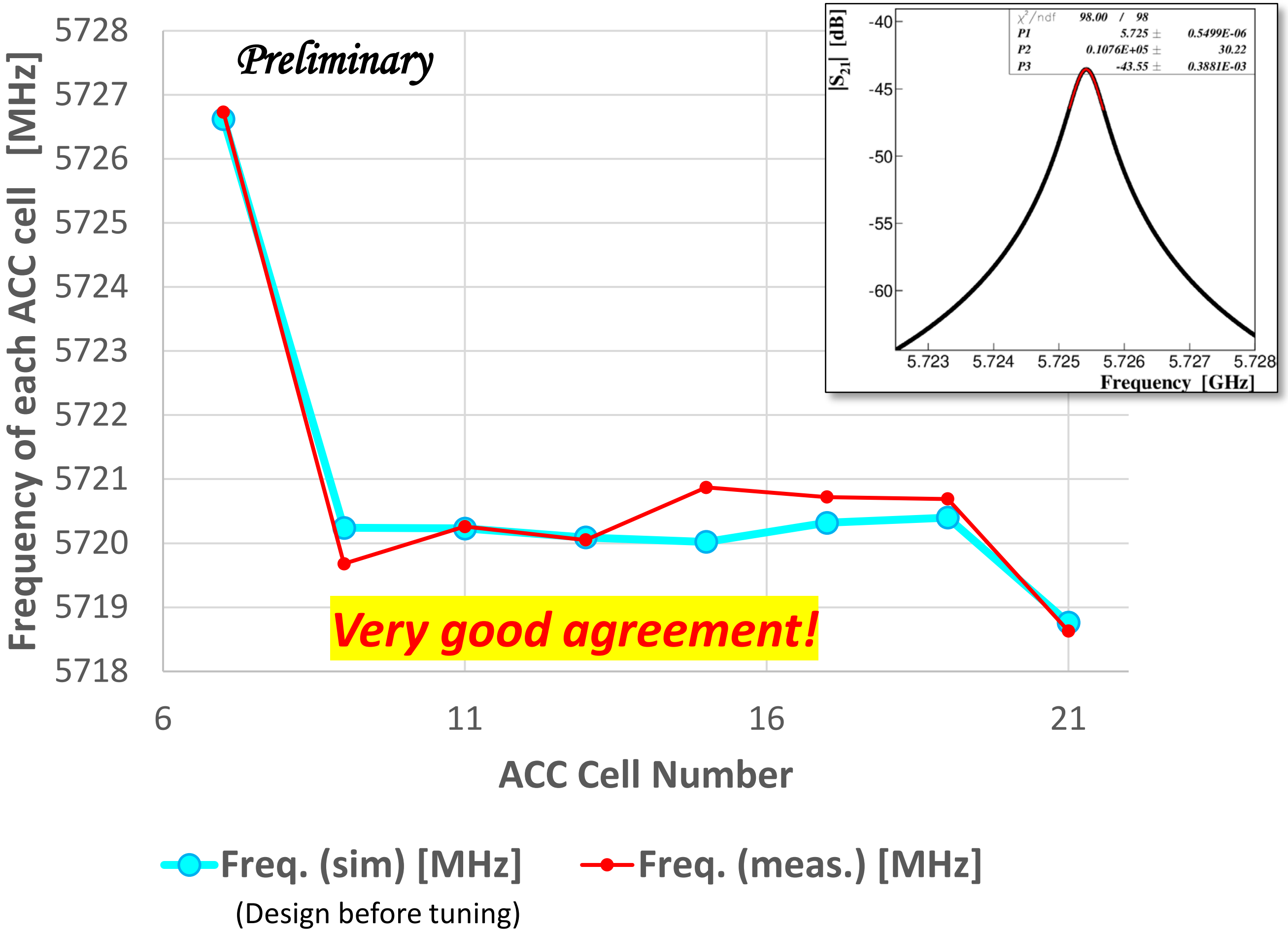
(just clamped, not yet brazed)

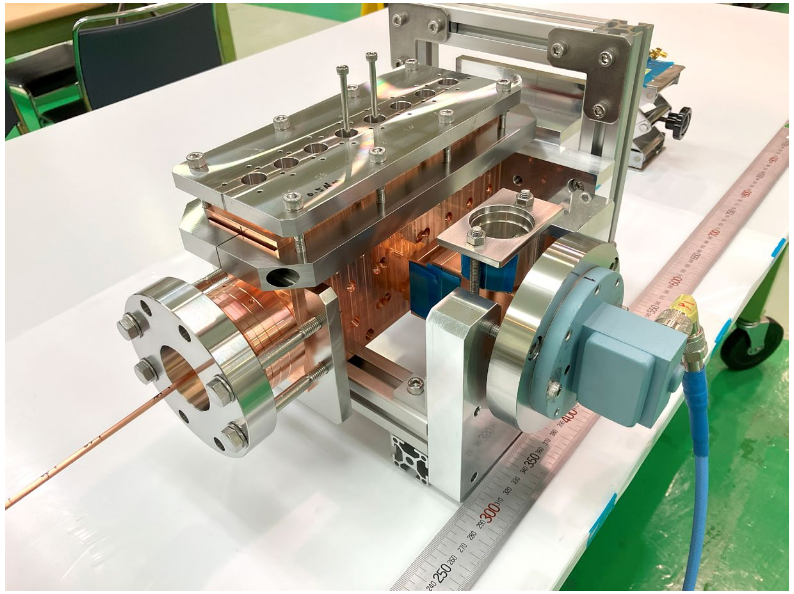


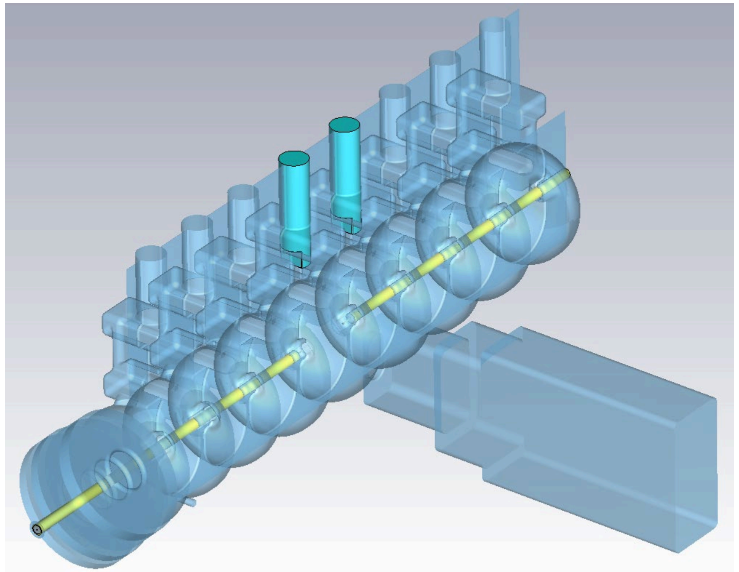


Low-power RF measurement: frequency of ACC each cell

- ✓ Before bonding (brazing)
- ✓ No frequency tuning yet



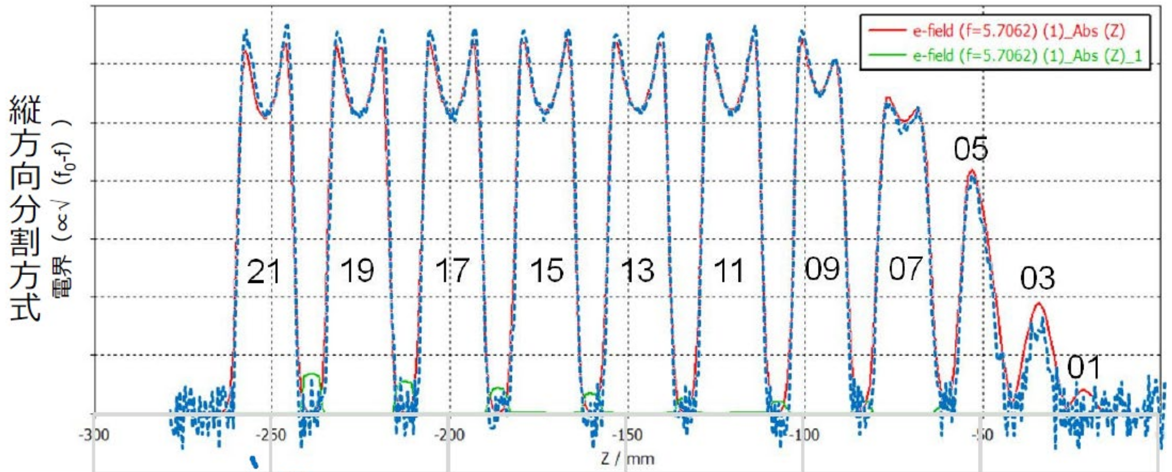


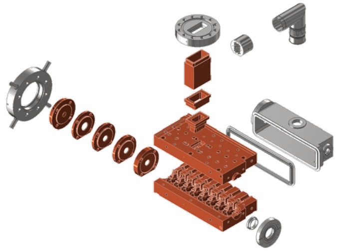


Low-power RF measurement: bead-pull

Longitudinally-split type

Preliminary



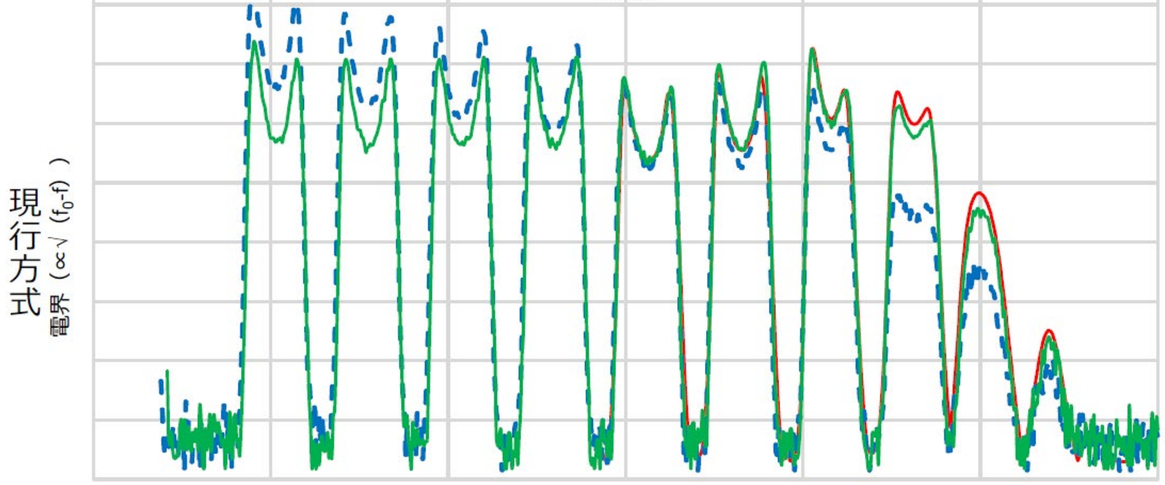


Red: simulation (design)

Blue: meas. before freq. tuning (before brazing)

Very good agreement with the design even before tuning!

Conventional disk type

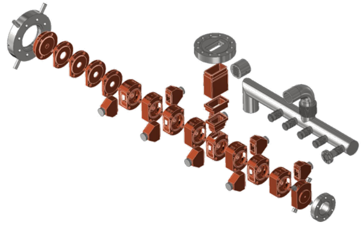


Red: simulation (design)

Blue: meas. before freq. tuning (after brazing)

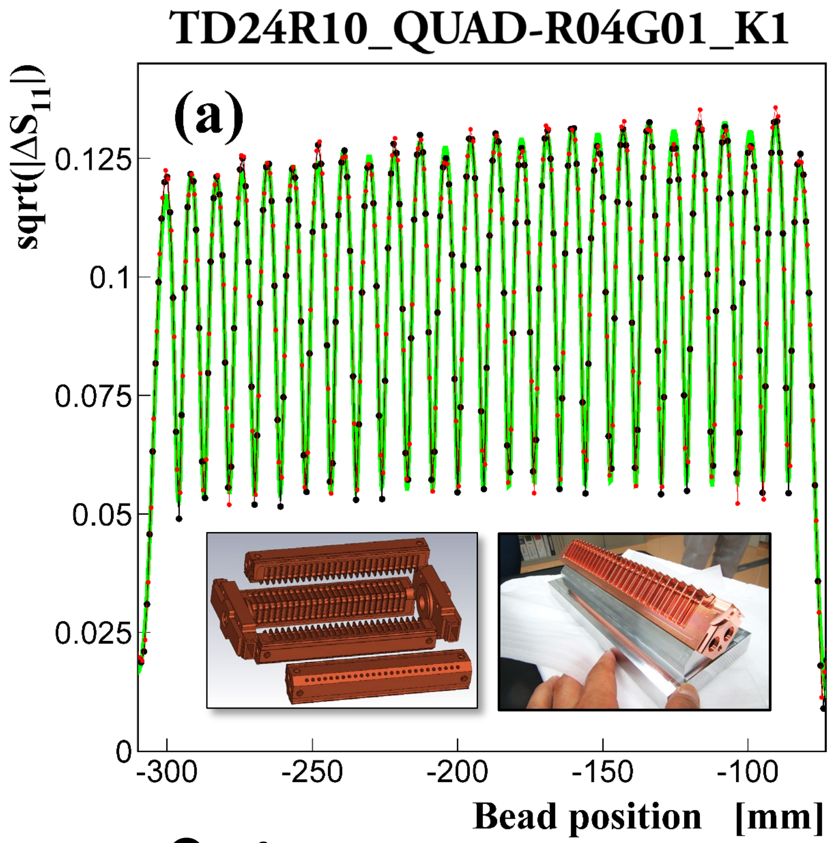
Green: meas. after freq. tuning (≈ design)

Significant difference between before and after tuning



[Cf.] Bead-pull meas. for CLIC prototype WG-damped accelerating structures (traveling wave) before freq. tuning

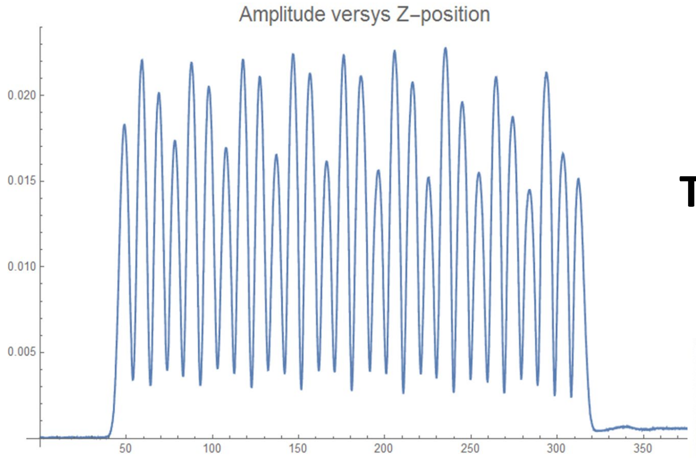
Longitudinally-split type



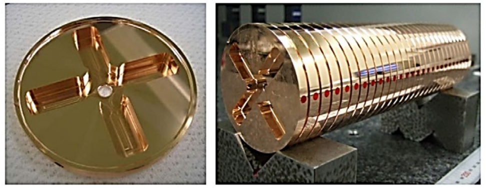
Before EBW
After EBW
--- Design

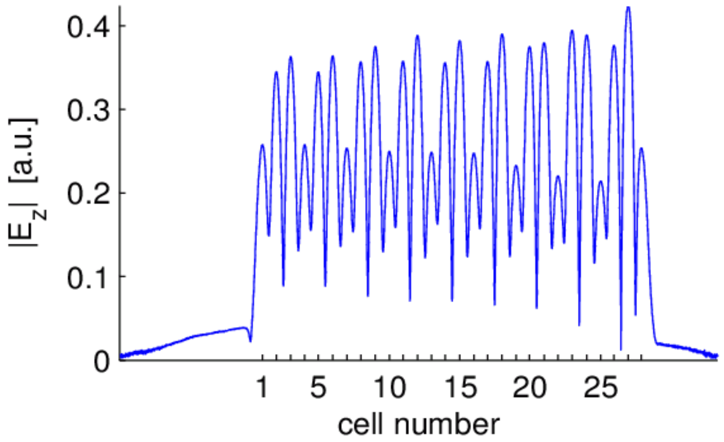
Very good agreement even before tuning!

Disk type



TD26CC-K1





TD26-CLEX-N6

Large standing wave before tuning

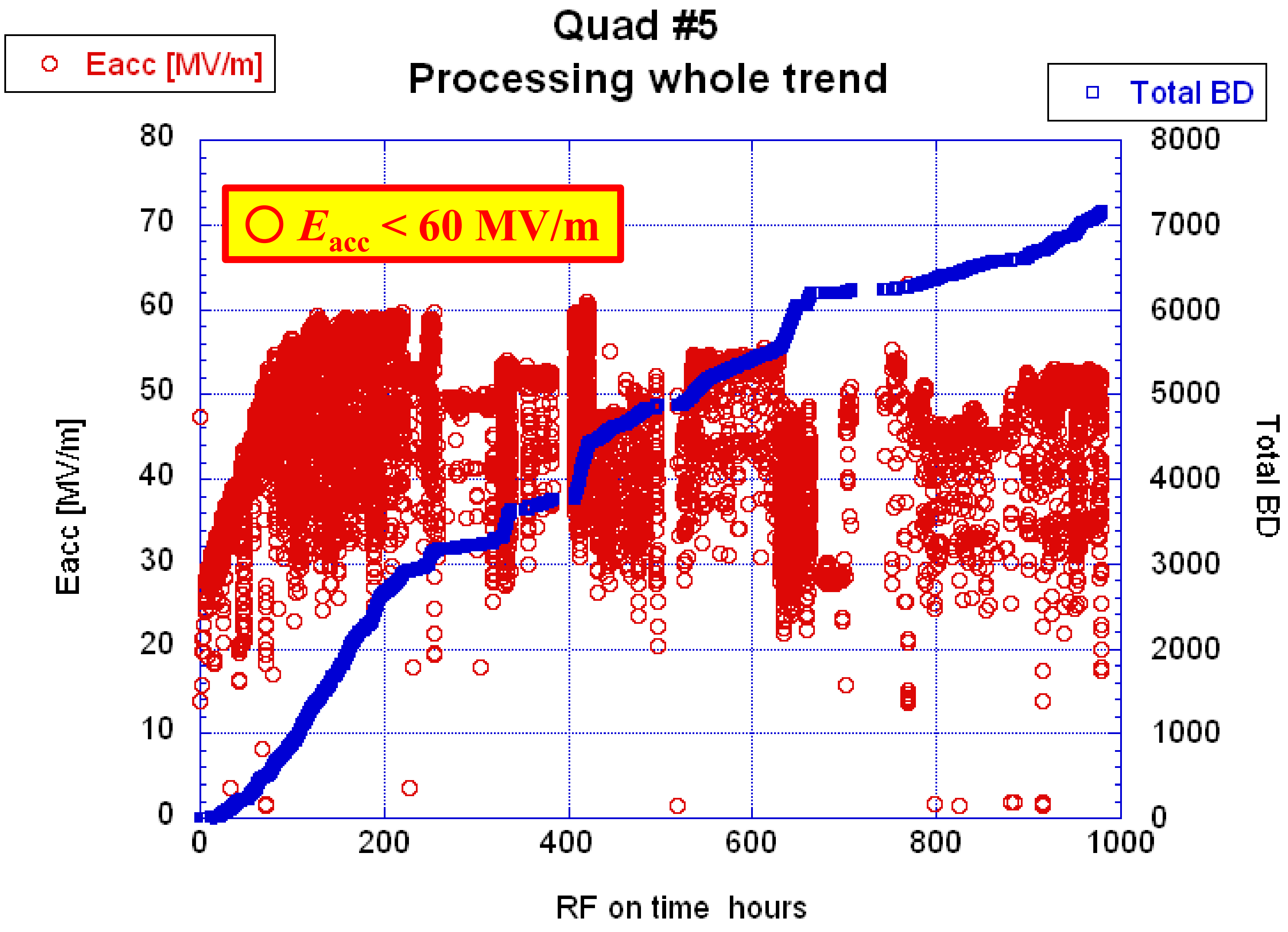
Summary and future plans

- We have established the longitudinally-split structure fabrication method at X-band.
  - Demonstrated by the high-gradient test for the single-cell structure
  - Not yet demonstrated for the full-scale structure
- We are applying it to the compact medical linac (C-band).
  - High-power performance demonstrated for the single-cell structure
  - Full-scale prototype fabrication just completed
  - The measured cell frequencies and field profile are in very good agreement with the design even before frequency tuning
  - Feeling superiority of the longitudinally-split structure fabrication method over the disk-type one
  - Schedule:
    - Brazing and frequency tuning to be performed soon
    - First beam test to be perform in the near future
      - → Measuring energy spectra, radiation doses, and yield of X-ray
      - → Feedback to the 2nd prototype
- Quantitative comparison of cost-effectiveness between the longitudinally-split and disk-type fabrication methods for the linac with (almost) the same specifications to estimate sustainability effects

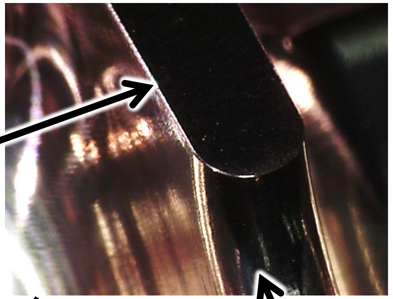
Thank you for your attention

Backup slide

HG test of TD18_QUAD at Nextef1 in 2009



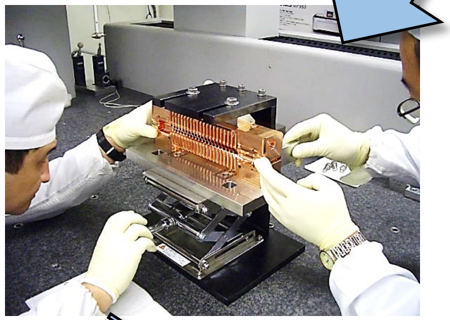
Ultraprecision machining (profile tolerance: 5μm)

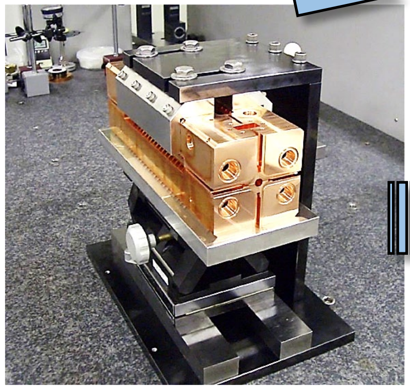


R50μm round chamfer

Iris

Precision alignment (5μm)





No bonding among the quadrants

Into a vacuum chamber