RF emission spectra in laser-plasma acceleration of protons

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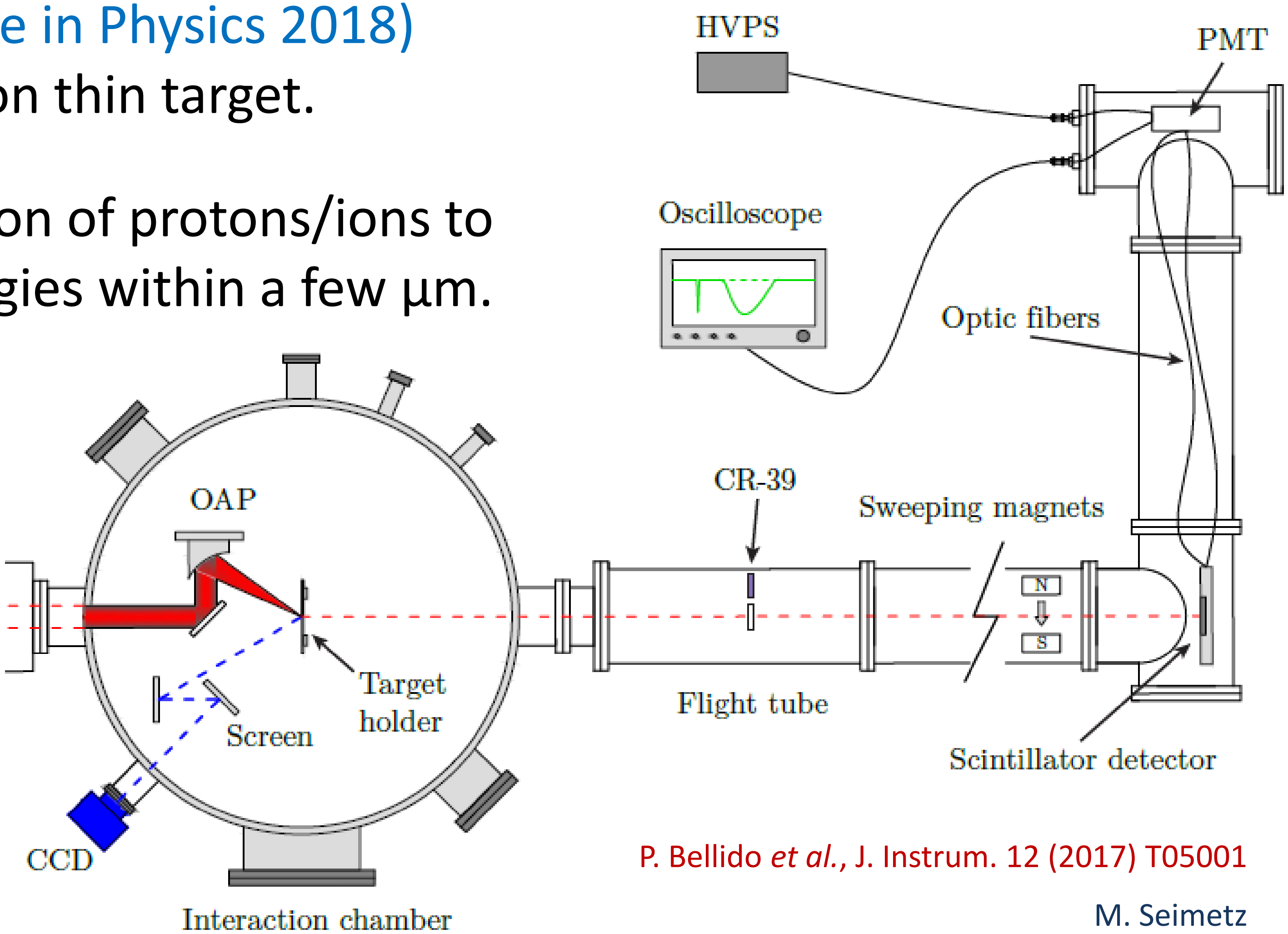
Laser-ion acceleration

Ultra-short, ultra-intense laser pulse
(CPA, G. Mourou and D. Strickland, Nobel Prize in Physics 2018)
focalized on thin target.

Acceleration of protons/ions to MeV energies within a few μm.



P. Bellido *et al.*, J. Instrum. 12 (2017) T05001

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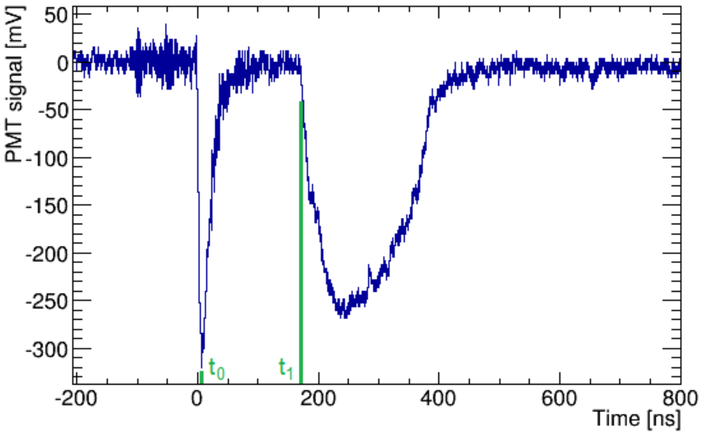
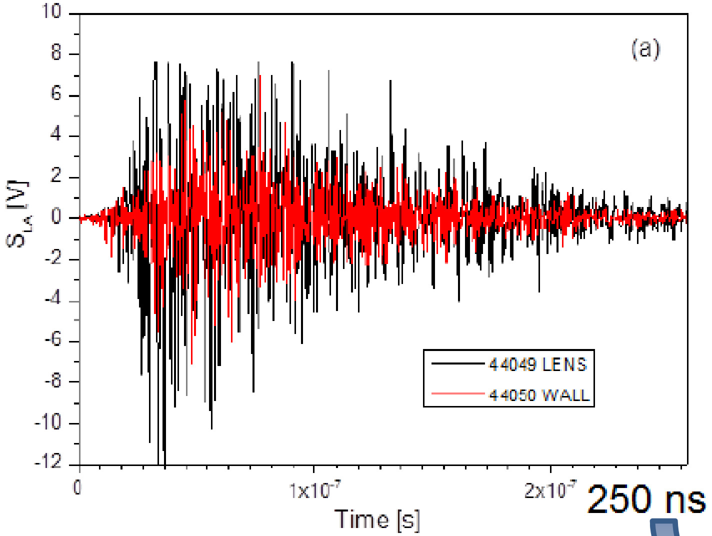
Electromagnetic pulse (EMP)



P. Bellido *et al.*, J. Instrum. 12 (2017) T05001

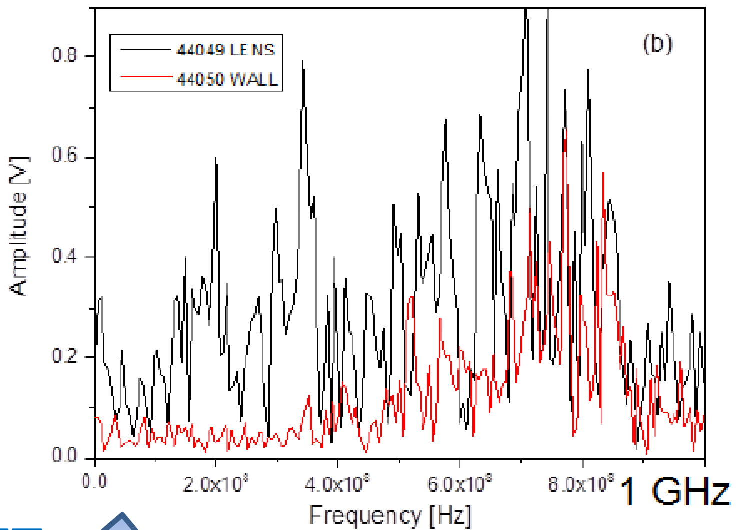
Can be observed as noise on top of detector signal…

… or picked up by dedicated antennas inside or outside the vacuum system.



M. De Marco *et al.*,
J. Phys. Conf. Series 508 (2014) 012007

FFT



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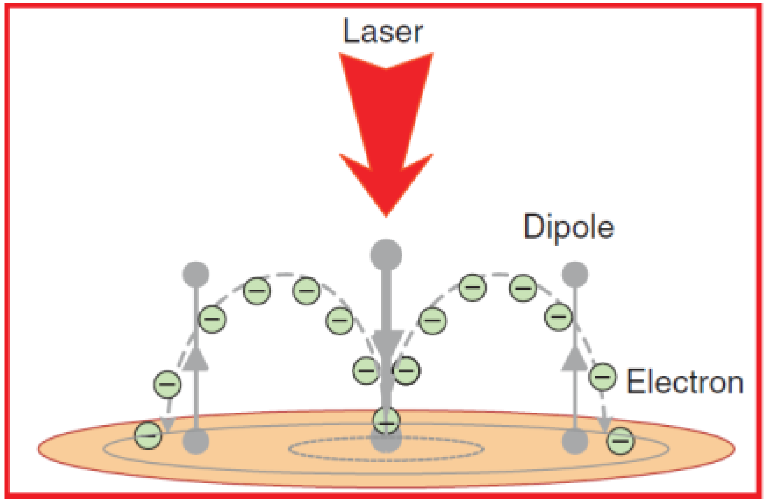
Electromagnetic pulse (EMP)

Three sources of rf pulse (EMP):
- Plasma plume
- Neutralization currents in target holder
- Oscillations of vacuum system by impact of charged particles.



Z.-Y. Chen *et al.*, Physica Scripta 83 (2011) 055503

Aim: Simulate rf emission spectra to
- Identify distinct sources in experimental data
- Understand systematic differences between data sets
- Find means to suppress EMP.

Method: Numerical simulation of eigenmodes of vacuum system treated as rf cavities.

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Eigenmodes of rf cavity

Starting point: Calculate eigenfrequencies of cylindrical vessel.
Analytical approach: (M.J. Mead *et al.*, Rev. Sci. Instrum. 75 (2004) 4225)

Cylinder of height, *l*, and radius, *a*:

TM_{010} mode: $f_0 = \frac{2.045\, c}{2\pi\, a}$

TE_{111}: $f_0 = \frac{c}{2l}\sqrt{1 + \left(\frac{2l}{3.41a}\right)^2}$

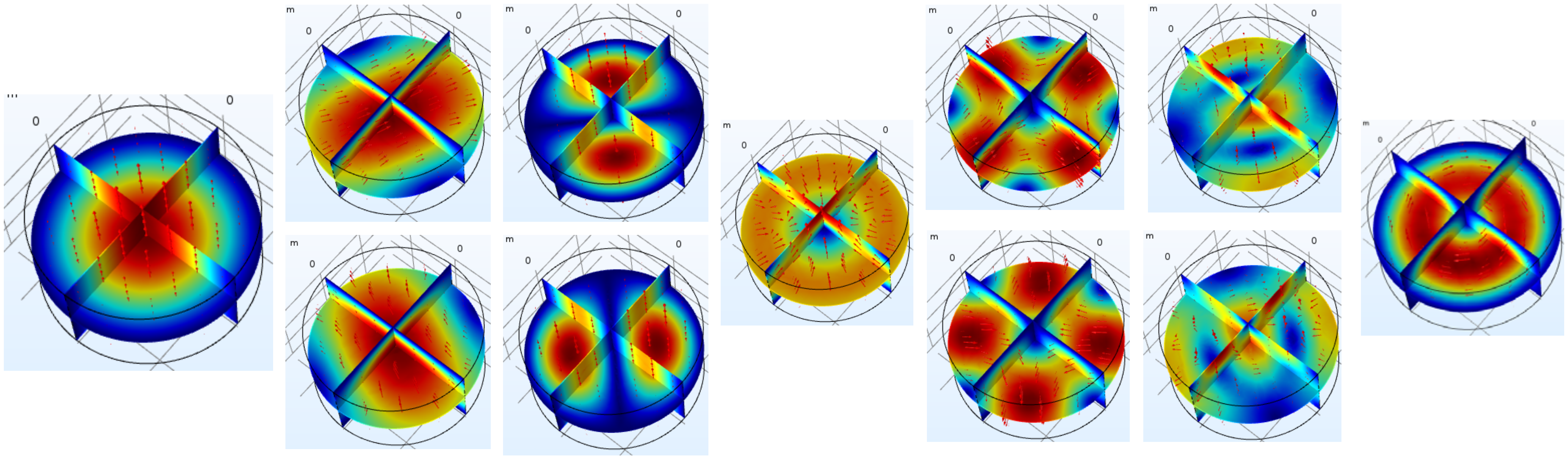
Alternative (for complex geometries): Numerical calculation.
COMSOL Multiphysics 5.3a, RF Module
Tutorial example: Application ID 9618
M. De Marco *et al.*, J. Instrum. 11 (2016) C06004

Numerical solution of Maxwell's equations,

$$\nabla \times (\mu_r^{-1} \nabla \times \boldsymbol{E}) - \frac{\omega^2}{c^2}\left(\varepsilon_r - \frac{i\sigma}{\omega\varepsilon_0}\right)\boldsymbol{E} = 0\,.$$

Eigenmodes of rf cavity

Simple, metallic cylinder:



TM_{010}	TE_{111}	TM_{110}	TM_{011}	TE_{211}	TM_{111}	TE_{011}
382 MHz	579	609	629	697	788	788

Metallic cylinder with glass cover:

↑ +15 MHz	-4 ↓	↑ +21	↑ +5	-4 ↓	↑ +14	-3 ↓

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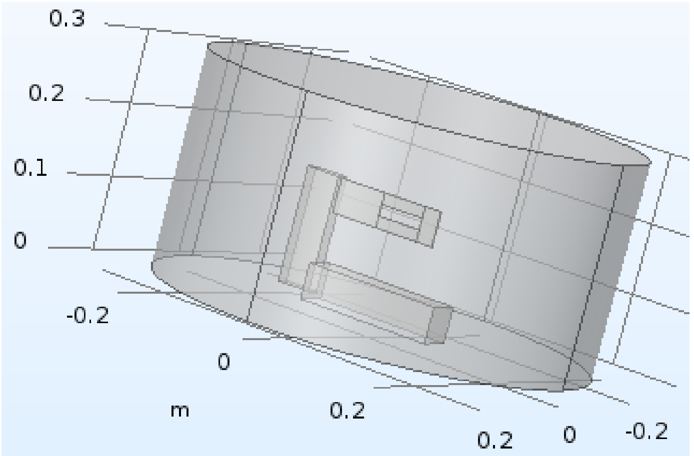
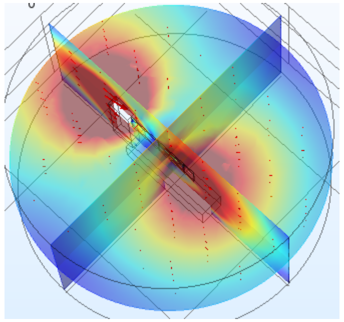
Cavity with internal components



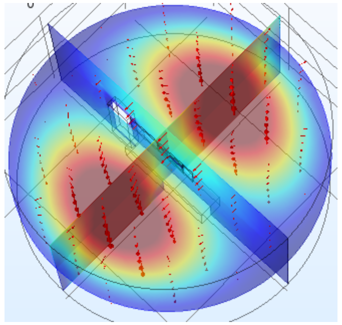
Internal components act like antennas.
COMSOL Multiphysics 5.3a, RF Module
Tutorial example: Application ID 8715
(linear λ/2 antenna)

Effects:

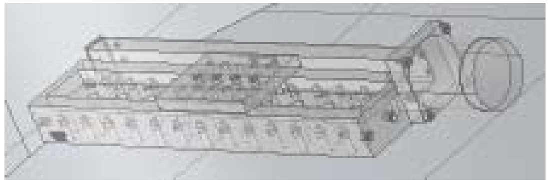
- Additional mode (239 MHz)
- Breaking of angular symmetry, line splitting



141 ⇔ MHz



Coarse model of geometry seems sufficient; fine details (*e.g.*, stepper motor) just increase the computation time.



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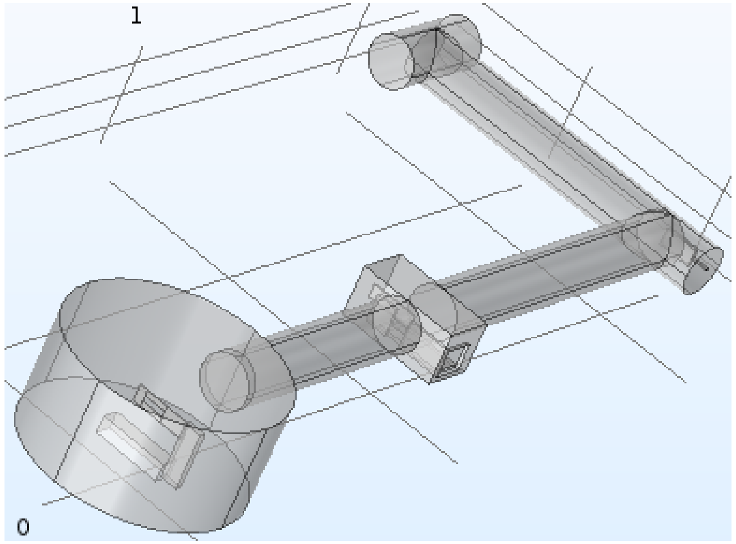
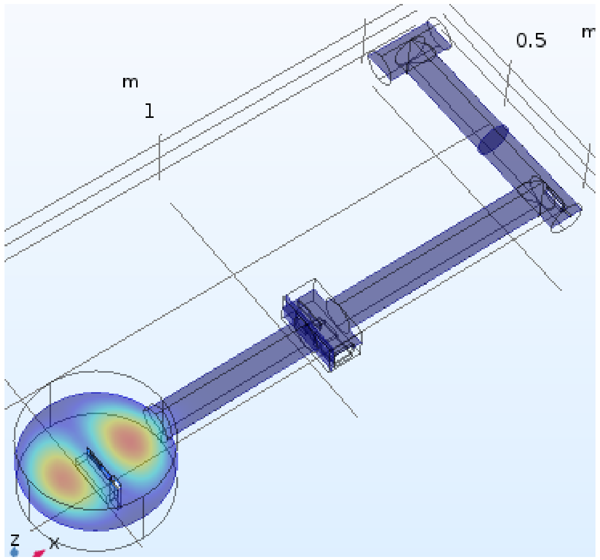
Complete vacuum system



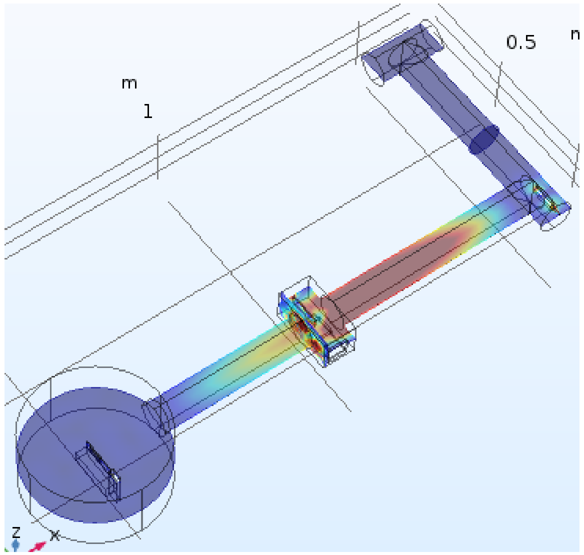
Introduce vacuum tubes and additional, internal components. Observations:

- Individual modes of vessel like before
- Individual modes of other tubes
- Coupled modes at higher frequencies.

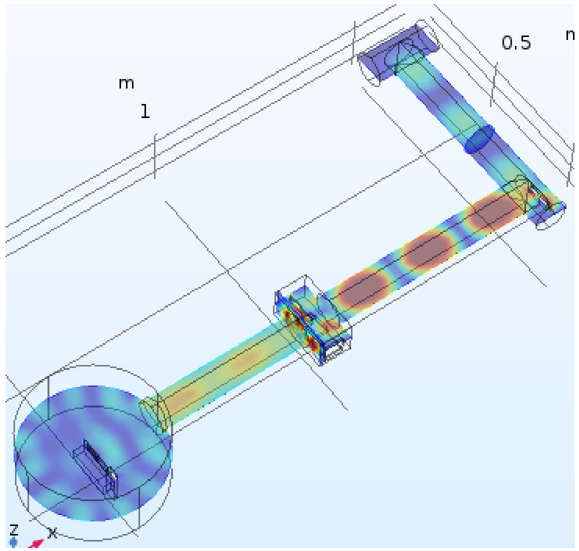
635 MHz



1177 MHz



1262 MHz



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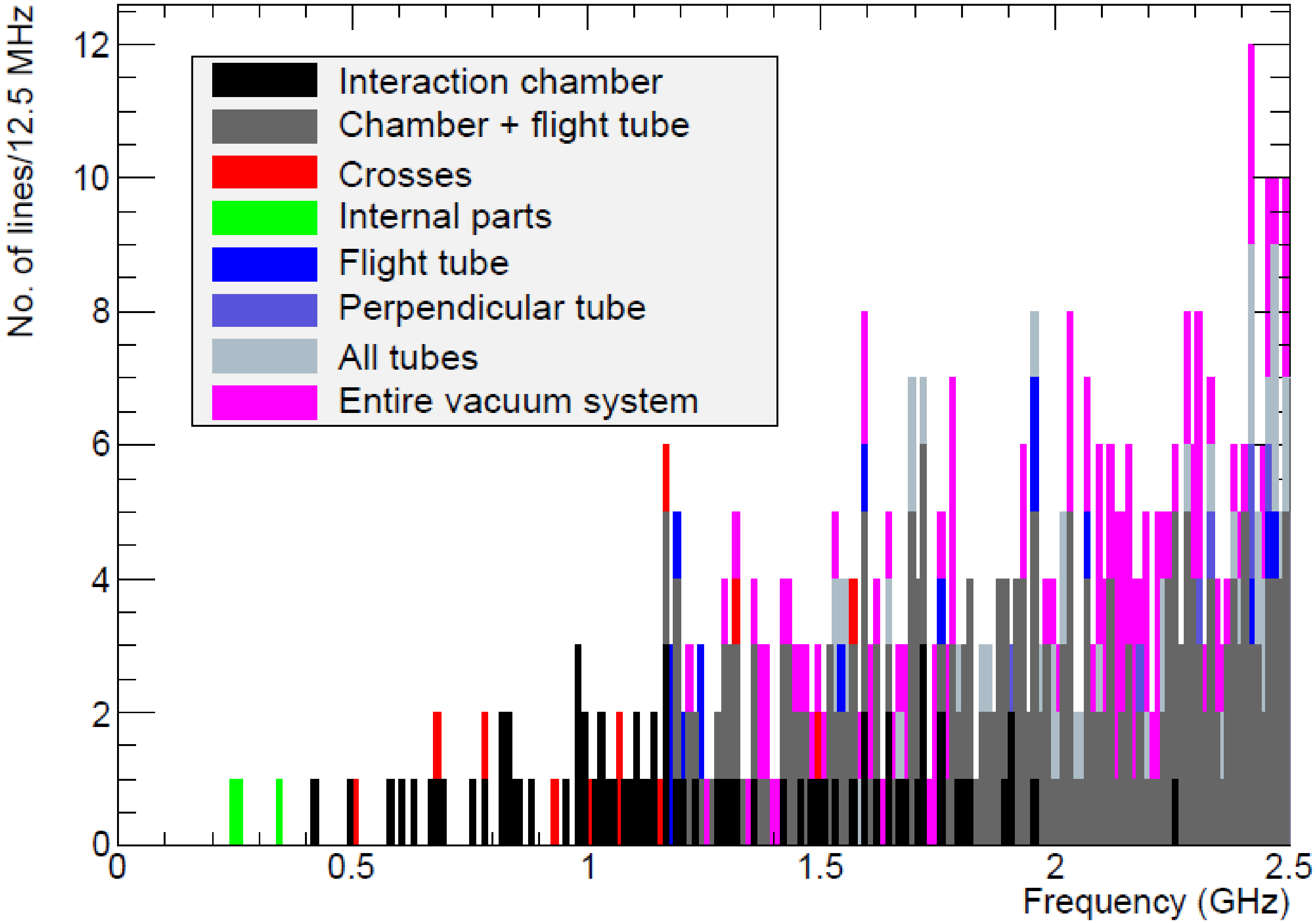
Eigenfrequency spectrum

About 550 eigenmodes from 0 to 2.5 GHz.



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Eigenfrequency spectrum

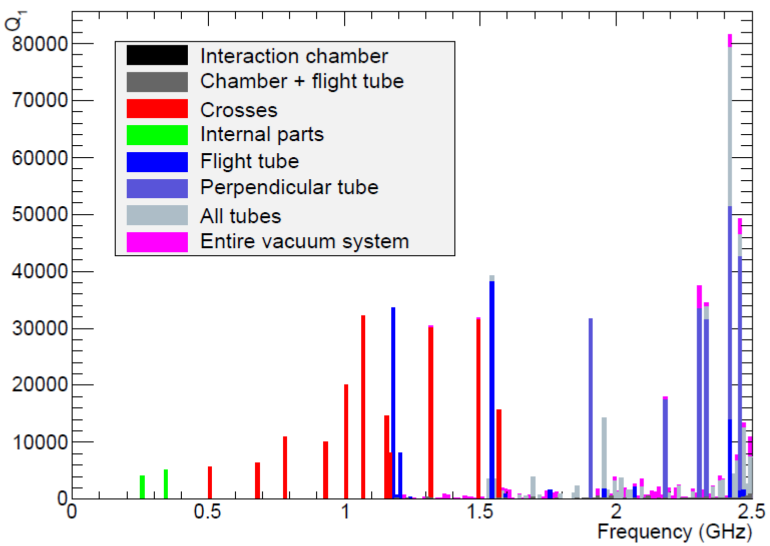
Classification by Q-factor? Two versions (numerically close for ideal cavity). Here, $Q_1 \ll Q_2$ due to glass cover of main vessel.

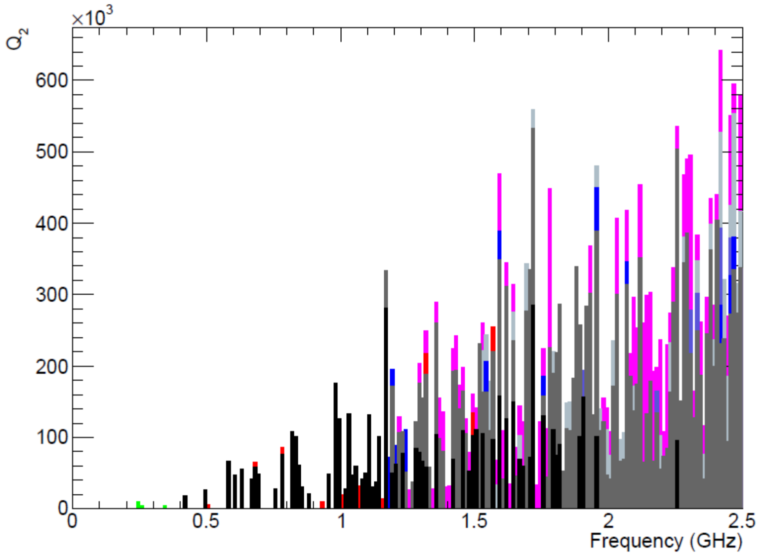
$$Q_1 = \pi f_0 / \lambda$$

λ: damping factor

$$Q_2 = 2\pi f_0 W_t / P_d$$

W_t : stored energy
P_d : dissipated power





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Conclusions and outlook

About 550 eigenmodes from 0 to 2.5 GHz:

- Many related to individual parts
  ⇒ spectra do not change entirely after adding single components
- Internal parts modify spectra of hollow cylinders
- Some additional modes due to internal antennas
- Few eigenmodes below 1 GHz, many at higher frequencies
- Relative weight of single lines?

Next steps:

- Simulation of excitation mechanisms?
  (charge deposition, electric currents)
- Phenomenological comparison to experimental spectra.

Thank you for your attention!