Higher Harmonic SRF Cavities for Upgrade of BESSY II Storage Ring

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DESY Accelerator Physics Seminar

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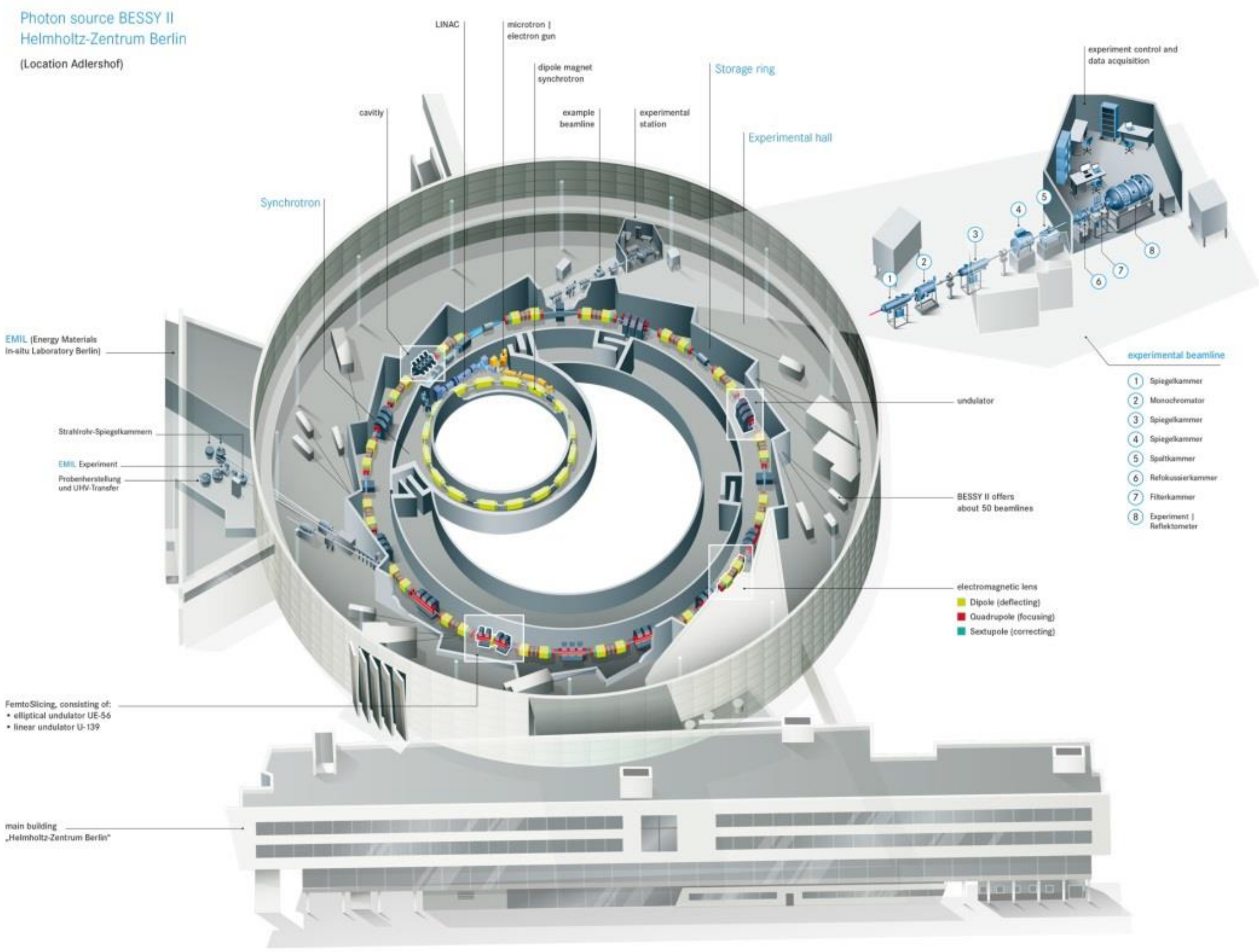
Outline

- Introduction to BESSY II storage ring
- SRF Upgrade - BESSY VSR & Highlights
- SRF Cavity Specific Designs
- Beam Loading & Cold Parking
- HOM Power Levels in SRF Module
- Outlook

BESSY II Storage Ring

- BESSY II is a 1.7 GeV synchrotron radiation source operating for 20 years in Berlin
- Core wavelength in the range from Terahertz region to hard X rays



BESSY II Parameters	
Lattice	DBA
Circumference	240 m
Energy	1.7 GeV
Current	300 mA
RF Frequency	500 MHz
RF Voltage	1.5 MV
Bunch Length	15 ps
Emmitance	6 nm rad

The Concept of BESSY VSR

BESSY II @ present

Normal conducting cavity system

- ❖ Low alfa operation only 12 days/year (all beamlines) ------- Low flux
- ❖ Femtoslicing is continuously operated (only 1 beamline) -- Low flux

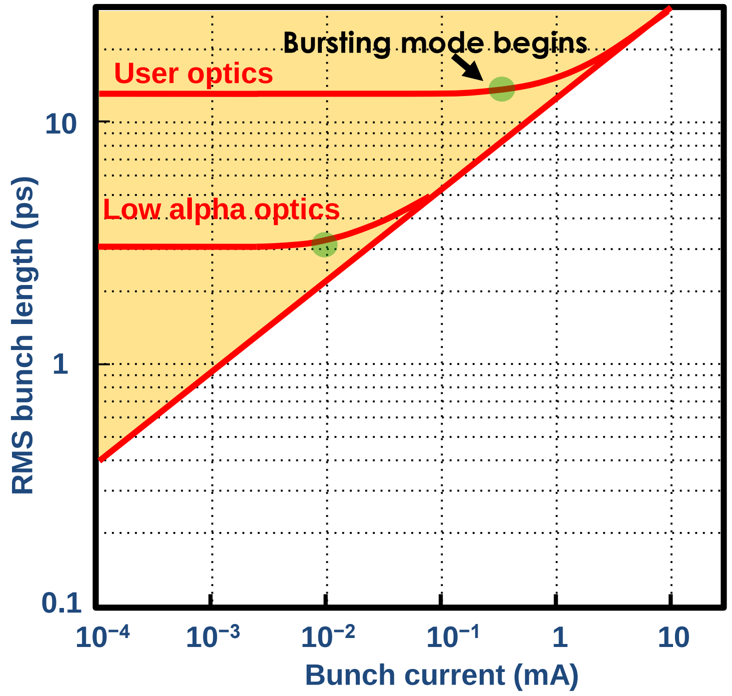
Can we design a system offering both possibilities simultaneously?

- Limited pulse length in storage ring

$$\sigma \propto \sqrt{\frac{\alpha}{\dot{V}_{\mathrm{rf}}}}$$

Machine optics

- At high current beam becomes unstable
- For ps pulses, flux is reduced by nearly 100



The Concept of BESSY VSR

BESSY II @ present

Normal conducting cavity system

- ➢ Supply short pulses down to 1.5 ps (100 × more bunch current)
- ➢ Low α permits few 100 fs pulses
- ➢ Configure BESSY^{VSR} so 1.5 ps and 15 ps bunches can be supplied simultaneously for maximum flexibility and flux!

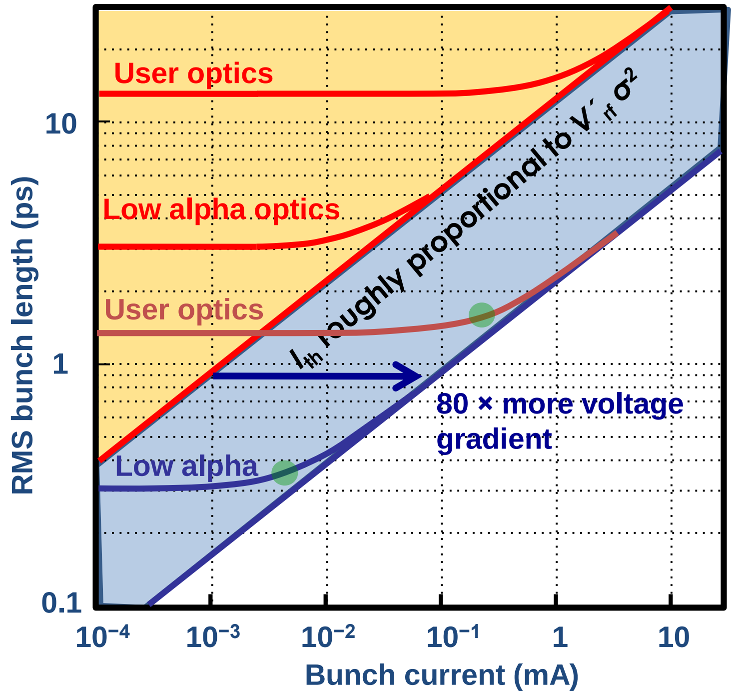
- Limited pulse length in storage ring

$$\sigma \propto \sqrt{\frac{\alpha}{\dot{V}_{rf}}}$$

Machine optics

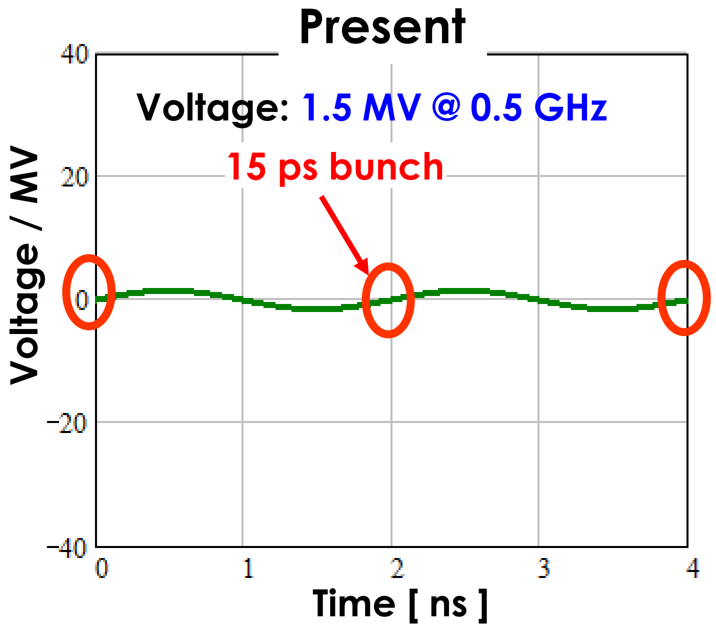
Hardware (RF cavities)

- At high current beam becomes unstable
- For ps pulses, flux is reduced by nearly 100

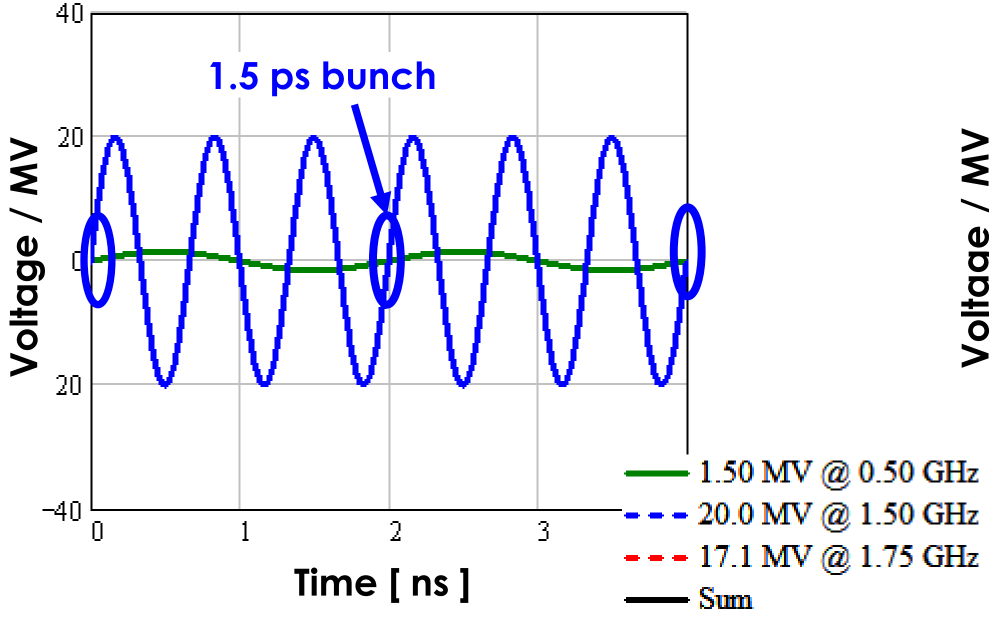


SC Upgrade →

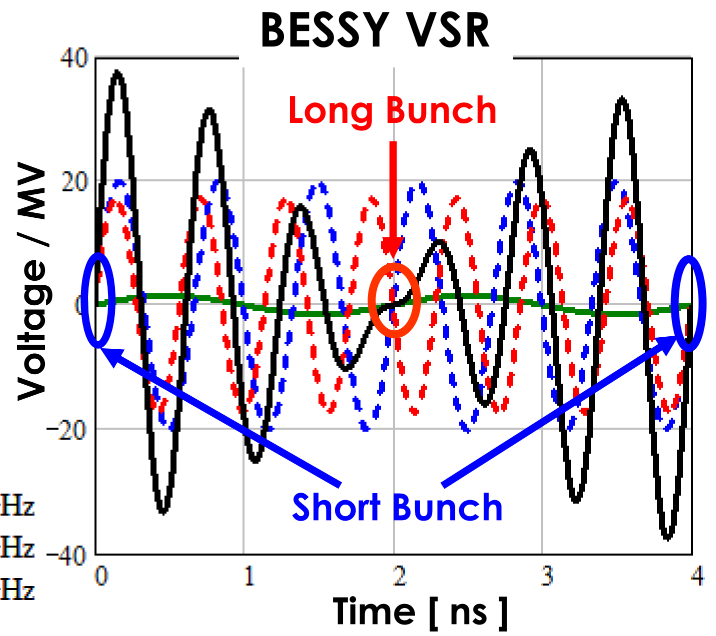
G.Wüstefeld et al. „Simultaneous long and short electron bunches in the BESSY II storage ring“ , IPAC2011



$$\dot{V} \propto V \times f_{rf} = 0.75\ MV \times GHz$$



$$\dot{V} \propto V \times f_{rf} = 30\ MV \times GHz$$



$$\dot{V} \propto V \times f_{rf} = 60\ MV \times GHz$$

- 1.5GHz and 1.75GHz ---- RF beating (modulate RF focusing)
- Odd (voltage cancelation, 15 ps bunches)
- Even (voltage addition, 1.1 ps)

BESSY II, SC Upgrade – BESSY VSR

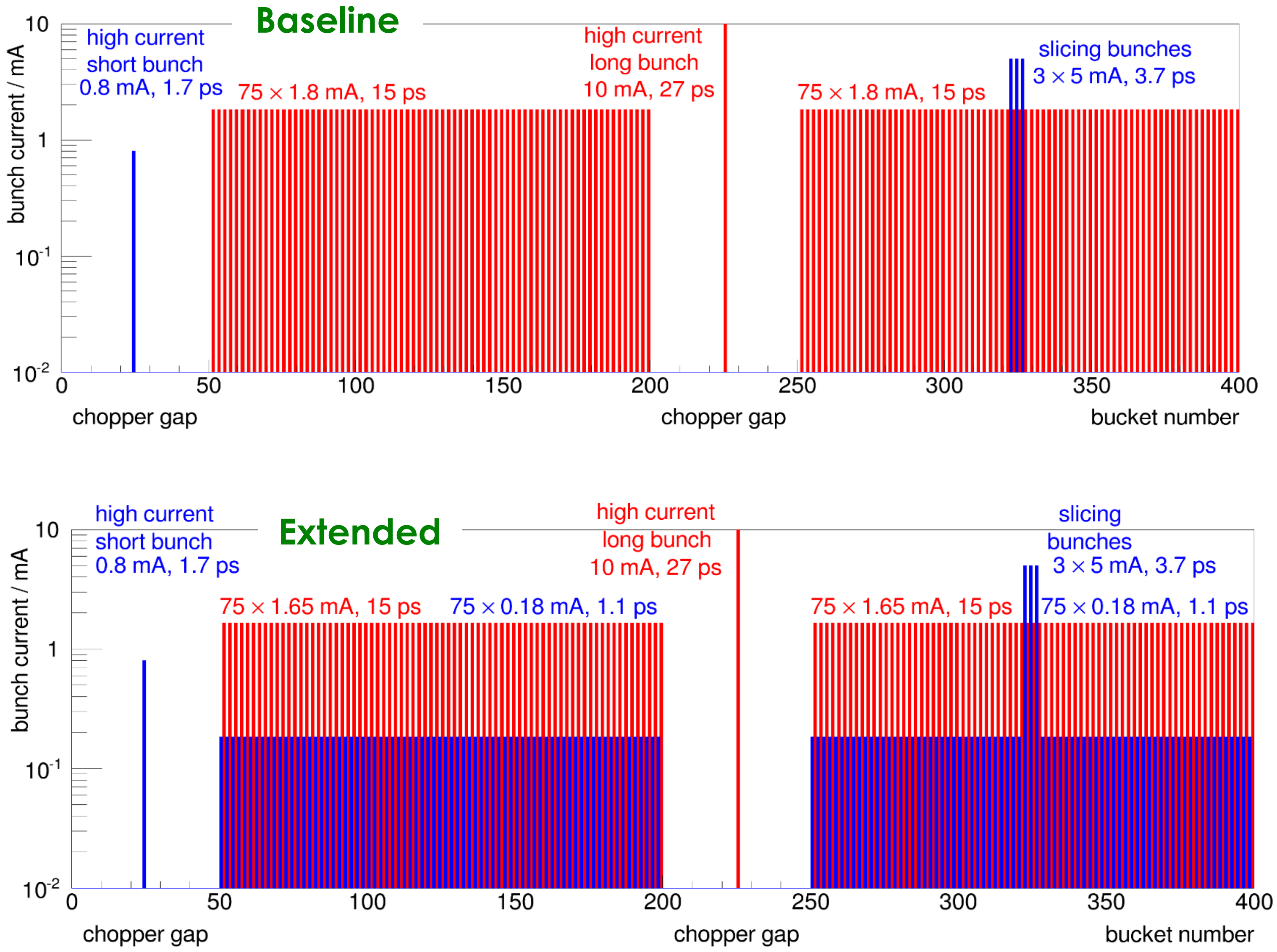
BESSY VSR Filling Patterns

- **High concentration of long bunches populated with high current**
  (flux hungry users)

- **Few high current - short bunches**
  (slicing bunches …)

More short bunches (Extended)

- **High Population of long & short bunches at the same time**



BESSY II SC Upgrade – BESSY VSR

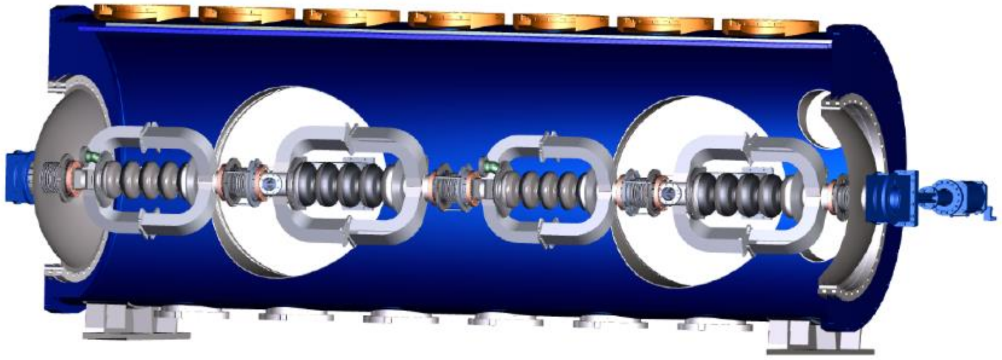
- Simultaneous Store of long & short bunches

SC Upgrade

BESSY VSR

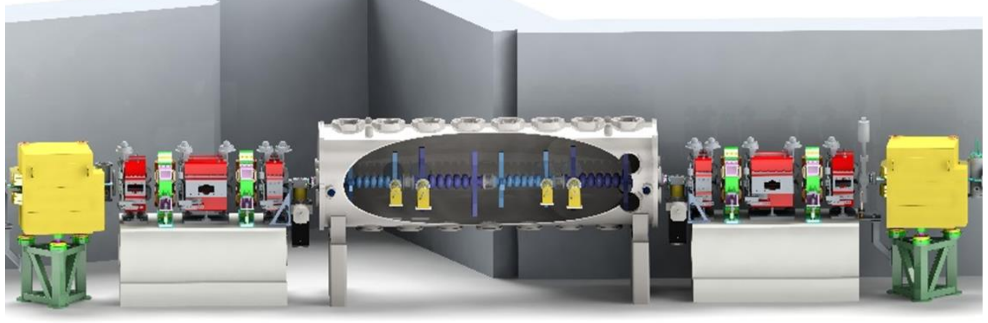
Variable pulse length **S**torage **R**ing

- **SRF SYSTEM:** 2@1.5 GHz & 2@1.75 GHz



BESSY VSR

Helmholtz-Zentrum Berlin



CHALLENGES

- CW operation @ high field levels E=20MV/m
- Peak fields on surface (discharges, quenching)
- High beam current (Ib=300mA),
- Cavity HOMs must be highly damped (CBIs)
- Exotic cavity design (damping end-groups)
- Integrating in existing storage ring
- Transparent Parking of SRF Module.

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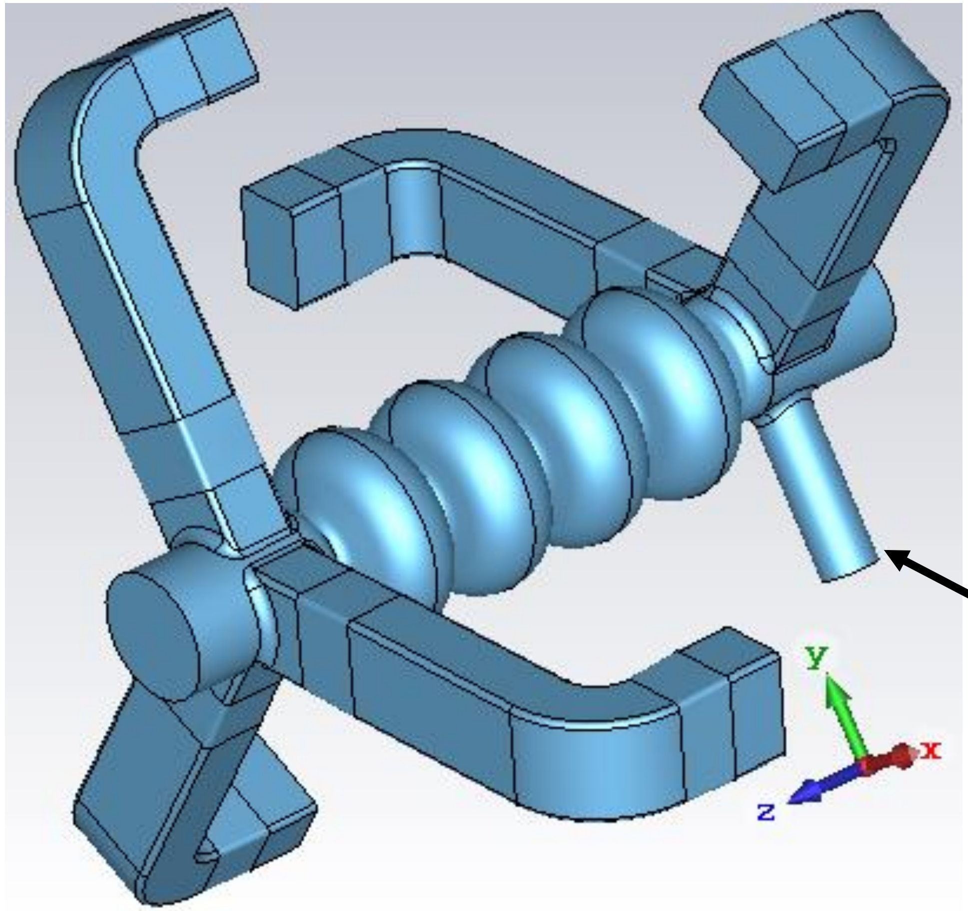
BESSY VSR SRF Cavity Designs

- Tune fundamental mode: field flatness, R/Q …
- Control cavity HOM spectrum (off-resonance condition) during the design.

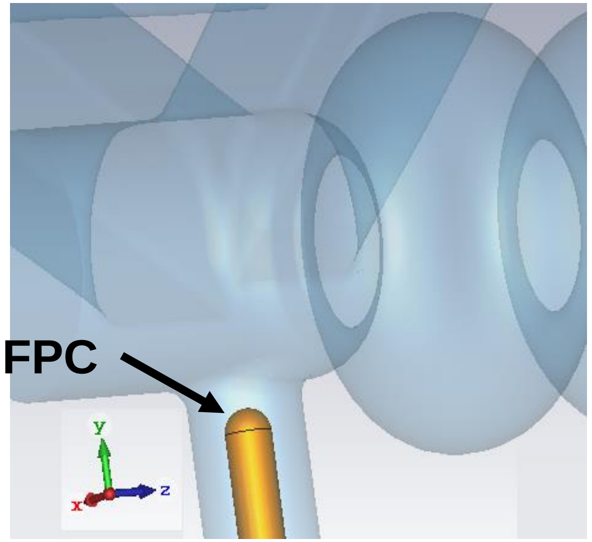
Strong HOM Damped SRF Cavity Concepts

Cavity with HOM WG Dampers



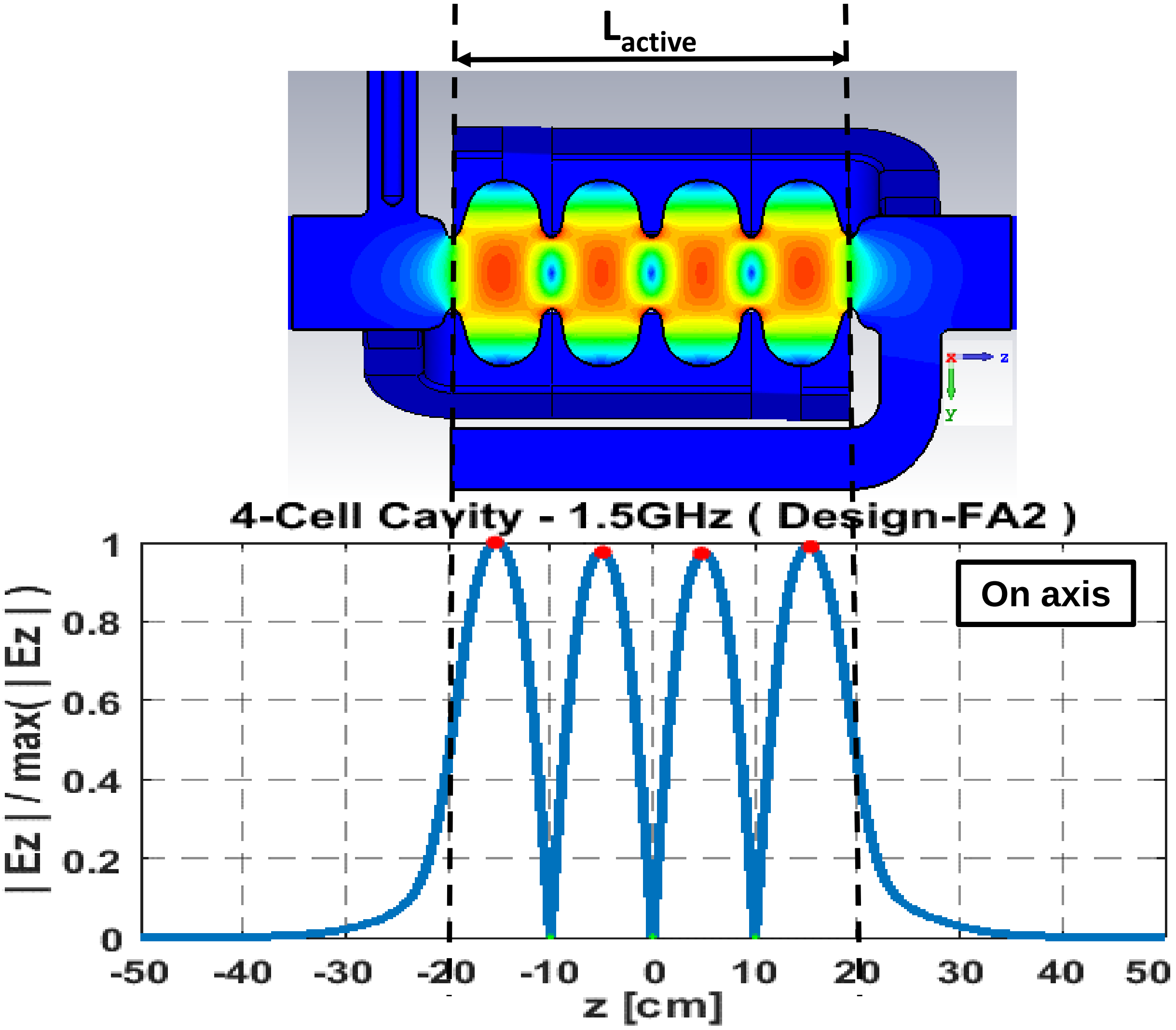
- 5 x Waveguide dampers, HOM loads (warm)
- Large beampipe radius – better HOM propagation
- Waveguides are below cutoff for fundamental → can be moved close to the cavity for heavy damping.

FPC



BESSY VSR SRF Cavity Designs

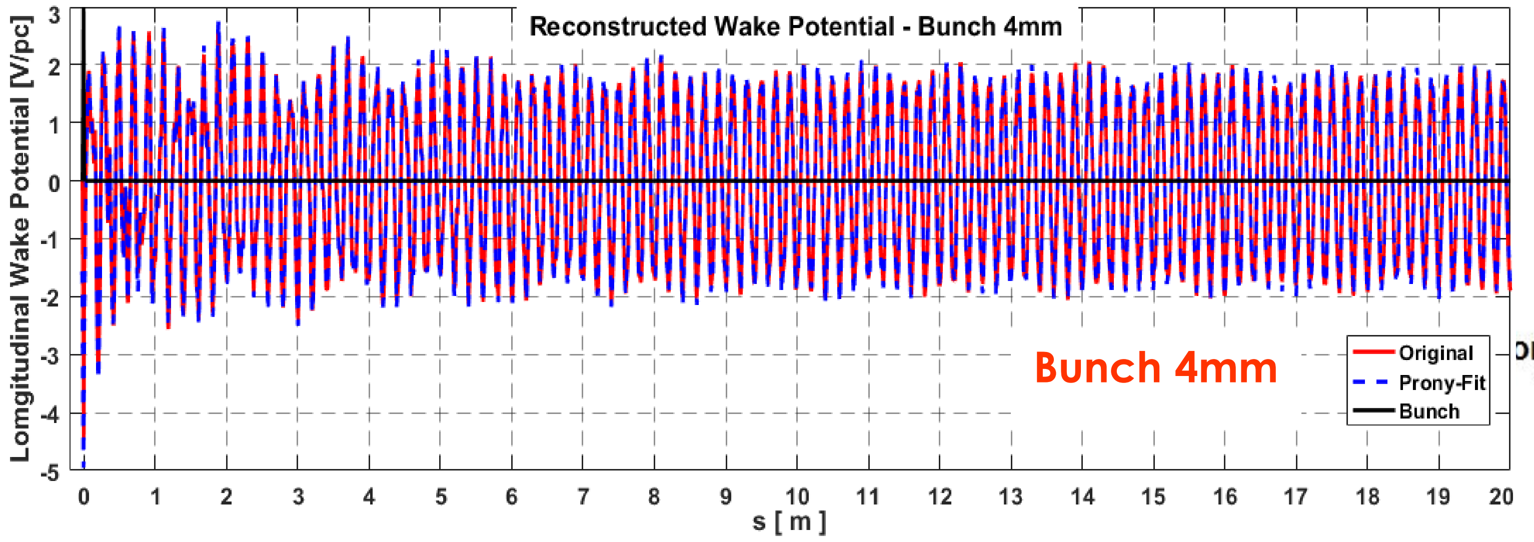
Simulation Results – for both Cavity (TM_{010} π-mode)			
	1.5GHz	1.75GHz	Design goal
Number of Cells	4		
L_{active}	0.4 m	0.344 m	
Frequency [GHz]	1.4990	1.7489	3^{th} & 3.5^{th} harm. of 499.65 MHz
Q_{ext}	$4.99*10^7$	$4.28*10^7$	
G [Ω]	277.63	275.42	
E_{pk} / E_{acc}	2.32	2.30	≤ 2.4
B_{pk} / E_{acc} [mT / (MV/m)]	4.98	5.13	≤ 5.3
R/Q [Ω]	386	380	≥ 90 per cell
Field Flatness - μ_{ff}	97%	99 %	≥ 95%

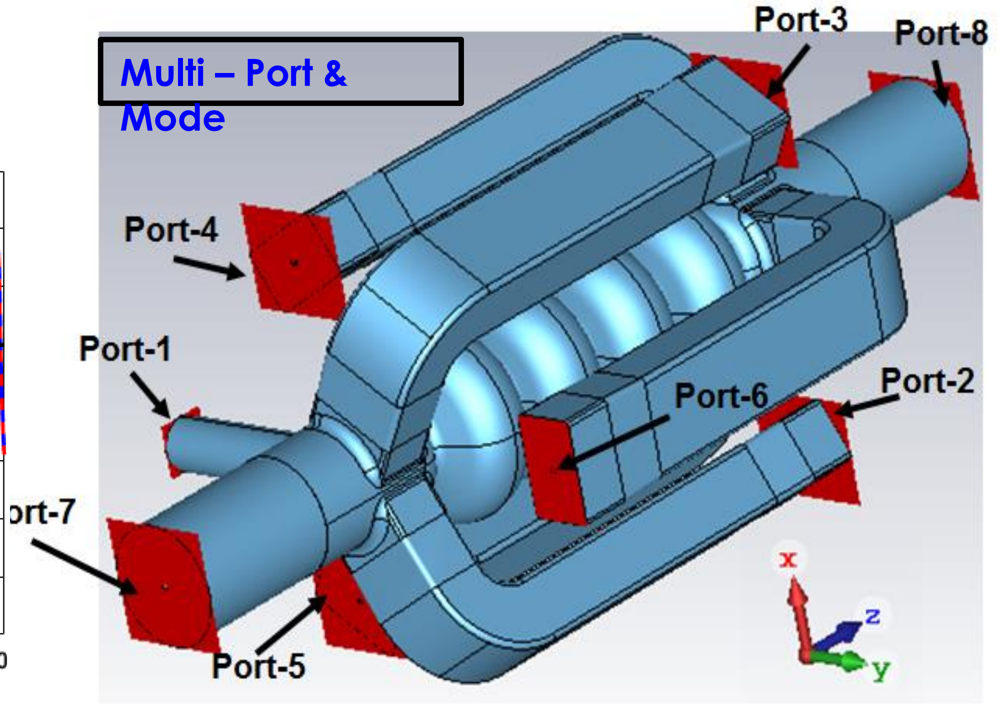


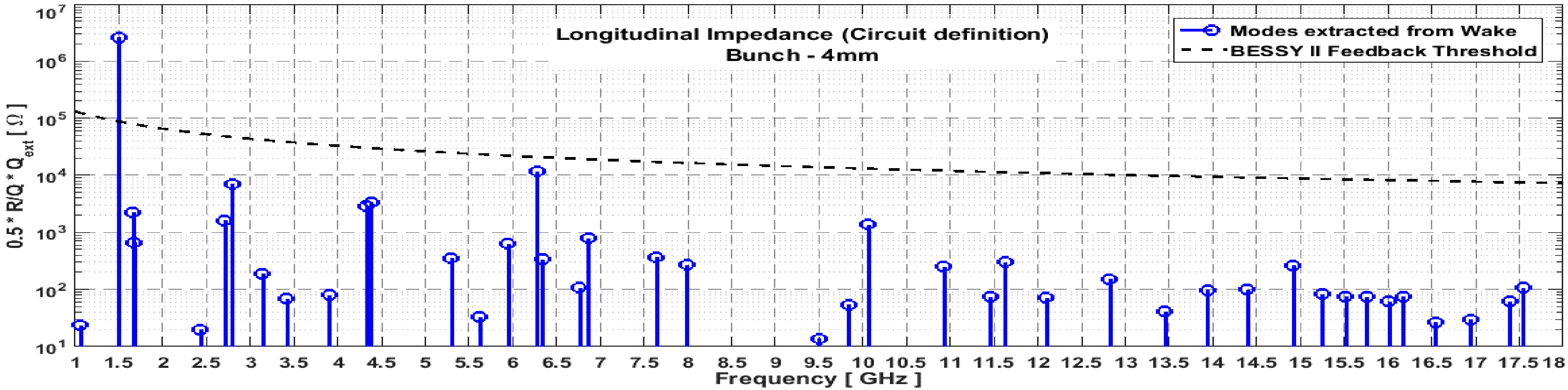
Wakefield Simulations for HOM Spectrum Control

Long Range Wakefield Simulation

(Off-axis XY=2.1mm, 4mm bunch, 20m wake length)

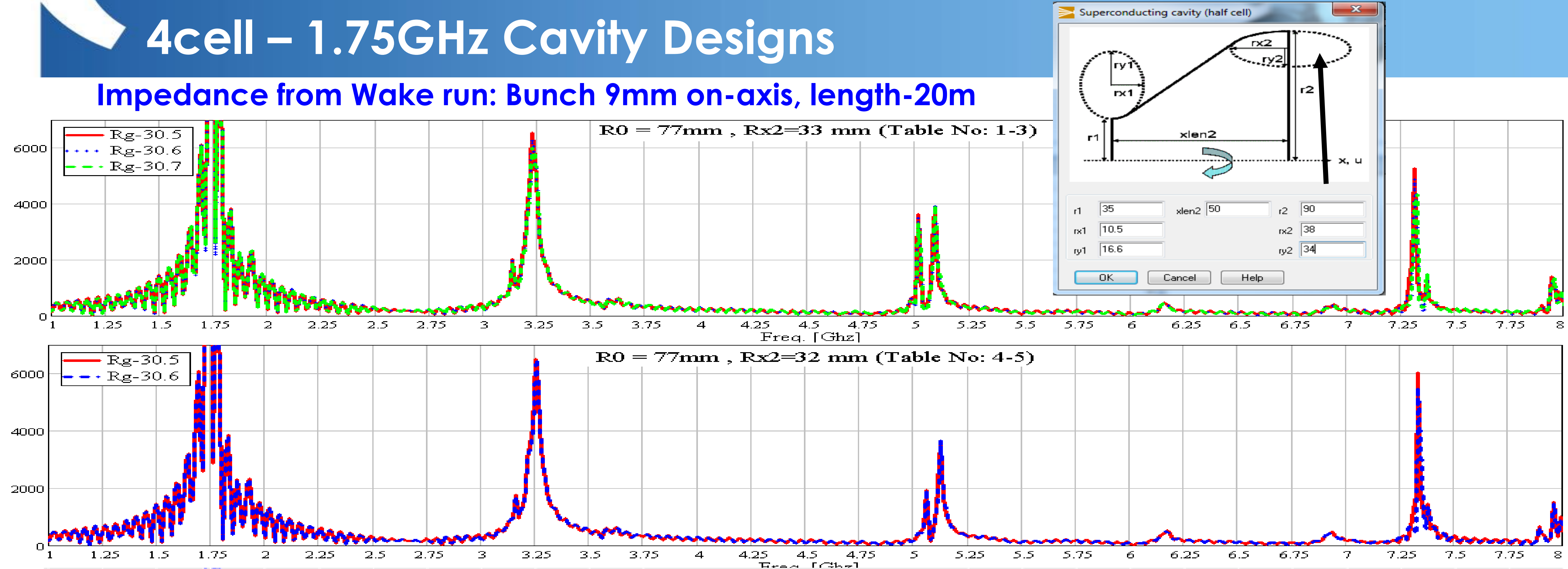


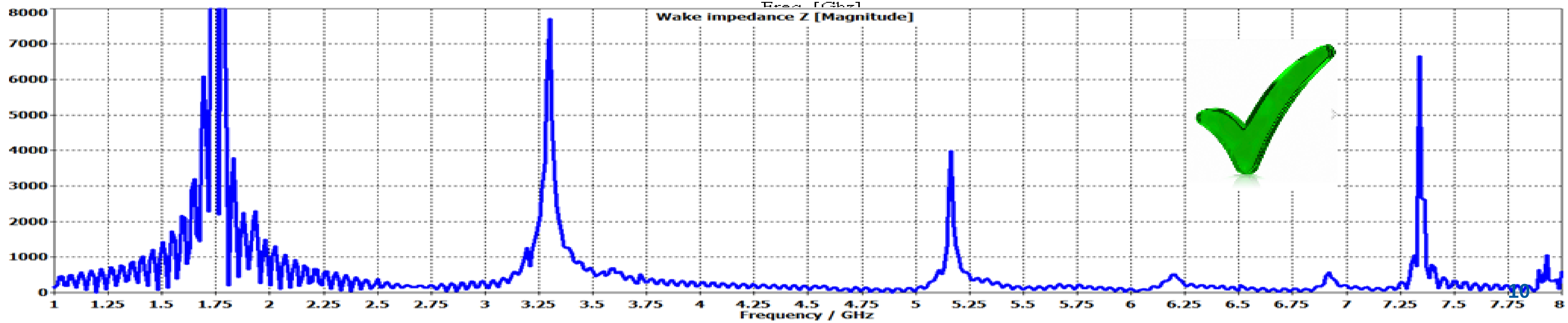




4cell – 1.75GHz Cavity Designs

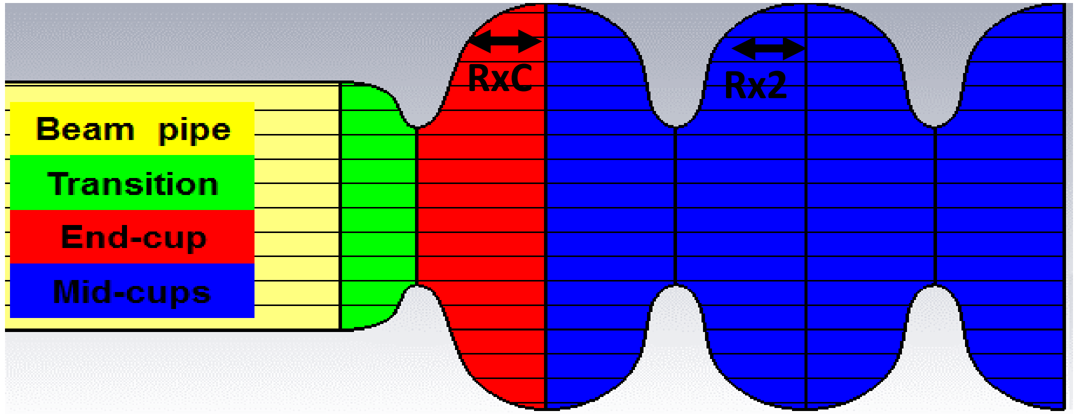
Impedance from Wake run: Bunch 9mm on-axis, length-20m

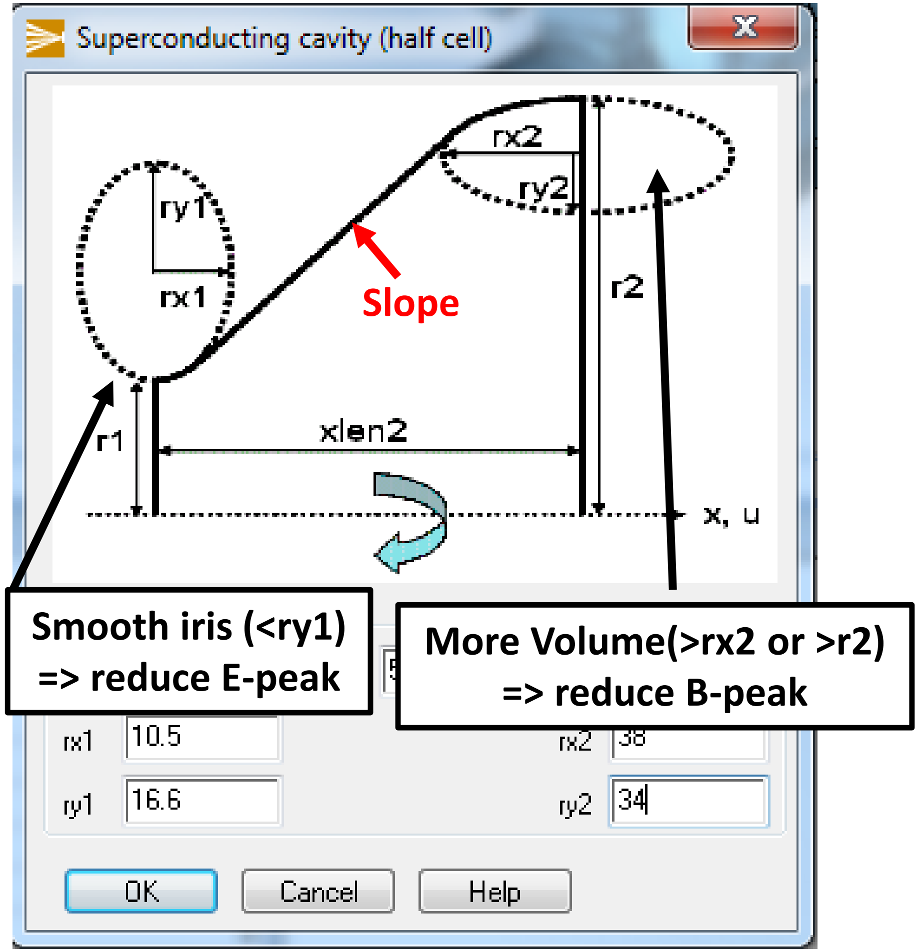




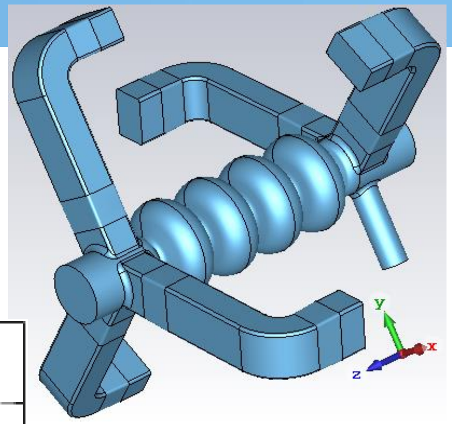
Geometry Parameters for Accelerating Mode & HOM Control

- **Rx2/RxC** – field flatness (not sensitive on other parameters)
- **HOM spectrum shift is sensitive on cell-slope**
  (for tuned fundamental)
- **Design:**
  1. **Fix iris radius (Shunt impedance)**
  2. **Ensure field flatness >95% (Rx2/RxC , fixed slope)**
  3. **Tune fundamental frequency by r2, check B-peak.**
  4. **Check HOM spectrum**



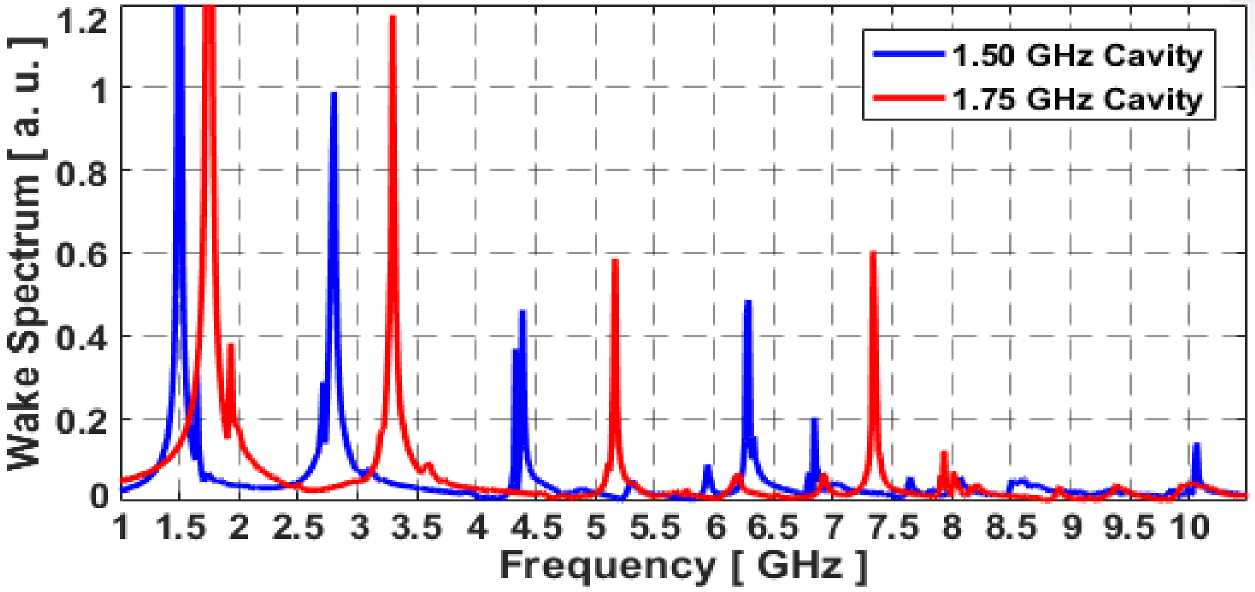


HOM Power of Single Cavity – VSR Baseline beam



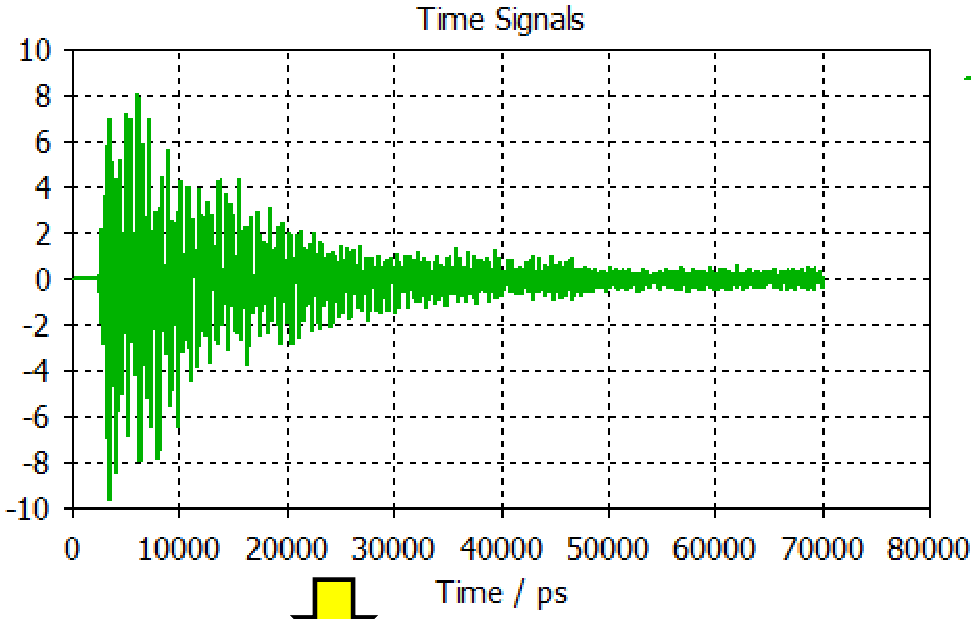
Spectrally Weighted with "Baseline" pattern

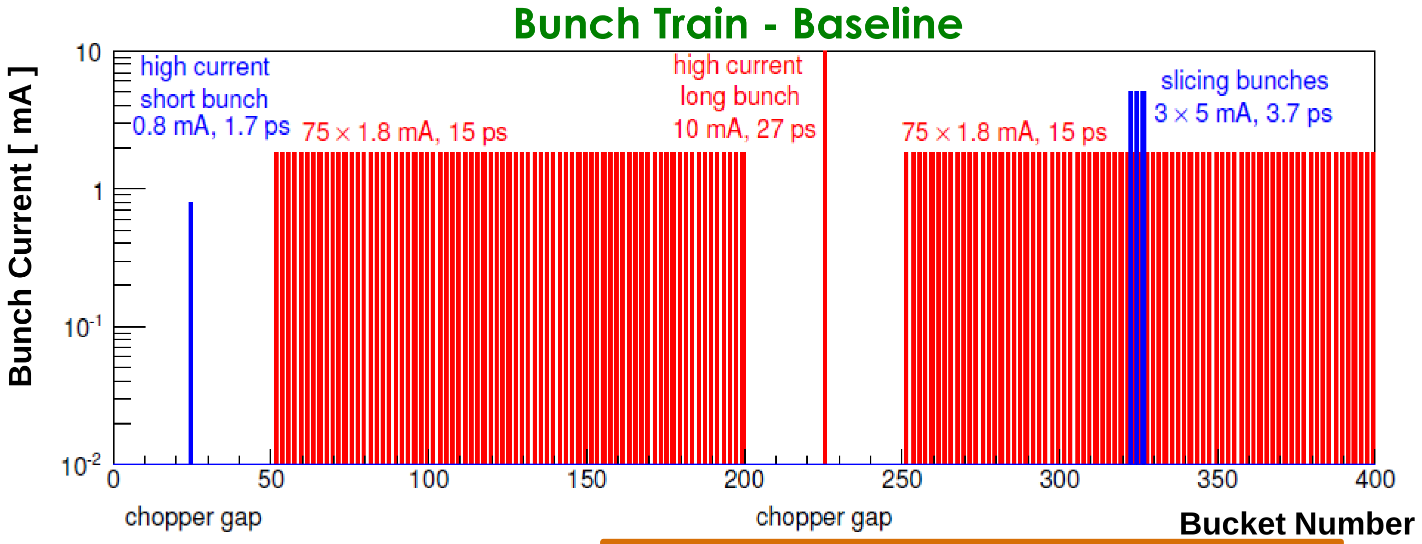
Cavity Type	1.5GHz	1.75GHz
Port No.	HOM Power [W]	
1 – FPC(1)	37.9	33.8
2 – WG(1)	105.3	154.7
3 – WG(1)	103.8	151.4
4 – WG(2)	88.5	108.3
5 – WG(2)	90.2	109.8
6 – WG(2)	90.6	111.6
7 – BmP(Upstream)	235.4	200.5
8 – BmP(Downstream)	327.1	275.9
Total Coherent	**1079**	**1146**
None-Coherent	**1293**	**1300**



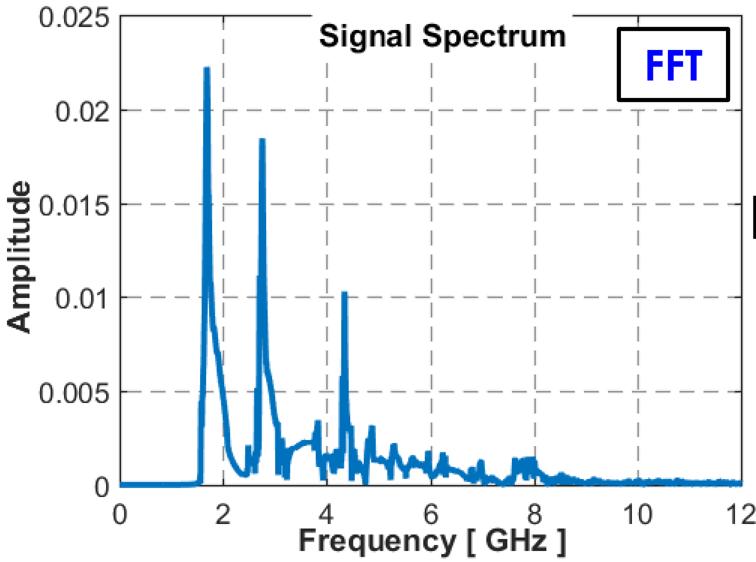
- **Both cavities are not hitting any of beam resonances that are multiple of 250MHz (Coherent and none-coherent powers are at the same level).**
- **Cornell's ERL cavities are designed to run at about 100-200W HOM Power.**

Signal Spectral Weighting Technique





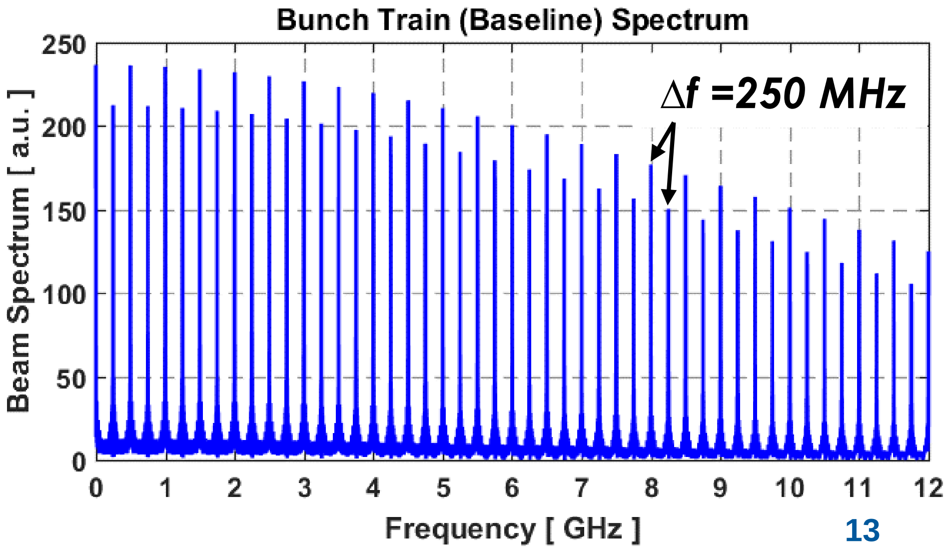
$$\tilde{I}_b(\omega) = f_{rev} \sum_n q_n \cdot e^{-0.5 \cdot \omega^2 \sigma_n^2} \cdot e^{j\,\omega\, t_{0,n}}$$



Spectral weighting of port signal & Power per freq. bins (FFT)

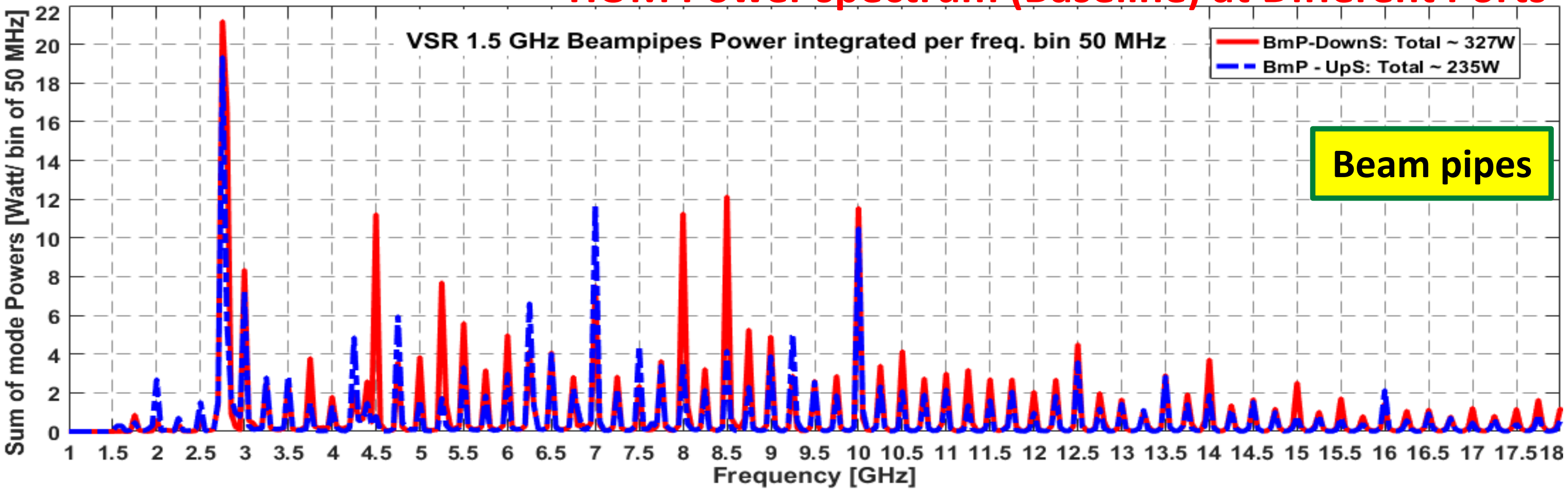
$$P(\omega) = \left| \frac{\tilde{I}_b}{\tilde{I}_0} \mathcal{F}(\omega) \right|^2$$

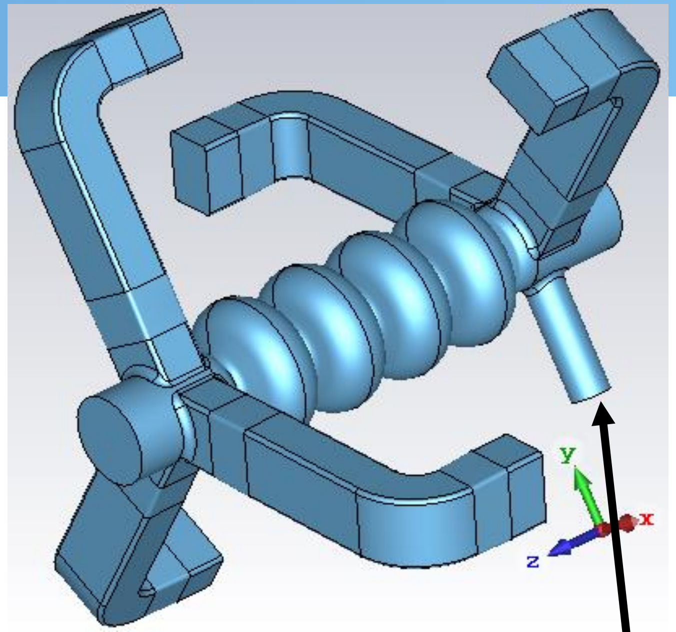
$\tilde{I}_0$ - Simulated single bunch

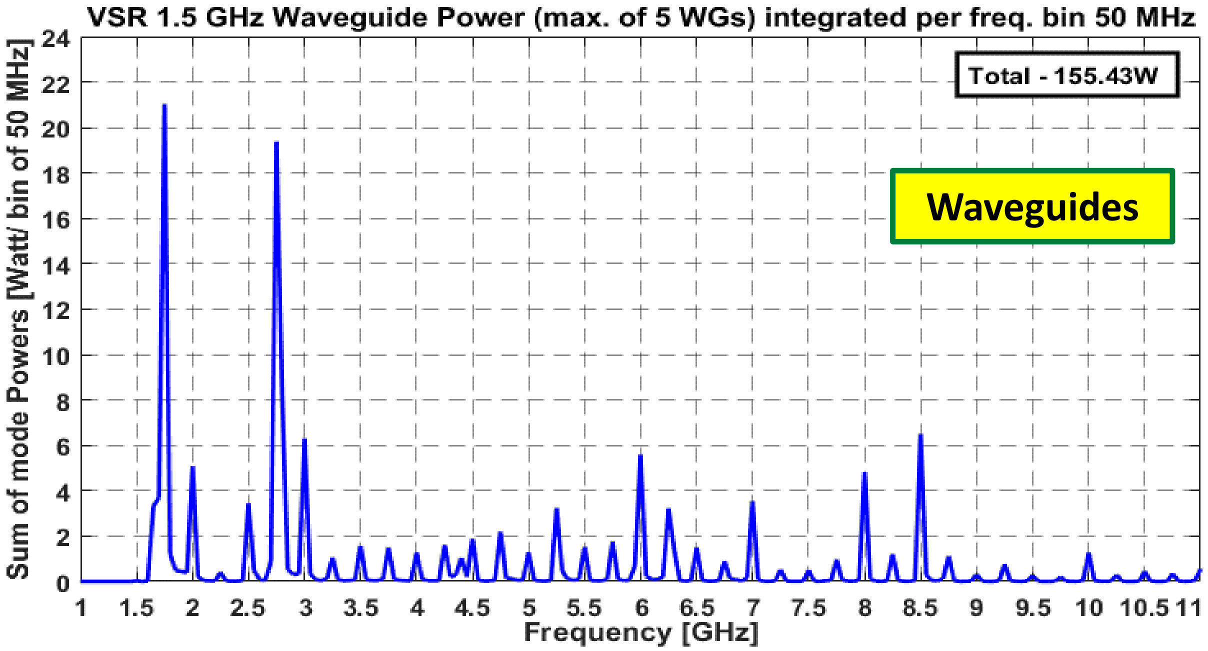


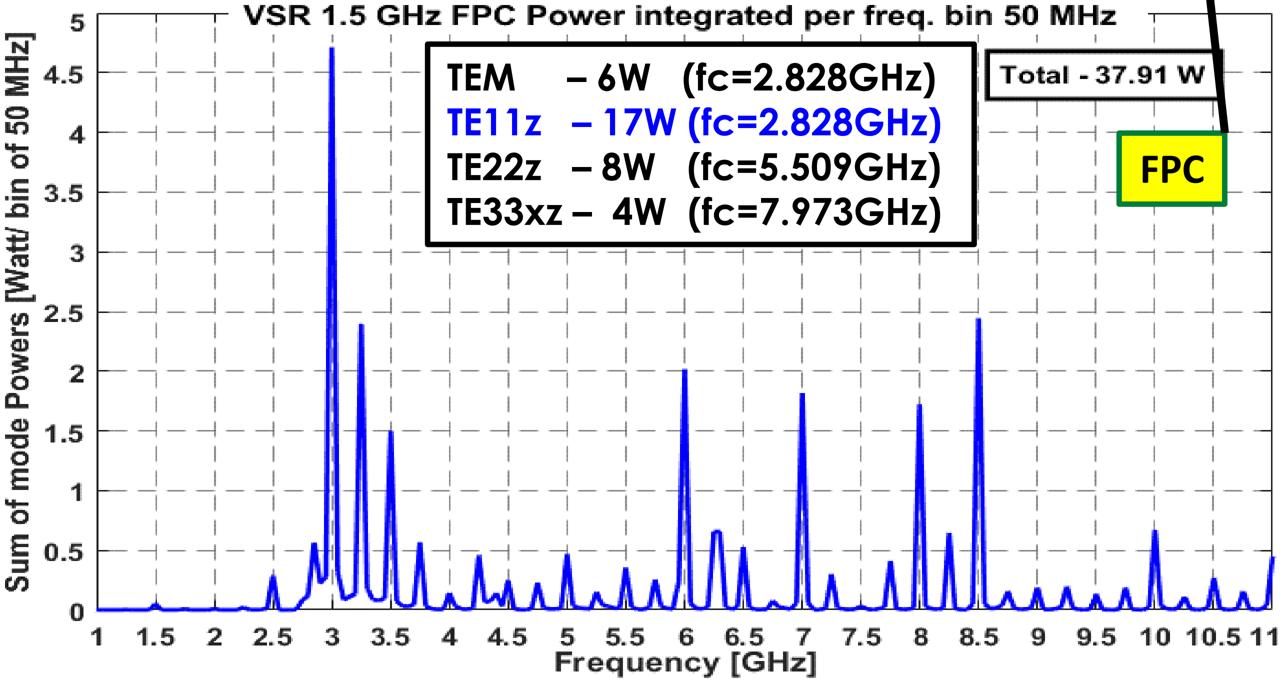
HOM Power of Single Cavity 1.5GHz

HOM Power spectrum (Baseline) at Different Ports





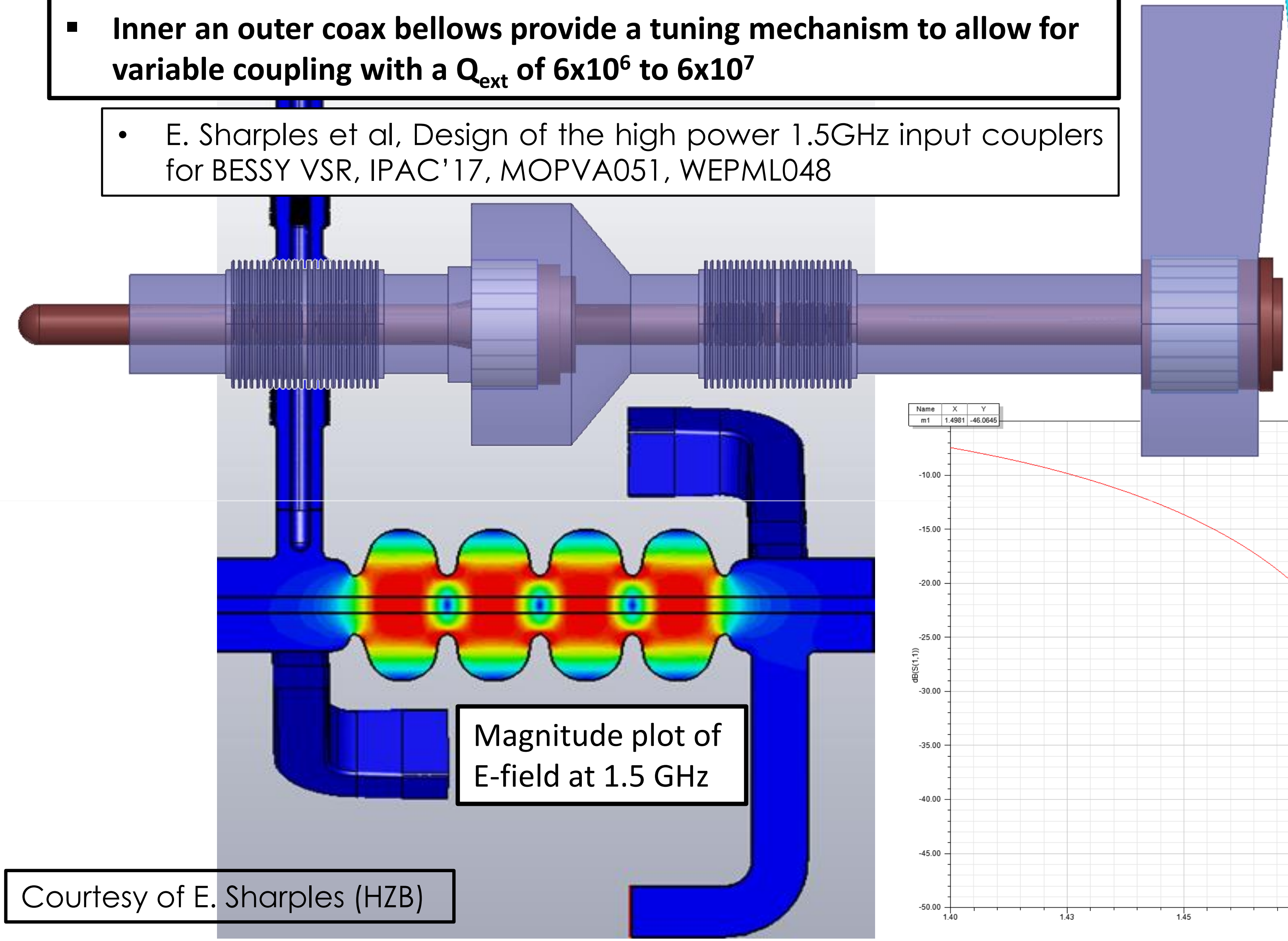




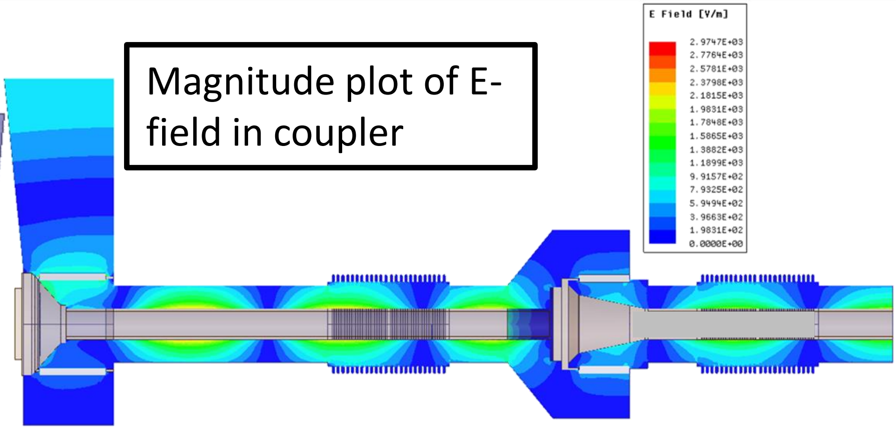
Design of the 1.5 GHz BESSY VSR coupler

- **Coax coupler diameters: 49 mm x 20 mm.**
- **Two ceramic windows to maintain vacuum.**
- **Inner an outer coax bellows provide a tuning mechanism to allow for variable coupling with a Q_{ext} of $6x10^6$ to $6x10^7$**

- E. Sharples et al, Design of the high power 1.5GHz input couplers for BESSY VSR, IPAC'17, MOPVA051, WEPML048

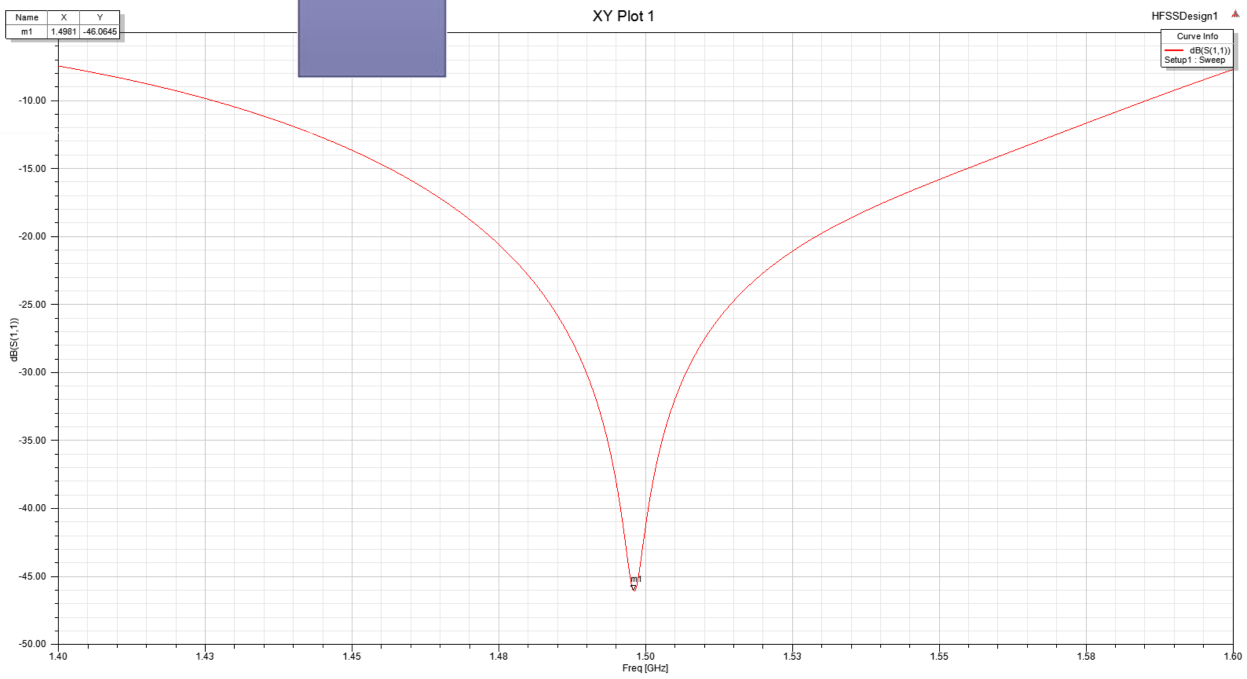


Magnitude plot of E-field at 1.5 GHz



Magnitude plot of E-field in coupler

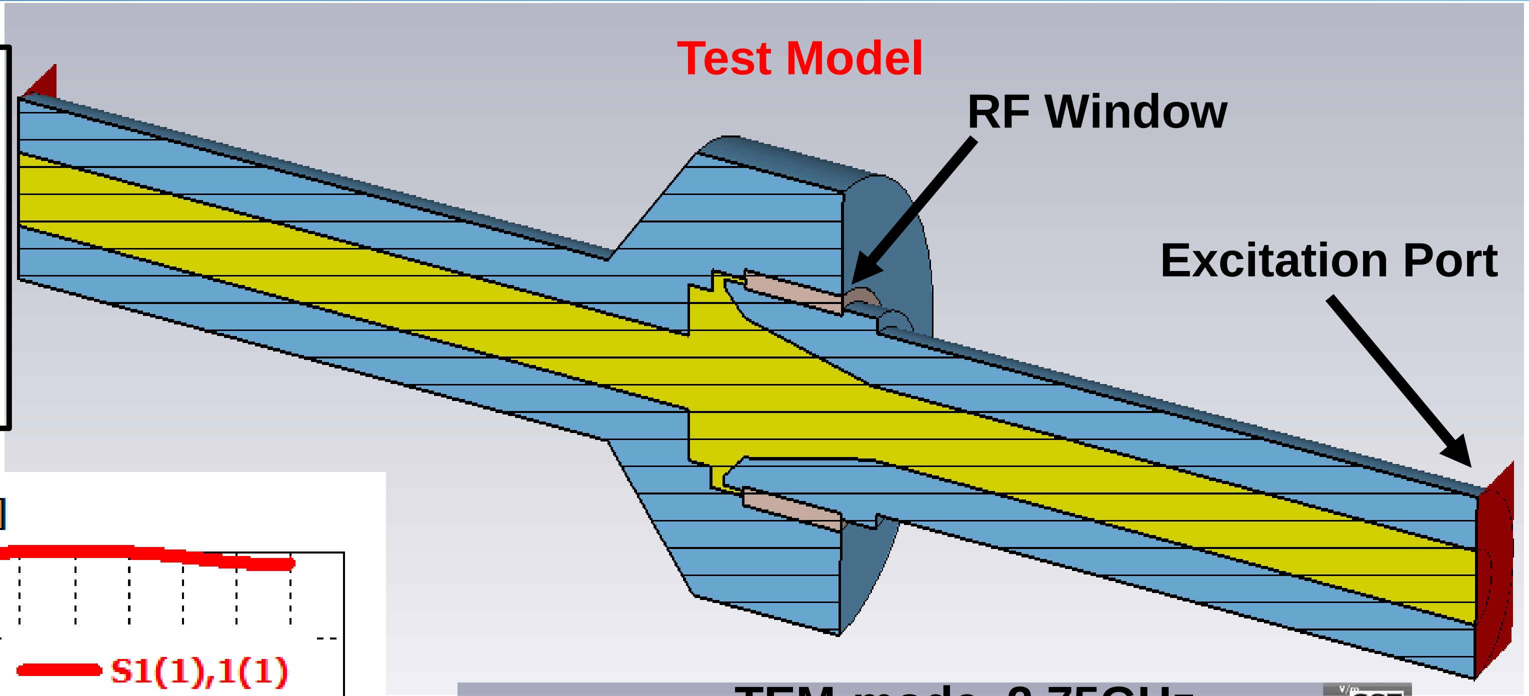
S11 Plot
Magnitude of -46 dB at 1.498 GHz

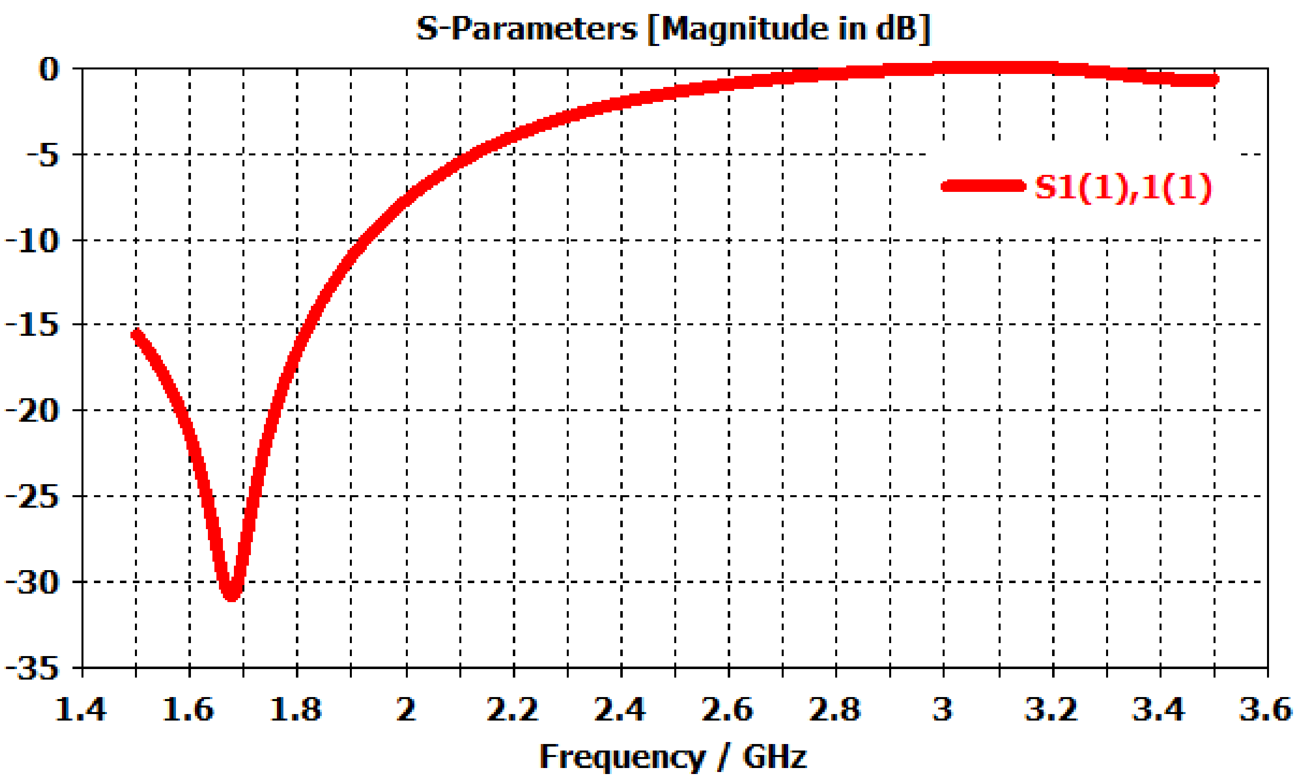


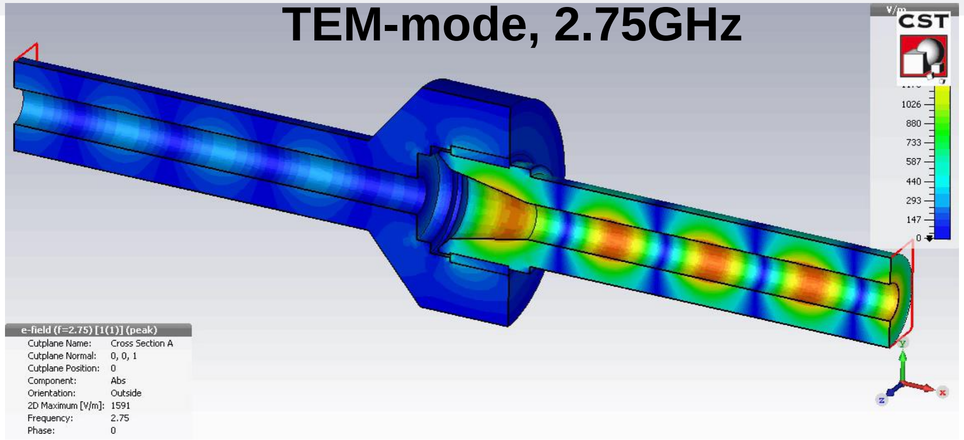
Courtesy of E. Sharples (HZB)

FPC characteristics for HOMs

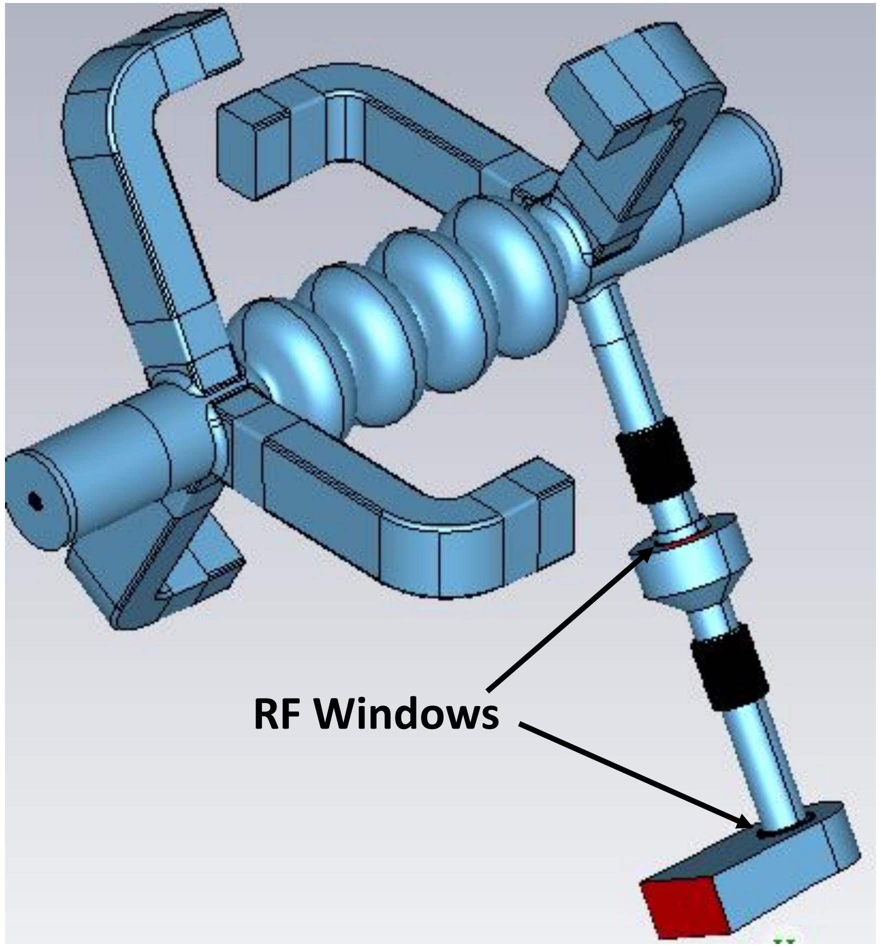
- In FPC at higher frequencies (HOMs) the EM waves are mainly reflected back from first RF windows – forms standing wave. True for all coax modes – TEM, TE11 …
- One should include the first half of the FPC in wake & Eigenmode simulations – to analyze how this fact reflects on HOM power balance & to avoid possible trapped mode in end-group.





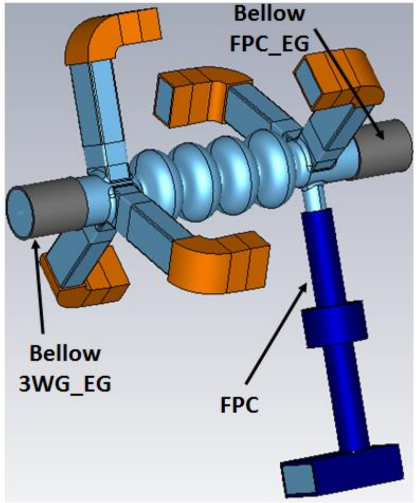


HOM Powers for 1.5GHz Cavity Full-Model (incl. FPC)



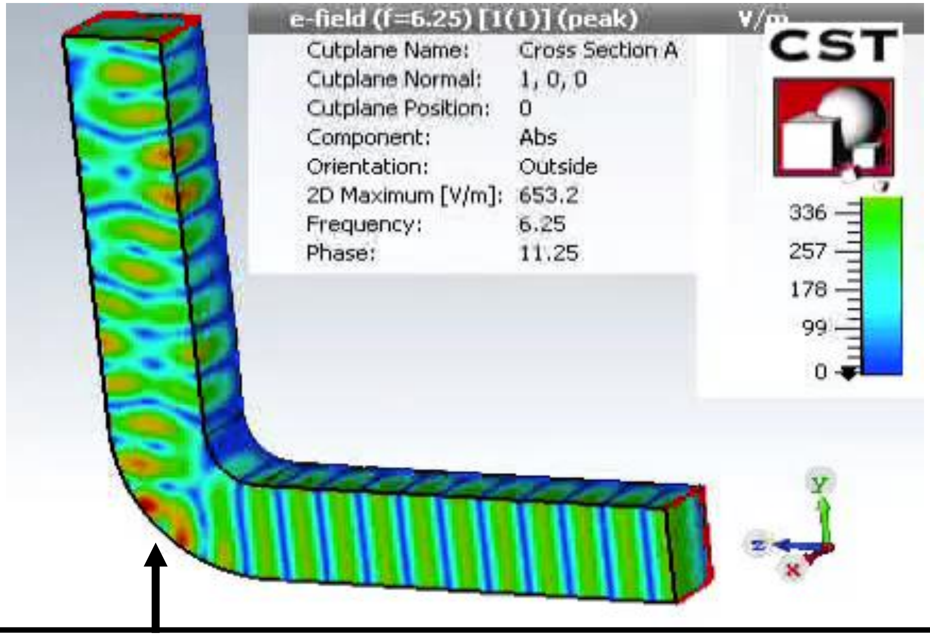
Dielectric losses are included in Wake simulation

HOM Power Levels & Distribution for Baseline-FP (Wake Simulation - Bunch=9mm onAxis)		
Ports	Model mit FPC	Model ohne FPC
FPC(1)	2.89 ↓	25.86
WG(1)	93.78 ↑	91.62
WG(1)	93.78 ↑	91.62
WG(2)	87.35	87.94
WG(2)	87.35	87.94
WG(2)	97.00	98.26
BmP(1)	213.11 ↑	205.58
BmP(2)	269.97	270.79
Sum	945.24	959.62



- With full coupler model the HOM power in FPC is reduces significantly.
- This HOM power is redistributed into the closest ports, i.e. 2 x HOM waveguides of corresponding end-group & beam pipe.

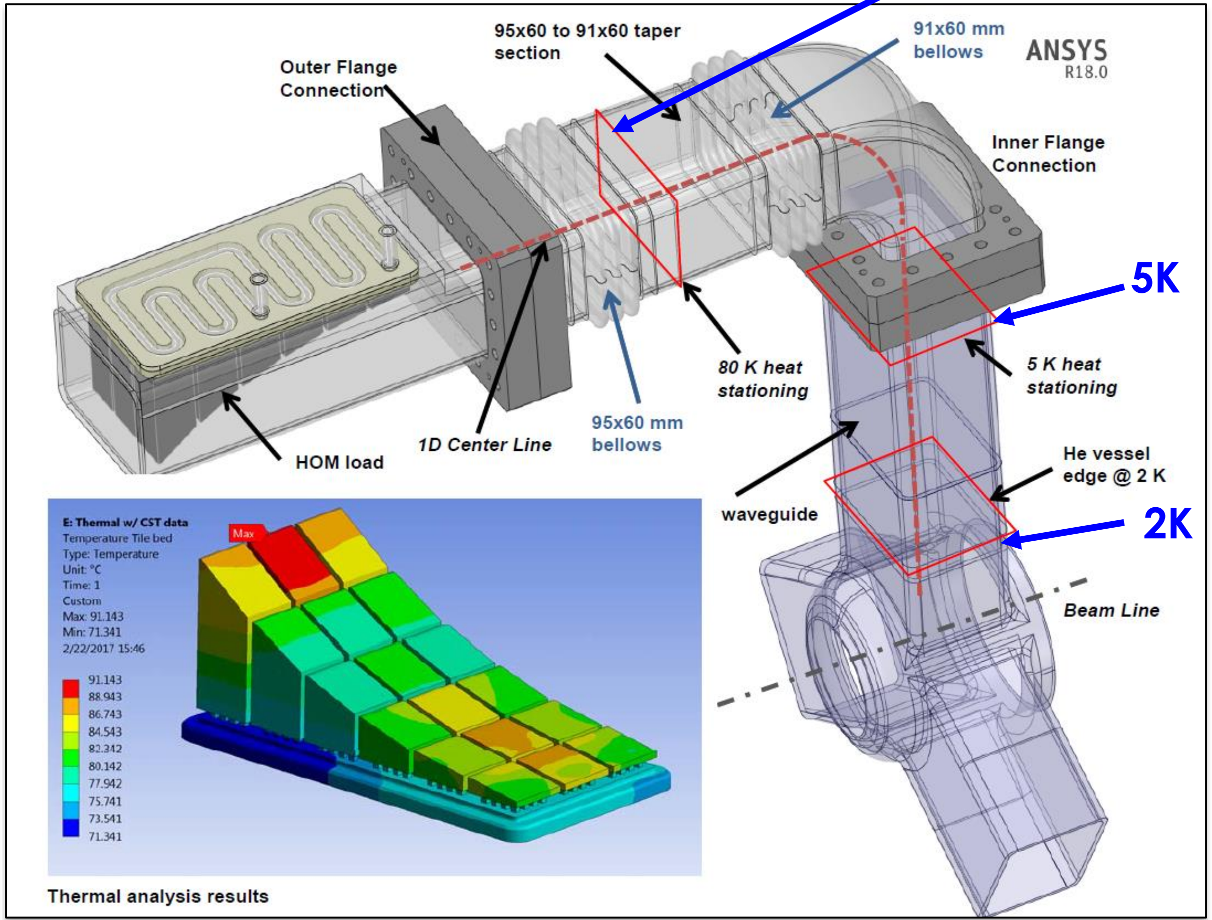
Waveguide Bend Broadband Characteristics & HOM Loads



- Low reflection (broadband) from the WG bend is for bending radius = 30mm or bR ≥ 100mm.

- TE10 mode couples into different modes after bend: TE10, TE11, TM11…, depending on excitation frequency & the cutoff of each WG mode !
- At high frequencies the TE10 is scattered from the bend into several modes, i.e. acts as mode mixer.
- At optimized 30mm inner bending radius the reflection is minimal in broadband frequency sense.

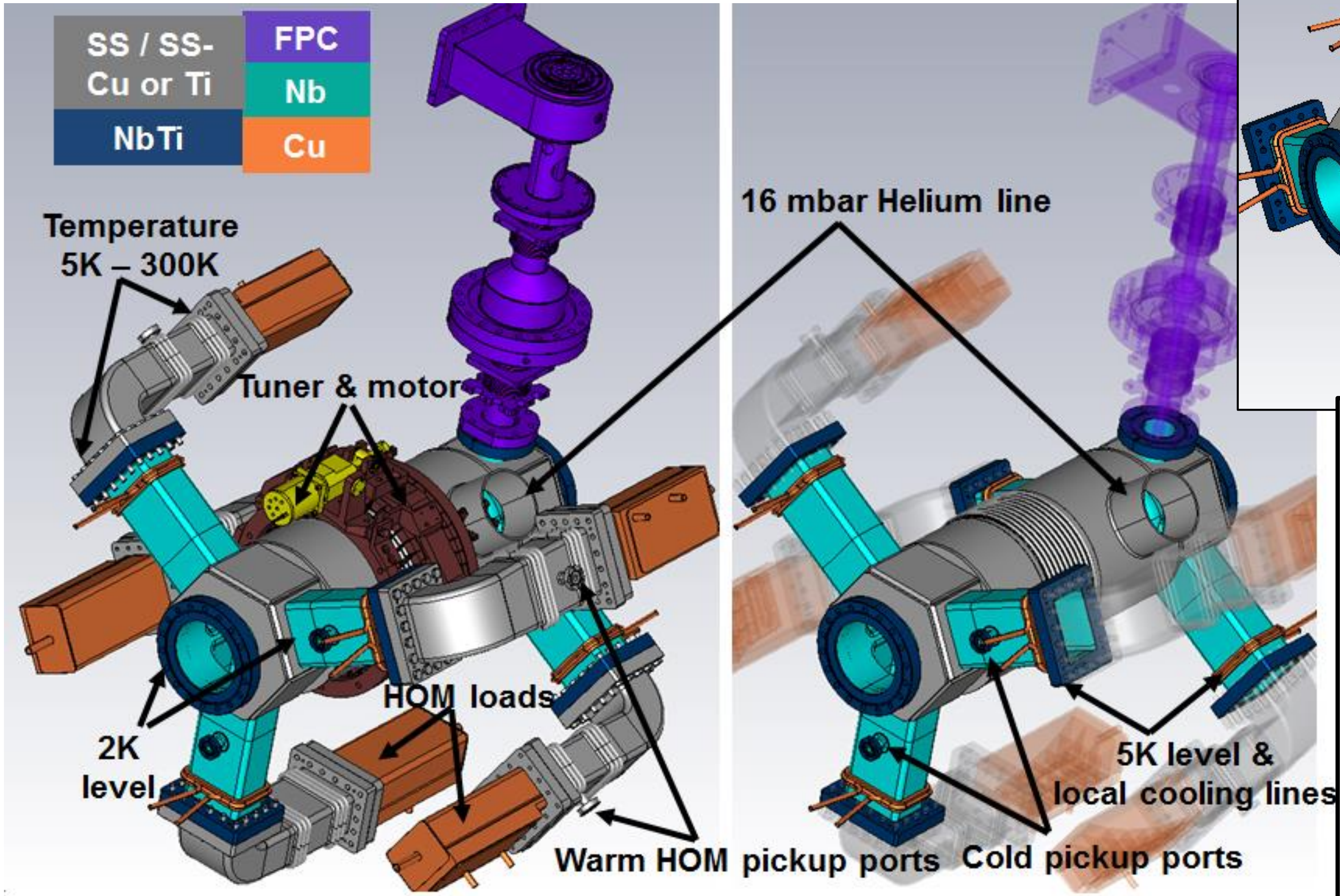
- Water-cooled HOM loads (room temperature 300K)
- Specifications: 460W per load
- Design, fabrication and tests @ JLab

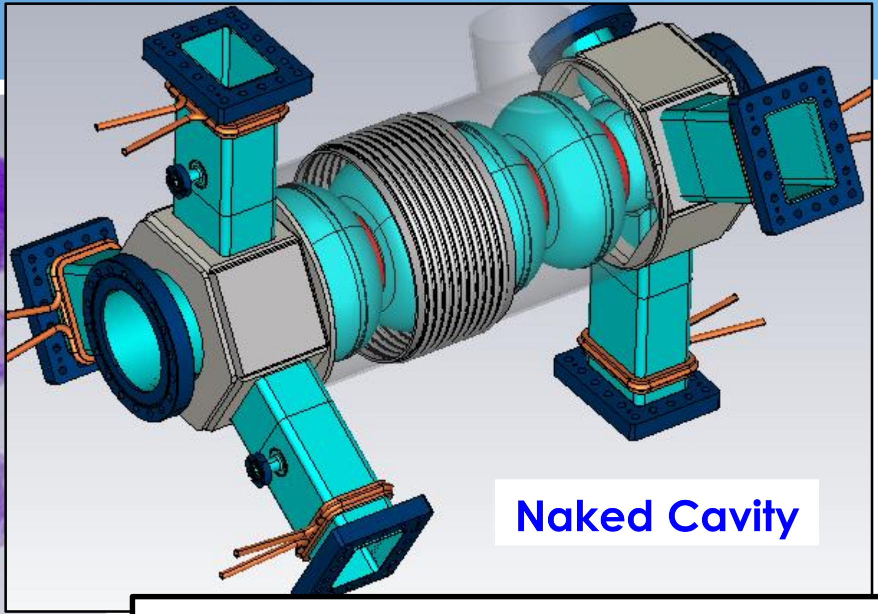


Courtesy of Jefferson Lab

- L. Guo et al, Development of waveguide HOM loads for BERLinPro and BESSY-VSR SRF cavities, IPAC'17, MOPVA130

BESSY VSR SRF Cavities

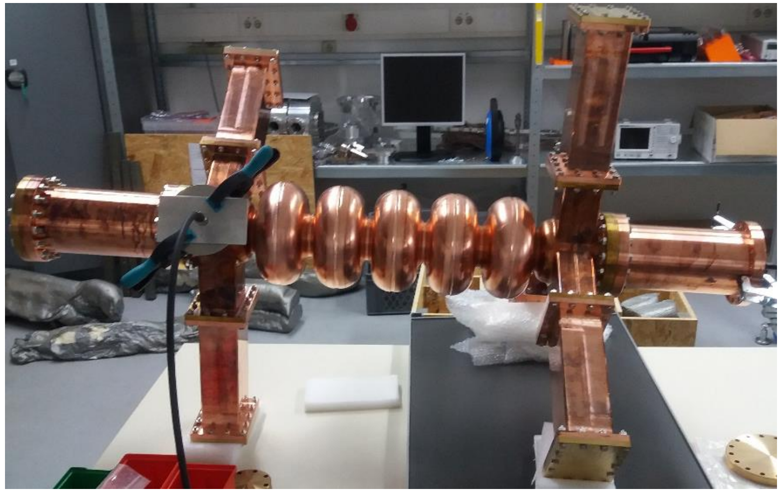


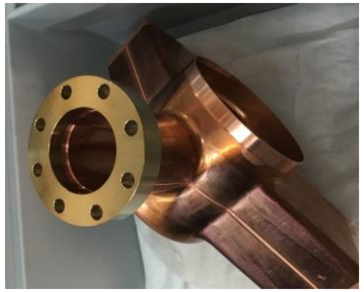


- Baking temperature ~ 700^{0}C, because of Helium-vessel parts.
- Nb inner surface removal ~ 200μm total is planned with BCP. The homogeneity of removal in HOM dampers should be checked.
- In waveguide NbTi flanges VATSEAL gaskets will be used – cold test is planned. At all other flanges – diamond gaskets.
- Looking solutions for cooled WG-flange concept.

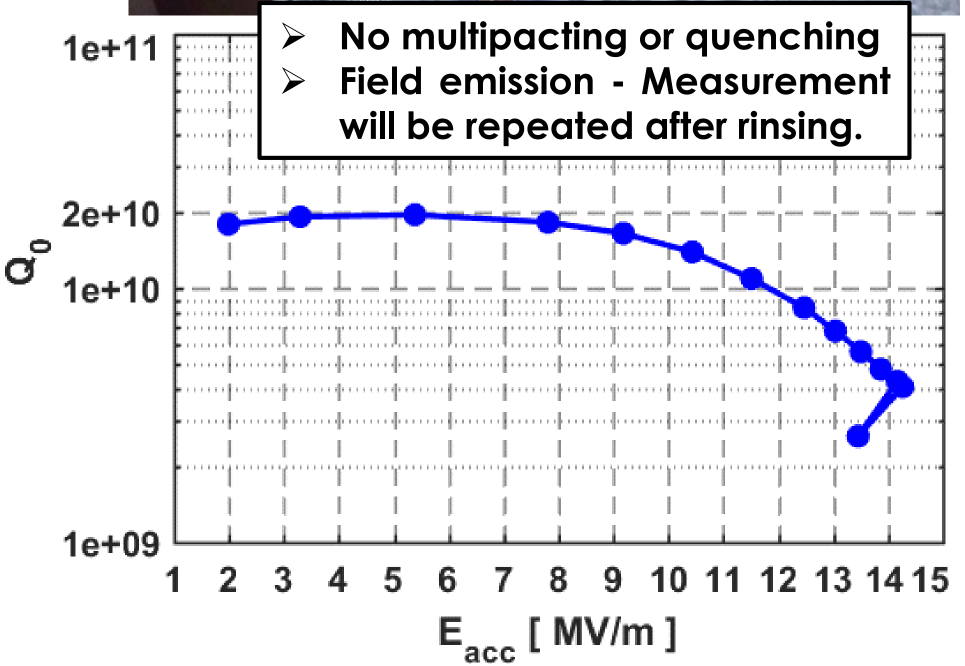
BESSY VSR: Cavity Prototypes

1.5 GHz 5-cell Copper prototype





1.5 GHz Single-cell Nb prototype



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Application of Wakefield Theory

Trev = 800 ns is directly related with RF buckets thus cavity frequency should be taken 1.5GHz as 3rd harmonic of 500MHz one.

Single Bunch

$$V_s(\omega,t) = q_0 \cdot 2 \cdot K_{loss} \cdot \cos[\omega \cdot t] \cdot e^{-\frac{\omega}{2*Q_L}t} = Z \cdot I_b\, e^{-0.5\cdot\omega^2\sigma_t^2} \cdot \frac{\omega\, T}{2\, Q_L} \cos[\omega \cdot t] \cdot e^{-\frac{\omega}{2*Q_L}t}$$

$\omega = 2\,\pi \cdot f$ – resonant frequency of cavity mode

$Z = R/Q \cdot Q_L$ – corresponding impedance (Linac def. - $P = \frac{V^2}{R/Q*Q_L}$)

Cavity Parameters

$K_{loss} = \frac{1}{4} \cdot R/Q \cdot \omega \cdot e^{-0.5\cdot\omega^2\sigma_t^2}$

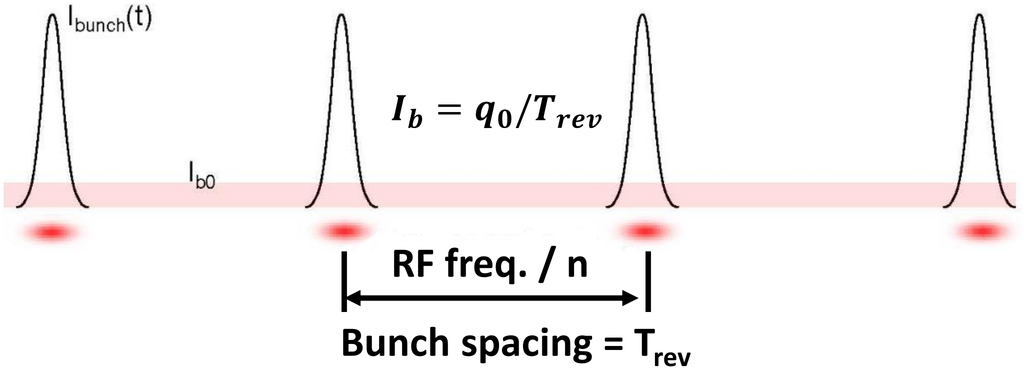
$Z = R/Q \cdot Q_L$, $I_b = q_0/T$

$R/Q = 386\,\Omega$

$Q_L = 5 \cdot 10^7\ (SC)\,,10^4\ (warm)$

$T_{rev} = 800\ ns\,,\ T_{buck} = 2\ ns$

Periodic Bunch

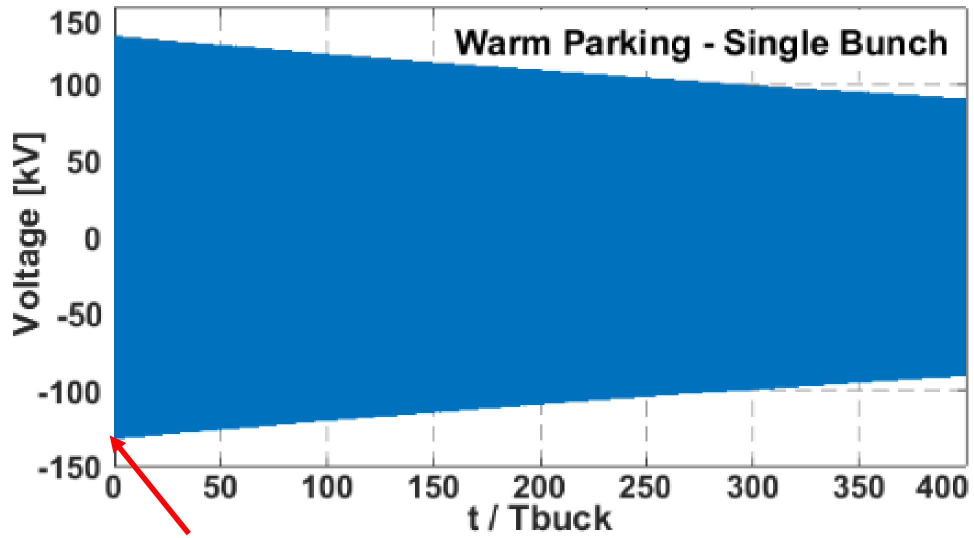


Define: T=T_{rev} , $t \in [0,T]$

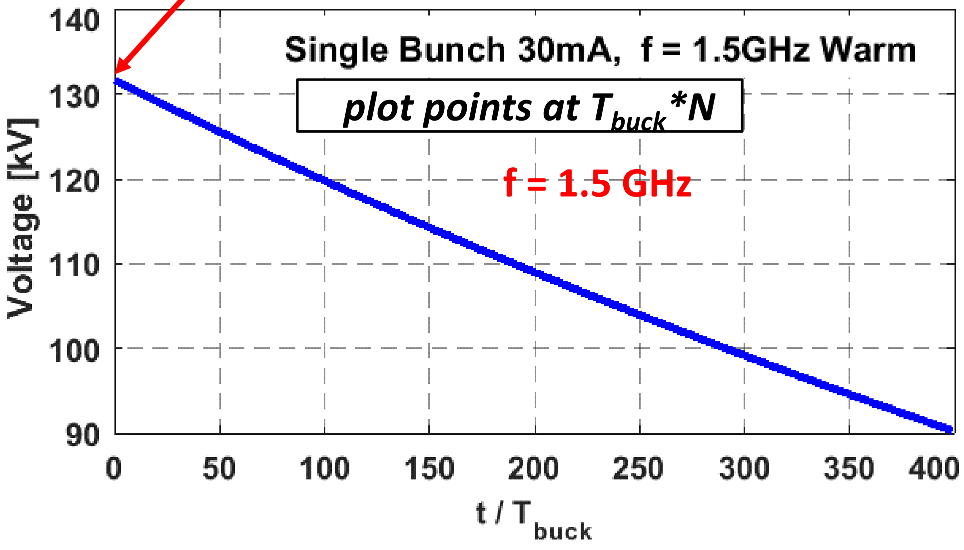
$$V(\omega,t) = \sum_{n=0}^{\infty} V_s(\omega, t+n\cdot T) = V_s(\omega,t) \cdot Re\left[\left(1 + \frac{e^{-\frac{\omega}{2*Q_L}T}}{e^{j\,\omega\,T} - e^{-\frac{\omega}{2*Q_L}T}} + \frac{e^{2\,j\,\omega\,t}}{1 - e^{j\,\omega\,T - \frac{\omega}{2*Q_L}T}}\right)/\left(1 + e^{2\,j\,\omega\,t}\right)\right] \xrightarrow{\omega\,T\,=\,2\,\pi\,N} V_s(\omega,t) \cdot \frac{1}{1 - e^{-\frac{\omega}{2*Q_L}T}}$$

- In case of $f_{rev} \ll \frac{f}{2*Q_L}$, $V(\omega,t) \to V_s(\omega,t)$. Is not applicable to BESSY ring.

Single Periodic Bunch – Steady State Cavity Voltages

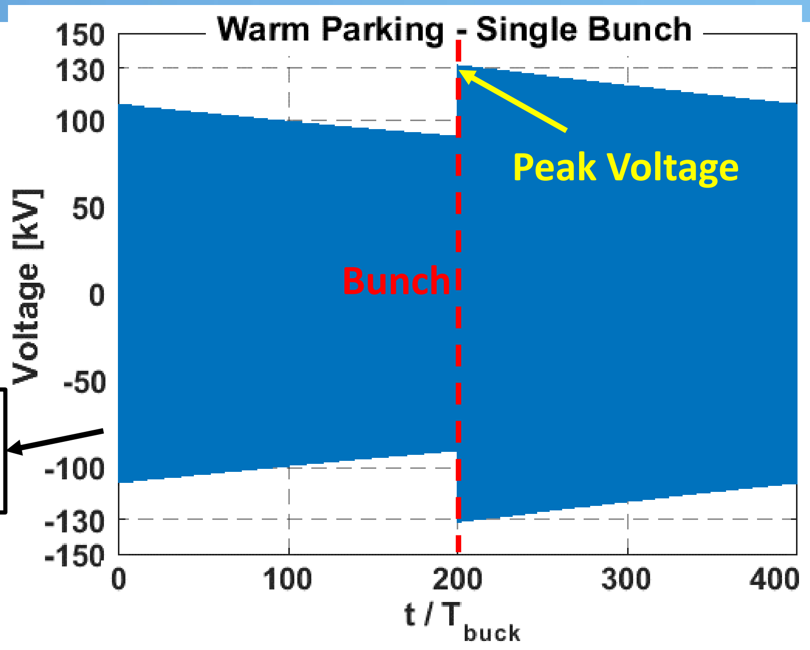


Bunch

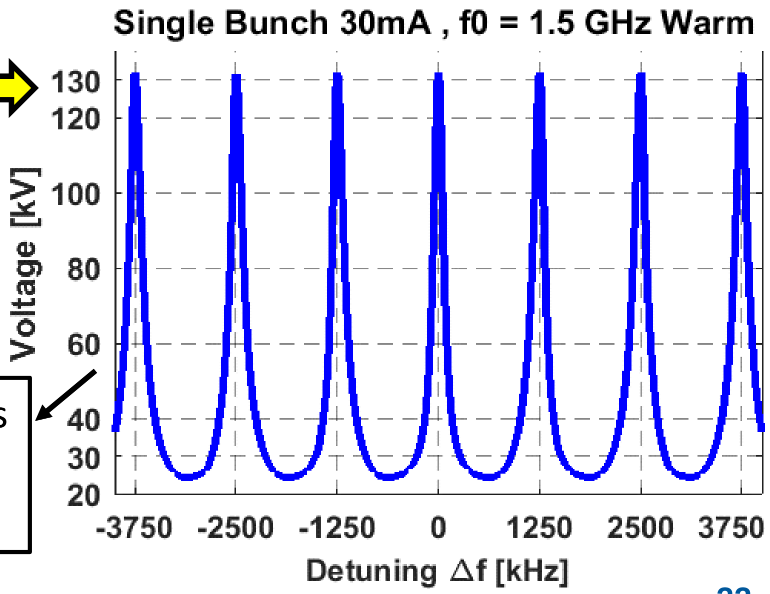


Single Bunch
$I_b = 30\ mA$
$\sigma_t = 35\ ps$
T_{rev} = 800 ns

Is required for any filling pattern construction.



Peak Voltage vs. Cavity Detuning

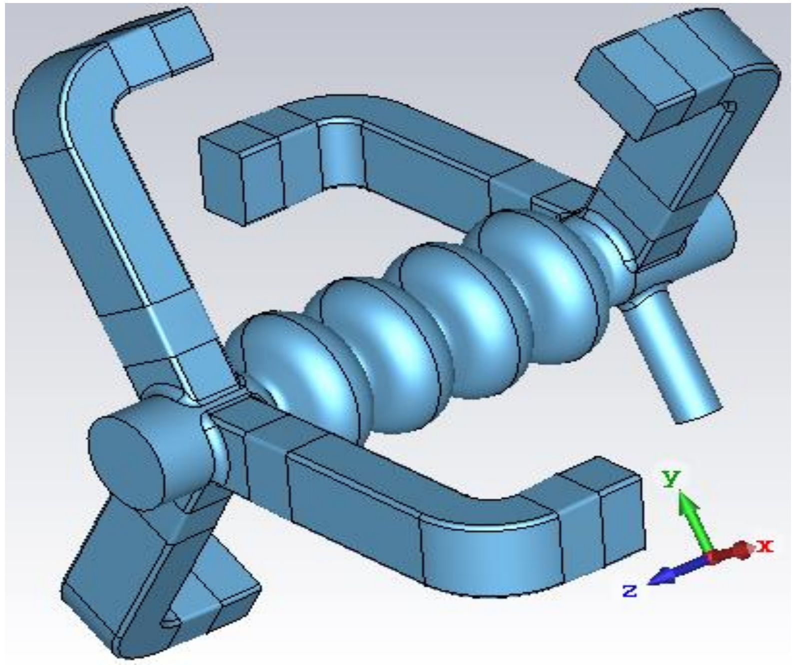


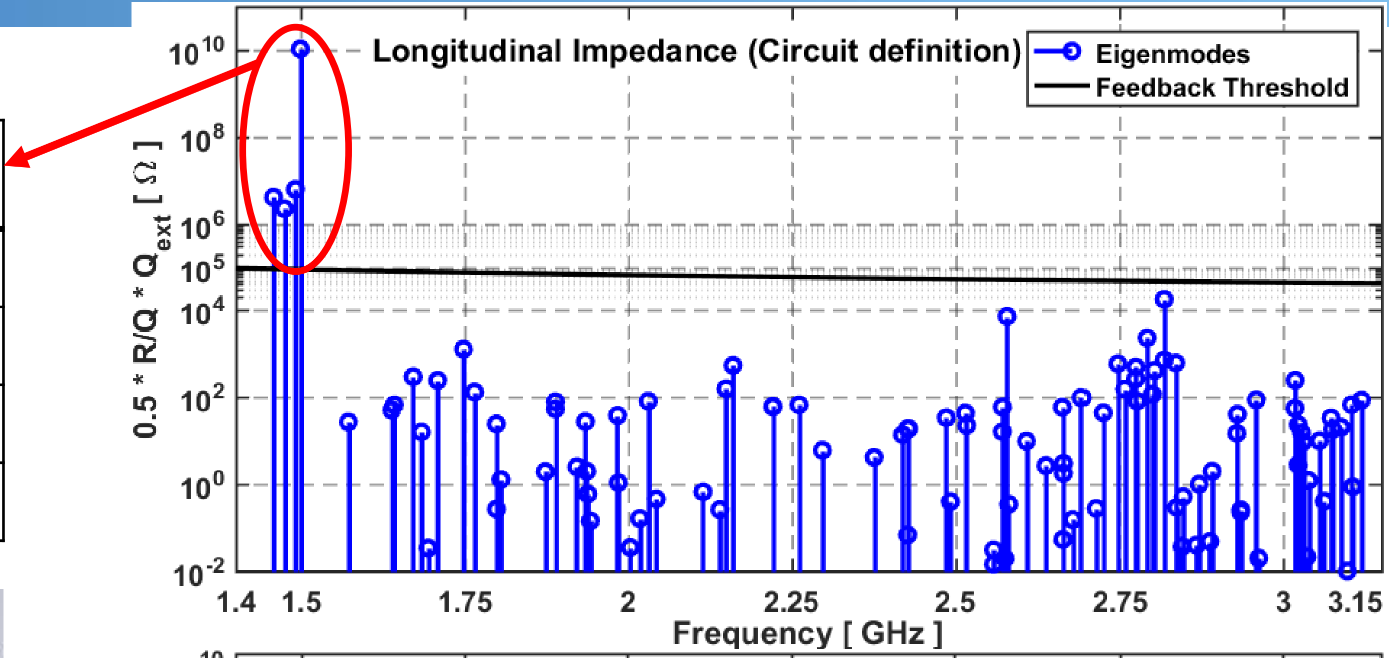
- Clearly seen 1.25 MHz harmonics
- Beam phase & peak voltage depends on detuning

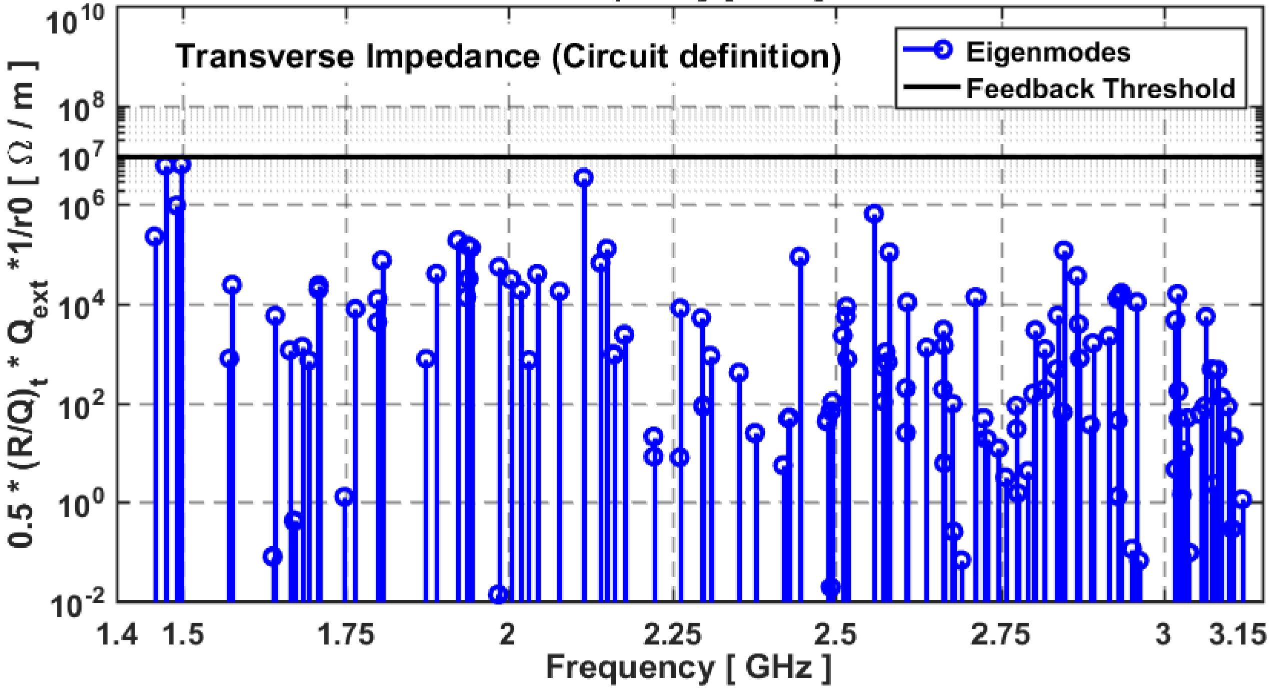
VSR 1.5GHz Cavity Impedances from Eigenmodes

Monopole Band

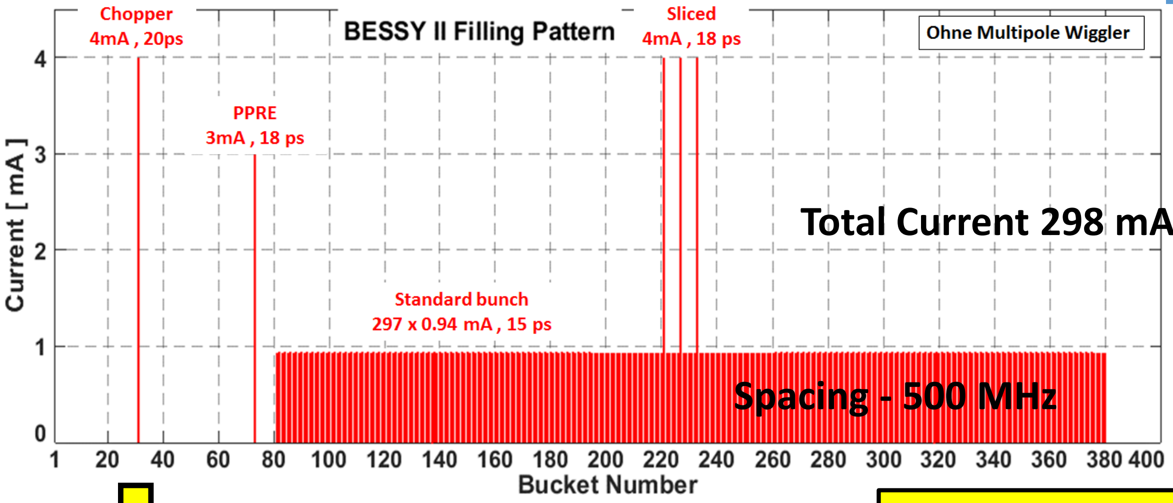
	Frequency [GHz]	R/Q [Ω]	Q_{ext}	Mode Type
1	1.49866	386	$5.00 \cdot 10^7$	π
2	1.49134	0.41	$2.98 \cdot 10^7$	2π/3
3	1.47424	0.09	$4.74 \cdot 10^7$	π/2
4	1.45785	0.05	$1.60 \cdot 10^8$	2π





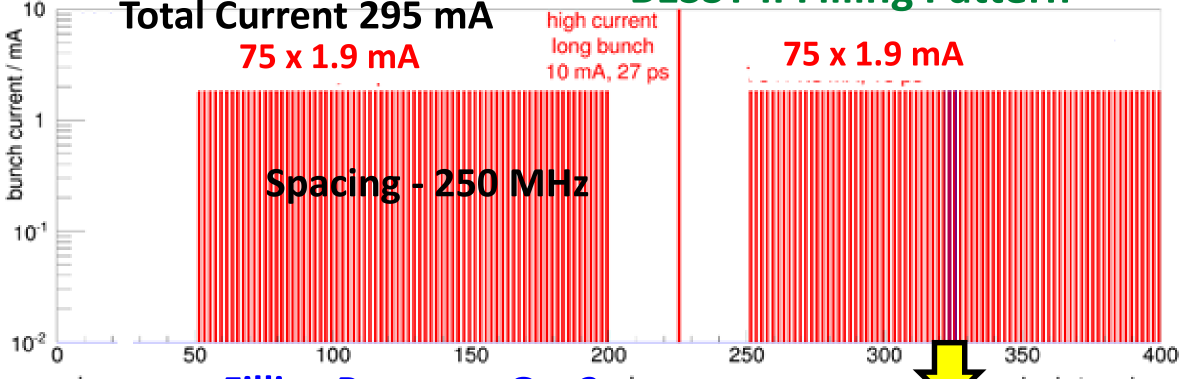


Cold Parking Monopole Mode Voltages vs. Detuning

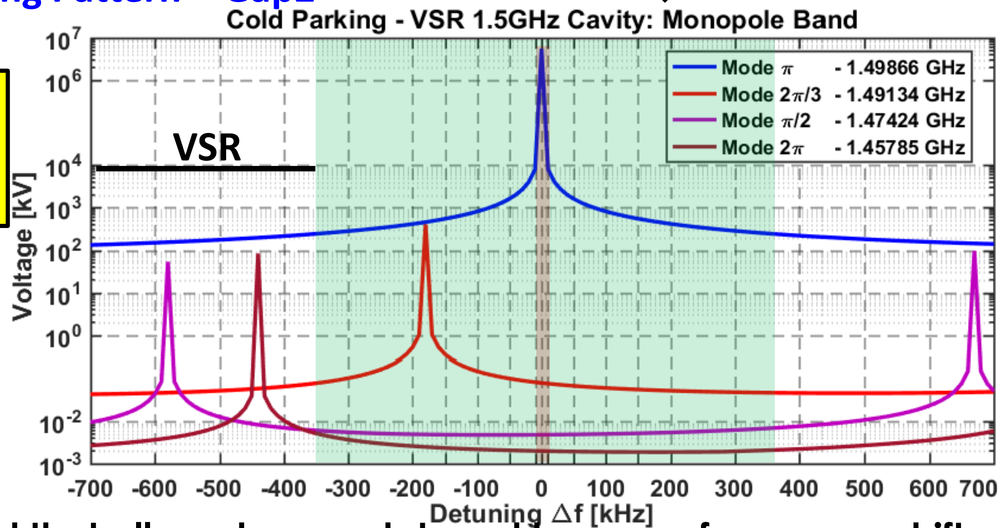


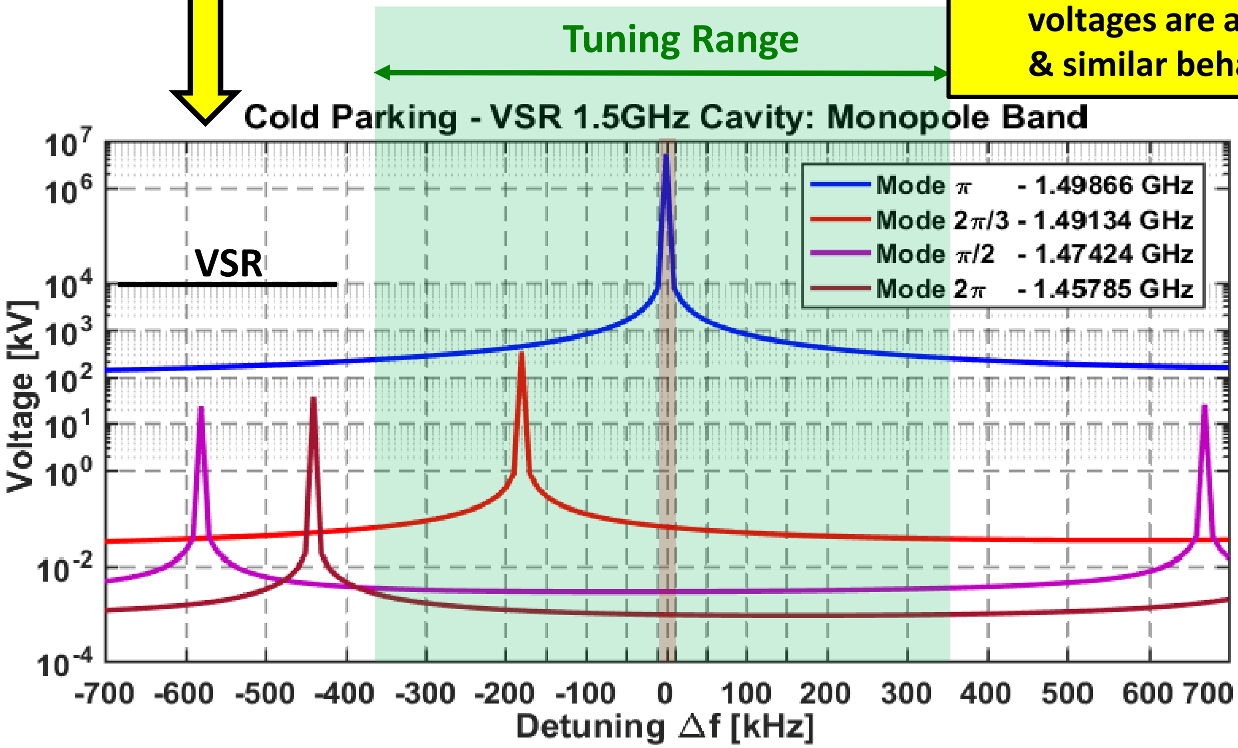
Filling Pattern – Gap1

BESSY II Filling Pattern



Filling Pattern – Gap2

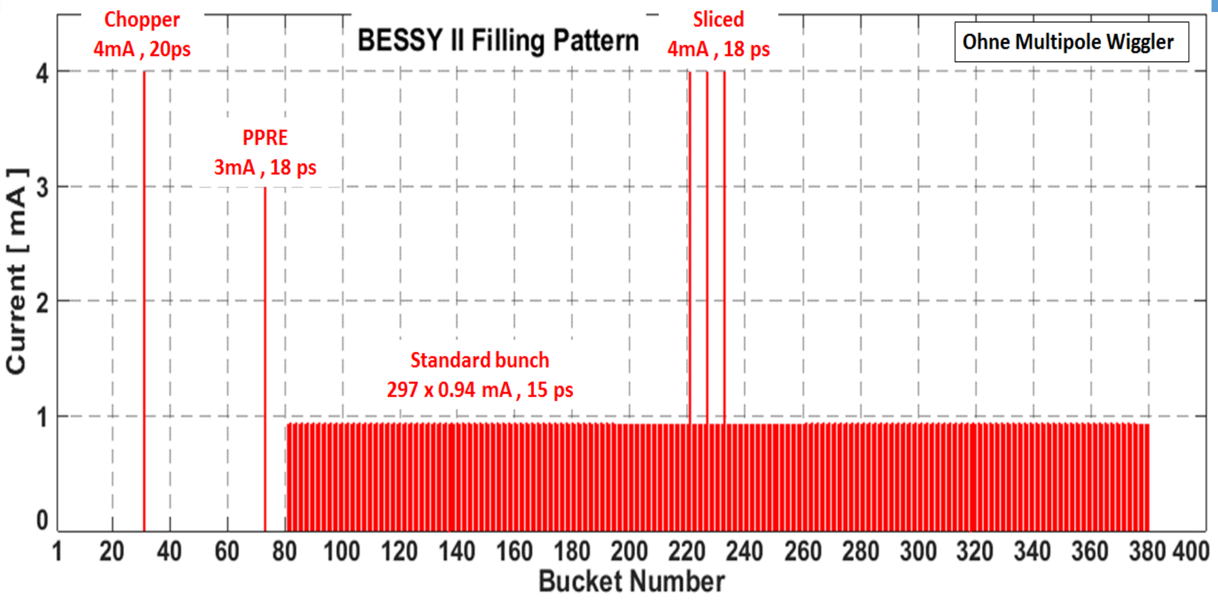


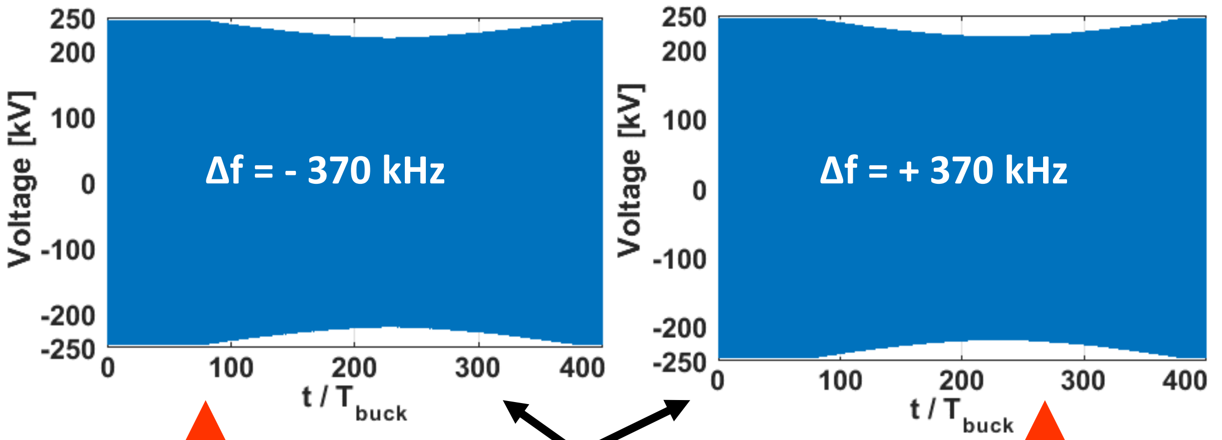


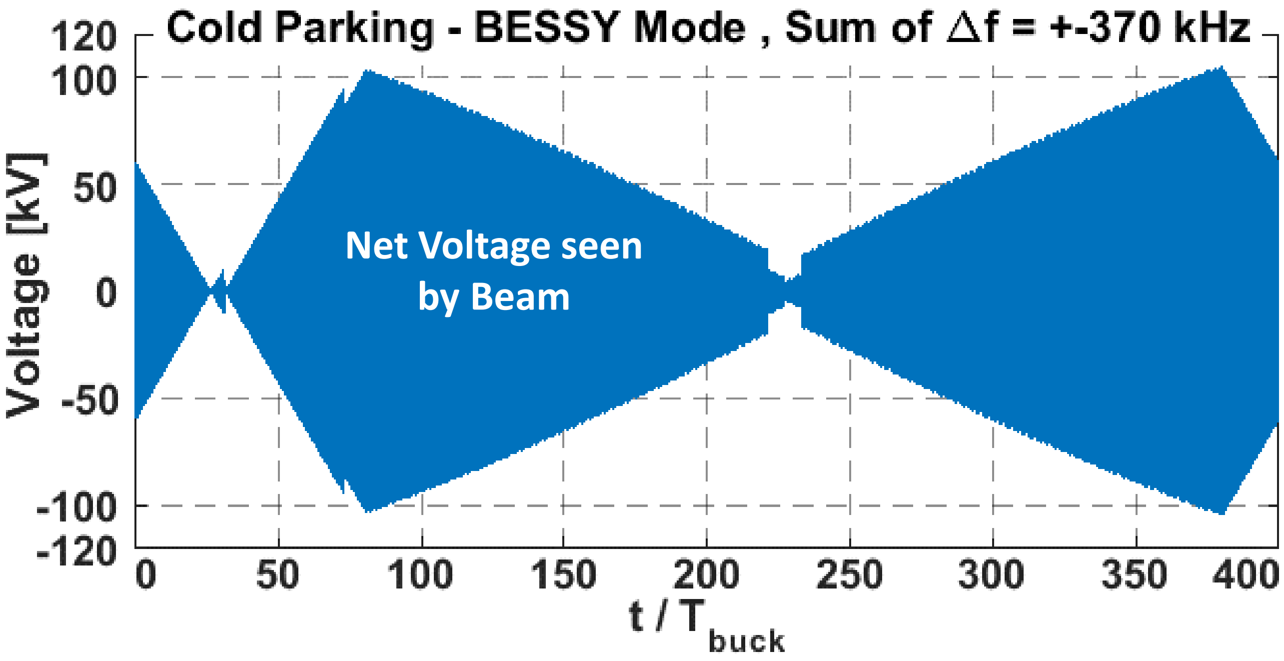
- For both filling patterns voltages are at the same level & similar behavior on detuning.

- Is assumed that all modes are detuned by same frequency shift as fundamental one.
- The 2π/3 mode has ~335kV voltage at ca. -180kHz detuning & is asymmetric with respect to tuning direction. Is important for cold parking operation.
- At VSR operation the residual monopole band modes will be excited very weekly and can be neglected.

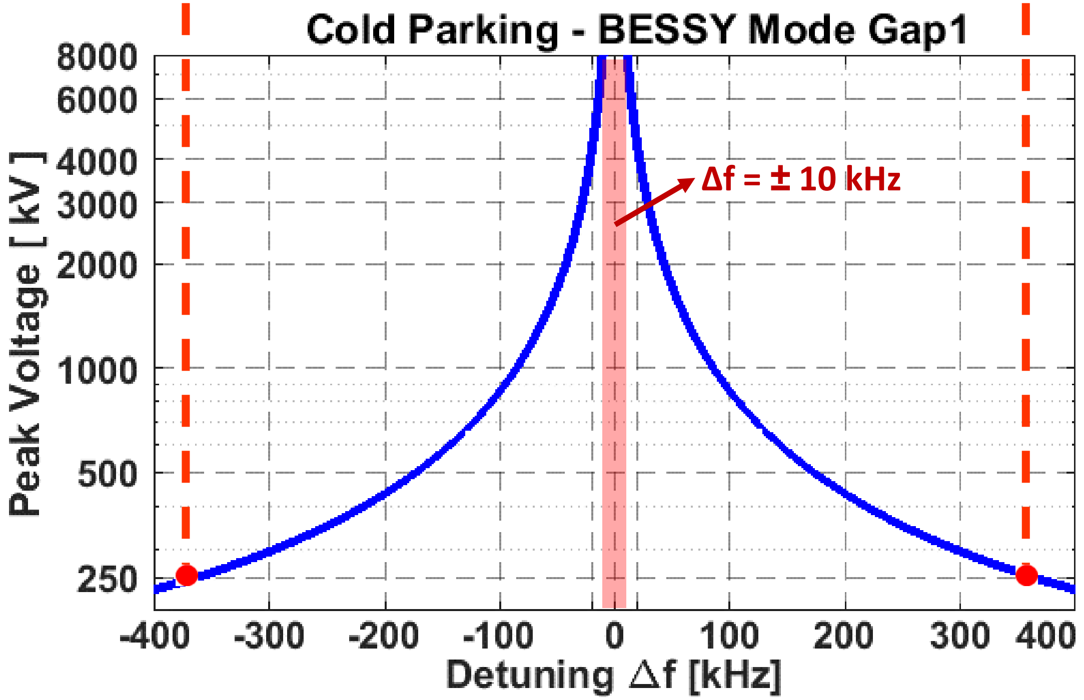
Cold Parking – Voltage profiles for Filling Pattern Gap1







- ➢ Beam phases are different

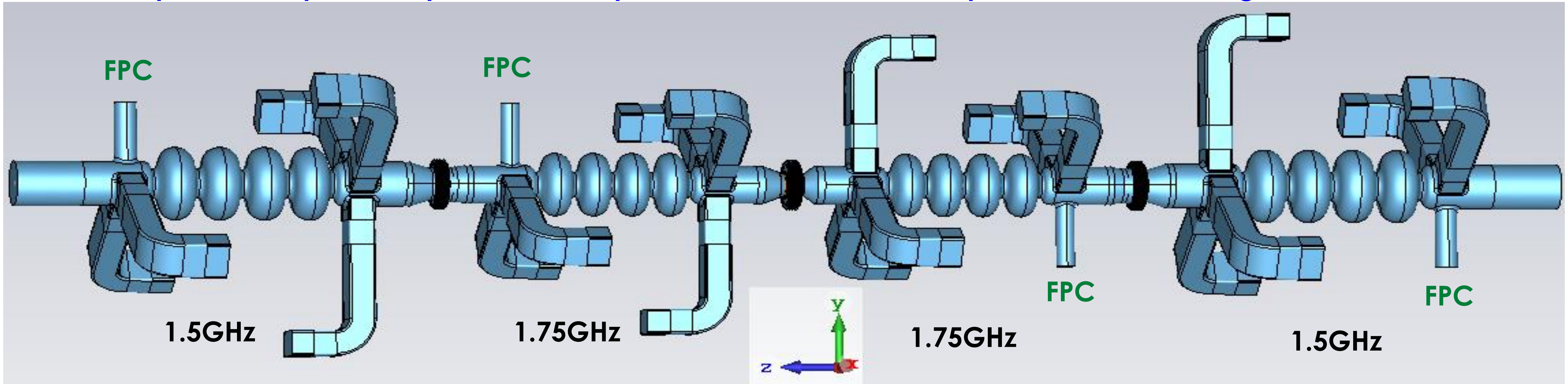


Outline

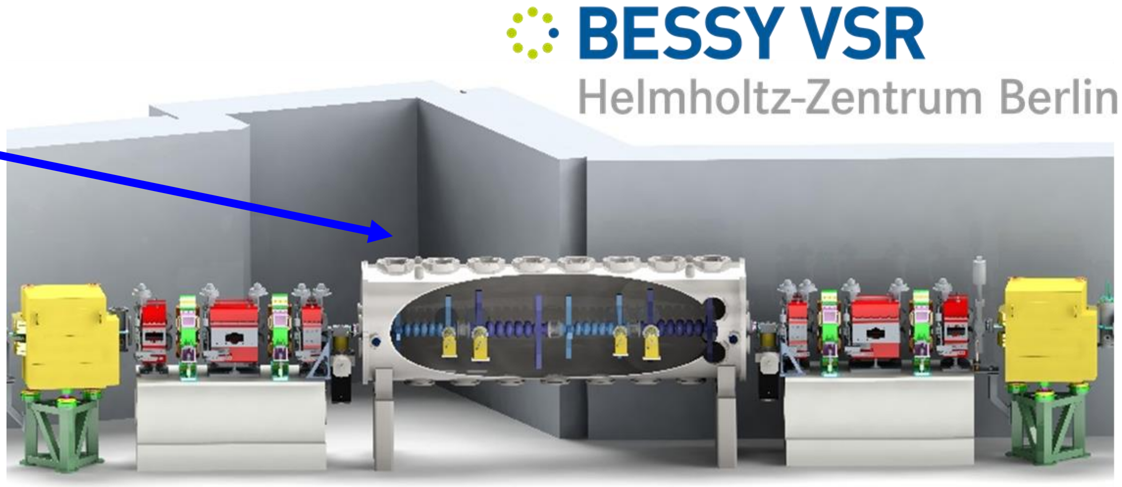
- Introduction to BESSY II storage ring
- SRF Upgrade - BESSY VSR & Highlights
- SRF Cavity Specific Designs
- Beam Loading & Cold Parking
- **HOM Power Levels in SRF Module**
- Outlook

Optimal Cavity Arrangement in the Module

Optimal Setup for Coupler Kick Compensation & HOM Power Equal Distribution Along the Module

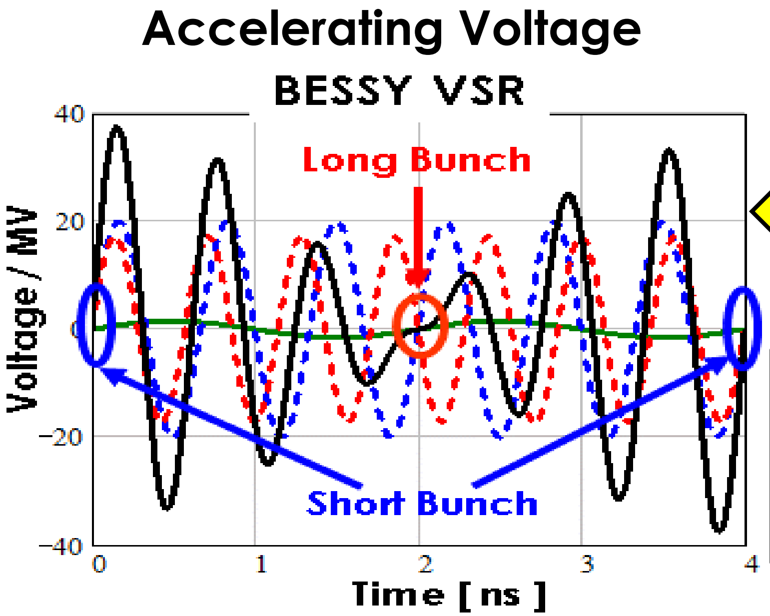


Space availability in the tunnel should be checked. On the back plane is synchrotron radiation beamline.



Coupler Kicks

RF Kick from Couplers with Same Orientation
(Fundamental Modes -1.5GHz & 1.75GHz)

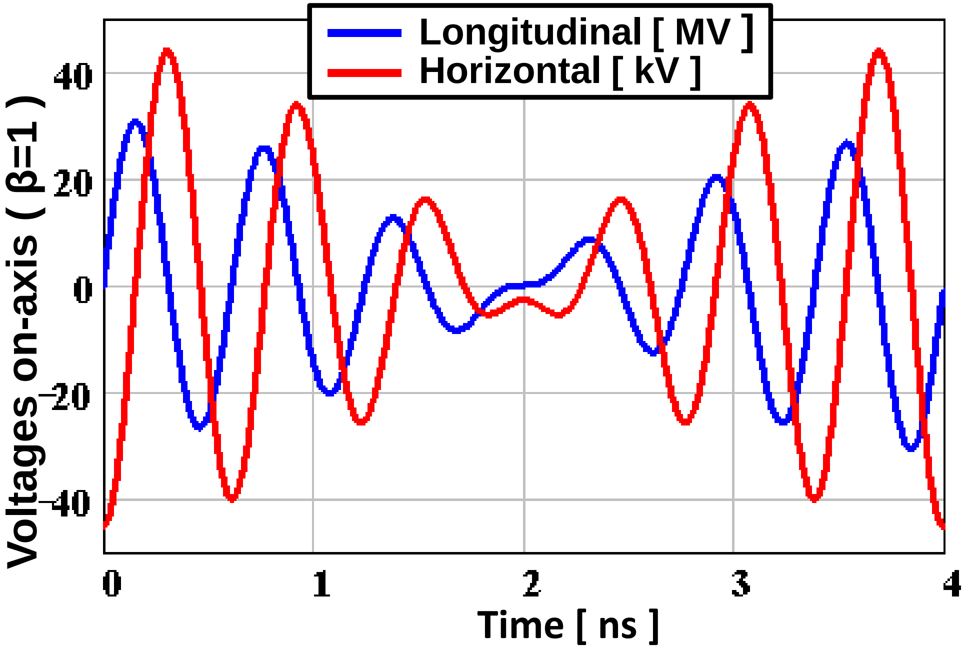


Acc. Voltages Amplitudes
1.500 MV @ 0.50 GHz
16.00 MV @ 1.50 GHz
14.14 MV @ 1.75 GHz

Trans. – Long. Voltage relations

$$\frac{|V_y|\ [kV]}{|V_z|\ [MV]} \sim 1.5$$

$(for\ both\ 1.5GHz\ \&\ 1.75GHz\ Cavities)$



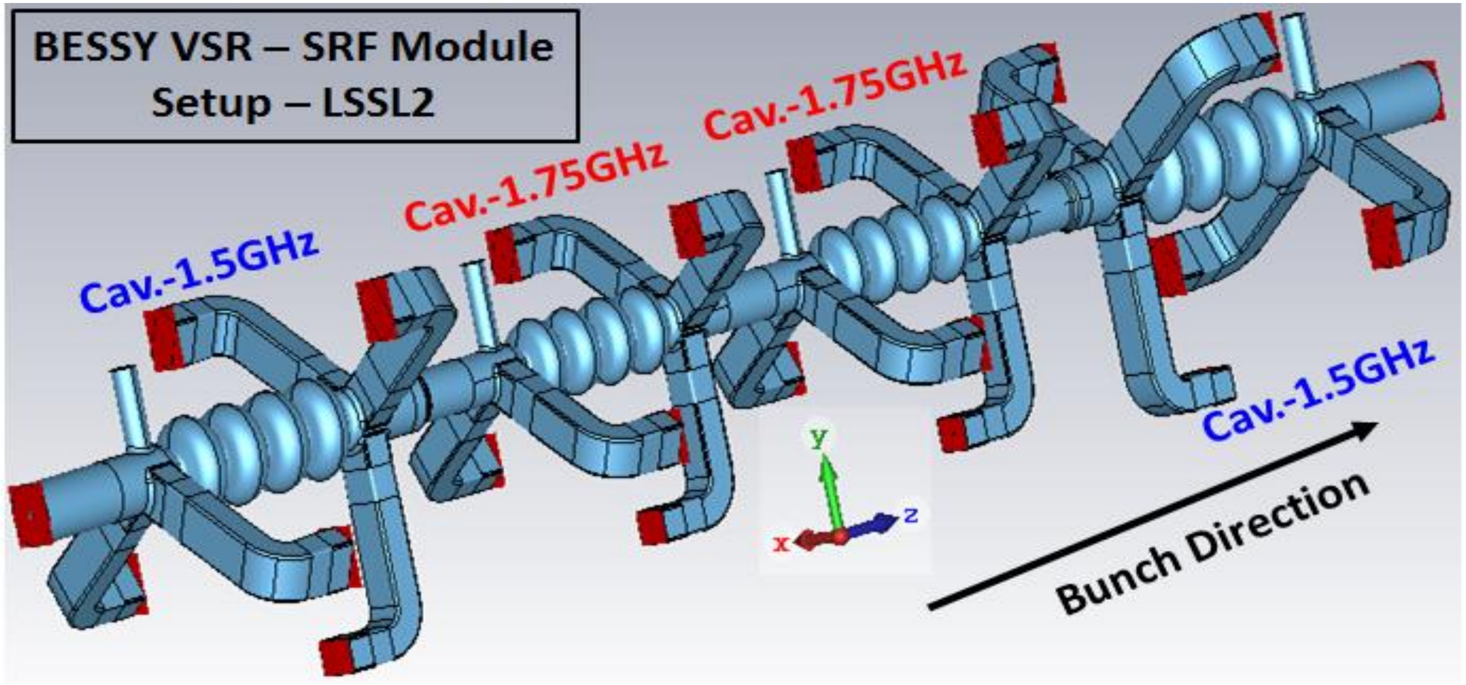
Coupler Kick (Fundamental Mode)

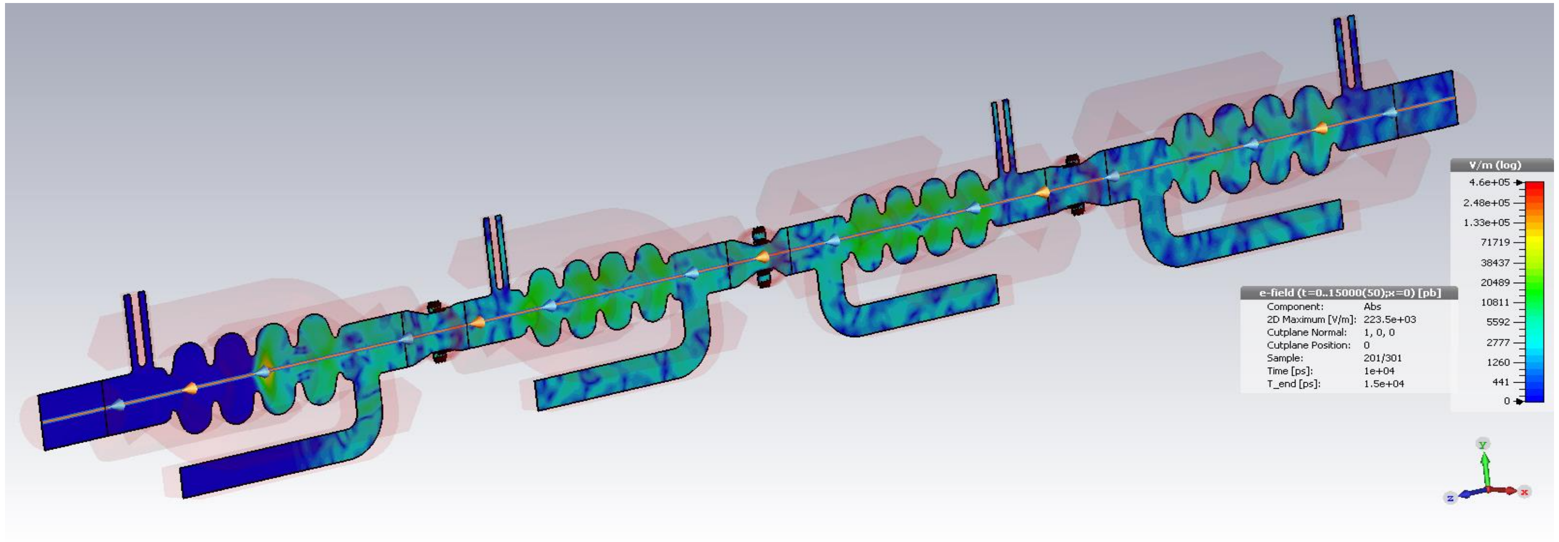
$max(V_y) \sim 45\ kV$

$$y' = eV_y/Energy \xrightarrow{1.7GeV} 27\ \mu rad$$

- A. Tsakanian et al, Study on RF coupler kicks of SRF cavities in the BESSY VSR module , IPAC'18, WEPML048
- T. Mertens et al, Impact of RF coupler kicks on beam dynamics in BESSY VSR, IPAC'18, THPAF084

HOM Power Levels in SRF Module





Wakefield Simulations

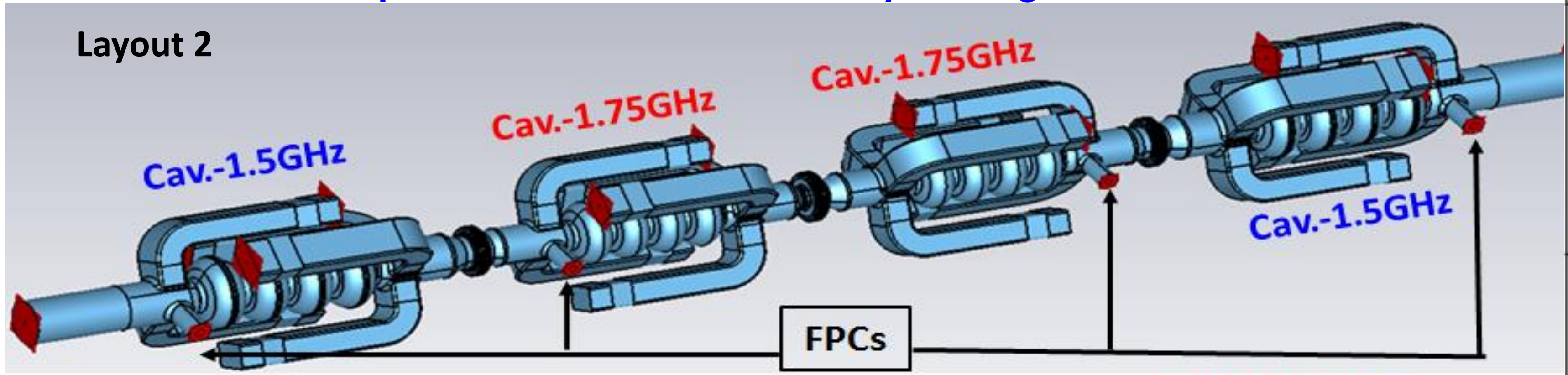
- Long Range Wakes~ 20m
- Spectral Weighting of all Port Signals with Beam Spectrum
- Expected HOM Power Levels & Spectrum
- Efficiency of HOM Damping

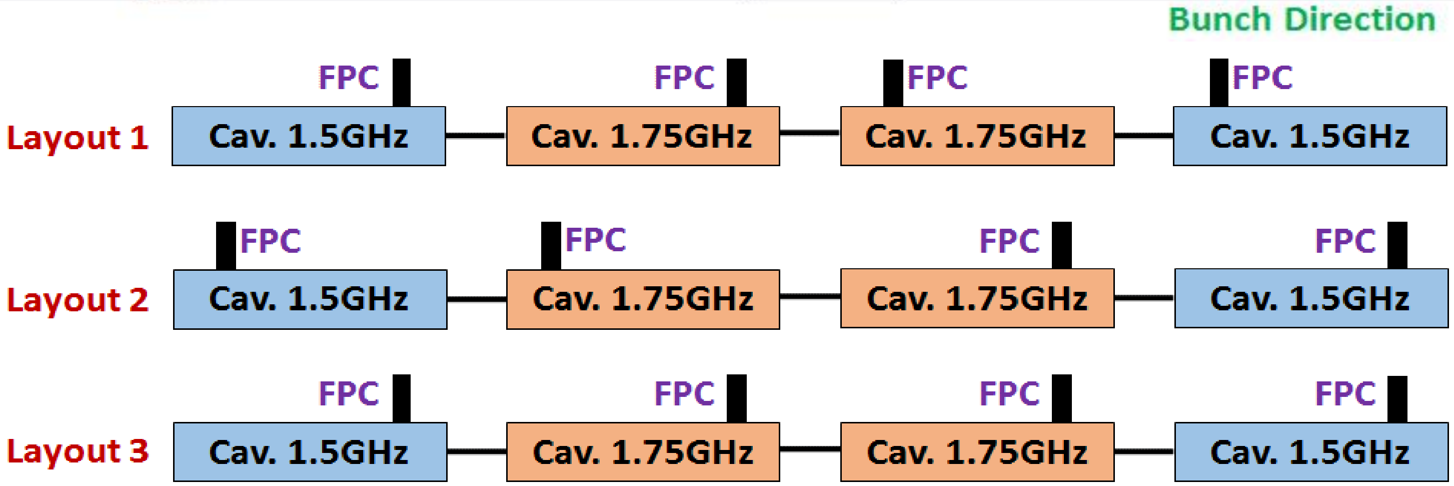
➢ Analyze different cavity arrangements in the module to reach optimal operation conditions with equally distributed power portions in warm HOM loads.

➢ Study on different FPC locations (Upstream - Downstream) to minimize the flown HOM powers & redirect to wavguide dampers. (RF window issues)

HOM Power Levels in SRF Module

Different FPC positions of the 4-cell cavity arrangement in SRF module

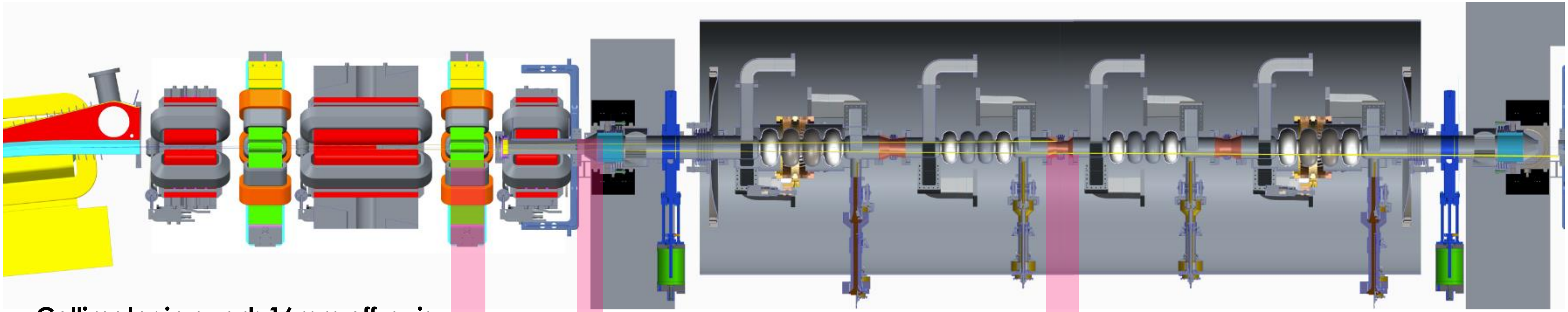




- Layout 2 is the optimal setup in terms of equally distributed HOM power portions along the SRF module.
- Low HOM power at FPC to protect RF windows.
- Technically difficult to achieve due to the limited space in the low-beta straight of the ring.

Component	Port	HOM Power [W]		
		Layout 1	Layout 2	Layout 3
Cavity 1.5 GHz Upstream	FPC(1)	25	28	61
	WG(1)	115	107	206
	WG(1)	115	107	206
	WG(2)	136	157	74
	WG(2)	136	157	74
	WG(2)	172	193	90
Cavity 1.75 GHz Upstream	FPC(1)	66	67	73
	WG(1)	267	265	305
	WG(1)	267	265	305
	WG(2)	204	187	179
	WG(2)	204	187	179
	WG(2)	243	213	220
Cavity 1.75 GHz Downstream	FPC(1)	107	72	114
	WG(1)	314	261	316
	WG(1)	314	261	316
	WG(2)	171	245	171
	WG(2)	171	245	171
	WG(2)	203	282	211
Cavity 1.5 GHz Downstream	FPC(1)	59	25	74
	WG(1)	208	112	203
	WG(1)	208	112	203
	WG(2)	74	143	80
	WG(2)	74	143	80
	WG(2)	90	184	83
BmP	Upstr.	230	300	230
	Downstr.	363	380	290
Total		4534	4693	4515

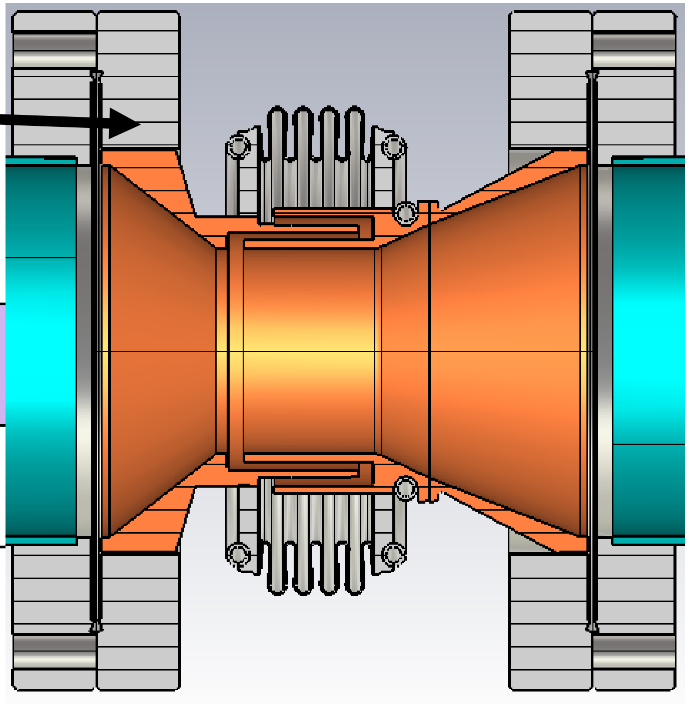
Synchrotron Light Power Depositions



Collimator in quad: 16mm off-axis

Moveable collimator in taper: ≤16mm off-axis

Collimator shielded bellow: 26mm radius



Mandatory to fetch power outside the module or at 5K-level

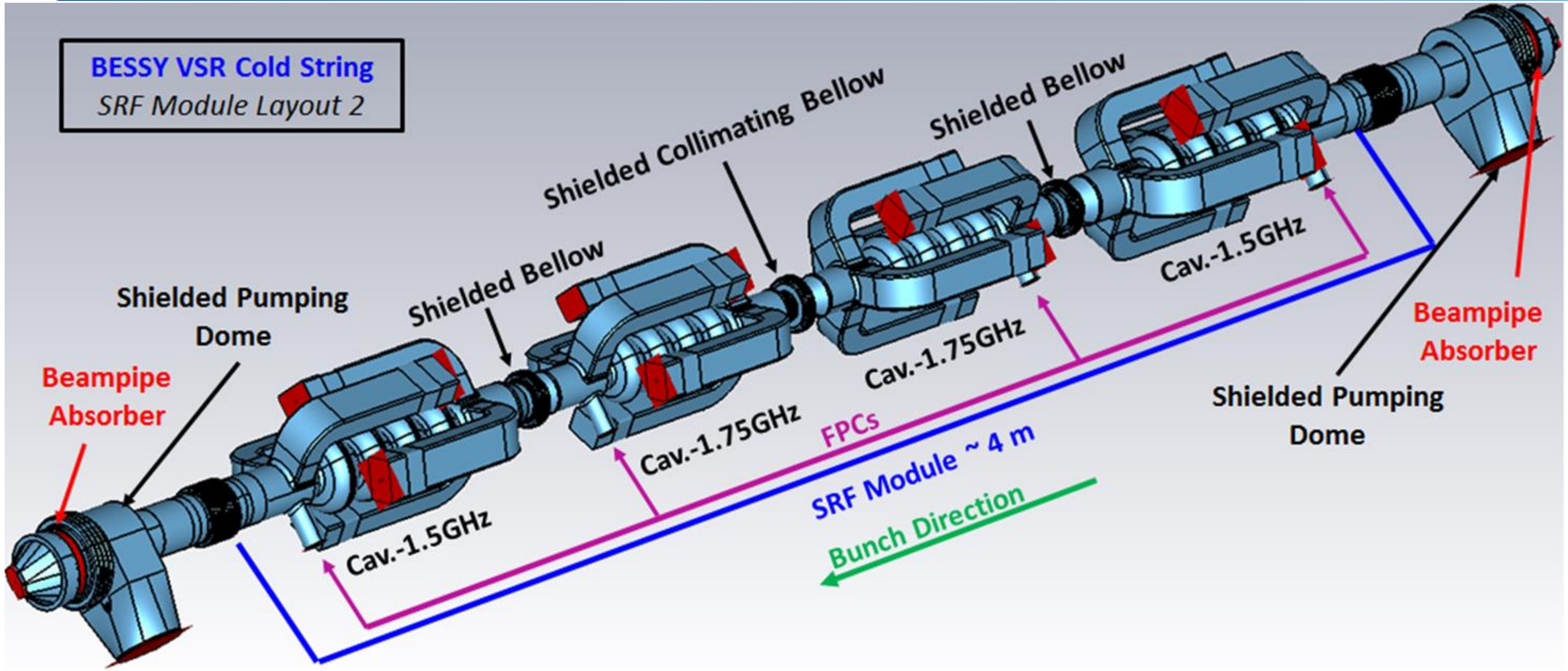
P_{rad} @ …	… collimator in quadrupole	… on moveable collimator	… collimating bellow	… leaving cold module
Moveable not activated	63 W	0 W	11 W	15.3 W

Data courtesy of Markus Ries

- H.-W. Glock et al, Design of the beamline elements in the BESSY VSR cold string, IPAC'18, THPMF033

Courtasy of H.-W. Glock

HOM Power Distribution in Cold String

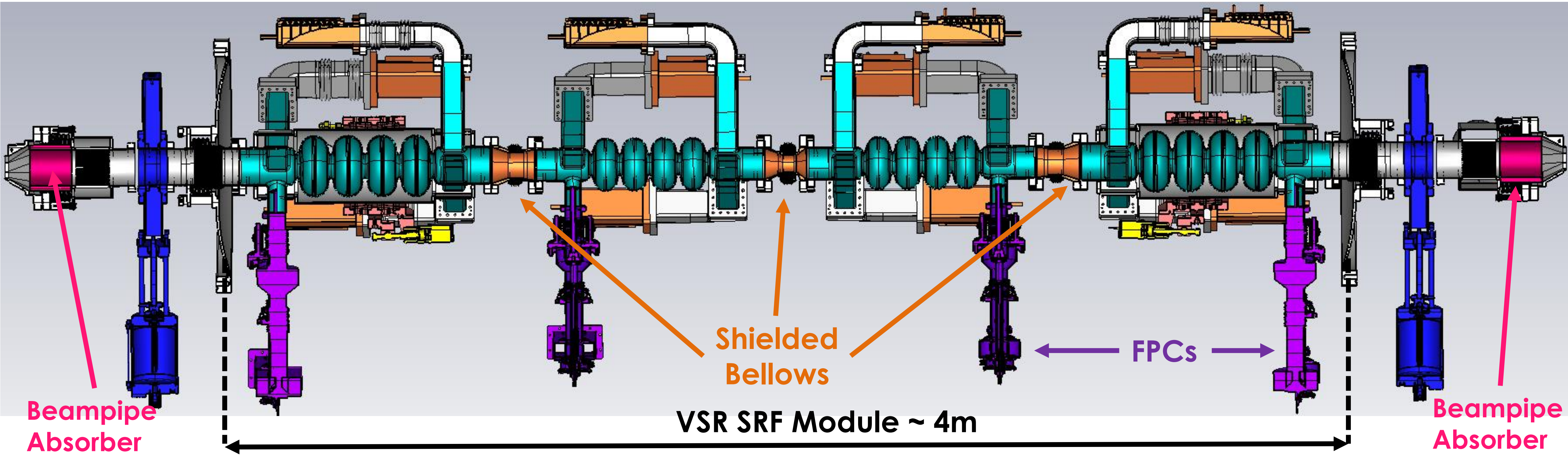


Component	Port	HOM Power [W] Baseline 300mA	Extended 300mA	Single 30mA
Cavity 1.5 GHz Upstream	FPC(1)	↑ 62	57	30
	WG(1)	↑ 197	170	139
	WG(1)	↑ 197	170	139
	WG(2)	166	145	133
	WG(2)	166	145	133
	WG(2)	202	180	137
Cavity 1.75 GHz Upstream	FPC(1)	66	62	40
	WG(1)	255	231	148
	WG(1)	255	231	148
	WG(2)	183	168	134
	WG(2)	183	168	134
	WG(2)	206	192	134
Cavity 1.75 GHz Downstream	FPC(1)	69	67	50
	WG(1)	258	228	180
	WG(1)	258	228	180
	WG(2)	249	229	123
	WG(2)	249	229	123
	WG(2)	284	260	125
Cavity 1.5 GHz Downstream	FPC(1)	↑ 33	31	26
	WG(1)	↑ 151	126	134
	WG(1)	↑ 151	126	134
	WG(2)	140	124	106
	WG(2)	140	124	106
	WG(2)	176	156	110
BmP	Upstr.	54	47	16
	Downstr.	143	126	46
Pump. Dome	Upstr.	20	18	7
	Downstr.	17	15	8
BmP Absorber	Upstr.	273	241	185
	Downstr.	367	320	247
Total		5170	4611	3357

- The HOM power at FPC end-groups of 1.5GHz cavities located at both ends of the module are significantly increased due to the warm components – outside of the module.
- The power levels & balance inside the module is unperturbed.
- The beam pipe absorber losses are underestimated, because of sparse field-probe sampling in dielectric. More accurate simulations are foreseen & 1-2kW power dissipation in two absorbers is expected (see ref.).

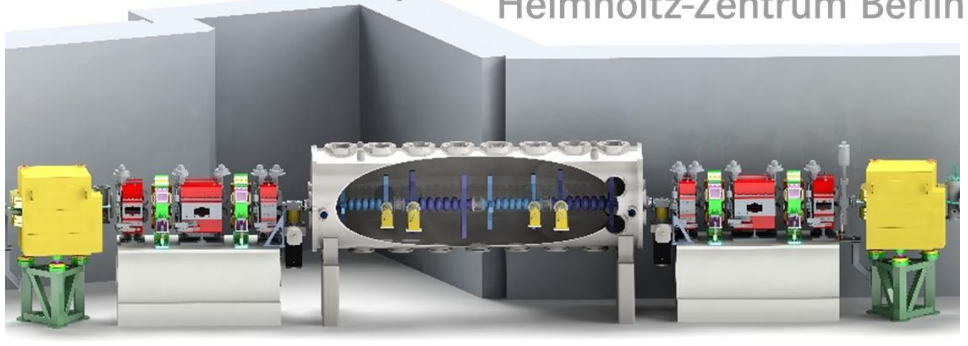
- A. Tsakanian et al, HOM power levels in the BESSY VSR cold string, IPAC'18, WEPML048
- T. Flisgen et al, Estimation of Dielectric Losses in Beam Pipe Absorbers, IPAC'18, THPAF084

Outlook

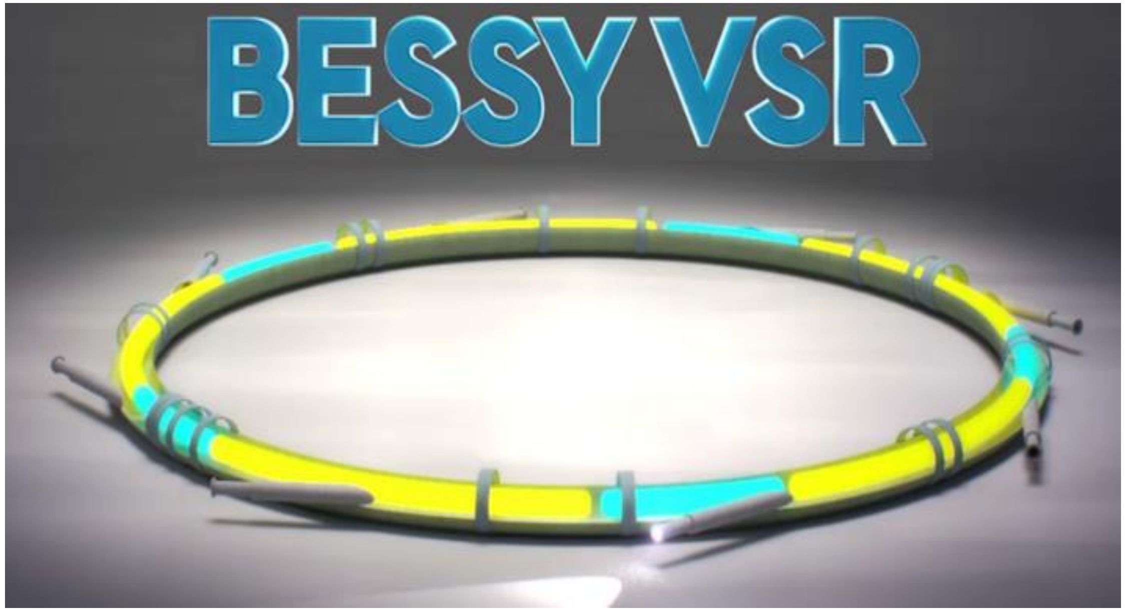


- Shielded bellows are required due to the cavity fundamental mode losses.
- Beampipe-absorbers for more HOM damping, especially excited by interaction with warm components.
- Synchrotron light collimating bellow is required at module center.
- Every component is optimized to fulfil off-resonance condition with respect to circulating beam.

BESSY VSR
Helmholtz-Zentrum Berlin



Outlook



Thank You for Your Attention !