DESIGN STUDIES FOR QUARTER-WAVE RESONATORS AND CRYOMODULES FOR THE RIKEN SC-LINAC

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DESIGN STUDIES FOR QUARTER-WAVE RESONATORS AND CRYOMODULES FOR THE RIKEN SC-LINAC

Coupler and CM design

Mechanical Simulations of QWR

RF Design of QWR

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OUTLINE

1. INTRODUCTION

- Why Superconducting Linac?
- RIKEN SC-LINAC

2.DESIGN STUDIES FOR QWR FOR RIKEN SC-LINAC

- Resonator Design
- Frequency Tuning
- Correction of Steering Effect by RF Magnetic Field
- Beam-loading Simulation
- Required RF Power
- External Q of Fundamental Power Coupler

3. PROTOTYPE

- Design of the Prototype Resonator
- Mechanical Study of the Resonator
- Surface Treatment
- Cryostat

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Why Superconducting Linac?

RIKEN RI-Beam Factory (2006-)

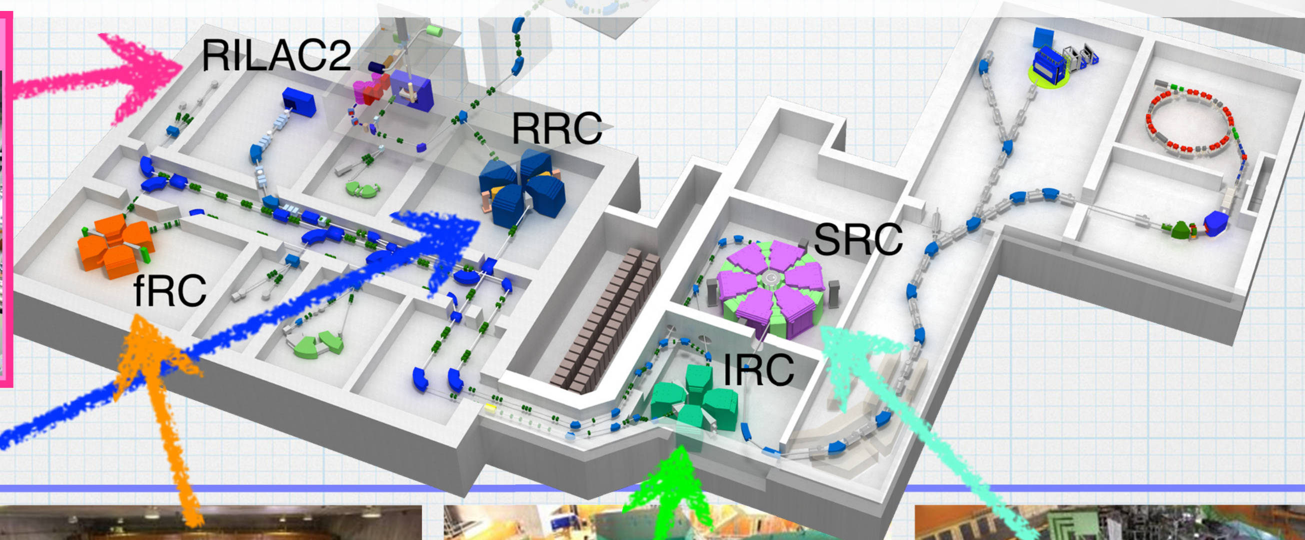
Mission: Expand the availability of **heavier RIB**

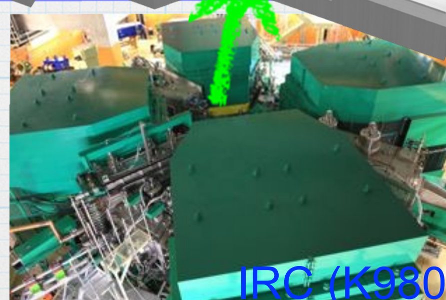
Beams: Wide Mass Range from **deuteron to uranium**

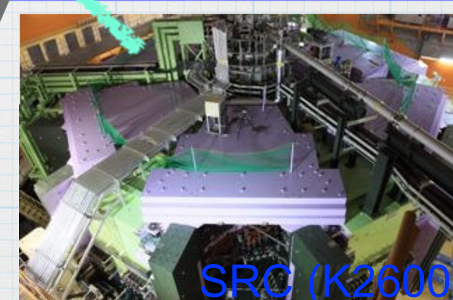
Primary Beam Energy **190-400 MeV/u**

Goal Beam Current **1 particle μA(c.w.)**

RILAC2 (-2012) Xe, U







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Beam intensity of U is not still intense enough to reach 1 pμA.

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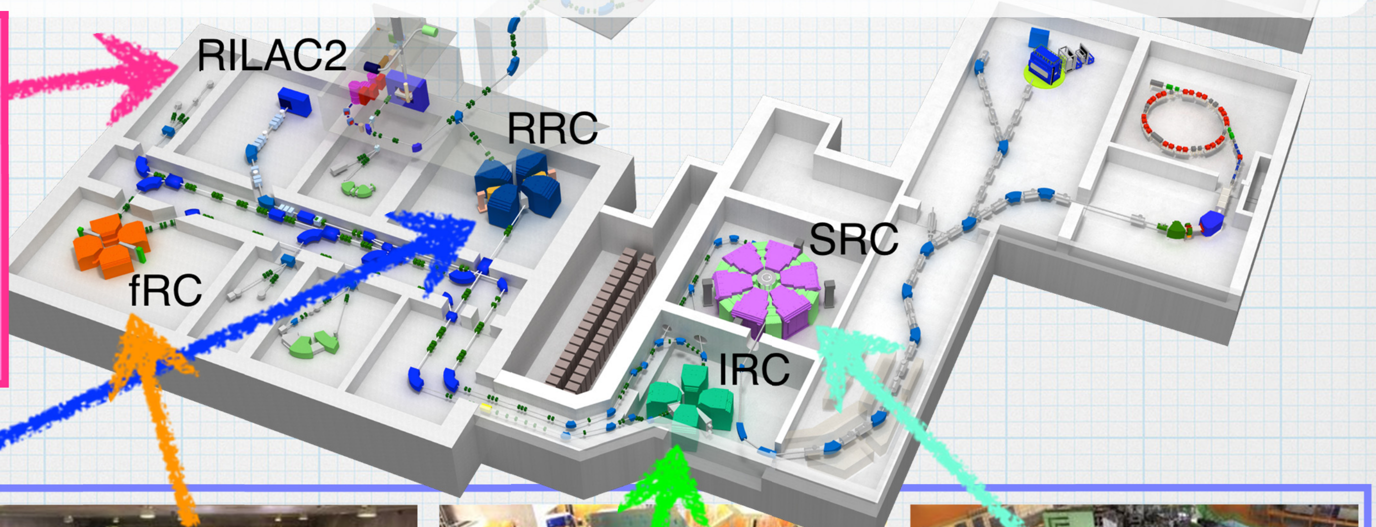

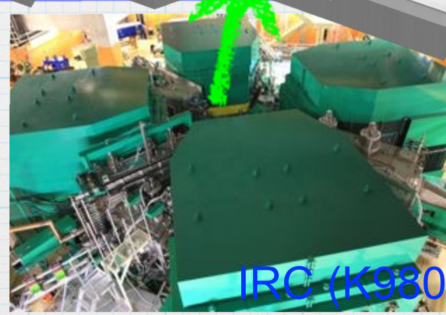

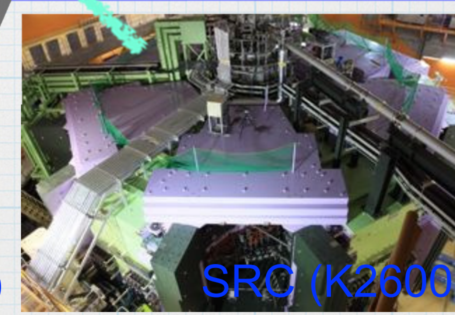

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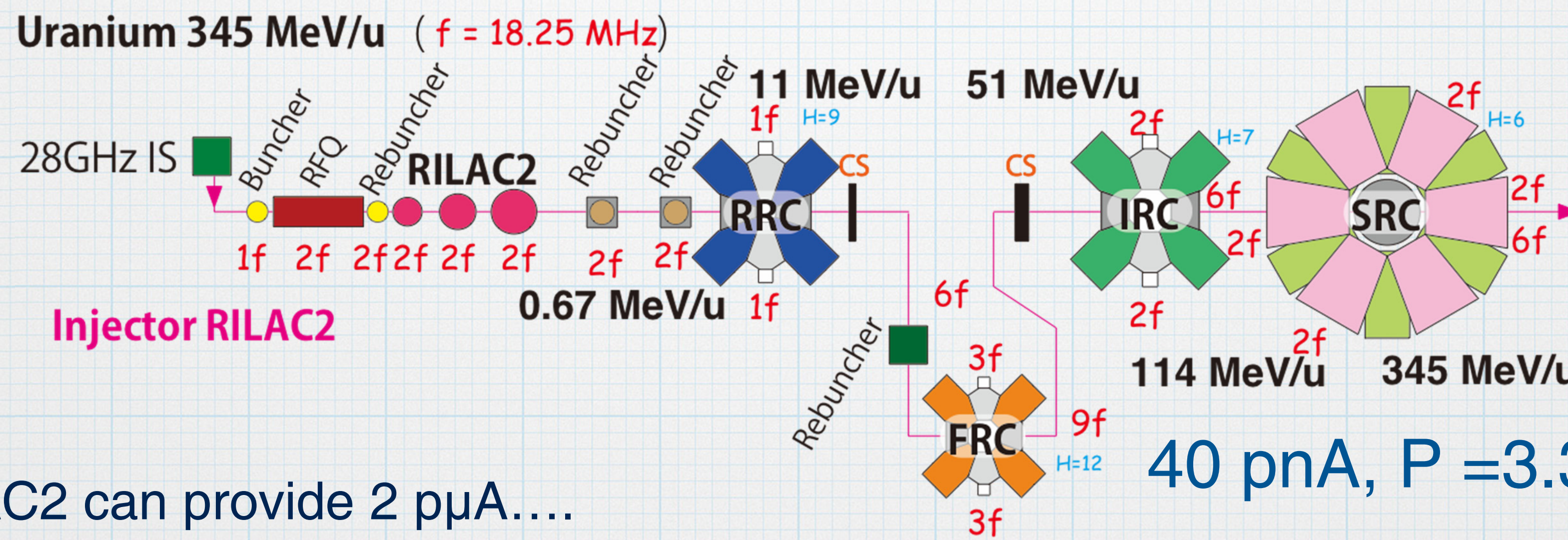


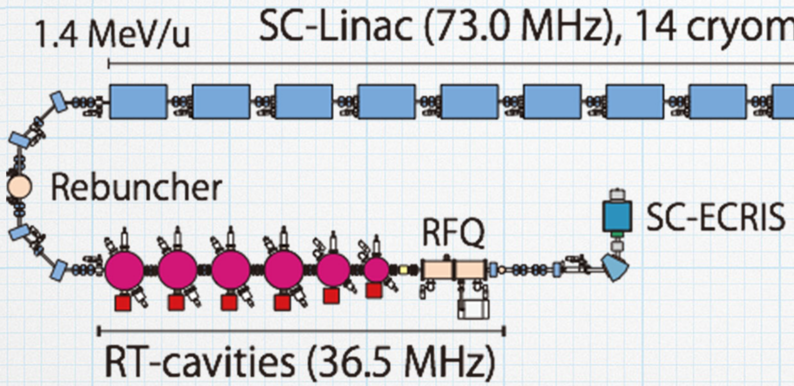
40 pnA, P =3.3 kW

RILAC2 can provide 2 pμA….

1. Low efficiency of charge stripping < 5%
2. RF Voltage of the RRC at 18.25 MHz is limited to 280 kV.
   →Difficulty with handling high power beam at the RRC.

RIKEN SC-LINAC

Beam: $^{238}U^{35+}$, 11.0 MeV/A,1 mA(C.W.)



Superconducting part

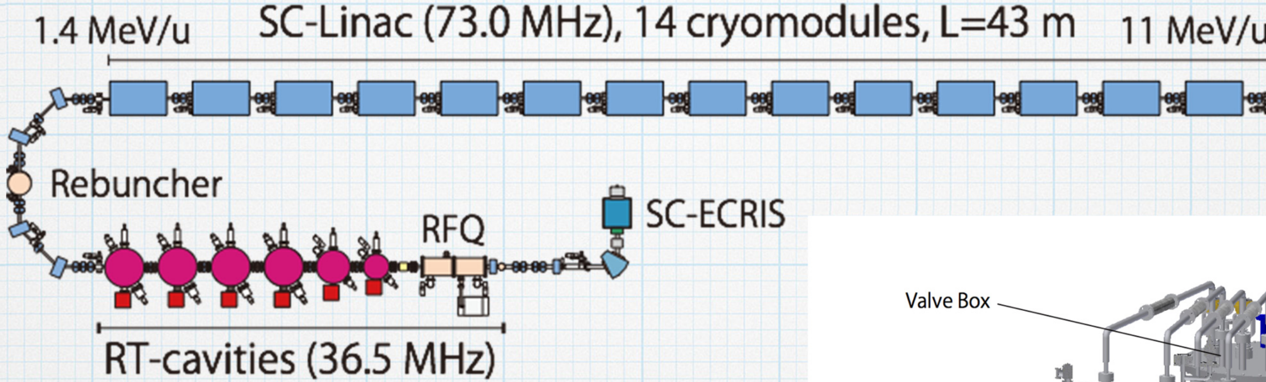
- Total Acceleration Voltage 65.3 MV
- 14 cryomodules, RT Doublets

Key Parameters for SC-LINAC.

Frequency	73 MHz
Duty	100%
A/Q	7
Input Energy	1.4 MeV/A
Output Energy	11.0 MeV/A
Synchronous Phase	-25 deg.
No. of QWRs	56
No. of Cryomodules	14
No. of Doublets	14
Total Length	43 m
Beam Loading	0.95-1.31 kW/cavity

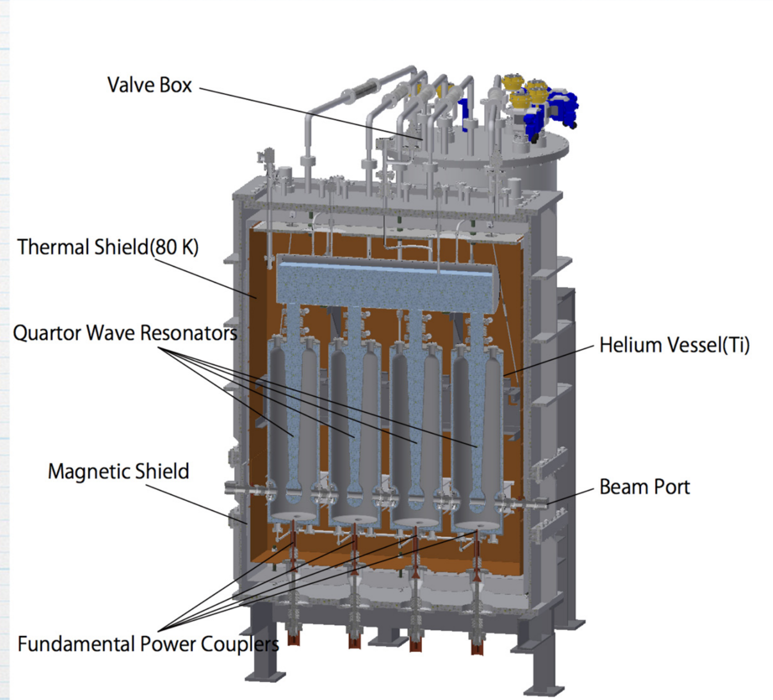
RIKEN SC-LINAC

Beam: $^{238}U^{35+}$, 11.0 MeV/A,1 mA(C.W.)



Superconducting part

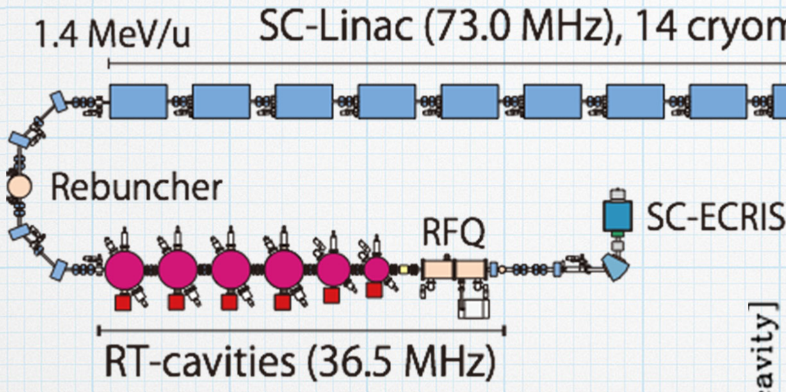
- Total Acceleration Voltage 65.3 MV
- 14 cryomodules, RT Doublets
- Each cryomodule houses 4 QWRs.
  - Operating temperature 4.5 K
  - Valve box is separated from the cryomodule
  - Single-stage thermal shield (80K)
  - Coupling tunable FPC (5 kW, Q_{ext}～10^6)



Conceptual Design of CM.

RIKEN SC-LINAC

Beam: $^{238}U^{35+}$, 11.0 MeV/A,1 mA(C.W.)



Superconducting part

- Total Acceleration Voltage 65.3 MV
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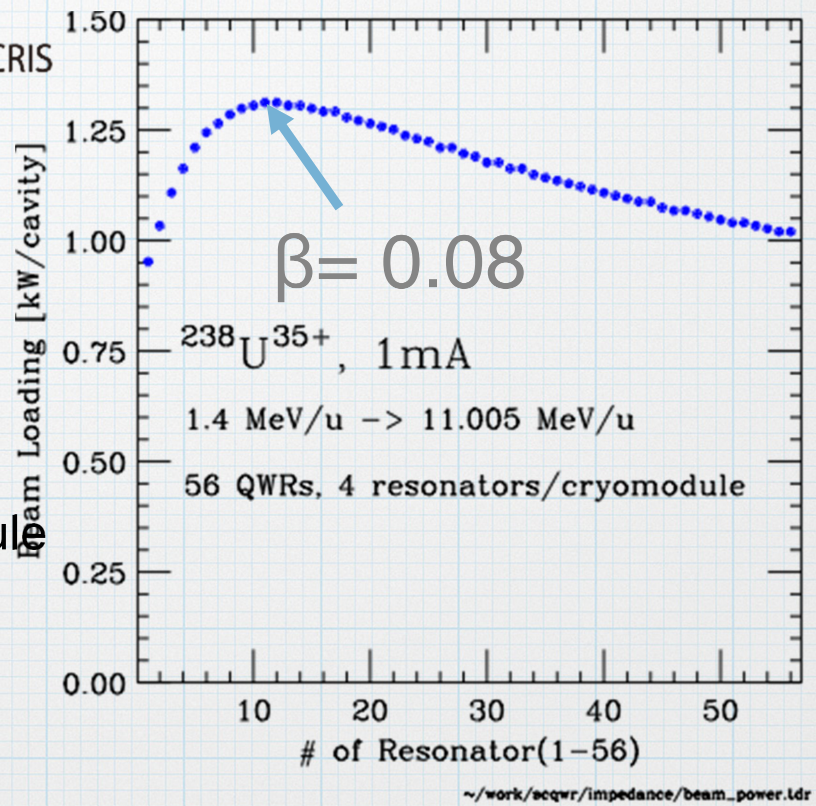
- Each cryomodule houses 4 QWRs
  - Operating temperature 4.5 K
  - Valve box is separated from the cryomodule
  - Single-stage thermal shield (80K)
  - Coupling tunable FPC (5 kW, $Q_{ext}\sim10^6$)
- Beam Loading <1.3 kW/resonator



Beam Loading for QWRs.

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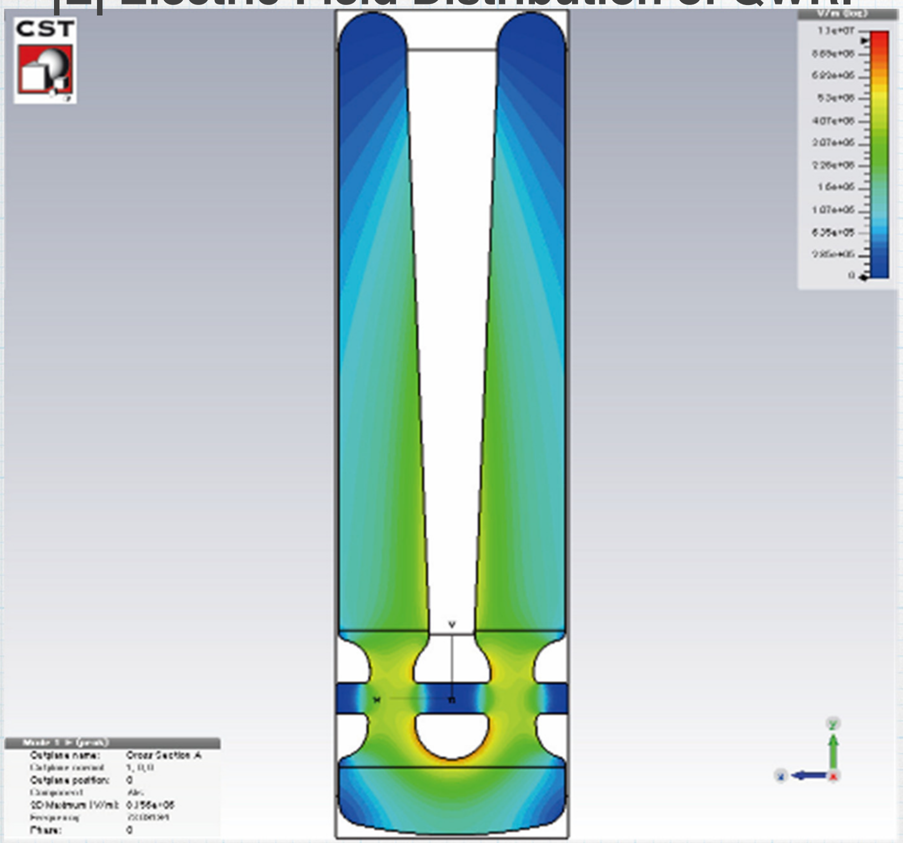
RESONATOR DESIGN

- λ/4-type TEM resonator made of bulk Nb

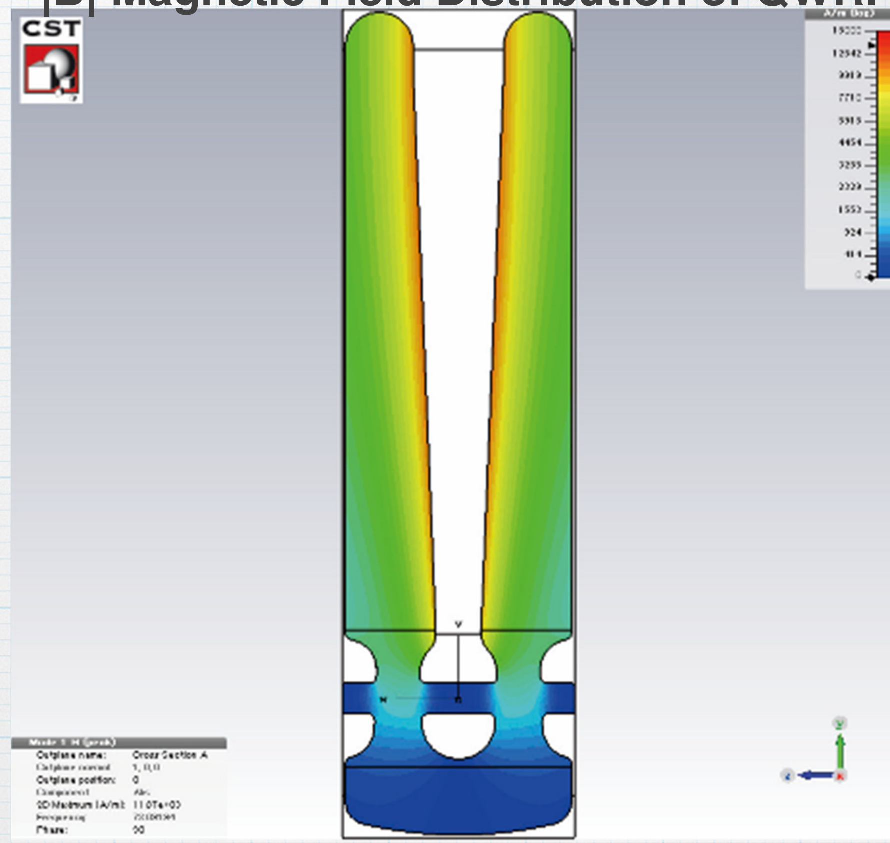
Key Parameters

Frequency	73 MHz
Duty	100%
Field Mode	π
Gap Voltage	0.8 MV
Aperture Diameter	40 mm

|E| Electric Field Distribution of QWR.



|B| Magnetic Field Distribution of QWR.



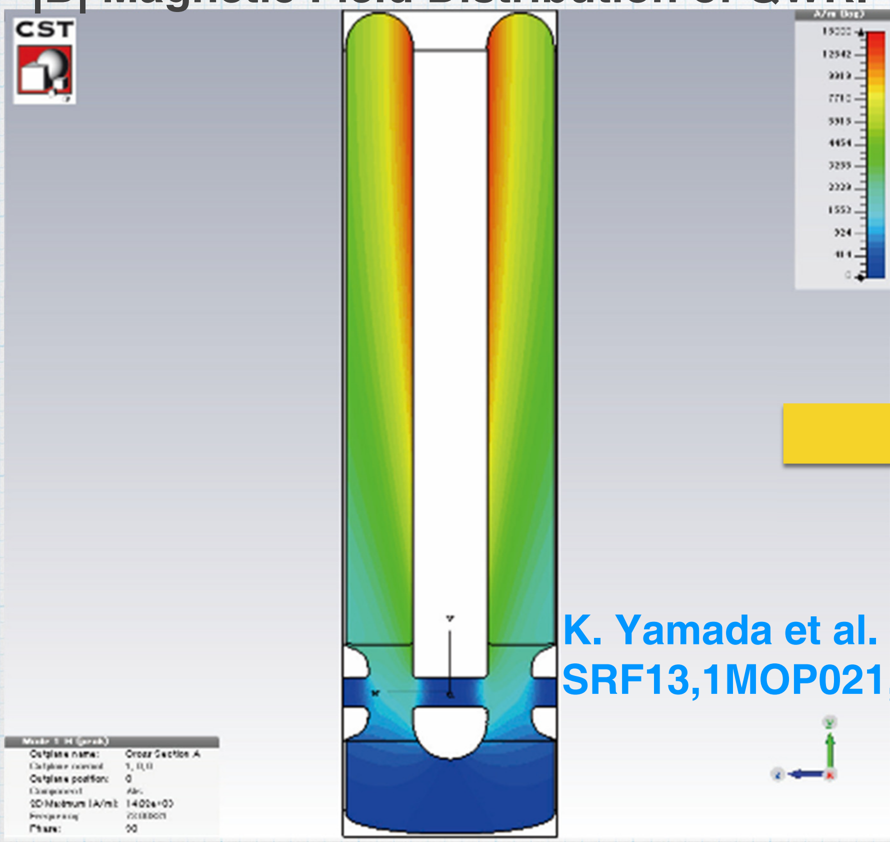
RESONATOR DESIGN

- λ/4-type TEM resonator made of bulk Nb
- Conical shape stem make the peak B field lower.

Key Parameters

Frequency	73 MHz
Duty	100%
Field Mode	π
Gap Voltage	0.8 MV
Aperture Diameter	40 mm

|B| Magnetic Field Distribution of QWR.



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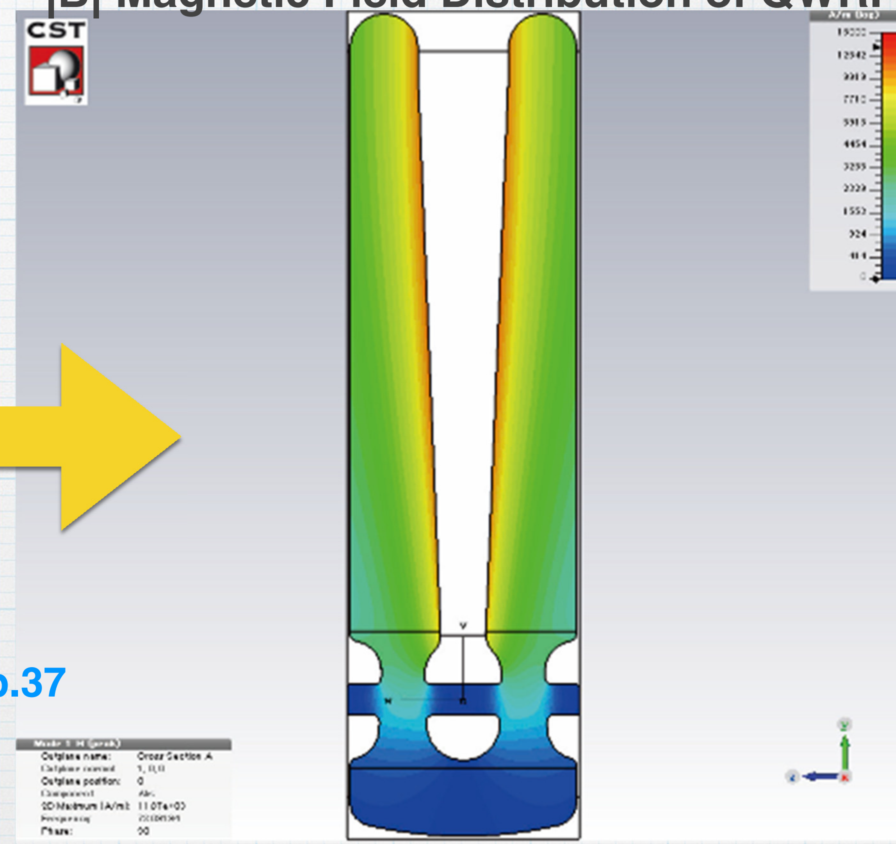


K. Yamada et al.
SRF13,1MOP021, p.37

RESONATOR DESIGN

- λ/4-type TEM resonator made of bulk Nb
- Conical shape stem
- Moderate acceleration gradient of 4.5 MV/m

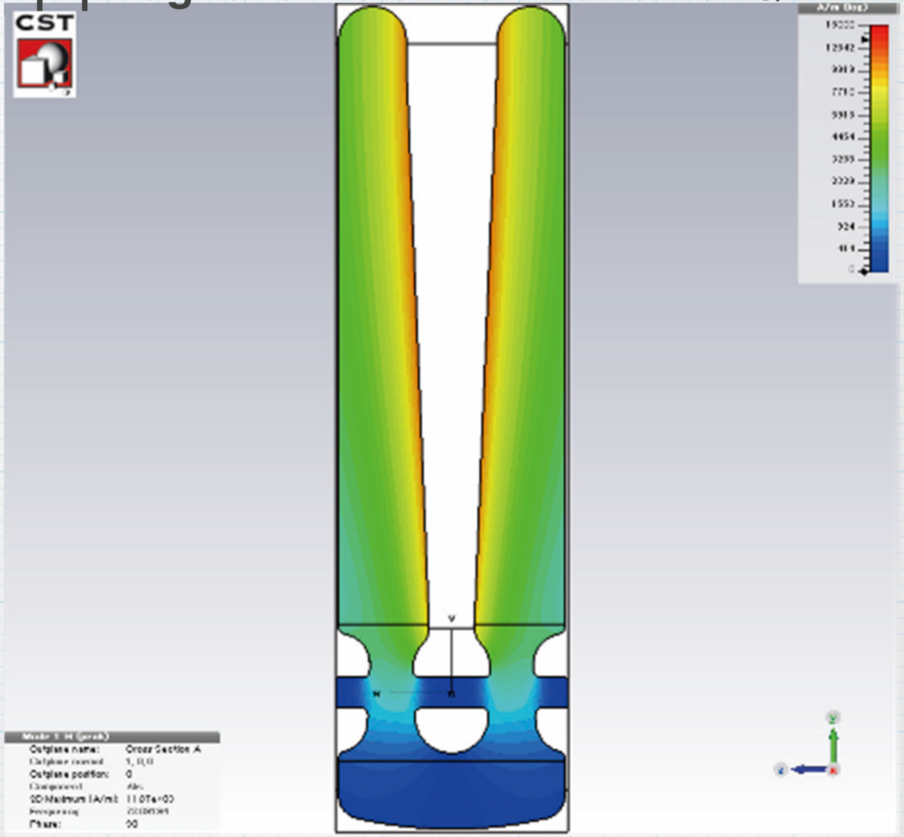
Key Parameters

Frequency	73 MHz
Duty	100%
Field Mode	π
Gap Voltage	0.8 MV
Aperture Diameter	40 mm

RF Characteristics from MWS simulation

G	22.6
R_{sh}/Q	718 Ω
Q_0 (Rs=25 nΩ)	8.9×10^8
E_{acc}	4.5 MV/m
E_{peak}/E_{acc}	6.0
B_{peak}/E_{acc}	9.5 mT/ MV/m

|B| Magnetic Field Distribution of QWR.



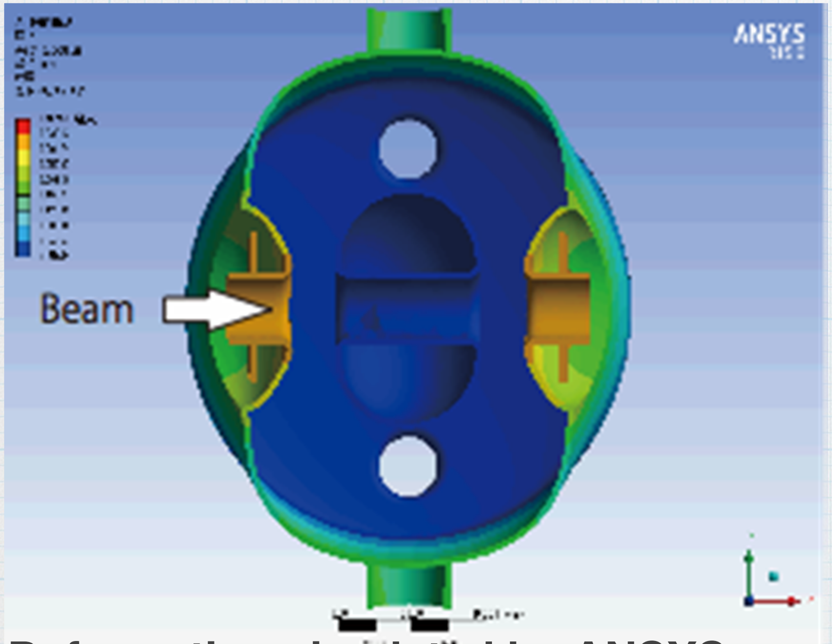
FREQUENCY TUNING

- **Cold tuning system for QWR**

  Press the beam port azimuthally reducing the gap length

  Pros: High sensitivity to the deformation

  Cons: Limited Installation space between QWRs



Deformation simulated by ANSYS

FREQUENCY TUNING

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  Press the beam port azimuthally reducing the gap length

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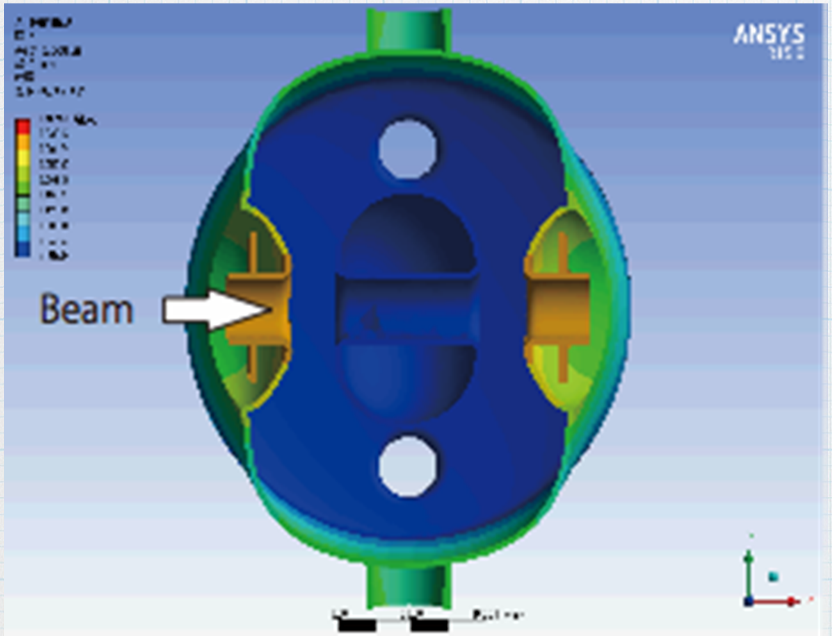
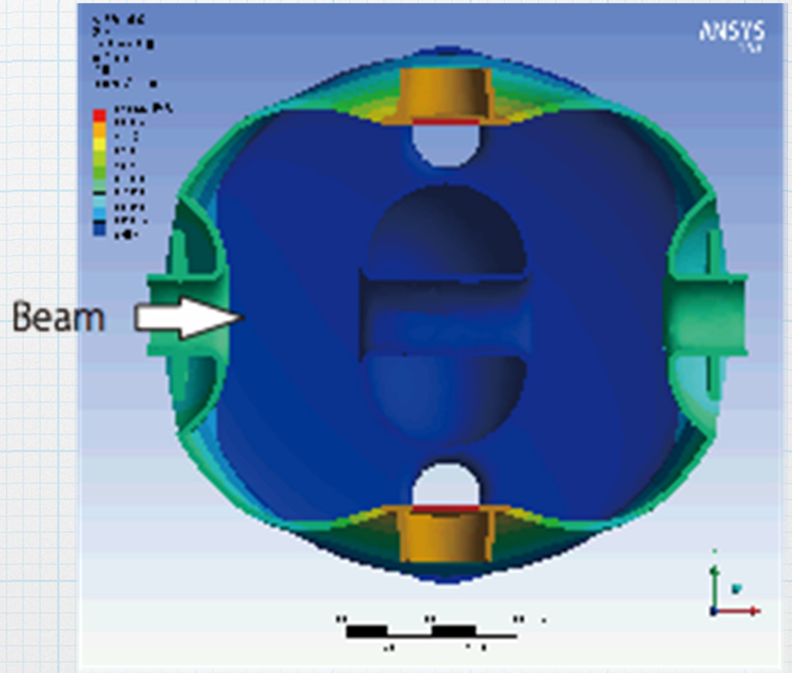
  Cons: Limited Installation space between QWRs

  Squeezing the outer cylinder perpendicular to the beam axis

  Pros: Large space for installation

  Cons: Low sensitivity to the deformation





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- **Cold tuning system for QWR**
  Press the beam port azimuthally reducing the gap length
    Pros: High sensitivity to the deformation
    Cons: Limited Installation space between QWRs
  Squeezing the outer cylinder perpendicular to the beam axis
    Pros: Low sensitivity to the deformation
    Cons: Large space for installation
- **Mechanical simulations using ANSYS 15.0.7**
  Wall thickness 4 mm, Young's modulus 125 MPa, Poisson ratio 0.38

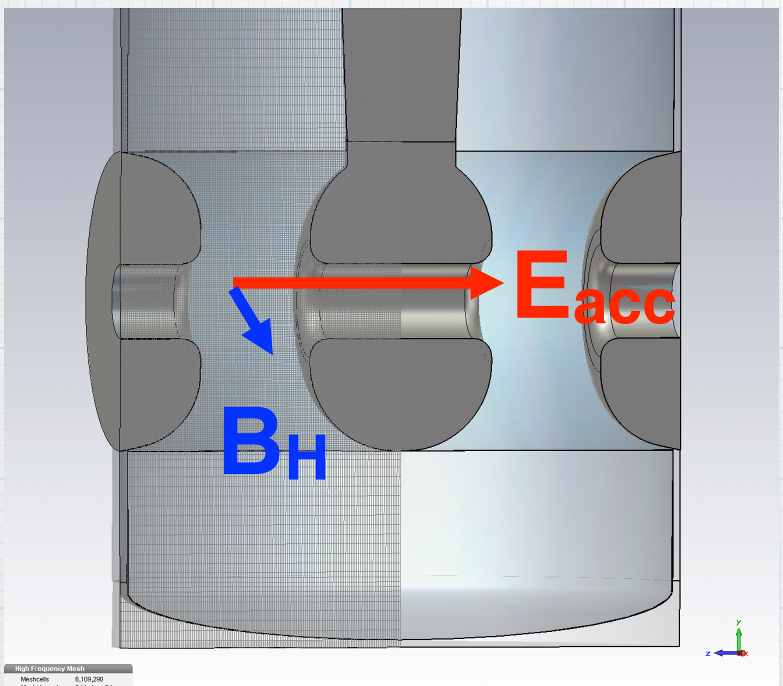
Load 5,000 N	Beam Ports	Side Cylinders
Max. Deformation [mm]	0.375	0.448
Max. Stress [MPa]	116	205
Δf [kHz]	-9.40	6.23
Seinsitivity [kHz/mm]	**-24.75**	**13.84**

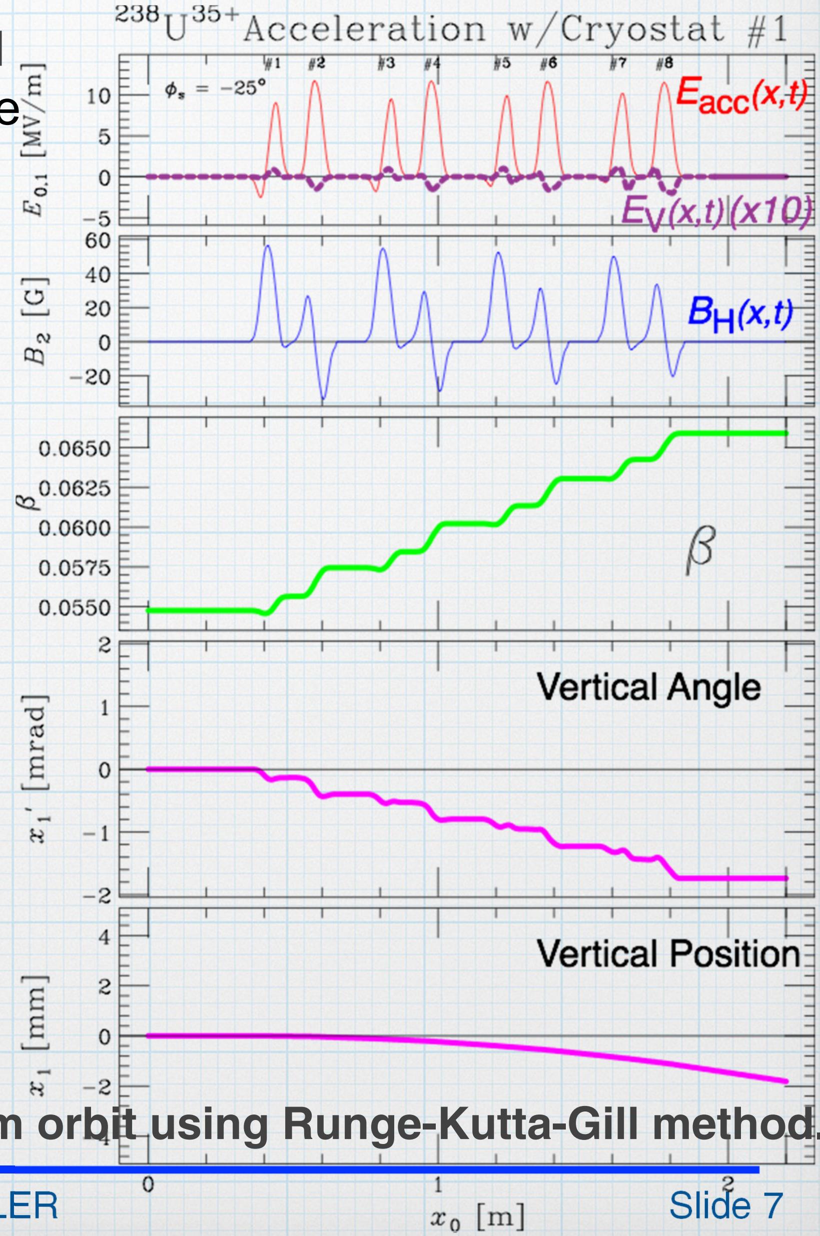
Frequency tuning range must be set so that the mechanical stress does not exceed yield stress. → ***Further mechanical study is required.***

CORRECTION OF STEERING EFFECT

- **RF magnetic field kicks beams downward**

  Horizontal components of B is not zero due to the asymmetrical structure of the QWR.





Beam orbit using Runge-Kutta-Gill method.

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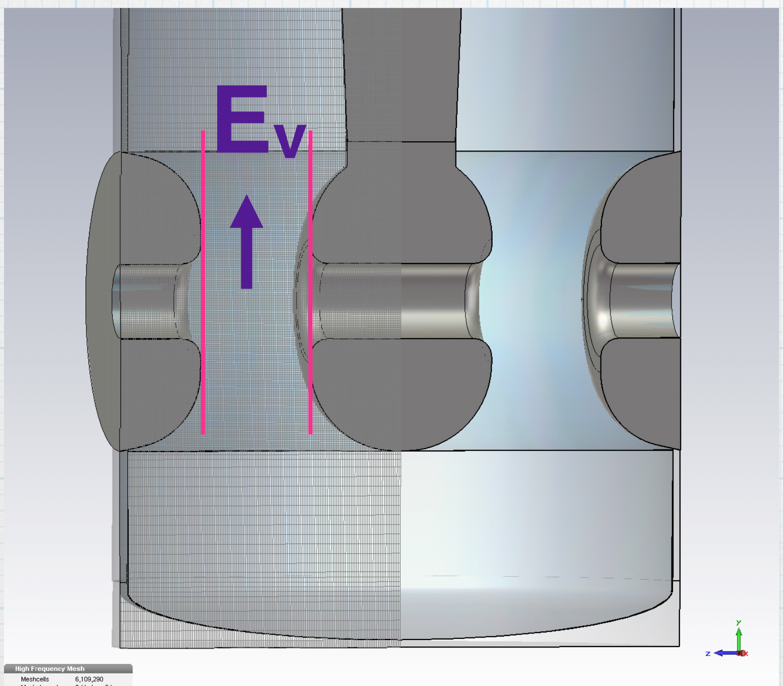
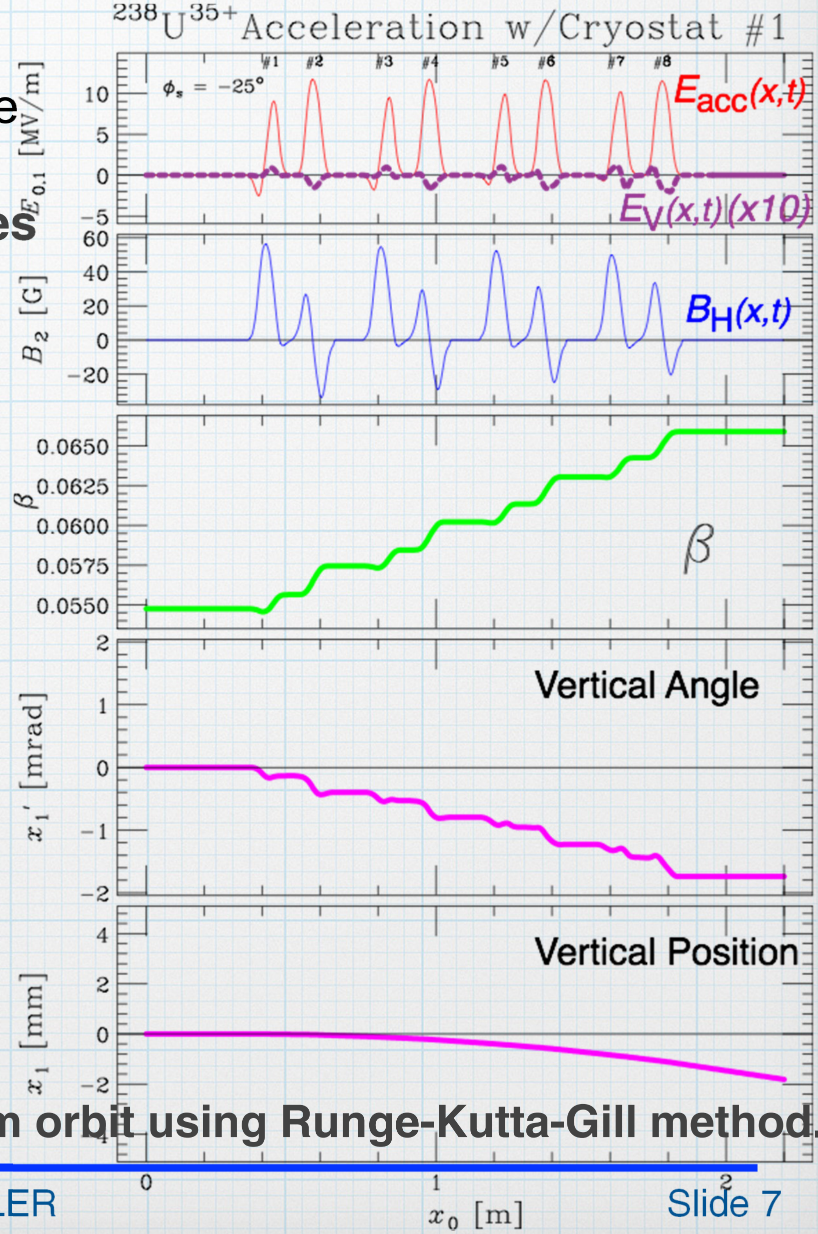
  P.N. Ostroumov and K.W. Shepard,
  Phys. Rev. ST Accel. Beams 4(2001)110101





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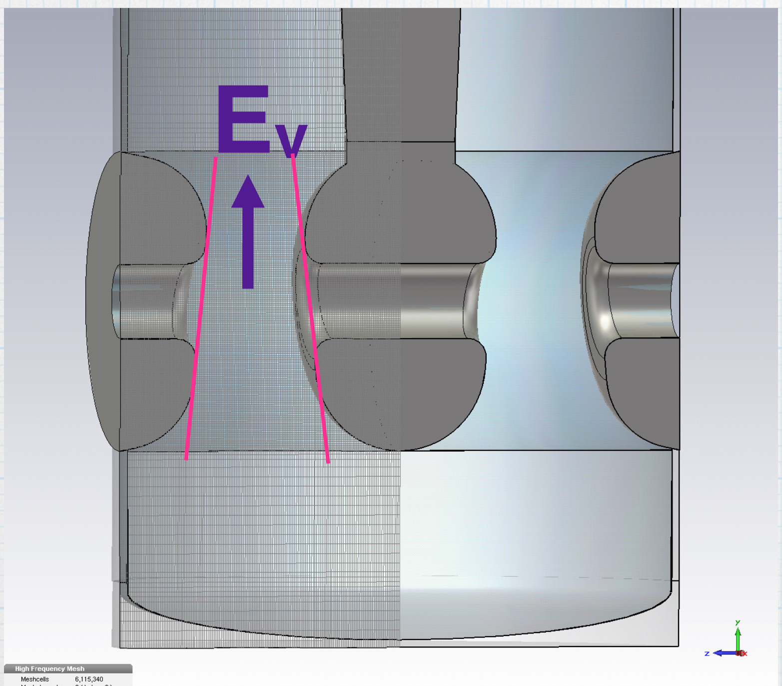
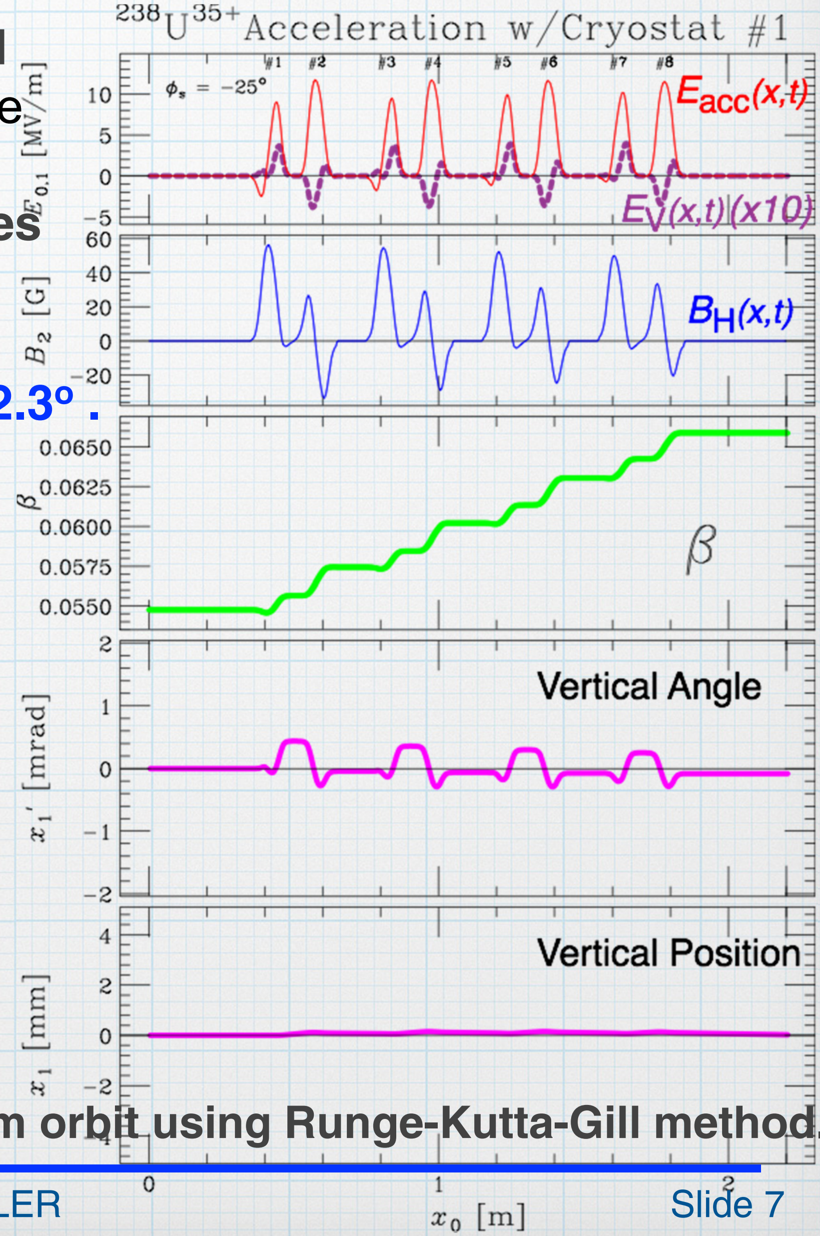
Vertical position shift is cancelled with θ_c = 2.3º .





Beam orbit using Runge-Kutta-Gill method.

BEAM-LOADING SIMULATION

- Conservation Law (current, energy)
- Linear Superposition

→ *Beam induced fields is obtained separately from fields generated by rf power source.*

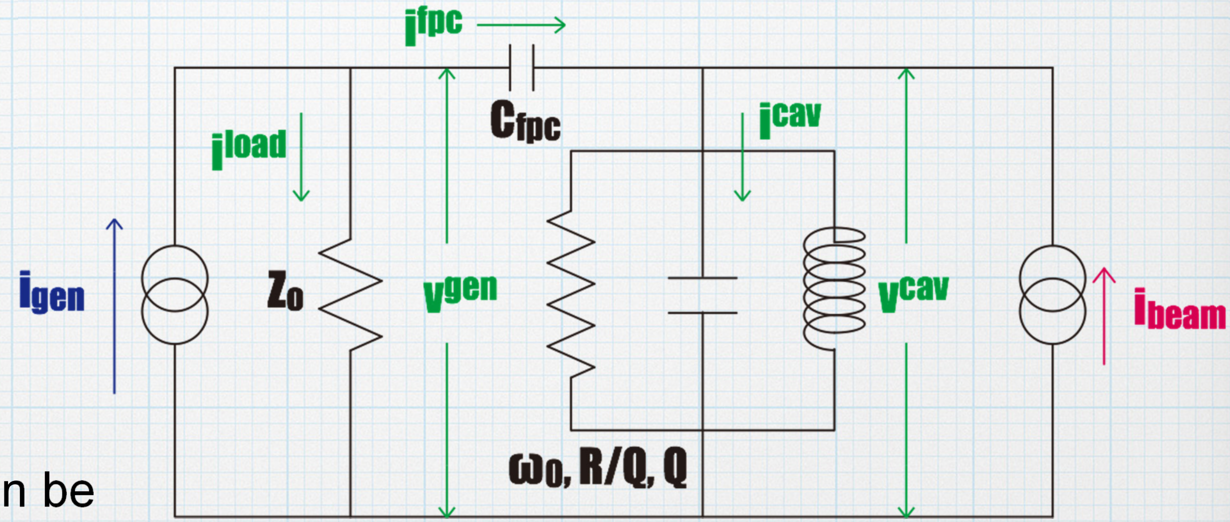
$$f_0 = 73.0\,\mathrm{MHz},\ V_0^{\mathrm{cav}} = 1.6\,\mathrm{MV},\ I_{\mathrm{beam}} = 1.0\,\mathrm{mA},\ \mathrm{TTF} = 0.90,\ \phi_{\mathrm{s}} = -25.0^\circ$$

- **Resonator**

$$\omega_0 = 2\pi \times 73.0 \times 10^6\ \mathrm{rad/s}$$

$$\left.\begin{array}{r} R/Q = 700 \\ Q = 8.9 \times 10^8 \end{array}\right\}\text{MWS}$$

$$P_0 = \frac{|V^{\mathrm{cav}}|^2}{(R/Q)\cdot Q} = 4.11\ \mathrm{W}$$



- **Beam-Loading**

  Beam-Loading effect can be simulated by an additional current source.

$$P_{\mathrm{beam}} = \mathrm{TTF} \times V^{\mathrm{cav}} \times \cos\phi_s \times I_{\mathrm{beam}} = 1.305\,\mathrm{kW} \quad \text{i.e.} \quad Q_{\mathrm{beam}} = 2.8 \times 10^6$$

$$i_{\mathrm{beam}} = -2 \times I_{\mathrm{beam}} \times \mathrm{TTF}\ \ (f_{\mathrm{beam}} = f_{\mathrm{rf}}) \qquad \left(Q_{\mathrm{beam}}^{-1} \equiv Q_0^{-1} \cdot \frac{P_{\mathrm{beam}}}{P_0}\right)$$

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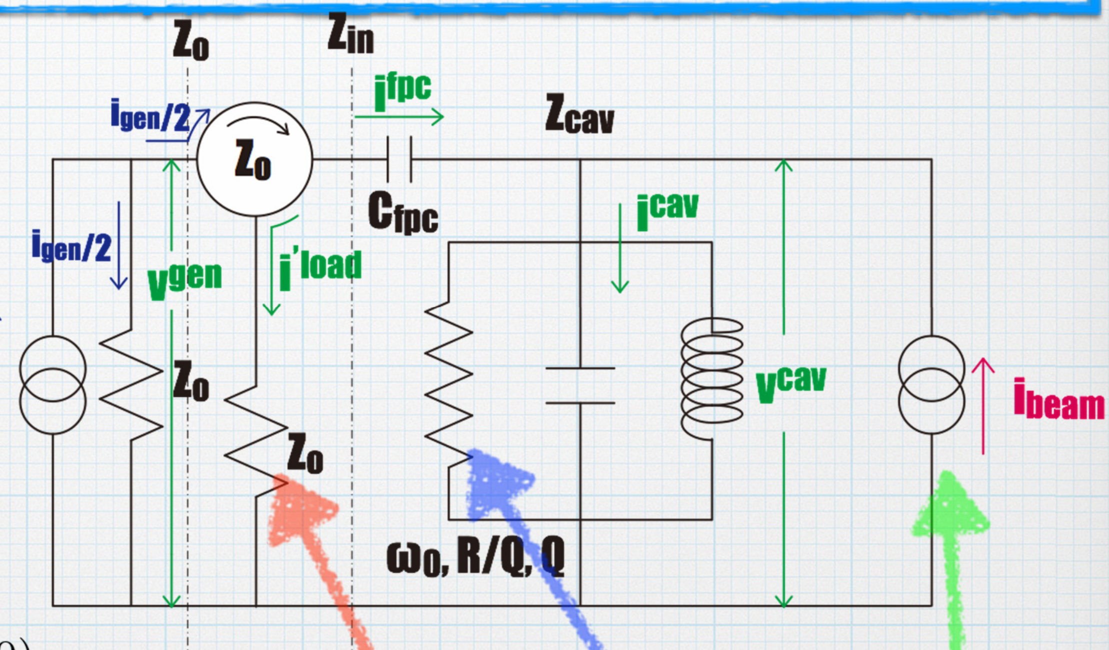


- **RF Losses**

$$P_0 = \frac{|V^{\rm cav}|^2}{2 \cdot i_{\rm cav}}$$

$$P'_{\rm load} = \frac{1}{2}\frac{|i'_{\rm load}/2|^2}{Z_0}$$

$$i'_{\rm load} = i_{\rm load} - i_{\rm gen}/2$$

- **Beam-Loading**

$$P_{\rm beam} = {\rm real}\left(\frac{V^{\rm cav} \cdot i^*_{\rm beam}}{2}\right) \quad (\leq 0)$$

- **Generator Power**

$$P'_{\rm gen} = {\rm real}\left(\frac{V^{\rm gen} \cdot i^*_{\rm gen}}{2}\right) \quad (\equiv 2 \times P_{\rm av})$$

Energy Conservation

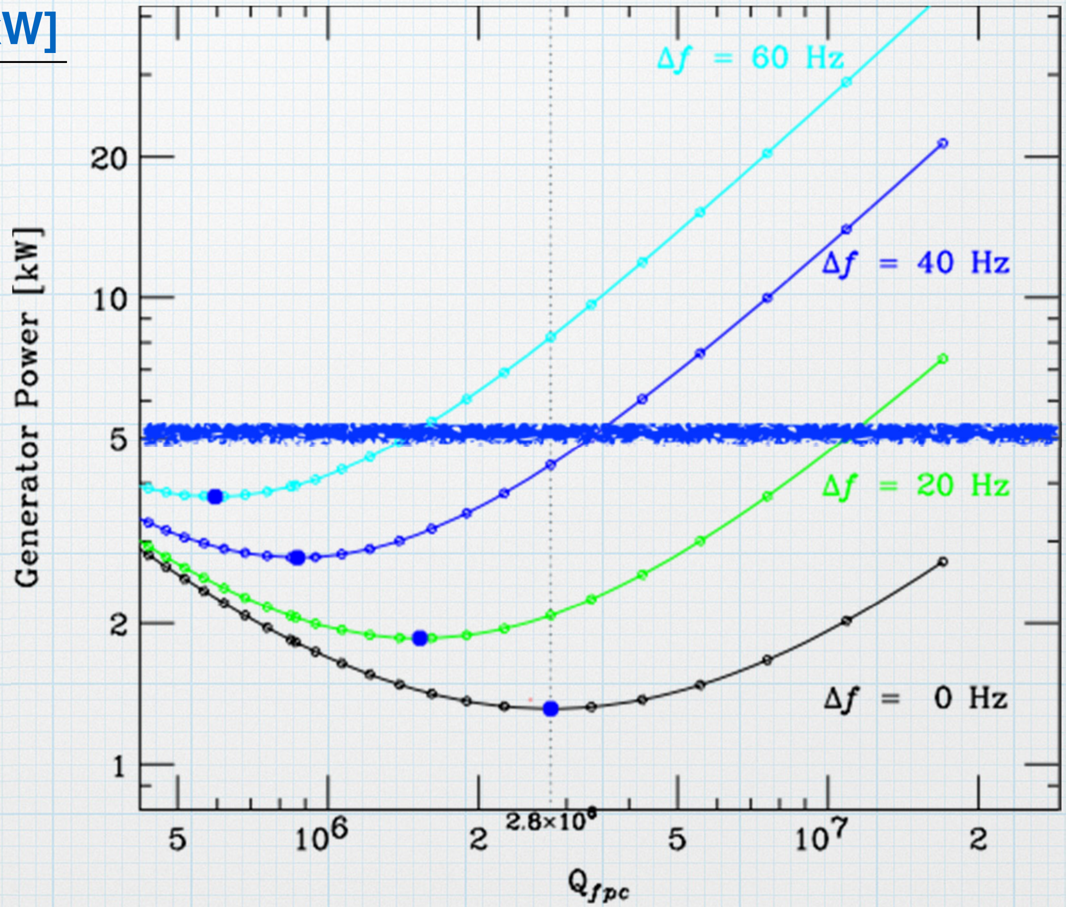
$$P_{\rm av} = P'_{\rm load} + P_0 - P_{\rm beam}$$

REQUIRED RF POWER WITH Δf

- **Optimum Q:**
  Q_{ext} minimum point, varies according to cavity detuning.

Δf [Hz]	Q_{opt}	RF Power [kW]
0	2.79E+06	1.31
20	1.53E+06	1.86
40	8.68E+05	2.77
60	5.94E+05	3.74

P_{in} < 5 kW



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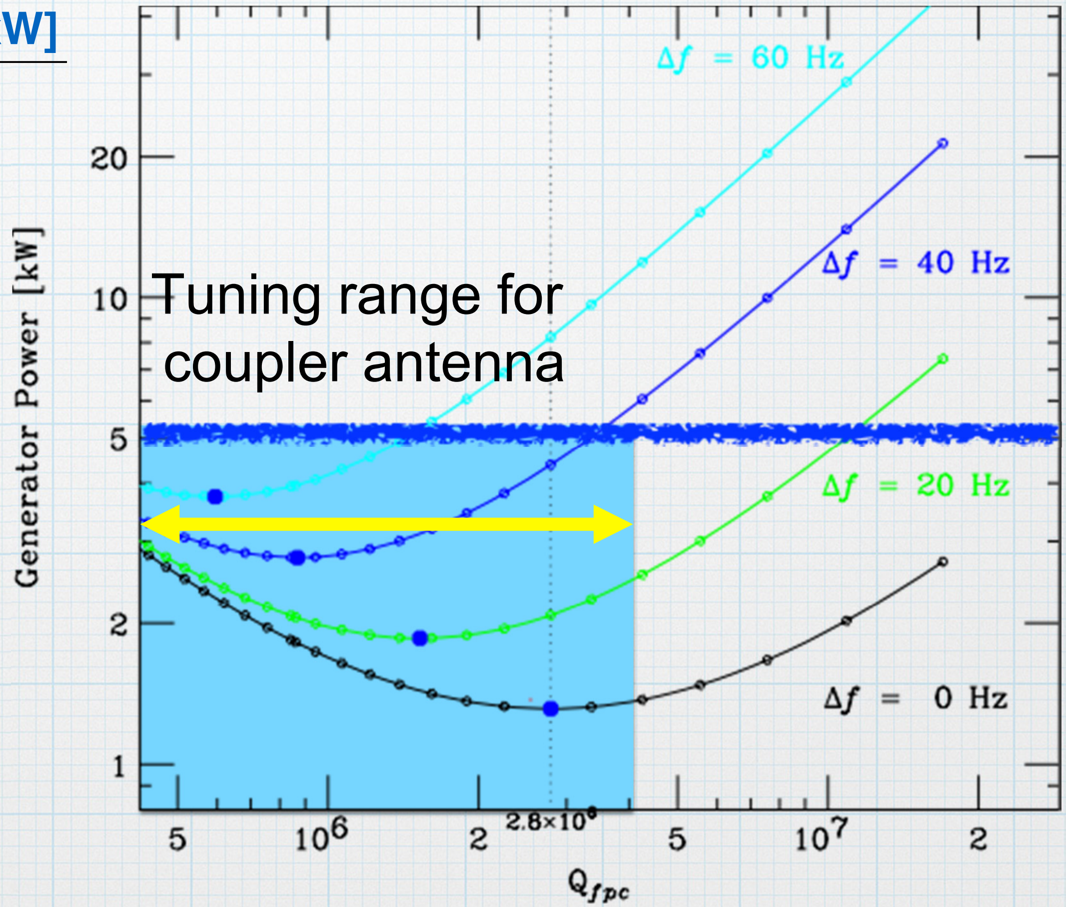


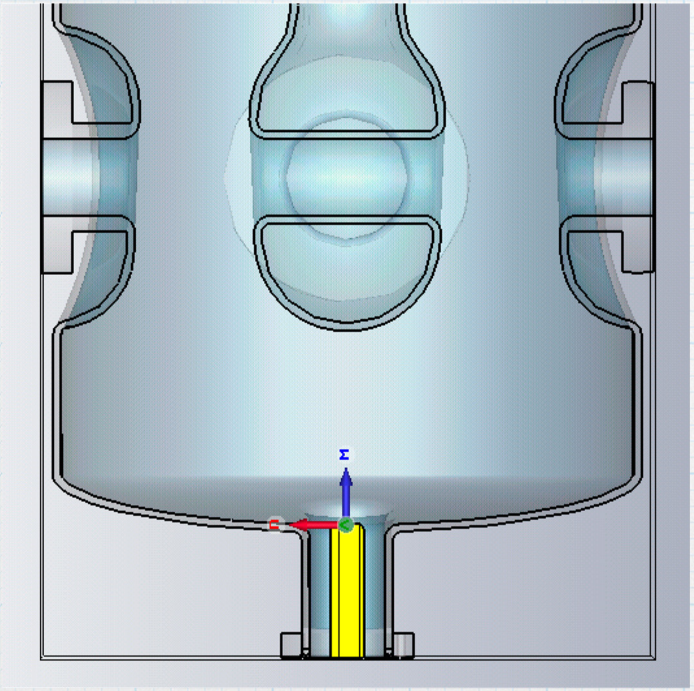
- **Coupling:**
  Q_{ext} must be chosen considering Q_{opt} w/ cavity detuning.

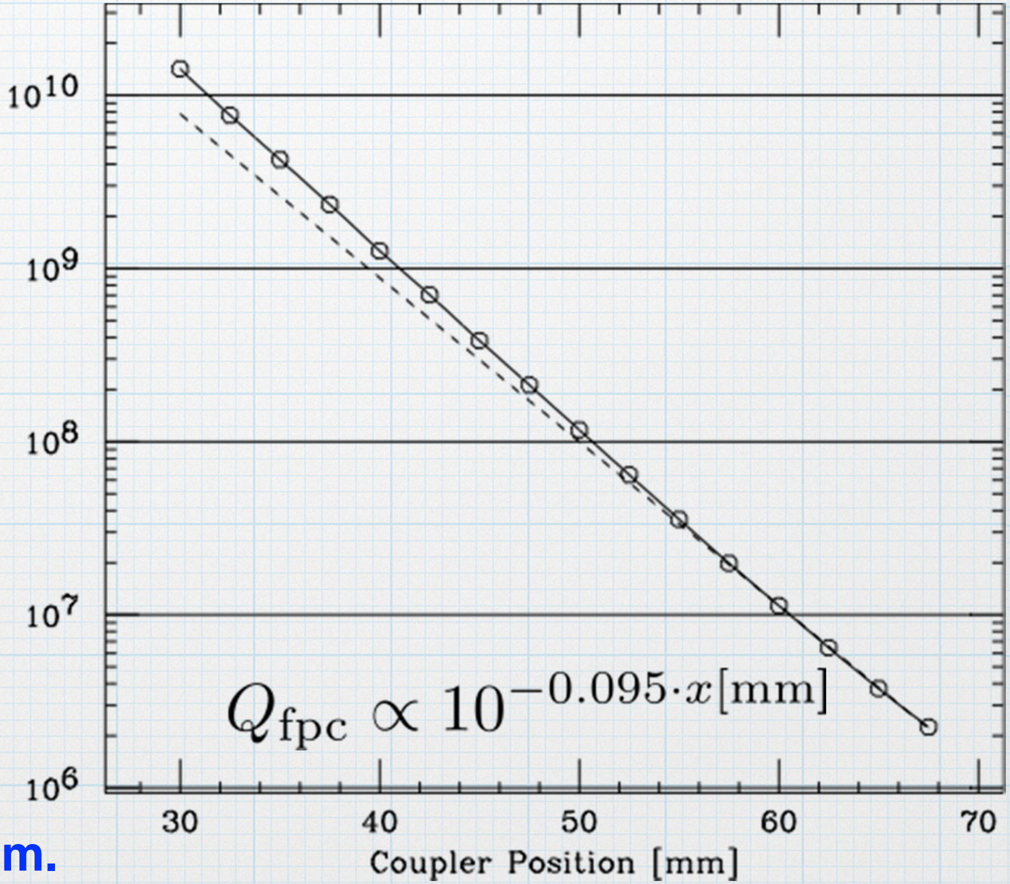
EXTERNAL Q FOR FPC

- **Variable Coupling to Choose Q_{ext}:**

  Q_{ext} obtained by a simulation using MWS

  →The stroke of ±5 mm for the coupling antenna changes Q_{ext} by a factor of 10.





Antenna stroke should have ±5 mm.

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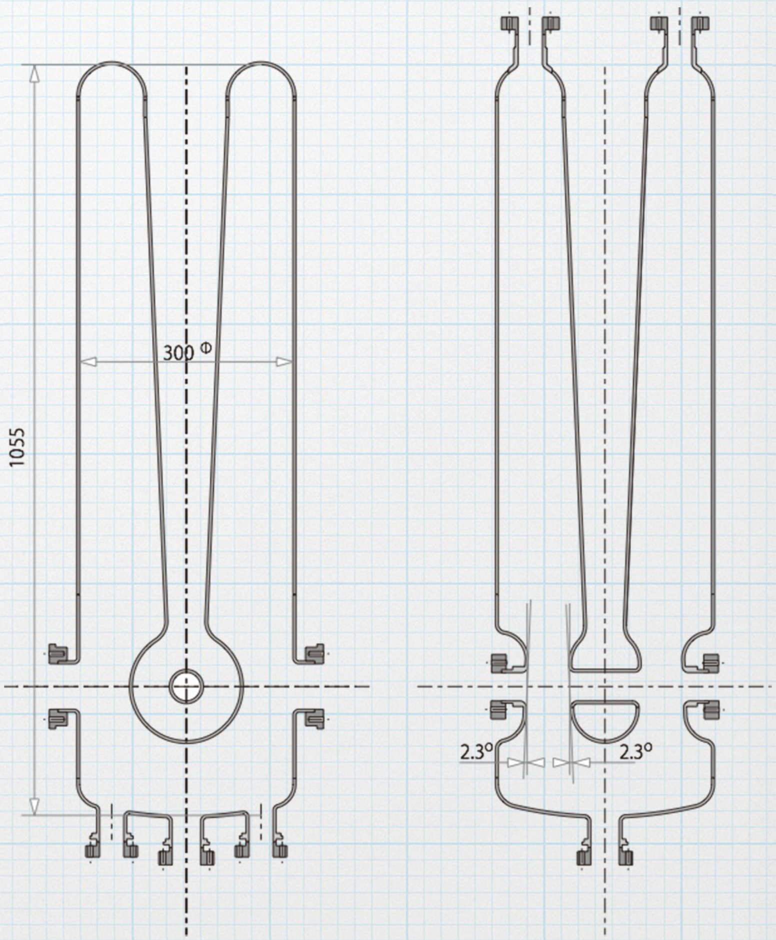
PROTOTYPE OF QWR

- **PROJECT:** *Prototyping the SC-QWR for low β heavy-ions such as d, α, and C started at RIKEN. Goal of this project is acceleration test of very intense beams from RIKEN LINAC Booster.*
- **RF Design:**
  - -Operation frequency is 75.5 MHz.
  - -Design of 73.0 MHz QWR has been modified. (H=1055 mm)
  - -Beam energy 6 MeV/u (β=0.113)
  - -Drift tube faces are tilted by 2.3^o

Resonator	75.5 MHz	73.0 MHz
G	23.3	22.6
$R_{sh}/Q[\Omega]$	714	718
Q_0 (Rs=25 nΩ)	$9.3x10^8$	$8.9x10^8$
E_{acc}[MV/m]	4.5	4.5
E_{peak}/E_{acc}	6.3	6.0
B_{peak}/E_{acc}[mT/ MV/m]	10.6	9.5



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- **Mechanical Design:**

-Bulk Nb sheet (4 mm)

-Parts Partitioning (Blue lines)

-Corner R around the ports,shape of the bottom lid, and etc. has been modified (Red lines).

-9 Ports:

2 cleaning ports at the top,

2 beam ports,

2 side test ports

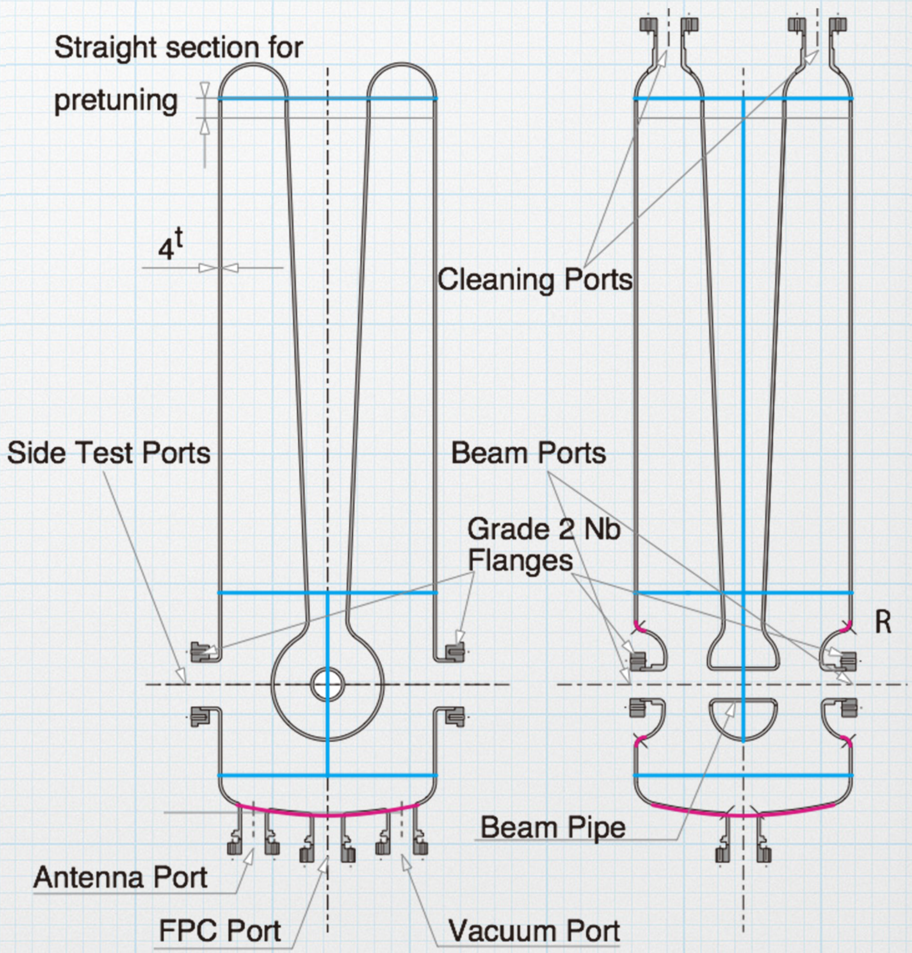
FPC port,

Pickup antenna port,

vacuum port on the bottom

-Straight section for pre-tuning

-Stiffener



MECHANICAL STUDY OF THE RESONATOR

- **STIFFENER:**

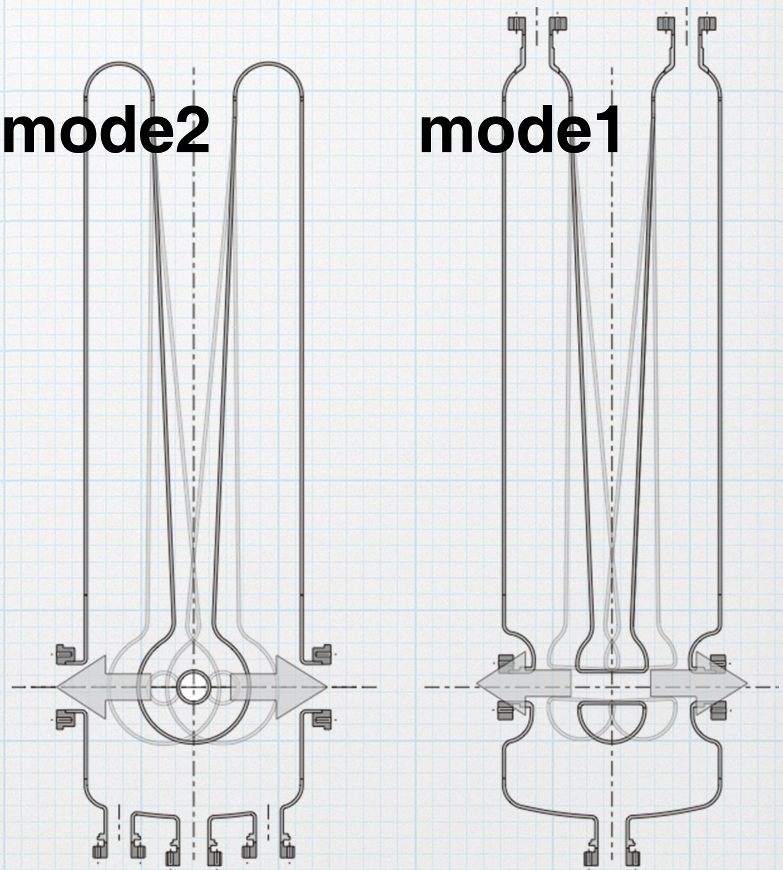
  A rib-structure mounted to the top torus part to suppress the deformation by atmospheric and He pressure and the mechanical vibration of the stem.

- **Simulations of Pendulum Mode Vibration:**

  -Azimuthal direction = **mode 1**

  → sensitive to resonant frequency

  -Perpendicular to the beam direction = **mode 2**



MECHANICAL STUDY OF THE RESONATOR

- **Purpose of STIFFENER:**
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- **Pendulum Mode Vibration:**
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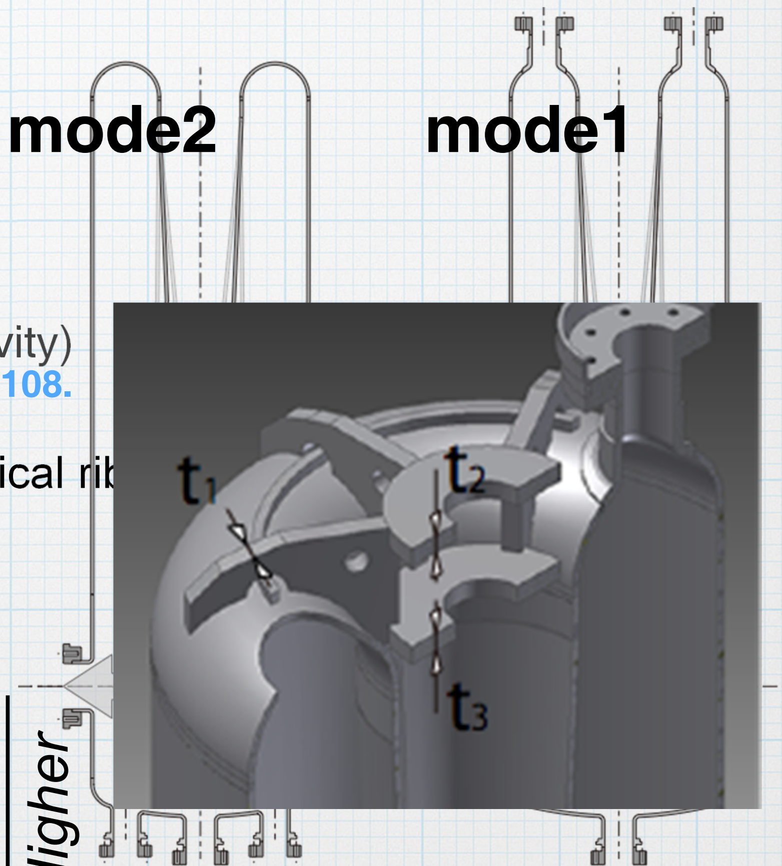
  → sensitive to resonant frequency
  -Perpendicular to the beam direction = **mode 2**



- **Structure of Stiffener** (similar to SPIRAL2 cavity)
  G. Devanz et. al., SRF2015, MOP02, p. 108.
  -Vertical ribs with 6-fold symmetry
  -Pair of donut-shaped disks attached to the vertical rib
  -Circumferential half rings (pair)
- **Modal Analysis by ANSYS**

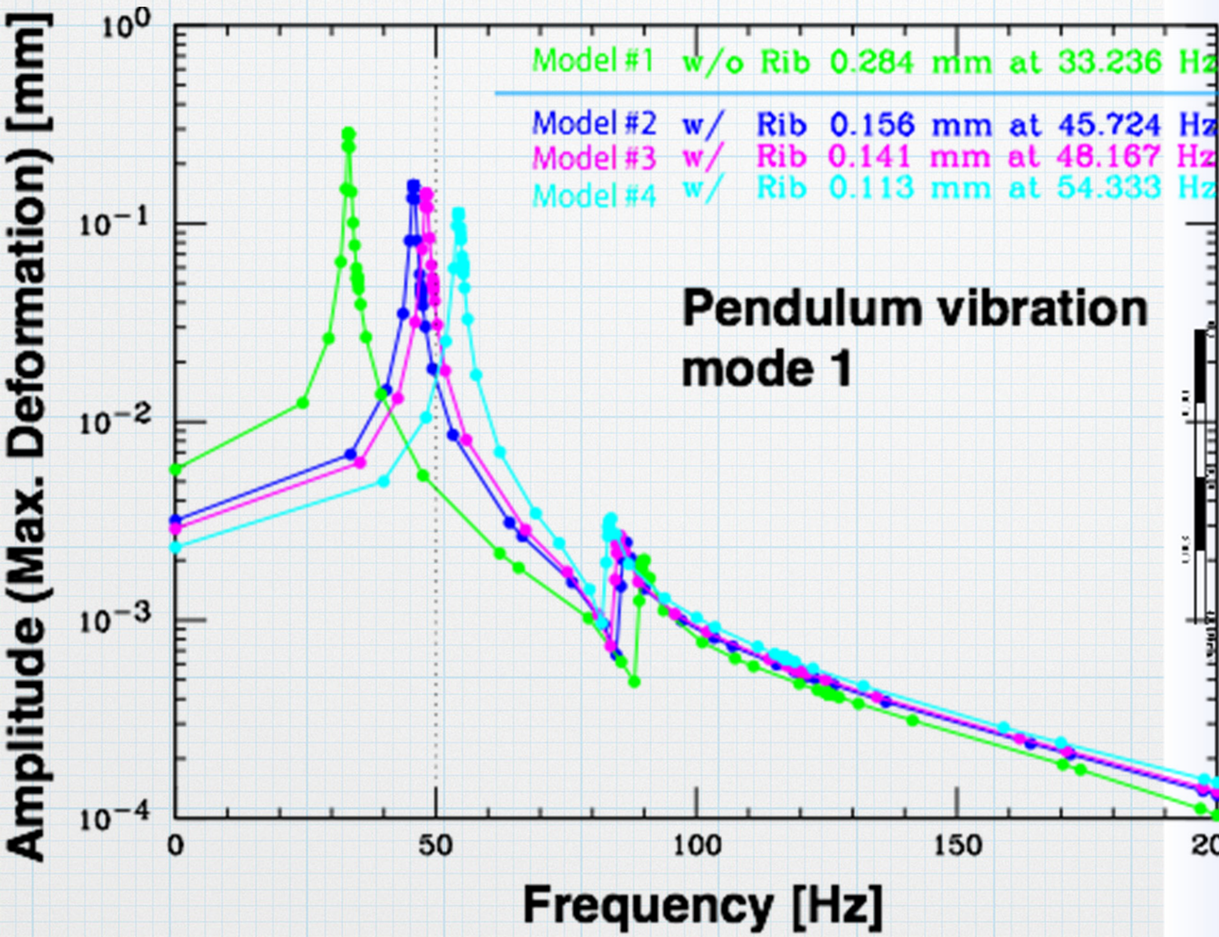
#	t1(mm)	t2(mm)	t3(mm)	δZ(mm)	f1(Hz)	f2(Hz)
1	no	no	no	0.254	32.5	33.5
2	5	5	5	0.073	45.7	47.2
3	5	10	10	0.067	48.2	49.4
4	10	10	10	0.051	54.3	55.2

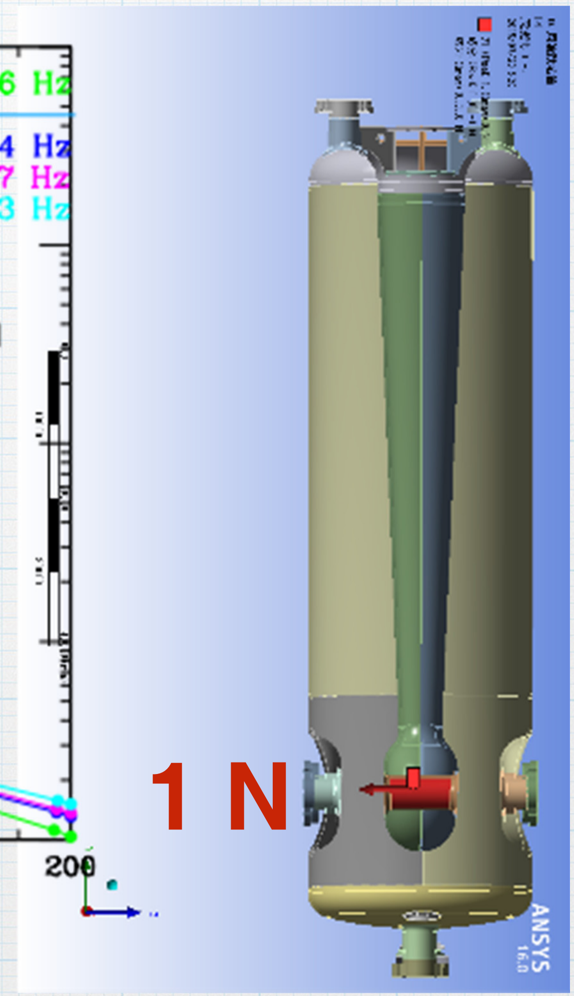
More Rigid ↓ Smaller ↓ Higher ↓

MECHANICAL STUDY OF THE RESONATOR

- **Frequency Response:**

  1 N added on beam pipe





It must be avoided to match to 50 Hz (frequency of commercial power)

SURFACE TREATMENT

Cleaning procedure of the inner surface of the resonator is one of the most important issues in the fabrication of bulk Nb resonator.

- Fairly standard processing.
- Processing should be made under clean circumstances.
- Local BCP might be effective for pre-tuning.

Light BCP → HPR → Annealing → BCP → HPR → Baking

Procedure of surface preparation.

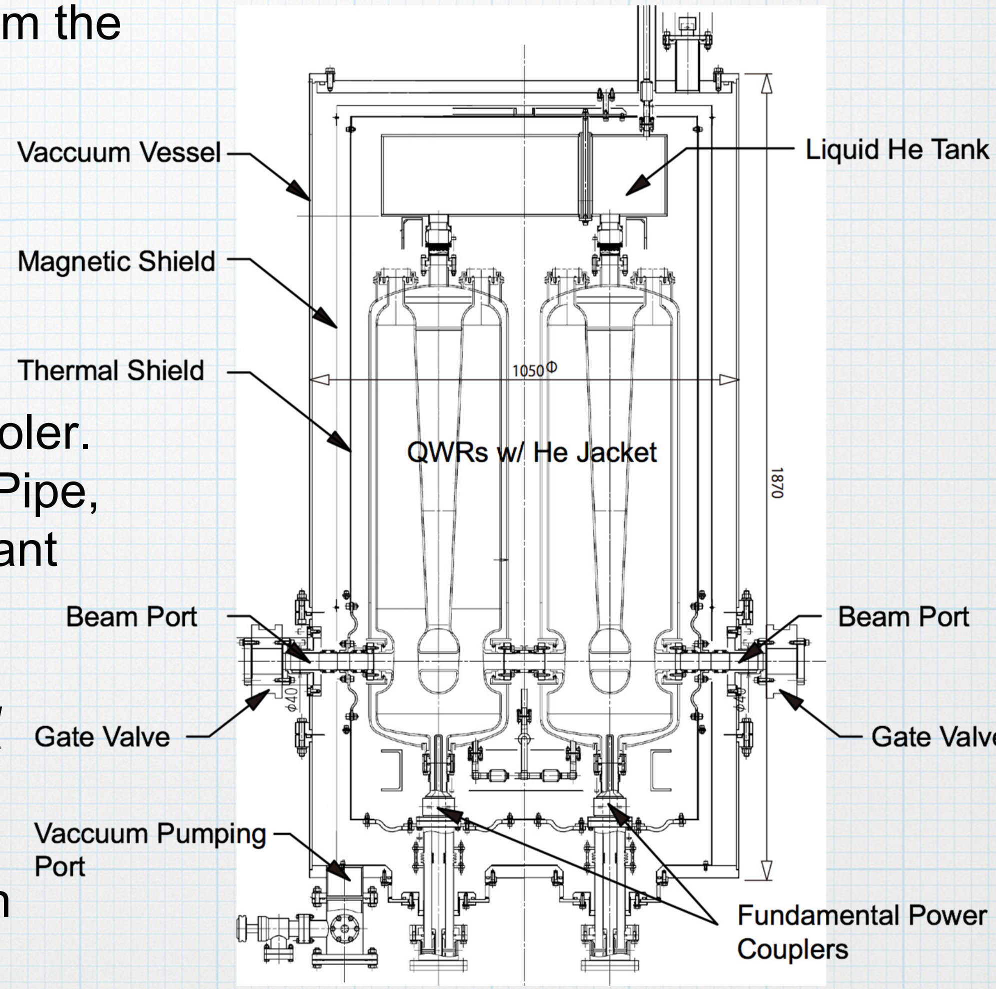
-Manufacturing and surface preparation will be made by Mitsubhisi Heavy Industries Co., Ltd

Poster:A. Miyamoto et. al., THPB029

-1st vertical test is planned be held at AR-Higashi (KEK) from March 2016

CRYOSTAT

- **BASIC CONCEPT:**
  -_Resonator vacuum_ is separated from the vacuum of the cryostat.
  -_FPC has coupling tunable_ mechanism which enables tuning without warming up or release of vacuum.
  -_Single-stage thermal shield_ (40 K) which is cooled with a small cryo-cooler.
  -_Thermal transitions_ of FPC, Beam Pipe, Vacuum pipe and so on play important role to reduce thermal conduction from the part of room temperature.
  -_Room temperature magnetic shield_
- **THERMAL FLOW ESTIMATION:**
  -Total thermal flow considering dynamic losses and heat conduction into 4 K and 40 K parts are 5 and 15 W/resonator, respectively.
- **FUNDAMENTAL POWER COUPLER**



Poster:K. Ozeki et. al., THPB084

SUMMARY

- New project to construct a superconducting linac is proposed aimed at intensity upgrade of uranium beams of RIKEN RIBF.
- Design studies for superconducting cryomodule for low β section, including quarter wave resonator, fundamental power coupler, and cold tuner have been made.
- Prototyping of an SC-QWR for very intense ion-accelerator started.
- 1st vertical test is planned to be performed in March 2016 at KEK.
- Manufacturing of the test cryomodule will be made in 2016 and cooling test will be performed in March 2017.

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Thank you for your attention.

Photo taken at the kick-off meeting on July 10, 2015 @RIKEN, Wako