Development of an S-band parallel-coupled polarizable transverse deflecting cavity for S³FEL

Jiahang Shao

2026.10.14

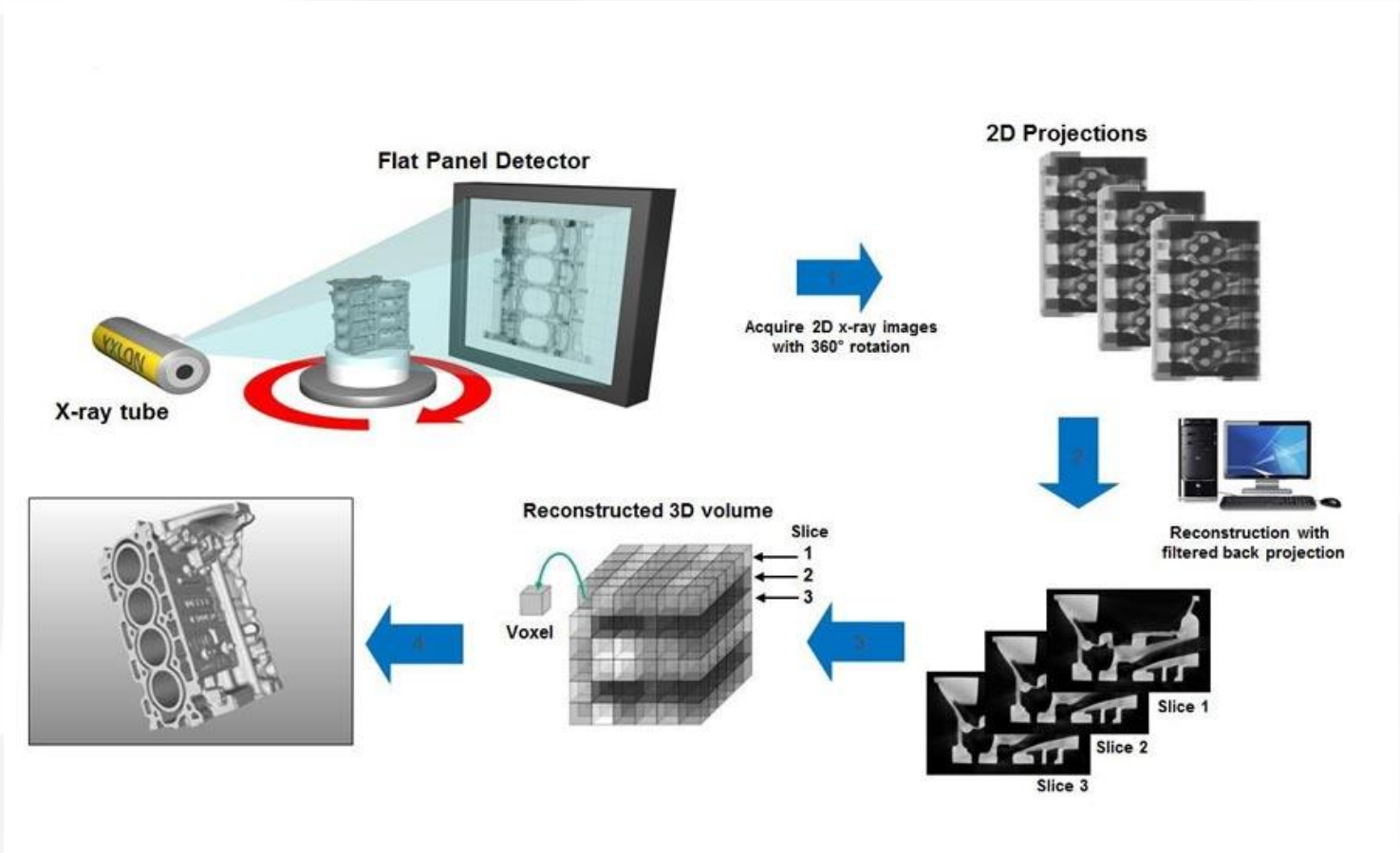
Shenzhen Superconducting Soft X-ray FEL (S^3FEL)

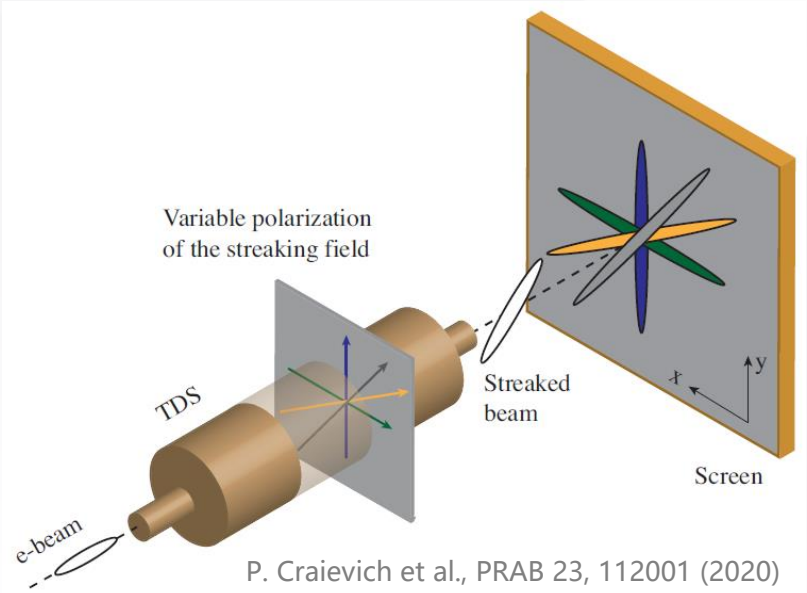


- Recently funded FEL project in Shenzhen, Guangdong
- CW accelerator with 1 MHz repetition rate
- 2.5 GeV beam for lasing at 1-30 nm

Multi-dimensional beam diagnostics

- **A polarizable transverse deflecting cavity (TDC) enables multidimensional phase-space reconstruction for high-brightness electron beams**



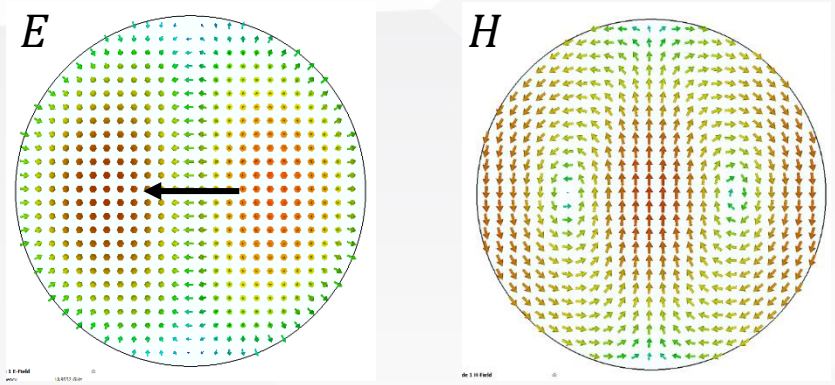


P. Craievich et al., PRAB 23, 112001 (2020)

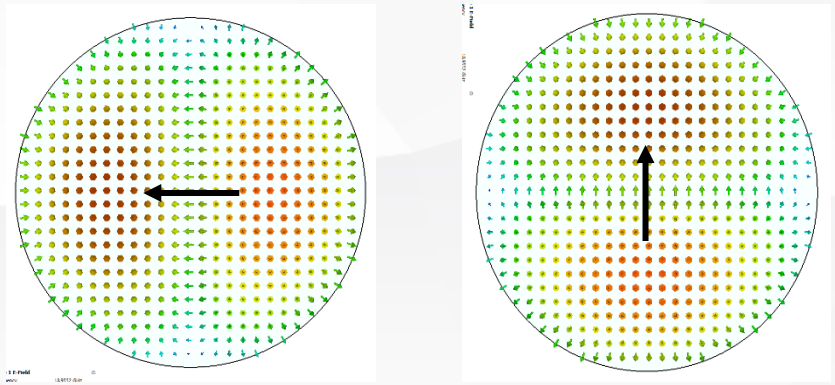
$$R_{\mathrm{rot}} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & k\cos\theta & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & k\sin\theta & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ k\cos\theta & 0 & k\sin\theta & 0 & 0 & 1 \end{pmatrix}$$

Polarization of transverse deflecting modes

- Two orthogonal, degenerate TM_{11}-like modes with polarization defined by the on-axis transverse electric field
- Unintended polarization rotation due to geometric imperfections and tuning-induced deformation

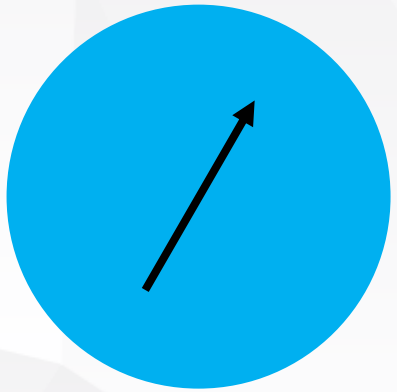


$$\frac{d\vec{p}}{dt} = q(\vec{E} + \vec{v} \times \vec{B})$$

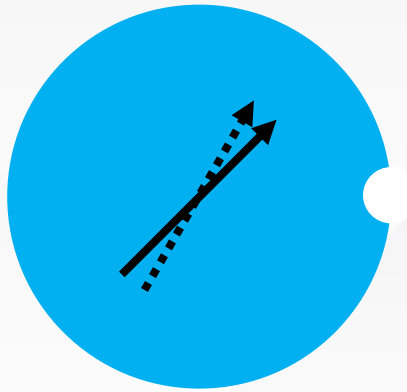


Horizontal polarization

Vertical polarization



Ideal



After tuning

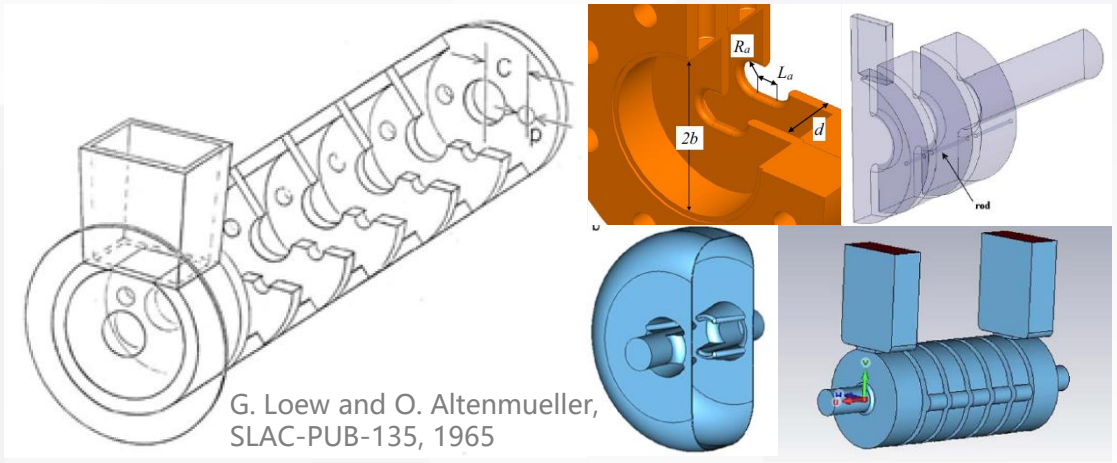
$$|\Delta\theta| \propto \frac{|\kappa|}{|f_x - f_y|} \qquad \kappa \propto \int_{\Delta V} \left(\mu_0 H_x^* H_y - \varepsilon_0 E_x^* E_y\right) dV$$

Weak-coupling and small-angle approximation

Different approaches to polarization control

Fixed polarization using asymmetric cells

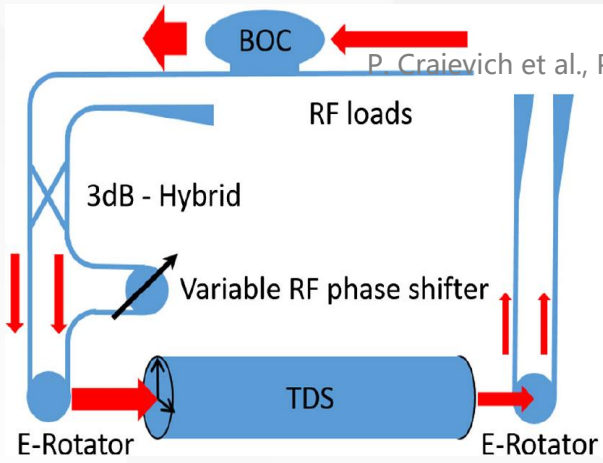
$$f_{source} = f_x \neq f_y$$



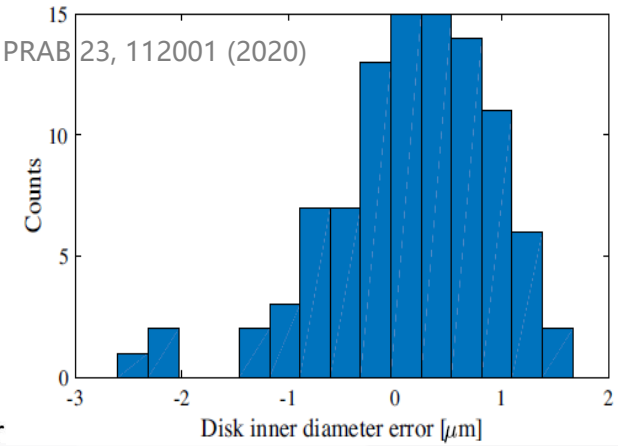
G. Loew and O. Altenmueller, SLAC-PUB-135, 1965

Variable polarization using symmetric cells

$$f_{source} = f_x = f_y$$

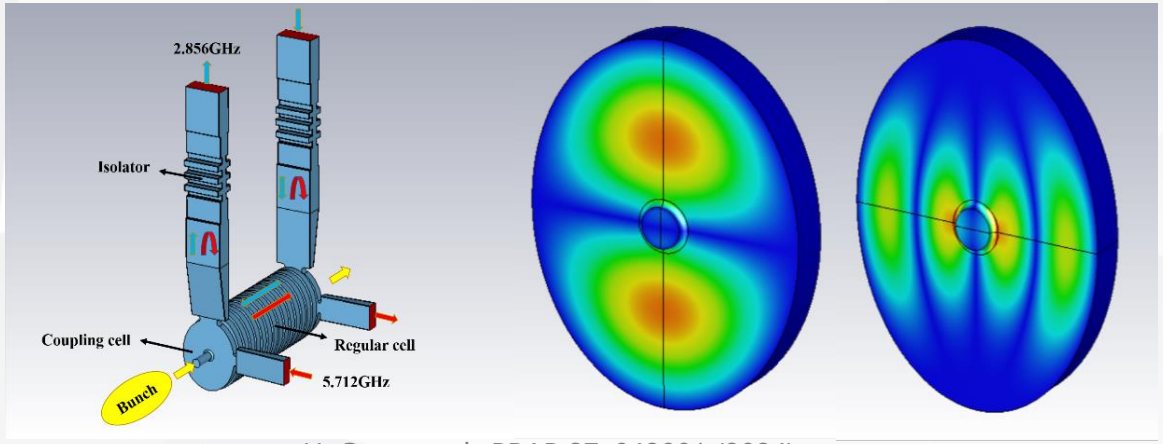


P. Craievich et al., PRAB 23, 112001 (2020)



Variable polarization using dual-mode cells

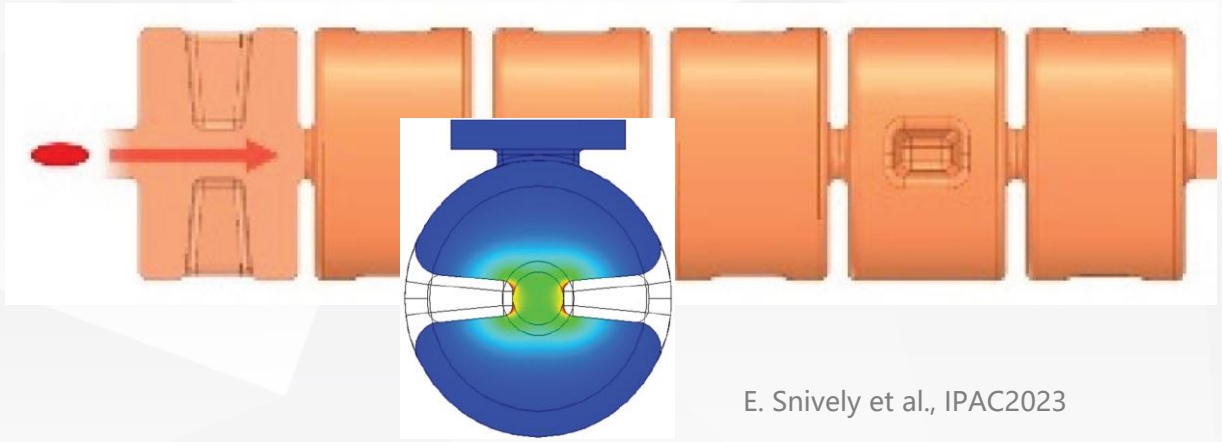
$$f_{source,1} = f_x = 0.5 f_y = 0.5 f_{source,2}$$



H. Gong et al., PRAB 27, 042001 (2024)

Variable polarization using orthogonal asymmetric cells

$$f_{x,1} \neq f_{y,1} = f_{source,1} = f_{x,2} \neq f_{y,2}$$



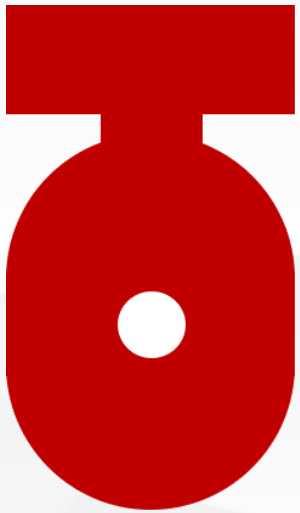
E. Snively et al., IPAC2023

Proposed parallel-coupled polarizable TDC

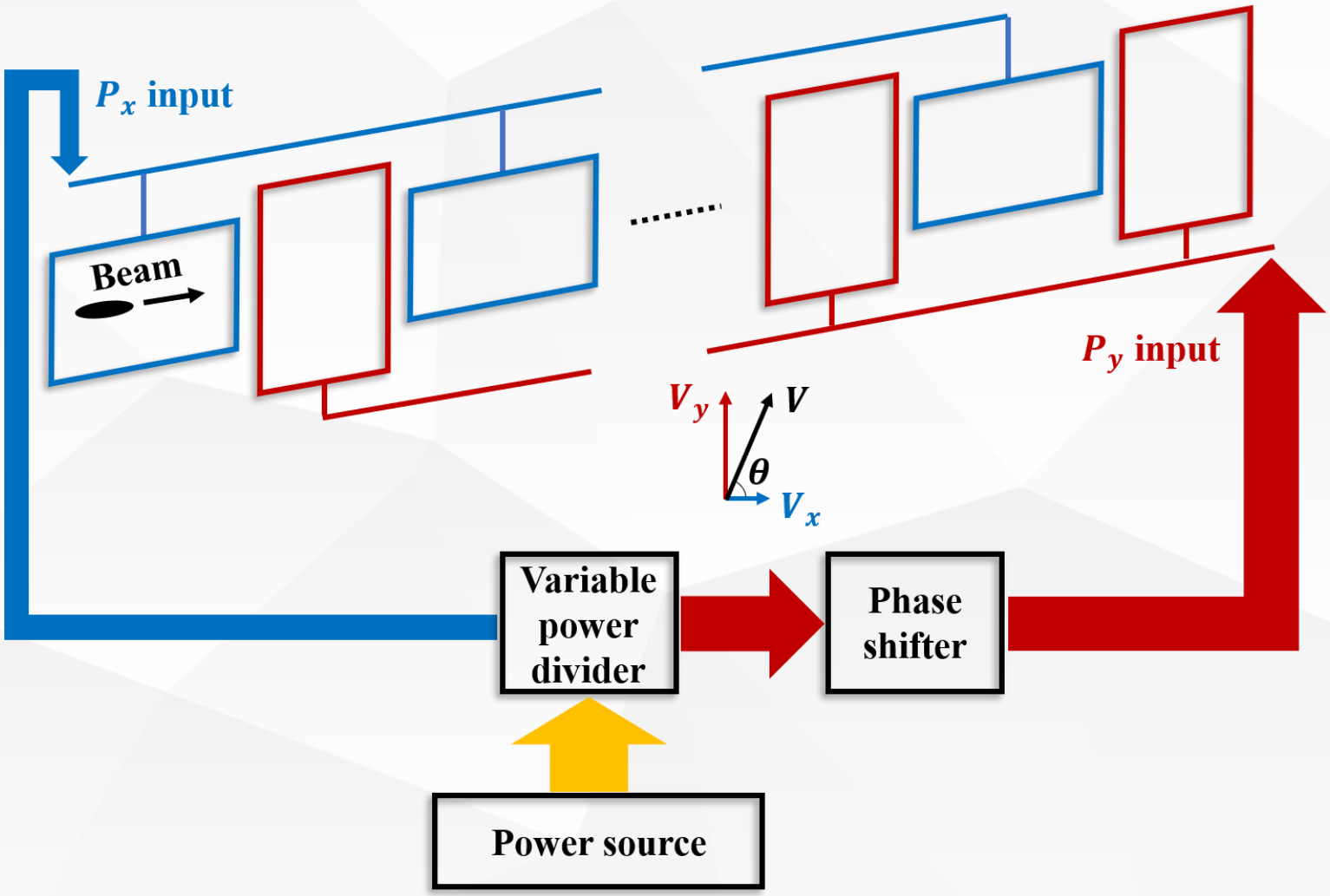
- Targets: variable polarization, ease of fabrication and tuning, single-frequency operation, compactness
- Solution: orthogonal asymmetric cells with parallel feeding



$V_x \propto \sqrt{P_x}$



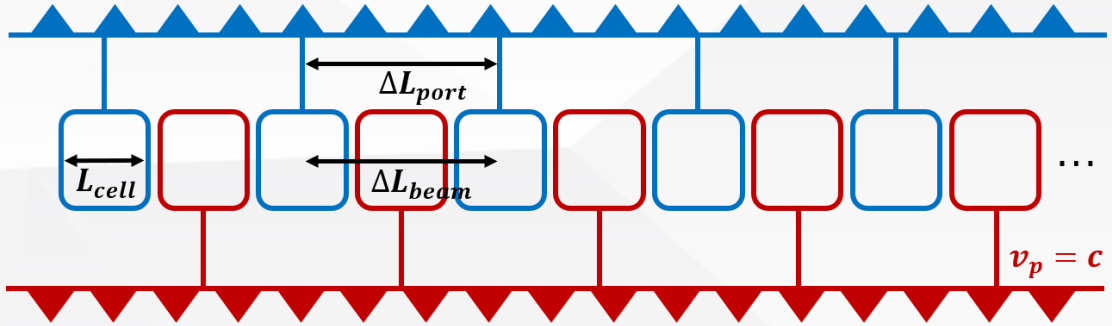
$V_y \propto \sqrt{P_y}$



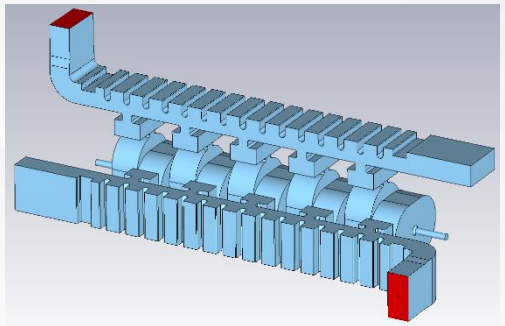
Configuration and operating principle

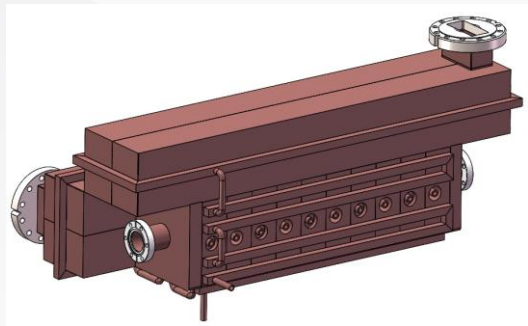
$$\frac{\triangle L_{port}}{v_p} + N \times T_{RF} = \frac{\triangle L_{beam}}{c}$$

Stand-alone cells with slow-wave waveguides

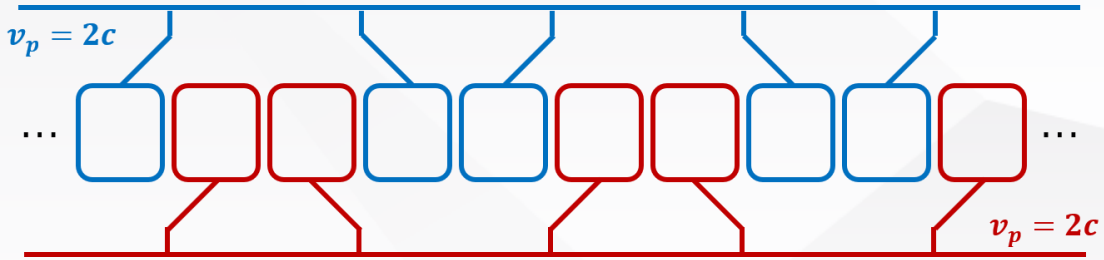


Challenge: final brazing of the long waveguides

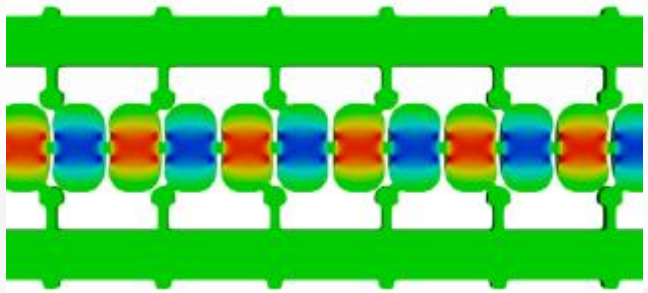




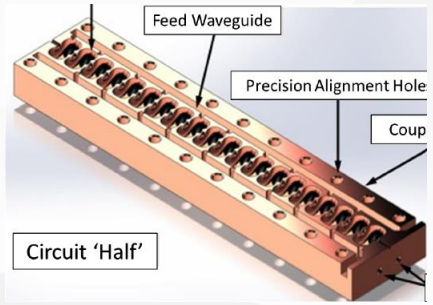
Paired cells with fast-wave waveguides



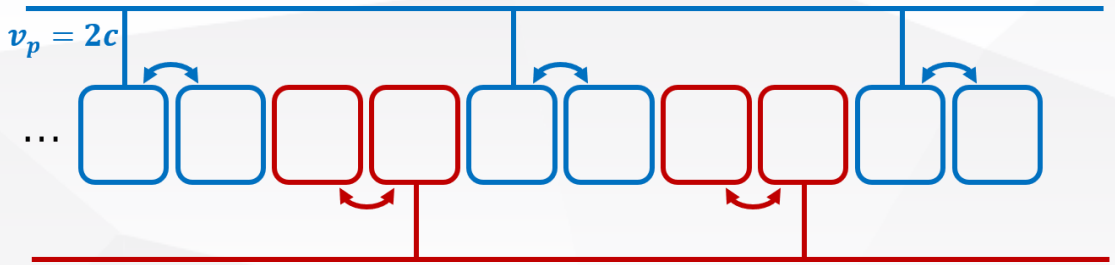
Potential reduction in Q due to four-quadrant fabrication

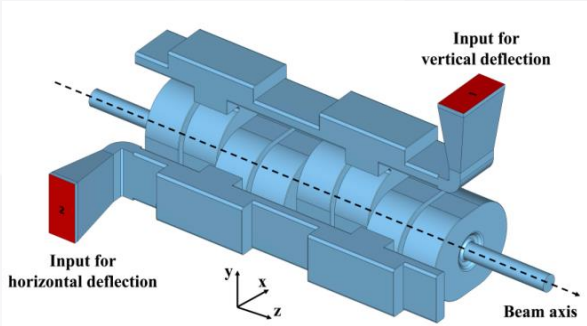


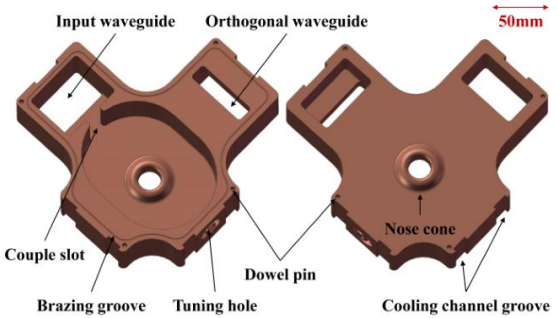
S. Tantawi et al., PRAB 23, 092001 (2020)



Coupled cells with fast-wave waveguides

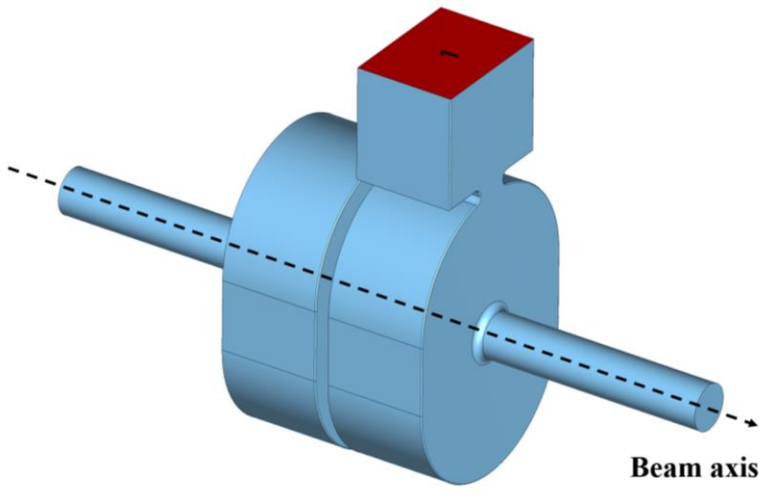


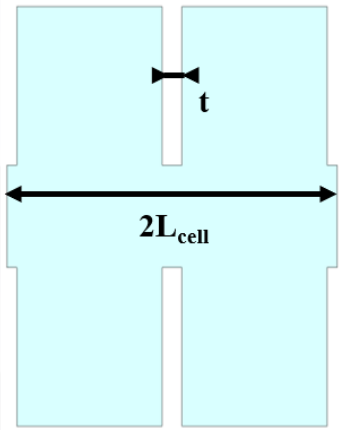


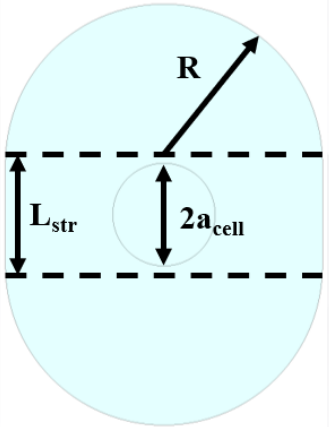


Design of the deflecting chain

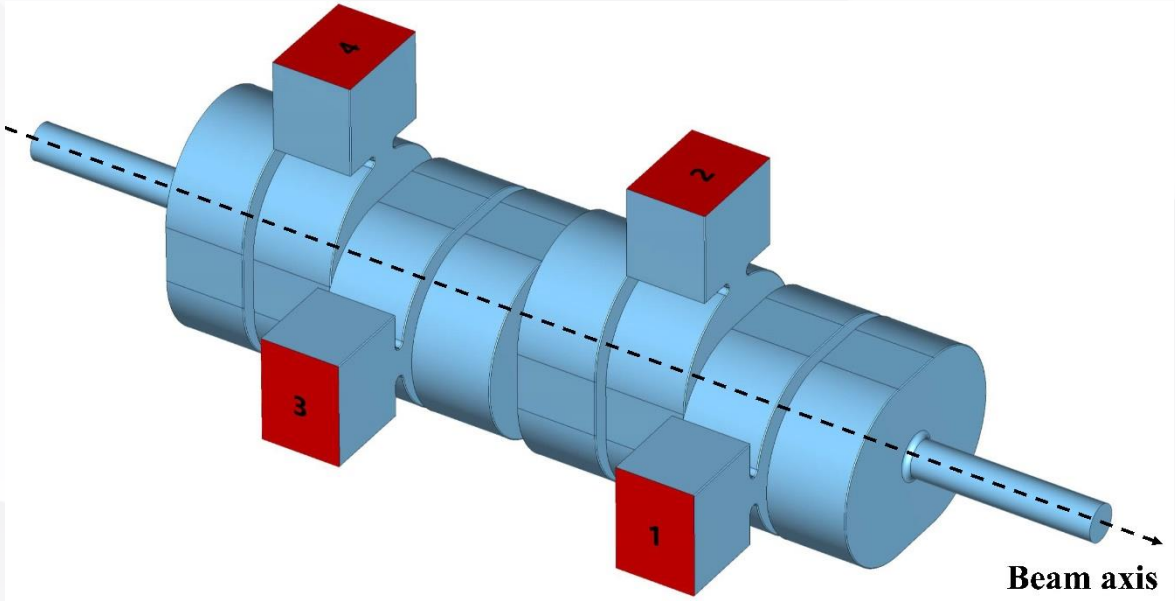
- Design objectives for units: 0/π mode separation, orthogonal mode splitting, high shunt impedance, and critical external coupling

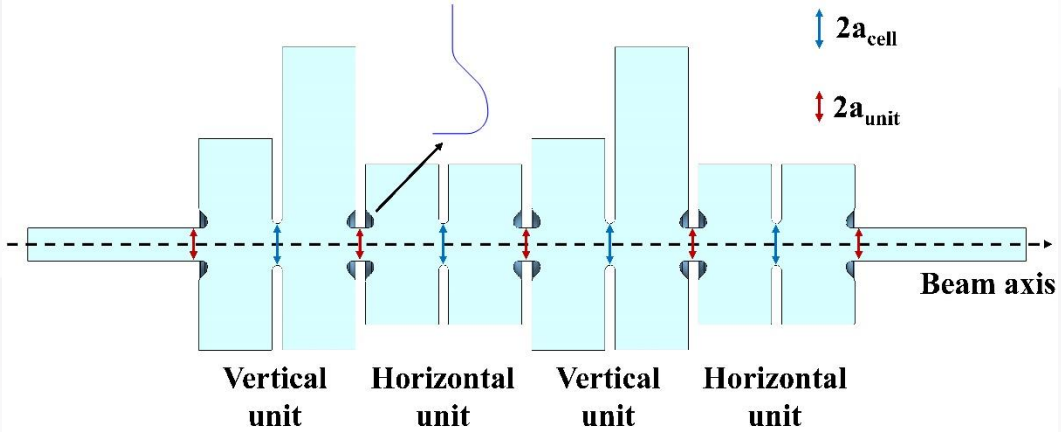






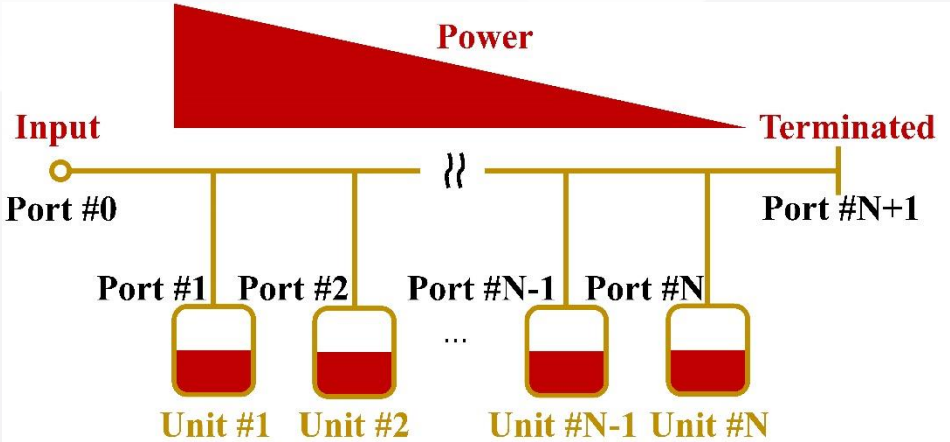
- Chain design objective: high RF isolation between adjacent deflecting units

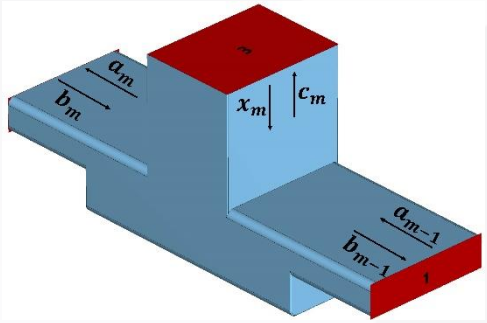




Design of the parallel-feeding network

➢ **Design objectives: equal RF power distribution and appropriate phase advance for beam synchronization**

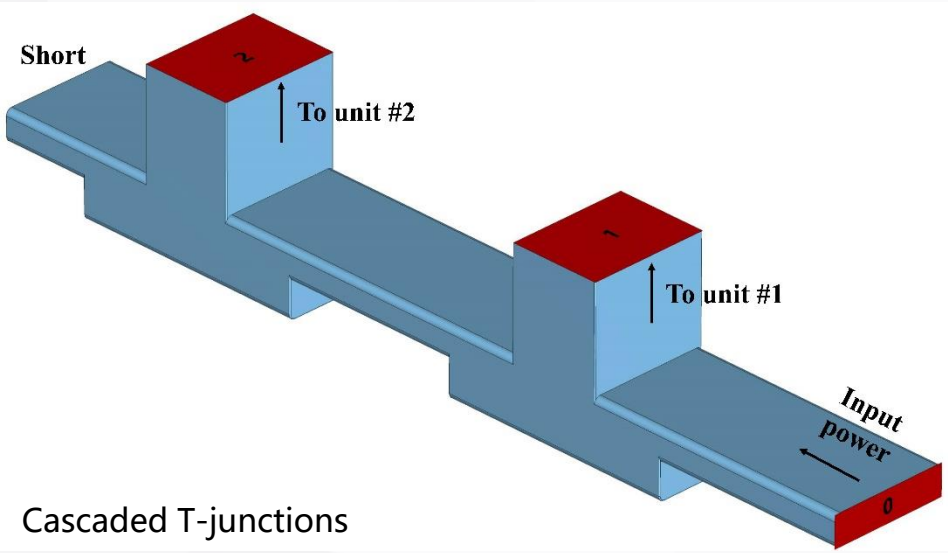




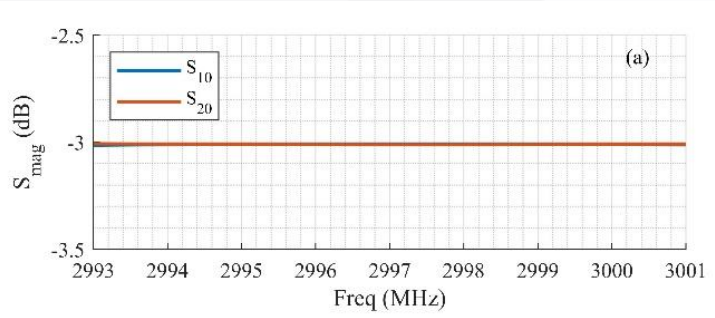
Single T-junction

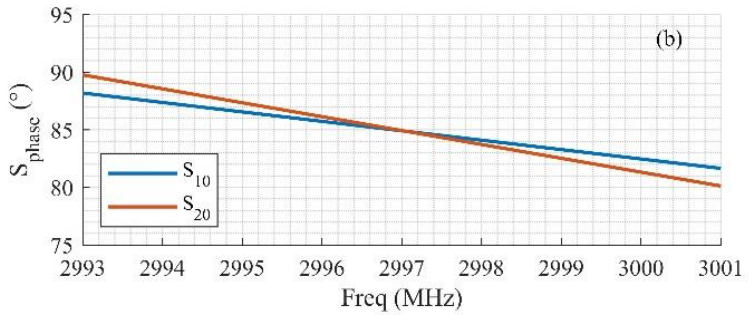
$$S_{Tj,opt} = \begin{bmatrix} 0.200 & 0.800 & 0.566e^{j\phi} \\ 0.800 & 0.200 & -0.566e^{j\phi} \\ 0.566e^{j\phi} & -0.566e^{j\phi} & 0.600e^{2j\phi} \end{bmatrix}$$

$$S_{Tj,CST} = \begin{bmatrix} 0.199 & 0.801 & 0.565e^{j\phi} \\ 0.801 & 0.199 & -0.565e^{j\phi} \\ 0.565e^{j\phi} & -0.565e^{j\phi} & 0.601e^{2j\phi} \end{bmatrix}$$

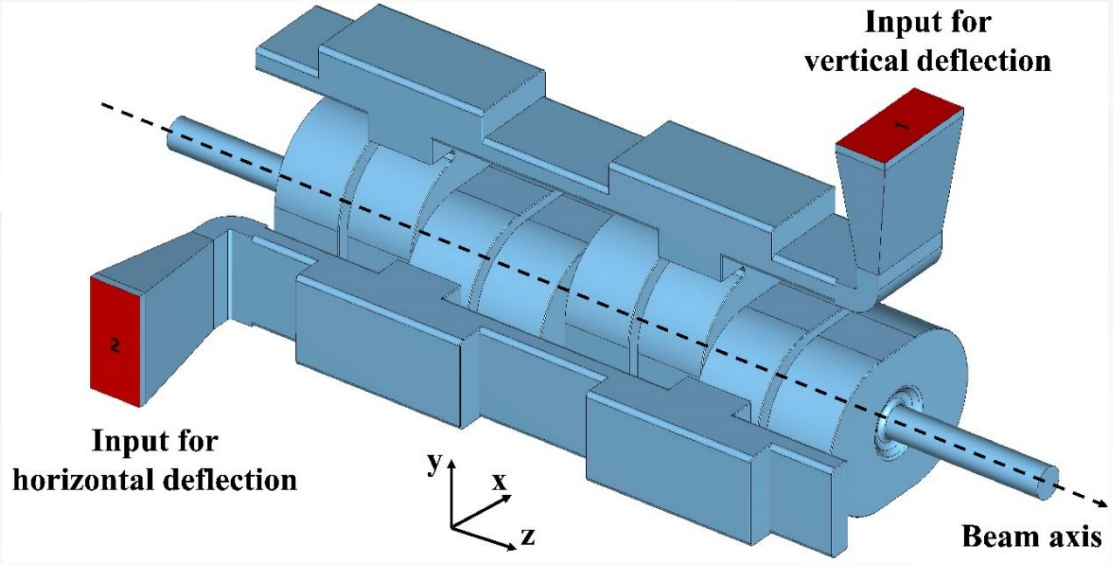


Cascaded T-junctions

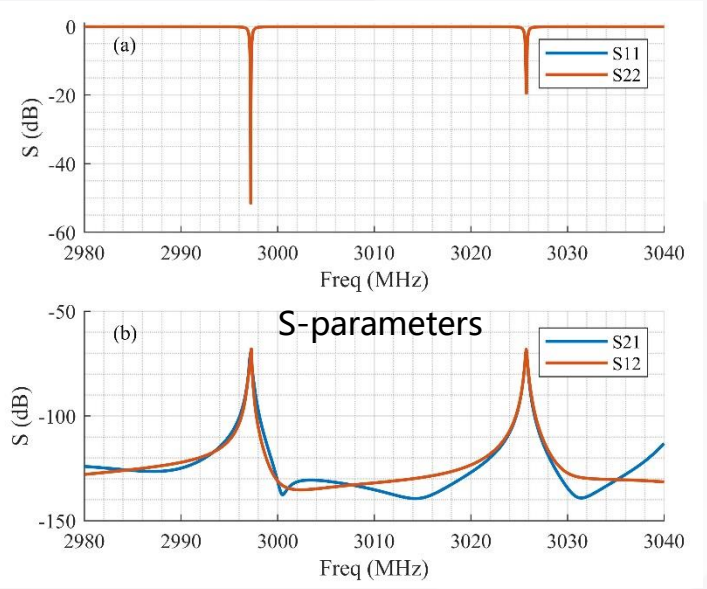


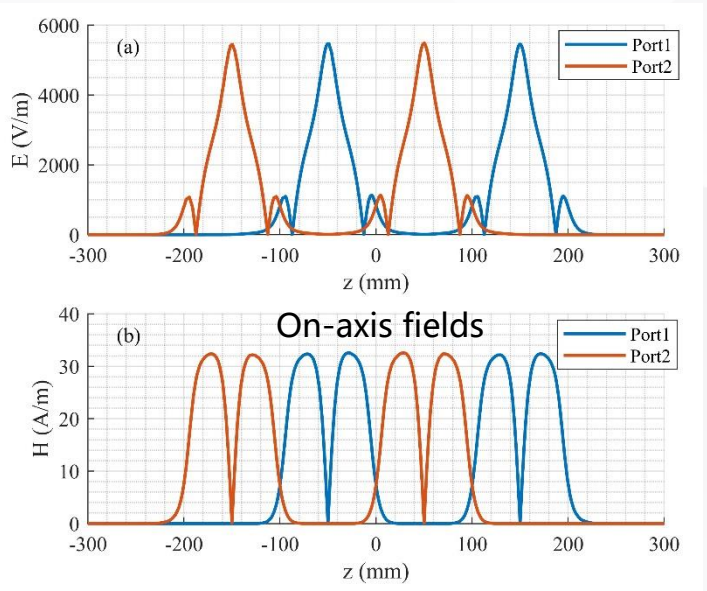


Performance of the complete structure

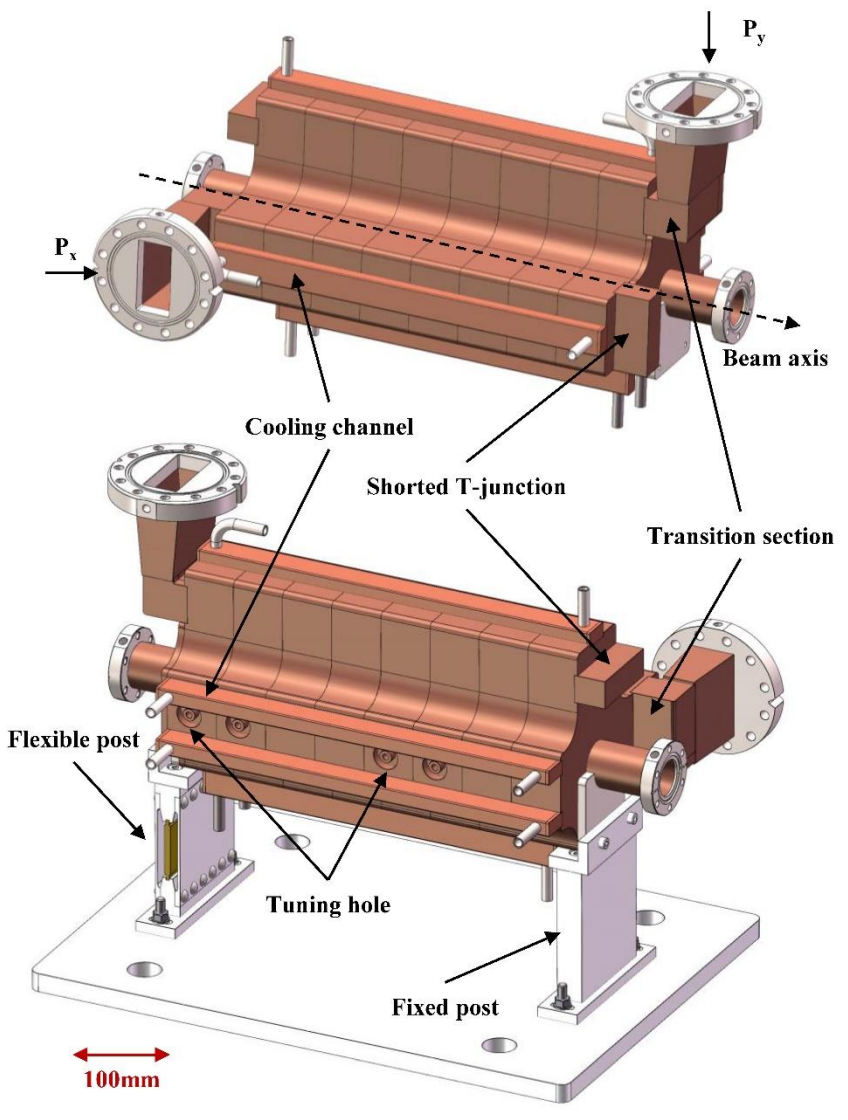


Parameter	Value
Deflecting unit	
Number of cells	2
Longitudinal mode	π-mode
Frequency	2997.22 MHz
$\triangle f_{long}$	28.53 MHz
$\triangle f_{trans}$	420.62 MHz
$r_\perp$	28.13 MΩ/m
Q_0	18532
Deflecting chains	
Number of units	4 (2 horizontal + 2 vertical)
Total length	400.09 mm (beam pipe not included)
V_{def}	6.28 MV
$E_{surface,max}$	83.21 MV/m
$H_{surface,max}$	456.05 kA/m
$S_{c,max}$	2.76 MW/mm^2
TDC assembly	
$r_{\perp,TDC}$	27.96 MΩ/m
$Q_{0,TDC}$	18481
$V_{def,TDC}$	6.26 MV
$E_{surface,max}$	81.74 MV/m
$H_{surface,max}$	451.35 kA/m
$S_{c,max}$	2.72 MW/mm^2

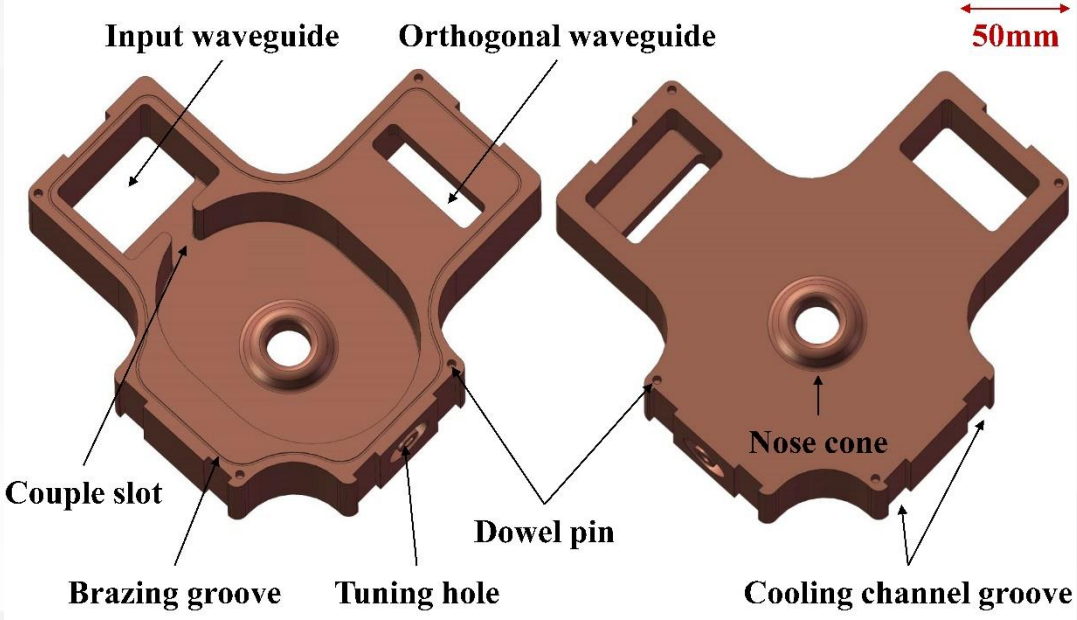


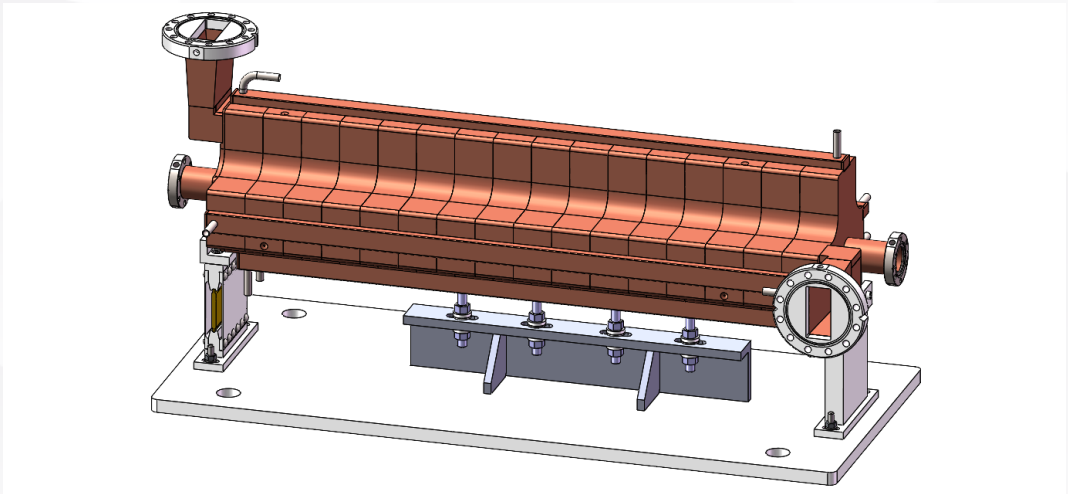


Mechanical design



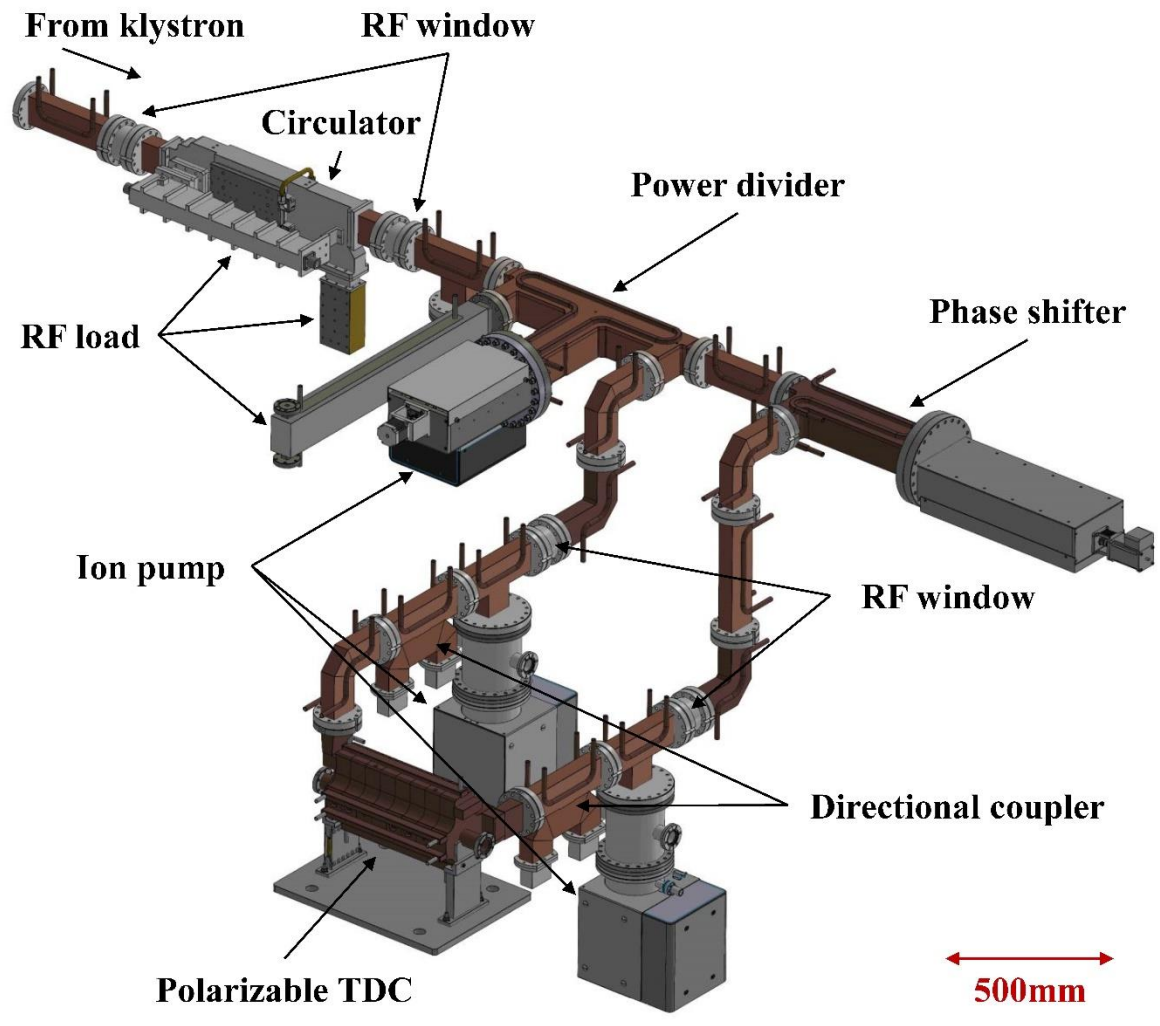
The first prototype: 2997.22 MHz



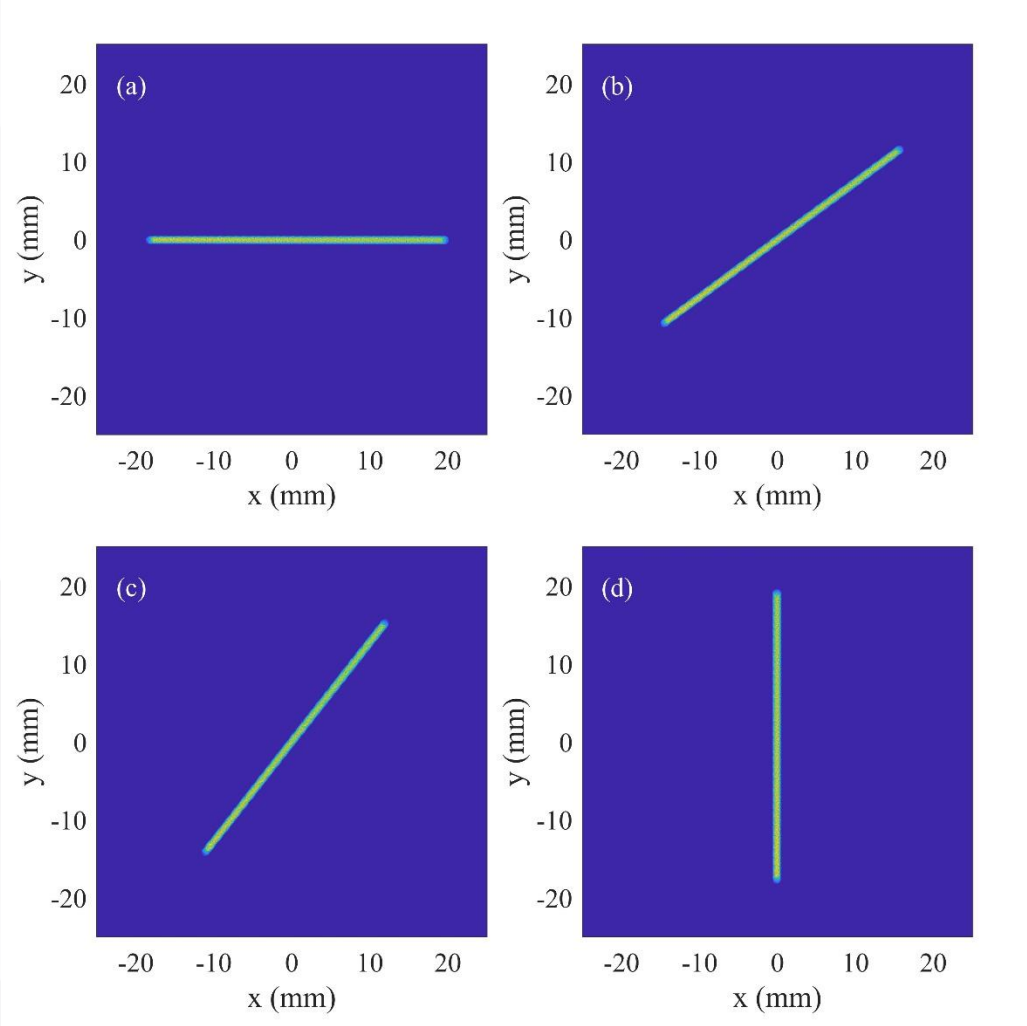


The second prototype: 2856.00 MHz

RF system and beam dynamics verification



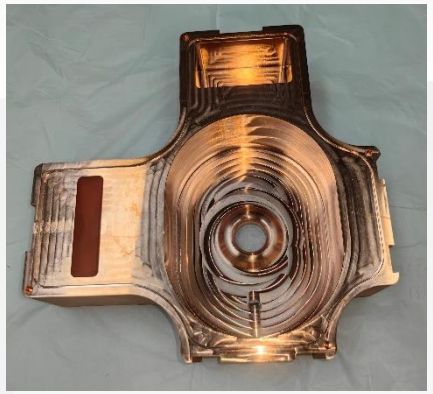
System layout



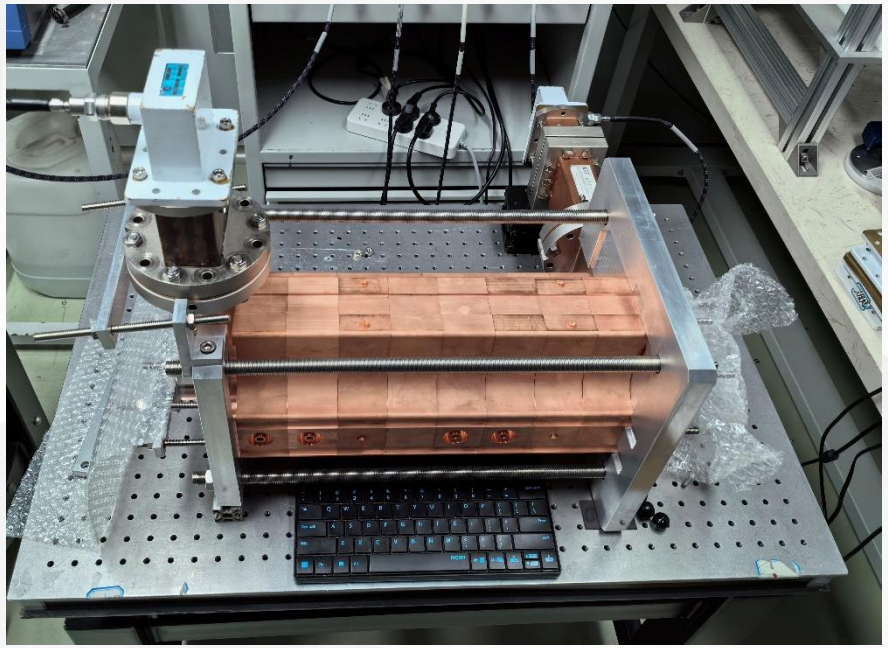
Simulation by ASTRA

Fabrication and initial test of the first prototype

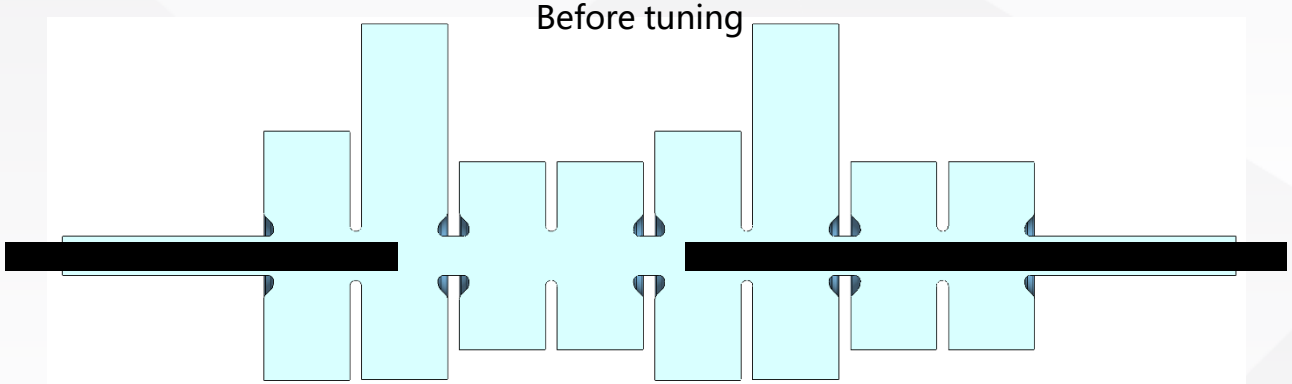
➢ **The first prototype has been developed to validate fabrication and tuning procedures**



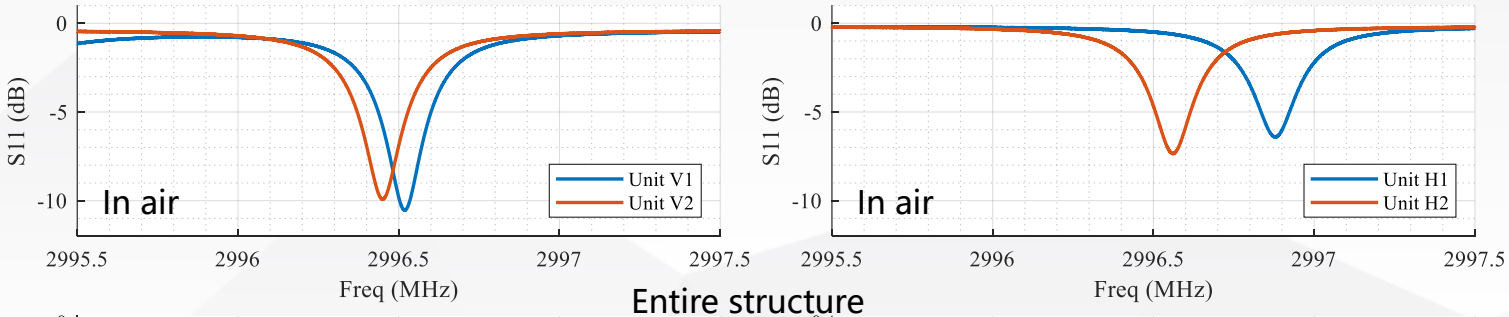




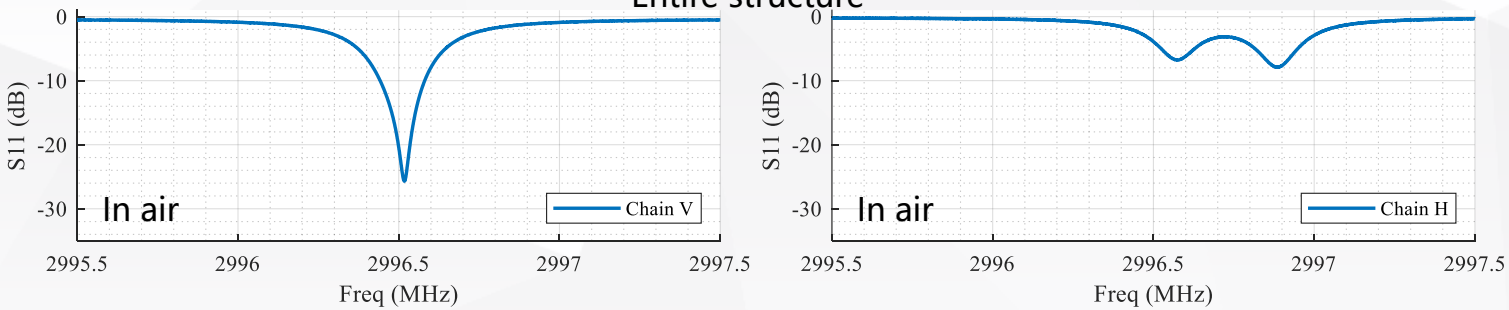
Before tuning



Single unit measurement with detuning probes

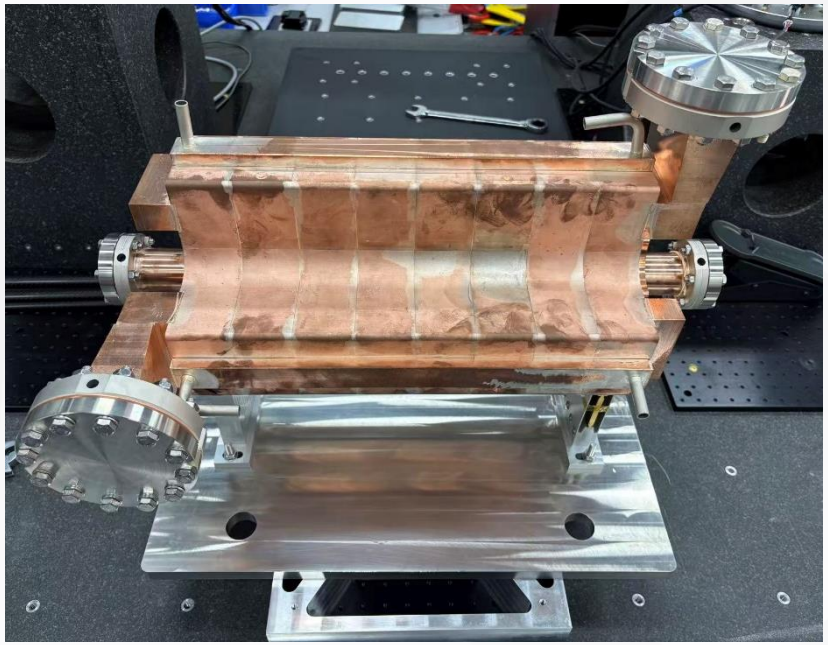


Entire structure



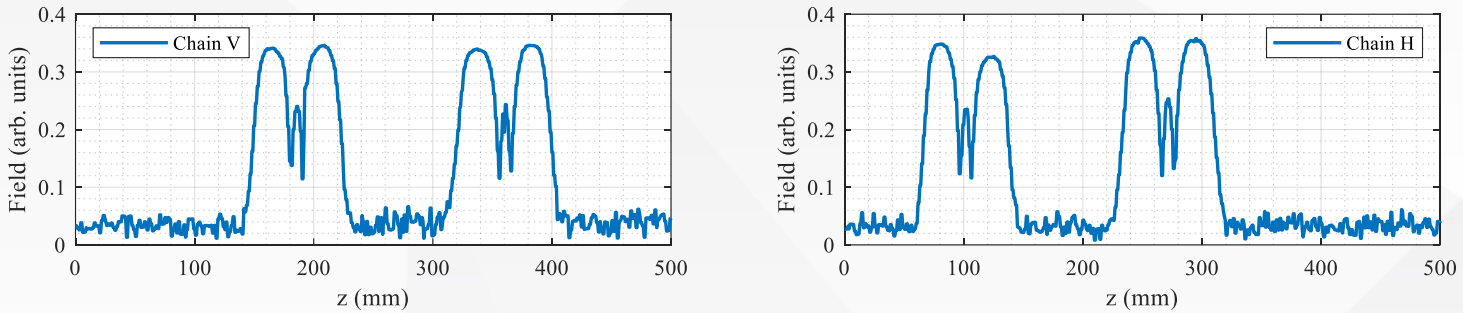
RF tuning of the first prototype

- **Both deflecting chains were successfully tuned to nearly identical resonant frequencies with low RF reflection and good on-axis field balance**

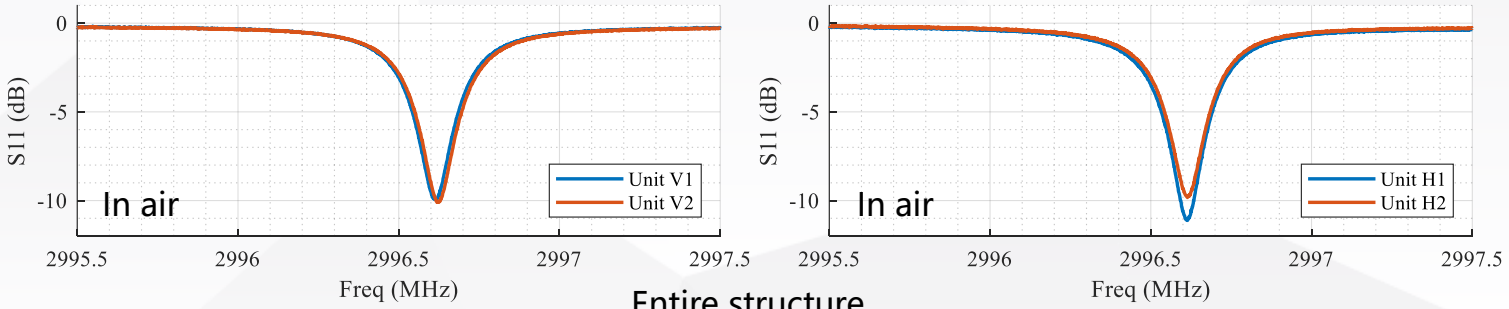


Parameter	Value	
	Chain V	Chain H
Operation temperature (°C)	29.2	
Frequency (MHz)	2997.226	2997.224
Quality factor	18342	18156
VSWR	1.03	1.06
Field balance	0.98	0.95

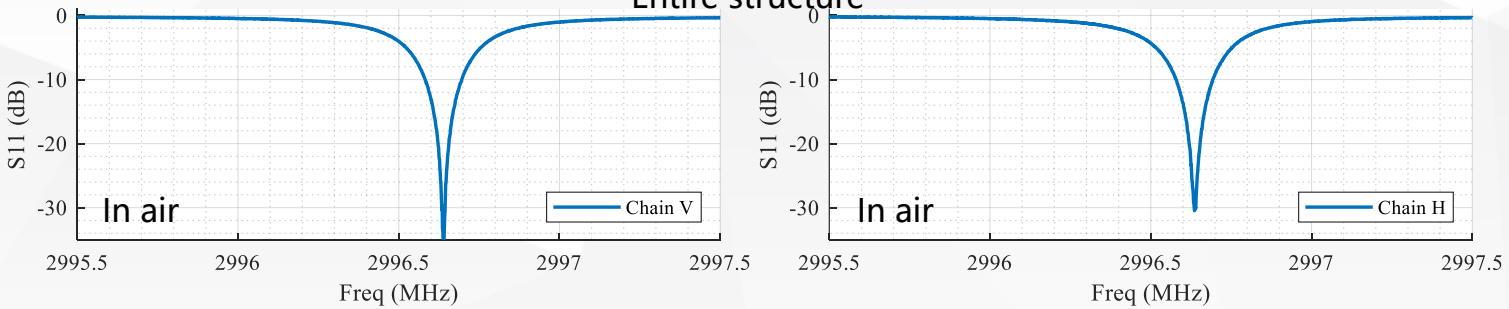
After tuning



Single unit measurement with detuning probes

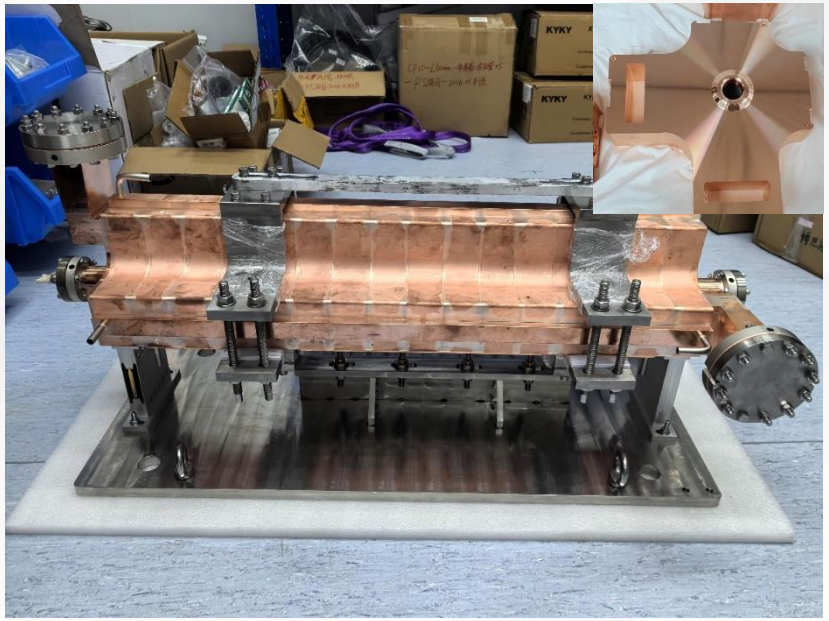


Entire structure



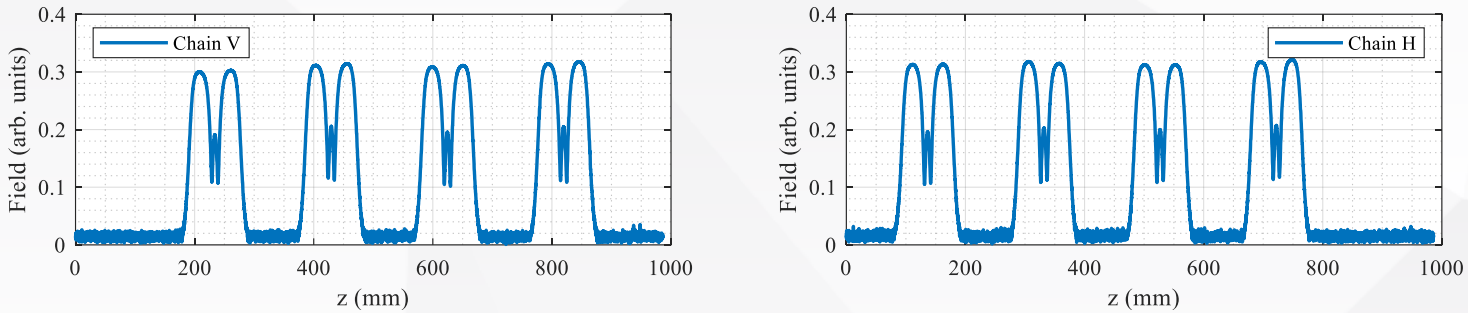
Fabrication and tuning of the second prototype

➢ **The second prototype has been developed for proof-of-principle experiments at the Dalian Coherent Light Source**

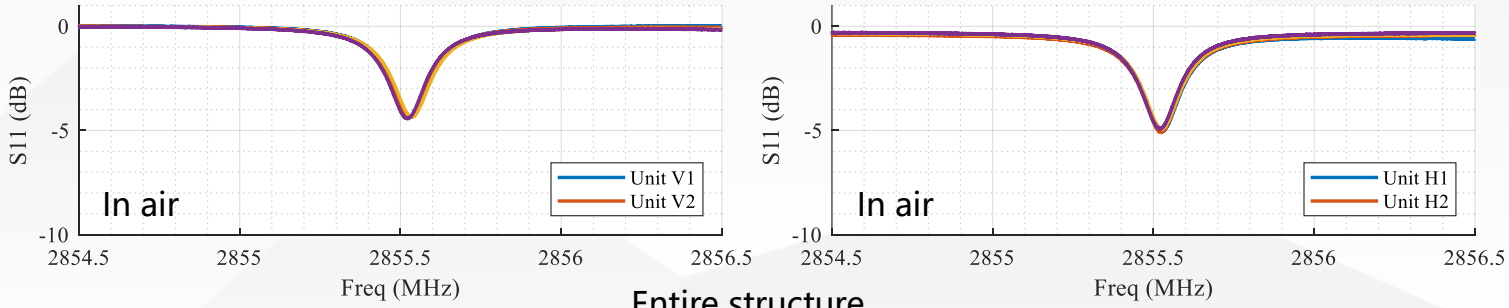


Parameter	Value	
	Chain V	Chain H
Operation temperature (°C)	28.0	
Frequency (MHz)	2856.000	2856.004
Quality factor	19256	19054
VSWR	1.01	1.06
Field balance	0.97	0.99

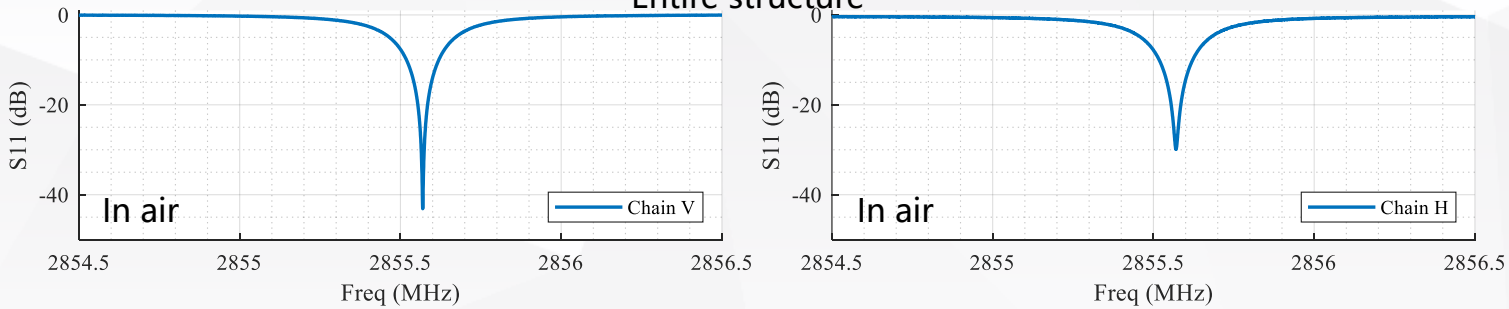
After tuning



Single unit measurement with detuning probes

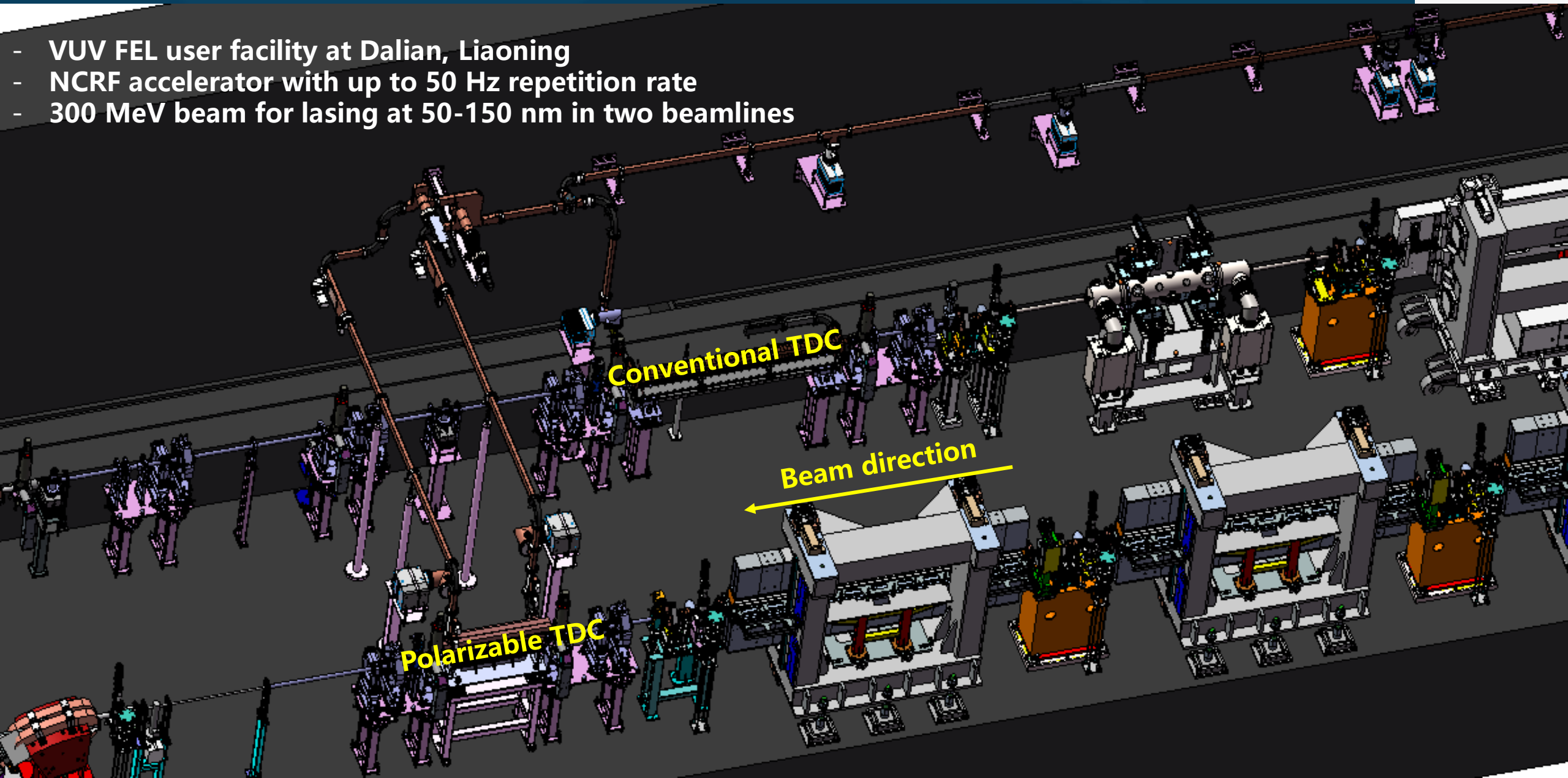


Entire structure



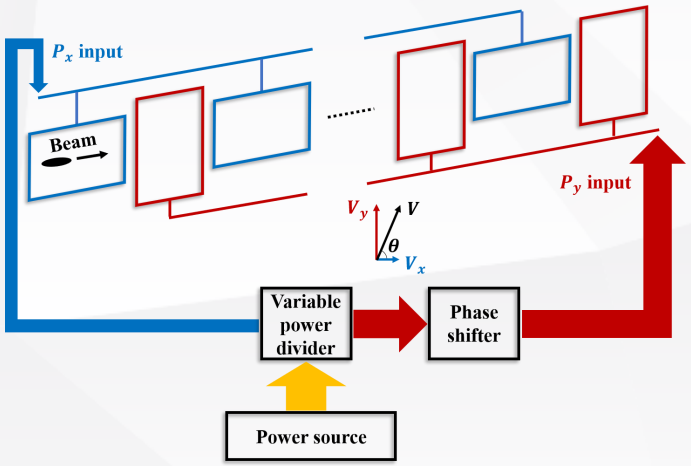
Beamline layout of proof-of-principle experiments

- VUV FEL user facility at Dalian, Liaoning
- NCRF accelerator with up to 50 Hz repetition rate
- 300 MeV beam for lasing at 50-150 nm in two beamlines

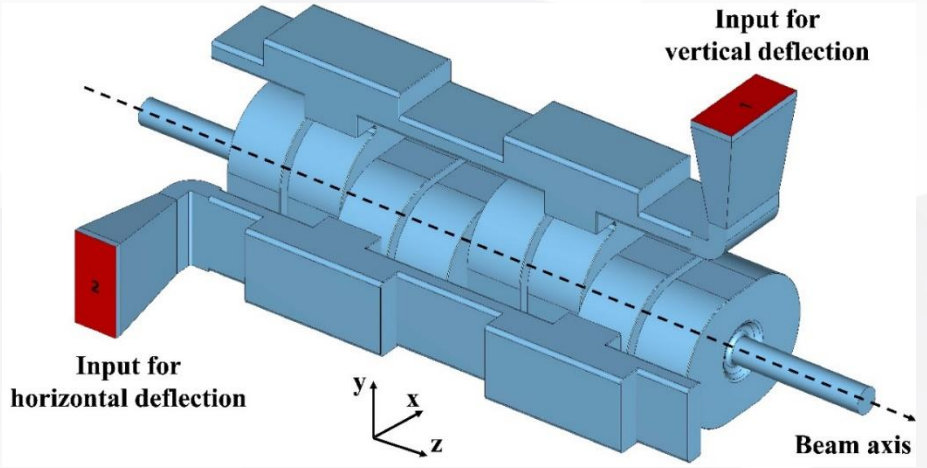


Conclusions and outlook

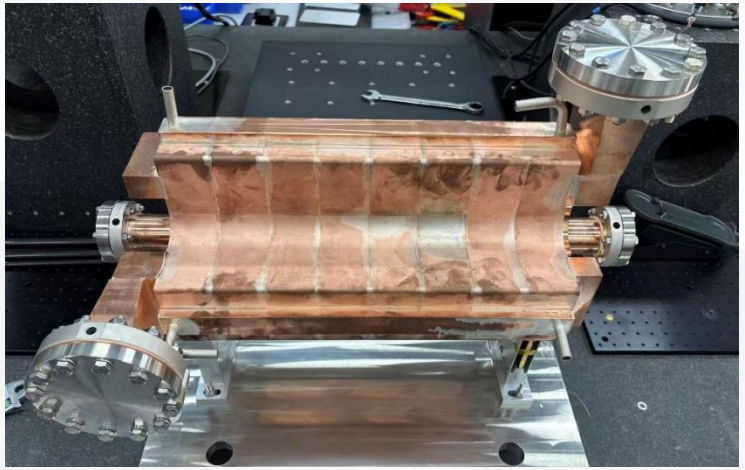
- An S-band polarizable TDC based on two independently fed, interleaved orthogonal deflecting chains has been developed
  - RF simulations demonstrate effective mode separation and low coupling between the two deflecting chains
  - Beam dynamics simulations validate variable polarization
- Two prototypes have been successfully fabricated and tuned
  - Nearly identical resonant frequencies, low RF reflection, good on-axis field balance
- Proof-of-principle experiments are scheduled at Dalian Coherent Light Source
  - High-power RF testing
  - Polarization control
  - Multi-dimensional phase space reconstruction



Concept



Design



Prototype

➢ Acknowledgements
- ❖ The pre-research project of S³FEL
- ❖ Professors Huaibi Chen, Jiaru Shi, and Hao Zha (Tsinghua University)
- ❖ Dalian Coherent Light Source

Thanks!