Trapped Mode Analysis of the SLAC Rotatable Collimator Design for the LHC Phase II Upgrade

Liling Xiao

Present at CREN LHC Collimation Working Group Meeting

March 1, 2010

SLAC NATIONAL ACCELERATOR LABORATORY

LARP

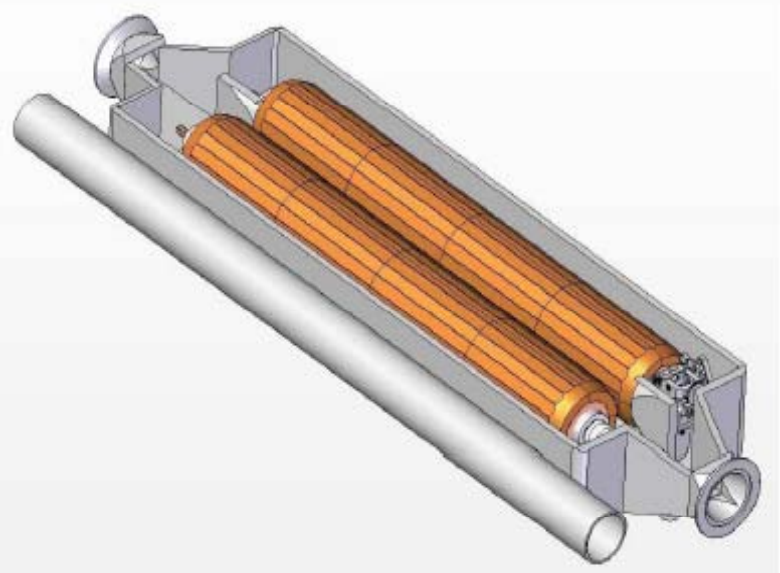
OUTLINE

- **Original Collimator Design for the LHC Operation**
  - Longitudinal Trapped Mode Calculations
  - Transverse Trapped Mode Calculations
  - Heating Analysis
- **Current Collimator Design for the SPS Testing**
  - Longitudinal Trapped Mode Calculations
  - Transverse Trapped Mode Calculations
  - Heating Analysis
- **Summary**

SLAC Rotatable Collimator

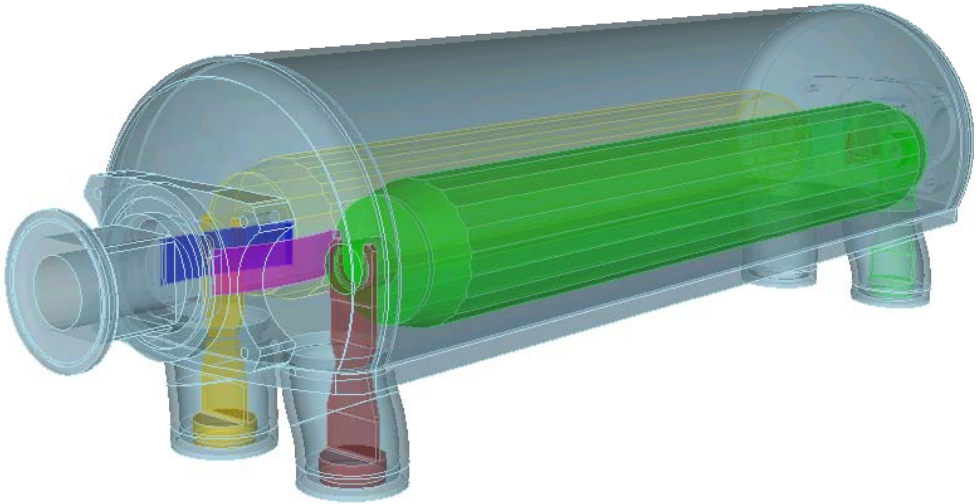
LHC Operation

Original design
Jaw's opening = 2mm / 42mm



SPS Testing

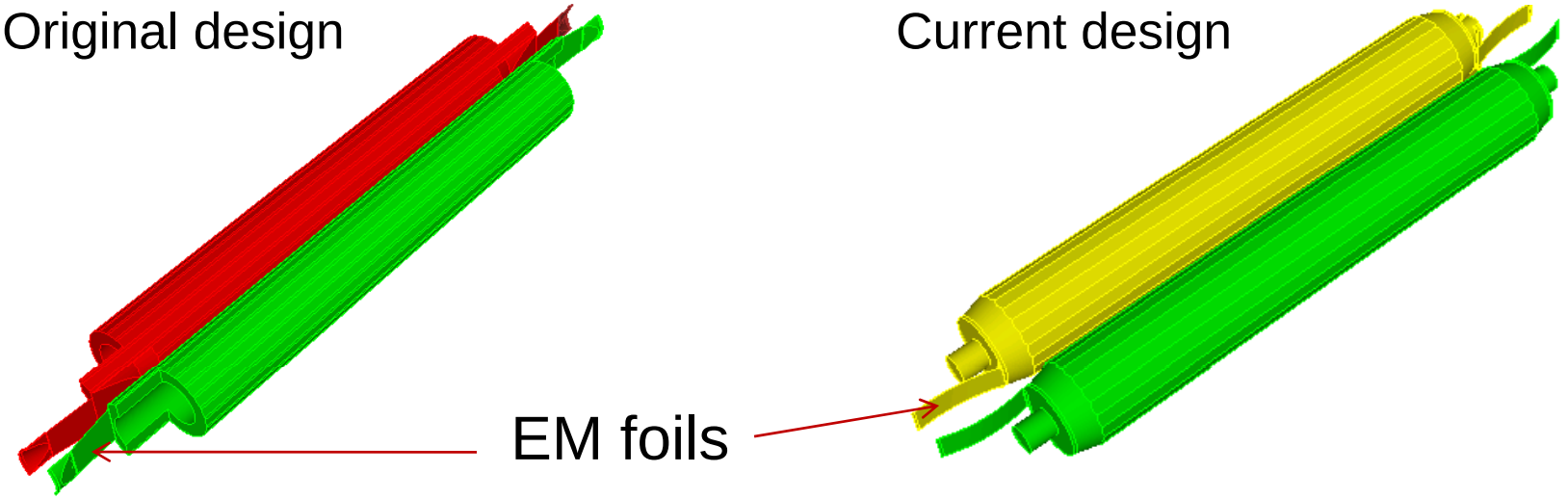
Current design
Jaw's opening = 2mm / 60mm



Courtesy Steven Lundgren

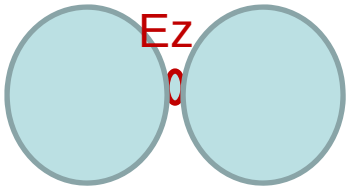
Vacuum tank is made of stainless steel (sigma=0.116e7s/m); jaws and EM foils are made of copper (sigma=5.8e7s/m)

Rotatable Jaw



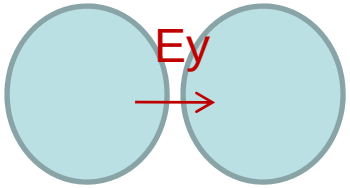
- There are 20 facet faces on each cylindrical jaw surface.
- The two jaws can be rotated.
- The two jaws will move in and out during operation.

Trapped Mode Excitation in Collimator



Longitudinal Modes

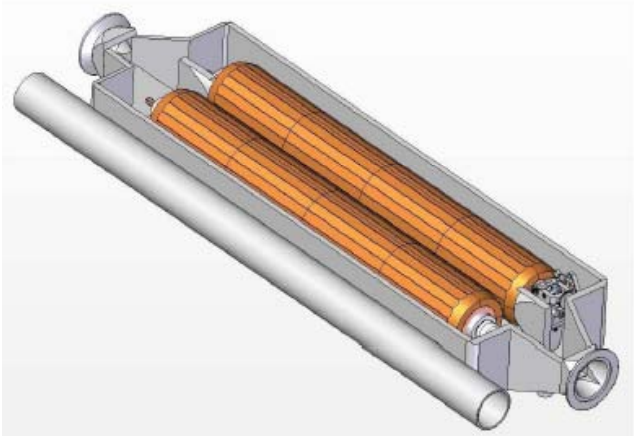
When the beam passes through the collimator, the longitudinal modes with Ez component on z beam axis can be excited resulting in energy loss and collimator power dissipation.



Transverse Modes

When the beam crosses the collimator at an y-offset, the transverse modes with Ey component between the two jaws are excited generating a transverse kick in the y-direction as well as couple-bunch instability.

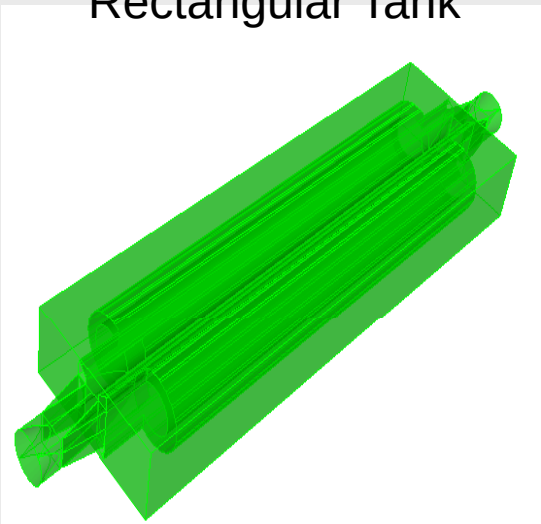
Original Models – LHC Operation



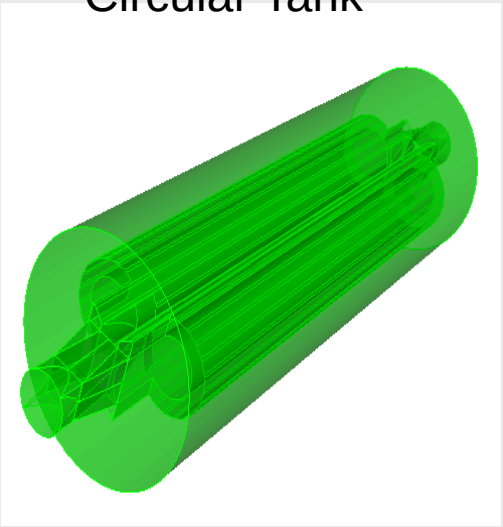
R_beampipe=42mm, Fc=2.1GHz

Jaw's opening=2mm / 42mm

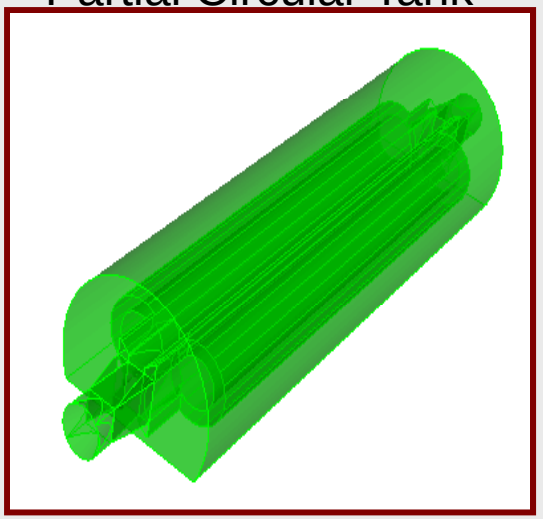
Rectangular Tank



Circular Tank



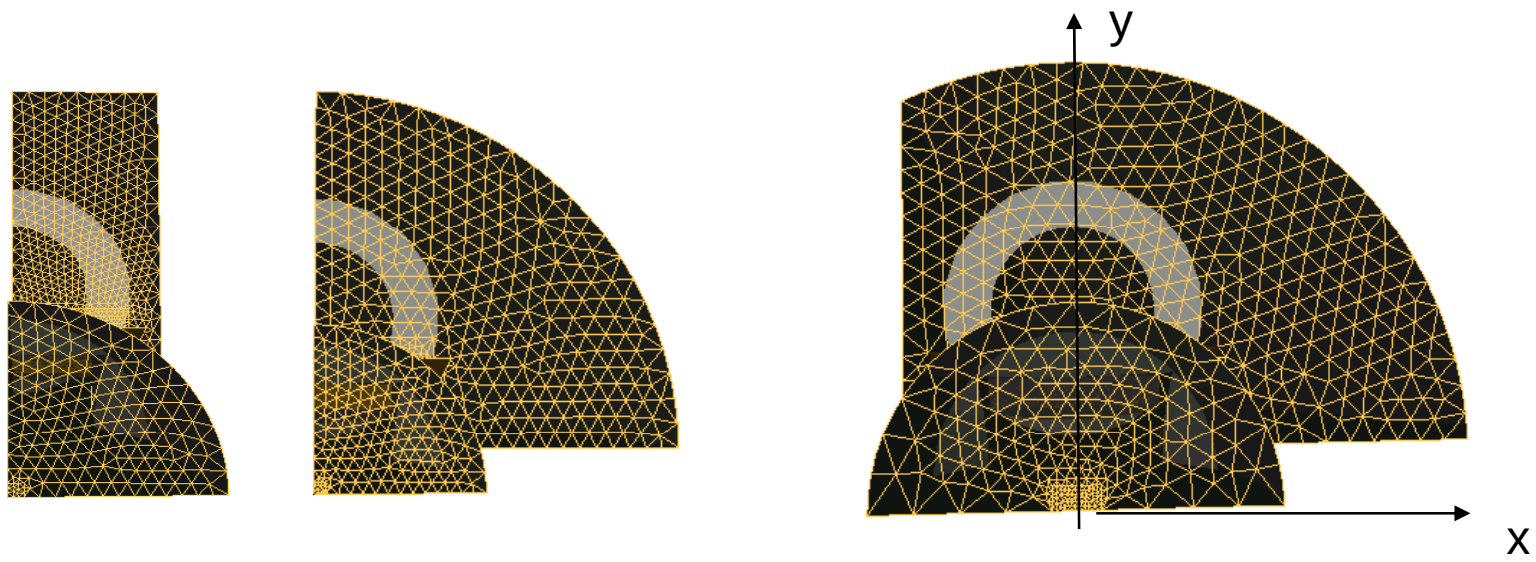
Partial Circular Tank



Eigensolver Omega3P

Mode Calculation with Omega3P

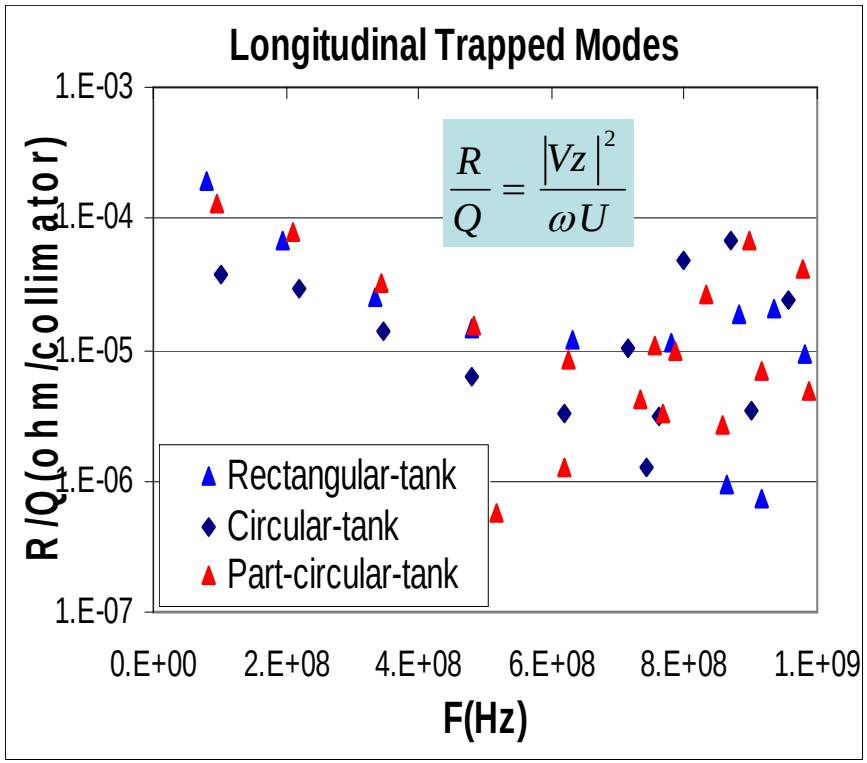
- ***Tetrahedras with 2nd order curved surface***
- ***Denser mesh along beam path plus 3rd order basis functions***

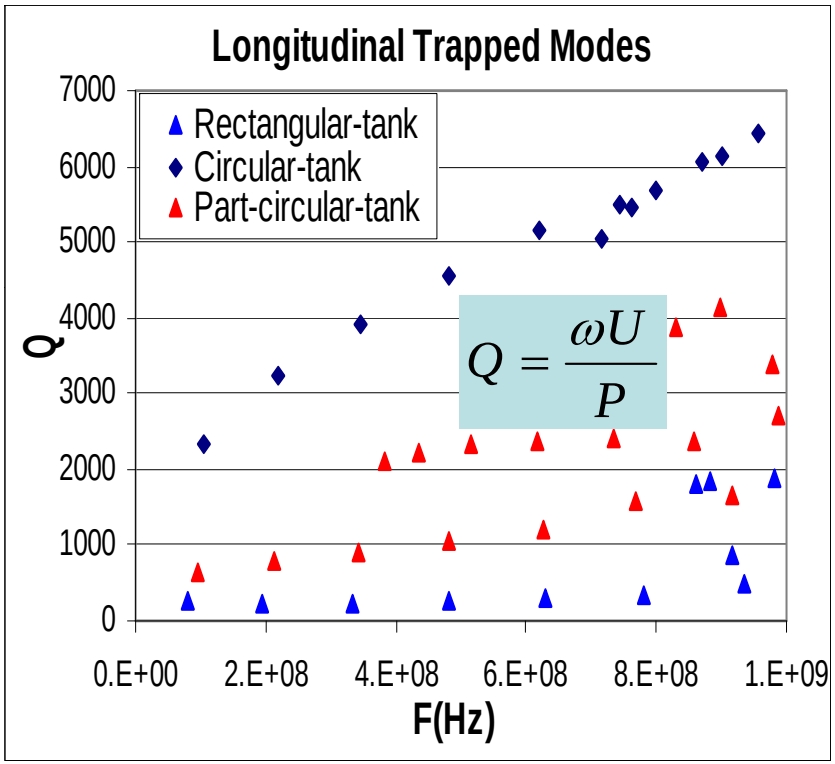


Finite Element Mesh

Longitudinal Modes – LHC

fully inserted jaws, jaw gap=2mm



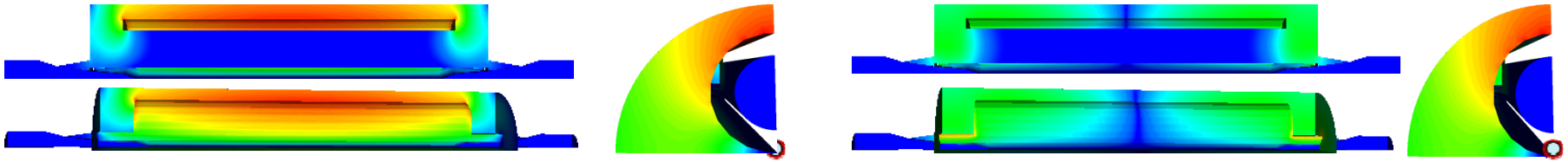


The longitudinal modes have similar R/Qs in the three vacuum chamber designs, but have higher Qs in the circular design and lower Qs in the rectangular design.

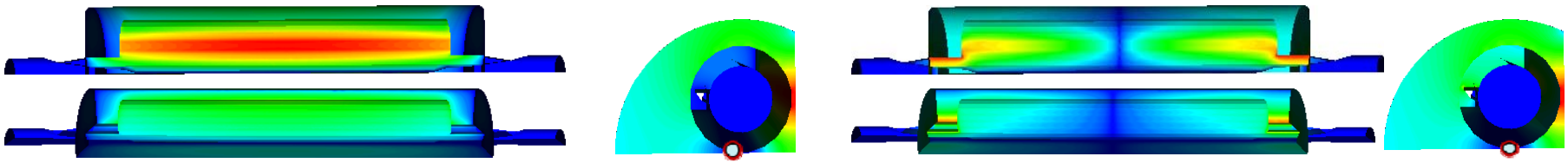
Lowest Longitudinal Modes - LHC

E-field | Jaw gap=2mm | B-field

f1=80MHz, Q=258. The trapped mode locates between the jaw and chamber wall. It is TEM-like mode and Q is the lowest.



*f1=103MHz, **Q=2340**. The trapped mode spreads around the jaw. It is cavity like mode. Q is the highest.*



f1=97MHz, Q=648. The trapped mode locates between the jaw and support plate as well as spreads around the jaw. Q is moderate.

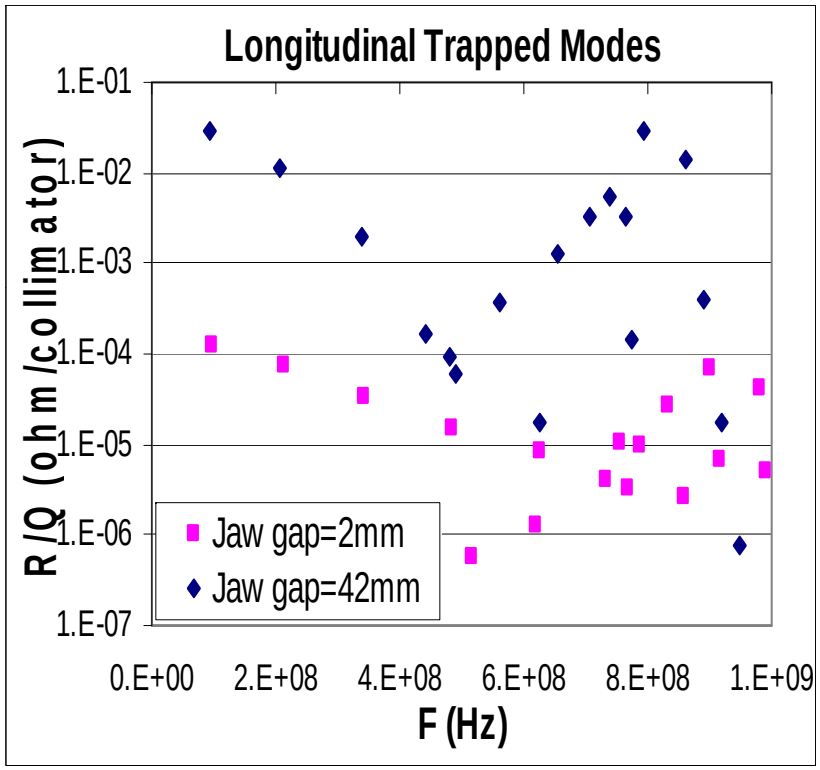
The longitudinal modes in the circular vacuum chamber are cavity like modes and have more fields spreading around the jaws.

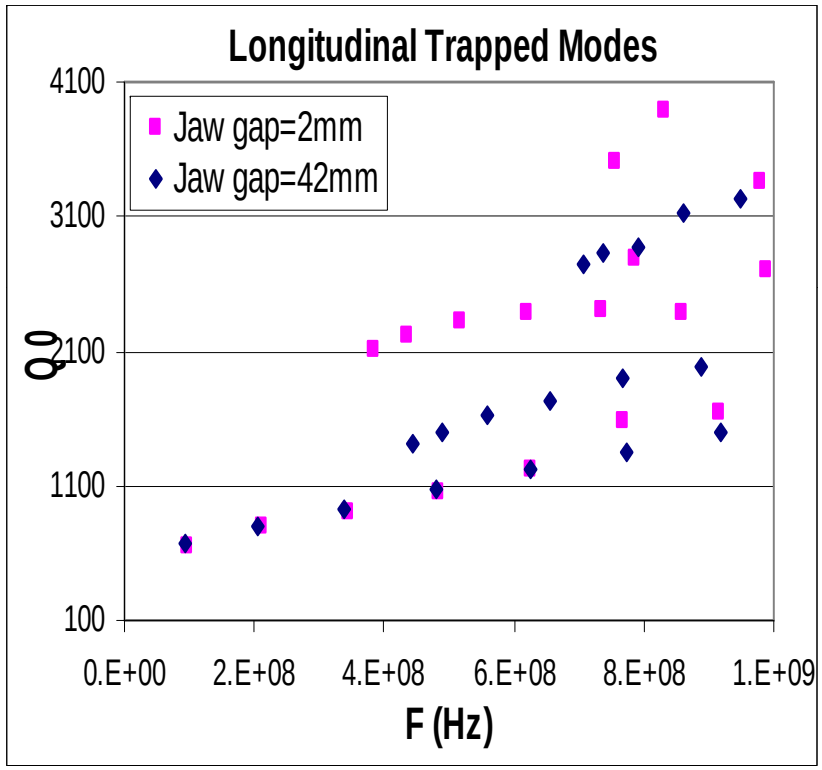
SLAC NATIONAL ACCELERATOR LABORATORY

LARP

Two Jaw Gaps – Longitudinal Modes

Partial Circular Tank

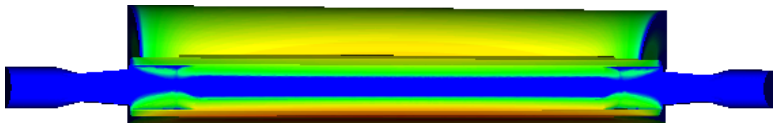


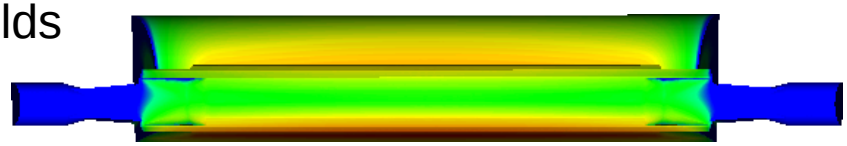


The longitudinal modes have higher R/Q for fully retracted jaws than for fully inserted jaws.

Lowest Longitudinal Modes

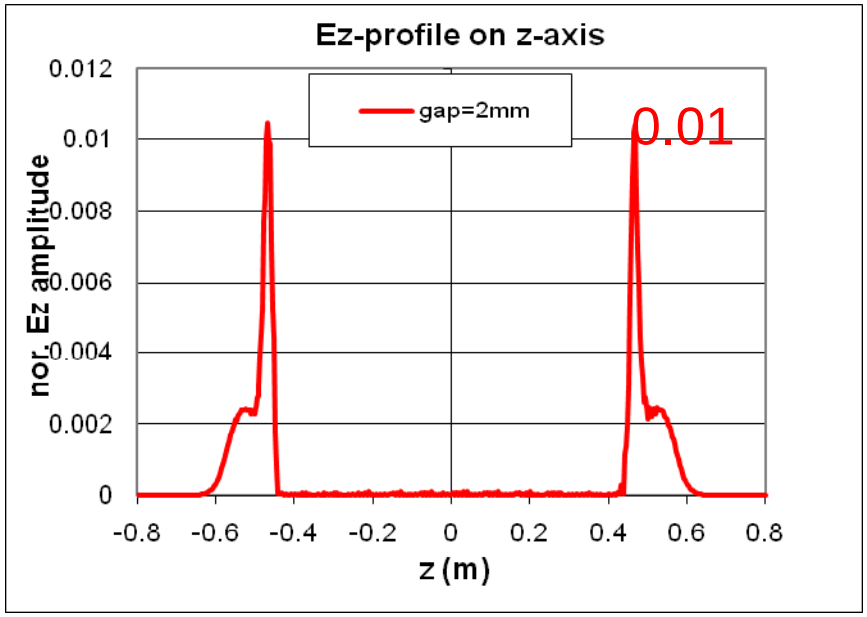
E-fields

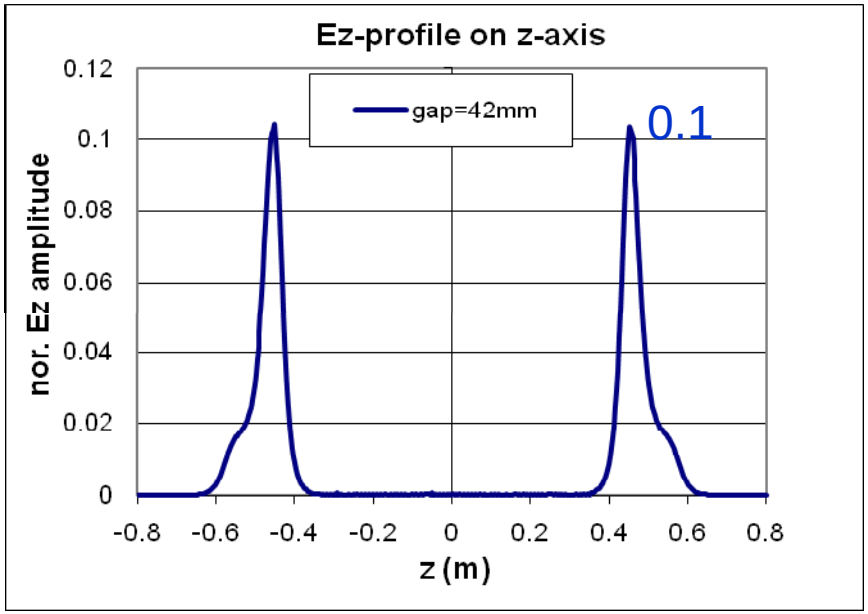




Gap=2mm, F=97.2MHz,
R/Q=1.28e-4ohm/collimator

Gap=42mm, F=92.7MHz,
R/Q=2.97e-2ohm/collimator

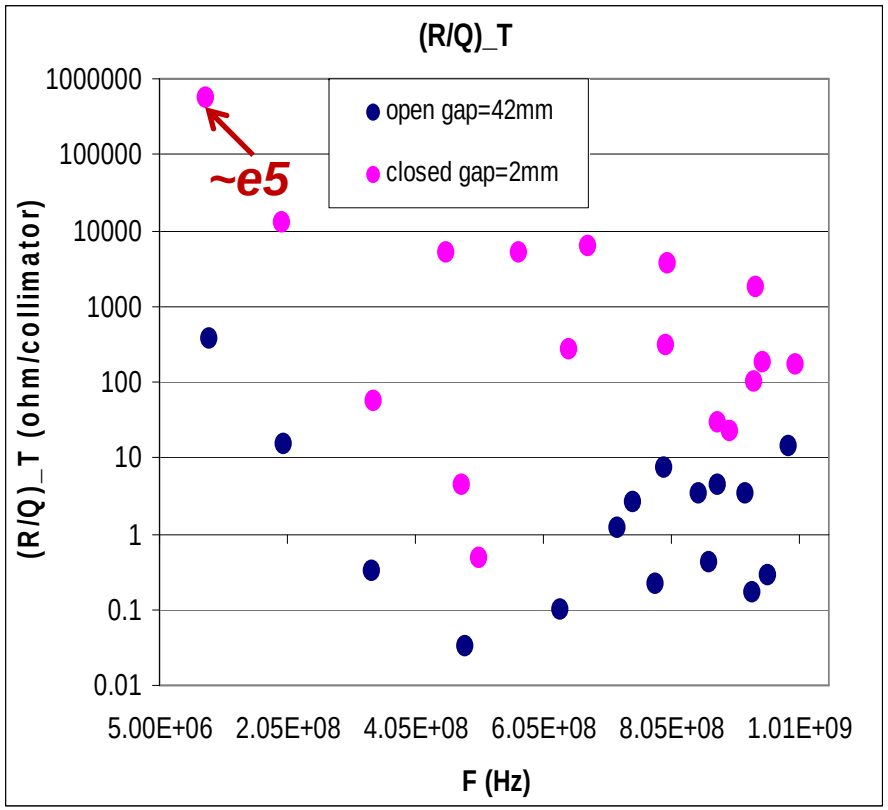




The longitudinal modes exist in the transition regions. There are more Ez fields in the transition regions along the beam path when the jaws are fullv retracted.

Two Jaw Gaps – Transverse Modes

Rectangular Tank

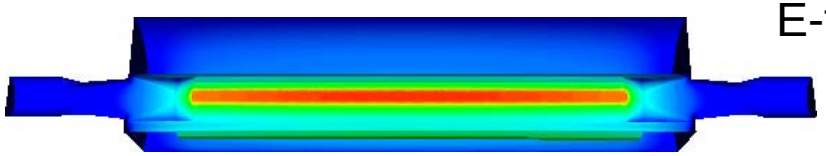


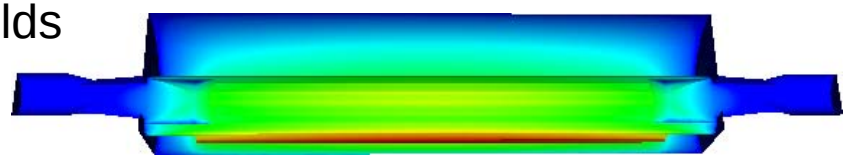
$$\left(\frac{R}{Q}\right)_T = \frac{|V_T|^2}{\omega U} = \frac{|V_z|^2 / (r_0 * \omega / c)^2}{\omega U}$$

The transverse modes have higher R/Q_T for fully inserted jaws than for fully retracted jaws in rectangular tank vacuum chamber design. It should be true for the partial circular vacuum chamber design.

Lowest Transverse Modes

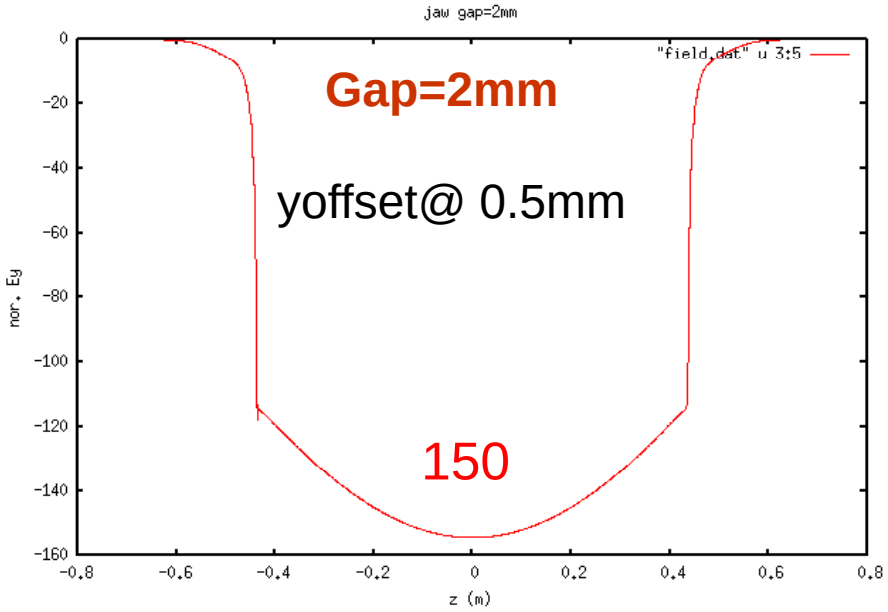
E-fields

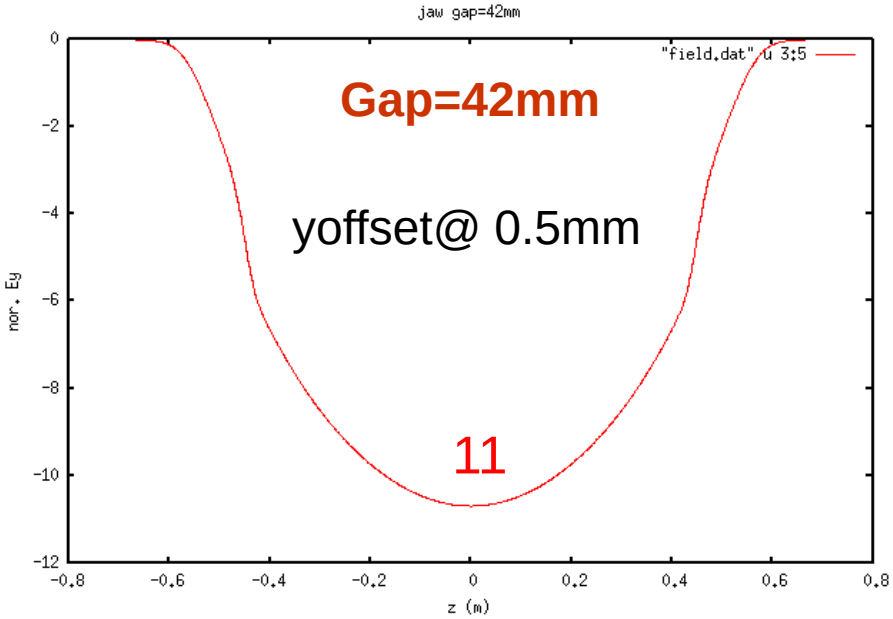




Gap=2mm, F=84.2MHz,
R/Q_T=8.20e5ohm/collimator

Gap=42mm, F=97.5MHz,
R/Q_T=4.90e2ohm/collimator





Due to the small gap of the jaws, the Ey component is very strong over the full length of the collimator for the fully inserted jaws.

Original Design

- *The longitudinal modes have higher Qs in the circular vacuum chamber design, and lower Qs in the rectangular vacuum chamber design.*

- *When the two jaws are fully retracted, there are more Ez components generated in the transition regions along the beam path. Max. R/Q_z ~ 3e-2 ohm/collimator*

- *When the two jaws are fully inserted, there are stronger Ey components generated over the full length of the collimator. Max. R/Q_T ~ 8.2e+5 ohm/collimator*

Resonant Heating from Trapped Modes

Resonant power losses are due to the excitation of these trapped modes. Assuming all bunches are in phase with them and mode decay is lower from bunch to bunch ($T_d >> T_b$):

$$P = I^2 \sum (\frac{R}{Q})_i e^{-\omega_i^2 \sigma^2 / c^2} * Q_i,$$

$$I = 0.582\,A$$

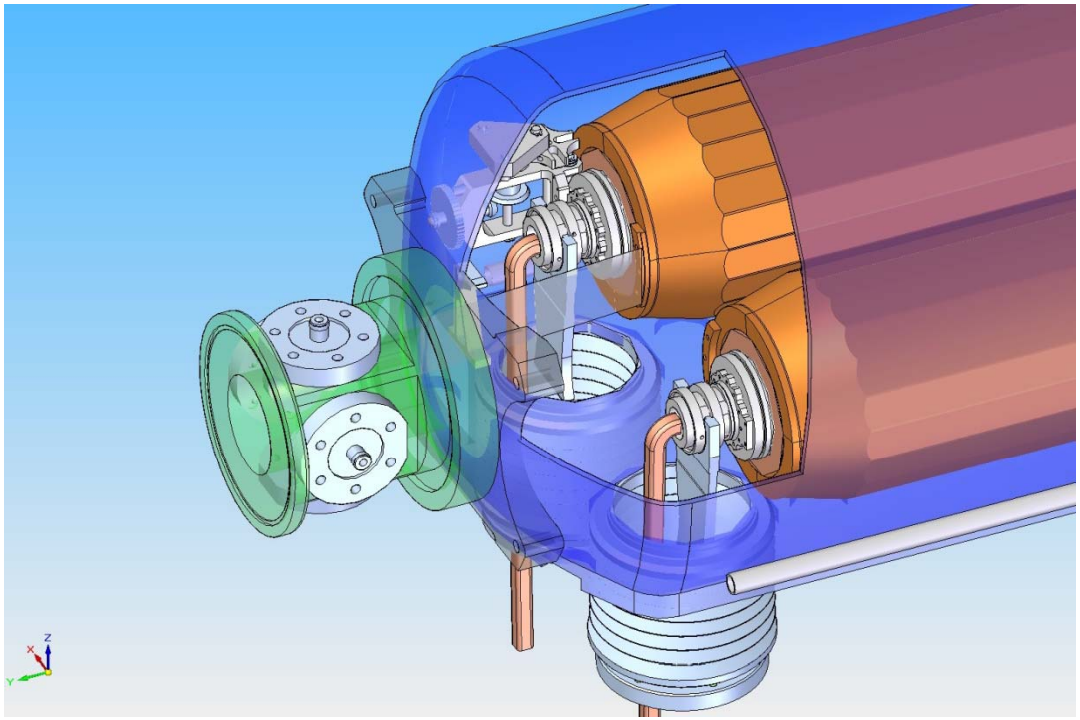
$$P(cir.) = 65W$$

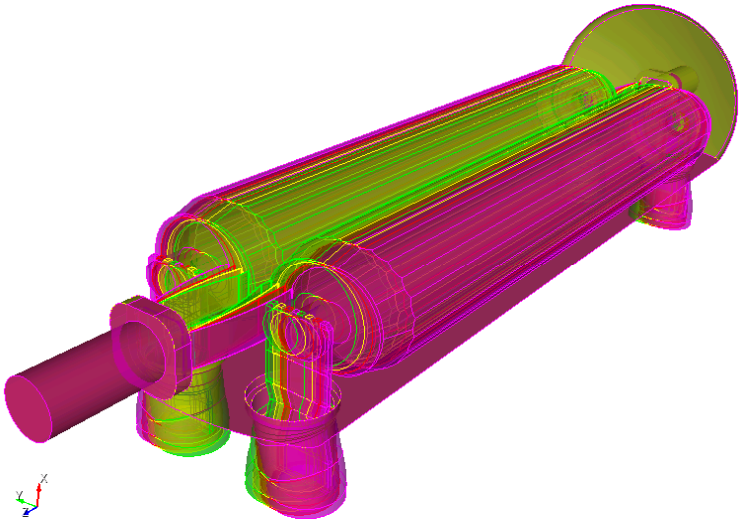
$$P(rec.) = 6.5W$$

$$P(part - cir.) = 38W$$

Current Model – SPS Testing

Courtesy Steven Lundgren



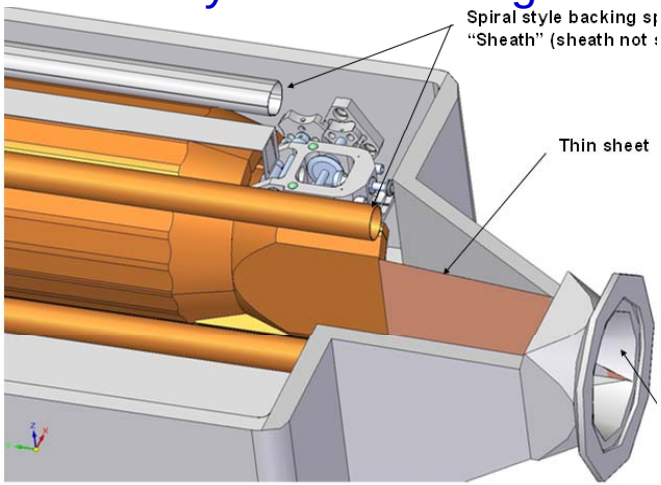


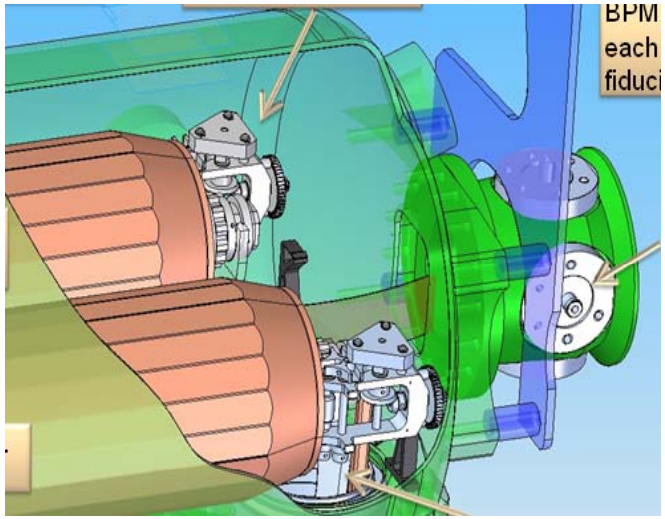
R_beampipe=30.5mm

Jaw's opening=2mm / 60mm

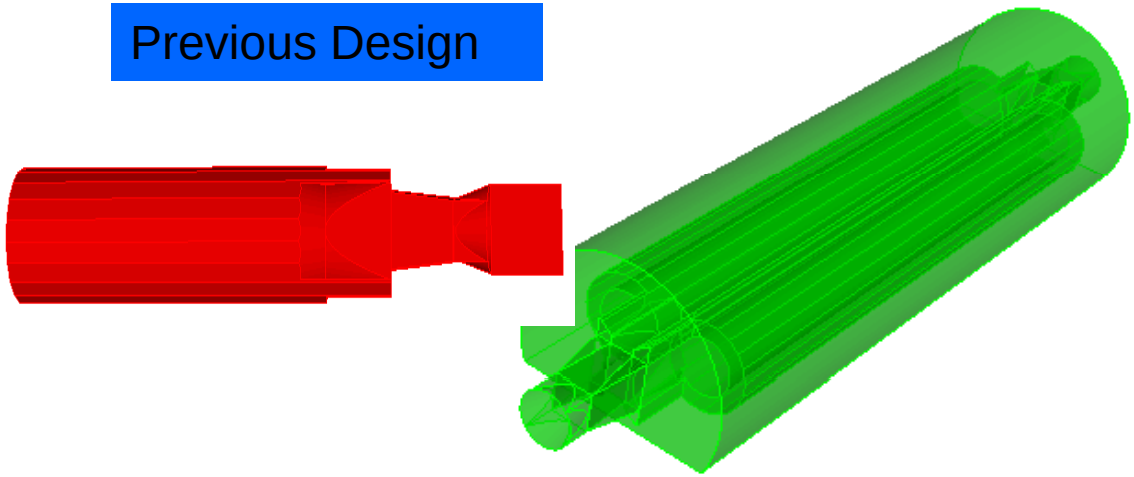
Current / Original Models

Courtesy Steven Lundgren

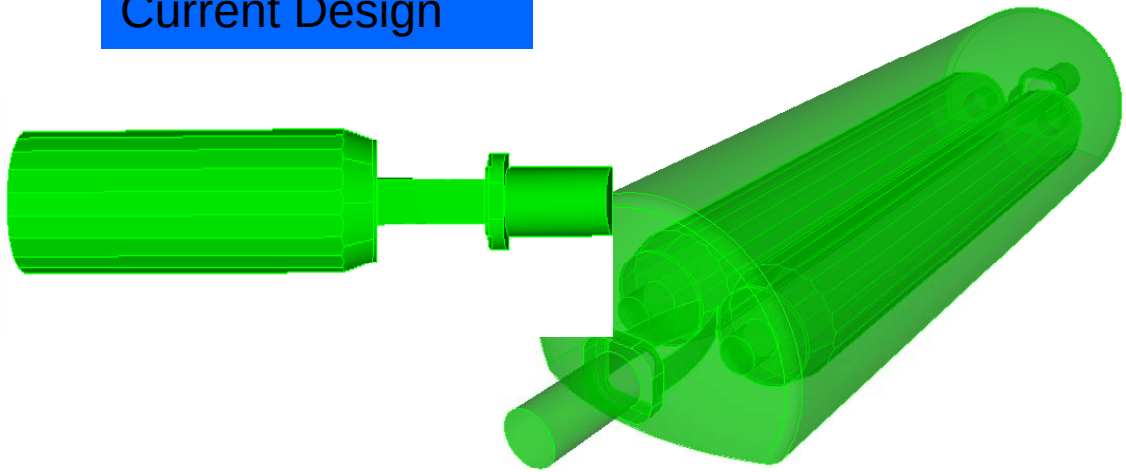




Previous Design

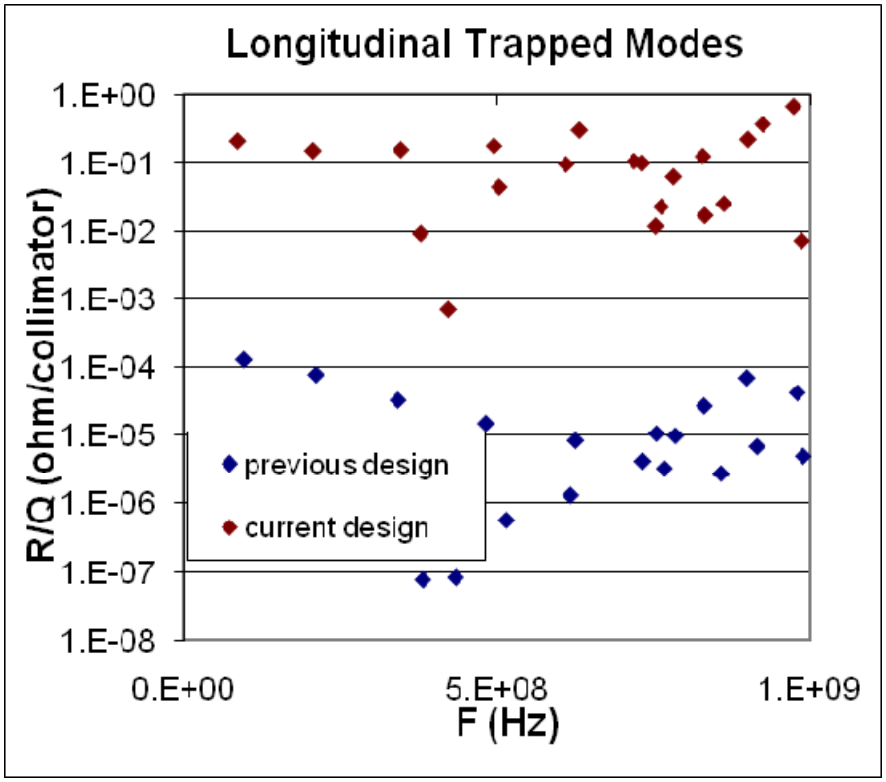


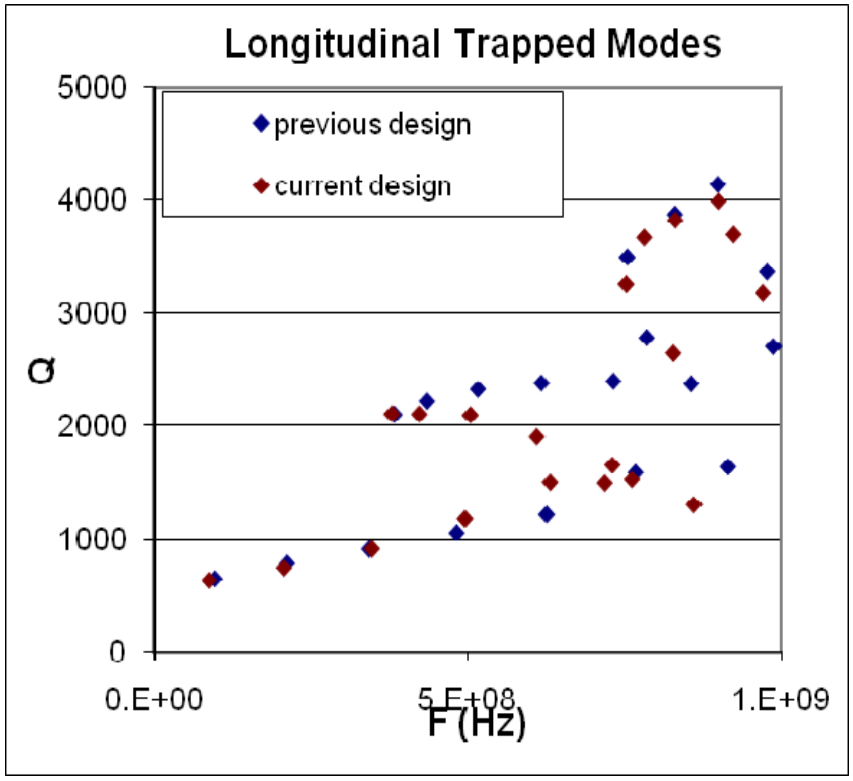
Current Design



Longitudinal Modes

fully inserted jaws, jaw gap=2mm



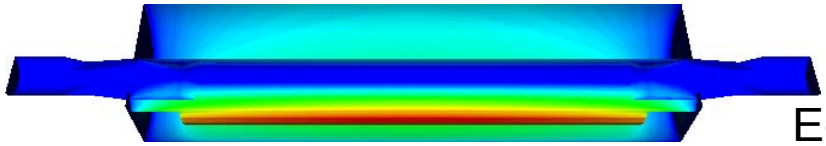


The longitudinal modes have higher R/Qs in the current design than in the original design.

Lowest Longitudinal Modes

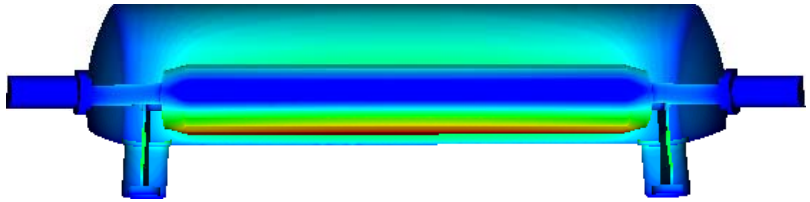
fully inserted jaws, jaw gap=2mm

LHC



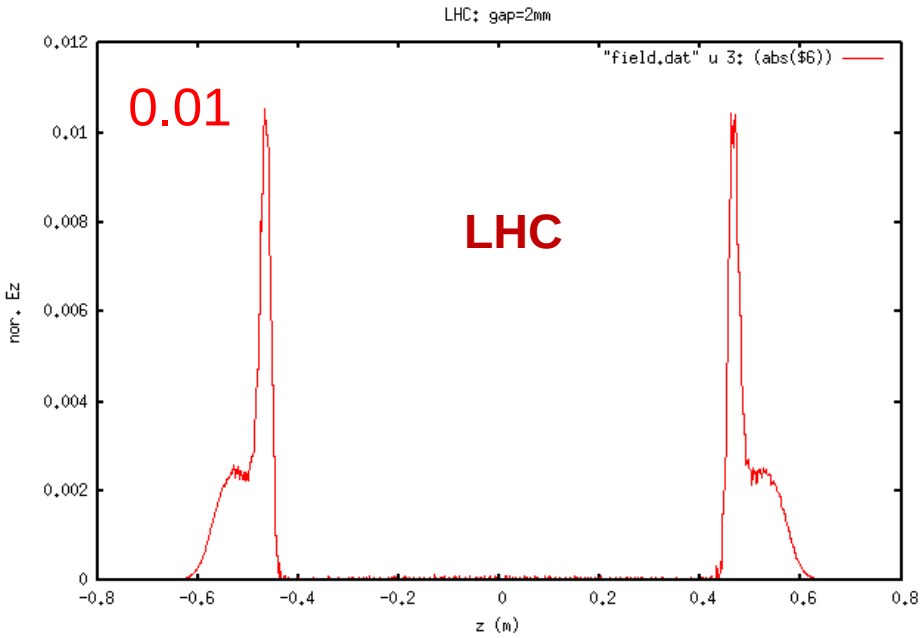
E-fields

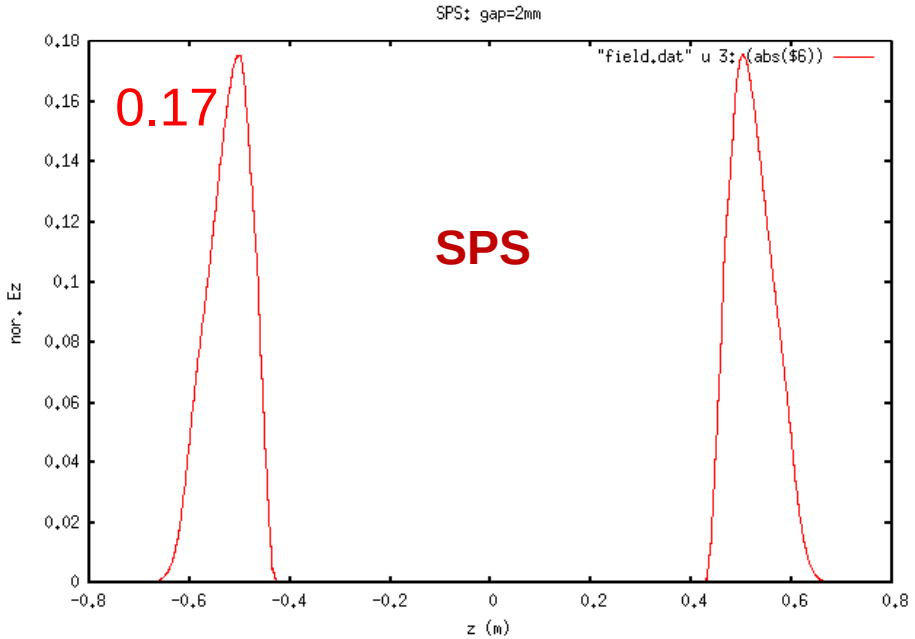
SPS



F=97.2MHz, R/Q=1.28e-4ohm/collimator

F=87.4MHz, R/Q=2.10e-1ohm/collimator



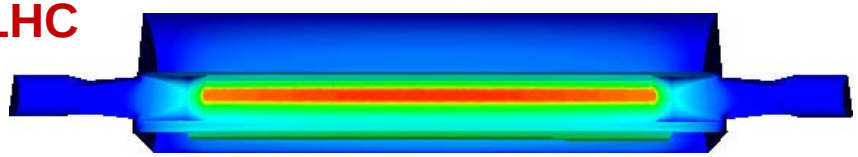


In the current design, there are more Ez fields in the transition regions.

Lowest Transverse Modes

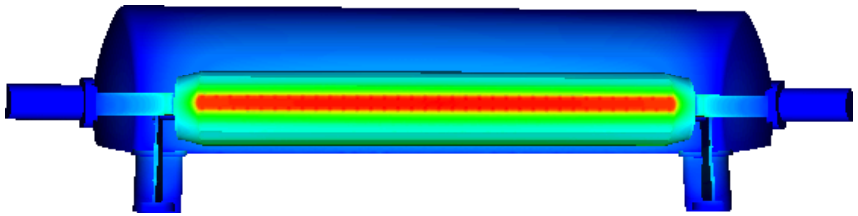
fully inserted jaws, jaw gap=2mm

LHC

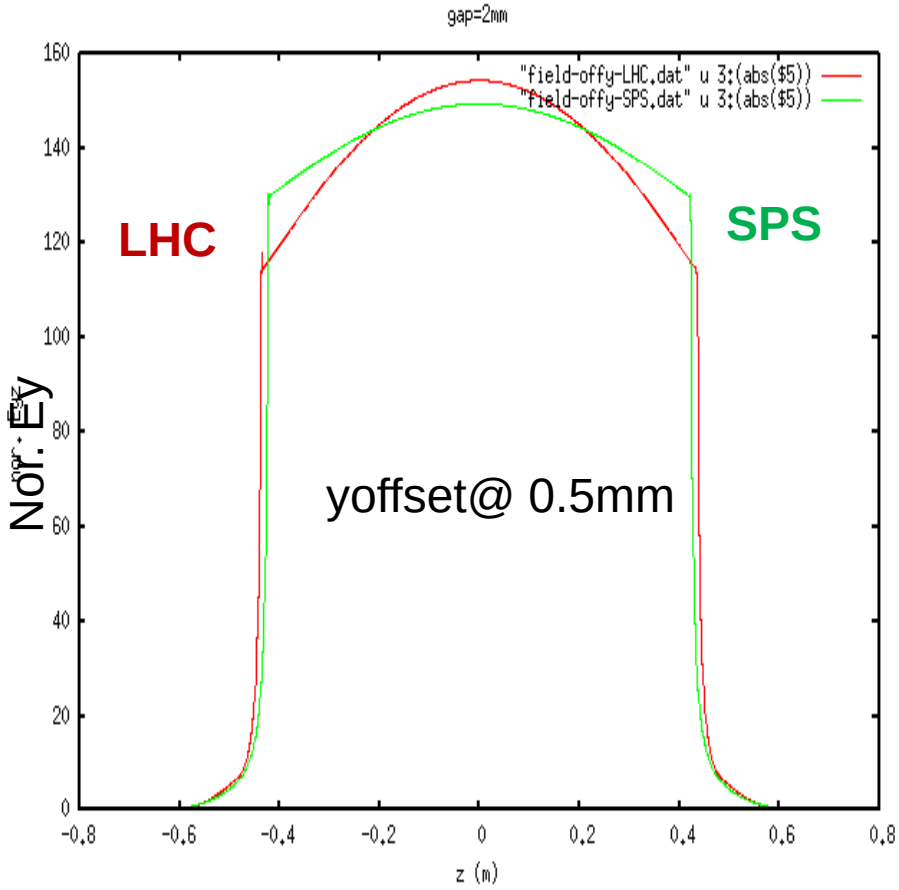


F=84.2MHz, R/Q_T=8.20e5ohm/collimator

SPS



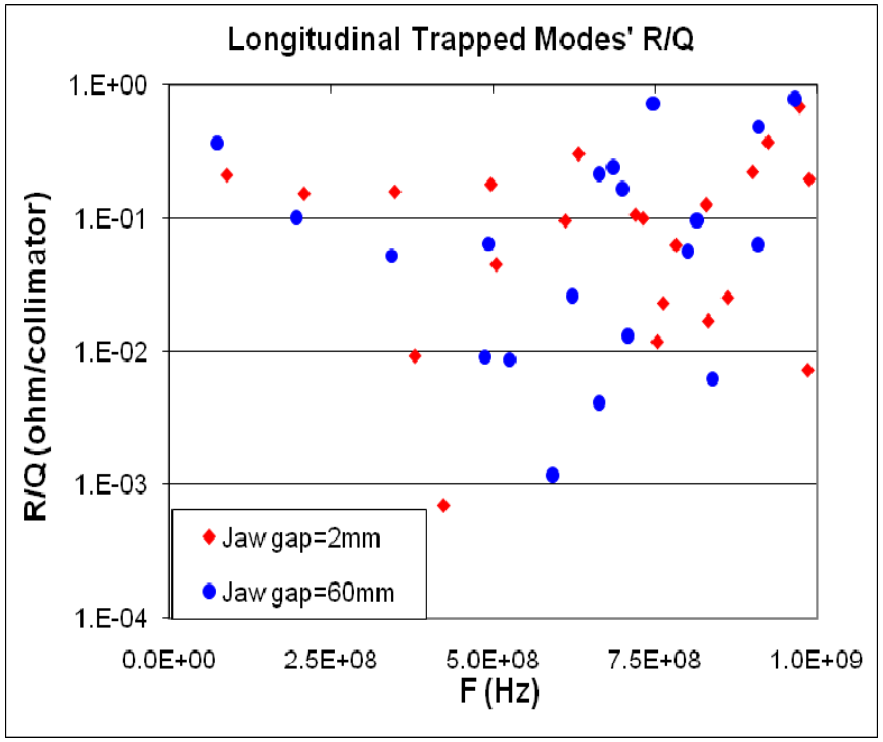
F=62.9MHz, R/Q_T=5.5e6ohm/collimator

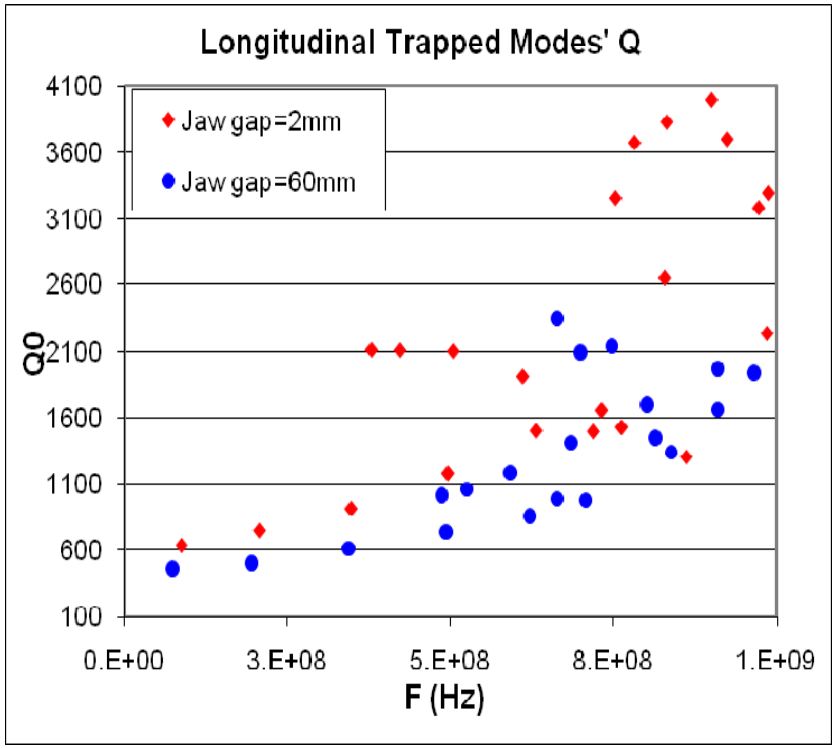


There are similar Ey components in the straight section in the current and original designs.

Two Jaw Gaps – Longitudinal Modes

Current Design

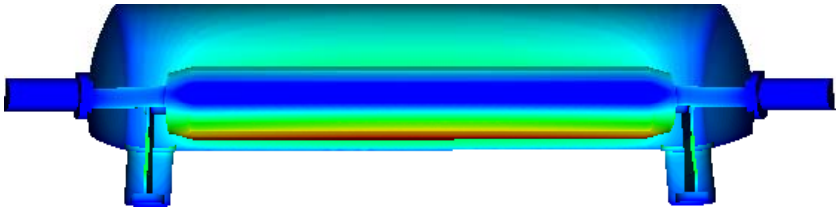




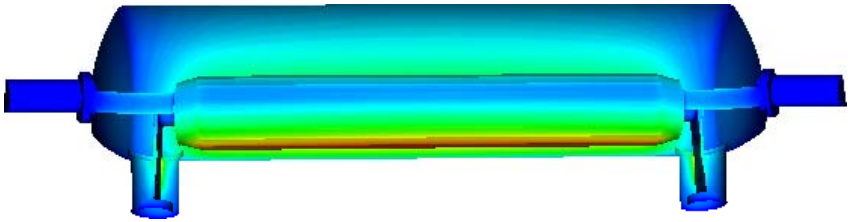
The longitudinal modes have similar R/Q for the fully inserted jaws and the fully retracted jaws in the current design for the SPS testing.

Lowest Longitudinal Modes

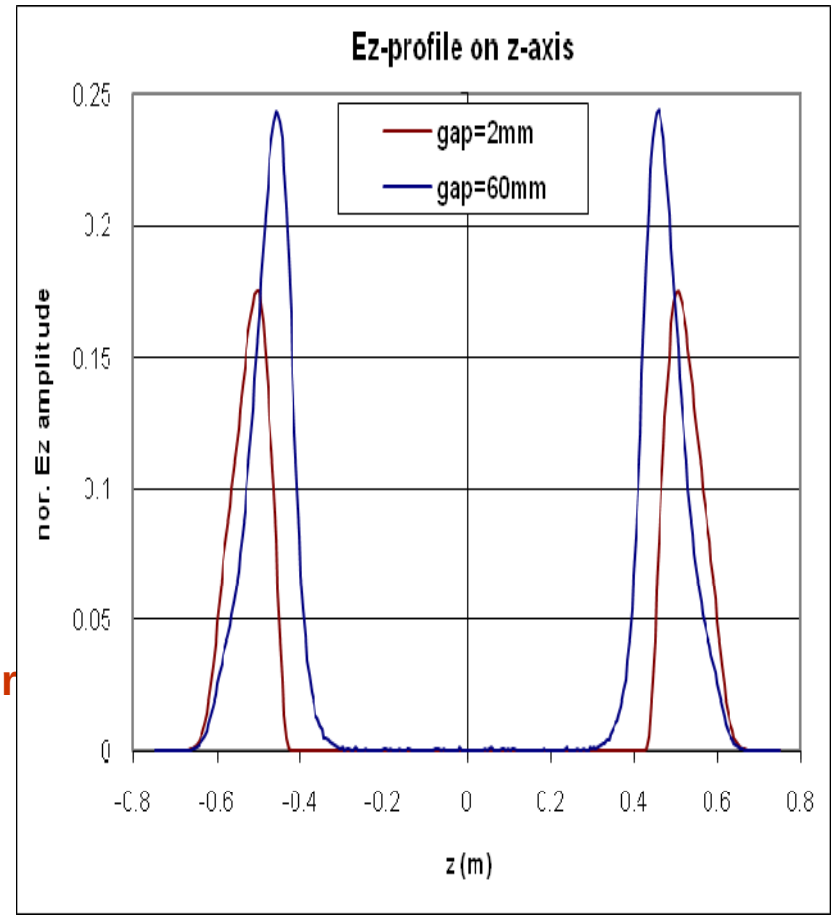
E-field



Gap=2mm: F=87.4MHz, R/Q=2.10e-1ohm/collimator



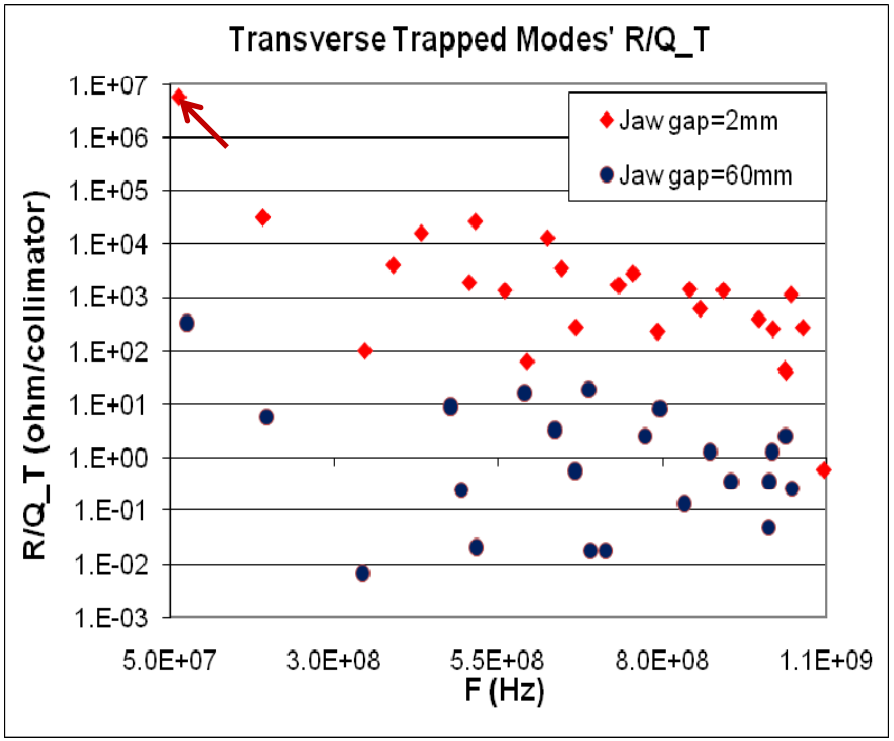
Gap=60mm: F=73.6MHz, R/Q=3.65e-1ohm/collimator

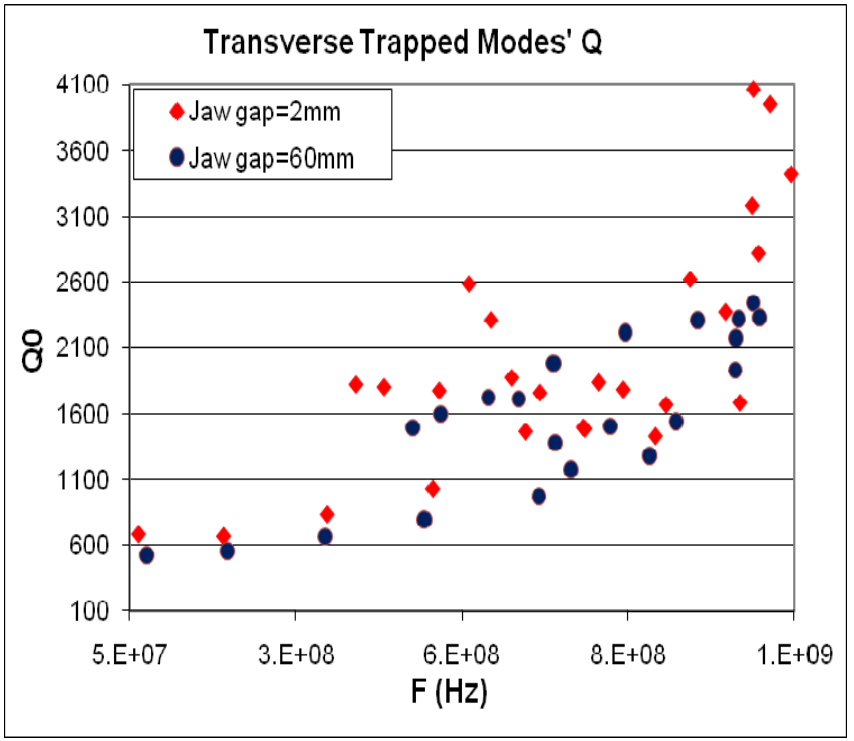


In the current design, the narrow EM foils can only perturb the Ez fields along the beam path without changing it significantly when the jaw gap varies.

Two Jaw Gaps – Transverse Modes

Current Design

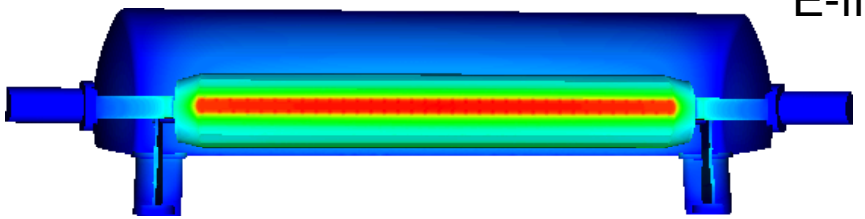




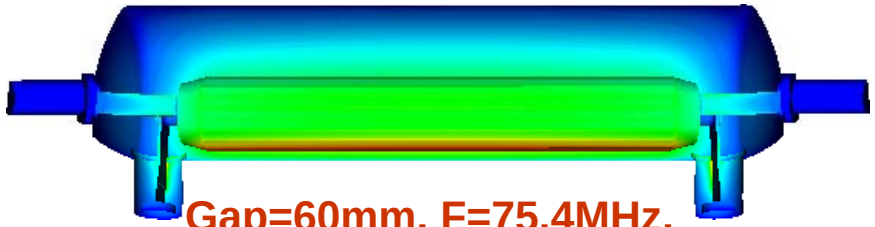
The transverse modes have strong R/Q_T for fully inserted jaws than for fully retracted jaws. It is the same as the original design.

Lowest Transverse Modes

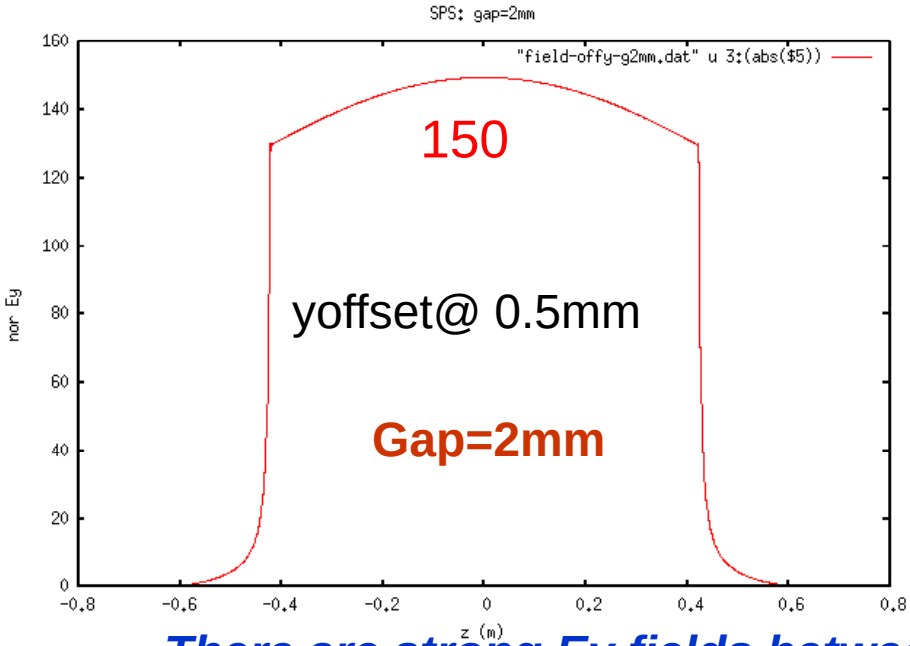
E-field

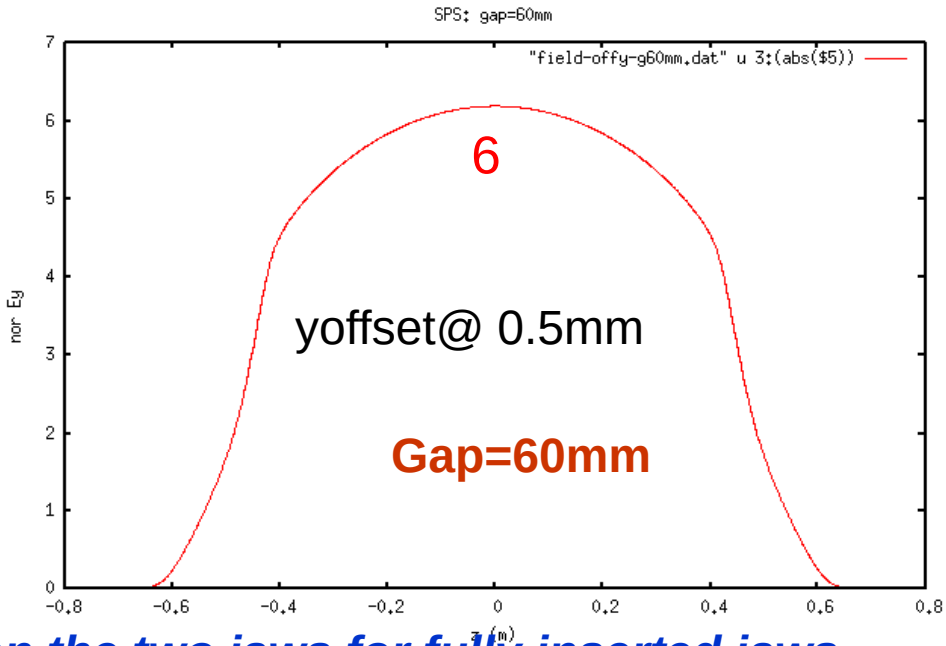


Gap=2mm, F=62.9MHz,
R/Q_T=5.5e6ohm/collimator



Gap=60mm, F=75.4MHz,
R/Q_T=3.3e2ohm/collimator





There are strong Ey fields between the two jaws for fully inserted jaws.

Current Design

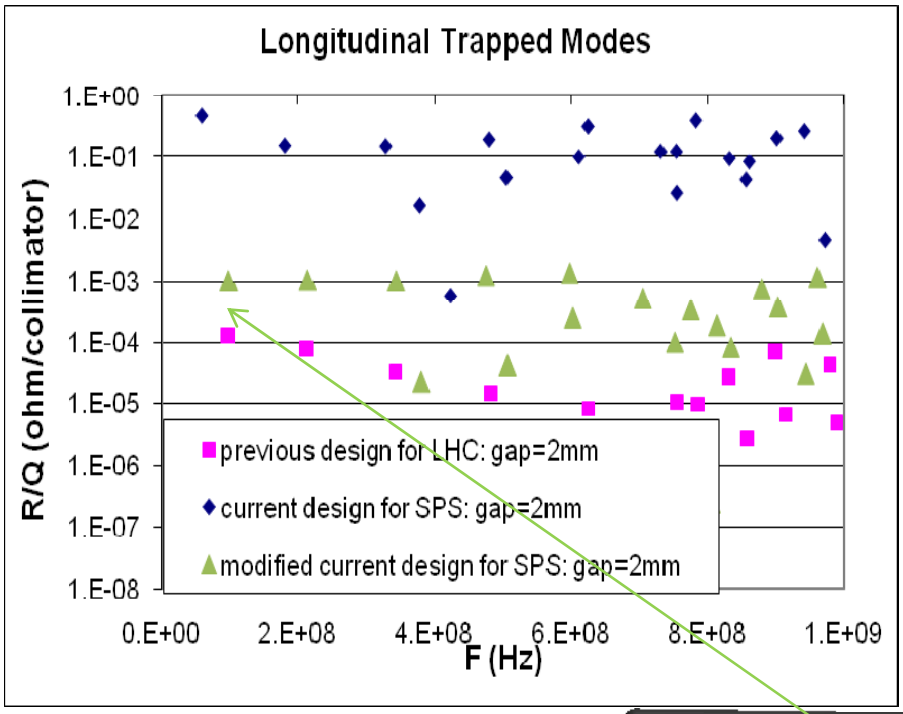
- *The longitudinal modes have higher R/Qs for fully inserted jaws in the current design than in the original design.*
- *The transverse modes in the current design don't change significantly with new transition parts.*
- *Unlike the original design, the longitudinal modes have similar R/Qs for the fully inserted jaws and for the fully retracted jaws. Max. R/Q < 3.6e-1 ohm/collimator*
- *Like the original design, the transverse modes have higher R/Qs for the fully inserted jaws than for the fully retracted jaws. Max. R/Q_T ~ 5.5e+6 ohm/collimator*

Resonant Heating from Trapped Modes

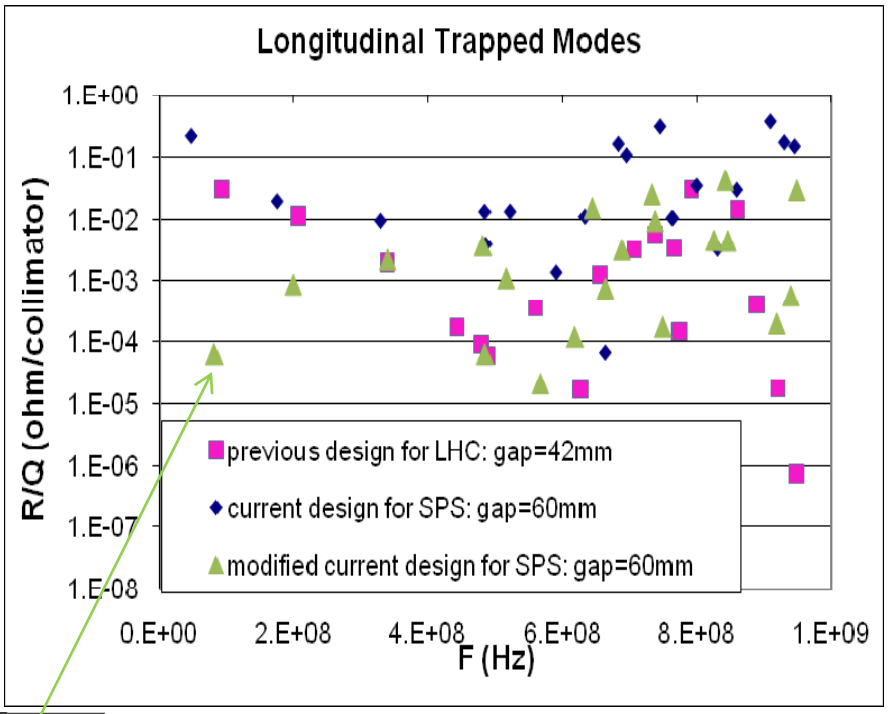
<2GHz	Max. Power at the worst case	Jaw gap=2mm	Jaw gap=42mm	Jaw gap=60mm
Original Design for the LHC Nominal Operation I=0.582A	Rectangular Tank with old jaw design		**6.7 W**	
	Circular Tank with old jaw design		**67 W**	
	Partial-Circular Tank with old jaw design		**38 W**	
Current Design for the SPS Testing I=0.23A	Partial-Circular Tank with new jaw design	**109 W**		**127 W**
Current Design for the LHC Operation I=0.582A	Partial-Circular Tank with new jaw design	**700 W**		**815 W**

Transition Part VS. R/Q

fully inserted jaws



fully retracted jaws



Modified current design

Increasing the height of the EM foils can reduce the lower longitudinal modes R/Q effectively, thus reduce the beam heating.

Discussion

- *What is the impedance budget? What are the trapped mode parameters in the CERN collimator design?*

- *Modifying the transition part can reduce the longitudinal modes R/Q_z. However, it can't change the lowest transverse mode R/Q_T.*

- *If the lowest transverse mode will cause a problem, we will put more efforts to reduce the lowest transverse mode R/Q_T by modifying the collimator geometry and Qext by adding the ferrite files in the collimator.*

Summary

- All trapped modes below 2GHz in the SLAC original and current rotatable collimator designs are calculated using Omega3P, and their RF heating effects are evaluated.
- The longitudinal trapped modes in the cylinder vacuum chamber design have higher Q-value.
- The longitudinal trapped modes in the current collimator jaw design have higher R/Q than in the original collimator jaw design.
- Modified the transition part between the jaws and the vacuum chamber tank can reduce the longitudinal modes R/Q, thus reduce the beam energy loss and heating.
- The heating due to the transverse trapped modes is negligible, *but the transverse kick on the beam needs to be evaluated for fully inserted jaws.*

Special thanks to Fritz Caspers for his helpful discussions and advice.