Preliminary Design of RF system for FFA at CSNS

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Outline

I. Introduction to the Requirements of RF System

II. Preliminary RF Cavity Design

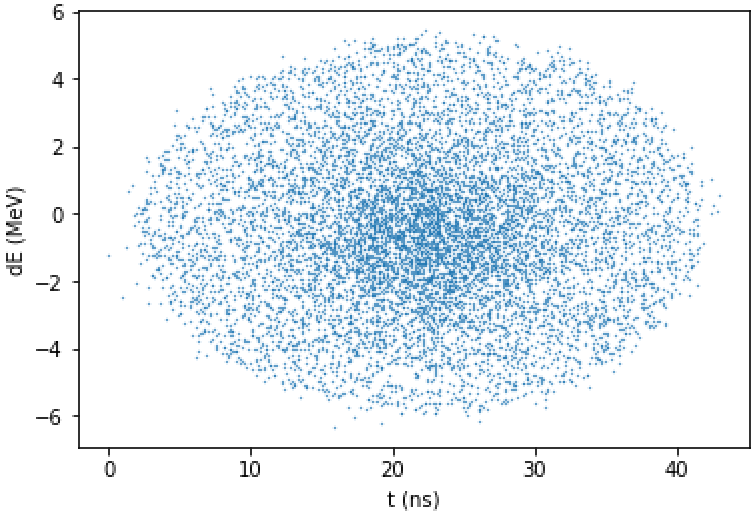
III. High-Power RF Analysis

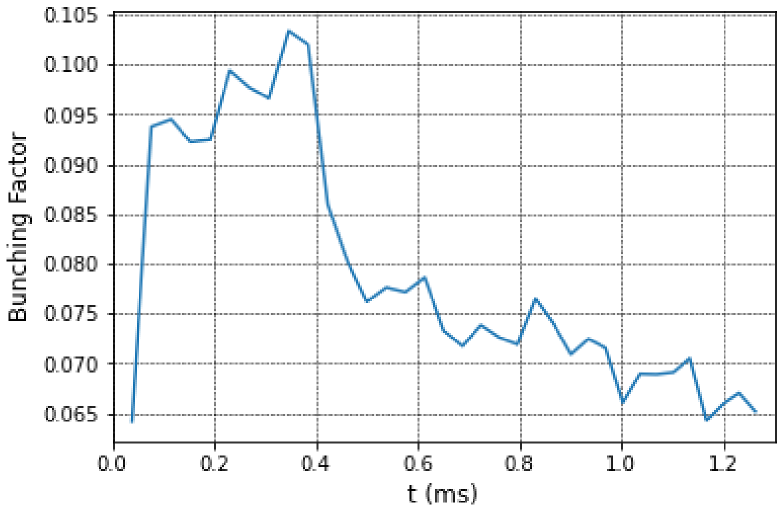
IV. Summary and Future Work

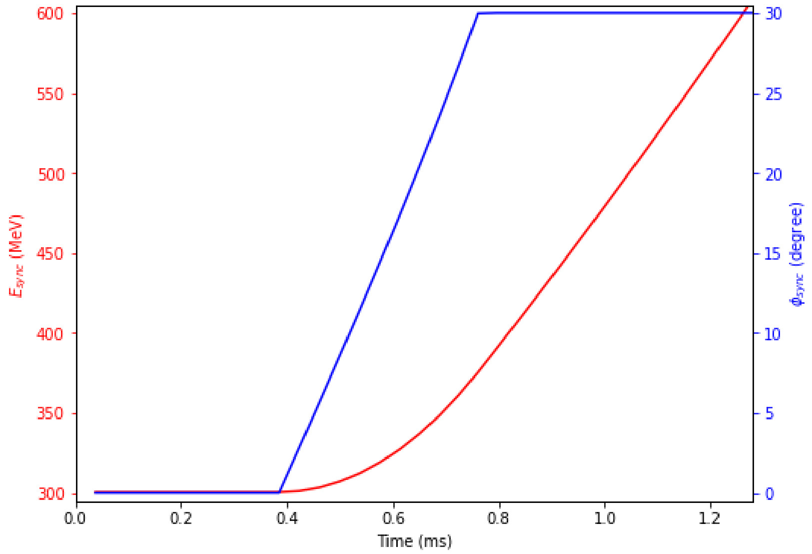
1.1 Beam dynamics design for short bunch (< 10 ns)

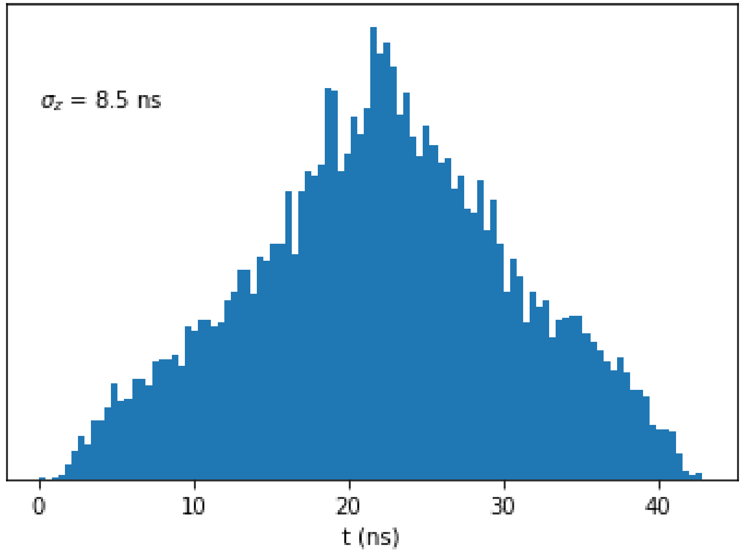
Main parameters used	
Harmonic number	1
RF frequency (MHz)	2.598-3.163
Transition gamma	2.50959
RF voltage per turn (kV)	300
Synchronous phase (°)	30
Acceleration time (turn/ms)	3500/1.26
Chopper duty	0.8

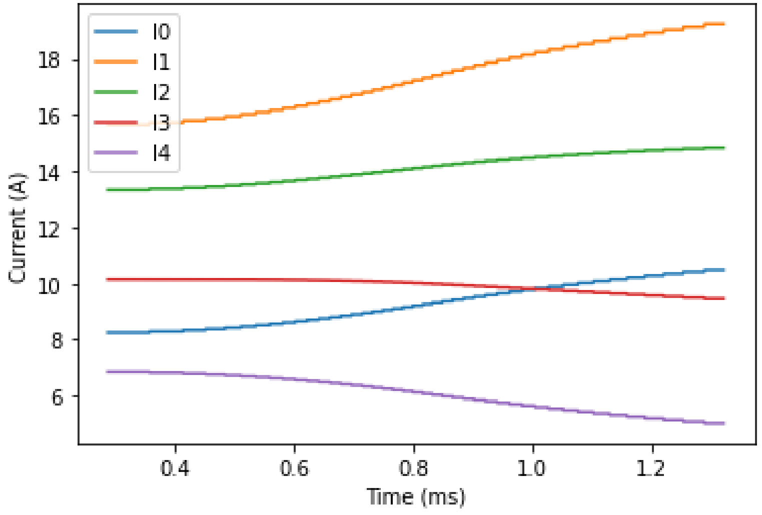
Simulation Results





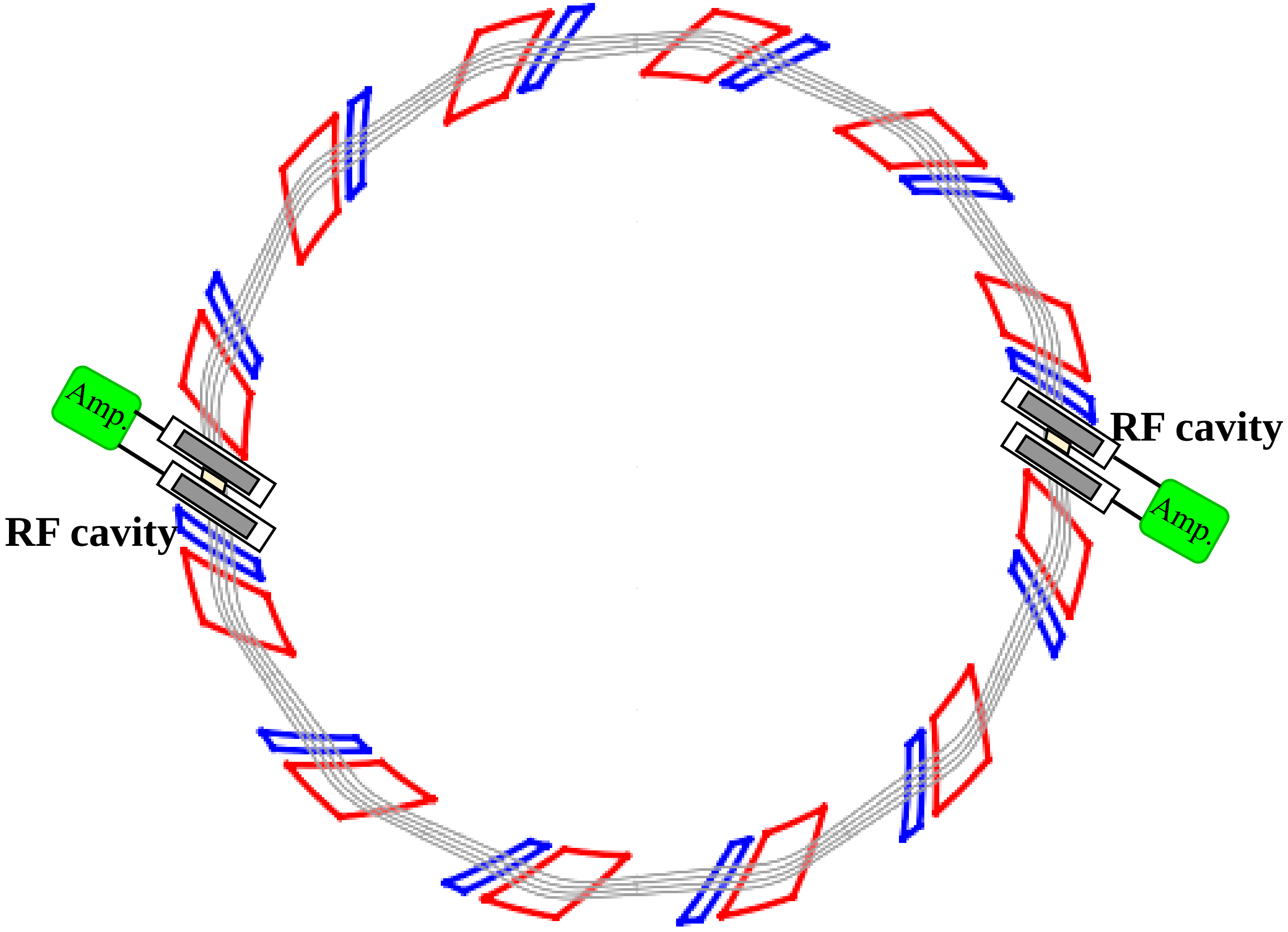






1.2 Requirements for RF systems

Two straight sections (1.8 m each) reserved for RF cavity installation



Schematic view of the FFAG

We must employ high-gradient MA-loaded cavity

Main RF parameters	
Energy range (MeV)	300~600
Harmonic number	1
RF frequency (MHz)	2.598-3.163
Core material	Magnetic alloy
Cavity length (m)	< 1.8
Number of cavities	2
Number of gaps per cavity	3
RF voltage per gap (kV)	50
Acceleration gradient (kV/m)	> 83
RF voltage per turn (kV)	300
Synchronous phase (°)	30
Acceleration time (ms)	1.3
Repetition rate (Hz)	25

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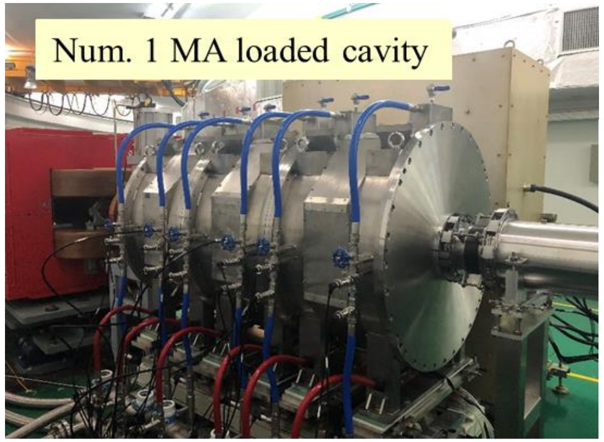
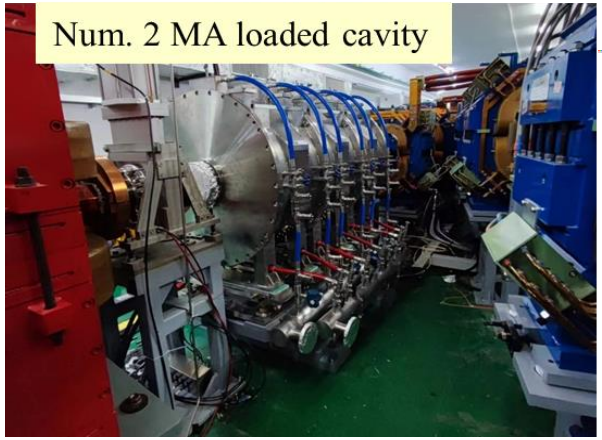
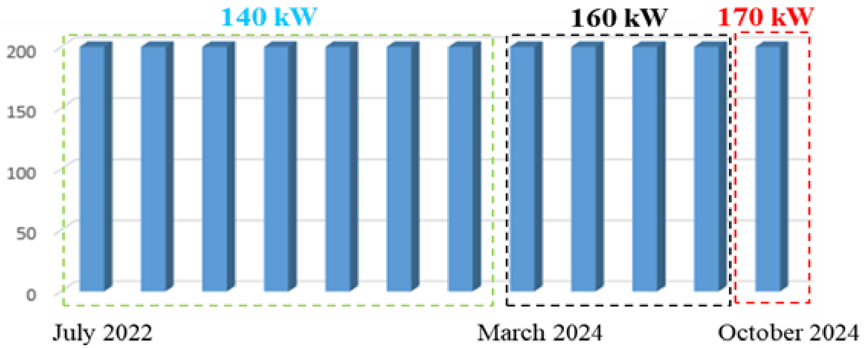
2.1 High-Gradient Wideband MA Cavity Foundation

- **High-gradient and wideband MA cavities have been successfully developed for CSNS RCS**
  - **Peak gradient: 50 kV/m; Frequency range: 1-5 MHz**
  - **Two MA cavities have been operating stably for over 10,000 hours**

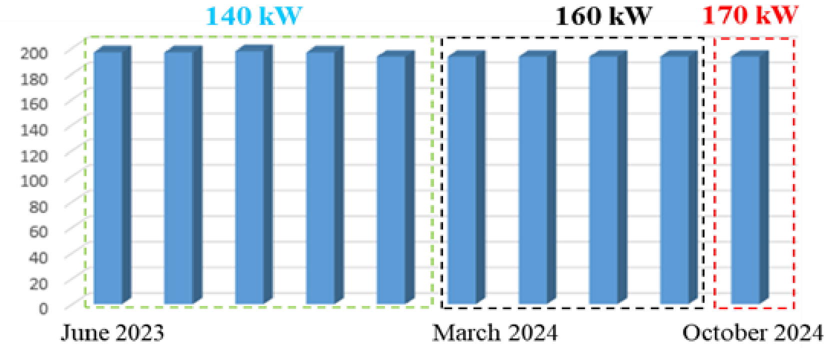


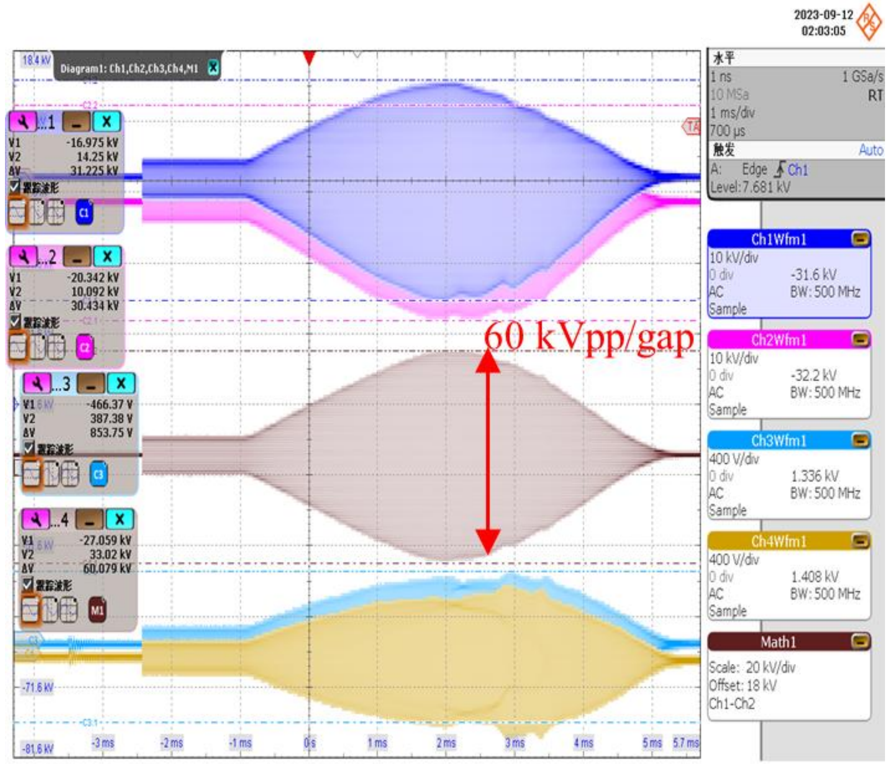


Impedance of Num. 1 MA cavity



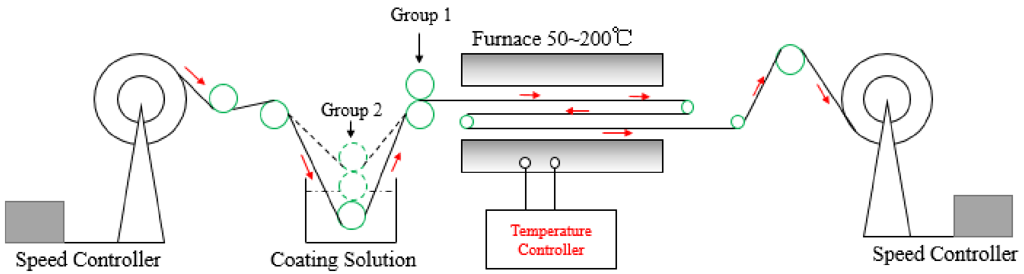
Impedance of Num. 2 MA cavity

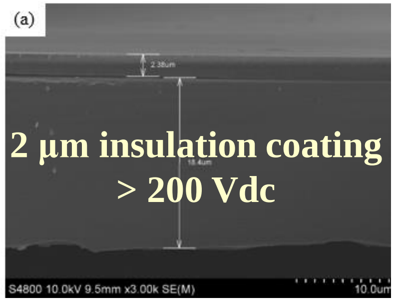




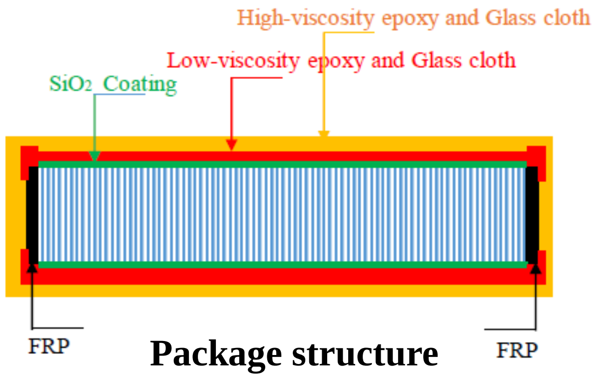
2.2 Key technologies for developing MA cores

☐ Micron-level high-insulation and low-stress inorganic coating





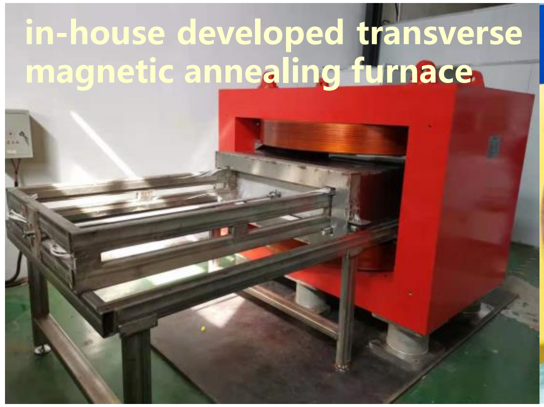
☐ Low-stress waterproof packaging process

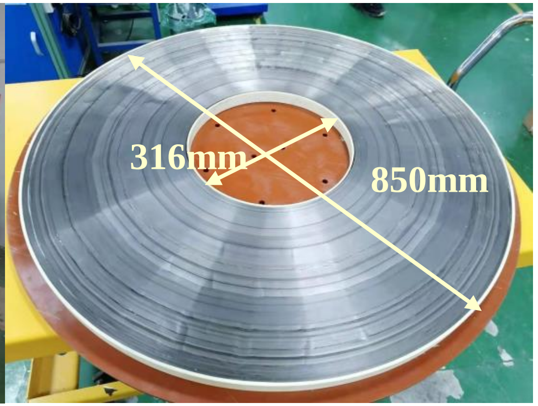


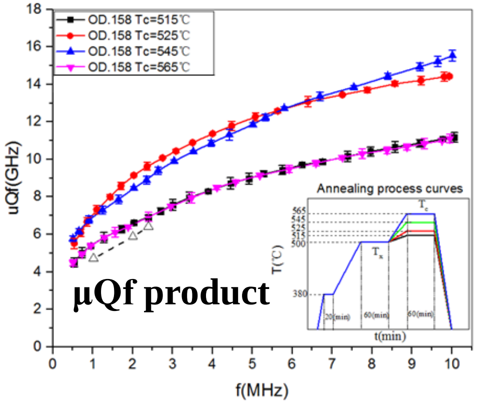
Package structure

☐ Winding and annealing for large-sized MA core

High-performance MA core: achieving a relatively high level internationally







Curing fixture

Low vacuum environment + fixture

Ensure the adoption of direct water cooling to deal with high power density

The key technologies of insulation, waterproofing, and annealing provide a solid foundation for the development of large-sized, racetrack-shaped MA cores for FFA

2.3 Preliminary design of MA core for FFAG

The inner dimensions of core should have enough horizontal aperture. The mean radius varies by 0.8 m.

The outer dimensions of core are limited by the size of furnace.

The 25 mm thickness of core is a common specification.

- **Inner dimensions of core**

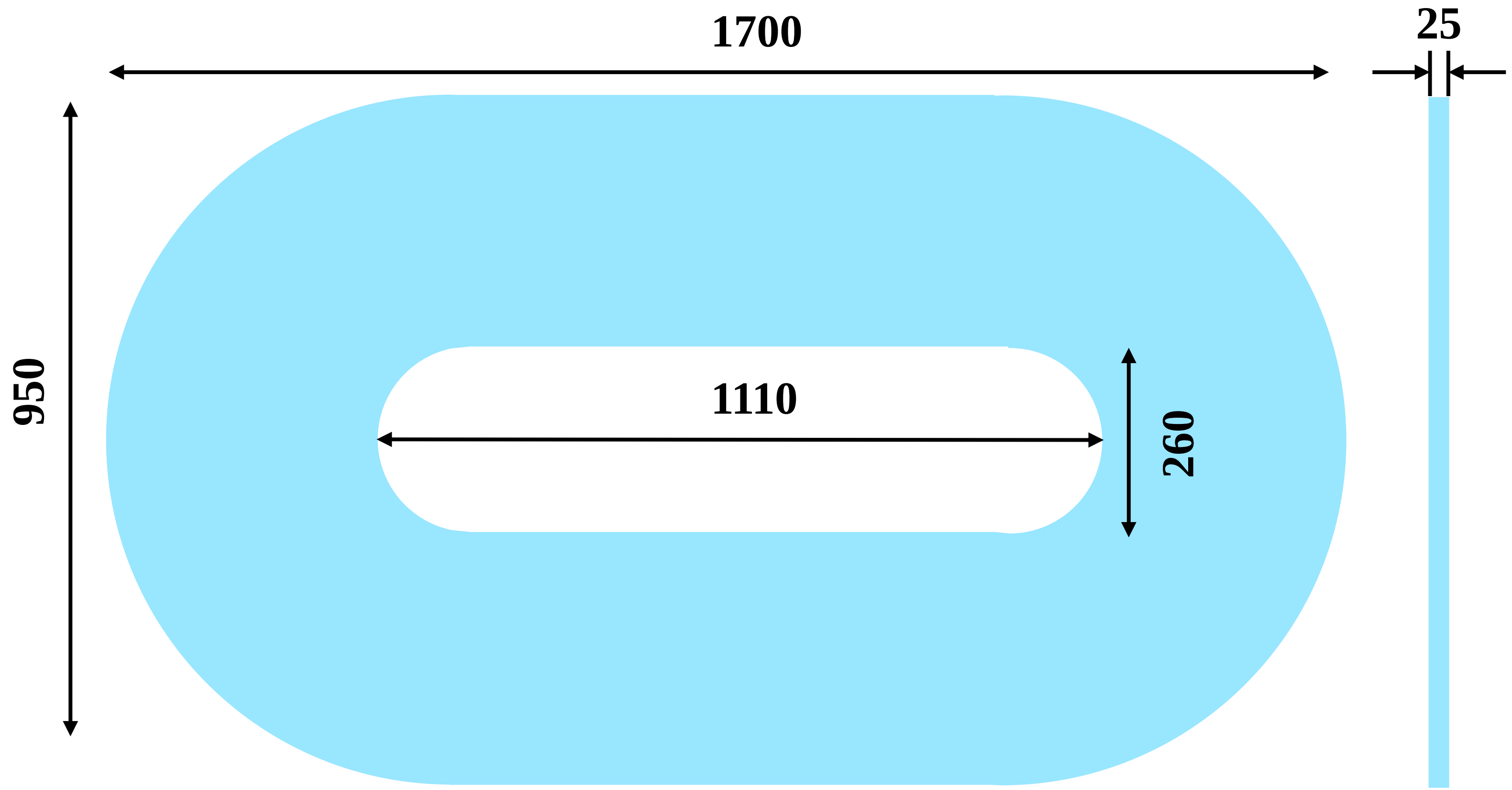
  1110 (H) × 260 (V) mm

- **Outer dimensions of core**

  1700 (H) × 950 (V) mm

- **Core thickness**

  25 mm



2.4 Estimation of core impedance

Equations for racetrack core impedance calculation

$$Z = f\mu_0(\mu'' + j\mu')t\ln\frac{\overline{r_1}}{\overline{r_0}}$$

$$\overline{r_1} = l_1/2\pi$$

real part $R_p = f\mu_0\frac{\mu'^2 + \mu''^2}{\mu''}t\ln\frac{\overline{r_1}}{\overline{r_0}}$

$$\overline{r_0} = l_0/2\pi$$

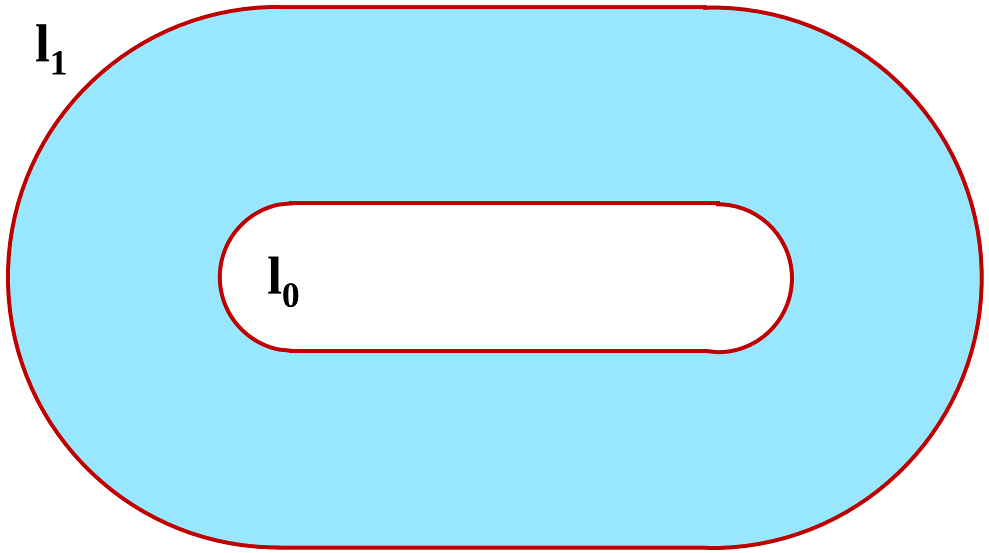
μ_0: permeability of vacuum

f: frequency

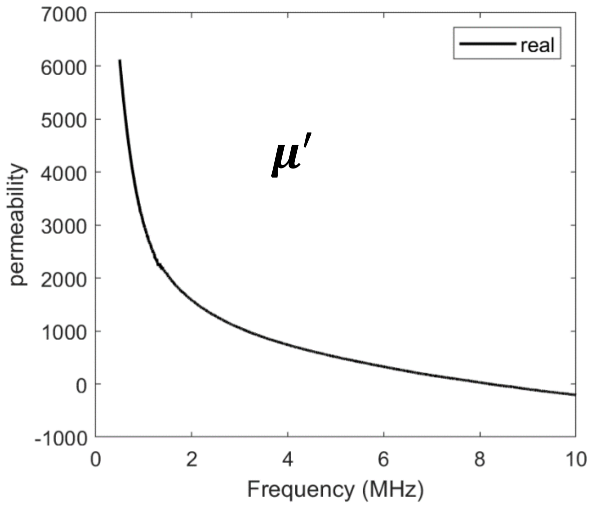
$\mu = \mu'$- $j\mu''$: magnetic permeability

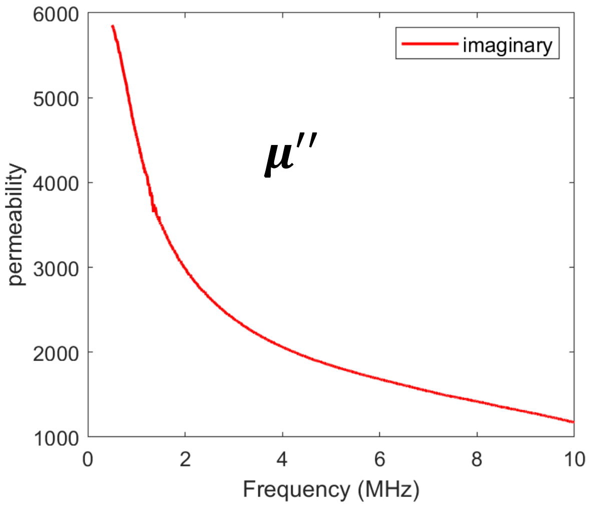
t: thickness

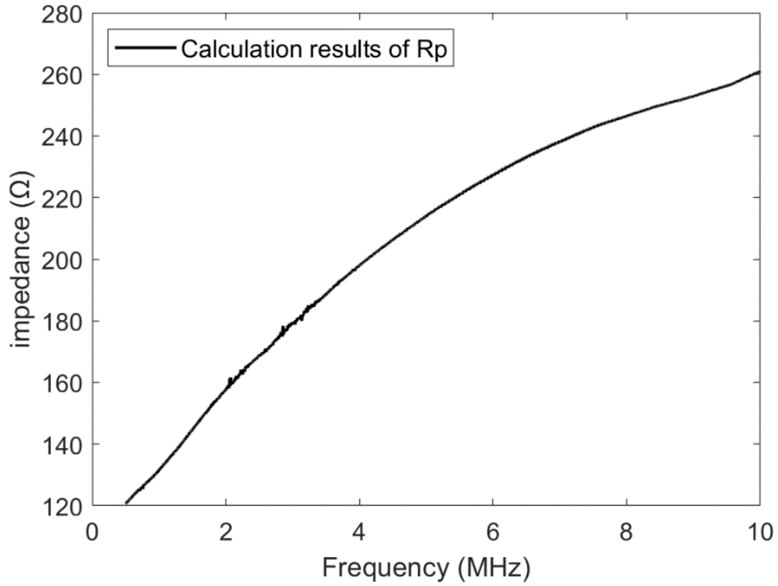
$\overline{r_1}$ and $\overline{r_0}$: equivalent outter and inner radius



Measurements of the core used in CSNS RCS





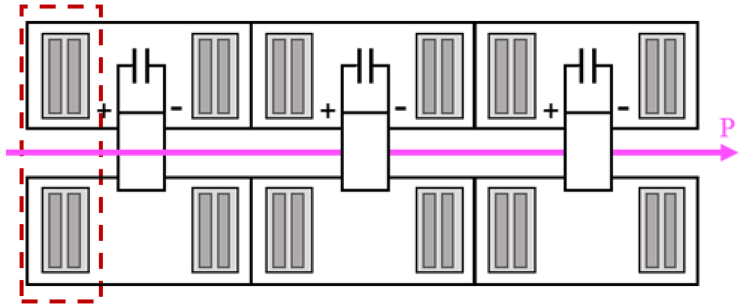


2.5 Power density in the core

V_{gap}: 50 kV $\quad$ $$\text{power} = \frac{V^2}{2R_P}$$ $$\text{power\_density} = \frac{\text{power}}{\text{volume}}$$ The volume of the core: ~3×10^4 cm^3

☐ Case 1: 2 core per tank

tank

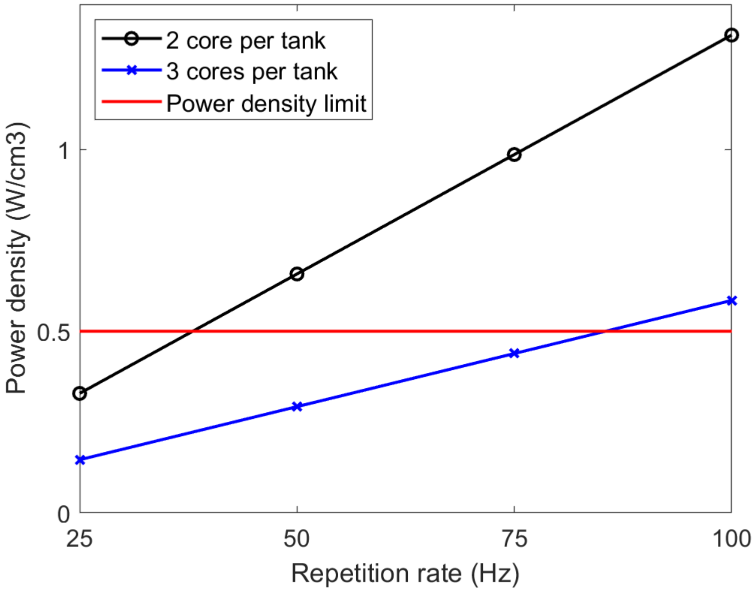


1434 mm

Power density: 0.657 W/cm³ at 50 Hz repetition rate

- can work under 25 Hz

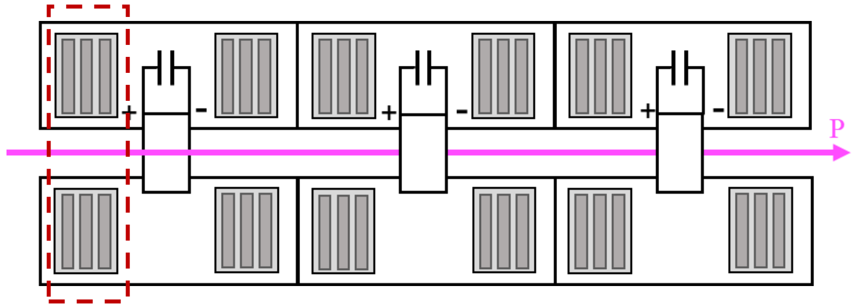
Comparison of power density in the core under two different cases



The power density limited at 0.5 W/cm³

☐ Case 2: 3 cores per tank

tank



1800 mm

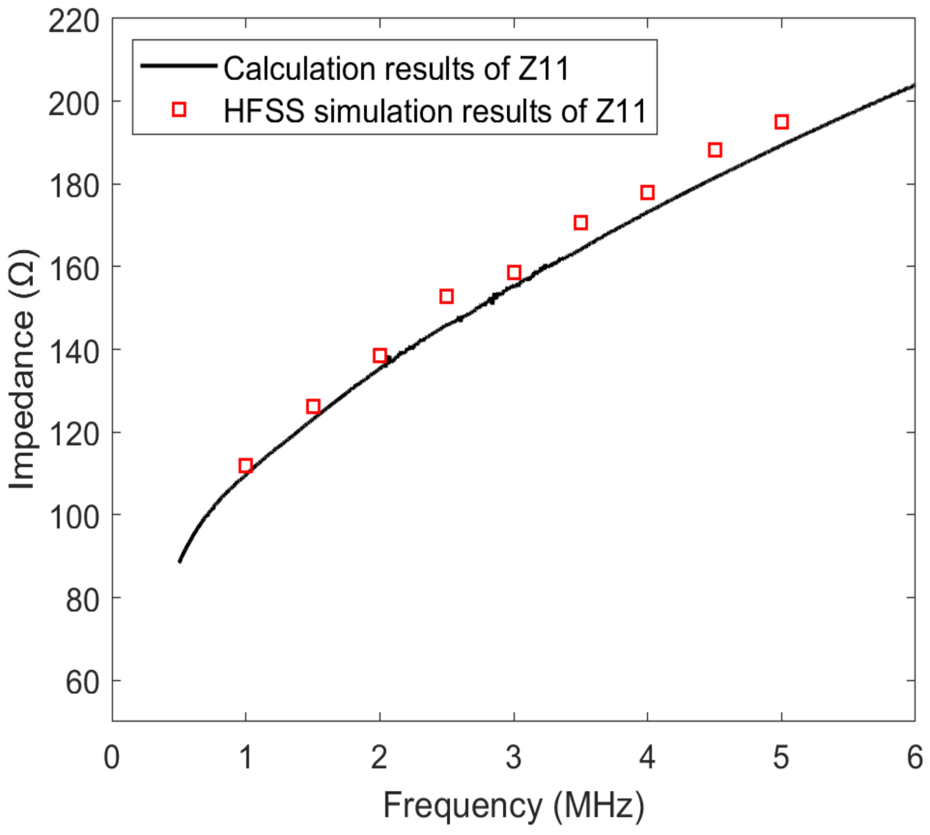
Power density: 0.438 W/cm³ at 75 Hz repetition rate

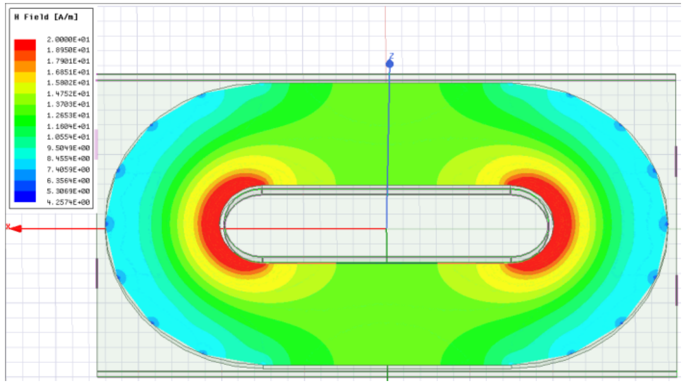
- Suitable for 25~ 50 Hz operation
- Will be adopted

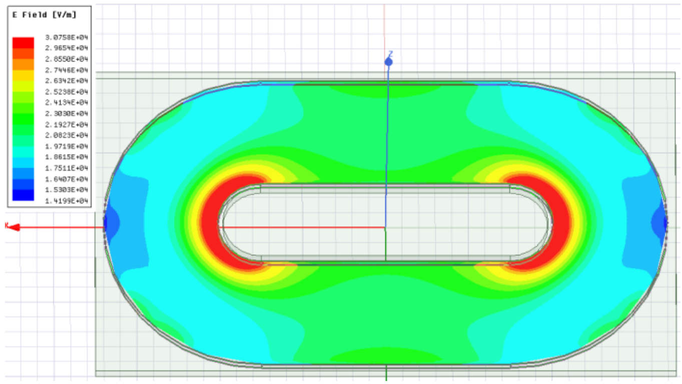
The power density is limited by the surface temperature of the MA core; excessive power will burn out the packaging.

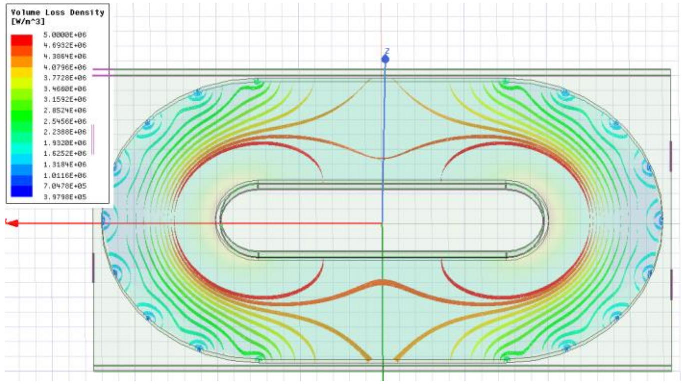
2.6 HFSS electromagnetic simulation

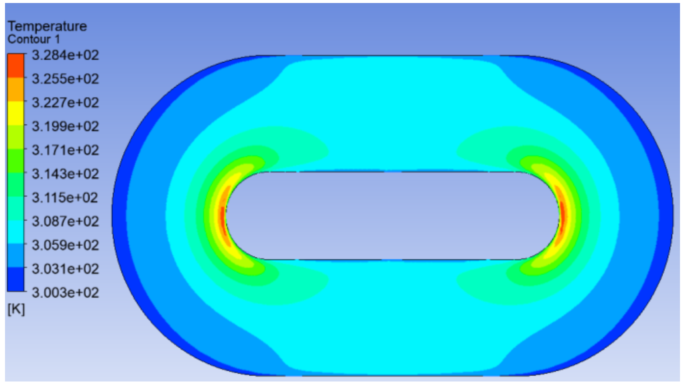
- **To obtain the power loss density of MA core, electromagnetic simulation was conducted using HFSS**
  - **The simulated impedance aligns well with calculations**
  - **Experimental validation is planned to verify the power loss density distribution**
- **The power loss density can be imported into Fluent as thermal source for temperature analysis**







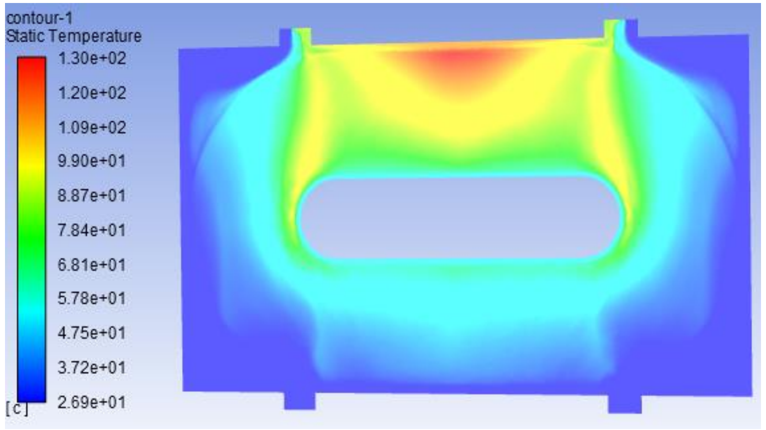


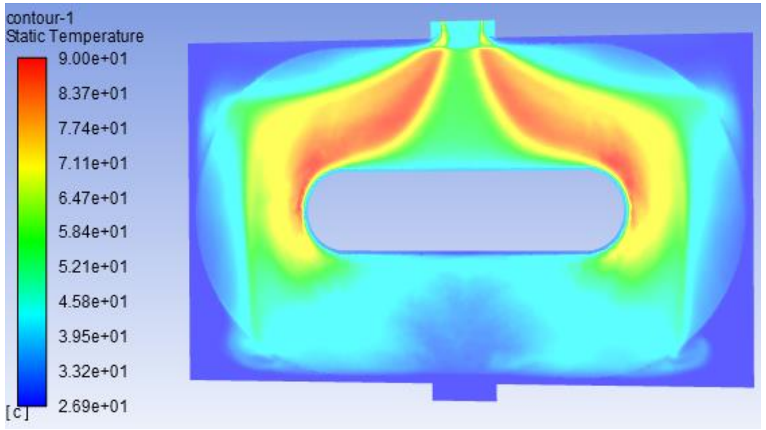


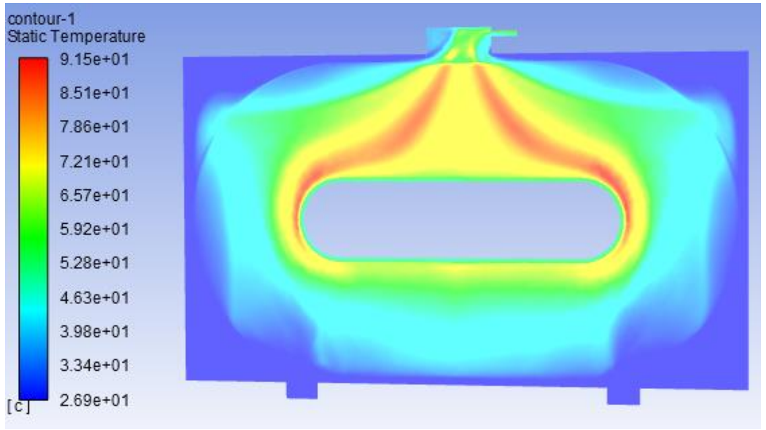
2.7 Fluid-thermal simulation

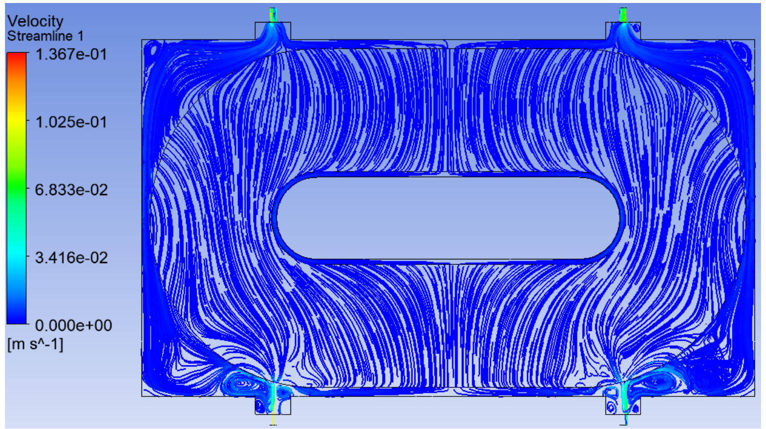
- **Preliminary fluid-thermal simulations have been carried out in Fluent**
  - **Inlet/outlet positioning significantly affects temperature distribution**
- **Guide vanes will be designed to improve cooling efficiency to keep T < 100°C @ 0.5 W/cc**

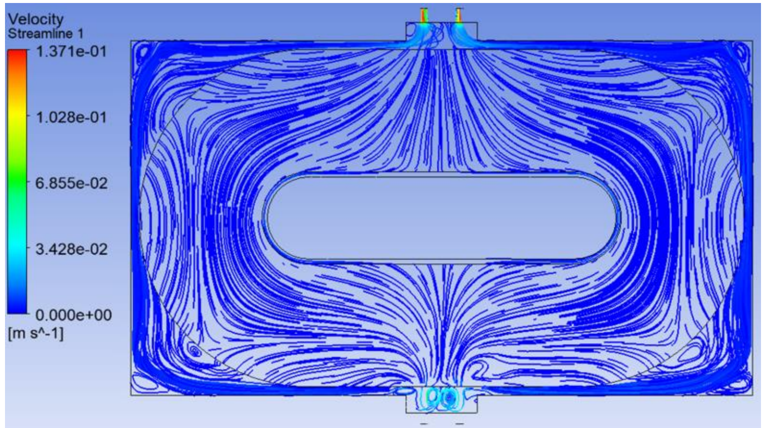
Maximum temperature: 130 °C | **Maximum temperature: 90 °C** | **Maximum temperature: 91.5 °C**

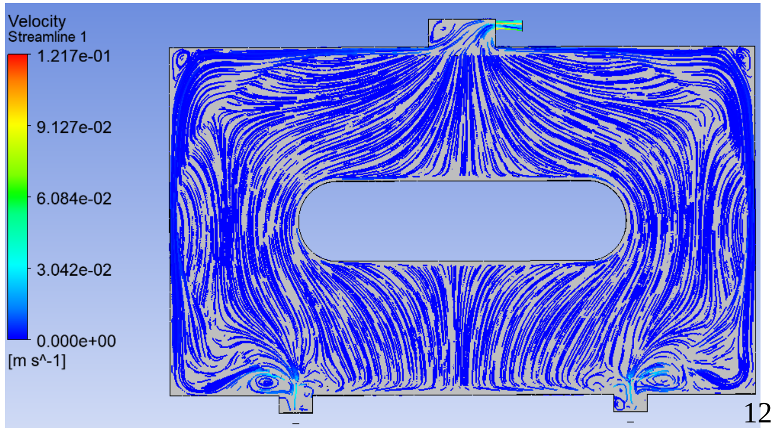










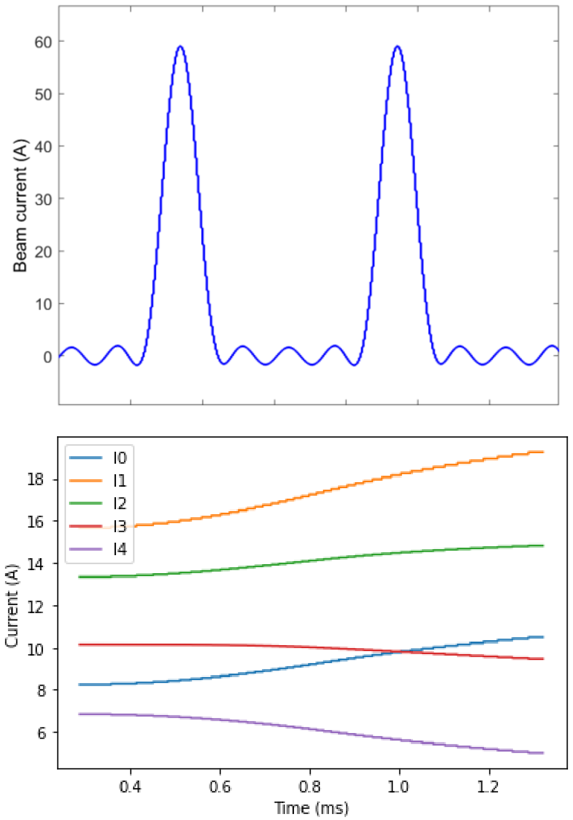


Outline

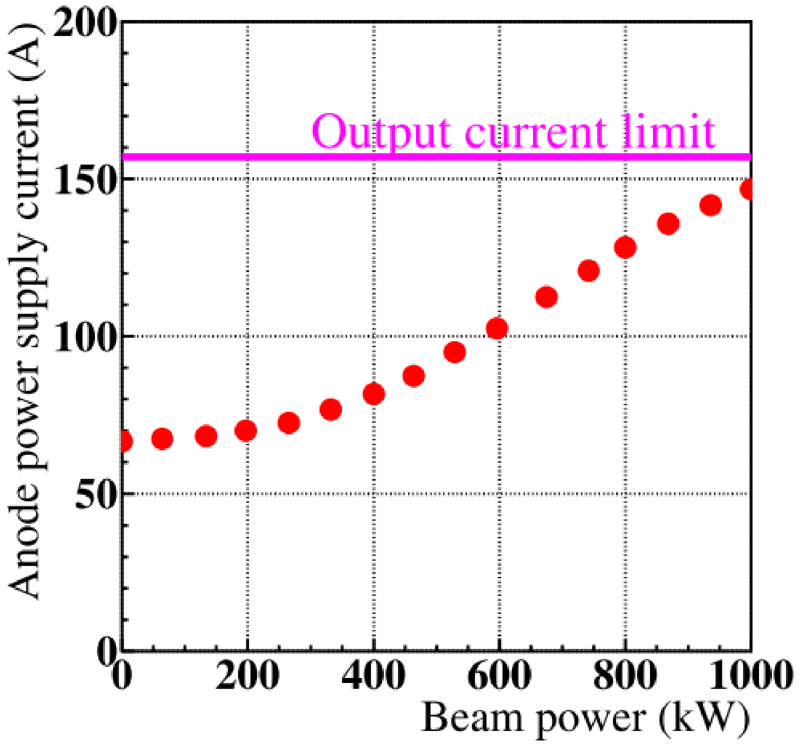
3.1 HPRF determines the final performance

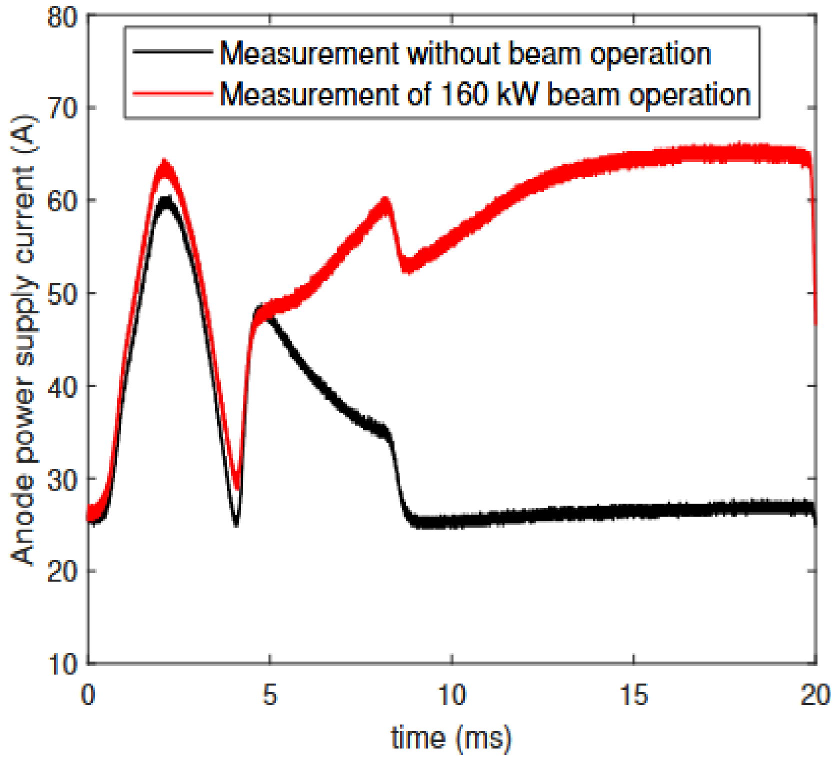
- **High power RF system provides high gradient RF voltage and heavy beam loading compensation**
  - **Critical to RF performance (per J-PARC RCS & CSNS RCS experience)**
  - **CSNS FFA beam circulating current is comparable to both RCS systems**
- **Analysis of HPRF operation for CSNS FFAG is necessary**

CSNS FFA beam current



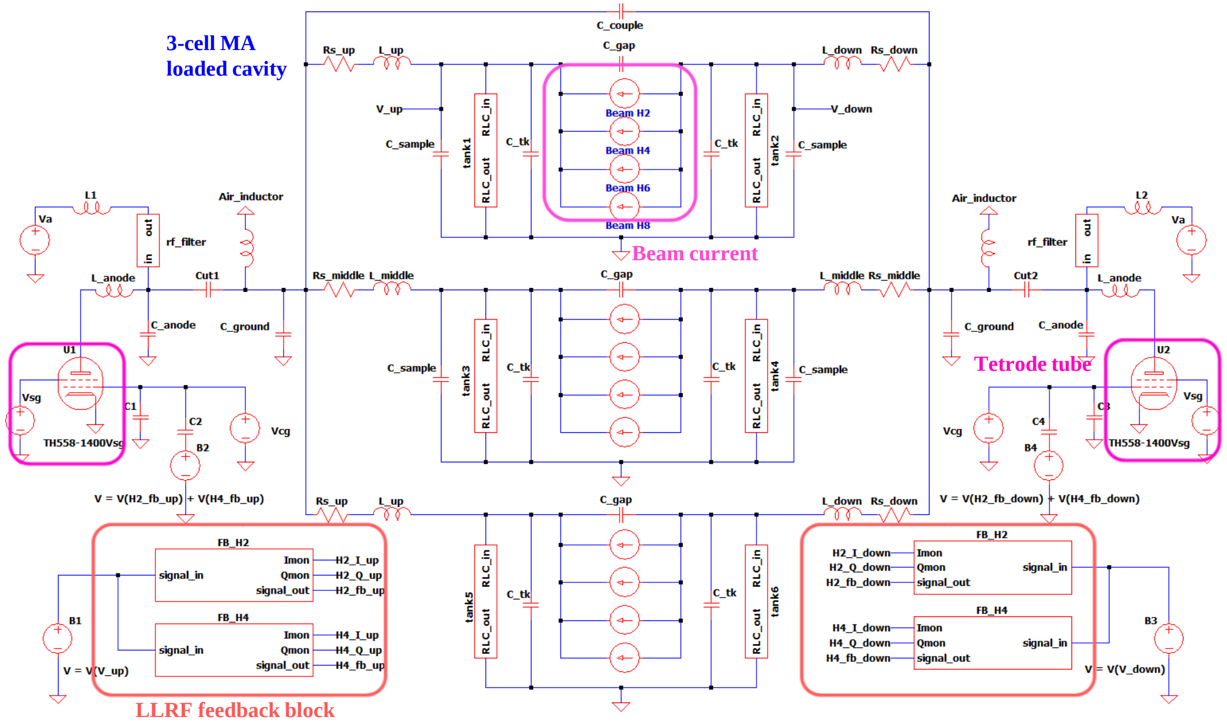
HPRF operation of J-PRAC RCS and CSNS RCS





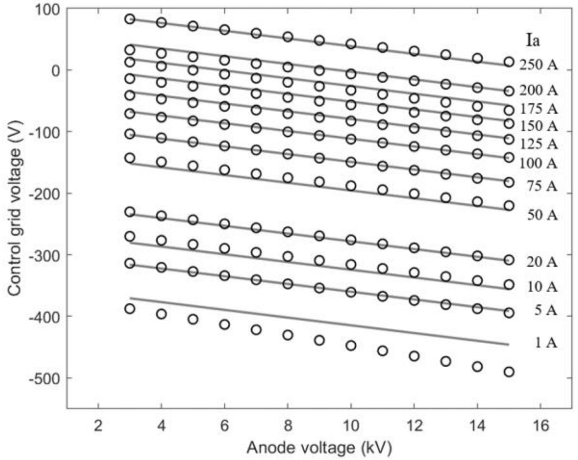
3.2 Method for Analyzing of tetrode operation

- **To investigate the tetrode operating condition, a system-level model have been developed**
  - **Includes MA-loaded cavity + tetrode tube + LLRF + beam**

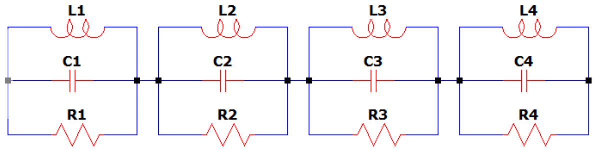


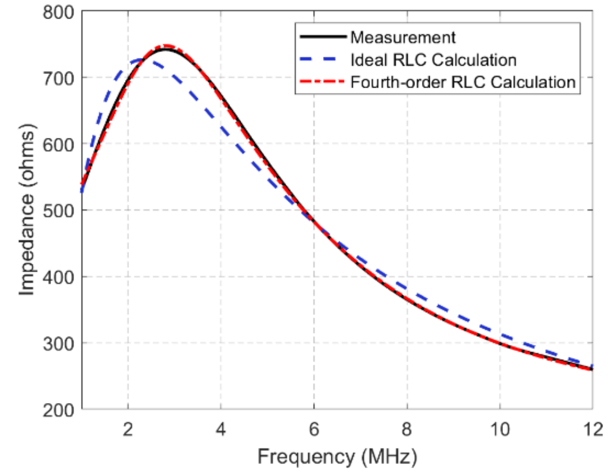
tetrode model

$$I_a = K\left(1 - e^{\left(-\frac{V_a}{AV_{sg}}\right)}\right)\left(\mu_{cg}V_{cg} + \mu_{sg}V_{sg} + V_a\right)^x$$



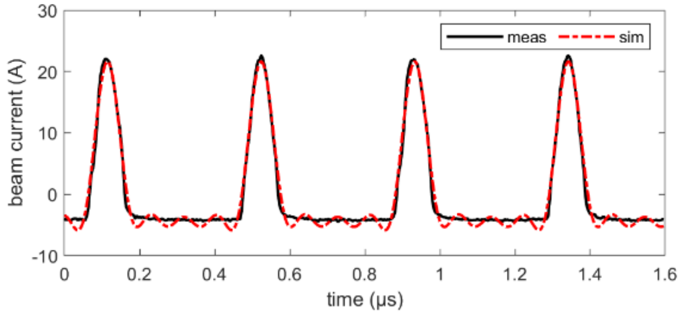
tank model



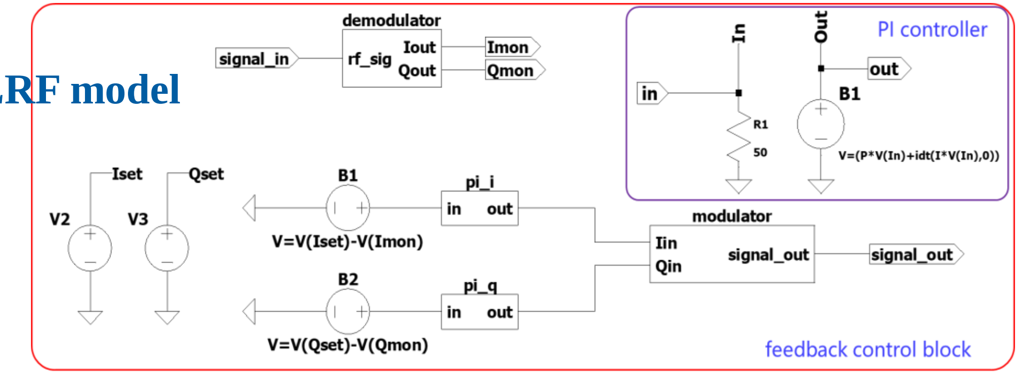


beam model

$$I_{beam} = \sum_{i=1}^{4} H_i * \sin(2\pi * h_{num} * i * f_{rev} * t + \varphi_{bi})$$



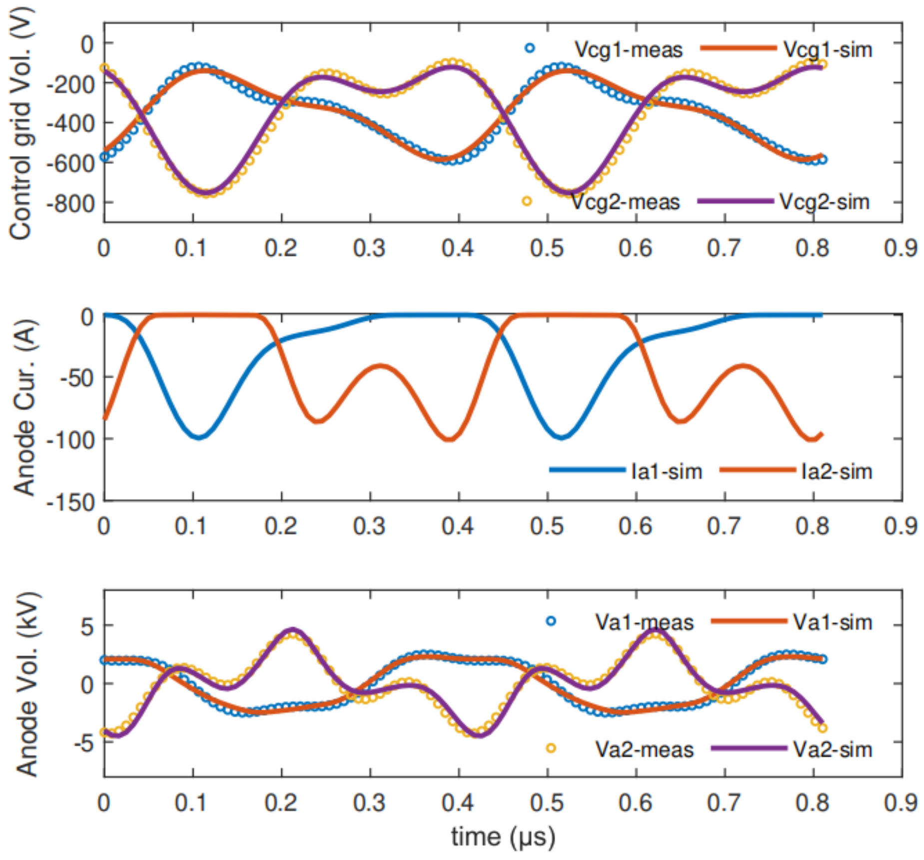
LLRF model



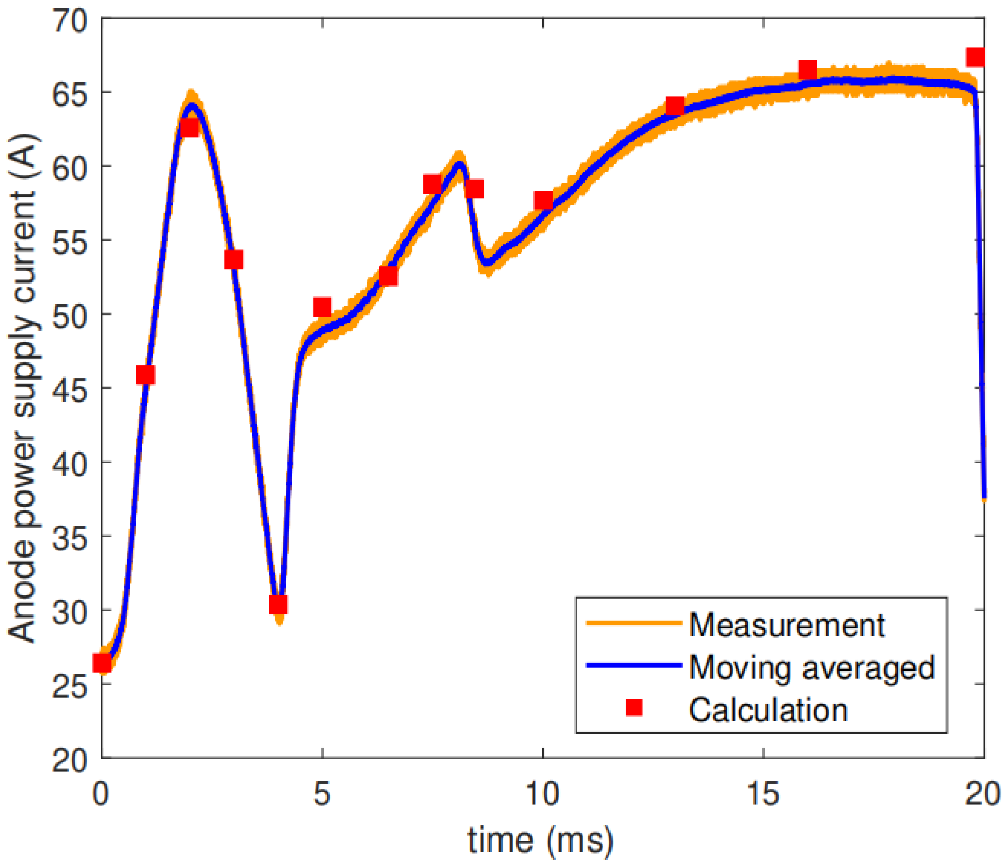
3.2 Method for Analyzing of tetrode operation

- **The simulation model accurately reproduces tetrode operation at 160 kW beam in CSNS RCS**
  - **Directly applicable to CSNS FFA**

RF voltages and currents

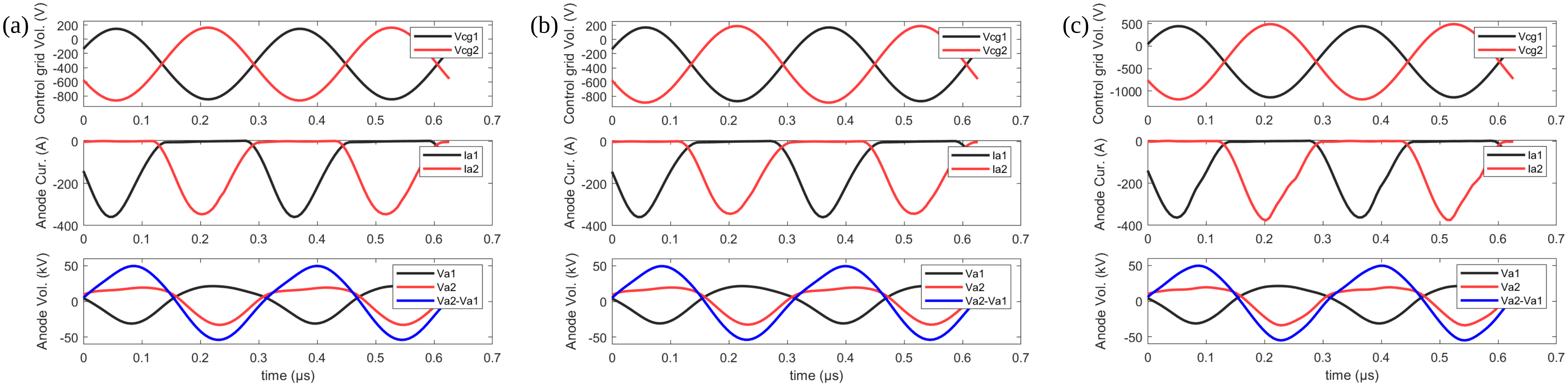


Anode power supply current



3.3 Analysis of tetrode tubes' operation

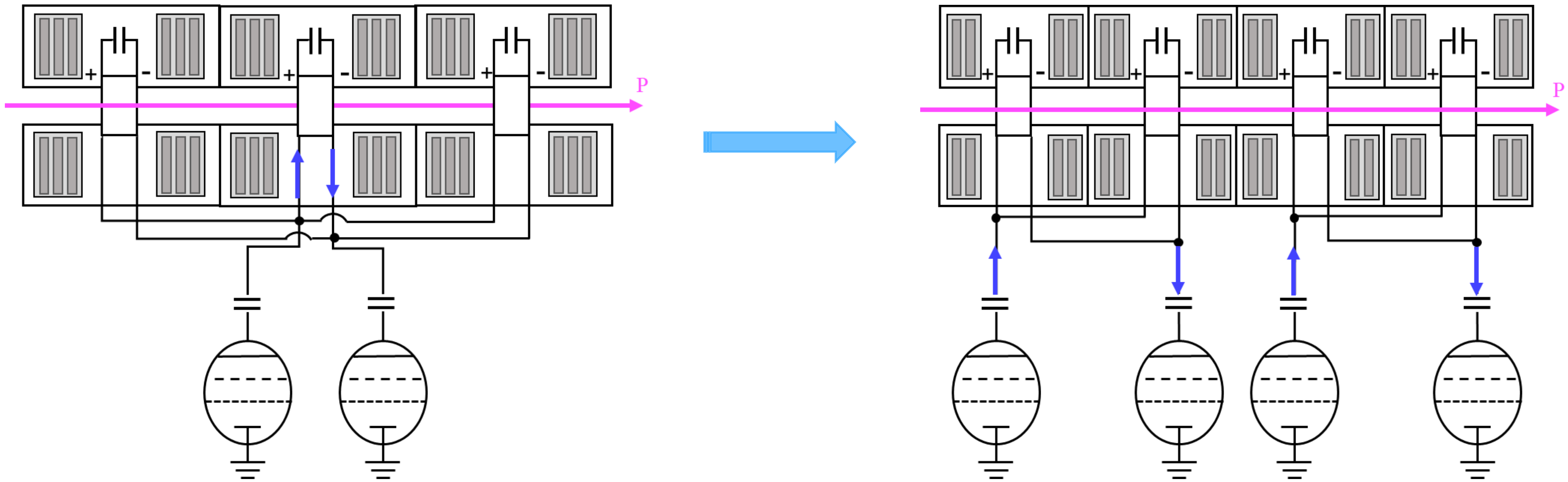
- **The operation of three candidate tetrodes was analyzed and compared for CSNS FFA**
  - **TH526B meets the operational requirements but is over-specified**
    - **New tetrode specification : Anode DC current > 120 A, Anode dissipation > 200 kW, maximum anode current > 500 A**



Tetrode tubes	Anode DC voltage	Anode DC current	Anode dissipation	Anode Max. current
TH525A - 1500Vsg[a]	30 kV	105 A	62 kW @ 50 Hz < 1900 kW	360 A < 550 A
TH526B - 1500Vsg[b]	30 kV	108 A	65 kW @ 50 Hz < 1000 kW	360 A < 550 A
4CW250KB - 1800Vsg[c]	30 kV	105 A	59 kW @ 50 Hz < 250 kW	377 A > 350 A, not applicable

3.4 Possible optimization

- **A new cavity configuration of 2 cores/tank × 8 tanks is under consideration**
  - **Gap voltage reduced: 50 → 37.5 kV/gap; DC anode voltage < 25 kV**
  - **Gaps per tetrode: 3 → 2 → Smaller current required for beam loading compensation**
- **Increased number of tetrodes; Reduced per-tetrode cost and power requirements**
  - **Less anode DC voltage, anode current, and anode power dissipation**

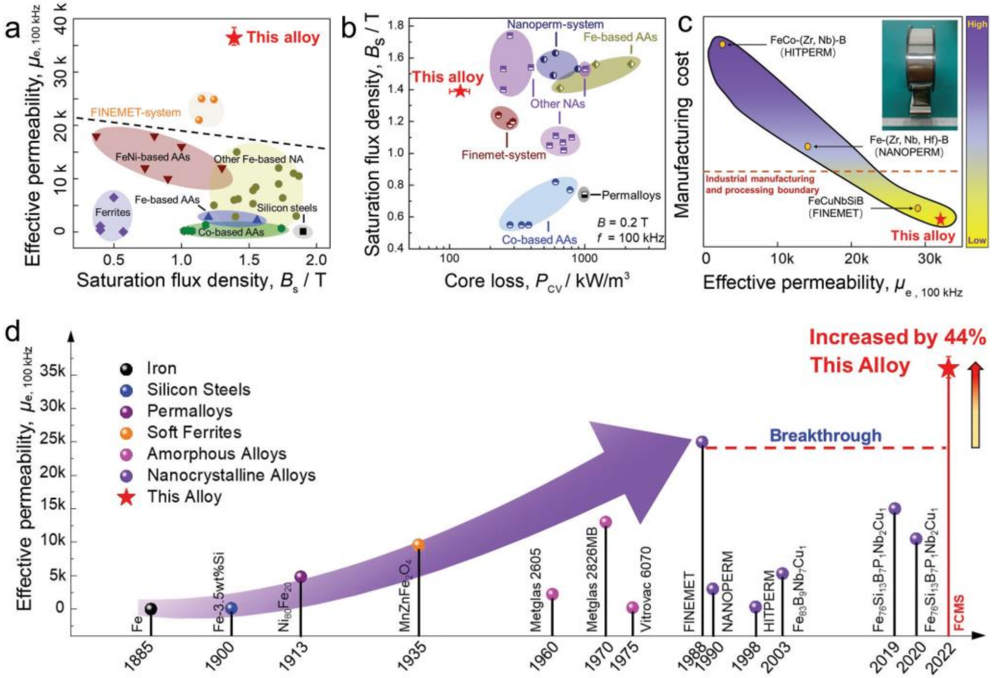


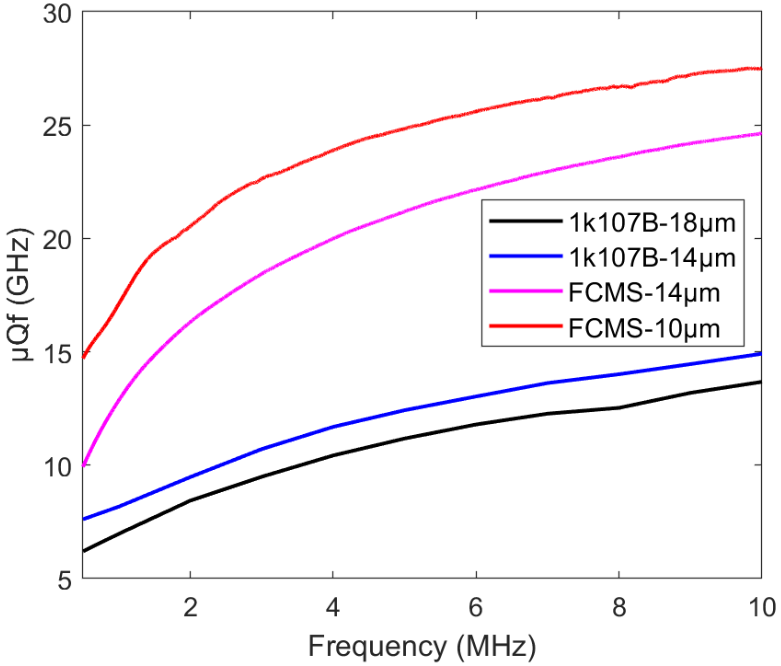
4. Summary and Future work

- **The MA core for FFA RF system was designed with dimensions of 1700 (H) × 950 (V) × 25 mm**
  - **A larger furnace will be developed; New material is under development for higher μQf**
- **The cavity was designed with a configuration of 3 cores/tank × 6 tanks**
  - **An alternative configuration of 2 cores/tank × 8 tanks is under consideration**
- **Preliminary fluid-thermal simulations have been conducted**
  - **A highly efficient cooling structure will be designed to ensure temperature < 100°C @ 0.5 W/cc**
- **A method for analyzing HPRF operation was developed**
  - **The results will guide tetrode selection and further optimization of the RF system**

Recent breakthrough!

New alloy: FCMS ($Fe_{75.5}Co_{0.5}Mo_{0.5}Cu_1Nb_{1.5}Si_{13}B_8$) shows promising properties compared to the conventional 1k107B ($Fe_{73.5}Cu_1Nb_3Si_{15.5}B_7$)





Thank you for your attention!