LCWS2023
INTERNATIONAL WORKSHOP ON LINEAR COLLIDERS

IHEP high efficiency, high power klystron development

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On behalf of CEPC RF power source team
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Outline

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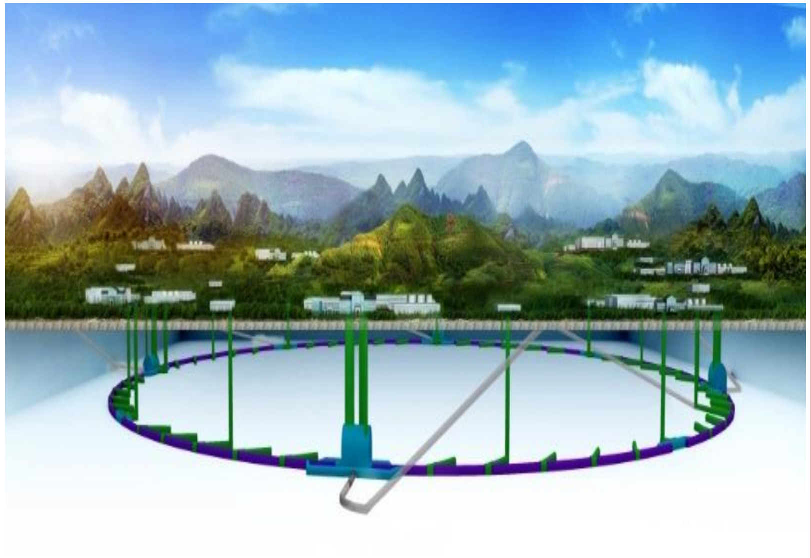
- **IHEP&CEPC (Circular Electron & Positron Collider)**
- **Klystron**
  - Design consideration
  - R&D Status
    - 1st prototype
    - 2nd (HE klystron) prototype
    - 3rd (MBK) design and fabrication progress
    - C&S band klystron design
- **Summary**

IHEP (Institute of High Energy Physics, CAS)

BEPC @ Beijing Campus

CSNS @ Dongguan Campus

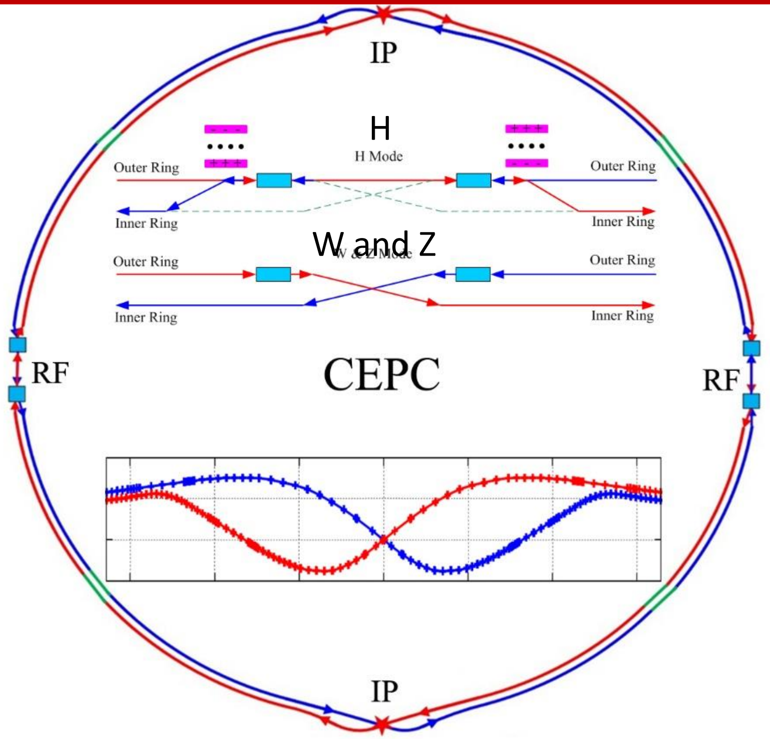
HEPS @ Beijing Huairong Campus



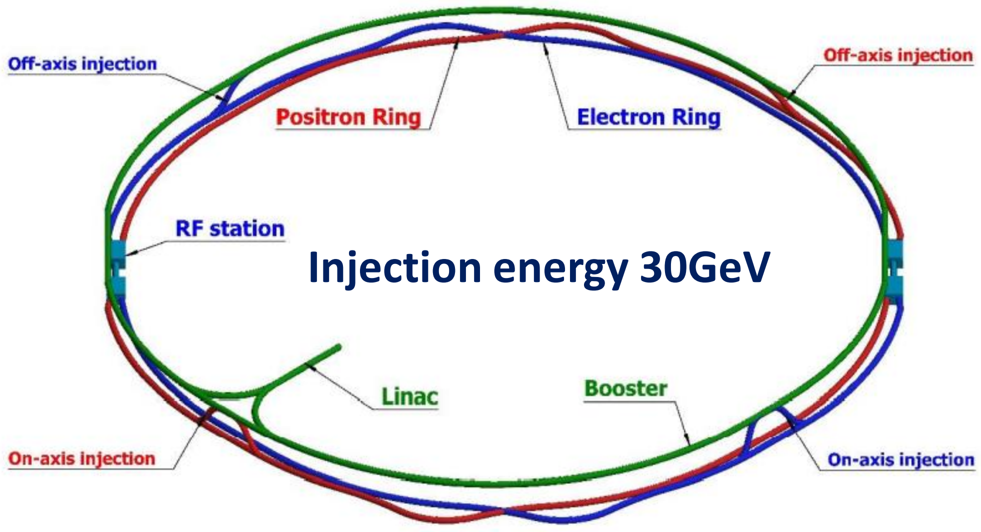
CEPC @?

CEPC TDR Layout

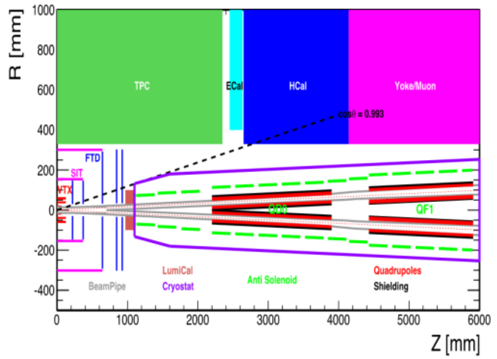
CEPC as a Higgs Factory： ttbar, H, W, Z, followed by a SppC ~100TeV



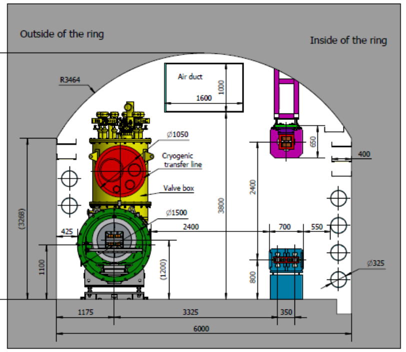
CEPC collider ring (100km)

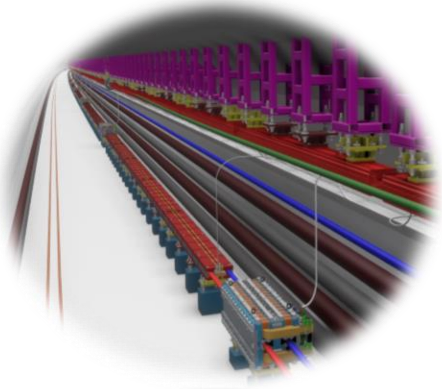


CEPC booster ring (100km)

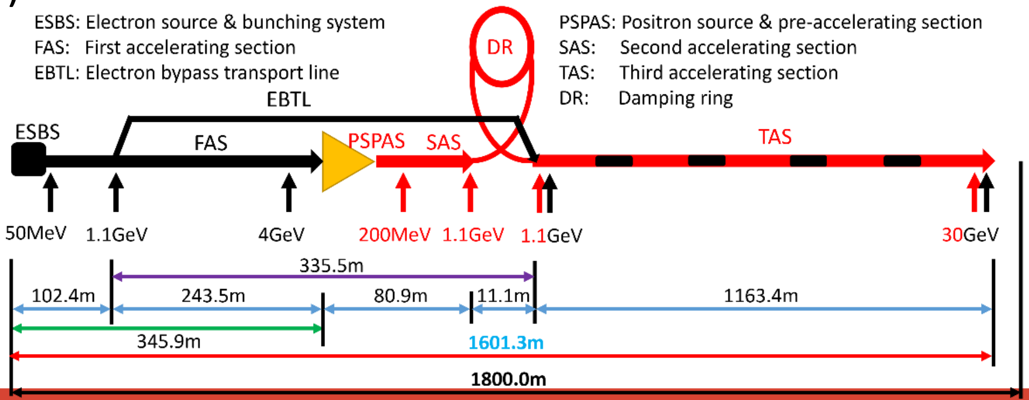


TUNNEL CROSS SECTION OF THE ARC AREA





CEPC Linac injector of 30GeV



RF Power source choice

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The Collider beam power is more than 60 MW. The increase in efficiency of RF power sources is considered a high priority issue.

RF power sources - efficiencies

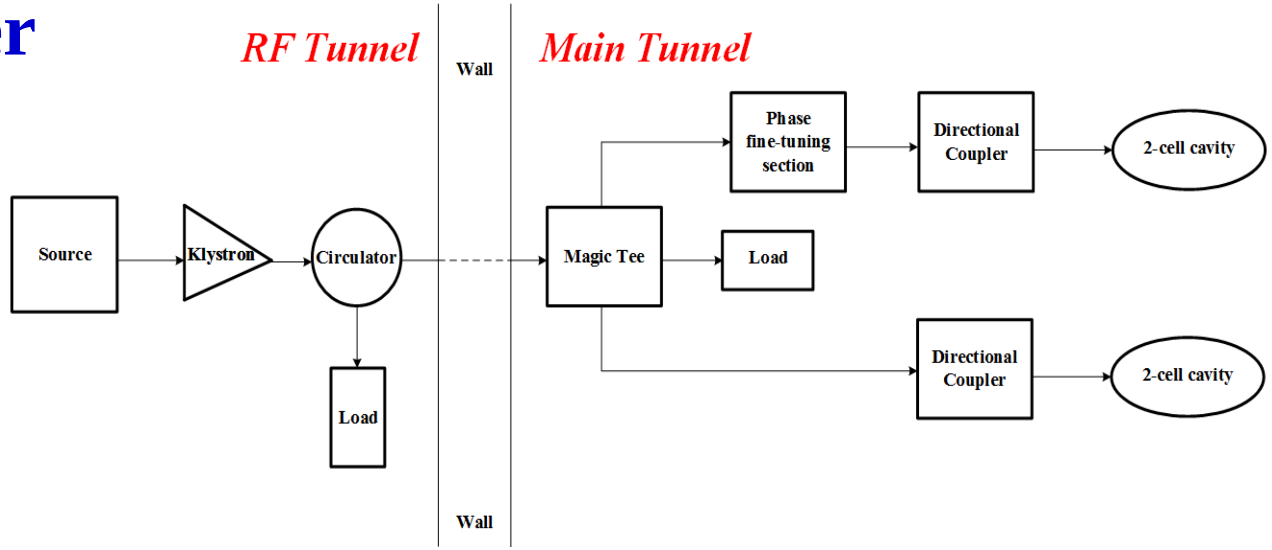
	Tetrodes	IOTs	Klystrons	SSA	Magnetrons
f range:	DC–400MHz	(200–1500)MHz	300 MHz – 1 GHz	DC – 20 GHz	GHz range
P class (CW):	1 MW	1.2 MW	1.5 MW	1 kW @ low f	< 1MW
typical η:	85% - 90% (class C)	70%	65%	60%	90%
Remark	Broadcast technology, widely discontinued			Requires P combination of thousands!	Oscillator, not amplifier!

High power klystrons are the more attractive choice because of their high efficiency, low cost and more stable than IOT and SSA for CEPC collider.

Design consideration

P band klystron for CEPC Collider

Parameters	Value
Freq.(MHz)	650
Klystron QTY.	**96**
Klystron power(kW)	**800 CW**
1 to 2 SC cavity	



C&S band klystron for CEPC Linac

Parameters	S	C
Freq.(MHz)	2860	5720
Klystron QTY.	**33**	**236**
Klystron power(MW)	**80**	**50**
RF structure distribution	1-to-2&1-to-4	1-to-2

System overall efficiency

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CEPC Collider SRF Wall Plug Efficiency

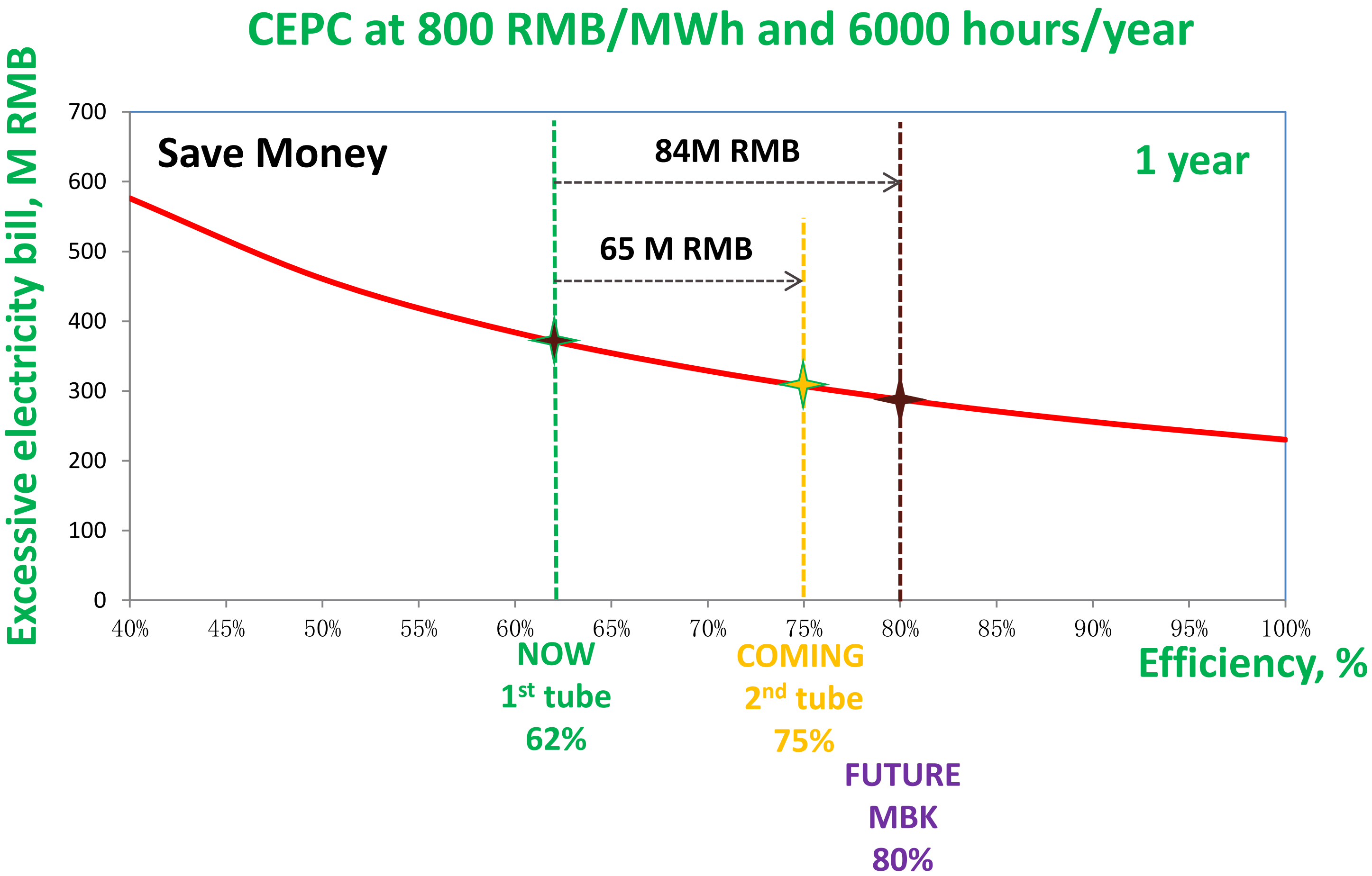
Wall to PSM power supply/modulator	95%
Modulator to klystron	96%
Klystron to waveguide	75%
Waveguide to coupler	95%
Coupler to cavity	~100%
Cavity to beam	~100%
Overall efficiency	**~65%**

The critical factor is klystron efficiency

Much higher efficiency, less energy consumption.

Cost consumption

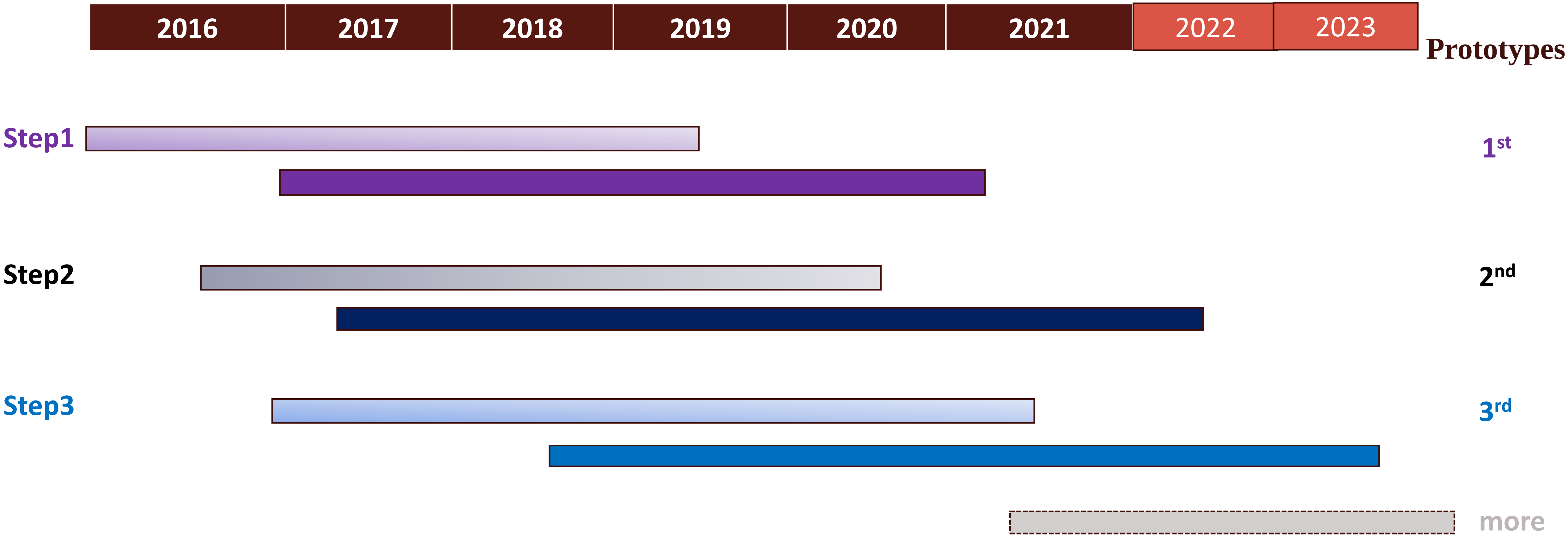
Efficiency impact on operation cost ***(Only considering operation efficiency of klystrons)***



R&D Status

R&D strategy and plan

3 or more klystron prototypes



Efficiency: 60% - - - - → 70% - - - - → 80%

Design Scheme

- Scheme 1: Traditional way for 65% efficiency
- Scheme 2: With high voltage gun (110 kV/9.1 A), low perveance (**HE**)
- Scheme 3: MBK, 54 kV/20A electron gun (8 beams) (**HE**)

Parameter	Scheme1(1st prototype)	Scheme2(2nd)	Scheme3(3rd)
Freq. (MHz)	650	650	650
Voltage (kV)	82	110	54
Current (A)	16	9.1	20(2.5×8)
Beam No.	1	1	8
Perveance (μP)	0.65	0.25	1.6(0.2×8)
Efficiency (%)	65	~80	>80
Power(kW)	800	800	800(100×8)

1st prototype milestone

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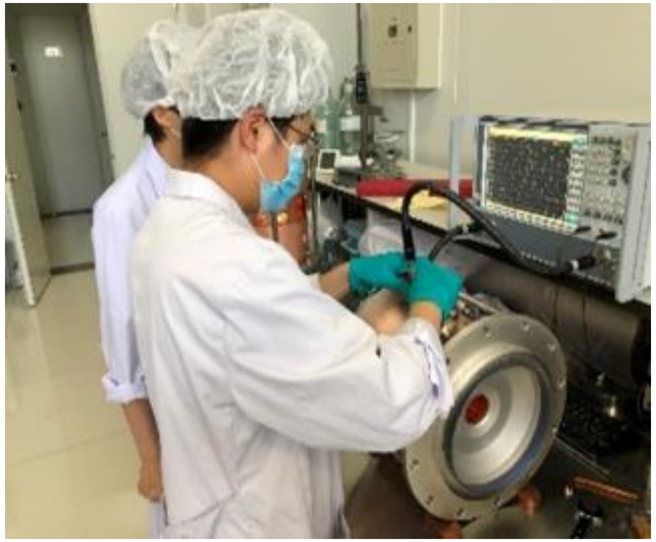
- Oct. 2017 Design report
- May 2018 Mechanical design review
- Mar. 2019 Window fabrication
- Apr. 2019 Collector brazing
- Sep. 2019 Prepressing of electron gun
- Oct. 2019 Klystron bake out
- Dec. 2019 Delivered to IHEP
- Mar. 2020 High power test at IHEP

Cavity brazing and cold test

Cavity brazing

Leak test

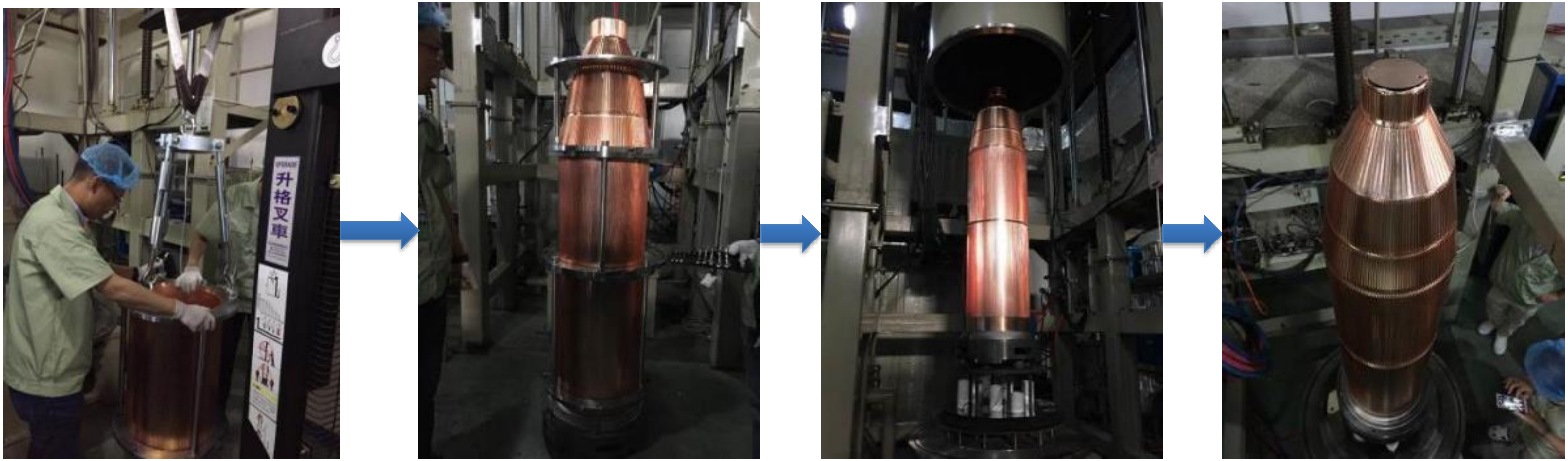


Cold test

Parameters		1st	2nd	3rd	4th	5th	6th
Frequency（MHz）	Design	650.5	649.5	1293.5	669.2	668	649.5
	Measure	650.2	649.29	1293.1	668.98	668.68	649.15
Q_e	Design	291.4					67
	Measure	292.2					69.4

The measured frequency is within design scope.

Collector brazing



Collector brazing

Gun processing

Temperature measurement

Gun processing

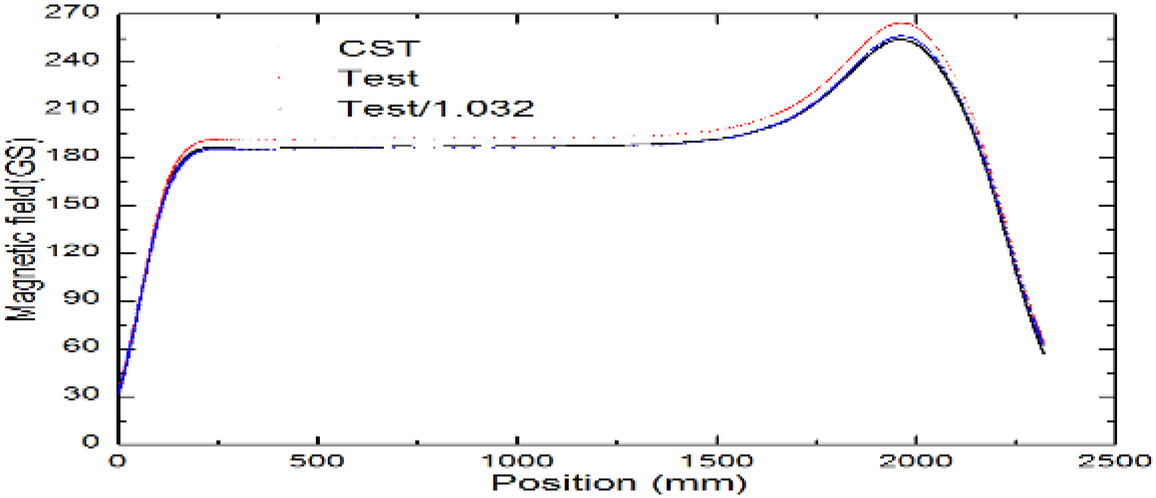
Auxiliary components

Girder

Oil tank

Coil

Coil measurement



There is about 3% error between the measurement results and the simulation values. The excitation current of the solenoids will be adjusted to meet the design requirements.

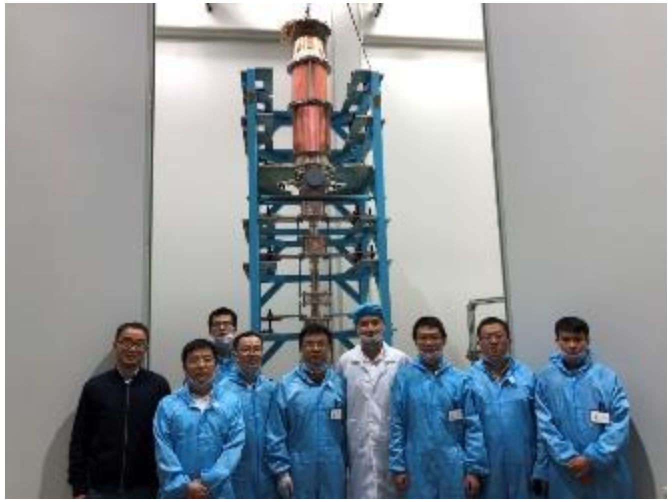
Final assemble

Component leak test

Cavity assembly

Collector assemble

Final welding



Completed assembly

Baking out

Prototype installation

Top view

1^{st} prototype high power test results

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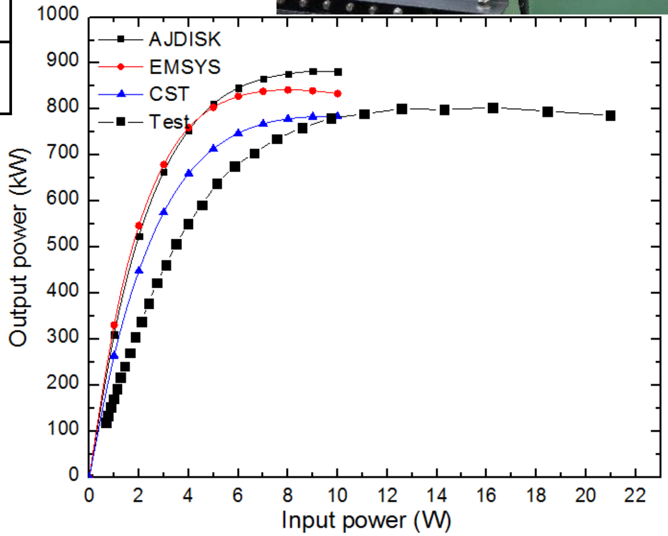
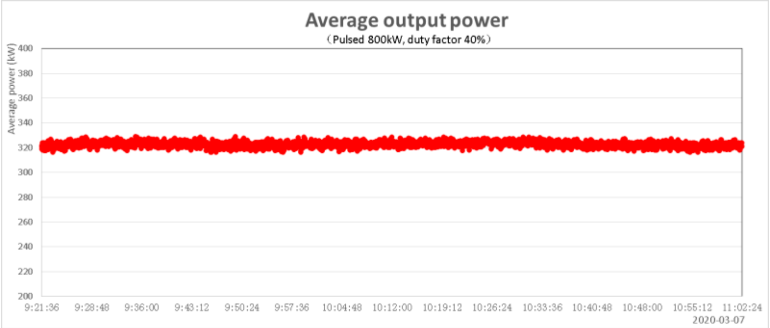
◆700kW CW and 800kW pulsed power with 62% efficiency

Parameters	Design	Test
Operating frequency (MHz)	650	650
Beam Voltage (kV)	81.5	80
Beam Perveance ($\mu A/V^{3/2}$)	0.65	0.7
Efficiency(%)	65	62
Saturation Gain(dB)	≥45	47
Output power(kW)	800	800
1 dB Bandwidth(MHz)	≥1	1.8

High power test stand





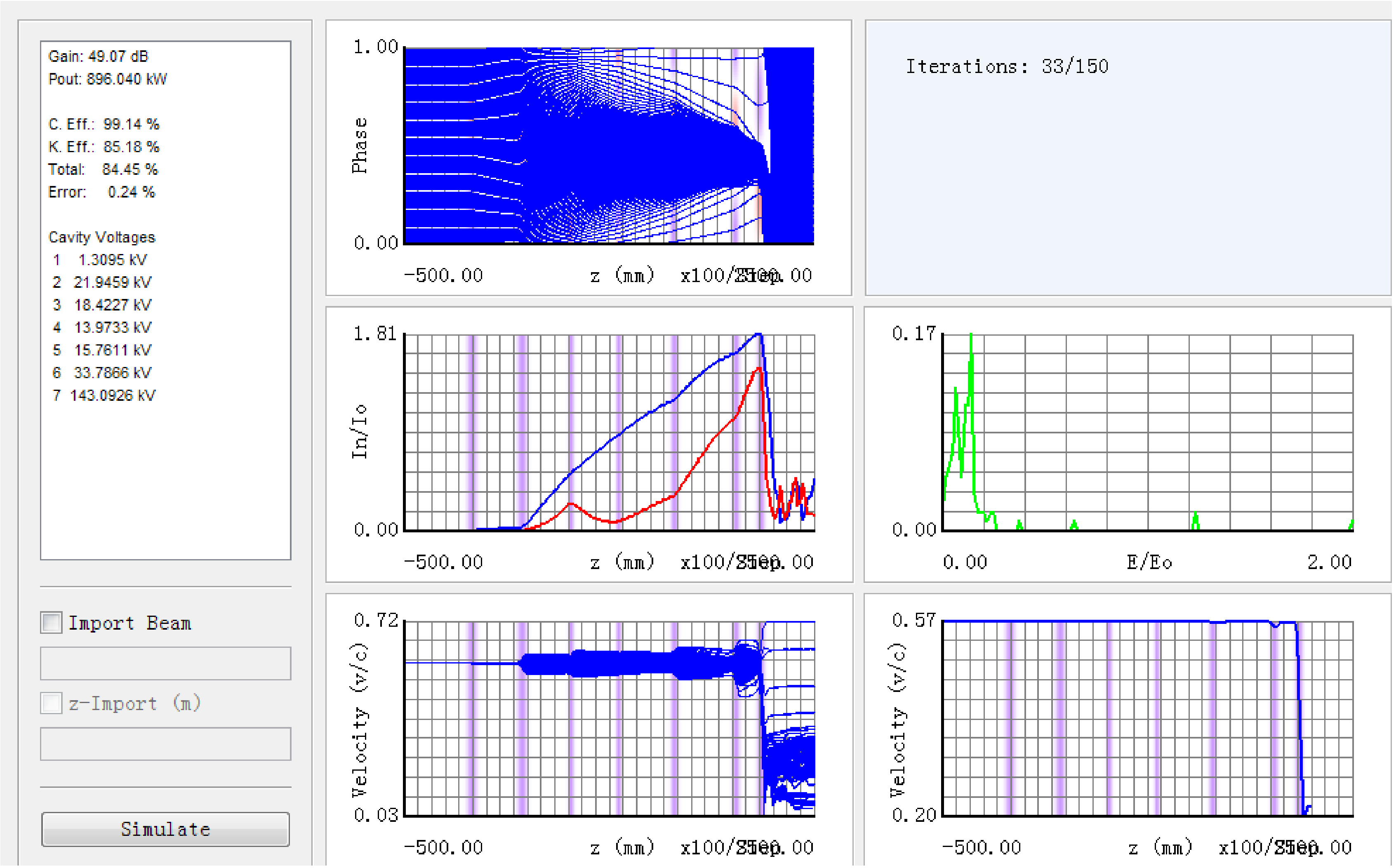
Pulsed 800kW

HE Klystron Milestone

- Jan., 2021: Klystron manufacture started
- Jul., 2021: Parts fabrication completed
- Nov., 2021: Gun processing and klystron baking out
- Dec., 2021: Klystron delivered to IHEP
- Mar., 2022: Klystron conditioning started
  - ① Cold high voltage conditioning
  - ② Cathode activation
  - ③ High voltage conditioning
  - ④ RF Conditioning(Pulsed and CW)
- Jul., 2022: **CW 630kW/Eff. 70.5%**

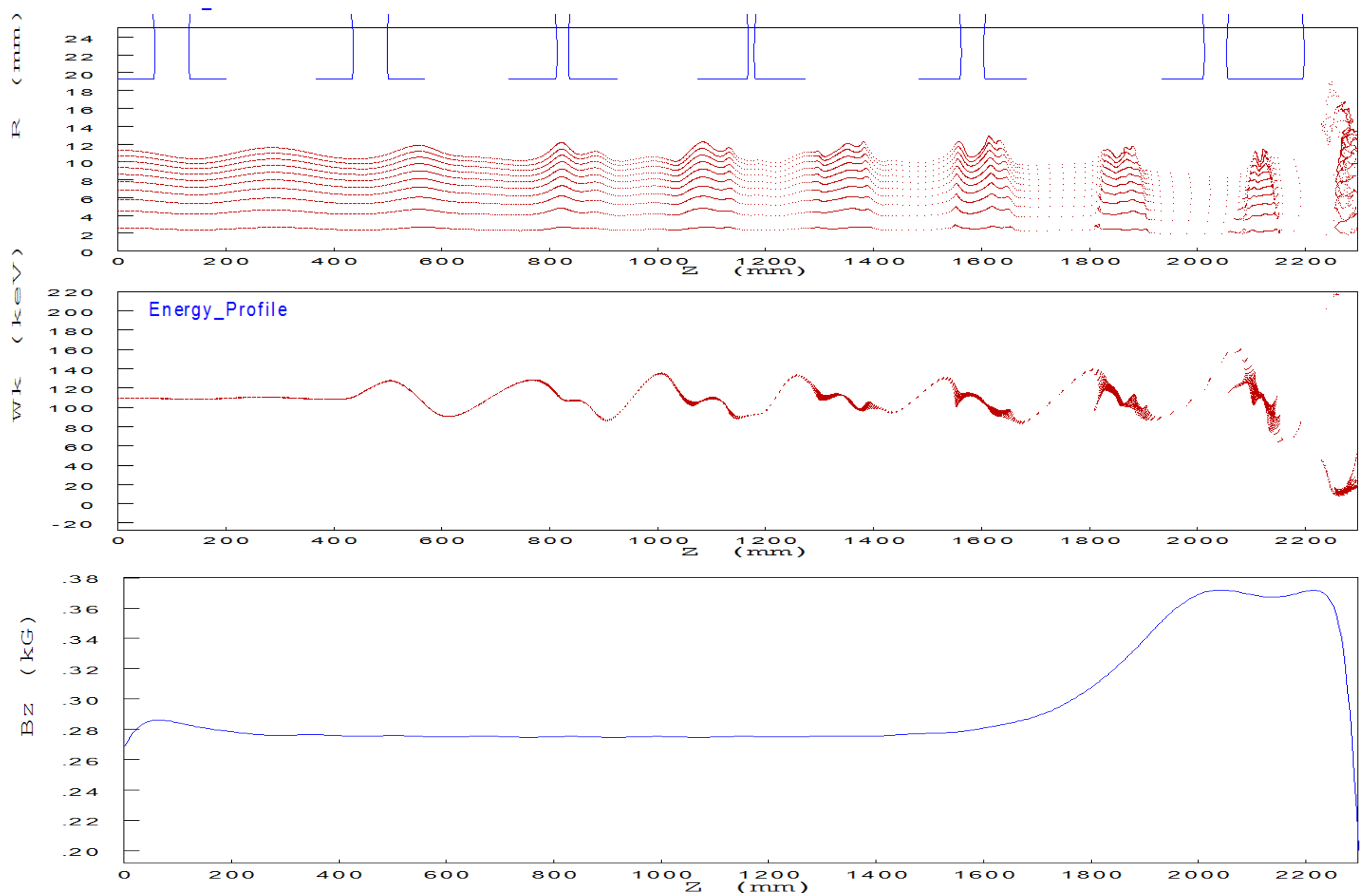
Beam dynamic simulation

AJDISK 1D efficiency:84.45



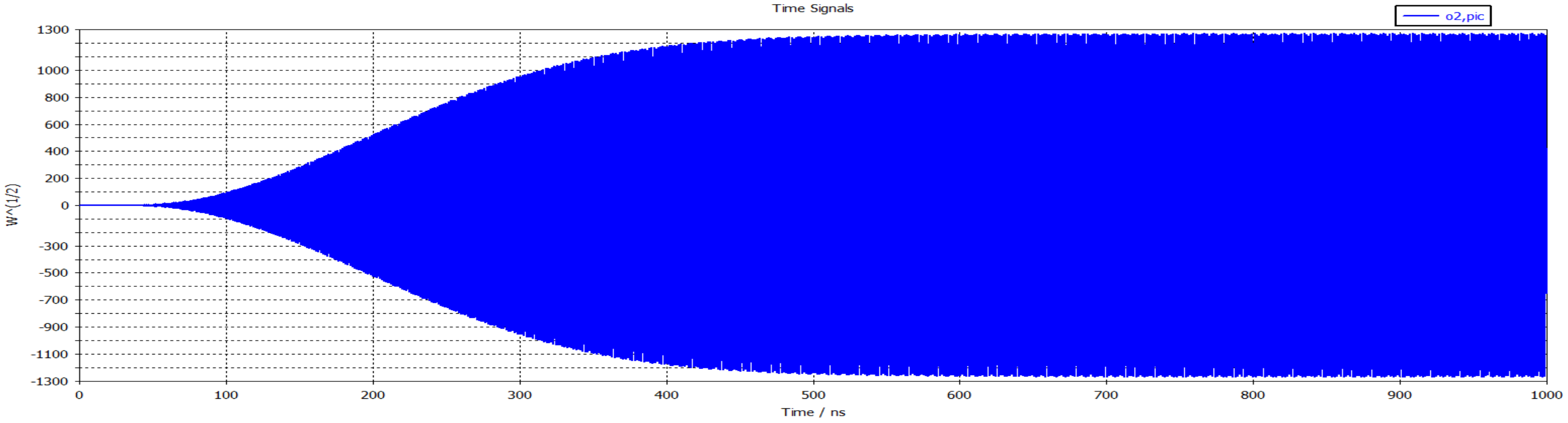
Beam dynamic simulation

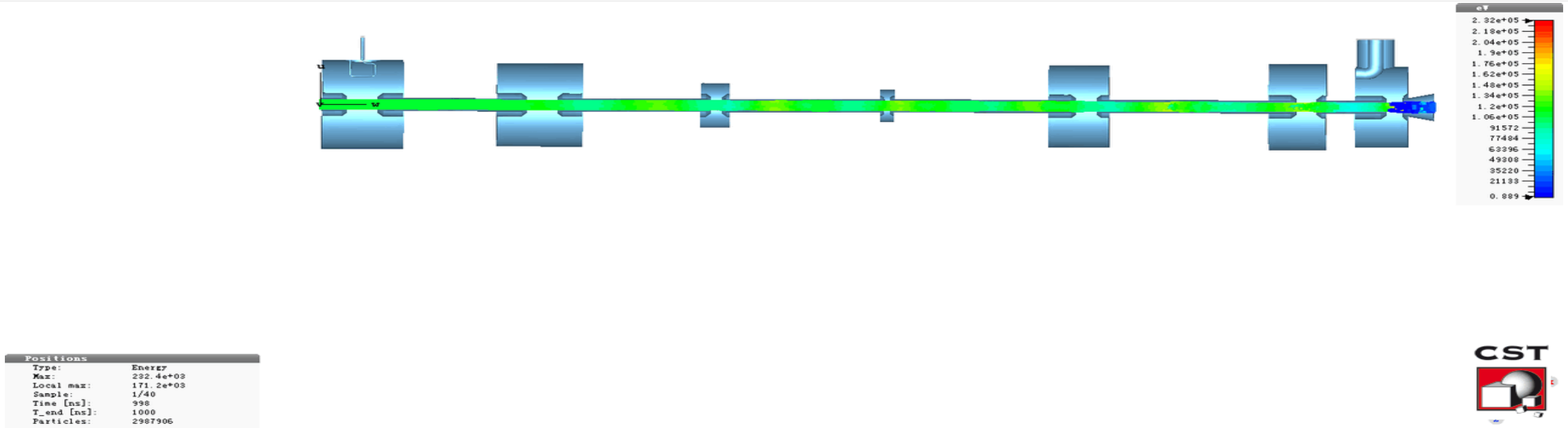
EMSYS2.5D efficiency: 79.3%



Beam dynamic simulation

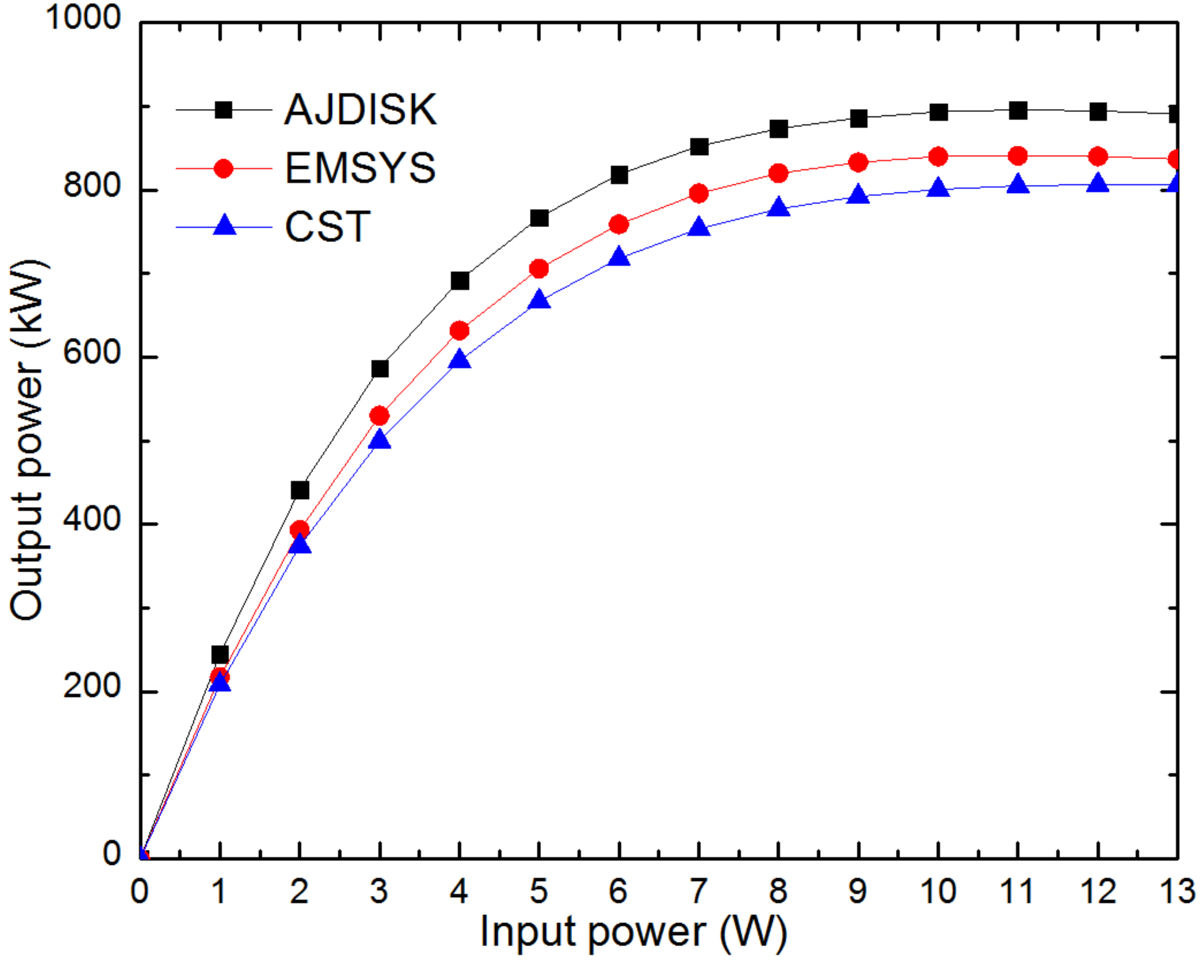
CST3D efficiency:77%   Output power:808.3kW(Beam power 1.05MW)

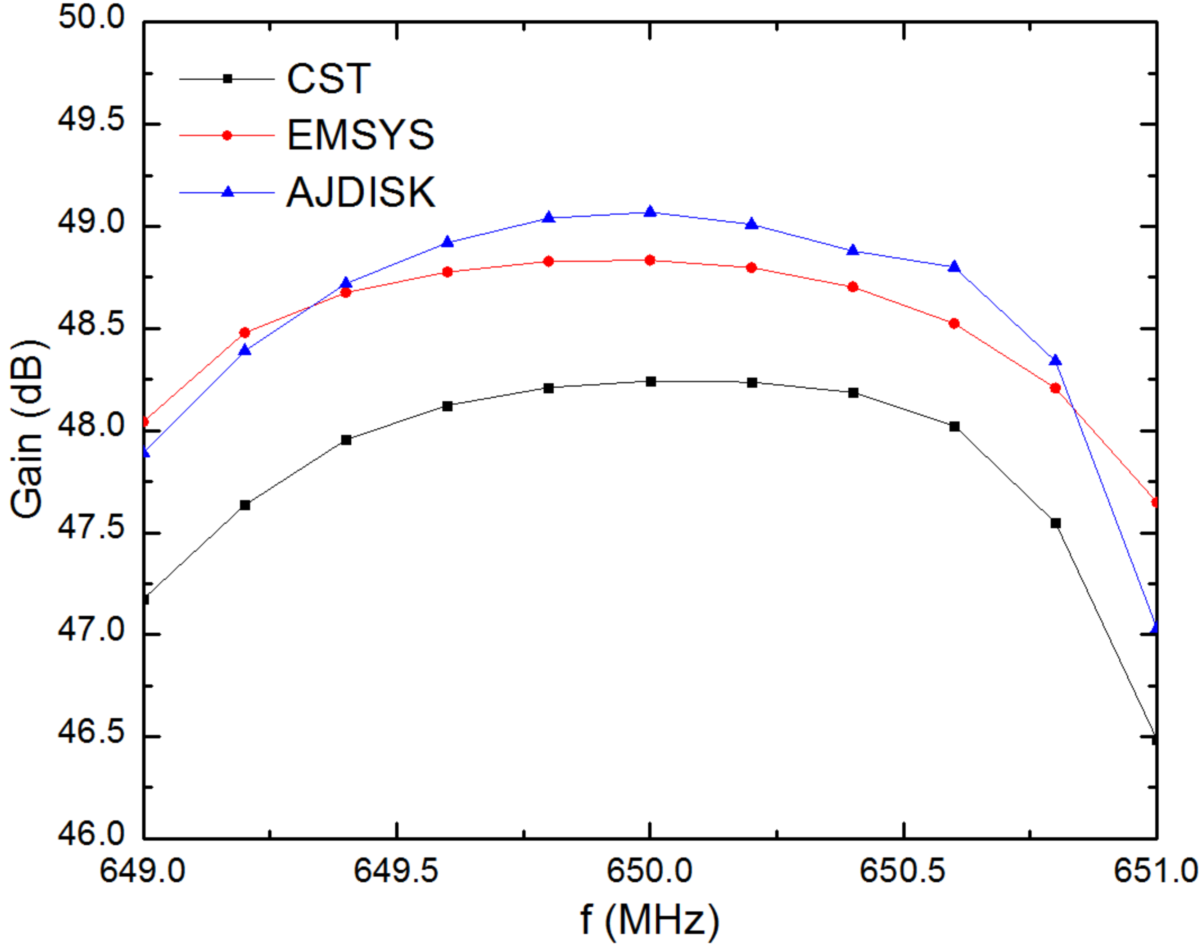




Transfer curve and bandwidth

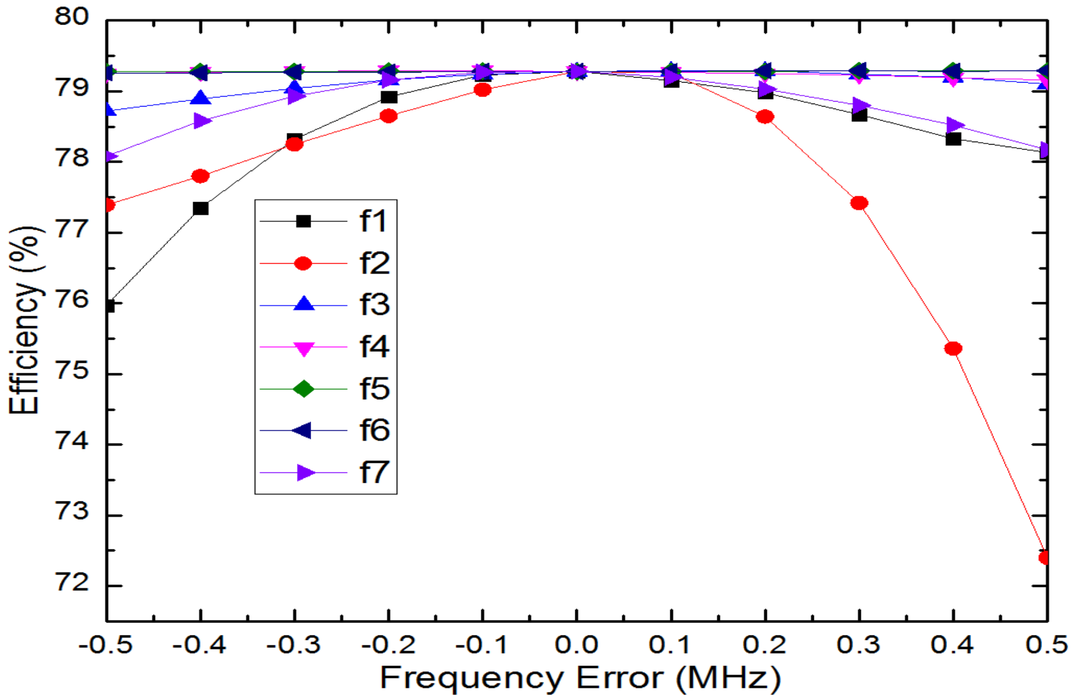
Gain(3D): 48.3dB
Bandwidth(2.5D): ≥0.8MHZ





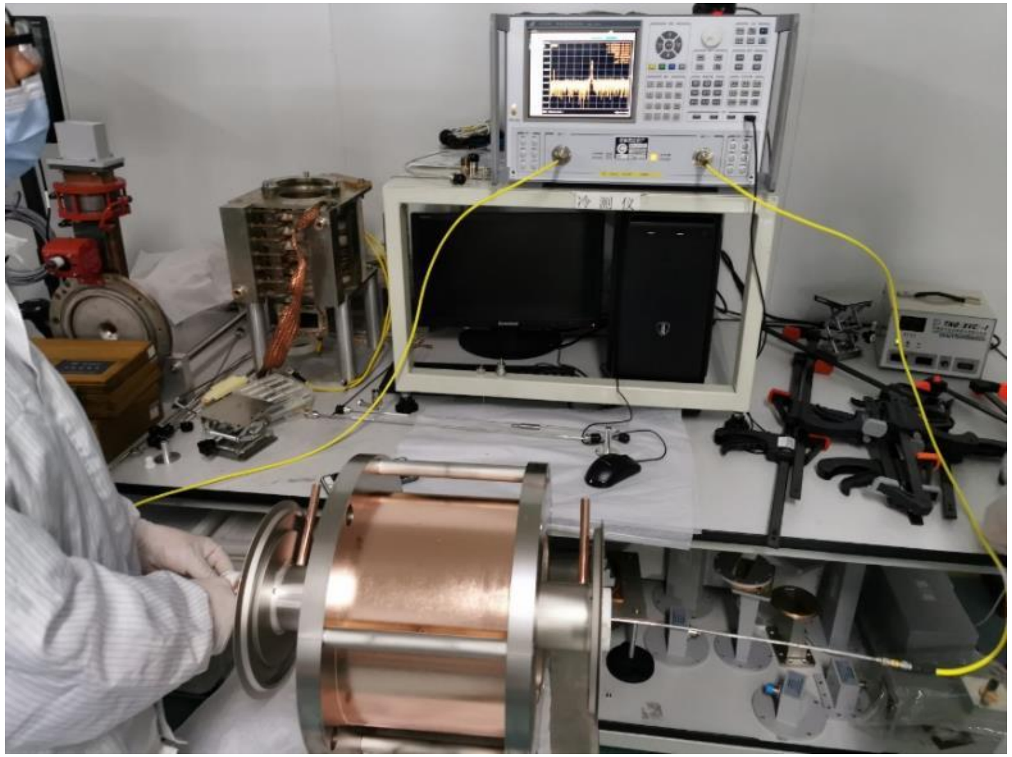
Frequency error analysis

- Frequency error analysis in EMSYS(2.5D) with constant input power.
- For cavity frequency near the klystron center frequency such as f1,f2,f7, especially f2,the efficiency is more susceptible due to rapid impedance(or gain) change, which can get back by adjusting input power.
- Frequency tolerance : f1,f2,f7 ±0.2MHz, others ±0.5MHz

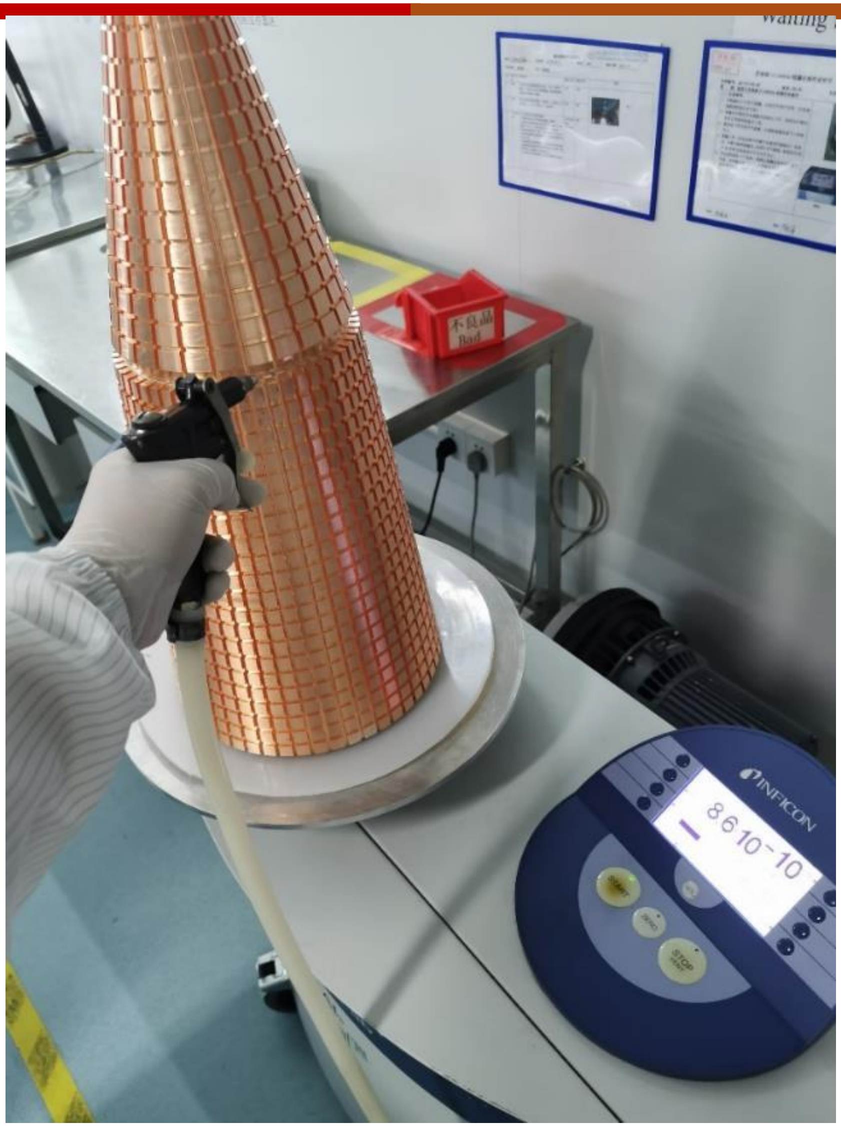


Fabrication processing

Electron gun



Cold test



Collector body

Electron gun processing

Cathode Temp. 975 degree C @Fil. 27V/6A

Klystron final assembly

Klystron final assembly

Klystron baking out

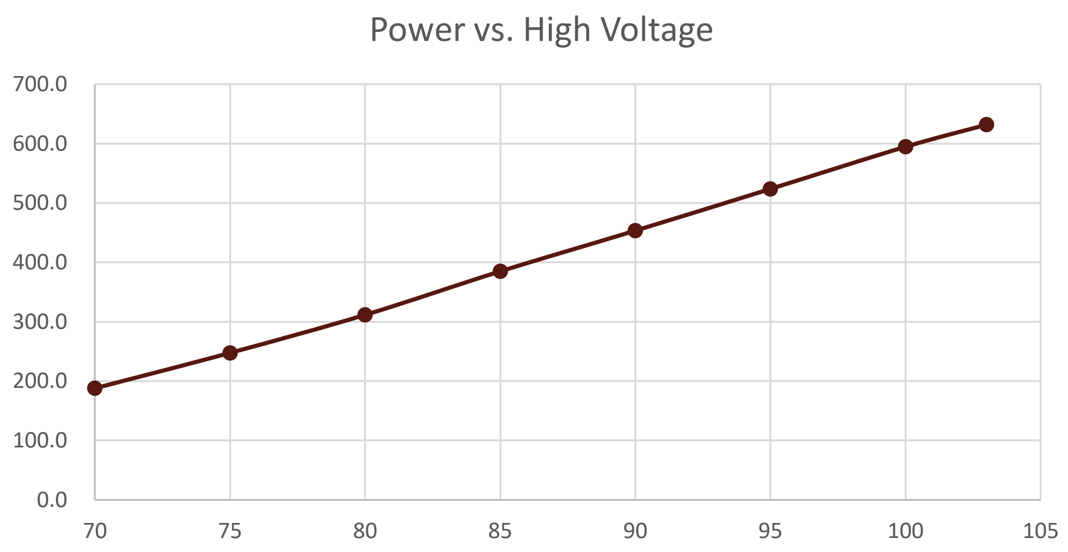
High power test preparation

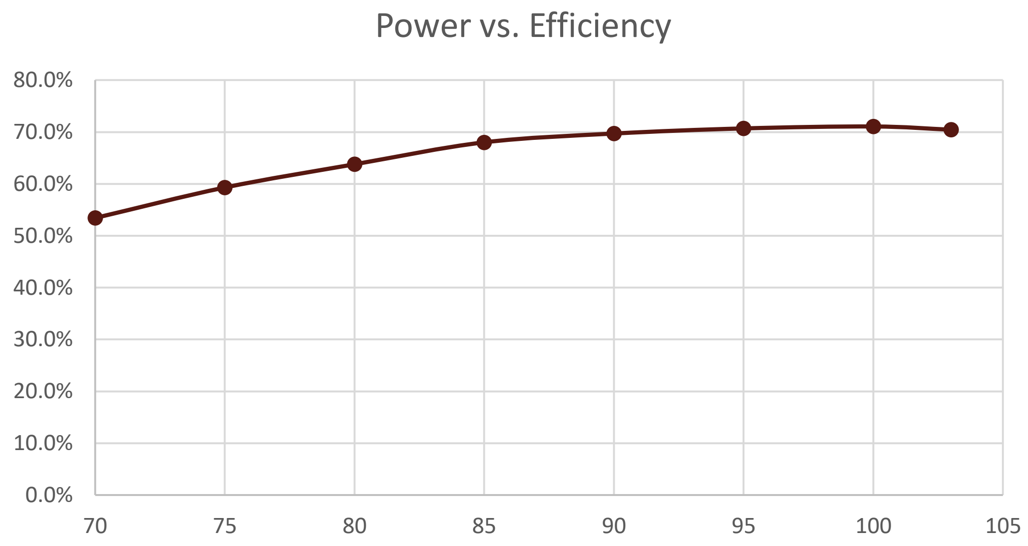




Klystron is in place in IHEP PAPS site

High power conditioning





On Jul.5, 2022

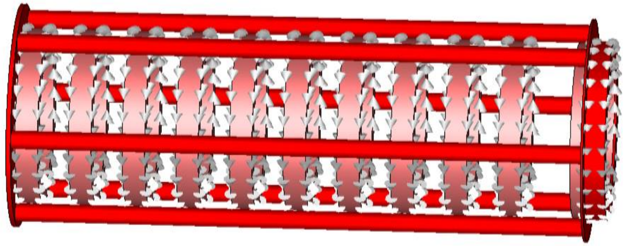
CW power: 630kW

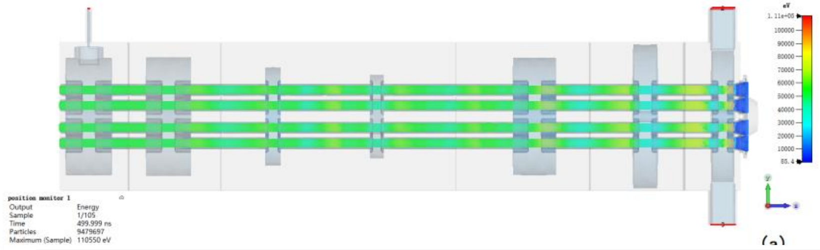
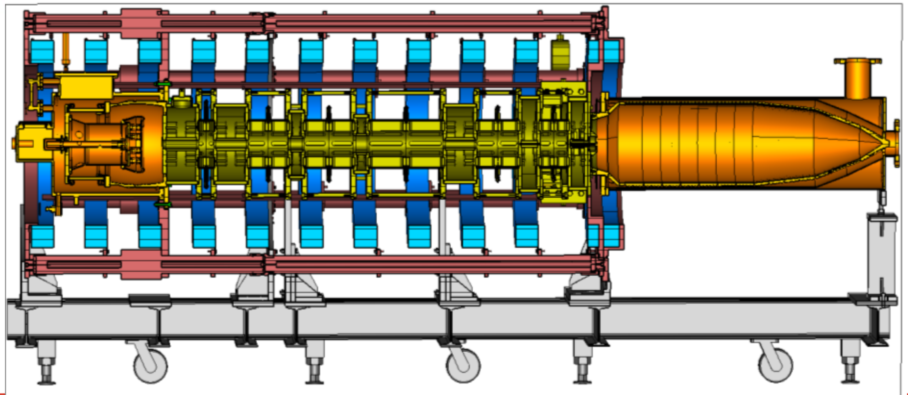
Eff. : 70.5%

MBK design and fabrication status

MBK physical and mechanical design

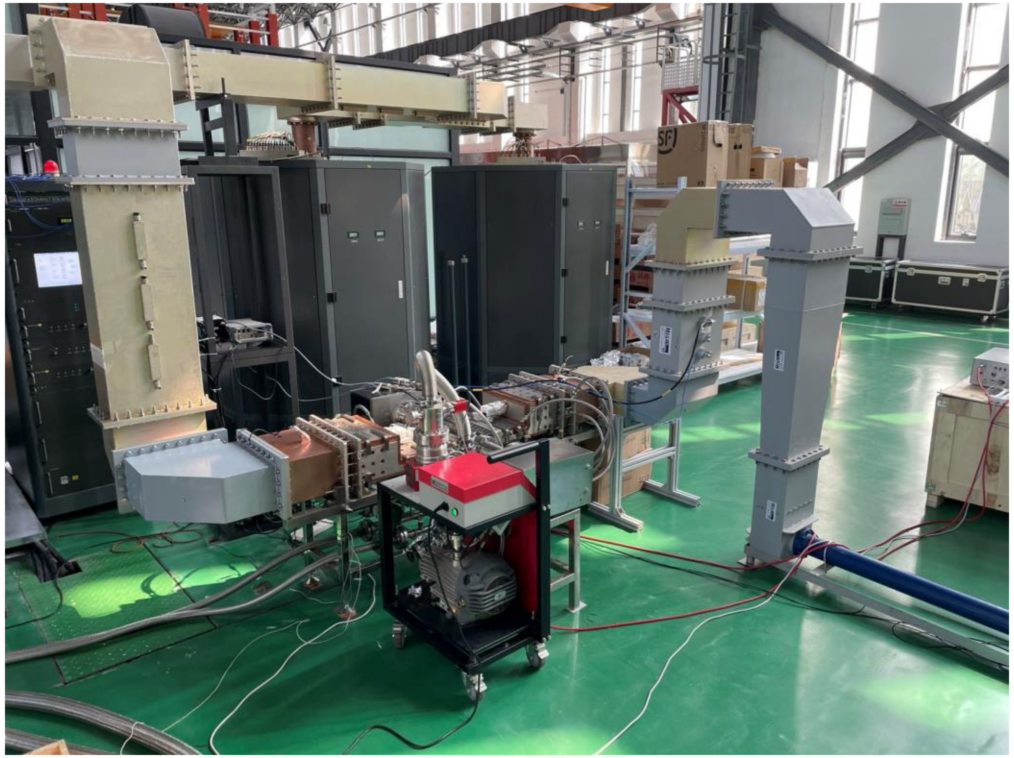
Parameters	Value
Frequency	650 MHz
Output Power	800 kW
Efficiency	80.5%
$1dB$ bandwith	±0.75 MHz
Beam voltage	54 kV
Beam current	2.51*8 A
Beam number	8



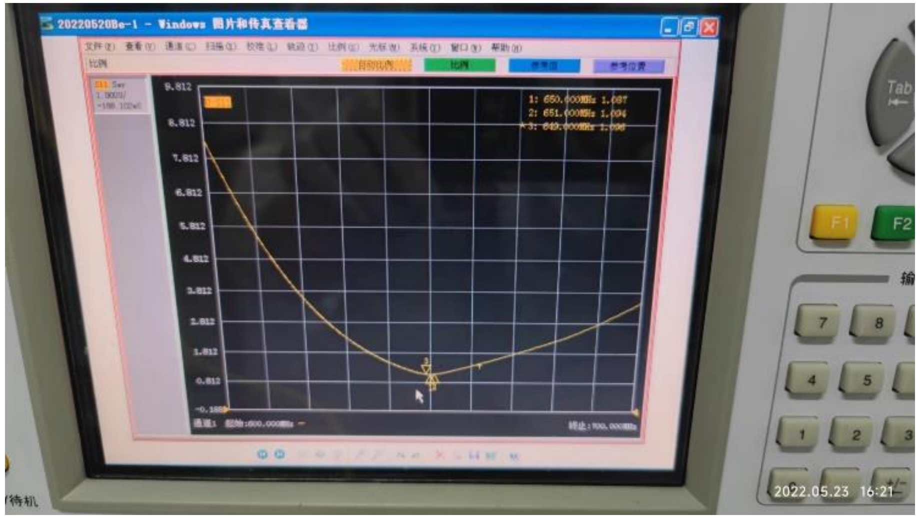



MBK Fabrication Status

- Fabrication of two types of output window prototype is completed.
- The high power conditioning was been processed with solid state amplifier at PAPS site.



High power conditioning site

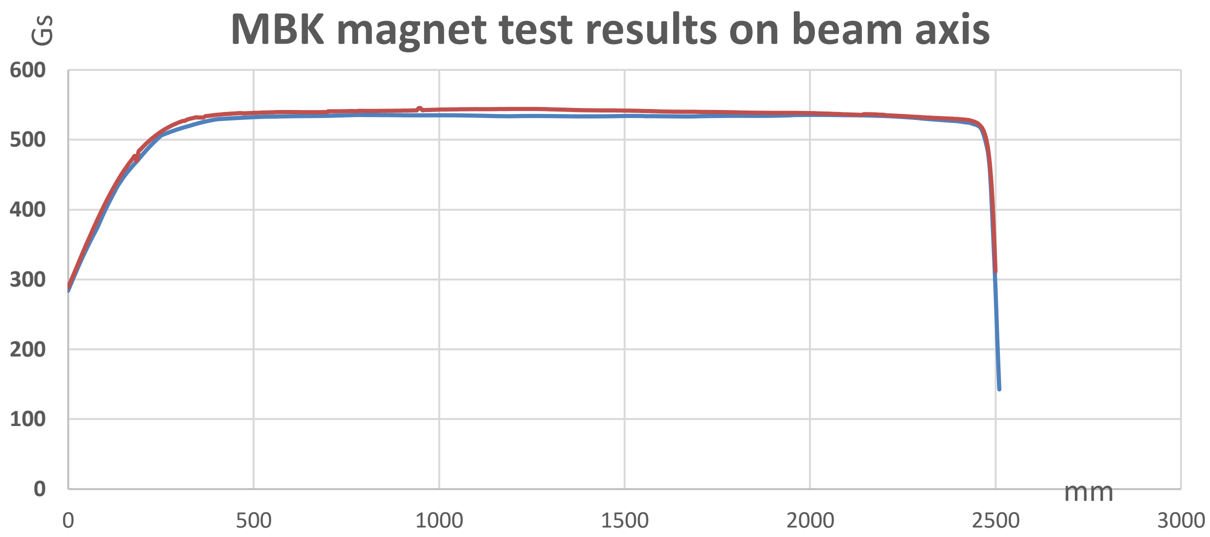


Test result	Alumina	Beryllium oxide
VSWR@651MHz	1.048	1.089
VSWR@650MHz	1.034	1.084
VSWR@649MHz	1.052	1.096

MBK Fabrication Status

●The experimental cavity is completely manufactured with mechanical tuning device.

●Fabrication of MBK beam tester is completed(including electron gun, collector, focusing coil) and has been delivered to IHEP last month. It will be tested in the near future.



MBK Coils and field value

MBK beam tester

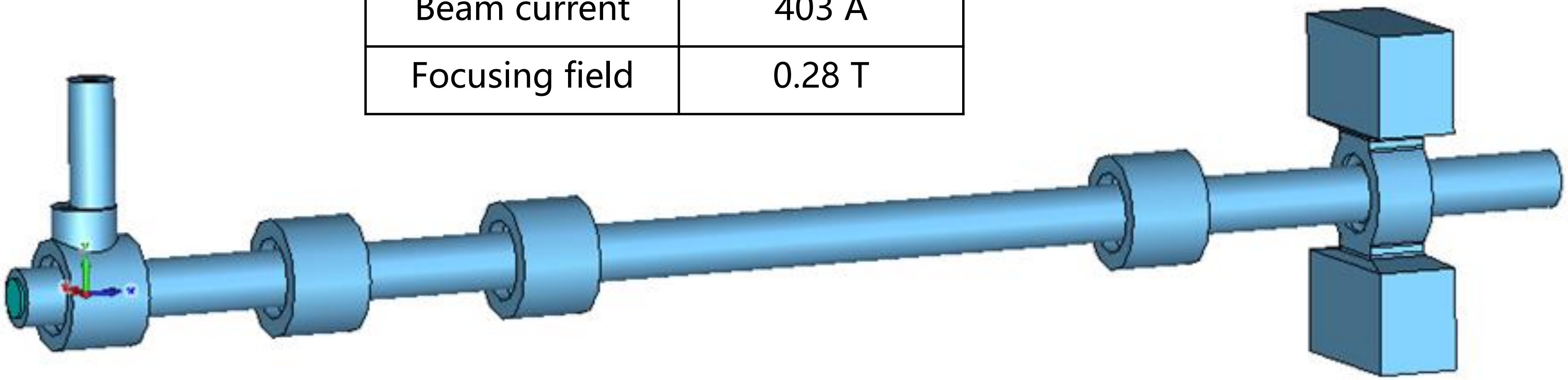
C band and S band klystron

Type	QTY	Freq.(MHz)	Structure type
S-band klystron	33	2860	1 1-to-1，standard-bunch 3 1-to-2，standard acc. structure. 8 1-to-2，large aperture acc. structure 21 1-to-4, standard acc. structure.
C-band klystron	**236**	**5720**	**1-to-2，standard acc. structure.**

Huge quantity on C band klystron

Development of 80 MW C-Band Klystron

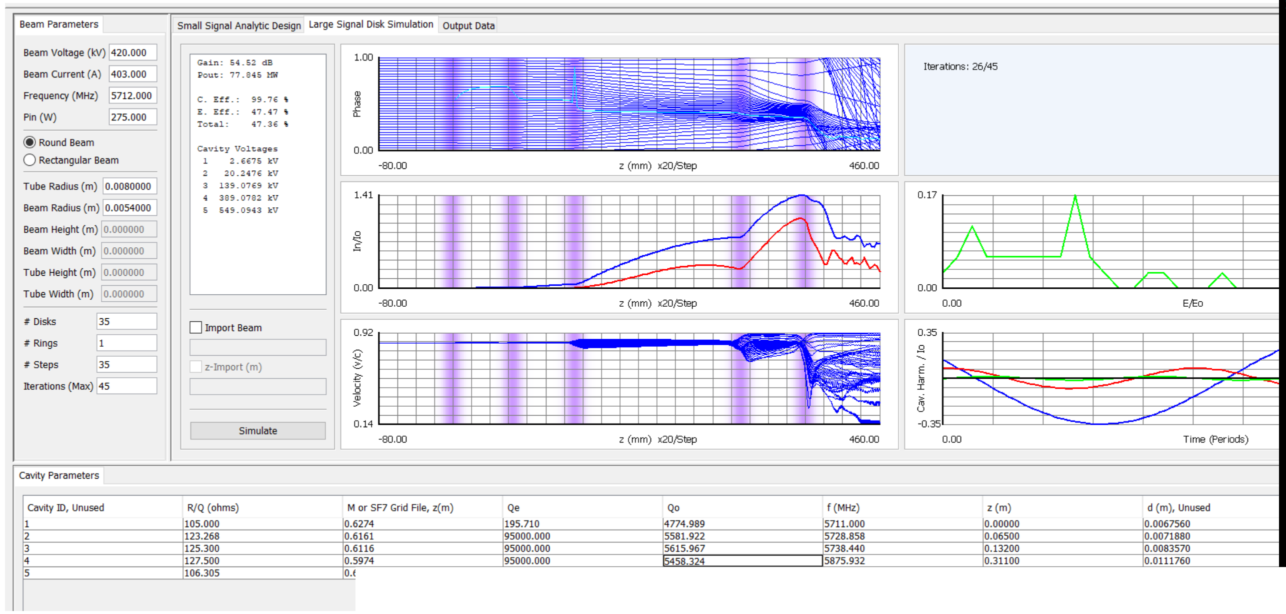
Parameters	Value
Frequency	5720 MHz
Output Power	80MW
Drive power	250 W
Gain	54 dB
Efficiency	47%
$3dB$ bandwith	±5MHz
Beam voltage	420 kV
Beam current	403 A
Focusing field	0.28 T

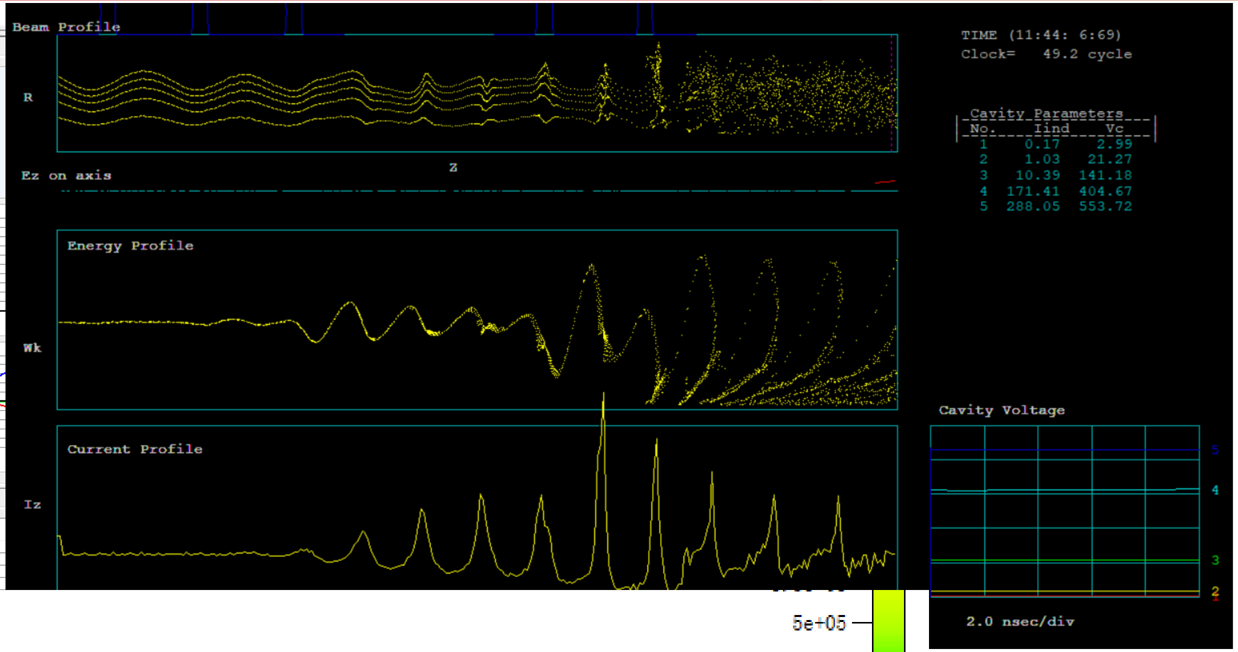


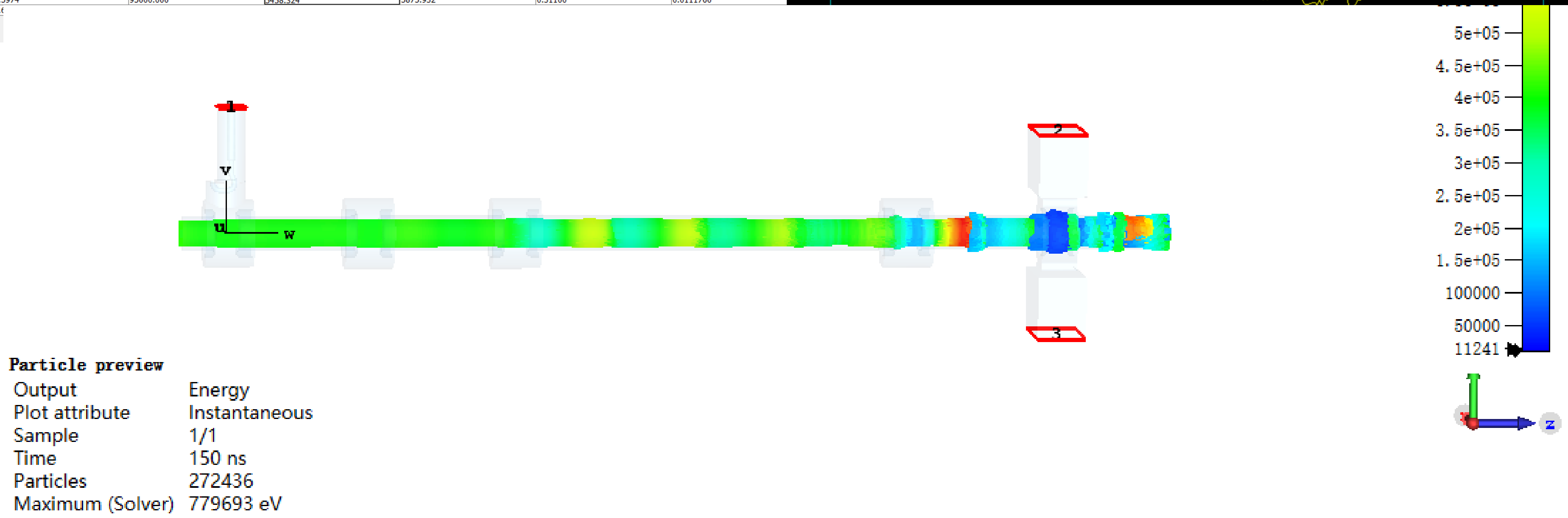
Characteristic Parameters

Type of Cavity		Frequency	Q_e	R/Q	Harmonics
Input	Re-entrant	5711	195.7	105	1
2nd	Re-entrant	5729	95000	123	1
3rd	Re-entrant	5738	95000	125	1
4th	Re-entrant	5876	95000	127	1
Output	Re-entrant	5725	18.22	106	1

Beam dynamic simulation

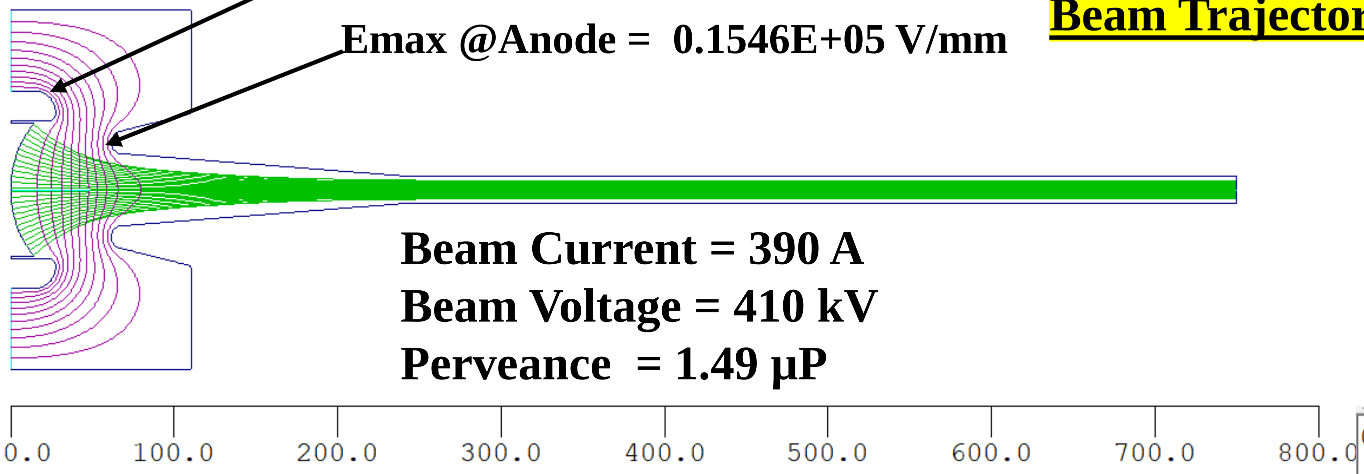






Beam optics design simulation

Beam Trajectories



Beam Current = 390 A
Beam Voltage = 410 kV
Perveance = 1.49 µP

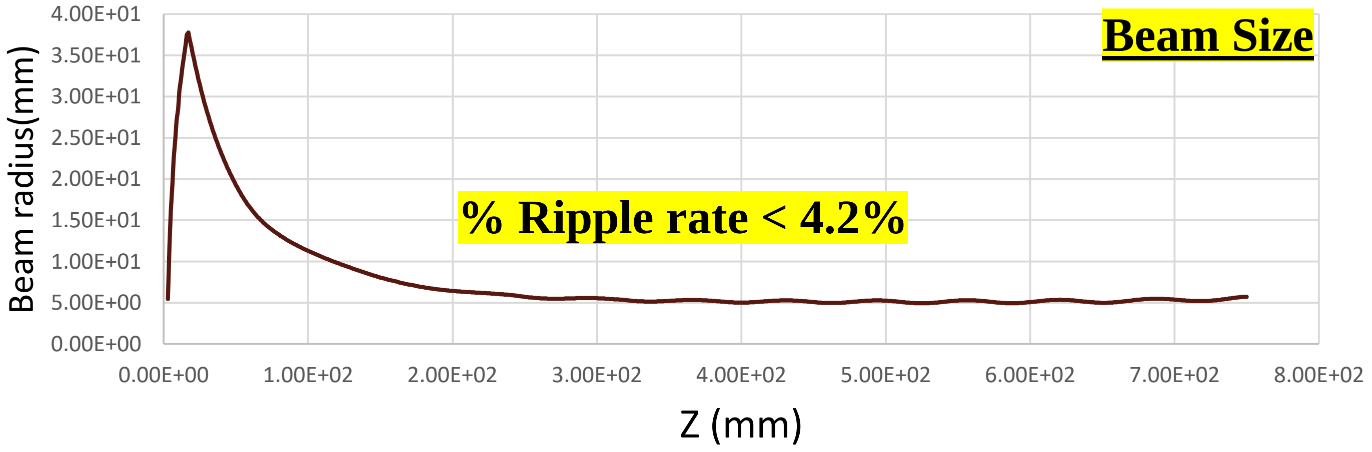
Beam Current

```
iteration n= 50
xrl=       0.9995 epsl=       1e-007
SLOR iterations n=  146 err= 9.753e-008
```

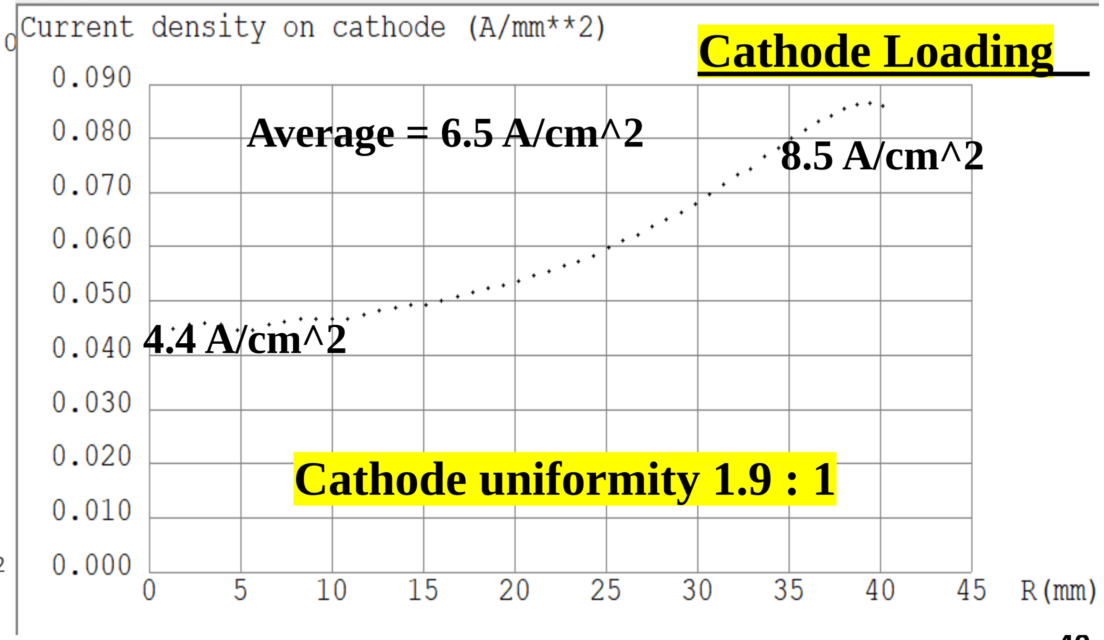
Zcross	Rmax	Ibeam	Em.r
100	11.29	390.1	0.05948
125	9.51	390.1	0.07844
150	8.047	390.1	0.1276
175	7.032	390.1	0.09426
200	6.433	390.1	0.1187
225	6.148	390.1	0.08293

```
interval:          260 < z <          700
Rmax =        5.5739 mm,      Rmin =        5.1147 mm
```

Beam Size

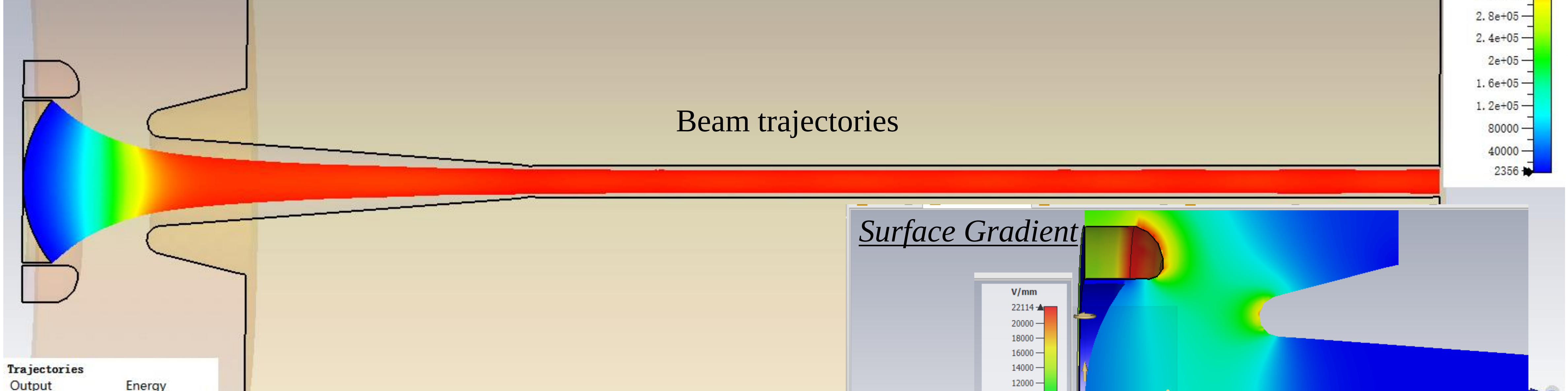


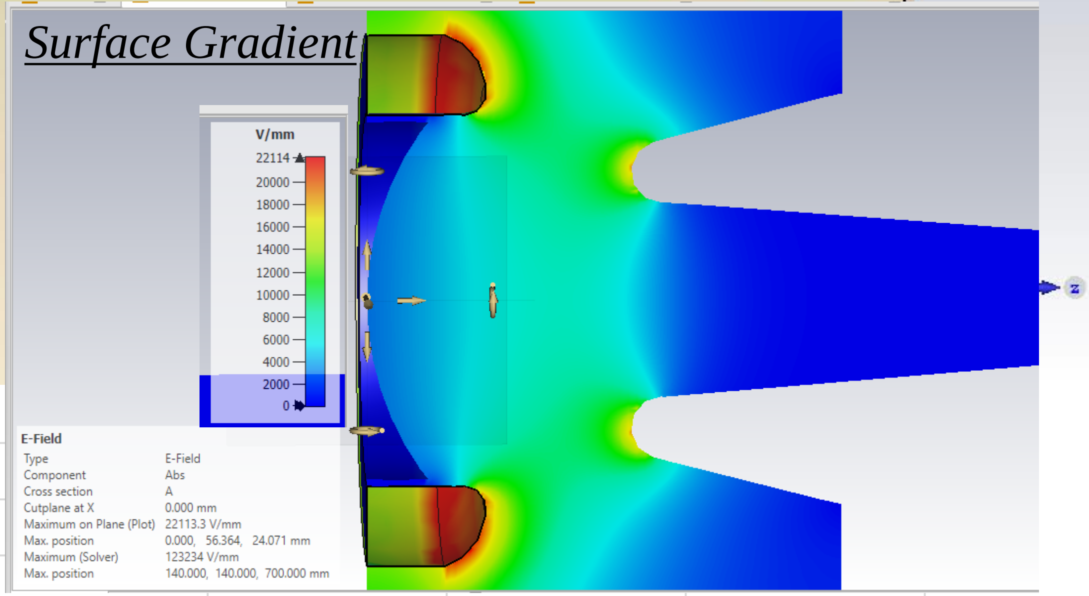
Cathode Loading

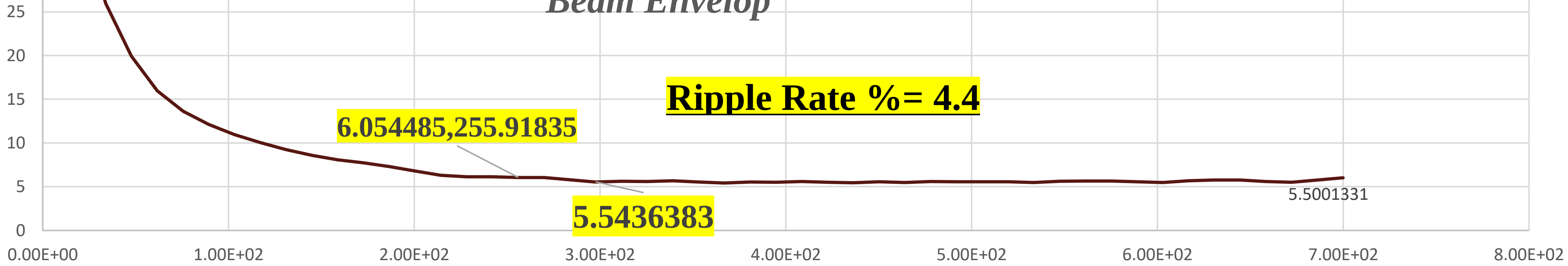


Cathode uniformity 1.9 : 1

GUN simulation result in CST

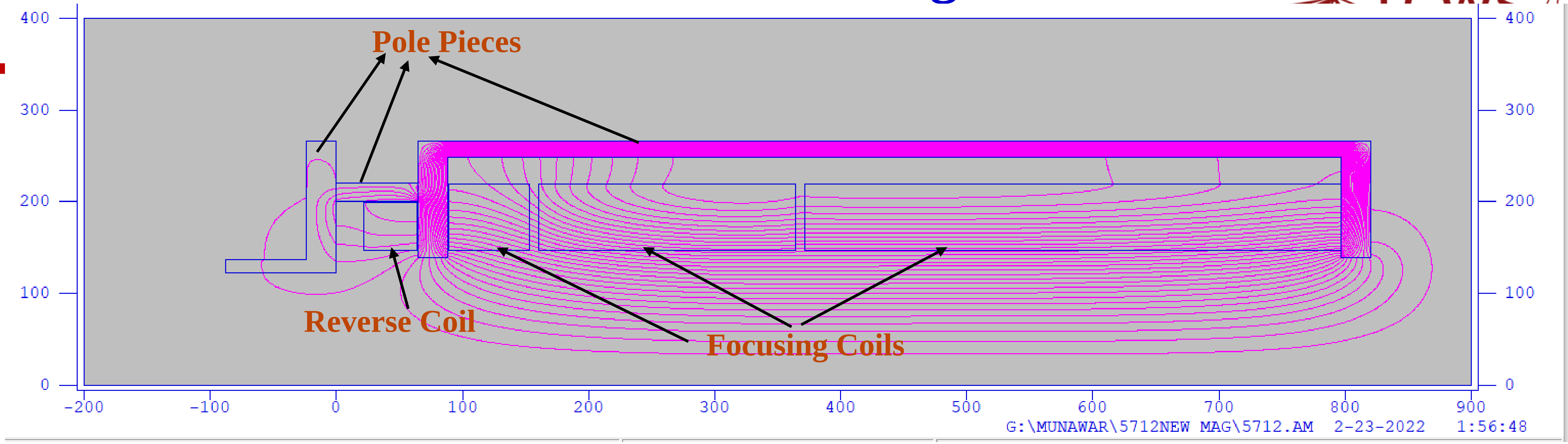


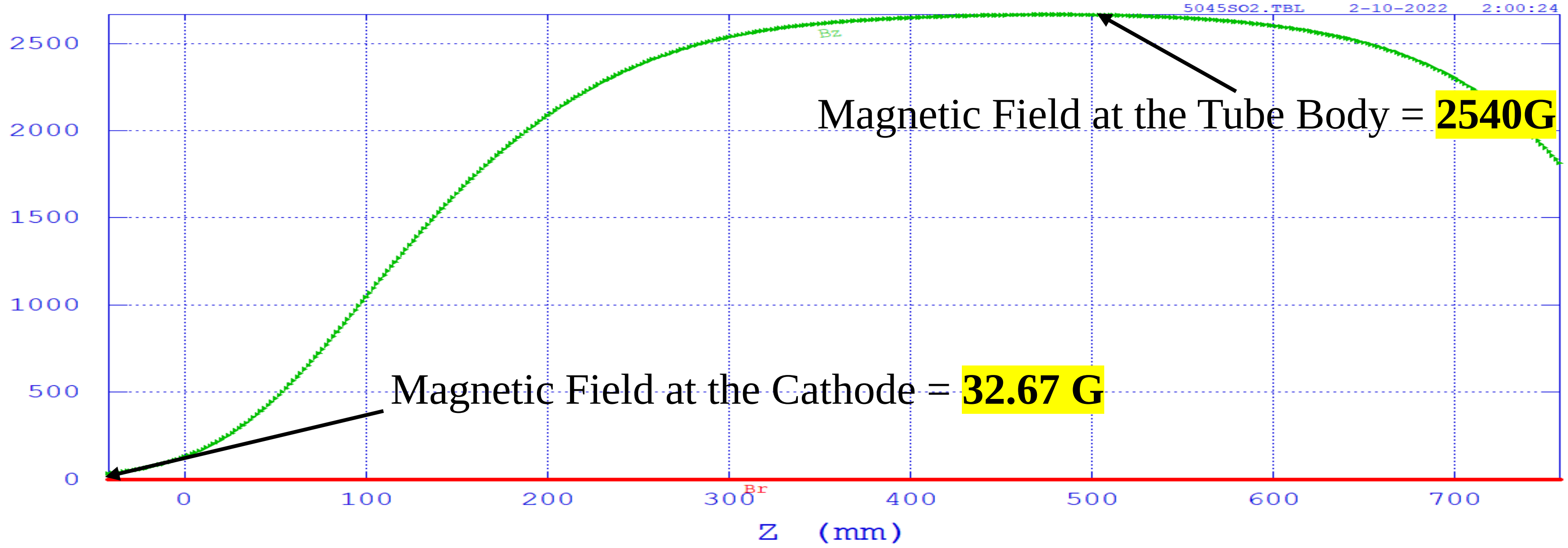




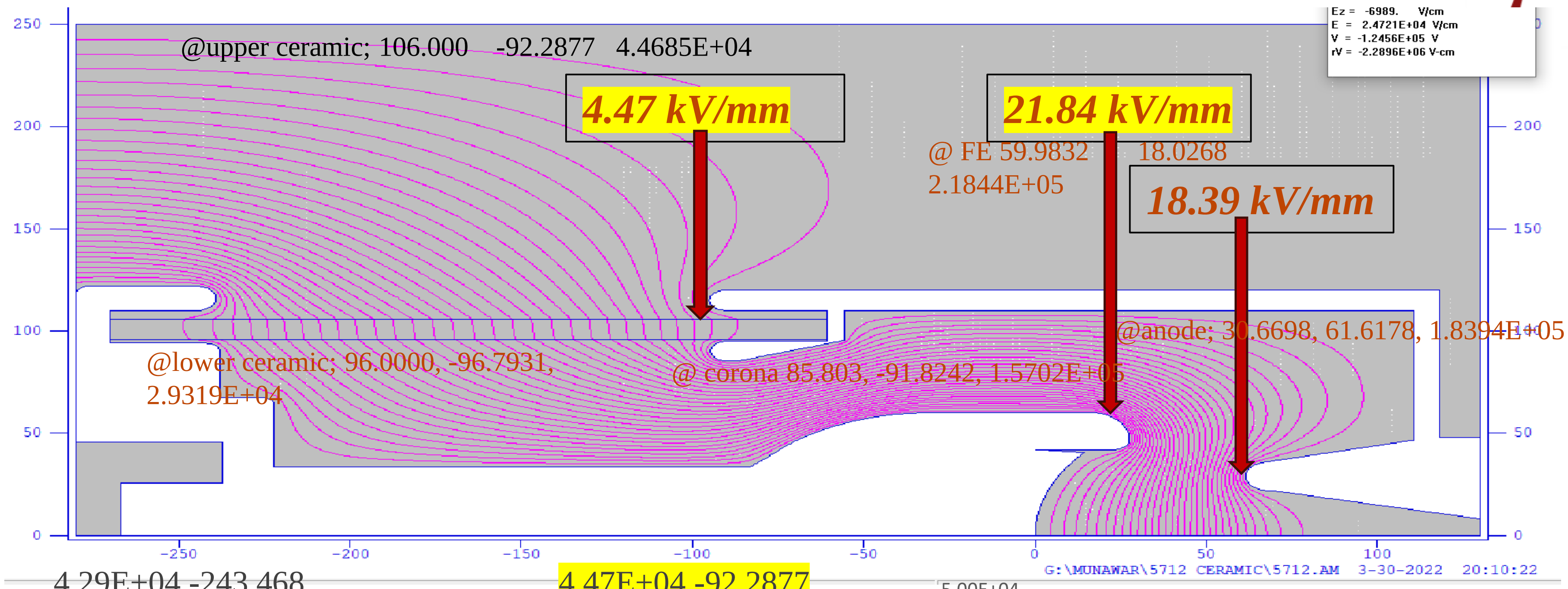
Ripple Rate %= 4.4

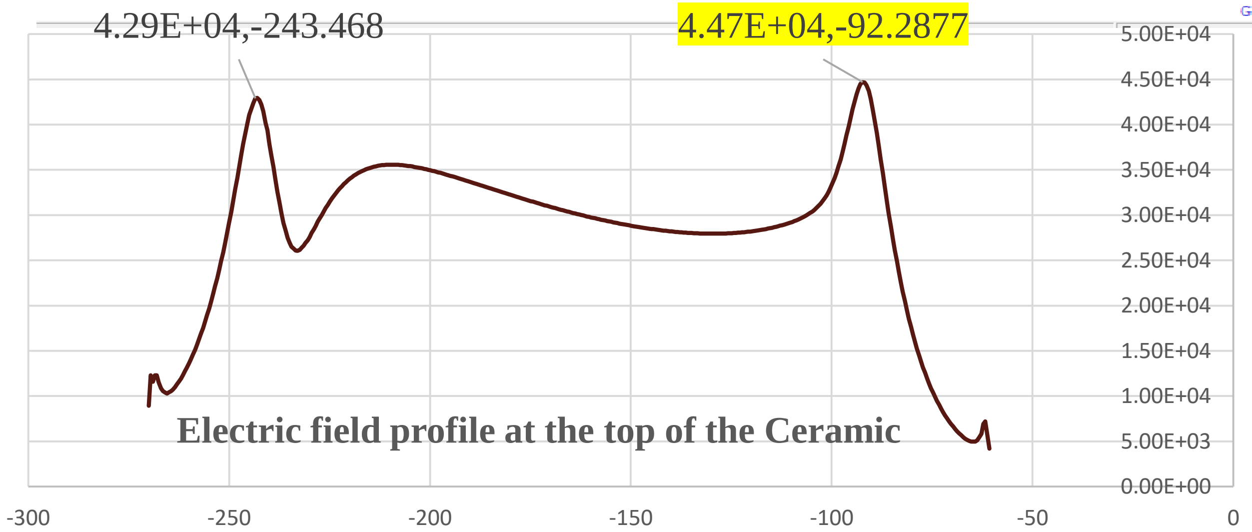
Solenoid Design

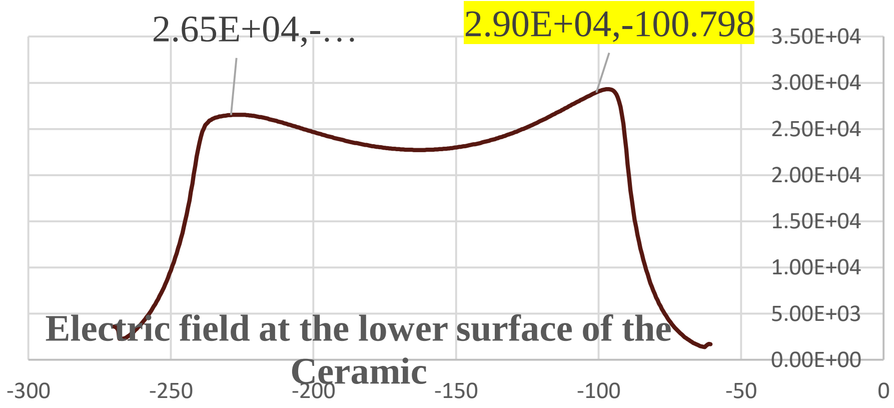




Surface gradient at beam optic & ceramic







S Band klystron parameters

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The RF power source system of CEPC LINAC includes 33 sets of pulsed klystron operating at a frequency of 2860MHz. The power of these klystron are excepted to be 80MW.

Parameters	Value
Operating frequency	2860MHz
Output power	80MW
RF pulsed width	4μS
Beam voltage	350kV
Beam current	414A
Beam μperveance	2.0
Efficiency	55%

Summary

- HE klystron is being developed, efficiency of 60% and 70% has been achieved, 80% efficiency is expected to be reached by the end of this year.
- Development of S and C band 80MW klystron for CEPC Linac is also in progress.

Thanks for your attention!