RF Cavity

Wencheng Fang

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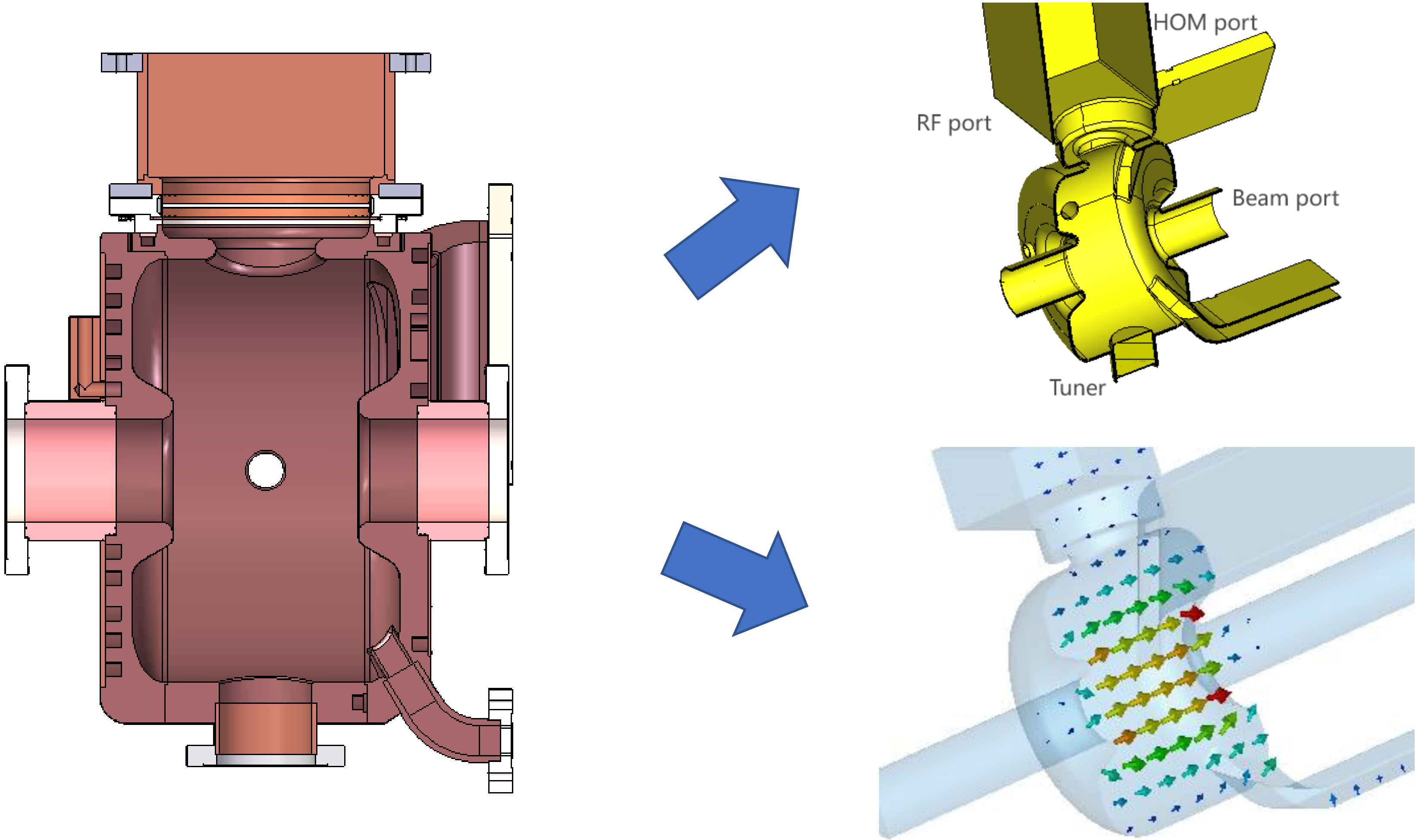
SSRF

中国科学院上海高等研究院
SHANGHAI ADVANCED RESEARCH INSTITUTE, CHINESE ACADEMY OF SCIENCES

What’s RF Cavity?



Boundary

- ☐ Copper
- ☐ Steel
- ☐ Niobium
- ☐ Others…

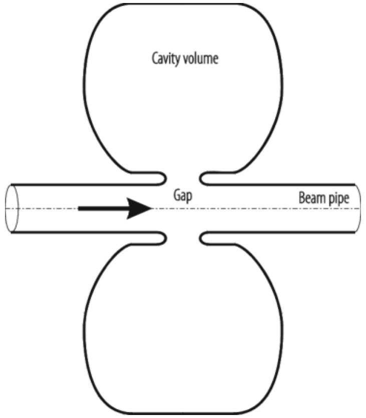
Space

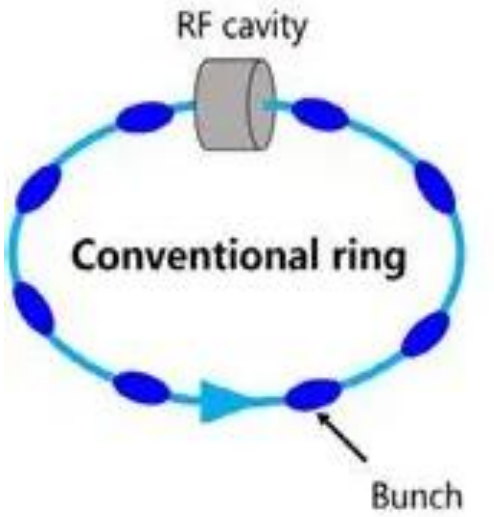
- ☐ Vacuum
- ☐ Air
- ☐ Dielectric
- ☐ Others…

NC Copper boundary + Vacuum space in this course!

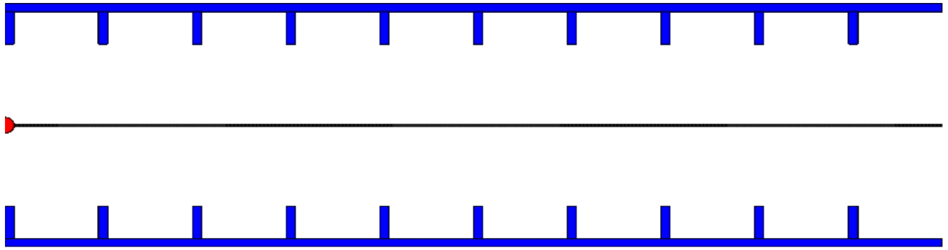
Typic RF cavities

1. Single-cell RF cavity in electron ring

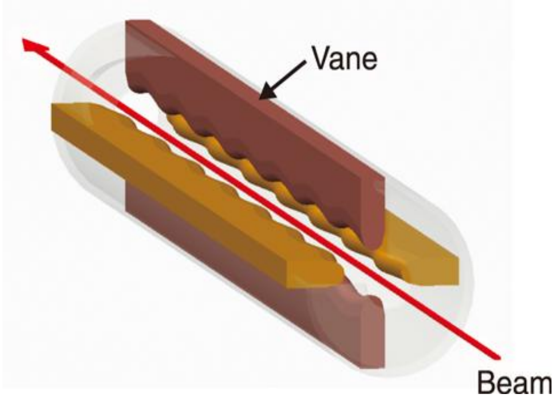




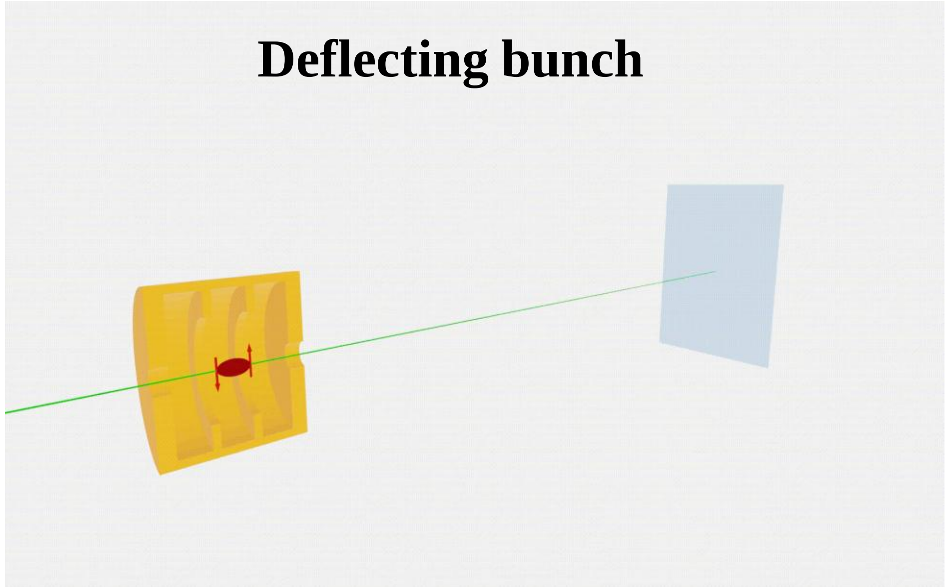
2. Multi-cell accelerating structure in linac



Focusing and acceleration



3. RFQ, DTL cavity in proton and ions injector



4. Multi-cell Deflecting cavity

- ➢Look back to basic theory
- ➢NC accelerating structure
- ➢Deflecting cavity
- ➢NC RF cavity for light source

Basic Theory: Maxwell Equations

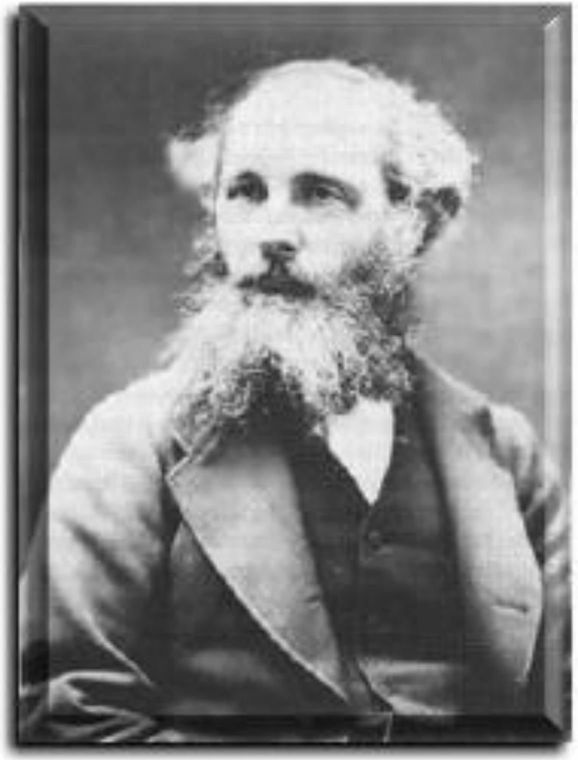
Where:
J is the current density
E is the electric field intensity
D is the electric flux density
H is the magnetic intensity field
B is the magnetic flux density
p is the charge density

Faraday's Law $\nabla\times\mathbf{E}=-\frac{\partial\mathbf{B}}{\partial t}$

Ampère's Law $\nabla\times\mathbf{H}=\frac{\partial\mathbf{D}}{\partial t}+\mathbf{J}$

Gauss' Law (Electricity) $\nabla\bullet\mathbf{D}=\rho$

Gauss' Law (Magnetism) $\nabla\bullet\mathbf{B}=0$



James Clerk Maxwell

Look back to basic theory in RF cavity

$$\nabla \times \mathbf{E}(\mathbf{r},t) = -\frac{\partial}{\partial t}\mathbf{B}(\mathbf{r},t) \quad \Big|\nabla\times$$

taking the curl on both sides

$$\nabla \times \nabla \times \mathbf{E}(\mathbf{r},t) = \nabla \times \left(-\frac{\partial}{\partial t}\mathbf{B}(\mathbf{r},t)\right) \quad \Big|$$

exchanging curl and time derivative

$$\nabla \times \nabla \times \mathbf{E}(\mathbf{r},t) = -\frac{\partial}{\partial t}\left(\nabla \times \mathbf{B}(\mathbf{r},t)\right) \quad \Big|$$

applying the material law B=μH

$$\nabla \times \nabla \times \mathbf{E}(\mathbf{r},t) = -\frac{\partial}{\partial t}\left(\nabla \times \mu\mathbf{H}(\mathbf{r},t)\right) \quad \Big|$$

constant permeability in vacuum

$$\nabla \times \nabla \times \mathbf{E}(\mathbf{r},t) = -\mu\frac{\partial}{\partial t}\nabla \times \mathbf{H}(\mathbf{r},t) \quad \Big|$$

using Ampère’s law

$$\nabla \times \nabla \times \mathbf{E}(\mathbf{r},t) = -\mu\frac{\partial}{\partial t}\left(\frac{\partial}{\partial t}\mathbf{D}(\mathbf{r},t) + \mathbf{J}(\mathbf{r},t)\right) \quad \Big|$$

deriving expression in brackets

$$= -\mu\frac{\partial^2}{\partial t^2}\mathbf{D}(\mathbf{r},t) - \mu\frac{\partial}{\partial t}\mathbf{J}(\mathbf{r},t)$$

Wave equation

$$\nabla \times \nabla \times \mathbf{E}(\mathbf{r},t) = -\mu \frac{\partial^2}{\partial t^2}\mathbf{D}(\mathbf{r},t) - \mu \frac{\partial}{\partial t}\mathbf{J}(\mathbf{r},t)$$

| applying the material law D=εE

$$= -\varepsilon\mu \frac{\partial^2}{\partial t^2}\mathbf{E}(\mathbf{r},t) - \mu \frac{\partial}{\partial t}\mathbf{J}(\mathbf{r},t)$$

$$\nabla \times \nabla \times \mathbf{E}(\mathbf{r},t) + \varepsilon\mu \frac{\partial^2}{\partial t^2}\mathbf{E}(\mathbf{r},t) = -\mu \frac{\partial}{\partial t}\mathbf{J}(\mathbf{r},t)$$

curl-curl equation

$$\nabla\Big(\underbrace{\nabla \cdot \mathbf{E}(\mathbf{r},t)}_{\frac{\rho(\mathbf{r},t)}{\varepsilon}}\Big) - \nabla^2\mathbf{E}(\mathbf{r},t) + \varepsilon\mu \frac{\partial^2}{\partial t^2}\mathbf{E}(\mathbf{r},t) = -\mu \frac{\partial}{\partial t}\mathbf{J}(\mathbf{r},t)$$

| for charge-free in the vacuum

$$\nabla^2\mathbf{E}(\mathbf{r},t) - \varepsilon\mu \frac{\partial^2}{\partial t^2}\mathbf{E}(\mathbf{r},t) = \mu \frac{\partial}{\partial t}\mathbf{J}(\mathbf{r},t)$$

wave equation (with excitation)

Wave equation

Wave equation with excitation

$$\nabla^2\mathbf{E}(\mathbf{r},t) - \varepsilon\mu\frac{\partial^2}{\partial t^2}\mathbf{E}(\mathbf{r},t) = \mu\frac{\partial}{\partial t}\mathbf{J}(\mathbf{r},t)$$

Reminding: vacuum in the RF cavity, far from the sources, excitation vanishes

$$\nabla^2\mathbf{E}(\mathbf{r},t) - \varepsilon\mu\frac{\partial^2}{\partial t^2}\mathbf{E}(\mathbf{r},t) = \mathbf{0}$$ with speed of light $$c = \frac{1}{\sqrt{\varepsilon\mu}}$$

RF field works on the constant frequency ω in the RF cavity, then wave equations is:

- Take-home
- Derivation

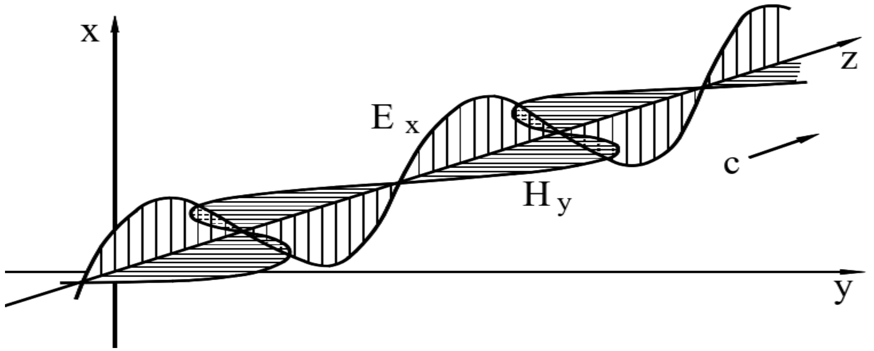
$$\nabla^2\vec{E} + k^2\vec{E} = 0$$

$$\nabla^2\vec{H} + k^2\vec{H} = 0$$

Wave number

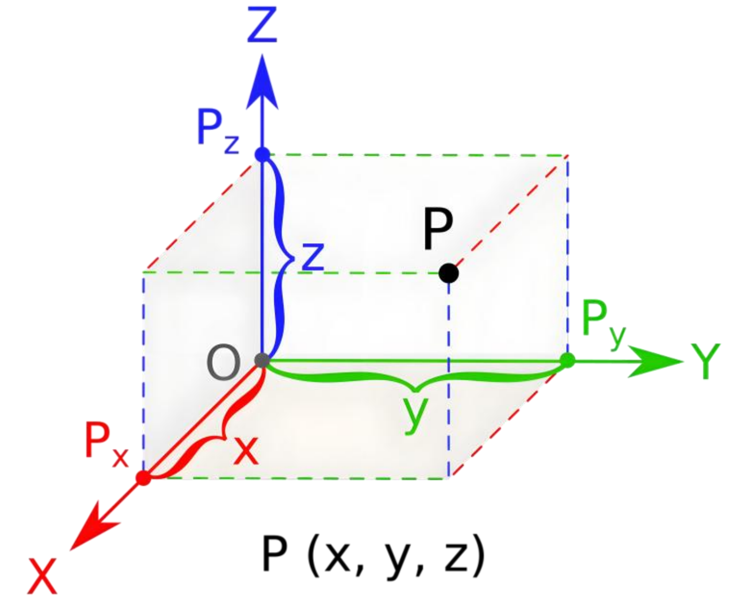
Wave vector

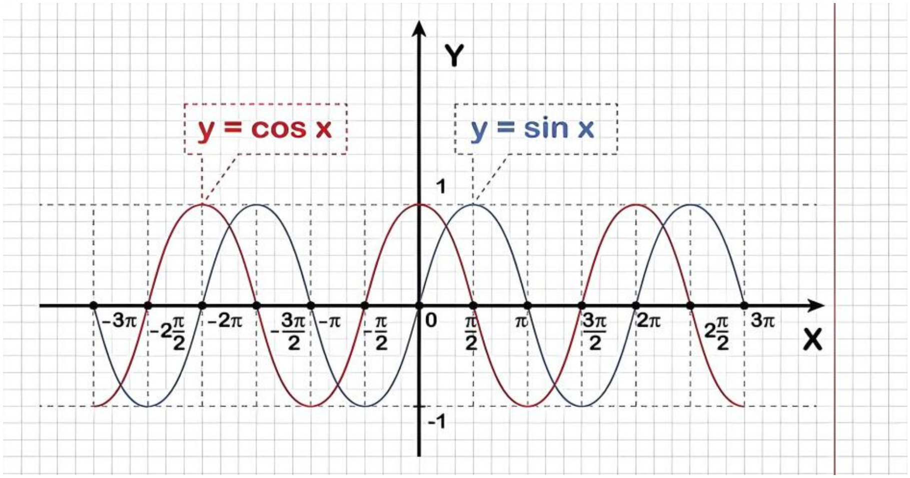
$$k^2 = \omega^2\varepsilon\mu$$



Plane Wave propagating in +z-Direction in free space

RF field in rectangular waveguide

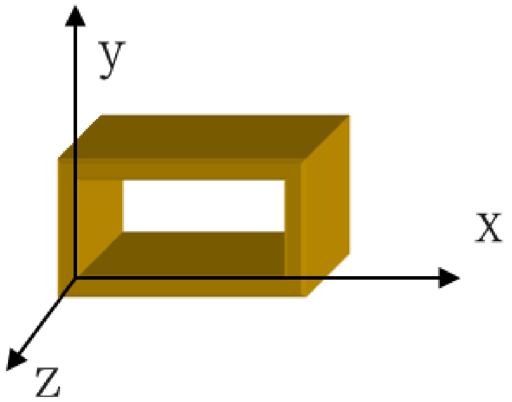




Cosine and Sine in all directions: X, Y, Z.

Cartesian coordinate system

$$E(x, y, z),$$
$$H(x, y, z)$$



TE$_{mnp}$ mode

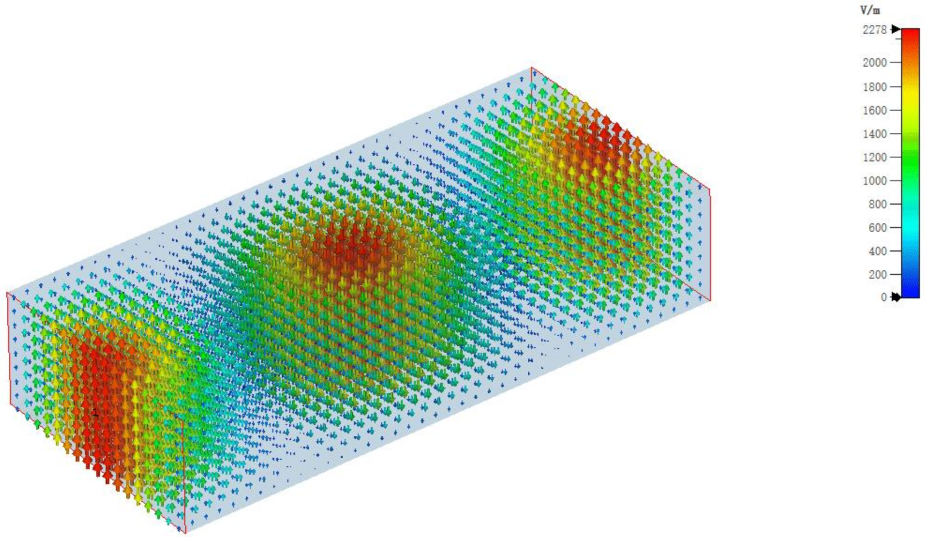
$$\underline{E}_x = -\underline{C}^H \frac{n\,\pi}{b} \cos(\frac{m\,\pi}{a}x)\ \sin(\frac{n\,\pi}{b}y)\ e^{\pm ik_z z}\ ,$$
$$\underline{E}_y = \underline{C}^H \frac{m\,\pi}{a} \sin(\frac{m\,\pi}{a}x)\ \cos(\frac{n\,\pi}{b}y)\ e^{\pm ik_z z}\ ,$$
$$\boxed{\underline{E}_z = 0\ ,}$$
$$\underline{H}_x = \pm\frac{k_z}{\omega\mu}\underline{E}_y\ ,$$
$$\underline{H}_y = \mp\frac{k_z}{\omega\mu}\underline{E}_x\ ,$$
$$\underline{H}_z = -\underline{C}^H \frac{k^2 - k_z^2}{i\omega\mu} \cos(\frac{m\,\pi}{a}x)\ \cos(\frac{n\,\pi}{b}y)\ e^{\pm ik_z z}\ .$$

TM$_{mnp}$ mode

$$\underline{H}_x = \underline{C}^E \frac{n\,\pi}{b} \sin(\frac{m\,\pi}{a}x)\ \cos(\frac{n\,\pi}{b}y)\ e^{\pm ik_z z}\ ,$$
$$\underline{H}_y = -\underline{C}^E \frac{m\,\pi}{a} \cos(\frac{m\,\pi}{a}x)\ \sin(\frac{n\,\pi}{b}y)\ e^{\pm ik_z z}\ ,$$
$$\boxed{\underline{H}_z = 0\ ,}$$
$$\underline{E}_x = \mp\frac{k_z}{\omega\varepsilon}\underline{H}_y\ ,$$
$$\underline{E}_y = \pm\frac{k_z}{\omega\varepsilon}\underline{H}_x\ ,$$
$$\underline{E}_z = \underline{C}^E \frac{k^2 - k_z^2}{i\omega\varepsilon} \sin(\frac{m\,\pi}{a}x)\ \sin(\frac{n\,\pi}{b}y)\ e^{\pm ik_z z}\ .$$

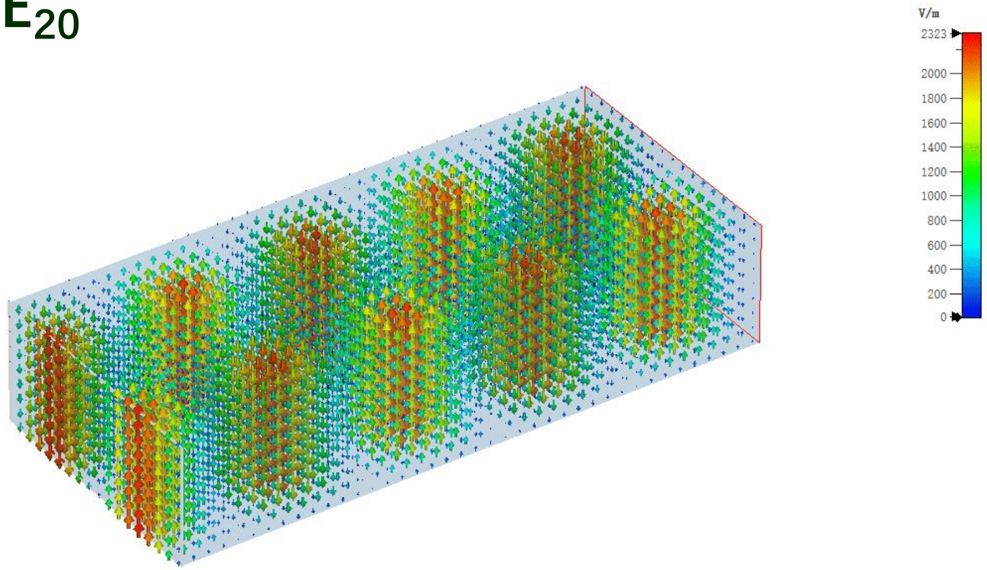
RF field in rectangular waveguides

- TE_{10}

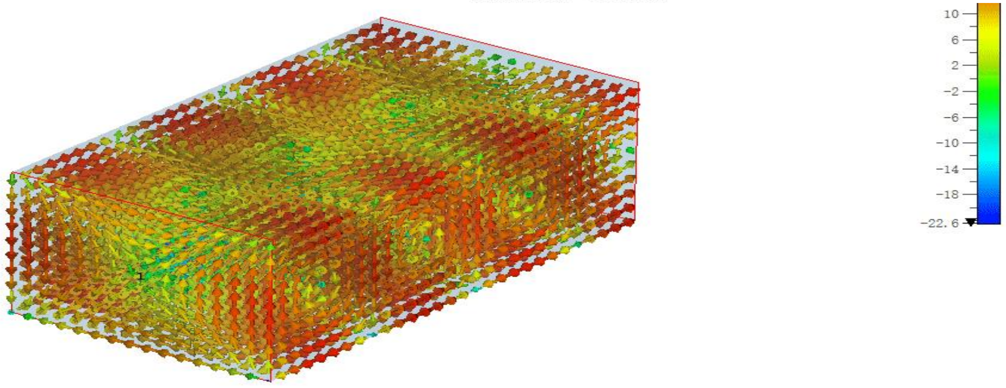


e-field (f=9200) [1]
Frequency 9200 MHz
Phase 0 °
Maximum (Plot) 2278.38 V/m

- TE_{20}



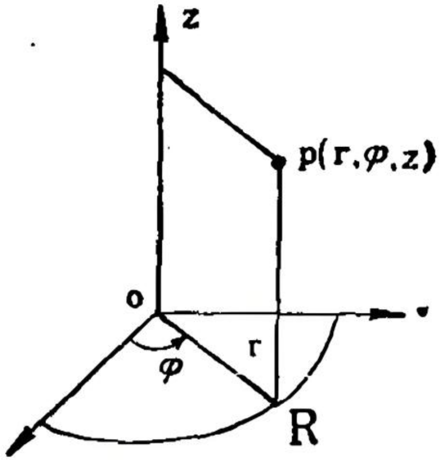
e-field (f=1.91e+4) [1(2)]
Frequency 19100 MHz
Phase 0 °
Maximum (Plot) 2323.13 V/m



- TE_{11}

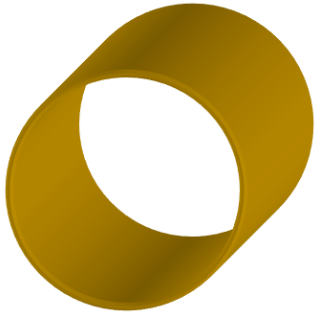
h-field (f=2.5e+4) [1(3)]
Frequency 25000 MHz
Phase 0 °
Maximum (Plot) 17.3689 dB(A/m)

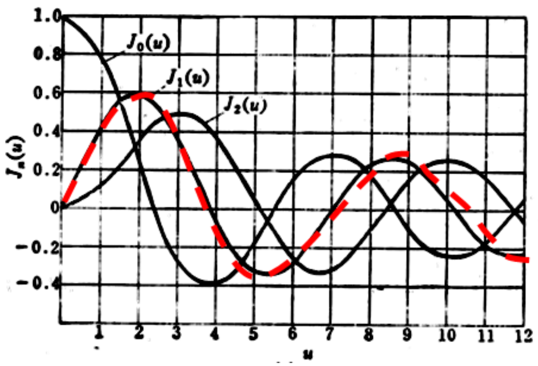
RF field in Circular waveguides



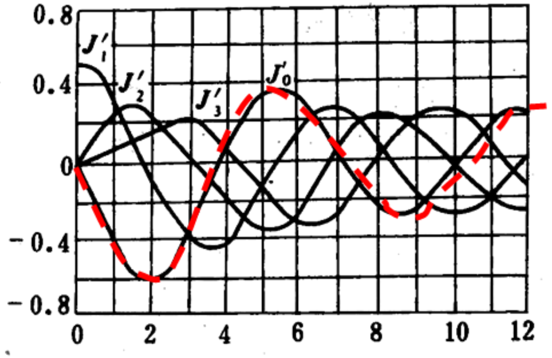
Cylindrical coordinate system

$$E(r,\varphi,z),$$
$$H(r,\varphi,z)$$





Bassel Functions $J_n(k_c r)$



Derivative functions $J_n'(k_c r)$

- ☐ **Cosine and Sine in φ, *z* directions**
- ☐ **However Bassel in r directions**

TE$_{mnp}$ mode

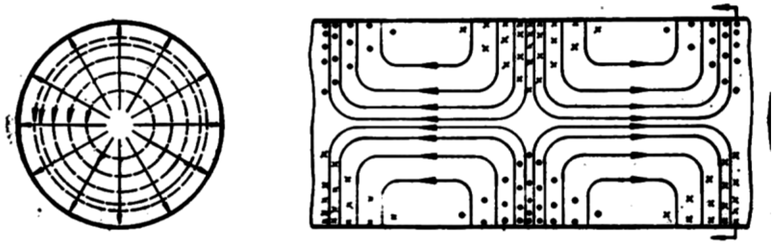
$$\begin{cases} E_z = 0 \\ E_r = \dfrac{jn\omega_0\mu_0}{k_c^2 r} H_m J_n(k_c r)\sin[n(\phi-\phi_0)]e^{-jk_z z} \\ E_\phi = \dfrac{jn\omega_0\mu_0}{k_c} H_m J_n^{'}(k_c r)\cos[n(\phi-\phi_0)]e^{-jk_z z} \\ H_z = H_m J_n(k_c r)\cos[n(\phi-\phi_0)]e^{-jk_z z} \\ H_r = -\dfrac{jk_z}{k_c} H_m J_n^{'}(k_c r)\cos[n(\phi-\phi_0)]e^{-jk_z z} \\ H_\phi = \dfrac{jnk_z}{k_c^2 r} H_m J_n(k_c r)\sin[n(\phi-\phi_0)]e^{-jk_z z} \end{cases}$$

TM$_{mnp}$ mode

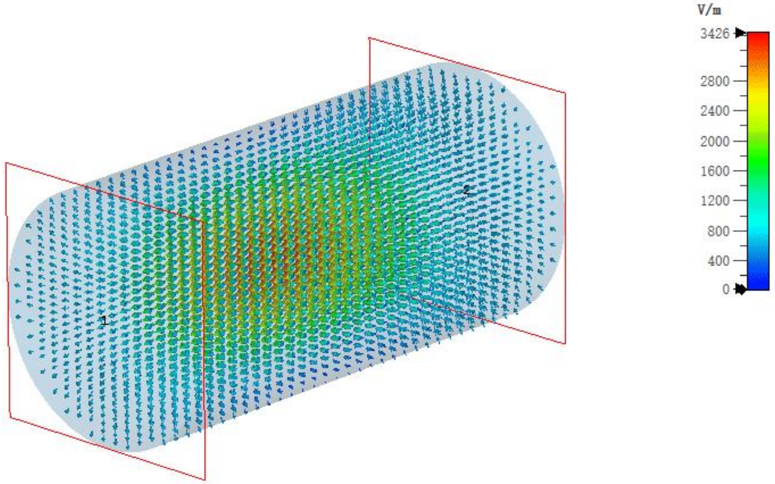
$$\begin{cases} E_z = E_m J_n(k_c r)\cos[n(\phi-\phi_0)]e^{-jk_z z} \\ E_r = -\dfrac{jk_z}{k_c} E_m J_n^{'}(k_c r)\cos[n(\phi-\phi_0)]e^{-jk_z z} \\ E_\phi = \dfrac{jnk_z}{k_c^2 r} E_m J_n(k_c r)\sin[n(\phi-\phi_0)]e^{-jk_z z} \\ H_z = 0 \\ H_r = -\dfrac{jn\omega_0\varepsilon_0}{k_c^2 r} E_m J_n(k_c r)\sin[n(\phi-\phi_0)]e^{-jk_z z} \\ H_\phi = -\dfrac{jn\omega_0\varepsilon_0}{k_c} E_m J_n^{'}(k_c r)\cos[n(\phi-\phi_0)]e^{-jk_z z} \end{cases}$$

RF field in Circular waveguides

- TM$_{01}$

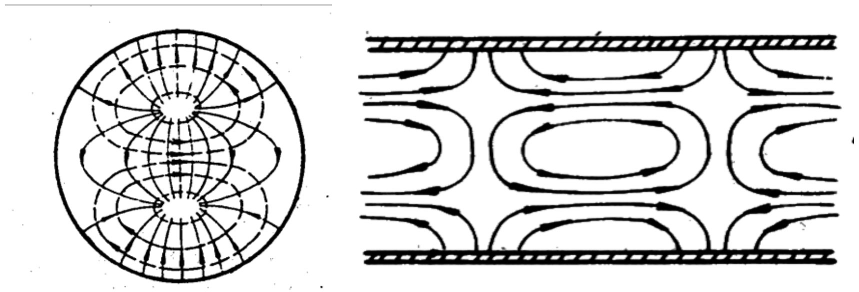


Acceleration Mode

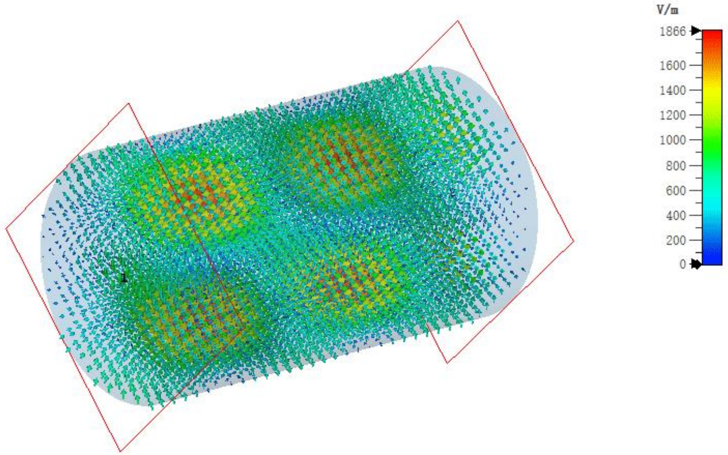


e-field (f=1.2e+4) [1(3)]
Frequency 12000 MHz
Phase 0 °
Maximum (Plot) 3425.93 V/m

- HEM$_{11}$



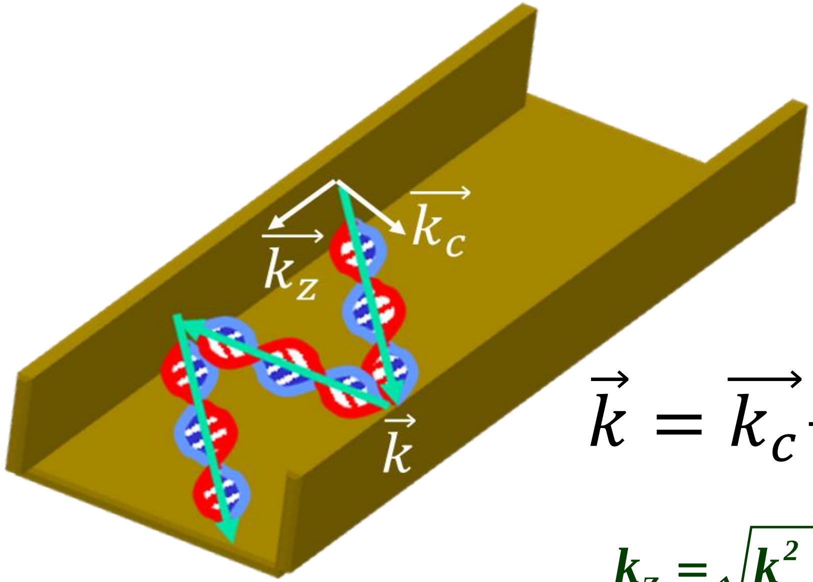
Deflecting Mode



e-field (f=1.4e+4) [1(7)]
Frequency 14000 MHz
Phase 0 °
Maximum (Plot) 1865.61 V/m

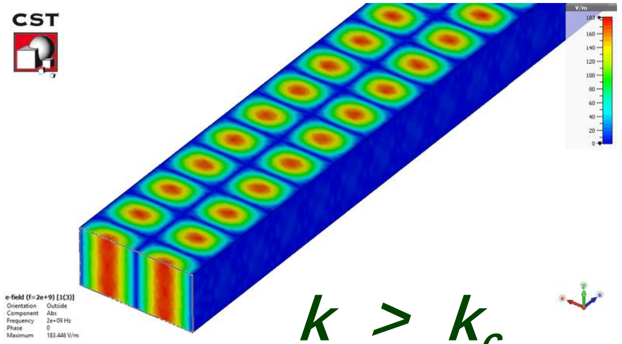
Cut-off frequency and dispersion

Wave is reflected many times during propagation in the waveguide.

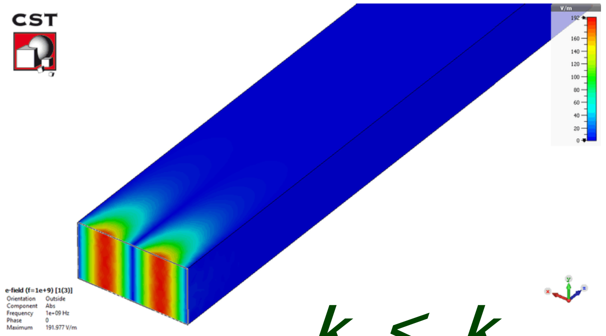


$$\vec{k} = \vec{k_c} + \vec{k_z}$$

$$k_z = \sqrt{k^2 - k_c^2}$$



$k > k_c$

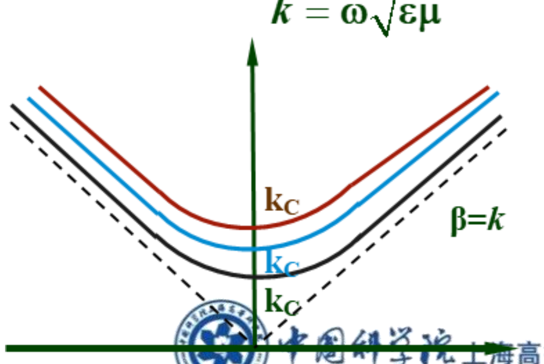


$k < k_c$

$k_c = 2\pi f_c$ is cut-off frequency

Rect. $k_{c(mn)} = \sqrt{(\frac{m\pi}{a})^2 + (\frac{n\pi}{b})^2}$

Circ. $k_c \; in \; J_n(k_c r)$



$$\nabla^2 \vec{E} + k^2 \vec{E} = 0$$
$$\nabla^2 \vec{H} + k^2 \vec{H} = 0$$
$$k^2 = \omega^2 \varepsilon\mu$$

$$E_Z = E_Z(x,y)e^{\mp jk_Z Z}$$
$$H_Z = H_Z(x,y)e^{\mp jk_Z Z}$$

$$\nabla_T^2 E_Z(x,y) + k_c^2 E_Z(x,y) = 0$$
$$\nabla_T^2 H_Z(x,y) + k_c^2 H_Z(x,y) = 0$$
$$k_c^2 = k^2 - k_Z^2$$

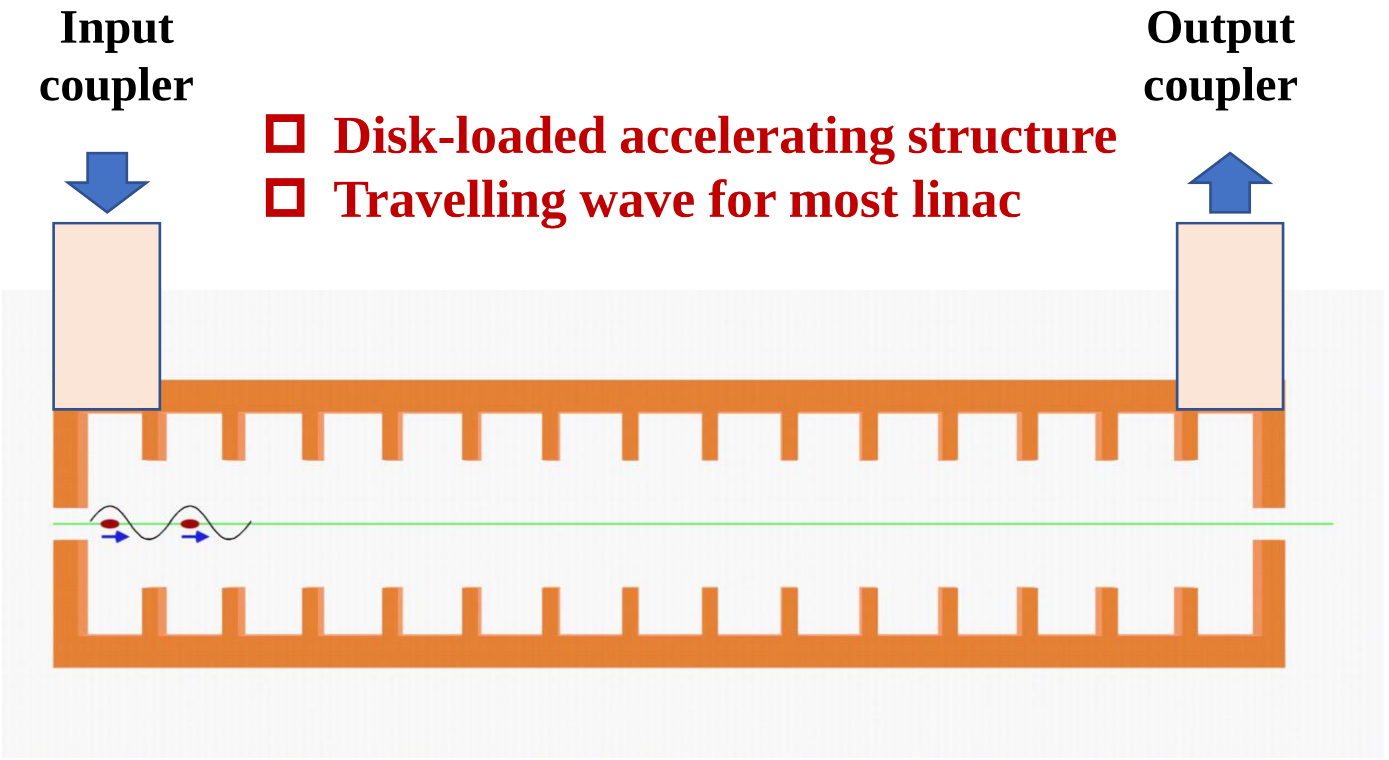
Some types of RF cavity

- ☐ **Accelerating structures**
- ☐ **Deflecting RF cavity**
- ☐ **NC Single-cell RF cavity**

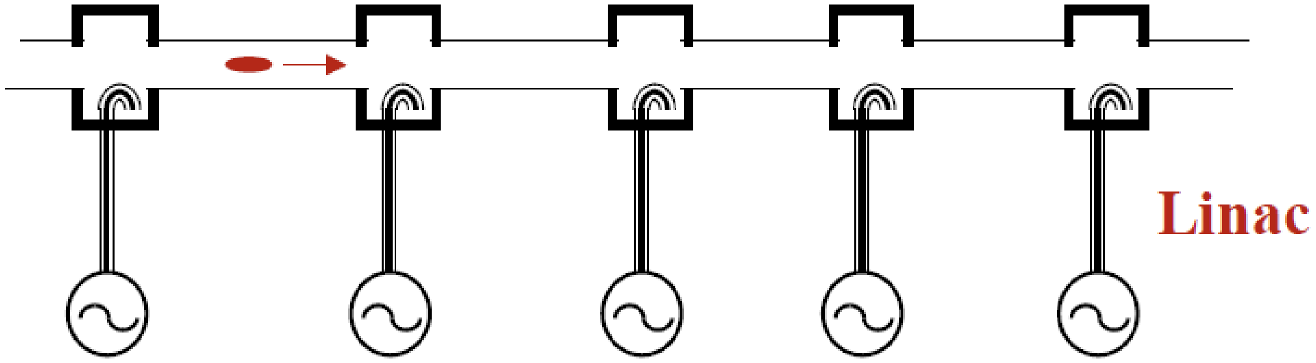
Accelerating structures for linac

$$E_p = q \cdot E_z \cos \underset{\underset{0}{\|}}{\boxed{(\omega t - \beta z)}} \cdot L$$

E_p: Energy gain in the structure
q : Charge of particle
E_z: Accelerating gradient
ω: Frequency of RF structure
β: Vp/c, phase velocity of RF field.
L: Length of accelerating structure

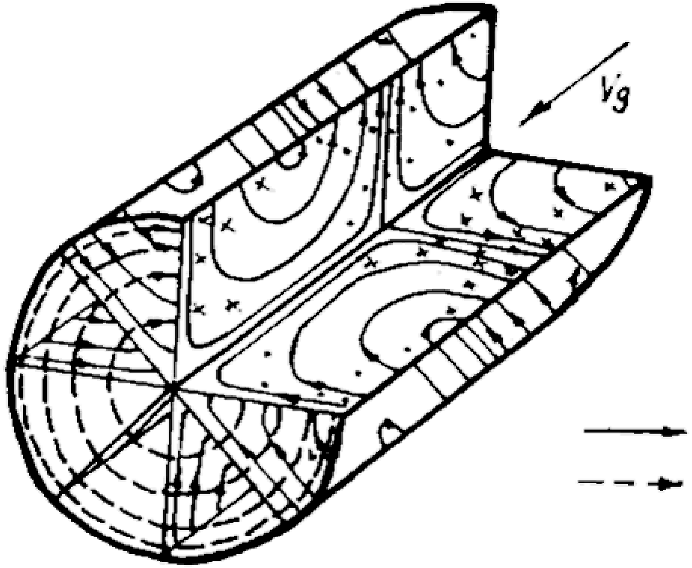


☐ **Disk-loaded accelerating structure**
☐ **Travelling wave for most linac**



☐ Synchronization acceleration
☐ Cascaded for linac

Why disk-loaded? Not constant circular waveguide?



TM01

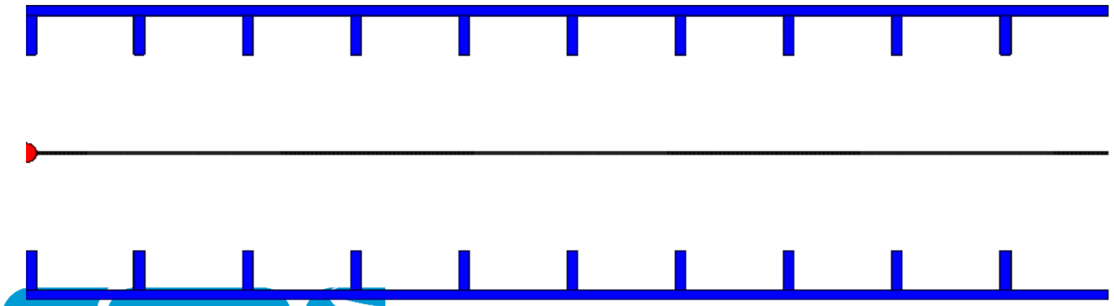
$$E_z = E_o J_o(k_c r)\cdot\cos(\omega t-\beta z) \qquad \beta=\frac{\omega}{V_p}$$

$$k_c^2=(\frac{\omega}{c})^2-(\frac{\omega}{V_p})^2>0 \qquad V_p>c$$

- Take-home
- In physics?

In order to propagate RF field and synchronize particle and RF phase together, constant circular waveguide is not able to used for acceleration directly, and disk-loaded structure can slow the phase velocity to match the light speed c.

Periodic structure, Floguet theorem

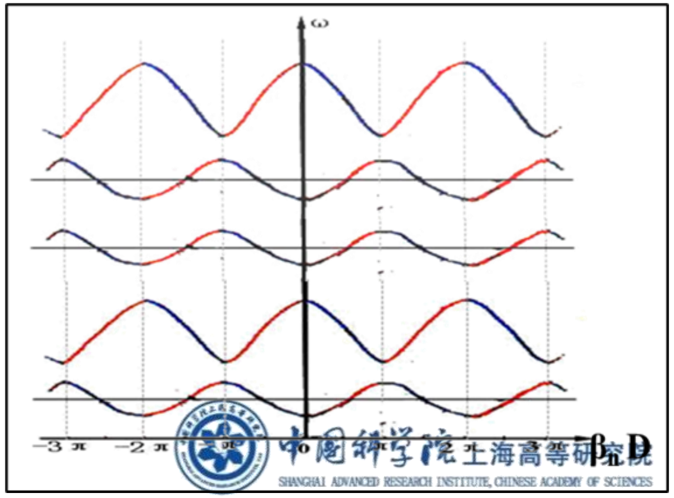


$$E_z = j\sum_{n=-\infty}^{\infty} E_n J_0(\chi_n r)e^{j(\omega t-\beta_n z)}$$

$$E_r = -\sum_{n=-\infty}^{\infty}\frac{E_n\beta_n}{\chi_n}J_1(\chi_n r)e^{j(\omega t-\beta_n z)}$$

$$H_\theta = -\omega\varepsilon_0\sum_{n=-\infty}^{\infty}\frac{E_n}{\chi_n}J_1(\chi_n r)e^{j(\omega t-\beta_n z)}$$

$$E_\theta = H_r = H_z = 0$$



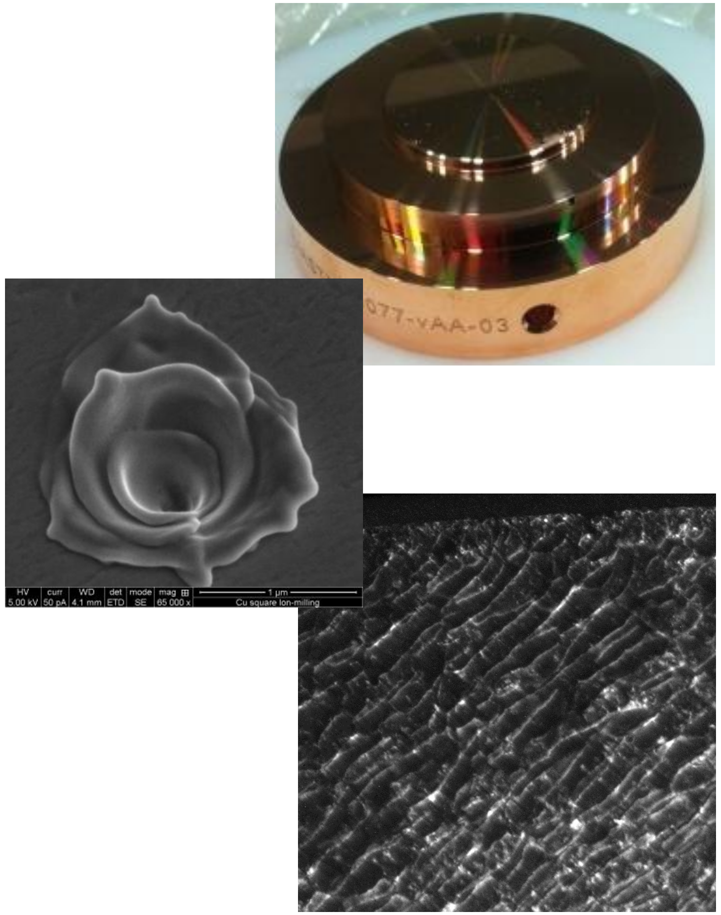
High gradient is key issue on R&D

- ☐ 1928 Fowler-Nordheim $I_F = \frac{1.54\times10^{-6}\times10^{4.52\varphi^{-0.5}} A_e\beta^2E^2}{\varphi}\mathbf{exp}\left(-\frac{6.53\times10^9\varphi^{1.5}}{\beta E}\right)$
- ☐ 1957 W. D. KILPATRICK $WE^2e^{-K_1/E} = K_2$
- ☐ 1983 W. Peter Modified Kilpatrick formula $f = (62/E)\, e^{17E}$

DC、Low frequency

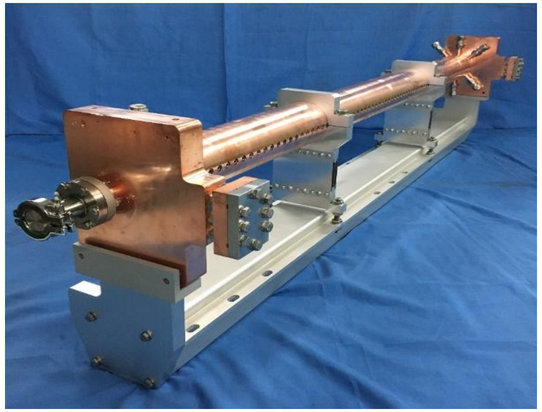
- ☐ 1989 Wang, Juwen Field-emission $I_{FE} = \frac{5.7 \times 10^{-12} \times 10^{4.52\varphi^{-0.5}} A_e(\beta E)^{2.5}}{\varphi^{1.75}} e^{-K\varphi^{1.5}/\beta E}$
- ☐ 2009 A. Grudiev Modified Poynting vector $S_c = Re\{\bar{S}\} + g_c \cdot Im\{\bar{S}\}$
- ☐ 2011 Z. Insepov Surface damage $MTBF = BJ^n e^{-E_a/kT}$
- ☐ 2012 K. Nordlund Dislocation enthalpy $$R_{BD} = a' c_0 E_i^{-E_i/k_BT} E_0^{E_0\Delta V/k_BT} \\ = ae^{\varepsilon_0\Delta V/k_BT}$$
- ☐ 2018 Eliyahu Zvi Engelberg Fluctuation of moving dislocation $\tau \sim \exp\left\{\gamma\left(1 - \frac{E}{E_0}\right)\right\}$
- ☐ 2022 Zhou Liuyuan Modified dislocationg fluctuation $R_{BD} \simeq C \exp\left\{\gamma\left(1 - \sqrt{\frac{\sigma_L}{\sigma_0}}\right)\right\} \sim \exp(\xi\sigma_L)$

RF, Microwave
X/C/S-band



Typical accelerating structures for linac

	S-band	C-band	X-band
Structure	SLAC/PAL-FEL	SPring-8/SXFEL	NLC/GLC
RF Frequency	2856 MHz	5712 MHz	11424 MHz
Structure Length	3 m	1.8 m	0.6 m
Filling time	830 ns	286 ns	105 ns
Shunt impedance	53 ~ 60 MΩ/m	53.1 MΩ/m	48.8 ~ 77.8 MΩ/m
Operational Gradient	20 MV/m	40 MV/m	65-80 MV/m



How to design the accelerating structure

- Aperture range a/λ – wakefields
- Optimization for high RF efficiency
- Attenuation factor
- Total length
- Group velocity range
- High field suppression
- Beam loading calculation

Longitudinal $SWR: W(s) = \frac{Z_0 c}{\pi a^2} e^{-1.16(s/mm)^{0.55}}$

Transverse $SWR: W(s) = \frac{2Z_0 c}{\pi a^4} (1 - e^{-0.89(s/mm)^{0.87}})$

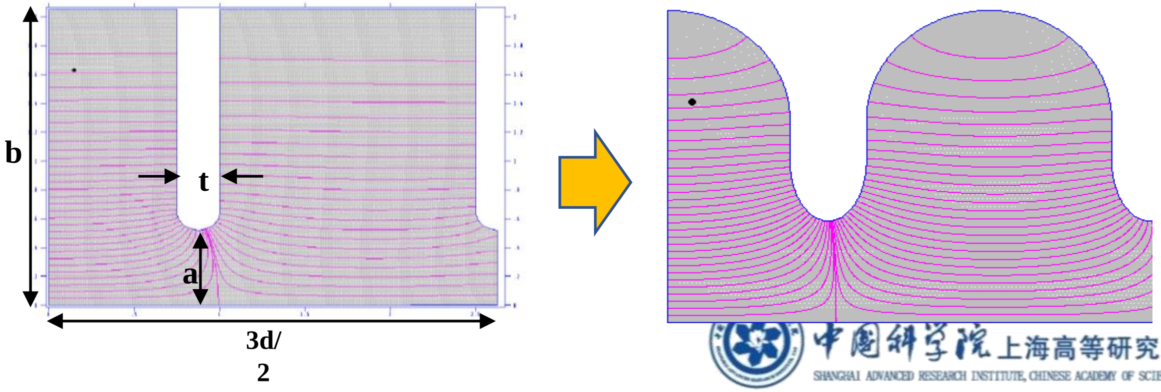
Shunt impedance $Rs = \frac{E^2}{P_l}$

Group velocity $v_g = \frac{\omega L}{Q} \{[1-(1-e^{-2\tau})z/L]/(1-e^{-2\tau})\}$

Peak field $S_c = \mathrm{Re}\{\bar{S}\} + g_c \cdot \mathrm{Im}\{\bar{S}\},$ and more···

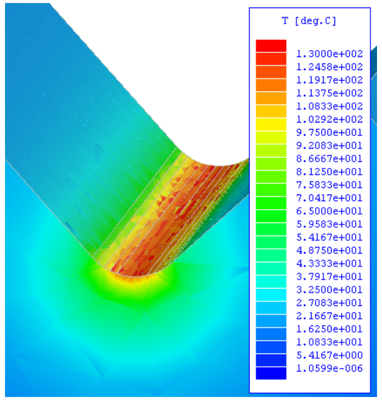
For FEL and light source:

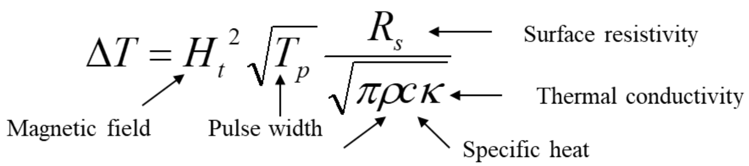
- Good beam quality: large aperture a/λ
- Higher impedance: high mode, 3pi/4, 4pi/5, 5pi/6
- Lower field distribution: round cell, elliptical iris



Coupler design

1. Coupler Problem and Resolutions
    - Pulse Heating Reduction
        - Fat lips
        - Waveguide couplers
    - Symmetry feed for correction of dipole modes
    - Racetrack cavity for correction of quadruple modes





$$\Delta T = H_t^{\,2}\sqrt{T_p}\,\frac{R_s}{\sqrt{\pi\rho c\kappa}}$$

Surface resistivity

Thermal conductivity

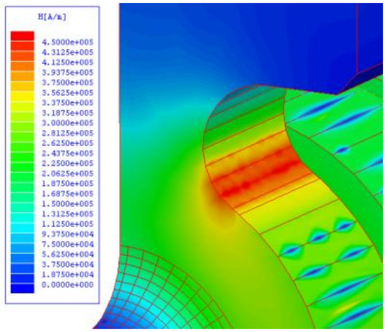
Magnetic field

Pulse width

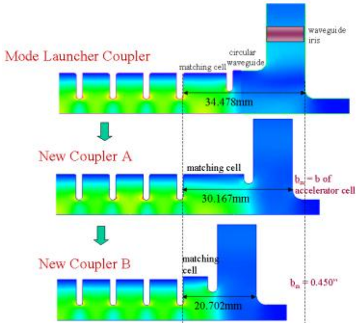
Specific heat

2. Some Coupler Types
    - Iris coupling
    - Mode convertor coupling
    - Compact coupler

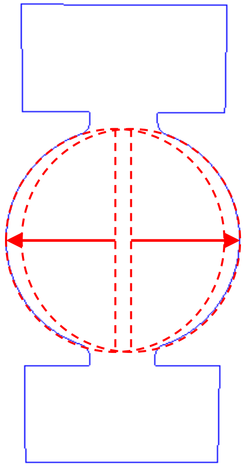
3. Coupler simulation
    CST
    HFSS
    Multi-physics simulation



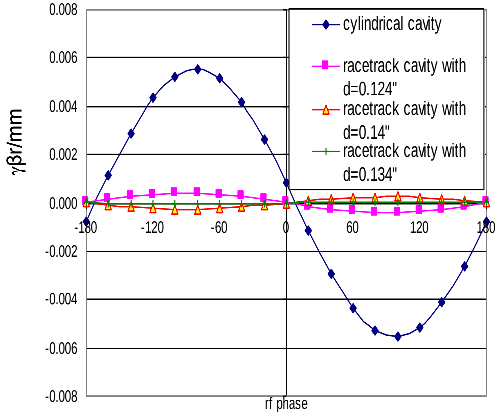
Iris coupling
High pulse heating
More symmetric
Low energy (S-band)



Mode launcher
low pulse heating
asymmetric
High energy (C/X-band)

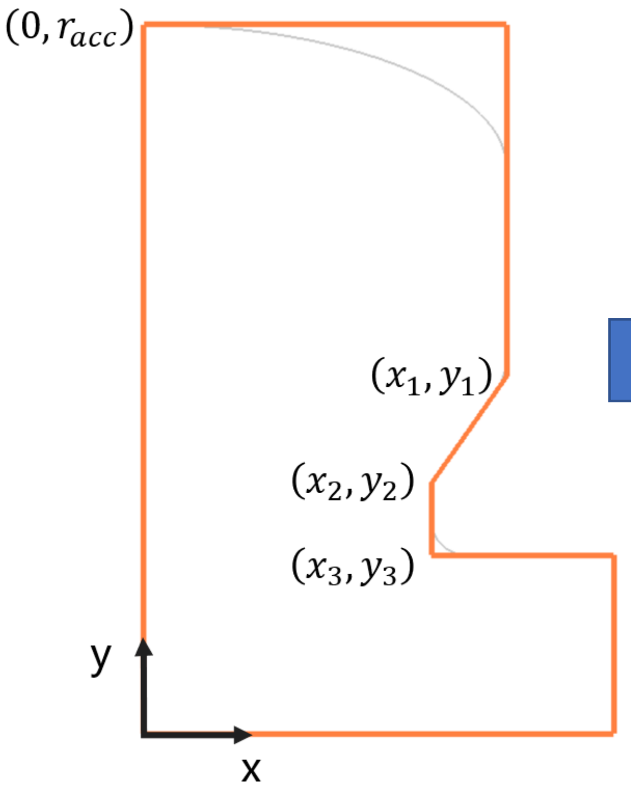


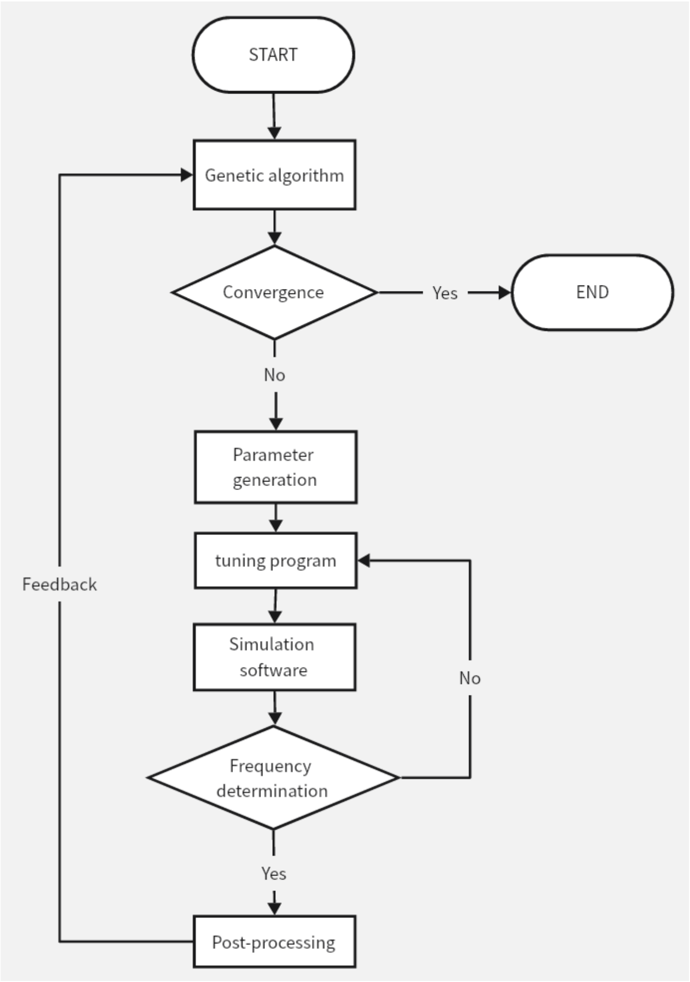
Racetrack coupler

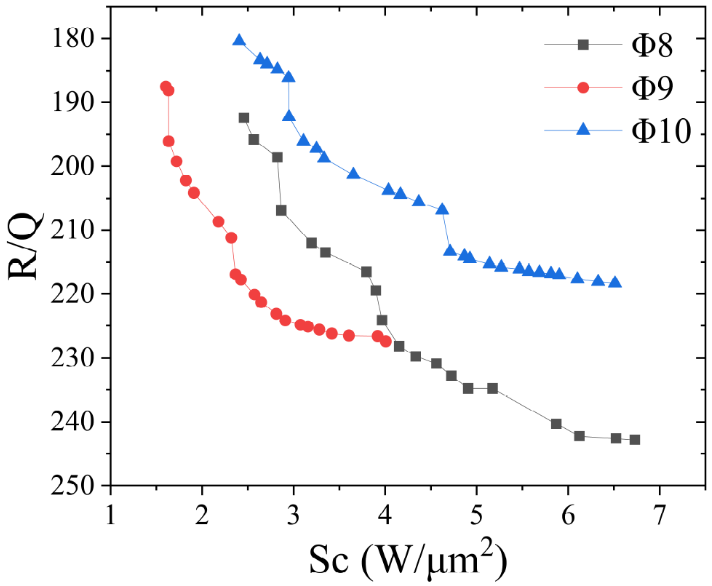


Genetic algorithm used for optimization

- Many size and angle parameters as input, and many targets should be opzimized as well
- Genetic algorithm is used to improve the efficiency of high gradient AC optimization




START
Genetic algorithm
Convergence
Yes
END
No
Parameter generation
tuning program
Simulation software
No
Frequency determination
Yes
Post-processing
Feedback



SSRF

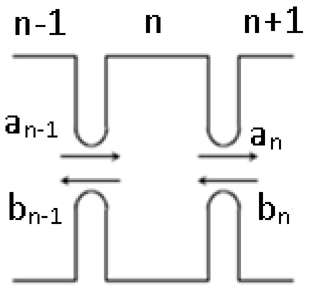
中国科学院 上海高等研究院
SHANGHAI ADVANCED RESEARCH INSTITUTE, CHINESE ACADEMY OF SCIENCES

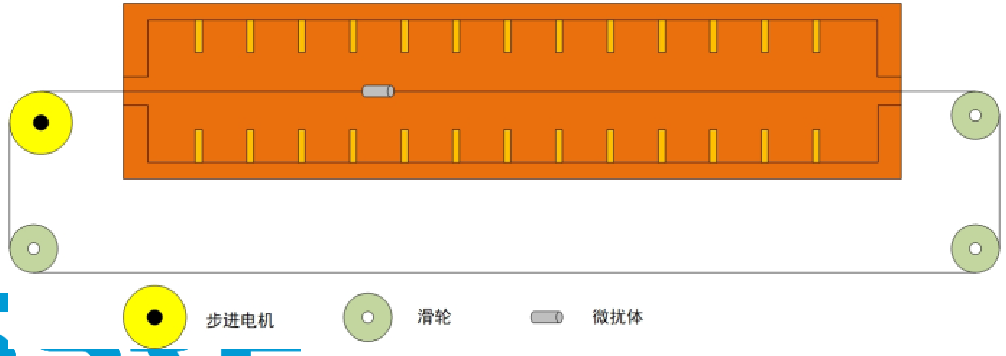
Bead-pulled RF measurement and tuning

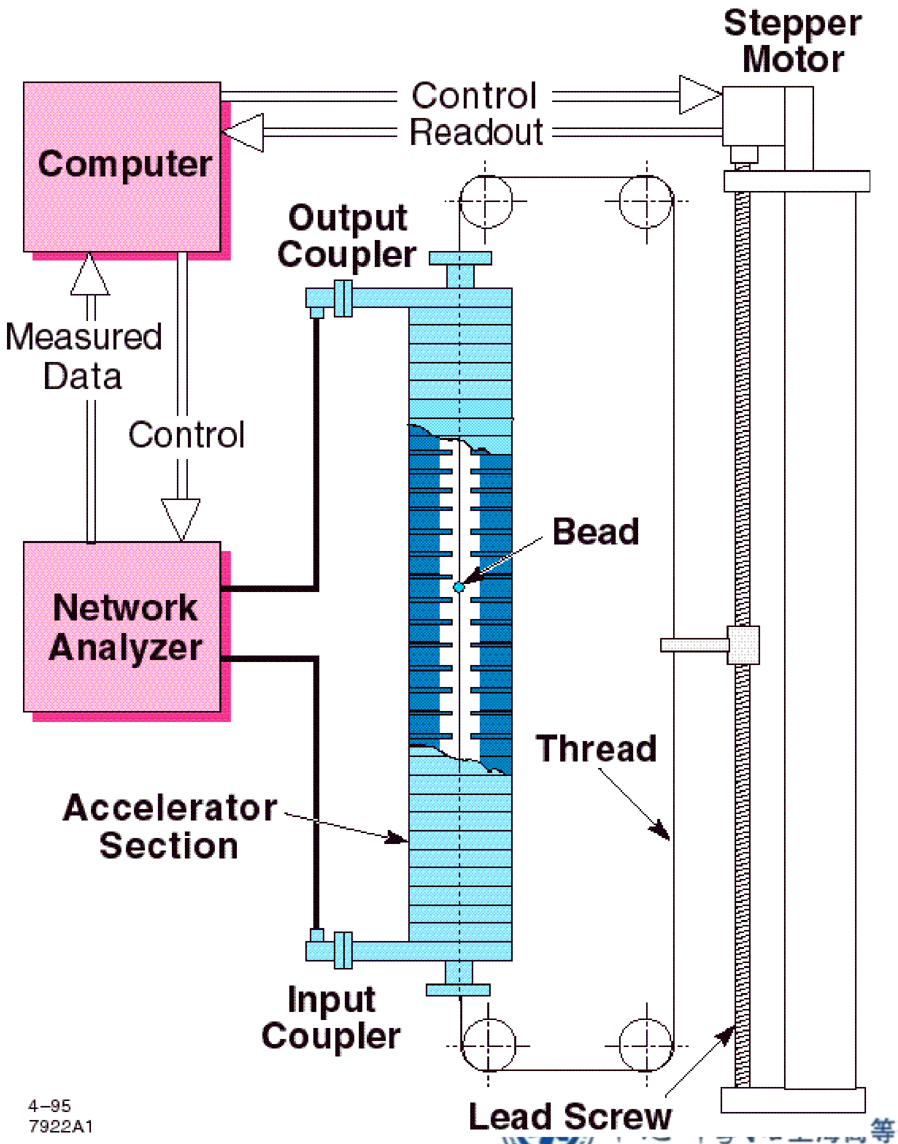
$$2P_i(\Gamma_p - \Gamma_a) = -j\omega[k_e E_a^2 - k_m H_a^2]$$

$$\Delta S11 = S11_p - S11_a = -\frac{j\omega k_e}{P_i} E_z^2$$

$$S_n e^{j\theta_n} = \frac{b_n e^{j\phi_n} - b_{n+1} e^{j(\phi_{n+1} - 2\pi/3)}}{a_n e^{j\psi_n}} = A + jB$$

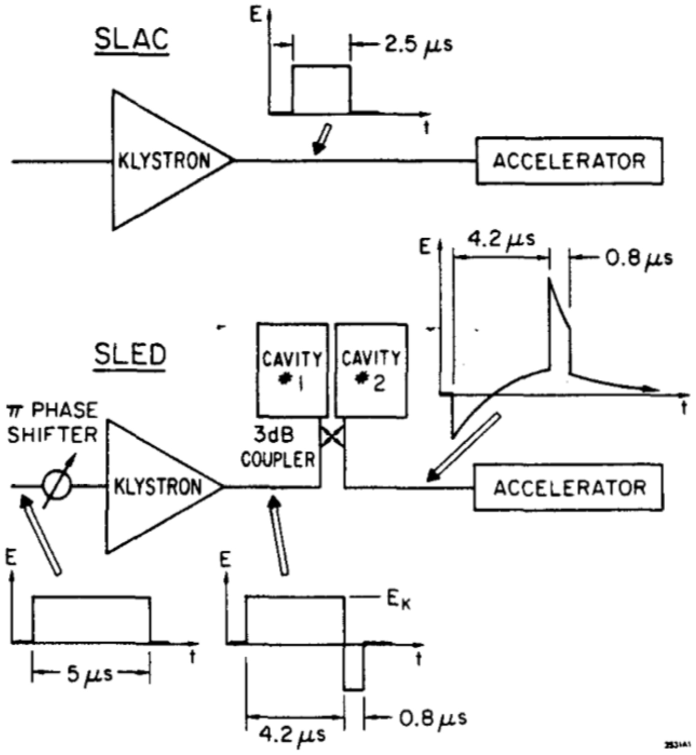


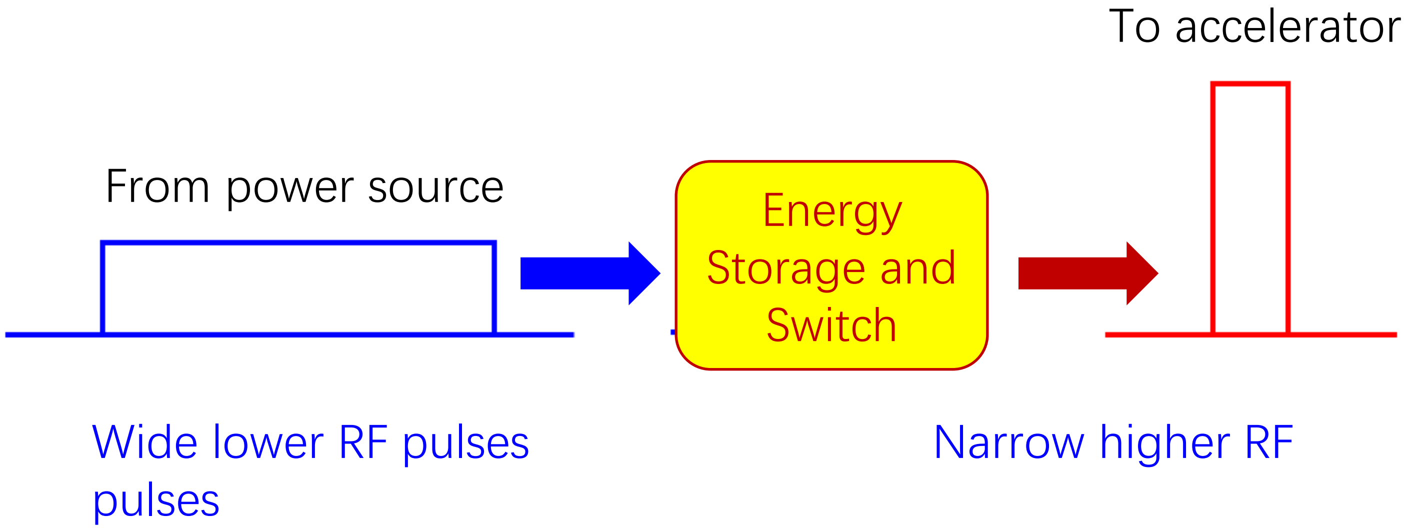




Pulse Compressor to improve high gradient

- Extremely high RF power is needed for high gradient accelerators
- High peak RF power limitation for pulsed sources





To accelerator

From power source

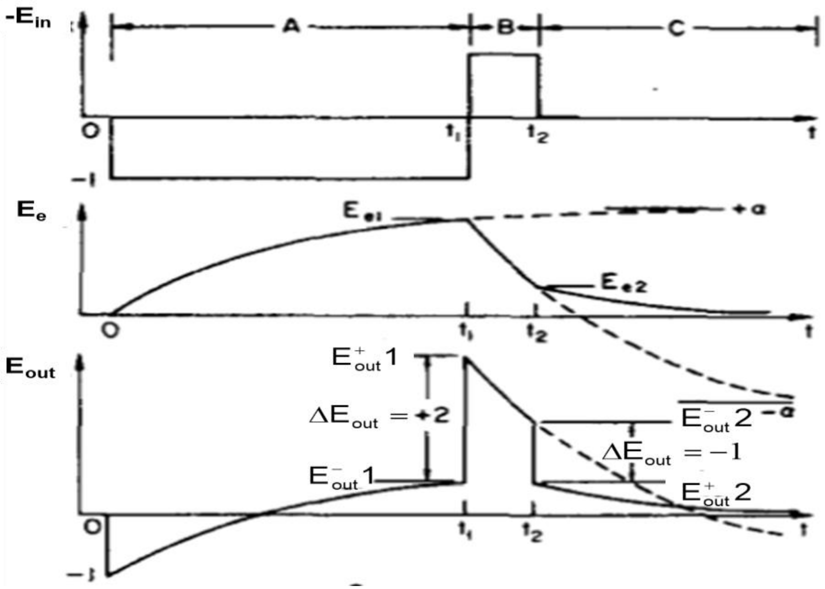
Energy Storage and Switch

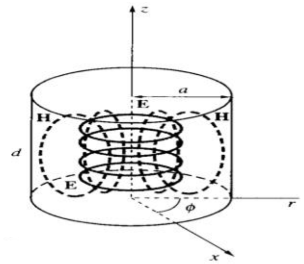
Wide lower RF pulses
pulses

Narrow higher RF

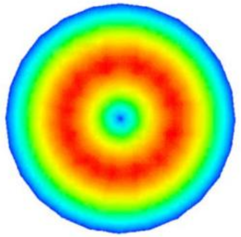
SLED

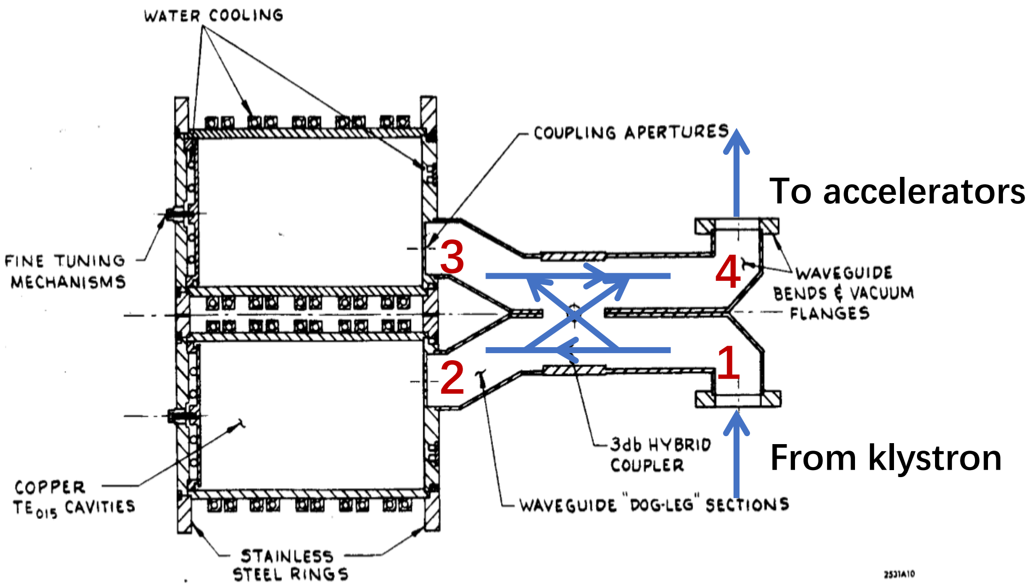
Waveforms for SLED System

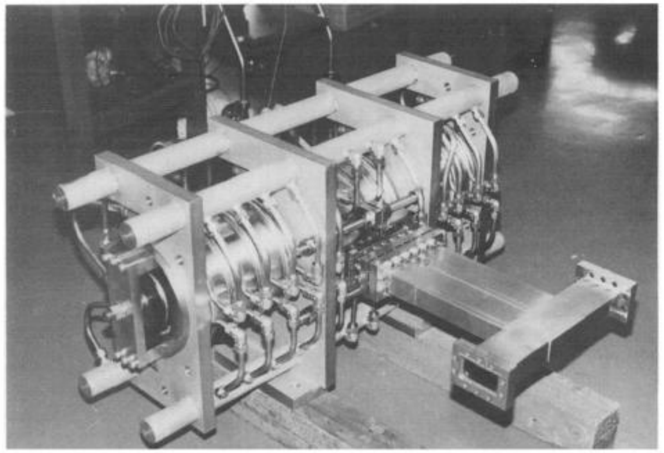




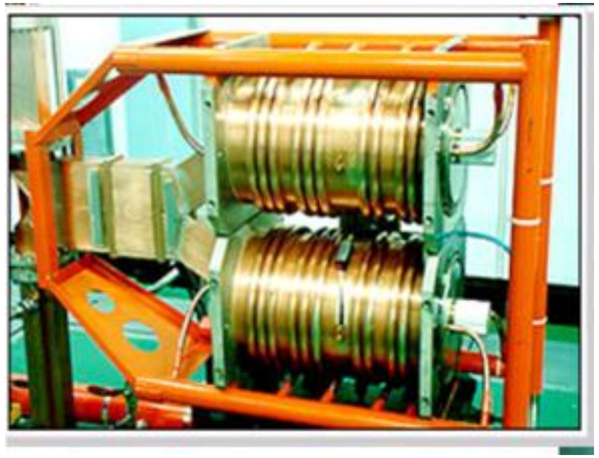
TE$_{01N}$ field pattern.



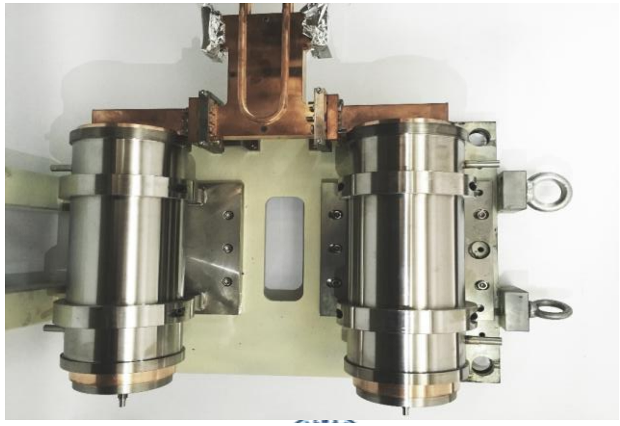




S-band, KEK, ATF&KEKB, Japan 1992.

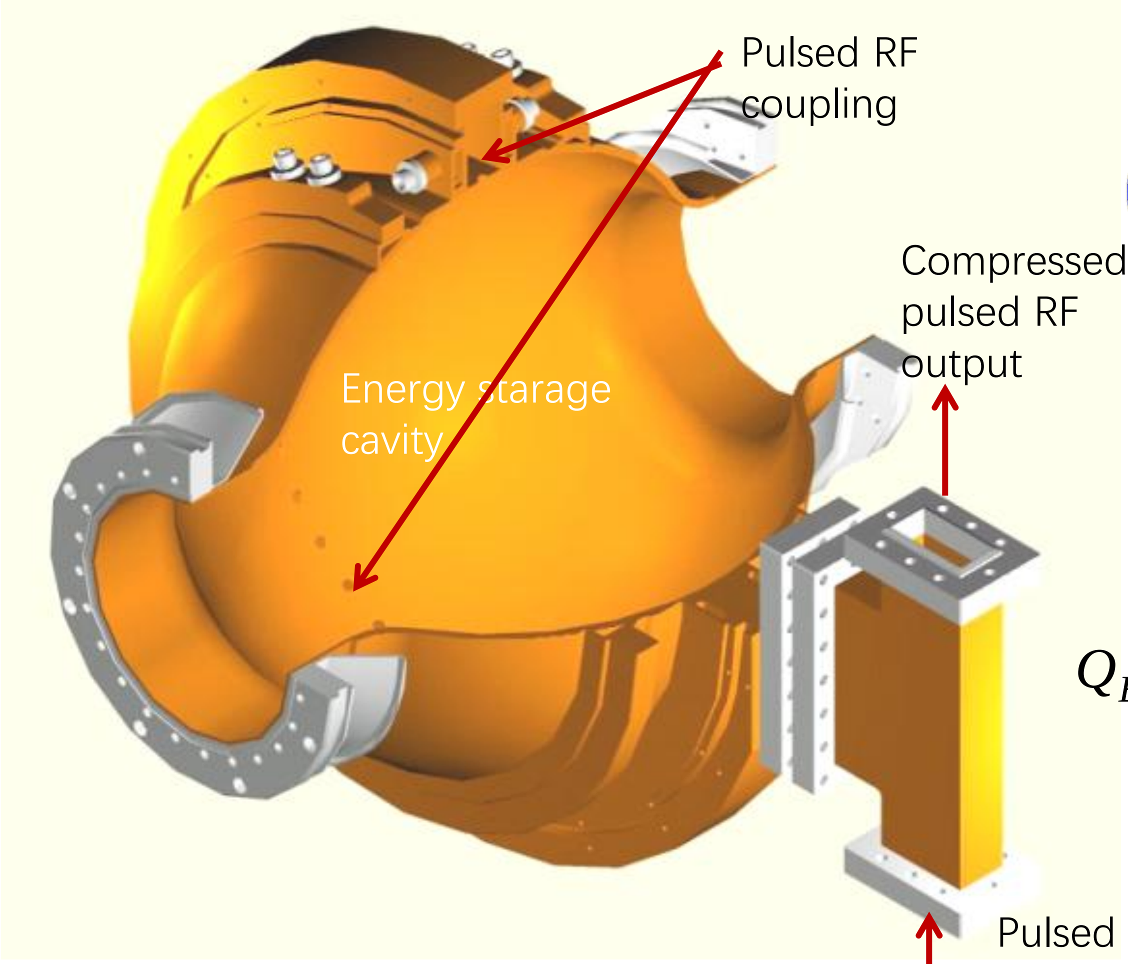


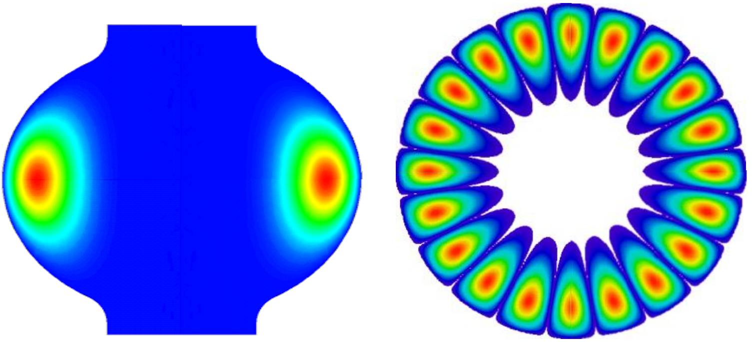
S-band, Pohang, Korea, 1994



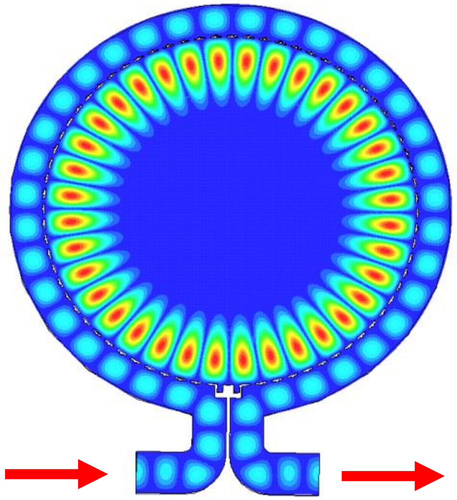
C-band, SXFEL, Shanghai, 2016

Barrel Open Cavity (BOC)

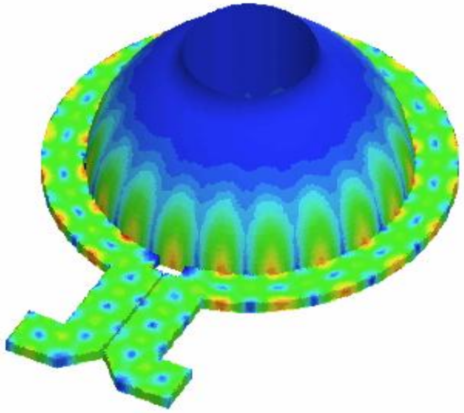


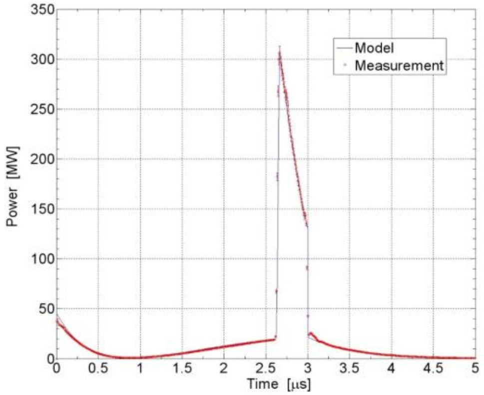

Side view Top view

Amplitude of electric field



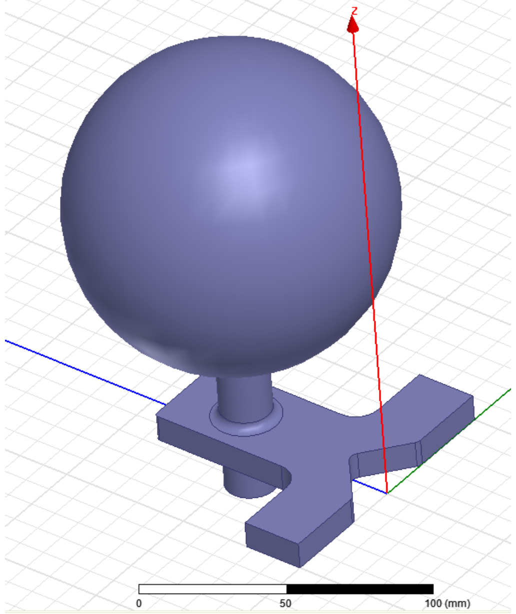
$$Q_E = \frac{a}{\sigma_s}$$

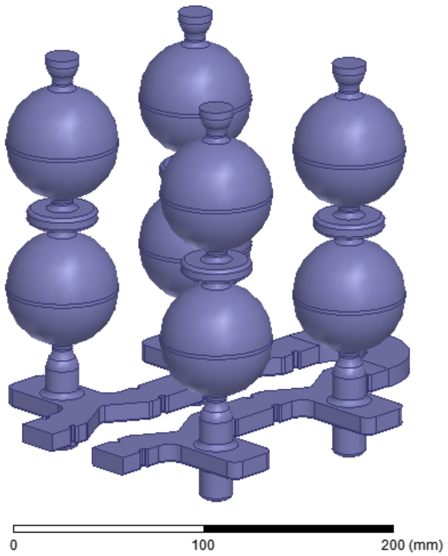

Magnitude of magnetic field

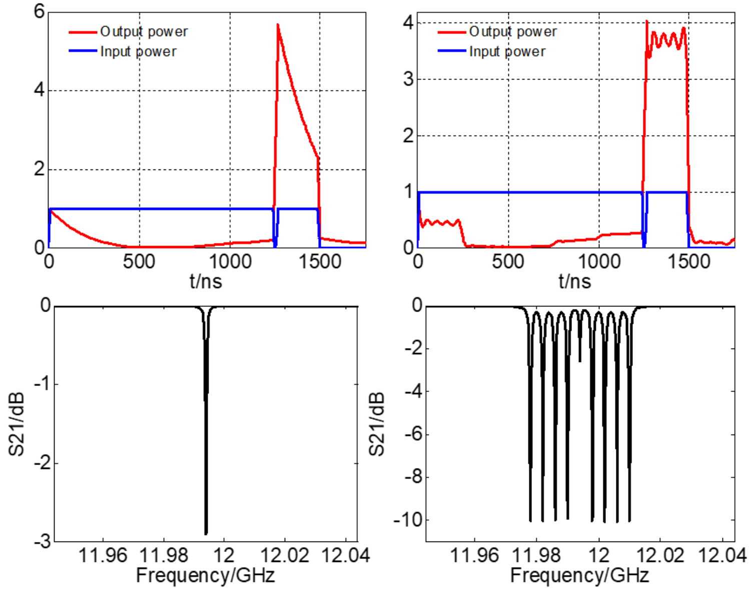


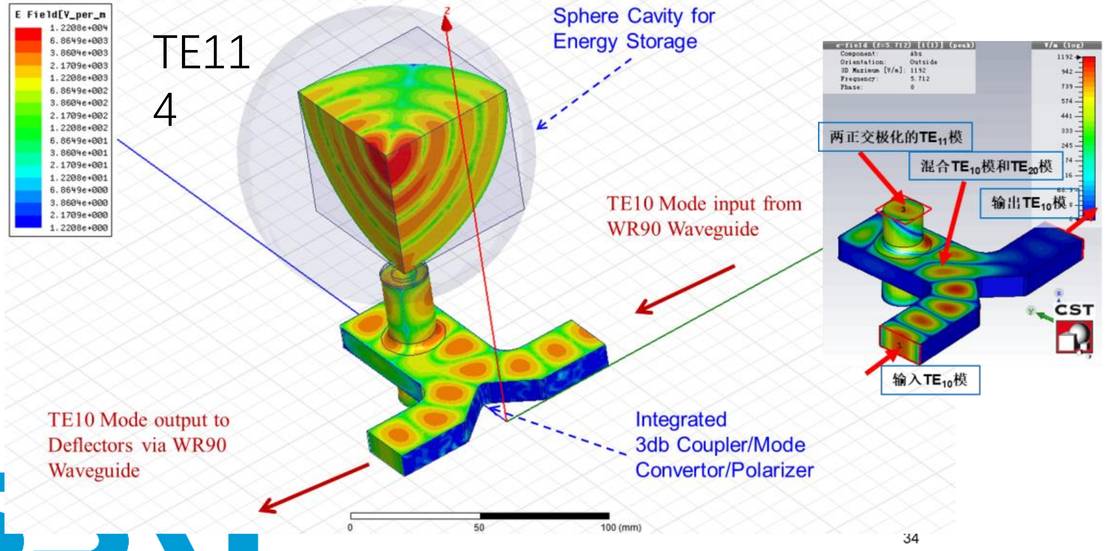
An example of Whispering Gallery Mode cavity:
TM10,1,1, Q0= 197800, f = 2.9985 GHz, β= 6

New spherical Pulse compressor (Flat-top output)









Sphere Cavity for Energy Storage

TE10 Mode input from WR90 Waveguide

TE10 Mode output to Deflectors via WR90 Waveguide

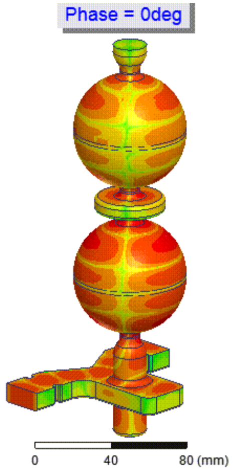
Integrated 3db Coupler/Mode Convertor/Polarizer

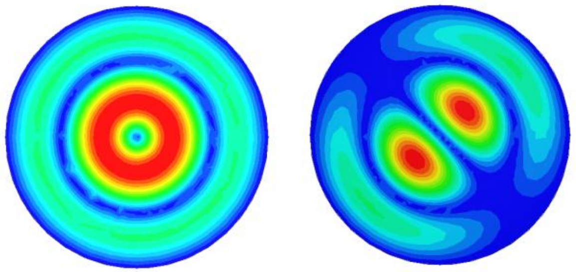
两正交极化的TE_{11}模

混合TE_{10}模和TE_{20}模

输出TE_{10}模

输入TE_{10}模

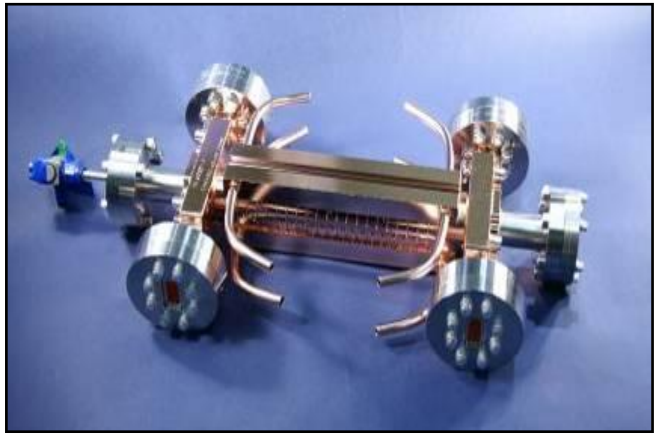




- Cavity operation mode TE012

RF system of high gradient accelerating structure

Accelerating structure

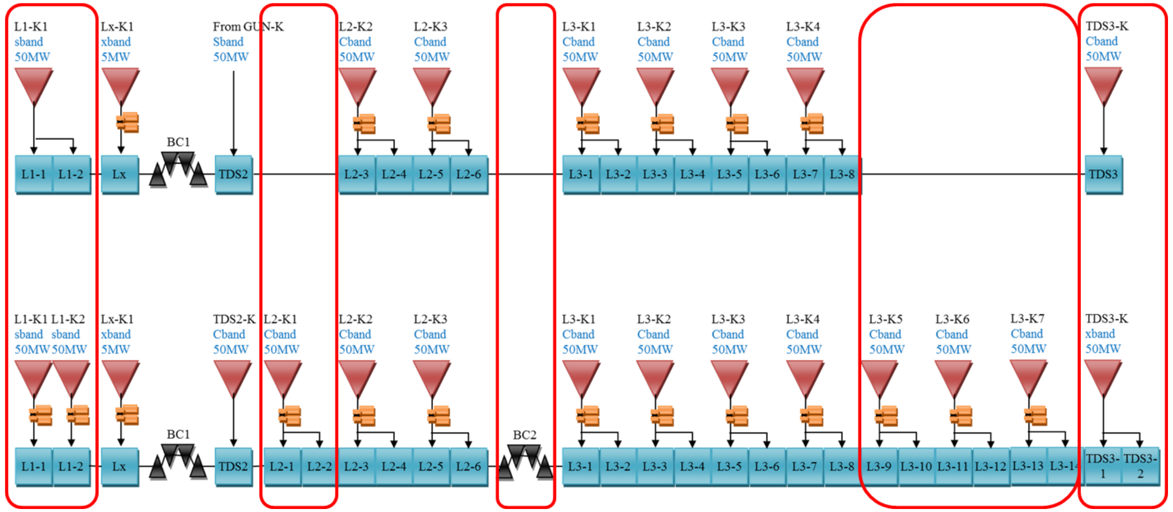


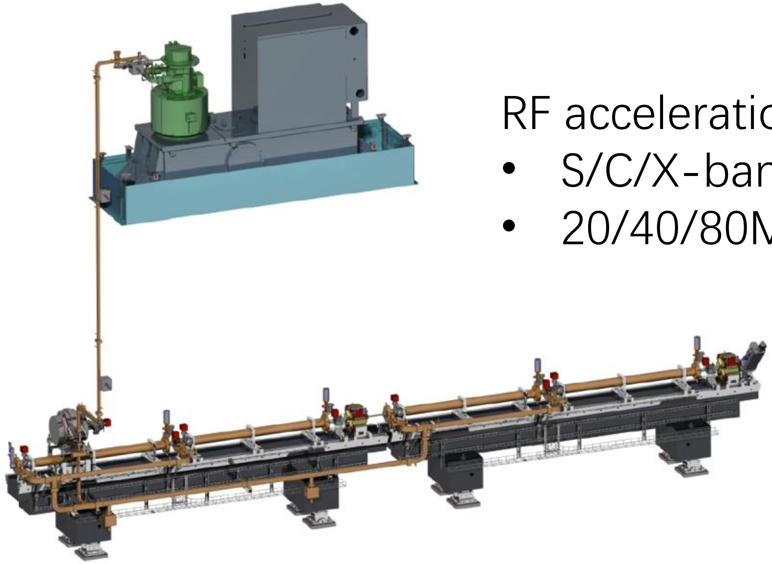
Pulse compressor

Waveguide system

Klystron

Low-level RF control

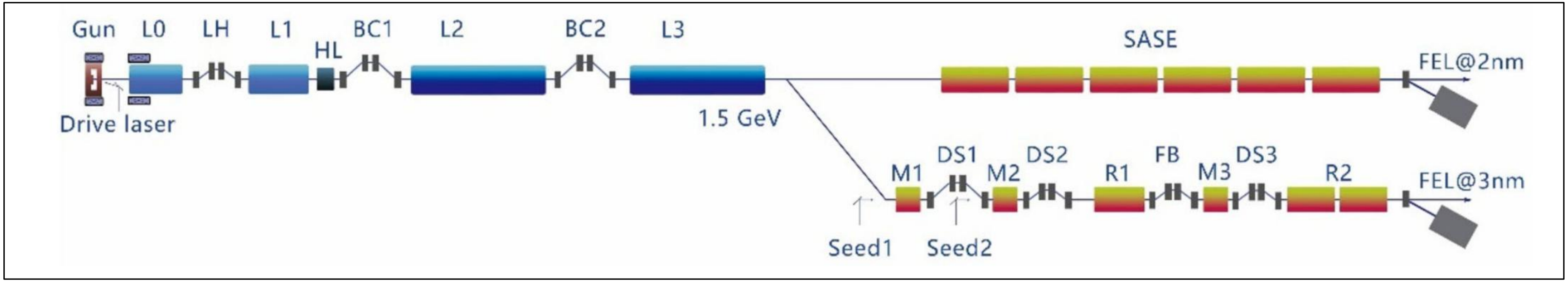


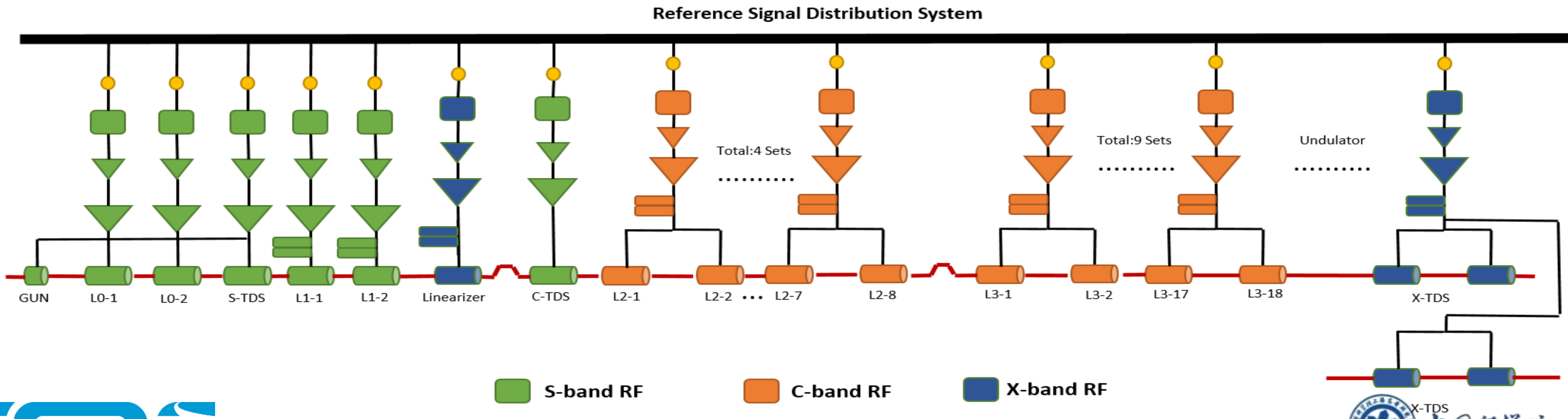


RF acceleration unit

- S/C/X-band
- 20/40/80MV/m

Linac example: NC RF system at SXFEL





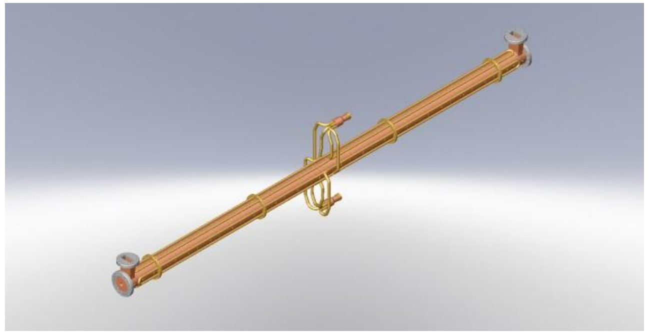
S-band accelerating structures at SXFEL

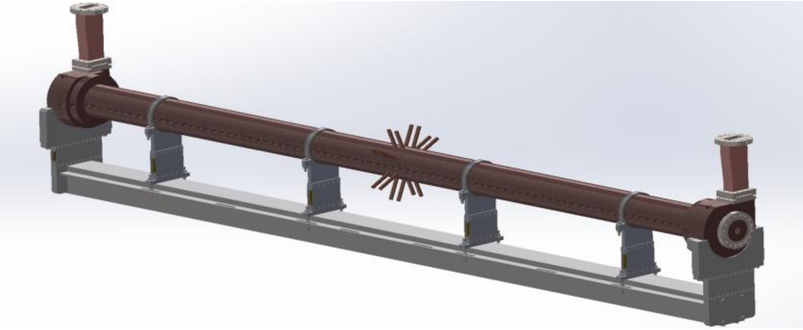
- ❑ Single port-> dual port, race track ->dual-port, dual mode.

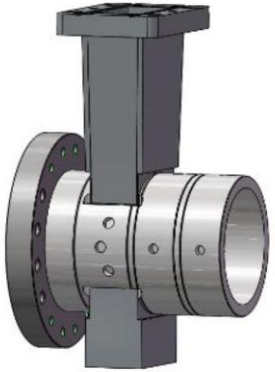
Single-port, side coupling
Outer water cooling
Multi-pole field
Max gradient: 17MV/m

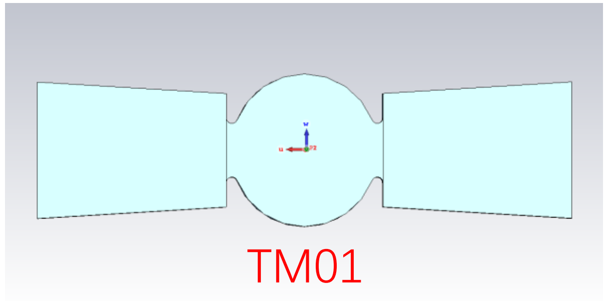
Dual-port, side coupling
Racetrack coupler
Assembling asymmetrically
Inner water cooling
Max gradient: 23MV/m

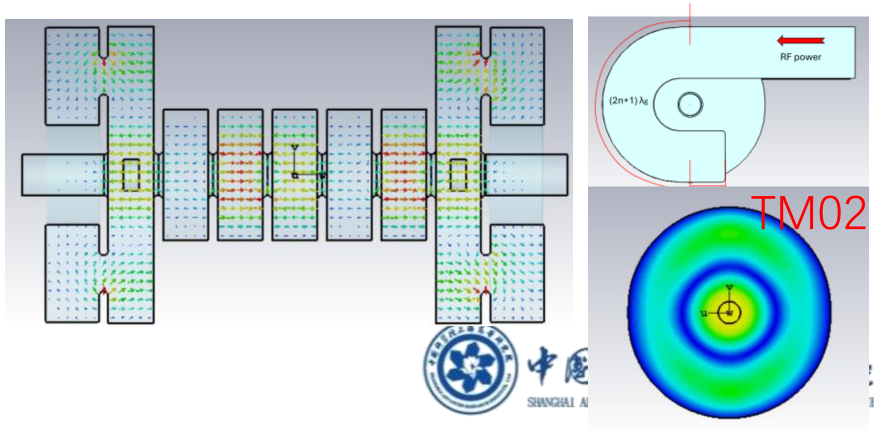
Dual feed, one-port
Racetrack coupler
Perfect symmetry
Inner water cooling
Max gradient: 23MV/m





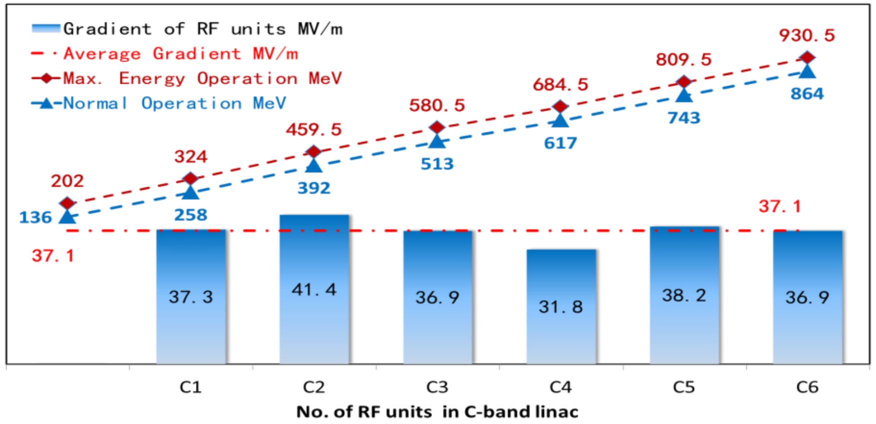


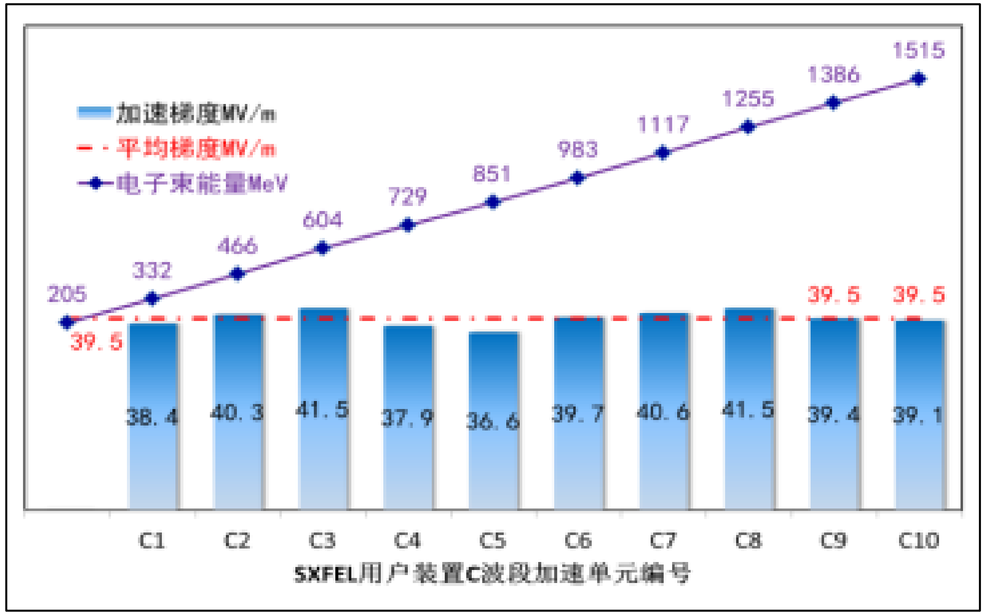


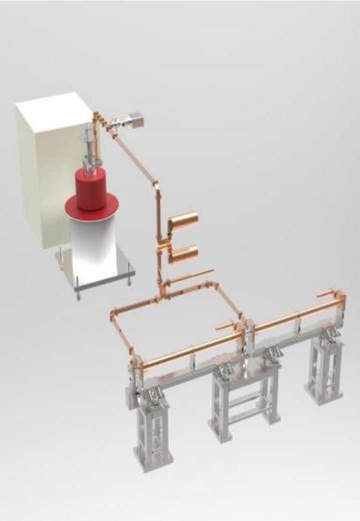


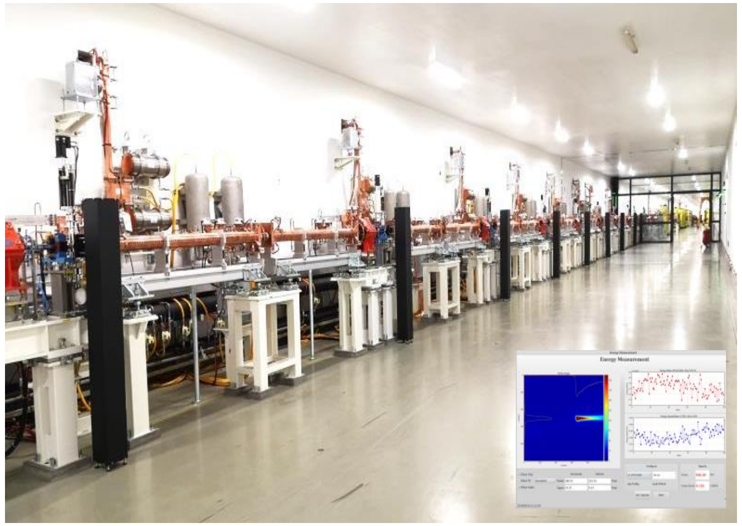
C-band accelerating structures at SXFEL

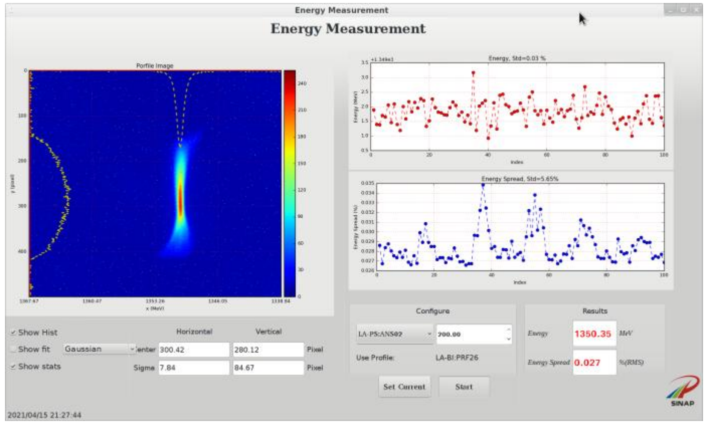
SWISSFEL*	SACLA**	SXFEL-TF	SXFEL-UF
28 MV/m	35 MV/m	37.1 MV/m	39.5 MV/m











Energy Measurement

☑ Show Hist
☐ Show fit Gaussian
☑ Show stats

	Horizontal	Vertical	
Center	300.42	280.12	Pixel
Sigma	7.84	84.67	Pixel

Configure

LA-PS:ANS02 200.00

Use Profile: LA-BI:PRF26

Set Current Start

Results

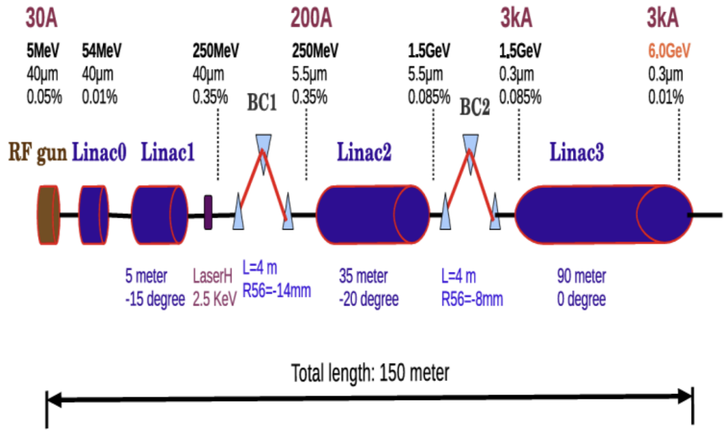
Energy 1350.35 MeV

Energy Spread 0.027 %(RMS)

2021/04/15 21:27:44

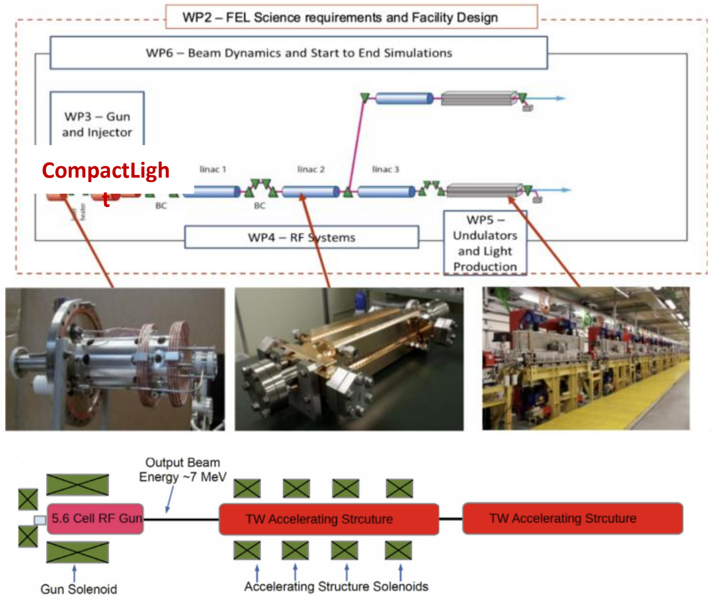
Linac example 2: Compact XFELs based on X-band technology

- A 6-GeV hard XFEL based on X-band photoinjector and linac is proposed by SLAC in 2012.
- The CompactLight design study, launched by a team of 22 International Laboratories and two Industries in January 2018. The main linac is based on very high-gradient X-band accelerating structures.
- SXFEL, LCLS, FERMI ELETTRA, Swiss FEL and PAL XFEL used X-band accelerating structrure and deflecting structure for linerizer and diagnostic.



A 6 GeV Hard XFEL based on X-band at SLAC

Y. P. Sun, et al. PRAB 15 (2012): 030703



CompactLight based on X-band RF gun and linac

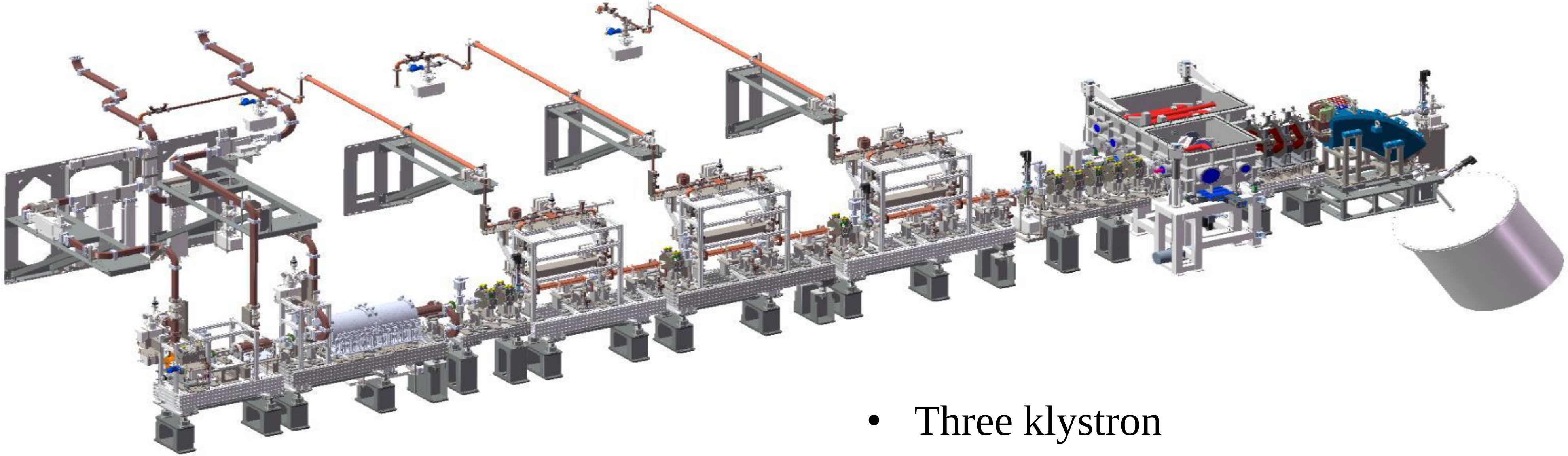
D. González-Iglesias, et al., NIM, A 1014 (2021) 165709.

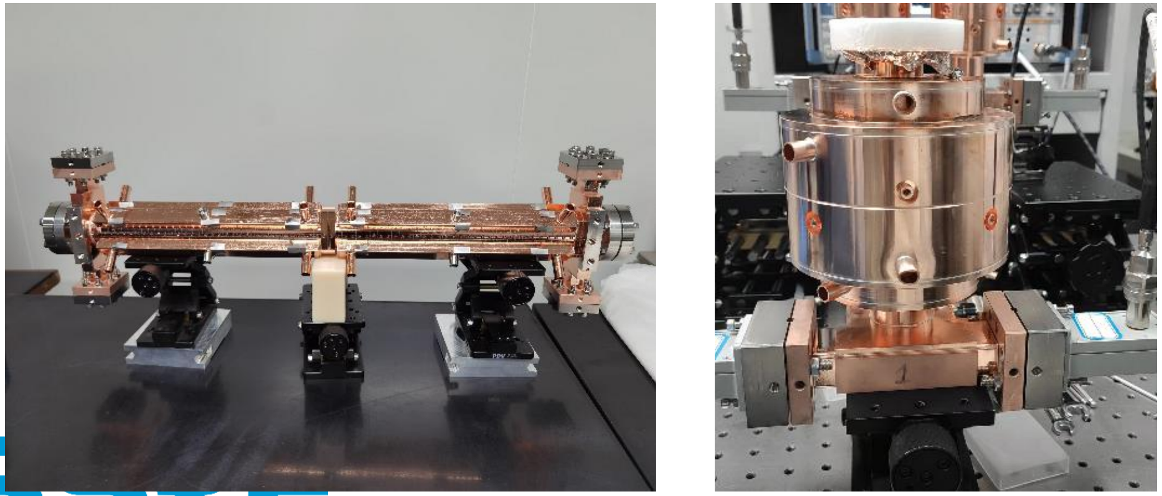
X-band accelerating structure and deflecting structure applied on SXFEL for linerizer and diagnostic.

X. X. Huang, et al., NIM, *A 854 (2017) 45-52.*

J. H. Tan, et al., NIM, *A 930 (2019) 210-219.*

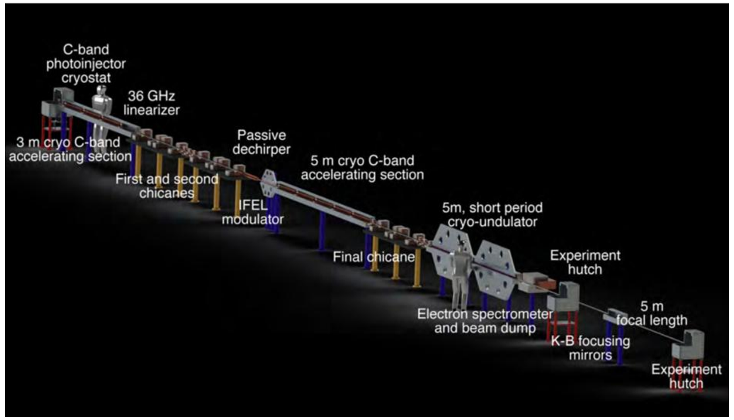
Linac example 3: X-band linac for VIGAS at Tsinghua University



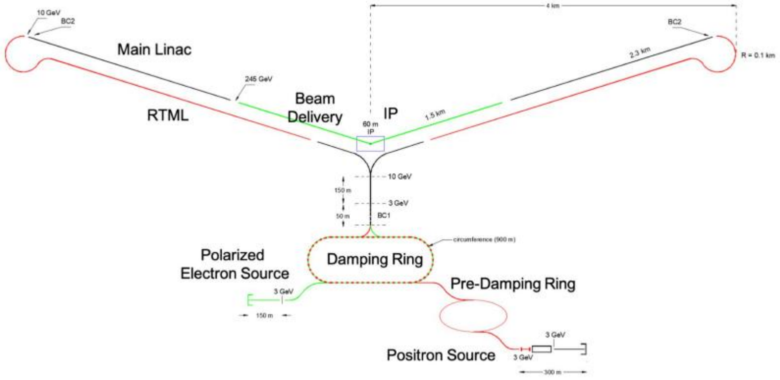


- Three klystron
  - Each 50 MW, 1.5us
- Three pulse compressor (SLED I type)
- Six X band high gradient structures
  - Average gradient >= 80 MV/m
  - Energy gain per structure > 50 MeV
  - Filling time < 150 ns
- 91 MW at Xacc w/ PC gain factor as 4.5

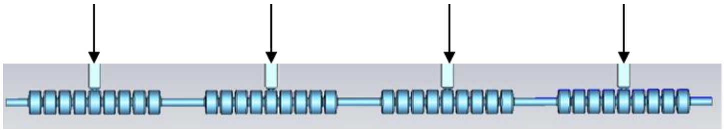
Next： Cryogenic high gradient accelerating structures



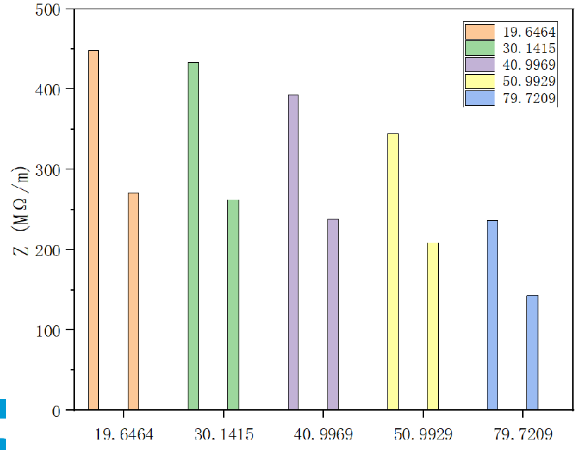
Cryogenic for ultra compact FEL

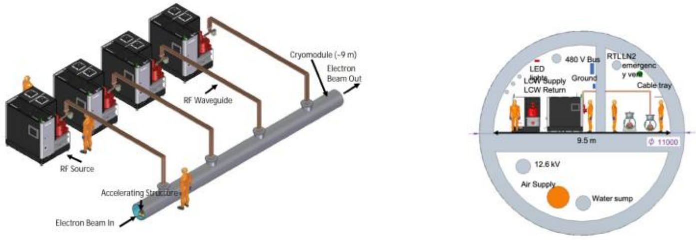


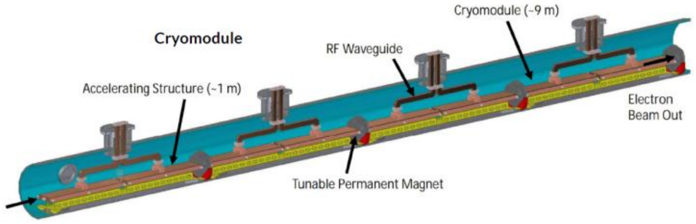
- C3: Cooled Copper Collider
- total length: 33 km->8 km，250/550GeV



Parameter	Value	Unit
Frequency	5712	MHz
Temperature	20-50	K
Shunt impedance@20K	0.0037	Ω
Gradient E_{acc}	65/80	MV/m
Meterial	Copper	
RRR	500	
Cooling	Helium	

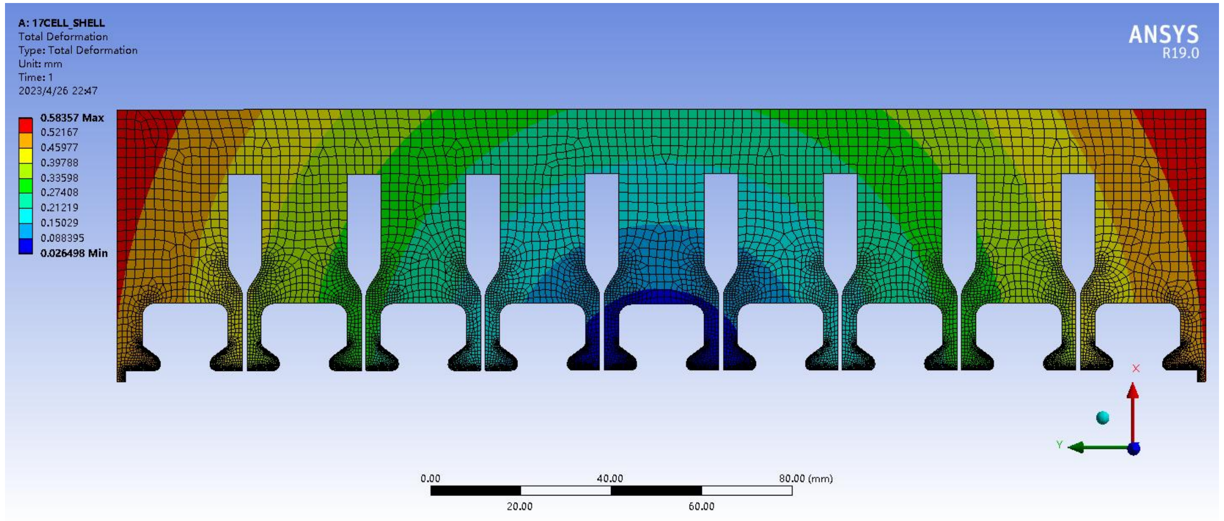


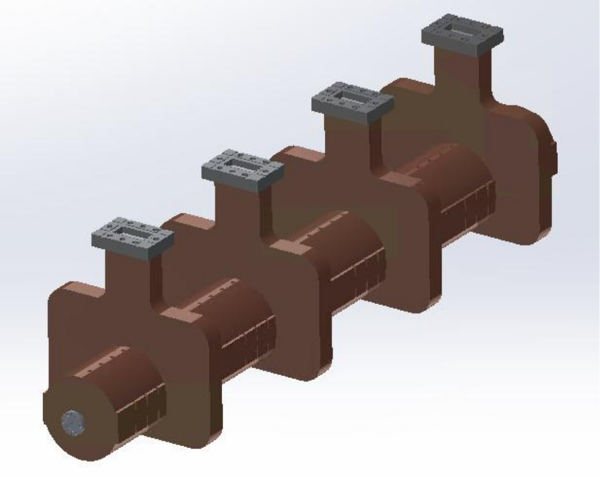


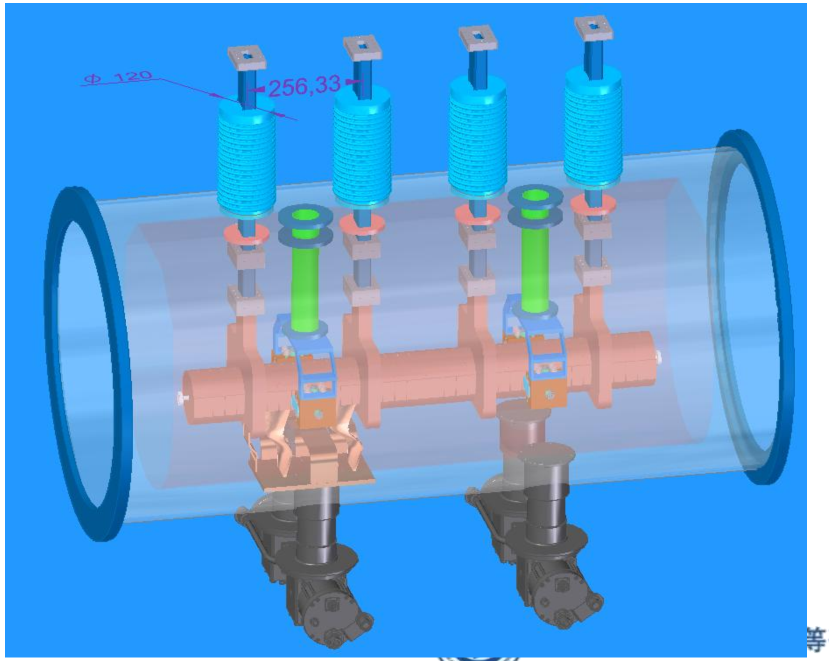


- C-band cryogenic module for C3
- 460MΩ/m
- 20-80K（27K for UC-XFEL；80K for C3)
- Peak electrical field: 140MV/m

Cryogenic RF cavity







- ☐ The structure dynamic thermal load is 80W@40K.
- ☐ Static thermal load 20W/40K.
- ☐ Plus 50%, total thermal load 150W@40K.
- ☐ The number of chillers is 4.
- ☐ For each chiller, the length and thickness of the cooling belt of the structure are calculated according to 75W@30K
- ☐ The fabrication of first cryogenic system prototype will carried out recently.

Some types of RF cavity

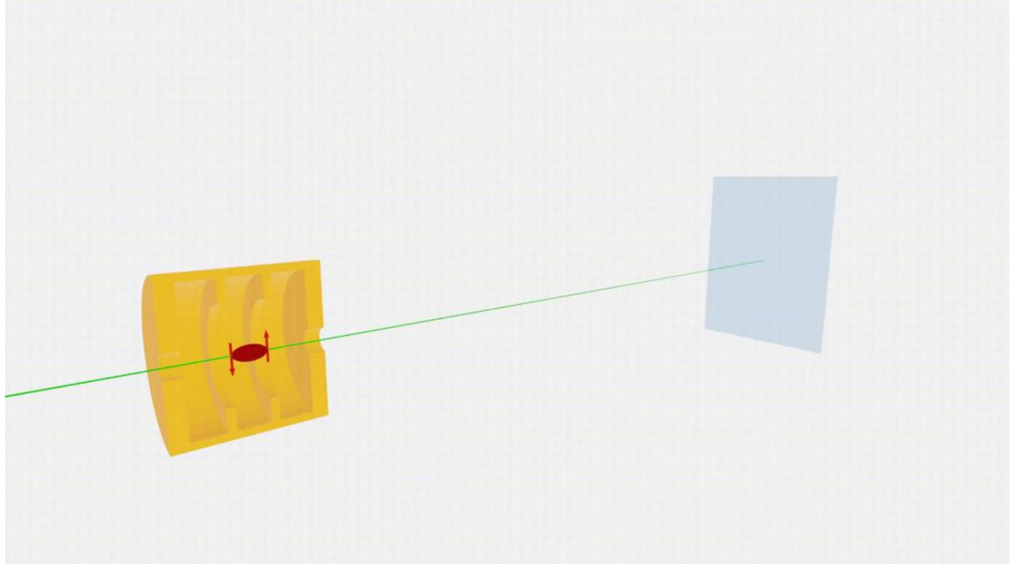
- ☐Accelerating structures
- ☐**Deflecting RF cavity**
- ☐NC Single-cell RF cavity

Deflecting RF cavity for beam diaganotics

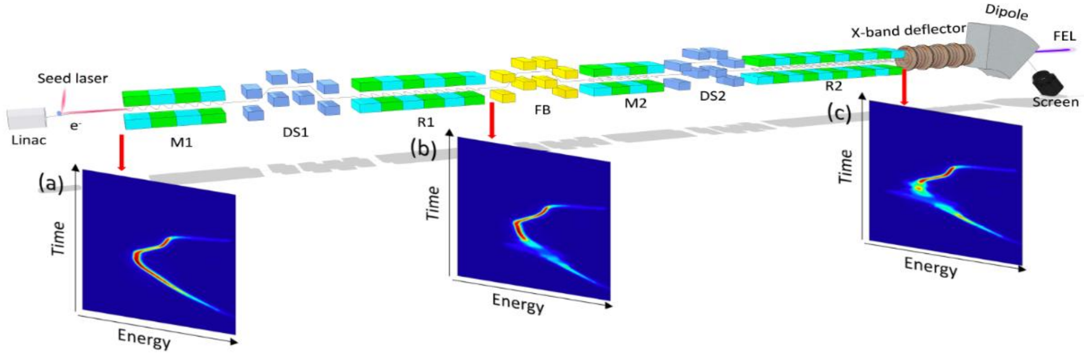
Principal of operation of the TM11 transverse deflecting RF cavity to measure bunch length, diagnose beam-laser synchronize and real-time lasing spectrum on a profile monitor.

$$eV_\perp \approx n\frac{\lambda}{2\pi c\Delta t}\sqrt{\frac{\varepsilon_N Emc^2}{\beta_d}}$$

$V_\perp$: *Deflecting voltage*
Δt : *time or length resolution*
$1/\lambda$: *frequecy of cavity*
ϵ : *Emittance*
E : *beam energy*
β_d : *twiss parameter*



X-band deflector can diagnose beam length in the scale of 10-20fs

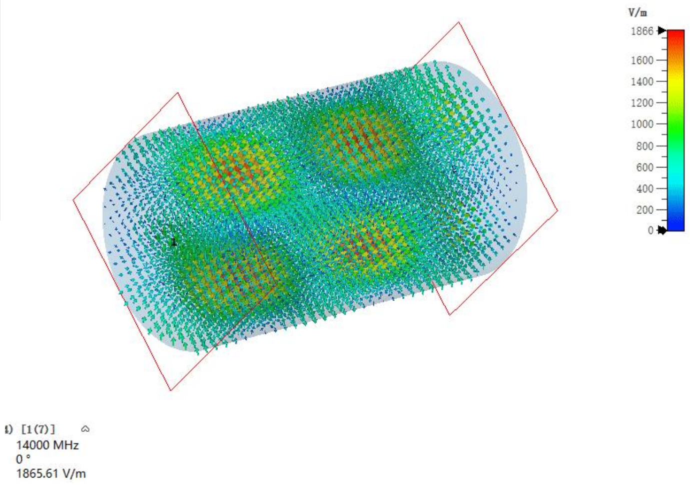


- ☐ Beam-laser synchronization: 10fs
- ☐ Real-time FEL lasing diagnostics

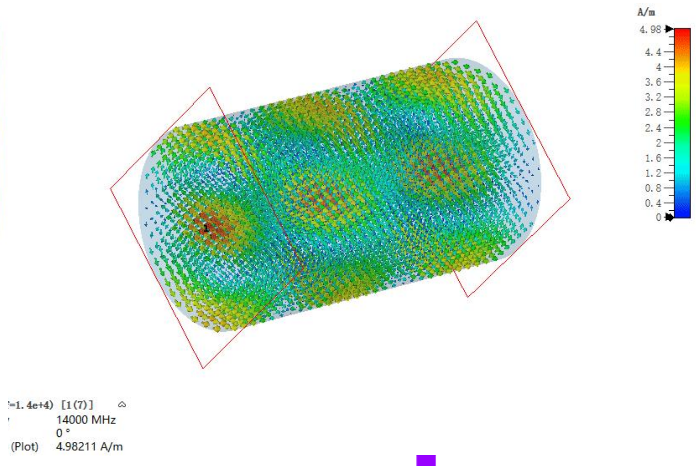
RF design of deflecting cavity

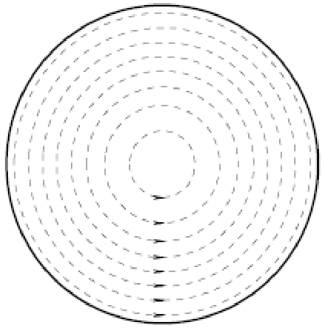
RF mode in the deflector is mixed with TM11 and TE11, called HEM11. TM11 is located in de the middle of cell, and TE11 is located on the iris tip. The structure is constant impedance.

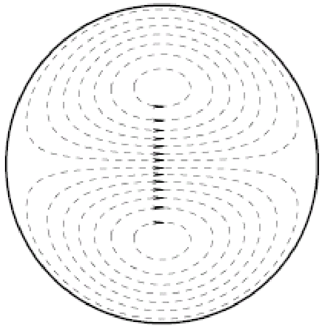
HEM11 E-Field

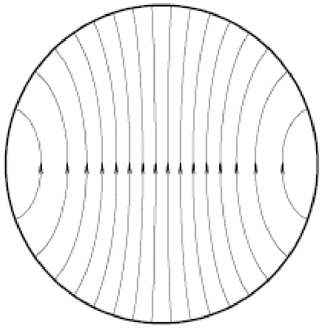


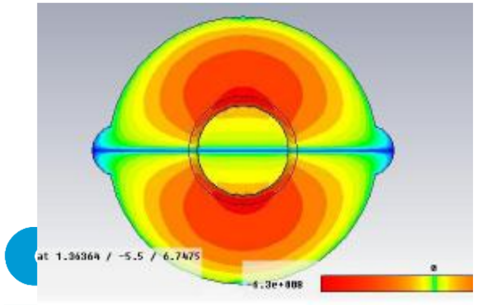
HEM11 H-Field

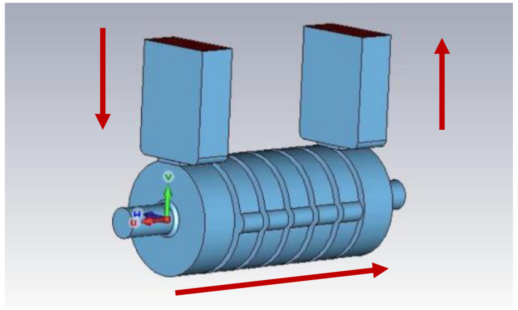


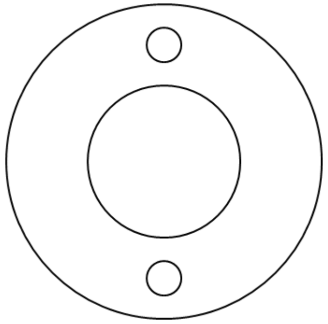

TM01

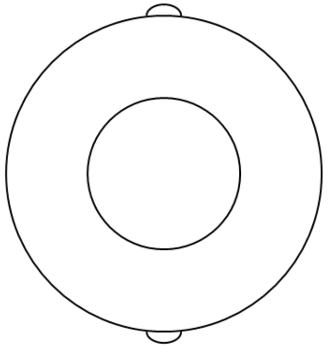

TM11

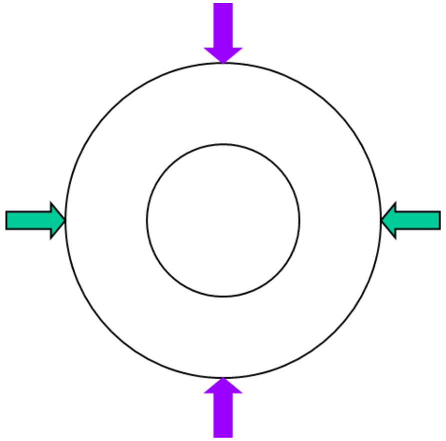

TE11





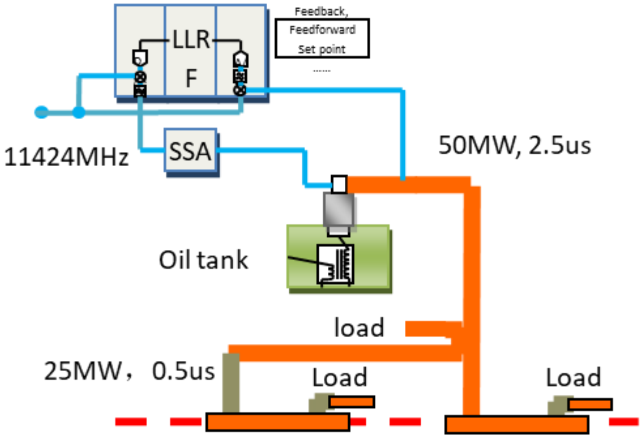

Two holes
(LOLA Structures)

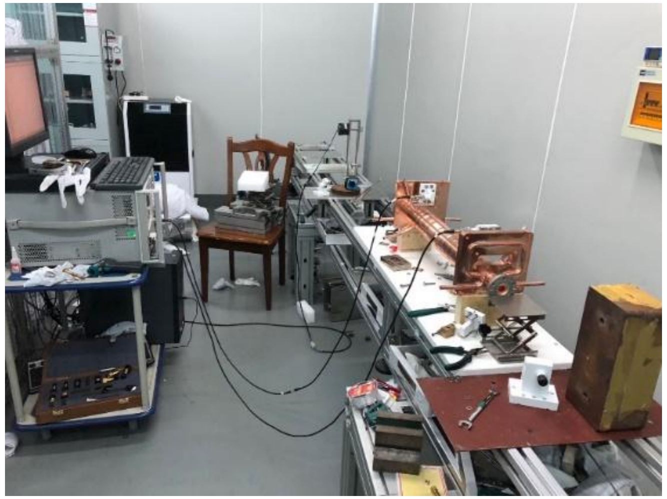

Two caved-ins
on cell ID surfaces

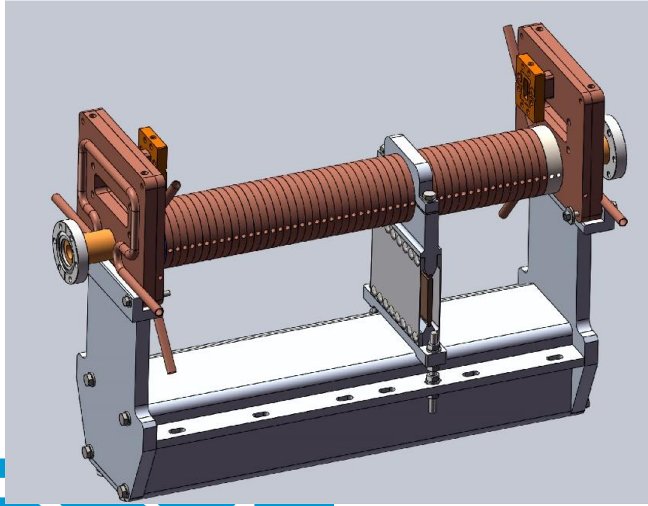

Deforming using
two more tuning holes

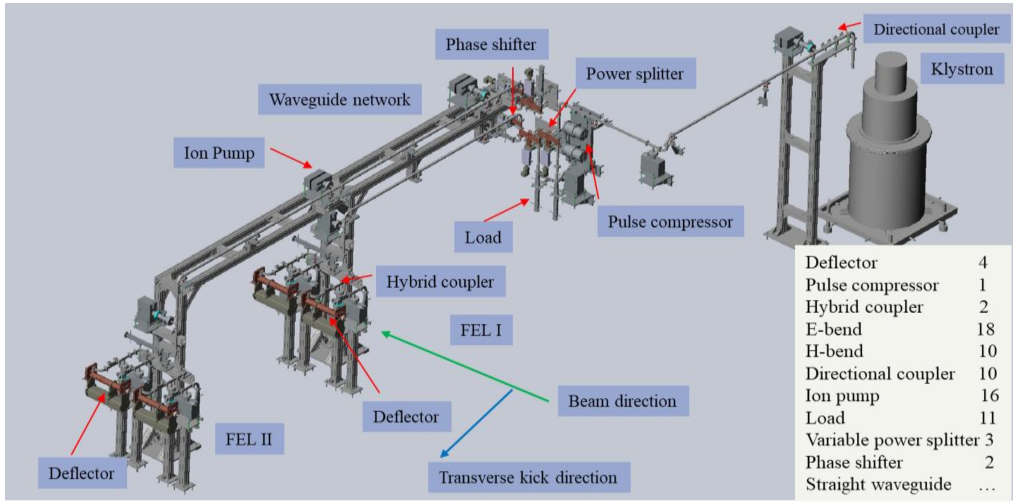
X-band deflecting cavities in SXFEL

- ☐ Dual-coupler design for new deflector
- ☐ One power unit for SXFEL
- ☐ Two deflector units for SXFEL

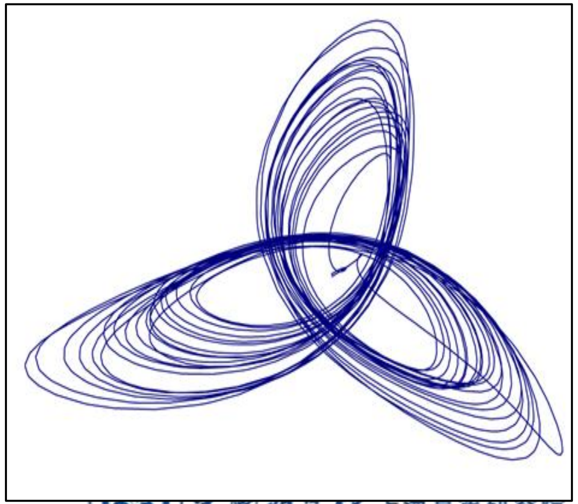




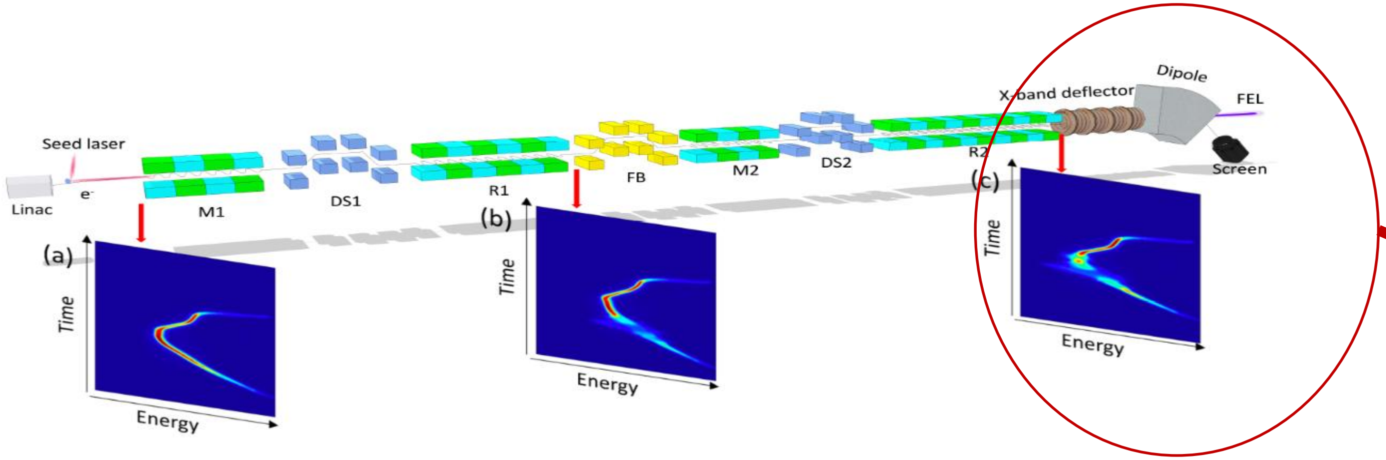


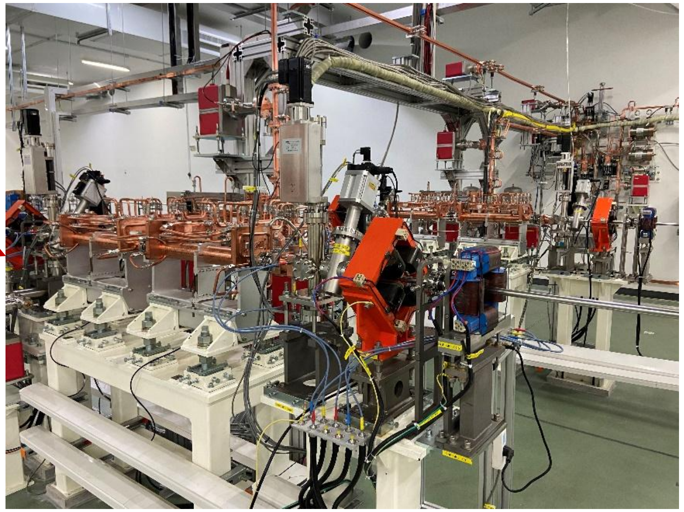


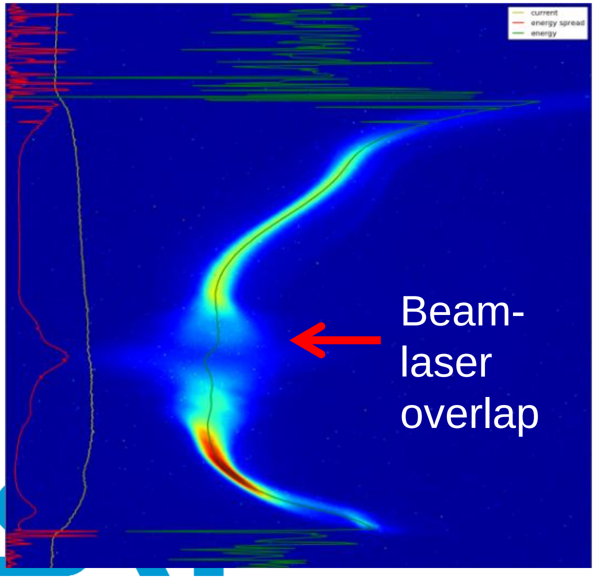
Deflector	4
Pulse compressor	1
Hybrid coupler	2
E-bend	18
H-bend	10
Directional coupler	10
Ion pump	16
Load	11
Variable power splitter	3
Phase shifter	2
Straight waveguide	…



Beam-laser overlap and lasing feature real-time diagnostics at SXFEL



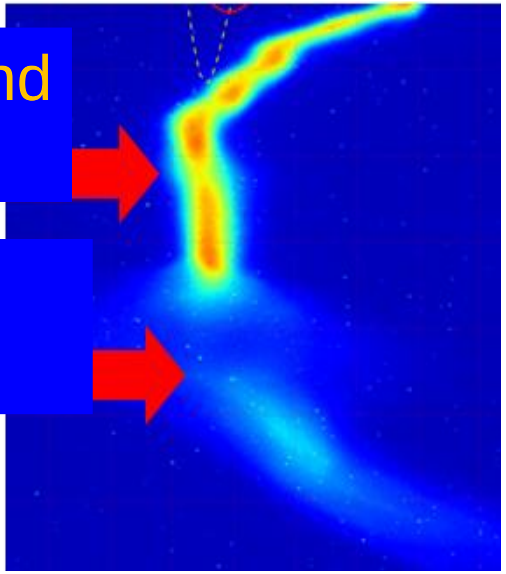


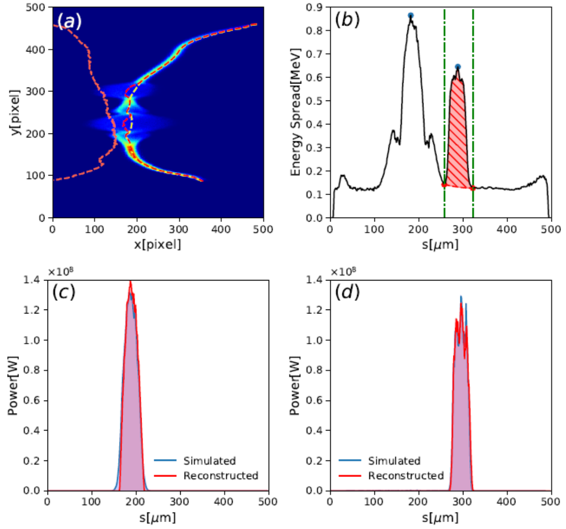


Beam-laser overlap

Second stage

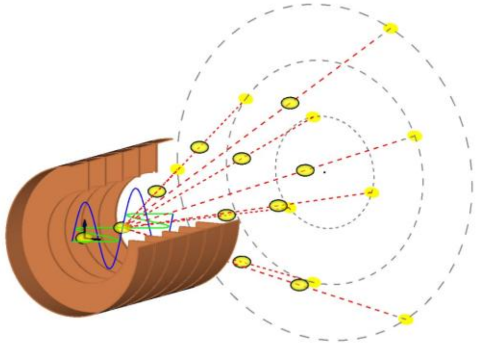
First stage

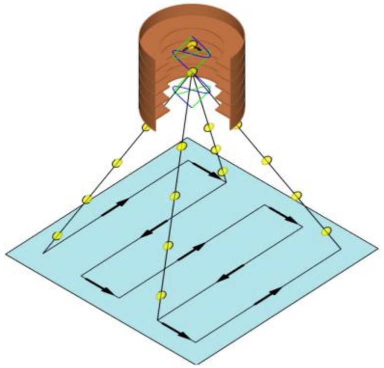




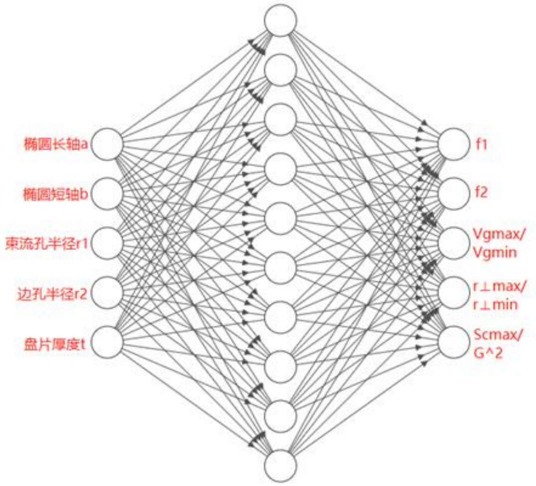
New Dual-mode deflector for variable polarization

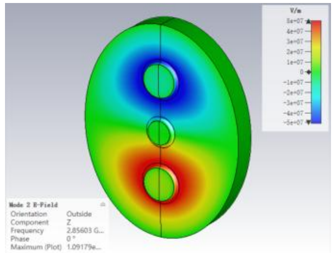
1. HEM01 on 2856 MHz, HEM02 on 5712 MHz
2. 6-D (x, x′, y, y′,z, z′) Tomography, FLASH scanning
3. Neural network and MOGA for optimize the RF structure
4. Two-port for coupling two modes independently.



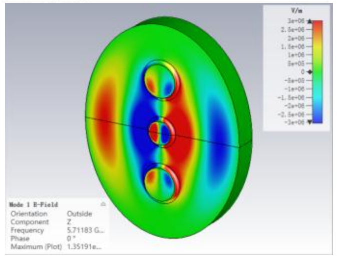


PRAB Editor’s suggestion

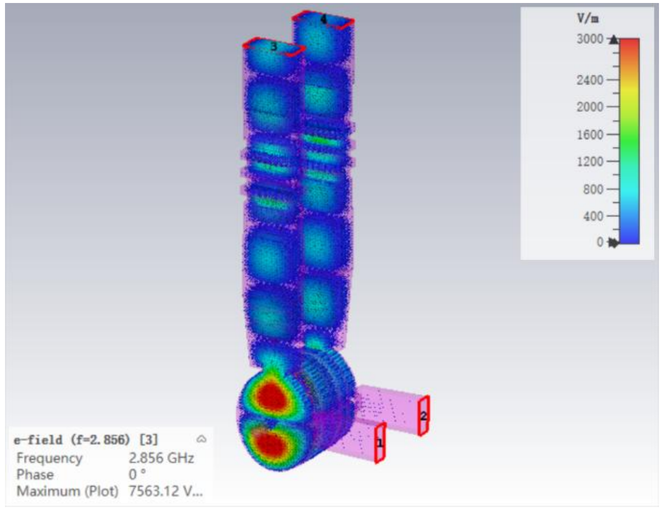




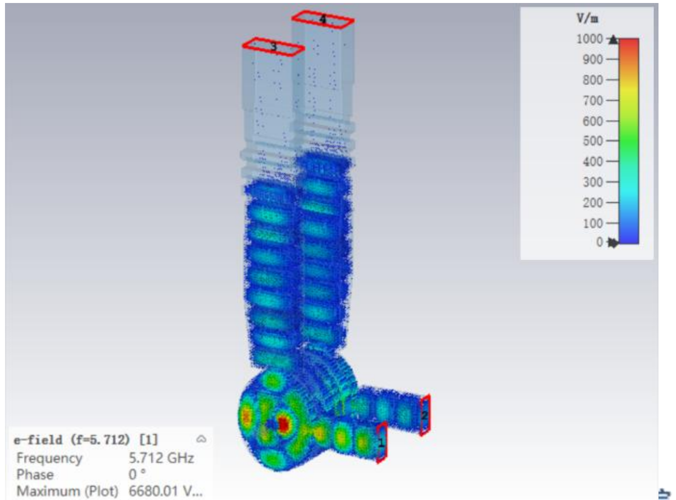
Mode 2 E-Field
Orientation Outside
Component Z
Frequency 2.85603 G...
Phase 0 °
Maximum (Plot) 1.09179e...



Mode 1 E-Field
Orientation Outside
Component Z
Frequency 5.71183 G...
Phase 0 °
Maximum (Plot) 1.35191e...



e-field (f=2.856) [3]
Frequency 2.856 GHz
Phase 0 °
Maximum (Plot) 7563.12 V...



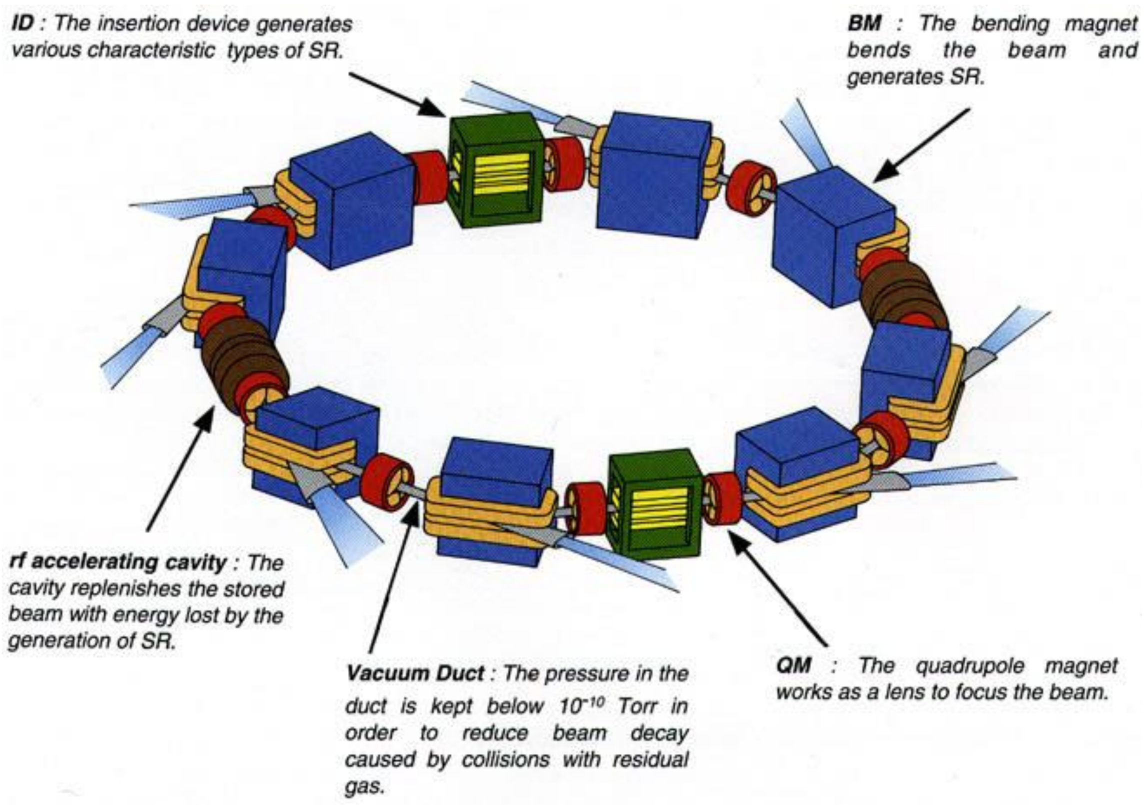
e-field (f=5.712) [1]
Frequency 5.712 GHz
Phase 0 °
Maximum (Plot) 6680.01 V...

SHANGHAI ADVANCED RESEARCH INSTITUTE, CHINESE ACADEMY OF SCIENCES

Some types of RF cavity

- ☐Accelerating structures
- ☐Deflecting RF cavity
- ☐**NC Single-cell RF cavity**

Normal conducting single-cell RF cavity for light source



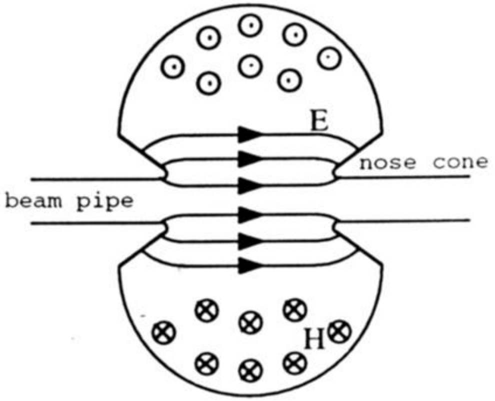
ID *: The insertion device generates various characteristic types of SR.*

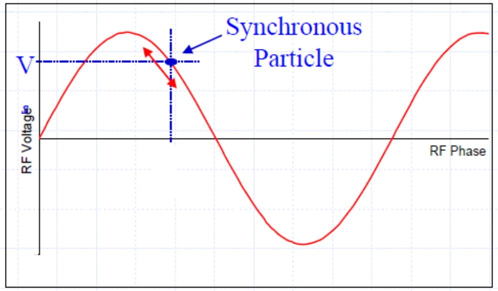
BM *: The bending magnet bends the beam and generates SR.*

rf accelerating cavity *: The cavity replenishes the stored beam with energy lost by the generation of SR.*

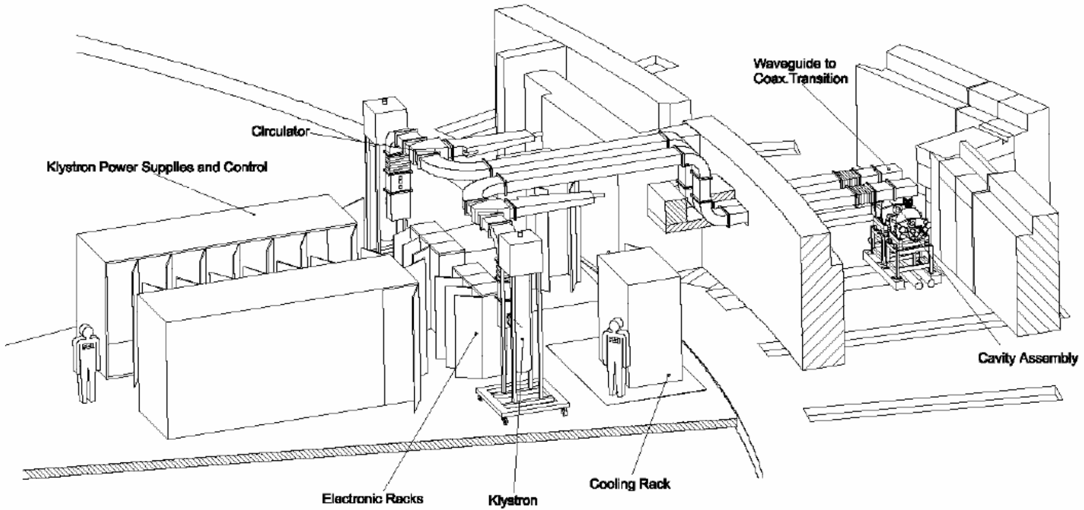
Vacuum Duct *: The pressure in the duct is kept below 10^{-10} Torr in order to reduce beam decay caused by collisions with residual gas.*

QM *: The quadrupole magnet works as a lens to focus the beam.*





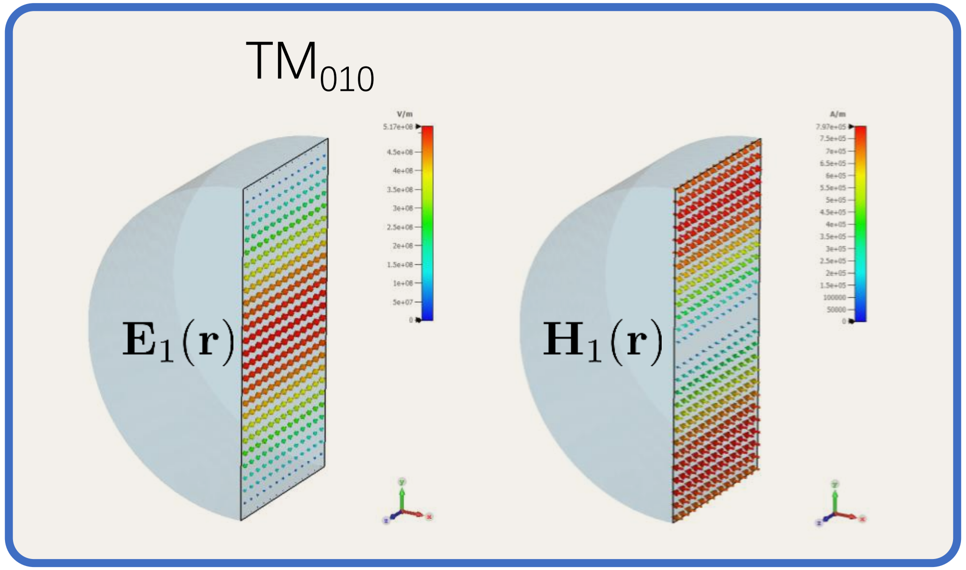
$$V_{rf} = V_c \sin(\omega_{rf} t + \phi)$$

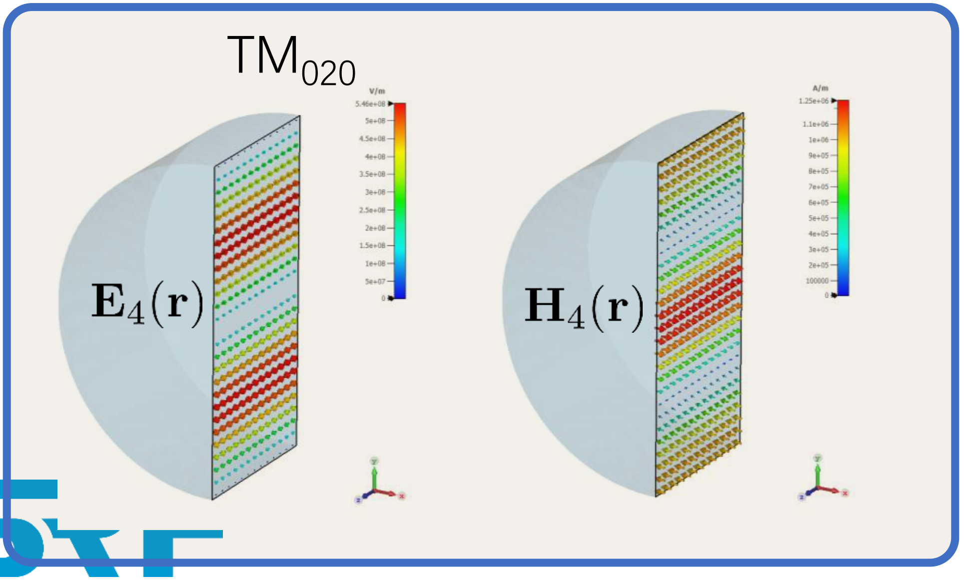


Function of RF cavity in light source

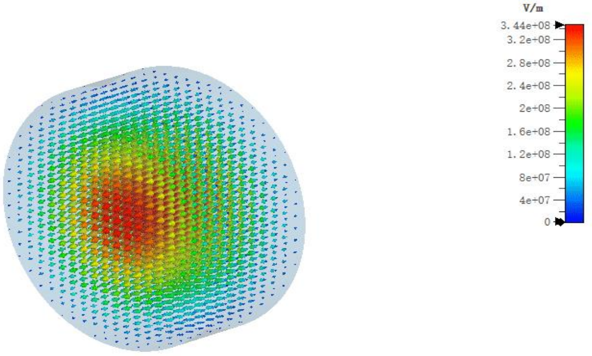
- Delivers the energy to electrons for compensating the energy loss due to Synchrotron radiation and interactions with beam chamber impedance, or ramping the electron beam to higher energy;
- Establishes RF voltage to capture and focus the electrons into bunches;
- Controls beam parameters, such as bunch length, beam lifetime, etc.;
- Provides damping effects to the electron motions by synchrotron radiation and RF acceleration.

Standing wave “Pillbox” model of single-cell RF cavity





TM010
E-Field



$$E_z = E_0 J_0(k_c r) \cdot \cos(\omega t - \beta z)$$

TW+

Phase 0 °
Maximum (Plot) 3.44442e+08 V/m

$$+$$

$$E_z = E_0 J_0(k_c r) \cdot \cos(\omega t + \beta z)$$

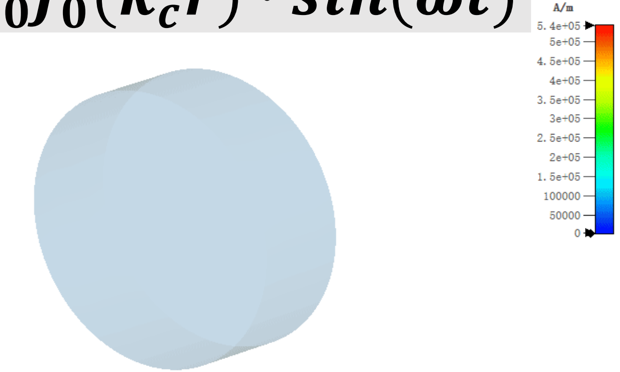
TW-

$$\|$$

$$E_z = E_0 J_0(k_c r) \cdot sin(\omega t)$$

SW

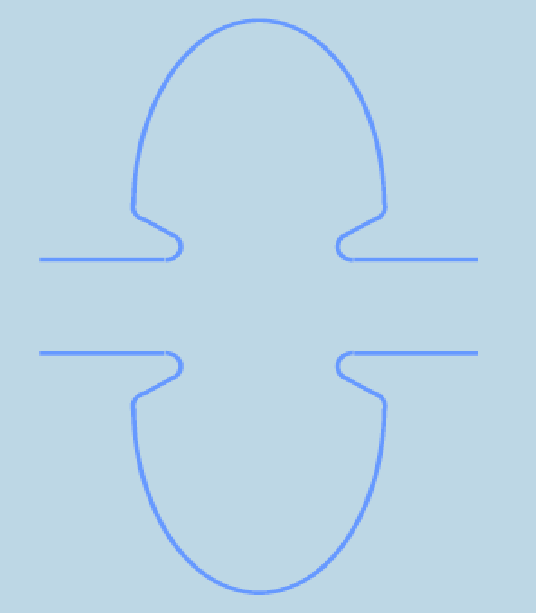
TM010
H-Field

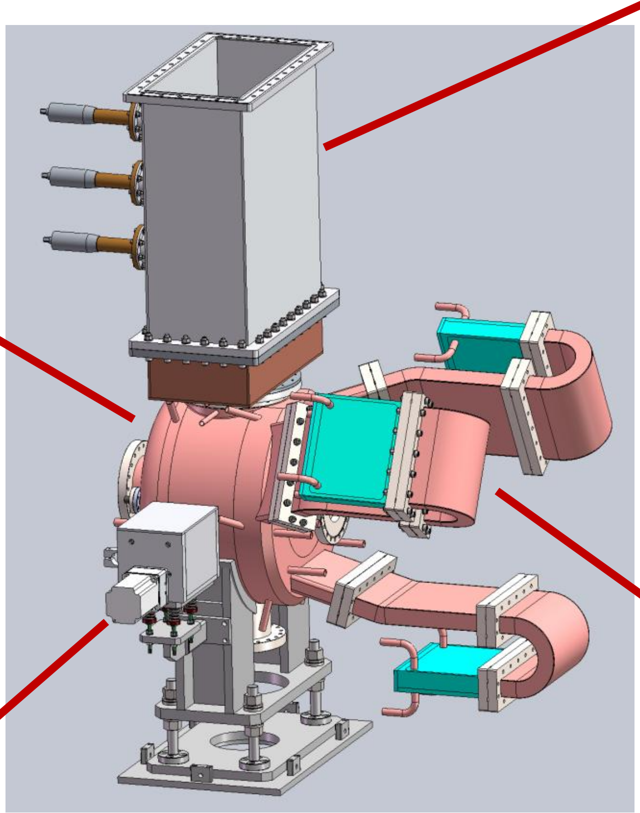


Mode 1 H-Field
Frequency 7649.52 MHz
Phase 0 °
Maximum (Plot) 540312 A/m

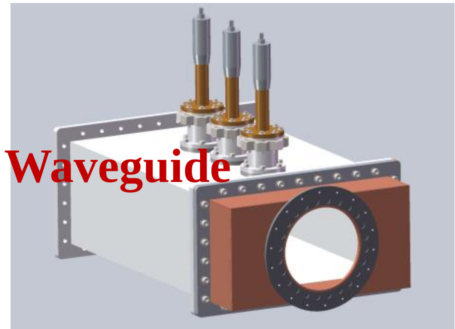
Some key components of RF cavity

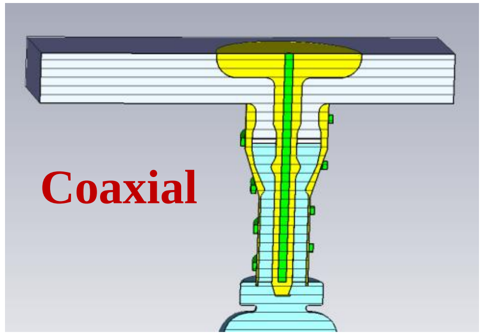
Main cavity, high R/Q



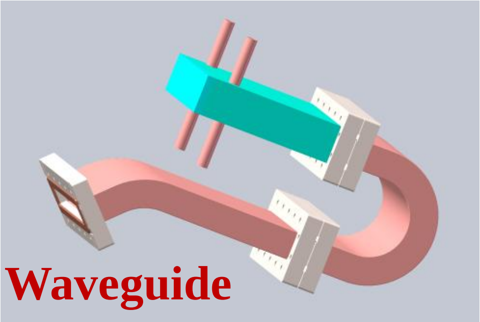


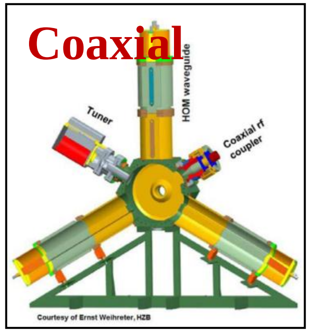
Coupler, power input



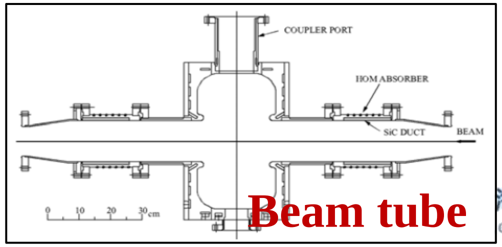


HOM damper, three types

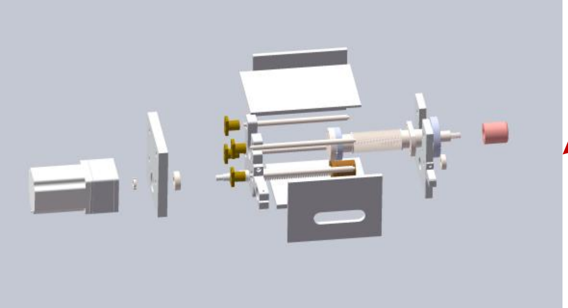




Courtesy of Ernst Weihreter, HZB



Tuner on frequency



Some key parameters of RF cavity

Shunt impedance $R = \frac{V_c^2}{P_c} = \frac{(E_0 \cdot L)^2}{P_c}$

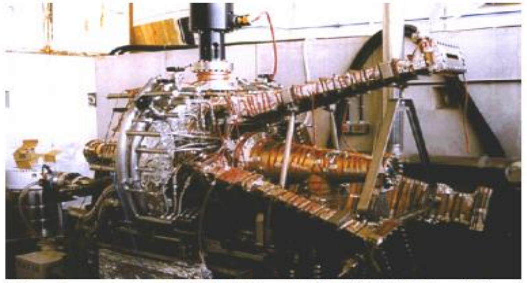
Effective Shunt impedance $R_s = \frac{V_e^2}{P_c} = \frac{(E_0 \cdot T \cdot L)^2}{P_c} = R \cdot T^2$

T: Transition factor

Quality factor $Q_0 = \frac{\omega U}{P_c}$

Normalized impedance $R/Q = \frac{V_c^2}{\omega U}$

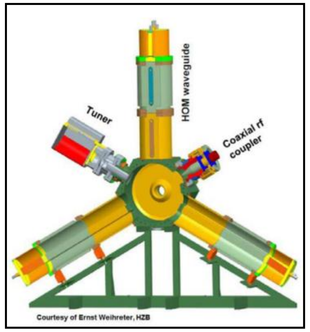
Some typic single-cell RF cavities

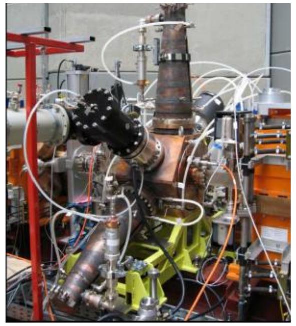


Daphne cavity, 368.2 MHz, 250 kV, 2 MΩ, L=1.9m

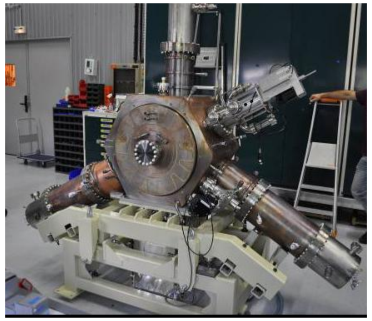
KEK ARES cavity, 509 MHz, 500 kV, 1.7 MΩ

BESSY-II 500MHz

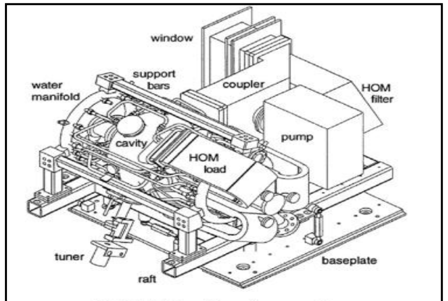




ESRF 352.2 MHz

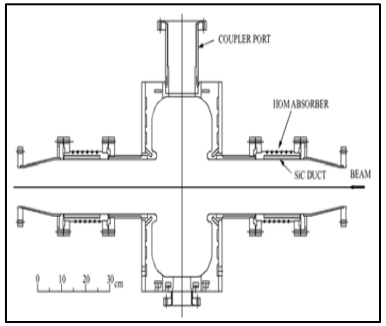


PEP-II 476MHz

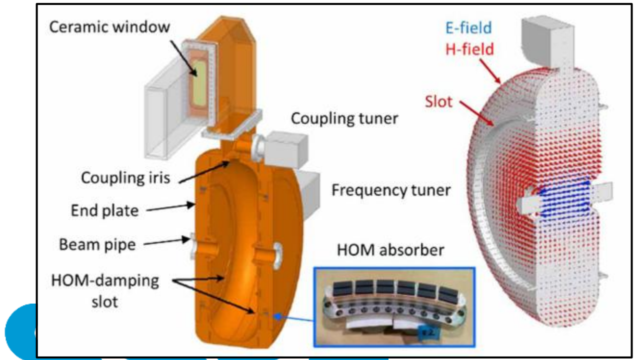


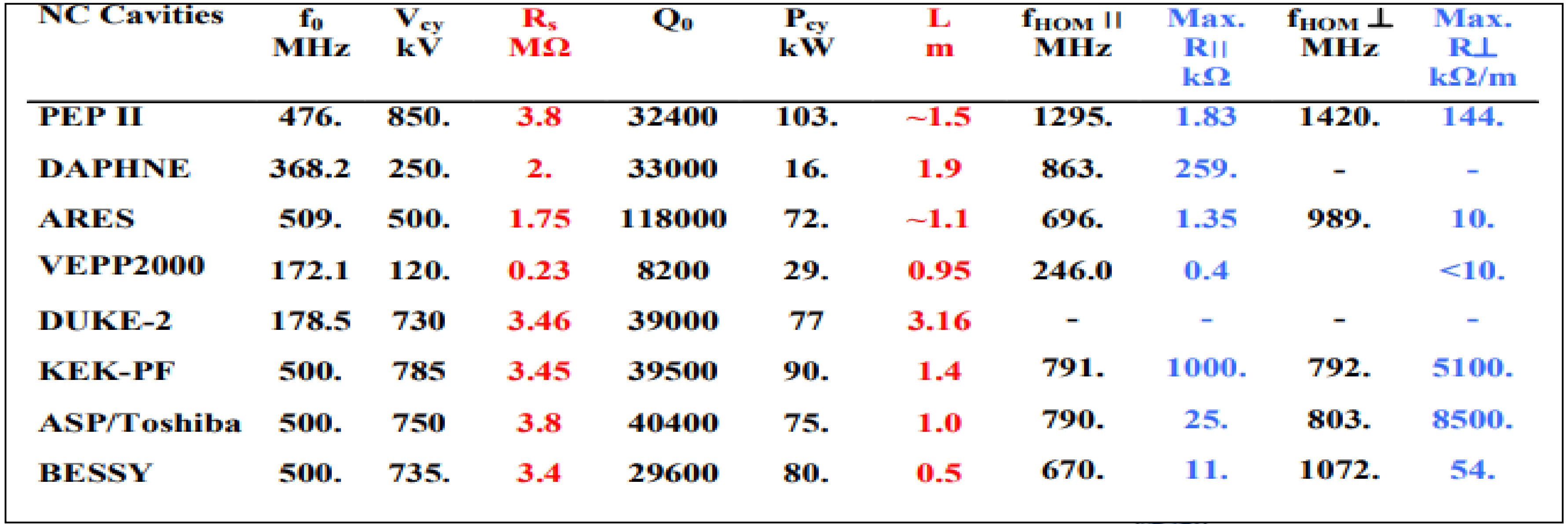
PEP-II RF cavity raft assembly

KEK-PF 500MHz



Spring-8 TM_{020}

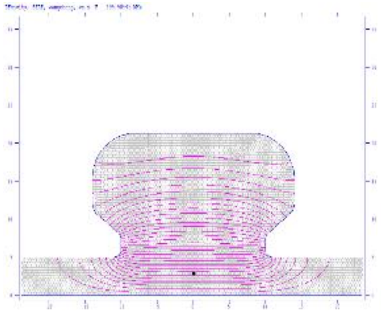


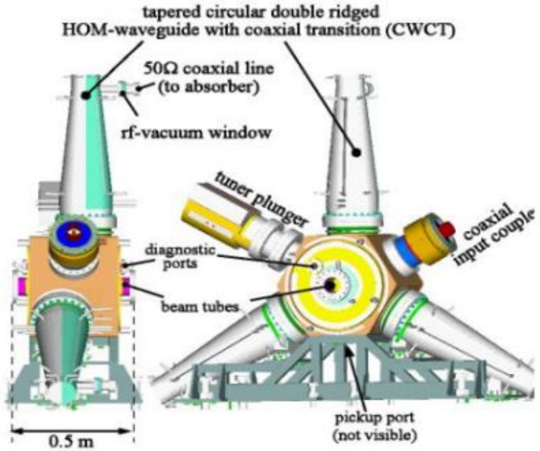


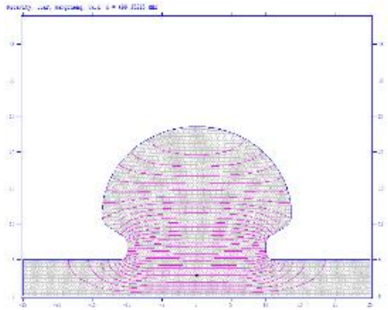
NC Cavities	f_0 MHz	V_{cy} kV	R_s MΩ	Q_0	P_{cy} kW	L m	f_{HOM} ‖ MHz	Max. R‖ kΩ	f_{HOM} ⊥ MHz	Max. R⊥ kΩ/m
PEP II	476.	850.	3.8	32400	103.	~1.5	1295.	1.83	1420.	144.
DAPHNE	368.2	250.	2.	33000	16.	1.9	863.	259.	-	-
ARES	509.	500.	1.75	118000	72.	~1.1	696.	1.35	989.	10.
VEPP2000	172.1	120.	0.23	8200	29.	0.95	246.0	0.4		<10.
DUKE-2	178.5	730	3.46	39000	77	3.16	-	-	-	-
KEK-PF	500.	785	3.45	39500	90.	1.4	791.	1000.	792.	5100.
ASP/Toshiba	500.	750	3.8	40400	75.	1.0	790.	25.	803.	8500.
BESSY	500.	735.	3.4	29600	80.	0.5	670.	11.	1072.	54.

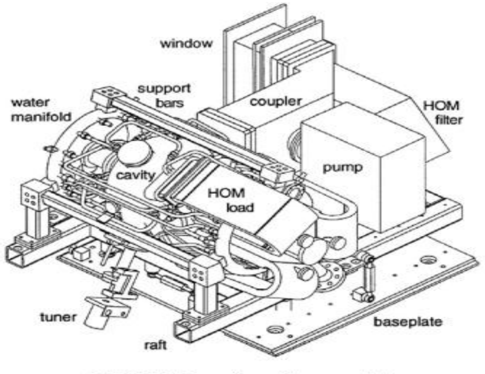
Example on new R&D at SARI: BESSY + PEP-II

Bessy Cavity





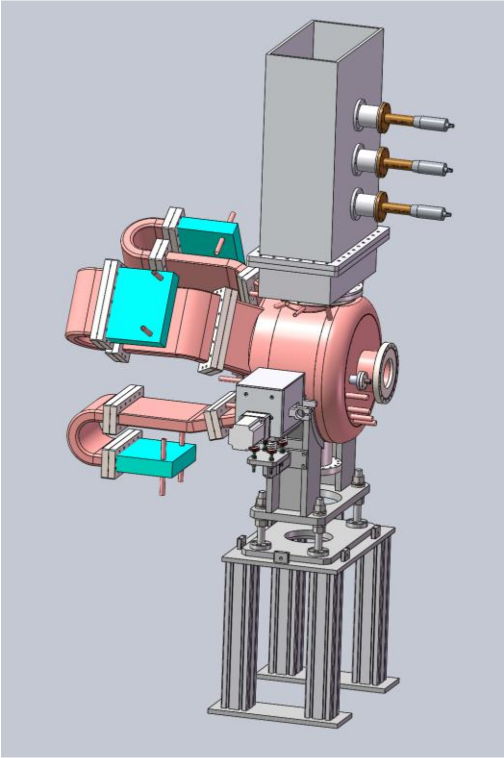


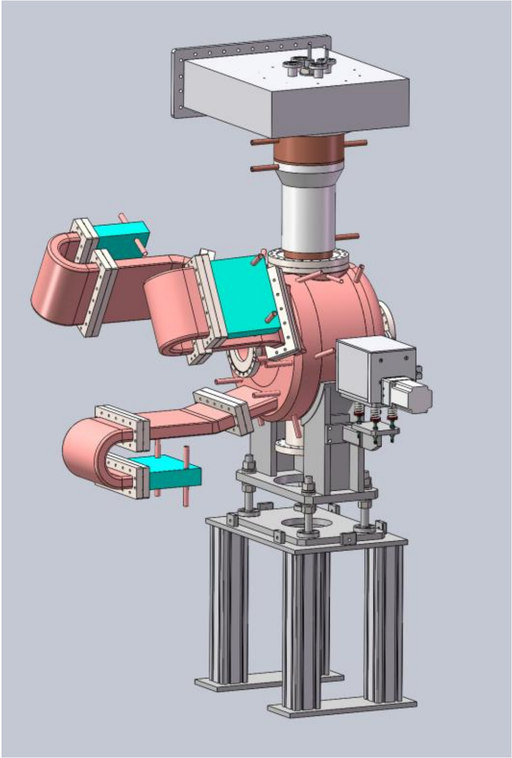


PEP-II RF cavity raft assembly

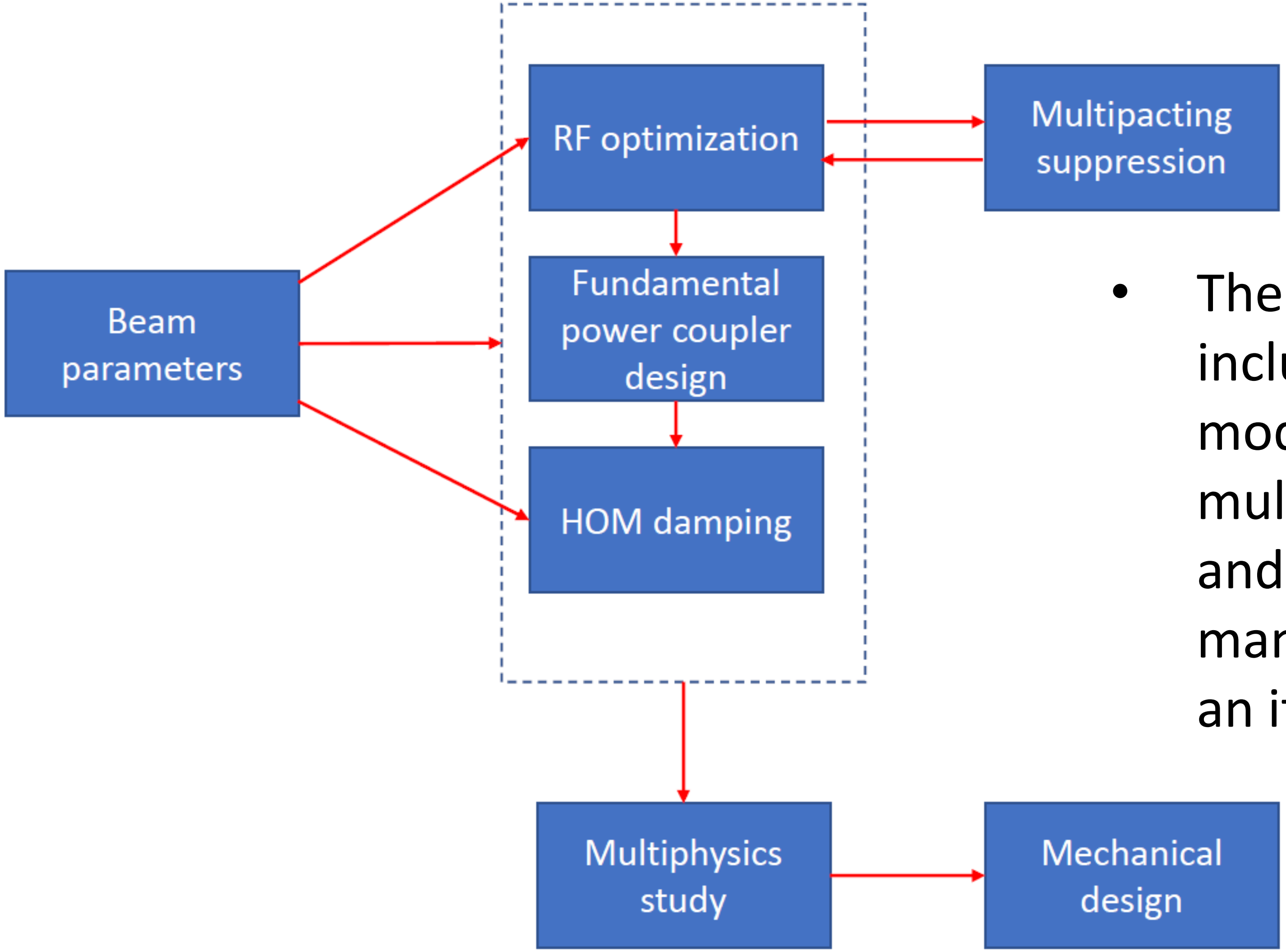
PEP-II HOMers

Bessy Cavity + PEP-II HOM, two types of coupler



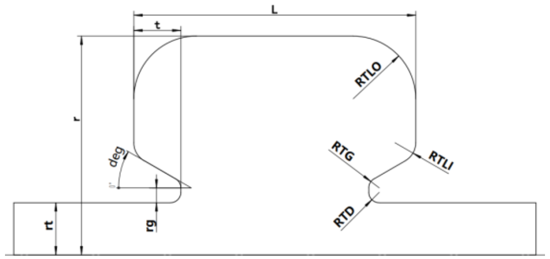


Design of the RF cavity



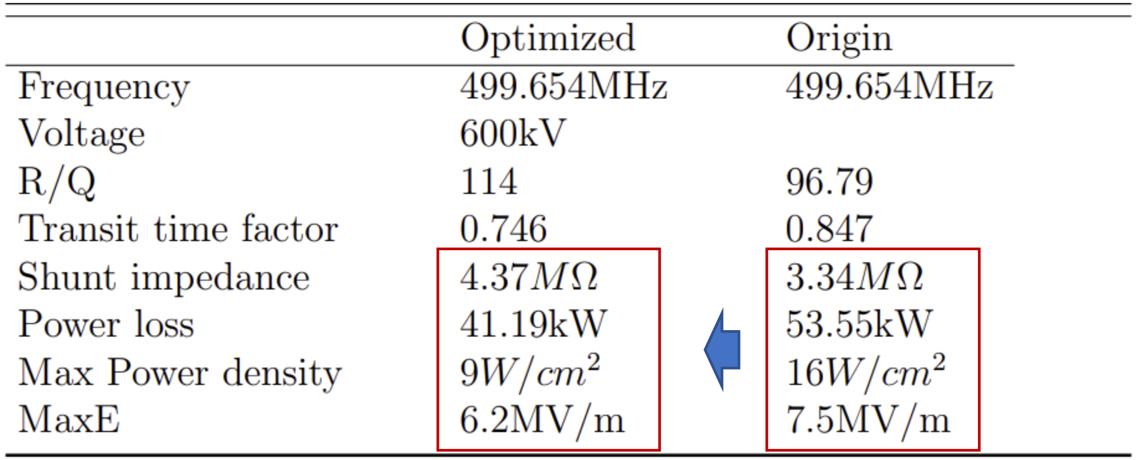
- The design of the RF cavity includes the fundamental mode optimization, the multipacting suppression, and the HOM-damping and many other progress, and is an iterative process.

Design of the RF cavity —— MOGA

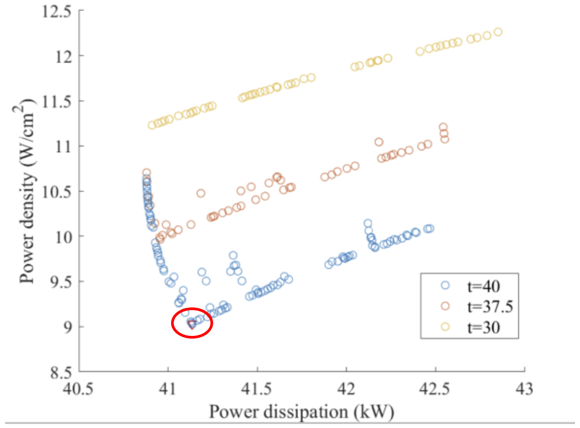


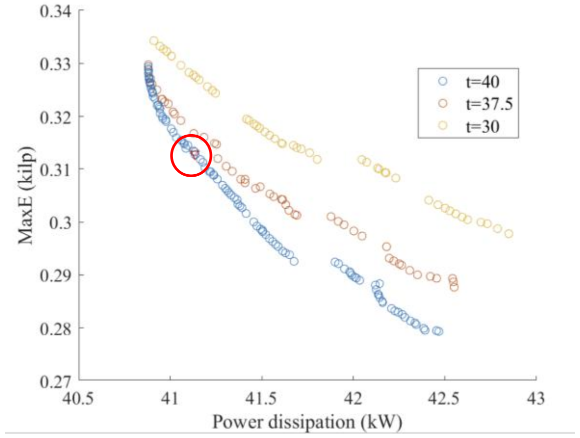
Multi-objective evolutionary algorithm for the cavity optimization

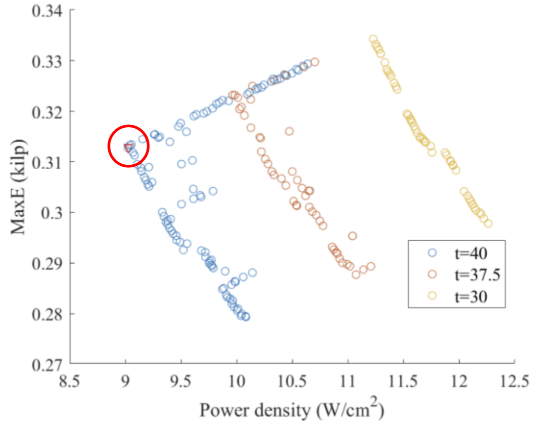
Objective	Constraint
With V*T=600kV	RF frequency 499.65~0.2MHz
Minimize P	Cavity radius<30cm
Minimize Pden	Beam tube=100mm
Minimize E	



	Optimized	Origin
Frequency	499.654MHz	499.654MHz
Voltage	600kV	
R/Q	114	96.79
Transit time factor	0.746	0.847
Shunt impedance	$4.37M\Omega$	$3.34M\Omega$
Power loss	41.19kW	53.55kW
Max Power density	$9W/cm^2$	$16W/cm^2$
MaxE	6.2MV/m	7.5MV/m

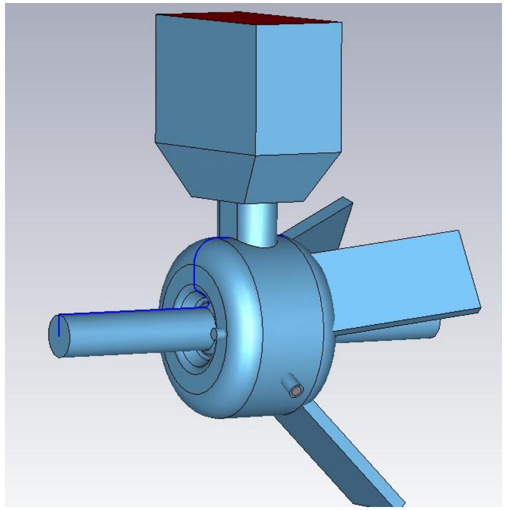


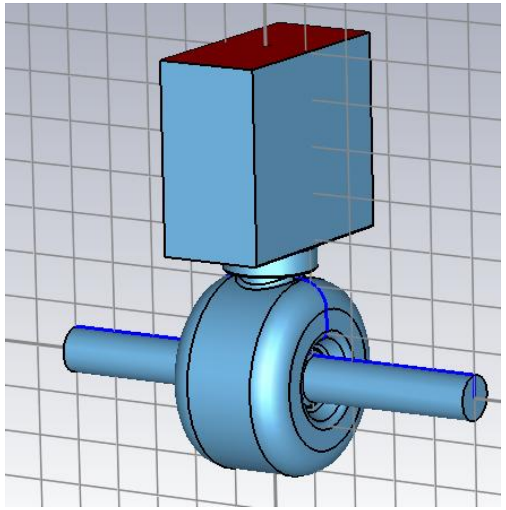


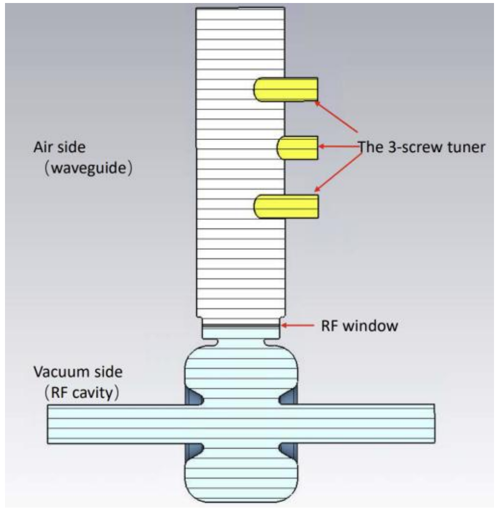


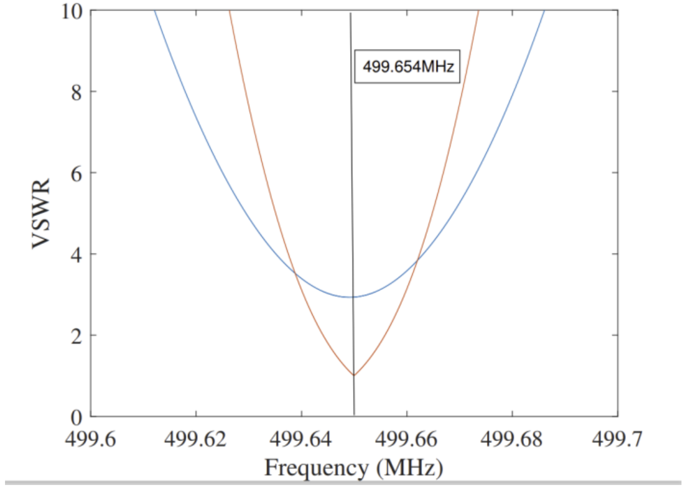
- Positive between power dissipation and power density
- Maximum electric field and power density are mutually exclusive.

Design of the coupler

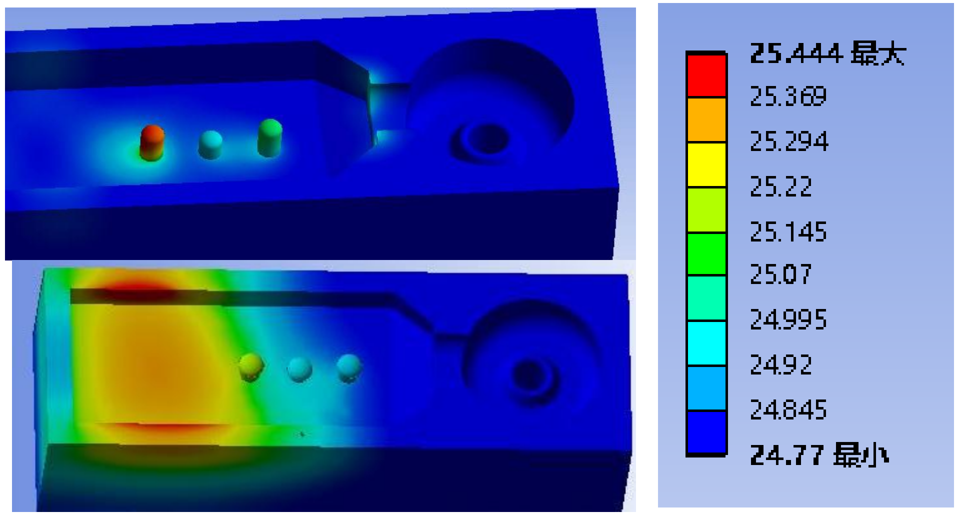




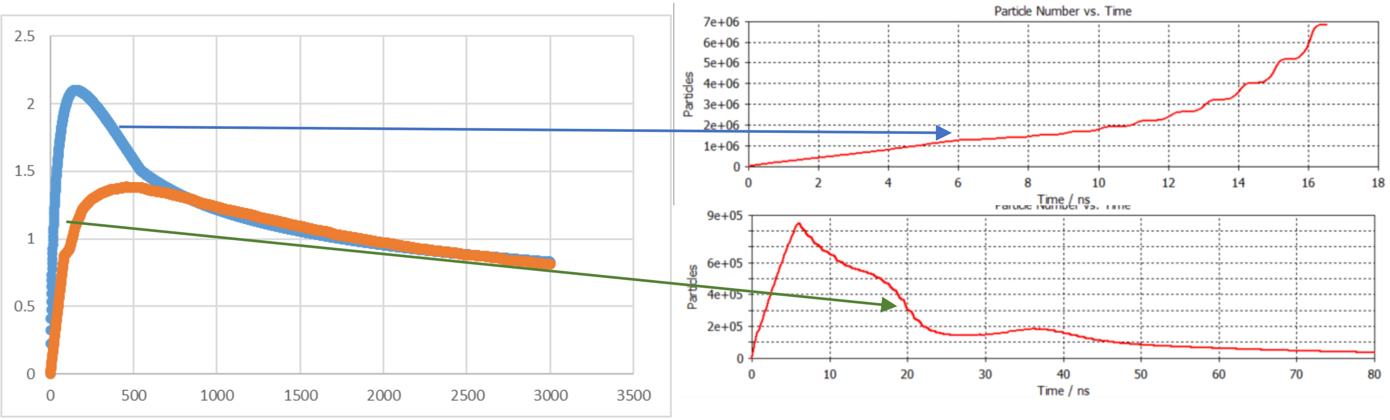


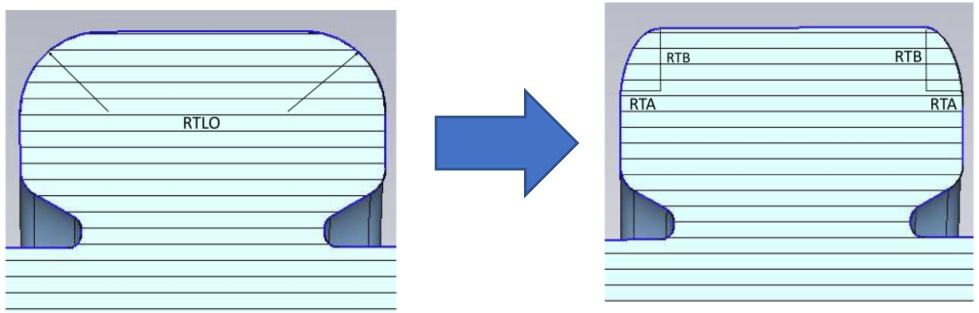


- Rectangular waveguide coupler, with circular ceramic RF window.
- Preserve the possibility of the coaxial coupler (iteration design)
- The function of adjustable coupling is realised by adopting a 3-screw tuner
- Simulation shows that the temperature rises little in the 3-screw tuner.



Multipacting

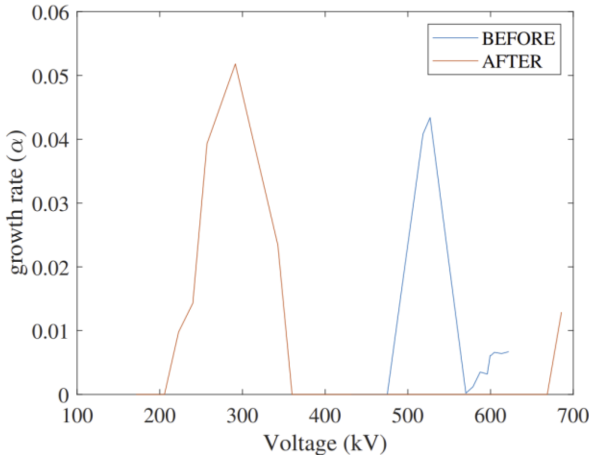


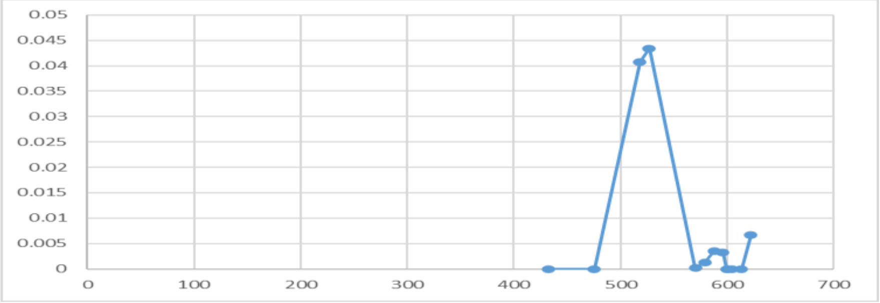


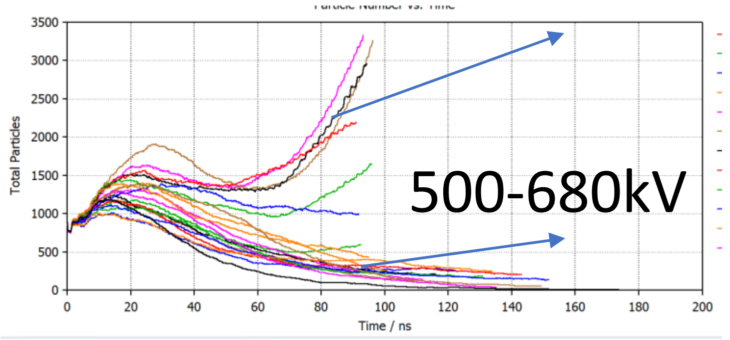
Round

Ellipse

- Simulation of the multipacting in the CW cavity
- SEY in CST particle studio
- Modify the geometry of the cavity to move the multipact area



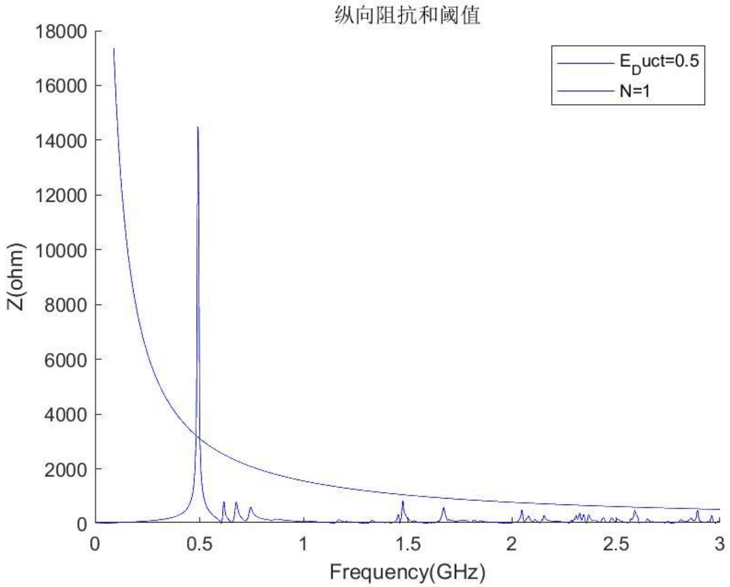


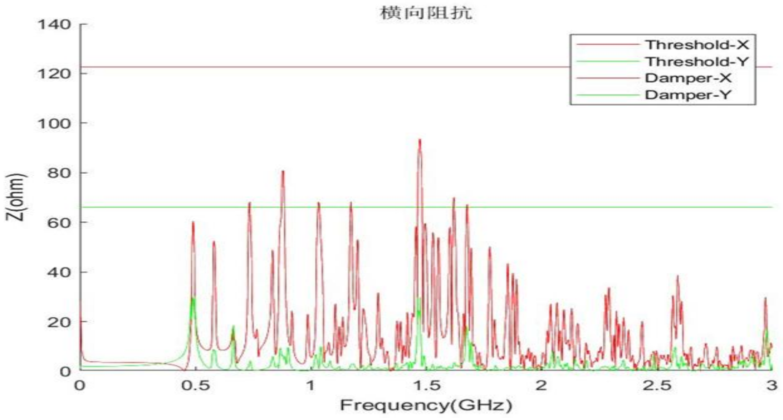


420-460kV

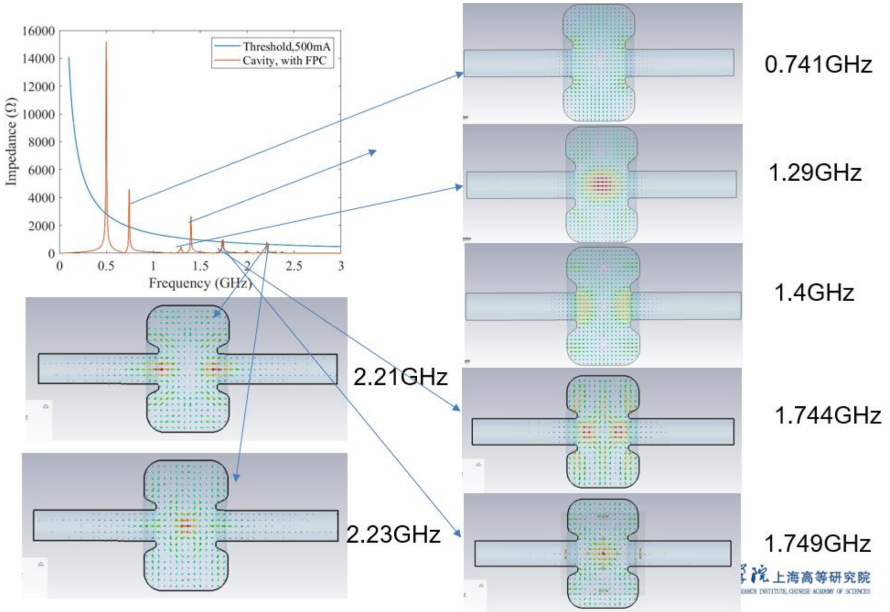
500-680kV

HOM-damping



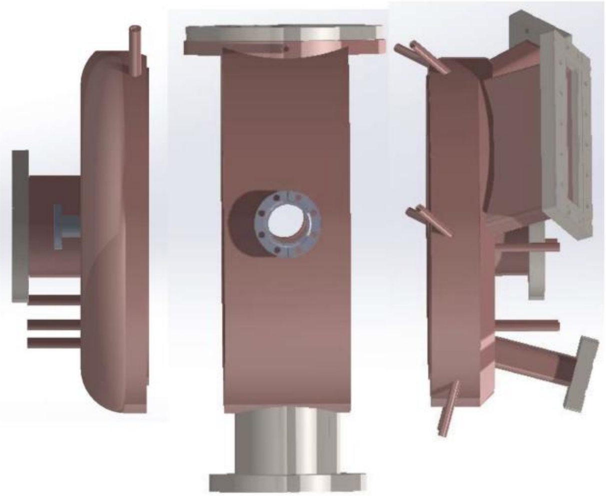


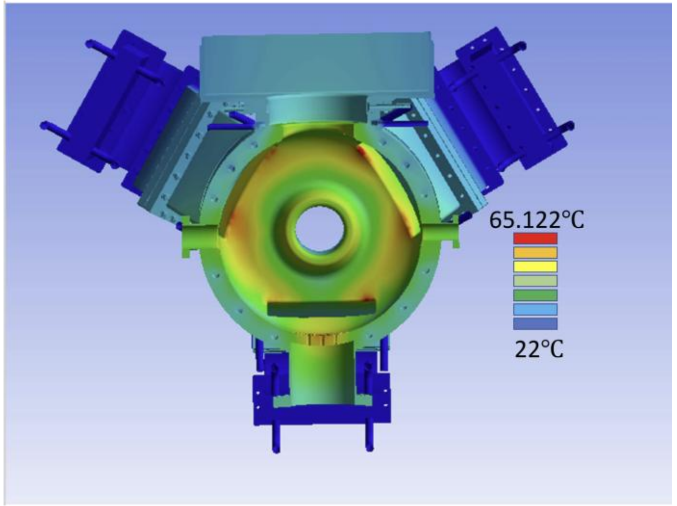
$$Z^{threshold}_{longitudinal} = \frac{1}{N f_{HOM}} \frac{2EQ_s}{eI\alpha\tau_L} \qquad Z^{threshold}_{transverse} = \frac{1}{N f_{rev}} \frac{2E}{eI\beta_{trans}\tau_{trans}}$$

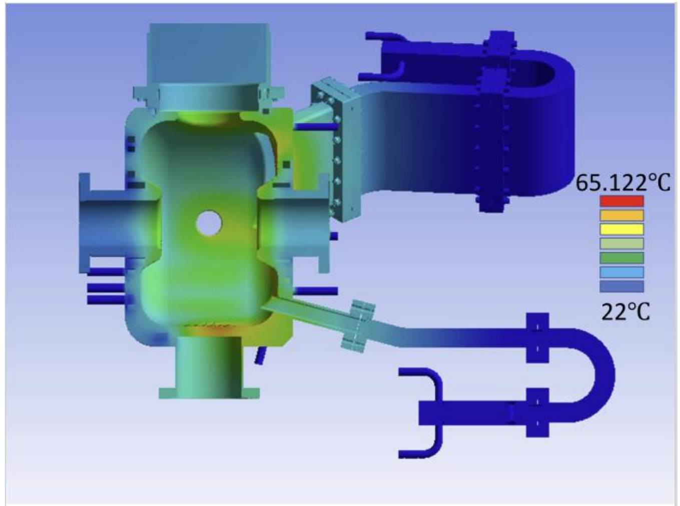


Mode frequency	R/Q	Q	R($M\Omega$)
754MHz	37.79	32500	0.613
1305MHz	9.14	63700	0.291
1420MHz	20.99	35700	0.375
1768MHz	5.51	41100	0.113
1821MHz	5.48	58600	0.161
2023MHz	3.21	89700	0.144
2127MHz	1.29	60600	0.0392

Multiphysics analyzation

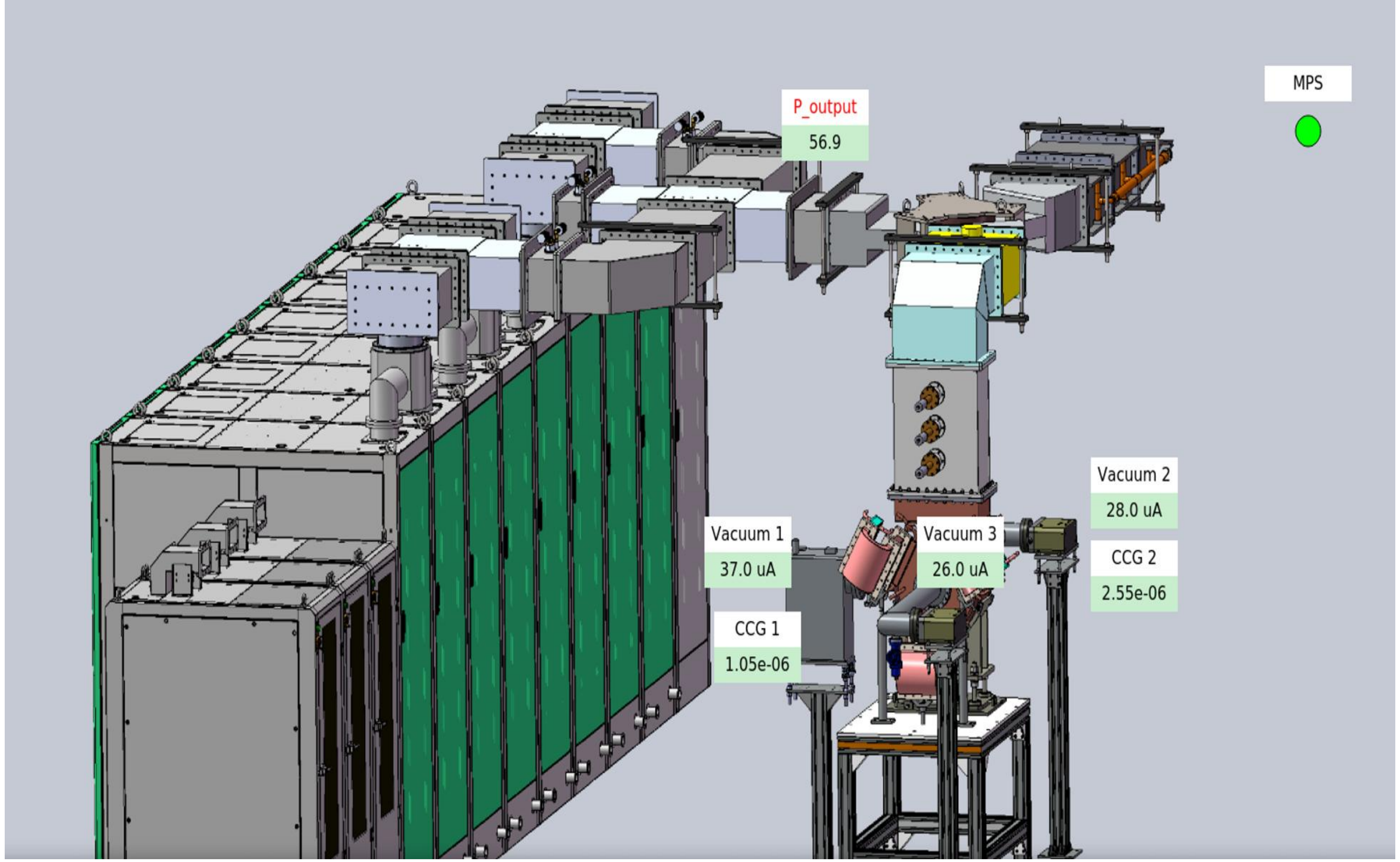






- Highest temperature rise: 44K, at the corner of the HOM load
- Deformation caused by the temperature rise will result in the frequency shift by 282kHz
- The frequency shift will be corrected by the tuner

Fabrication and high power test



P_output
56.9

MPS ●

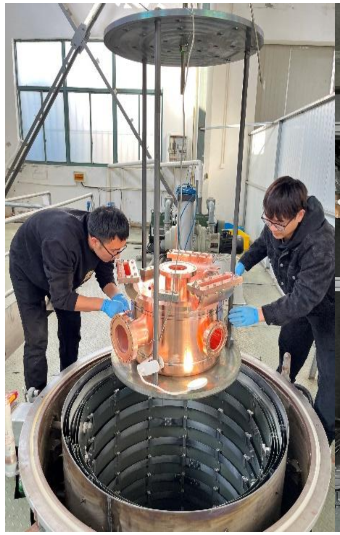
Vacuum 1
37.0 uA

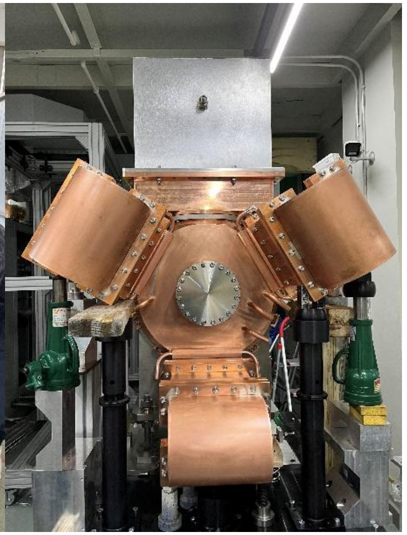
CCG 1
1.05e-06

Vacuum 3
26.0 uA

Vacuum 2
28.0 uA

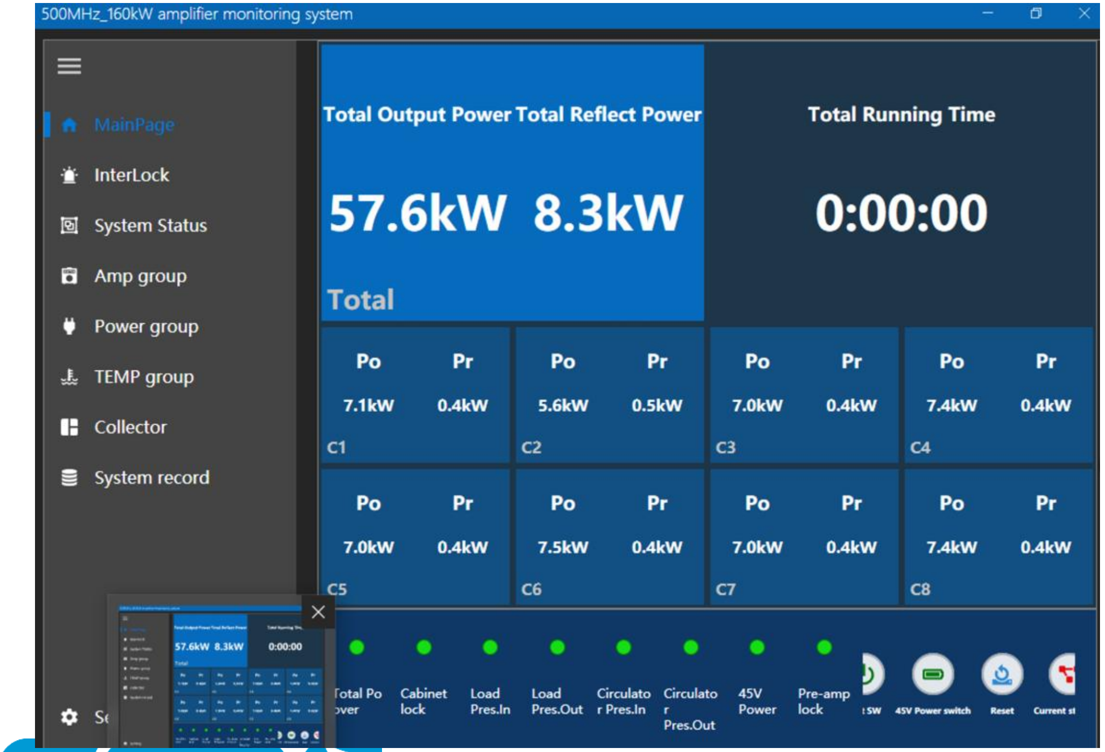
CCG 2
2.55e-06





The results of high power test

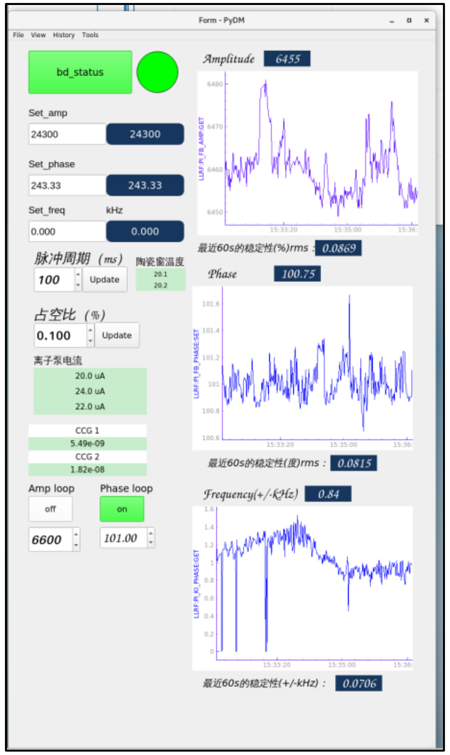
- ☐ Cavity voltage: 600 kV (only 40% duration, 20kW)
- ☐ RF stability: better than 0.1%, 0.1 degree (rms)
- ☐ Vaccum: $7*10^{-10}$ torr (static), $5*10^{-9}$ torr (power on)


500MHz_160kW amplifier monitoring system

Total Output Power Total Reflect Power: 57.6kW 8.3kW (Total)

Total Running Time: 0:00:00

	Po	Pr
C1	7.1kW	0.4kW
C2	5.6kW	0.5kW
C3	7.0kW	0.4kW
C4	7.4kW	0.4kW
C5	7.0kW	0.4kW
C6	7.5kW	0.4kW
C7	7.0kW	0.4kW
C8	7.4kW	0.4kW


Form - PyDM

bd_status ●

Set_amp: 24300 | 24300

Set_phase: 243.33 | 243.33

Set_freq kHz: 0.000 | 0.000

脉冲周期（ms）: 100 Update

陶瓷窗温度: 20.1 20.2

占空比（%）: 0.100 Update

离子泵电流: 20.0 uA 24.0 uA 22.0 uA

CCG 1: 5.49e-09

CCG 2: 1.82e-08

Amp loop: off 6600

Phase loop: on 101.00

Amplitude 6455

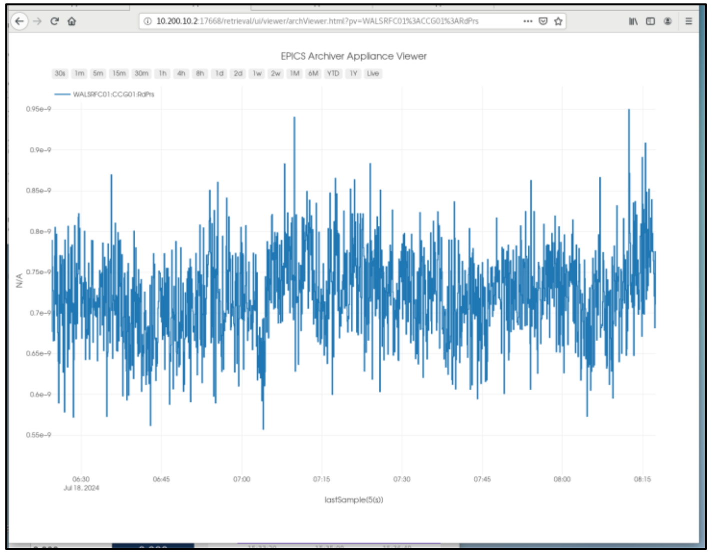
最近60s的稳定性(%)rms：0.0869

Phase 100.75

最近60s的稳定性(度)rms：0.0815

Frequency(+/-kHz) 0.84

最近60s的稳定性(+/-kHz)：0.0706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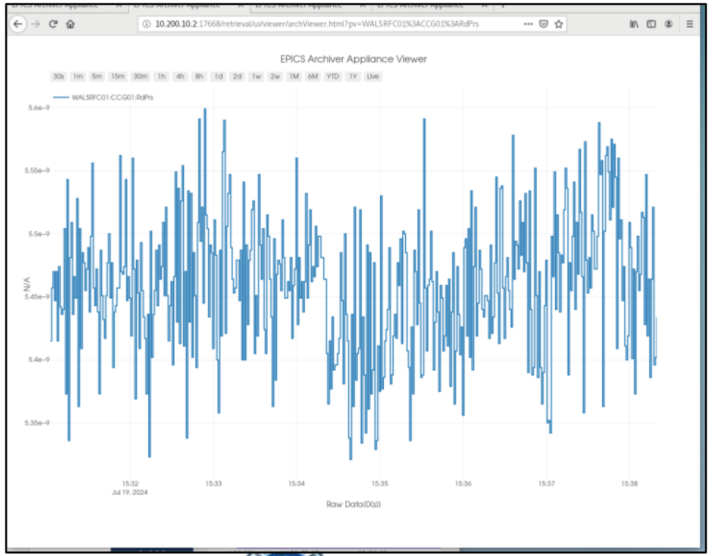

10.200.10.2:17668/retrieval/ui/viewer/archViewer.html?pv=WALSRFC01%3ACCG01%3ARdPrs

New dual-mode cavity design for compact SR

- Compact light source needs both main cavity and 3rd harmonic cavity
- Dual-mode only needs one straight section

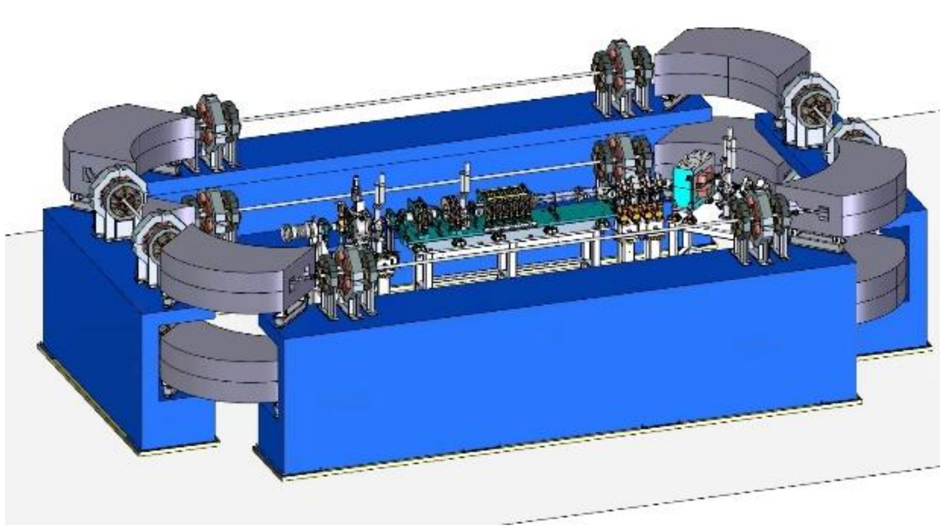
☞ Superposition field of main RF field and harmonic RF filed

RF field seen by the bunch for main RF and higher harmonic cavities

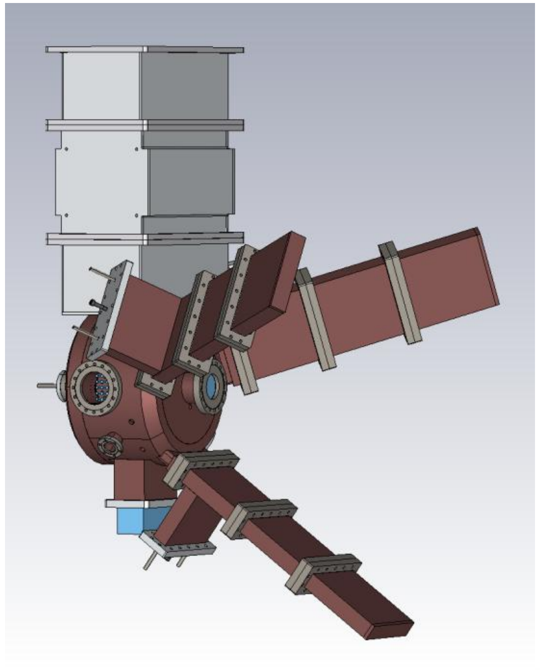
$$E_z = E_1 \cos(kz) \cdot \sin(\omega t + \varphi_0) + E_n \, cos(nkz) \cdot \sin(n\omega t + \phi_n)$$

RF voltage seen by the bunch for main RF and higher harmonic cavities

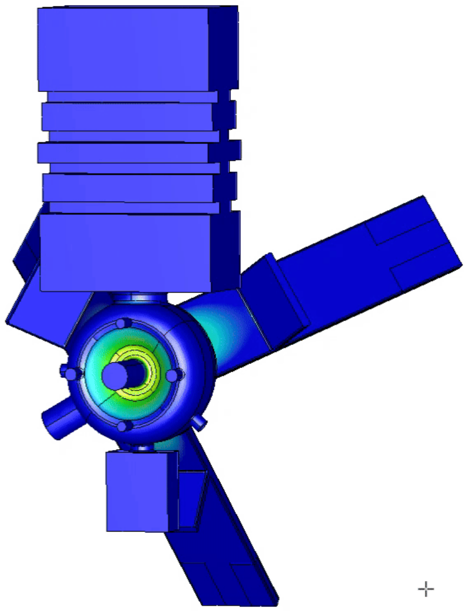
$$V(\phi) = V_1 \, cos(\omega t + \phi_s) + V_n \, cos(n\omega t + n\phi_n)$$



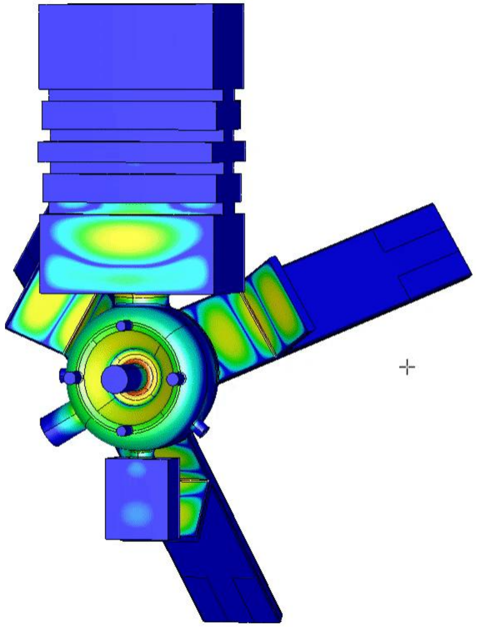
TM010 + TM020 cavity



TM010 500MHz



TM020 1.5GHz



Thanks for your attention!