HOM impedance and power calculations for the RCS SRF cavities

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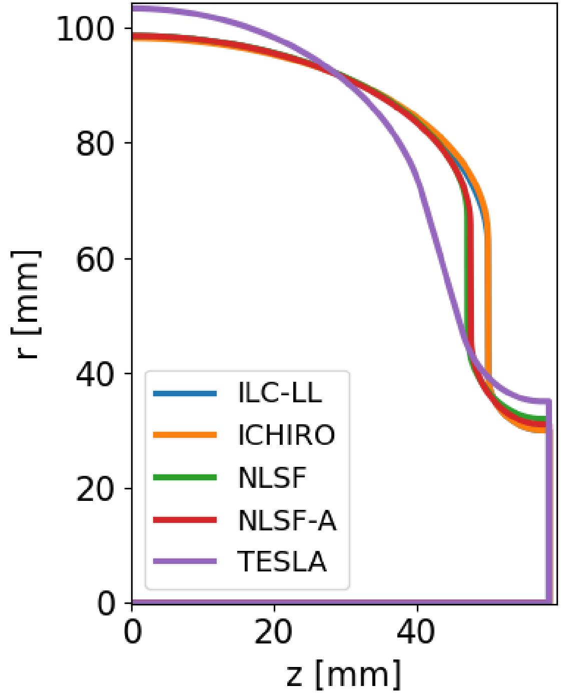
Content

- Survey of low-loss cavity geometries from the literature
- Analysis of NLSF cavity considering different numbers of cells and operating frequency
- Preliminary study of HOM damped cavities and comparison to the transverse impedance threshold
- Summary

Survey of low-loss cavity geometries from the literature

Survey of low-loss cavity geometries from the literature

- Four low-loss cavities from the literature were analysed: ILC-LL, ICHIRO, NLSF, NLSF-A [1]
- The TESLA cavity geometry [2] is included in the analysis



[1] N. Juntong, R.M. Jones, High-gradient SRF Cavity with minimised surface E.M. fields and superior bandwidth for the ILC, Proceedings of SRF2009, Berlin, Germany. https://accelconf.web.cern.ch/SRF2009/papers/thppo024.pdf

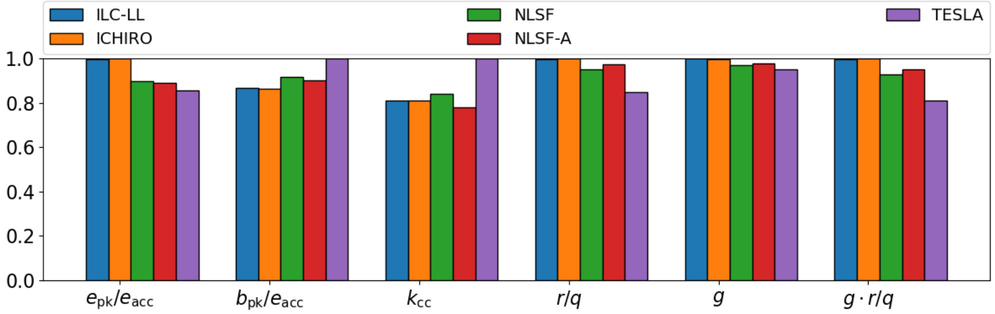
[2] B. Aune et al., Superconducting TESLA cavities, Physical Review Special Topics - Accelerators and Beams, Volume 3, 092001 (2000).

Survey of low-loss cavity geometries from the literature: FM and HOM figures of merit

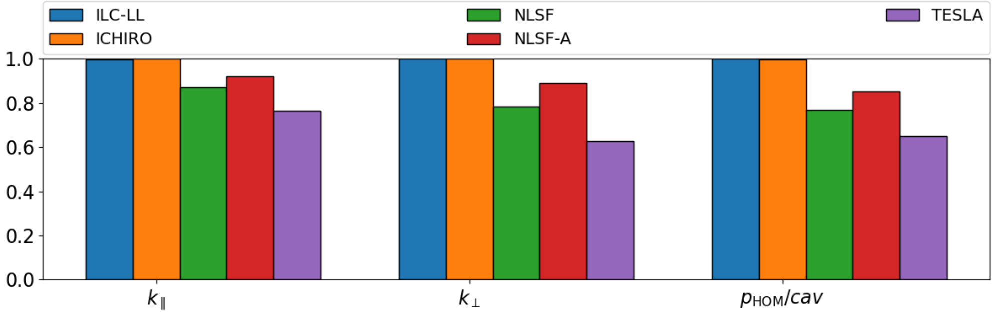
- No significant difference in the relevant quantities of interest of the analysed cavities except the TESLA cavity geometry properties

	NLSF	TESLA
$R/Q[\Omega]$	1148.0	1022.47
$G[\Omega]$	276.46	271.07
$G.R/Q[10^4\Omega^2]$	31.74	27.72
E_{pk}/E_{acc}	2.08	1.99
$B_{pk}/E_{acc}[\frac{mT}{MV/m}]$	3.83	4.17
$\lvert k_{FM}\rvert(\sigma = 13.0\text{ mm})[V/pC]$	2.0679	1.8418
$\lvert k_{\parallel}\rvert(\sigma = 13.0\text{ mm})[V/pC]$	3.355	2.932
$k_{\perp}(\sigma = 13.0\text{ mm})[V/pC/m]$	59.63	47.61

Reference values: Figures of merit for the NLSF cavity geometry



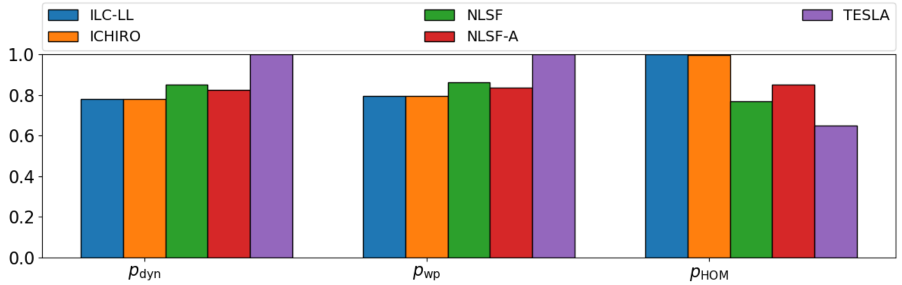
Bar plot of normalised fundamental mode (FM) figures of merit



Bar plot of normalised higher-order mode (HOM) figures of merit

Survey of low-loss cavity geometries from the literature: HOM and Dynamic Power Loss Comparison

- HOM power per cavity is around 10 kW for analysed cavities. (Caveat: values calculated for 9 mid-cells)



Bar plot of normalised dynamic power loss, wall plug power and total HOM power

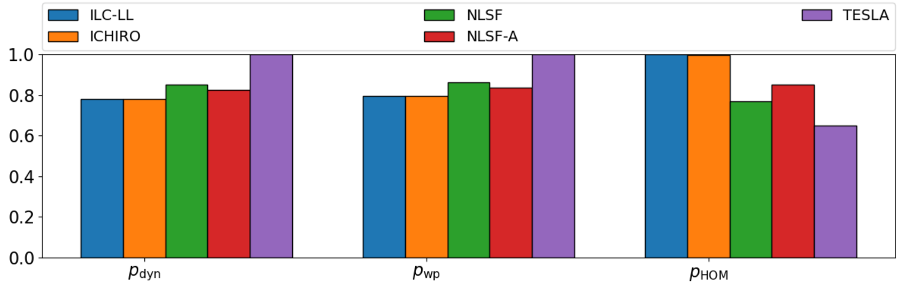
RCS Stage 1: Beam current=20.38 mA; Bunch length=13 mm, $E_{acc} = 30\text{MV/m}$, $Q_0 = 1e10$

	ILC-LL	ICHIRO	NLSF	NLSF-A	TESLA
N_{cav}	670	670	671	670	671
P_{stat}[kW]	4.99	4.98	4.99	4.99	4.99
P_{dyn}[kW]	55.1	55.05	60.19	58.38	70.65
$P_{HOM}/\text{cav}(\sigma = 13.0\text{ mm})$[kW]	13.89	13.86	10.67	11.85	9.04
$P_{HOM}(\sigma = 13.0\text{ mm})$[kW]	9307.39	9283.06	7162.29	7937.26	6066.59

Static, dynamic and HOM power loss

Survey of low-loss cavity geometries from the literature: HOM and Dynamic Power Loss Comparison

- HOM power per cavity is around 10 kW for analysed cavities. (Caveat: values calculated for 9 mid-cells without beam pipe)
- NLSF cavity is selected for further analysis



Bar plot of normalised dynamic power loss, wall plug power and total HOM power

RCS Stage 1: Beam current=20.38 mA; Bunch length=3 mm, $E_{acc} = 30\mathrm{MV/m},\ Q_0 = 1e10$

	ILC-LL	ICHIRO	NLSF	NLSF-A	TESLA
N_{cav}	670	670	671	670	671
P_{stat}[kW]	4.99	4.98	4.99	4.99	4.99
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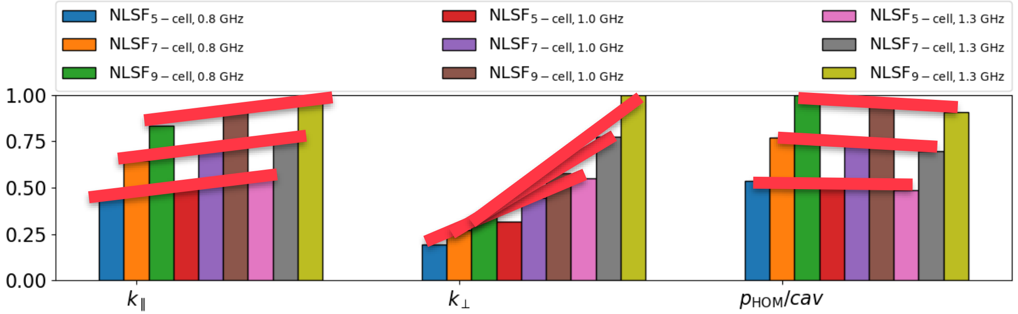
Static, dynamic and HOM power loss

Analysis of the NLSF cavity geometry

Analysis of NLSF cavity considering different numbers of cells and operating frequency

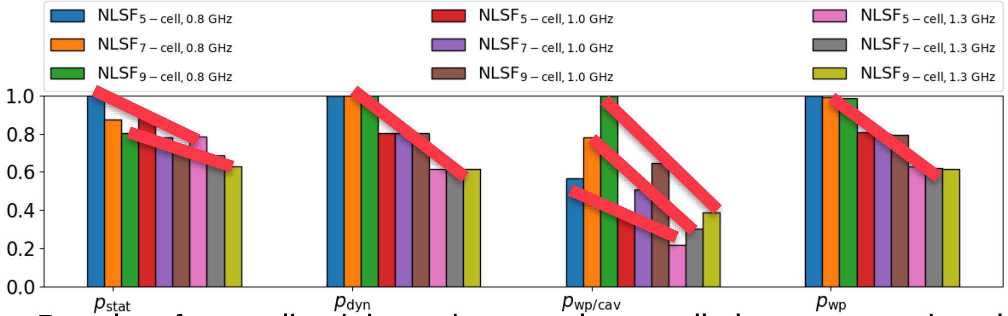
- Considered frequencies
  - 800, 1000, 1300 MHz



Bar plot of normalised higher-order mode (HOM) figures of merit

	$NLSF5_{1.3GHz}$	$NLSF7_{1.3GHz}$	$NLSF9_{1.3GHz}$
N_{cav}	1207	862	671
$P_{stat}[kW]$	6.21	5.42	4.99
$P_{dyn}[kW]$	56.6	56.6	56.6
$P_{HOM}/cav(\sigma = 13.0\ mm)[kW]$	5.73	8.2	10.67
$P_{HOM}(\sigma = 13.0\ mm)[kW]$	6918.45	7067.42	7162.29

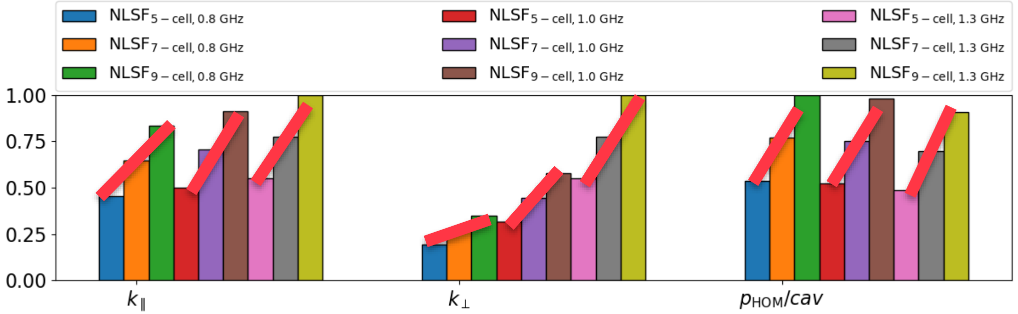
Reference values: total static, dynamic and HOM power per caity



Bar plot of normalised dynamic power loss, wall plug power and total HOM power

Analysis of NLSF cavity considering different numbers of cells and operating frequency

- Considered frequencies
  - 800, 1000, 1300 MHz
- Considered number of cells
  - 5, 7, 9 cells



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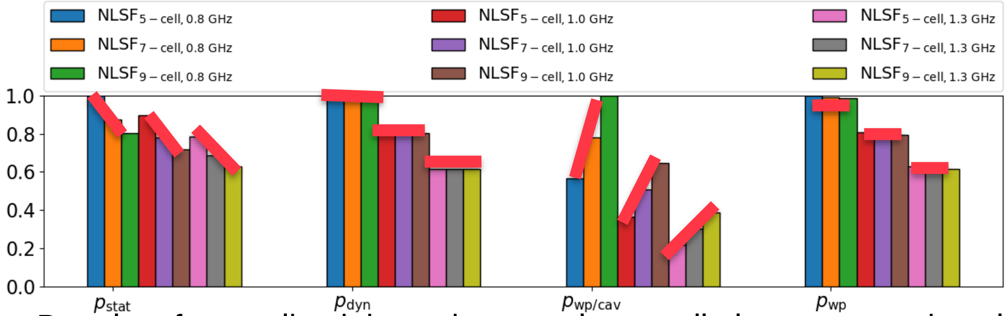
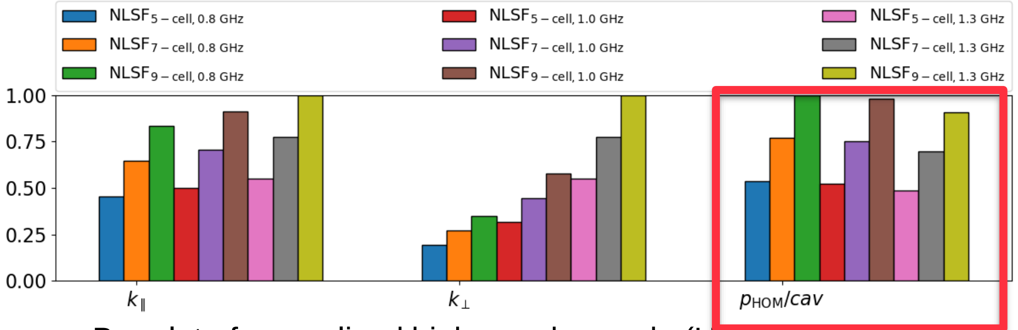


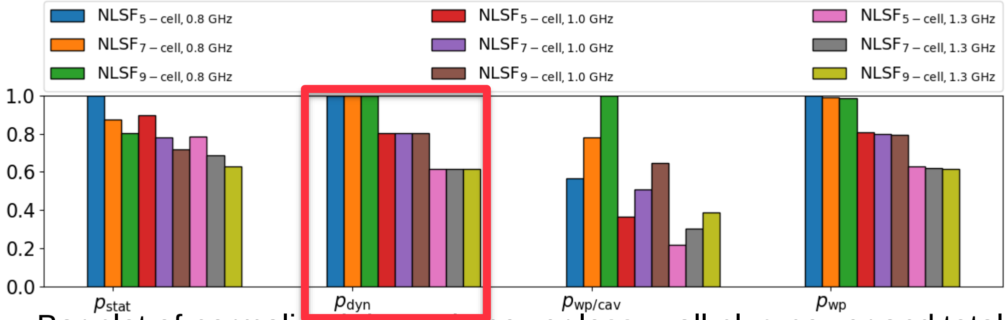
Bar plot of normalised dynamic power loss, wall plug power and total HOM power

Analysis of NLSF cavity considering different numbers of cells and operating frequency

- Higher frequencies?
  - Reduced dynamic losses
  - Negligible effect on HOM power/cav



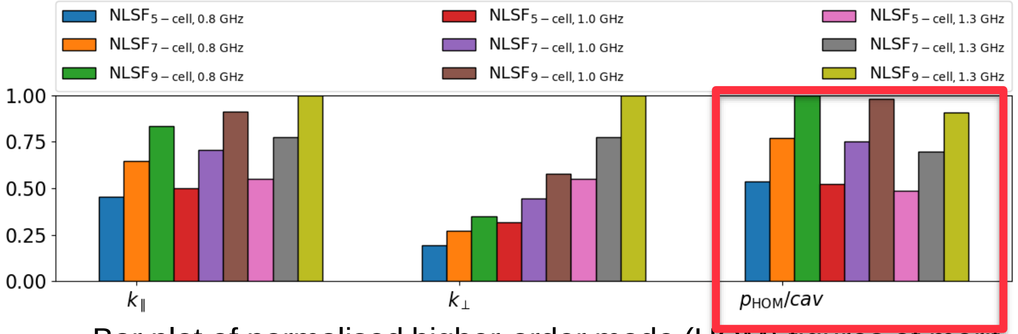
Bar plot of normalised higher-order mode (HOM) figures of merit



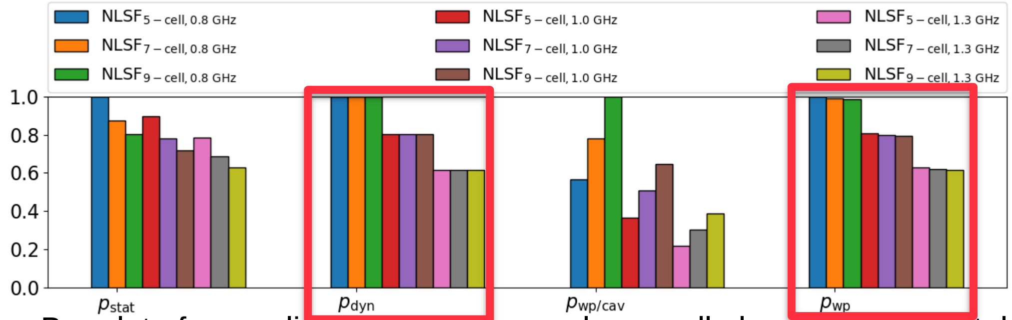
Bar plot of normalised dynamic power loss, wall plug power and total HOM power

Analysis of NLSF cavity considering different numbers of cells and operating frequency

- Higher frequencies?
  - Reduced dynamic losses
  - Negligible effect on HOM power/cav
- More cavity cells?
  - No effect on dynamic losses
  - Increased HOM power/cav



Bar plot of normalised higher-order mode (HOM) figures of merit



Bar plot of normalised dynamic power loss, wall plug power and total HOM power

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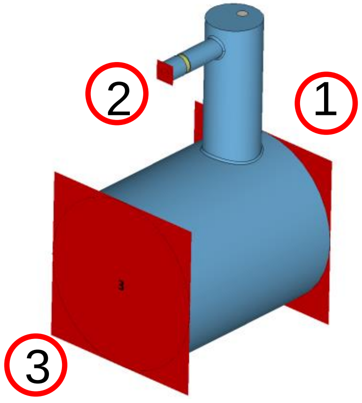
Preliminary Study of Damped Cavities and Comparison to Transverse Impedance Threshold

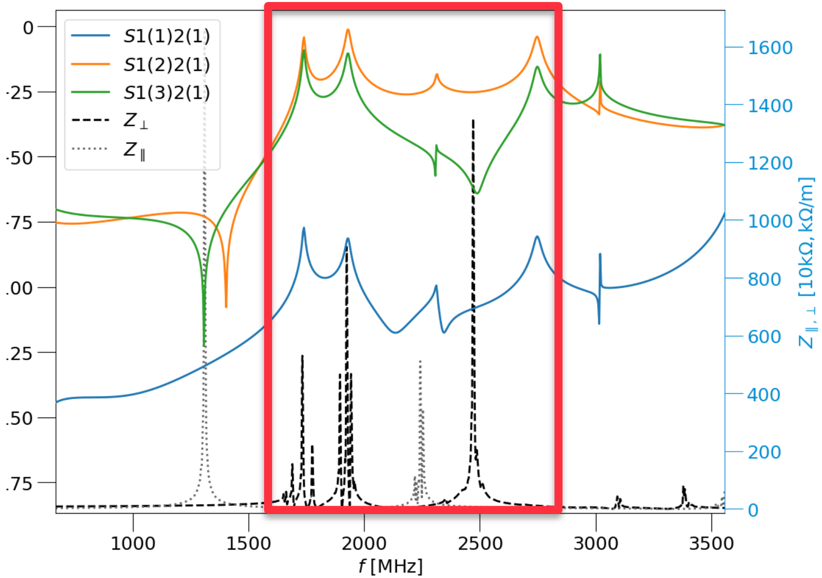
DQW HOM coupler

- A double quarter wave (DQW) coupler was optimised independently

- Further optimisation in a cavity+HOM coupler+FPC assembly required



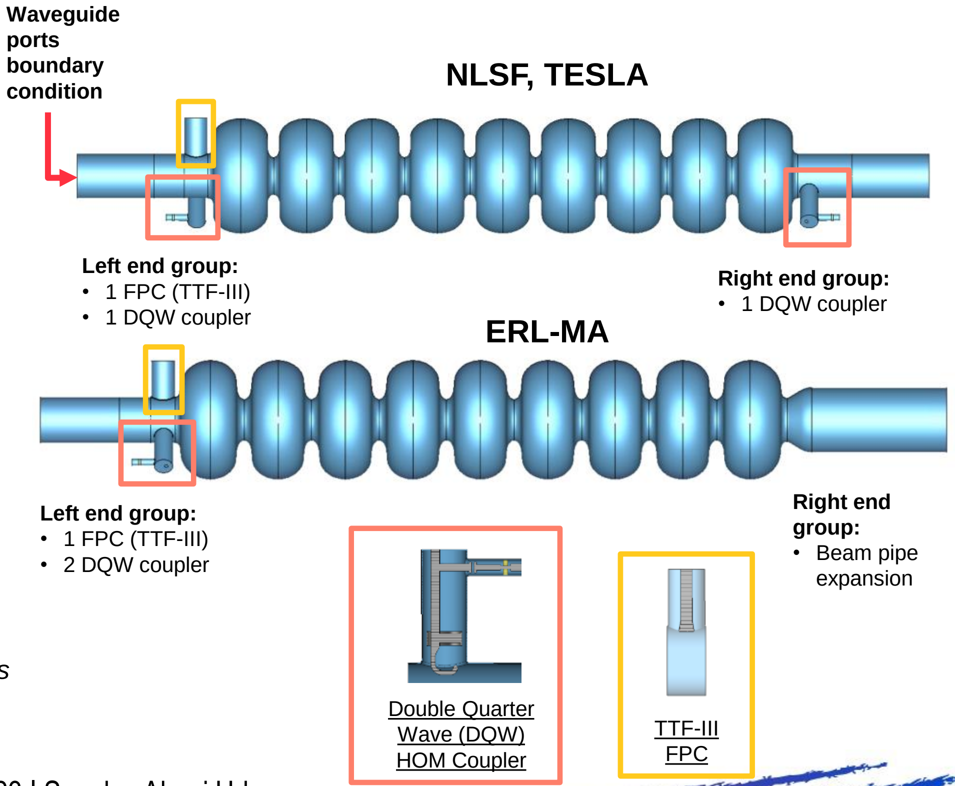
Simulation model for the Double Quarter Wave (DQW) HOM Coupler



Transmission curves of tuned DQW HOM coupler and longitudinal and transverse impedance of NLSF cavity.

Model setup: Cavity + FPC + HOM coupler

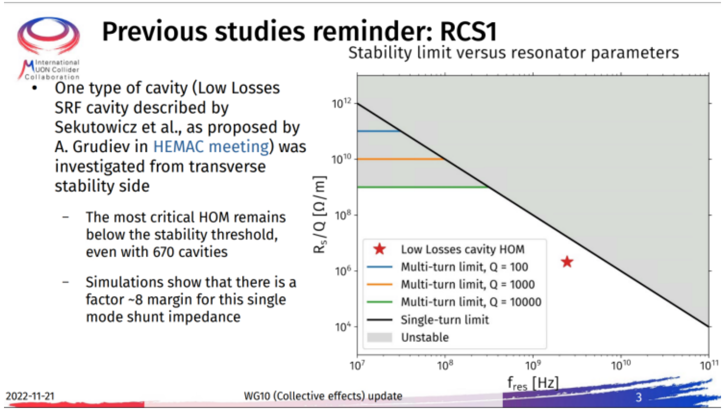
- The NLSF is compared to the TESLA cavity
- ERL [3] cavity geometry is included in the comparison because of the beampipe expansion at one end



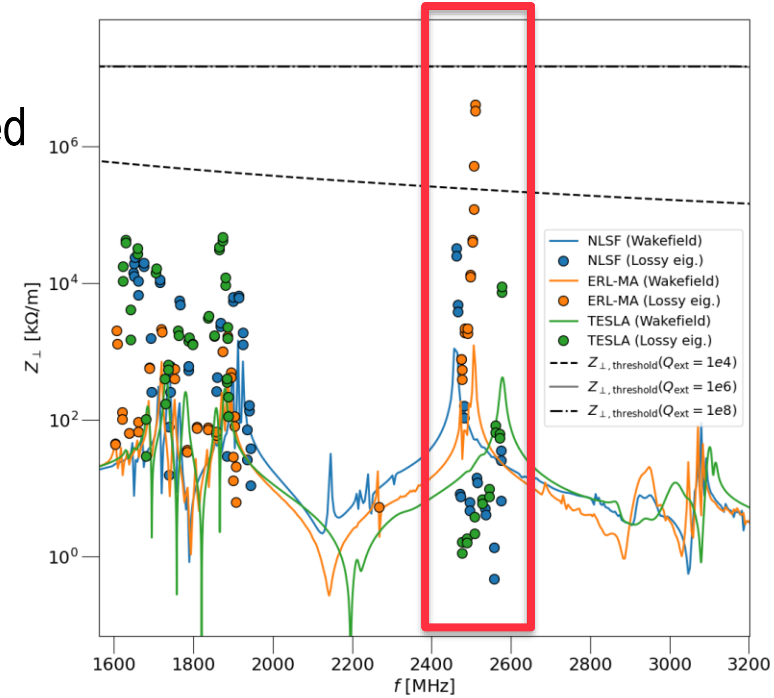
[3] V. Shemelin, Optimal choice of cell geometry for a multicell superconducting cavity, Cornell Laboratory for Accelerator-based Sciences and Education (CLASSE), Ithaca, New York 14853, USA, 11 November 2009. https://journals.aps.org/prab/pdf/10.1103/PhysRevSTAB.12.114701.

Transverse HOM impedance plot for analysed cavities

- The impedance threshold line was calculated for a fixed $Q_{ext} = 1E4, 1E6, 1E8$ as was done in [4]. See image below.



[4] Alexej Grudiev, Transverse stability in RCS and TESLA cavity Preliminary considerations



Lossy eigenmode and wakefield analysis transverse HOM impedance plot for analysed cavities

Transverse impedance stability threshold calculation

- For single-turn regime,

$$\left(\frac{R}{Q}_{\perp} \times f^2\right)_{\text{threshold}} = 100 \left[\frac{\mathbf{M\Omega}}{\mathbf{m}} \cdot \mathbf{GHz^2}\right]$$

$$Z_{\text{threshold}} = 100 \times \frac{Q_{\text{ext}}}{f^2}\left[\frac{\mathbf{M\Omega}}{\mathbf{m}}\right]$$

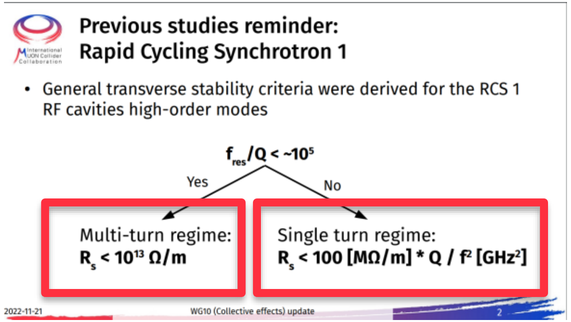
- For multi-turn regime

$$\left(\frac{R}{Q}_{\perp,} \times f^2\right)_{\text{threshold}} = \frac{10^7}{Q_{\text{ext}}} \times f^2 \left[\frac{\mathbf{M\Omega}}{\mathbf{m}} \cdot \mathbf{GHz^2}\right]$$

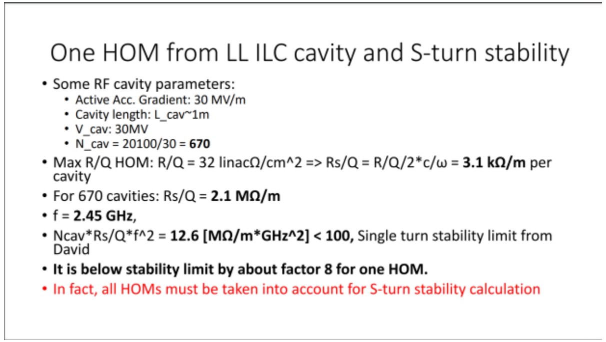
$$Z_{\text{threshold}} = 10^7 \left[\frac{\mathbf{M\Omega}}{\mathbf{m}}\right]$$

$$\left(Z = R_s = \frac{R}{Q} \times Q_{\text{ext}}\right)$$

- The transverse impedance threshold used for comparision is the minimum between the single-turn and multi-turn impedance instead of the $\frac{f}{Q} < 10^5$ condition as it provides the most stringent stability limit



[5] *D. Amorim, E. Métral, Working Group 10 (Collective effects) update*



[6] *Alexej Grudiev, Transverse stability in RCS and TESLA cavity Preliminary considerations*

Comparision of maximum transverse R/Q mode impedance with threshold values

	$\max\left(\frac{R}{Q_\perp}\right)$	$f_{\max\left(\frac{R}{Q_\perp}\right)}$	$Q_{\text{ext,max}\left(\frac{R}{Q_\perp}\right)}$	$\frac{f}{Q_{\text{ext}}}$	$\max\left(\frac{R}{Q_\perp}\right) \times N_{\text{cavs}} \times f^2$	$\left(\frac{R}{Q_\perp} \times f^2\right)_{\text{threshold}}$ (Single turn regime)	$\left(\frac{R}{Q_\perp} \times f^2\right)_{\text{threshold}}$ (Multi turn regime)	factor
	[kΩ/m]	[GHz]	[.]	[GHz]	$[\text{M}\Omega/\text{m} \cdot \text{GHz}^2]$	$[\text{M}\Omega/\text{m} \cdot \text{GHz}^2]$	$[\text{M}\Omega/\text{m} \cdot \text{GHz}^2]$	
NLSF	2.303	2.462	1.42E+04	1.734E+05	9.35	100	4268.62	10.7
ERL-MA	1.7614	2.51	2.34E+06	1.07E+03	7.43	100	26.92	3.62
TESLA	2.06	2.577	4.35E+03	5.9E+05	9.17	100	15266.50	10.9
***ILC-LL [1][2]**	3.1	2.45	2E+05	1.23E+04	12.6	100	300.13	8

*The transverse HOM impedance comparison for the ILC-LL as calculated by Alexej Grudiev is included only in this table for comparison

[1] Alexej Grudiev, SRF cavity parameter model for HEC RF system design, June 2021, *https://indico.cern.ch/event/1049297/contributions/4408625/attachments/2268943/3852893/20210622_RFcavity%20parameter%20model%20for%20HE%20moun%20accelrators.pdf*

[2] J. Sekutowicz, Design of a low-loss SRF cavity for the ILC, Particle Accelerator Conference, Knoxville, Tennesse, 2005, https://accelconf.web.cern.ch/p05/papers/tppt056.pdf.

NLSF: Comparison of $Z_{\perp}$ and $Z_{\perp,\text{threshold}}$

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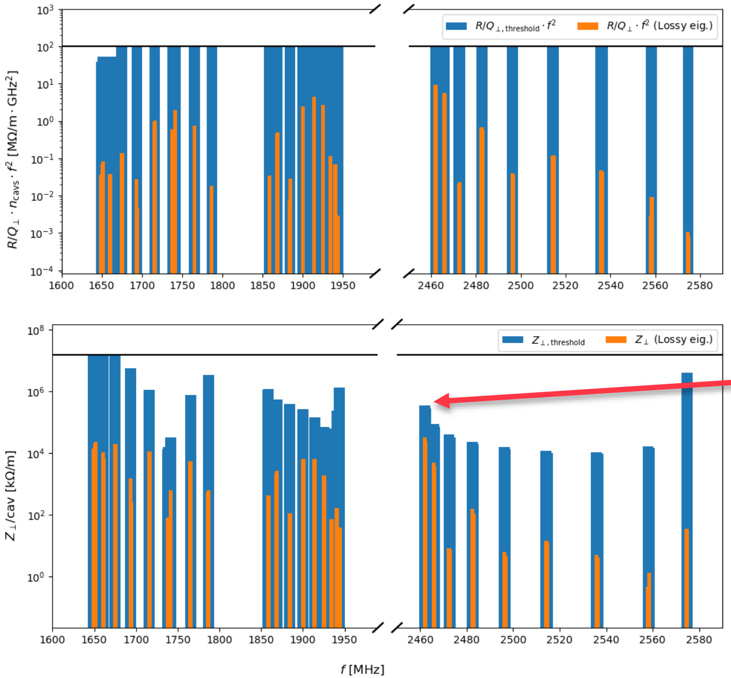
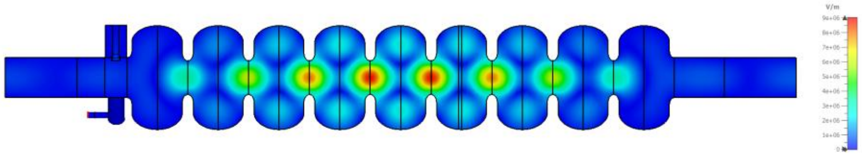


Transverse impedance of dipole modes in first and second HOM dipole passband and transverse impedance threshold bar plot for the NLSF cavity geometry

Trapped TE121 Mode



f [MHz]	Q_{ext}	$\frac{R}{Q_{\perp}}$ [kΩ/m]	Z [MΩ/m]
2460	1.34E+04	2.45	32.99

ERL-MA: Comparison of $Z_{\perp}$ and $Z_{\perp,\mathrm{threshold}}$

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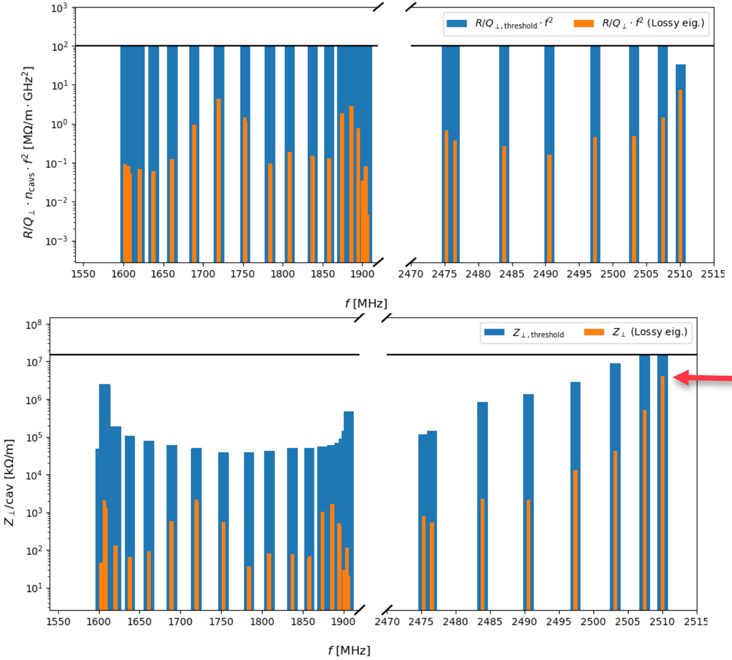
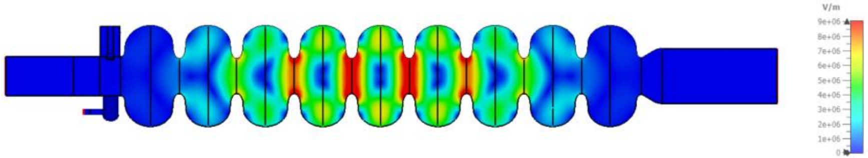


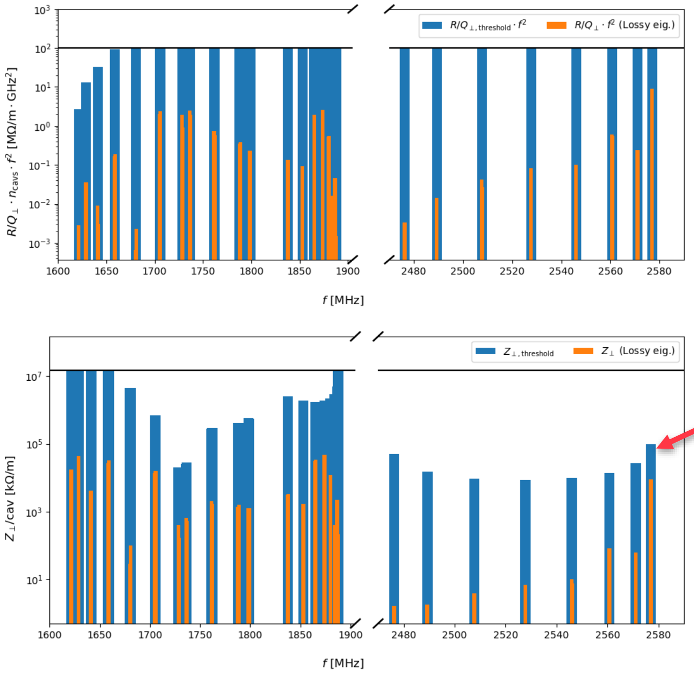
Transverse impedance of dipole modes in first and second HOM dipole passband and transverse impedance threshold bar plot for the ERL-MA cavity geometry

Trapped TE121 Mode

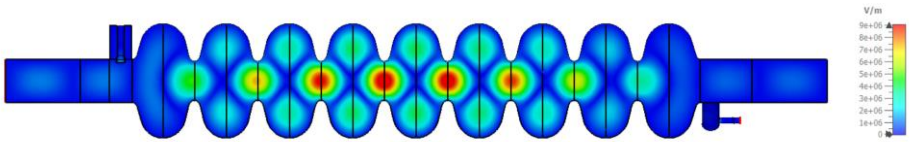


f [MHz]	Q_{ext}	$\frac{R}{Q}_{\perp}$ [kΩ/m]	Z [MΩ/m]
2510	2.34E+06	1.76	4118.82

TESLA: Comparison of $Z_{\perp}$ and $Z_{\perp,\text{threshold}}$



Trapped TE121 Mode



f [MHz]	Q_{ext}	$\frac{R}{Q_{\perp}}$ [kΩ/m]	Z [MΩ/m]
2577	4.35E+03	2.06	8.97

Transverse impedance of dipole modes in first and second HOM dipole passband and transverse impedance threshold bar plot for the TESLA cavity geometry

Summary

- The maximum impedance of the analysed cavities is less than the transverse impedance threshold values by different factors. The least suitable, considering the impedance threshold value, is the ERL-MA cavity geometry
- The HOM impedance could be reduced further by optimising the HOM couplers and increasing the number of couplers
- The TE121 mode is a trapped mode, and the cavity geometry(ies) need to be optimised to allow this mode to propagate to the end cells for proper damping
- A HOM power of around10kW is expected. This value can be halved by reducing the number of cells per cavity at the cost of an increased number of cells

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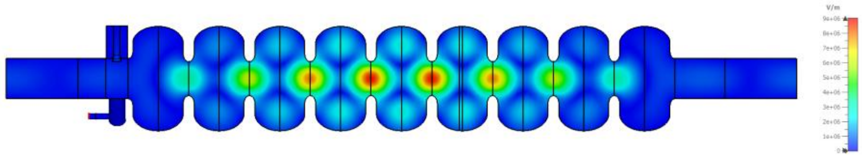
Thank you for your attention

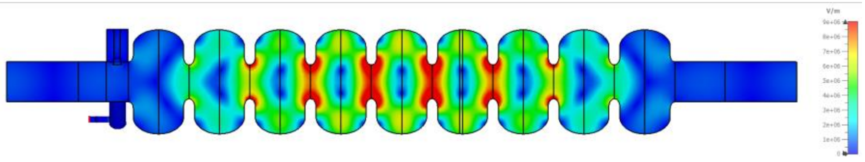
International

NLSF: Trapped TE121 Mode @~2470MHz

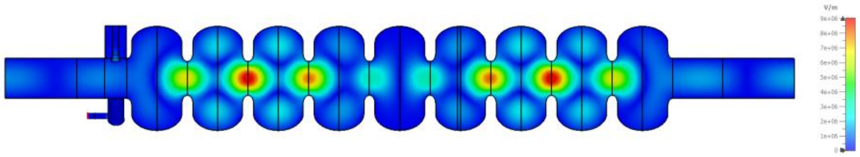
E-Fields scaled to a maximum of 9 MV/m



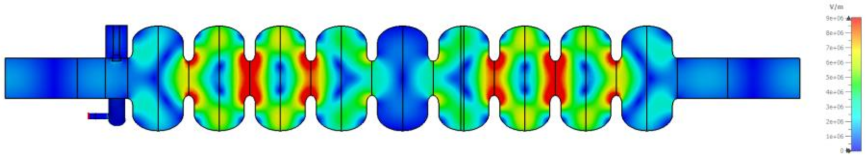
f [MHz]	Q_{ext}	$\frac{R}{Q}_{\perp}$ [kΩ/m]	Z [MΩ/m]
2460	1.34E+04	2.45	32.99



f [MHz]	Q_{ext}	$\frac{R}{Q}_{\perp}$ [kΩ/m]	Z [MΩ/m]
2460	1.18E+04	2.37	28.11



f [MHz]	Q_{ext}	$\frac{R}{Q}_{\perp}$ [kΩ/m]	Z [MΩ/m]
2470	3.62E+03	1.47	5.35

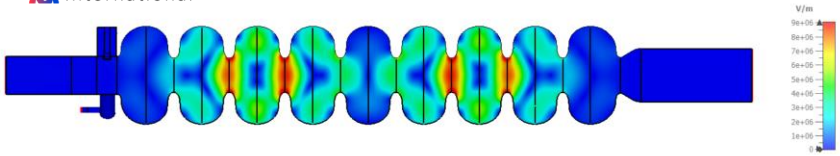


f [MHz]	Q_{ext}	$\frac{R}{Q}_{\perp}$ [kΩ/m]	Z [MΩ/m]
2470	2.99E+03	1.45	4.34

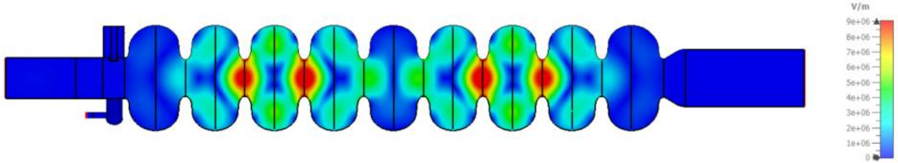
International

ERL-MA: Trapped TE121 Mode @~2510MHz

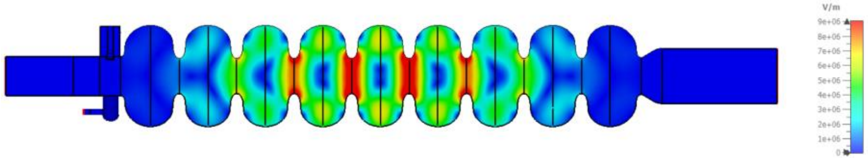
E-Fields scaled to a maximum of 9 MV/m



f [MHz]	Q_{ext}	$\frac{R}{Q}_{\perp}$ [kΩ/m]	Z [MΩ/m]
2507	3.54E+05	0.345	122.26



f [MHz]	Q_{ext}	$\frac{R}{Q}_{\perp}$ [kΩ/m]	Z [MΩ/m]
2507	1.49E+06	0.348	519.97



f [MHz]	Q_{ext}	$\frac{R}{Q}_{\perp}$ [kΩ/m]	Z [MΩ/m]
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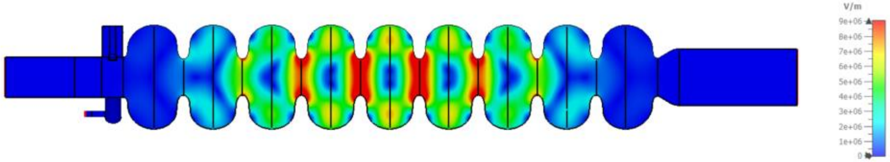
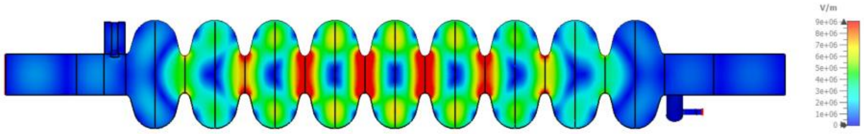


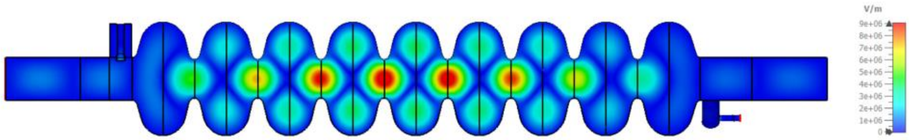
f [MHz]	Q_{ext}	$\frac{R}{Q}_{\perp}$ [kΩ/m]	Z [MΩ/m]
2510	1.88E+06	1.76	3315.73

TESLA: Trapped TE121 Mode @~2577MHz

E-Fields scaled to a maximum of 9 MV/m



f [MHz]	Q_{ext}	$\frac{R}{Q_\perp}$ [kΩ/m]	Z [MΩ/m]
2577	3.64E+03	2.05	7.47



f [MHz]	Q_{ext}	$\frac{R}{Q_\perp}$ [kΩ/m]	Z [MΩ/m]
2577	4.35E+03	2.06	8.97