Variable pulse length Storage Ring BESSY-VSR
Opportunities and Challenges

Andreas Jankowiak
on behalf of the BESSY VSR team

Helmholtz-Zentrum Berlin / BESSY II
• **BESSY II**
  - strong support for timing experiments

• **Upgrading BESSY II to BESSY VSR**
  - variable pulse length storage ring
  - increasing the phase space density orthogonal to DLSR / LER

• **The BESSY VSR project**
  - funding, status, timeline

• **The challenges**
  - bunch length versus bunch charge
  - high current, HOM damped cw SRF cavities
  - module integration
    - reducing dirt, avoiding synchrotron radiation hitting cavities, …
BESSY II – 1.7 GeV VUV / soft X-ray 3rd generation light source

Construction 1992 – 1998, in user operation since 1999

- Energy/current: 1.7 GeV / 300 mA
- Emittance: 5 nm rad
- Pulse length: 15 ps (rms)
- Circumference: 240 m
- Straight sections: 16
- Undulators / MPW+WLS: 12 / 1+2
- Beamlines: 45 in user operation, thereof 34 simultaneous

ca. 5000 h user operation, 3200 user visits / a

TopUp:
$\Delta I \sim 0.5 \text{ mA} @ 300 \text{ mA}$

Injection efficiency:
Monday: maintenance

9 days
Timing Experiments well supported @ BESSY II

~2 weeks true SB (single bunch): 13.5 mA / Bunch, 27 ps
~2 weeks low α, MB (multi bunch): 0.025 mA or 0.33mA /Bunch, 5 ps (non-bursting/bursting)

All other weeks:
femto slicing / pseudo single bunch in parallel to high current (300 mA) operation

see e.g. R. Müller, Proc. IPAC16, IPAC17
Nearly all SR facilities in the second decade of their operational life are aiming for an emittance/brilliance/coherence upgrade (ESRF, PETRA III, Spring-8, APS, ALS, DIAMOND, SOLEIL, ELETTRA SLS, …) following DLSR concepts

Need to go for multi-bend achromat lattices
new magnet systems, new vacuum system due to smaller apertures, sometimes new injector, lifetime issues = radiation issues, …
→ significant dark time for users (e.g. ESRF = 19 months 2018-2020)

At HZB we are following an different upgrade path for BESSY II
Conserving photon brilliance for all user and add short pulse operation (@ all beam lines) in parallel
→ BESSY-VSR
Today: short pulses, low flux

1.5 MV @ 500 MHz rf-systems = $2\pi$ 0.75 MV GHz

→ reduce $\alpha$ by 100 = low-alpha operation with 1/10 bunch length

→ limited average current ($\sim$ 1/100)

→ rather “dark” operation mode

Future: short pulses, high flux

supply additional high voltage at high frequency: 32 MV @ 1.5 GHz

→ short 1.9 ps pulses with same current as in standard user op.

→ forced low-alpha mode permits even $\sim$ 400 fs
high voltage (20 MV/m) cw multi-cell SC cavities allow to increase the total voltage gradient by two orders of magnitude → ca. 1/10 bunch length @ constant bunch current

Combining two RF systems with different frequencies (1.5 GHz & 1.75 GHz) generates long and short buckets, which can be filled individually to generate optimized fill pattern.

J. Feikes, P. Kuske, G. Wüstefeld EPAC 2006
G. Wüstefeld, A. Jankowiak, J. Knobloch, M. Ries, IPAC 2011
• 300 mA average current
• camshaft single bunches (short and long) in gaps
• 100 ns gaps → for single bunch separation by chopper

**multi functional / multi user hybrid mode**

ps short single bunch, high current single bunch, slicing bunches, high average brilliance, background of intense CSR/THz radiation

**preserving BESSY II emittance and TopUp**

→ 5 nm rad, lifetime > 5h, average inj. eff. > 90%

*Andreas Jankowiak, BESSY VSR – Opportunities and Challenges, 7th LER Workshop, ARIES, CERN, 16.01.2018*
BESSY-VSR – Adding the dimension of time (high rep. rate ps pulses)

“Beating the complexity of matter through the selectivity of soft X-rays”
One cryo-module with:

2 x 4 cell @ 1.5 GHz & 2 x 4 cell @ 1.75 GHz
operating at 1.8 K LHe temperature
active length: 1.50 m with 20 MV/m
total gradient: \(2\pi 50\,\text{MV} \times \text{GHz} \times \text{x 60 increase}\)
BESSY-VSR – Time line

2015
- Technical Design Study ready
- Application to Helmholtz Association submitted (strategic investment, 19 Mio€ + 10 Mio€ HZB)
- Scientific evaluation of application, result: “outstanding” project
- Full support by German Committee for Research with SR

2016
- VSR not prioritised; application maintained
- Exploring other funding sources, support of Berlin and local admin
- Start of 2 R&D projects for SRF cavity development and bunch2bunch beam diagnostic (3a, 3.0 Mio€)

2017
- Successful applied for EFRE funding (via State of Berlin) → 7.5 Mio€ of the necessary funding = SupraLab@HZB
- 11.8 Mio€ granted by Helmholtz Association
- 10.0 Mio€ HZB funds
>> BESSY VSR fully funded << – total invest ca. 30 Mio€
- project team set up – additional positions (15) nearly filled
- cryo plant tendered and ordered

2018
- tendering cavities & SSA transmitter
- installation & commissioning cryo-plant
- prep. phase cryo-module 2 x 1.5 GHz (assembly, test, beam test)
- full BESSY VSR 2 x 1.5 GHz & 2 x 1.75 GHz (assembly, test, user operation)

implementation within “standard” shutdowns 2018 – 2021 + ca. additional 15 weeks
BESSY-VSR – Main challenges

• **short, intense bunches - scaling behaviour bunch-length vs. current**

• **development and operation of high gradient superconducting cavities**
  - 1.5 GHz and 1.75 GHz @ 20 MV/m gradient cw
  - → 200W @ 1.8 K cooling plant (30% margin), 260 W @ 4.5K, 2 kW @ 50 K
  - → particle free (clean) vacuum around cavity straight, 10⁻¹⁰ mbar
  - → module integration (space, synchrotron radiation) in general

• **control of coupled bunch instabilities**
  - induced by sc cavity impedance, higher order modes of sc cavities
  - → proper HOM damping design of sc cavities, waveguide HOM dampers
  - → sufficiently strong bunch by bunch feedback

• **operation with large (transient) beam loading and in regime of possible Robinson instability**
  - lifetime reduction, phase shift over bunch train, losses
  - → careful set up and control of RF-parameters
  - → appropriate low-level RF-control

• **top up operation: injection from booster in short VSR bunches, lifetime**
  - bunch length in booster 60 ps, injection efficiency > 90%
  - → bunch “compression” in booster at least by factor 2 needed
Highly charged short bunches are limited by the **CSR bursting instability**

unstable bunches are not lost, they **blow up in energy spread and length**

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**bunch length – current relation**

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**stable bunches**

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**unstable bunches**

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P. Kuske, M. Ries, G. Wüstefeld
CSR-driven longitudinal instability of short bunches – predictions of VFP-solver with parallel plate model for BESSY VSR (in black)

Threshold Current / mA

Zero Current Bunch Length / ps

1.0

5 3 2 1.5 1.0

1/2π \cdot \text{d}Vrf/\text{dt} [\text{MV/ns}]

0 20 40 60 80

VFP-solution:
\alpha = 0.00073, Vrf variable
BESSY-VSR

including inductive impedance
→ justifies 1.9 ps @ 0.8mA
Due to space restrictions (4.3m free length in straight) number of cells per cavity = 4

- 4-cell design is validated and closed.
- Total module Voltage 29.7 MV (@20 MV/m)
- Bunch length 1.9 ps @ 0.8 mA (zero current = 1.2 ps)


Calculated impedance budget for single cavity (eigenmode analysis)
Full Module Long Range Wakefield Simulation
(Off-axis XY = 2.1 mm, 9 mm bunch, 20 m wake length)

BESSY VSR – SRF Module Setup – LSSL2

**BESSY VSR module – HOM power levels**

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**Total** | 4245 W | **4225 W** | 4457 W | 4432 W

**HOM Power [W]**

**1.5 GHz Cavities**

**1.75 GHz Cavities**

**1.5 GHz**
BESSY VSR module - Synchrotron Radiation in SRF Cavity Straight

Integrated power inside module ~ 67 W @ 1.8 K

Maximum power density on iris ~ 230 W / cm²

M. Ries et al.
integration of one “warm”=outside and one “cold”=inside module collimator

integrated power inside module $\sim 0 \text{ W} @ 1.8 \text{ K}$
integrated power inside module $\sim 11 \text{ W} @ 5 \text{ K}$

2do: orbit stability margins, MPS

M. Ries et al.
BESSY VSR three frequency nc/sc RF system – Beam loading

2 x 100 ns gaps lead to strong beam loading at pseudo-passive SRF cavities

long bunches are affected most as the delicate balance of canceling gradients is disturbed

affected quantities:
- arrival time (phase transient)
- focusing gradient (bunch length transient)

→ Touschek lifetime reduced by up to 50%

The two 100ns gap for bunch separation by chopper makes some “pain”

M. Ruprecht, PhD thesis and Proc. IPAC
Fighting beam loading with nc 500 MHz cavities: h+2

- one out of 4 NC active 500 MHz cavities detuned by 2 revolution harmonics
- bunch arrival time measured using a streak camera

potential Touschek lifetime increase for BESSY VSR ~ 50%
TRIBs – A way to overcome the transient beam loading issues?

TRIBs = Transverse Resonance Island Buckets (P. Goslawski, M. Ries, F. Kramer, et al.)

TRIBs at BESSY II
A new Bunch Separation Scheme

- Operating machine close to horizontal 3rd order resonance
- Minor impact on linear beam optics expected

2nd stable fix point & orbit

BESSY II standard setting

BESSY II TRIBs setting at 3rd order resonance

TRIBs = Transverse Resonance Island Buckets

BESSY II working point (17.85, 6.73)
BESSY II TRIBs at 3rd order (17.66, 6.73)
TRIBs – It is real (@BESSY II and @MLS)

TRIBs at BESSY II

Proof of Principles Studies:

- Current can be shuffled between both orbits without losses
- Separation at user beamlines is promising
- TopUp injection is possible (if all current is stored on core orbit)

Twin Orbit User Test Week
19. – 25. February 2018

TRIBs - the long term objective:

- Verify if TRIBs bunch separation scheme could be a realistic operation mode for storage ring light sources
- Possible bunch separation scheme for short and long bunches at BESSY VSR
- Strengthen timing user community: 2\textsuperscript{nd} fill pattern, tailored for timing experiments stored on 2\textsuperscript{nd} orbit

Bending magnet beamline, source point image

TRIBs Scheme, 2\textsuperscript{nd} fill pattern stored on 2\textsuperscript{nd} orbits
**TRIBs at BESSY II – Separation and Twiss Parameters of TRIBs orbit**

F. Kramer, PhD thesis in preparation

**Horizontal beam offset**

**Dispersion function**

**Beta function**

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**Equilibrium Emittance:**

BESSY II std.: 7 nm rad
TRIBs core orbit: 8 nm rad
TRIBs island orbit: 9 nm rad
targets for BESSY VSR module installation:
particle free installation / clean vacuum +15m / below 10^{-10} mbar at module

“Operating SRF systems reliably in a “dirty” accelerator” workshop, September 2017, HZB
https://www.helmholtz-berlin.de/events/operating-srf/index_en.html
approach re-design

- fewer, longer vacuum chambers
  → less fragmentation, fewer connections, easier pre-assembly
- NEG coated chambers
- improved ion pump nozzles with smaller ion pumps
- new dipole supports
- additional gate valves
- new BMPs
- new synchrotron radiation absorbers

approach installation (particle free installation)

- pre-assembly in cleanroom
- “portable” clean enclosure (laminar flow boxes) to assemble remaining connections
Pressure profile - currently and with planned improvements

graphic courtesy Volker Dürr and Christian Kalus
The “beating” principle of the BESSY VSR scheme with its short bunches leads to a reduction in phase acceptance compared with today's BESSY II standard bucket → “shooting a camel through the eye of an needle” = bunch length booster needs to be reduced

Radiation protection at BESSY II require for TopUp operation:
- maintaining > 90% injection efficiency on a 4h average
- each single shot needs to be above 60%
Improving the longitudinal acceptance of BESSY II / BESSY VSR

Injection efficiency as a function of phase between booster and storage ring

Scans to determine the phase acceptance of the present BESSY II buckets

1D model assumes no transverse effects

The Red curve is a convolution of a Gaussian (bunch) and Flat top (bucket)

Black is the prediction for the short buckets in BESSY VSR assuming the present conditions

Green shows the increase in Injection efficiency from shorter bunch lengths in the Booster

Shortening the bunch length from the booster from ca. 60 ps to ca. 30 ps would be sufficient.


Andreas Jankowiak, BESSY VSR – Opportunities and Challenges, 7th LER Workshop, ARIES, CERN, 16.01.2018
combines brilliance with short pulses, 
→ structure and dynamics

opens a new regime of storage ring operation, 
→ future combination of DLSR + VSR ?

is attractive for the portfolio of light sources, 
→ unique, complementary to FEL sources

is the ideal and cost effective upgrade of BESSY II 
→ addressing the needs of the existing user community, attracting new users
Light matters!

THANK YOU FOR YOUR ATTENTION