GEFÖRDERT VOM

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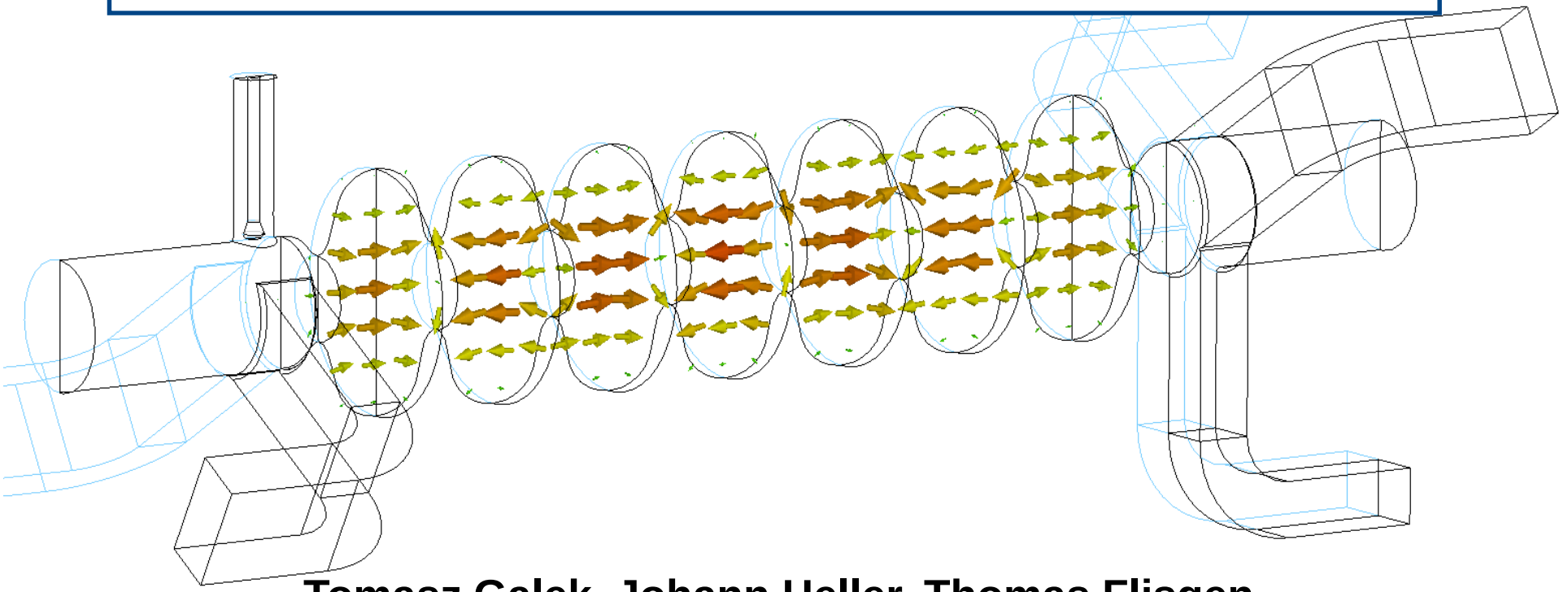
Application of State-Space Concatenation Scheme to Chains of SRF Cavities



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Workshop on High Order Modes in Superconducting Cavities 2016

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- Introduction – current/past projects
- SSC validation – example for BESSY-VSR
- bERLinPro
  - Different module configurations due to BBU considerations
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- BESSY-VSR
  - Chain-wise field flatness
  - Funny modes
  - Dipole excitation

bERLinPro

bERLinPro - Berlin **E**nergy **R**ecovery **Lin**ac **Pro**ject,

Picture: courtesy of HZB

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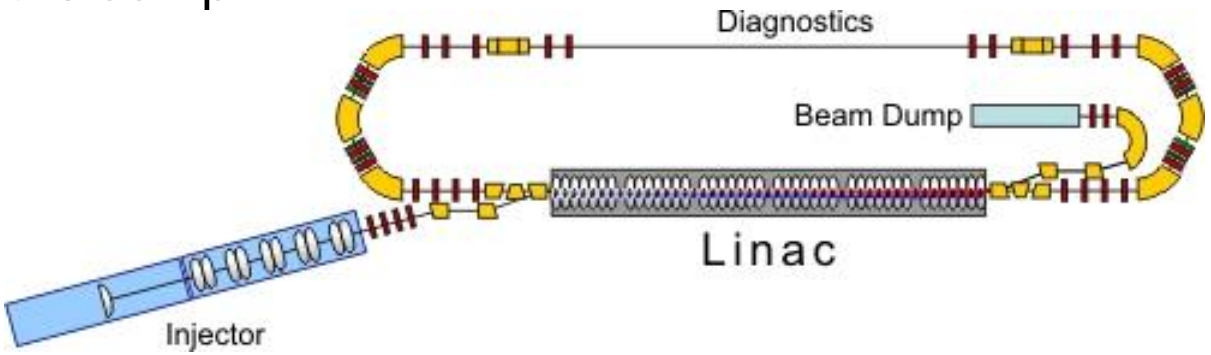
http://www.helmholtz-berlin.de/

bERLinPro

HZB Helmholtz Zentrum Berlin bERLinPro

bERLinPro - Berlin **E**nergy **R**ecovery **Lin**ac **Pro**ject,

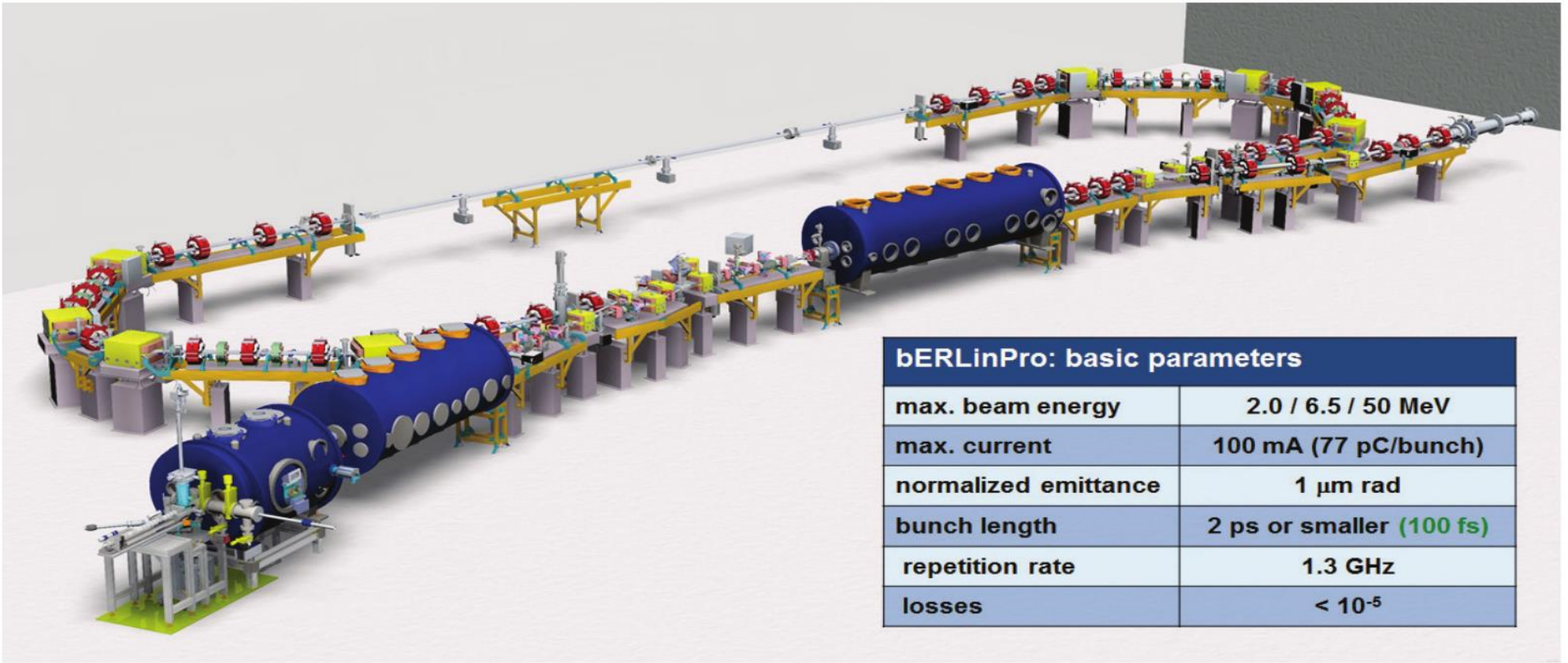
ERL technology demonstrator - electrons will be injected continuously, accelerated in the main linac, perform one revolution around the ring, continue through the main linac where their energy will be recovered, and in the end the beam will be discarded in the dump.



Picture: courtesy of HZB

A. Jankowiak, M. Abo-Bakr, W. Anders, T. Kamps, J. Knobloch, B. Kuske, O. Kugeler, A. Matveenko, A. Meseck, A. Neumann, T. Quast, J. Rudolph,
BERLinPro - a compact demonstrator ERL for high current and low emittance beams,
LINAC 10, Tsukuba, Japan, 2010.

bERLinPro - Berlin Energy Recovery Linac Project



bERLinPro: basic parameters	
max. beam energy	2.0 / 6.5 / 50 MeV
max. current	100 mA (77 pC/bunch)
normalized emittance	1 µm rad
bunch length	2 ps or smaller (100 fs)
repetition rate	1.3 GHz
losses	< 10^{-5}

M. Abo-Bakr et al.,
PROGRESS REPORT OF THE BERLIN ENERGY RECOVERY PROJECT bERLinPro,
Proceedings of IPAC 2015, paper TUPWA018, Richmond, VA, USA

BESSY^{VSR} – planned upgrade

BESSY^{VSR} - The **V**ariable pulse-length **S**torage **R**ing

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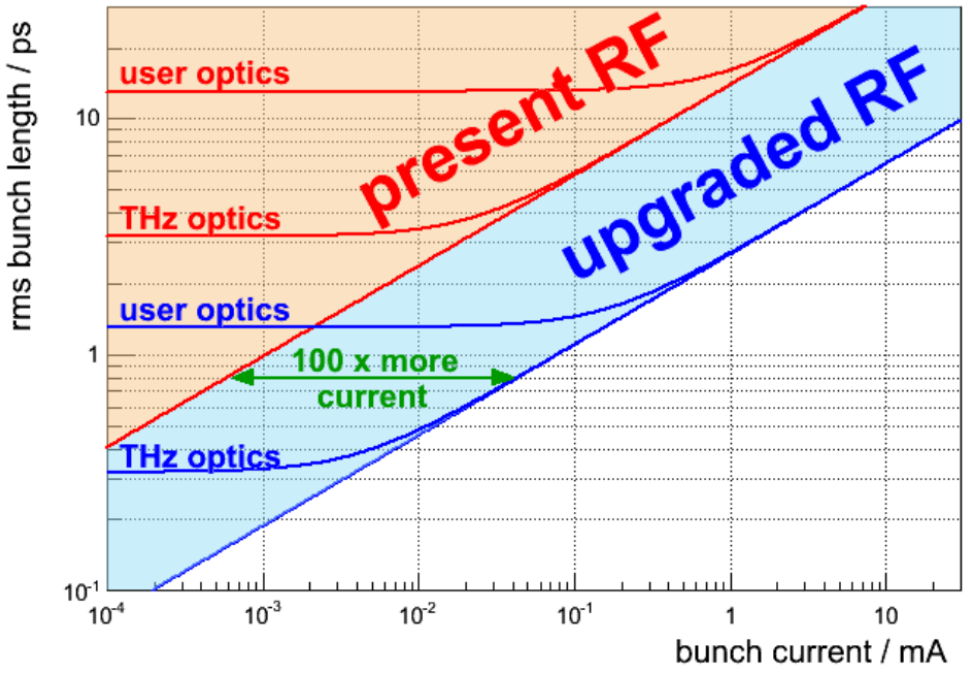
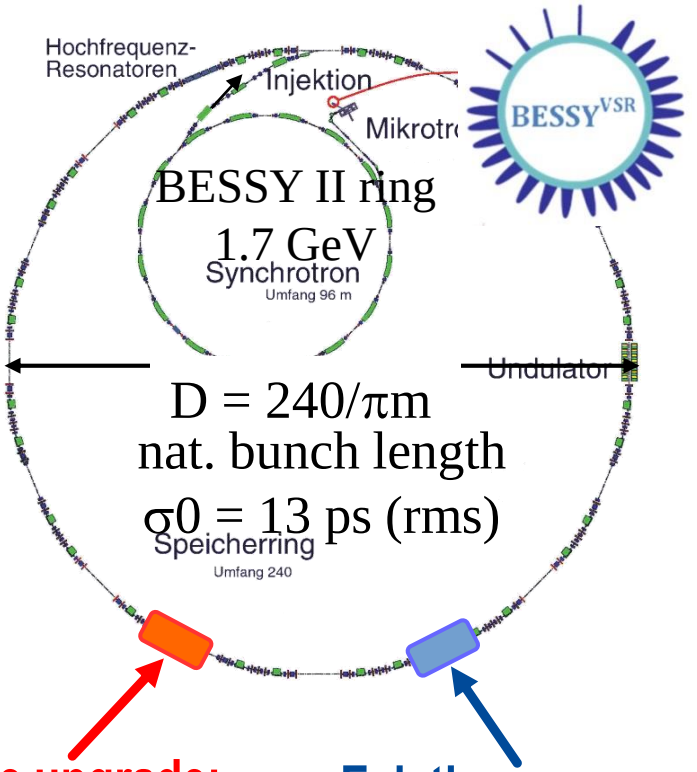
Picture: courtesy of HZB

http://www.helmholtz-berlin.de/zentrum/zukunft/vsr/

Planned upgrade – additional bunch compressing SRF cavities

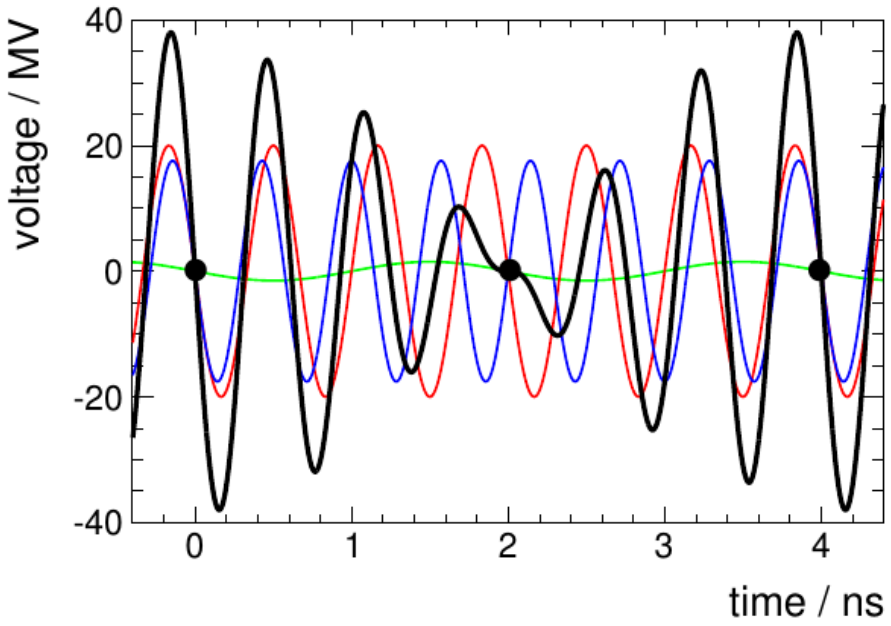


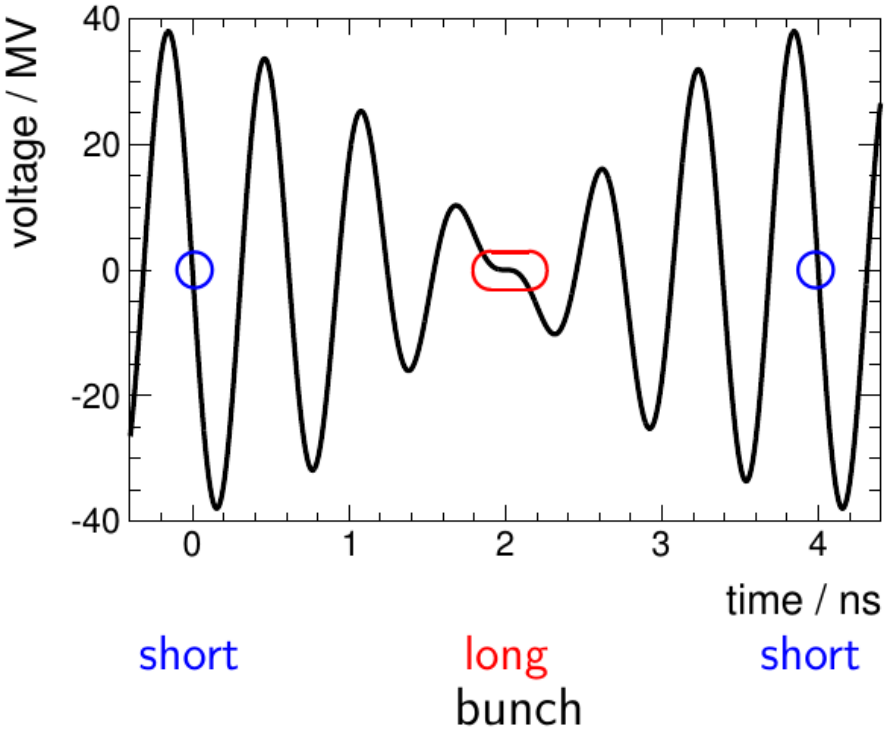


Future upgrade:
2 additional RF-structures
1. 1.50 GHz, 25.0 MV
2. 1.75 GHz, 21.4 MV

Existing:
4 RF-cavities
0.5 GHz , 1.5 MV

G. Wüstefeld A. Jankowiak, J. Knobloch, M. Ries,
Simultaneous Long and Short Electron Bunches in the BESSY II Storage Ring,
IPAC 2011, San Sebastian, Spain, 2011





- Normal rf cavity
  $U' = 2\pi\ 0.5\ 1.5\,\mathrm{GHz\,MV}$
- 1st sc cavity
  3rd harmonic
  $U' = 2\pi\ 1.5\ 20\,\mathrm{GHz\,MV}$
- 2nd sc cavity
  3.5th harmonic
  $U' = 2\pi\ 1.75\ 17.1\,\mathrm{GHz\,MV}$
- Beating pattern, large and small gradient U'

Figures and text:
courtesy of P. Goslowski, HZB

State-Space Concatenation - Validation

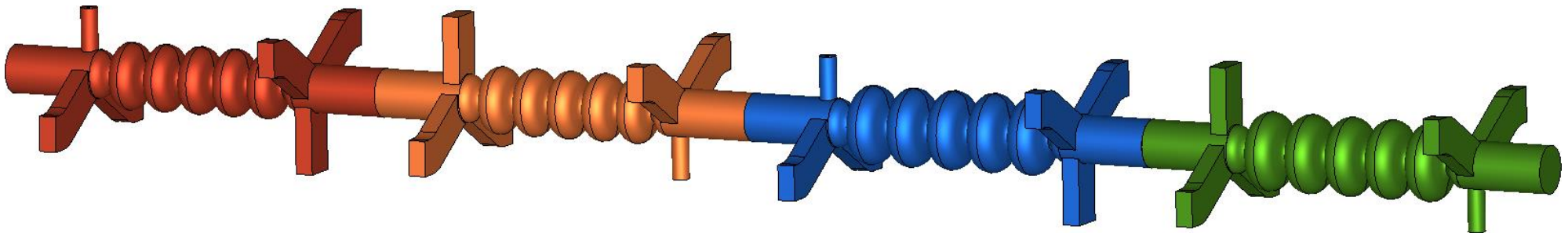
State-Space Concatenation - Validation

More details about the method itself – talks by Thomas Flisgen and by Johann Heller

Test structure – example prepared for BESSY-VSR:
2x 1.5 GHz + 2x 1.75 GHz cavities

CST MWS vs SSC

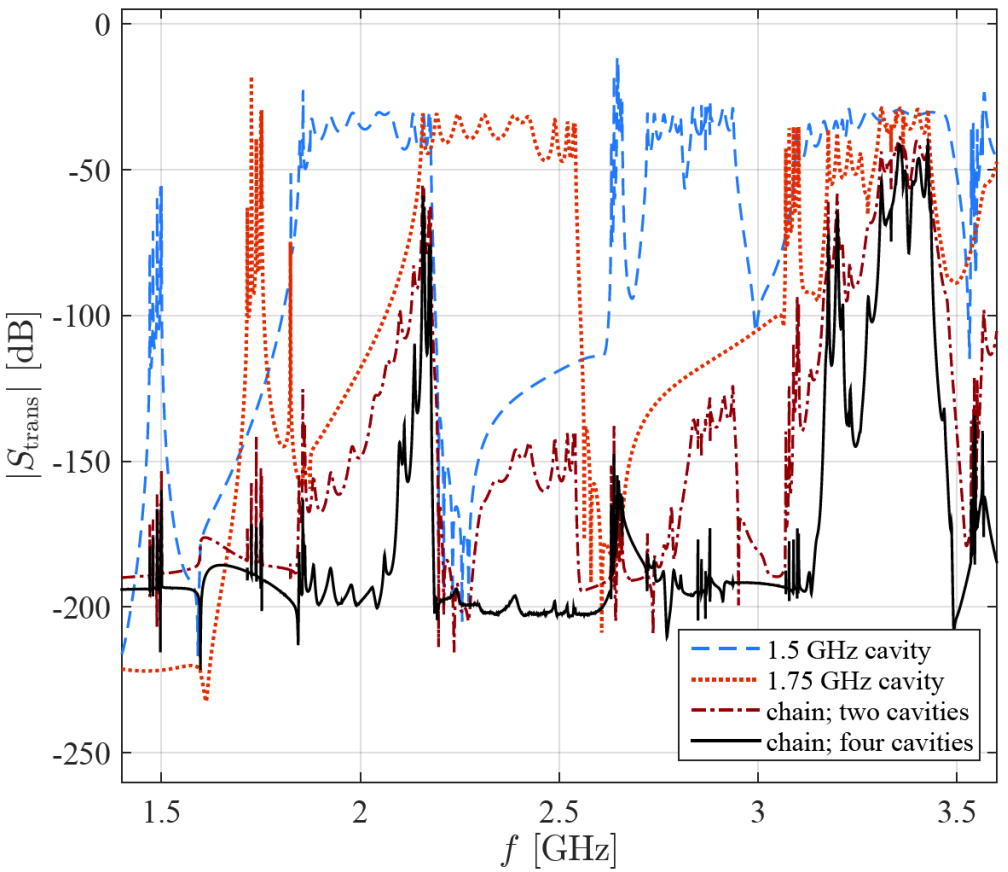
1.75 GHZ **1.75 GHz** **1.5 GHz** **1.5 GHz**

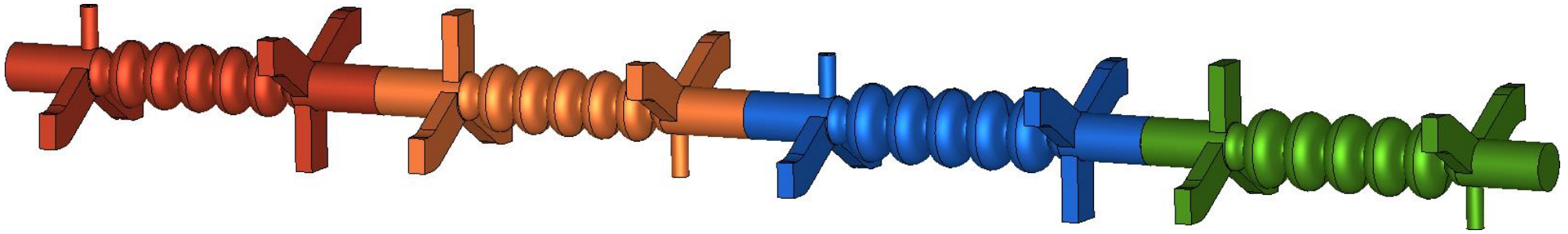


HOMs in four cavity chain

Qext estimated using:

- **Eigenmode solver** in CST MWS 2014 (**only single cavities**)
- **Frequency Domain Solver** - FMOR solver in CST MWS 2014 + Vector Fitting (VF) using transmission S-parameter spectra (**4x cav. chain – coarse mesh**)
- **State Space Concatenation** scheme (T. Flisgen+ J. Heller)

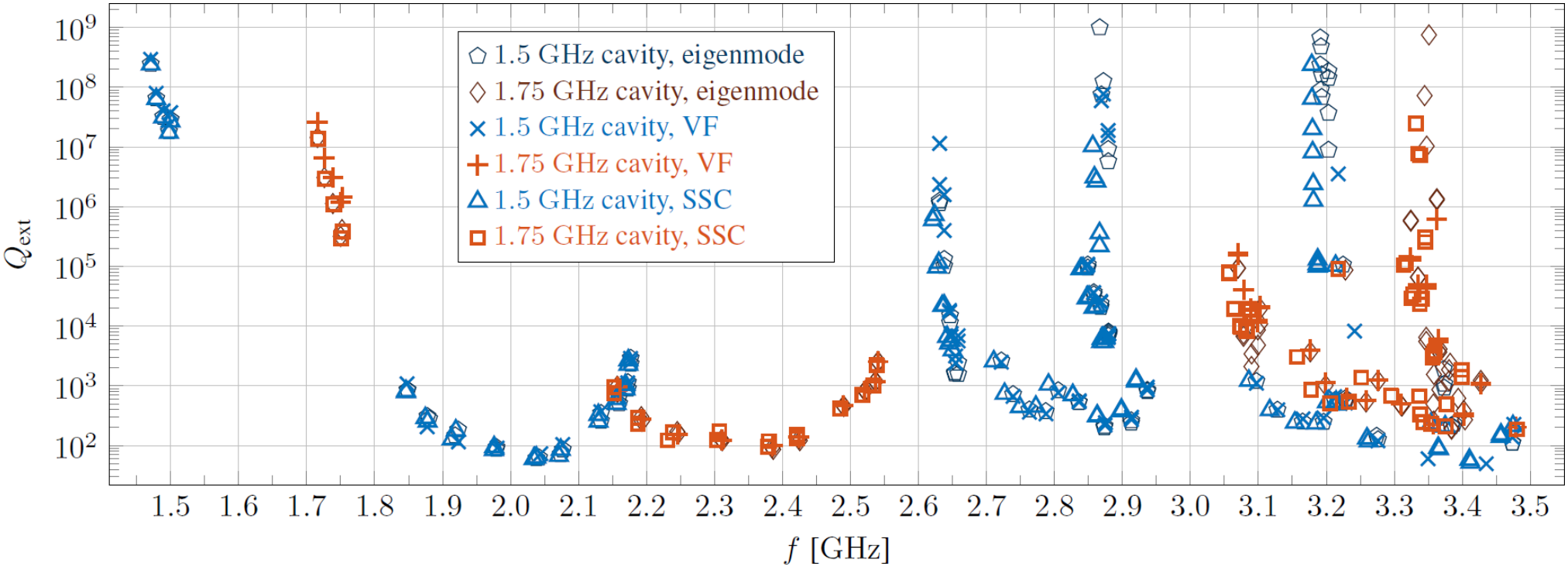




Cornell mid-cell design in a chain of four cavities

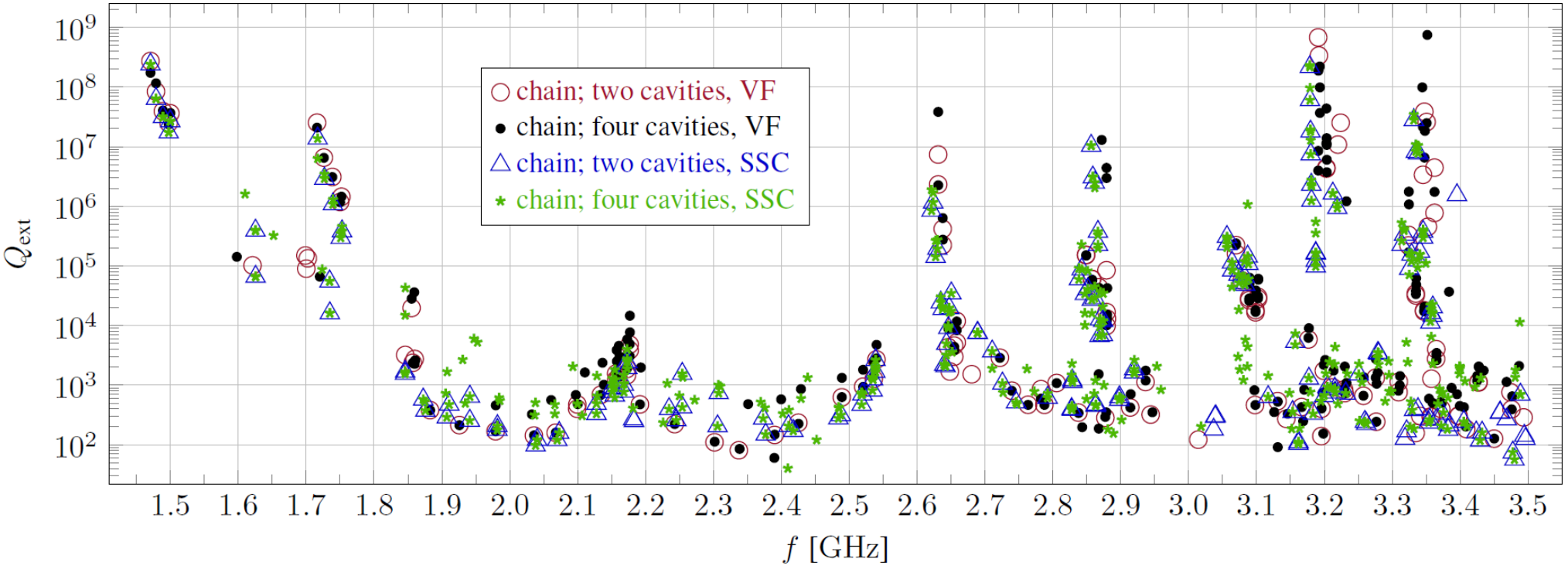
Comparison of Qext values obtained with three different methods, eigenmode calculations, VF and SSC, for single 1.5 GHz and 1.75 GHz cavities.

Spurious beam-pipe and waveguide modes were cut out for clarity.



Cornell mid-cell design in a chain of four cavities

Comparison between Qext factors obtained using VF and SSC methods. The difference of frequency and Qext values can be contributed to different meshes used for VF and SSC, tetrahedral and hexahedral, respectively. Also evaluation frequency of the port modes impedances plays and important role (talk of J. Heller, this conference)



bERLinPro – chain of three 1.3 GHz cavities

bERLinPro module configurations – BBU considerations

Two possible module configurations, downstream cavity rotated

(a) l+r+l-

(b) r+r+l-

Module model components

Modules simulated:

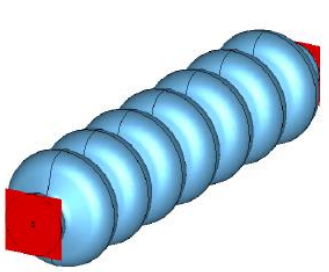
1x Cavity

1x Left HOM coupler

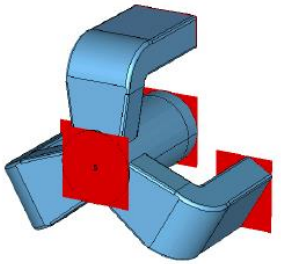
1x Left Input coupler

1x Right HOM coupler

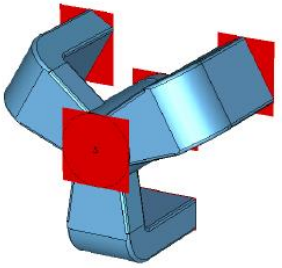
1x Right Input coupler



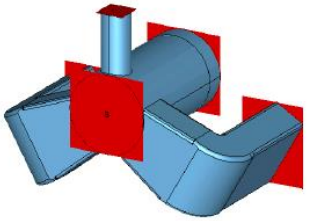
(a) Cavity



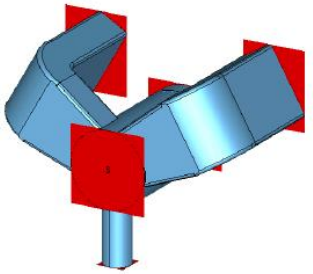
(b) Left HOM coupler



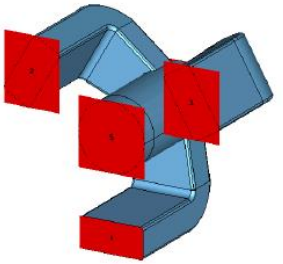
(c) Left HOM coupler rotated



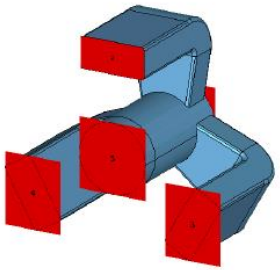
(d) Left input coupler



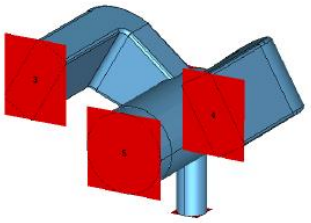
(e) Left input coupler rotated



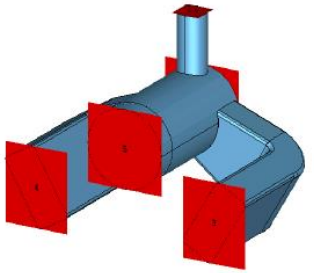
(f) Right HOM coupler



(g) Right HOM coupler rotated



(h) Right input coupler



(i) Right input coupler rotated

SSC simulation details

Separate module model components

Structure name	Meshcells	3D Modes	2D Portmodes	Port location	Time
Cavity Fig. 2a	322500	600	[10,10]	$[z_-\ ,\ z_+]$	5h 15 min
Left HOM coupler Fig. 2b	472140	200	[10,5,5,5,10]	$[z_-\ ,z_-\ ,z_-\ ,z_-\ ,\ z_+]$	5h 39 min
Left Input coupler Fig. 2d	436128	200	[10,5,5,1,10]	$[z_-\ ,z_-\ ,z_-\ ,y_+\ ,\ z_+]$	5h 9 min
Right HOM coupler Fig. 2f	472140	200	[10,5,5,5,10]	$[z_-\ ,z_+\ ,z_+\ ,z_+\ ,\ z_+]$	5h 27 min
Right Input coupler Fig. 2f	436128	200	[10,1,5,5,10]	$[z_-\ ,y_-\ ,z_+\ ,z_+\ ,\ z_+]$	5h 9 min
					$\sum$ 2d 5h 18 min

Concatenation

After the reduced order models are obtained, they are concatenated in MATLAB to the reduced order model of the full structure.

The SSC concatenation, computation of external quality factors Qext, and R/Q takes roughly **50 minutes**.

All of the computations have been performed in a frequency range from 0 GHz to 4 GHz on a Intel® Xeon® CPU E5-2687W @ 3.4 GHz with 256 GB of RAM.

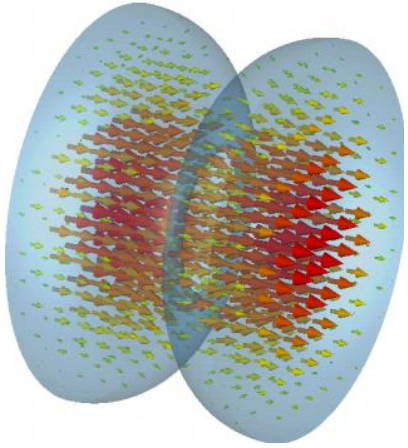
Band Structure Analysis

Parameter sweep eigenmode simulations for just a single cell, with periodic boundary conditions (PBC). 50 modes up to 4.0 GHz were calculated for every single one of 37 sweeps (1 day total time).

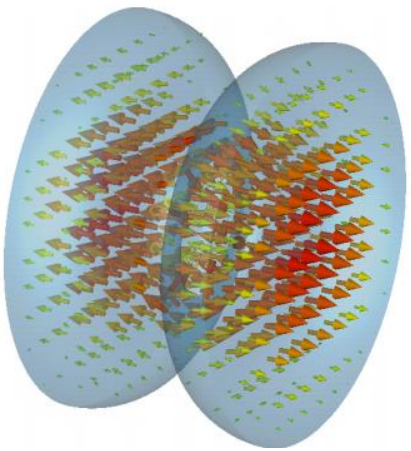
Results:

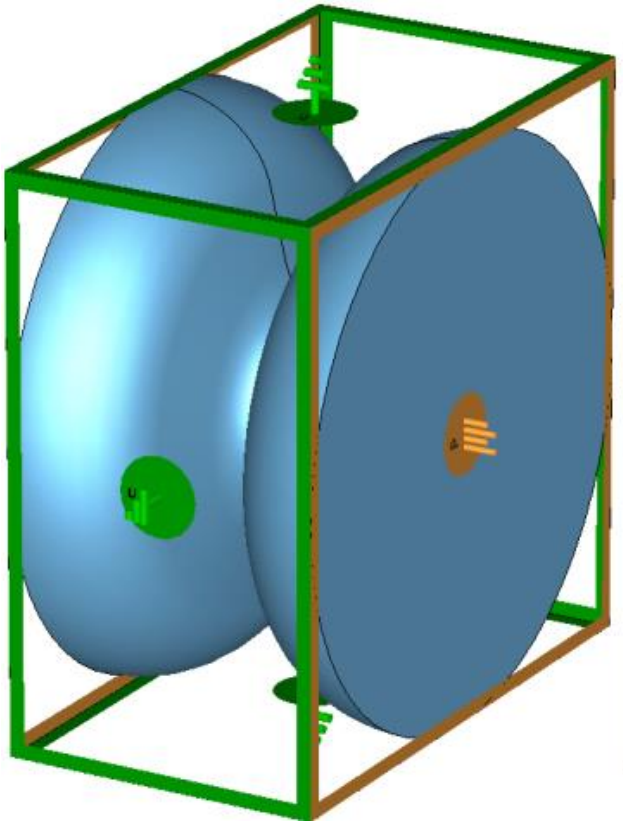
0-mode and π-mode frequency band shape,
R/Q values on and off-axis,
R/Q long. and transversal

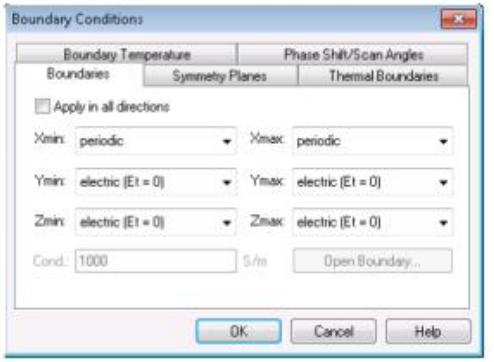
0° shift
0-mode

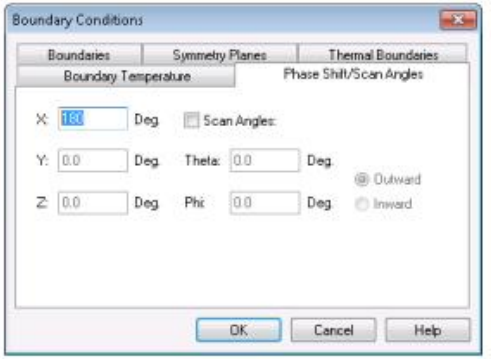


180° shift
π-mode









Band Structure Analysis

Number of modes within one passband depends on number of cells in the cavity. Exploiting the fact that the phase shift of all the modes within the band is regularly spaced between 0° and 180° one can calculate analytically all the band modes

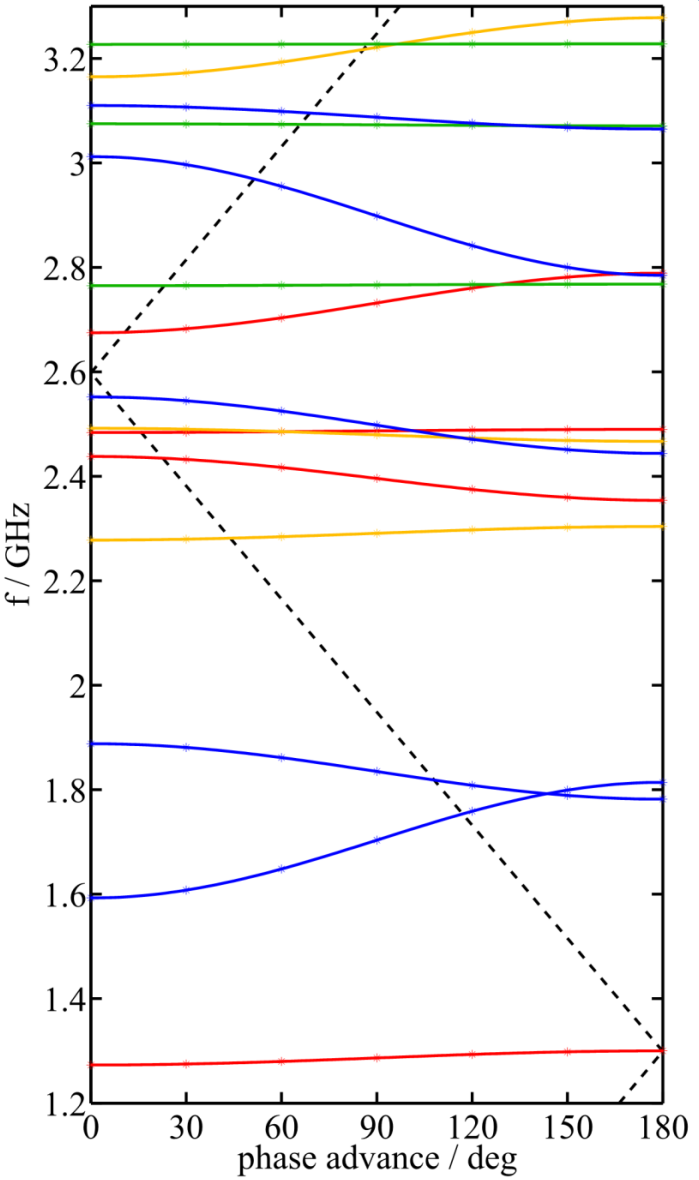
$$f_m = \frac{f_0 + f_\pi}{2}\left[1 - \frac{k_{cc}}{2}\cos(\varphi_m)\right]$$

$$\varphi_m = \frac{m}{N_{tot} - 1}$$

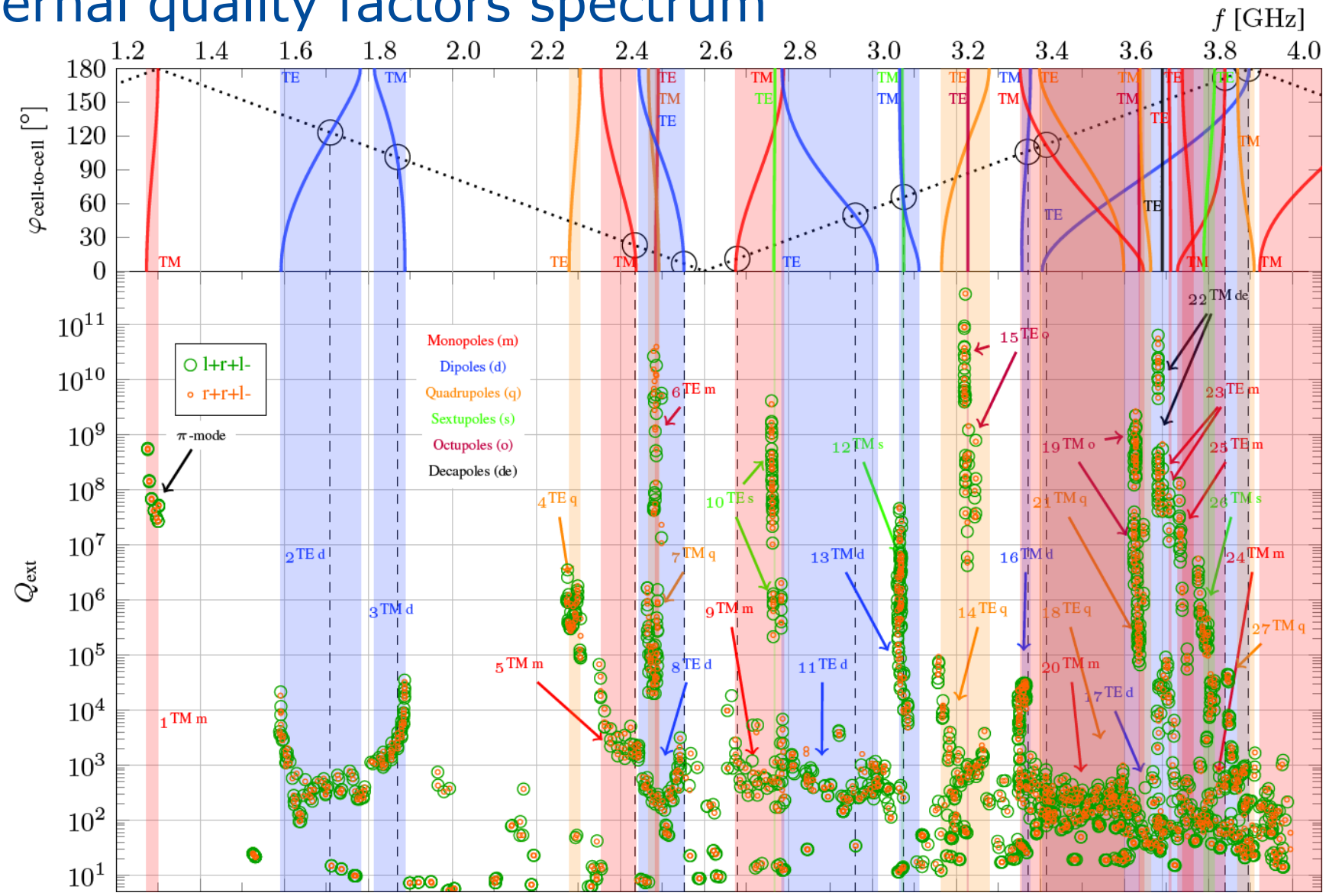
$$\text{where } m = 0, 1, 2, ..., N_{tot} - 1$$

The cell-to-cell coupling factor specifies the passband width

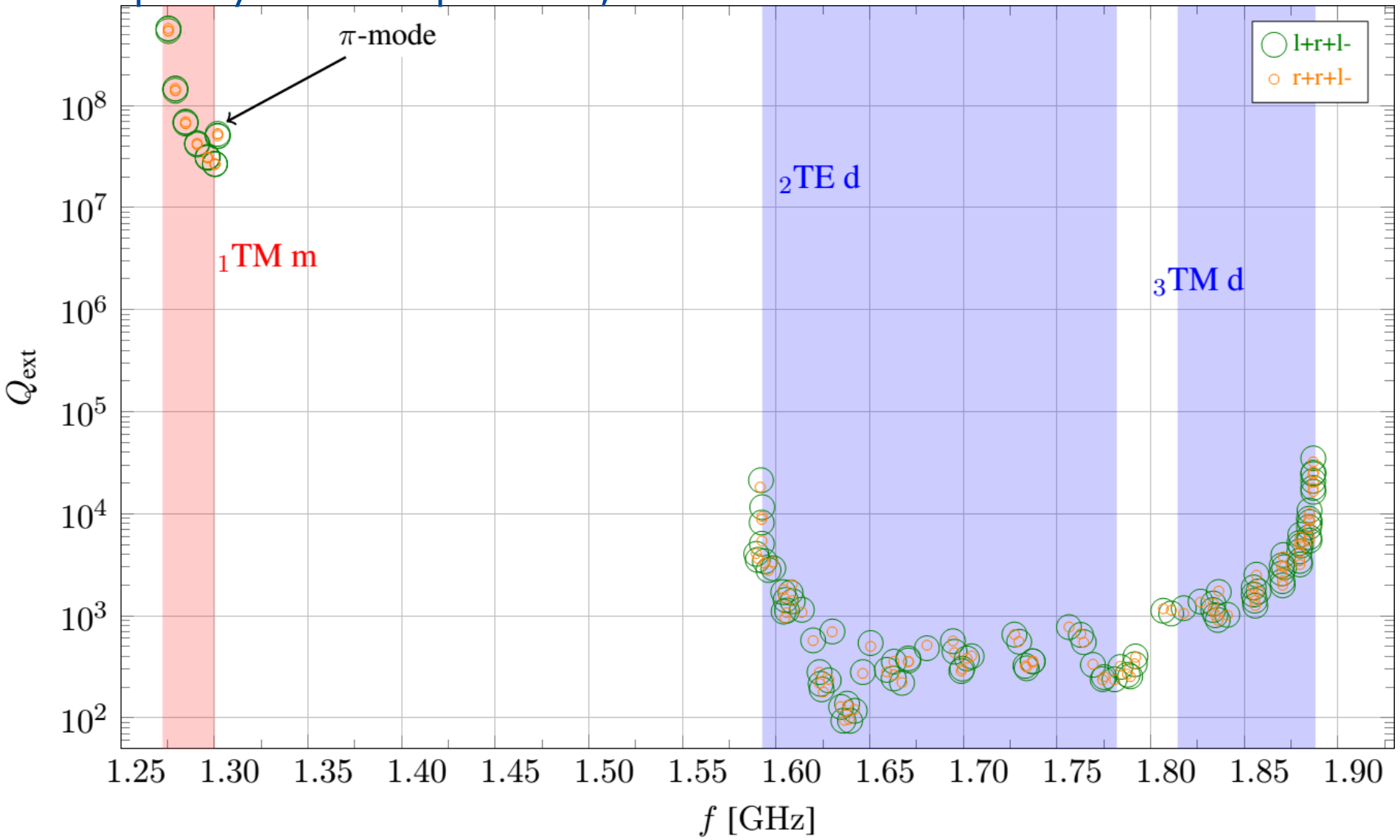
$$k_{cc} = 2 \cdot \frac{f_\pi - f_0}{f_\pi + f_0}$$



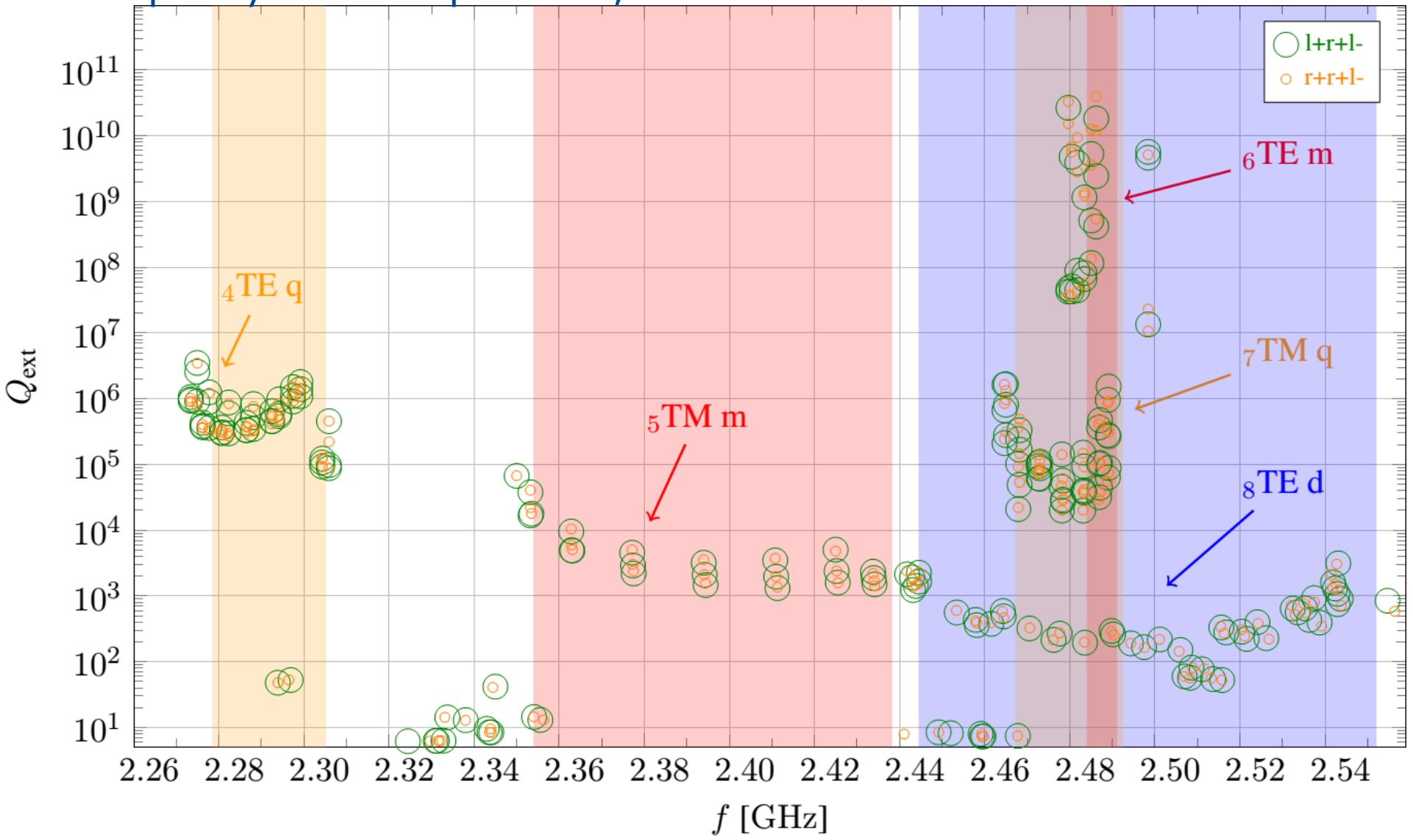
External quality factors spectrum



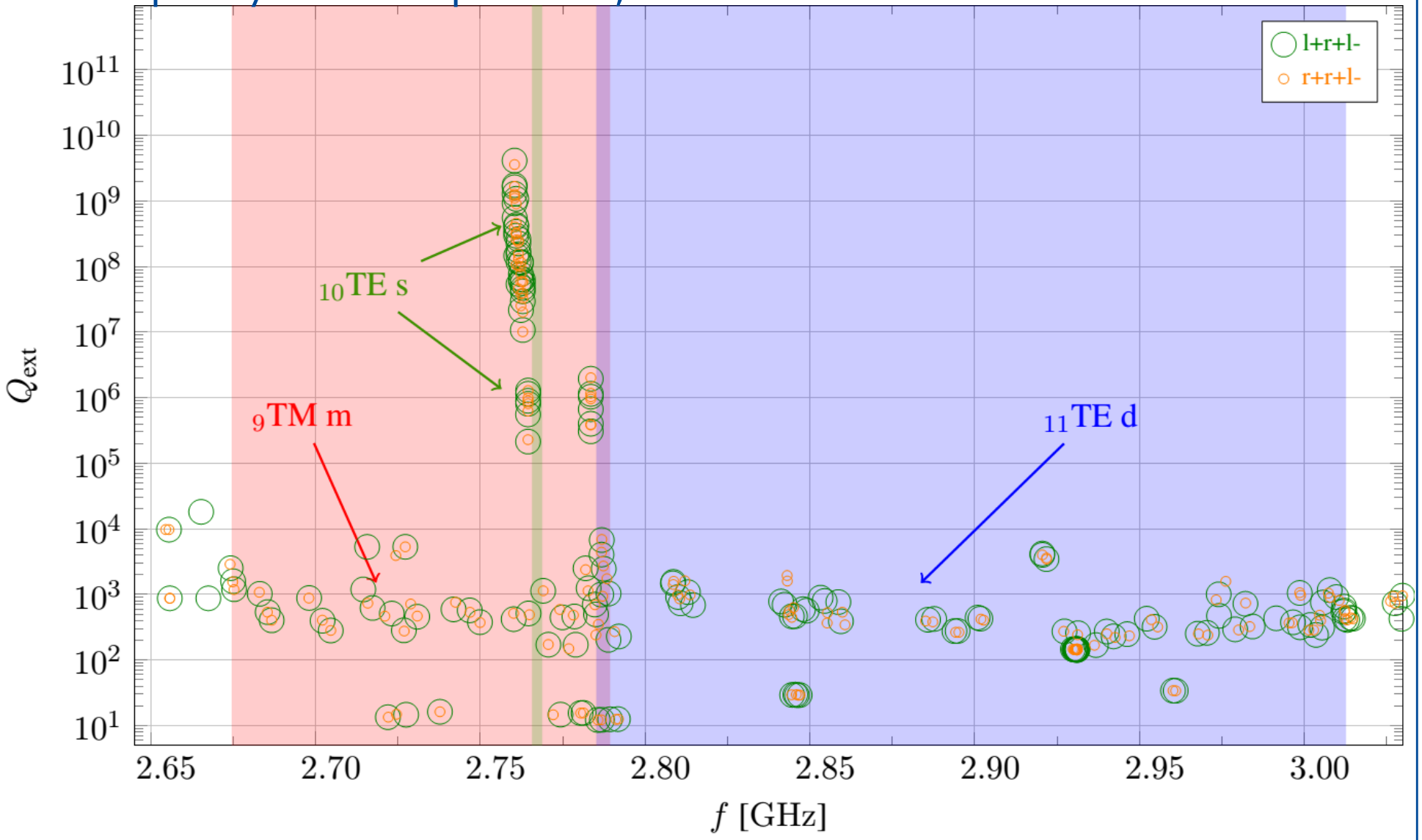
External quality factors spectrum, zoom 1.25 Ghz – 1.9 GHz



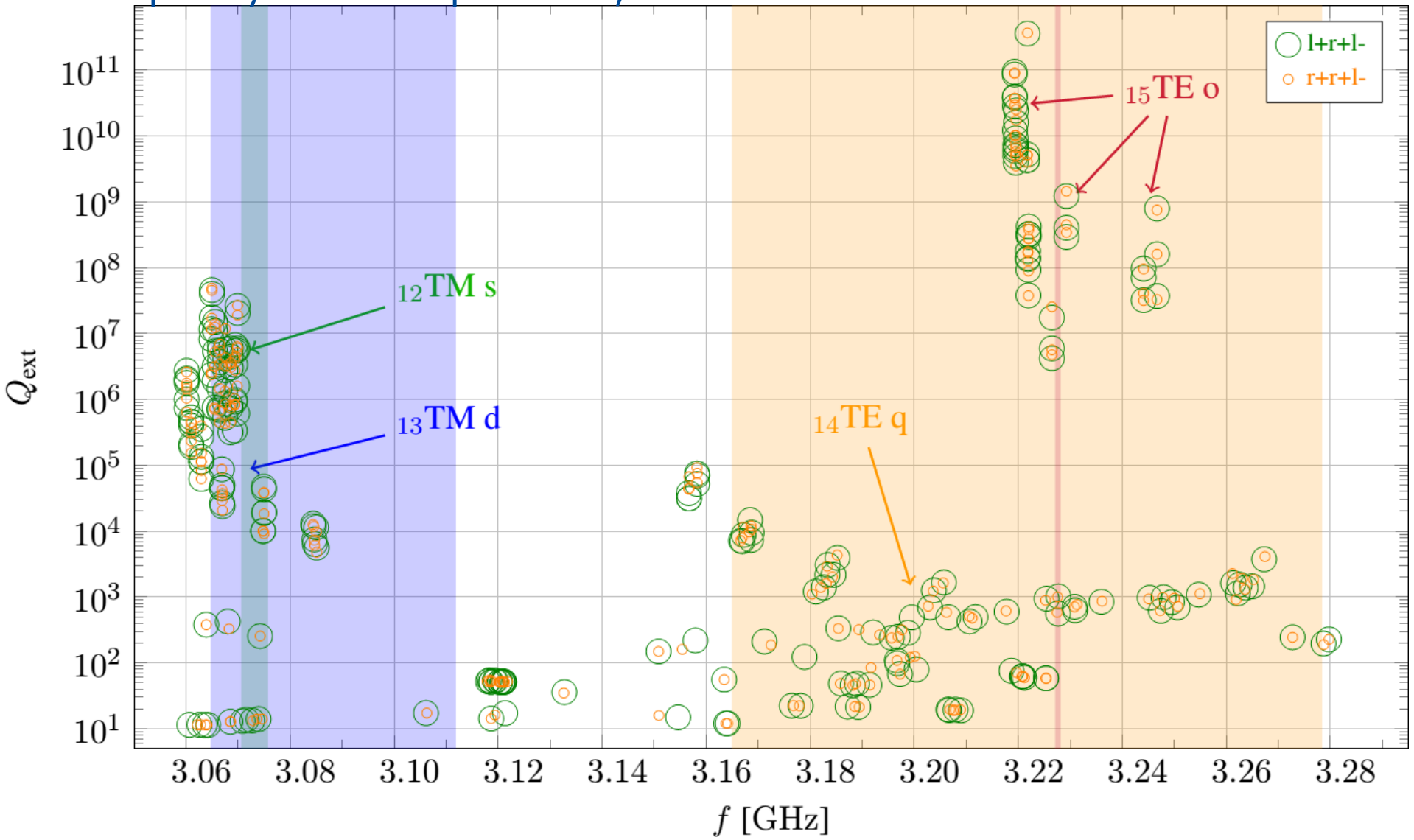
External quality factors spectrum, zoom 2.25 Ghz – 2.55 GHz



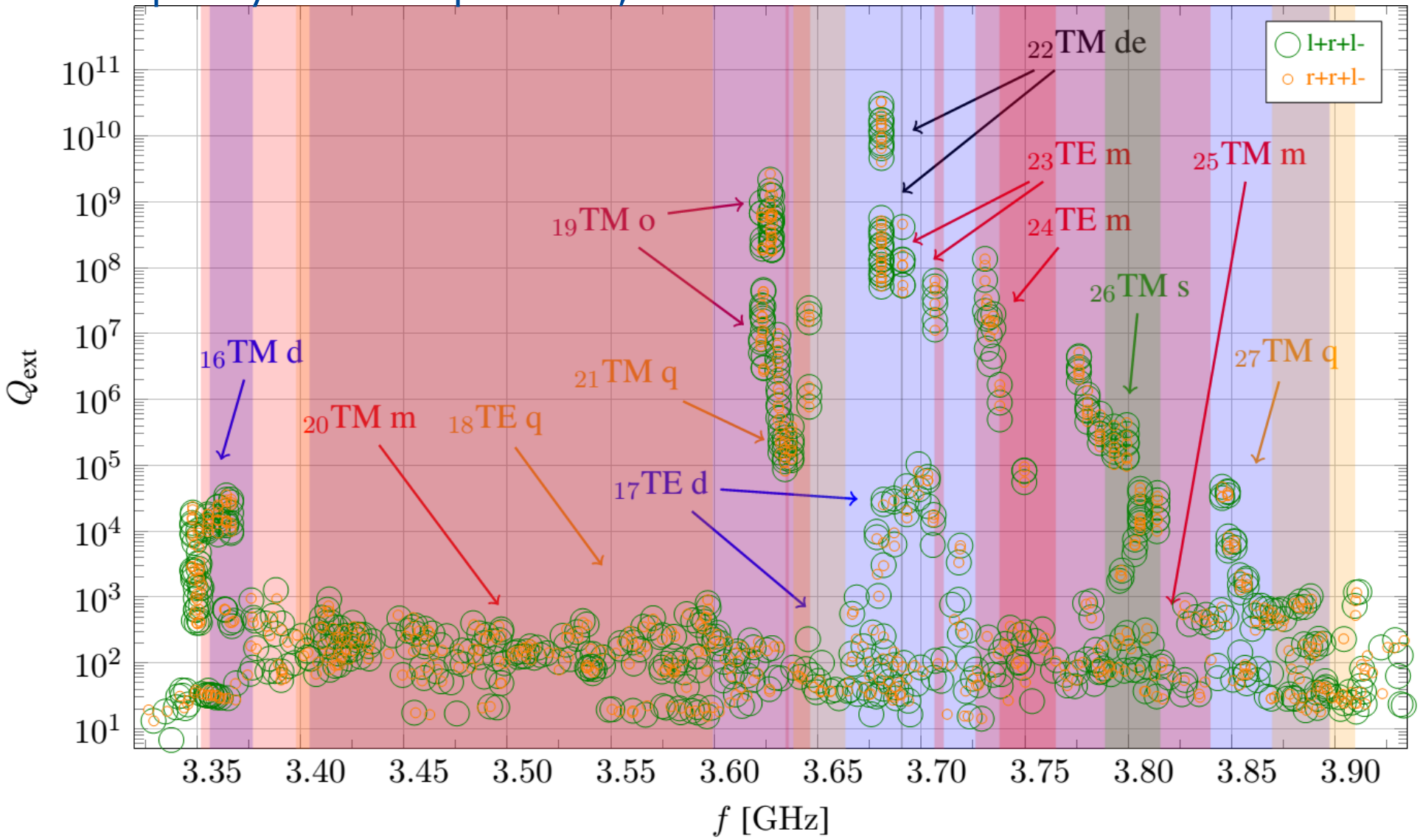
External quality factors spectrum, zoom 2.65 Ghz – 3.05 GHz



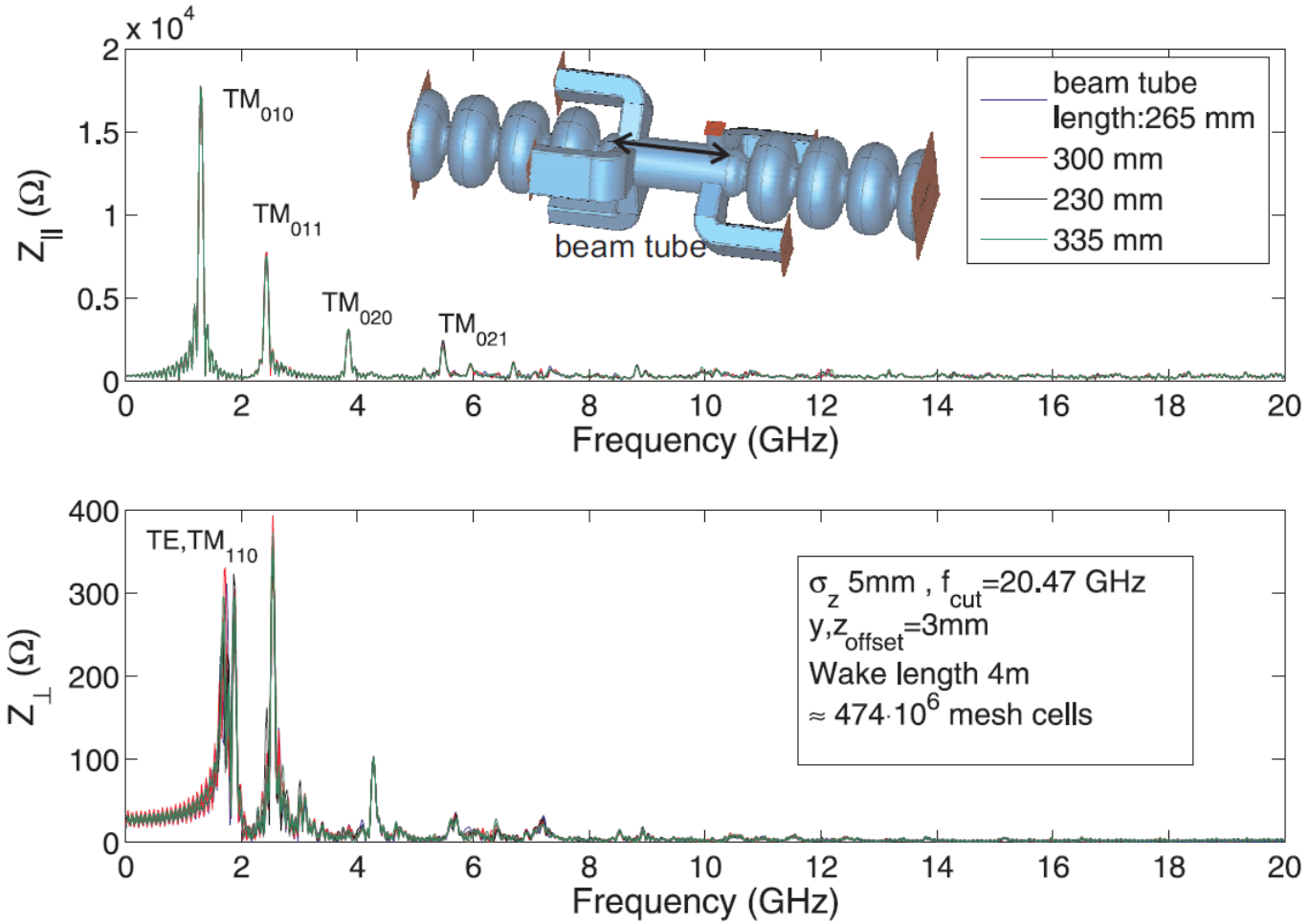
External quality factors spectrum, zoom 3.05 Ghz – 3.29 GHz



External quality factors spectrum, zoom 3.3 Ghz – 4.0 GHz

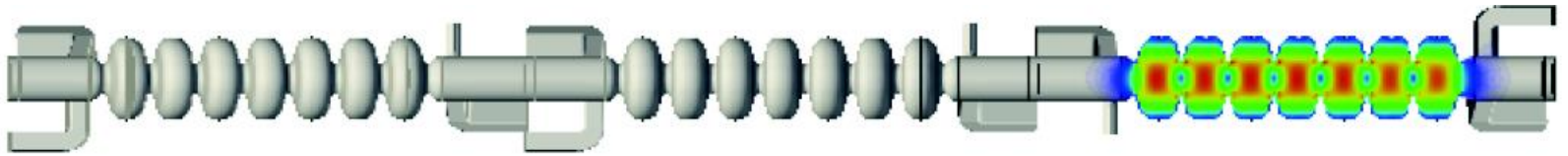


Impedance Spectrum

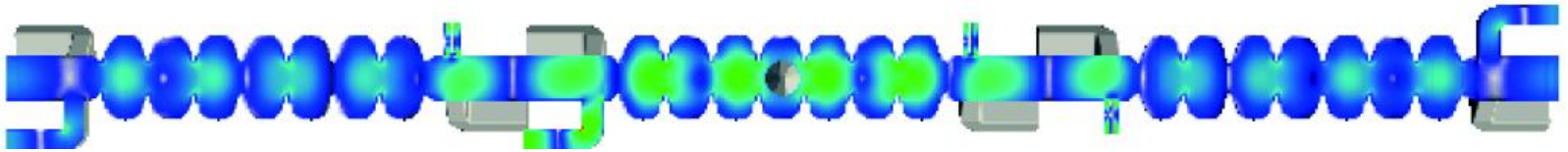


A. Neumann et al., UPDATE ON SRF CAVITY DESIGN, PRODUCTION AND TESTING FOR bERLinPro, Proceedings of SRF2015, paper THPB026, Whistler, BC, Canada

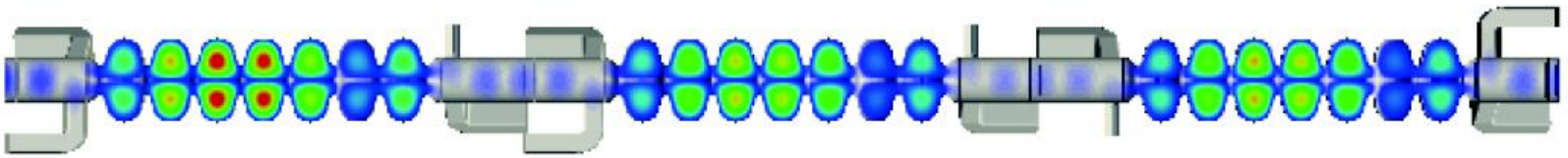
Field plots of some special modes in the bERLinPro chain



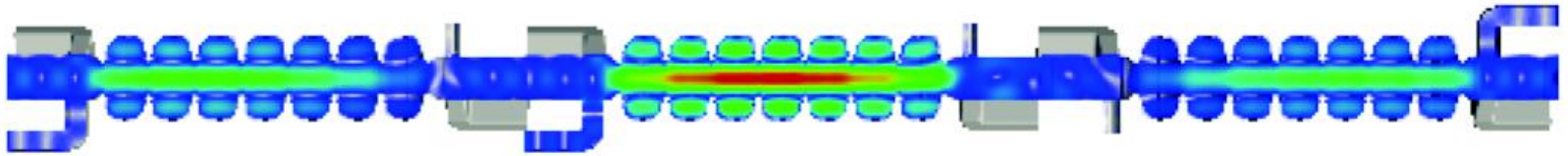
1.3017 GHz
pi-mode



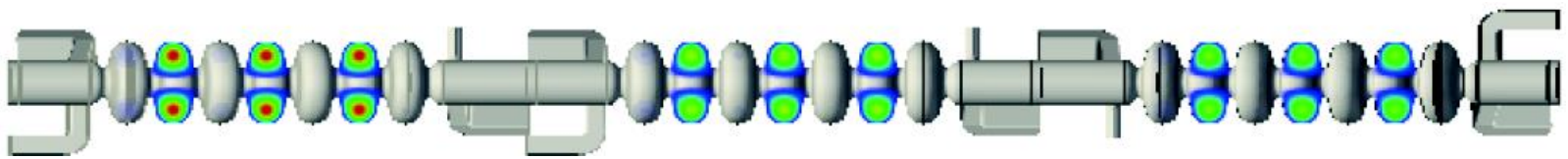
1.6725 GHz
TE dipole



2.2973 GHz
TE quad.
high Qext



2.6741 GHz
TM mono.
high R/Q



3.2218 GHz
TE octu.
highest Qext

BESSY-VSR – chain of four cavities

Chain-wise field flatness, Cornell mid-cell, Rbp = 55 mm

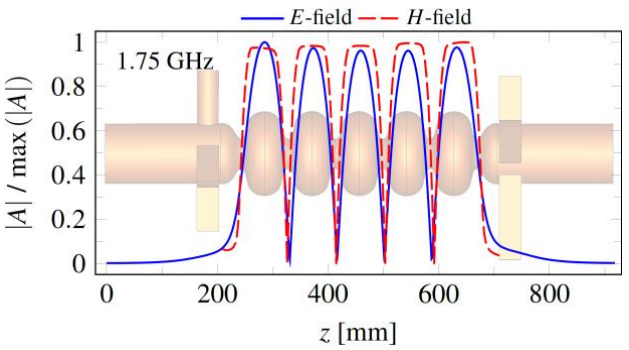
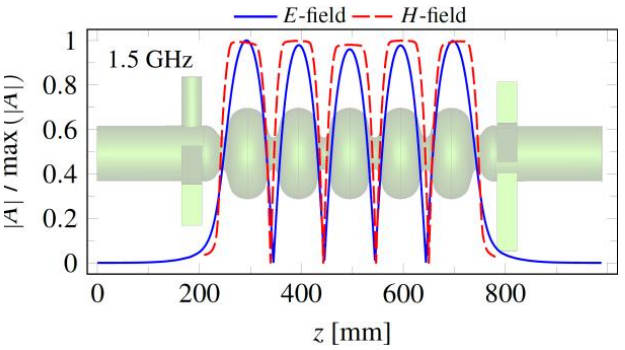


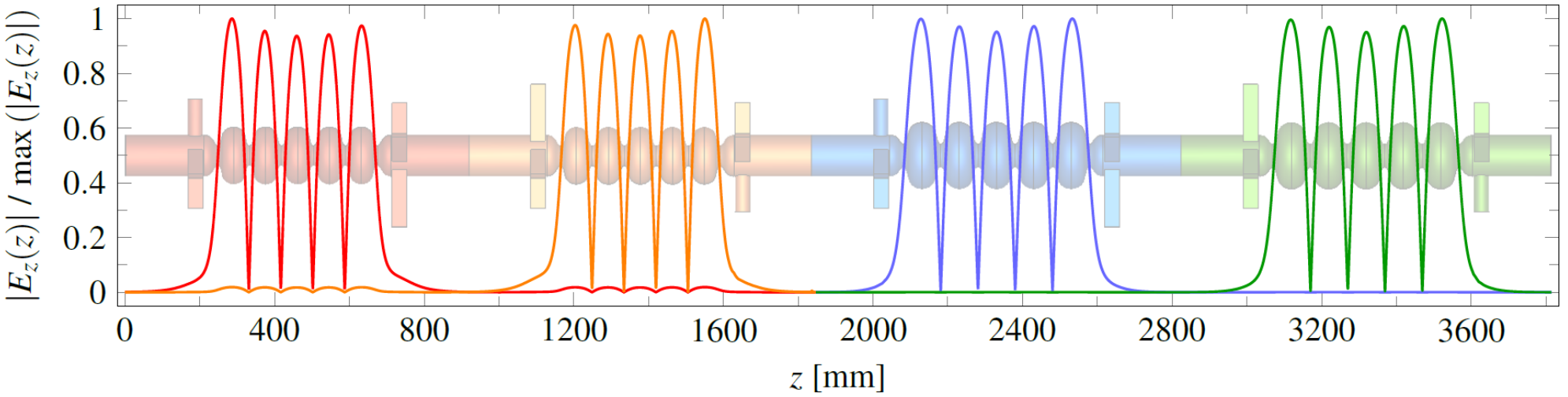
Table 1: Single Cavities

Cavity	η_{E_z} [%]	η_{W_H} [%]	R/Q [Ω]
1.5 GHz	98.51	99.56	545.6
1.75 GHz	98.57	99.28	540.5

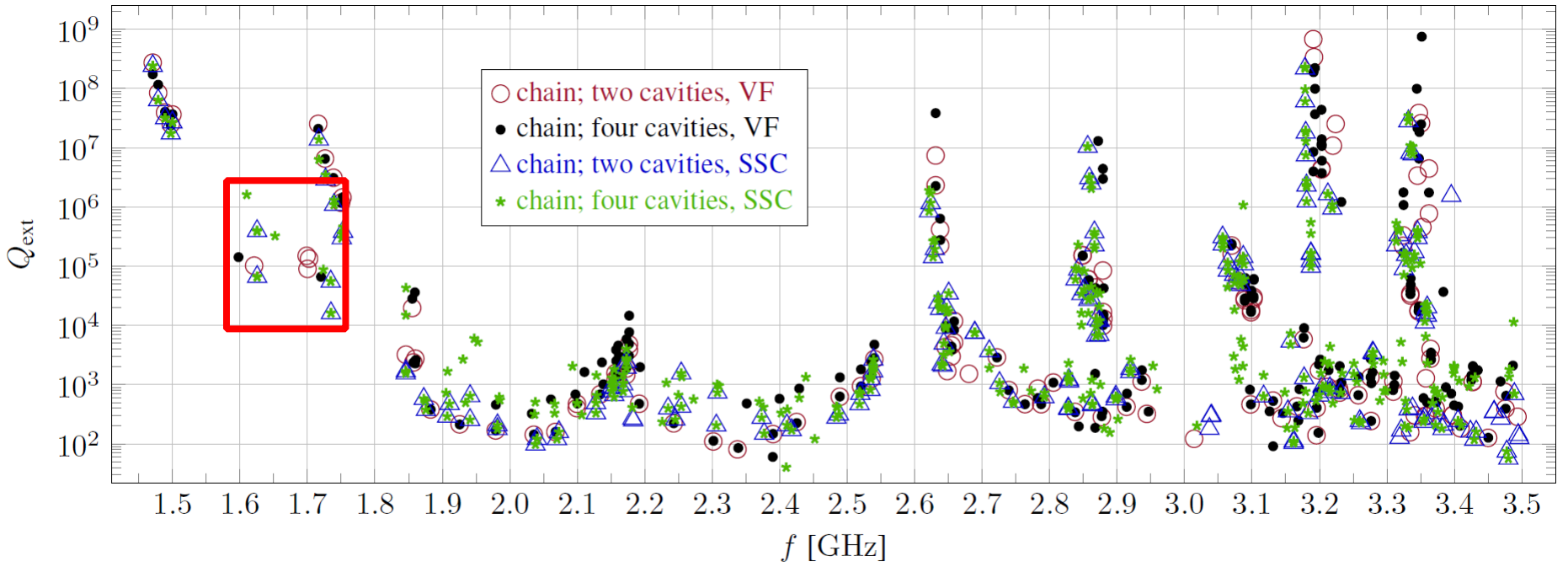
Table 2: Cavities in a Chain

Cavity	1st	2nd	3rd	4th
f [GHz]	1.75	1.75	1.5	1.5
η_{E_z} [%]	97.59	97.64	98.13	98.14
R/Q [Ω]	535.1	560.4	552.6	551.5



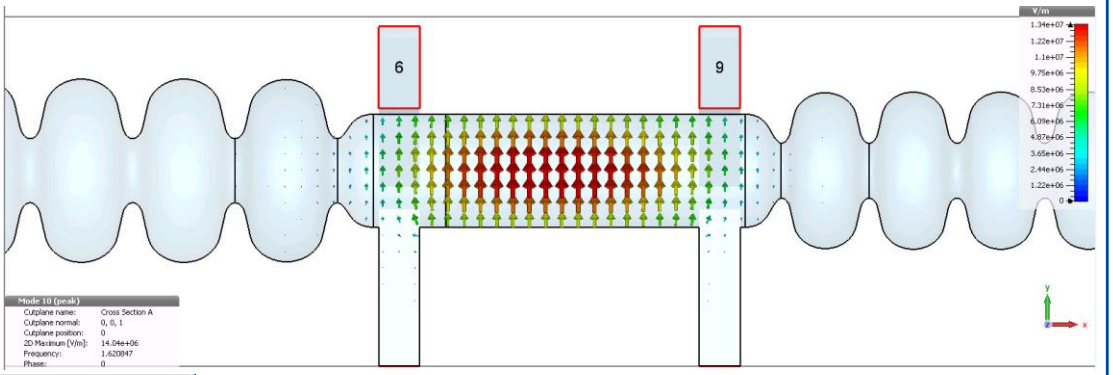


What are the modes between fund. bands?

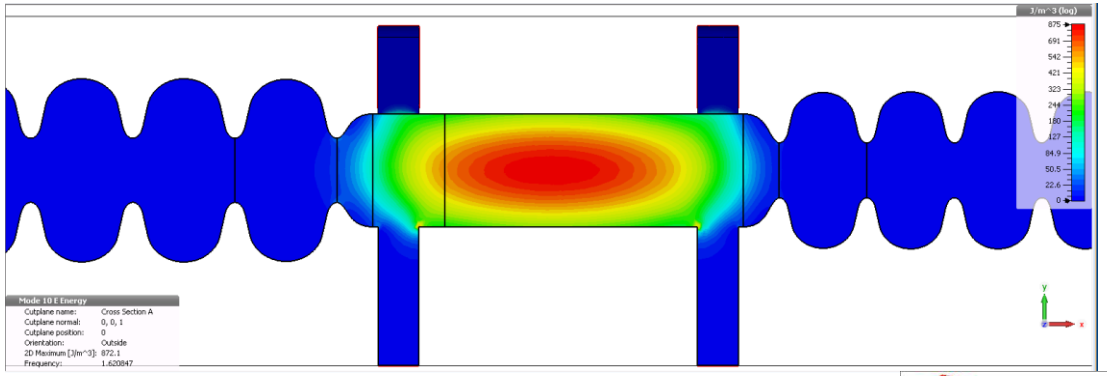


Trapped beam-pipe modes – 1.62 GHz

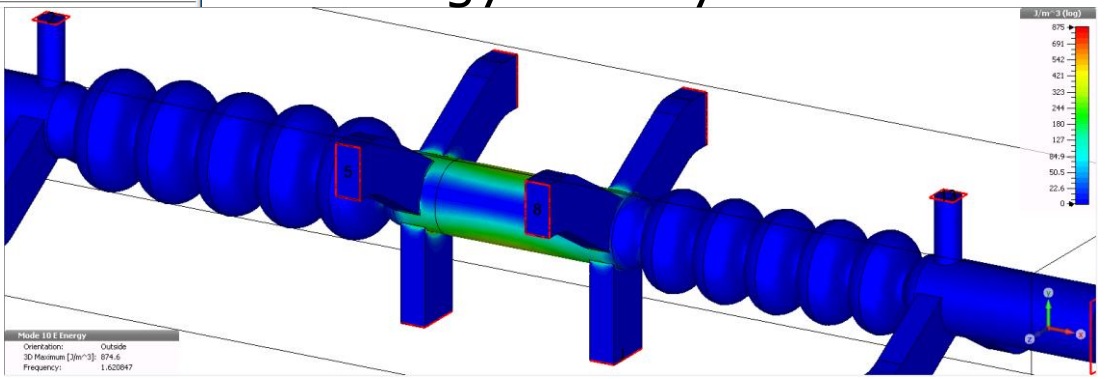
$R/Q_{\perp} = 1.49\ \Omega$ and $1.48\ \Omega$



E-field

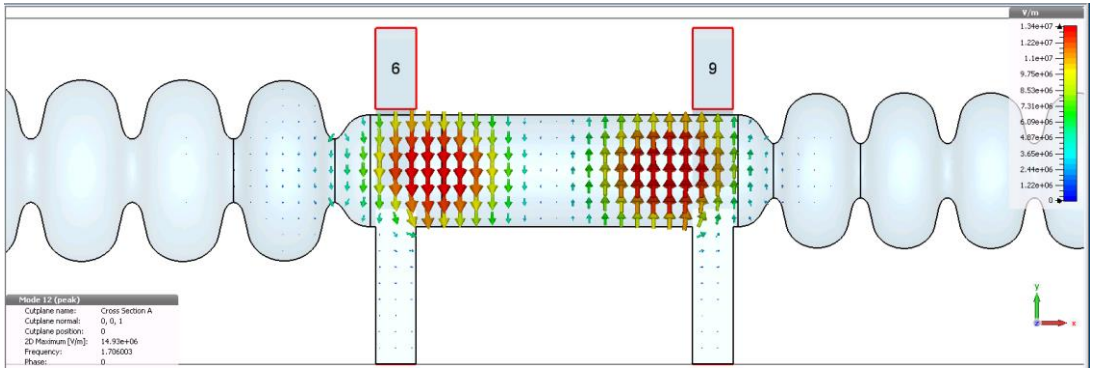


E-energy density

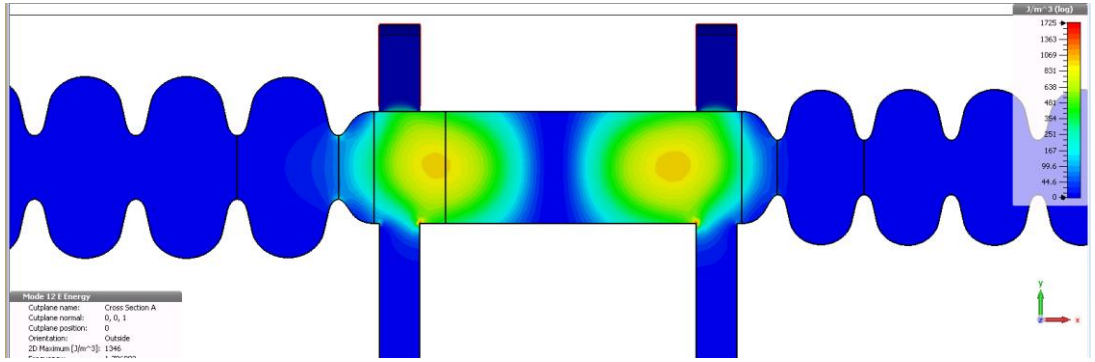


Trapped beam-pipe modes – 1.706 GHz

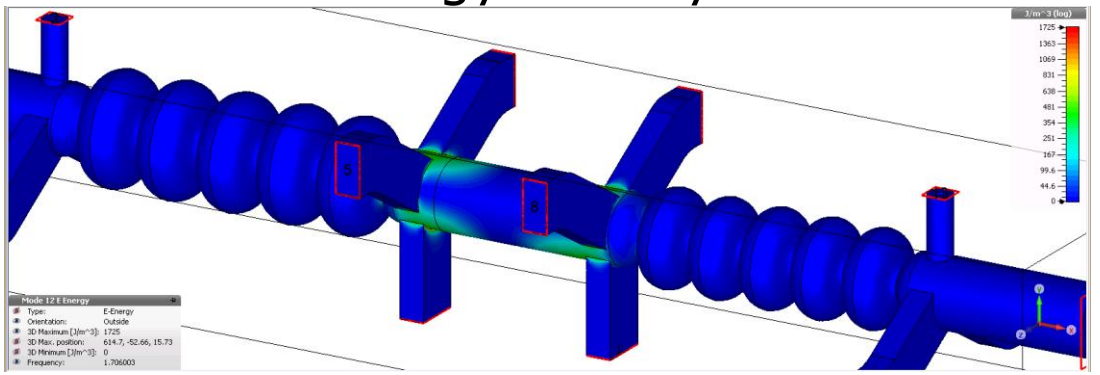
$R/Q_{\perp} = 24.3\ \Omega$ and $24.45\ \Omega$



E-field



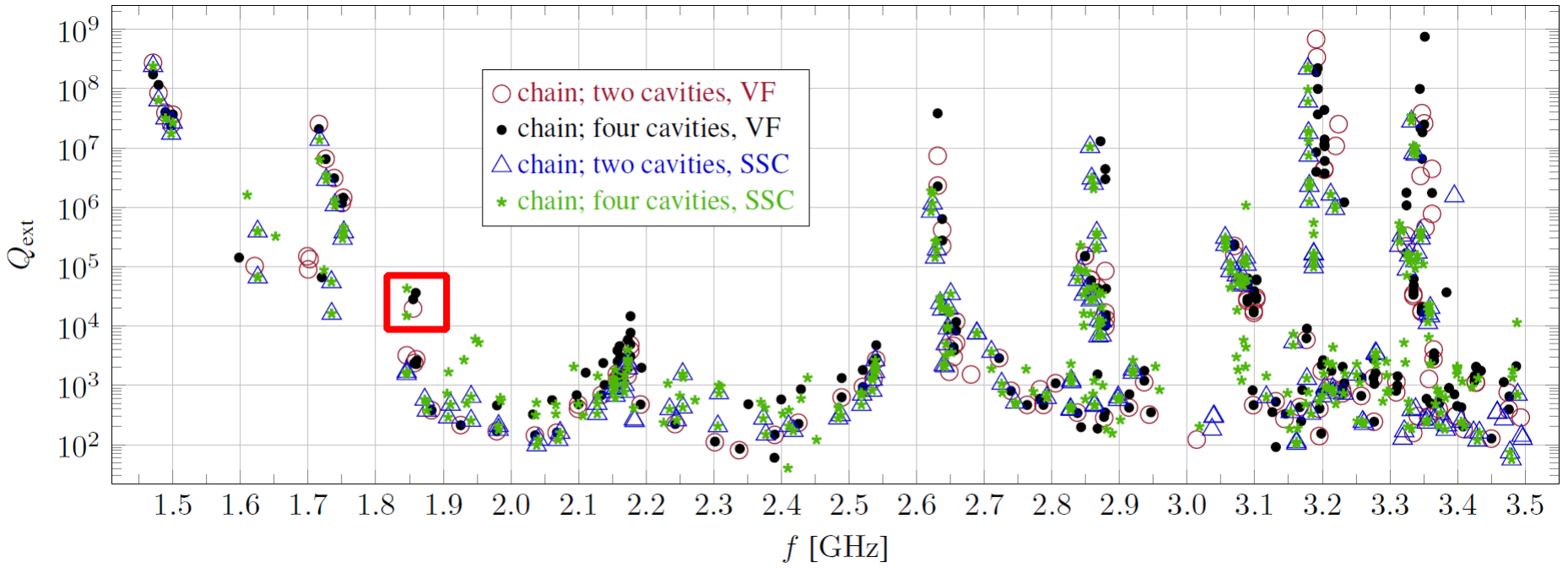
E-energy density



Trapped dipole beam-pipe and cavity modes – 1.86 GHz

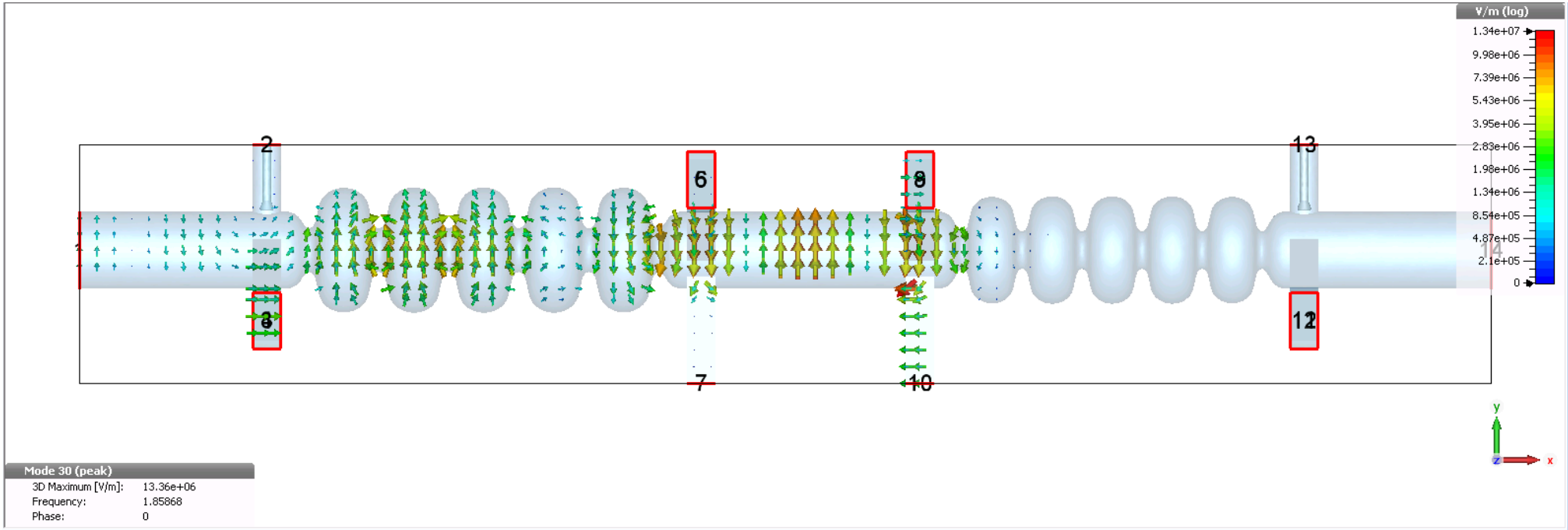
These modes show up in models with both Cornell and HZB mid-cell designs. These modes depend only on the beam-pipe radius.

$R/Q_{\perp} = 4.1\ \Omega$ and $5.8\ \Omega$



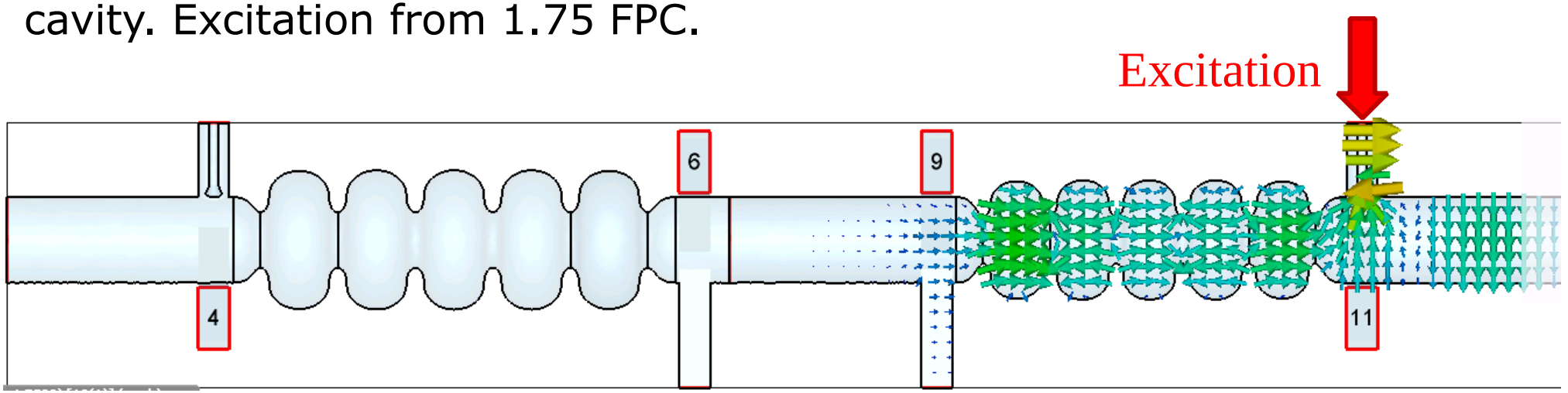
Trapped dipole beam-pipe and cavity modes – 1.86 GHz

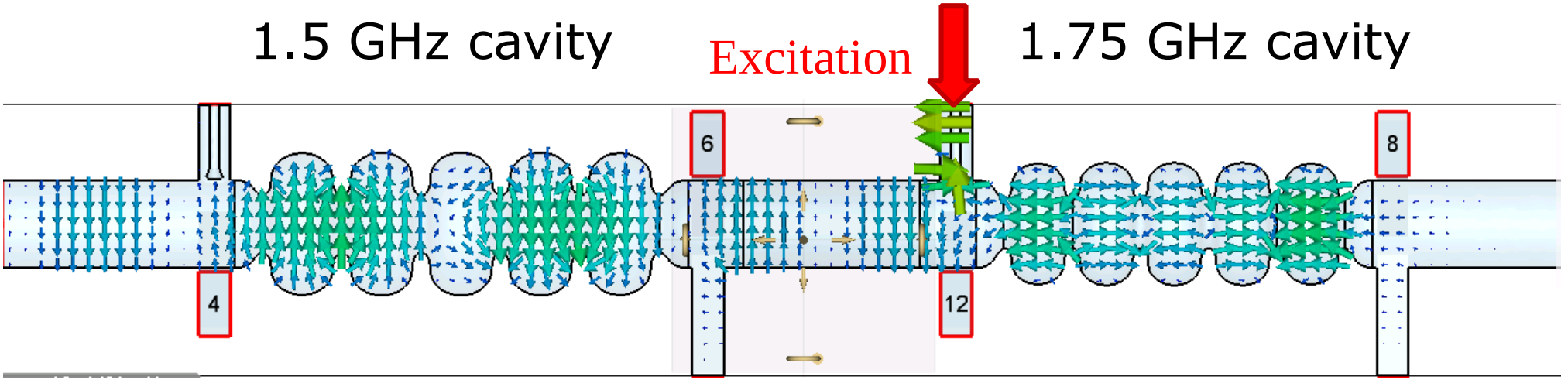
E-field



Band overlap – chain of two cavities, irides radii > tesla

Rbp = 55 mm, 1.5 GHz cavity + slightly detuned (8.3 MHz) 1.7583 GHz cavity. Excitation from 1.75 FPC.





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