SRF Implementation in BESSY VSR for Picosecond X-ray Pulse Production

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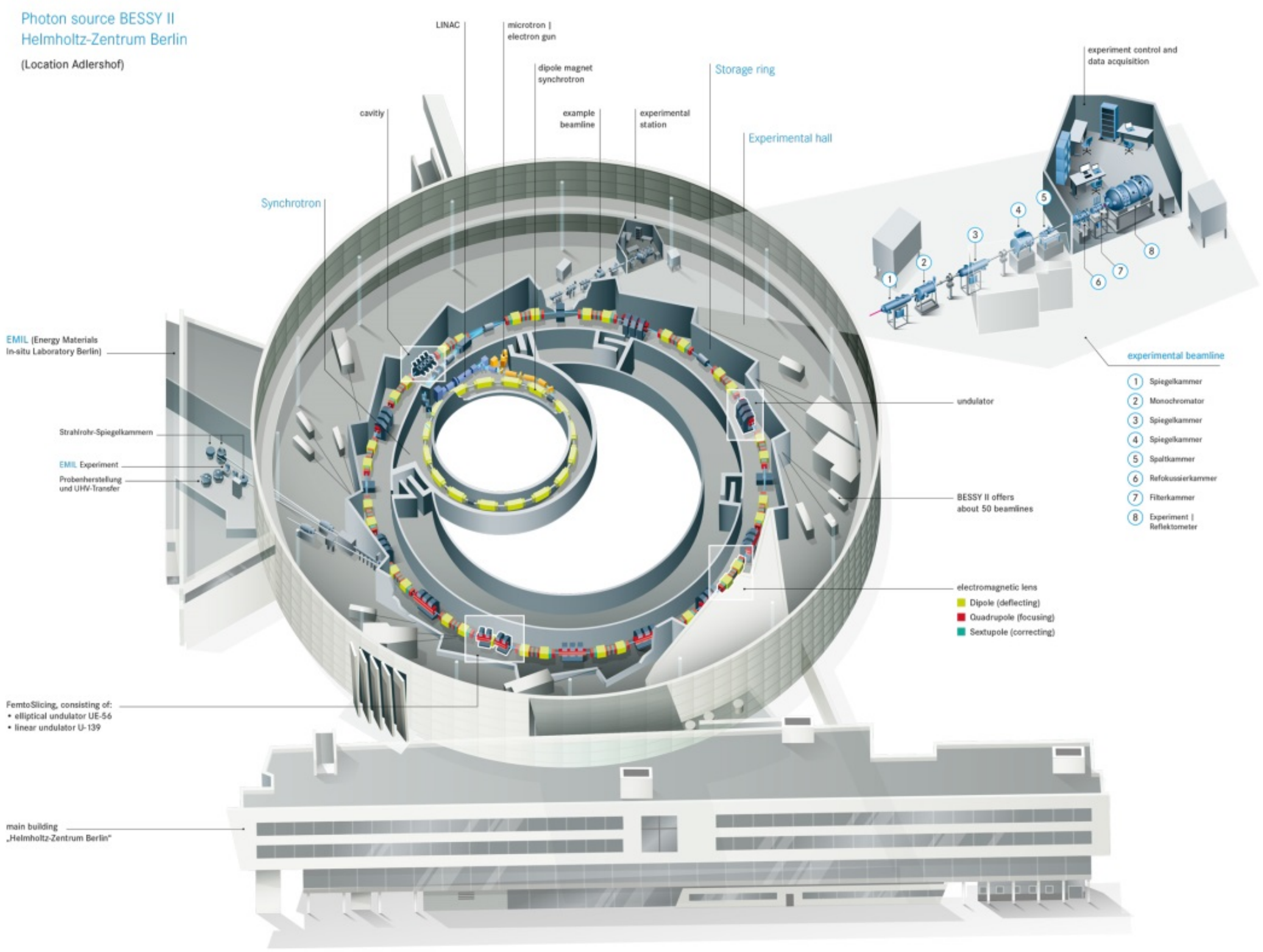
Outline

- Introduction to BESSY II storage ring
- SRF Upgrade - BESSY VSR & Highlights
- SRF Cavity Specific Designs
- 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

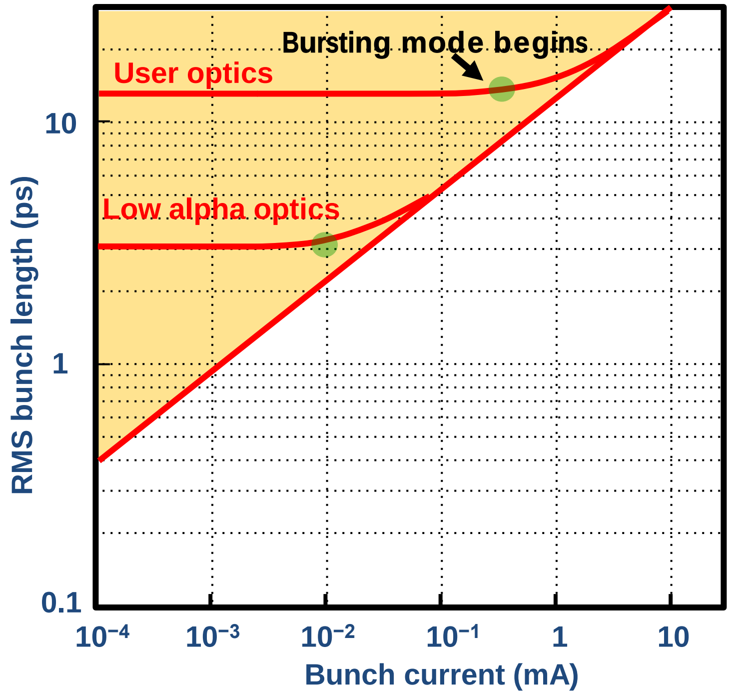
❖ Femtoslicing is continuously operated (only 1 beamline) -- Low flux

- Limited pulse length in storage ring

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

- At high current beam becomes unstable

- For ps pulses, flux is reduced by nearly 100



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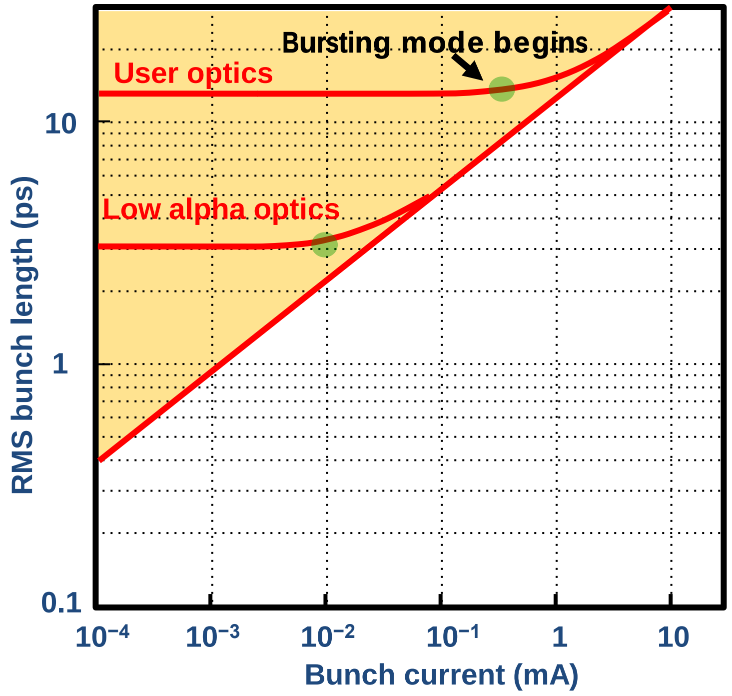
$$\sigma \propto \sqrt{\frac{\alpha}{\dot{V}_{\mathrm{rf}}}}$$

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

❖ 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?

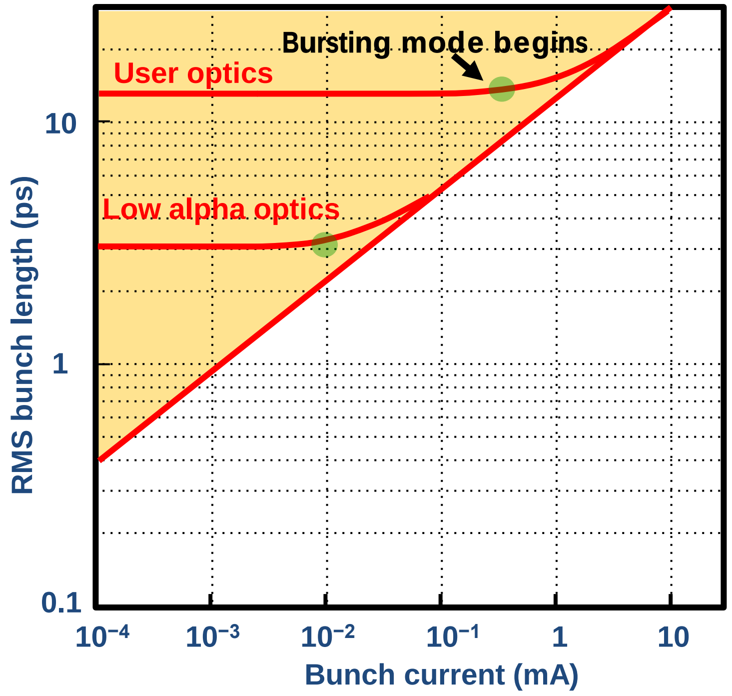
- Limited pulse length in storage ring

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

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

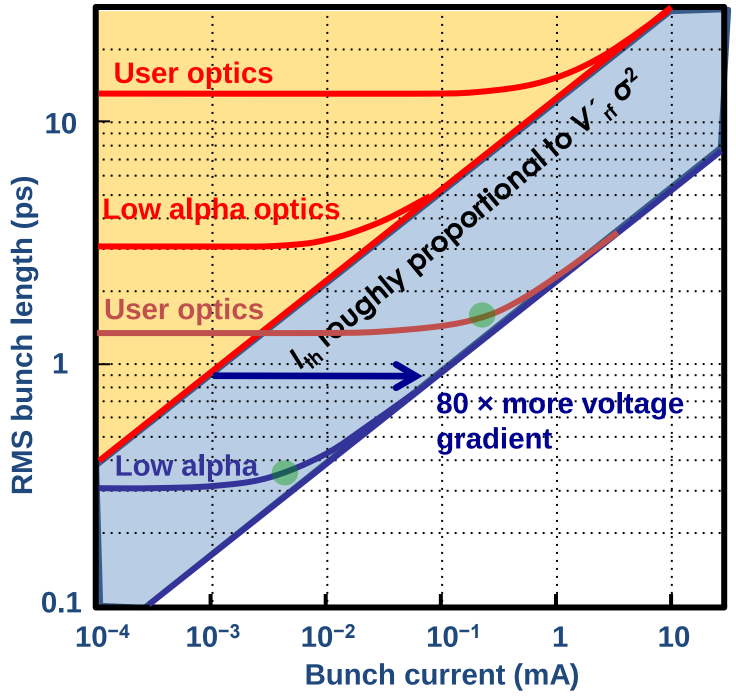
Normal conducting cavity system

- 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

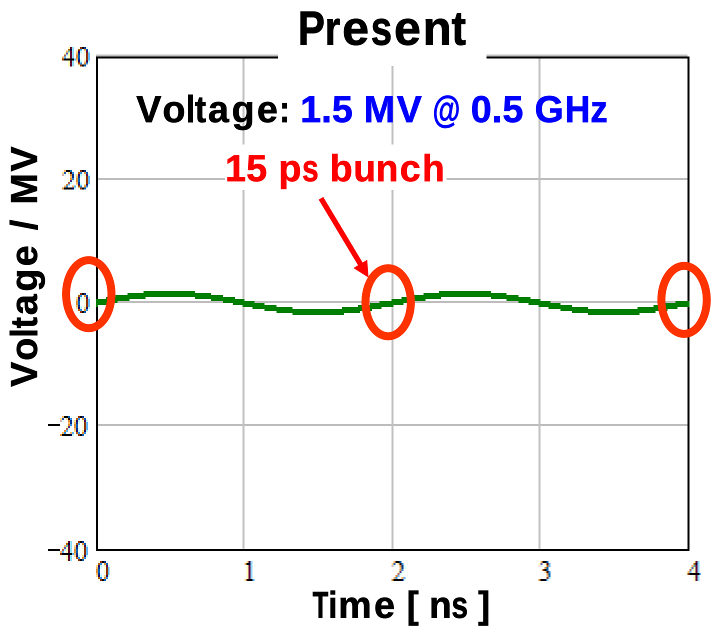


- ➢ Supply short pulses down to 1.5 ps (100 × more bunch current)
- ➢ Low α permits few 100 fs pulses
- ➢ Configure BESSY^{VSR} so 1.5 ps and 15 ps bunches can be supplied simultaneously for maximum flexibility and flux!

BESSY II, SC Upgrade – BESSY VSR

SC Upgrade

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



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

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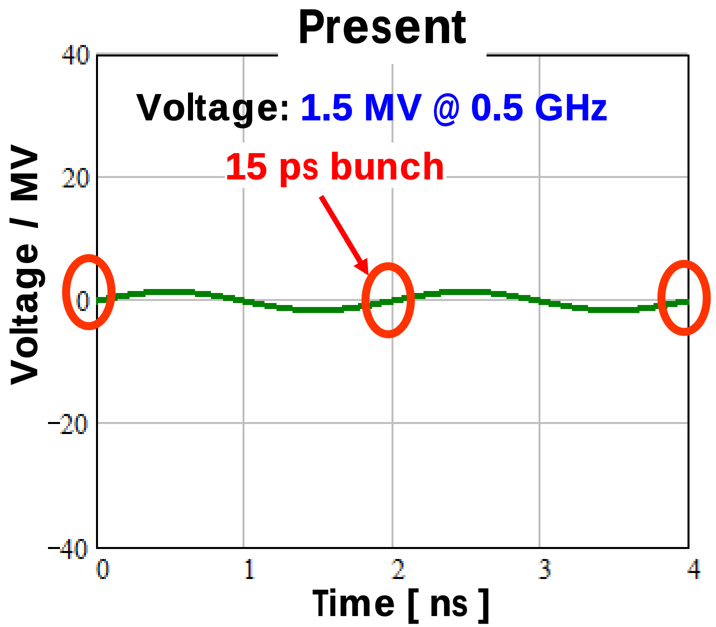

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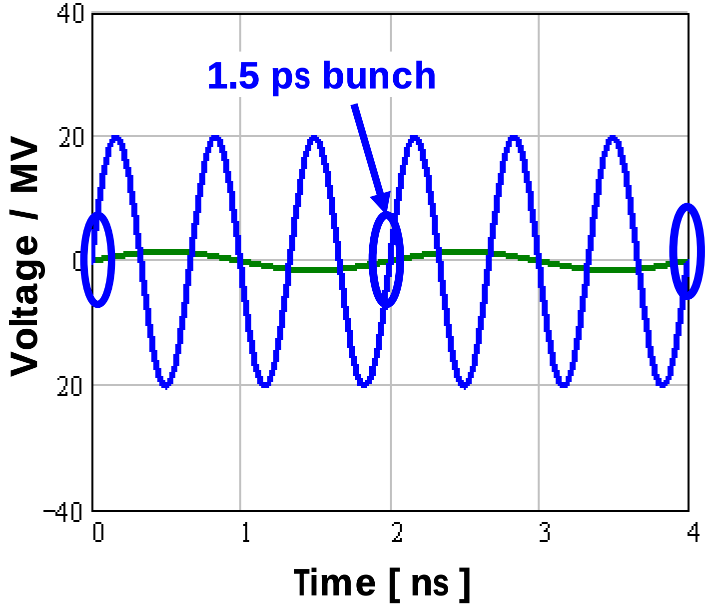

$$\dot{V} \propto V \times f_{rf} = 30\ MV \times GHz$$

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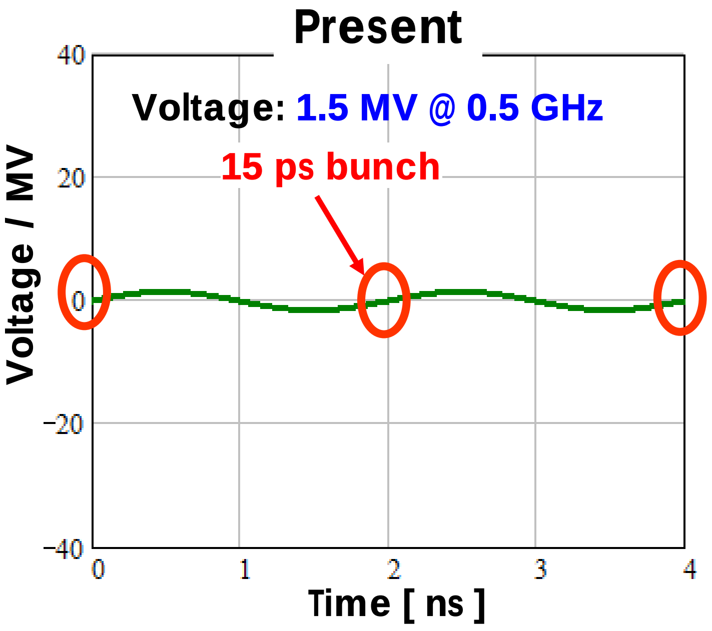
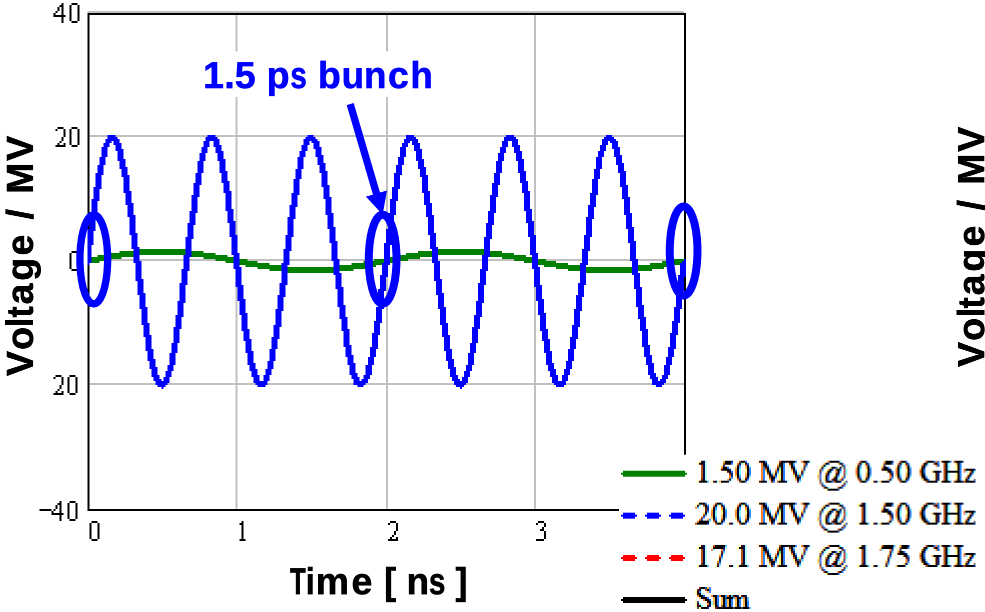
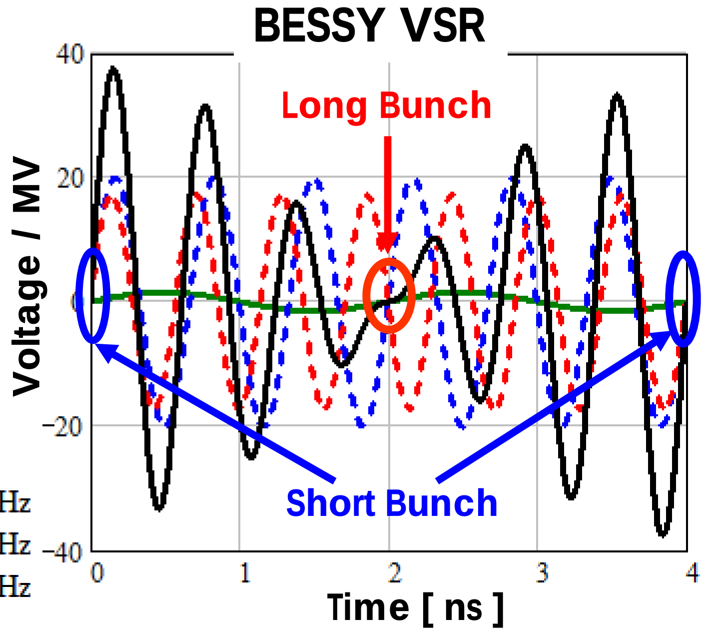


$\dot{V} \propto V \times f_{rf} = 0.75\ MV \times GHz$



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



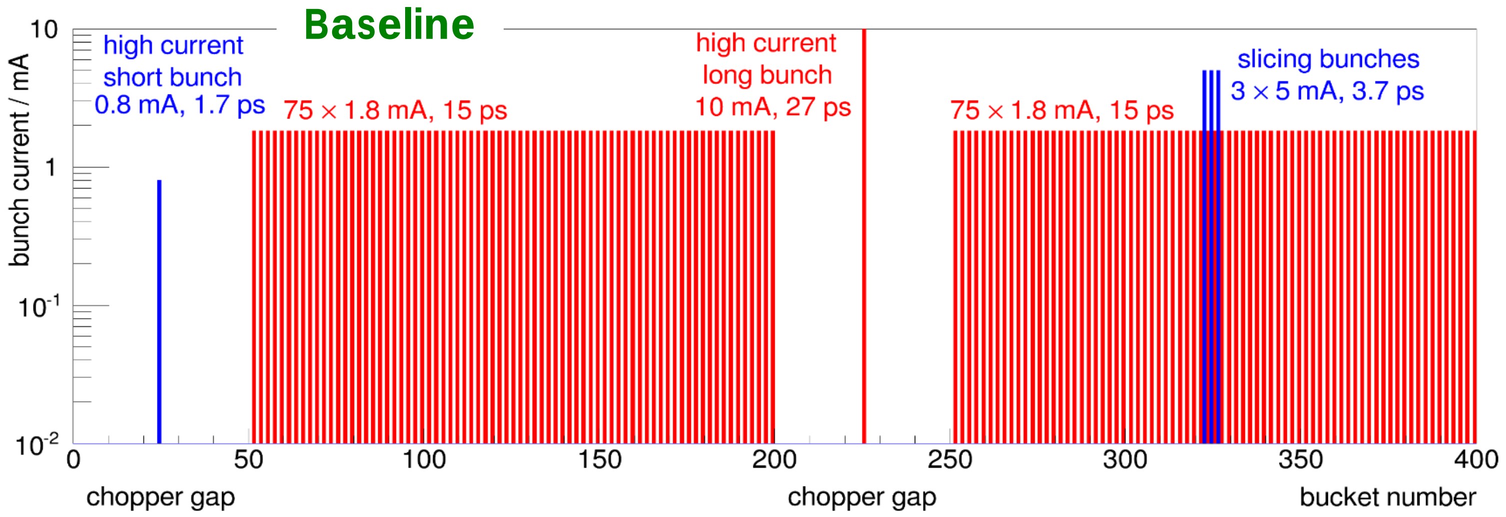
$\dot{V} \propto V \times f_{rf} = 60\ MV \times GHz$

- 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 …)



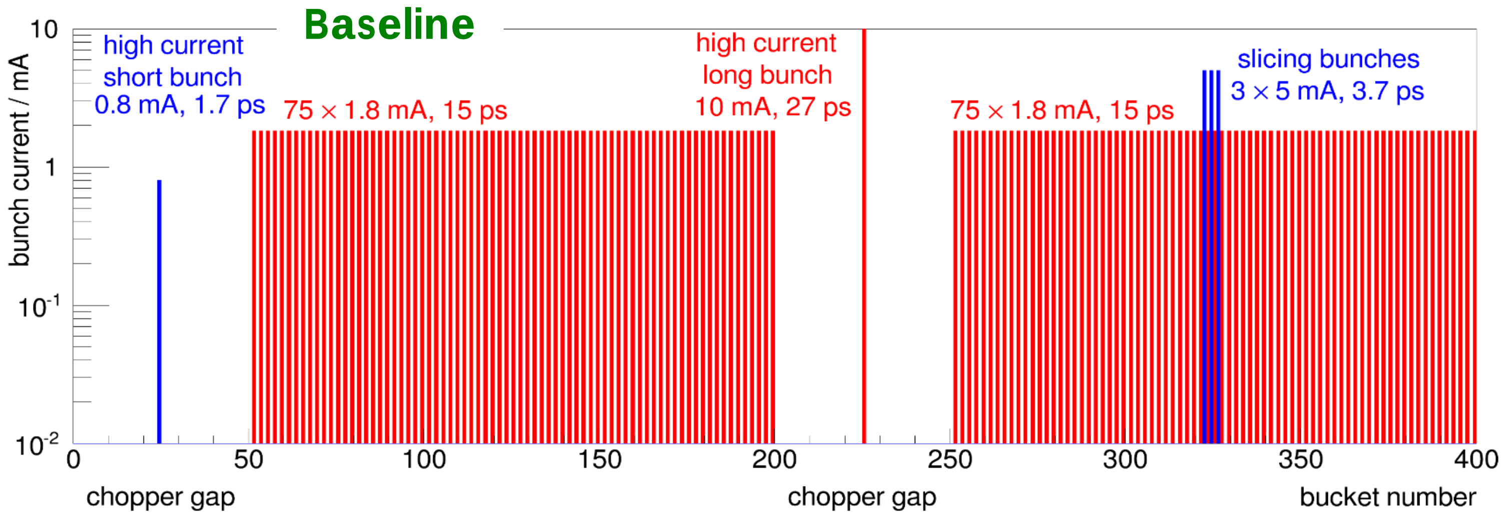
BESSY VSR Filling Patterns

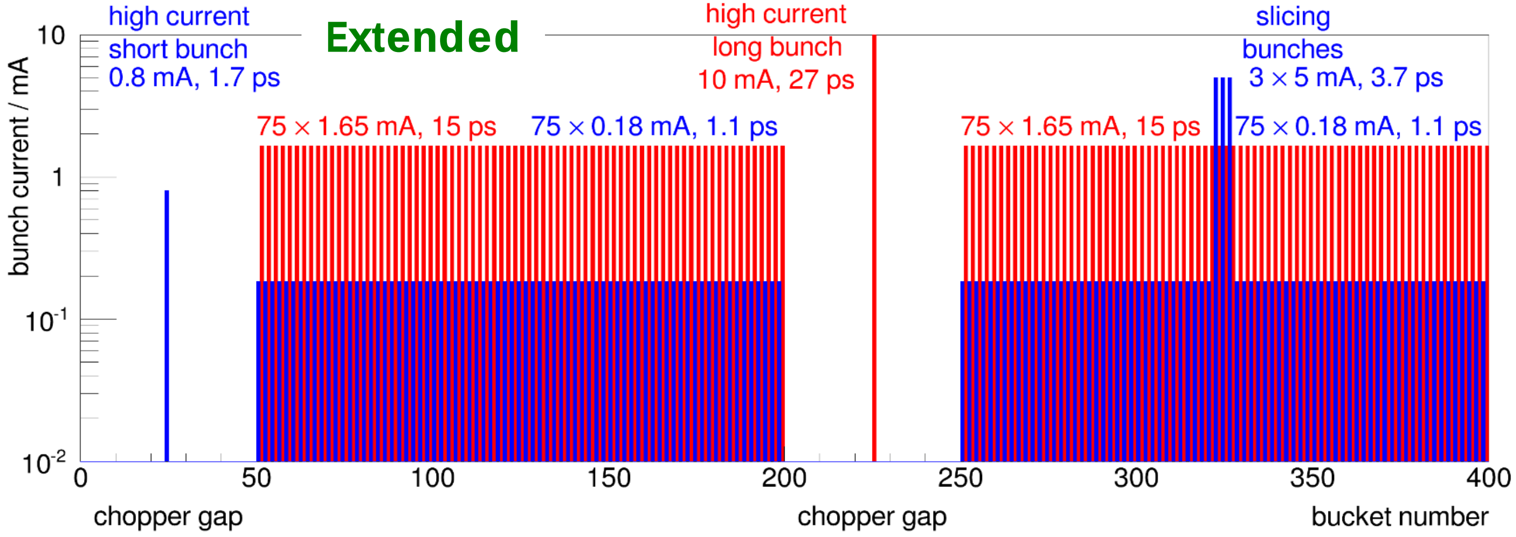
- **High concentration of long bunches populated with high current**
  (flux hungry users)

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

More short bunches (Extended)

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





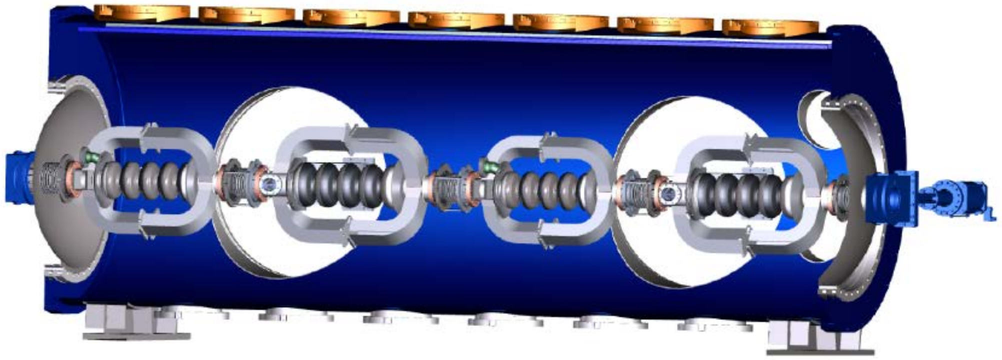
BESSY II SC Upgrade – BESSY VSR

- Simultaneous Store of long & short bunches

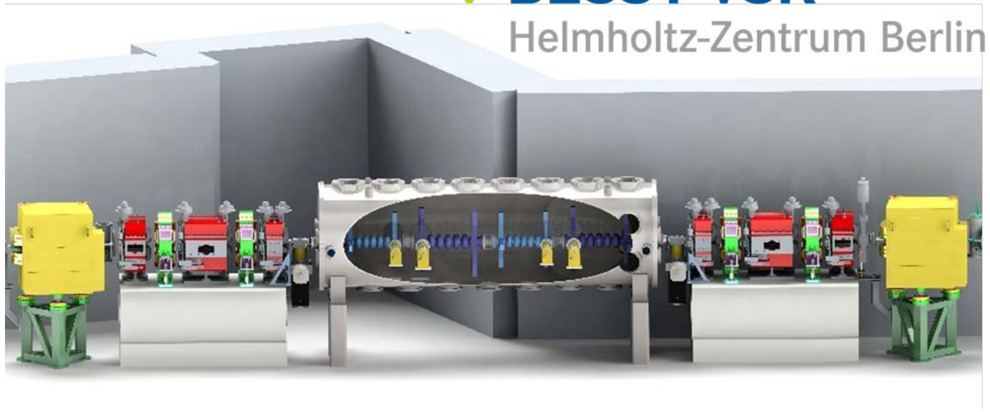
SC Upgrade

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

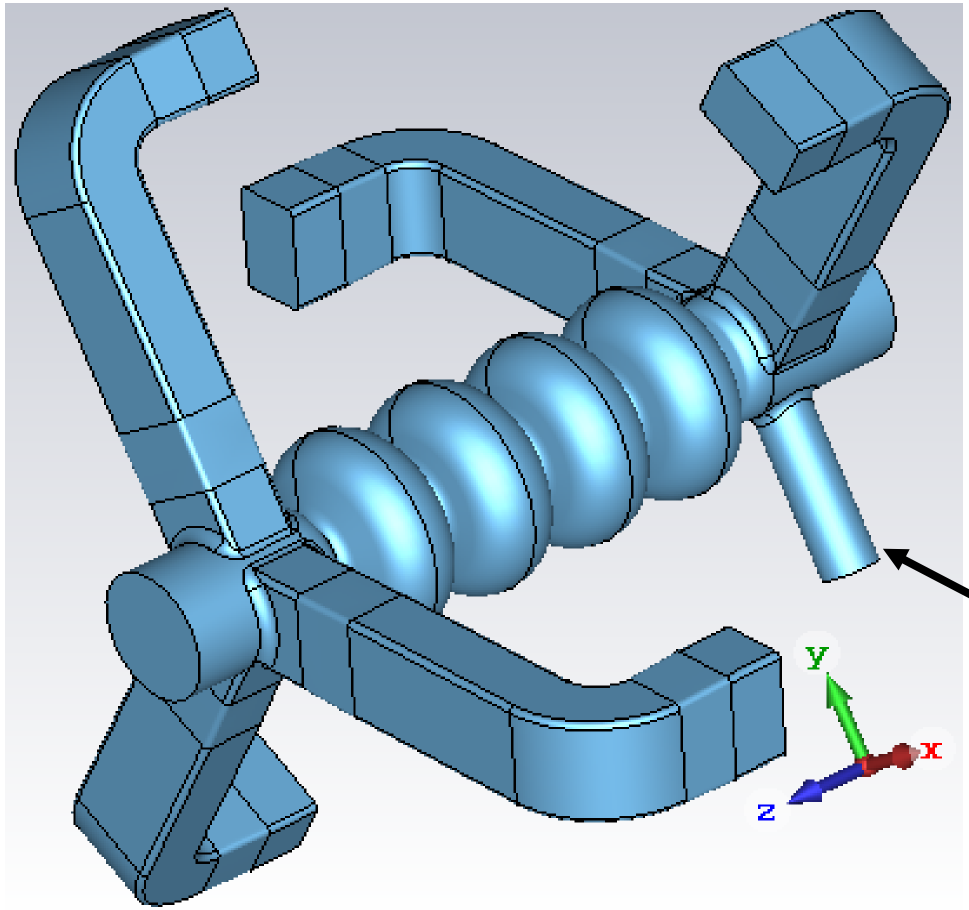
- **CW operation @ high field levels E=20MV/m**
- **Peak fields on surface (discharges, quenching)**
- **High beam current (Ib=300mA),**
- **Cavity HOMs must be highly damped (CBIs)**
- **Exotic cavity design (damping end-groups)**
- **Integrating in existing storage ring**
- **Transparent Parking of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

BESSY VSR SRF Cavity Designs

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

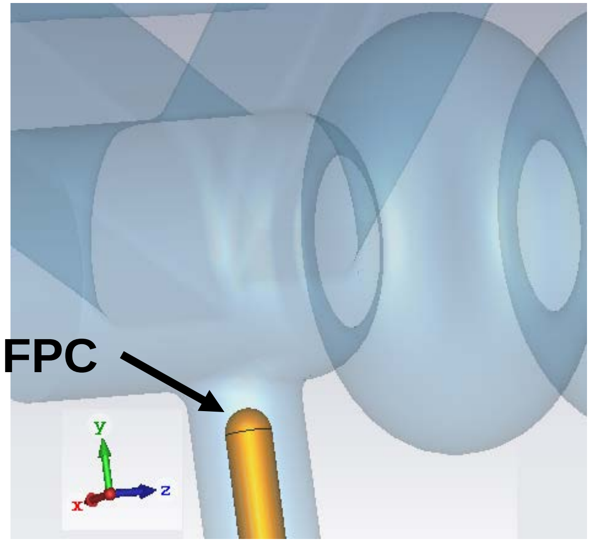
Strong HOM Damped SRF Cavity Concepts

Cavity with HOM WG Dampers



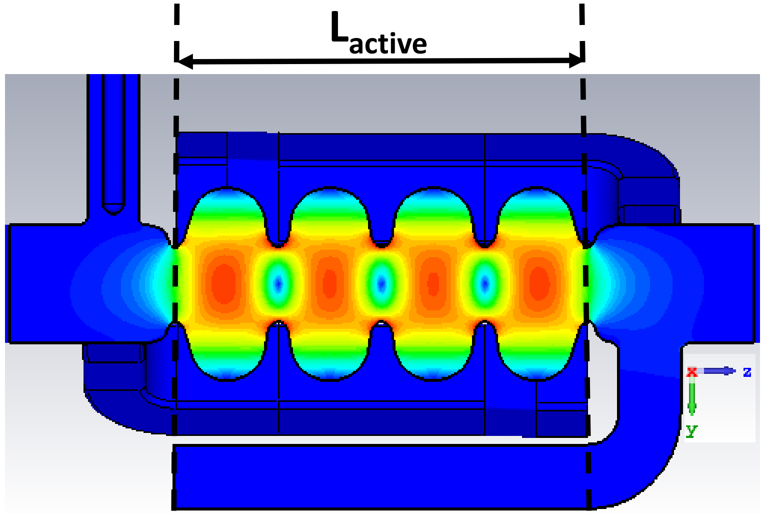
- 5 x Waveguide dampers, HOM loads (warm)
- Large beampipe radius – better HOM propagation
- Waveguides are below cutoff for fundamental → can be moved close to the cavity for heavy damping.

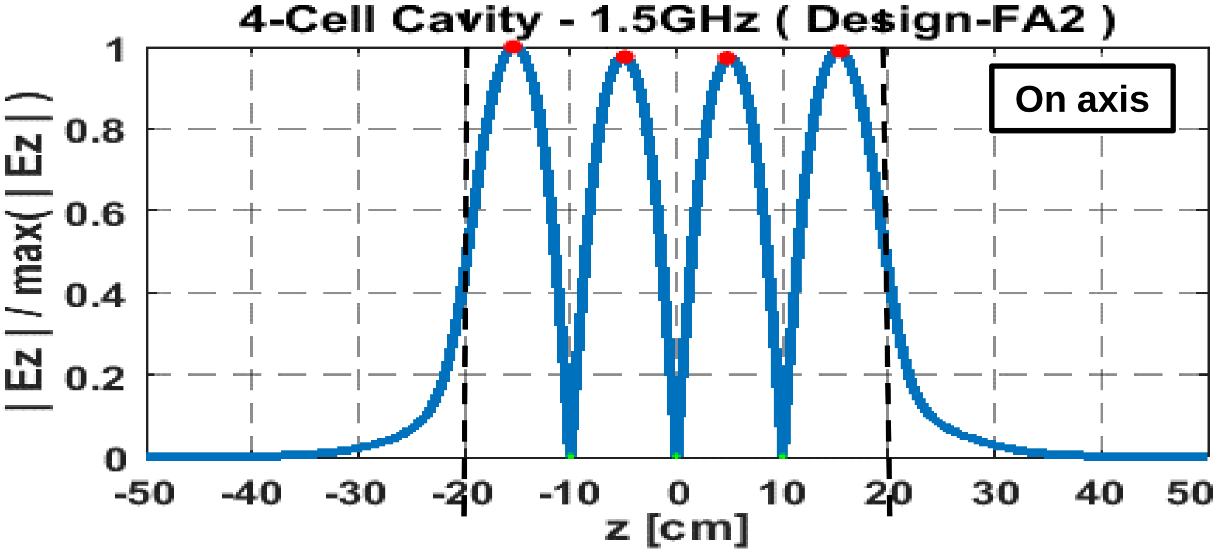
FPC



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%

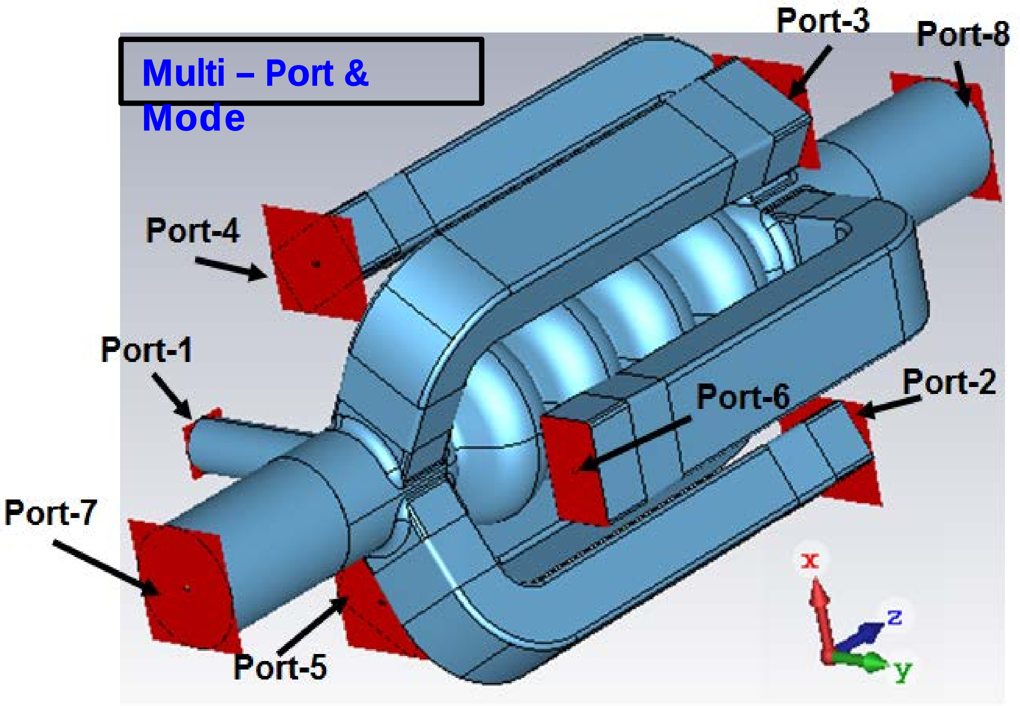




Wakefield Simulations for HOM Spectrum Control

Long Range Wakefield Simulation

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



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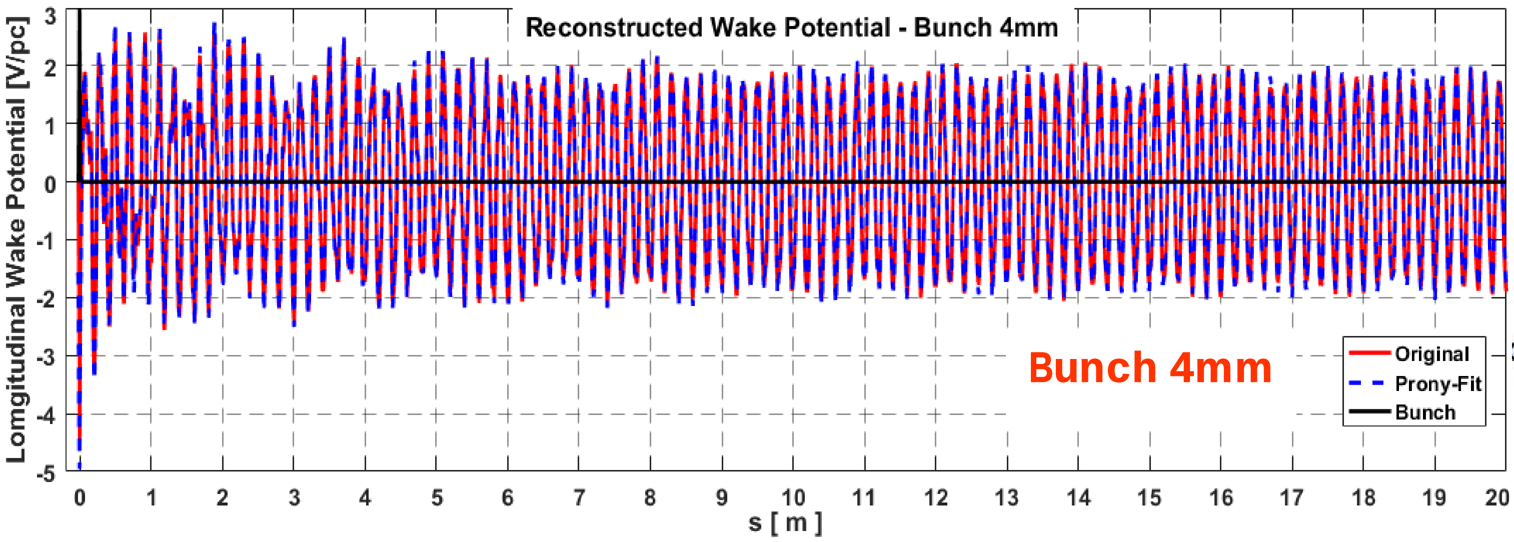
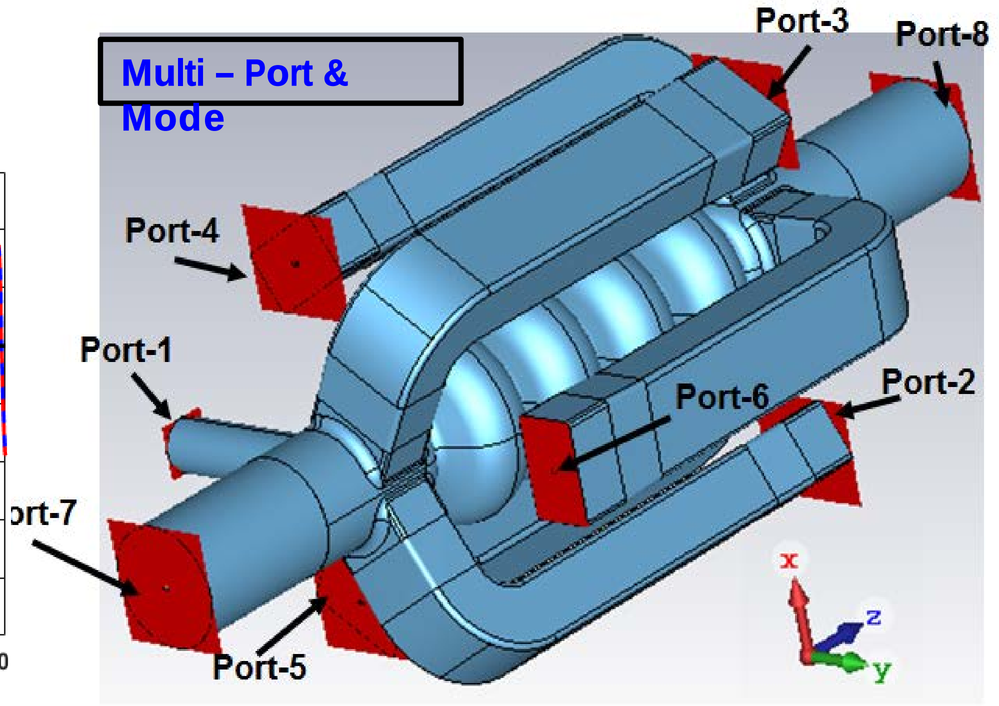
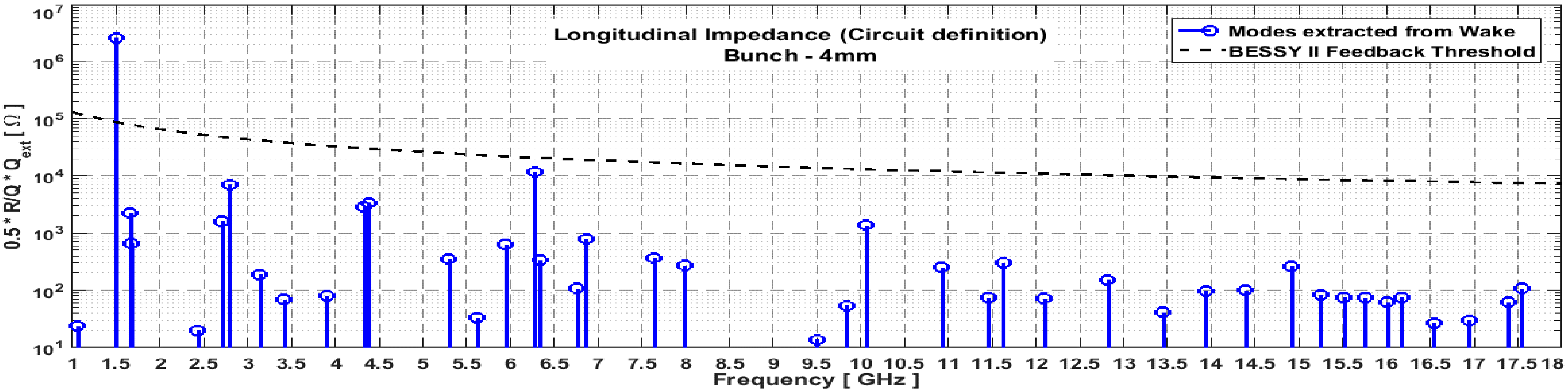
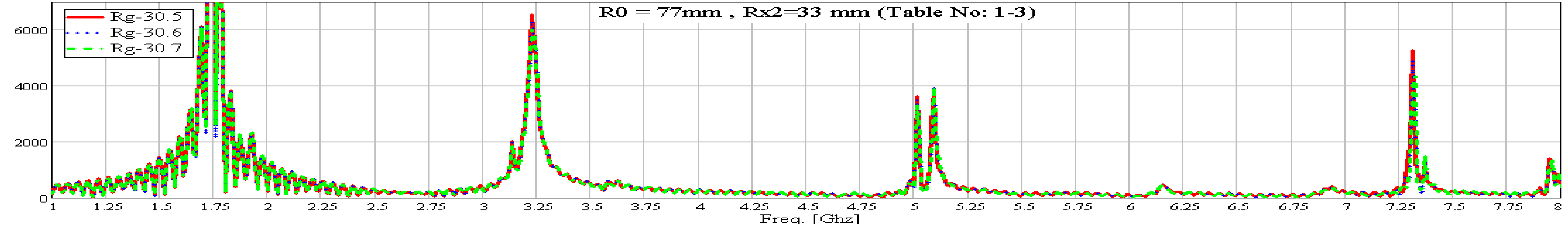


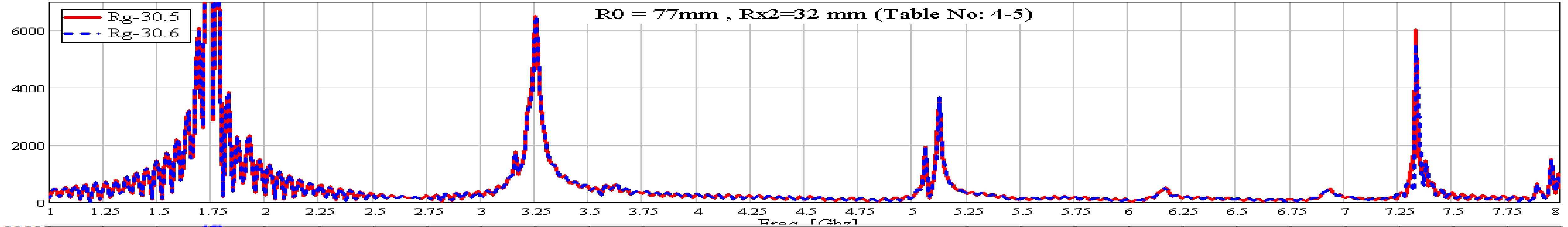


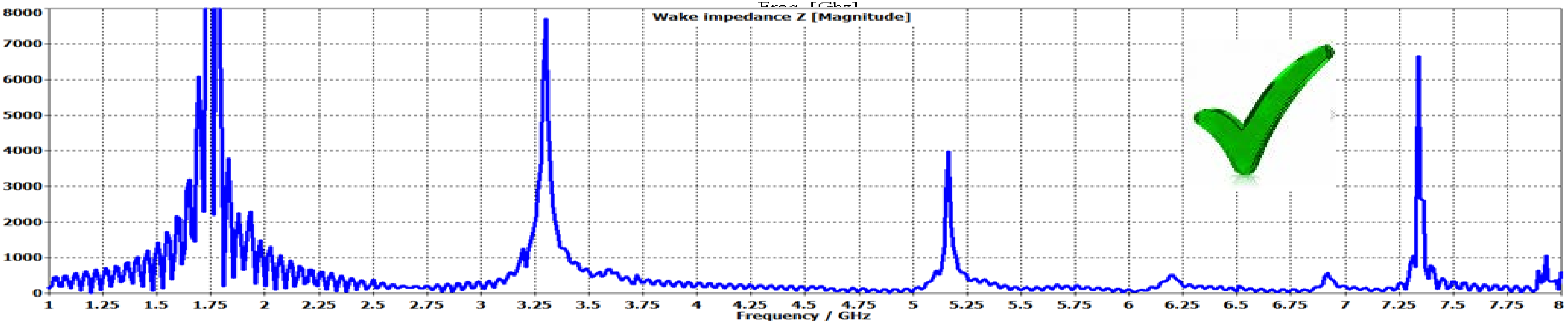


4cell – 1.75GHz Cavity Designs

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



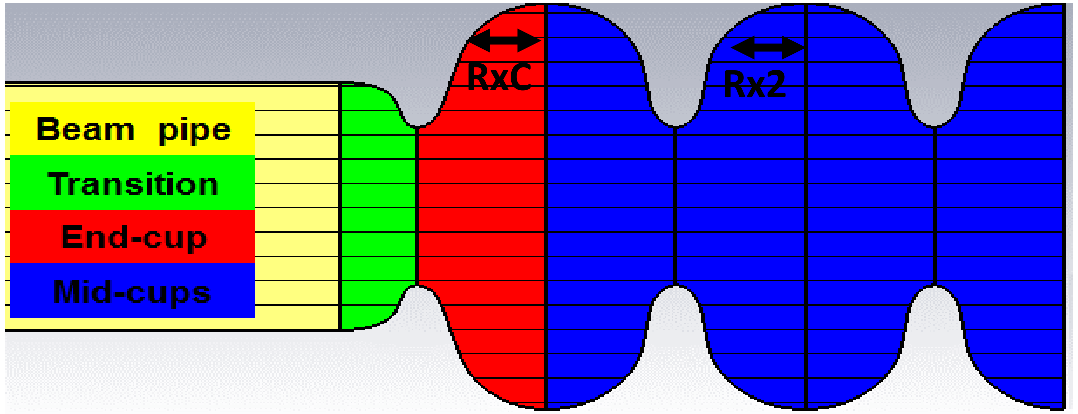


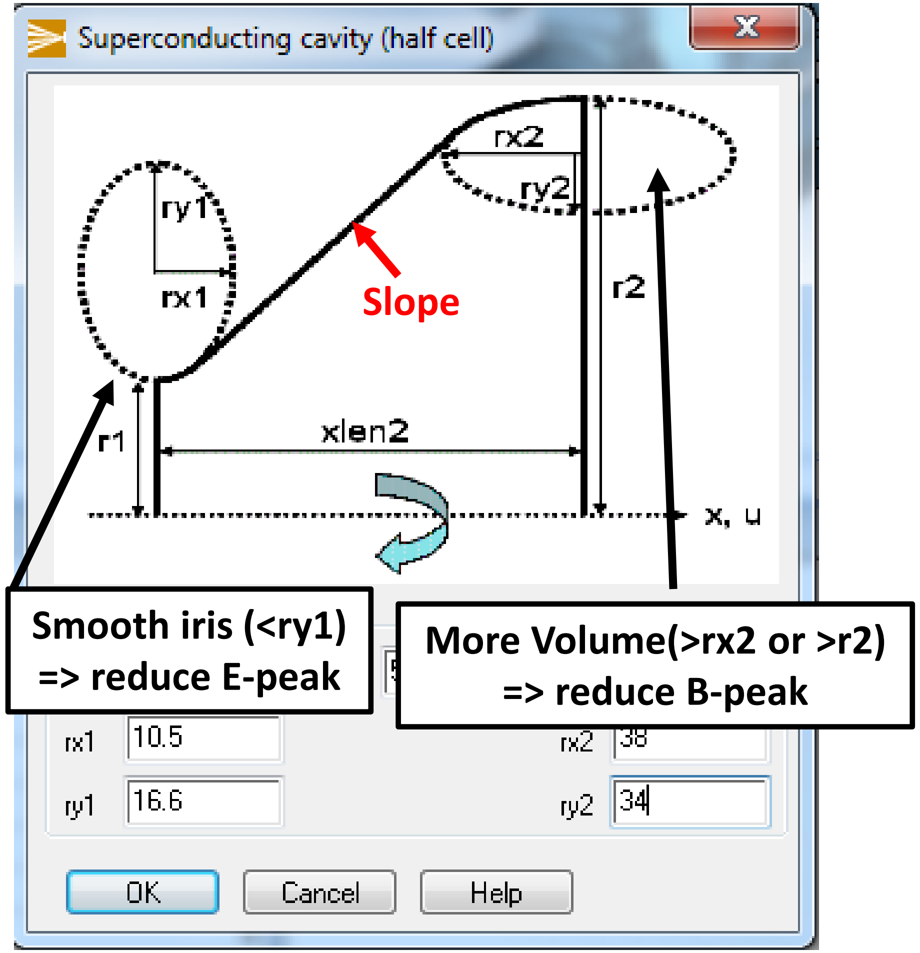


BESSY VSR SRF Cavity Designs

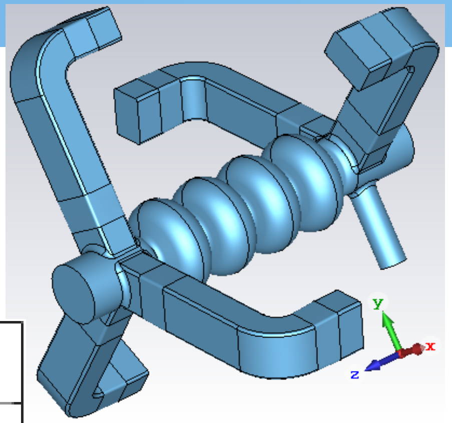
Geometry Parameters for Accelerating Mode & HOM Control

- **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



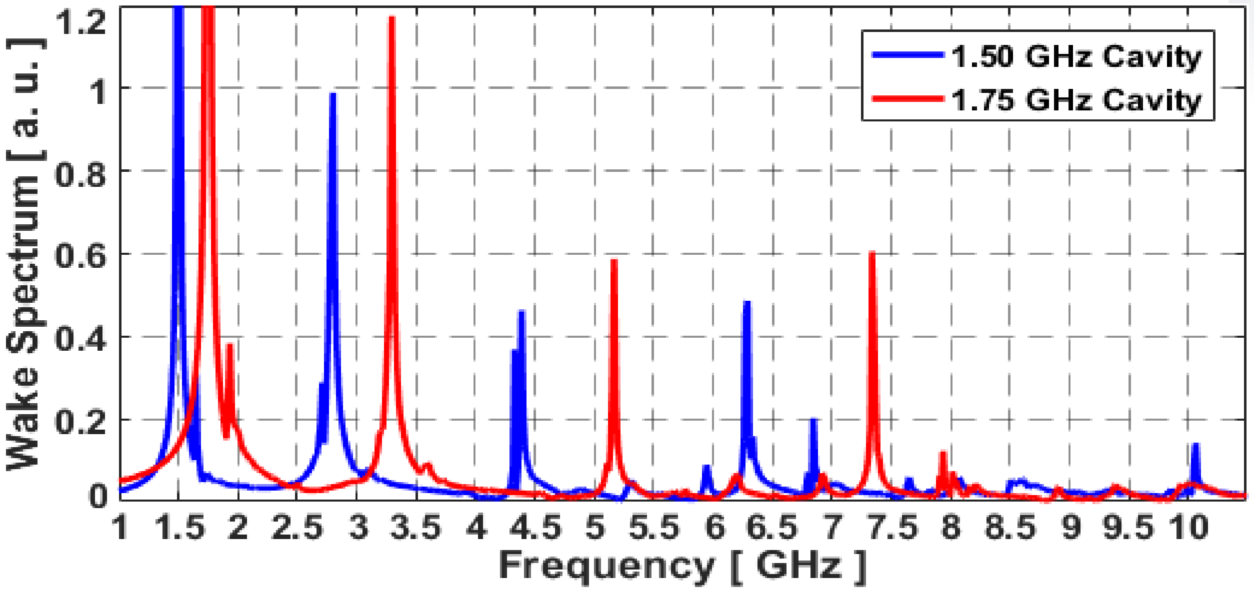


HOM Power of Single Cavity – VSR Baseline beam



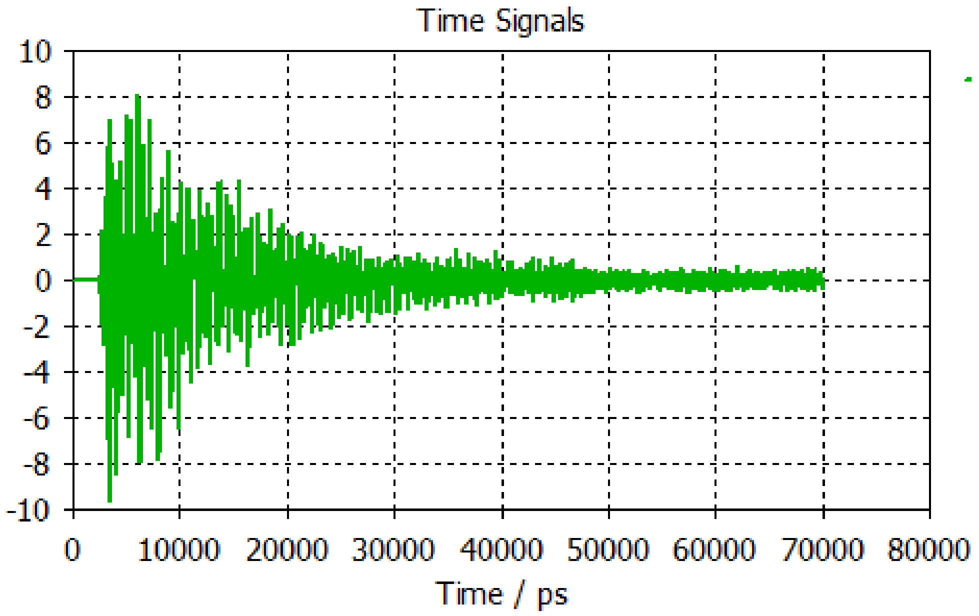
Spectrally Weighted with "Baseline" pattern

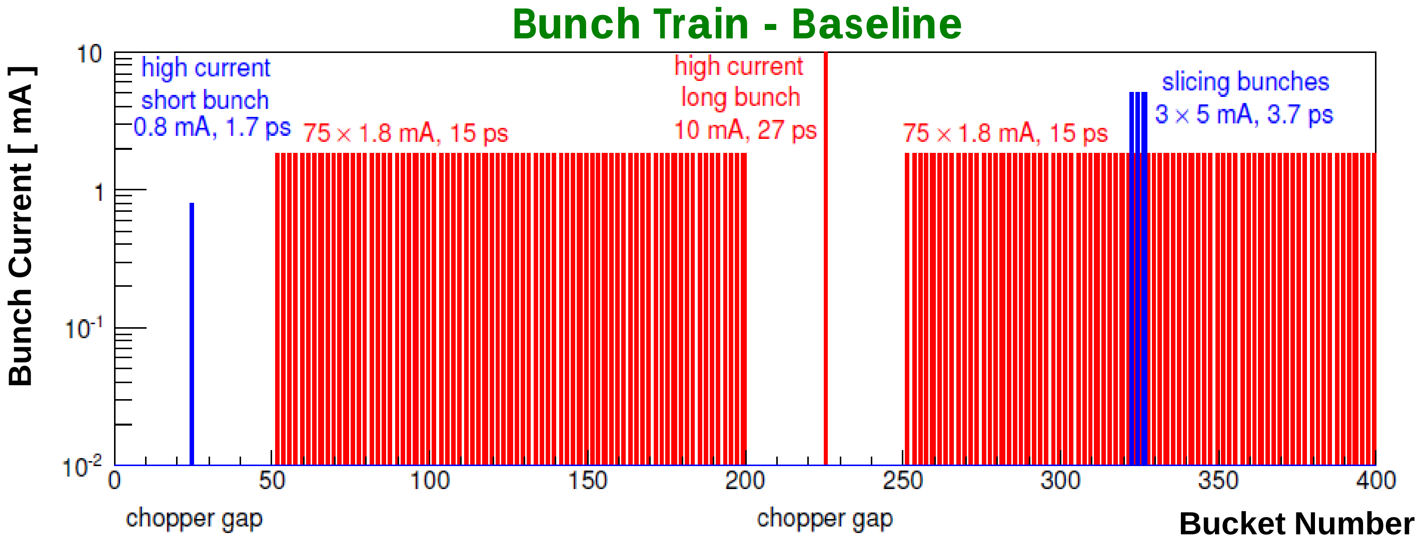
Cavity Type	1.5GHz	1.75GHz
Port No.	HOM Power [W]	
1 – FPC(1)	37.9	33.8
2 – WG(1)	105.3	154.7
3 – WG(1)	103.8	151.4
4 – WG(2)	88.5	108.3
5 – WG(2)	90.2	109.8
6 – WG(2)	90.6	111.6
7 – BmP(Upstream)	235.4	200.5
8 – BmP(Downstream)	327.1	275.9
Total Coherent	**1079**	**1146**
None-Coherent	**1293**	**1300**



- **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





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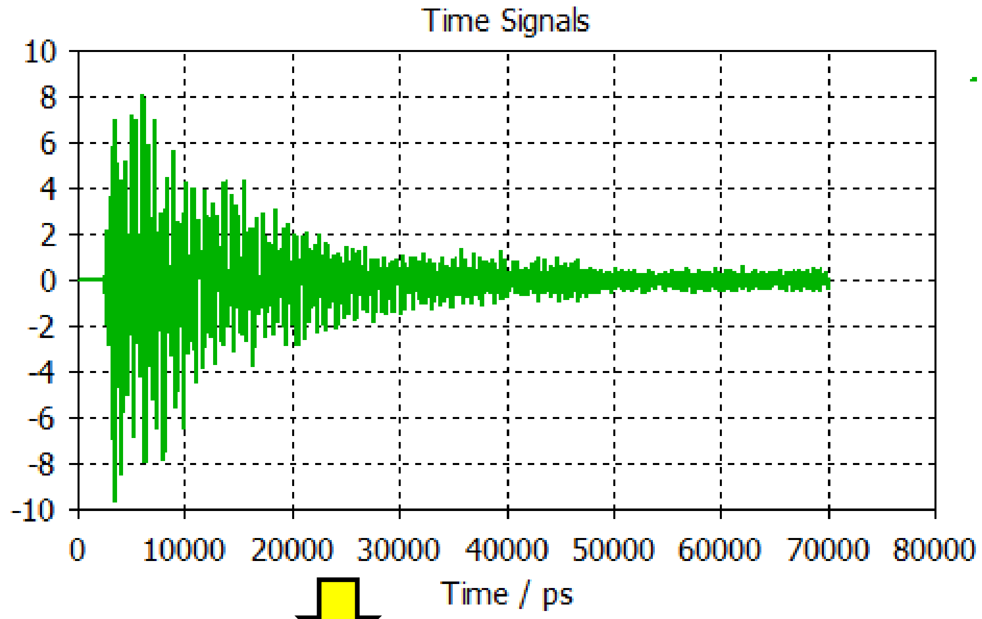
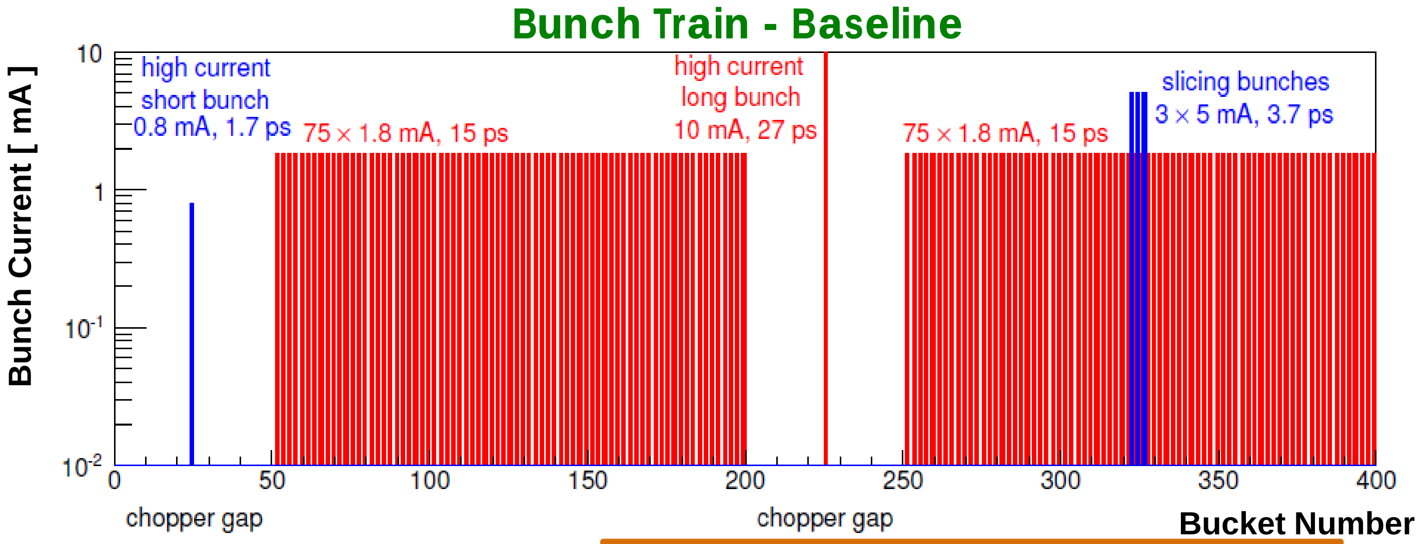
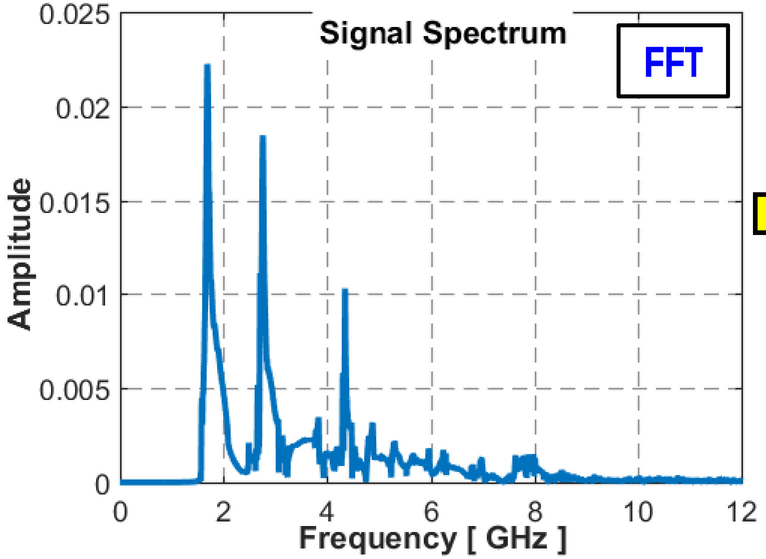




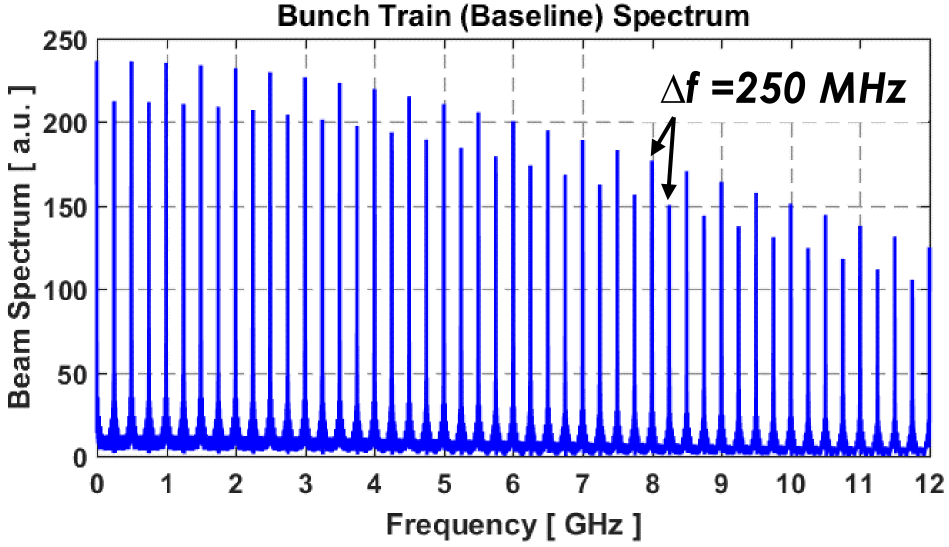
$$\tilde{I}_b(\omega) = f_{rev}\sum_n q_n \cdot e^{-0.5\cdot\omega^2\sigma_n^2}\cdot e^{j\,\omega\, t_{0,n}}$$



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

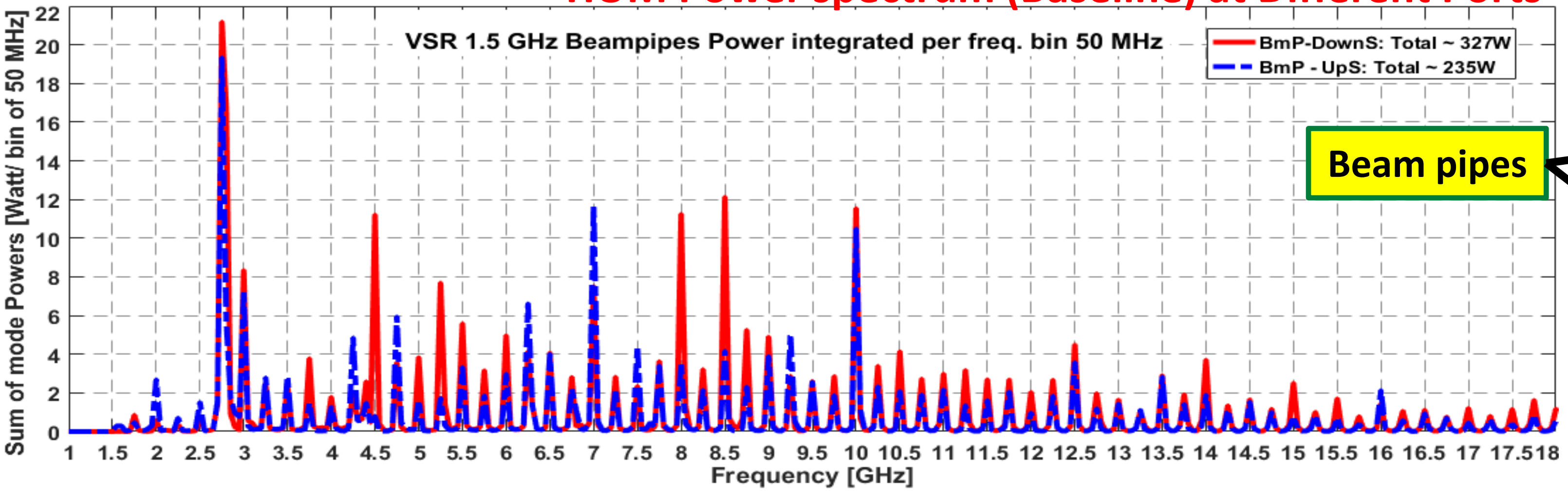
$$P(\omega) = \left|\frac{\tilde{I}_b}{\tilde{I}_0}\mathcal{F}(\omega)\right|^2$$

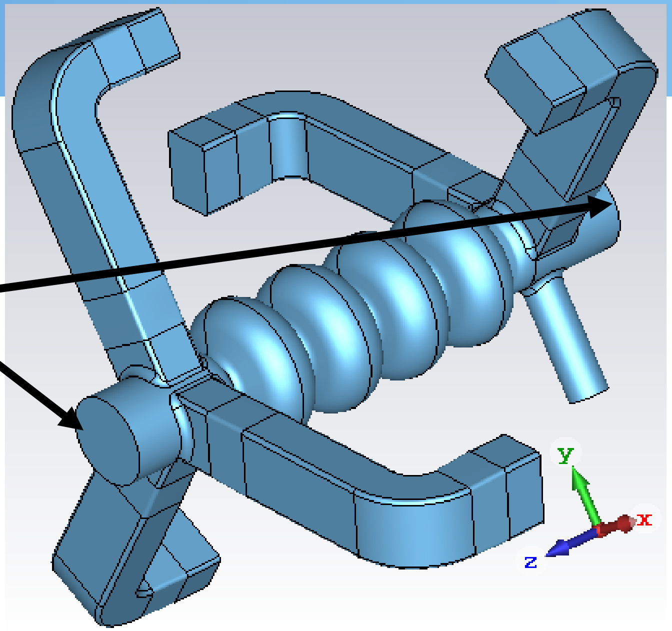
$\tilde{I}_0$ - Simulated single bunch



HOM Power of Single Cavity 1.5GHz

HOM Power spectrum (Baseline) at Different Ports





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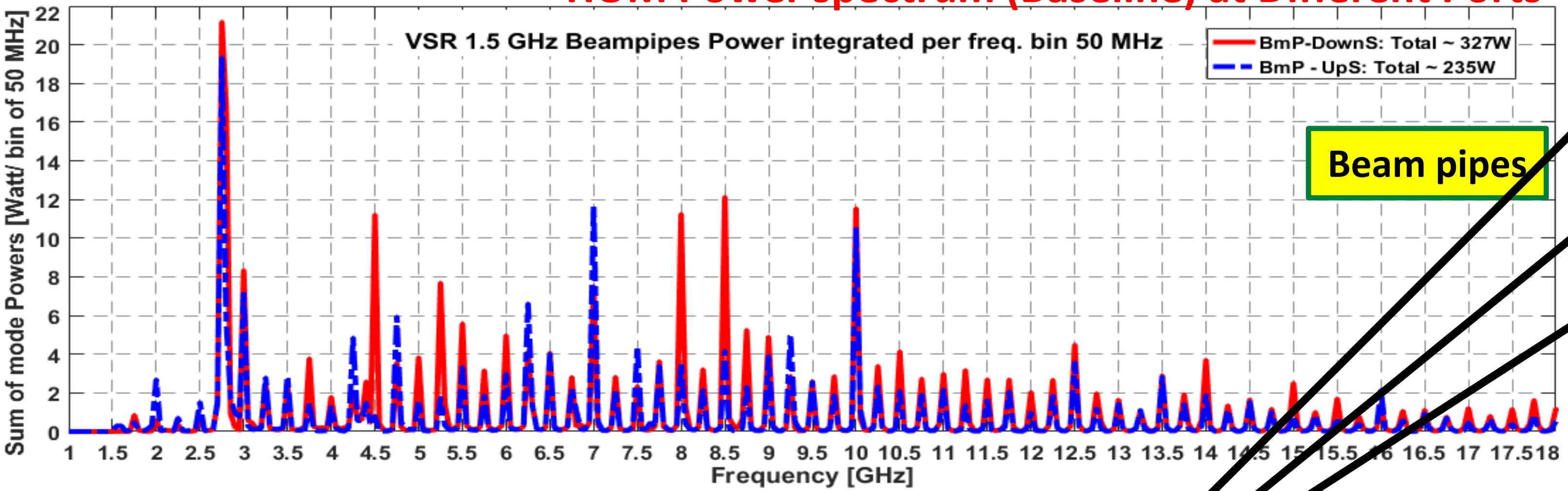

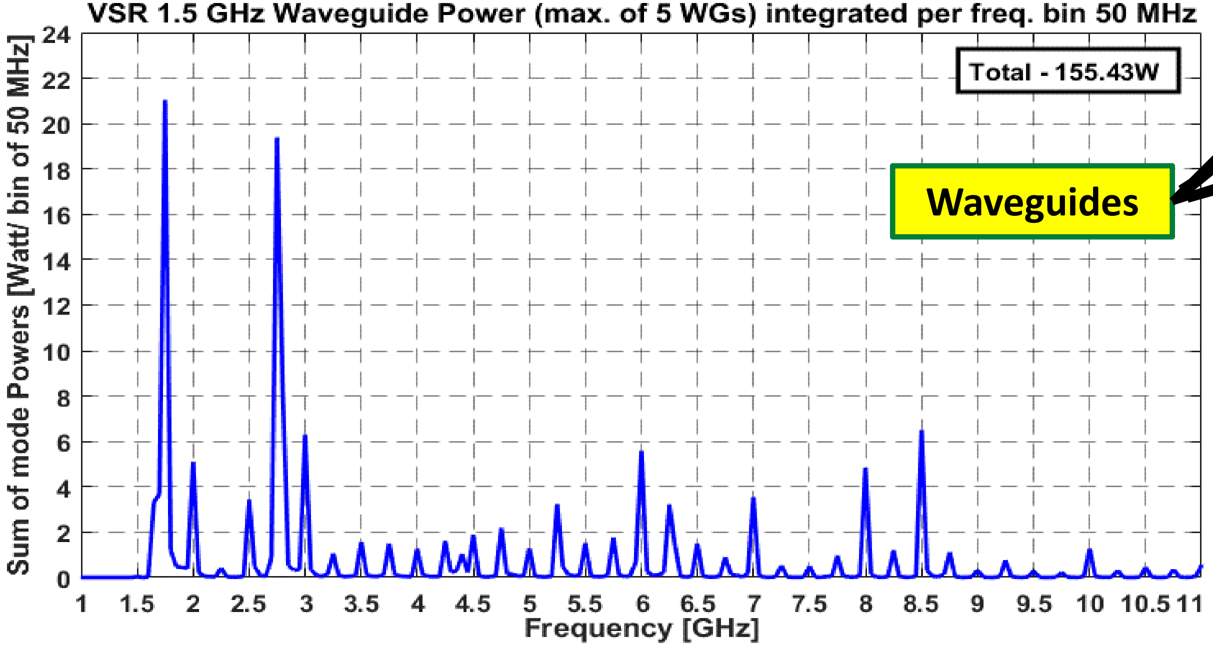

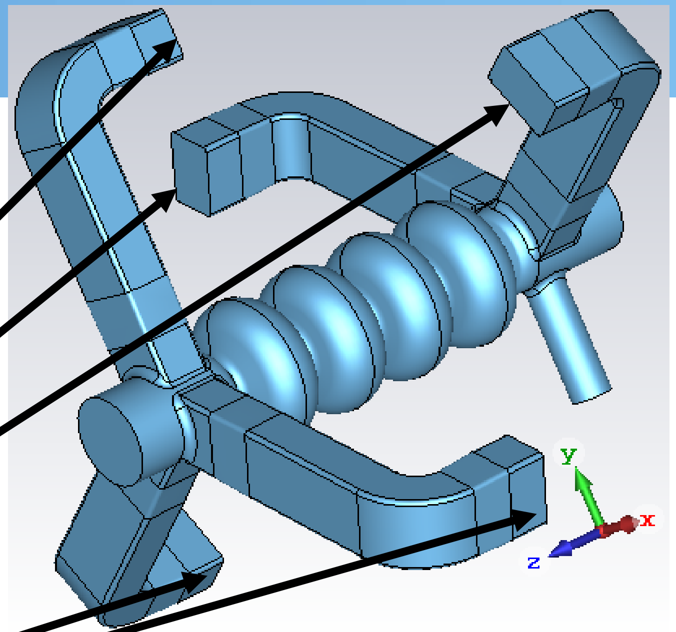

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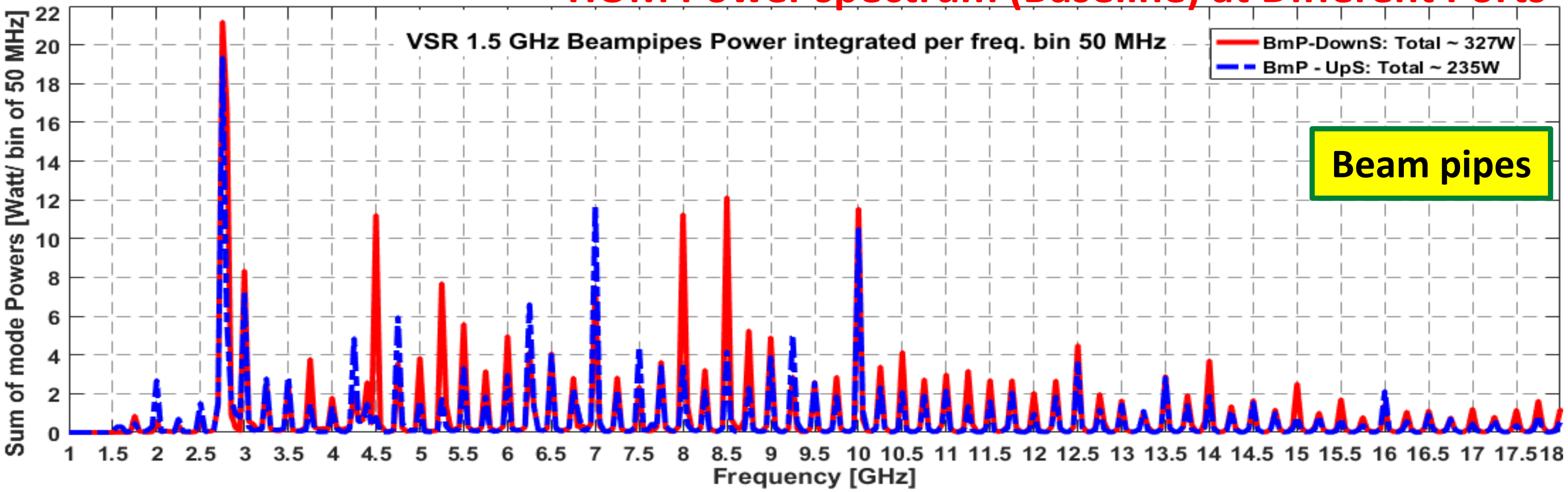
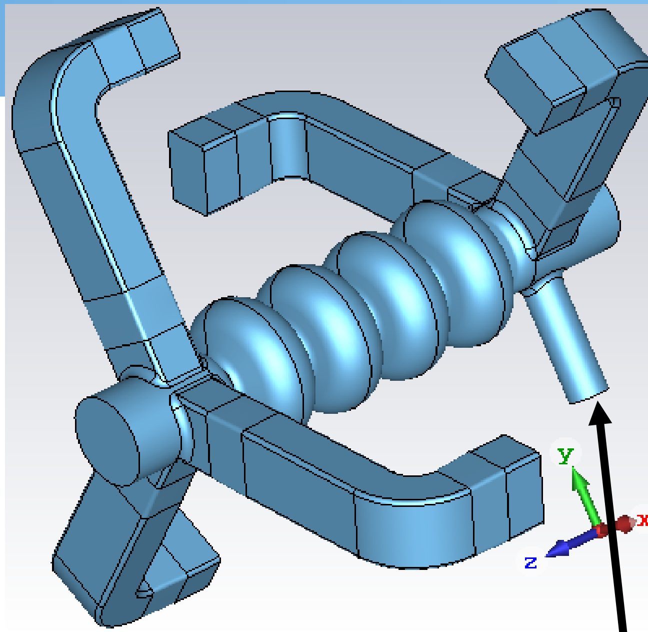
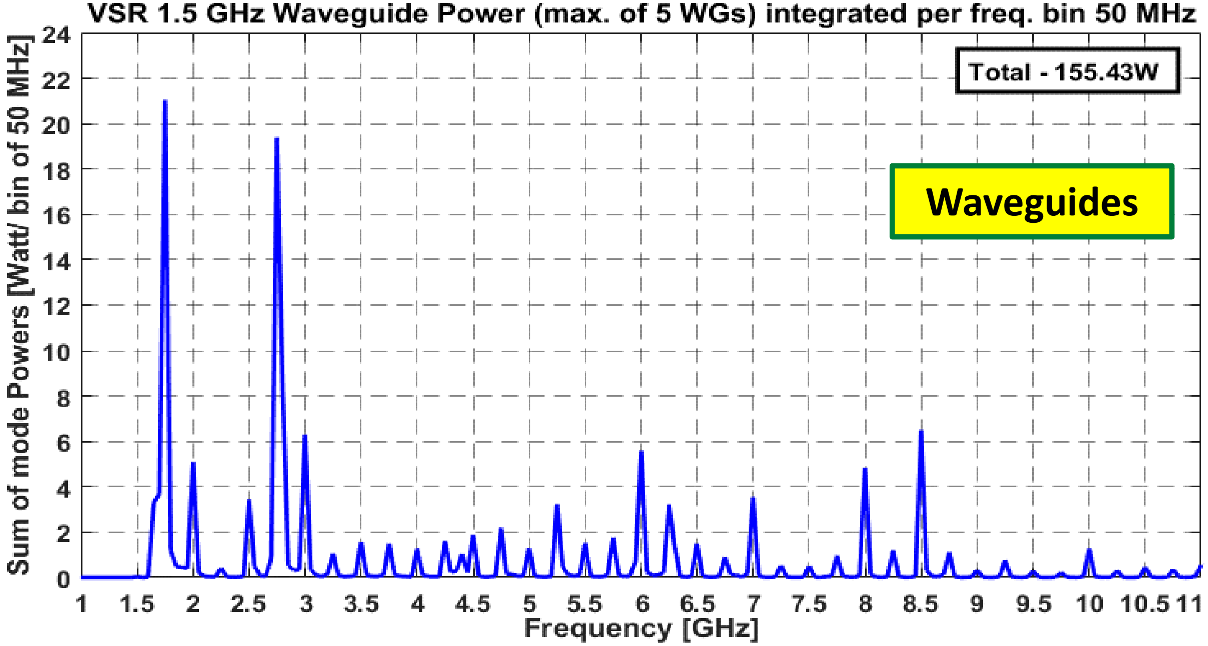
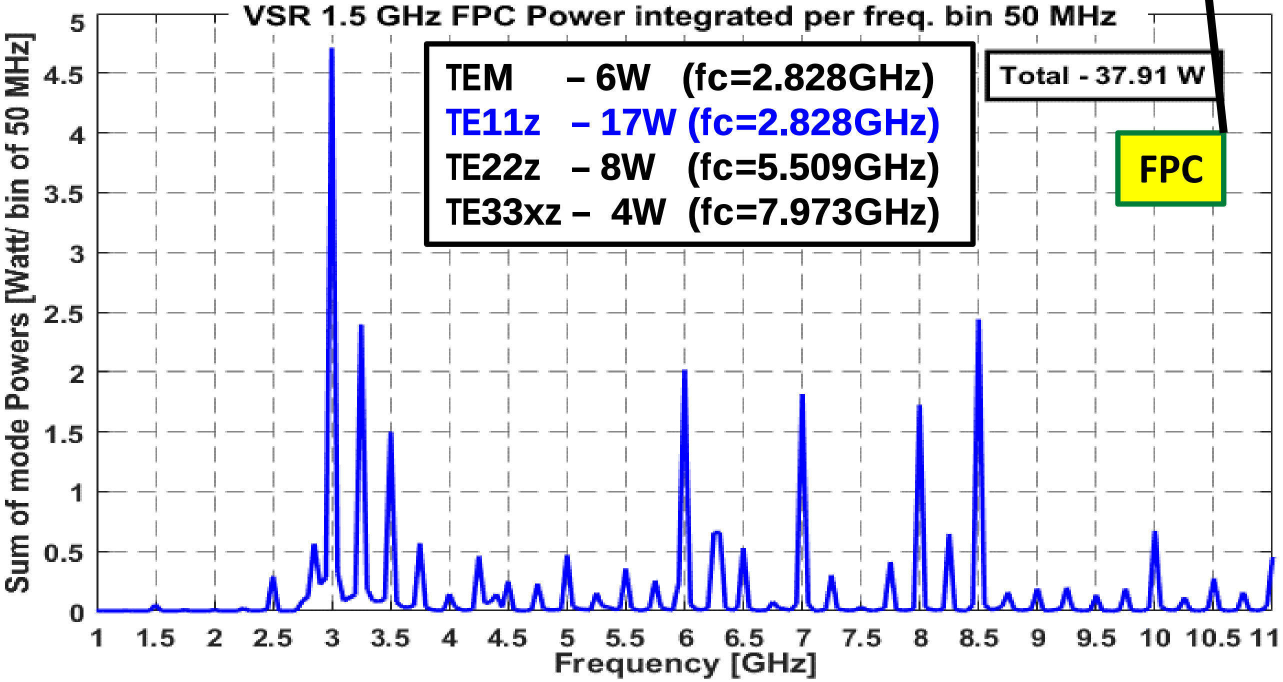




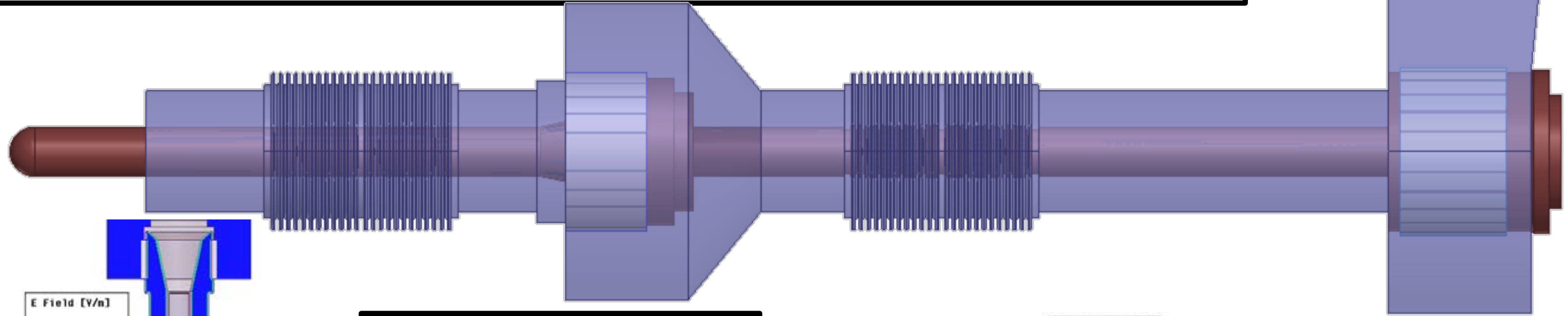


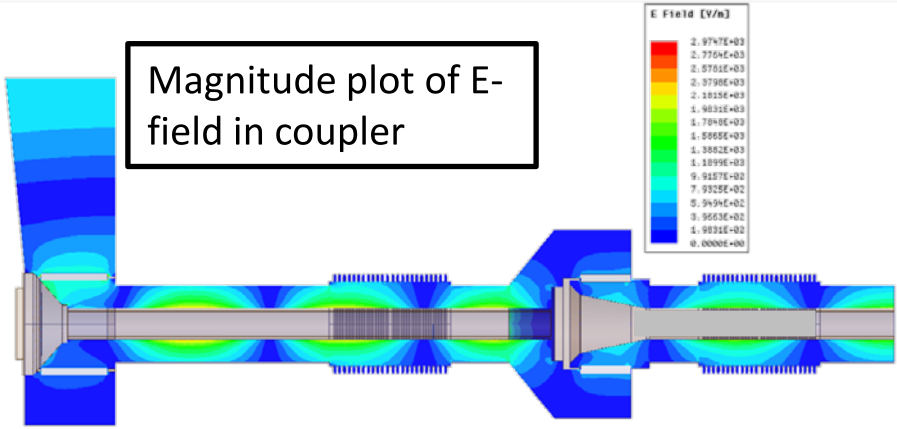


Design of the 1.5 GHz BESSY VSR coupler

HZB Helmholtz Zentrum Berlin
BESSY VSR

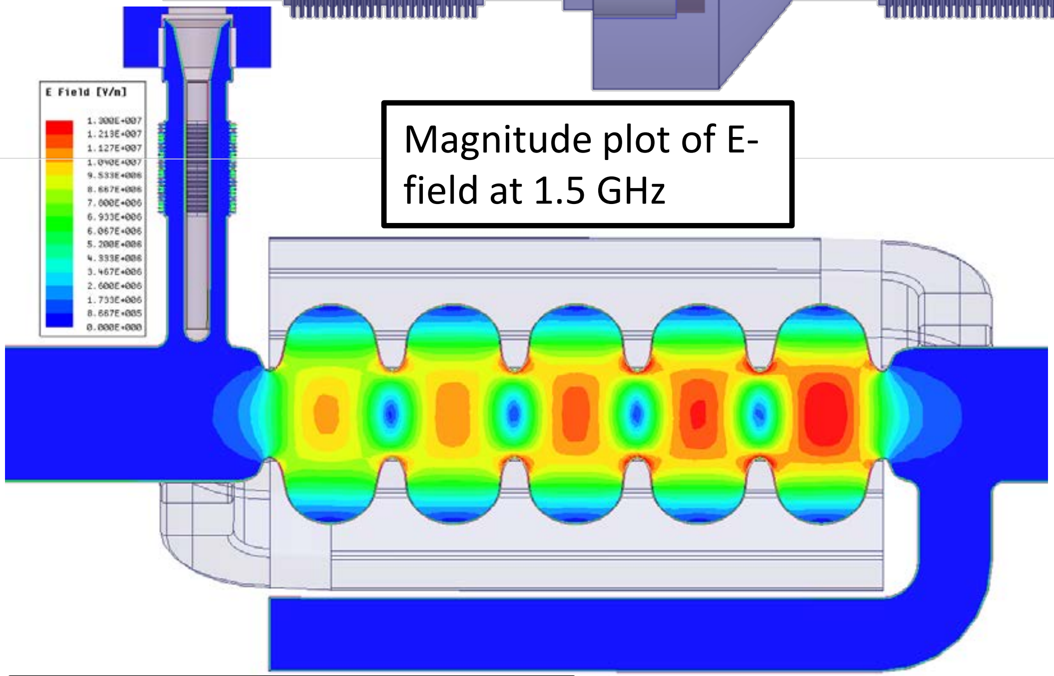
- Coax coupler diameters: 49 mm x 20 mm.
- Two ceramic windows to maintain vacuum.
- Inner an outer coax bellows provide a tuning mechanism to allow for variable coupling with a Q_{ext} of $6x10^6$ to $6x10^7$
- Rounded antenna tip



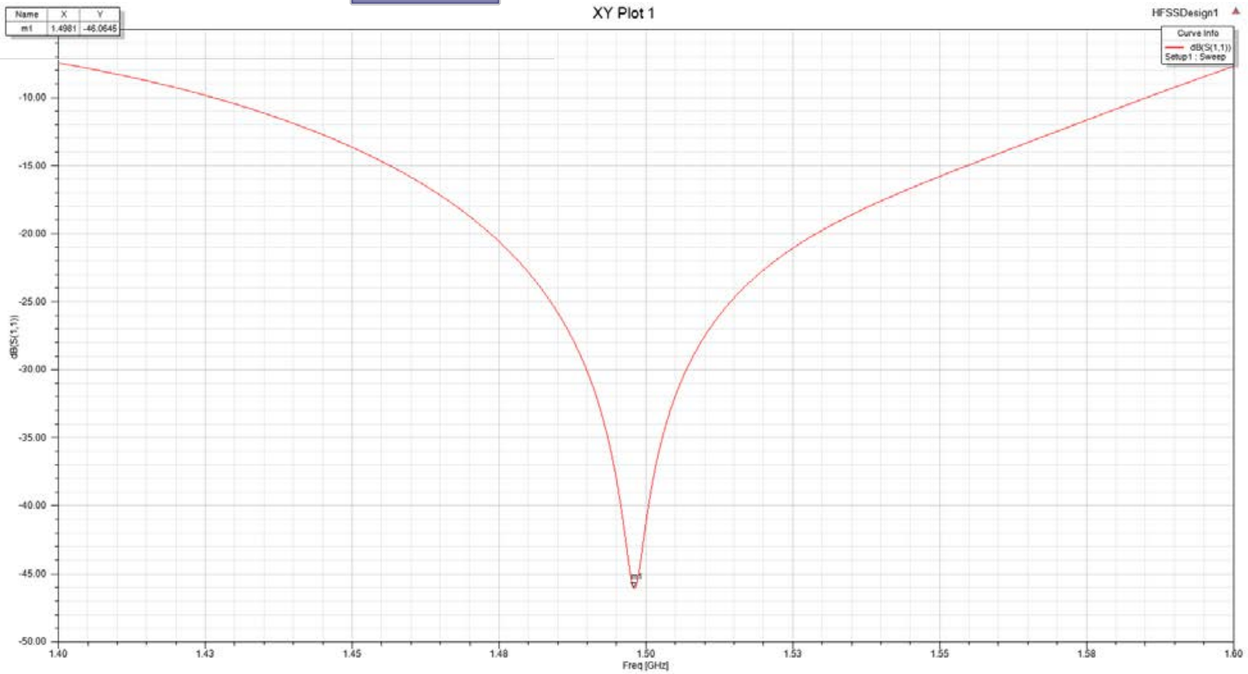


Magnitude plot of E-field in coupler

S11 Plot
Magnitude of -46 dB at 1.498 GHz



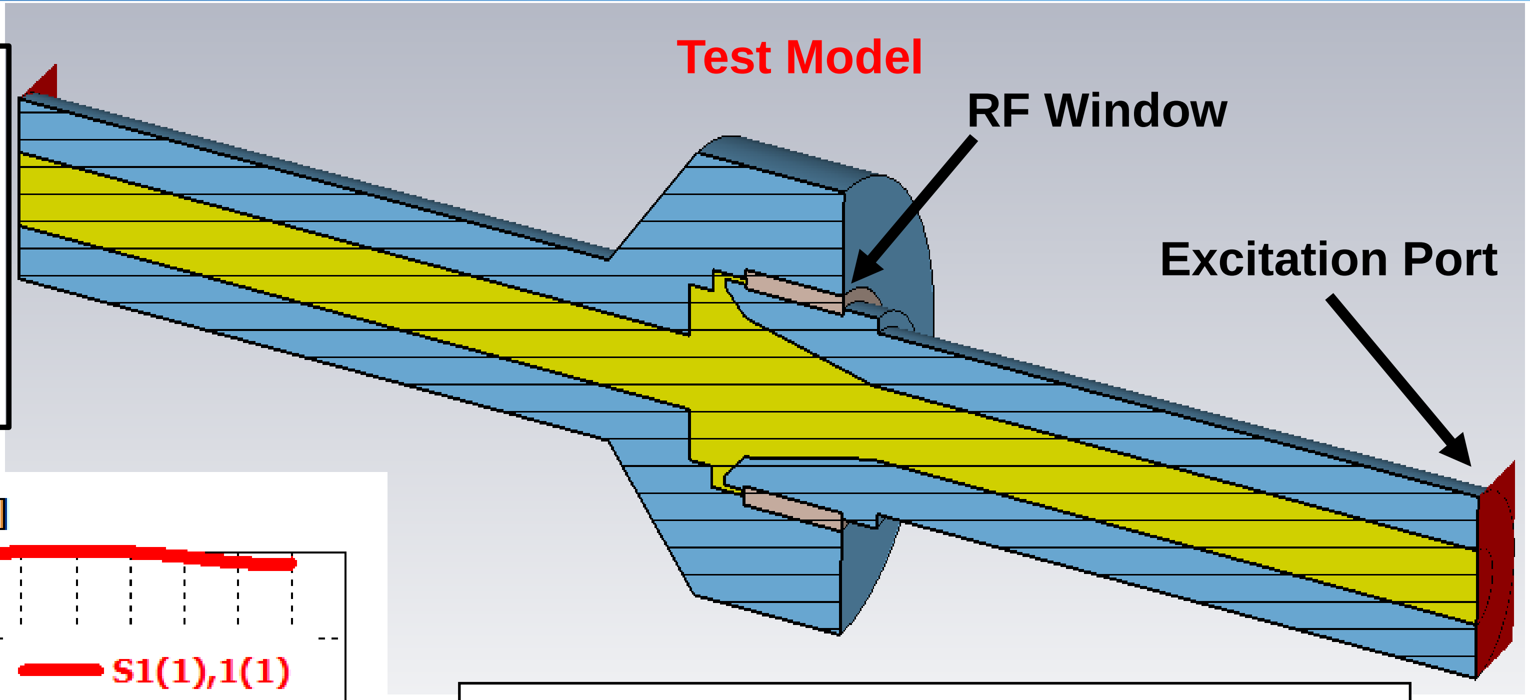
Magnitude plot of E-field at 1.5 GHz

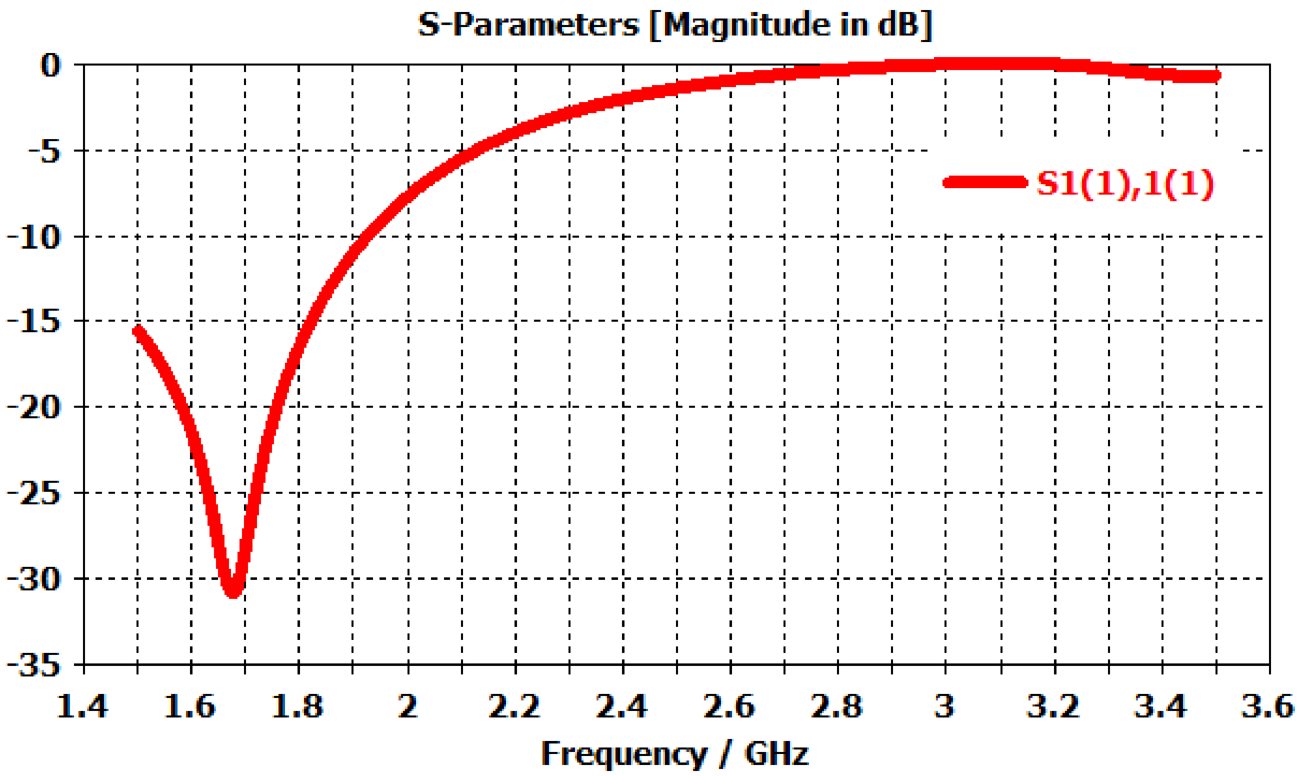


Courtesy of E. Sharples (HZB)

FPC characteristics for HOMs

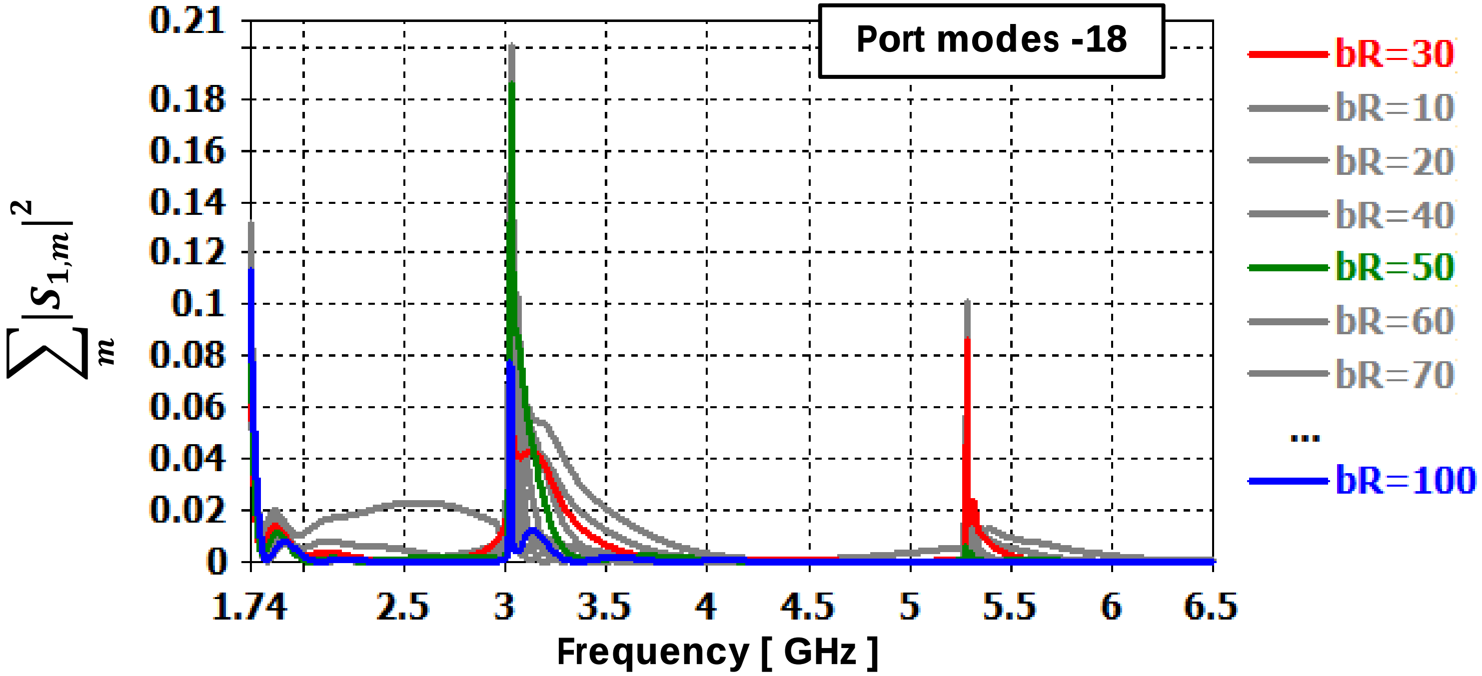
- In FPC at higher frequencies (HOMs) the EM waves are mainly reflected back from first RF windows – forms standing wave. True for all coax modes – TEM, TE11 …
- One should include the first half of the FPC in wake & Eigenmode simulations – to analyze how this fact reflects on HOM power balance & to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



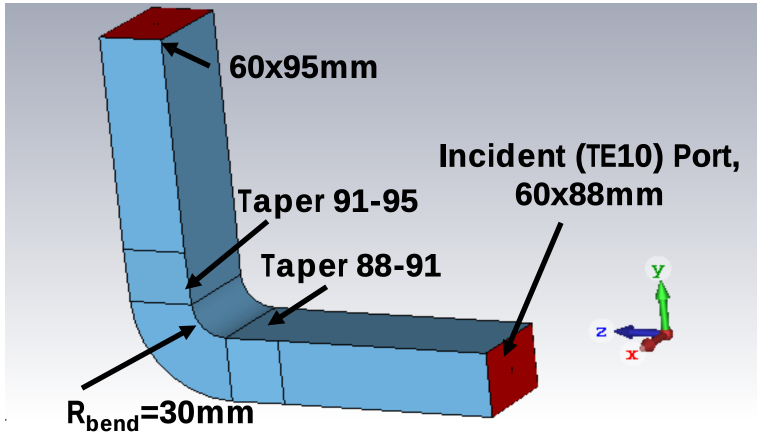


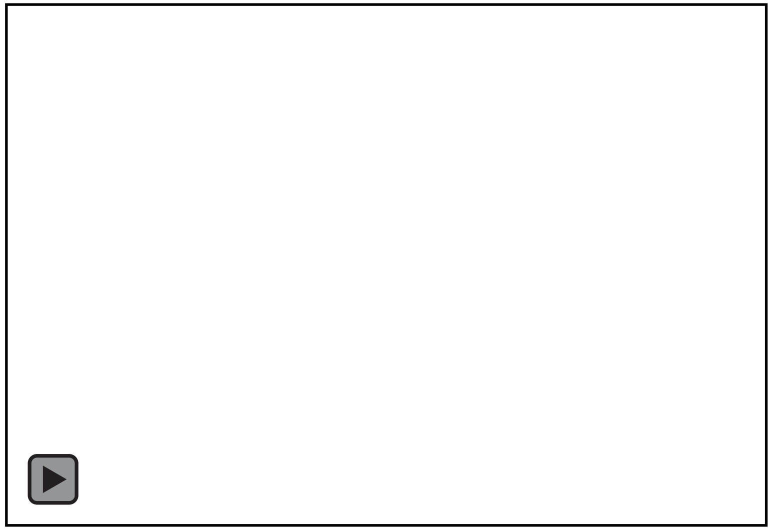
Waveguide Bend Broadband Characteristics

Reflection Broadband Behavior for TE10 Mode



WG Tapered 60 x 88_91_95mm



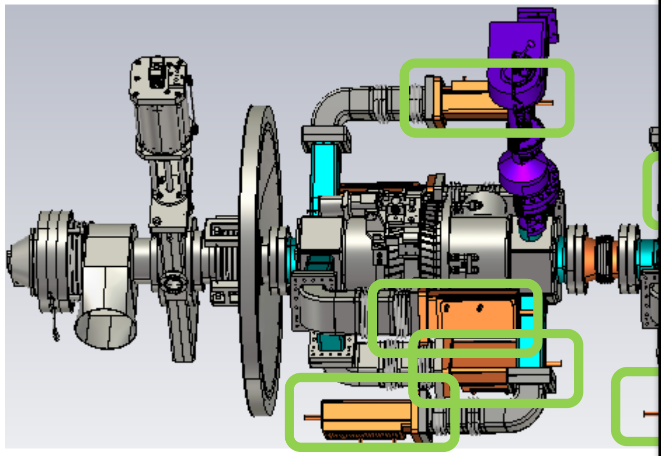


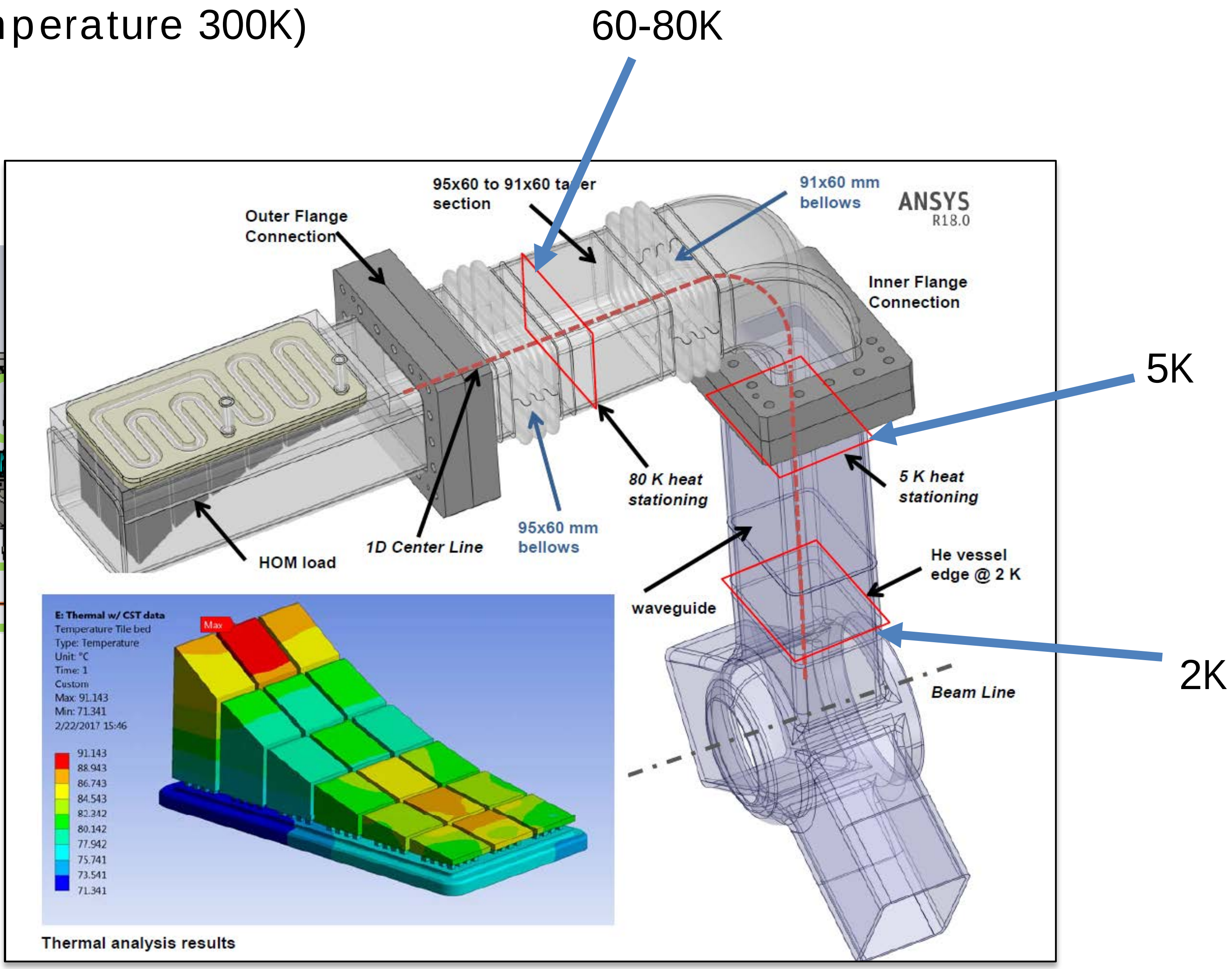
- Low reflection (broadband) from the WG bend is for bending radius = 30mm or bR ≥ 100mm.

- 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.

BESSY VSR Cold-String: HOM Loads

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



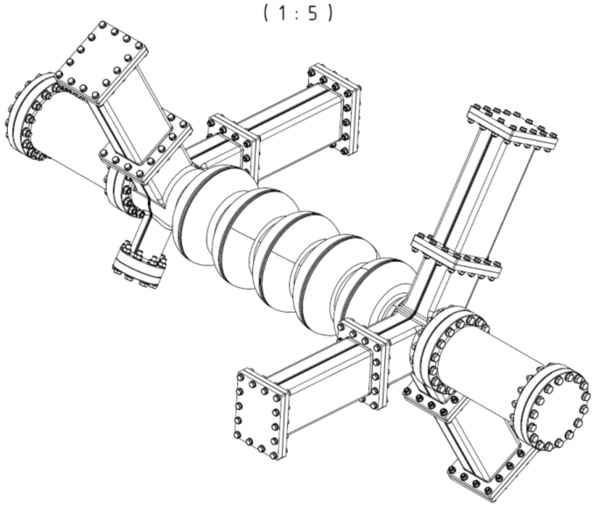


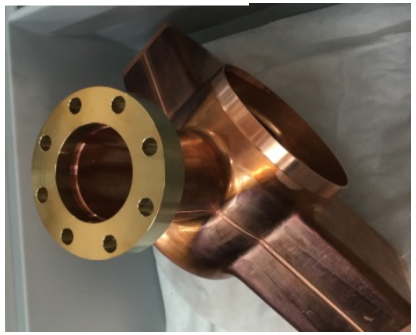
Thermal analysis results

Courtesy of Jefferson Lab

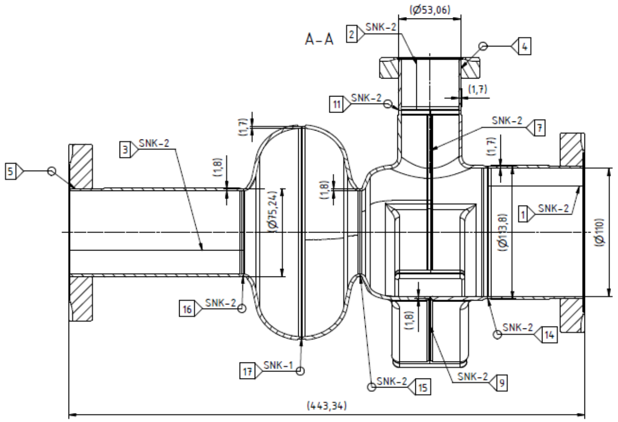
BESSY VSR: Prototypes

1.5 GHz 5-cell Copper prototype

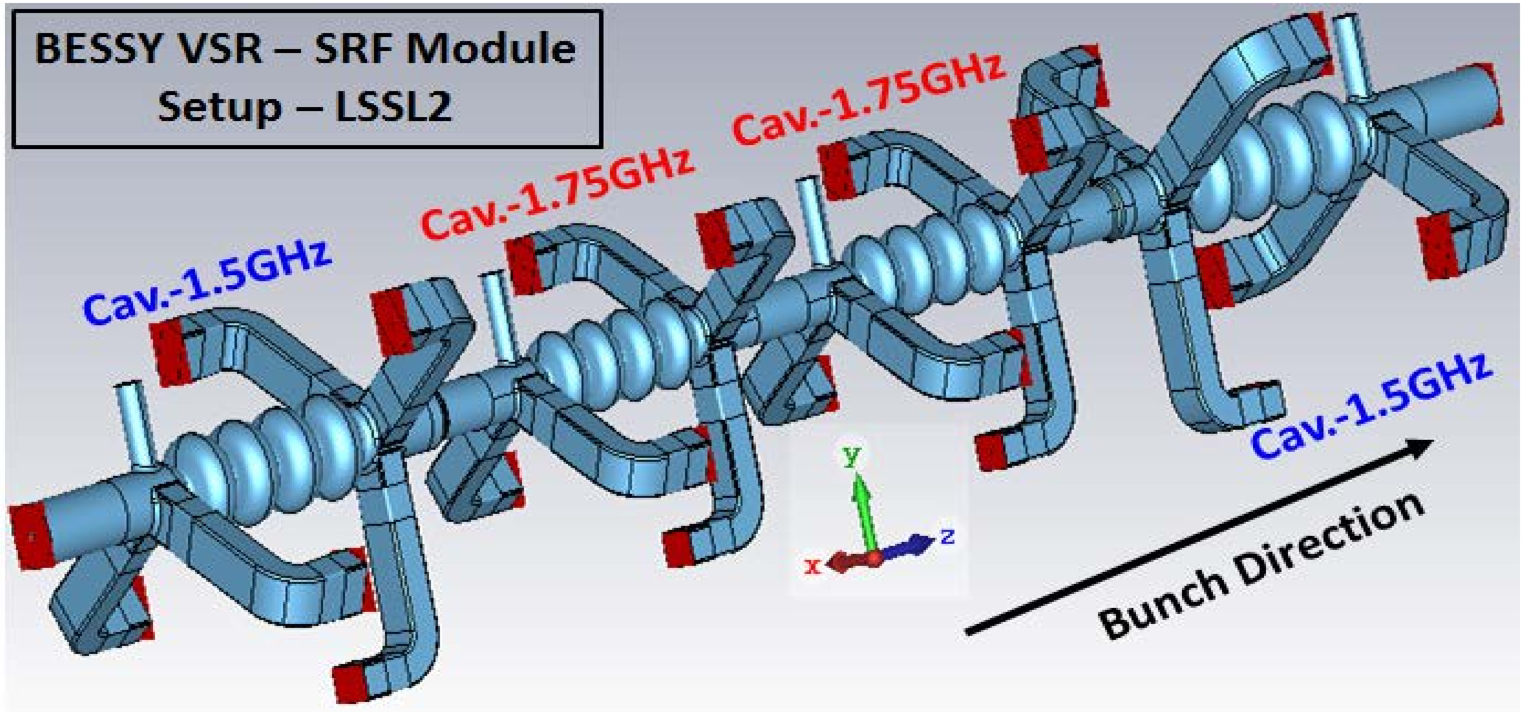




1.5 GHz Single-cell Nb prototype



HOM Power Levels in SRF Module



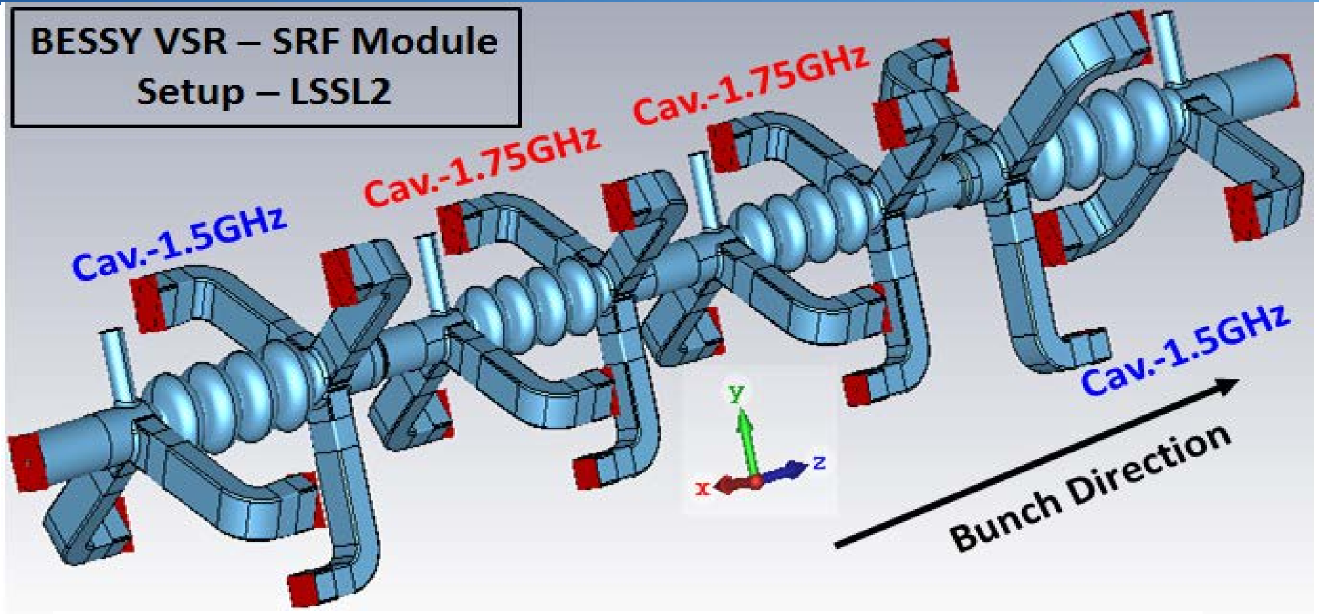
Wakefield Simulations

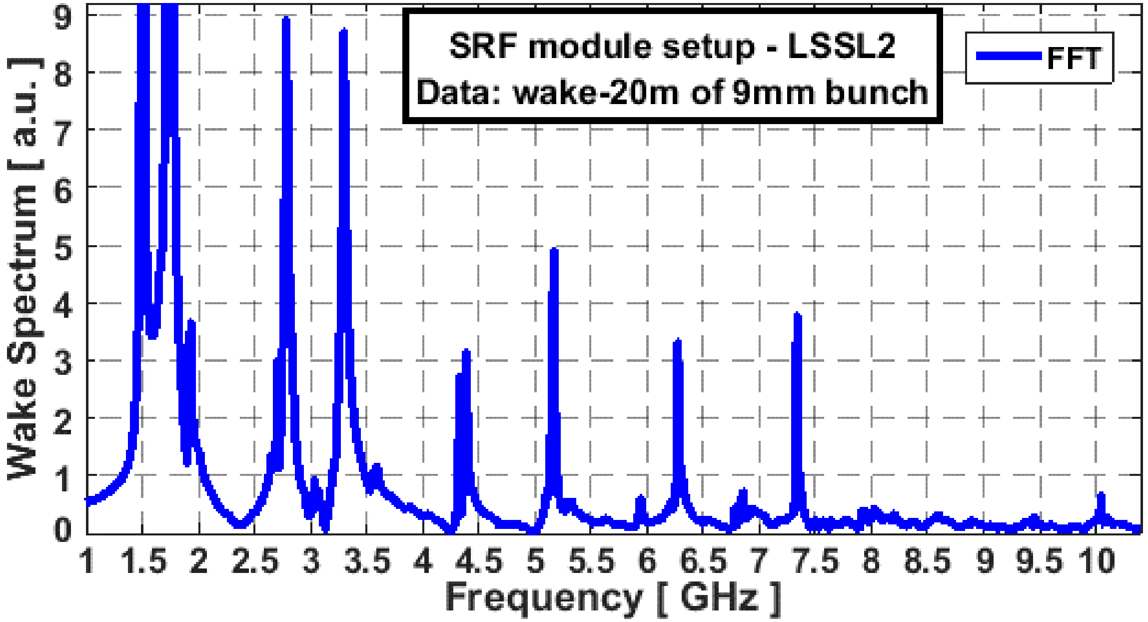
- Long Range Wakes~ 20m
- Spectral Weighting of all Port Signals with Beam Spectrum
- Expected HOM Power Levels & Spectrum
- Efficiency of HOM Damping

➢ 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





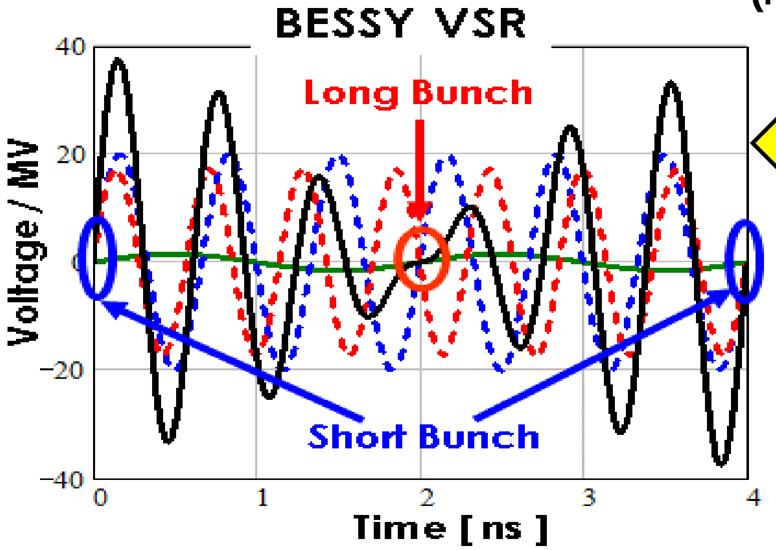
VSR Module Power Levels: Baseline Filling Patern

HOM Power [W]

	Port	LSSL1	LSSL2	SSLL1	SSLL2
1.5 GHz	1	28,9	28,9	102,2	58,6
	2	102,2	102,1	216,0	217,4
	3	102,2	102,1	216,0	217,4
	4	157,0	157,1	178,7	179,0
	5	157,0	157,1	178,7	179,0
	6	195,6	195,5	204,6	231,7
1.75 GHz Cavities	7	46,3	45,8	25,7	25,4
	8	230,3	230,1	140,2	140,1
	9	230,3	230,1	140,2	140,1
	10	163,2	163,7	165,5	165,9
	11	163,2	163,7	165,5	165,9
	12	221,8	221,3	225,7	223,6
	13	52,6	53,0	53,1	52,4
	14	249,6	247,2	254,2	251,8
	15	249,6	247,2	254,2	251,8
	16	185,2	163,9	195,2	171,1
	17	185,2	163,9	195,2	171,1
	18	240,9	199,9	263,6	207,6
1.5 GHz	19	96,2	24,2	59,7	23,7
	20	201,5	115,1	210,2	116,2
	21	201,5	115,1	210,2	116,2
	22	86,0	159,5	90,0	167,6
	23	86,0	159,5	90,0	167,6
	24	97,3	202,8	96,5	208,5
Beam pipes	25	246,6	246,1	227,6	225,0
	26	269,4	330,2	299,0	357,7
	Total	4245 W	4225 W	4457 W	4432 W

On-Axis Voltages of VSR Module

Accelerating Voltage



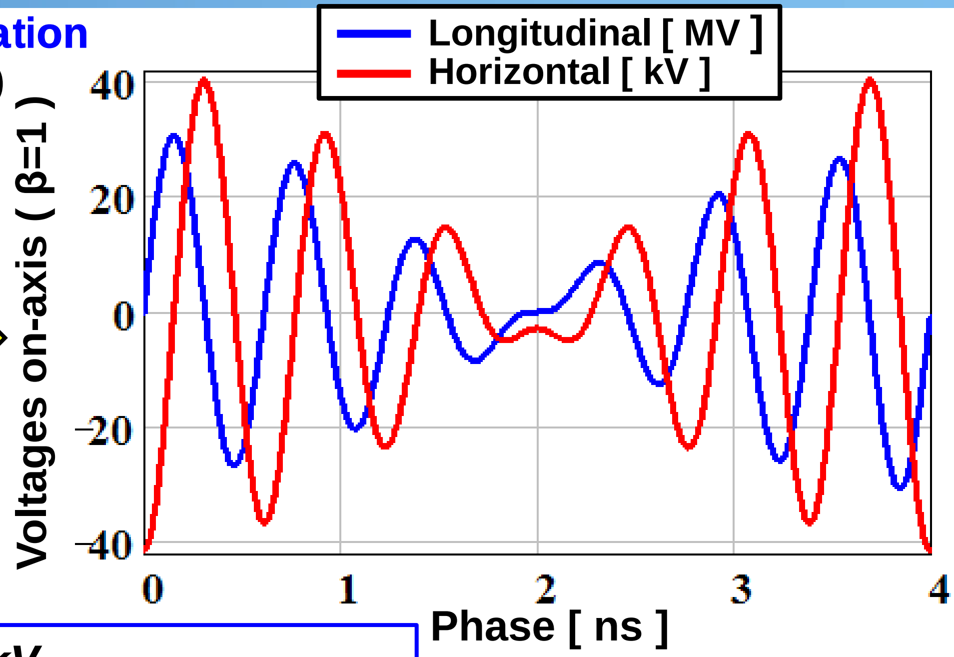
RF Kick from Couplers with Same Orientation

(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

$$\frac{|V_y|\ [kV]}{|V_z|\ [MV]} = \begin{cases} 1.3849\ (1.50\ \text{GHz}) \\ 1.3629\ (1.75\ \text{GHz}) \end{cases}$$

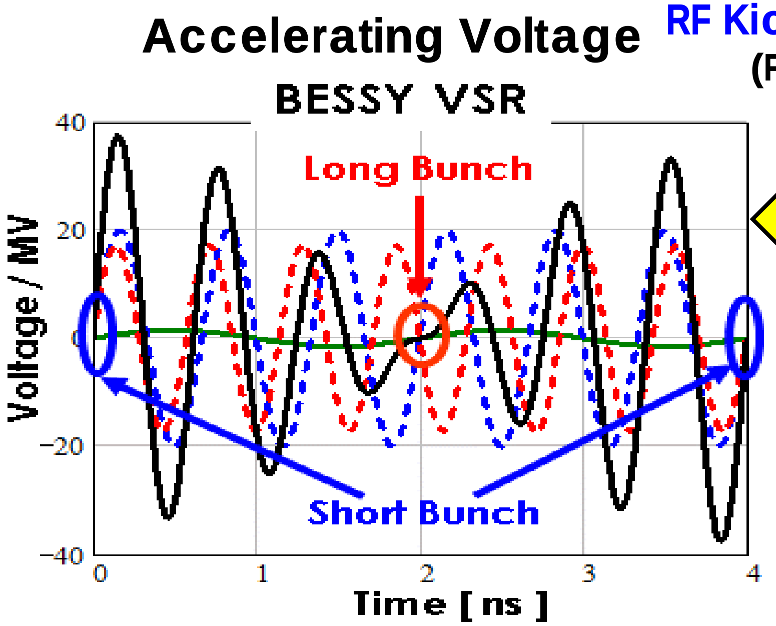


Coupler Kick
(Fundamental Mode)

max(V_y) = 41.43 kV

$$y' = eV_y/Energy \xrightarrow{\textit{1.7GeV}} 24.37\ \mu rad$$

On-Axis Voltages of VSR Module



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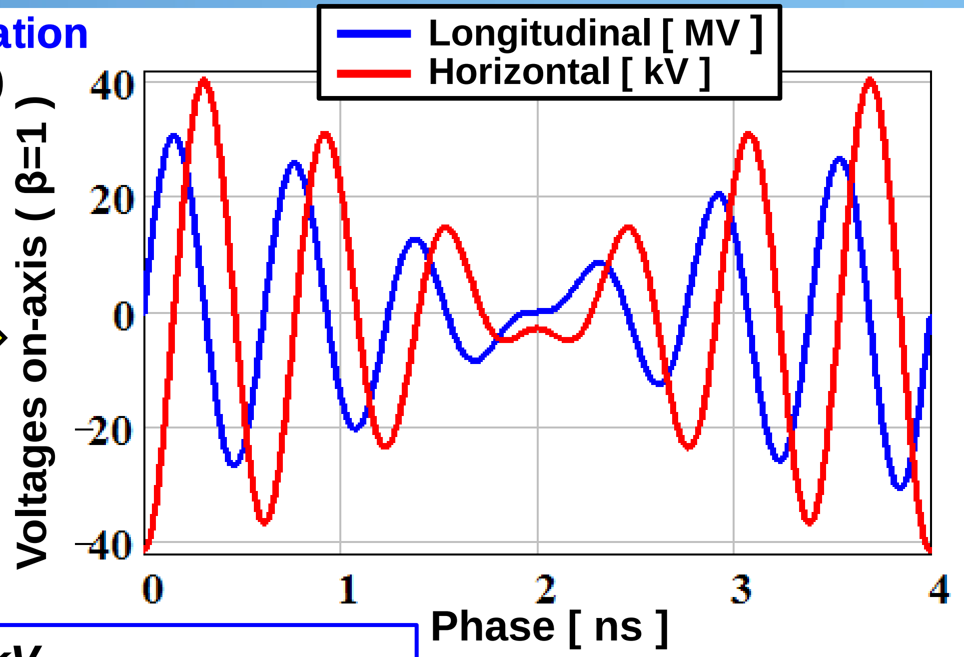

Coupler Kick
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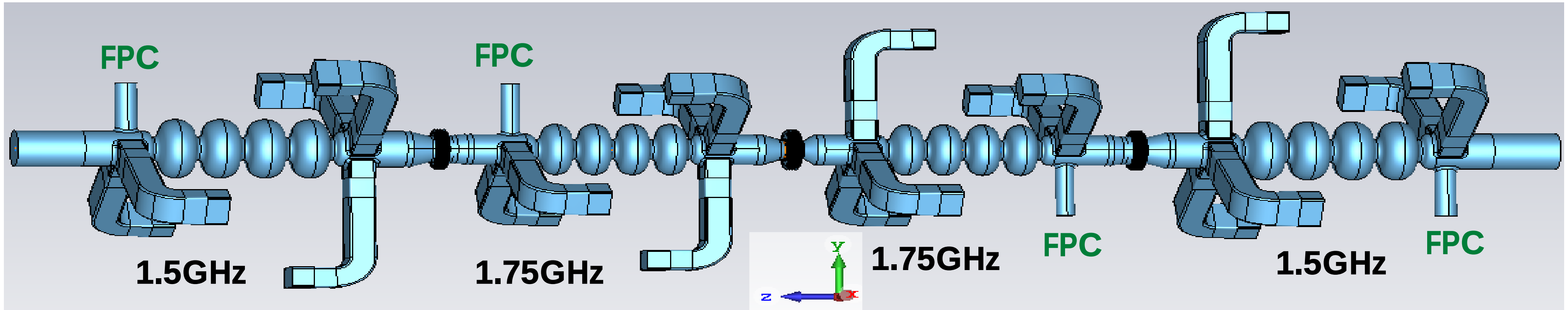
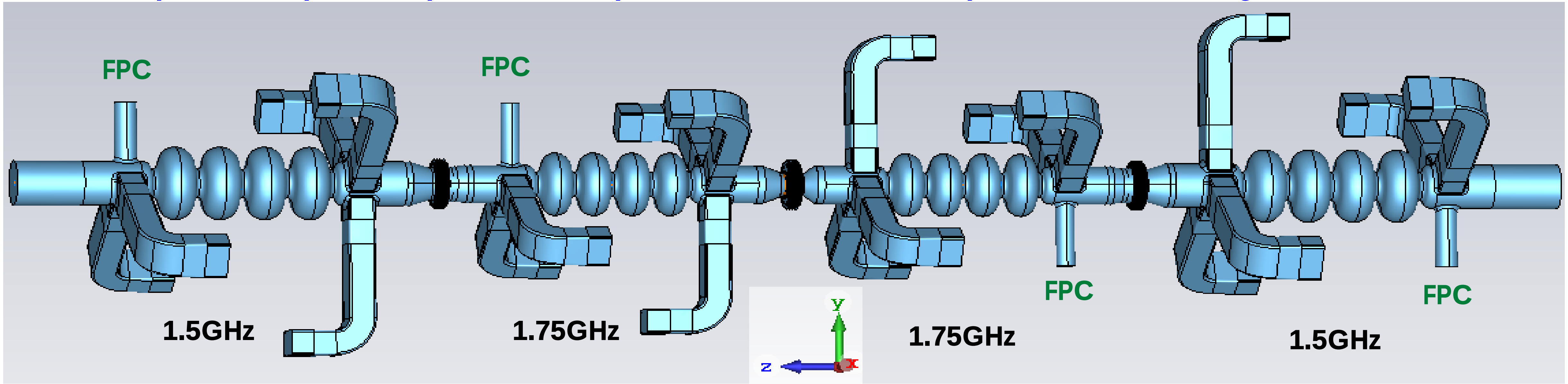
Optimal Setup for Coupler Kick Compensation & HOM Power Equal Distribution Along the Module

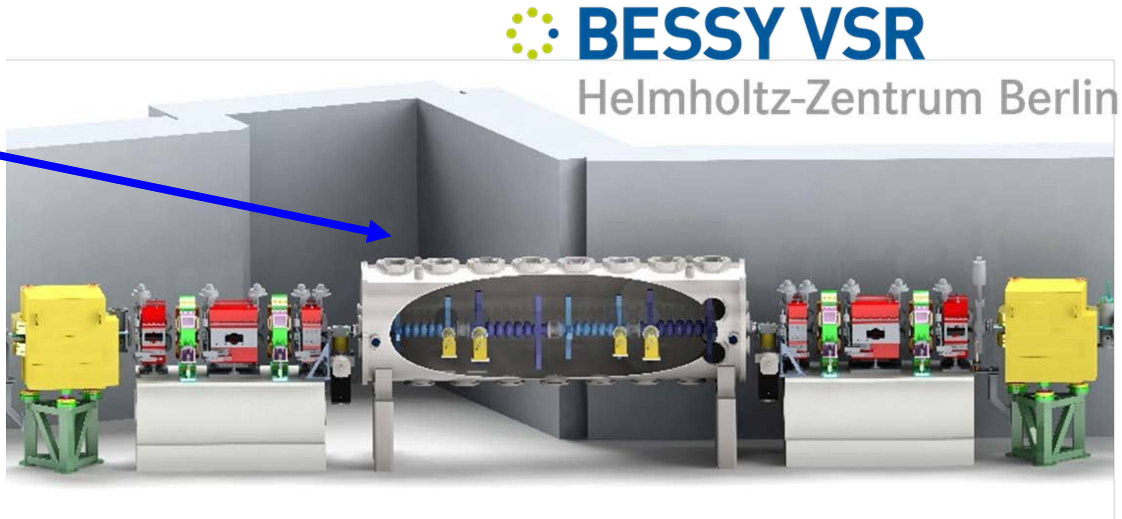


Optimal Cavity Arrangement in the Module

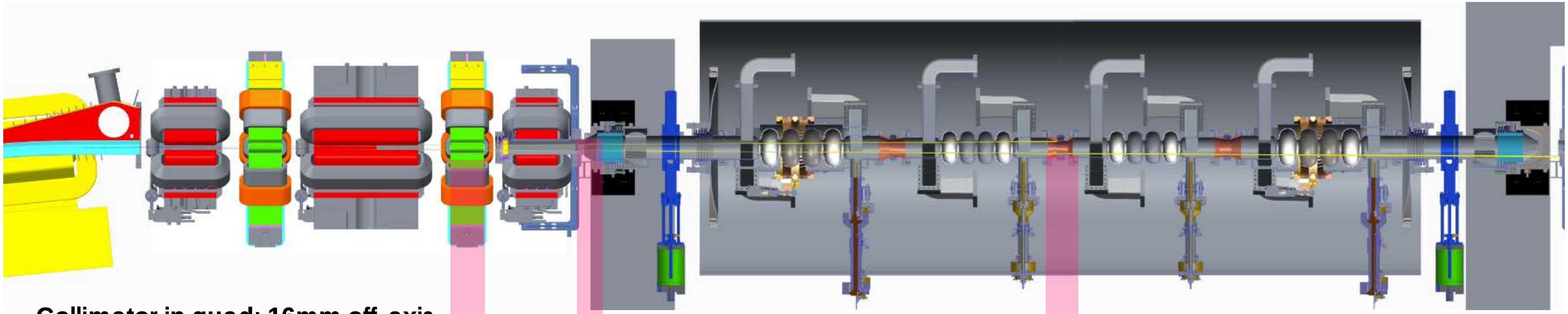
Optimal Setup for Coupler Kick Compensation & HOM Power Equal Distribution Along the Module



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



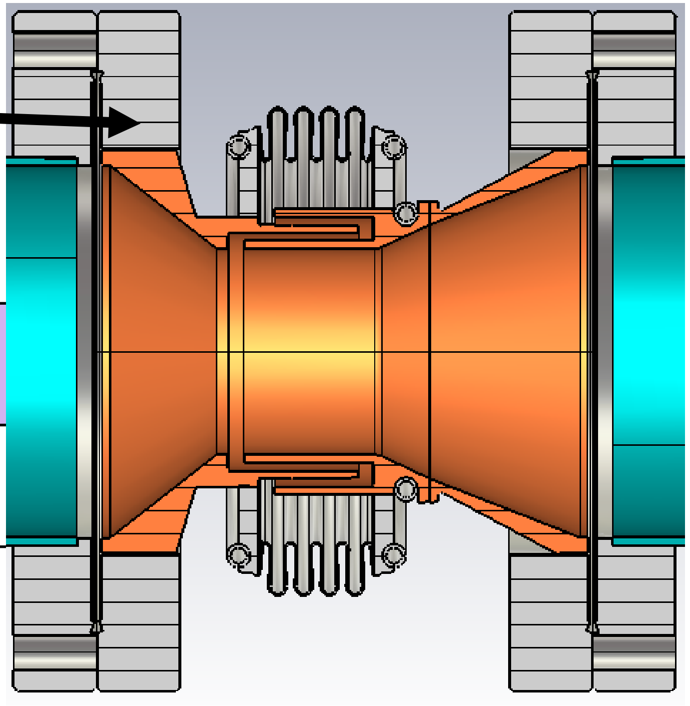
Synchrotron Light Power Depositions



Collimator in quad: 16mm off-axis

Moveable collimator in taper: ≤16mm off-axis

Collimator shielded bellow: 26mm radius



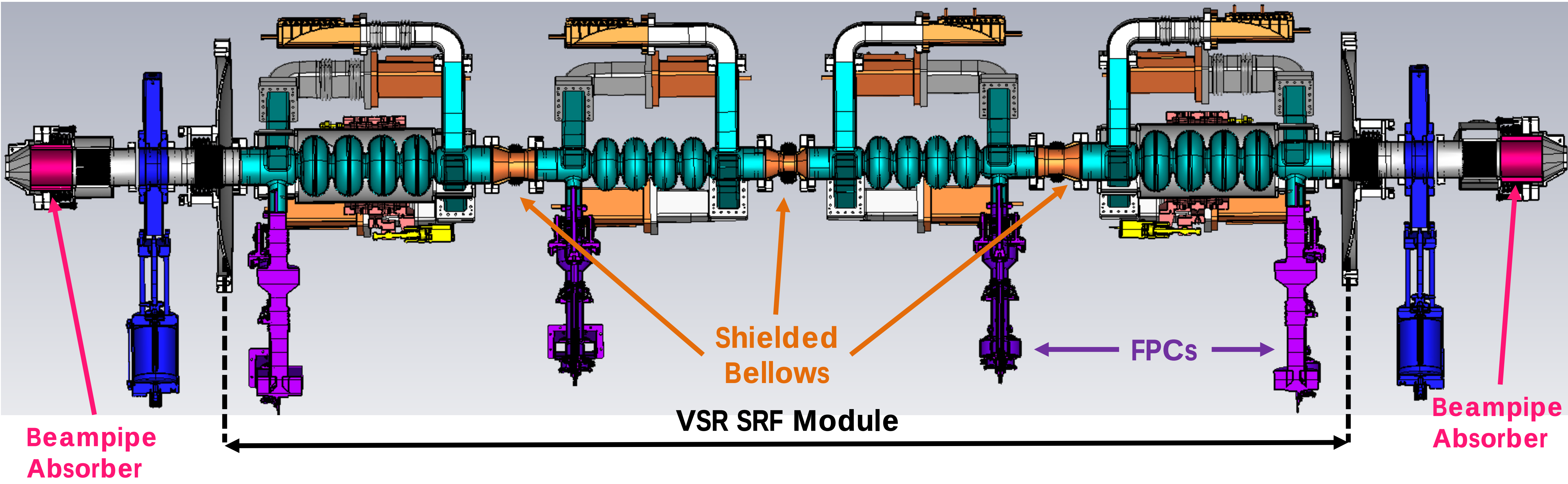
Mandatory to fetch power outside the module or at 5K-level

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

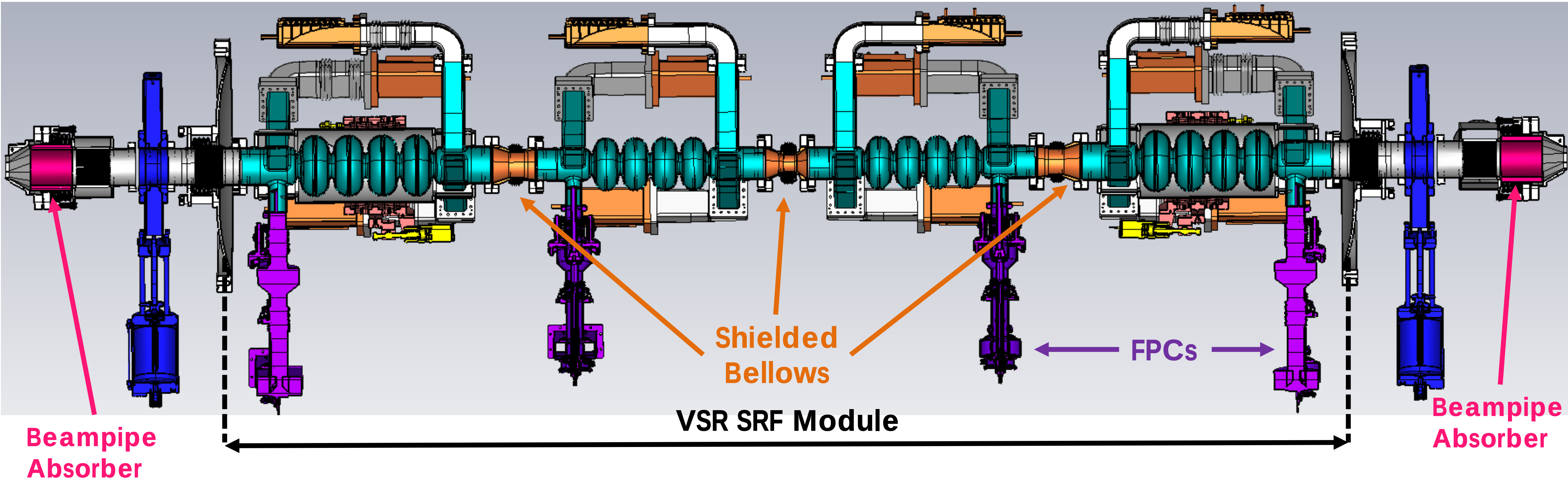
Data courtesy of Markus Ries

Courtasy of H.-W. Glock

Outlook


Beampipe Absorber
Shielded Bellows
FPCs
VSR SRF Module
Beampipe Absorber

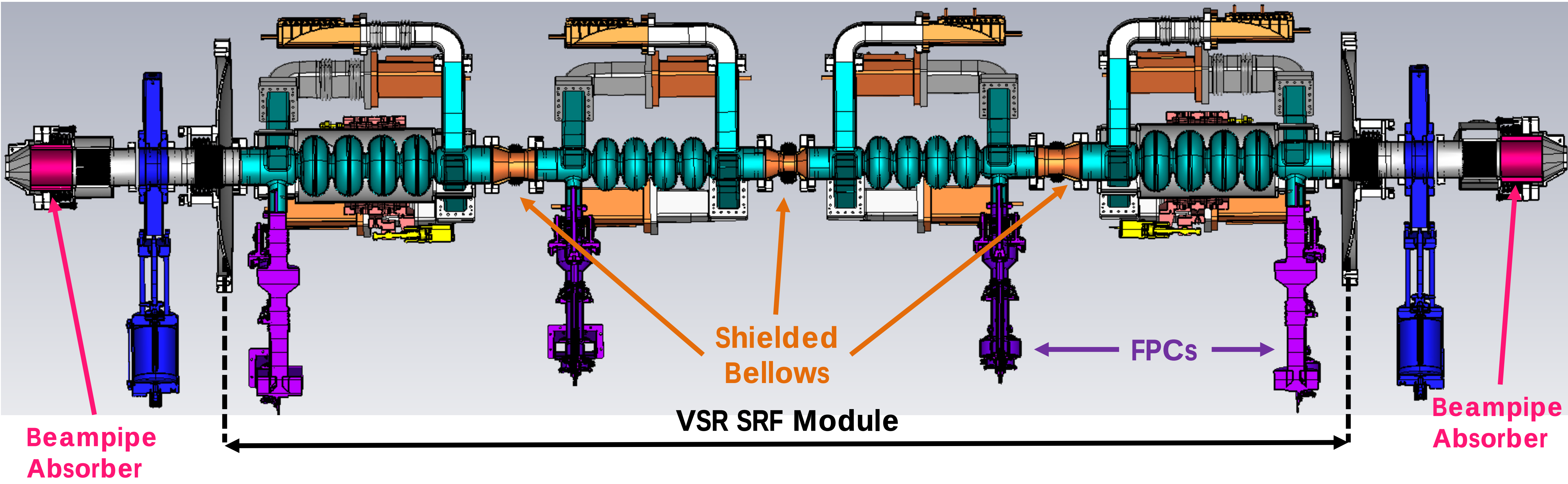
Outlook



- Study effects of undamped energy propagated throug the beam-pipes to the ring. Heating issues.
- Concatenation studies . Cavity-cavity coupling, energy damping and impedances.
- Sensitivity analyses on Cavity Deformations (Fabrication Tolorances)
- Thermal studies (waveguides, flanges...).
- Engineering challanges & solutons.

… **And much more ongoing R&D.**

Outlook



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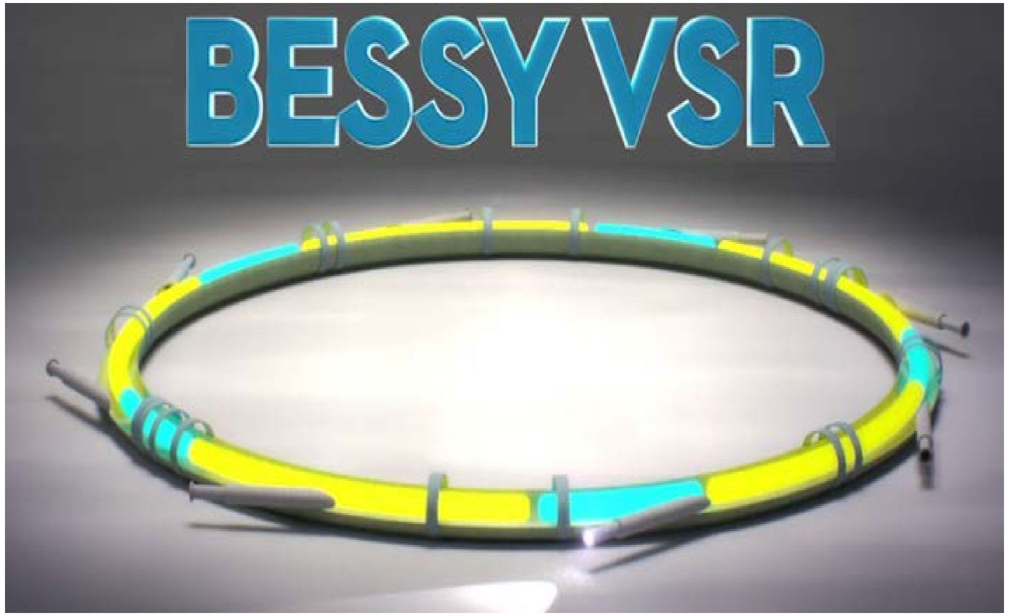
Outlook

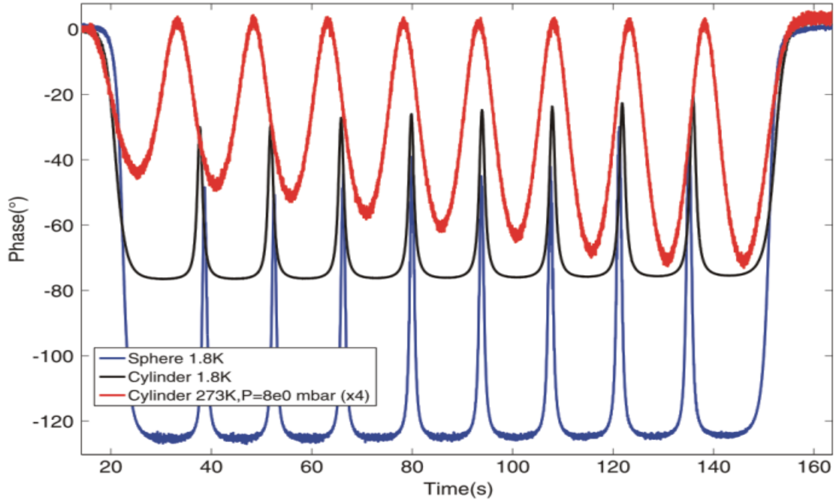


Let this Brilliant Light
to be ...

Thank You for Your Attention !

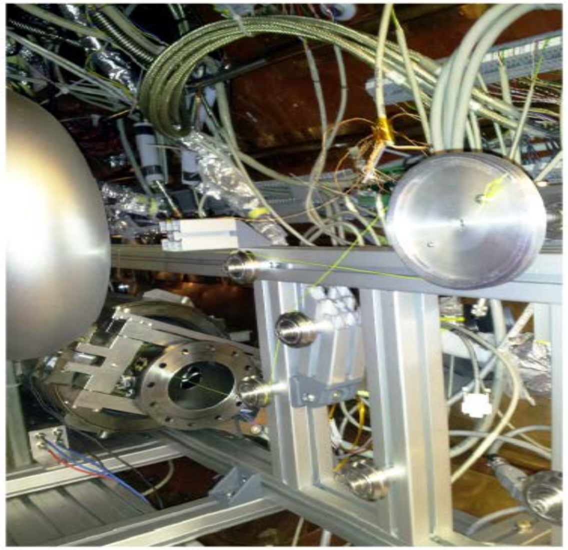
A COLD BEAD-PULL TEST-STAND FOR SRF CAVITIES

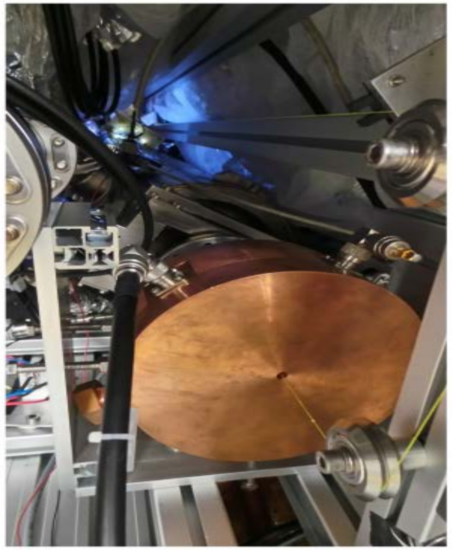
Fundamental -mode



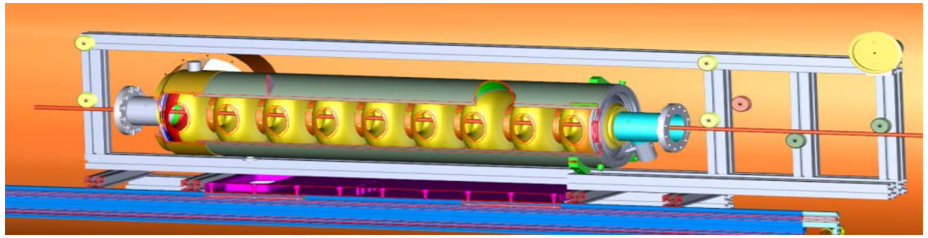
- 1st Cold bead-pull test stand commisioned and in operation
- Form factor of the bead extracted by means of a copper pillbox at 1.8 K
- Experimental study of the effects created by cooldown process and tuner actuation on field profile
- Sucessfully commisioned a 1.3GHz 9-cell Tesla cavity for the fundamental passband. Characteristic parameters such as R/Q can be experimentally determined.
- Study of the field profile and R/Q for different HOM modes

Cold Test-Stand





9-cell Tesla cavity mounted on the test-stand before the installation of the pillbox (a). Pill-box cavity mounted with the wire system inside the HobiCat cryomodule (Niobium 9-cell cavity hidden behind) (b).



Layout of the 9-cell Tesla cavity mounted within HoBiCaT test cryomodule [1,2].

Courtesy of A. Velez (HZB)

[1] A. Vélez, A. Frahm, J. Knobloch, A. Neumann "Developments on a cold-bead-pull test stand for SRF cavities". Proceedings of SRF2015, Whistler, BC, Canada. TUPB078.
[2] O. Kugeler, A. Neumann, W. Anders, and J. Knobloch, Review of Scientific Instruments 81, 074701 (2010).