Development of stochastic cooling components for HIAF Spectrometer-Ring

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Beam feedback and machine protection group

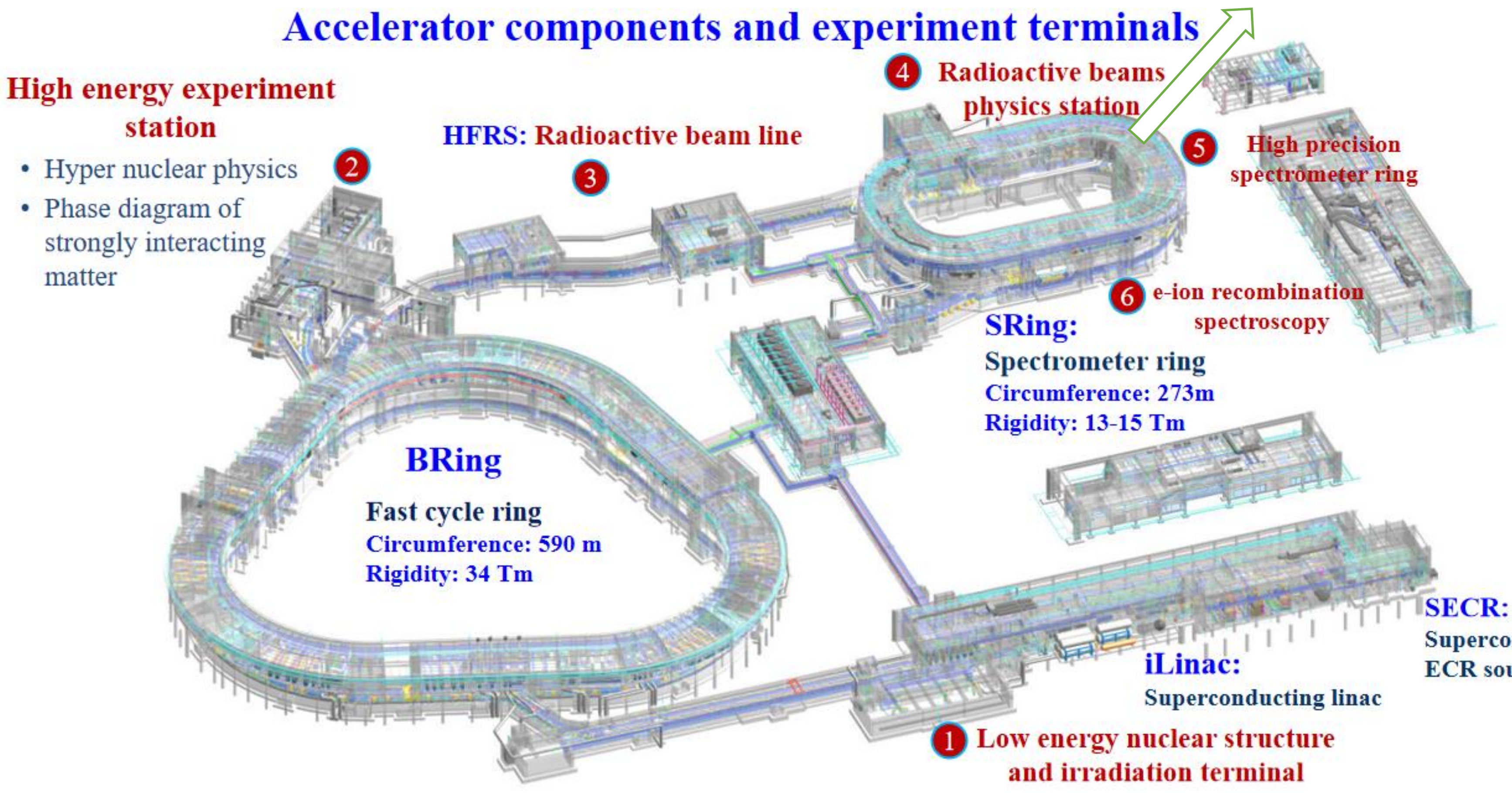
Outlines

- Development of stochastic cooling components for HIAF Spectrometer-Ring (High Intensity heavy-ion Accelerator Facility)

- **Motivation** for stochastic cooling on the SRing requirements by physics
- **SRing pickup/kicker** optimization and test with beam on CSRm
- **Notch filter** evaluation for SRing stochastic cooling
- **Broadband phase shifter** development for stochastic cooling

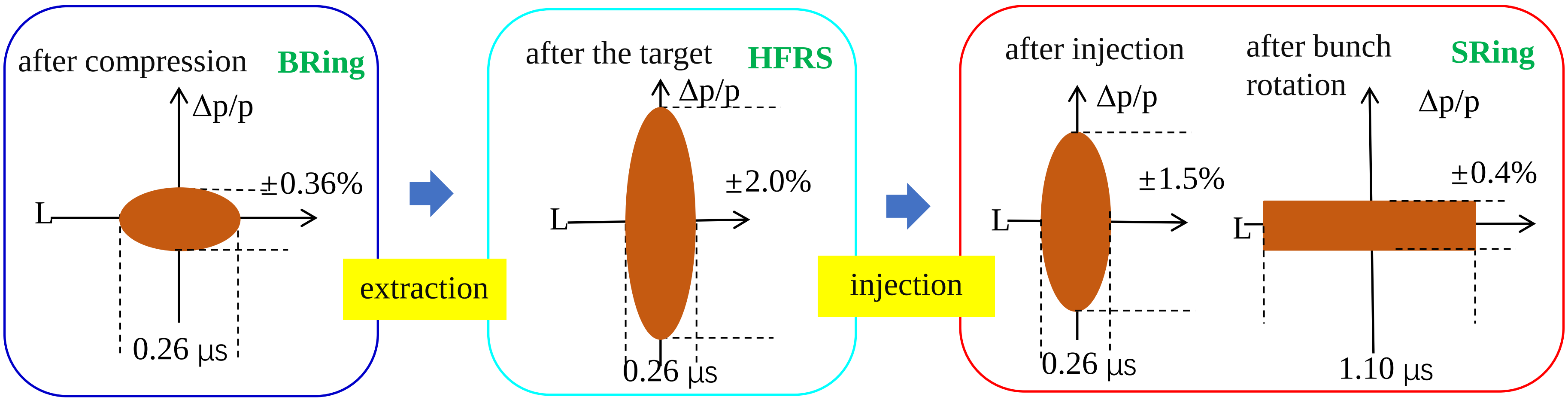
Layout of HIAF

Mass measurements of short-lived exotic nuclei, Rare Isotope Beam (RIBs) experiments, the internal target experiments.



BIM (Building information model) of HIAF facility

Cooling operation on the S-Ring



Δp/p $\varepsilon_x/\varepsilon_y$ 3σ   total cooling time < 2.3 s

precooling

Stochastic Cooling **SRing**

Δ p/p: ±0.40% → ±0.025 %

ε_x: 120 π mm·mrad → 5 π mm·mrad

ε_y: 40 π mm·mrad → 5 π mm·mrad

cooling time<1.2 s

electron cooling

Electron-Cooling **SRing**

Δ p/p: ±0.025% → ± 0.001%

ε_x/ ε_y: 5 π mm·mrad → 0.1 π mm·mrad

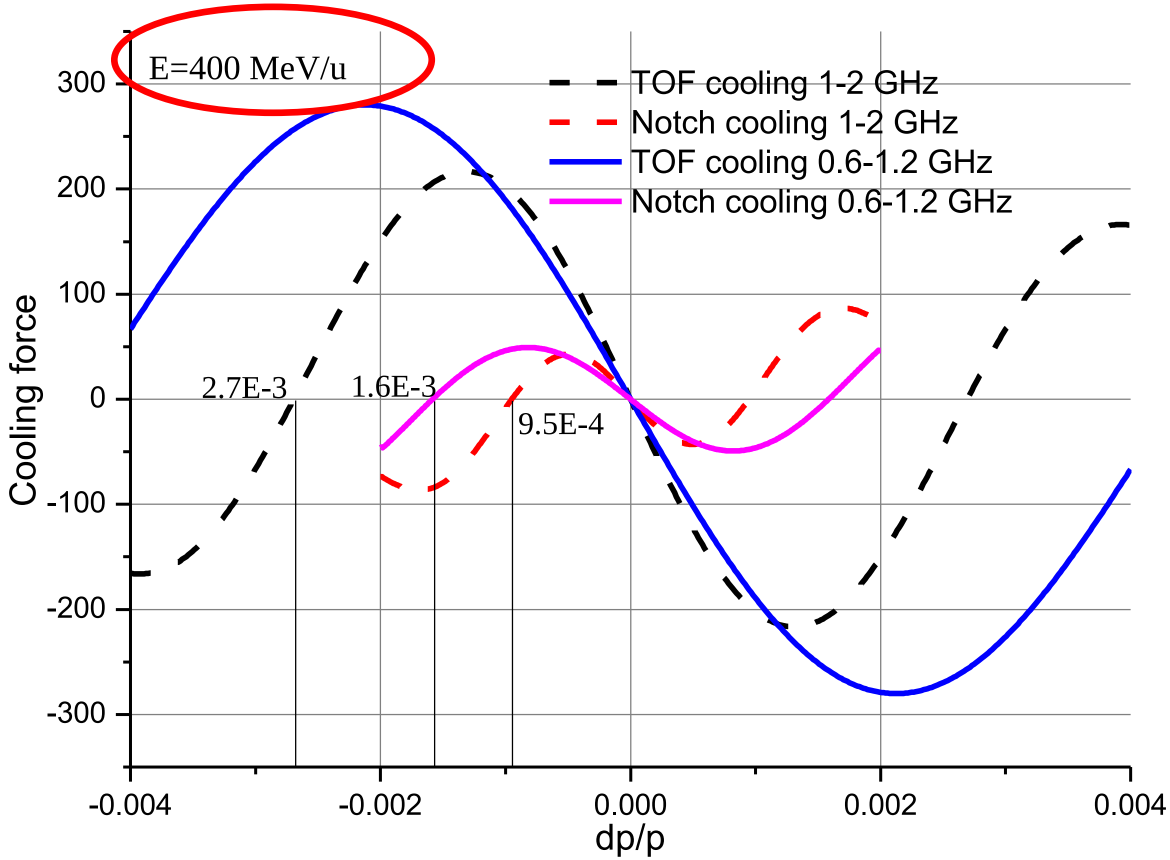
cooling time<1.0 s

Stochastic cooling will be performed to reduce the emittance to less than 5 pi mm.mrad, and Dp/p of 4.0e-3 to 2.5e-4 within 1.2 s for these RI beams.

Motivation for stochastic cooling on the S-ring; requirements by physics

- Precooling of the radio isotope beams
- Beam energy: 400 MeV/u-740 MeV/u (β: 0.71-0.83)
- Number of particles: $<1.0e5$
- Mass number: 100-200
- Atomic number: 40-80
- Lifetime: seconds
- Before cooling: $\varepsilon_H=200\ \pi$ mm mrad, $\varepsilon_V=40\ \pi$ mm mrad,
  $\Delta p/p=\pm4.0e\text{-}3\ (\pm3\sigma)$
- After cooling: $\varepsilon_{H,V}=6.25\ \pi$ mm mrad, $\Delta p/p=\pm3.6e\text{-}4\ (\pm3\sigma)$
  $\varepsilon_{H,V}=1.25\ \pi$ mm mrad, $\Delta p/p=\pm6.0e\text{-}5\ (1\ \sigma)$
- Cooling time < 1.2 s

Comparison of TOF and notch filter momentum acceptance at 400 MeV/u (beta = 0.71)



- For the beam energy below 400 MeV/u, 1-2 GHz can not be used, the cooling frequency should be below 1.2 GHz

SRing operating bandwidth: 0.6-1.2 GHz

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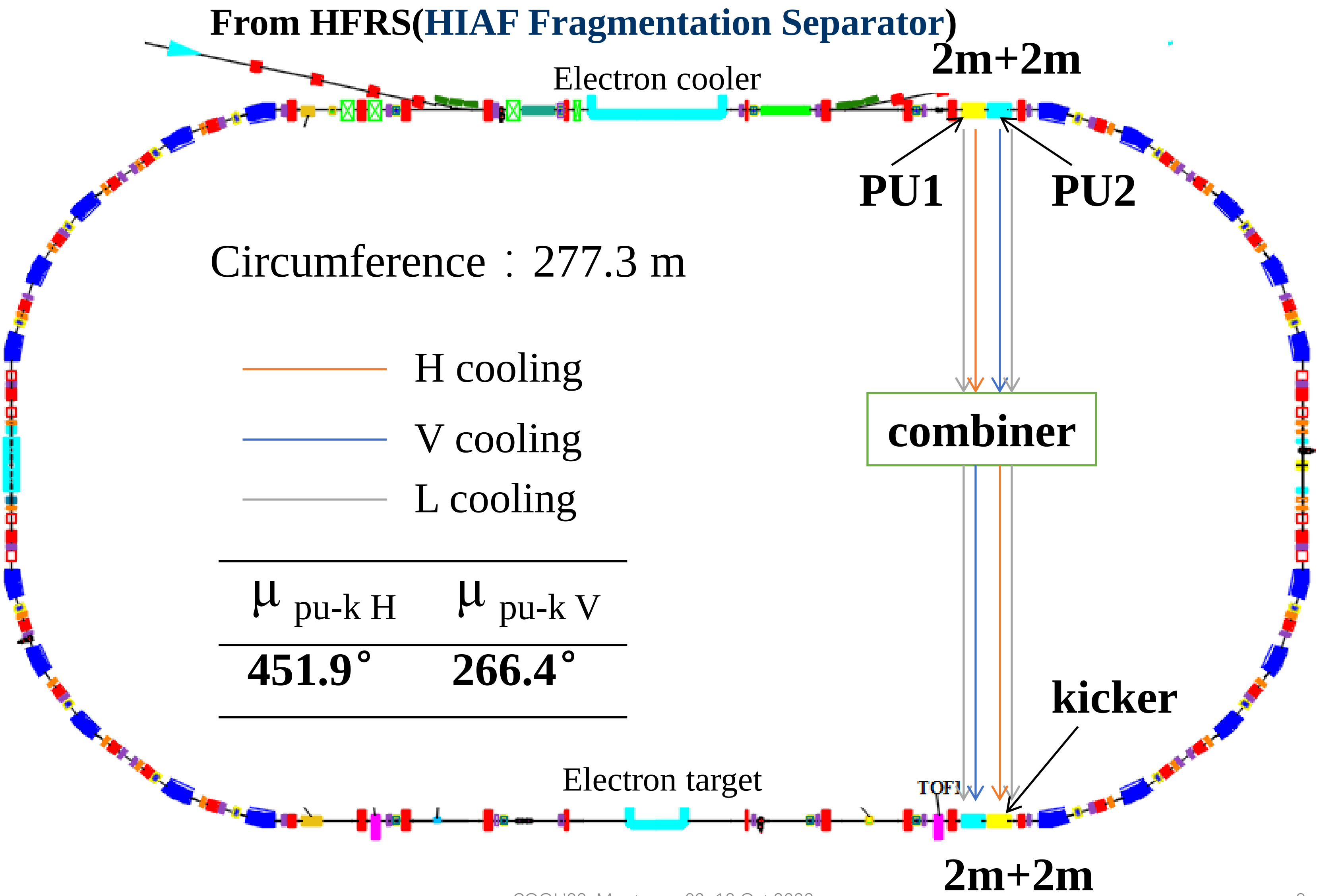
➢ Notch filter evaluation for SRing stochastic cooling

➢ **Broadband phase shifter** development for stochastic cooling

Layout of the PU and kicker of SRing stochastic cooling

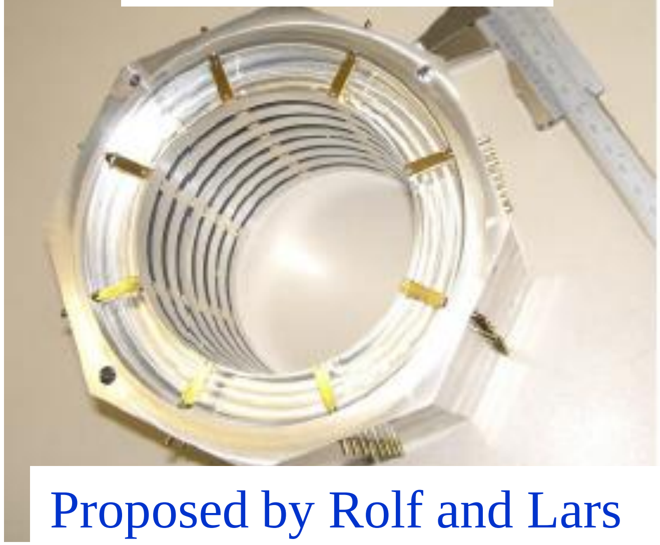


μ pu-k H	μ pu-k V
451.9°	**266.4°**

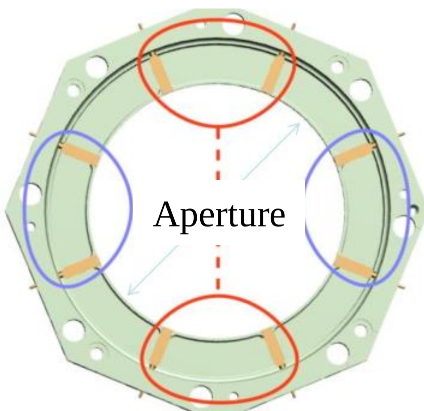
Pickup/kicker structure considered

- **Slot-ring structure: standing wave**
  Used in FAIR HESR stochastic cooling

Pickup for SRing

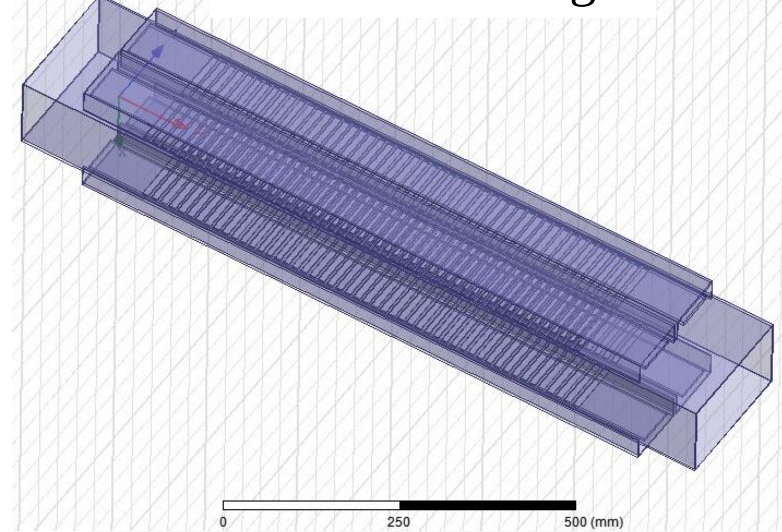


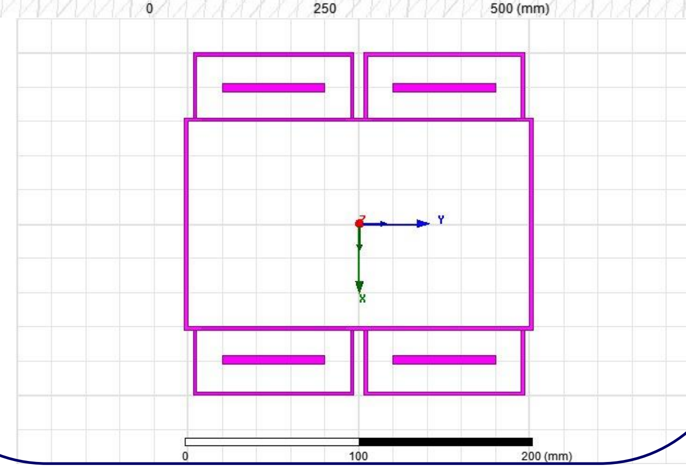
Proposed by Rolf and Lars



- **Faltin structure: travelling wave (beta =0.71)**

Kicker for SRing



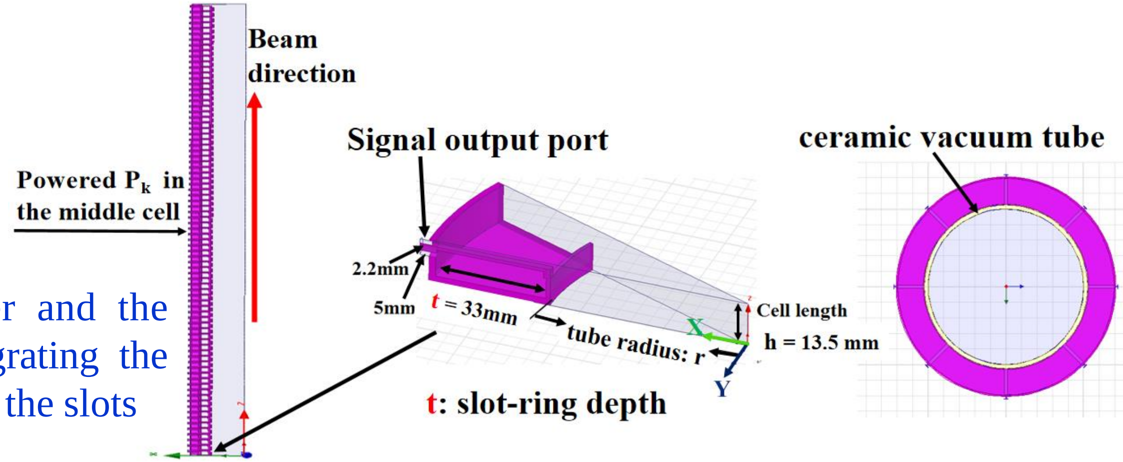


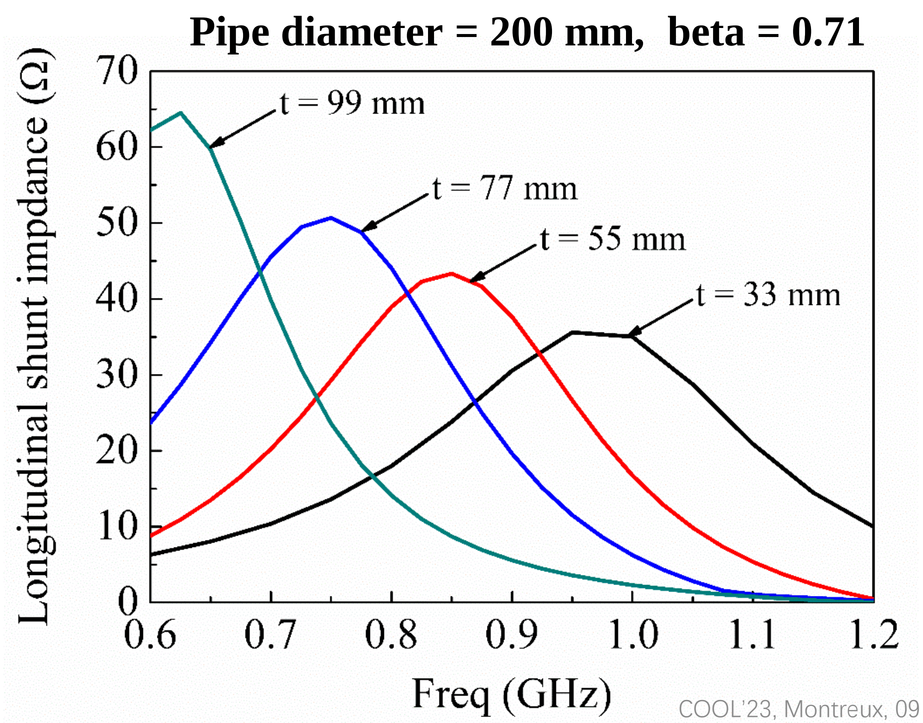
Slot-ring as pickup for SRing

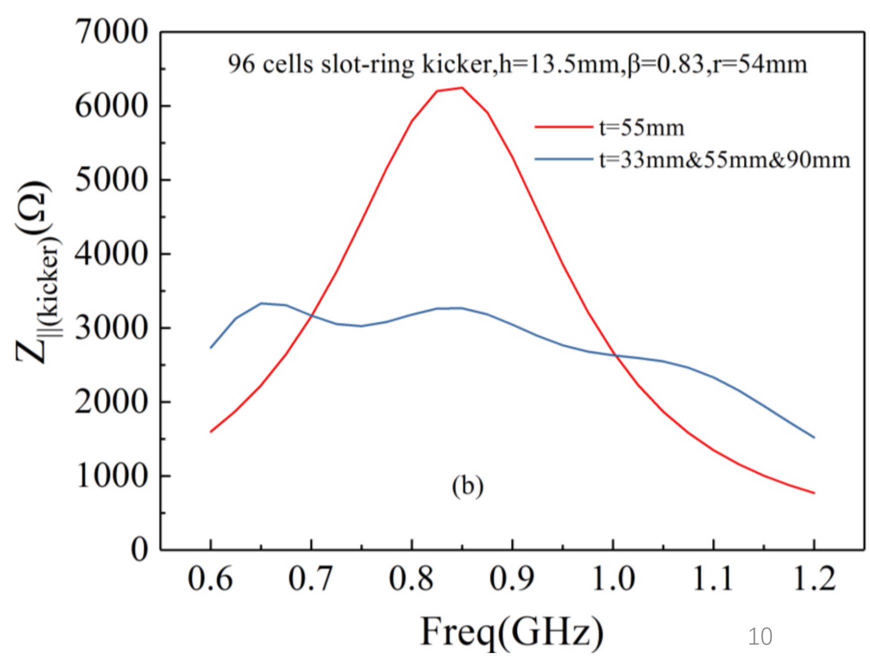
- Simulation ： HFSS
- Longitudinal shunt impedance

$$Z_{\|(kicker)} = Z_{\|} T^2 = \frac{|V^2|}{2P_k}$$

A power of 1 W is input into the kicker and the accelerating voltage is determined by integrating the electric field along a particle trajectory above the slots

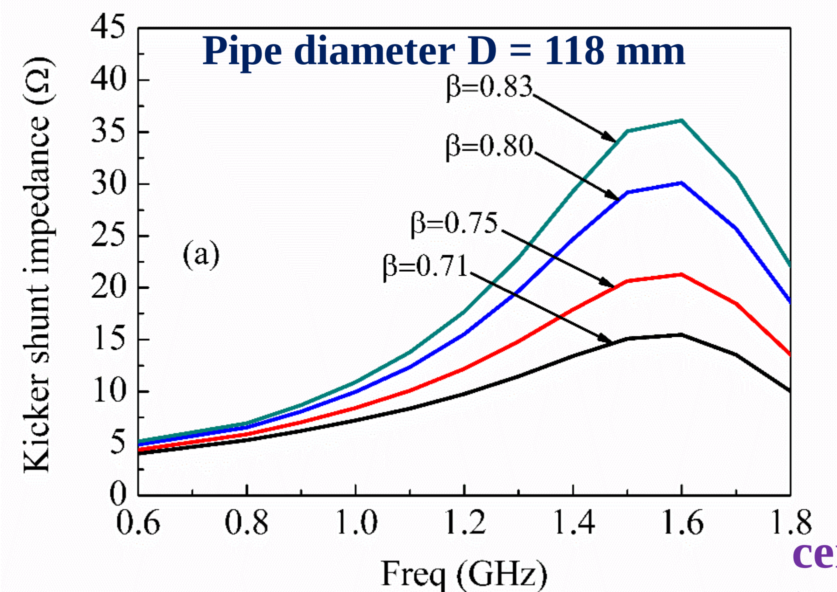


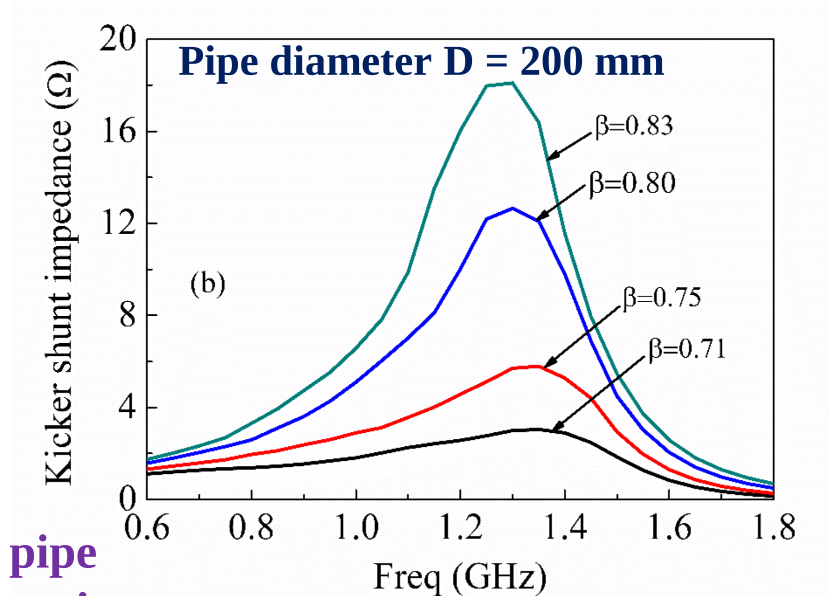




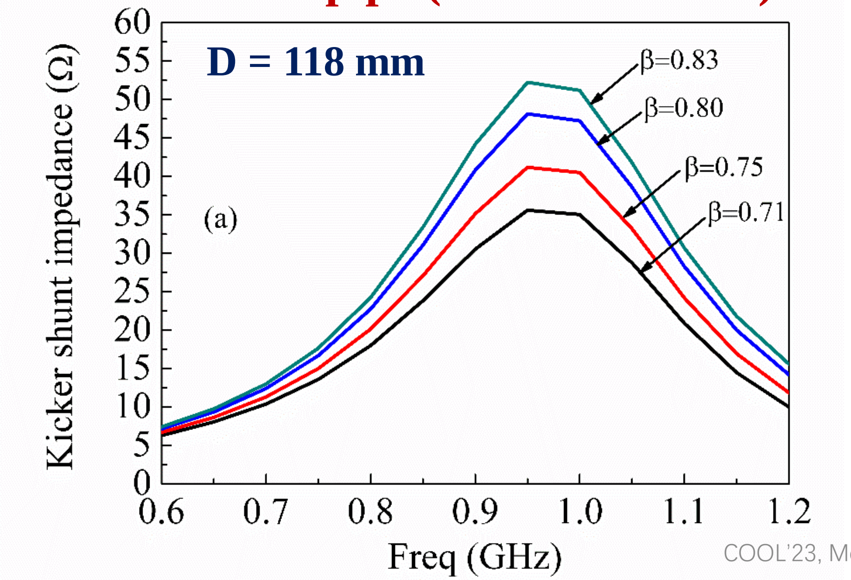
Slot-ring as pickup for SRing

➢ **Without ceramic pipe**

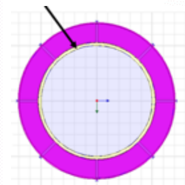


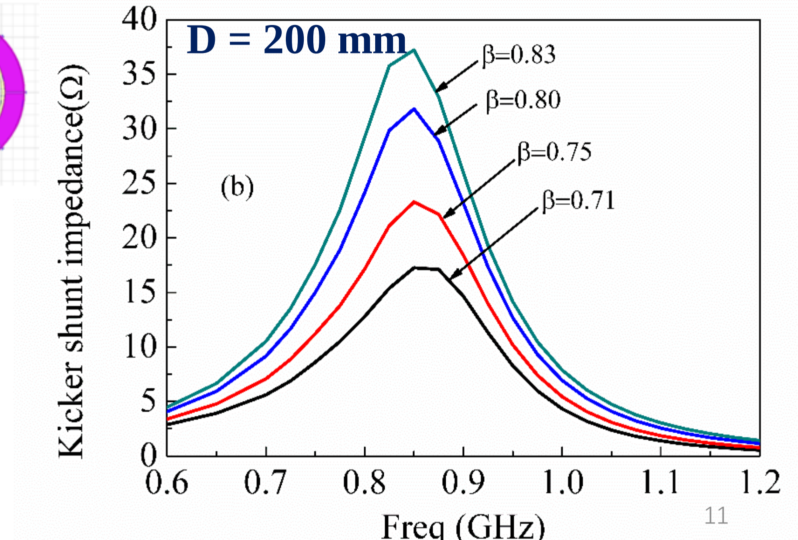


➢ **With ceramic pipe (8 mm thickness)**



ceramic pipe inside slot-ring

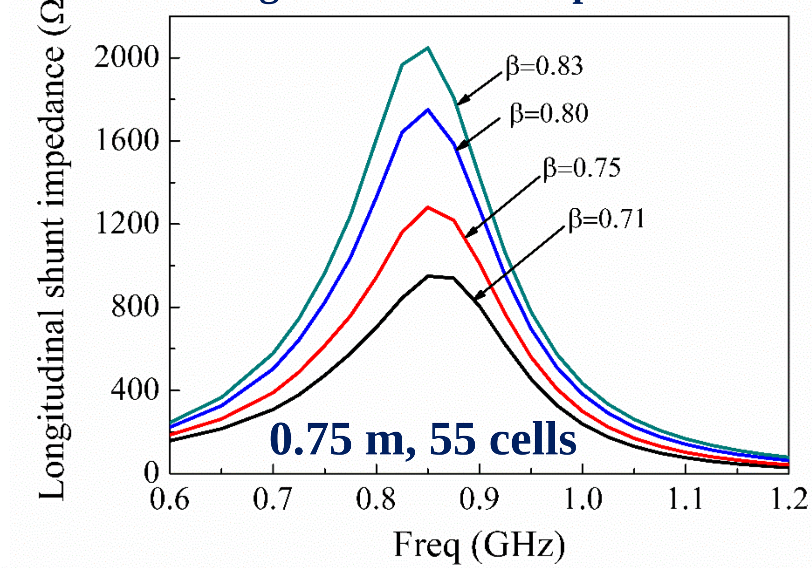




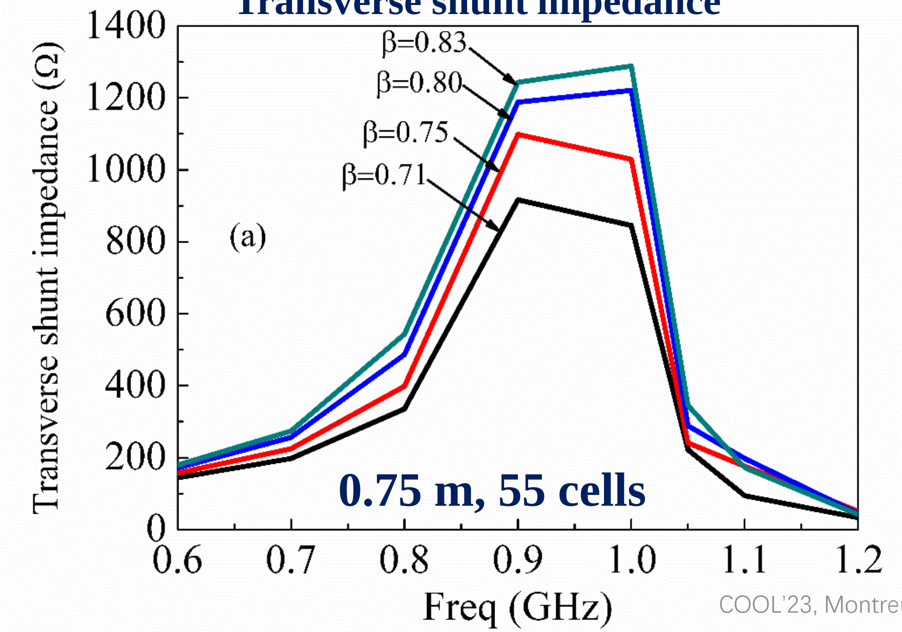
Slot-ring as pickup for SRing

0.75 m long,
55 cells

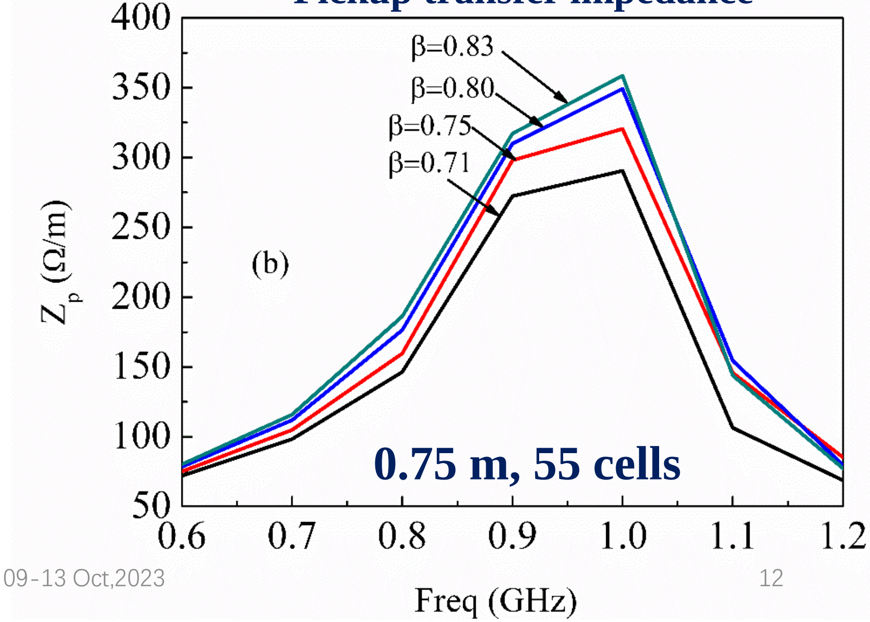
Longitudinal shunt impedance



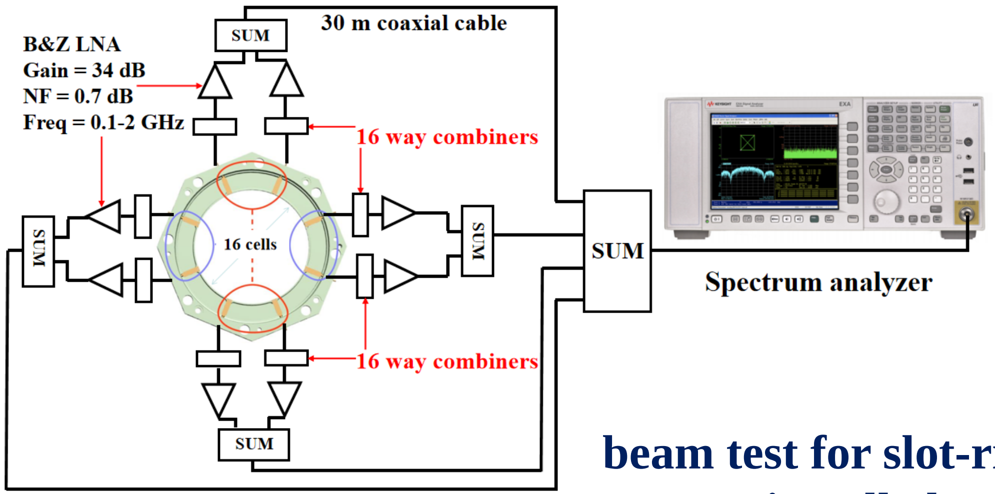
Transverse shunt impedance

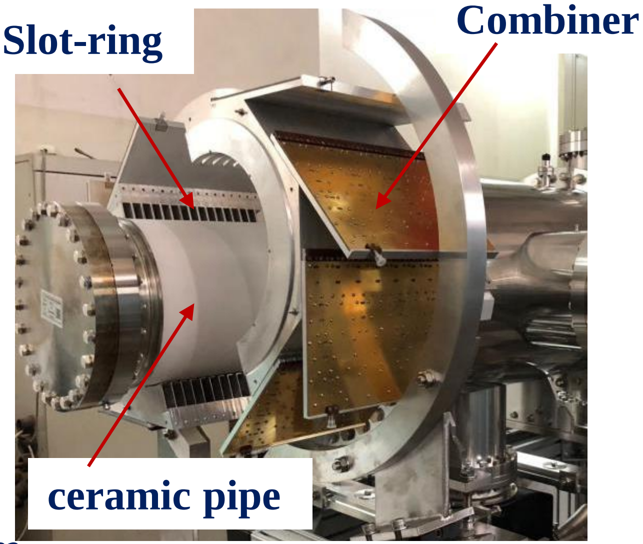


Pickup transfer impedance

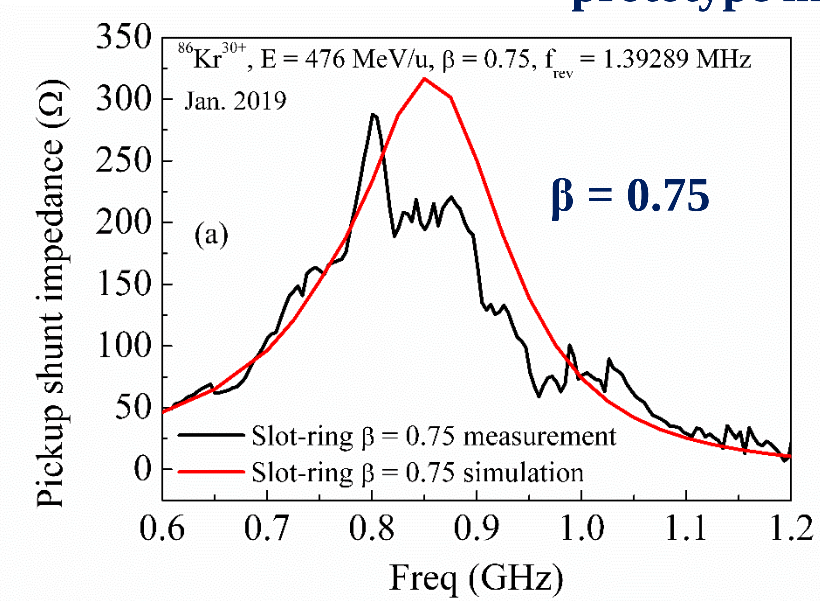


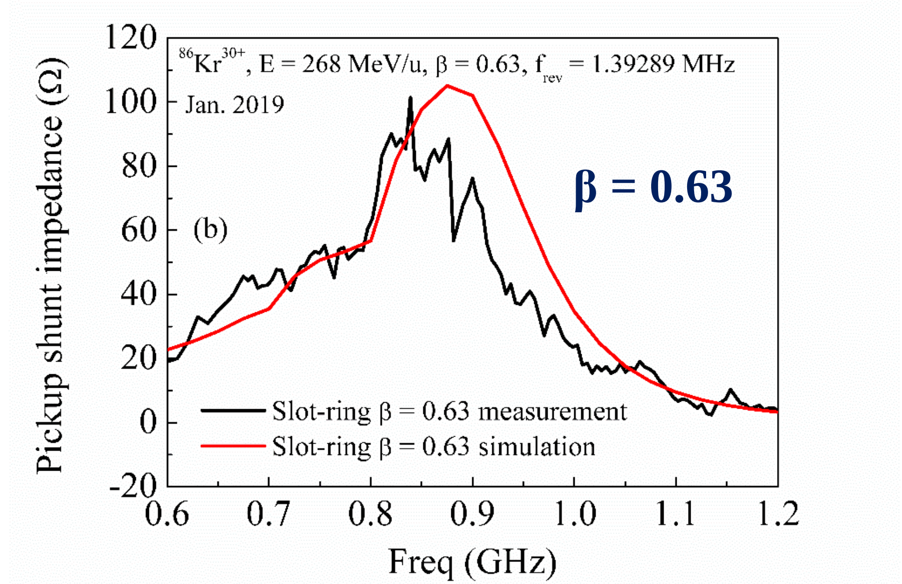
Slot-ring as pickup for SRing





beam test for slot-ring prototype installed on CSRm





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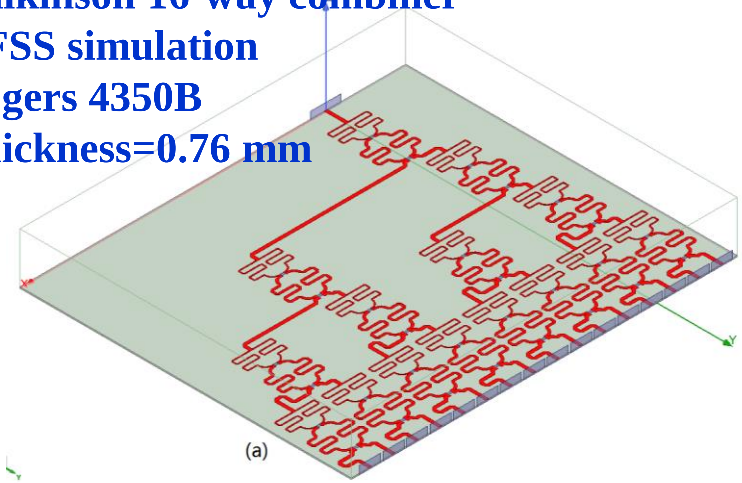
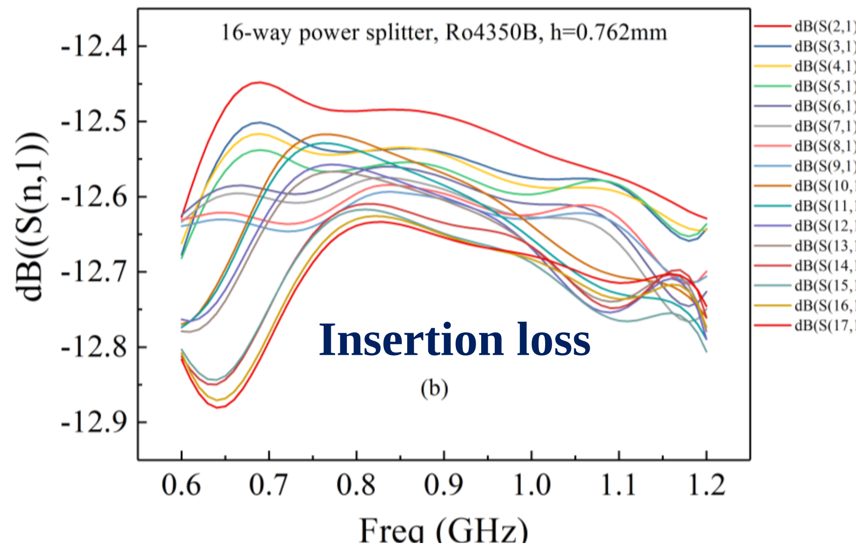
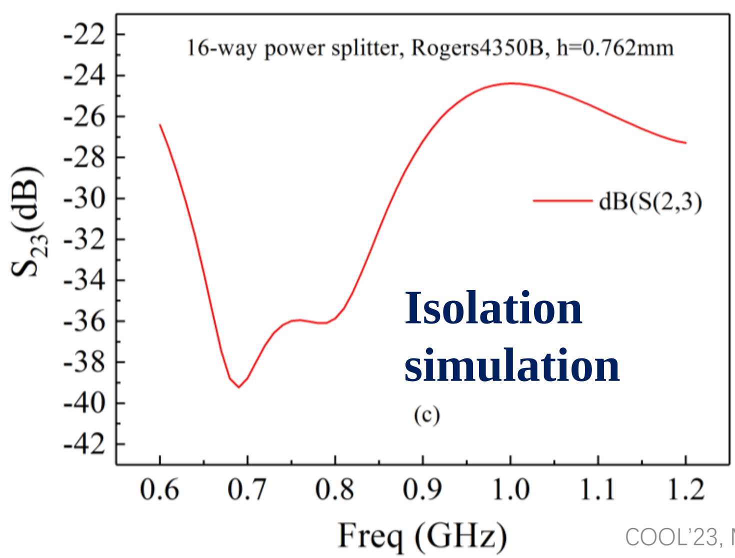
Slot-ring as pickup for SRing- 16 way combiner

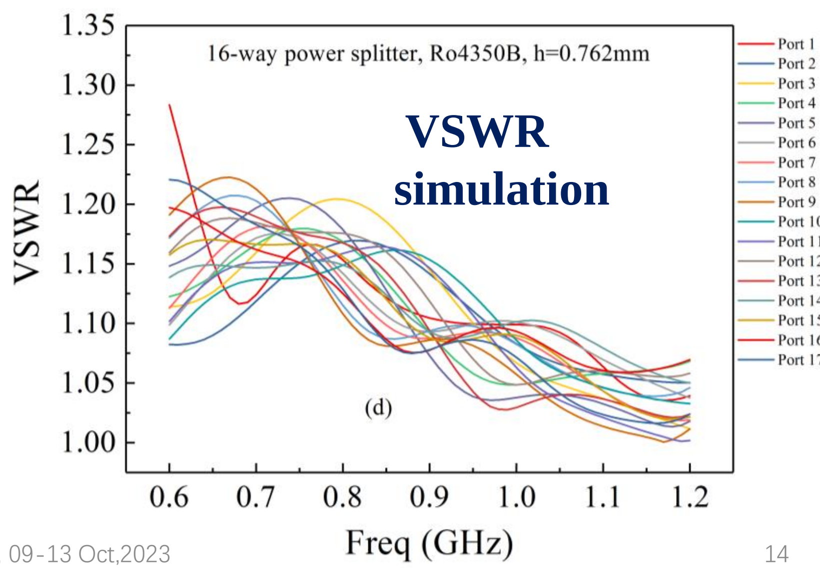
- Wilkinson 16-way combiner
- HFSS simulation
- Rogers 4350B
- Thickness=0.76 mm



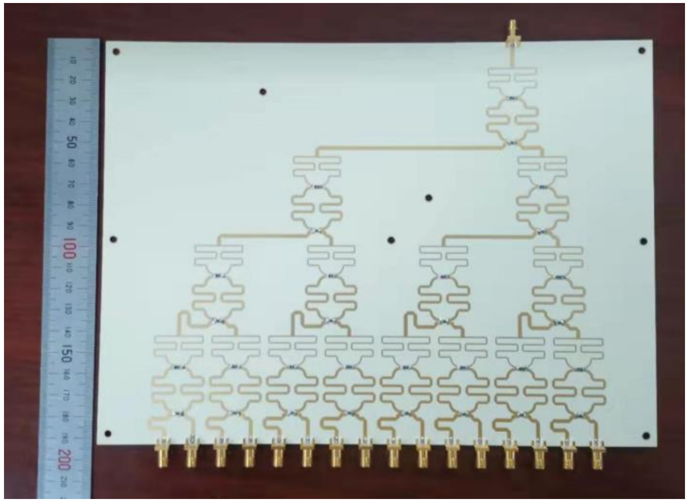
HFSS model



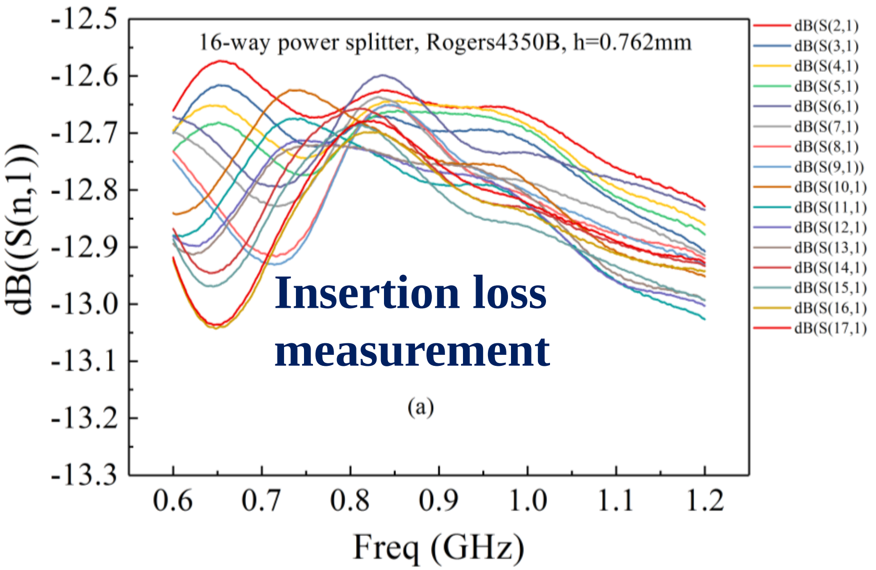


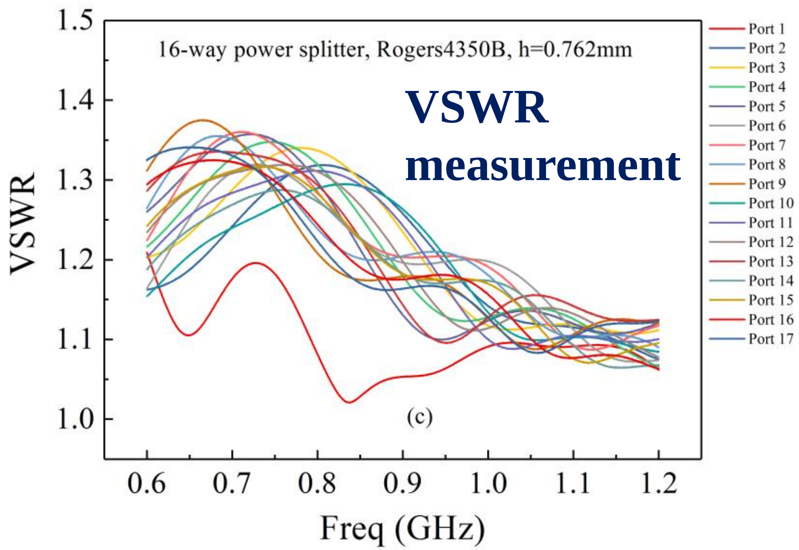


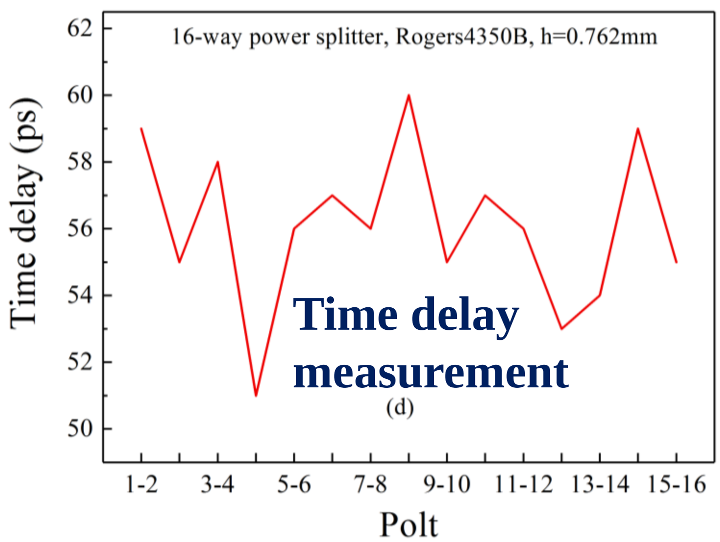
Slot-ring as pickup for SRing-16 way combiner



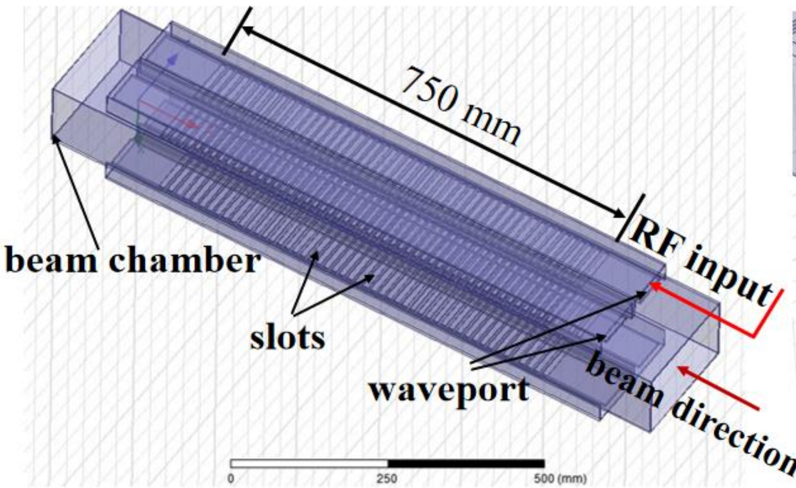
16-way combiner prototype



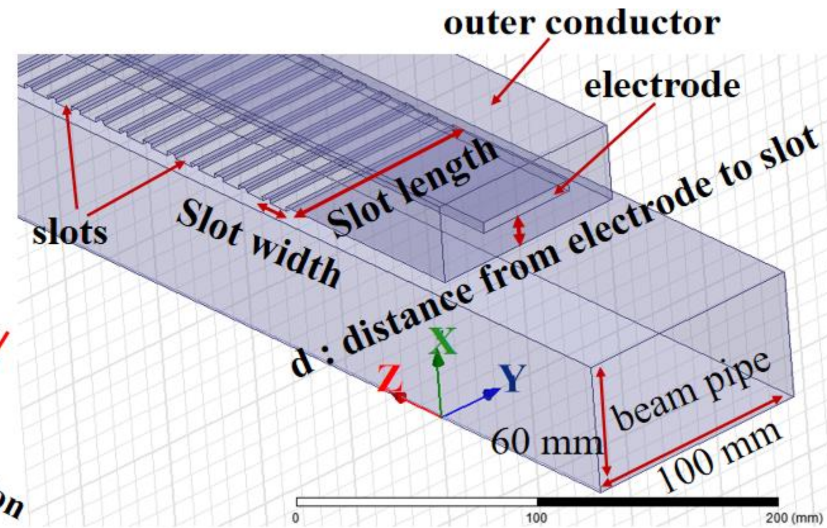




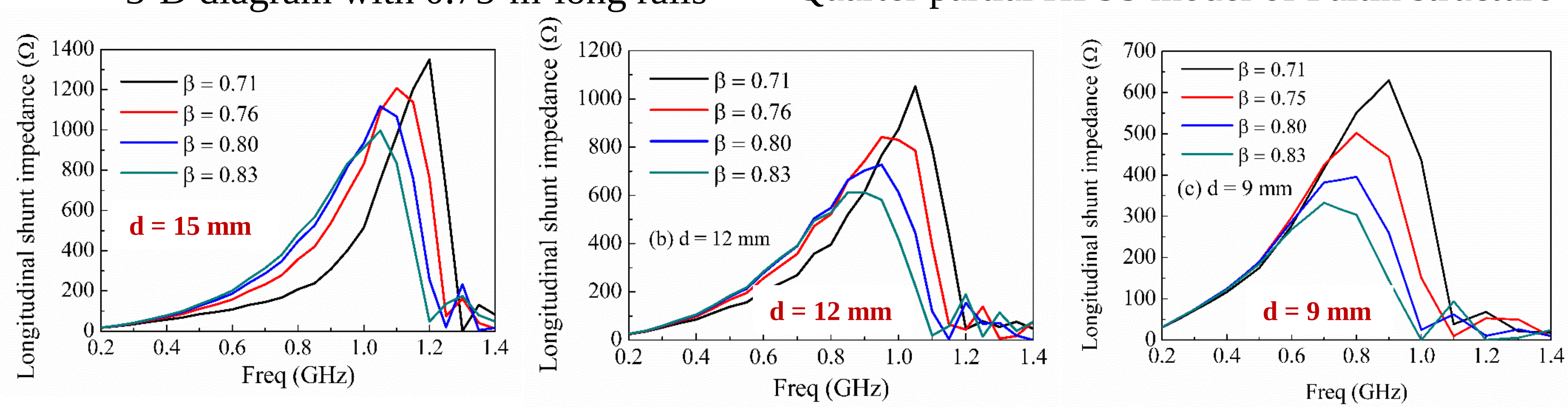
Flatin type as kicker for SRing



3-D diagram with 0.75-m-long rails

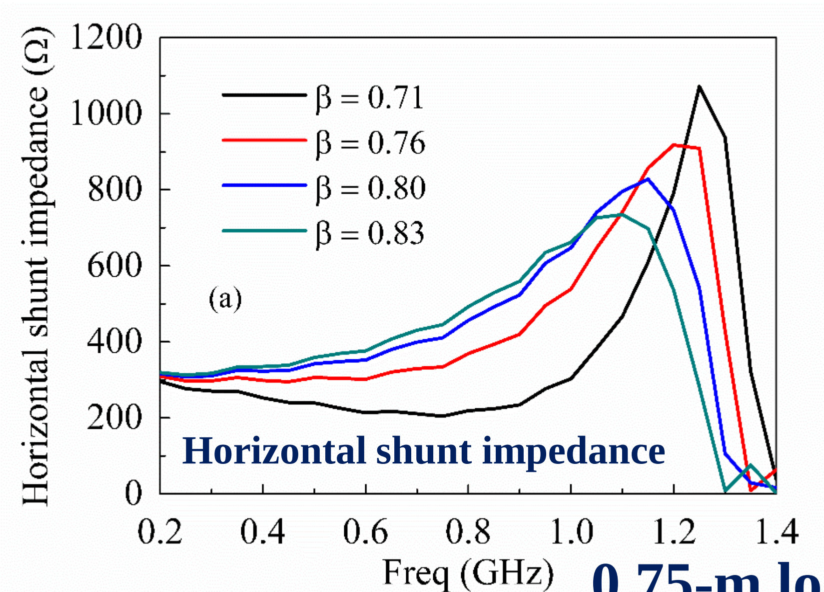


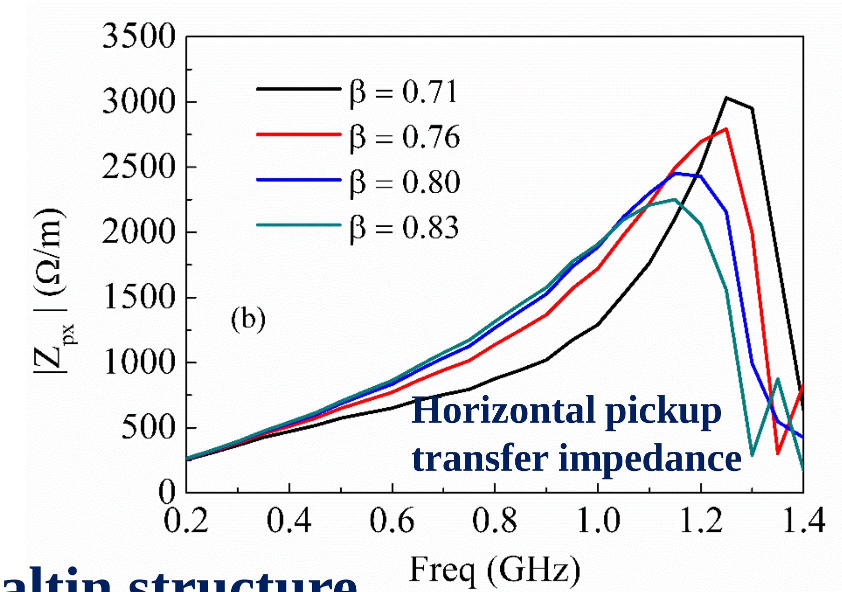
Quarter partial HFSS model of Faltin structure



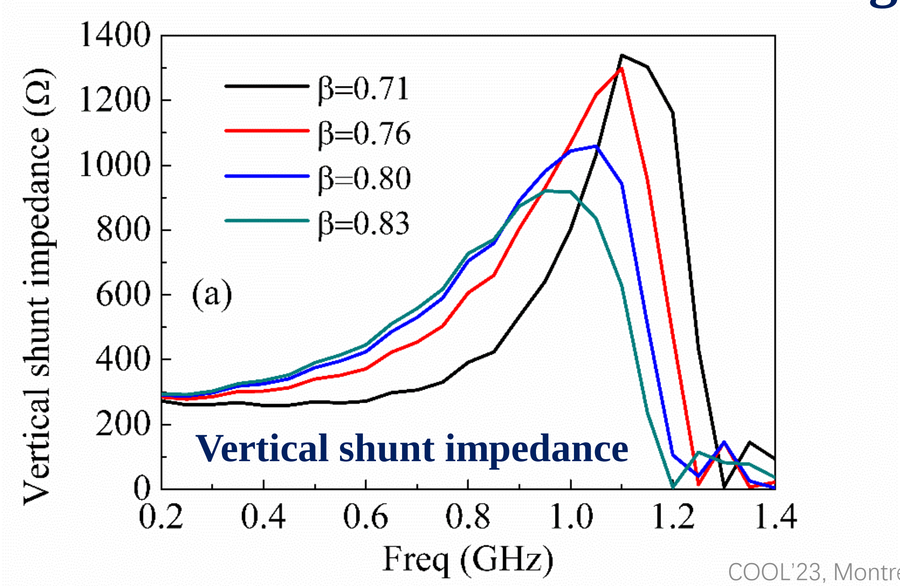
- the shunt impedance of the Faltin rail structure is sensitive to the beam velocity beta
- When we decrease d, the shunt impedance at a lower frequency improves, however, the peak value of shunt impedance deteriorates at higher frequencies

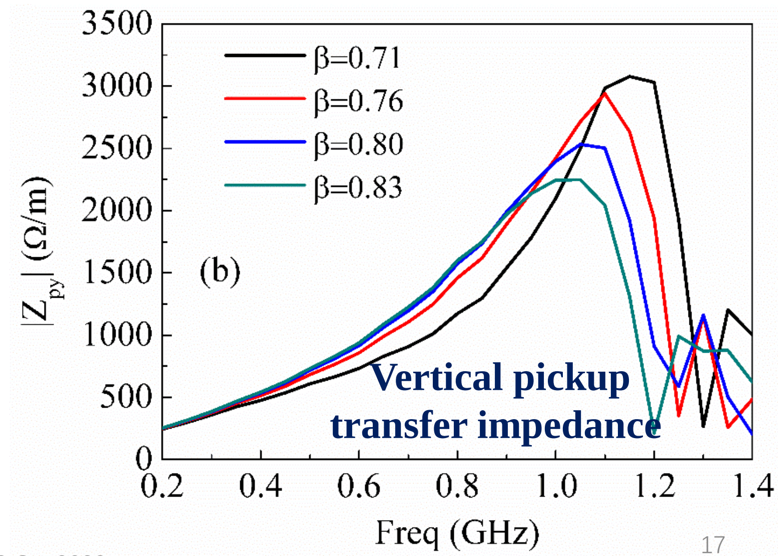
Flatin type as kicker for SRing



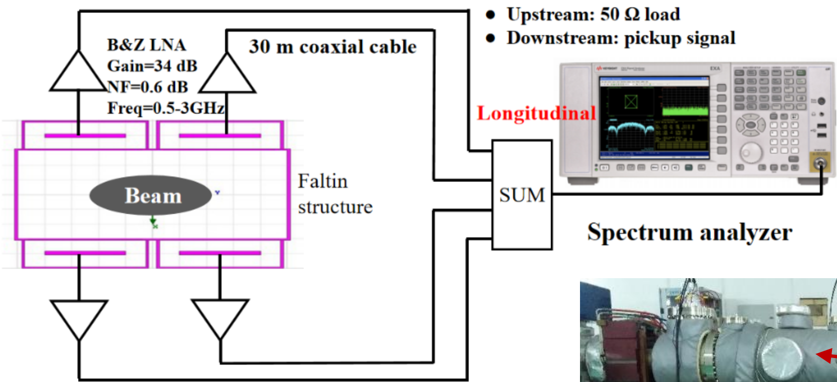


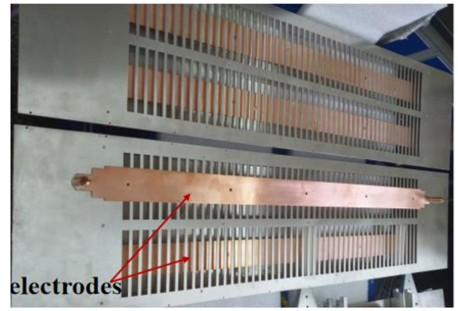
0.75-m long Faltin structure

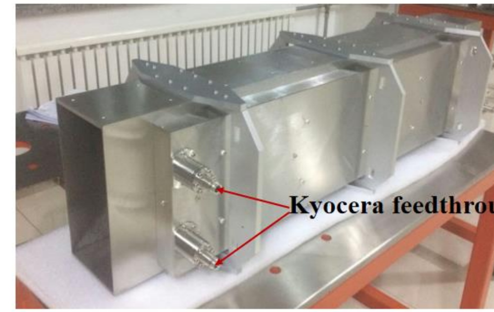


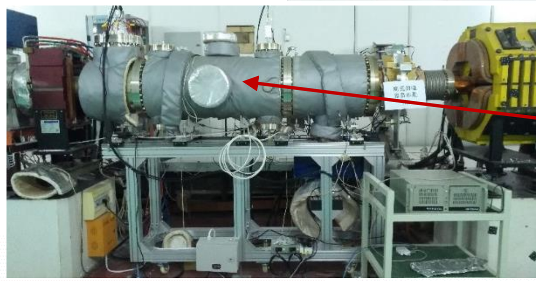


Flatin type as kicker for SRing

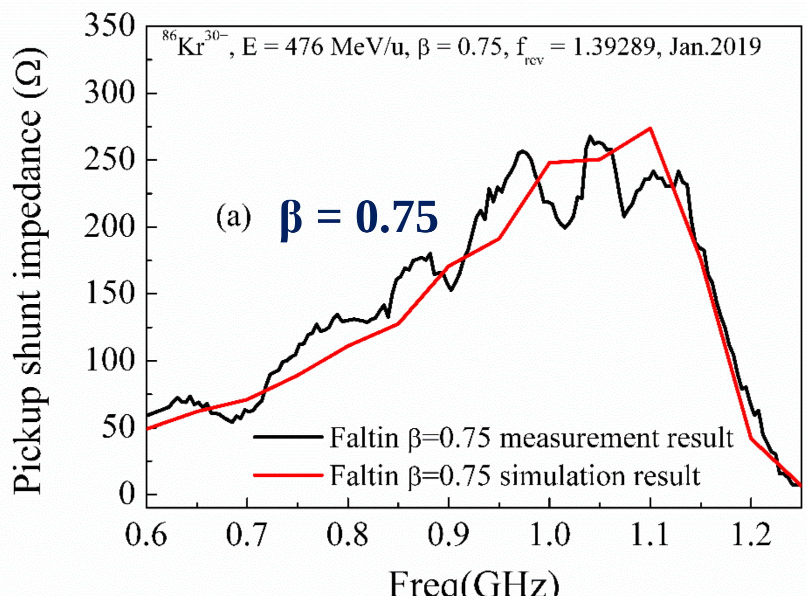


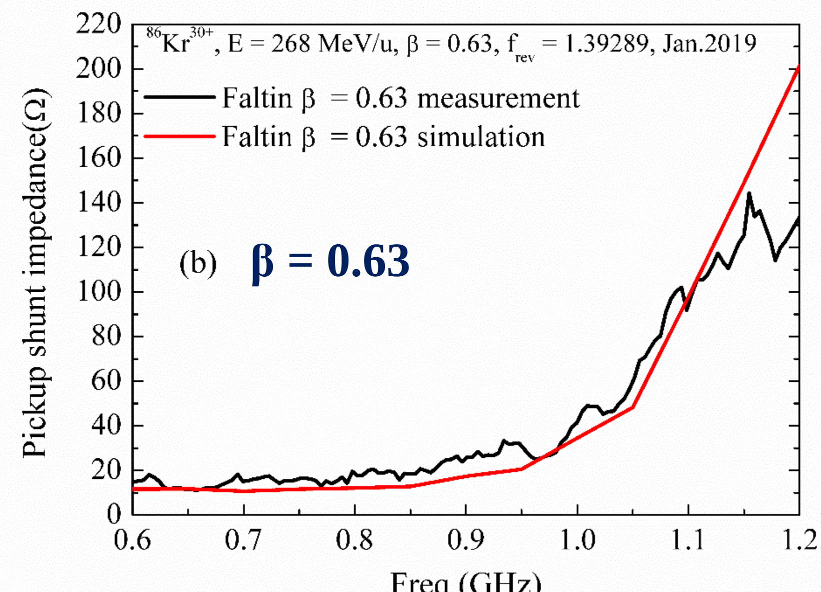






Flatin prototype has installed on CSRm for the beam test





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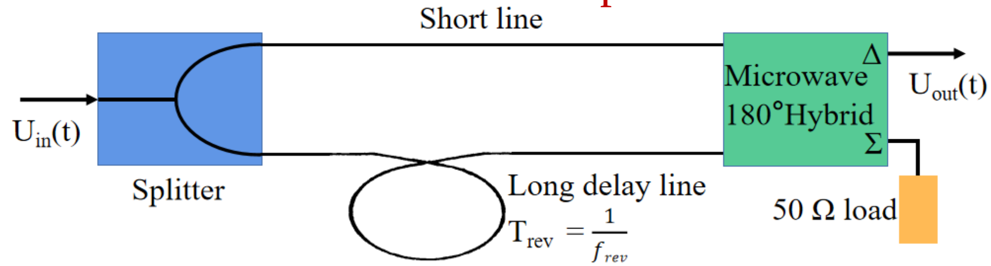
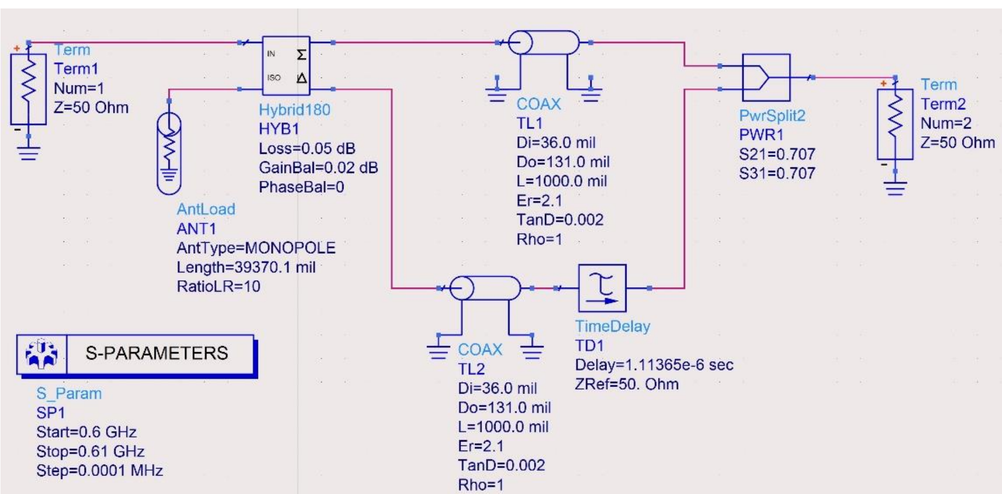
Notch filter for longitudinal cooling

- **TOF method:** is used as a first step to pre-cool
- **Notch filter method:** subsequently used to attain the lower momentum spread

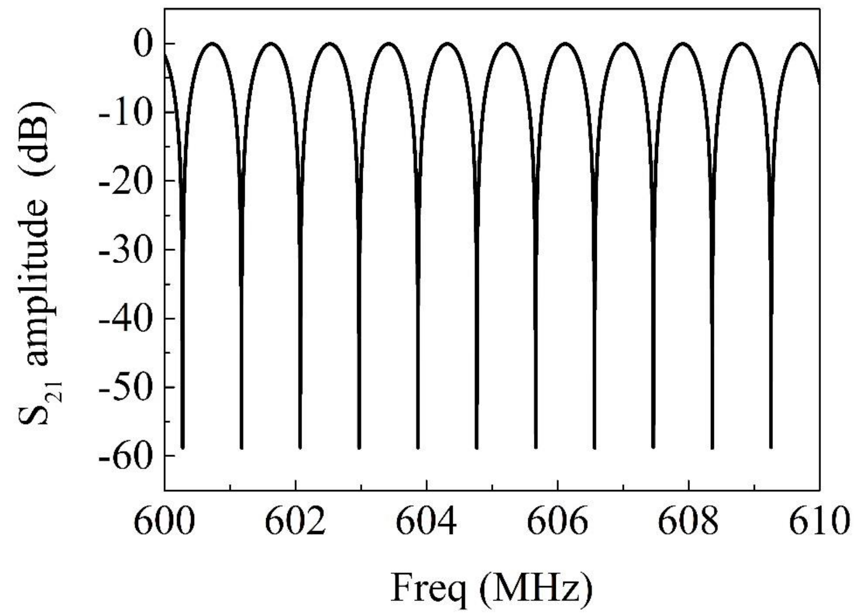
  - Larger notch depth
  - Lower frequency drift
  - compact structure



Schematic drawing of an ideal notch filter



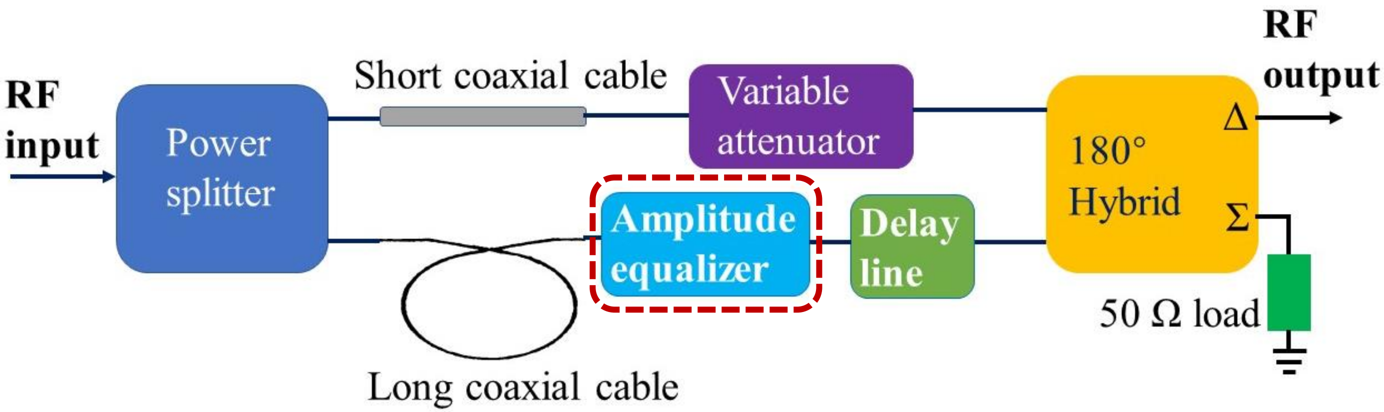
ADS S parameter simulation schematic diagram



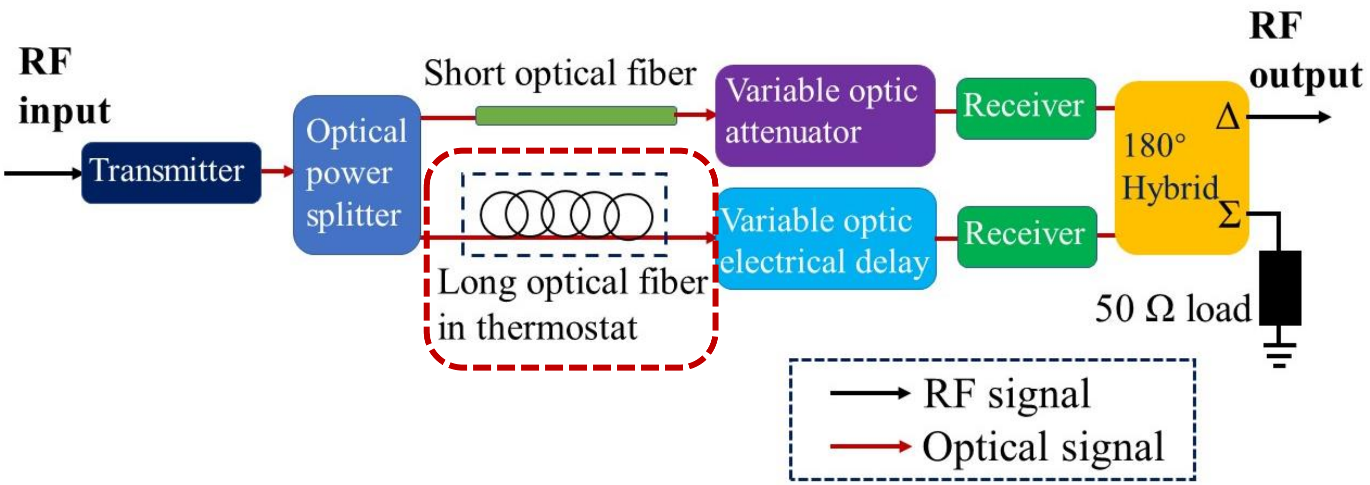
Notch depth VS frequency

Notch filter for longitudinal cooling

➢ **Type I: Coaxial notch filter with an amplitude equalizer**



➢ **Type II: Optical notch filter with phase-stabilized optical fiber**



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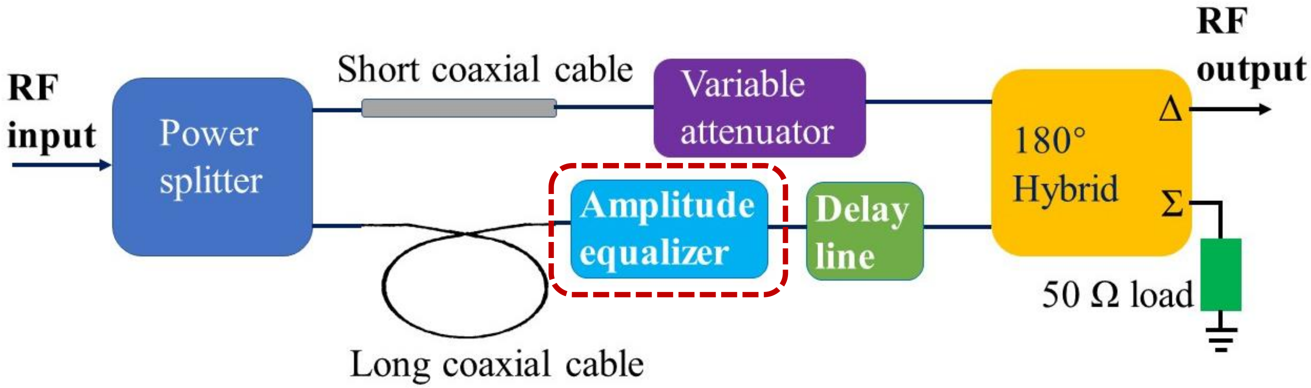
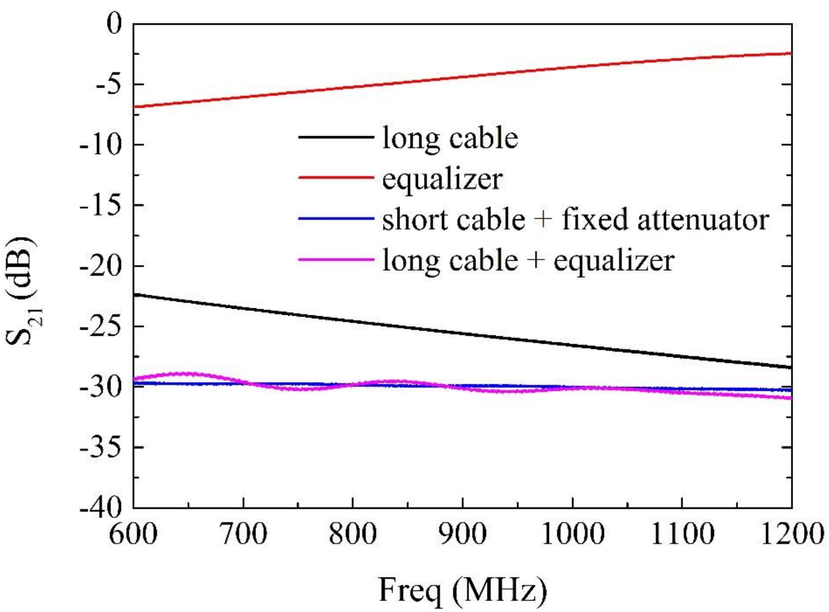
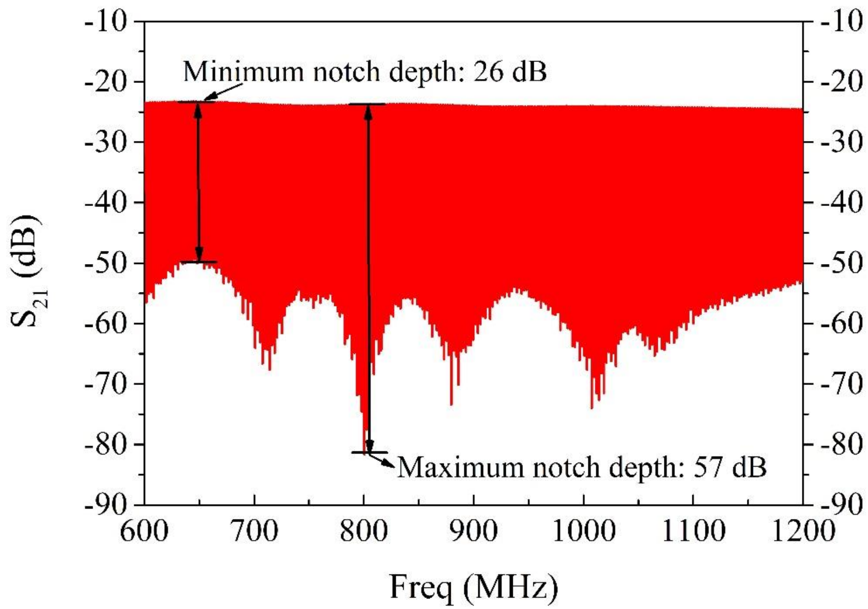
Notch filter for longitudinal cooling

- **Type I: Coaxial notch filter with an amplitude equalizer**

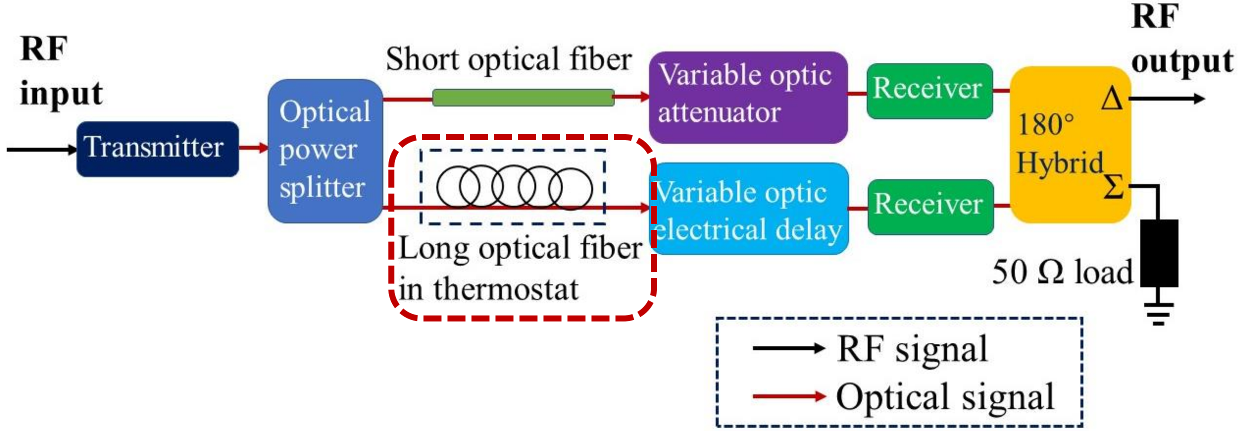


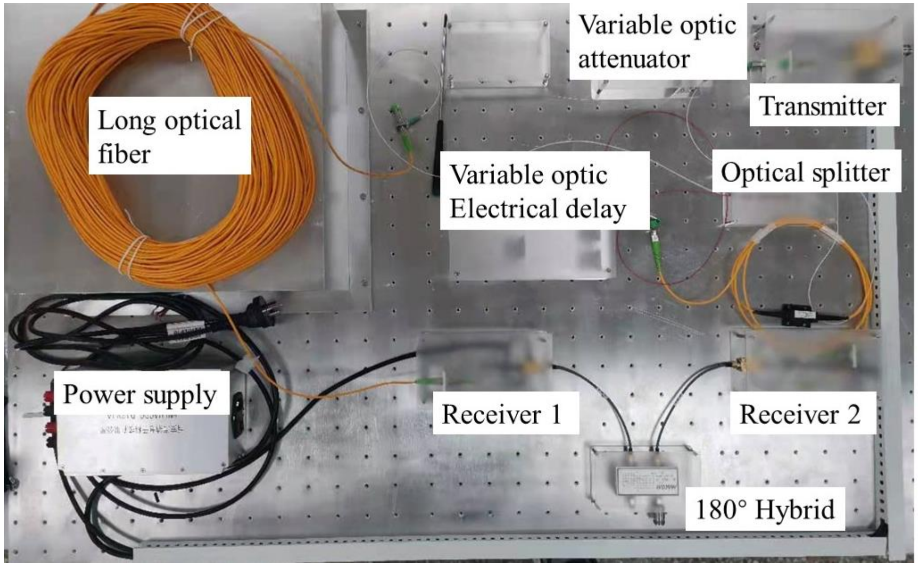


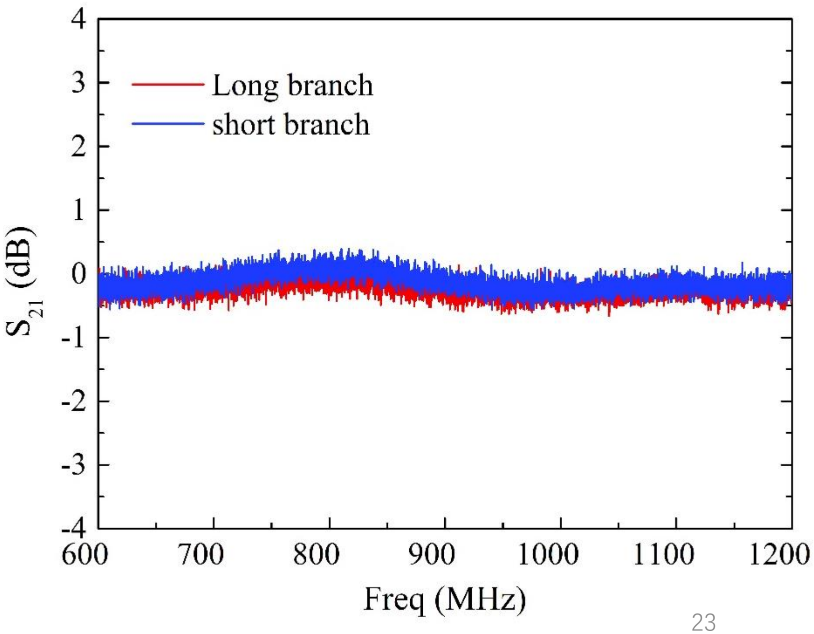


Notch filter for longitudinal cooling

➢ **Type II: Optical notch filter with phase-stabilized optical fiber**







Notch filter for longitudinal cooling

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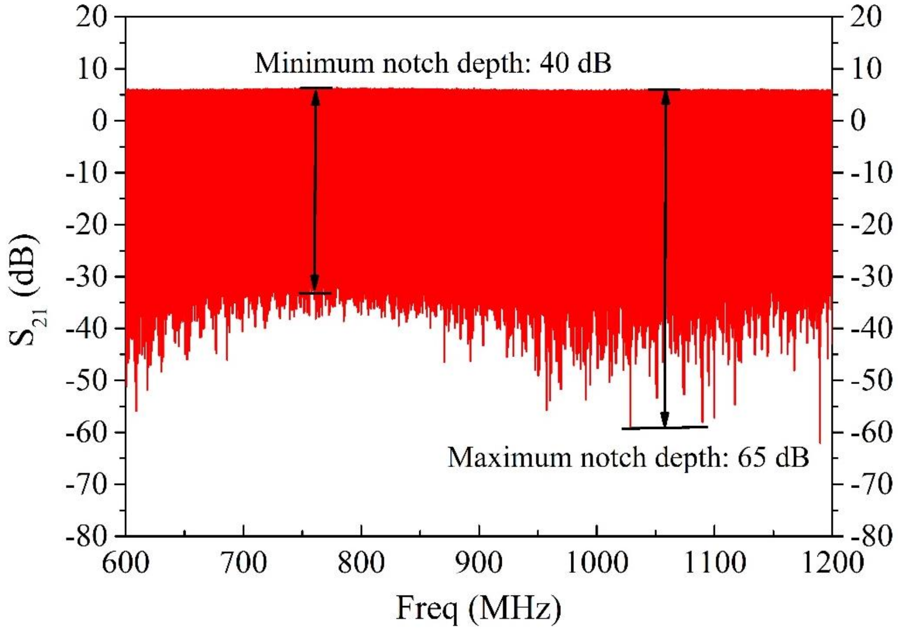

Notch frequency drift of two types of optical fibers including both 223 m normal and phase-stabilized optical fiber in the long branch.

Drift frequency (MHz)	Normal optical fiber (kHz/°C)	Phase-stabilized optical fiber (kHz/°C)
600	20.99	2.48
900	28.43	3.56
1200	39.76	6.67

at least a factor of 6 is improved!

Comparison of two type notch filters

	CERN AD Coaxial-type	HIRFL CSRe Coaxial-type	HIAF SRing Coaxial-type	HIAF SRing Optical-type
The minimum notch depth (dB)	20	15	26	**40**
The maximum notch depth (dB)	30	35	57	**65**

- we select the optical notch filter with phase-stabilized optical fiber for the SRing stochastic cooling system with the highest priority
- In the next step of this work, the optical fiber notch filter will be installed temporarily on CSRe in the beginning of 2024 to investigate the effect of longitudinal cooling and is planned to be used for experiments with secondary beams

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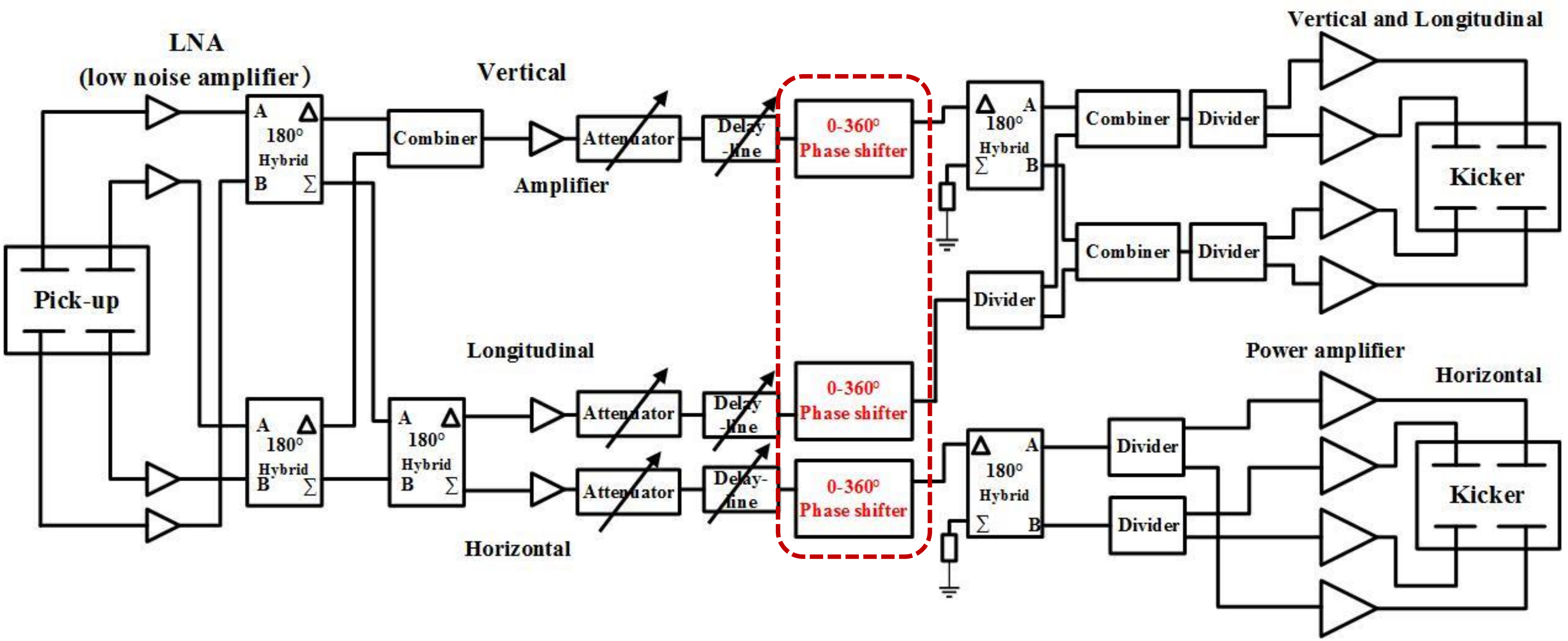
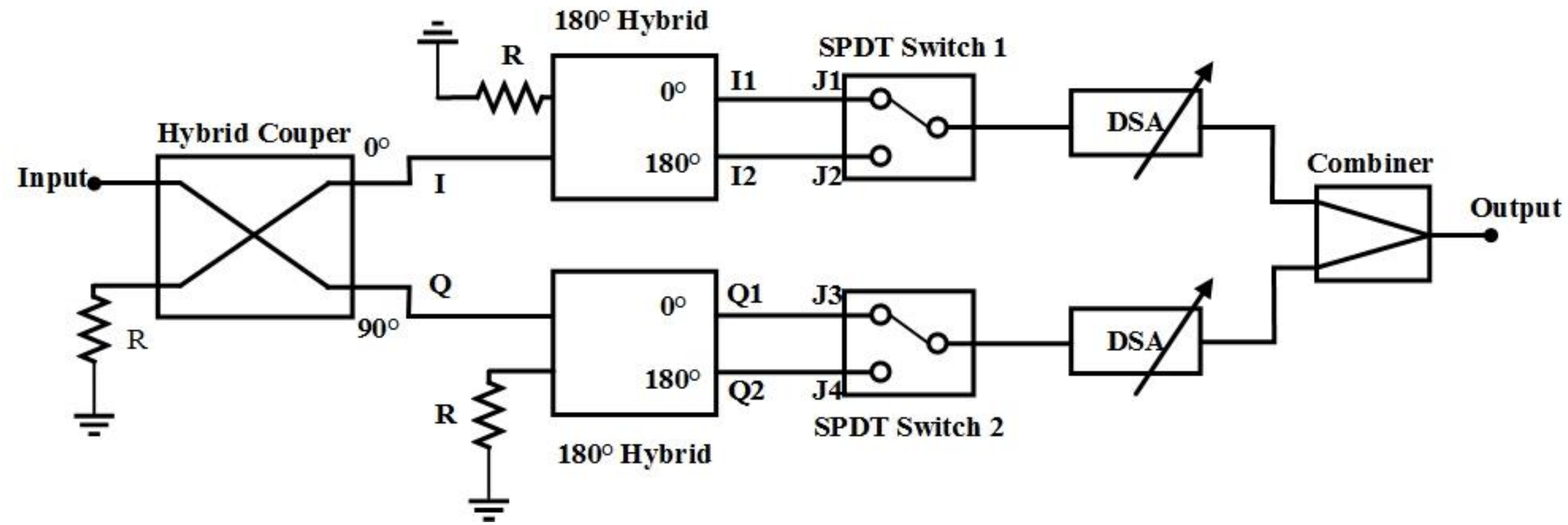
Broadband phase shifter



- Broadband phase shifter is one of the critical devices for SRing stochastic cooling system
- because it is essential for the correct sign of the momentum correction signal at the kicker

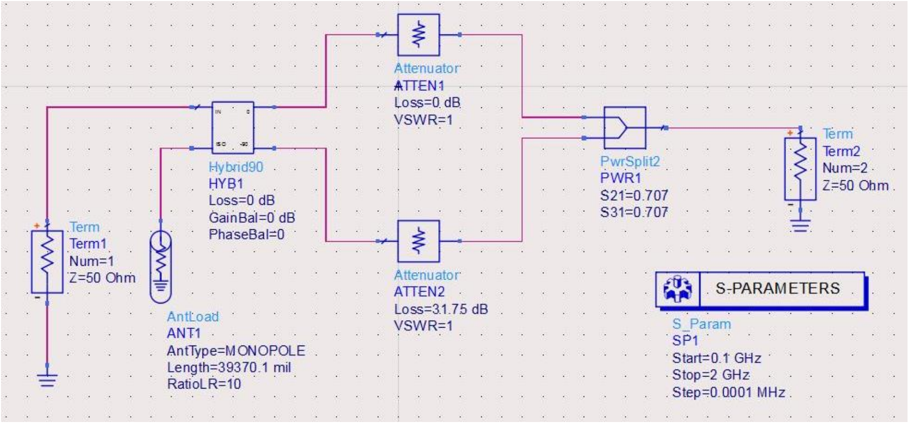
Broadband phase shifter

- **0.15 - 2 GHz phase shifter consists of:**
  - a 3 dB 90° Hybrid Coupler
  - two 180° Microwave Hybrids
  - two program-controlled attenuators (DSA)
  - two microwave switches (SPDT)
  - combiner

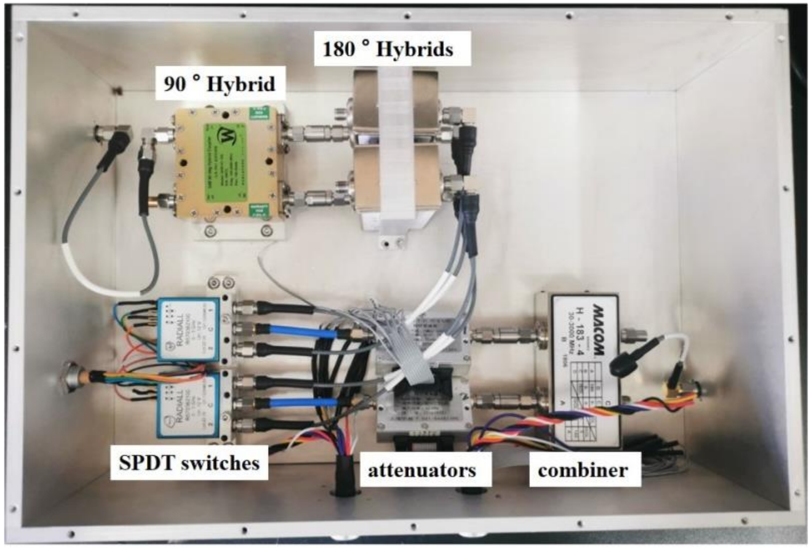


Block diagram of proposed method for the 0°- 360° broadband phase shifter

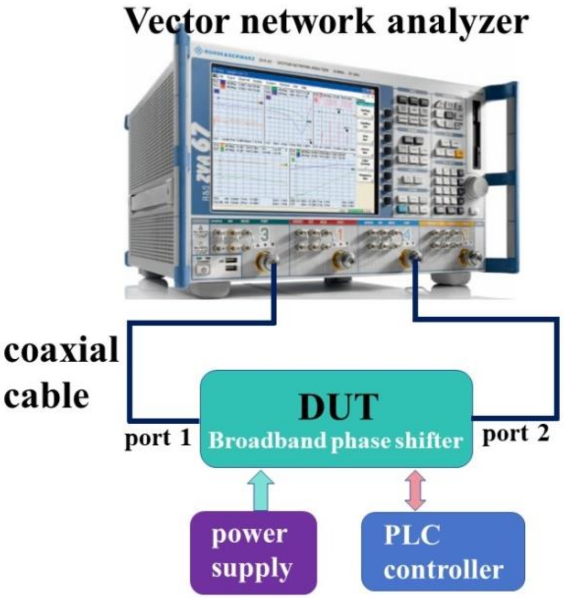
Broadband phase shifter



ADS phase simulation of S_{21} schematic diagram

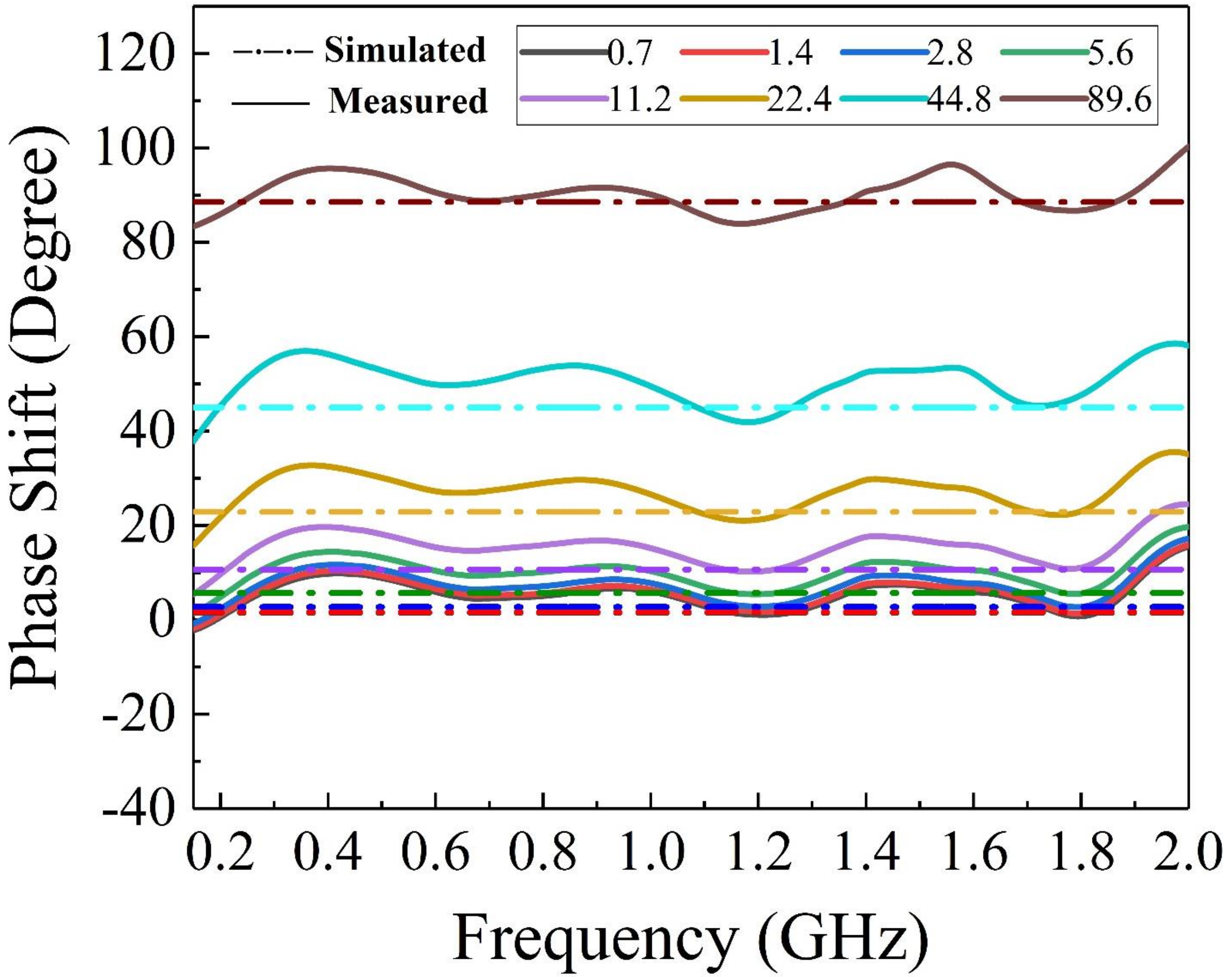


Photograph of the fabricated 0° - 360° phase shifter



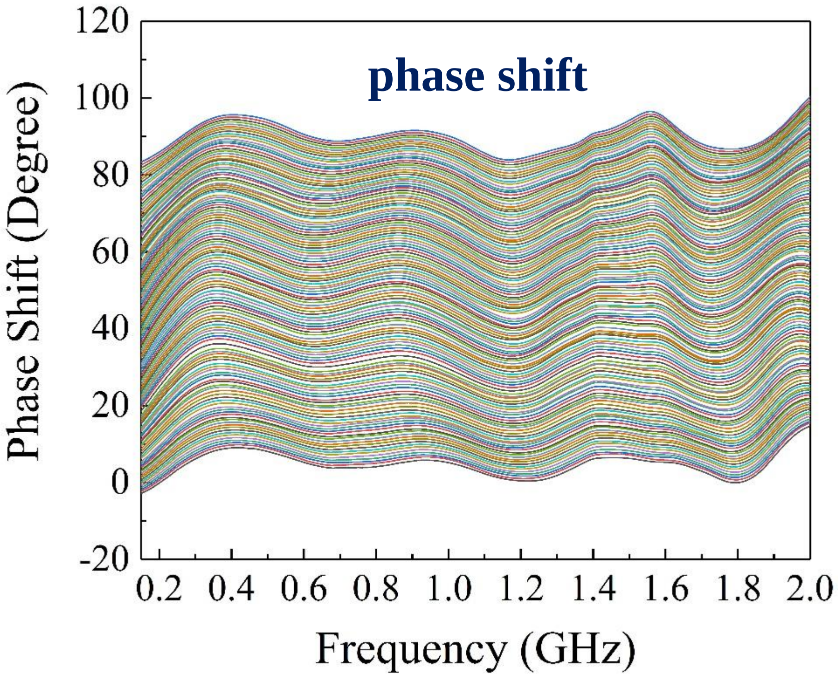
phase shifter test block diagram

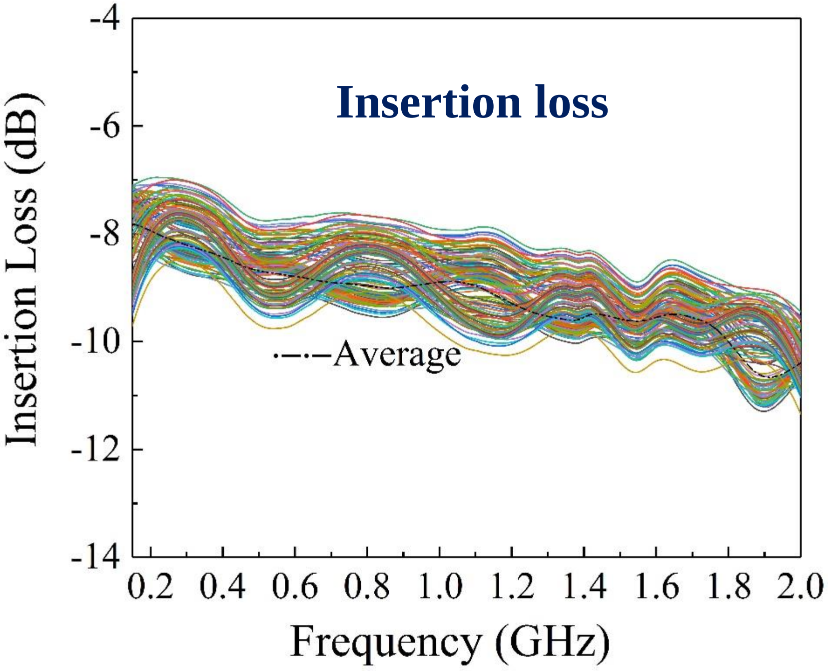
Broadband phase shifter



Measured and simulated main states phase shift of the 9-bit phase shifter

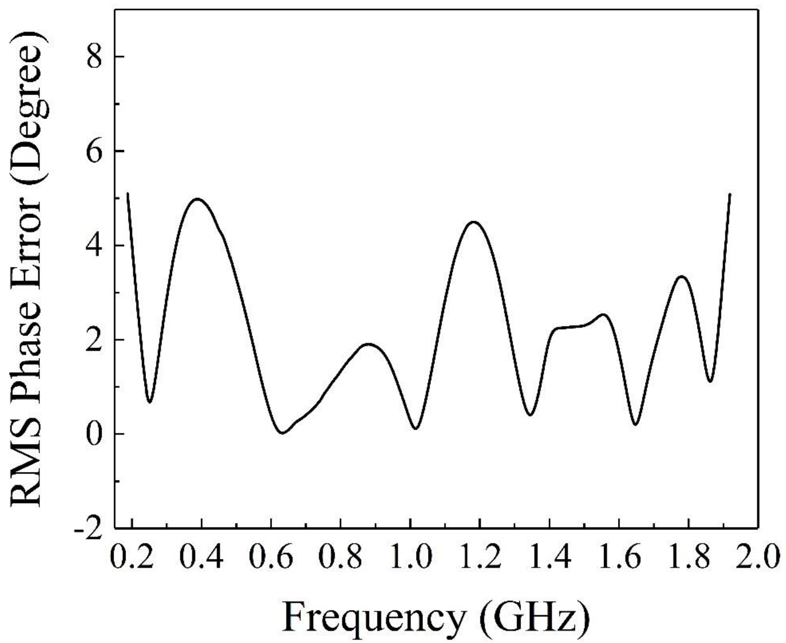
Broadband phase shifter

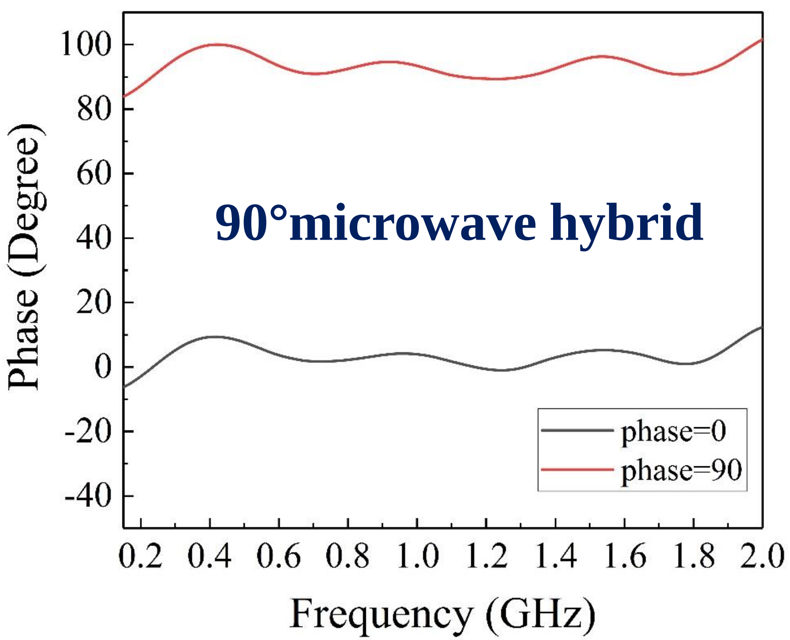




Measured phase shift and insertion loss of the 9-bit phase shifter with total 128 phase shift states and each phase shift step 0.7°in the range of 0°- 90°

Broadband phase shifter

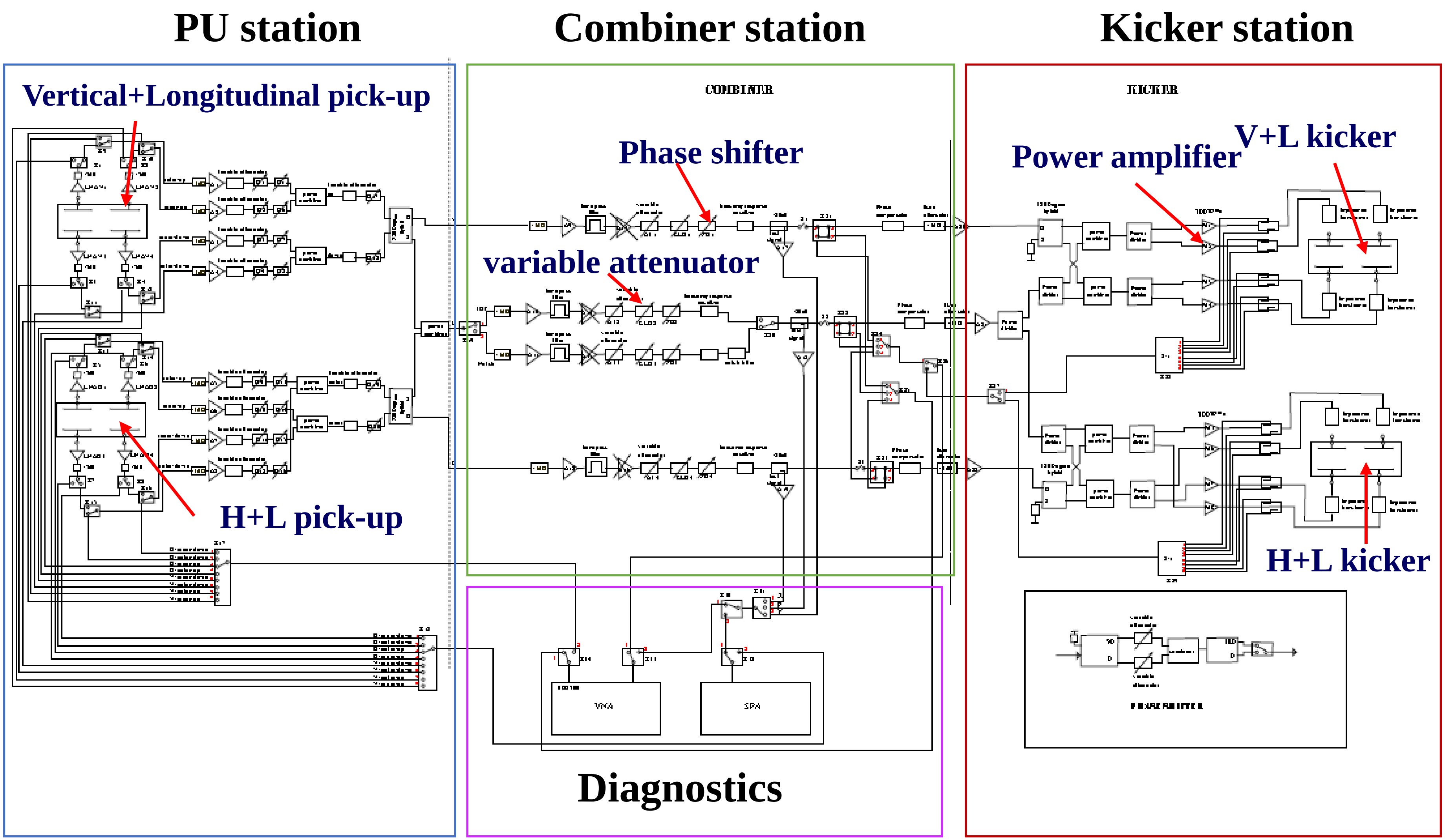




- From 0.15 GHz to 2 GHz, the RMS phase errors were less than 5°
- And the RMS phase error is mainly determined by the phase unbalance of the 90°microwave hybrid

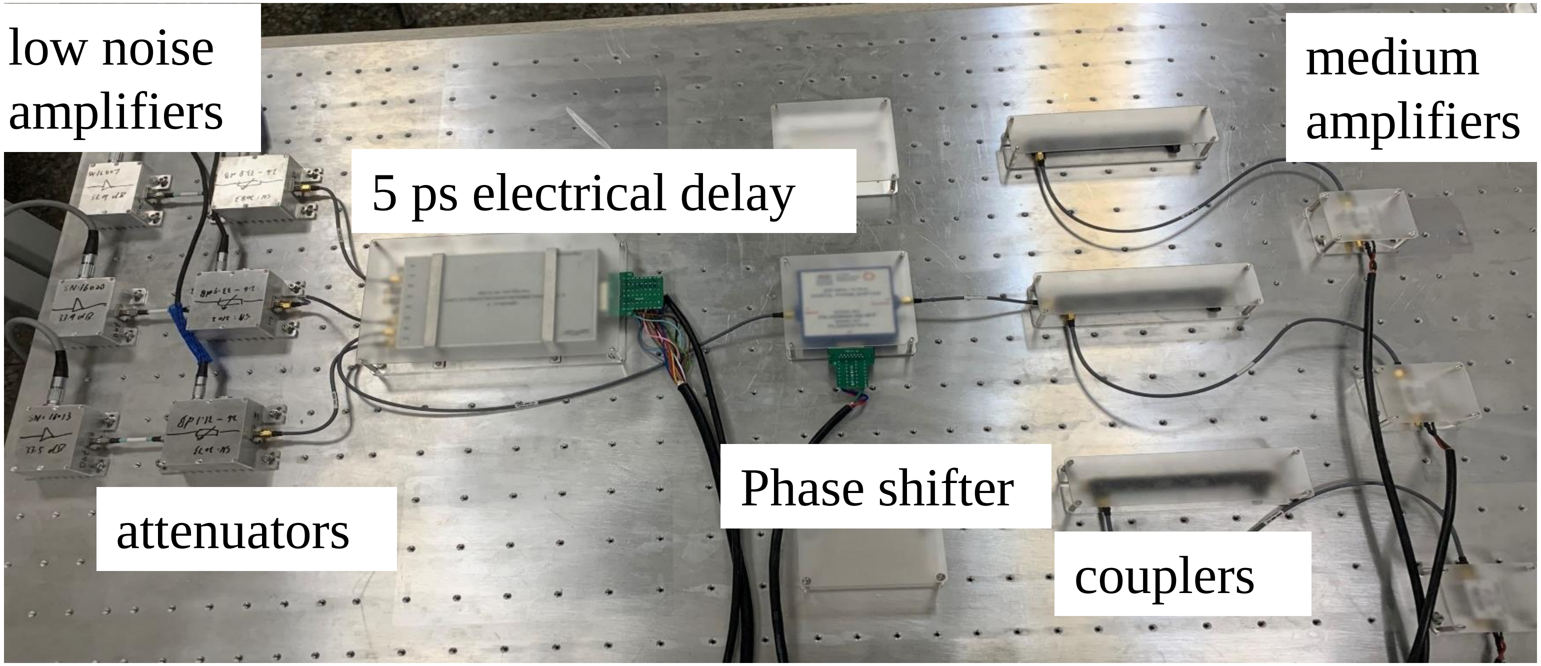
- ✓ Bandwidth: 0.15 GHz - 2 GHz
- ✓ Phase shift: 0° - 360°
- ✓ Insertion loss: 9 dB ± 2 dB
- ✓ Minimum phase step: 0.7 °
- ✓ Phase balance:< ± 10°
- ✓ Phase errors: < 5°
- ✓ S_{11}: < -15 dB
- ✓ S_{22}: < -10 dB

Signal transmission&procession



Signal transmission&procession

Partial combiner station hardware

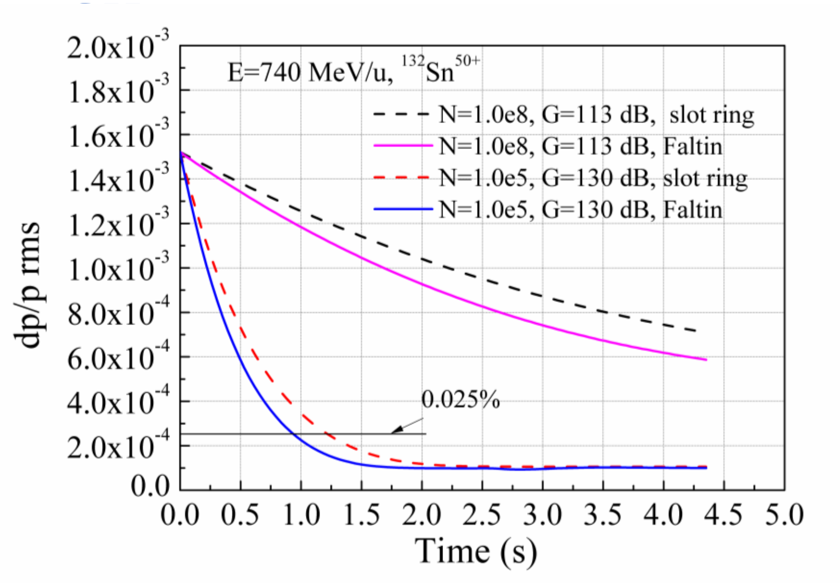


Cooling simulation parameters for SRing

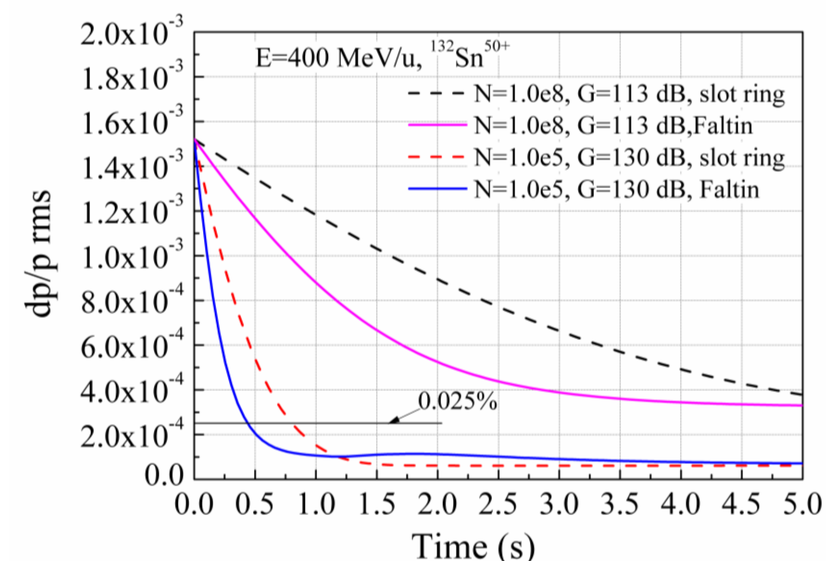
- Ion 132Sn50+
- Kinetic energy 740 MeV/u, 400 MeV/u
- Total number of RI 1.0e5, 1.0e8
- Initial momentum Δ p/p ±4.0e-3
- γ_t 3.317
- Local γ_t 2.568
- Bandwidth 0.6-1.2 GHz
- Number of slot rings for Pickup 64
- Number of slot rings for kicker 128
- Number of Faltin pickup (0.75 m) 2
- Number of Faltin kicker (0.75 m) 4
- Temperature (physical) 300 K
- Distance from pickup to kicker 75.25 m
- Dispersion at pickup/kicker 0.0 m

SRing TOF cooling simulation

740 MeV/u, $^{132}Sn^{50+}$, 0.6-1.2



400 MeV/u, $^{132}Sn^{50+}$, 0.6-1.2 GHz



RF power requirement for a $^{132}Sn^{50+}$ beam momentum cooling simulation in the bandwidth 0.6-1.2 GHz

Energy (MeV/u)	Particle Numbers	Gain (dB)	Type of Structure	RF Power (W)
400	1×10^5	130	Slot ring	50
			Faltin	60
	1×10^8	113	Slot ring	130
			Faltin	290
740	1×10^5	130	Slot ring	50
			Faltin	55
	1×10^8	113	Slot ring	300
			Faltin	370

Summary of SRing longitudinal cooling

	Rare isotope beam 400-740 MeV/u, 1.0e5 ions	Rare isotope beam 400-740 MeV/u, 1.0e8 ions
Before cooling	Δ p/p: ±4.0e-3 εx/ εy: 40 π mm·mrad	Δ p/p: ±4.0e-3 εx/ εy: 40 π mm·mrad
After cooling	Δ p/p: ±2.5e-4 εx/ εy: 5 π mm·mrad	Δ p/p: ±3.0e-4
Total cooling time	1.0 s	10 s

Summary

- Both a Faltin prototype traveling wave structure and a slot-ring prototype standing wave structure based on a ceramic vacuum chamber are evaluated. We select the slot-ring structure as the **pickup** and Faltin structure as the **kicker** of the SRing stochastic cooling system at present.

- A coaxial-type **notch filter** with an amplitude equalizer in the long branch and an optical-type notch filter with phase-stabilized optical fiber are discussed and evaluated. We select the optical notch filter with phase-stabilized optical fiber for the SRing stochastic cooling system with the highest priority.

- A 0.15-2 GHz **phase shifter** with 9-bit phase resolution is built. It can not only be used for both CSRe and SRing stochastic cooling system but also could be used for phased array systems.

Acknowledgements

My acknowledgements to the colleagues who helped us a lot those years for the stochastic cooling:

Fritz Caspers
Rolf Stassen
Lars Thorndahl
Fritz Nolden
……

Lastest civil construction for HIAF

2025-Huizhou, HIAF welcome all of you !

HIAF construction time schedule

2019	2020	2021	2022	2023	2024	2025	2026
Civil construction							
		Electric power, cooling water, compressed air, network, cryogenic, supporting system, etc.					
ECR design & fabrication			SECR installation and commissioning				
	Linac design & fabrication			iLinac installation and commissioning		Day one exp	
Prototypes of PS, RF cavity, chamber, magnets, etc.			fabrication	BRing installation & commissioning			Day one exp
				HFRS & SRing installation & commissioning			Day one exp
				Terminals installation			

- The ion source **SECR** will provide first beam early next year
- The low energy CW ion beam of **iLinac** is expected at the end of 2024
- The high energy pulse ion beam from **BRing** is in September of 2025
- The Day One Experiment in **SRing** will be in April of 2026

- ***Thank you for your attention!***
- ***Any comments welcomed!***