The 2024 International Workshop on the High Energy Circular Electron Positron Collider

# HIGH GRADIENT ACCELERATOR TECHNOLOGY DEVELOPMENT IN TSINGHUA UNIVERSITY

Jiaru Shi

on behalf of VIGAS team in THU

2024.10.24

# OUTLINE

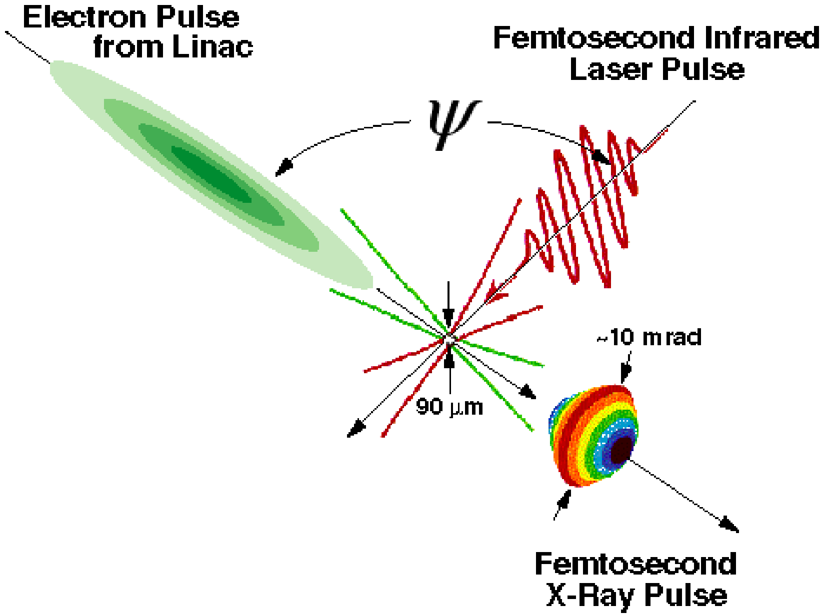
- Introduction
- Overview of VIGAS Accelerator System
- Development of X-band High-gradient structures
- Progress of the project
- Summary

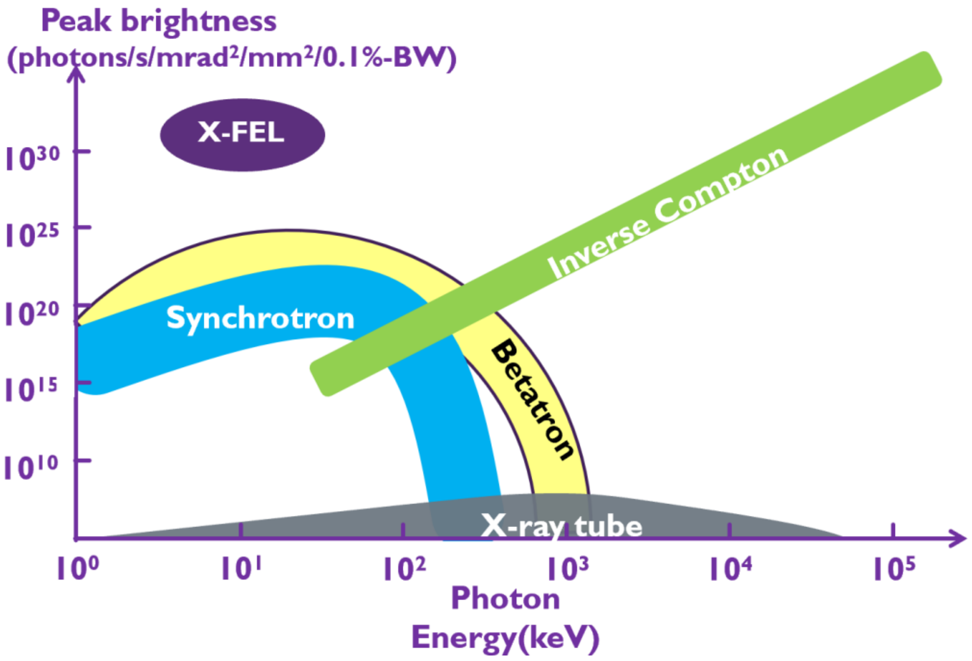
# INTRODUCTION

# INTRODUCTION

VIGAS: **V**ery compact Inverse-Compton-scattering **GA**mma-ray **S**ource

ICS




**Characteristics**

- Quasi-monochromatic
- Continuously adjustable X-ray energy
- Small source size ~10um
- Controllable polarization
- Ultra-short pulse length (fs~ps)

**Advantages**

- High peak brightness
- Gamma-ray
- Compact
- Affordable

# INTRODUCTION

Goals of VIGAS project:

- Gamma-ray energy: 0.2~4.8 MeV continuously adjustable
- Gamma-ray energy spectrum bandwidth(rms): <1.5% (w/ collimator)
- Photon production (photon/s):
  - $>4\times10^8$ @0.2~2.4 MeV; $>1\times10^8$ @2.4~4.8 MeV
- Photon production in 1.5% bandwidth (photon/s):
  - $>4\times10^6$ @0.2~2.4 MeV; $>1\times10^6$ @2.4~4.8 MeV
- Polarity: adjustable from linear to circular

# INTRODUCTION

- Gamma-ray energy: 0.2~4.8 MeV continuously adjustable

  Collision angle between electron bunch and laser: 180 degree

$$E_\gamma = \frac{4\gamma^2}{1 + \frac{a_0^2}{2} + \gamma^2\theta^2} E_L$$

$E_\gamma$ : Gamma energy
$E_L$ : Laser energy
$\gamma$ : Electron energy
$a_0$ : Normalized vector potential
$\theta$ : Observation angle

Laser energy:

- 800 nm: 1.54 eV
- 400 nm: 3.08 eV

- 200 keV gamma-ray @800nm & 92MeV electron
- 2.4 MeV gamma-ray @800nm & 320MeV electron
- 4.8 MeV gamma-ray @400nm & 320MeV electron

- Electron energy
  - Maximum > 320 MeV
  - Minimum < 92 MeV

# INTRODUCTION

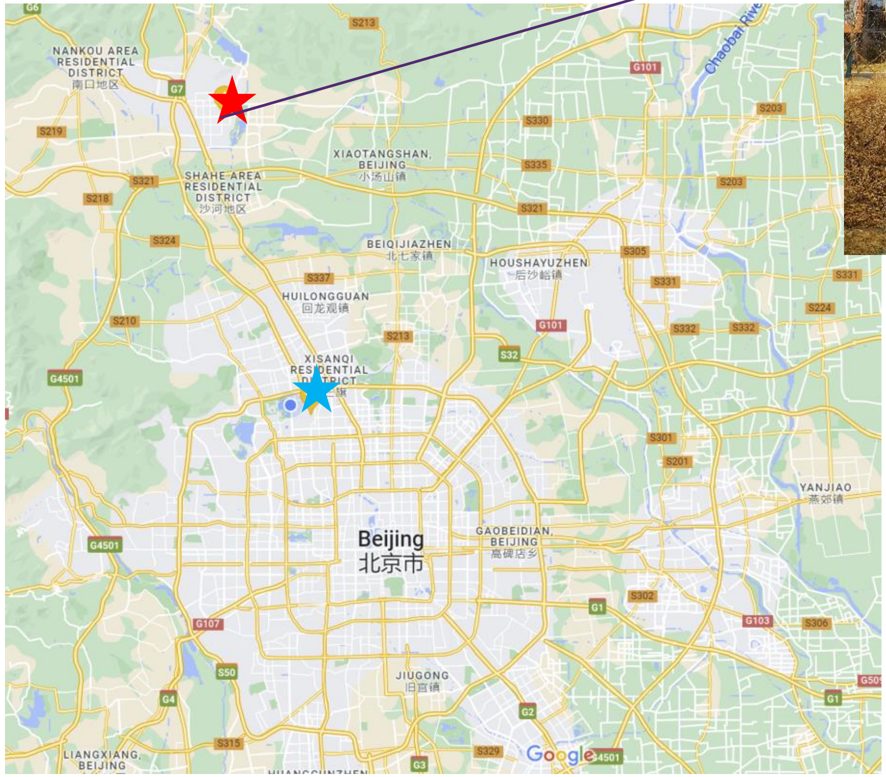
## Design parameters of accelerator system for VIGAS

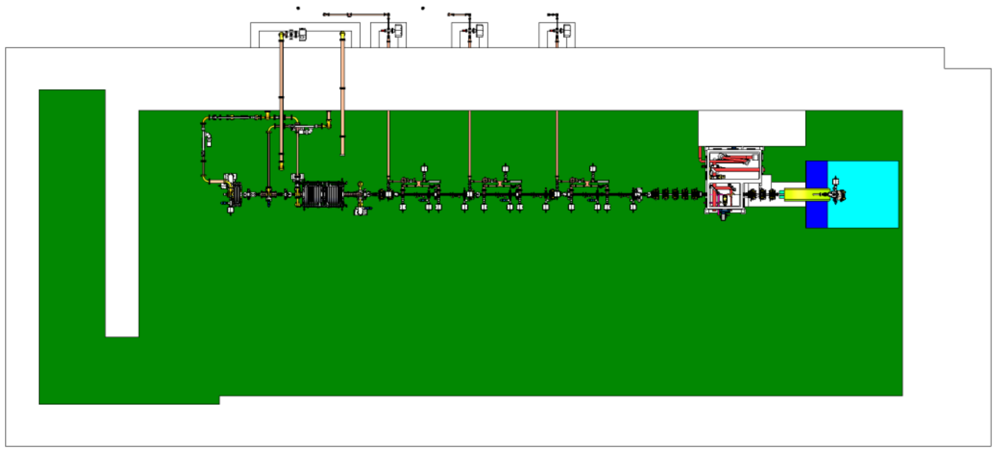
| Properties | Value |
|---|---|
| Electron energy | 50-350 MeV tunable |
| Charge | >= 200 pC |
| Normalized emittance | < 0.6 mm mrad |
| RMS bunch length | < 2 ps |
| RMS energy spread | < 0.3 % |
| RMS beam size at interaction point | < 20 um |
| Repetition | 10 Hz |

# INTRODUCTION

VIGAS: 5-year project funded by NSFC, led by Prof. Tang Chuanxiang.

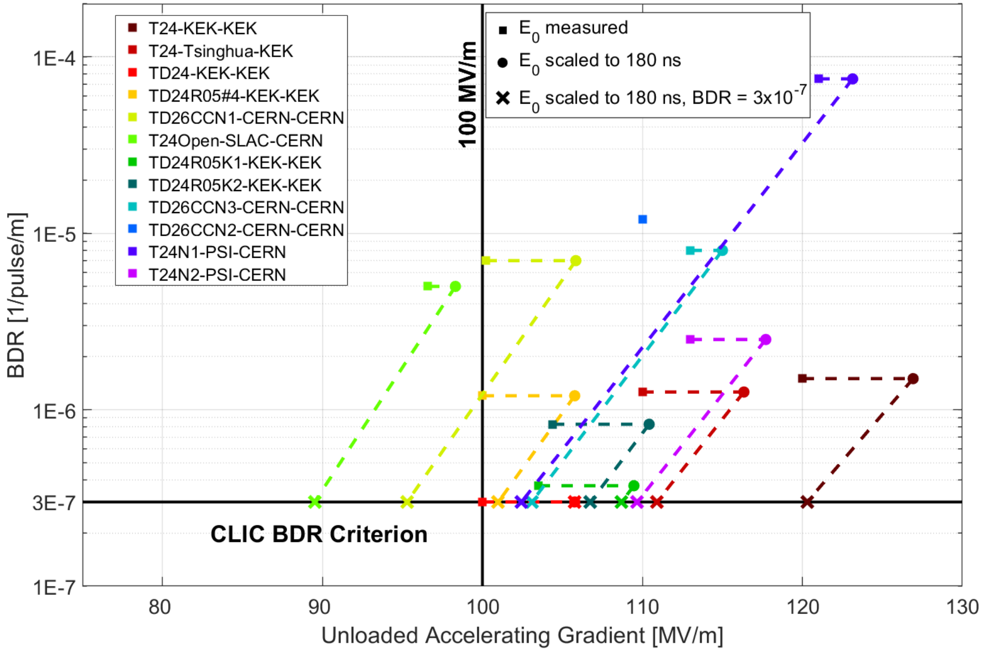
Building area ~ 48,000m$^2$
Bunker for VIGAS accelerator:
21m × 10 m



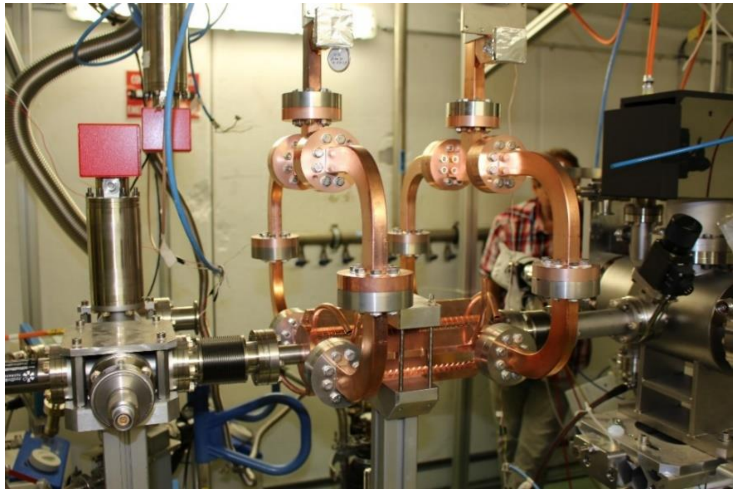



# X-BAND HIGH-GRADIENT ACCELERATING STRUCTURE AS MAIN LINAC

- X-band Normal Conducting technology was proposed for linear collider NLC/JLC, CLIC …
- > 100MV/m demonstrated globally
- ~km facility
- requires very low breakdown rate




- 80MV/m 62.5cm @ 11.424GHz chosen as the main linac design for our **12m-long 350MeV very compact facility**



https://doi.org/10.1103/PhysRevAccelBeams.21.061001,
https://doi.org/10.1103/PhysRevAccelBeams.20.052001

# OVERVIEW OF ACCELERATOR SYSTEM

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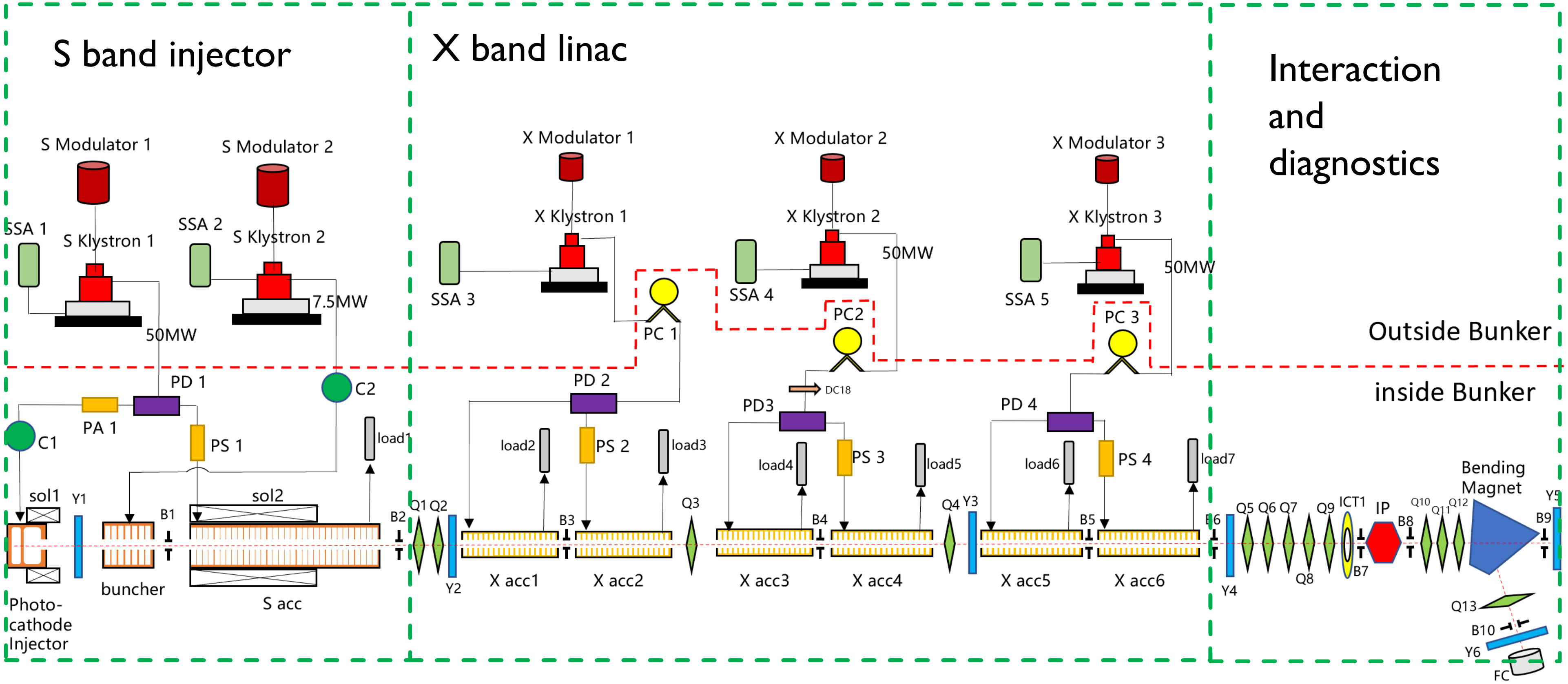
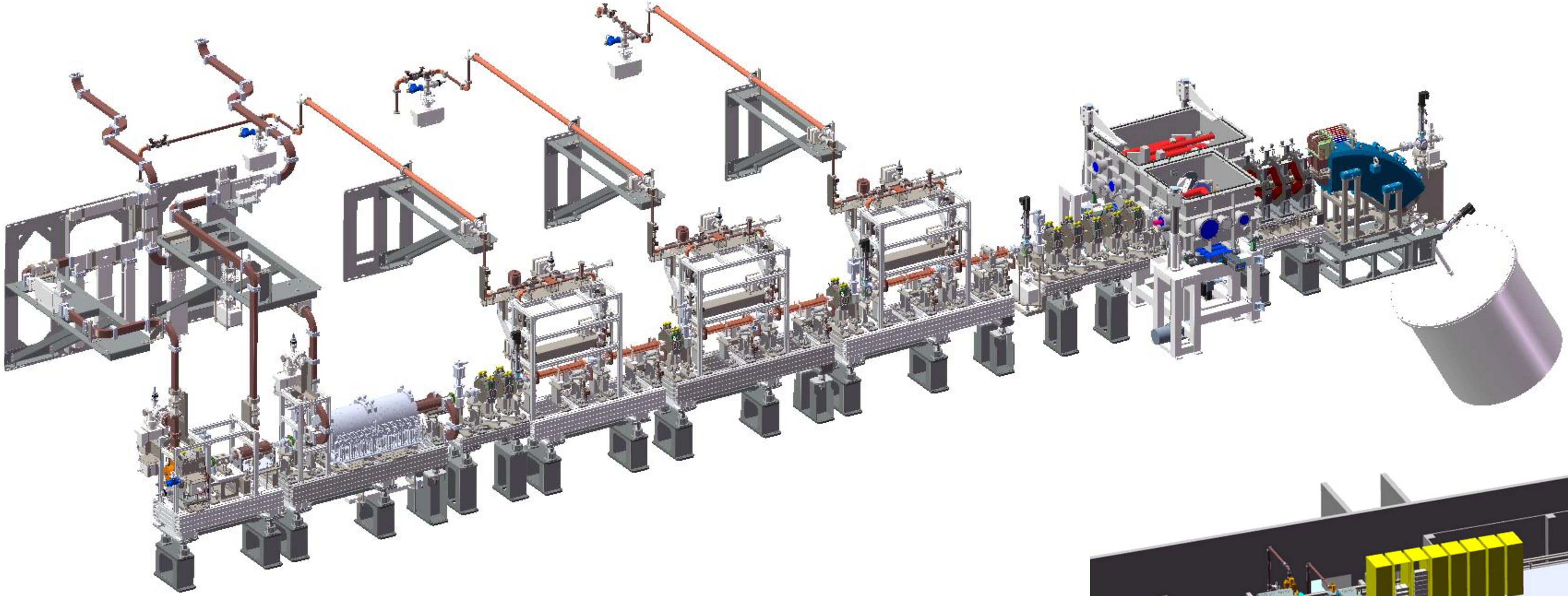
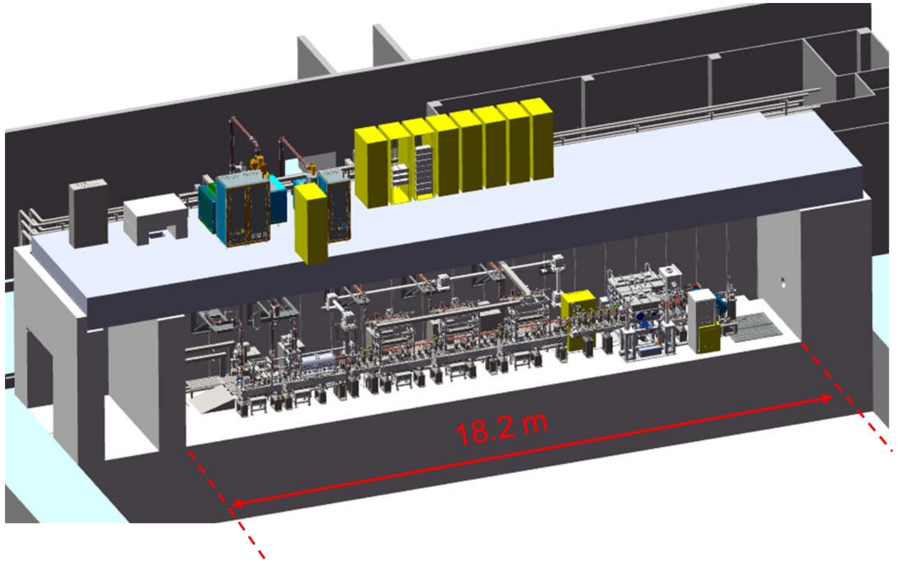



| Abbreviation | ACC | B | C | FC | ICT | IP | PA | PC | PD | PS | Sol | Y | Q |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Description | Accelerating Structure | Beam Position Monitor | Circulator | Faraday Cup | Integrating Current Transformer | Interaction Point | Power Attenuator | Pulse Compressor | Power Divider | Phase Shifter | Solenoid | YAG: Ce Screen | Quadrupole |

# OVERVIEW OF ACCELERATOR SYSTEM



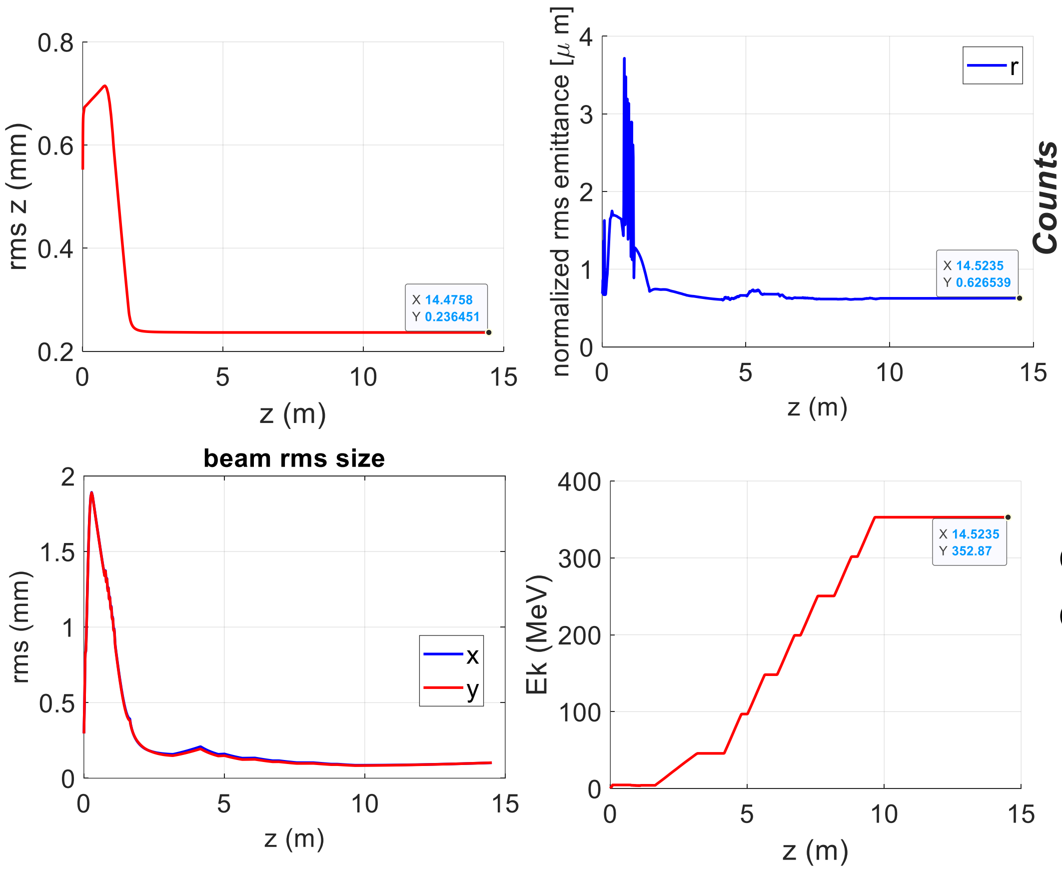


# BEAM DYNAMICS AND PHOTON GENERATION SIMULATION

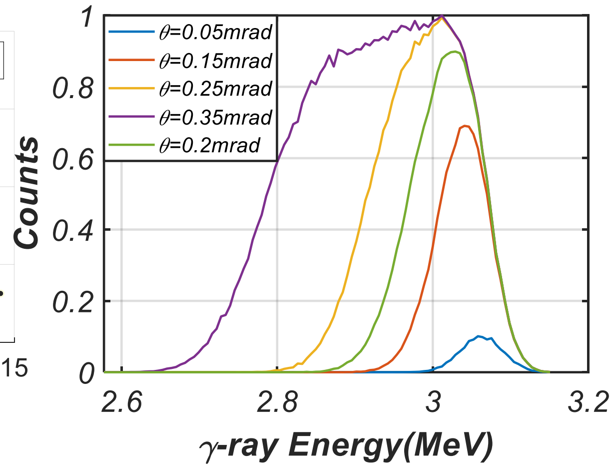
- S-band injector and X-band main linac
  - S-band RF buncher
  - 50-350MeV beam
  - 0.6mm*mrad
  - < 2ps, E spread <0.3%
  - Size <20um
  - Transverse jitter <3um
  - Rep. 10 Hz
- In simulation (CAIN)
  - Photons at 200pC, 10Hz
  - 2e9@800nm photons/s
  - 5e8@400nm photons/s

  - For 1.5% bandwidth fact of 1/100

S-band RF buncher



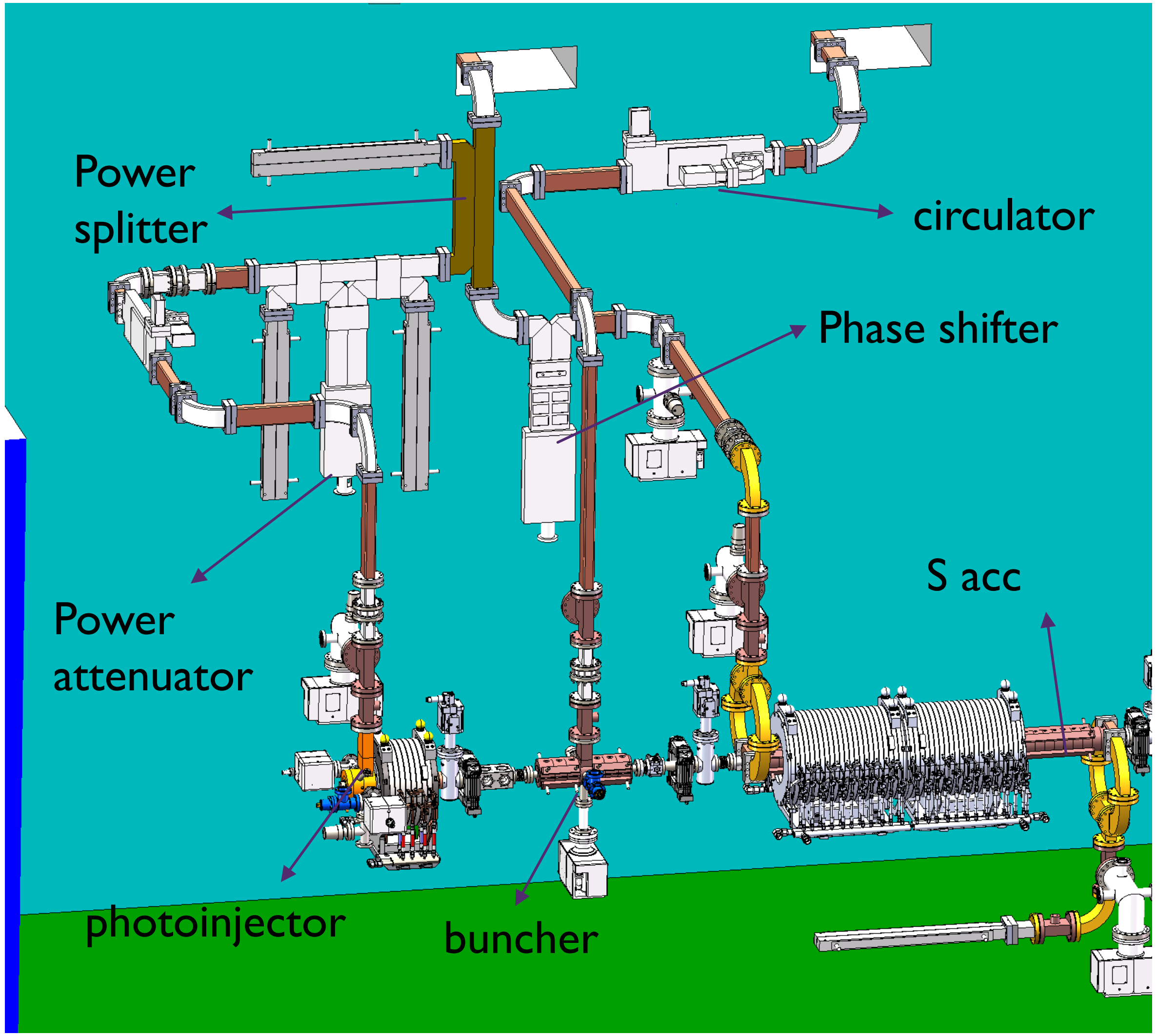

Beam parameters in simul.




Gamma Spectrum v.s. c angle
Case:360MeV-200pC-800nm

# S BAND INJECTOR

# S BAND WAVEGUIDE SYSTEM

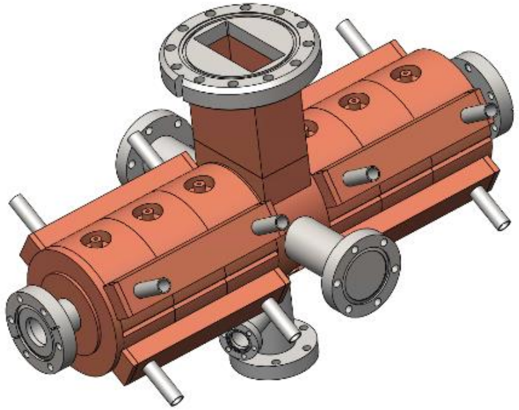



- 50 MW power from Canon E3730A feeds for photoinjector and S acc
  - 5dB power splitter
  - Phase shifter for S acc phase control
- 7.5 MW power from Canon E3772A feeds for buncher
- Consider RF loss due to waveguides and components:

| | Transmitted power (MW) | Needed power (MW) |
|---|---|---|
| Photoinjector | 11.7 | 7 |
| S acc | 29 | 21 |
| buncher | 6.4 | 3 |

# S BAND PHOTOCATHODE RF GUN, BUNCHER, ACC @ 2856MHZ

| Parameters | Value | Unit |
|---|---|---|
| $Q_0$ | 14000 | |
| E field on cathode | 100-120 | MV/m |
| Emitting charge | >200 | pC |
| Cathode material | Copper | |
| Quantum efficiency | $4 \times 10^{-5}$ | |
| Emittance | <0.6 | um |



7-cell Standing-wave
As buncher

1.5m long
Travelling-wave
Acc. Structure

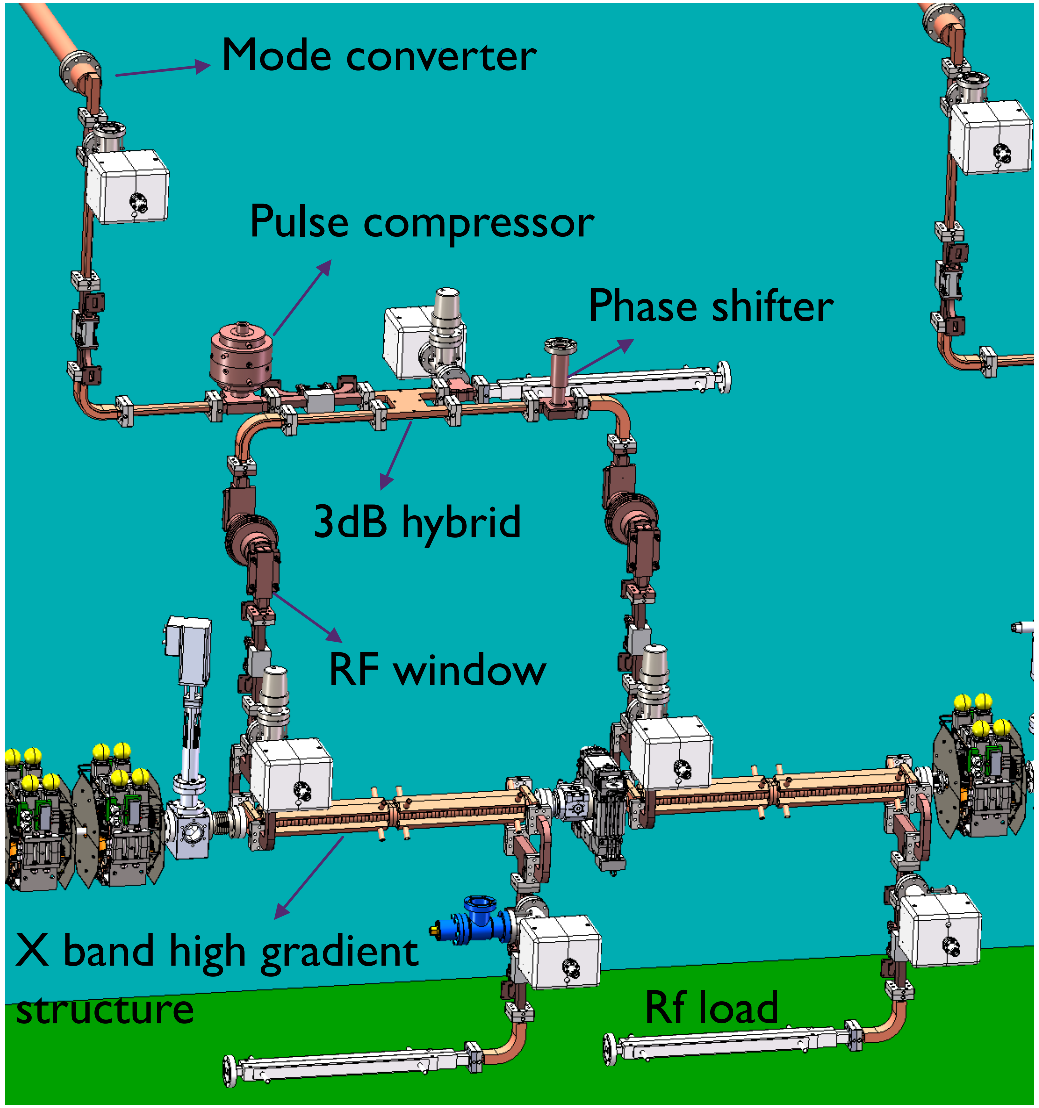
@135°

30MV/m @ 30MW

Zheng, Lianmin, et al. *NIMA* 834 (2016): 98-107.

# X BAND MAIN LINAC

# X BAND MODULE

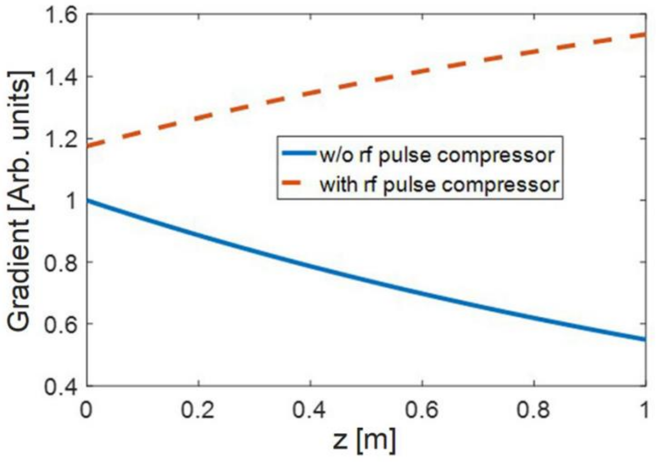


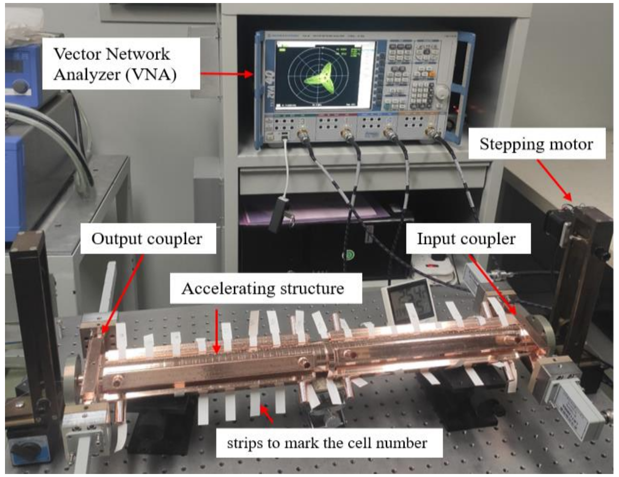

- One klystron
  - 50 MW, 1.5us
- One pulse compressor (SLED I type)
- Two X band high gradient structures
  - Average gradient >= 80 MV/m
  - Energy gain per structure > 50 MeV
  - Filling time < 150 ns
- rf loss from klystron to Xacc ~ 0.9dB
- 91 MW at Xacc w/ PC gain factor as 4.5

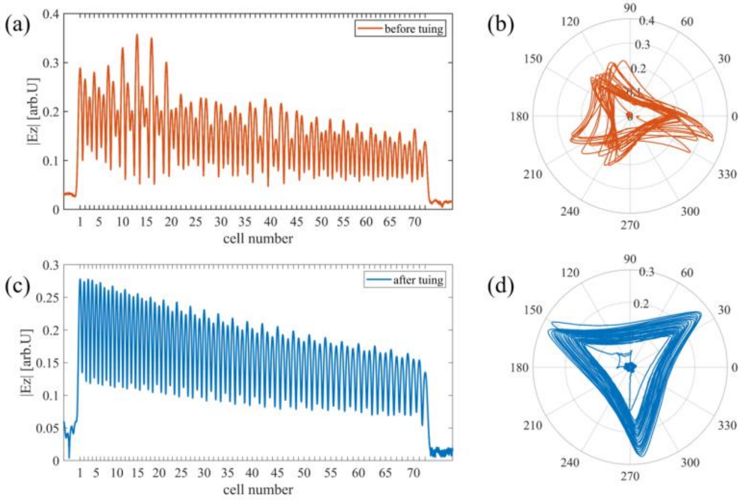
| | | | |
|---|---|---|---|
| XT72 | 6 | P.C. | 3 |
| mode convrt. | 6 | phase shifter | 3 |
| circ. wg | 6 | D.C. | 24 |
| RF window | 6 | pump. port | 21 |
| E-bend (90) | 20 | RF load | 9 |
| H-bend (U+90) | 24+6 | straight wg | 30 |
| H-T | 12 | 3dB hybrid | 3 |

# X BAND HG STRUCTURE

- The output pulse of a SLED-type pulse compressor decreases over time, which makes the field seen by the electron higher at the end of the linac when operating.
- This effect was alleviated in a constant-impedance (CI) structure due to the power loss along the linac.
- As a result, the CI structure has similar effective shunt impedance with the CG (constant-gradient) structure when operating with a pulse compressor.
- Considering the cost, CI structure was adopted at the beginning.



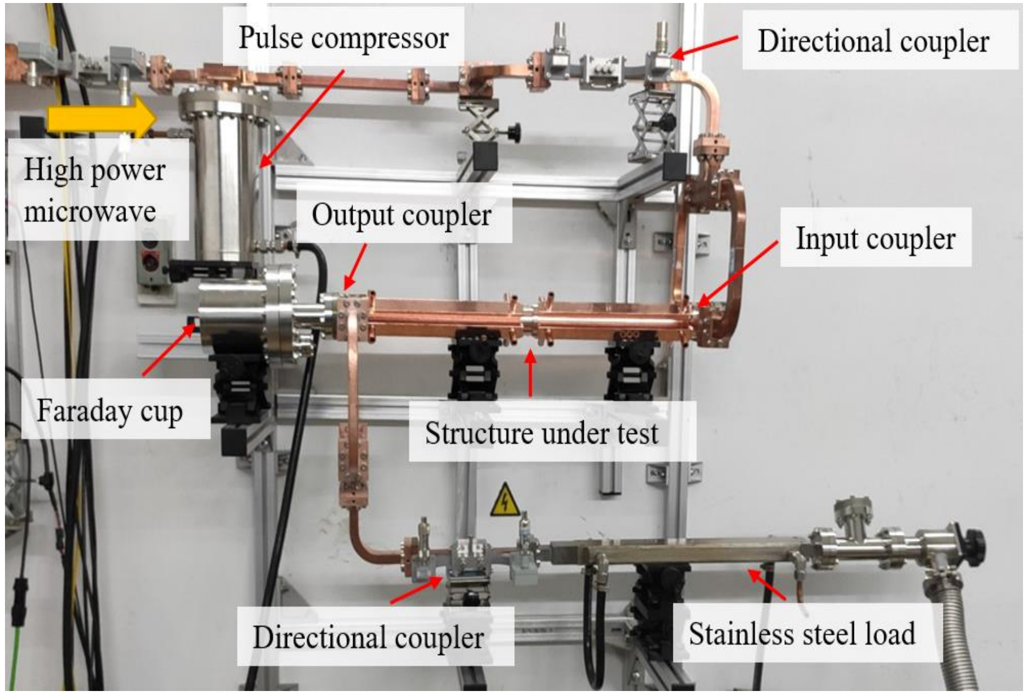



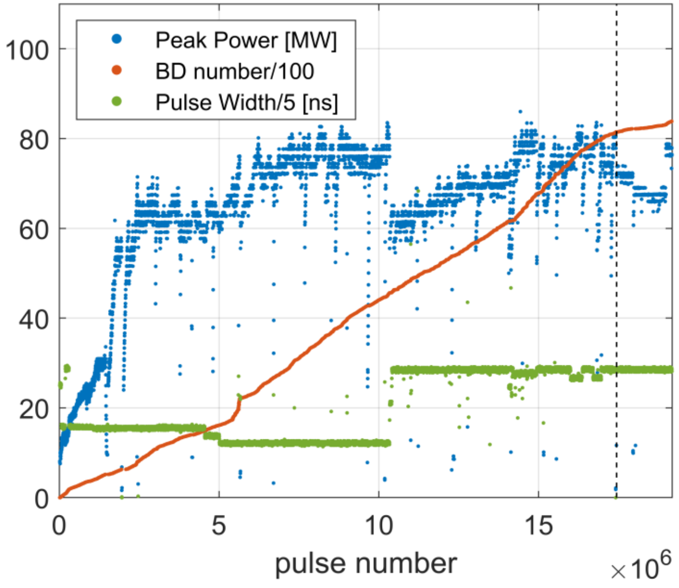



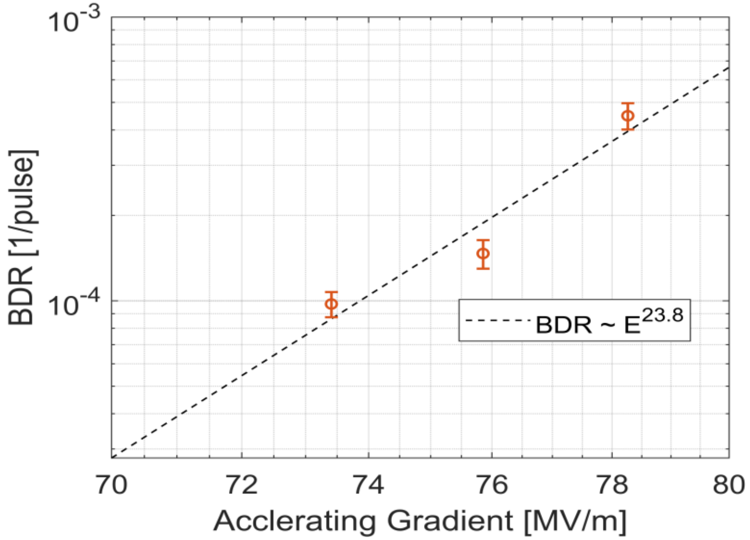

[1]Liu, J., et al., NUCL SCI TECH **31**(11): 1-11.   [2] Lin, Xiancai, NST

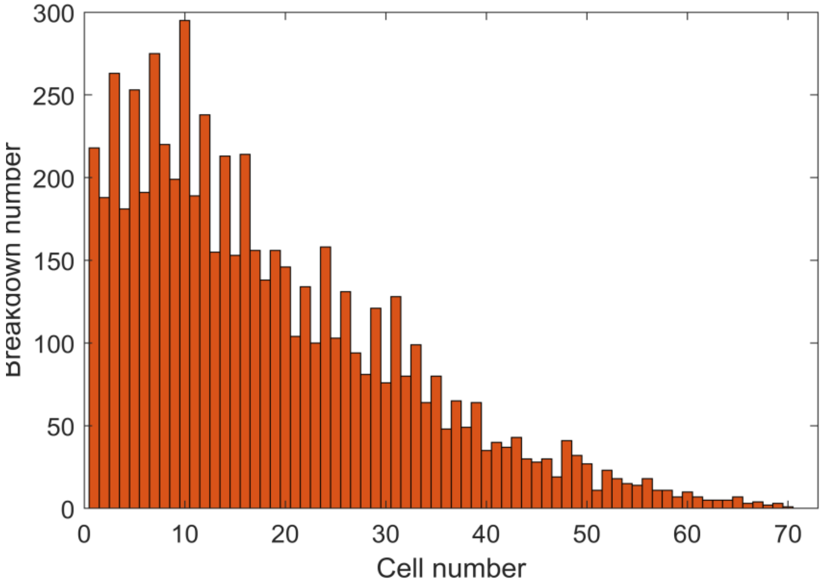
# X BAND HG STRUCTURE

- High power test with pulse compressor on
- 17 M pules conditioning +2M pulses
- Maximum gradient: ~ 80 MV/m @80 MW
- Total breakdown number: 8.4×10³, BDR~E^30
- Breakdown location strongly correlated to field in the structure
- In the 1st cell, Esurf ~220MV/m Sc~5



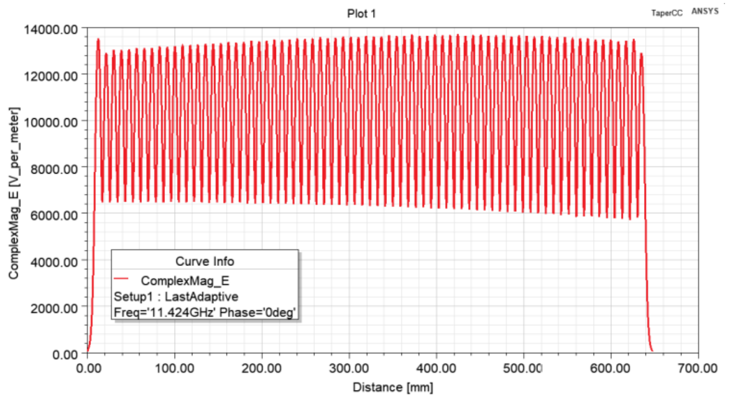



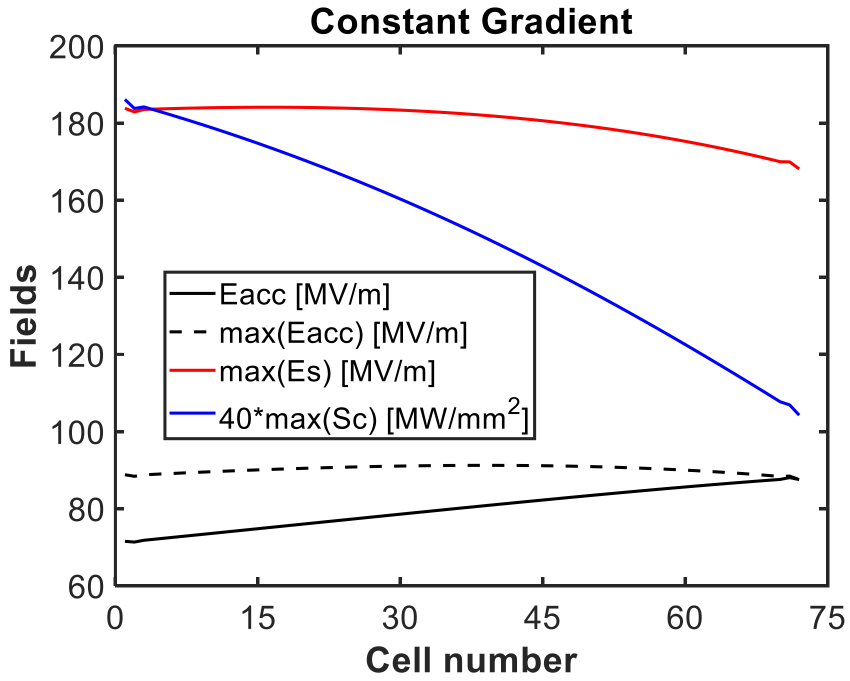



# X BAND HG STRUCTURE

- We switch to CG scheme with maximum surface field 20% lower than CI

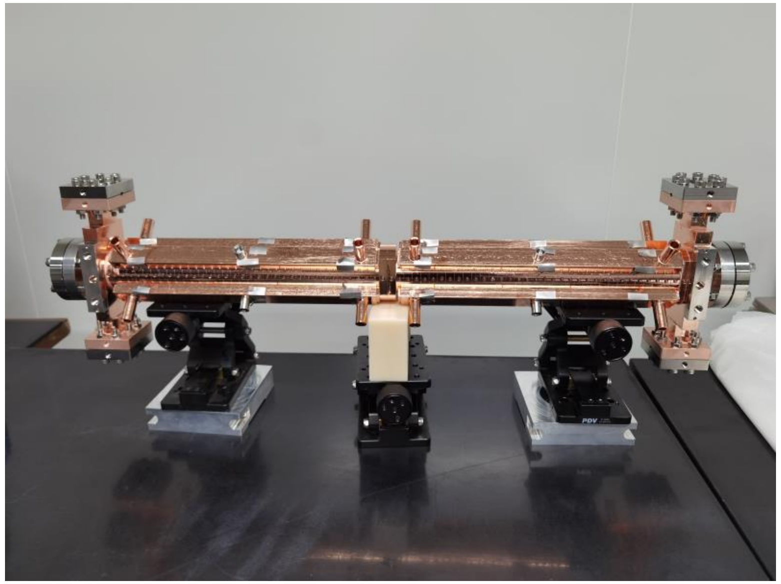


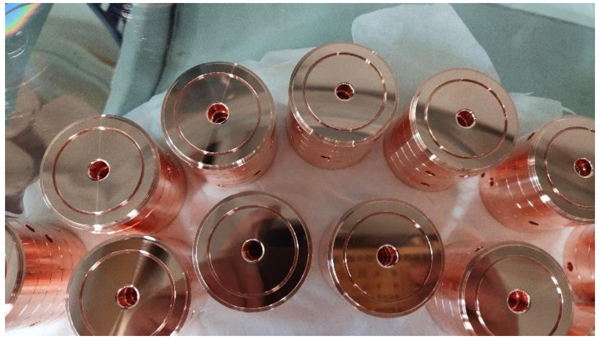

| Parameters | CI | CG |
|---|---|---|
| Iris aperture a [mm] | 3.5 | 3.92 ~ 3.12 |
| Iris thickness d [mm] | 1.8 | 1.8 |
| Shunt imp. R [MΩ/m] | 101 | 93 ~ 109 |
| Group velocity $v_g/c$ | 2.20% | 3.22% ~ 1.46% |
| Quality factor Q | 6990 | 7020 ~6970 |
| Filling time $T_f$ [ns] | 95 | 97 |
| $E_s$ [MV/m] | 224 | 185 |
| $S_c$ [MW/mm$^2$] | 5.65 | 4.50 |
| β of pulse compressor | 3.5 | 3.5 |
| Pin @80MV/m with pc [MW] | 81.3 | 80.1 |

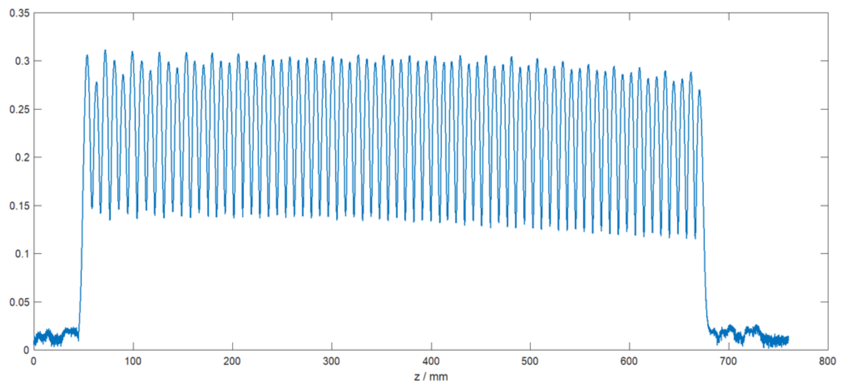


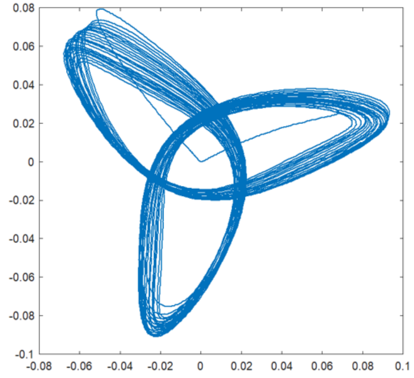
# X BAND HG STRUCTURE

- COST: CG 20% higher than CI
- (XT72#1-5): Tuning completed
- High power conditioning started from Oct. 20, 2023

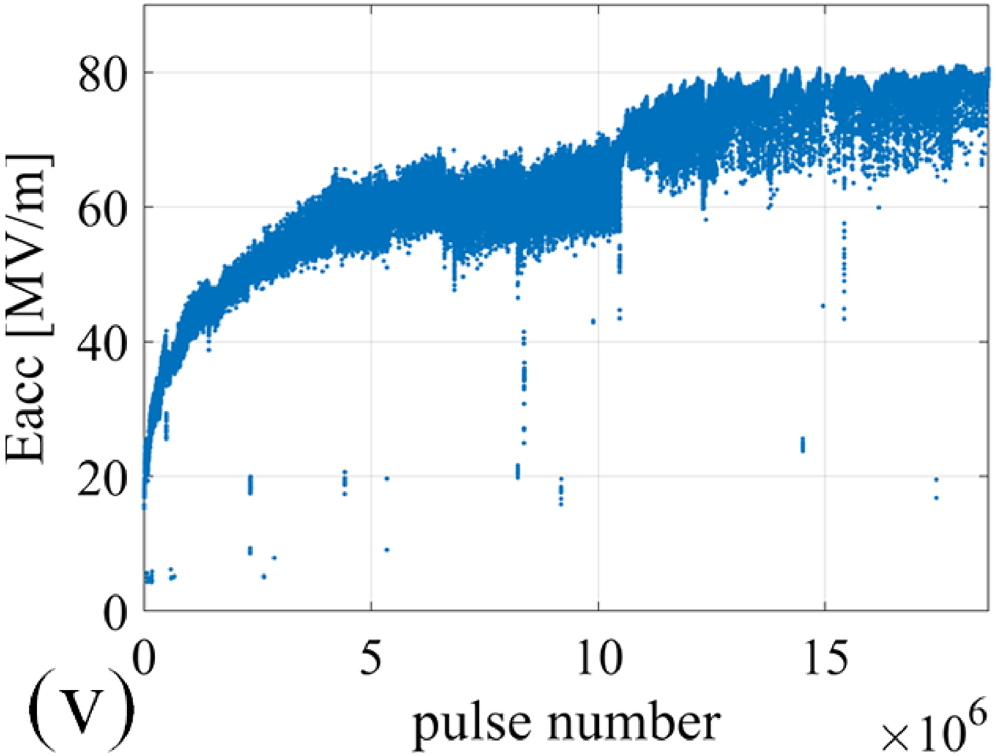






# HIGH-GRADIENT PERFORMANCE OF XT72 #1



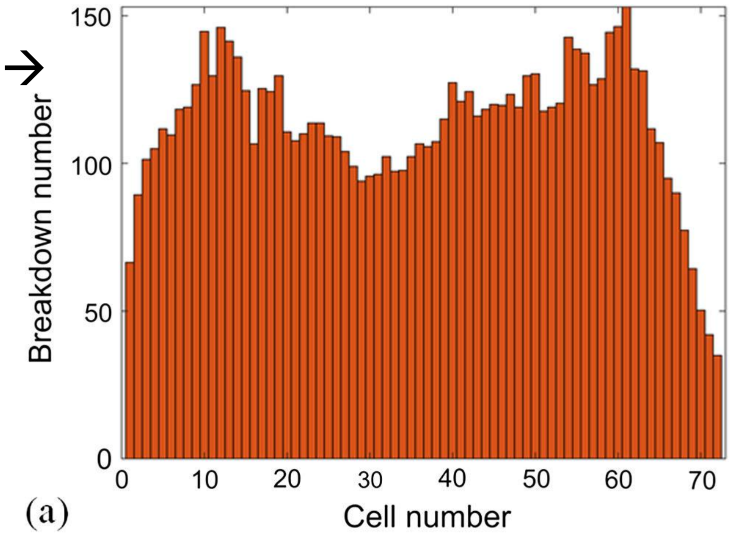

Gradient @ 80MV/m

BDR rate 1e-4

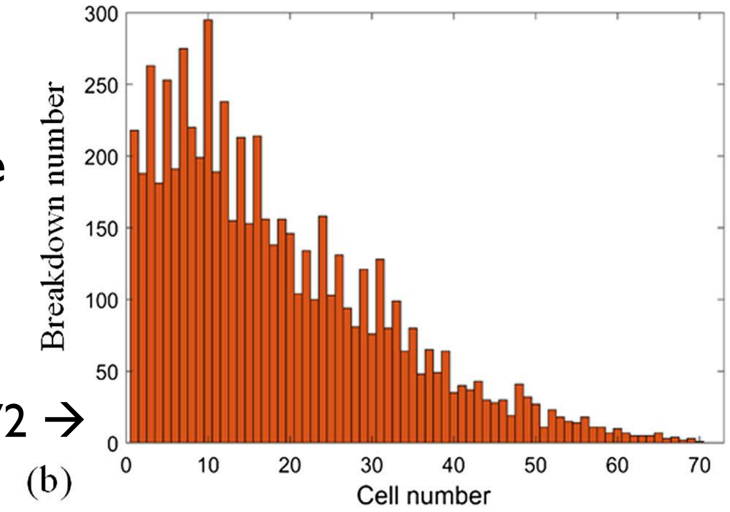
Breakdown event
evenly distributed
Compared with XC72 (CI)

XT72 has better performance

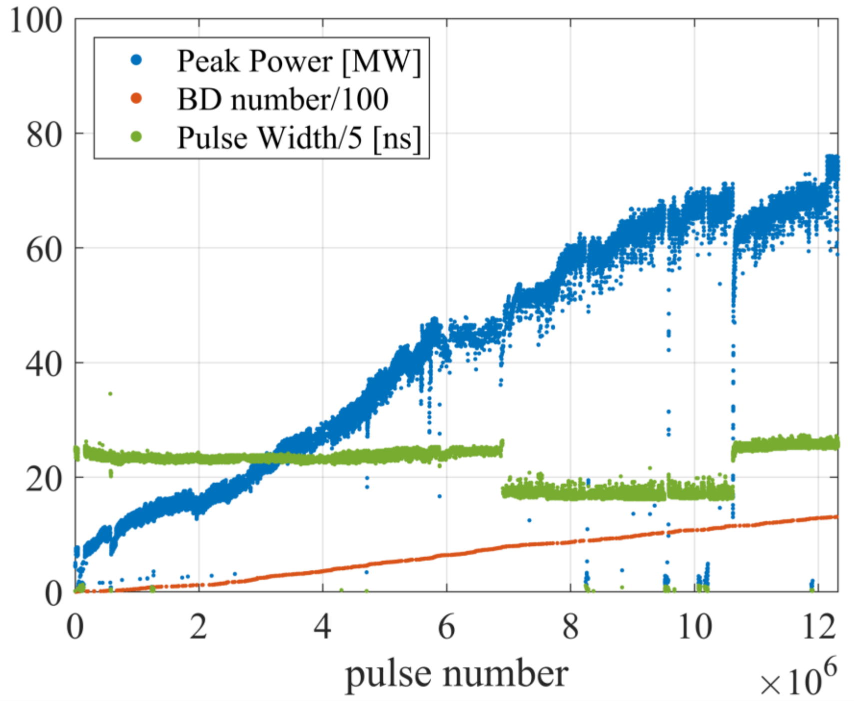
BD in XT72 →

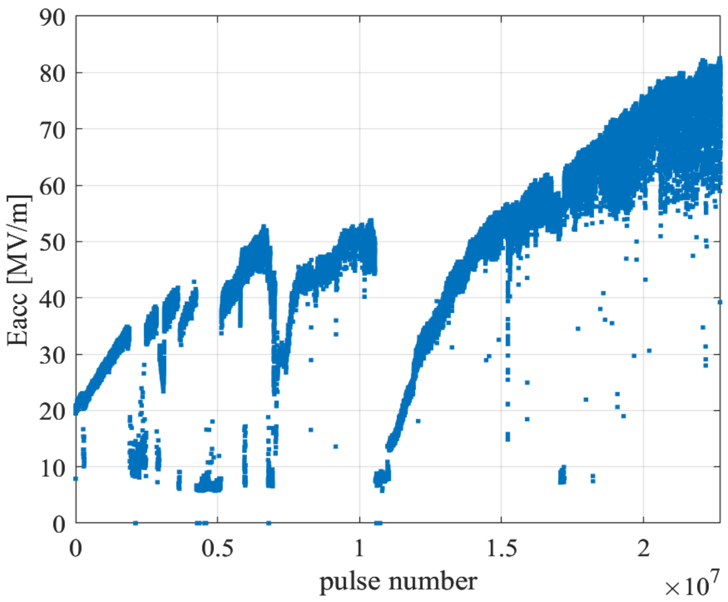


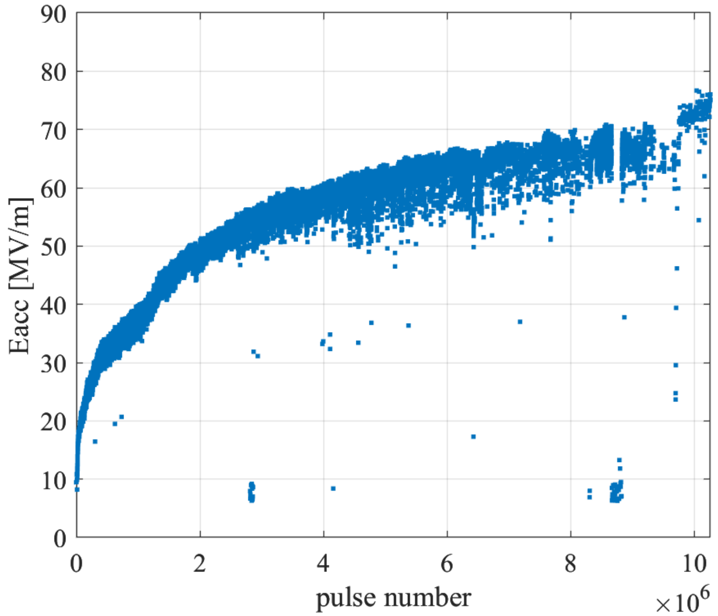

BD in XC72 →



# HIGH-GRADIENT PERFORMANCE OF XT72 #2—4

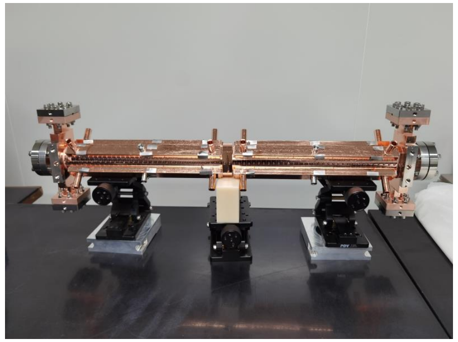


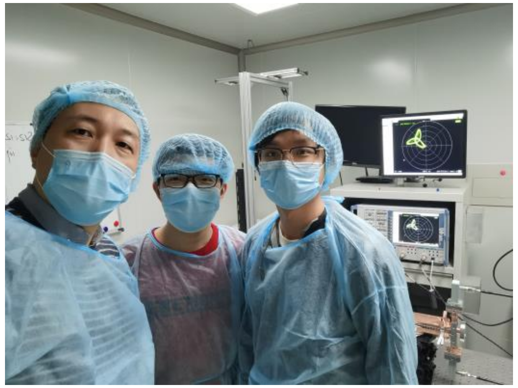



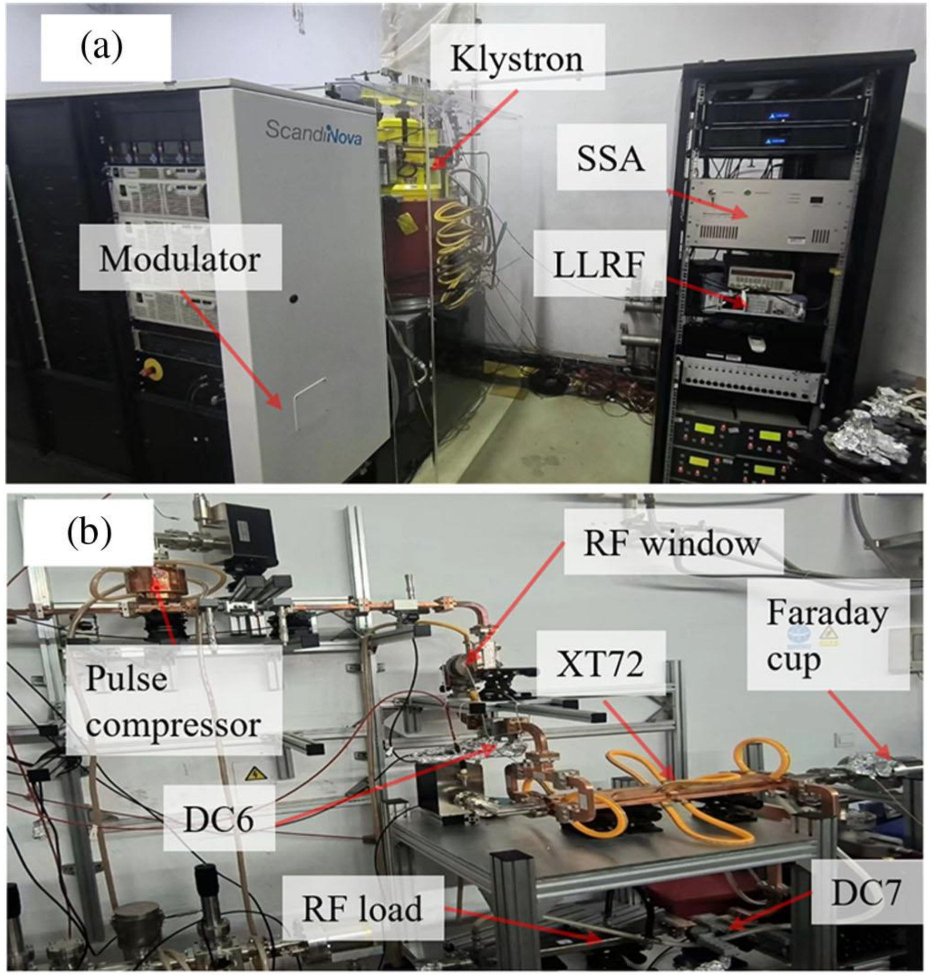




- #2, #3, #4 also conditioned
- To reach 80MV/m, ~15 million pulses
- About 100 hours of conditioning at 40Hz

# CONCERNS OF PRODUCTION








- Fabrication (Machining, cleaning, brazing, baking)
  - Can be parallel
- Tuning takes 1-2 days
- Conditioning takes time
  - With ONE test stand
  - Installation, pumping
  - ONE structure / month (trade off?)

# CONDITIONING

- Related with number of pulses
- LOG-LOG scale
- Breakdown rate v.s. No. of pulses

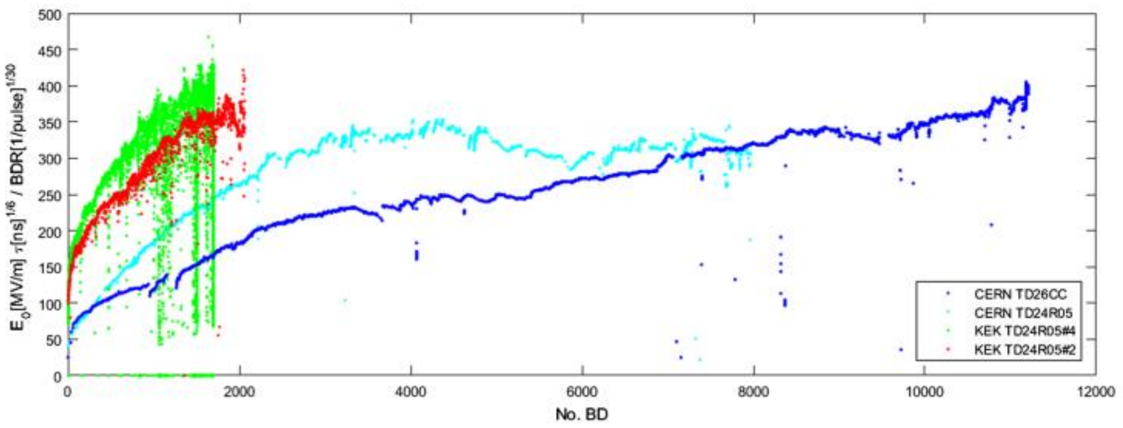



FIG. 4. Comparison of the scaled gradient vs number of accumulated breakdowns for several structures. When plotted with respect to the total accumulated number of breakdowns, the curves of the scaled gradient diverge significantly.

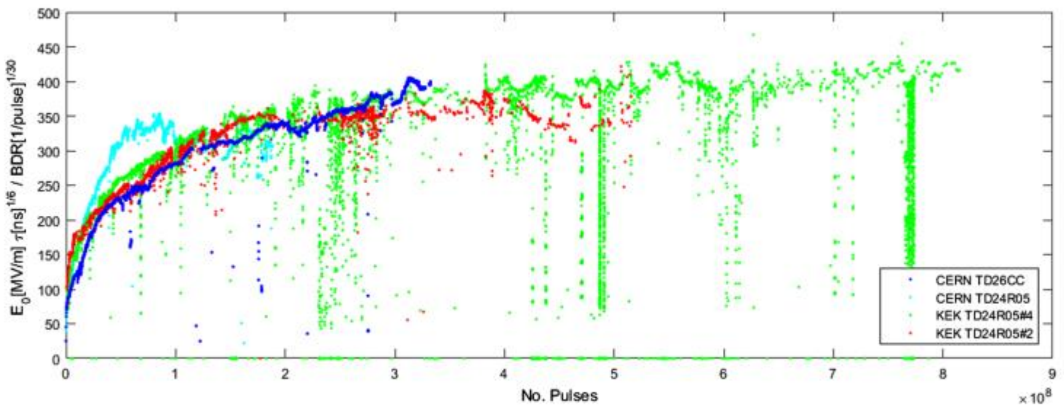



FIG. 3. Comparison of the scaled gradient vs number of accumulated pulses for several structures. Despite the different conditi approaches, the curves for the scaled gradient are similar.

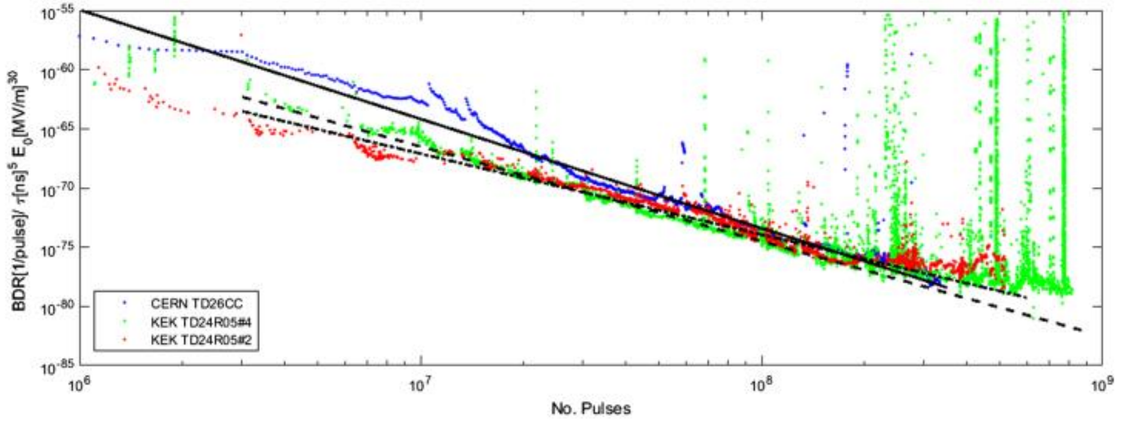
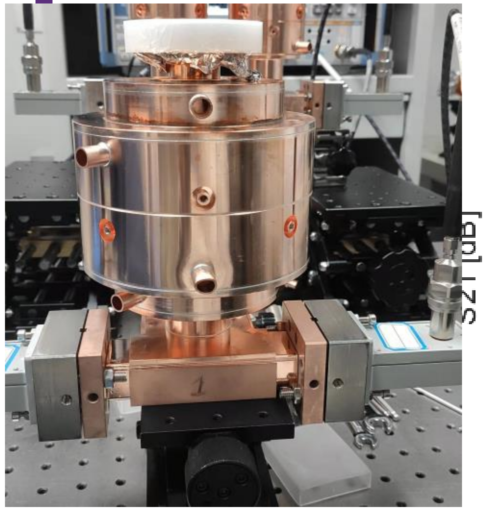
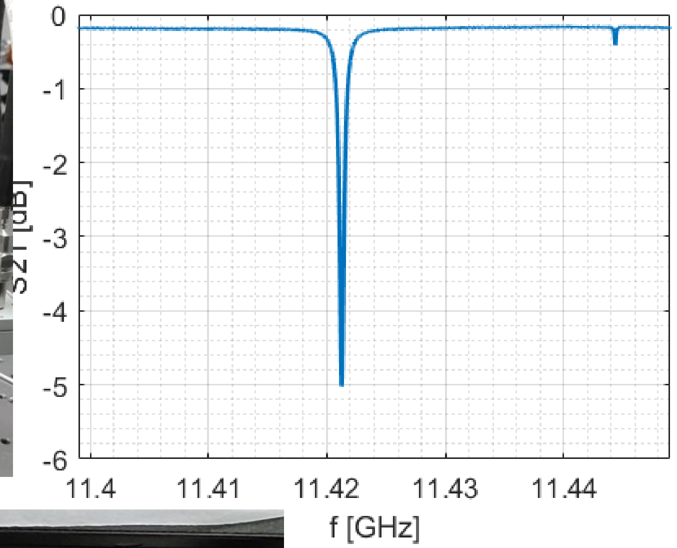



FIG. 5. Comparison of scaled BDR for different structures. The data are plotted in a log-log scale. The scaled BDR is decreasing monotonically with respect to the number of pulses. The curves are fitted with a power law.

https://doi.org/10.1103/PhysRevAccelBeams.19.032001 Alberto Degiovanni
Comparison of the conditioning of high gradient accelerating structures

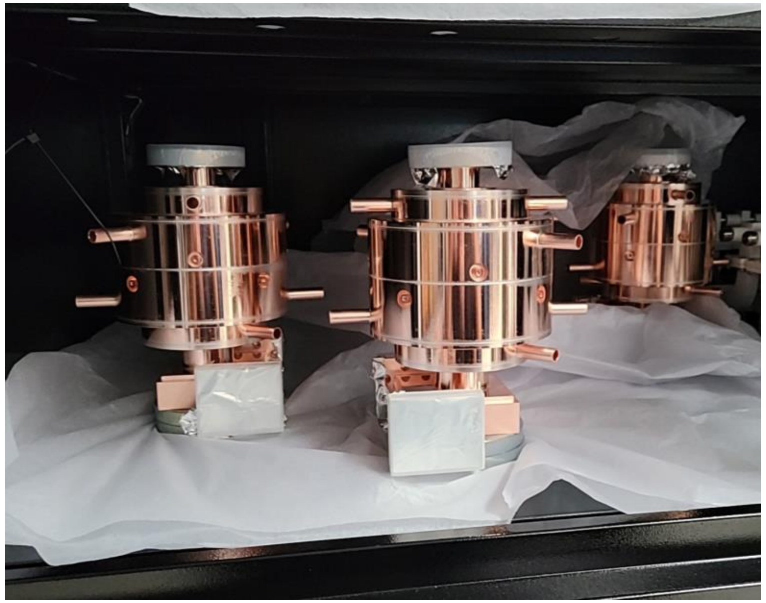
# X-BAND PULSE COMPRESSOR

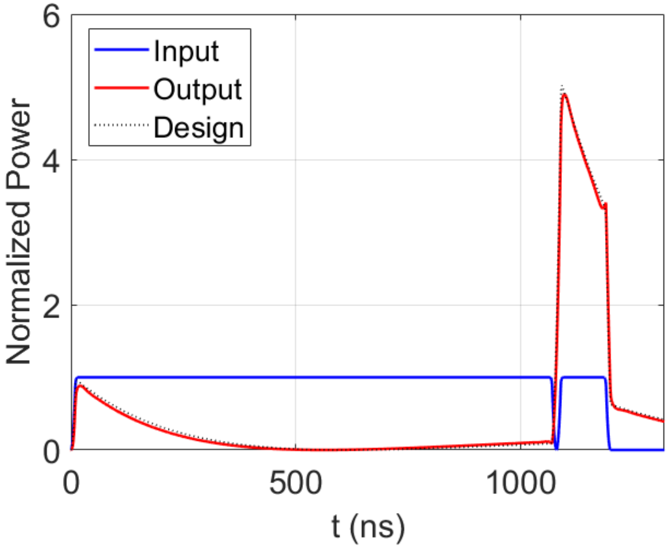


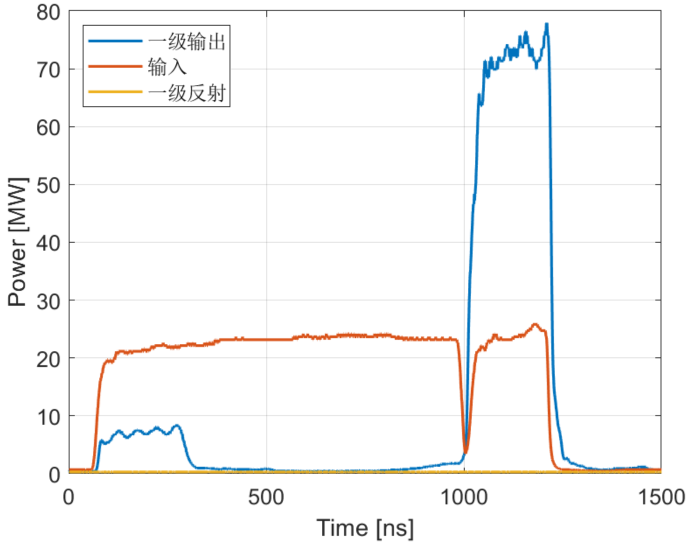



| | $f$ | $Q_0$ | $Q_e$ | $\beta$ |
|---|---|---|---|---|
| Design | 11.4240 | 9.2e4 | 2.63e4 | 3.5 |
| Measure | 11.4213 | 9.19e4 | 2.51e4 | 3.66 |
| Mode 1 | 11.4213 | 9.25e4 | 2.52e4 | 3.67 |
| Mode 2 | 11.4213 | 9.05e4 | 2.46e4 | 3.68 |

*Modes 1 and 2 are parameters of two polarization modes reconstructed from measured S-parameters ($TE_{114}$)





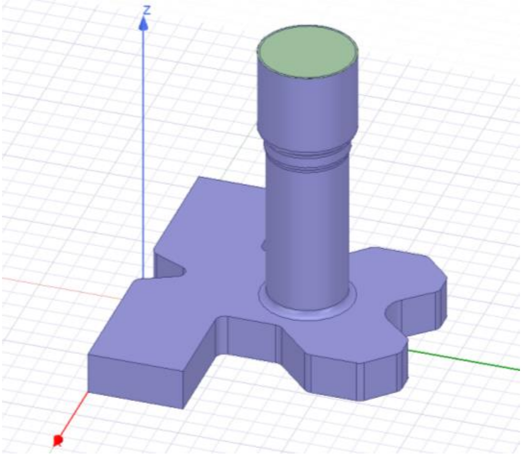



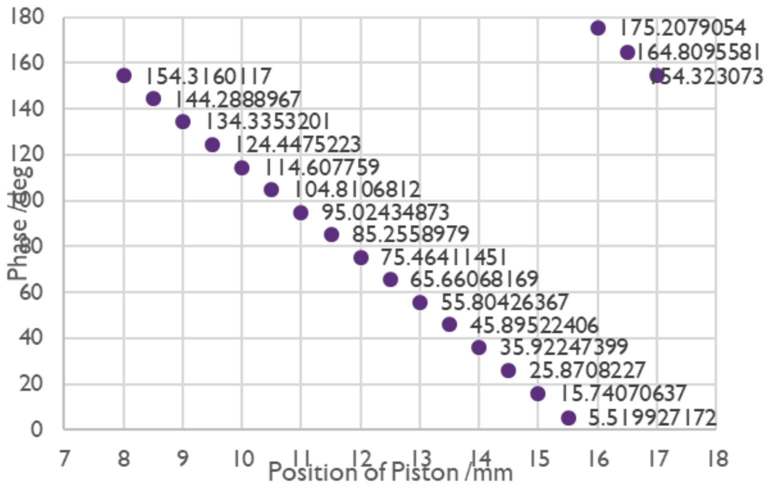

High power tested with cc

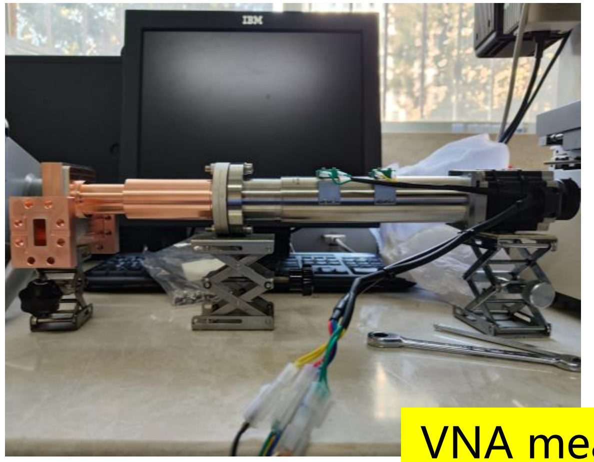
REF： Matthew Franzi et al. Phys. Rev. Accel. Beams 19, 062002 (2016)

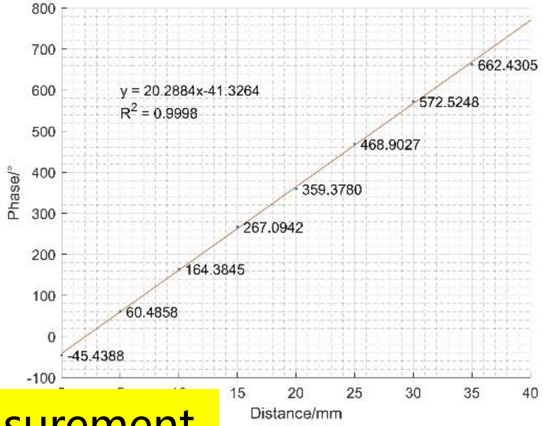
# X-BAND PHASE SHIFTER

- Adjust phase between AS in module
- RF phase v.s. position of piston 20°/mm
- S11 < -25dB, S21 > -0.1dB
- High-power tested to >85MW @150ns pulse width

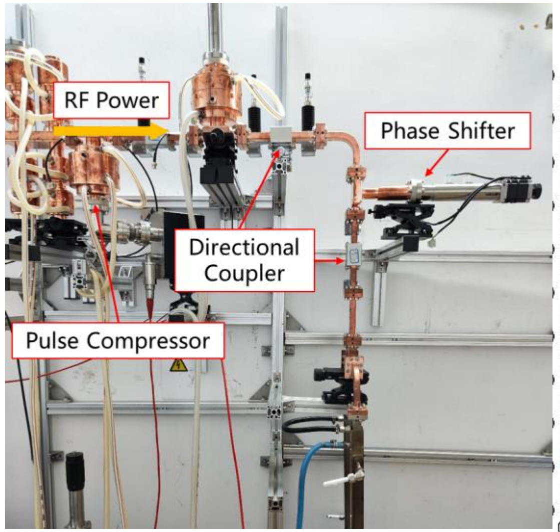


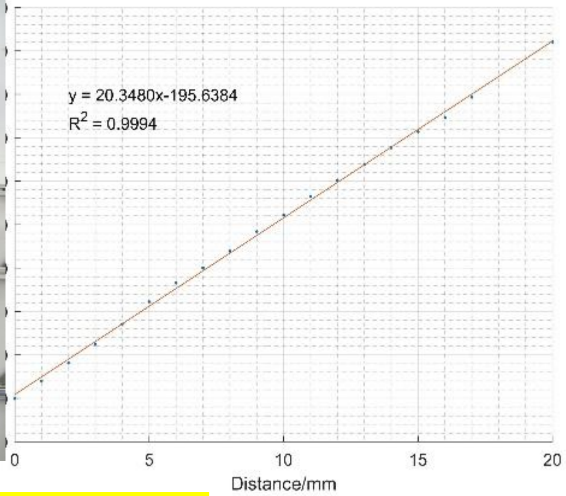





VNA measurement

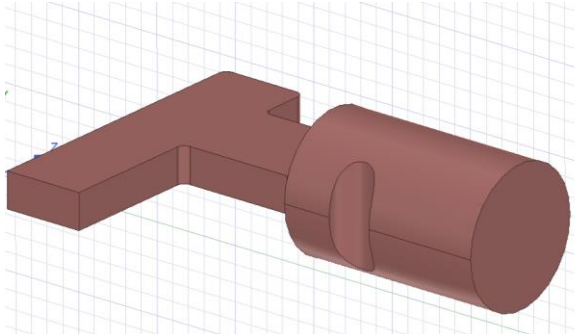



High power test

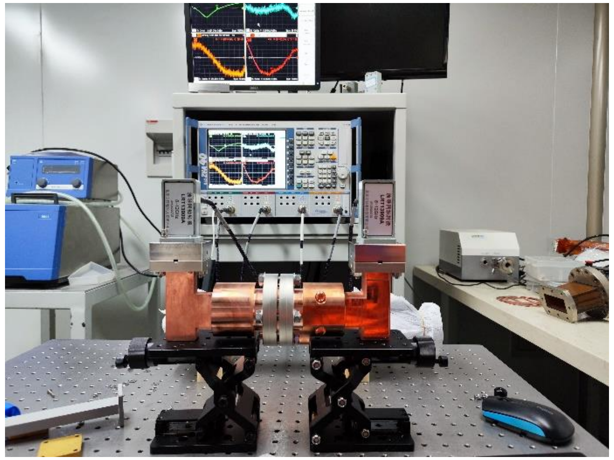
REF: Kamil Szypula et al., Status of prototype X-band RF components, HG2019

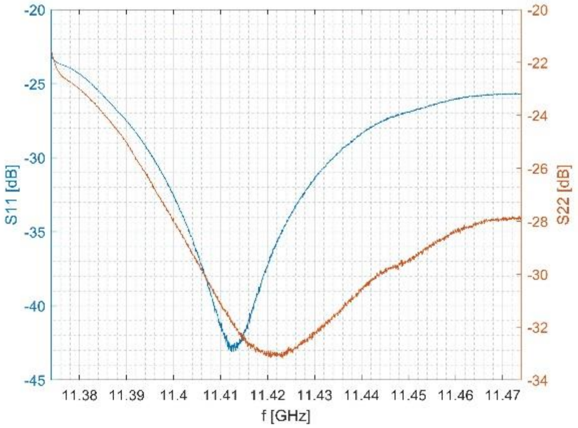
# X-BAND MODE CONVERTER

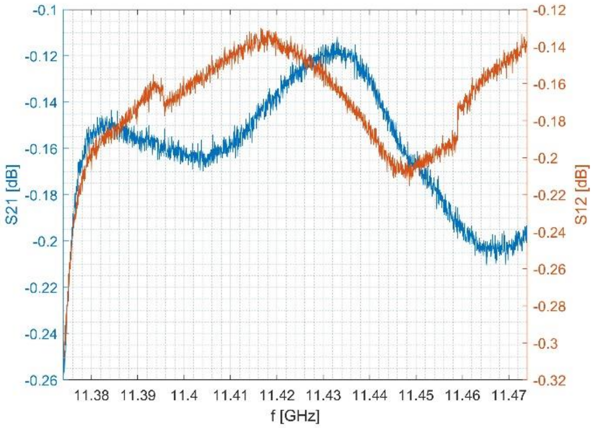


[1] S Kazakov et al.

Courtesy: V. Dolgashev

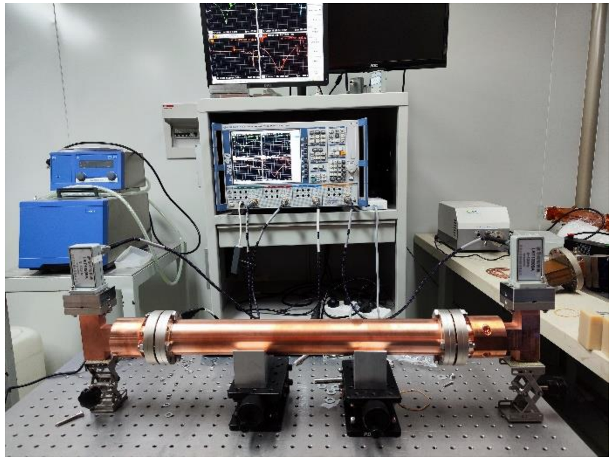


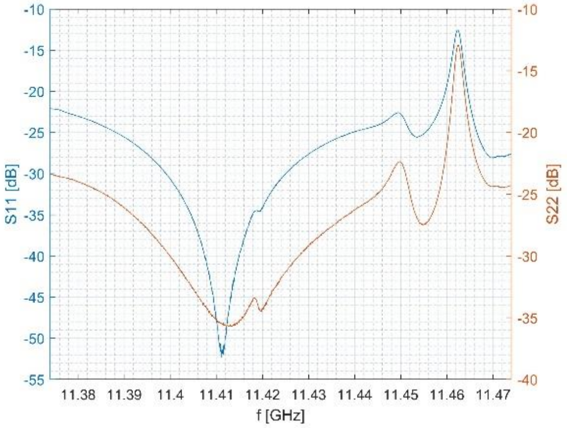


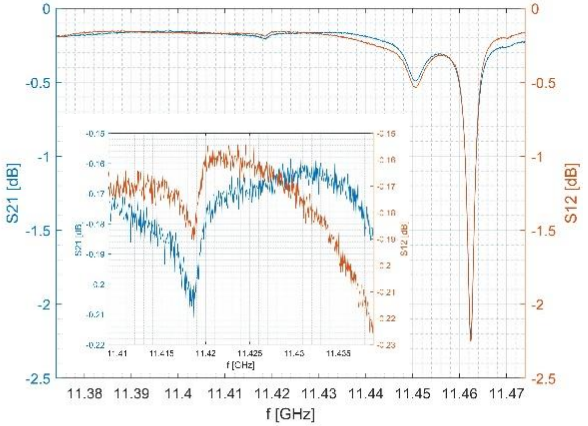




two converter directly

- S11 ~ -32dB, S21 ~-0.12dB



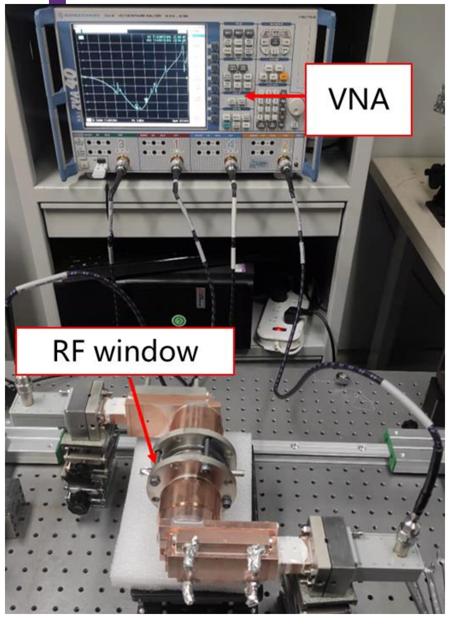


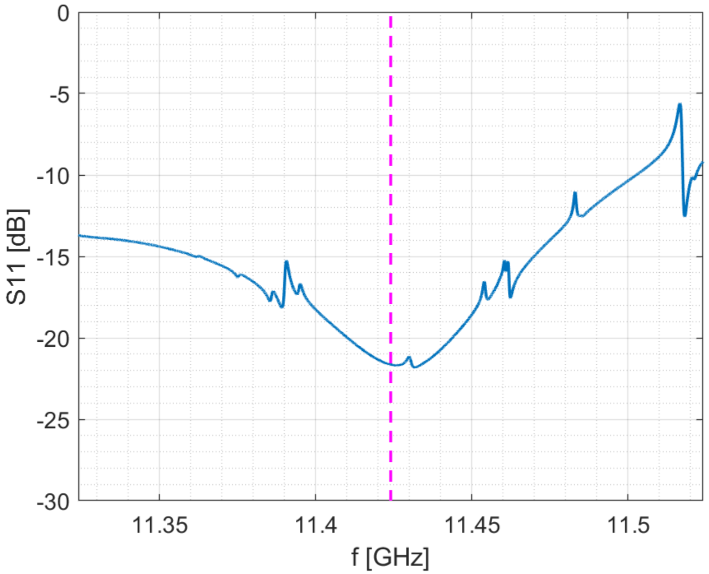




two converter and one circular waveguide,

S11 ~ -30dB, S21 ~ -0.16dB

# X-BAND RF WINDOW



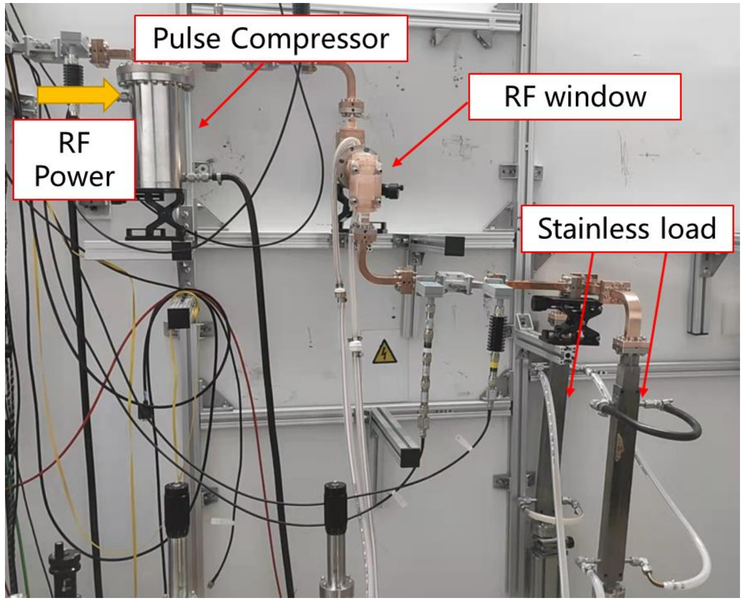



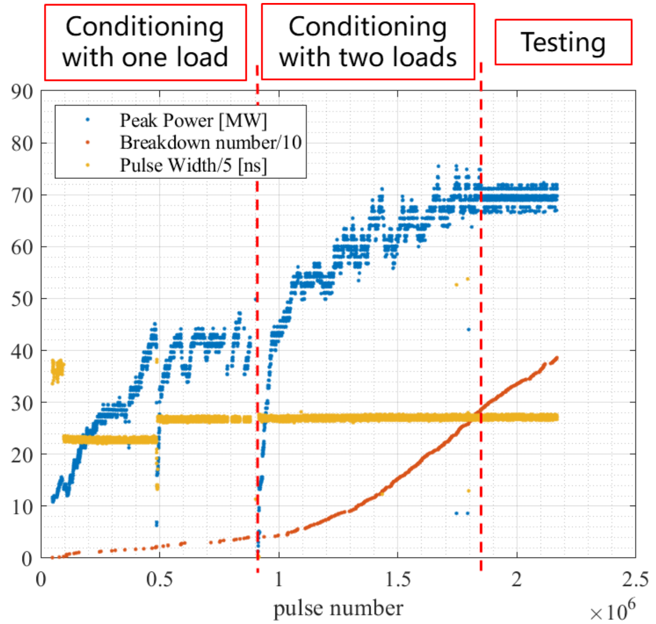

Low Power Test Results：

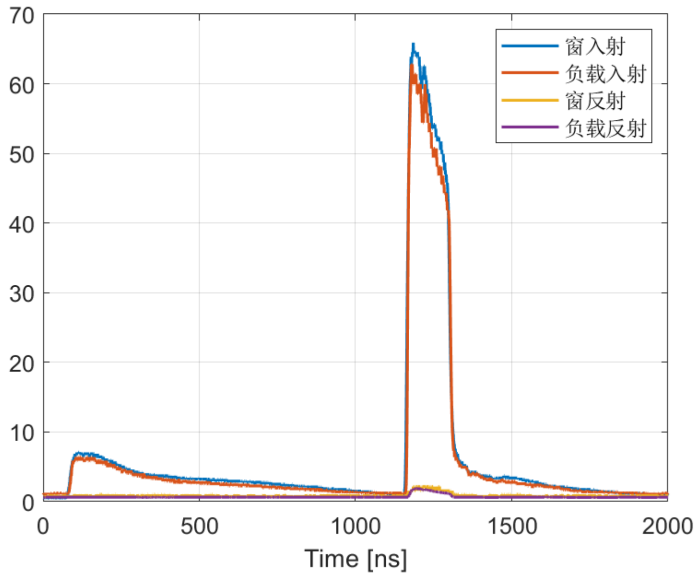
- S11 is below -20dB

**High Power Test** Results：

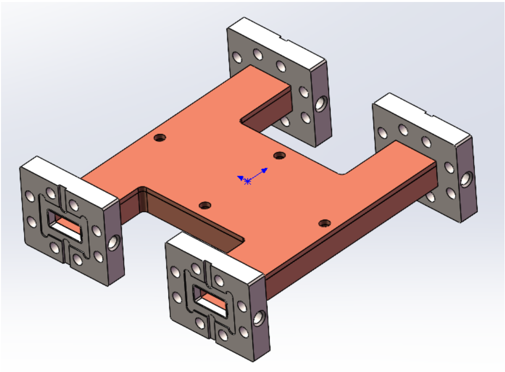
- Input power 60 MW, maximum electric field simulated at 40 MV/m
- Total RF breakdown rate during test is 3e-4

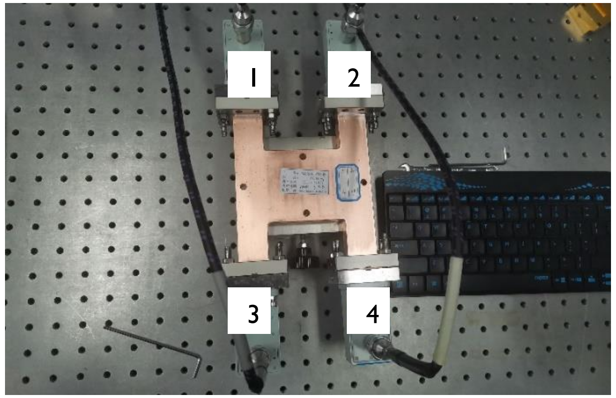


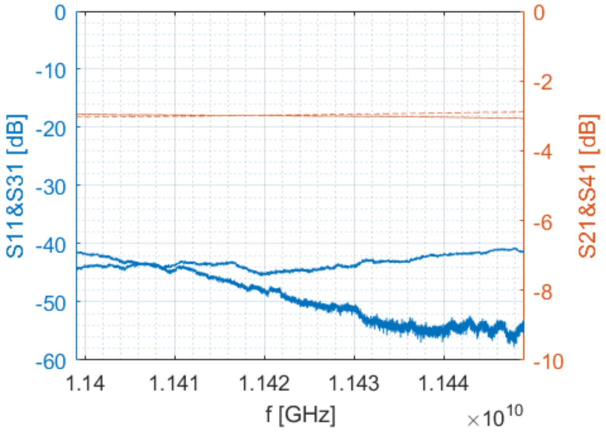



# X-BAND 3DB HYBRID

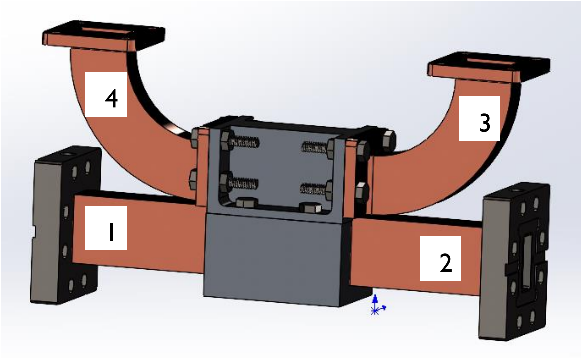


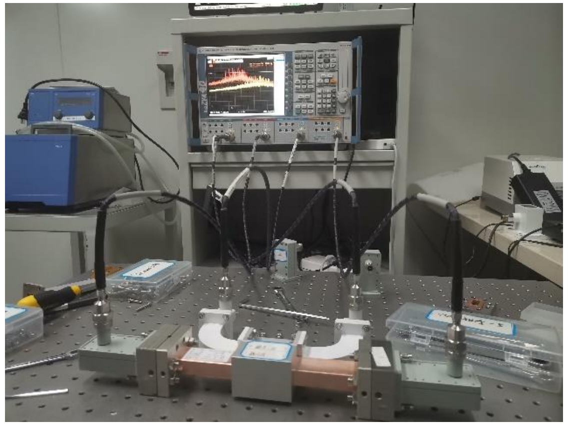


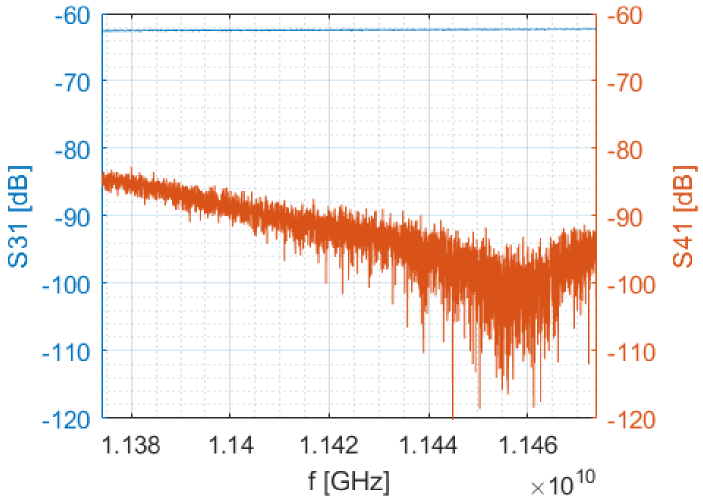




The S11s < -30dB
The S21s = -3dB.

# X-band Directional Coupler





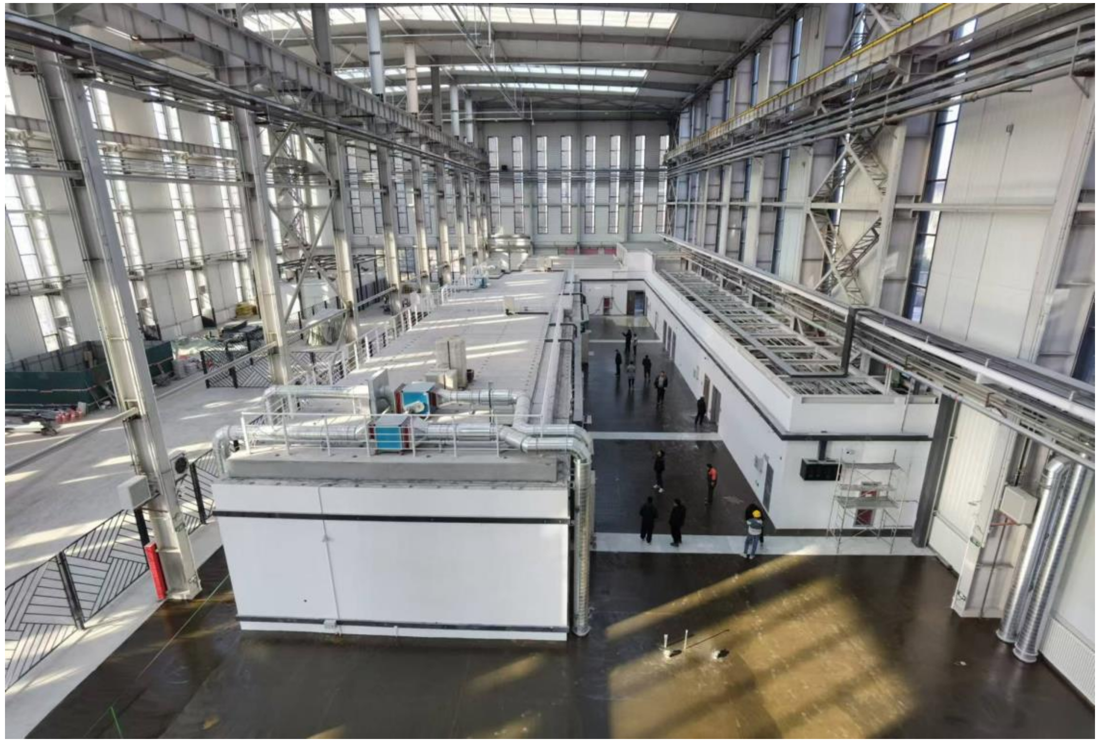

coupling ~ -61.5dB
direction: >30dB

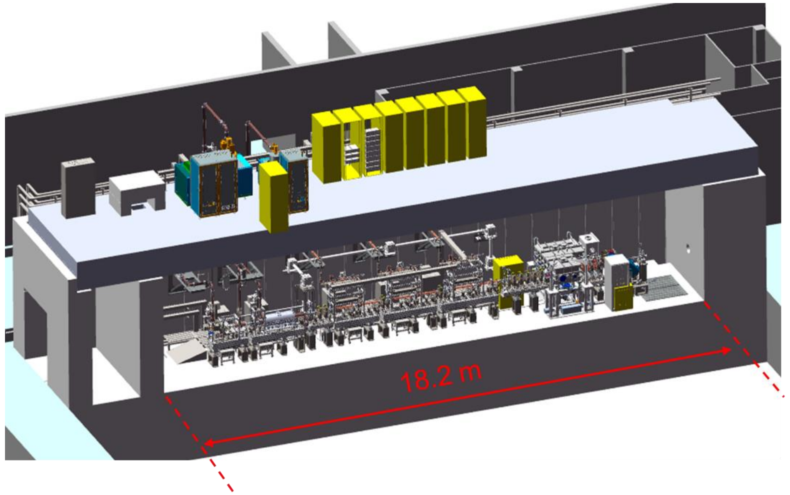
Courtesy: Igor Syratchev

# PROGRESS

2023.9

2024.6

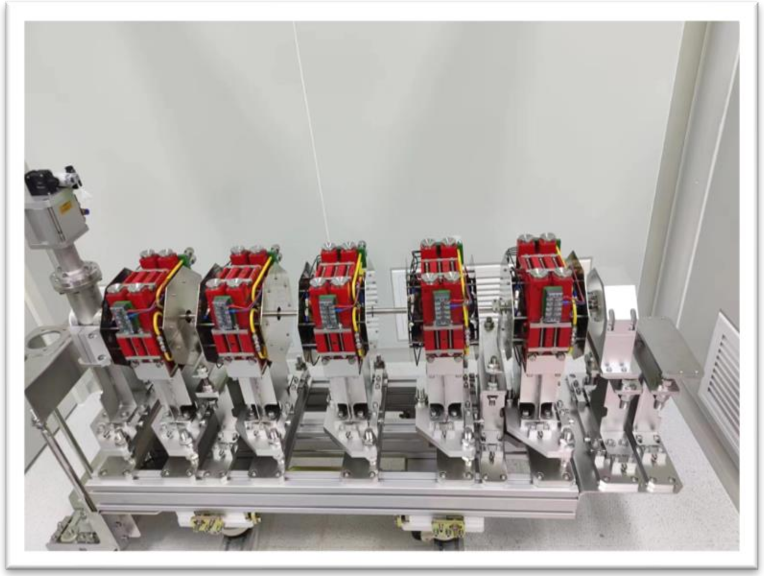


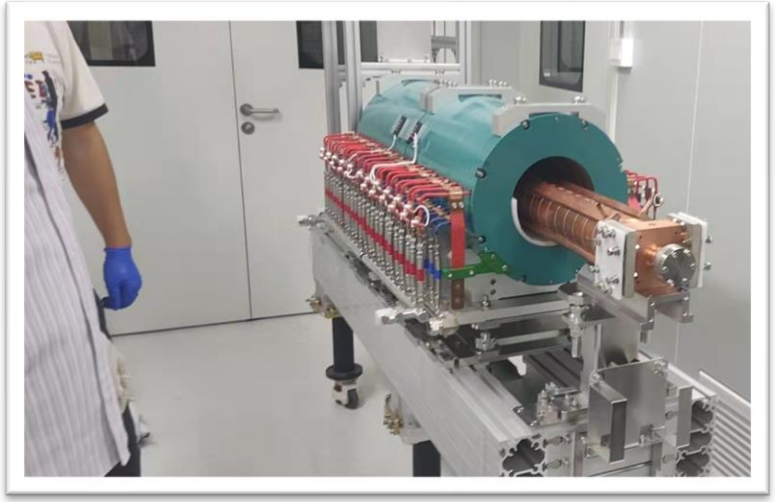



Bunk ready in mid 2024

# PROGRESS

- Clean room on campus for module installation
- Module install, and Vacuum SEALED, Pumped
- Between modules: valves, and bellows
- RF windows





# PROGRESS

2024.6

2024.10

X-band acc.

# SUMMARY

- VIGAS as a compact ICS source, total length ~13.5m, up to 350MeV beam energy, 4.8MeV photon
- Accelerator Design
  - RF components, Pulse compressor, magnets, pipes, Sband structures… READY
- X-band HG structure:
  - CI prototype (XC72) tested at 80MV/m
  - CG XT72#1 #2 #3 #4 conditioned to 80MV/m, #5 and #6 ready
- Installation complete soon
- Commissioning in the first quarter of 2025

# THANKS FOR YOUR ATTENTION