Study of Front-End RF Structures (RFQ and MEBT)

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Outline

- Research Motivation

- RFQ with different vane-end termination
- Double-gap MEBT rebuncher cavity
- Perturbation and RFQ

- Summary

Research Motivation

Radio Frequency Quadrupole (RFQ) is expensive

- **RFQ fabrication cost is very expensive because of modulation, brazing, mode stabilizer design, …**

- **Can mode stabilizer design be removed ?**

SNS MEBT rebuncher emits X-radiation

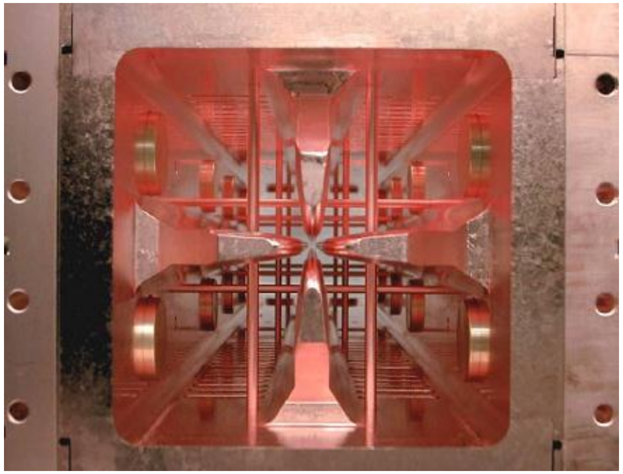
- **Rebuncher cavity 4 of SNS MEBT <u>emits X-radiation</u> after maintenance**

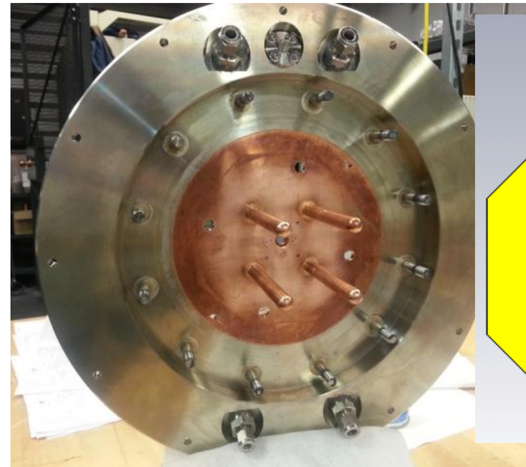
- **SNS MEBT system is not in Concrete tunnel**

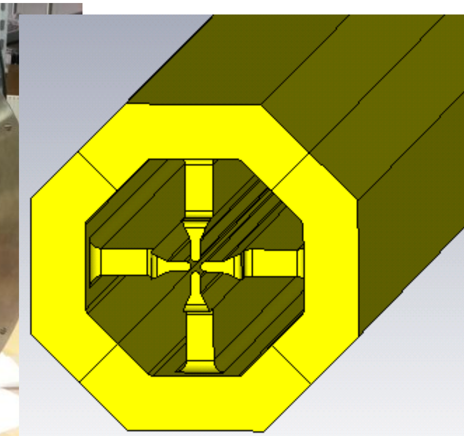
- **Can X-radiation be decreased by another cavity design ?**

New SNS RFQ has been installed

- <u>Existing vs. New RFQ </u>(RF vs. Mechanical)







	Existing RFQ	Spare RFQ
Composite	Copper + Glidcop shell	Copper
Shape	Rectanglar	Octagonal
Stabilization	Pi-mode stabilizing loop	Dipole stabilizer rods

- **Perturbation and RF tuning ?**

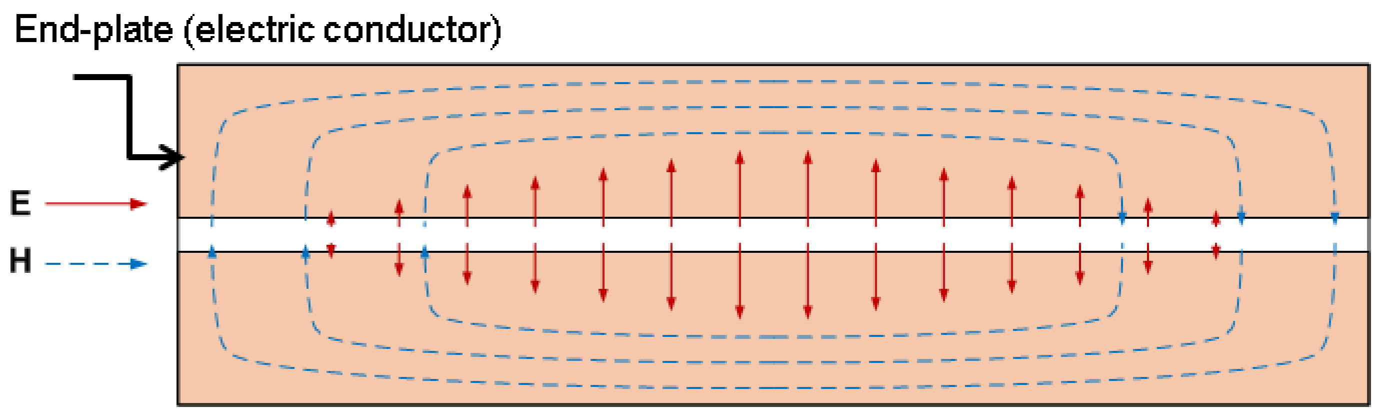
"The SNS," T. Wangler, J. Billen, and R. Keller, U. S. Particle Accelerator School, 2004.

RFQ with different vane-end termination (For cost effective RFQ)

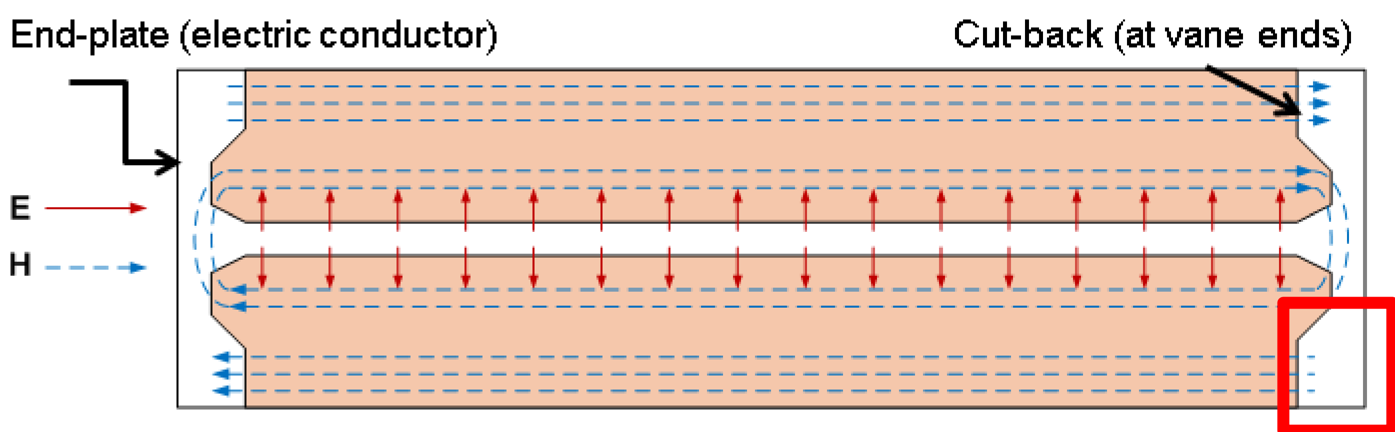
***Feasibility of folded and double dipole radio frequency quadrupole cavities for particle accelerators*, <u>Ki R. Shin</u>, Yoon W. Kang, and Aly E. Fathy, IEEE Transactions on Nuclear Science, Vol. 61, Issue 2.**

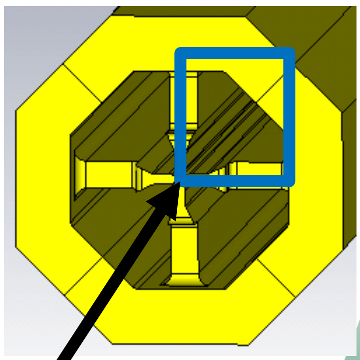
RFQ cut-back

- **RFQ requires vane end cut-backs to have uniform E - field**
- **Transverse resonance + Cut-back resonance**



RFQ without cut-back





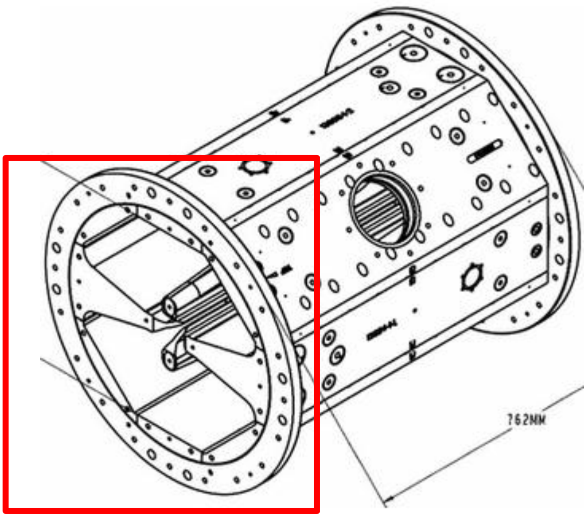
Same Frequency

RFQ with cut-back

Split coaxial structure for heavy-ion

- **Common RFQ has cut-backs on every four vane ends**
- **Split coaxial : a vane pair with short circuit condition**

  Another vane pair with cut-back
- **Interleaved (upstream ← → downstream)**



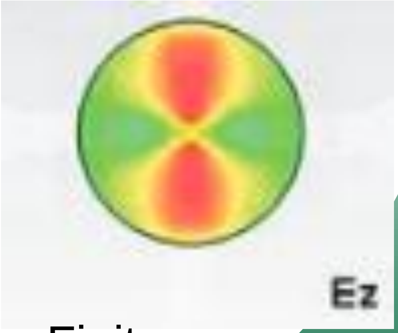
P. Ostroumov et al., "Development and beam test of a continuous wave radio frequency quadrupole accelerator," Phys. Rev. ST Accel. Beams 15, vol.15, Nov.2012

	Traditional	Split coaxial
Pro.	Symmetric ends	Better mode separation with short RFQ length
Con.	-	Asymmetric ends **(finite axial field)**

+

-

Zero
(at center)



Finite
(at center)

On-axis field at RFQ ends (Split coaxial)

- **Recent beam dynamics study at ATLAS states that these on-axis fields do not affect beam quality**

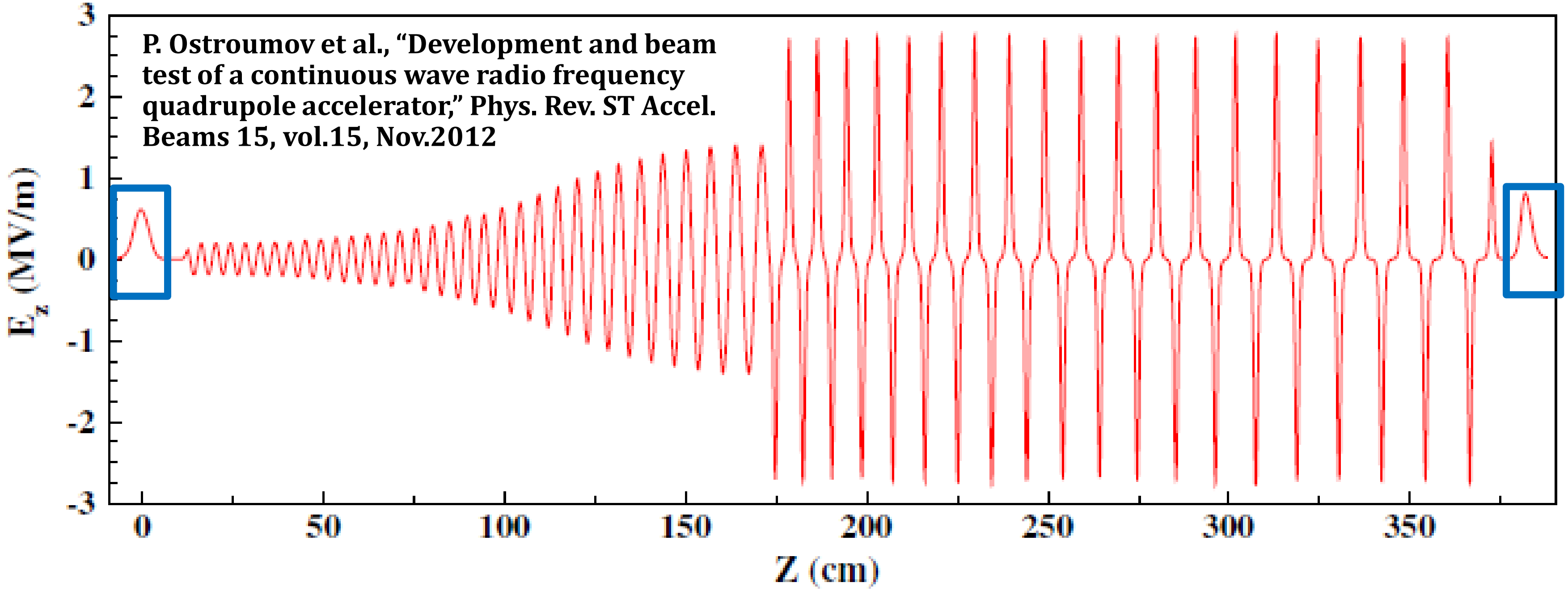


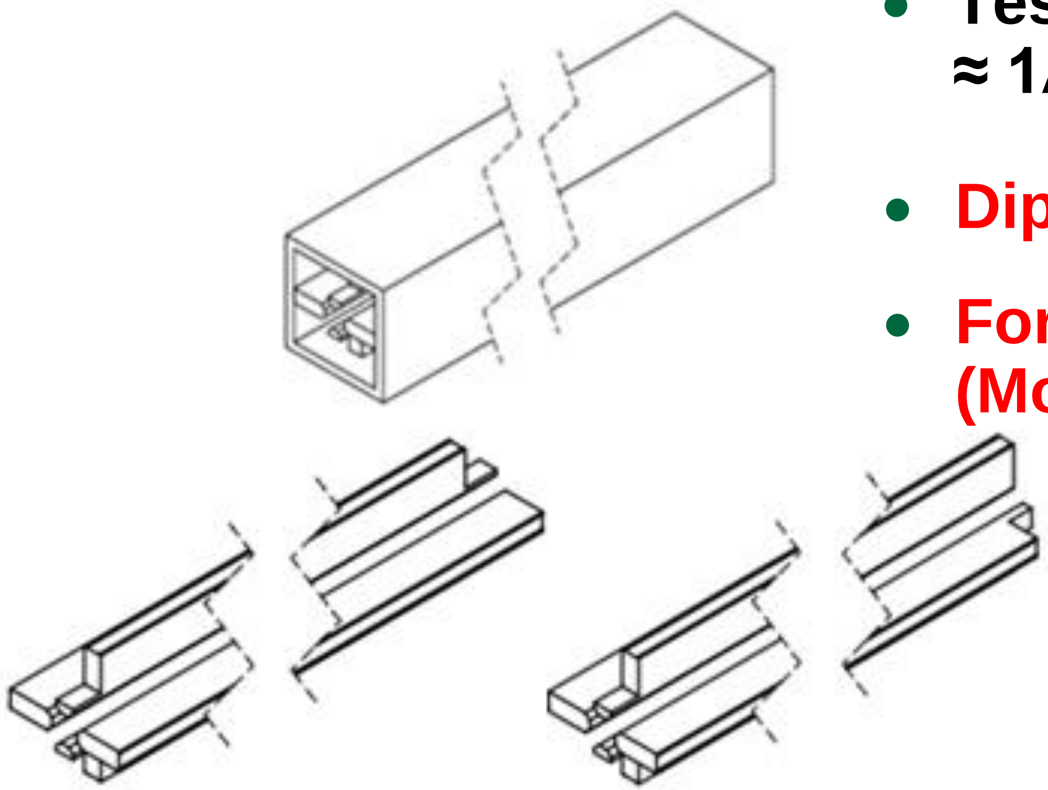
FIG. 2. On-axis longitudinal field along the RFQ.

"The Ez component of the field at the entrance extends over about 2 RF periods. <u>If the Ez(z) sign is the same over RF period, the average energy gain per RF period is equal to 0.</u>"

- **Asymmetric ends for light ion 4-vane RFQ ?**

Terminations for light ion 4-vane RFQ

- **Two possible terminations were studied at Chalk River**



- **Test model was built with ≈ 1λ length**
- **Dipole characteristics ?**
- **For long light ion RFQ ? (Mode separation ?)**

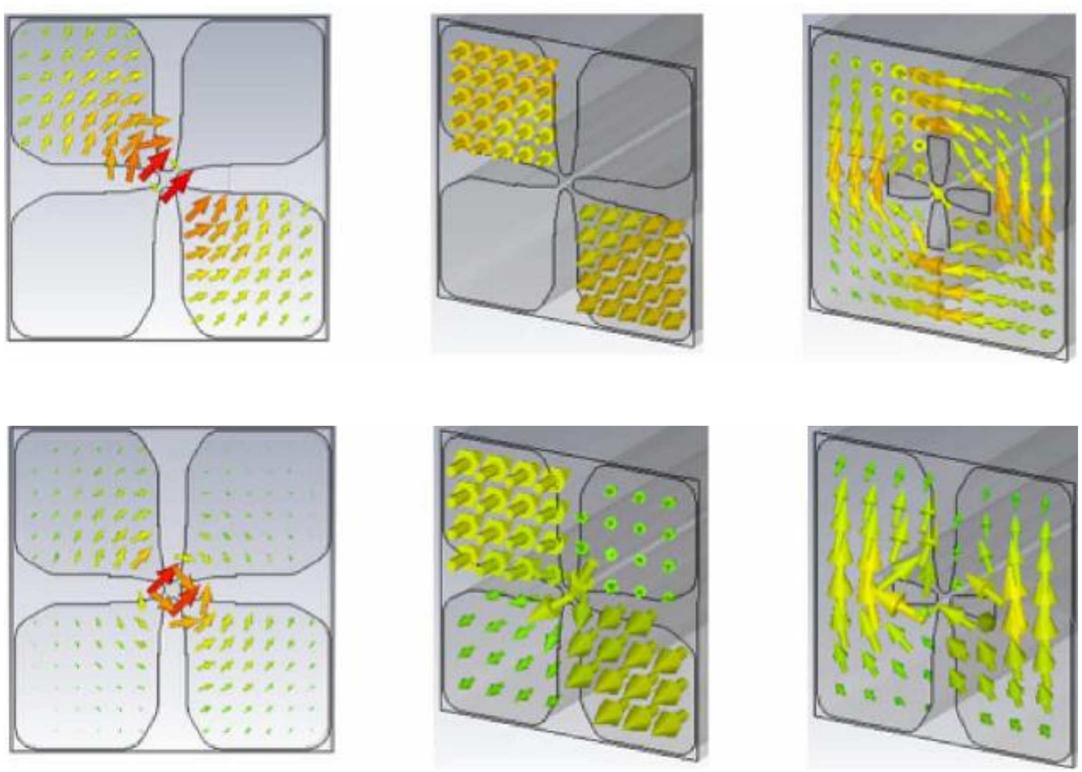
Double dipole (DD)
→Not Interleaved
→Dipoles do not degenerate

Folded dipole (FD)
→Interleaved
→Similar to split-coaxial

R. Hutcheon et al., "RFQ linac structure developments at CRNL," IEEE Trans. Nuc. Sci. 1983

Dipole mode in 4C / FD / DD RFQ (1)

- **Traditional RFQ (4C) generate dipole in two diagonal**
- **FD has finite fields in other quadrants as well**



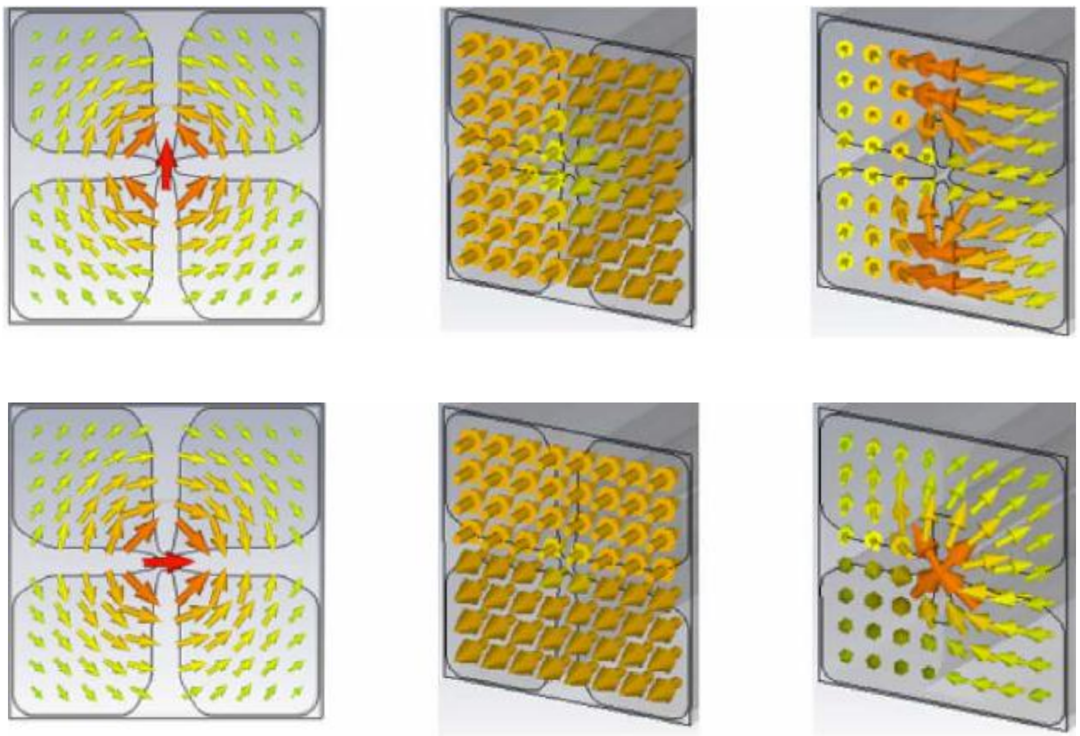
Traditional RFQs

Folded Dipole
(Unbalanced Transmission Line
→ Common mode currents excited through cut-back)
→ Gives Strong effects in short RFQ with more H/E coupling ratio

E field **H field** **H field (Cut-back)**

Dipole mode in 4C / FD / DD RFQ (2)

- **DD generate one dipole with open circuit-like end**
- **DD generate another dipole with short circuit-like end**
- **Similar frequencies with an harmonic order difference**



Double Dipole (open)
(DD_open ≈ <u>waveguide term</u>.)

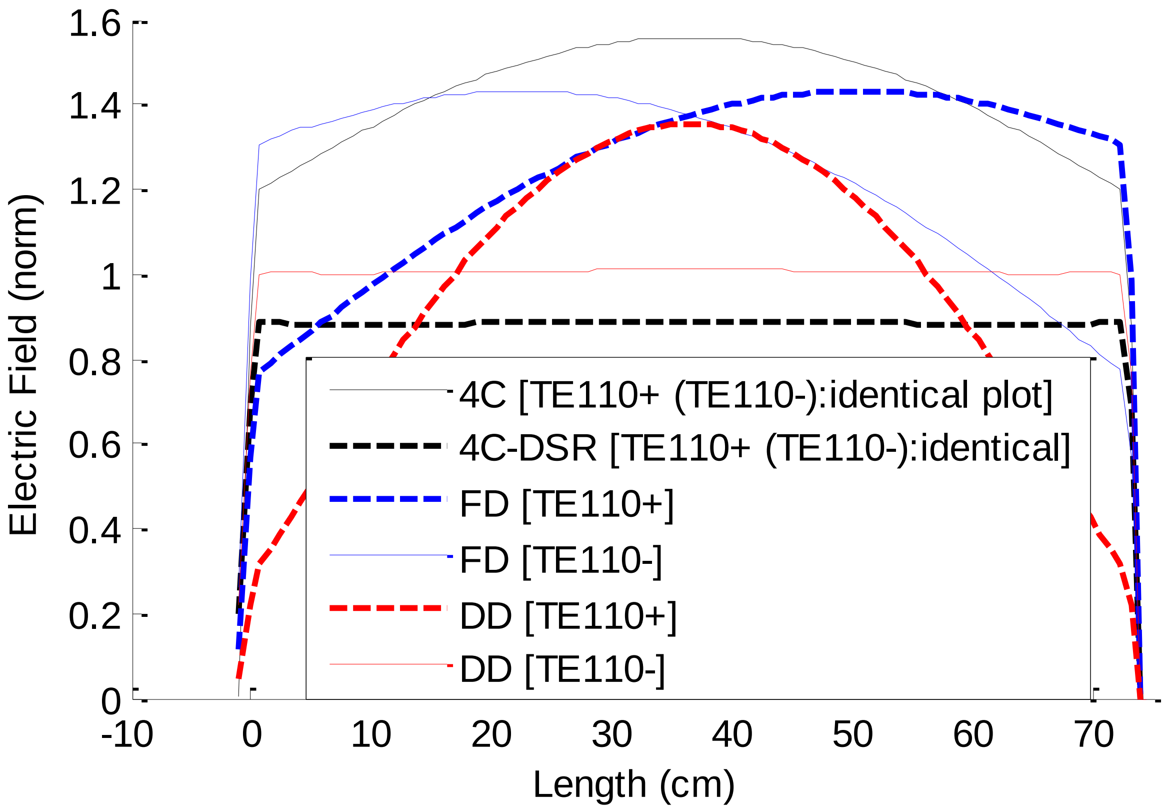
Do not degenerate, But related ?
(By an harmonic order)

Double Dipole (short)
(DD_short ≈ <u>cavity term</u>.)

E field **H field** **H field (Cut-back)**

Dipole field distribution in longitudinal direction

- **An example with 0.74 λ RFQ with SNS geometry**
- **4C / FD / DD and 4C-DSR (Dipole stabilizer rods)**



- 4C (unmatched)
- 4C + DSR (matched)
- DD_open (matched)

→ Because of axial capacitance

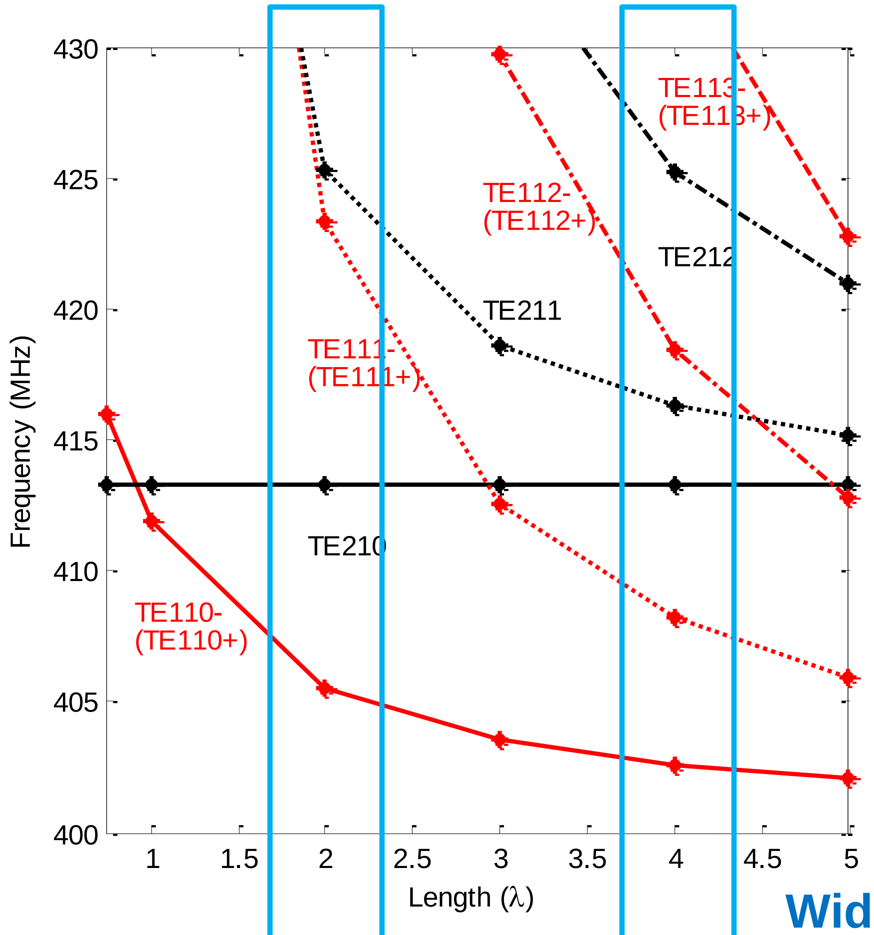
→ Higher cut-back capacitance in dipole

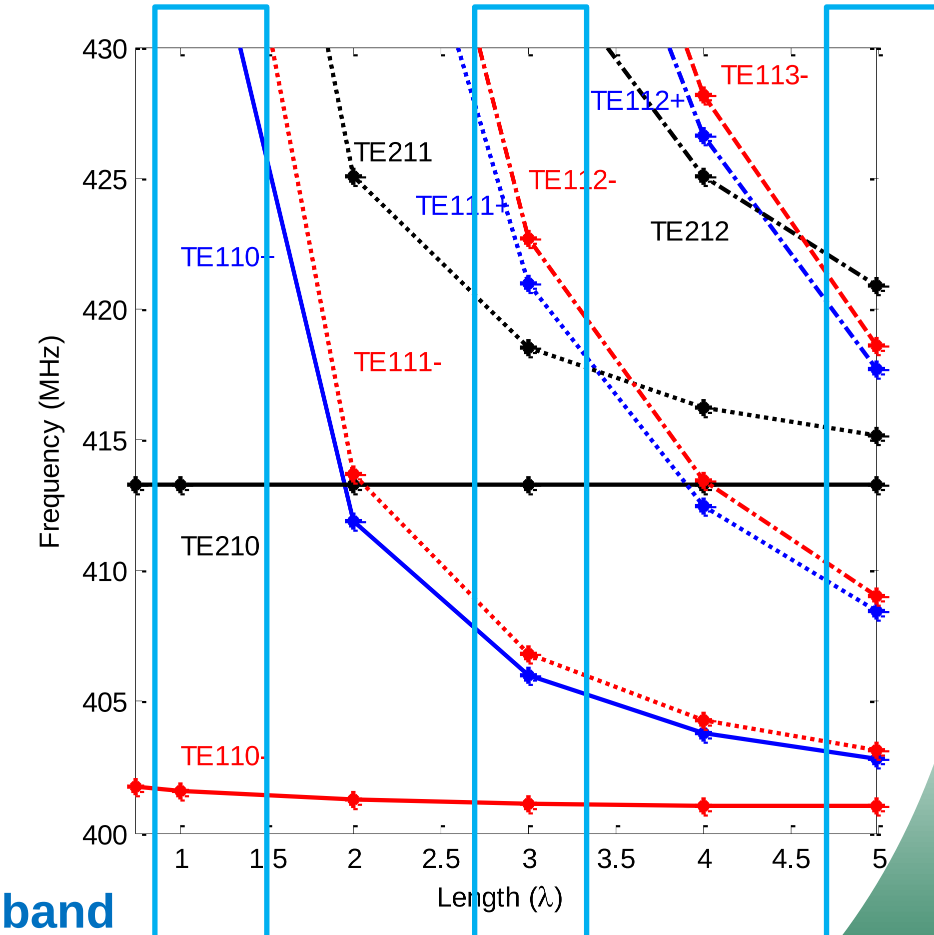
- DD_short (sinusoidal)

DD has unique dipole frequencies (similar to 4C +DSR)

RFQ mode spectrum by structure length :with SNS transverse geometry (1)

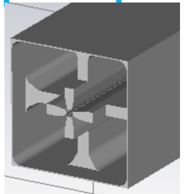
- **DD gives wideband exactly in where 4C RFQ does not**



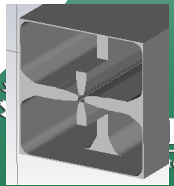


Wideband

4C RFQ (2λ, 4λ)

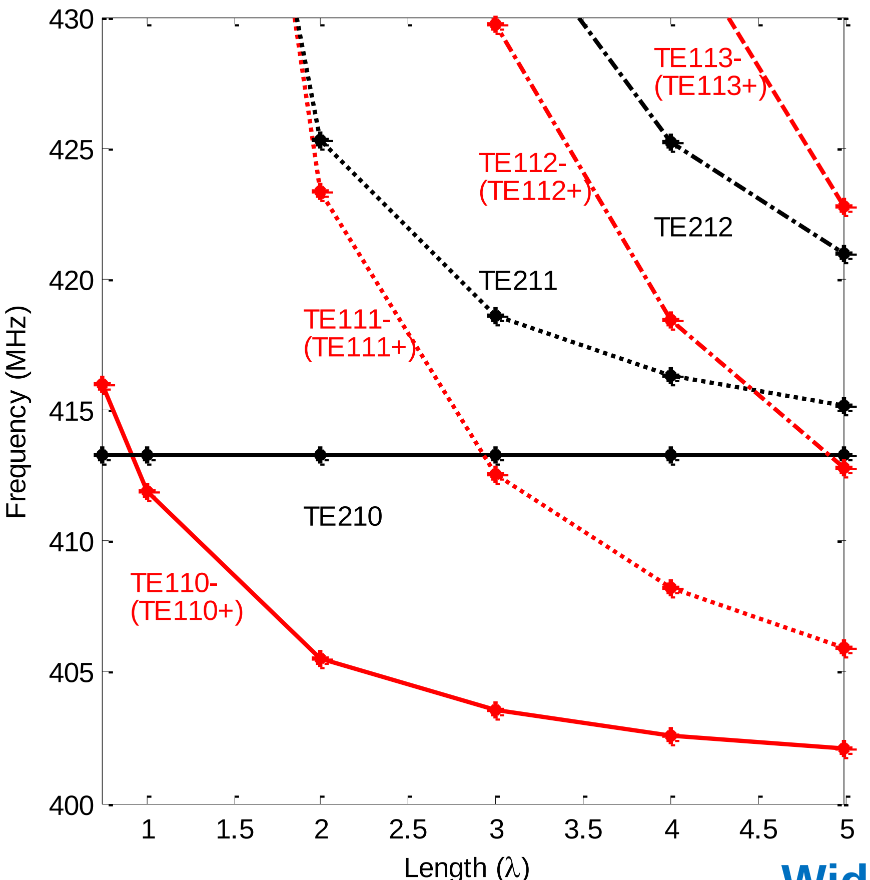


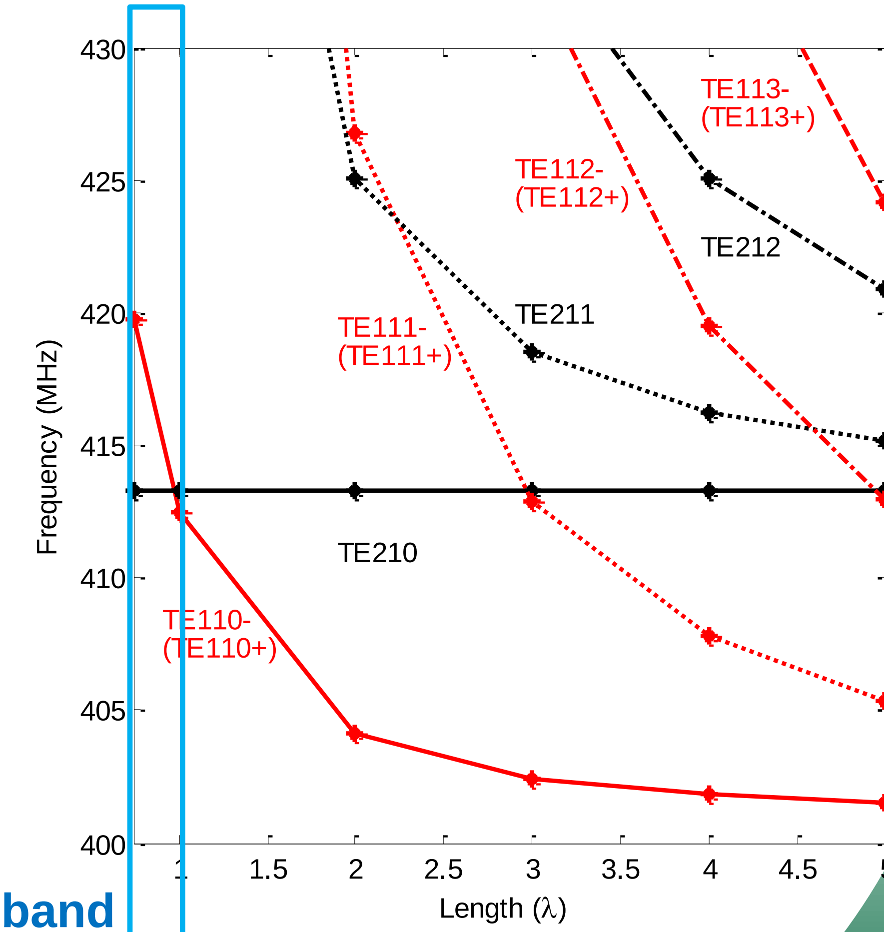
DD RFQ (≤1.5λ, 3λ, 5λ)



RFQ mode spectrum by structure length :with SNS transverse geometry (2)

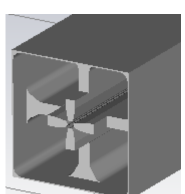
- As expected, FD scheme is useful in short RFQs



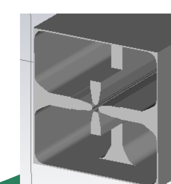


Wideband

4C RFQ



FD RFQ



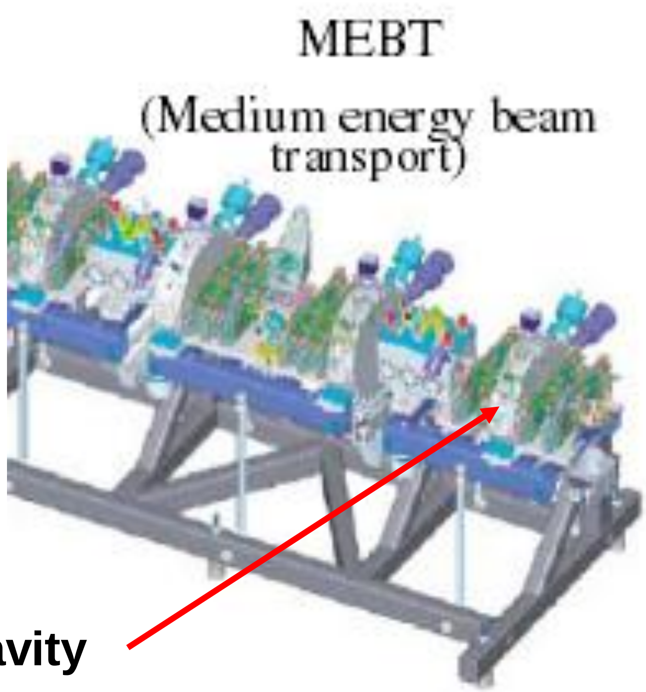
Short summary of Part I

- DD RFQ can be selectively used as well as 4C RFQ for fixed length RFQs

- FD RFQ can be useful for short RFQs

- RFQ design / tuning cost can be decreased (Stabilizer design may not be necessary)

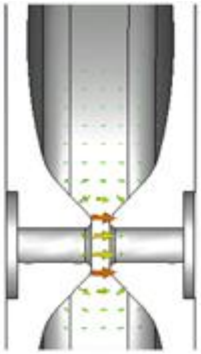
Double-gap MEBT rebuncher study



Rebuncher cavity

***Design guideline of a double-gap microwave rebuncher cavity for a 400 MHz, 2.5MeV energy light ion accelerator*, Ki R. Shin, Yoon W. Kang, and Aly E. Fathy, IEEE Transactions on Nuclear Science, Vol. 61, Issue 2.**

X-radiation issue and SNS MEBT



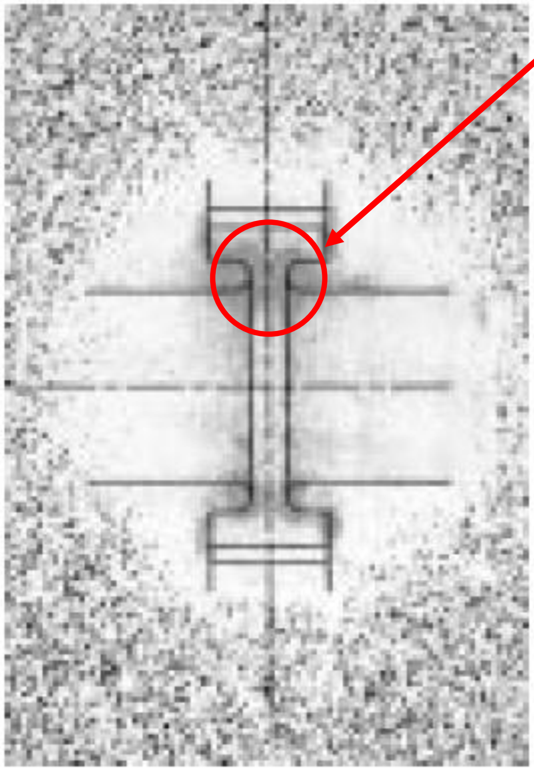
- SNS MEBT has 4 rebuncher cavities
- Cavity 4 with the highest operating gap voltage (120kV) emitted over 50~100 mRad X-radiation

  → Space with > 5 mRad is unoccupiable (radiation area)

- SNS MEBT system is outside of Concrete tunnel
- Another cavity design with reduced gap voltage ?

X-radiation, cavity gap voltage and field

- **X-radiation is determined by the gap voltage and field**



Klystron cavity (SLAC)

Radiation mostly comes from the high voltage / field gap

(1) $$J_X \propto i(t) \cdot V^n(t)$$

Jx : radiation intensity
***i(t)* : discharge current**
V(t) : gap voltage
n : 1.8 ~ 3.0

(2) $$i(t) \cong A E(t)^{2.5} e^{-\frac{B}{E(t)}}$$

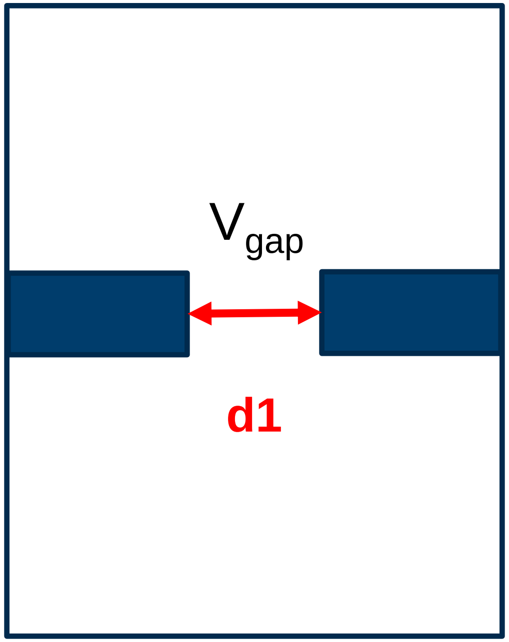
E(t) : electric field
A, B : constant

J. Wang and G. Loew, "Field emission and RF breakdown in high gradient room temperature linac structures," SLAC-PUB-7684, Oct. 1997.

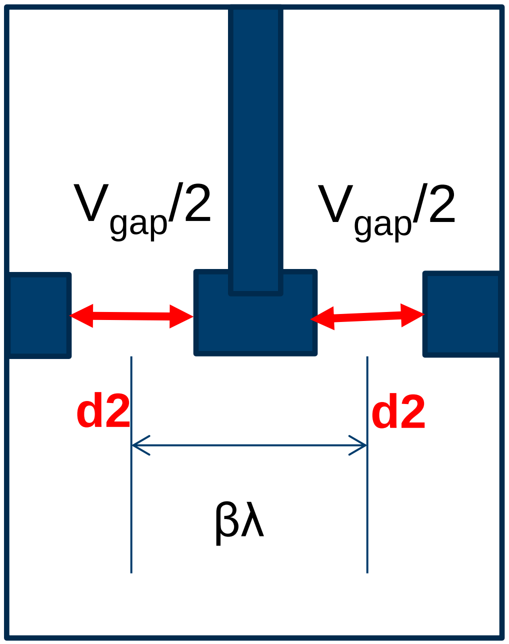
- **< 25% X-radiation is expected with double-gap**

Double-gap design and X-radiation

- **Double-gap design reduces the gap voltage as a half**
- **Similar gap size → decrease electric field**
- **TM cavity to provide similar cavity length (11.5 → 13.0cm)**



Single gap voltage
→ $V_{gap(tot)} = V_{gap}$



Double gap voltage
→ $V_{gap(tot)} = V_{gap}/2 + V_{gap}/2$

Gap size
d1 ≈ d2

Cavity parameter

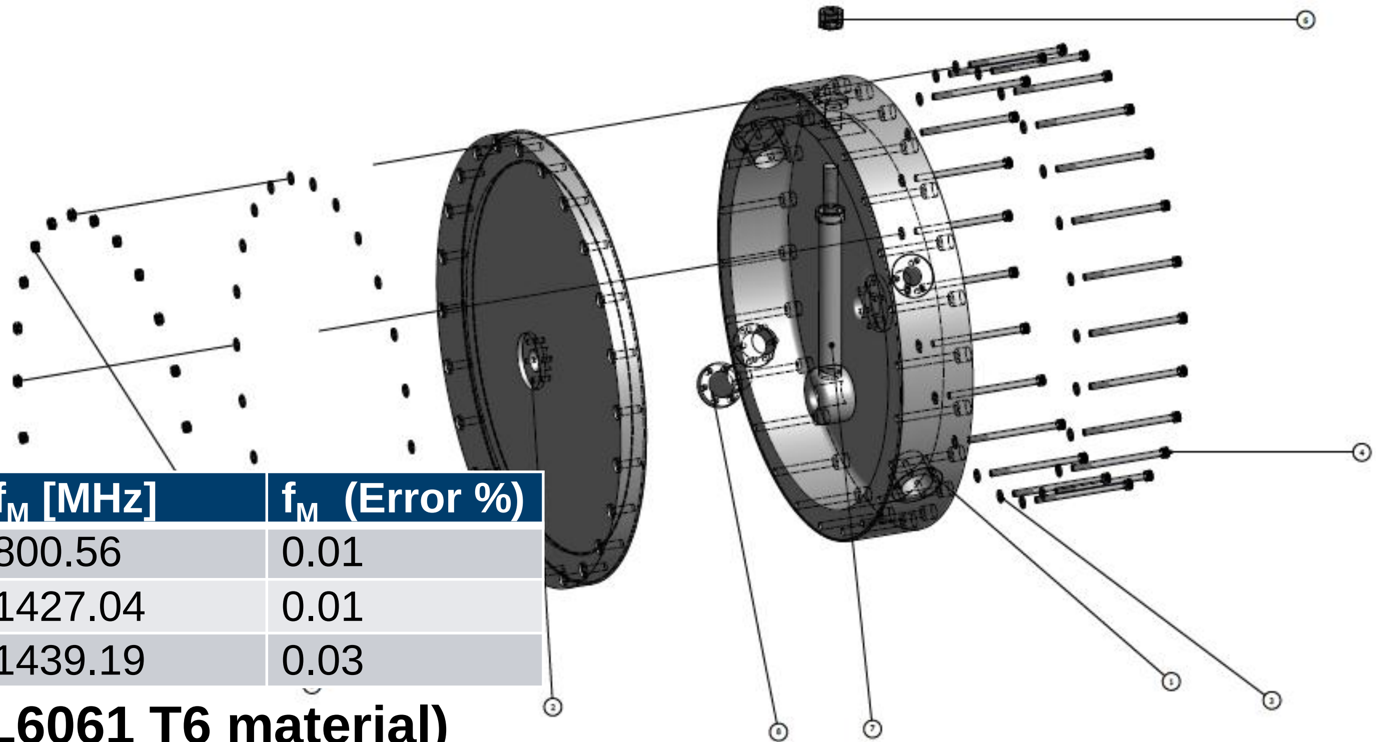
- **Single gap vs. Double gap – at 28.2 kW peak power**

	Single gap	Double gap (A)	Double gap (B)
Frequency f_0 (MHz)	401.9	400.3	**400.1**
Cavity length L (cm)	**11.48**	13.00	**13.00**
Gap size g (cm)	1.230	1.224 1.224	**1.423** **1.423**
Q (unloaded, copper)	21413	20773	**20903**
R/Q	29.35	29.17	**27.83**
R_s (Mohm)	0.629	0.592	**0.581**
V_0 (kV)	119.08	116.93	**114.55**
T	0.447	0.459	**0.452**
E_0 (MV/m)	2.32	1.94	**1.93**
E_{pk} (MV/m) [Kilpatrick]	**29.9** **[1.54]**	16.75 [0.86]	**13.26** **[0.68]**
H_{pk} (A/m)	**6565**	9323	**8644**

OAK RIDGE National Laboratory

Scaled model design and fabrication

- A ½ scale model is designed for low power demonstration
- RF measurements show good agreements with simulation



- Frequency

Mode	f_S [MHz]	f_M [MHz]	f_M (Error %)
TM010	800.49	800.56	0.01
TM110	1427.19	1427.04	0.01
TM110	1439.61	1439.19	0.03

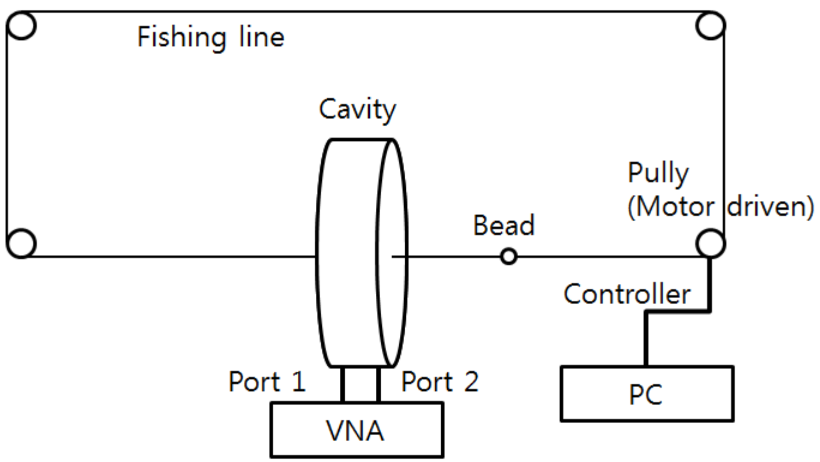
- Q (unloaded, AL6061 T6 material)

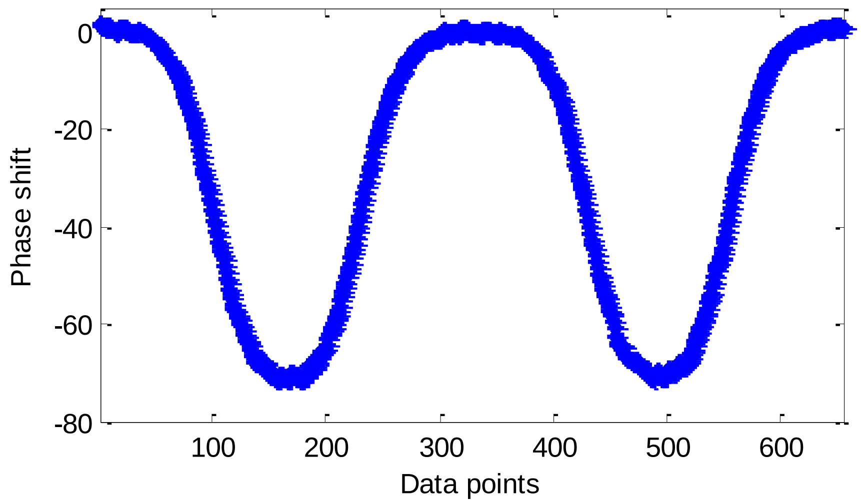
Mode	Q_S [MHz]	Q_M [MHz]	Q_M (Error %)
TM010	9286	8179	12
TM110	9474	7667	19
TM110	10567	9974	6

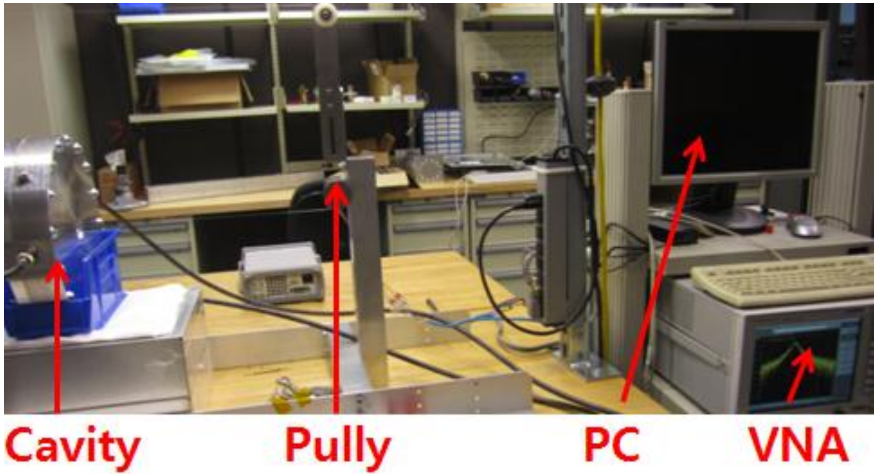
Explode view of cavity assembly (Autodesk Inventor)

Bead-pull measurement

- **Bead-pull measurement and R/Q calculation**





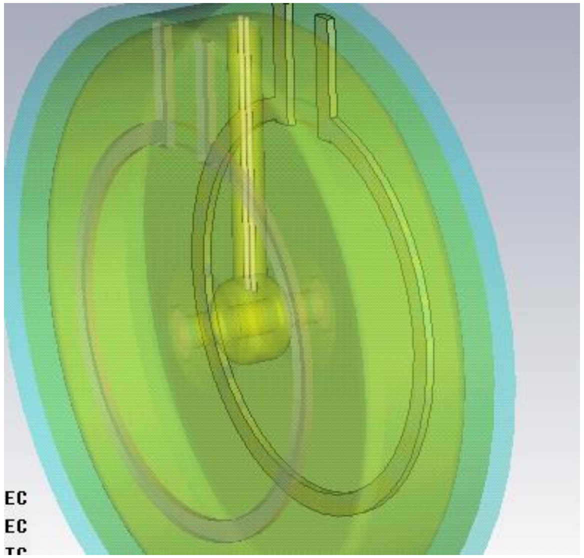


6.1% R/Q errors agrees well with expected errors about 3~7%

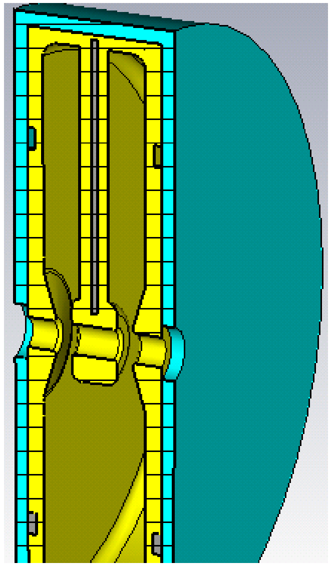
	Simulation	Measurement	Error
R/Q	27.83	26.12	6.1%
R_s (Mohm)	0.258	0.213	17.4%

Thermal analysis

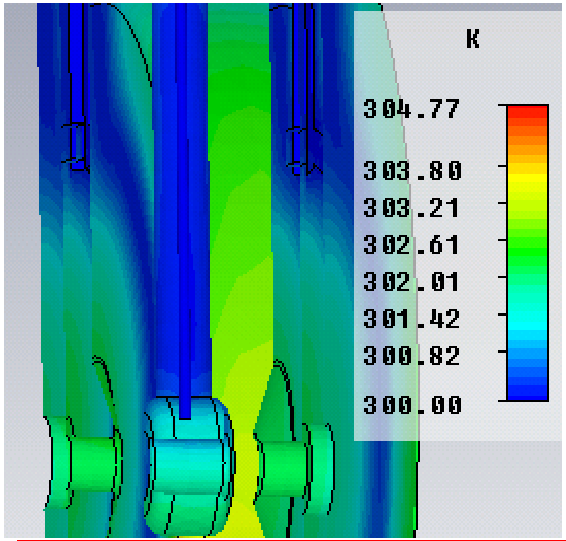
- **Drift tube assembly should be made by Copper**
- **Steel can be used for cavity body, but thick internal Copper plate is desirable**



Cooling channel in
Drift tube & cavity wall



Copper plate (0.61 in)
+
304 Stainless Steel (0.5 in)



ΔT Calculation

•CST (ΔT_{water} = 0)
→4.8 K (Zero Gradient)
→6.5 K (Expected)

Nose cone cooling is not necessary (Smaller capacitance)

Short summary of Part II

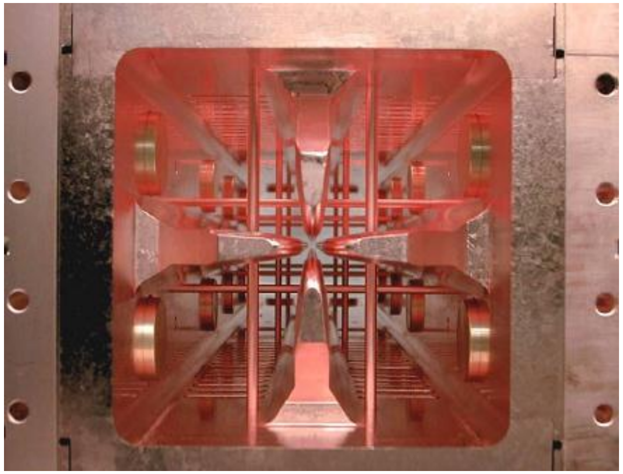
- Double-gap design would decrease X-radiation to << 25 % of single gap design
- RF power requirement remains almost the same
  → Cavity length increases from 11.5 to 13.0 cm
- Original beam performance can be maintained
  → Provides similar gap voltage and beam-line length
- Copper plate design method can prevent thermal issue

Perturbation and RFQ

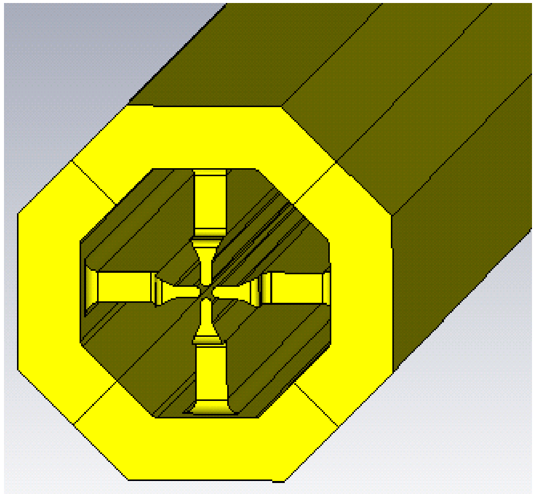
***Investigation of Electromagnetic Field Perturbation With Respect to Mechanical Imperfections in Radio Frequency Quadrupole (RFQ) Structure*, Ki R. Shin, Yoon W. Kang, Sang-Ho Kim, and Aly E. Fathy, IEEE Transactions on Nuclear Science, Vol. 59, Issue 5.**

RFQ Comparison

- Same modulation / beam dynamics design (Vane voltage = 83kV, Bore radius = 3.5mm)
- Existing RFQ: better RF mode separation (33 MHz >> 4.5 MHz)
- Spare RFQ: less sensitive to deform. by vacuum (18kHz << 119kHz)



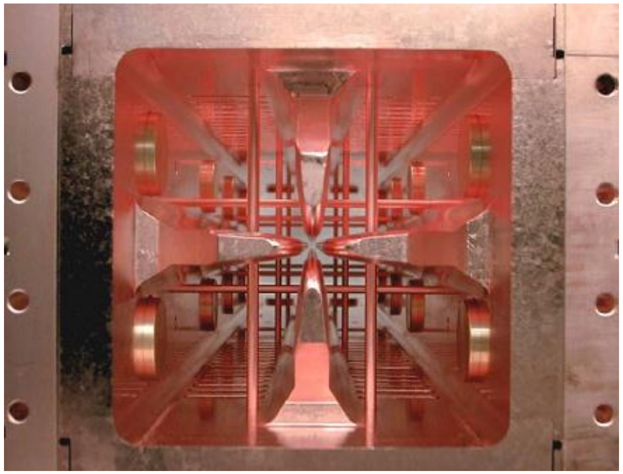
Existing RFQ



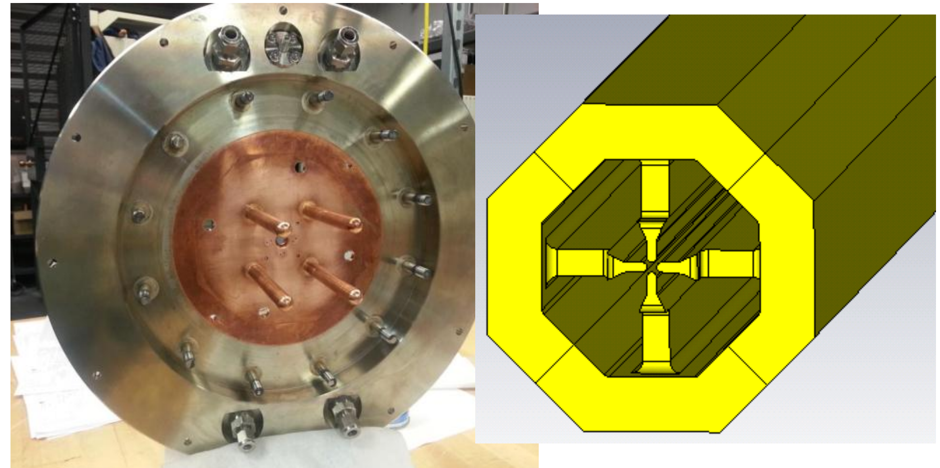
Spare RFQ

RF Mode Stabilization Methods

- **Pi mode stabilizing loop (PISL) / Dipole stabilizer rods (DSR)**



PISL (High Q Rect. Cavity + PISL)



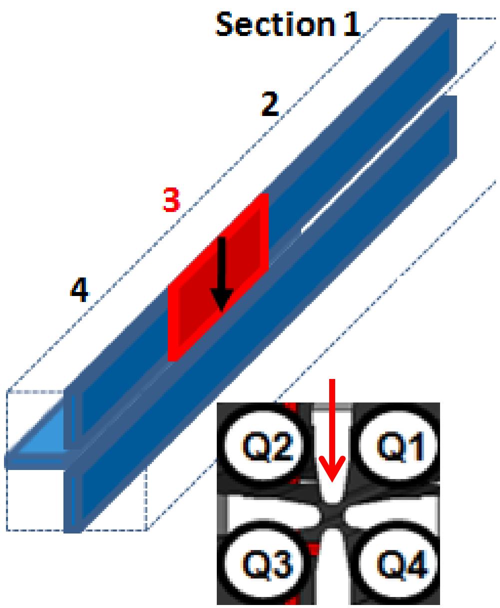
DSR (Medium Q Oct. Cavity + DSR)

	PISL	DSR
freq. (D)	Electrical short circuit to dipole modes (raises frequency)	Extra loading to dipole modes
freq. (Q)	Decreases (loading)	Ideally not affected
Power	6 ~ 8 % RF power	~ 1 % RF power

RF tuning ?

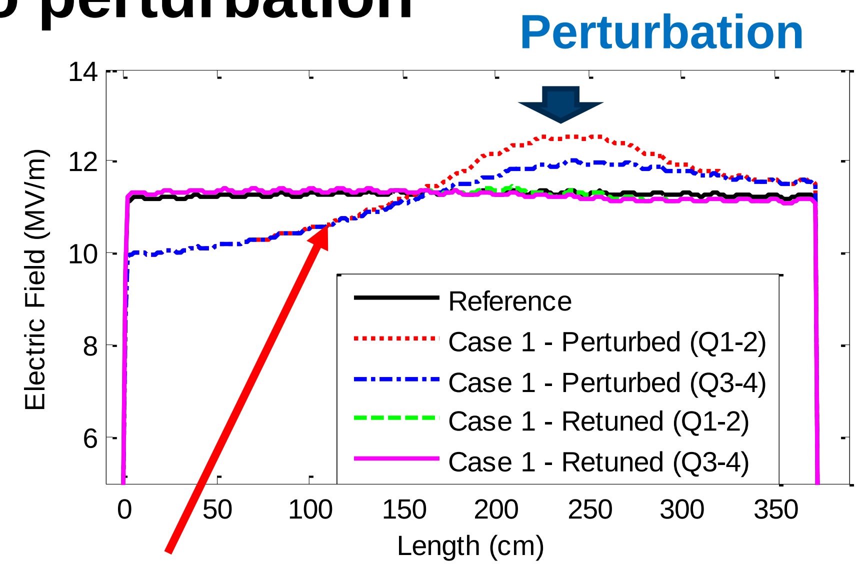
RF tuning of PISL RFQ vs. DSR RFQ

- **PISL RFQ is less sensitive to perturbation**
- **PISL RFQ is easier to tune**



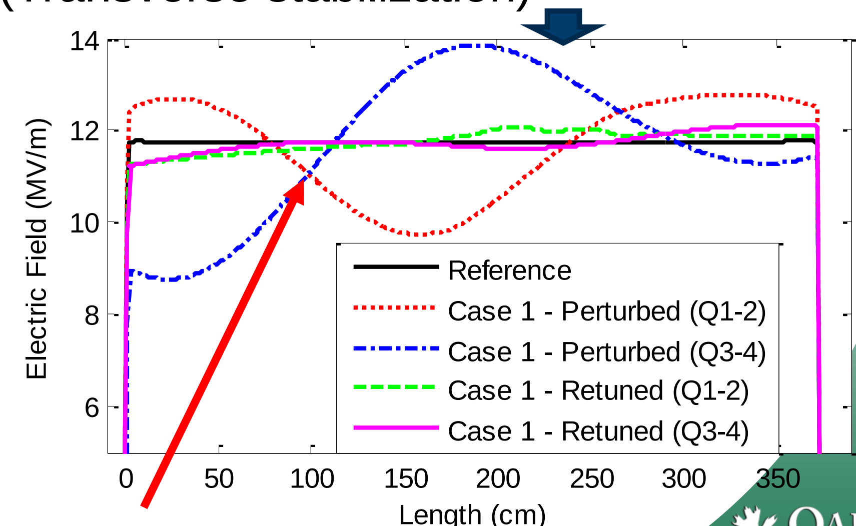
Simulation model
(Perturbation on section 3)

PISL RFQ



Similar trends (Transverse stabilization)

DSR RFQ



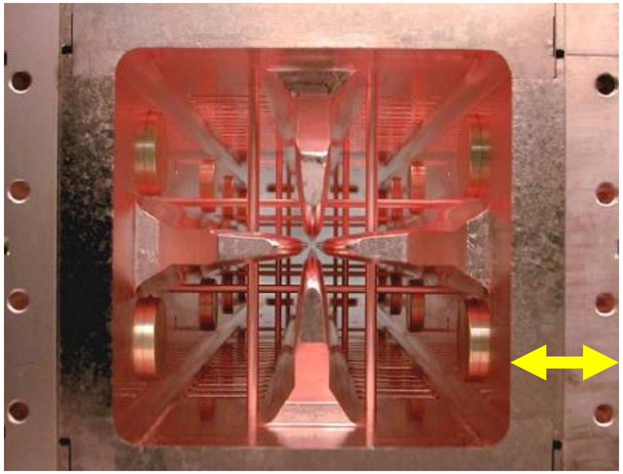
Different ratio (Source of perturbation ?)

Need more mechanical integrity

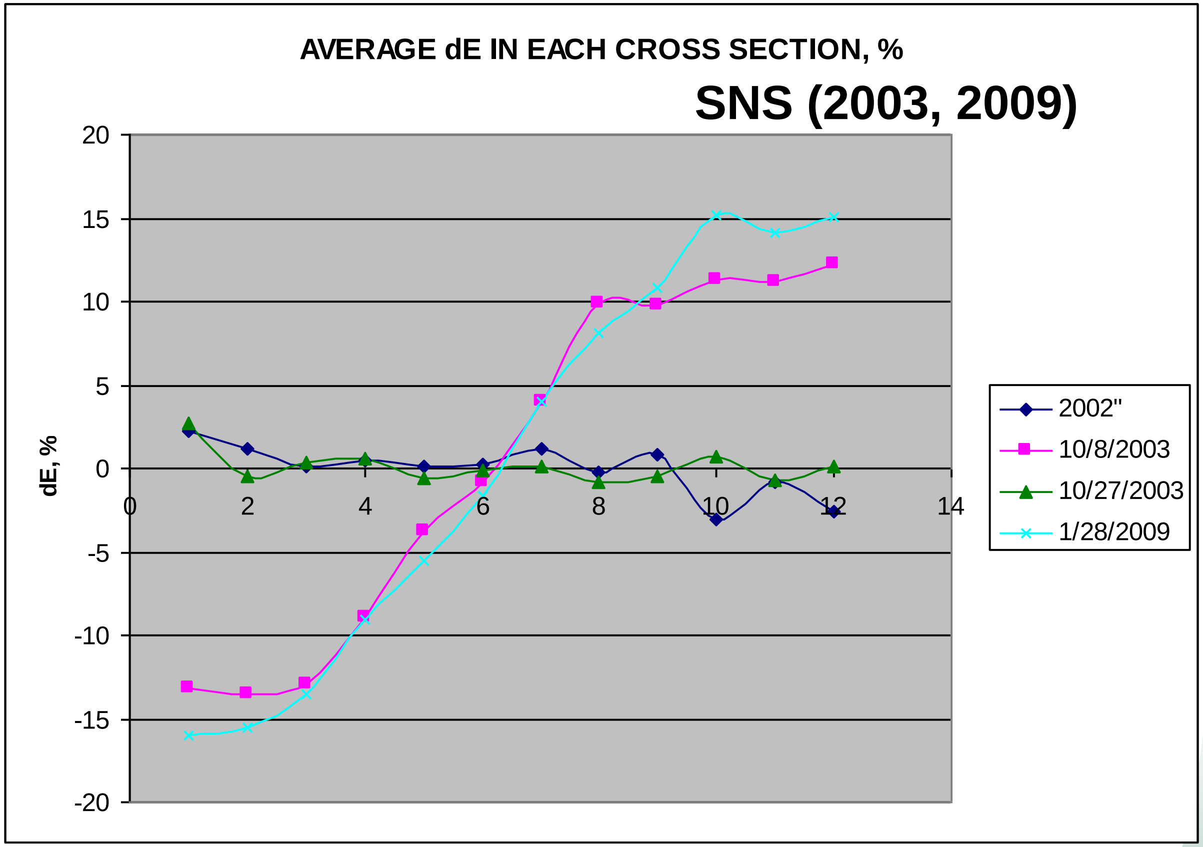
Special care for Installation

Source of RFQ frequency detuning (1)

- **Delamination**



Composite shell structure (200~400 kHz huge shift)

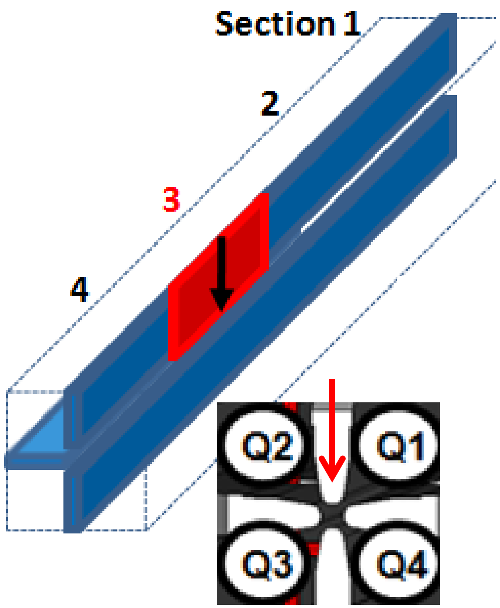


- **Sectional misalignment (Vertical > Horizontal)**
- **Vane tip fabrication error**

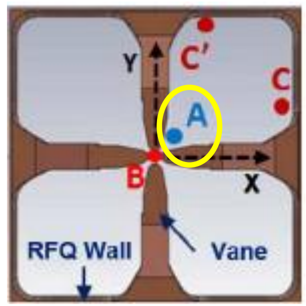
Mechanical Imperfection

A mechanical imperfection example (1)

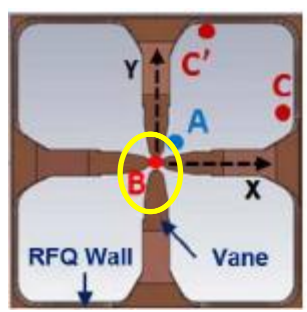
- Assume section 3 vane is vertically delaminated (75 um)
- Existing RFQ (delamination / misalignment)
- Spare RFQ (misalignment)



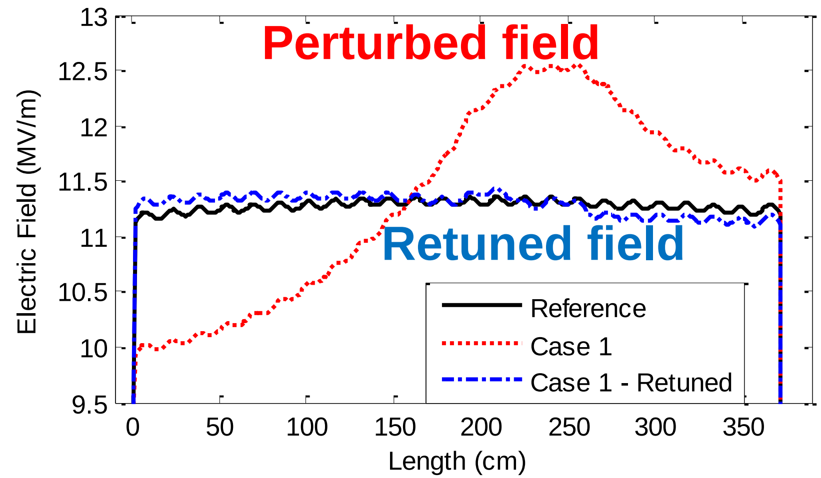
Simulation model (4 sections RFQ)

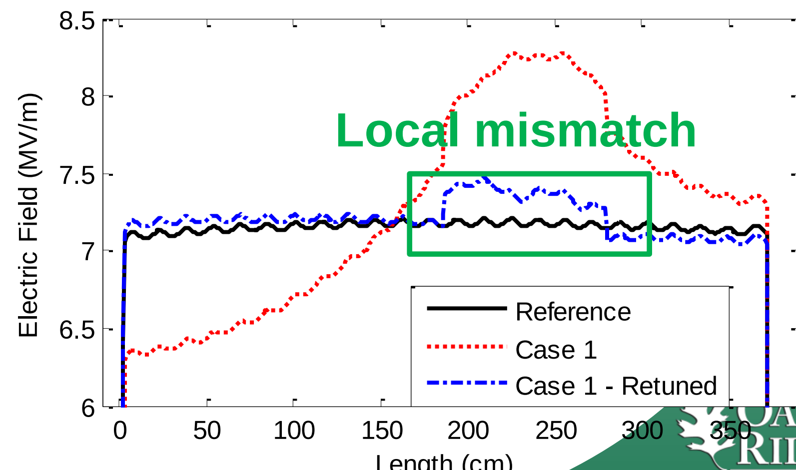


RF field (Measuring position)



RF field (Beam-axis position)





A mechanical imperfection example (2)

- **Local field mismatch affect quadrupole gradient**
- **Quadrupole gradient determines RFQ focusing**
- **Quadrupole gradient ~ f (Gap voltage V_0, Bore radius a)**

$$E_X = -\frac{XV_0}{a^2}x - \frac{kAV_0}{2}I_1(kr)\frac{x}{r}\cos(kz)$$

$$E_y = \frac{XV_0}{a^2}y - \frac{kAV_0}{2}I_1(kr)\frac{y}{r}\cos(kz)$$

$$E_Z = \frac{kAV_0}{2}I_0(kr)\sin(kz)$$

$$A_0 = -\frac{\partial E_x}{2\partial x} = \frac{\partial E_y}{2\partial y} = \frac{V_0}{2a^2}$$

A_0 : Quadrupole gradient
→ V_0/a^2 related
→ Determine Focusing X

RF Tuning can restore the gap voltage V_0

But, bore radius a is changed → A_0 detuned

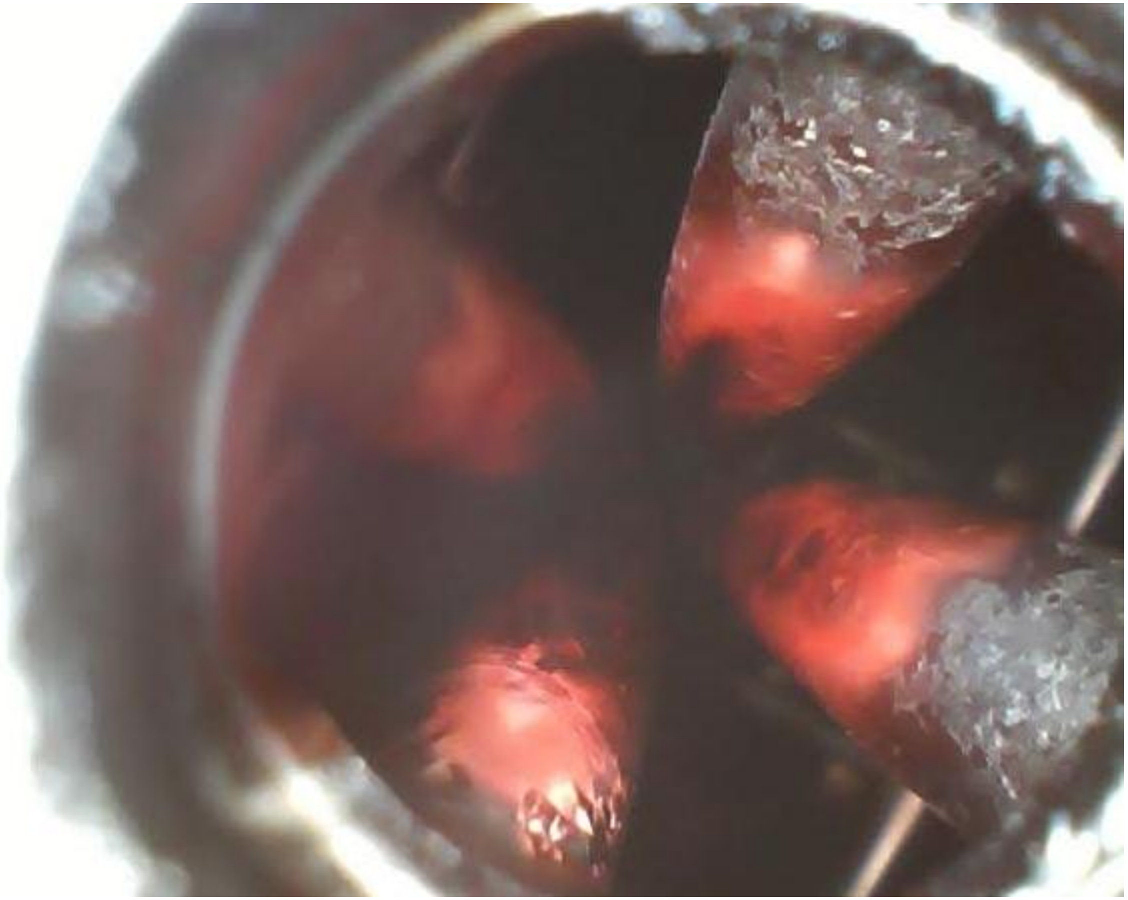
[Simulation, < 5 % [150μm], > 10% [>200μm]

Good RF tuning does not always promise good on-axis field

Existing / Spare RFQ Tolerance requirement can be similar

Source of RFQ frequency detuning (2)

- **Chemical deposition (Hydrogen, Cesium)**



Vane picture at RFQ upstream (by R. Welton)

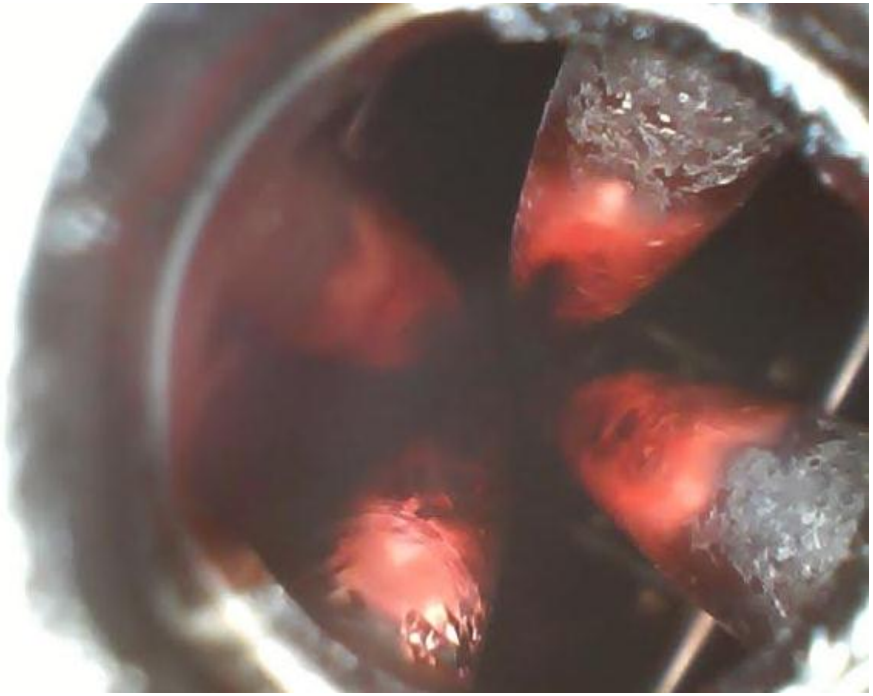
Causes freq. detuning at high duty beam

Arcing sometimes

Ongoing project: Frequency detuning by Chemical deposition

- **Q1) How chemical deposition causes frequency shift**

  → Need more clear answer (Electrical model ?)



- **Q2) Similar detuning effect for Spare RFQ ??**

  → Cut-back resonance + Transverse resonance ?

Summary

- **Folded / Double dipole RFQ design can be selectively utilized in future cost effective 4-vane RFQ design**

- **The proposed Double-gap MEBT rebuncher design is expected to relieve X-radiation issue**

- **New SNS RFQ installation is expected in near future**
- **Frequency detuning by mechanical imperfection is studied with 3D simulations**
- **Frequency detuning by chemical deposition will be investigated in future study with operation experiences**

For more detail…

- **Our work has been published in IEEE Transactions on Nuclear Science**

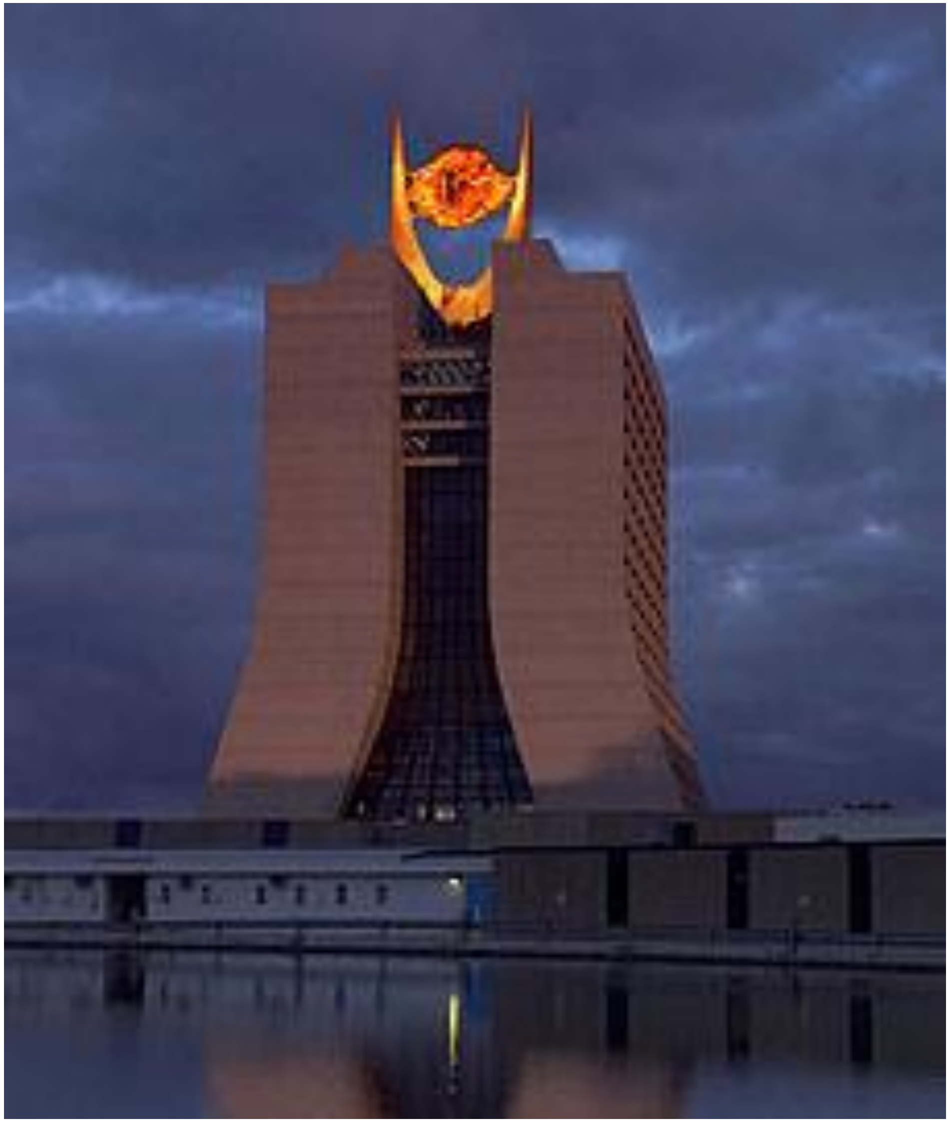
  ***[1] Feasibility of folded and double dipole radio frequency quadrupole cavities for particle accelerators*, Ki R. Shin, Yoon W. Kang, and Aly E. Fathy, IEEE Transactions on Nuclear Science, Vol. 61, Issue 2.**

  ***[2] Design guideline of a double-gap microwave rebuncher cavity for a 400 MHz, 2.5MeV energy light ion accelerator*, Ki R. Shin, Yoon W. Kang, and Aly E. Fathy, IEEE Transactions on Nuclear Science, Vol. 61, Issue 2.**

  [3] *Investigation of Electromagnetic Field Perturbation With Respect to Mechanical Imperfections in Radio Frequency Quadrupole (RFQ) Structure*, Ki R. Shin, Yoon W. Kang, Sang-Ho Kim, and Aly E. Fathy, IEEE Transactions on Nuclear Science, Vol. 59, Issue 5.

- **Printed copies are ready for you**

Questions ?



Selected Publications - RFQ

- <u>Ki R. Shin</u>, Yoon W. Kang, and Aly E. Fathy, "Feasibility of folded and double dipole radio frequency quadrupole cavities for particle accelerators," - IEEE Transactions on Nuclear Science, Vol. 61, Issue 2.

- <u>Ki R. Shin</u>, Yoon W. Kang, Sang-Ho Kim, and Aly E. Fathy, "Investigation of Electromagnetic Field Perturbation With Respect to Mechanical Imperfections in Radio Frequency Quadrupole (RFQ) Structure," - IEEE Transactions on Nuclear Science, Vol. 61, Issue 2.

- <u>Ki R. Shin</u>, Yoon W. Kang, Aly E. Fathy, and Mark S. Champion, "Radio frequency quadrupole cavity structure for particle accelerators-simulation and measurements,"– Proceedings of 2013 International Microwave Symposium, Seattle, WA.

- <u>Ki R. Shin</u>, Yoon W. Kang, Aly E. Fathy, and Mark S. Champion, "Investigation on double dipole four-vane RFQ structure," – Proceedings of 2013 Particle Accelerator Conference, Pasadena, CA.

Oak Ridge National Laboratory

Selected Publications - MEBT

- <u>Ki R. Shin</u>, Yoon W. Kang, and Aly E. Fathy, "Design guideline of a double-gap microwave rebuncher cavity for a 400 MHz, 2.5 MeV energy light ion accelerator with lower gap voltage and field," IEEE Transactions on Nuclear Science, Vol. 61, Issue 2, April 2014.

- <u>Ki R. Shin</u>, Yoon W. Kang, Aly E. Fathy, and Mark S. Champion, "Design and measurement of double gap buncher cavity proposed for reduction of X-ray radiation," – Proceedings of 2013 Particle Accelerator Conference, Pasadena, CA.

- <u>Ki R. Shin</u>, Yoon W. Kang, and Aly E. Fathy, "Double-gap MEBT rebuncher cavity design,"– Proceedings of 2012 International Particle Accelerator Conference, New Orleans, LA.

- <u>Ki R. Shin</u>, Yoon W. Kang, and Aly E. Fathy, "Design and multipacting simulation of double-gap buncher cavity," – Proceedings of 2012 National Radio Science Meeting, Boulder , CO.

Selected Publications – RF System

- Ki R. Shin, Yoon W. Kang, and Aly E. Fathy, "Broadband antenna matching network design and application for RF plasma ion source,"– Proceedings of 2011 Particle Accelerator Conference, New York, NY.
- Y. W. Kang, R. Fuja, T. Hardek, S. W. Lee, R. F. Welton, K. Shin et all, "RF improvements for Spallation Neutron Source H- ion source, Review of Scientific Instrument 81, 02A725 (2010).
- S. W. Lee, R. H. Goulding, Y. W. Kang, K. Shin and R. F. Welton, "Computer simulations for RF design of a Spallation Neutron Source external antenna H- ion source", Review of Scientific Instrument 81, 02A726 (2010).

Selected Publications - SRF

- Ki R. Shin, Yoon W. Kang, Jeffrey A. Holmes, and Aly E. Fathy, "Investigation of multi-cell cavity structure proposed for improved yield in hydroforming," – Proceedings of 2012 International Particle Accelerator Conference, New Orleans, LA.

- Jeffrey A. Holmes, Yoon W. Kang, K. R. Shin, and Aly E. Fathy, "Beam acceleration by a multicell RF cavity structure proposed for an improved yield in hydroforming," – Proceedings of 2012 International Particle Accelerator Conference, New Orleans, LA.

Career Objective in Fermilab

Be part of the Fermilab taskforce of PIP and LCLS putting my solid electromagnetic, RF and accelerator technology background and experience to serve in

The Great Fermilab Engineering Team