Higher Harmonic SRF Cavities for Upgrade of BESSY II Storage Ring

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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**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lattice</td>
<td>DBA</td>
</tr>
<tr>
<td>Circumference</td>
<td>240 m</td>
</tr>
<tr>
<td>Energy</td>
<td>1.7 GeV</td>
</tr>
<tr>
<td>Current</td>
<td>300 mA</td>
</tr>
<tr>
<td>RF Frequency</td>
<td>500 MHz</td>
</tr>
<tr>
<td>RF Voltage</td>
<td>1.5 MV</td>
</tr>
<tr>
<td>Bunch Length</td>
<td>15 ps</td>
</tr>
<tr>
<td>Emittance</td>
<td>6 nm rad</td>
</tr>
</tbody>
</table>
The Concept of BESSY VSR

**BESSY II @ present**

Normal conducting cavity system

- Low alpha 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

  \[ \sigma \propto \frac{\alpha}{\sqrt{V_{rf}}} \]

- 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
  \[ \sigma \propto \frac{\alpha}{\sqrt{V}} \]

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

Machine optics
Hardware (RF cavities)

![Diagram of Bunch current vs. RMS bunch length](image)
Voltage / MV

Time [ ns ]

Voltage: 1.5 MV @ 0.5 GHz

15 ps bunch

\[ V \propto V \times f_{rf} = 0.75 \, MV \times GHz \]

\[ V \propto V \times f_{rf} = 30 \, MV \times GHz \]

\[ V \propto V \times f_{rf} = 60 \, MV \times GHz \]

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

- 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 Storage Ring

BESSY VSR
Helmholtz-Zentrum Berlin

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

**CHALLENGES**

- CW operation @ high field levels E=20MV/m
- Peak fields on surface (discharges, quenching)
- High beam current (I_b=300mA),
- Cavity HOMs must be highly damped (CBIs)
- Exotic cavity design (damping end-groups)
- Integrating in existing storage ring
- Transparent Parking of SRF Module.
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 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.
### Simulation Results – for both Cavity (TM$_{010}$ π-mode)

<table>
<thead>
<tr>
<th></th>
<th>1.5GHz</th>
<th>1.75GHz</th>
<th>Design goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Cells</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$L_{\text{active}}$</td>
<td>0.4 m</td>
<td>0.344 m</td>
<td></td>
</tr>
<tr>
<td>Frequency [GHz]</td>
<td>1.4990</td>
<td>1.7489</td>
<td>3$^\text{rd}$ &amp; 3.5$^\text{th}$ harm. of 499.65 MHz</td>
</tr>
<tr>
<td>$Q_{\text{ext}}$</td>
<td>4.99$\times10^7$</td>
<td>4.28$\times10^7$</td>
<td></td>
</tr>
<tr>
<td>$G$ [Ω]</td>
<td>277.63</td>
<td>275.42</td>
<td></td>
</tr>
<tr>
<td>$E_{pk} / E_{acc}$</td>
<td>2.32</td>
<td>2.30</td>
<td>$\leq 2.4$</td>
</tr>
<tr>
<td>$B_{pk} / E_{acc}$ [mT / (MV/m)]</td>
<td>4.98</td>
<td>5.13</td>
<td>$\leq 5.3$</td>
</tr>
<tr>
<td>$R/Q$ [Ω]</td>
<td>386</td>
<td>380</td>
<td>$\geq 90$ per cell</td>
</tr>
<tr>
<td>Field Flatness - $\mu_{ff}$</td>
<td>97%</td>
<td>99 %</td>
<td>$\geq 95$%</td>
</tr>
</tbody>
</table>
Wakefield Simulations for HOM Spectrum Control

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

Reconstructed Wake Potential - Bunch 4mm

Bunch 4mm

Longitudinal Impedance (Circuit definition)
Bunch - 4mm

Modes extracted from Wake
- BESSY II Feedback Threshold
Impedance from Wake run: Bunch 9mm on-axis, length-20m

4cell – 1.75GHz Cavity Designs

R0 = 77mm, Rx2=33 mm (Table No: 1-3)

R0 = 77mm, Rx2=32 mm (Table No: 4-5)

Wake impedance Z [Magnitude]

Freq / GHz

[Graphs showing impedance plots for different scenarios]
Geometry Parameters for Accelerating Mode & HOM Control

- \( \text{Rx2}/\text{RxC} \) – field flatness (not sensitive on other parameters)
- \( \text{HOM spectrum shift} \) is sensitive on cell-slope
  (for tuned fundamental)
- Design:
  1. Fix iris radius (Shunt impedance)
  2. Ensure field flatness >95% (\( \text{Rx2}/\text{RxC} \), fixed slope)
  3. Tune fundamental frequency by \( r_2 \), check B-peak.
  4. Check HOM spectrum

Smooth iris (<\( ry_1 \)) => reduce E-peak
More Volume(>\( rx_2 \) or >\( r_2 \)) => reduce B-peak
HOM Power of Single Cavity – VSR Baseline beam

Spectrally Weighted with “Baseline” pattern

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

- 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

Time Signals

Bunch Train - Baseline

Bunch Current [ mA ]

Bucket Number

\[ \Delta f = 250 \text{ MHz} \]

\[ \mathcal{I}_b(\omega) = \sum_n q_n \cdot e^{-0.5 \cdot \omega^2 \sigma_n^2} \cdot e^{j \omega t_{0,n}} \]

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

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

\[ \mathcal{I}_0 - \text{Simulated single bunch} \]

Signal Spectrum

FFT

Bunch Train (Baseline) Spectrum

\[ \Delta f = 250 \text{ MHz} \]
HOM Power of Single Cavity 1.5GHz

HOM Power spectrum (Baseline) at Different Ports

Beam pipes

Waveguides

FPC

Total - 37.91 W

TEM – 6W (fc=2.828GHz)

TE11z – 17W (fc=2.828GHz)

TE22z – 8W (fc=5.509GHz)

TE33xz – 4W (fc=7.973GHz)
Coax coupler diameters: 49 mm x 20 mm.
- Two ceramic windows to maintain vacuum.
- Inner and outer coax bellows provide a tuning mechanism to allow for variable coupling with a $Q_{\text{ext}}$ of $6 \times 10^6$ to $6 \times 10^7$

- 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

S11 Plot
Magnitude of -46 dB at 1.498 GHz

Magnitude plot of E-field in coupler

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)

HOM Power Levels & Distribution for Baseline-FP (Wake Simulation - Bunch=9mm onAxis)

<table>
<thead>
<tr>
<th>Ports</th>
<th>Model mit FPC</th>
<th>Model ohne FPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>FPC(1)</td>
<td>2.89</td>
<td>25.86</td>
</tr>
<tr>
<td>WG(1)</td>
<td>93.78</td>
<td>91.62</td>
</tr>
<tr>
<td>WG(1)</td>
<td>93.78</td>
<td>91.62</td>
</tr>
<tr>
<td>WG(2)</td>
<td>87.35</td>
<td>87.94</td>
</tr>
<tr>
<td>WG(2)</td>
<td>87.35</td>
<td>87.94</td>
</tr>
<tr>
<td>WG(2)</td>
<td>97.00</td>
<td>98.26</td>
</tr>
<tr>
<td>BmP(1)</td>
<td>213.11</td>
<td>205.58</td>
</tr>
<tr>
<td>BmP(2)</td>
<td>269.97</td>
<td>270.79</td>
</tr>
<tr>
<td>Sum</td>
<td>945.24</td>
<td>959.62</td>
</tr>
</tbody>
</table>

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

Dielectric losses are included in Wake simulation.
Waveguide Bend Broadband Characteristics & HOM Loads

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

- 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.

- L. Guo et al, Development of waveguide HOM loads for BERLinPro and BESSY-VSR SRF cavities, IPAC’17, MOPVA130
Baking temperature ~ 700°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

- No multipacting or quenching
- Field emission - Measurement will be repeated after rinsing.

![Graph showing Q0 vs. Eacc (MV/m)]
Introduction to BESSY II storage ring

SRF Upgrade - BESSY VSR & Highlights

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Beam Loading & Cold Parking

HOM Power Levels in SRF Module

Outlook
BESSY VSR 1.5GHz Cavity Voltages at Cold Parking Regime

Application of Wakefield Theory

T_{rev} = 800 \text{ ns} is directly related with RF buckets thus cavity frequency should be taken 1.5GHz as 3^{rd} harmonic of 500MHz one.

Single Bunch

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

\[ \omega = 2 \pi \cdot f \] – resonant frequency of cavity mode

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

Cavity Parameters

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

\[ Z = R/Q \cdot Q_L \] , \( I_b = q_0/T \)

\[ R/Q = 386 \Omega \]

\[ Q_L = 5 \cdot 10^7 \text{ (SC)}, 10^4 \text{ (warm)} \]

\[ T_{rev} = 800 \text{ ns}, T_{bucket} = 2 \text{ ns} \]

Periodic Bunch

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

\[ V(\omega, t) = \sum_{n=0}^{\infty} V_s(\omega, t + n \cdot T) = V_s(\omega, t) \cdot Re \left[ \frac{1}{1 + e^{-\frac{\omega}{2Q_LT}}} + e^{2j\omega T} \frac{1}{1 - e^{-\frac{\omega}{2Q_LT}}} \cdot e^{\frac{\omega}{2Q_LT}} \right] \]

\[ \frac{\omega T = 2\pi N}{1 - e^{-\frac{\omega}{2Q_LT}}} \rightarrow V_s(\omega, t) \cdot \frac{1}{1 - e^{-\frac{\omega}{2Q_LT}}} \]

\[ \boxed{\text{In case of } f_{rev} \ll \frac{f}{2Q_L}, V(\omega, t) \rightarrow V_s(\omega, t). \text{ Is not applicable to BESSY ring.}} \]
Single Periodic Bunch – Steady State Cavity Voltages

**Single Bunch**

- $I_b = 30 \text{ mA}$
- $\sigma_t = 35 \text{ ps}$
- $T_{rev} = 800 \text{ ns}$

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

Is required for any filling pattern construction.

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**Bunch**

- $f = 1.5 \text{ GHz}$
- Peak Voltage vs. Cavity Detuning

- Plot points at $T_{buck}*N$

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**Peak Voltage vs. Cavity Detuning**

- Single Bunch 30mA, $f_0 = 1.5 \text{ GHz Warm}$

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**Warm Parking - Single Bunch**

- Voltage vs. $t / T_{buck}$
VSR 1.5GHz Cavity Impedances from Eigenmodes

**Monopole Band**

<table>
<thead>
<tr>
<th>Frequency [GHz]</th>
<th>R/Q [Ω]</th>
<th>R/Q*Q_{ext} [Ω]</th>
<th>Mode Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.49866</td>
<td>386</td>
<td>π</td>
</tr>
<tr>
<td>2</td>
<td>1.49134</td>
<td>0.41</td>
<td>2\pi/3</td>
</tr>
<tr>
<td>3</td>
<td>1.47424</td>
<td>0.09</td>
<td>π/2</td>
</tr>
<tr>
<td>4</td>
<td>1.45785</td>
<td>0.05</td>
<td>2\pi</td>
</tr>
</tbody>
</table>

Longitudinal Impedance (Circuit definition)

Transverse Impedance (Circuit definition)

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Cold Parking Monopole Mode Voltages vs. Detuning

- Filling Pattern – Gap1
  - Is assumed that all modes are detuned by same frequency shift as fundamental one.
  - The $2\pi/3$ mode has $\sim 335kV$ 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.

- Filling Pattern – Gap2
  - For both filling patterns voltages are at the same level & similar behavior on detuning.

- Spacing - 500 MHz
- Spacing - 250 MHz

- Total Current 298 mA
- Total Current 295 mA

- Cold Parking - VSR 1.5GHz Cavity: Monopole Band
  - VSR
  - Mode $\pi$ - 1.49866 GHz
  - Mode $2\pi/3$ - 1.49134 GHz
  - Mode $\pi/2$ - 1.47424 GHz
  - Mode $2\pi$ - 1.45785 GHz
Cold Parking – Voltage profiles for Filling Pattern Gap 1

- **Cold Parking**

- **BESSY II Filling Pattern**

- **Voltage profiles**

- **Current [mA]**
  - Chopper: 4mA, 20ps
  - PPRE: 3mA, 18ps
  - Standard bunch: 297 x 0.94 mA, 15 ps

- **Bucket Number**

- **Net Voltage seen by Beam**

- **Beam phases are different**

- **Δf = ± 10 kHz**

- **Δf = -370 kHz**

- **Δf = +370 kHz**
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
\[
\frac{|V_y|}{|V_x|} \approx 1.5 \\
(\text{for both 1.5GHz & 1.75GHz Cavities})
\]

\[
\max(V_y) \sim 45 \text{ kV}
\]

\[
y' = \frac{eV_y}{\text{Energy}} \quad \text{1.7GeV} \quad 27 \mu\text{rad}
\]

- 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, TTHAF084
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

- 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.
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

<table>
<thead>
<tr>
<th>$P_{\text{rad}} @ \ldots$</th>
<th>… collimator in quadrupole</th>
<th>… on moveable collimator</th>
<th>… collimating bellow</th>
<th>… leaving cold module</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moveable not activated</td>
<td>63 W</td>
<td>0 W</td>
<td>11 W</td>
<td>15.3 W</td>
</tr>
</tbody>
</table>

Data courtesy of Markus Ries

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

Courtesy of H.-W. Glock
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
- 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.
Thank You for Your Attention!