# PROGRESS OF ACCELERATOR SYSTEM FOR THE VIGAS PROJECT IN TSINGHUA UNIVERSITY

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ON BEHALF OF VIGAS TEAM IN THU

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# OUTLINE

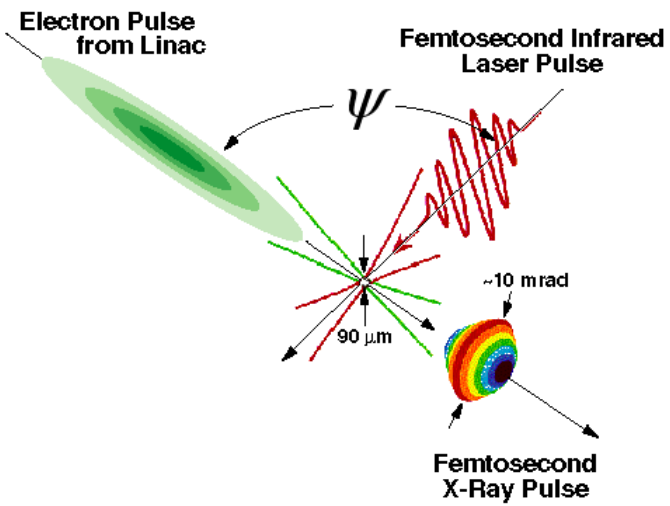
- Introduction
- Overview of Accelerator System
- The S-band Injector
- The X-band Linac
- Summary

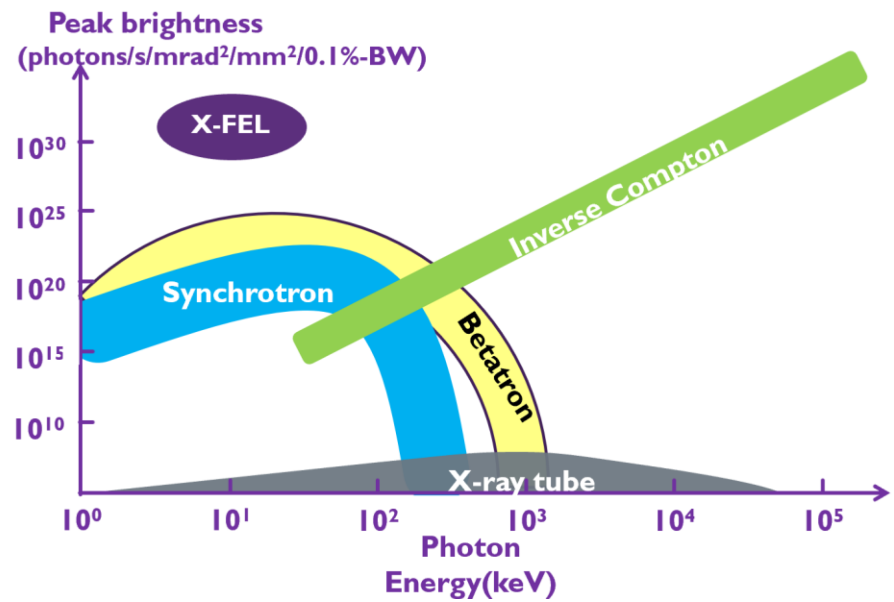
# INTRODUCTION

# INTRODUCTION

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

ICS




**Characteristics**

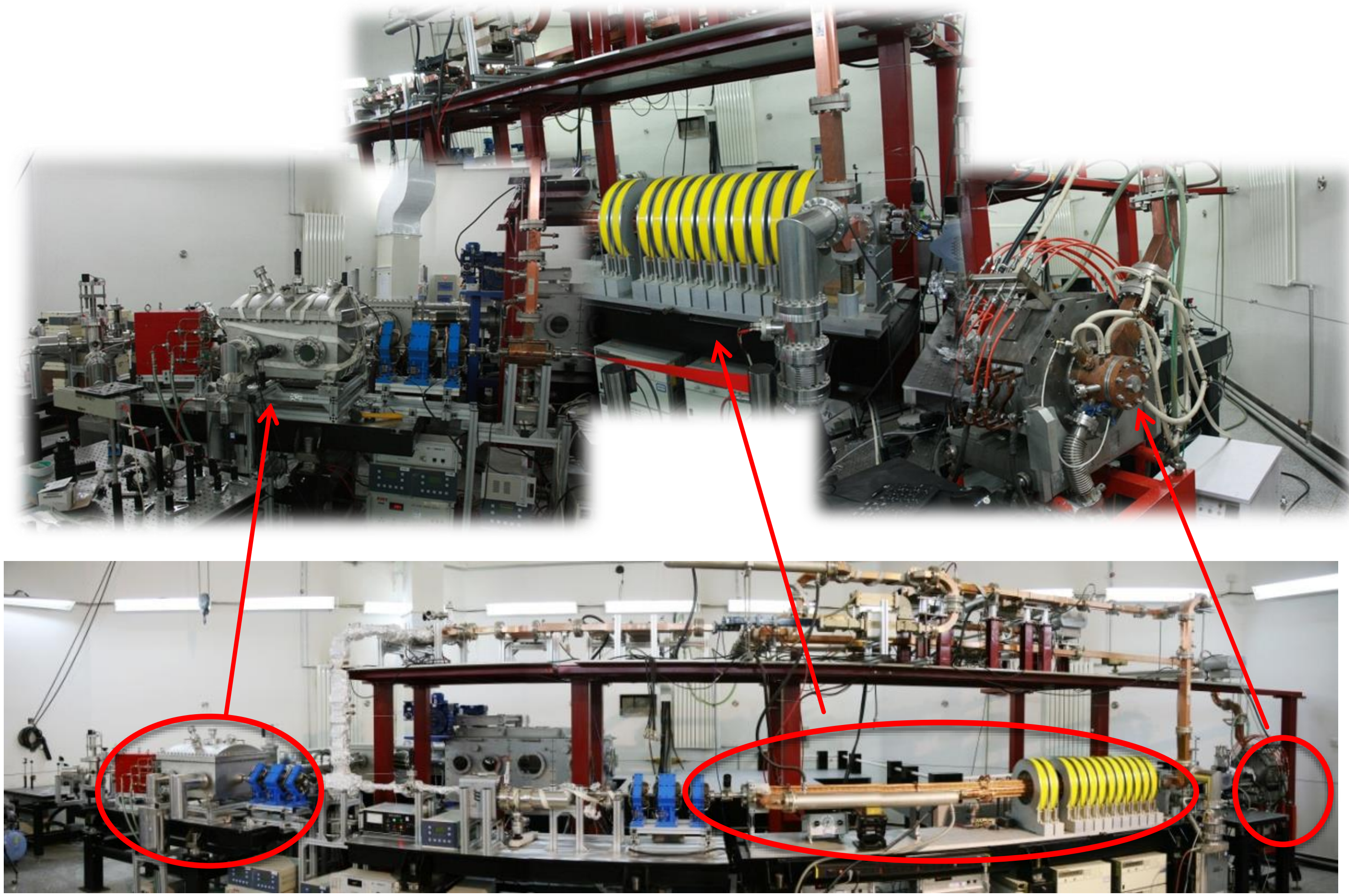
- Quasi-monochromatic
- Continuously adjustable X-ray energy
- Small source size ~10um
- Controllable polarization
- Ultra-short pulse length (fs~ps)

**Advantages**

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

# INTRODUCTION

## Tsinghua Thomson scattering X-ray source (TTX)



| Electron beam | |
|---|---|
| Energy | 45MeV |
| Bunch length | 1~4ps |
| Charge | ~0.7nC |
| Beam size | 30x25um |

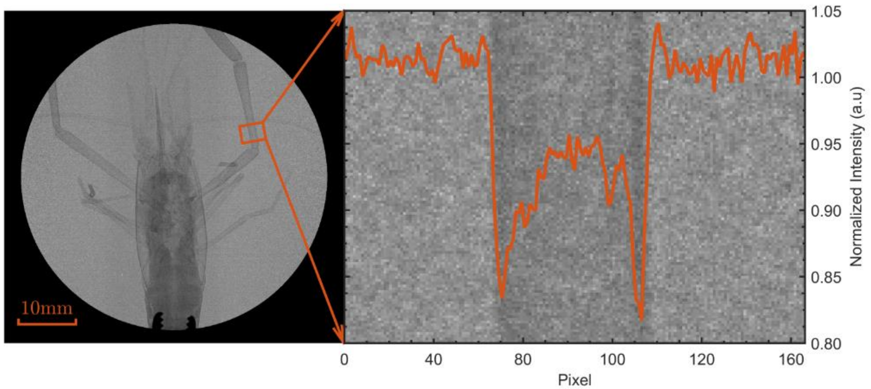
| Laser beam | |
|---|---|
| Wavelength | 800nm |
| Pulse duration | ~30fs |
| Pulse energy | ~500mJ |
| Beam size | ~30um |

| Parameters of Scattering X-ray | |
|---|---|
| Photon energy | 24(90deg) ~48(180deg) kev |
| Pulse duration | 0.16(90deg) ~3(180deg)ps |
| Number photons | $8.4X10^{6}$(90deg) ~$5.5X10^{7}$(180deg) |

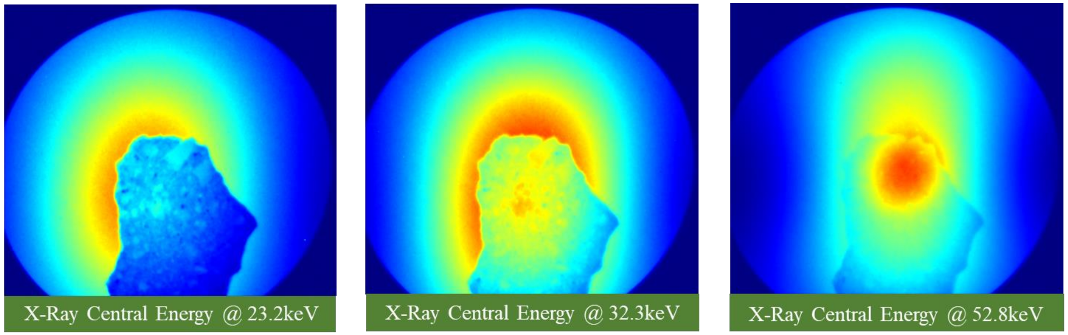
# INTRODUCTION

X-ray image examples at TTX

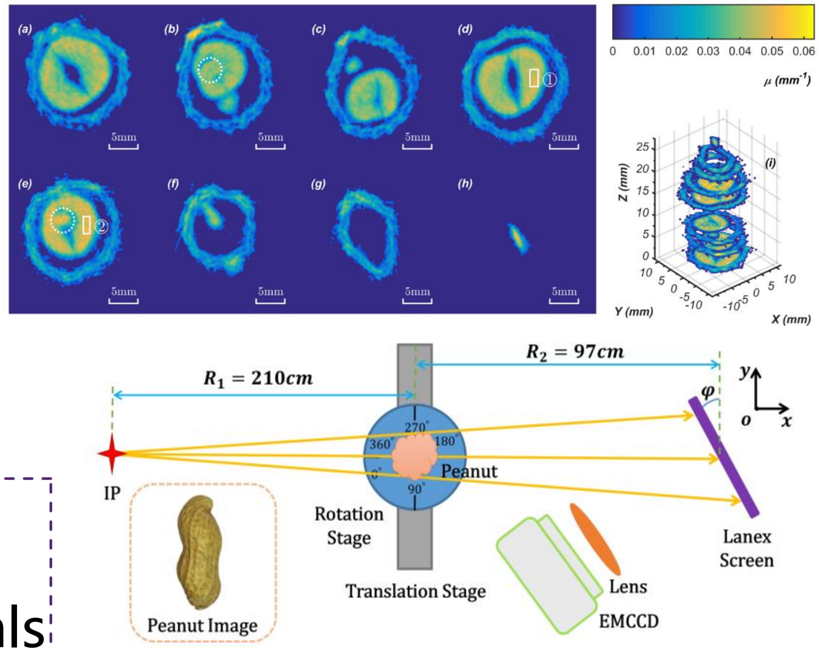
- ❑ X-ray phase contrast image

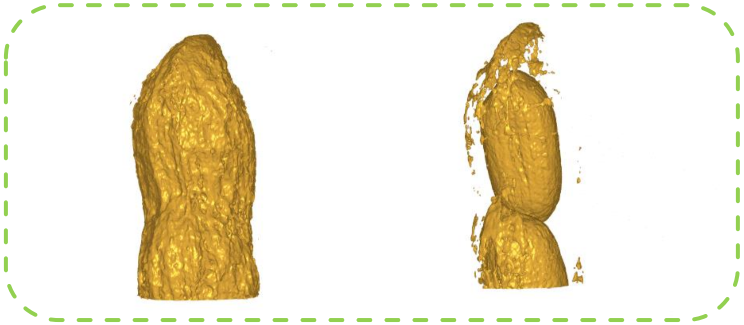



- ❑ Concrete diagnostics / different materials




- ❑ X-ray CT



*Chi, Zhijun, et al. "Recent progress of phase-contrast imaging at Tsinghua Thomson-scattering X-ray source", NIMB, 2017

# 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

- Photon production

Scattering cross section $\sigma_T \sim 6.652 \times 10^{-25} cm^2$

Electron intensity

Laser intensity

$$N_\gamma = \frac{f \sigma_T N_e N_l}{2\pi \sqrt{\sigma_{ey}^2 + \sigma_{ly}^2} \sqrt{\sigma_{ex}^2 + \sigma_{lx}^2}}$$

Repetition: 10Hz

Laser and electron focus spot size

- Bandwidth

$$\frac{\Delta E}{E_\gamma} = \sqrt{\left(\frac{\epsilon_n}{\sigma_e}\right)^4 + 4\left(\frac{\Delta\gamma}{\gamma}\right)^2 + \left(\frac{\Delta\omega_l}{\omega_l}\right)^2 + \left(\frac{1}{4}\left(\frac{\lambda_0}{\pi\sigma_l}\right)^2\right)^2}$$

Electron emittance and spot size

Electron energy spread

Laser bandwidth

Laser focus

In our case, in order to get the desired photon production and bandwidth:

- Electron beam size ~15um
- Bunch charge >= 200 pC
- Emittance < 1um
- Energy spread < 0.3%

# INTRODUCTION

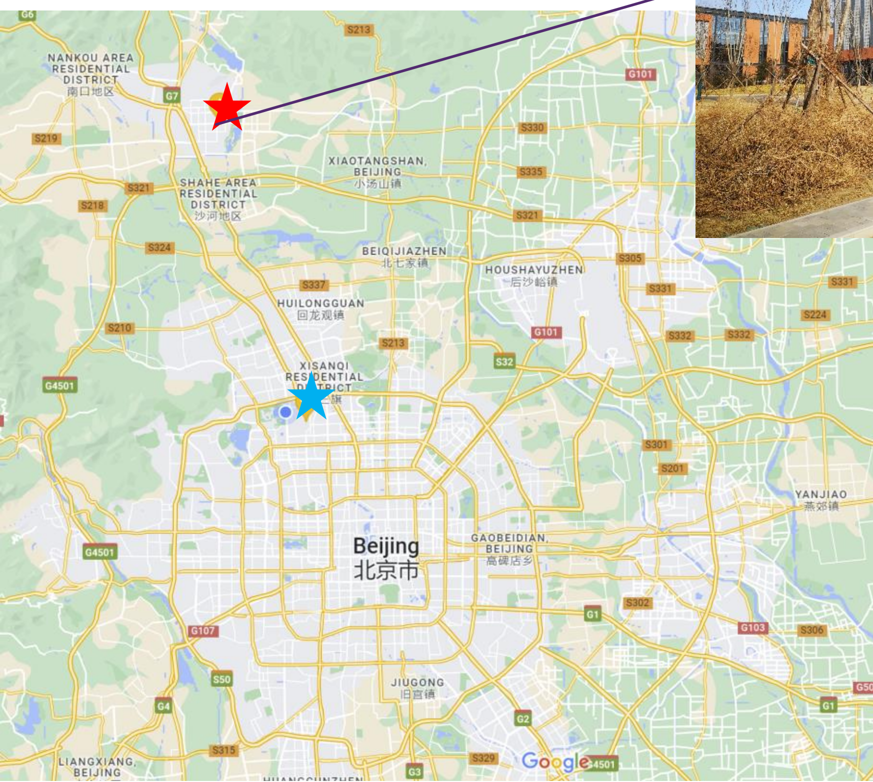
Design parameters of accelerator system for VIGAS

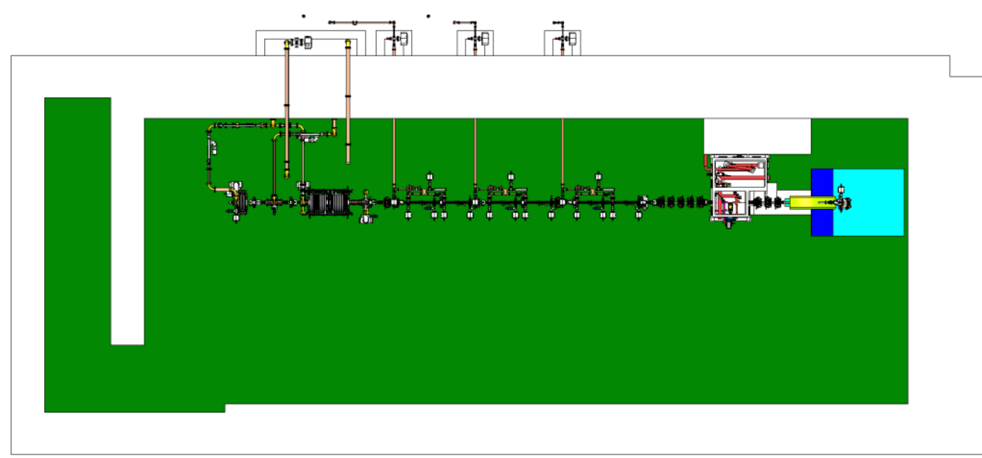
| **Properties** | **Value** |
| --- | --- |
| Electron energy | 50-350 MeV tunable |
| Charge | >= 200 pC |
| Normalized emittance | < 0.6 mm mrad |
| RMS bunch length | < 2 ps |
| RMS energy spread | < 0.3 % |
| RMS beam size at interaction point | < 20 um |

# 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



# OVERVIEW OF ACCELERATOR SYSTEM

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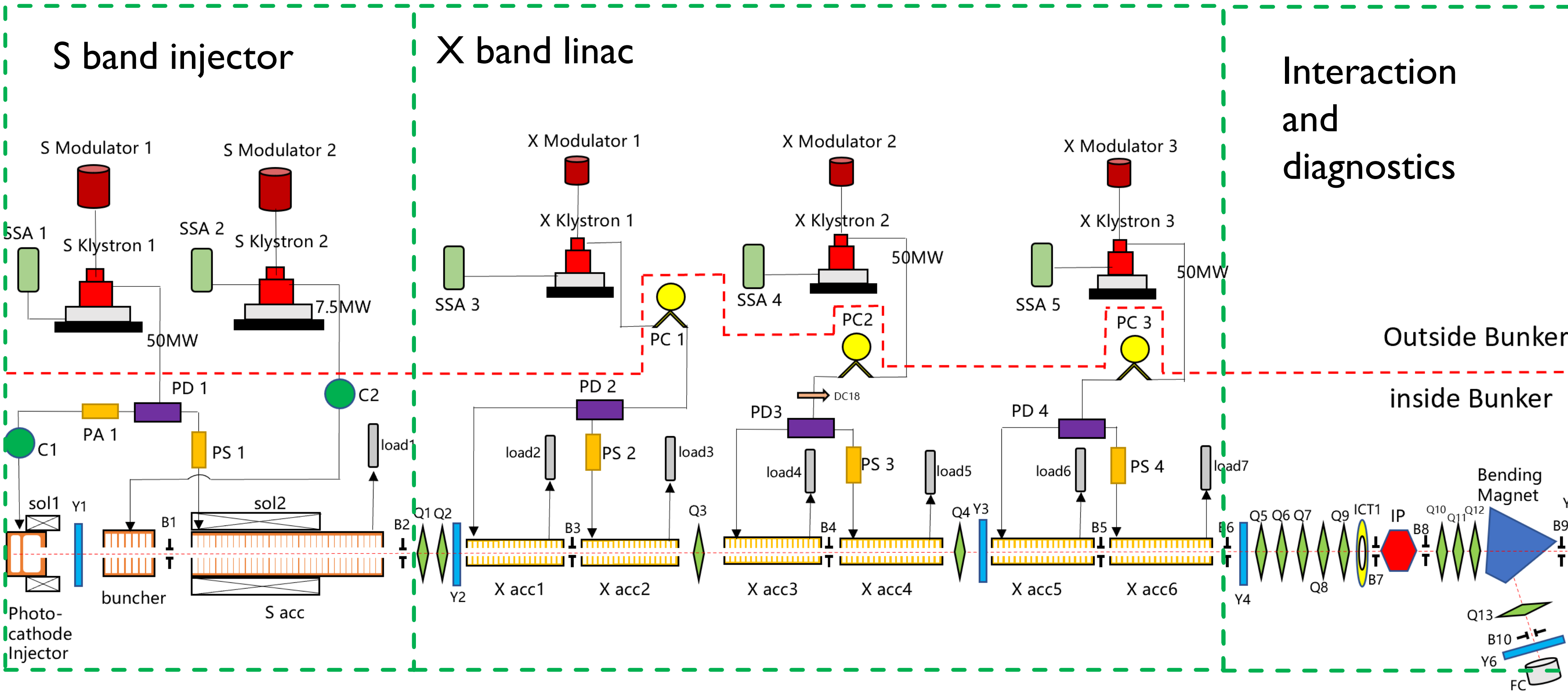
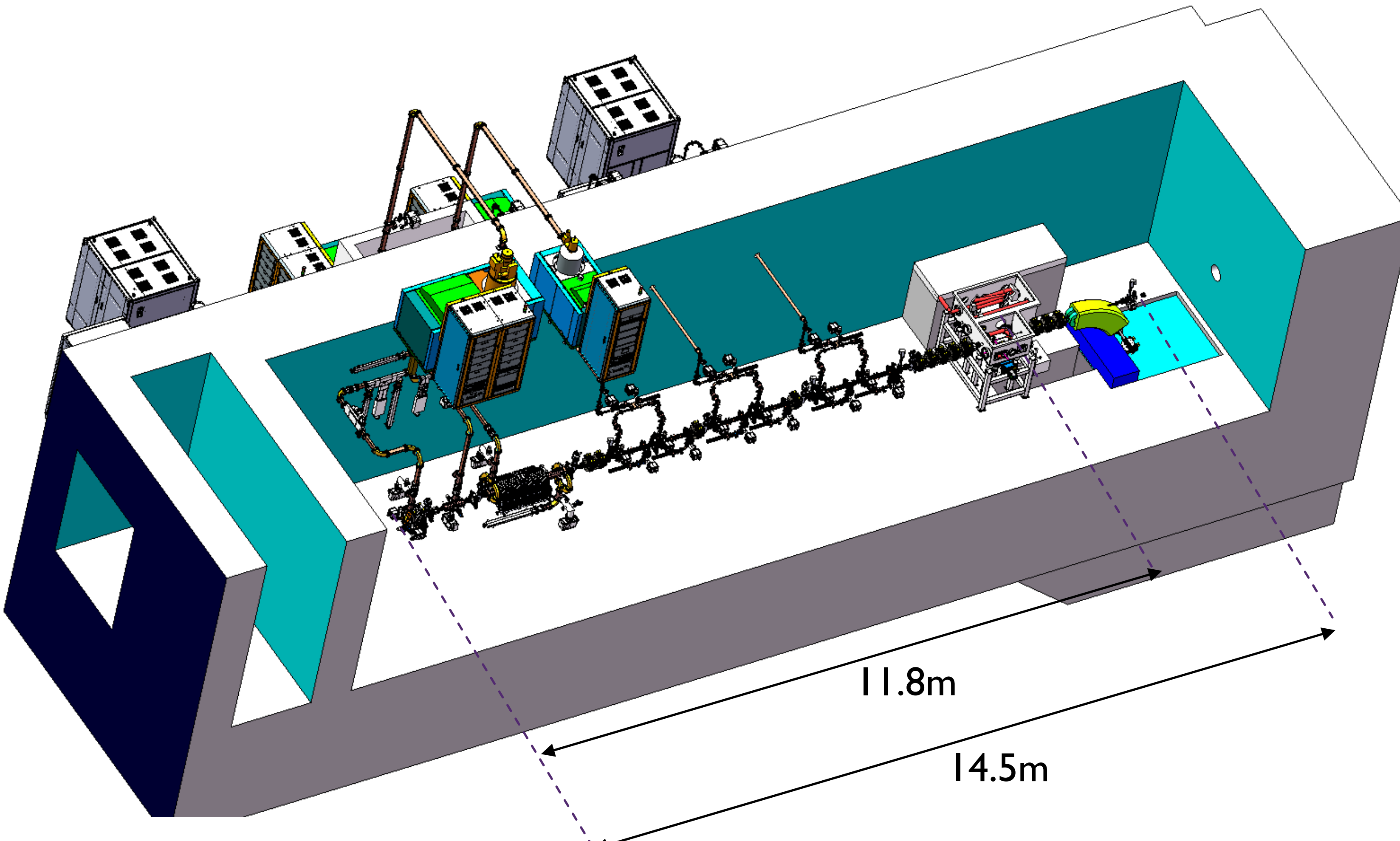


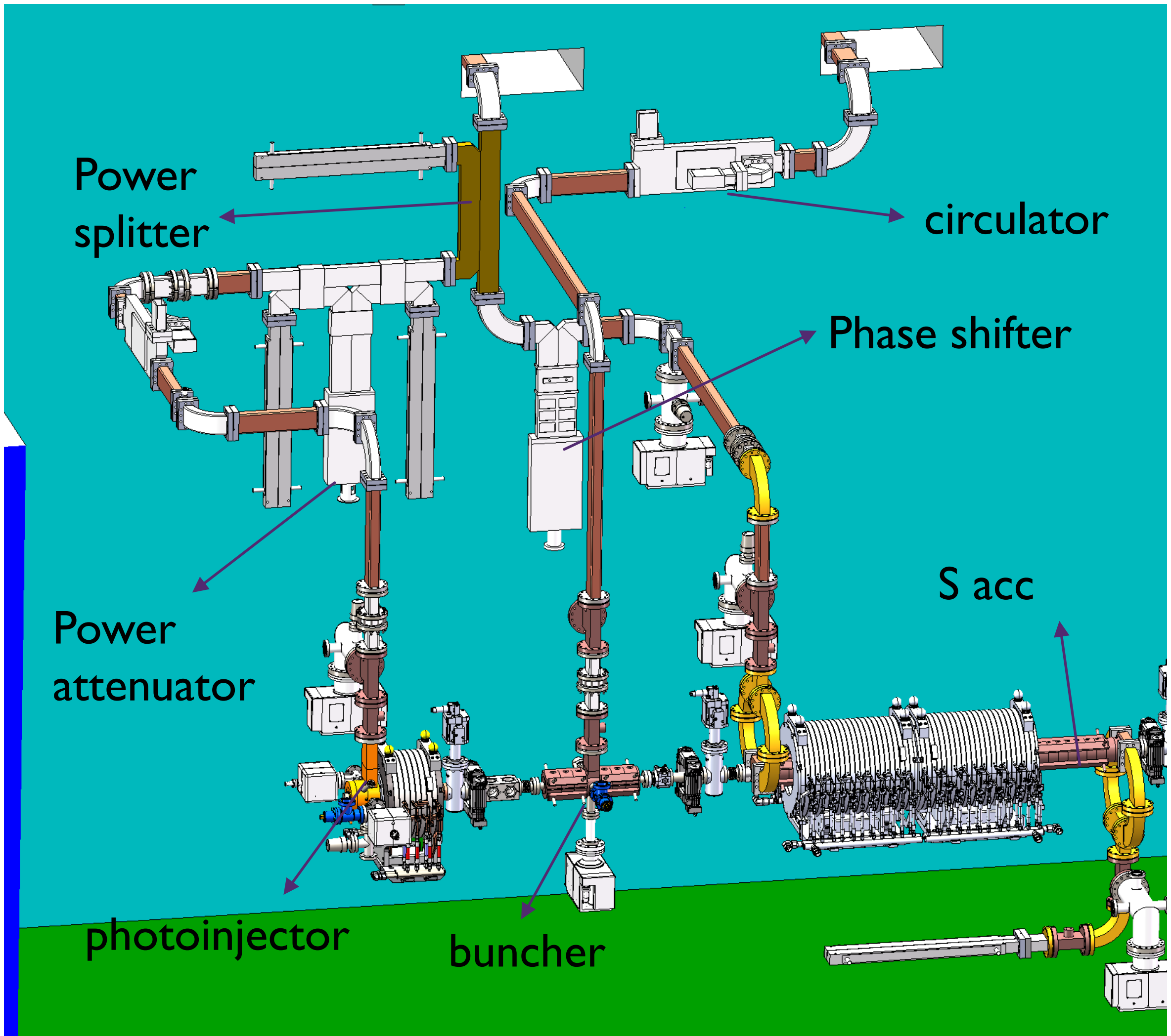

| Abbreviation | ACC | B | C | FC | ICT | IP | PA | PC | PD | PS | Sol | Y | Q |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Description | Accelerating Structure | Beam Position Monitor | Circulator | Faraday Cup | Integrating Current Transformer | Interaction Point | Power Attenuator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

# OVERVIEW OF ACCELERATOR SYSTEM



# S BAND INJECTOR

# S BAND WAVEGUIDE SYSTEM

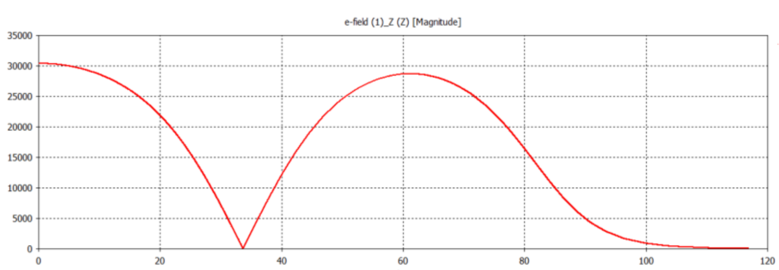



- 50 MW power from Canon E3730A feeds for photoinjector and S acc
  - 5dB power splitter
  - Phase shifter for S acc phase control
- 7.5 MW power from Canon E3772A feeds for buncher
- Consider RF loss due to waveguides and components:

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

# S BAND PHOTOINJECTOR

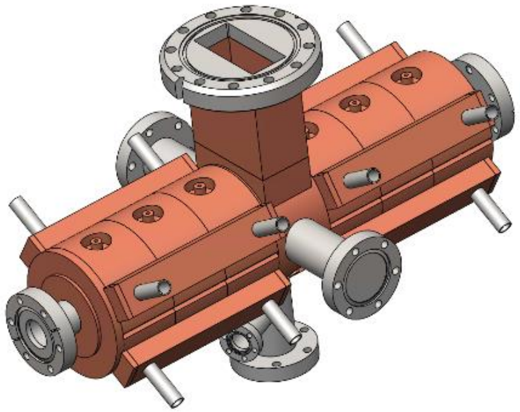
| Parameters | Value | Unit |
|---|---|---|
| PI mode frequency | 2856 | MHz |
| $Q_0$ | 14000 | |
| Coupling coefficient | 1-1.3 | |
| Working field strength | 100-120 | MV/m |
| Emitting charge | >200 | pC |
| Cathode material | Copper | |
| Quantum efficiency | $4x10^{-5}$ | |
| Emittance | <0.6 | um |
| Relative quadrupole field strength | $<2\times10^{-4}$ | |




- Fabrication fished
- Waiting for brazing

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

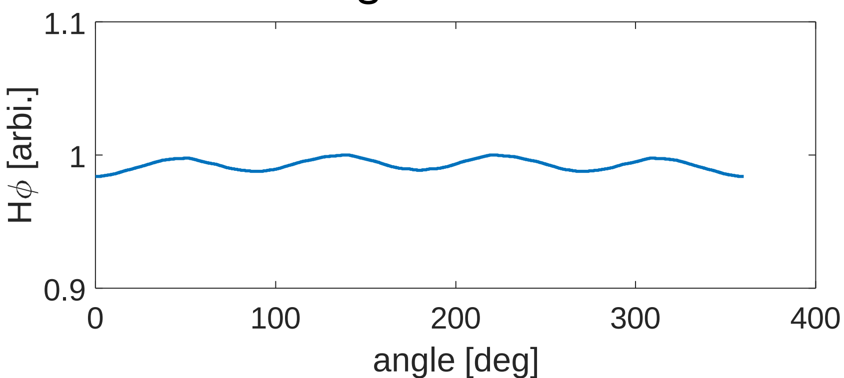
# S BAND BUNCHER



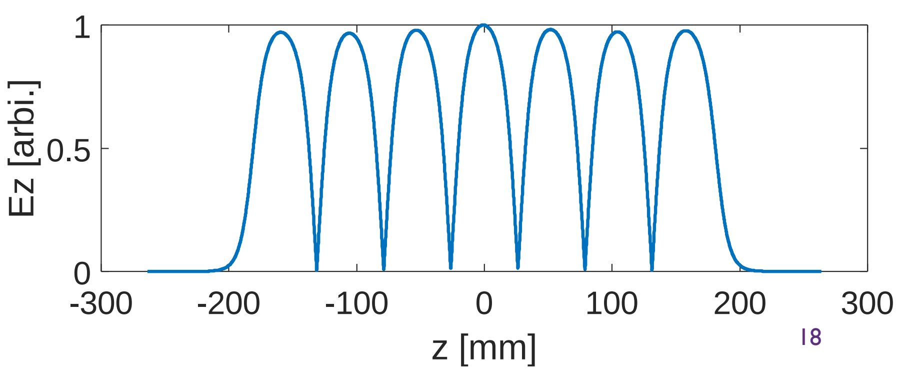
- Fabrication finished
- Waiting for tunning

| Parameters | Value | Unit |
| --- | --- | --- |
| PI mode frequency | 2.856 | GHz |
| $Q_0$ | 17000 | |
| Coupling coefficient | 1.2 | |
| Shunt impedance | 50 | MΩ/m |
| Working field strength | 23 | MV/m |
| Relative quadrupole field strength | <5e-4 | |

H field along azimuthal direction



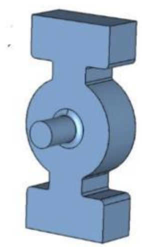

E field along axis

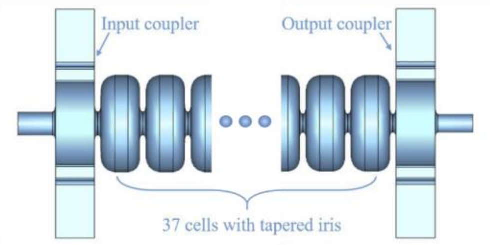


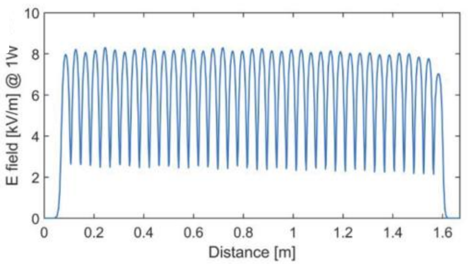
# S BAND ACC

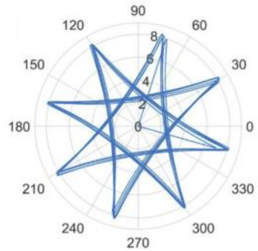
New design compared to TTX

| Parameters | New Design | TTX Design |
|---|---|---|
| Frequency | 2.856 GHz | 2.856 GHz |
| Phase advance | $3\pi/4$ | $2\pi/3$ |
| Length | 1.535 m | 3.048 m |
| Cell number | 39 | 86 |
| Iris radius | 10.22-8.13 mm | 13.11-9.55 mm |
| Iris thickness | 5.7 mm | 5.8 mm |
| Iris elliptical ratio | 1.8 | 1.3 |
| Filling time | 1050 ns | 830 ns |
| Group velocity | 0.72%-0.30% | 2.04%-0.65% |
| Shunt impedance | 66-72 MΩ/m | 53-60 MΩ/m |
| Average Gradient | 25.8 MV/m@ 21MW | 14.5 MV/m@ 30MW |





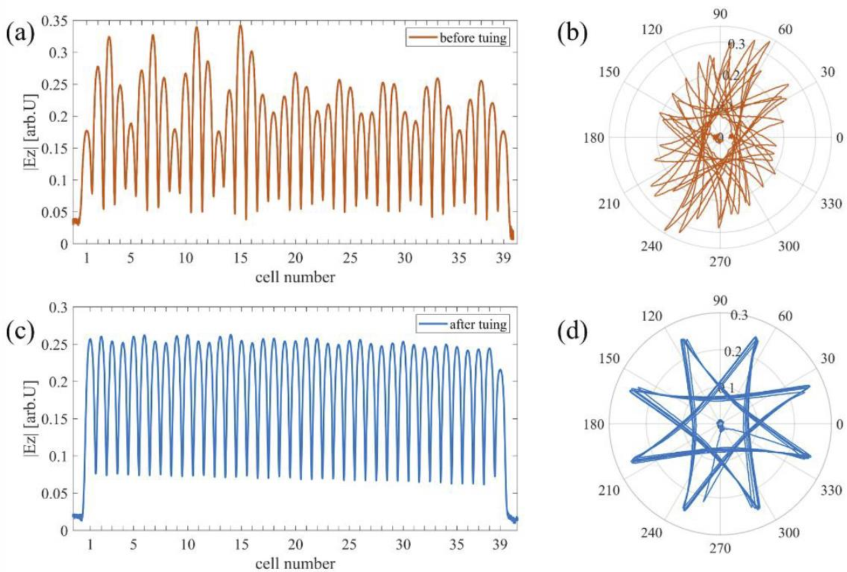
Parameters of the single cells with different phase advance

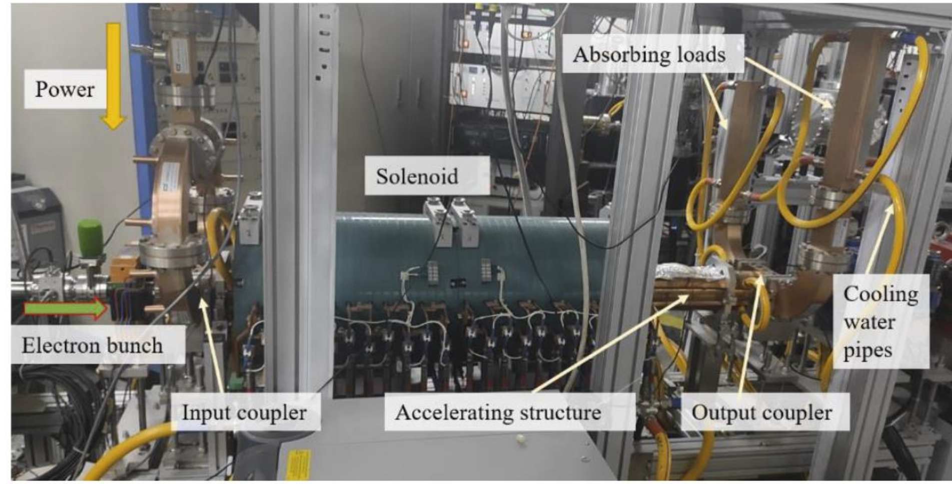
| Parameters | $2\pi/3$ | $3\pi/4$ | $5\pi/6$ |
|---|---|---|---|
| iris radius [mm] | 8.00 | 8.00 | 8.00 |
| $Q$ value | 15130 | 16438 | 17532 |
| Group velocity ($v_g/c$) | 0.368% | 0.296% | 0.208% |
| Shunt impedance $r/Q$ [MΩ/m] | 70.1 | 71.6 | 70.9 |

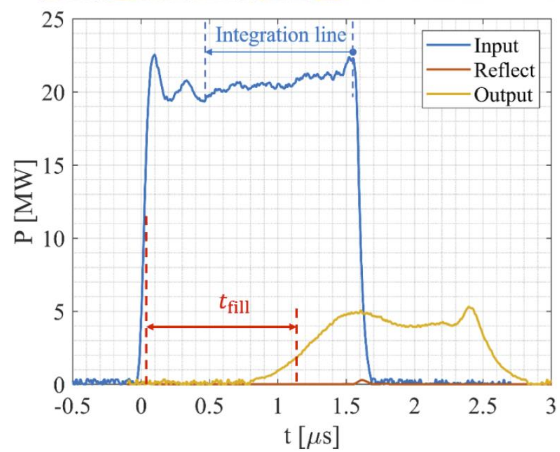
*Lin, Xiancai, et al. submitted to NIMA

# S BAND ACC

High power tested on TTX beamline



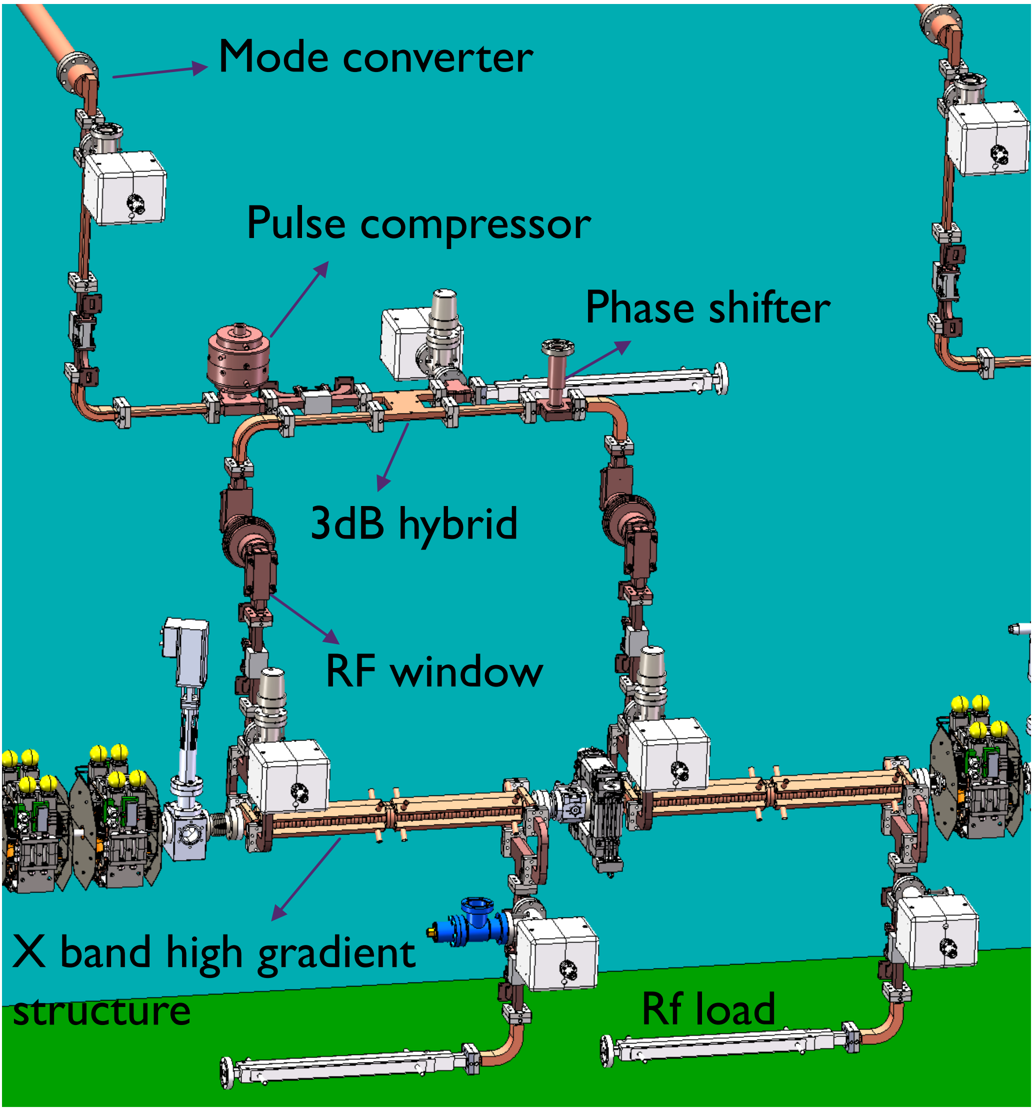

- Conditioning:
  - 120 hours
  - 4 million pulses

| Parameters | Measurement | Simulation |
|---|---|---|
| Frequency | 2.856 GHz | 2.856 GHz |
| Phase advance | 119.97° | 120° |
| Gradient @20.7MW | 24.2 MV/m | 25.7 MV/m |
| Filling time | 1090 ns | 1050 ns |

*Lin, Xiancai, et al. submitted to NIMA

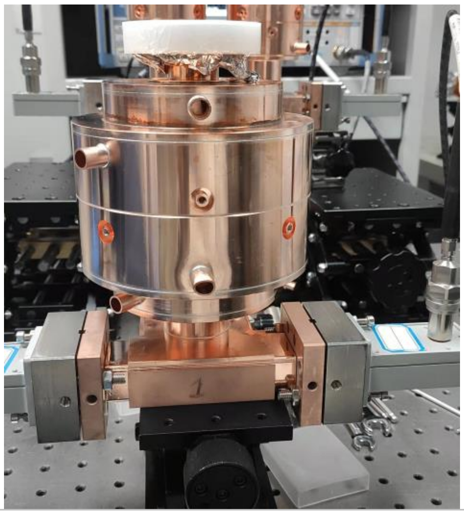
# X BAND LINAC

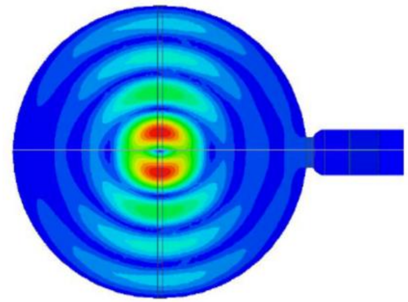
# X BAND MODULE

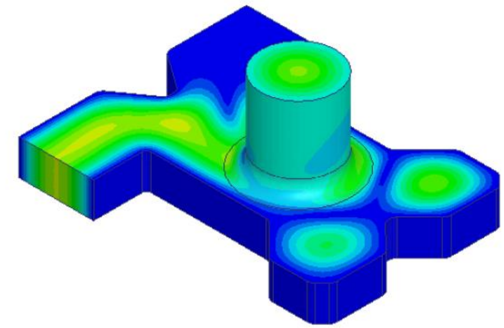


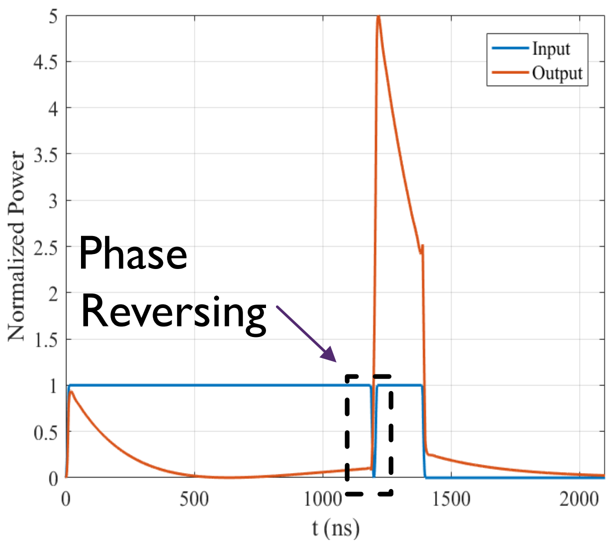

- One klystron
  - 50 MW, 1.5us
- One pulse compressor (SLED I type)
- Two X band high gradient structures
  - Average gradient >= 80 MV/m
  - Energy gain per structure > 50 MeV
  - Filling time < 150 ns
- Maximum rf loss due to waveguides and rf components from klystron to Xacc is about 0.9dB
- Peak power at Xacc input is about 91 MW if power compressor gives gain factor as 4.5

# X BAND POWER COMPRESSOR







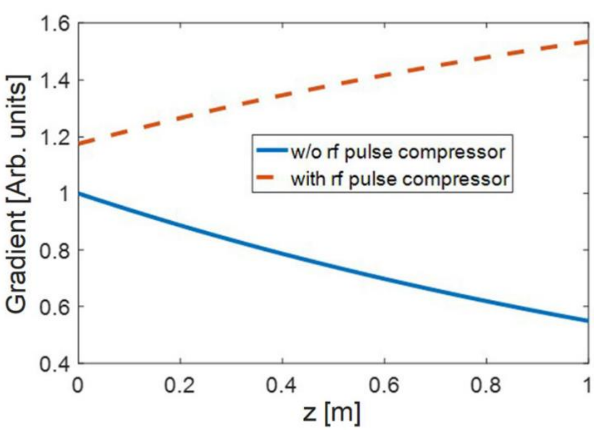


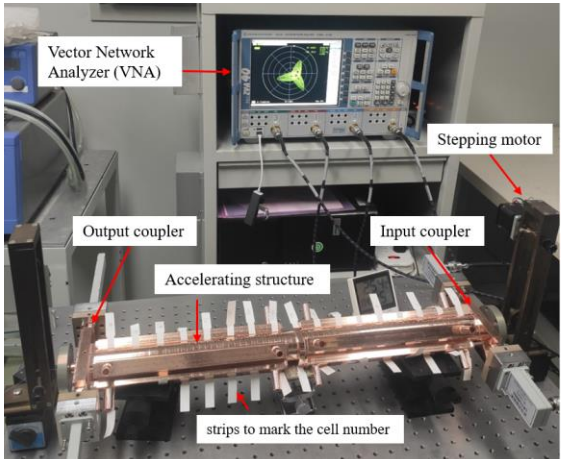

| Parameters | Value | Unit |
| --- | --- | --- |
| Frequency | 11.424 | GHz |
| Coupling ratio | 3.5 | |
| Mode | $TE_{114}$ | |
| Quality factor | 85000 | |
| Compression factor | 10 | |
| Power gain | 5 | |
| Reversing time | 20 | ns |

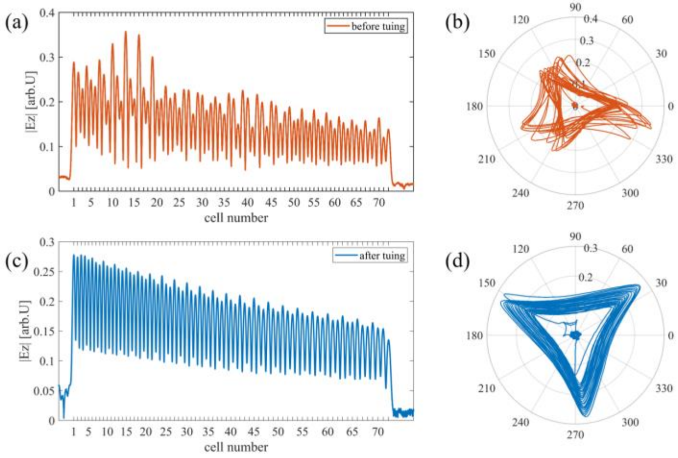
*Matthew Franzi et al. Phys. Rev. Accel. Beams 19, 062002 (2016)

# 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.



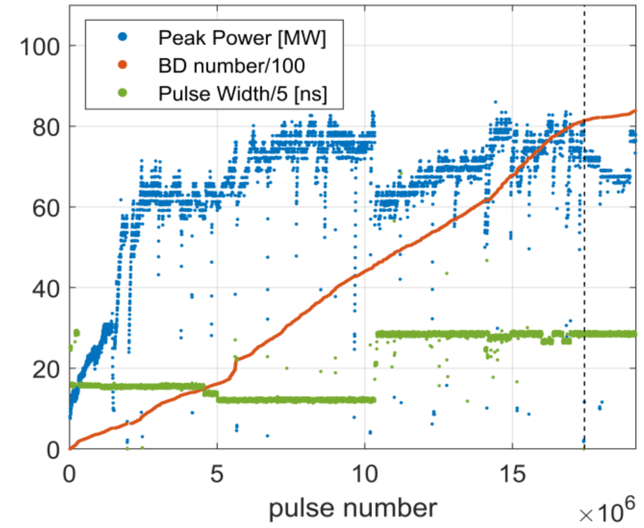



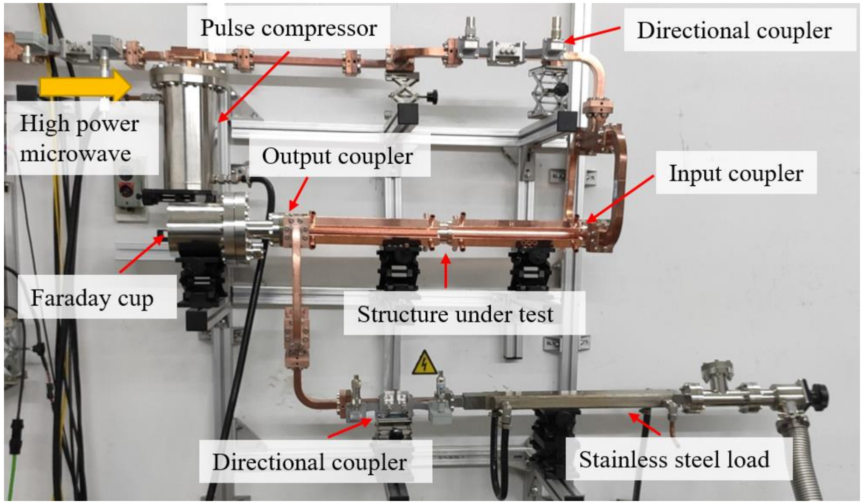



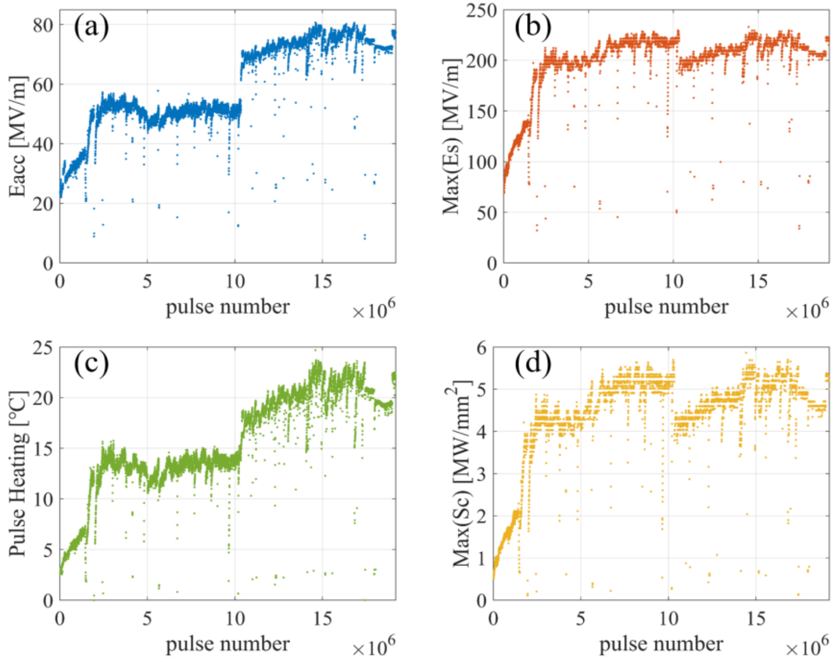

[1]Liu, J., et al., NUCL SCI TECH **31**(11): 1-11.   [2] Lin, Xiancai, submitted to NST

# X BAND HG STRUCTURE

- High power test at the Tsinghua X-band high-power test stand with pulse compressor on
- 17 million pules conditioning, 2 million pulses test
- Maximum gradient: ~ 80 MV/m
- The maximum input power: ~80 MW
- The overall breakdown number: $8.4\times10^3$

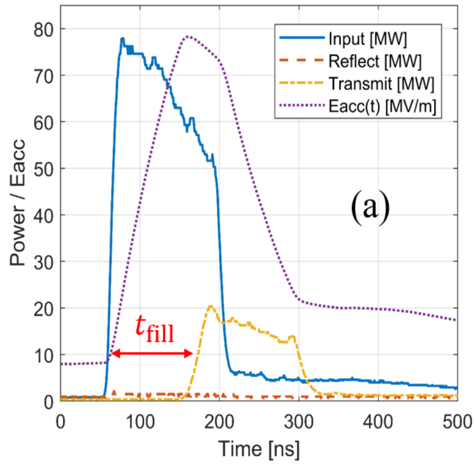


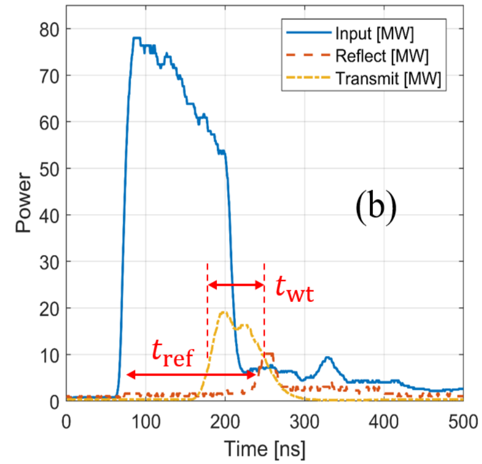



# X BAND HG STRUCTURE

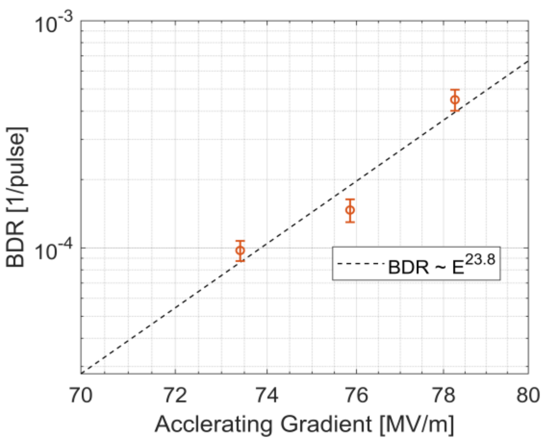
- The breakdown rate versus accelerating gradient is close to the 30-power law
- The breakdown distribution is obtained from the input, transmit and reflect waveform
- Breakdown strongly corelated to field in the structure (surface electric field reaches over 220 MV/m in the 1st cell)

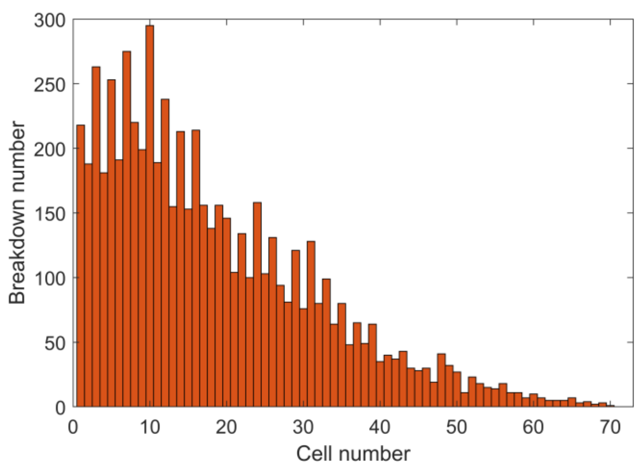



Normal waveform

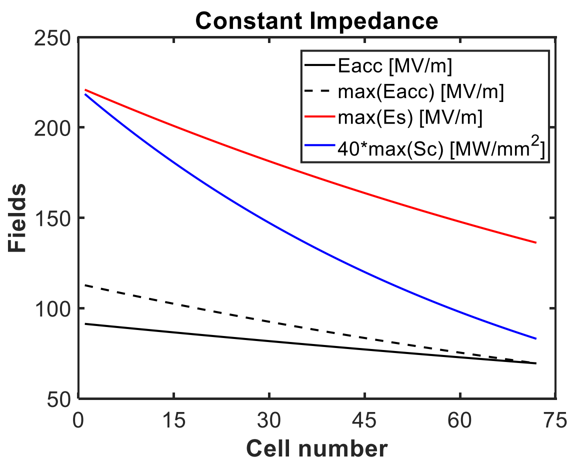



Breakdown waveform



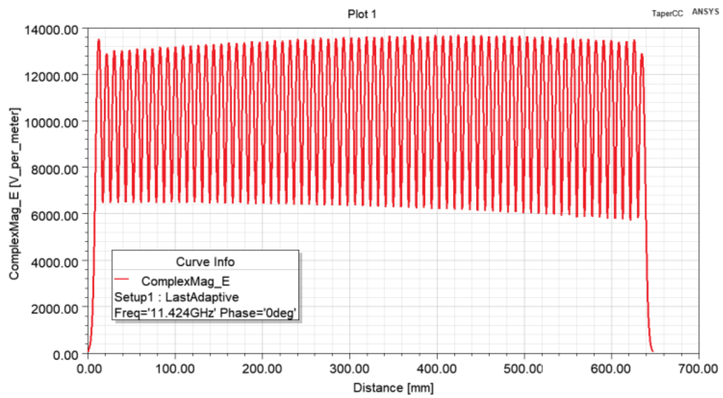

Breakdown position

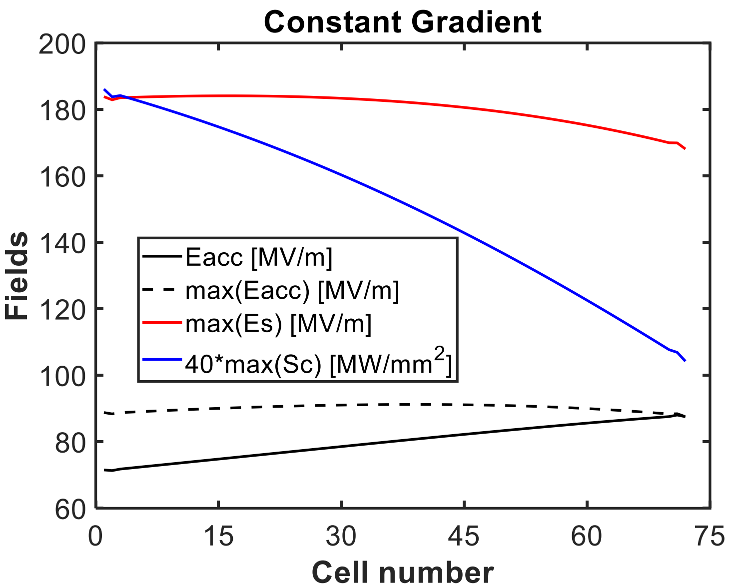


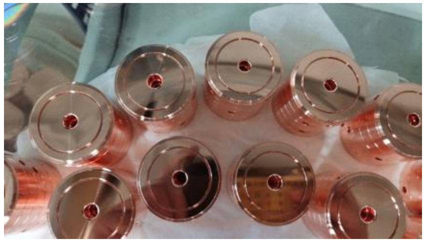
# X BAND HG STRUCTURE

- CI prototype: BDR is high at 80MV/m (~$10^{-3}$/pulse), condition period is long
- We switch to CG scheme with maximum surface field 20% lower than CI
- COST: CG 20% higher 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 |
| Power @80MV/m with pc [MW] | 81.3 | 80.1 |



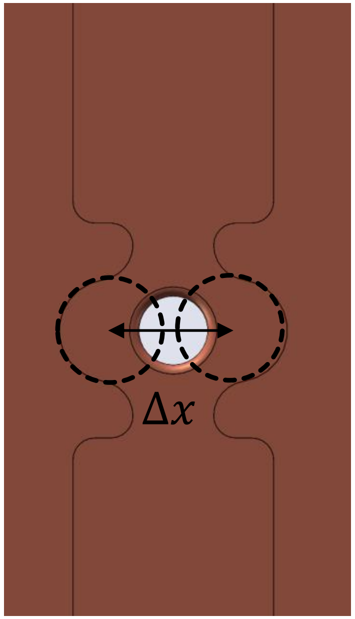



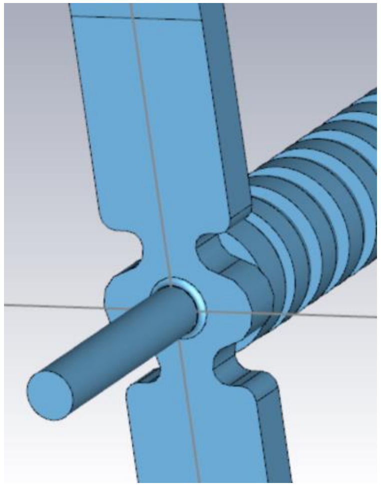
Waiting for brazing

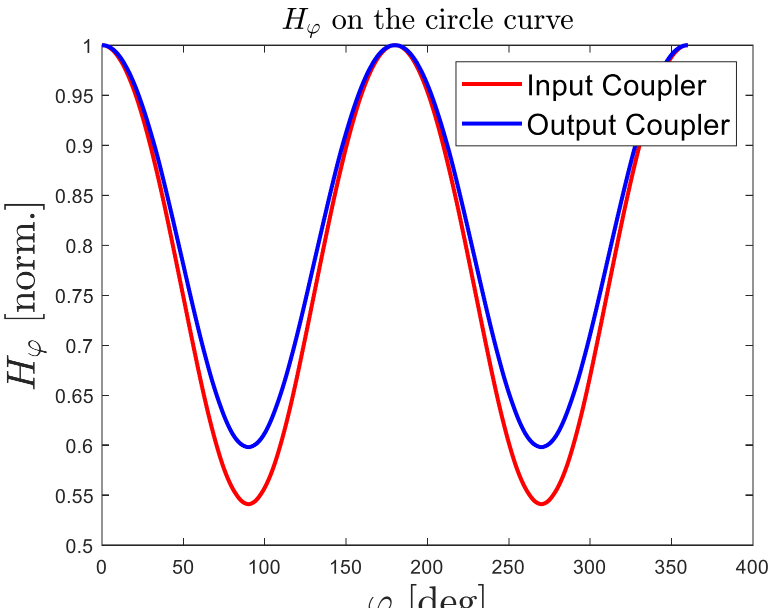
# X BAND HG STRUCTURE

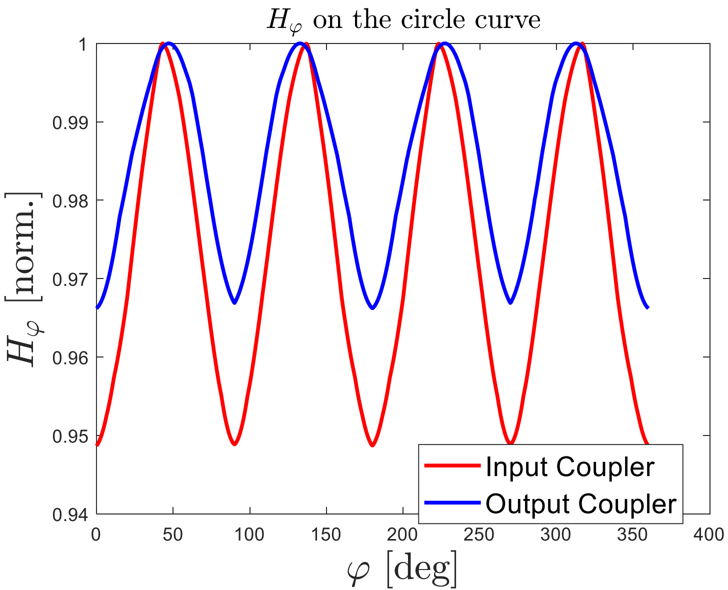
| | Field Mode | Quadrupole field strength (relative to monopole) |
|---|---|---|
| Regular coupler | Input Coupler | 0.29 |
| | Output Coupler | 0.25 |
| Racetrack coupler | Input Coupler | 8e-4 |
| | Output Coupler | 1e-3 |

Racetrack coupler



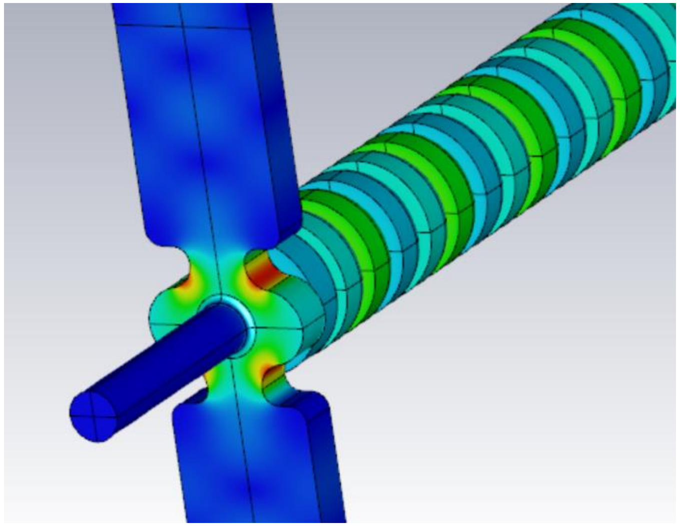



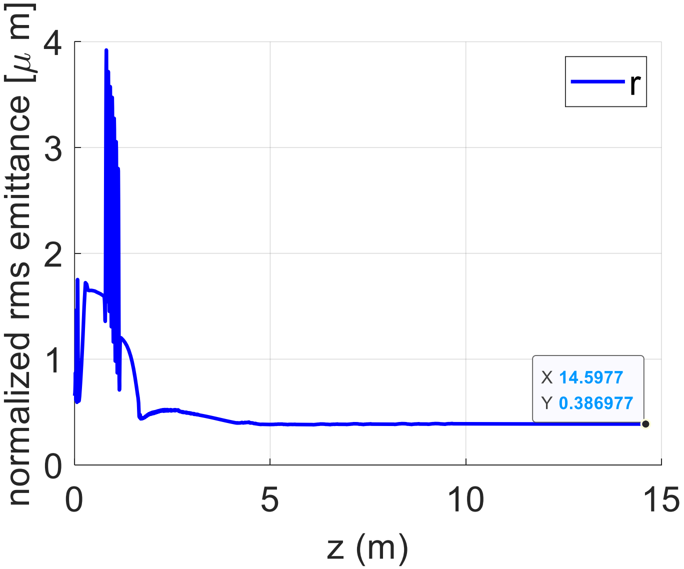


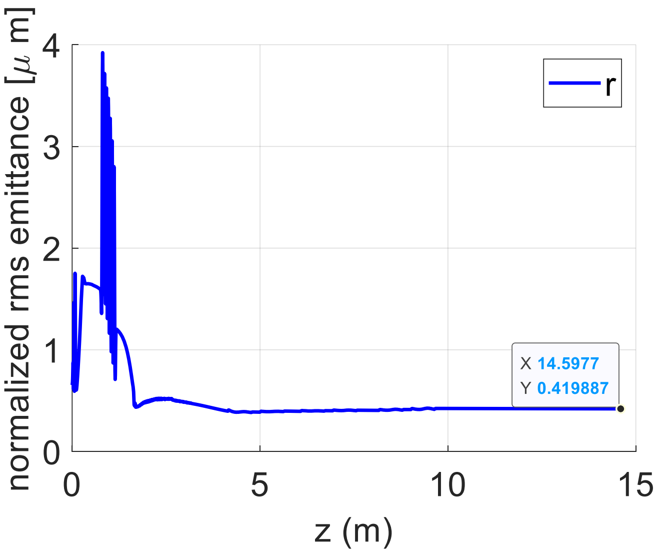



# X BAND HG STRUCTURE

- Beam dynamic simulation using 3D field map
  - Normalized emittance with regular coupler: 0.420 um
  - Normalized emittance with racetrack coupler: 0.387 um
- Pulsed heating at 80 MV/m:
  - Regular coupler: 20 Celsius
  - Racetrack coupler: 28 Celsius, acceptable





# SUMMARY

- Accelerator system design finished
  - RF components, beamline layout, waveguide layout, magnets….
- Crucial RF structures fabrication finished
  - S band photoinjector, buncher, S band accelerating structure, pulse compressors #1 , X band CG structure #1
- Conditioning the structures in Tsinghua University after this summer
- Design support mechanic components for beamline and waveguides
- Schedule installation on next March
- Hope to start VIGAS accelerator system commissioning in the next fall and get the first light in the first quarter of 2024

# THANKS FOR YOUR ATTENTION