BESSY VSR project for short X-ray pulse production

Adding advanced timing capabilities to storage rings

Andreas Jankowiak on behalf of the VSR project team
presented by Paul Goslawski

Institute for Accelerator Physics
Helmholtz-Zentrum Berlin, BESSY II / MLS

22th September 2017
NOCE2017, Arcidosso, Italy

Overview

- BESSY II @ HZB (Helmholtz-Zentrum Berlin)
  - Motivation for BESSY VSR
  - BESSY specialties: Time resolved user experiments at BESSY II

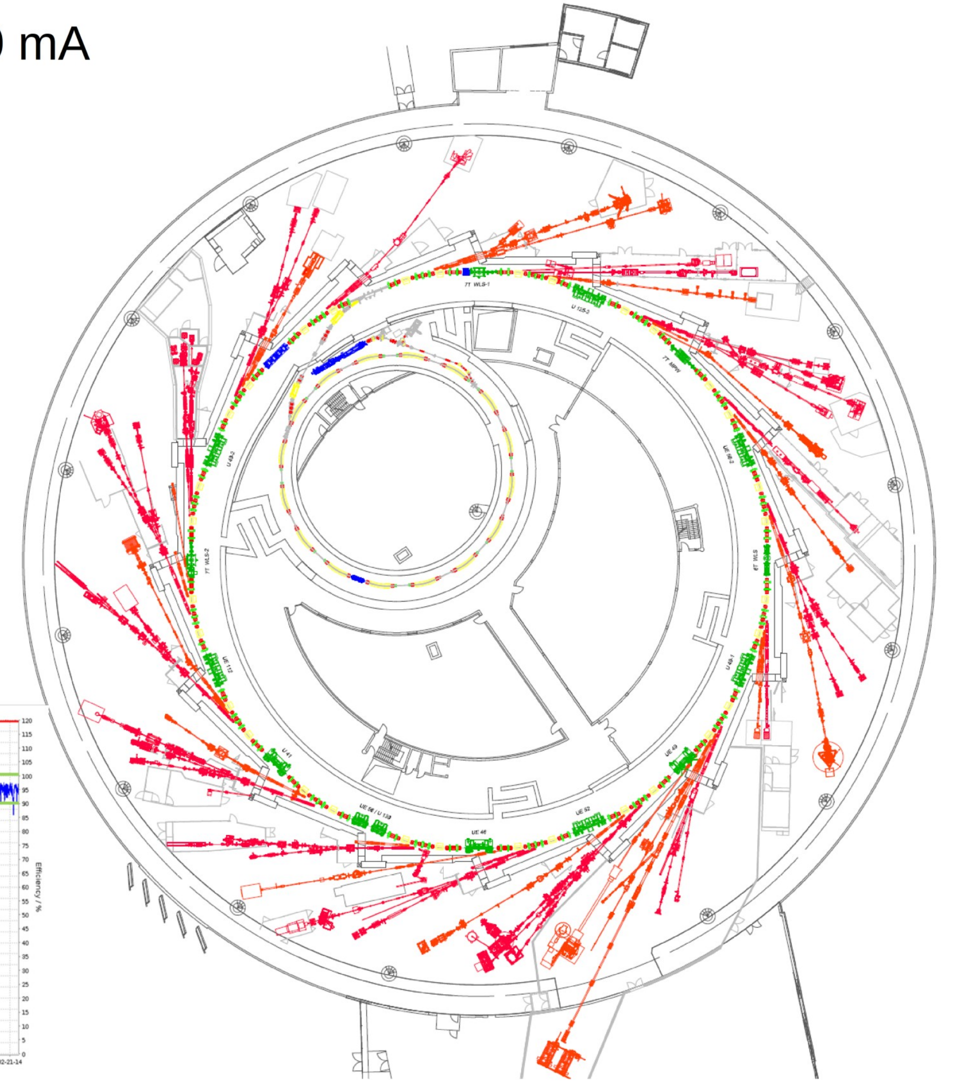
- From BESSY II to BESSY VSR
  - BESSY VSR – The Variable Pulse Length Storage Ring
  - Adding advanced timing capabilities to BESSY II

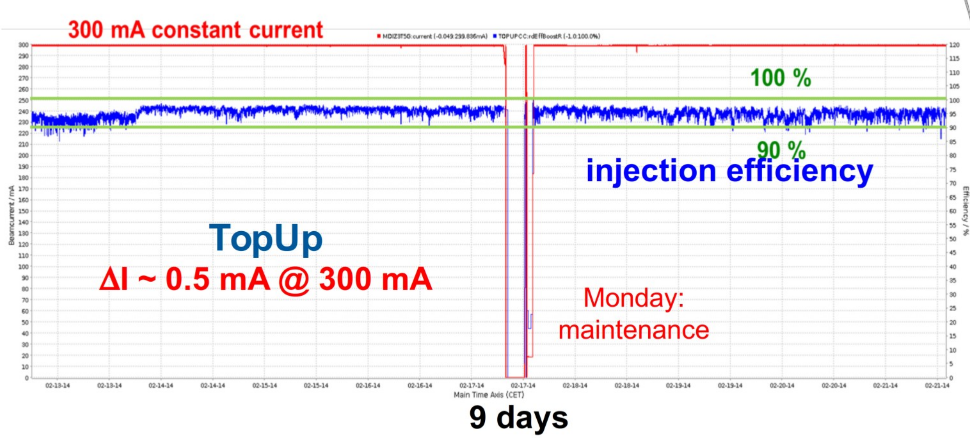
BESSY II: 3rd generation light source (UV / XUV / Soft X-Ray)

Successor of BESSY I, construction 1992 – 1998, user operation 1999

• Energy / Current	1.7 GeV / 300 mA
• Circumference	240 m (DBA)
• Emittance	5 nm rad
• Pulse length	15 ps
• Straight sections	16 / 14
• Undulat./MPW+WLS	12 / 1+2
• Beamlines (ID, Bend)	30, 20

5000 h user operation and
3000 user visits / year

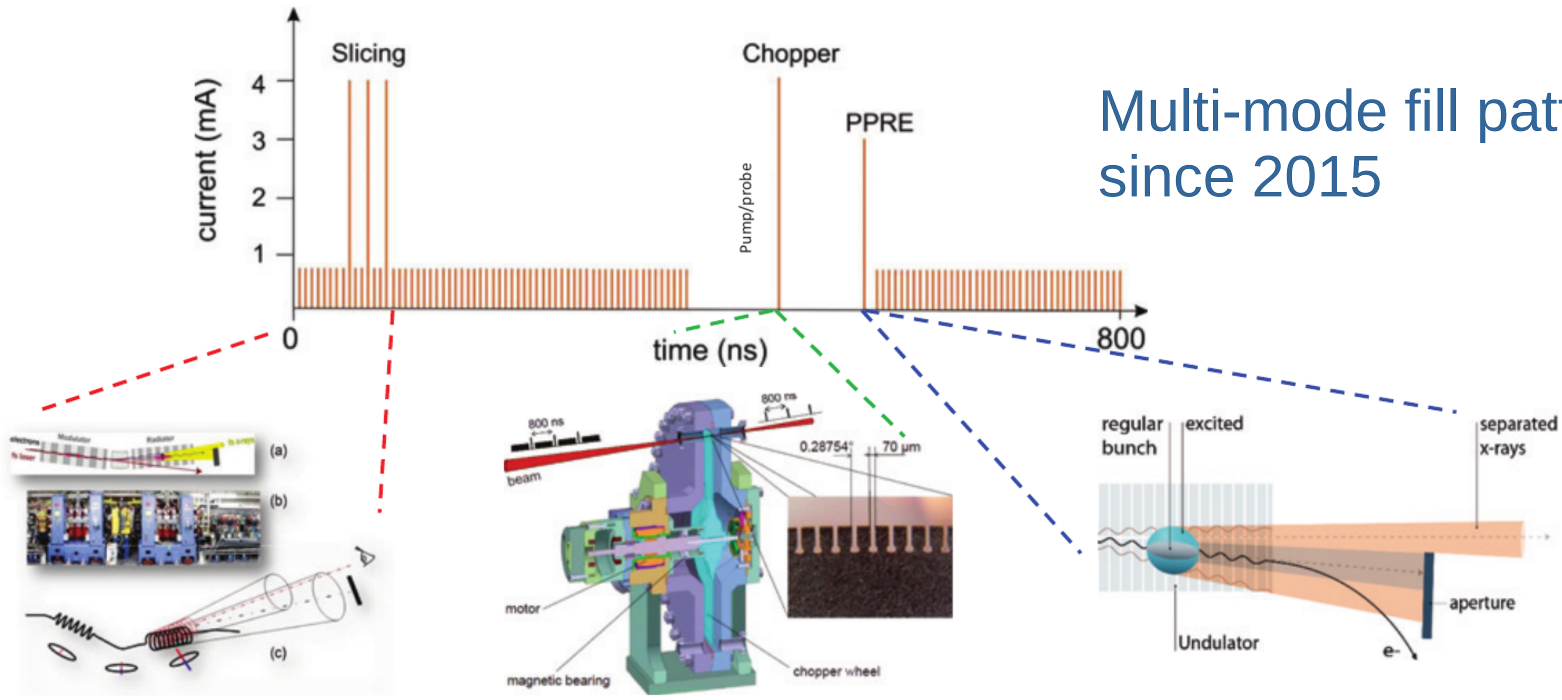




R.Müller et al., Proceedings of IPAC2016, Busan, Korea, WEPOW011

Timing Experiments are well supported @ BESSY II

- Multi Bunch Hybrid Fill pattern since 2015, multi-mode fill pattern
  - 300x multi bunch: 0.9 mA / bunch, 10 ps
  - 1x camshaft bunch: 4 mA, 17 ps, purity > 10^4 (pump, probe)
  - 1x PPRE bunch: 1.25 MHz, 800ns, 10^7 - 10^9 photons/s 0.1%BW for ARTOF setup (Pulse Picking Resonant Excitation)
  - 3x fs-slicing bunch: 4 mA / bunch, 17 ps -> 100 fs photon pulses, 10^6 photons/s 0.1%BW



Multi-mode fill pattern since 2015

BESSY II specialities: single and few bunch

C. Tusche, P. Goslawski et al., App. Phys. Lett. 108, 261602, (2016)

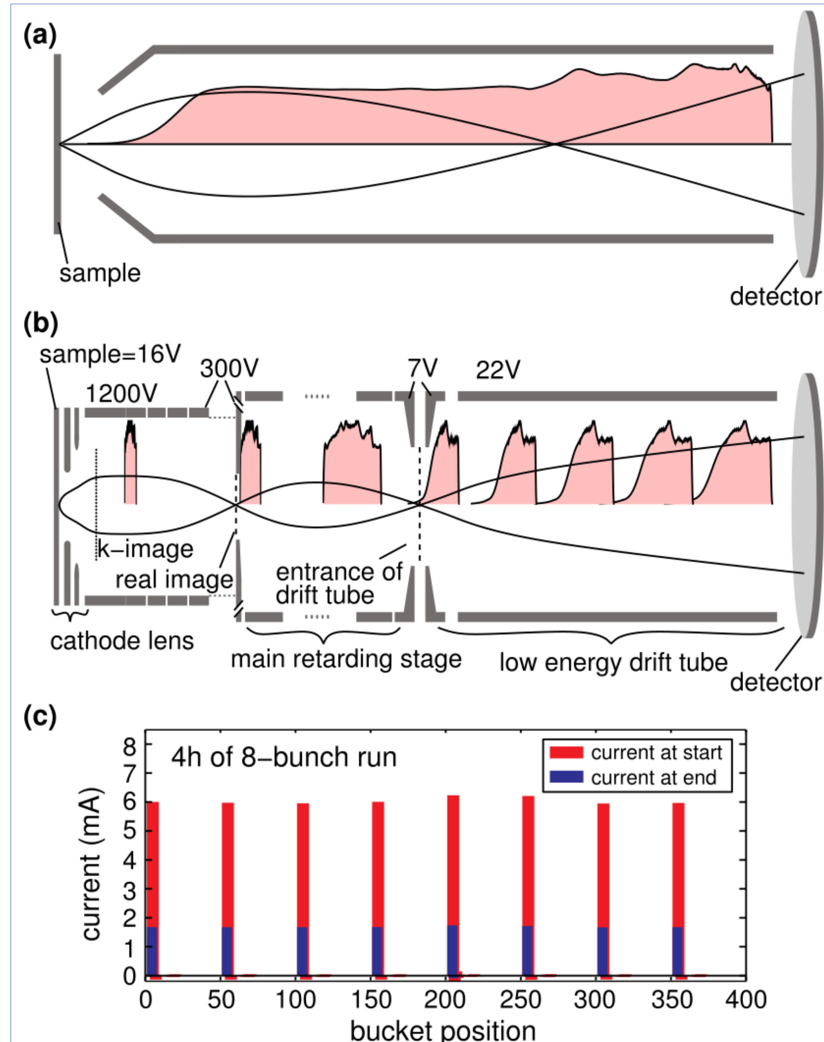
Timing Experiments are well supported @ BESSY II

- 2 - 4 weeks true single bunch (SB):
  1.25 MHz, 800ns, 13.5 mA, 27 ps

- Since 2017 few bunch:
  SB weeks weekends
  5 MHz, 200ns, 32mA,
  4 bunches x 8 mA / bunch, 21 ps

  or

  10 MHz, 100 ns,
  8 bunches



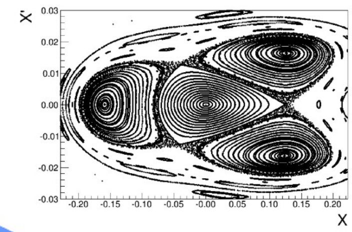
APPLIED PHYSICS LETTERS **108**, 261602 (2016)

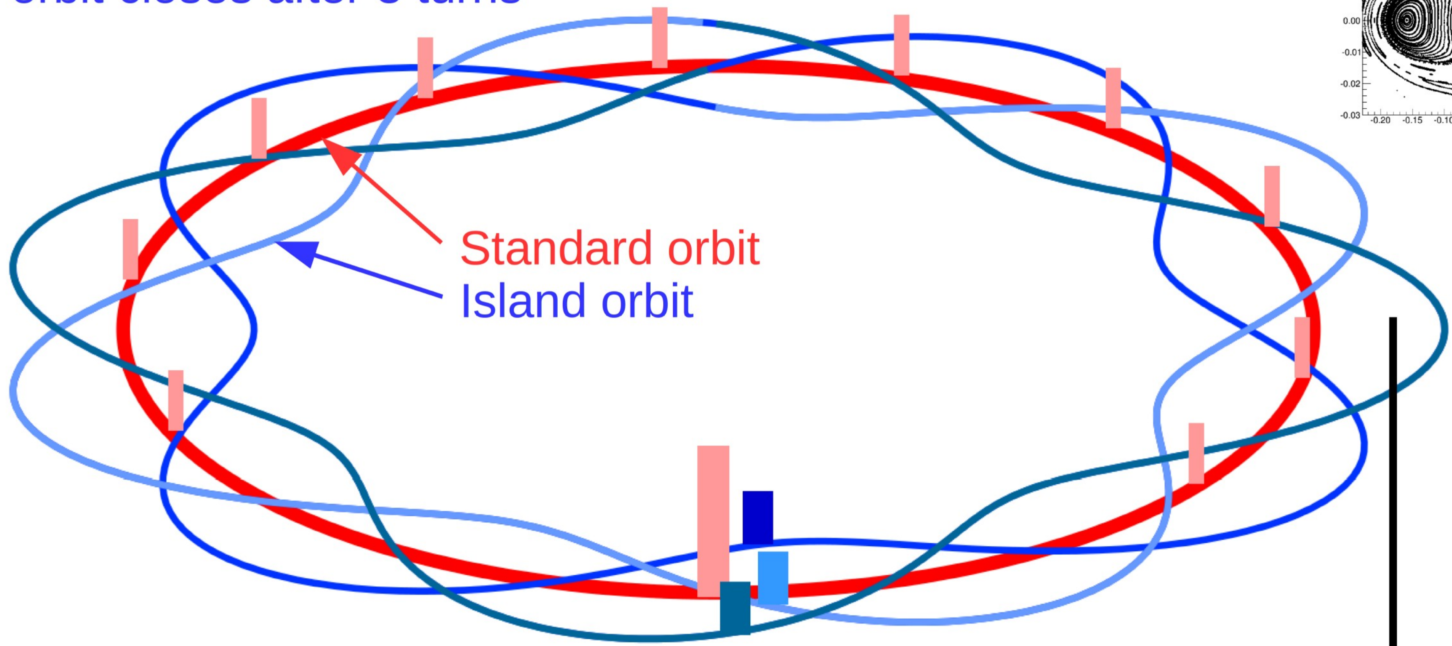
Multi-MHz time-of-flight electronic bandstructure imaging of graphene on Ir(111)

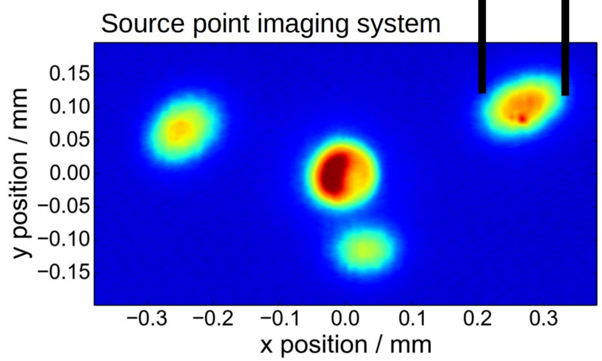
C. Tusche,[1,2,a)] P. Goslawski,[3] D. Kutnyakhov,[4] M. Ellguth,[1,4] K. Medjanik,[4,5] H. J. Elmers,[4] S. Chernov,[4] R. Wallauer,[4] D. Engel,[3] A. Jankowiak,[3] and G. Schönhense[4]

Separation scheme using Transverse Resonance Island Buckets (TRIBs)

3rd order resonance
Island orbit closes after 3 turns







Talk S4.1 – Th 16:30 h, M. Giovannozzi
Talk S4.2 – Th 17:00 h, P. Goslawski
"beams split in horizontal phase space"

Driving forces behind TRIBs – G.Wüstefeld, M.Ries, P.Goslawski
M. Ries et al., Proceedings of IPAC2015, Richmond, VA, USA, MOPWA021
P. Goslawski et al., Proceedings of IPAC2017, Copenhagen, Denmark, WEPIK057

BESSY II specialities: low α_c operation

M. Abo-Bakr et al., Phys. Rev. Lett. 88, 254801 (2002)

R.Müller et al., Proceedings of IPAC2016, Busan, Korea, WEPOW011
K. Holldack, C. Stamm, HZB, in preparation

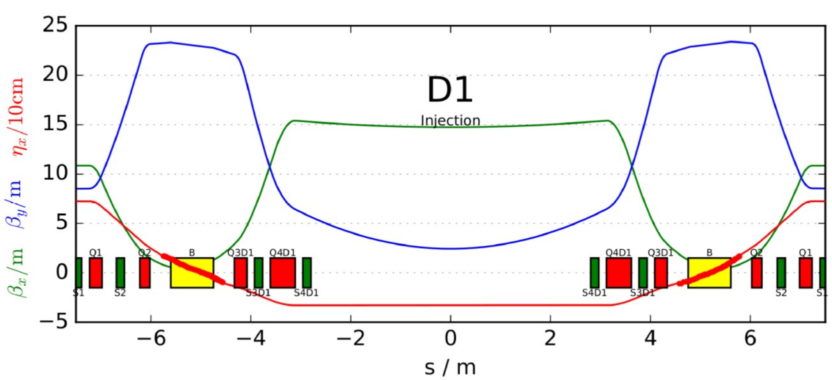
Timing Experiments are well supported @ BESSY II

- 2 - 4 weeks low α_c operation: 0.045 mA or 0.3 mA / bunch, 3 ps
  15 mA or 100 mA (non-bursting or bursting)

- Short bunches with low α_c:

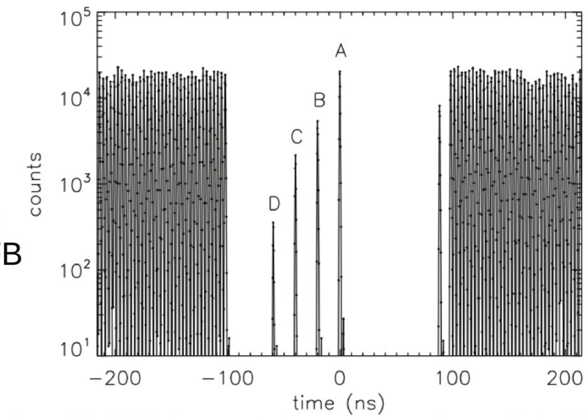
$$\sigma_0 = \delta_0 \cdot \sqrt{\frac{E_0}{f_0}\frac{\alpha_c}{V'}}$$

$$\alpha_c = \frac{1}{L_0}\oint \frac{D_x}{\rho}\, ds$$

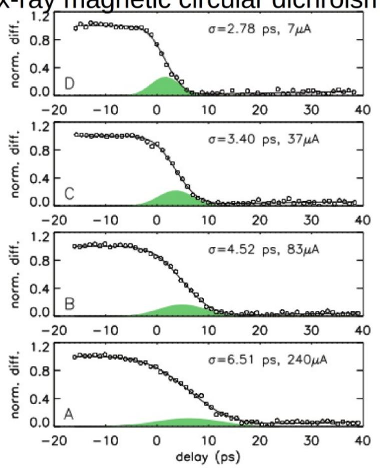


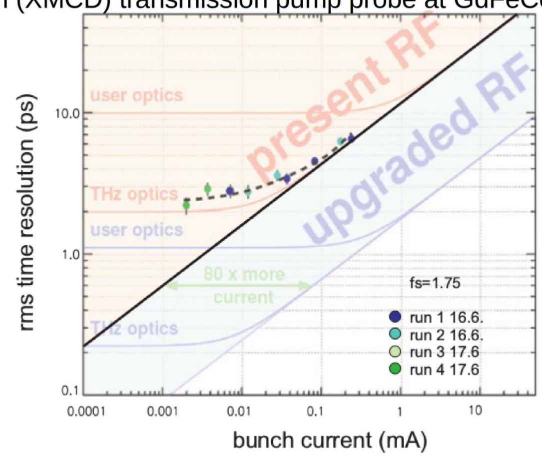
Further development:

- Exotic filling – VSR
- Target bunch current on demand with BBFB
- 240 µA - 6.5 ps
  7µA - 2.8 ps



For x-ray magnetic circular dichroism (XMCD) transmission pump probe at GdFeCo





Low emittance upgrade for 3rd generation light sources

- Many existing SR facilities in the 2nd decade of operation are aiming for an emittance, brilliance, spatial coherence upgrade
  - ESRF, Spring-8, APS, ALS, SLS, … following the DLSR concepts
  - Need to go for multi-bend achromat lattices **(global upgrade)**: new magnet system, new vacuum system due to smaller apertures, sometimes new injector/injection
  - Significant long dark time for users (1 – 2 years)

BESSY VSR – **V**ariable **P**ulse Length Storage **R**ing
HZB follows different upgrade path for BESSY II

- Conserving photon brilliance for all users and
- Add short intense pulse operation at all beam lines in parallel
- Shaping the longitudinal phase space by additional cavities **(local upgrade)**

- **Strengthen the Timing Experiment Community @ BESSY II / VSR**

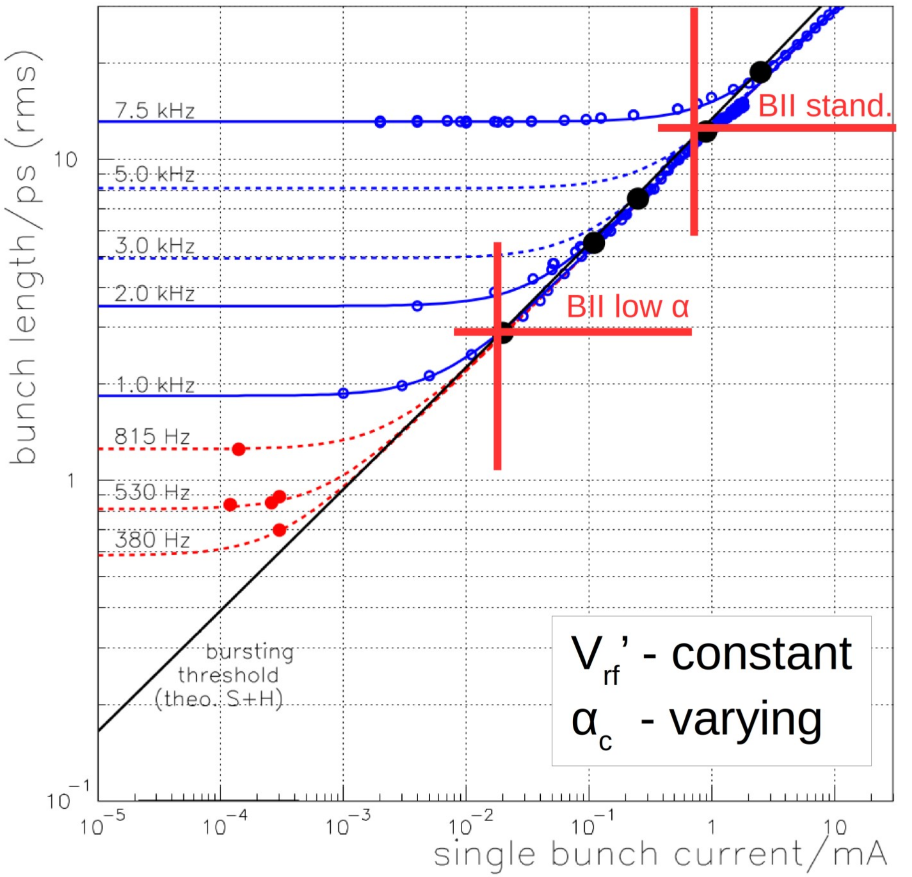
J. Feikes et al., Proceedings of EPAC2004, Lucerne, Switzerland, WEPLT051

Today: low α_c, low flux, short pulse

- Storable current limited by CSR instability – bursting threshold
- Reduction of α_c by 100 (5.0E-4 to 3.5E-5) shortens bunch length by 10, but reduces current by 100
- Machine is dark for other users: -> Only 2 weeks per year

$$\sigma_0 \sim \sqrt{\frac{\alpha_c}{V'_{\mathrm{rf}}}} \qquad I_{\mathrm{th.}} \sim \alpha_c$$

$$I_{\mathrm{th.}} \sim V'_{\mathrm{rf}}$$



Future: high gradient, high flux, short pulse

- Additional gradient -> high voltage at high frequency
- Bunch shortening, but at high α_c, allows to store higher current in short bunches

Short pulses in storage rings

Today: low α_c, low flux, short pulse

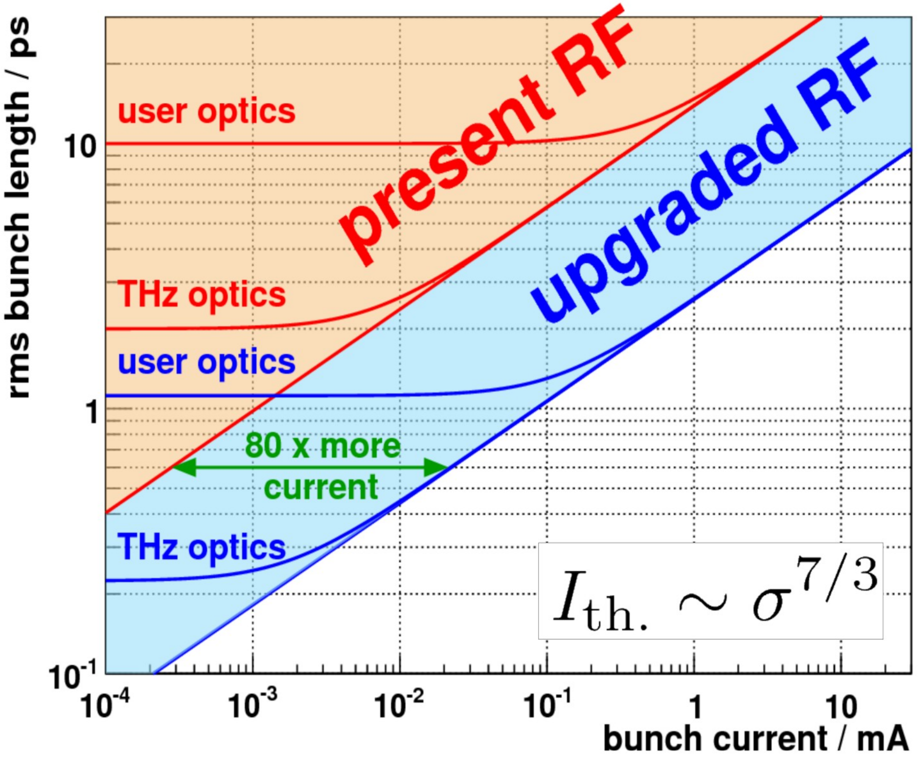
- Storable current limited by CSR instability – bursting threshold
- Reduction of α_c by 100 (5.0E-4 to 3.5E-5) shortens bunch length by 10, but reduces current by 100
- Machine is dark for other users: -> Only 2 weeks per year

$$\sigma_0 \sim \sqrt{\frac{\alpha_c}{V'_{\mathrm{rf}}}} \qquad I_{\mathrm{th.}} \sim \alpha_c$$

$$I_{\mathrm{th.}} \sim V'_{\mathrm{rf}}$$

Future: high gradient, high flux, short pulse

- Additional gradient -> high voltage at high frequency
- Bunch shortening, but at high α_c, allows to store higher current in short bunches



BESSY VSR first ideas

Proceedings of EPAC 2006, Edinburgh, Scotland MOPCH053

TOWARDS SUB-PICOSECOND ELECTRON BUNCHES: UPGRADING IDEAS FOR BESSY II *

J. Feikes, P. Kuske, G. Wüstefeld[1], BESSY, Berlin, Germany

Abstract

Sub-picosecond electron bunches are achieved with the BESSY low alpha optics and their lengths are measured [1]. The current in these short bunches is limited to the micro Ampere level, to avoid current dependent bunch lengthening. An upgrade of the BESSY II rf system is suggested to overcome this low current limitation
...
lengths in the user and THz optics are 13 ps and 3 ps, respectively.

SCALING EQUATION

The bunch length in the storage ring is described by two ... ases. One is the "zero current limit", where the ... independent on the current. This length σ is a

2006 - gradient upgrade:

But:
All bunches will be short!
350 x 0.86 mA @ 1.7 ps

-> severe impedance problems
and bad lifetime expected

-> more flexible solution needed

2011 – voltage beating scheme:
Short and long bunches
simultaneously

THPC014 Proceedings of IPAC2011, San Sebastián, Spain

SIMULTANEOUS LONG AND SHORT ELECTRON BUNCHES IN THE BESSY II STORAGE RING

G. Wüstefeld, A. Jankowiak, J. Knobloch, M. Ries, HZB, Berlin, Germany

bstract

We present first ideas of a scheme to develop BESSY II ... a variable electron pulse length storage ring. The fi... goal is, to fill BESSY II with short bunches of 1.5 ps ...th (rms) and long bunches of 15 ps length simultane... in the presently applied user optics. All insertion de... are operated as usual, i.e. the helical undulators and ...ld insertions. Long bunches of 1.5 mA current per ... twice the value of the present user optics, are filled ... second bucket. The other buckets can be filled with ...nches of up to 0.8 mA. The lower current value is ... to avoid increase in the bunch length and bunch ...ergy spread, predicted by scaling laws. The total current is e.g. limited by the HOM damping capabilities of the sc-cavities and the machine impedances.

This scheme is achievable with recent developments in sc-rf cavity technology driven by requirements of high cur...

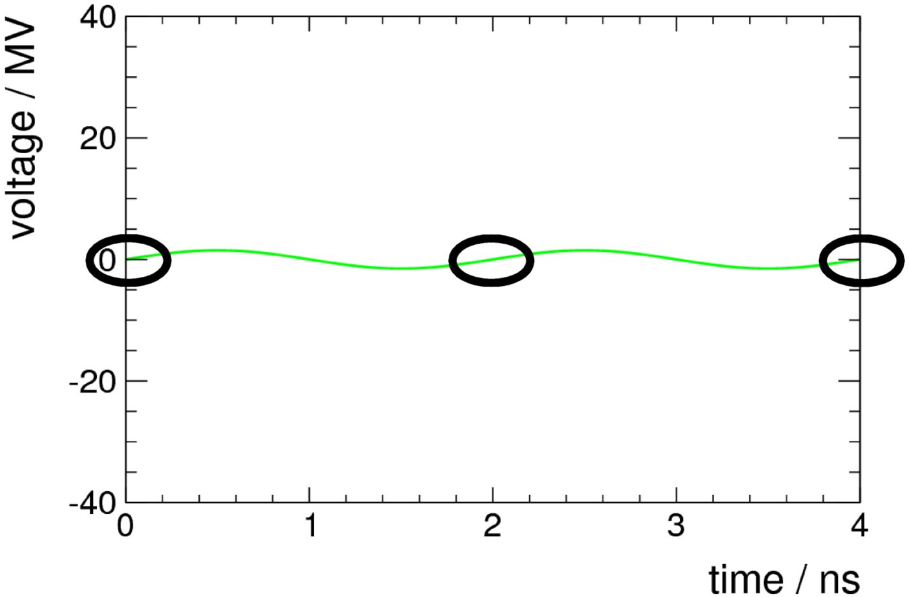
to alternating short and long bunches. At the high voltage gradient locations the bunches become shorter, a kind of longitudinal 'rf-focusing'.

From the zero current bunch length calculations we expect 10 times shorter bunches by this rf-focusing. The maximum achievable current is kept just below the bursting instability threshold, derived by scaling laws. For a fixed bunch length, the predicted threshold current for bursting is increased by a factor 100 compared to the present situation. The transverse beam optics does not change, the BESSY user optics or the BESSY low-α optics can be applied. For the coherent THz radiation a power increase of up to 10^4 is expected. In this note, we estimate bunch length and current limits from a set of rf-cavity parameters.

ALTERNATING BUNCH LENGTH SCHEME

Voltage beating scheme

Short and long bunches simultaneously

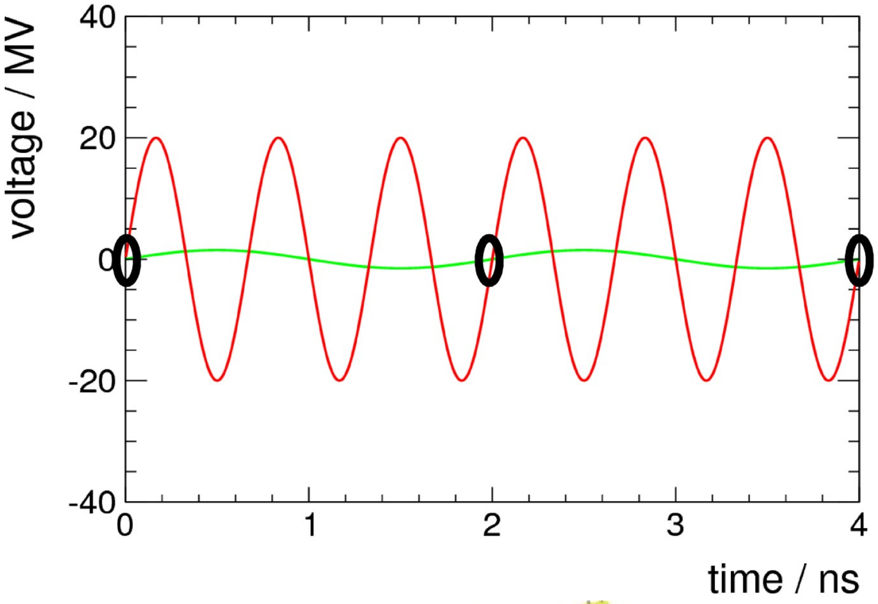


Cavity system for gradient manipulation

- Normal installed rf cavity
  V' = 2π 0.5 1.5 GHz MV

Voltage beating scheme

Short and long bunches simultaneously

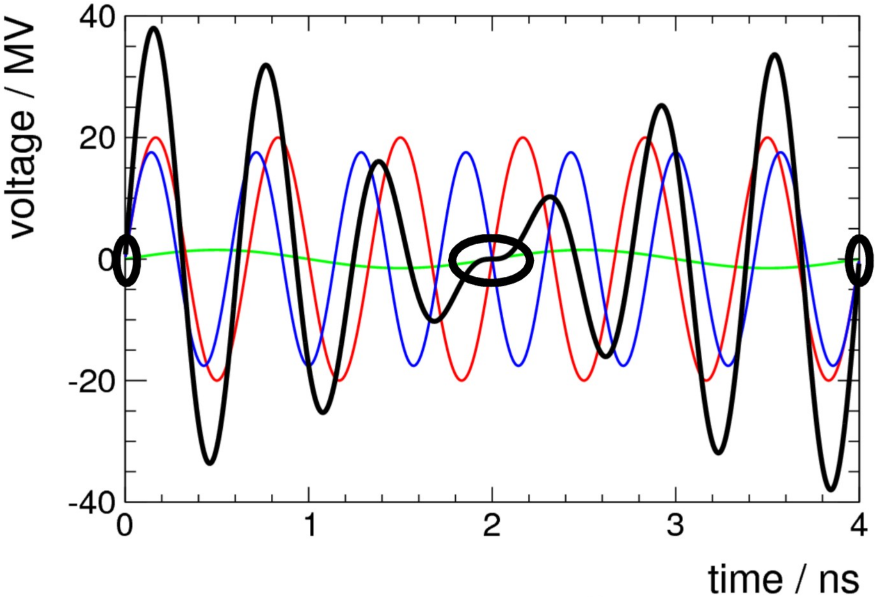


Cavity system for gradient manipulation

- Normal installed rf cavity
  $V' = 2\pi\ \ 0.5\ \ 1.5$ GHz MV
- 1st SC RF cavity, 3rd harmonic
  $V' = 2\pi\ \ 1.5\ \ 20$ GHz MV

Voltage beating scheme

Short and long bunches simultaneously

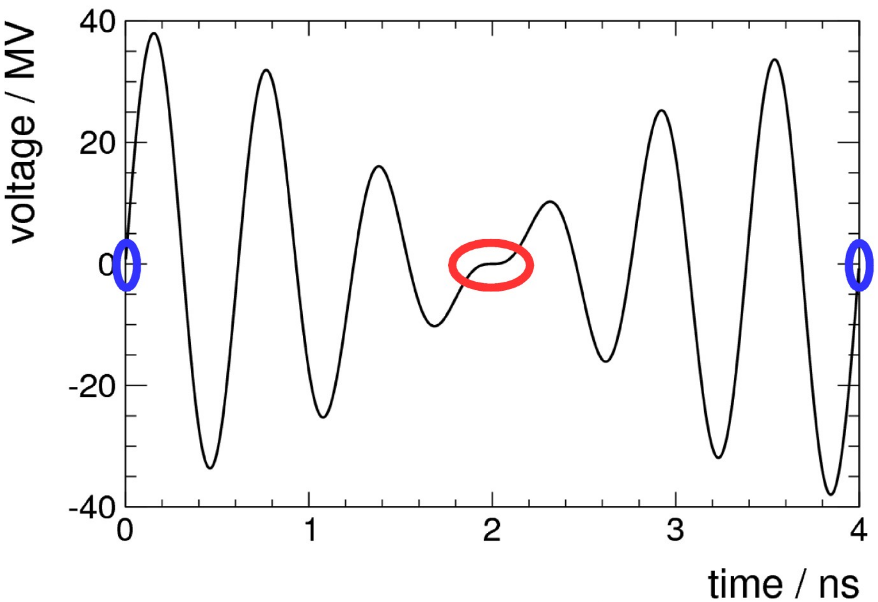


Cavity system for gradient manipulation

- Normal installed rf cavity
  V' = 2π 0.5 1.5 GHz MV
- 1st SC RF cavity, 3rd harmonic
  V' = 2π 1.5 20 GHz MV
- 2nd SC RF cavity, 3.5th harmonic
  V' = 2π 1.75 17 GHz MV
- In total   V'(BII)   = 0.75 GHz MV
  V'(VSR) = 60.0 GHz MV

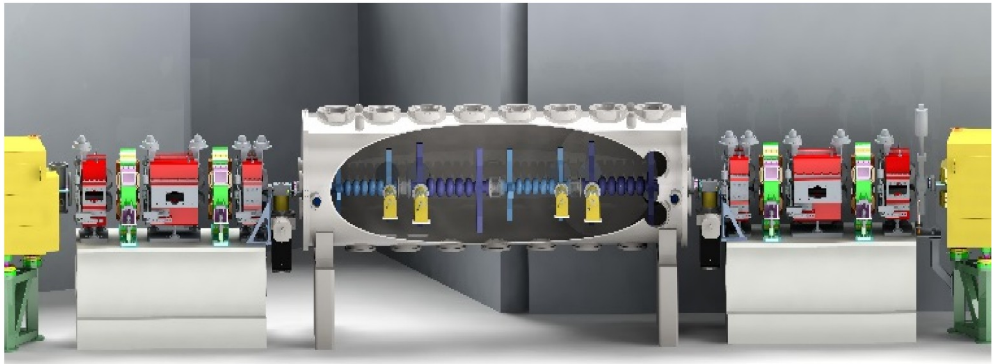
Voltage beating scheme

Short and long bunches simultaneously

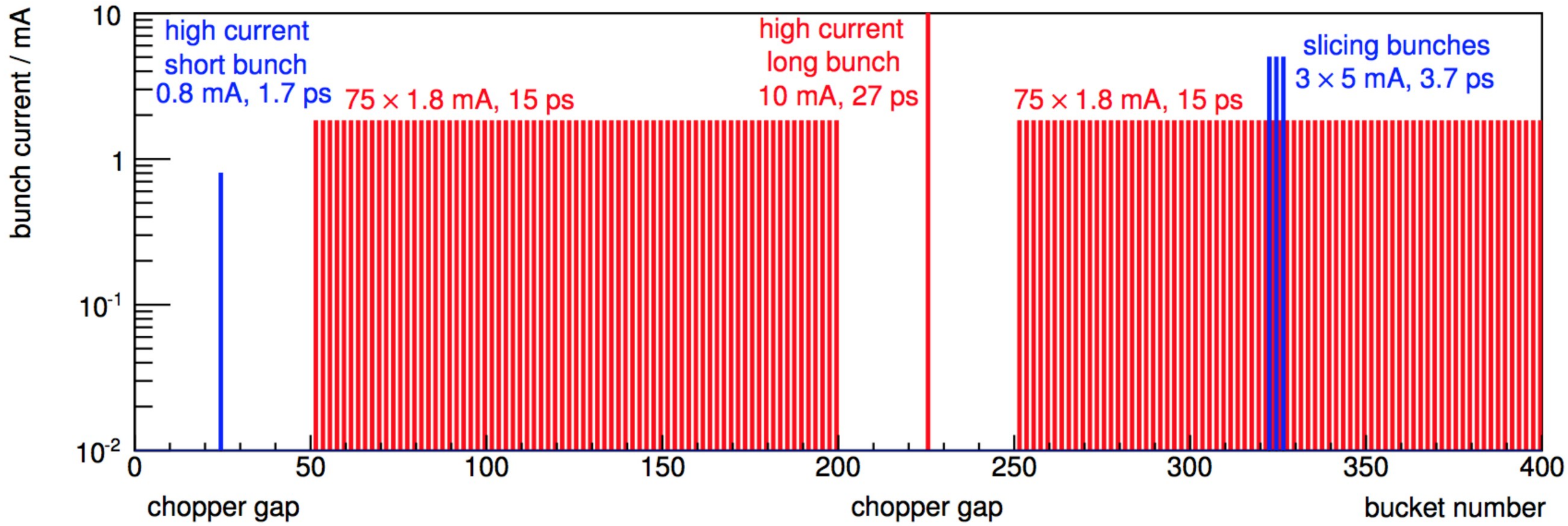


Cavity system for gradient manipulation

- Normal installed rf cavity
  V' = 2π 0.5 1.5 GHz MV
- 1st SC RF cavity, 3rd harmonic
  V' = 2π 1.5 20 GHz MV
- 2nd SC RF cavity, 3.5th harmonic
  V' = 2π 1.75 17 GHz MV
- In total V'(BII) = 0.75 GHz MV
  V'(VSR) = 60.0 GHz MV
- Voltage beating results in alternating large and small V'



BESSY VSR project parameters

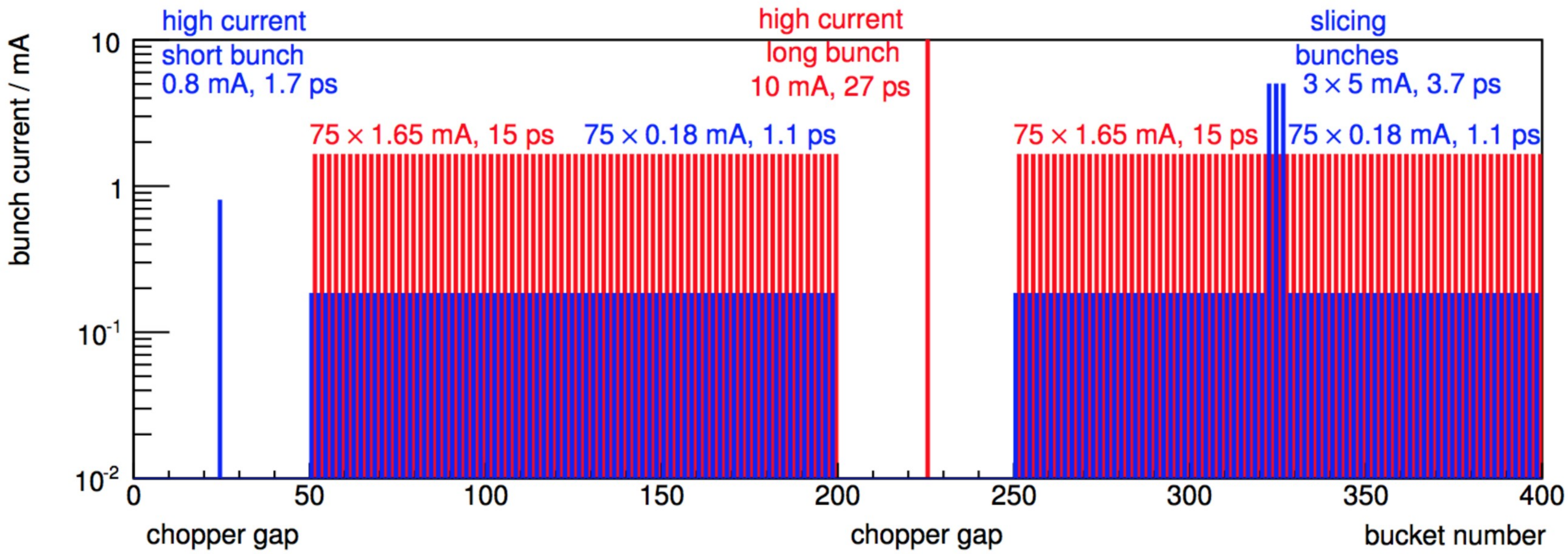


BESSY VSR multi functional fill pattern:

- ps short single bunch -> short intense X-Ray pulse for timing exp.
  -> short slicing bunches, high current camshaft bunch,
  -> multibunch train for high average brilliance

- Preserving BESSY II emittance and TopUp capabilities
  ε_x = 5 nm rad, lifetime > 5 h, average injection efficiency > 90 %

BESSY VSR project parameters



In low α_c mode:
400 fs @ 0.04 mA / bunch

BESSY VSR multi functional fill pattern:

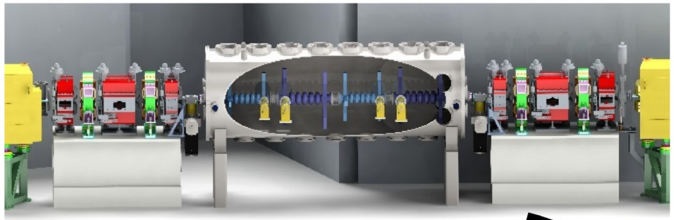
- ps short single bunch -> short intense X-Ray pulse for timing exp.
  -> short slicing bunches, high current camshaft bunch,
  -> multibunch train for high average brilliance
  -> background of intense CSR/THz radiation bunches

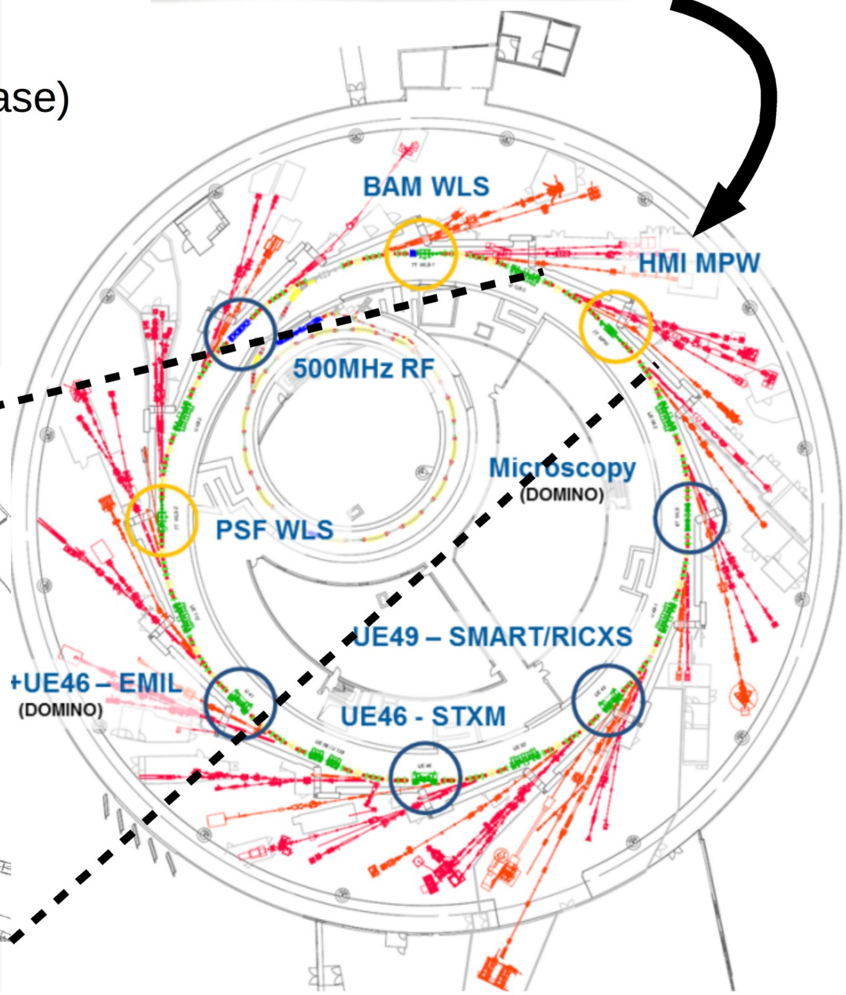
- Preserving BESSY II emittance and TopUp capabilities
  ε_x = 5 nm rad, lifetime > 5 h, average injection efficiency > 90 %

BESSY VSR technical realisation

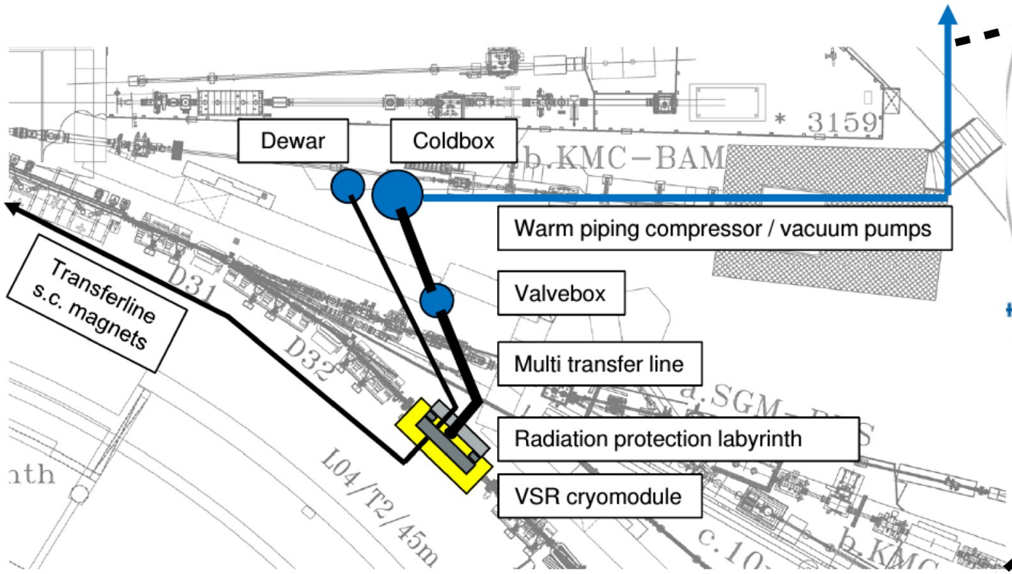
One cryo-module hosting:

2 x 4 cell @ 1.5 GHz and 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: V' = 2π 48 GHz MV (x 65 increase)
fits in one straight section
sacrificing the 7T Multipole Wiggler





Installation of the 1.8 K Cryo-System



BESSY VSR main challenges

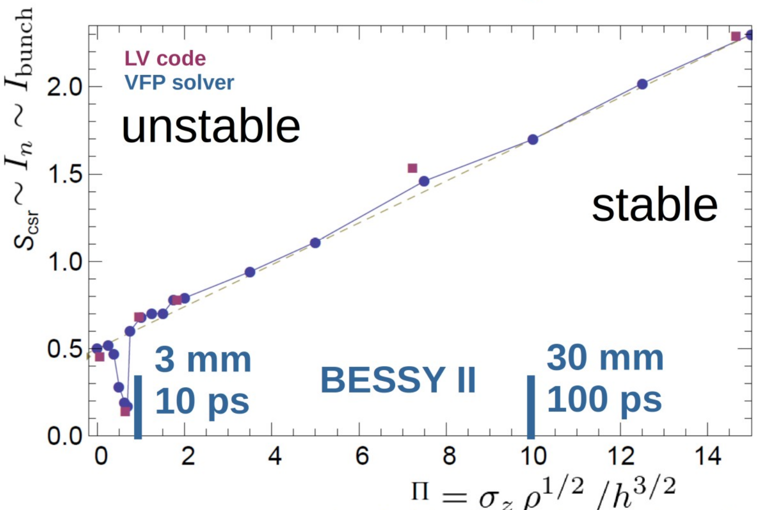
- Short intense bunches - scaling behavior bunch-length vs. current
- Developement and operation of high gradient superconducting cavities
  - 1.5 GHz and 1.75 GHz @ 20 MV/m gradient in cw
    -> 200W @ 1.8 K cooling plant (30% margin)
    -> particle free (clean) vacuum araound cavity straight, 10^{-10} mbar
- Control of coupled bunch instablilites
  - Induced by sc cavitiy impedance, higher order modes
    -> proper HOM damping desgin of sc cavities, waveguide HOM dampers
    -> sufficiently strong bunch by bunch feedback
- Operation with large transient beam loading
  - Phase shift over bunch train, lifetime reduction
    -> careful set up and control of RF-parameters
    -> appropriate low-level RF-control
- TopUp operation: injection into short VSR bunches
  - Bunch lenght from booster 70 ps, injection efficiency > 60% / 90%
    -> bunch compression in booster by factor 2 needed

NOCE: csr instability, scaling law

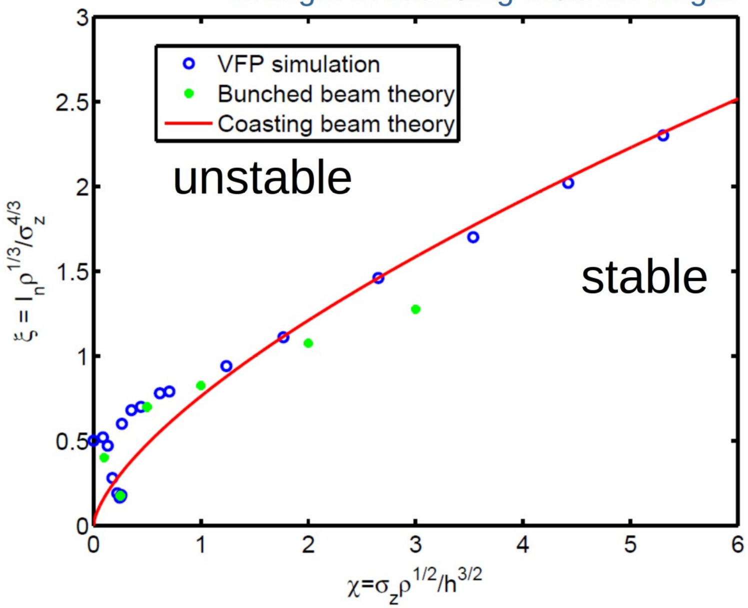
K. Bane et al., Proceedings of IPAC2010, Kyoto, Japan, TUPD078

Y. Cai, Proceedings of IPAC2011, San Sebastian, Spain, FRXAA01

Shielded CSR instability



strength of shielding ...bunch length



- Shielded CSR impedance
  Two plate model, vertical gap of vacuum chamber and bending radius
- Coasting beam theory describes bursting threshold for long bunch (2mm - 6ps)
  For shorter bunch length (< 5 ps) dip towards lower currents

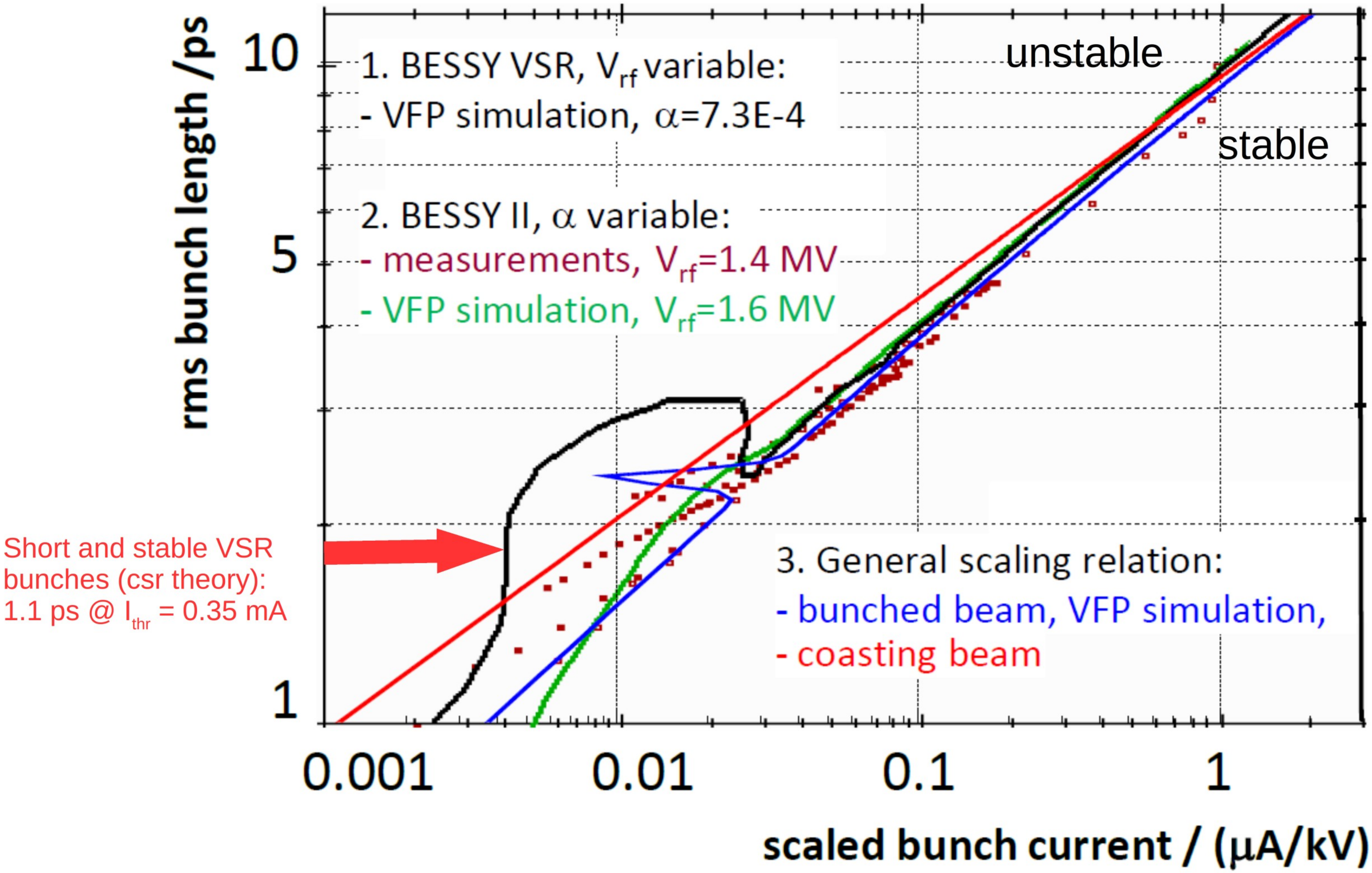
-> Impact on BESSY II / VSR parameter ?

Y.Cai IPAC2011:
"Avoid dip near χ = 0.25"

Discussion, Calculations by
G. Wüstefeld and P. Kuske

NOCE: csr instability, scaling law

A. Jankowiak et al., TDS BESSY VSR, doi:10.5442/R0001
P. Kuske, Proceedings of IPAC2015, Richmond, VA, USA, MOPWA020

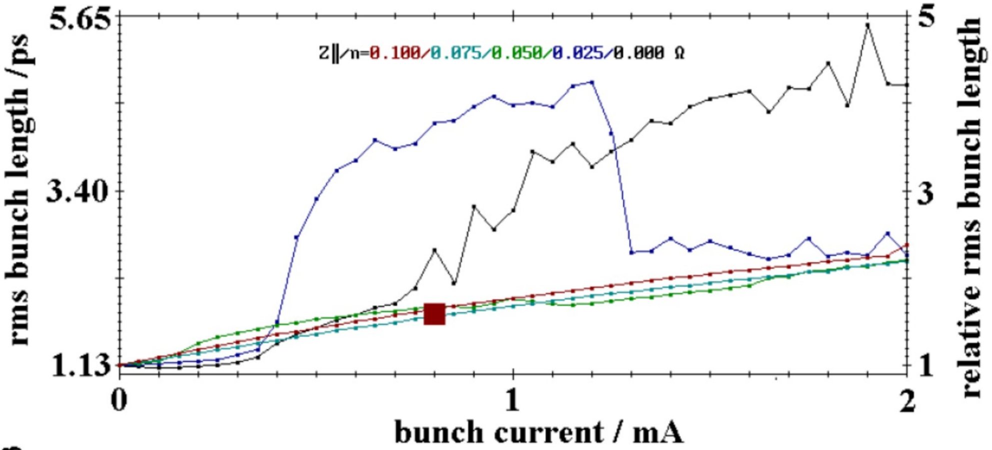


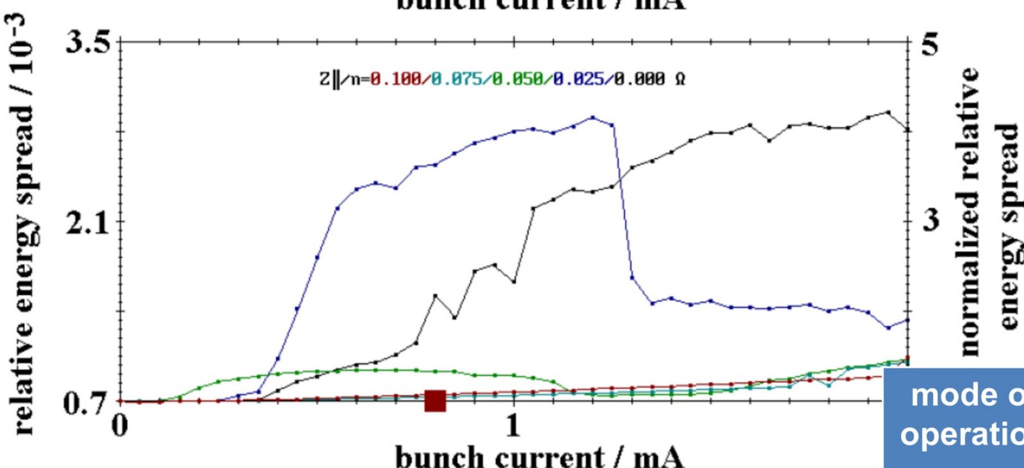
But: Streak camera show bunch elongation before bursting instability sets in -> additional impedance: inductive vacuum chamber imp.

NOCE: csr instability, scaling law

P. Kuske, Proceedings of IPAC2015, Richmond, VA, USA, MOPWA020
P. Kuske, BESSYII MAC2003

CSR instability with longitudinal inductive impedance of vacuum chamber





- Inductive impedance:

$$Z(n) = -iL \cdot \omega = -iL \cdot n \cdot \omega_0$$

with IZ/nI = 0.2 – 0.35 Ω
for σ_0 = 2 – 15 ps

for VSR: IZ/nI = 0.1 Ω,
but Impedance difficult to estimate for complex vacuum chamber

- Inductive impedance leads to potential well distortion with considerable bunch lengthening

Shielded CSR interaction together with inductive vacuum chamber impedance provides single bunch current limits:

mode of operation	threshold current / µA	rms bunch length @ threshold	longitudinal impedance |Z‖/n|
normal α	0 350 → 800	1.13 ps 1.23 → 1.70 ps	0 → ~ 0.10 Ω
low α	0 15 → 40	265 fs 280 → 400 fs	0 → ~ 0.04 Ω

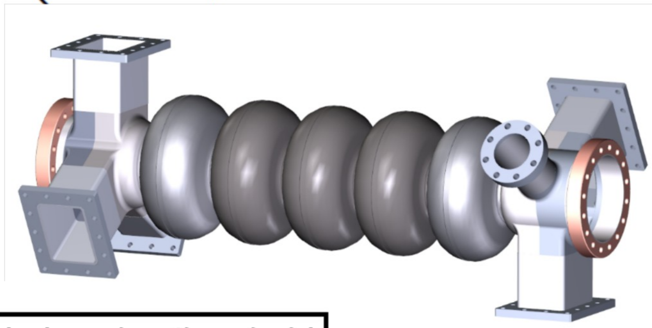
M. Ruprecht, PhD thesis, Humbold University Berlin, 2016

CBI driven by HOMs of Cavities

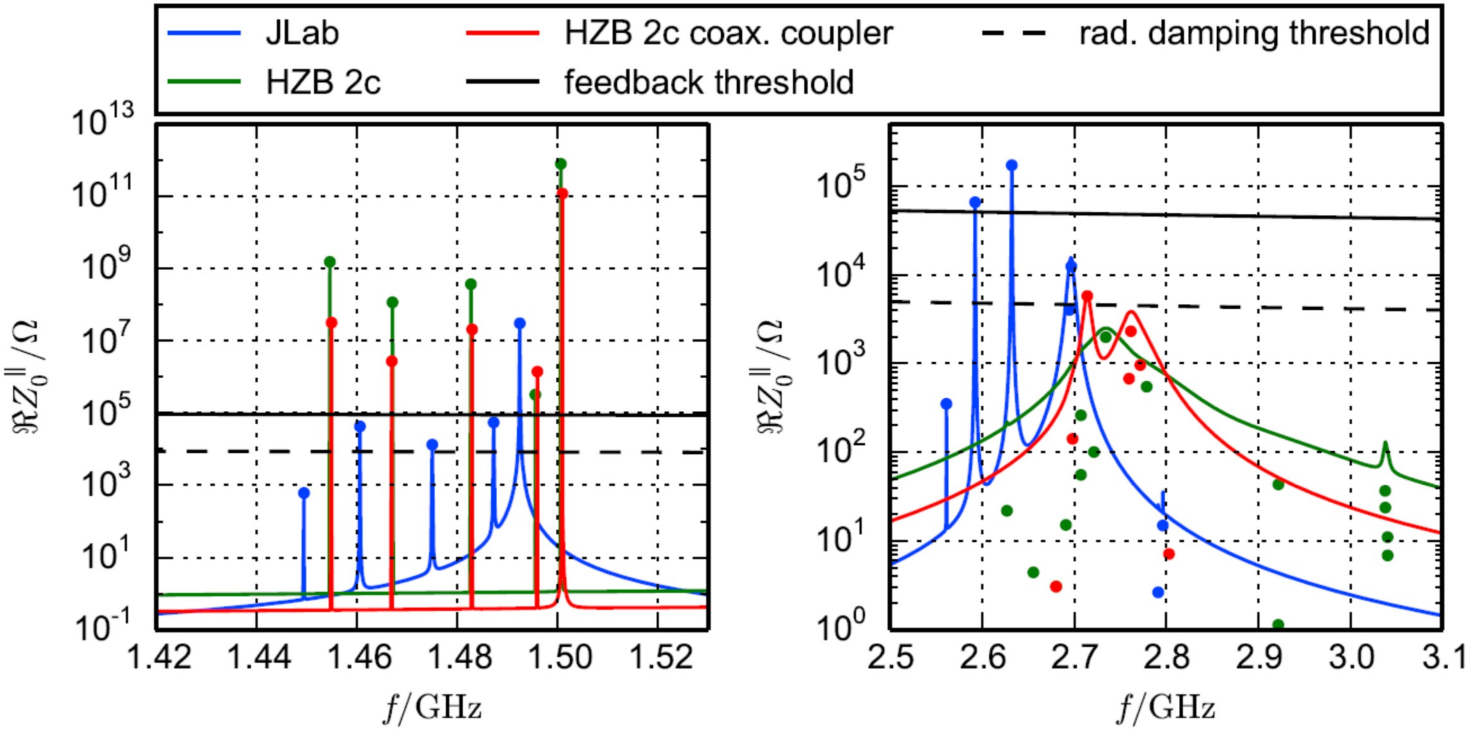
- Growth rate of even fill solutions:

$$\tau^{-1} = \frac{f_{\mathrm{rev}} I}{2E/e} \times \begin{cases} \beta_{x,y} \mathrm{Re}(Z_{\perp,x,y}(f)) & \text{transverse} \\ f \alpha \mathrm{Re}(Z_{\parallel}(f))/f_s & \text{longitudinal} \end{cases}$$

- Damping rate given by BBFB:
  trans: 4 ms^{-1} (60x syn. damp.)
  long: 1.33 ms^{-1} (10x syn. Damp.)



- **Longitudinal case:**



75% of HOM power damped in waveguide loads

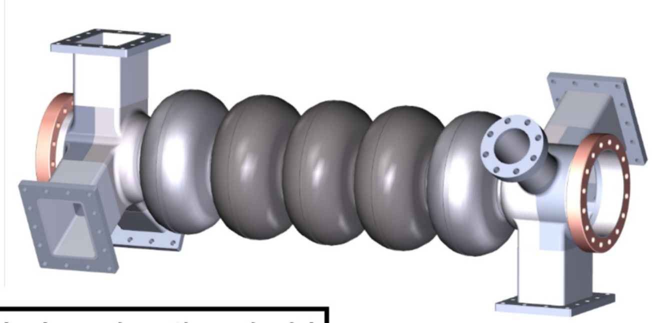
M. Ruprecht, PhD thesis, Humbold University Berlin, 2016

CBI driven by HOMs of Cavities

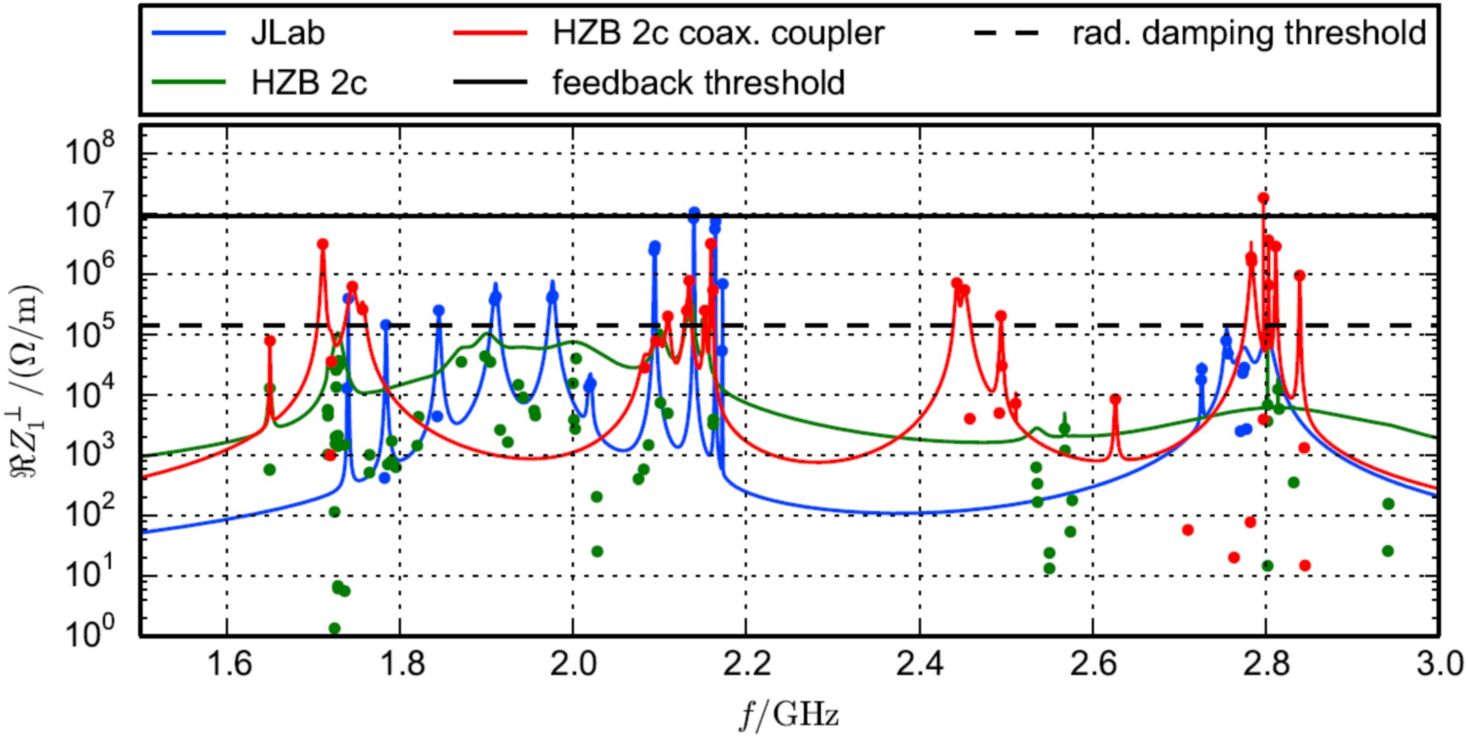
- Growth rate of even fill solutions:

$$\tau^{-1} = \frac{f_{rev} I}{2E/e} \times \begin{cases} \beta_{x,y} \mathrm{Re}(Z_{\perp,x,y}(f)) & \text{transverse} \\ f\alpha \mathrm{Re}(Z_{\|}(f))/f_s & \text{longitudinal} \end{cases}$$

- Damping rate given by BBFB:
  trans: 4 ms^{-1} (60x syn. damp.)
  long: 1.33 ms^{-1} (10x syn. Damp.)



- **Transverse case:**

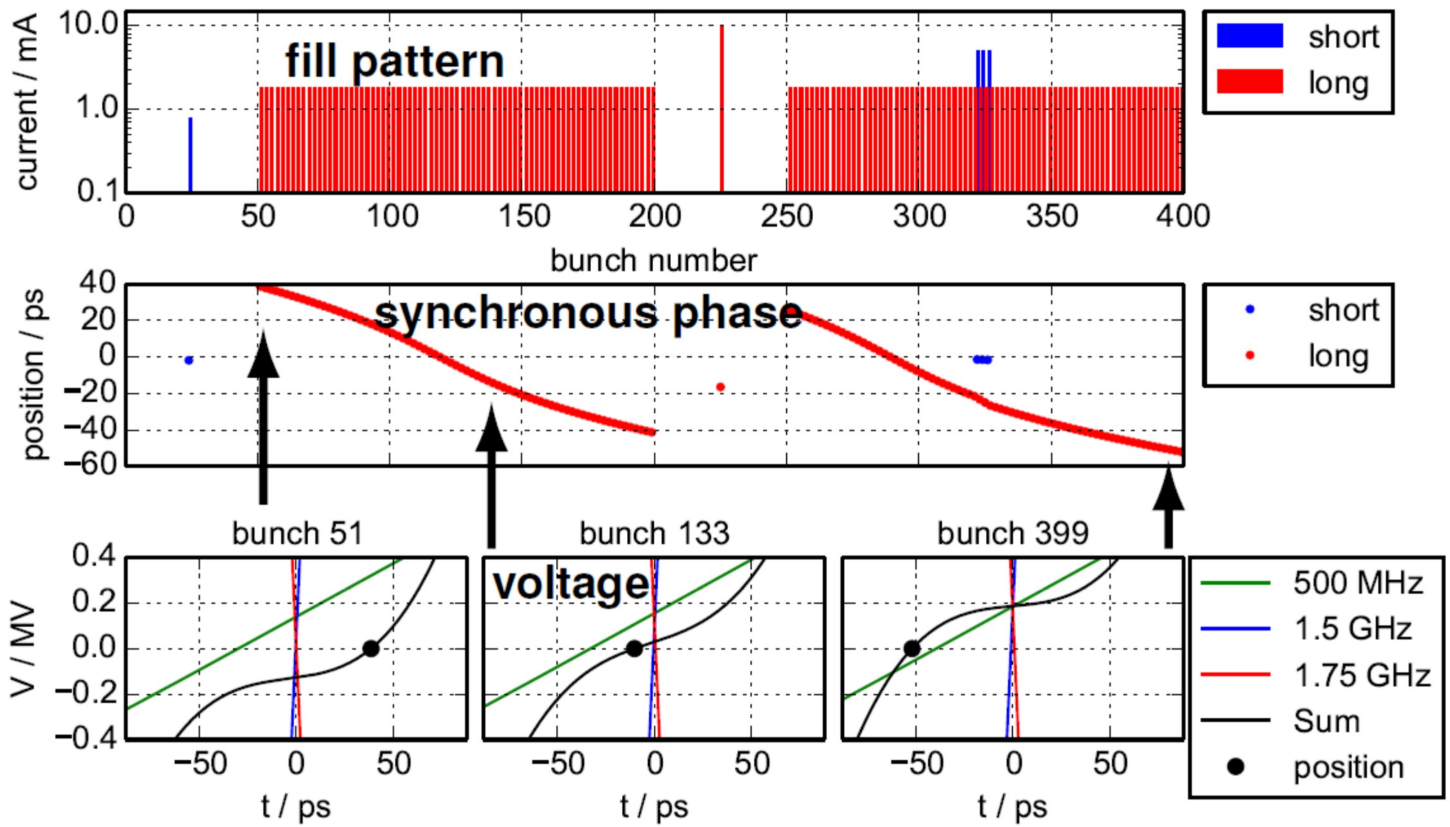


75% of HOM power damped in waveguide loads

M. Ruprecht, PhD thesis, Humbold University Berlin, 2016

Transient beam loading due to fill with gaps

- Gaps required for bunch separation with chopper
- SRF cavity impedance is purely reactive
- Changes in beam current result in phase change that cannot be compensated by the RF (insufficient power, bandwidth limited)
- Focusing gradient and hence bunch length varies along bunch train



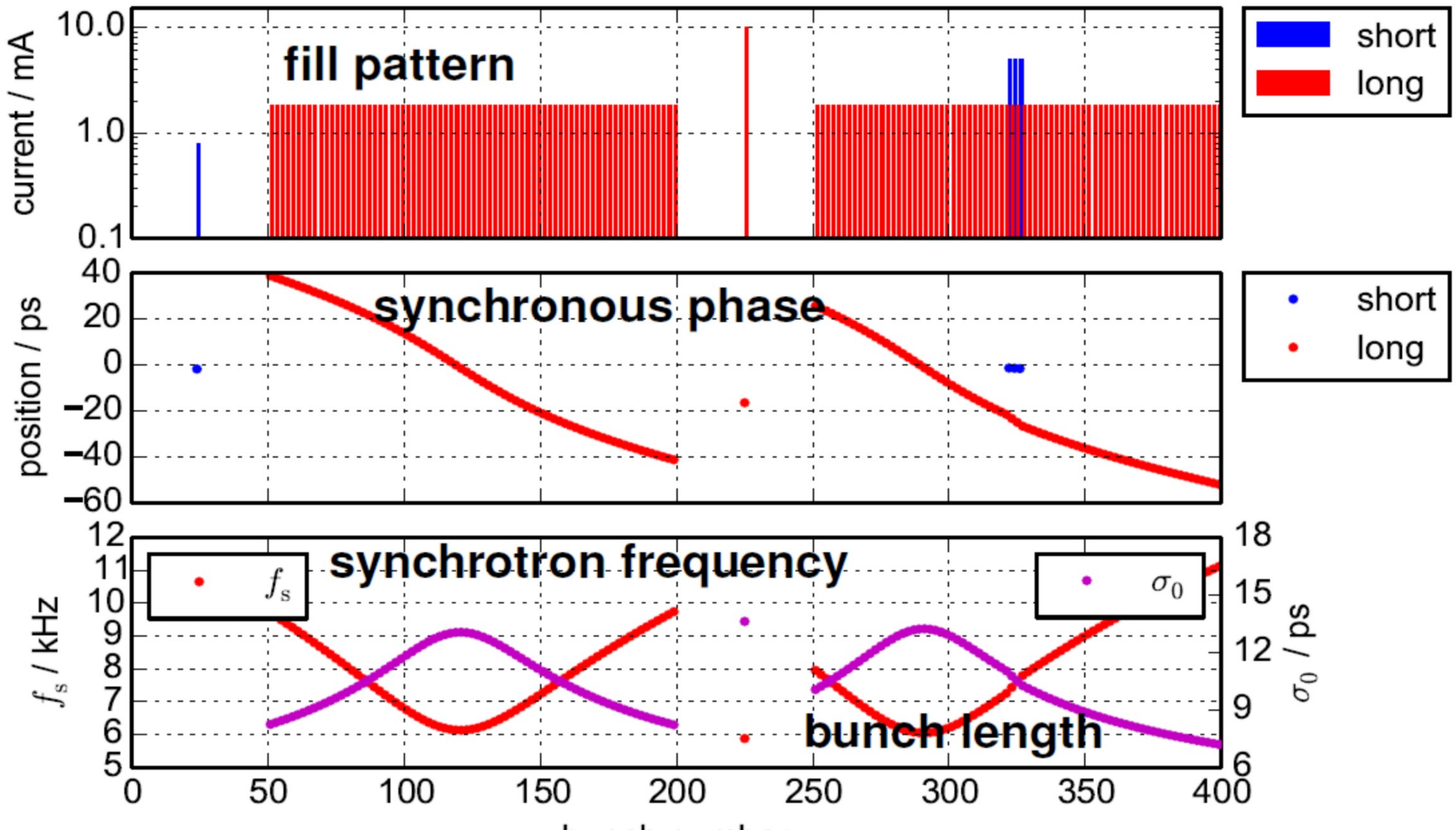
M. Ruprecht, PhD thesis, Humbold University Berlin, 2016

Transient beam loading due to fill with gaps

- Gaps required for bunch separation with chopper
- SRF cavity impedance is purely reactive
- Changes in beam current result in phase change that cannot be compensated by the RF (insufficient power, bandwidth limited)
- Focusing gradient and hence bunch length varies along bunch train

Reduced Touschek Lifetime

-> without gaps
-> new separation scheme (2ns)
-> TRIBs

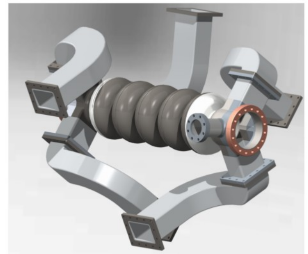


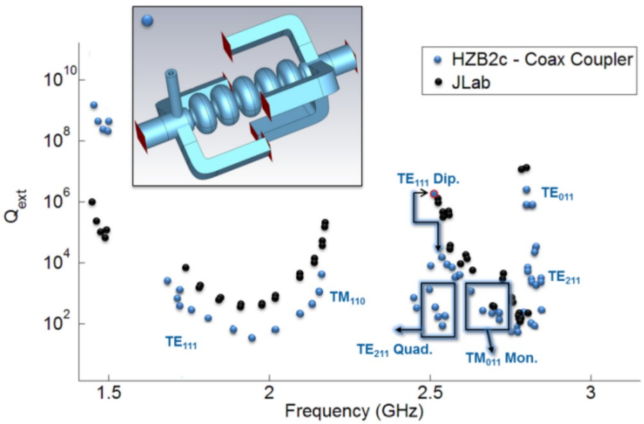
High-current CW SRF cavities – design and measurements

A. Velez et al.

Finialized Desgin of the 1.5 GHz Waveguide Damped Cavity

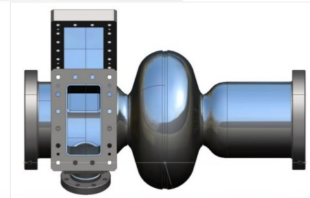
- Meets HOM damping specs.
- Synergy with bERLinPro

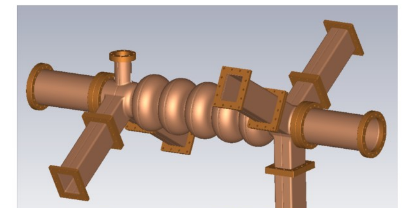


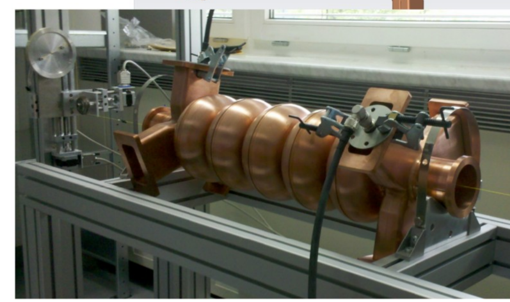


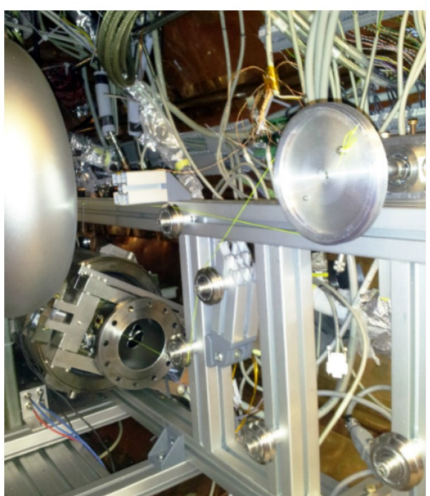
Prototypes ordered at RI (Research Instruments), tested now

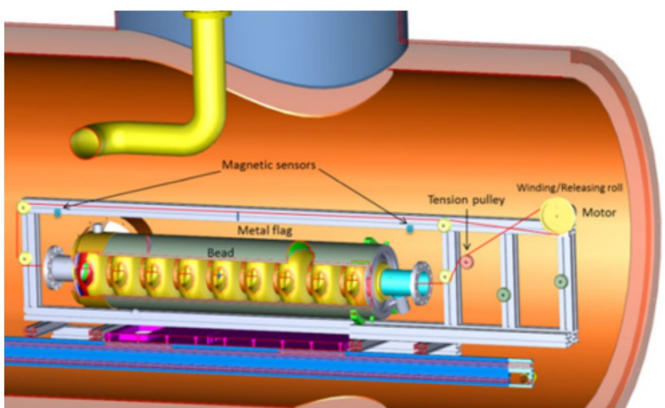
- 1.5 GHz Waveguide Damped 5cell Copper cavity
- 1.5 GHz Single Cell Niobium cavity











Warm Bead-Pull Test Stand & **Cold** Bead-Pull Test Stand in HoBiCaT

- Designed to characterize SRF cavities under sc conditions (1.8 K)
- Measurements of field profile, field flatness, R/Q

Fully equipped SRF cryo module - design

A. Velez et al. Proceedings of IPAC2017, Copenhagen, Denmark, MOPVA053

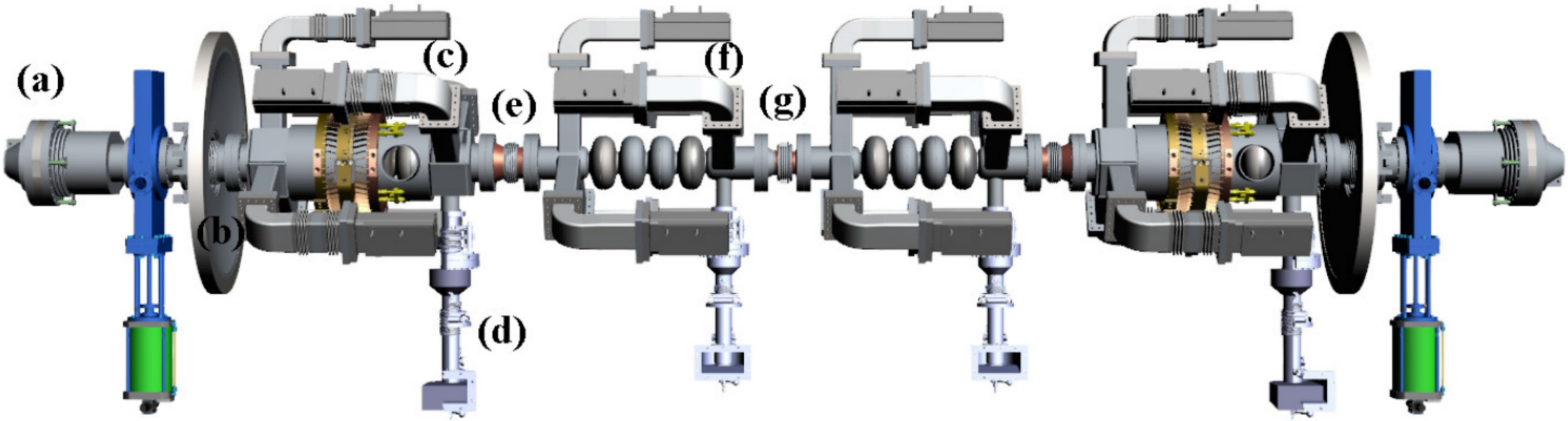
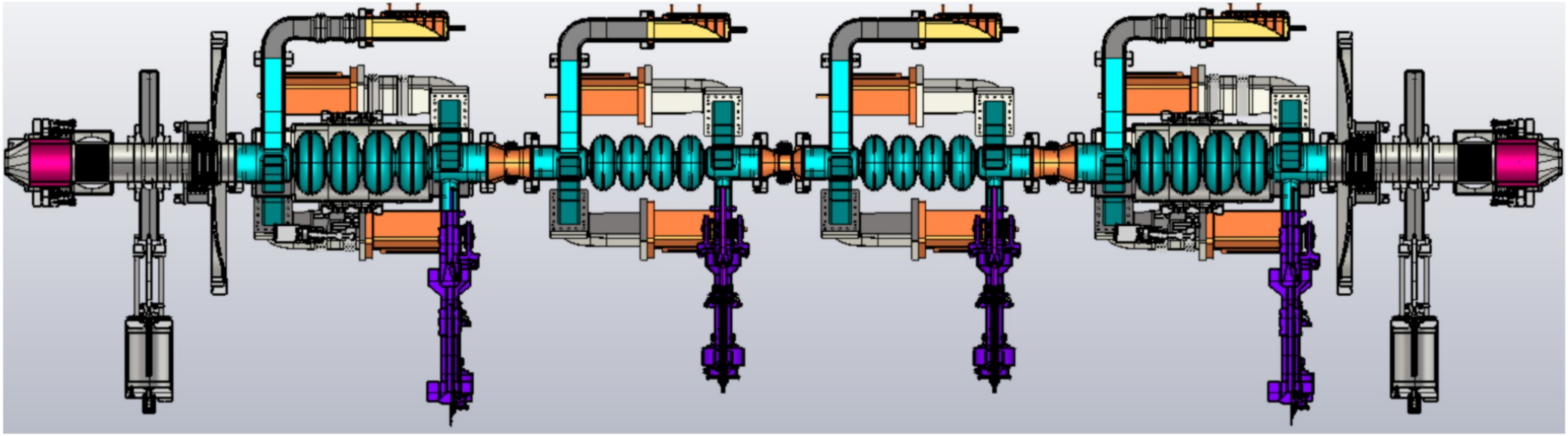


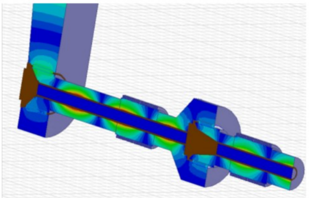
Figure 2: The BESSY VSR cold-string. Components named (left to right): Warm beam-pipe absorber including taper and pumping dome (a). Warm/Cold transition bellow (b). 1.5 GHz cavity with He vessel and blade tuner (c). 1.5GHz 16 KW HPC (d). Shielded bellow (e). Undressed 1.75 GHz cavity (f). Collimated shielded bellow (g).



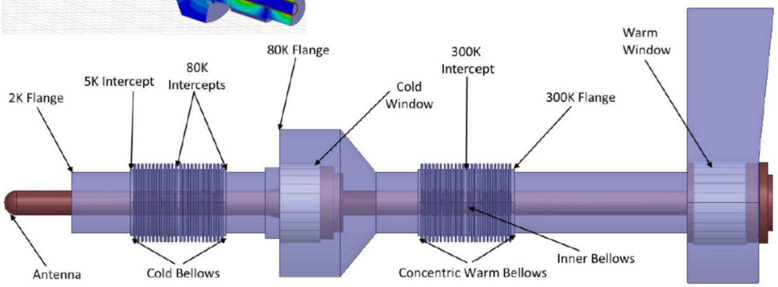
Coupler, Waveguide+Beampipe HOM Loads, Bellows

A. Velez et al. Proceedings of IPAC2017, Copenhagen, Denmark, MOPVA053
and references E.Sharples, A. Tsakanian, H.W. Glock, F. Glöckner

1.5 GHz 16 kW adjustable Power Coupler

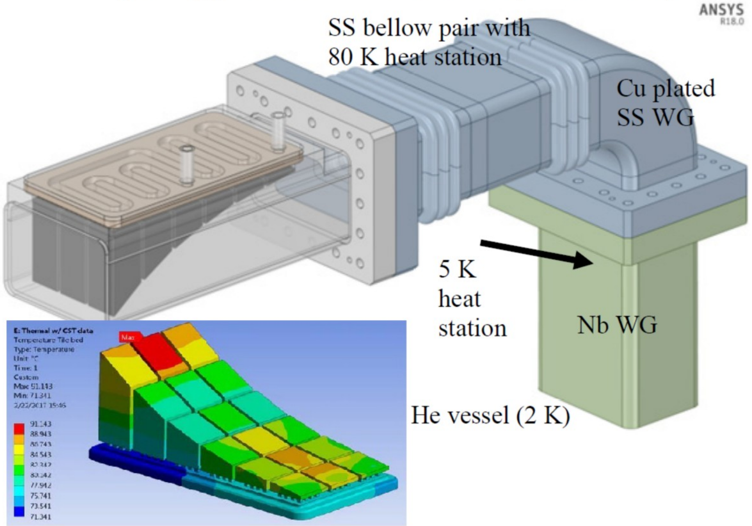


- Based on Cornell ERL inj. coupler
- EM Design and thermal design in advanced state

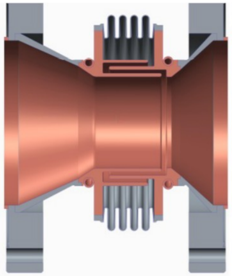


BESSY VSR HOM Waveguide Loads (75% of HOM power damped)

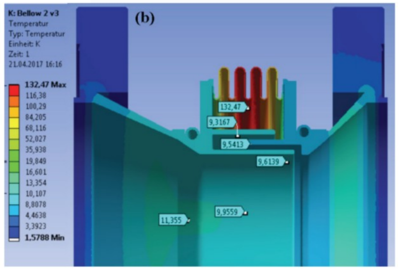
- Design and fabrication in progress with Jlab and CRADA (for 450 Watt)
- Synergy with bERLinPro (both SiC)



Shielded bellows to absorb syn. rad. from last bend

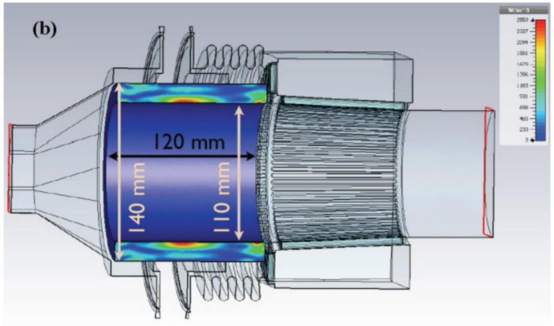


- 90 Watts from last bend into module, 63 Watts absorbed by collimator at entrance
- 11 Watt damped in structure, centered collimating shielded bellow



BESSY VSR HOM Beam Pipe Loads

- ~ 1.5 kW HOM Power up/downstream
- Based on SiC Coorstek SC-95 design developed by Argonne

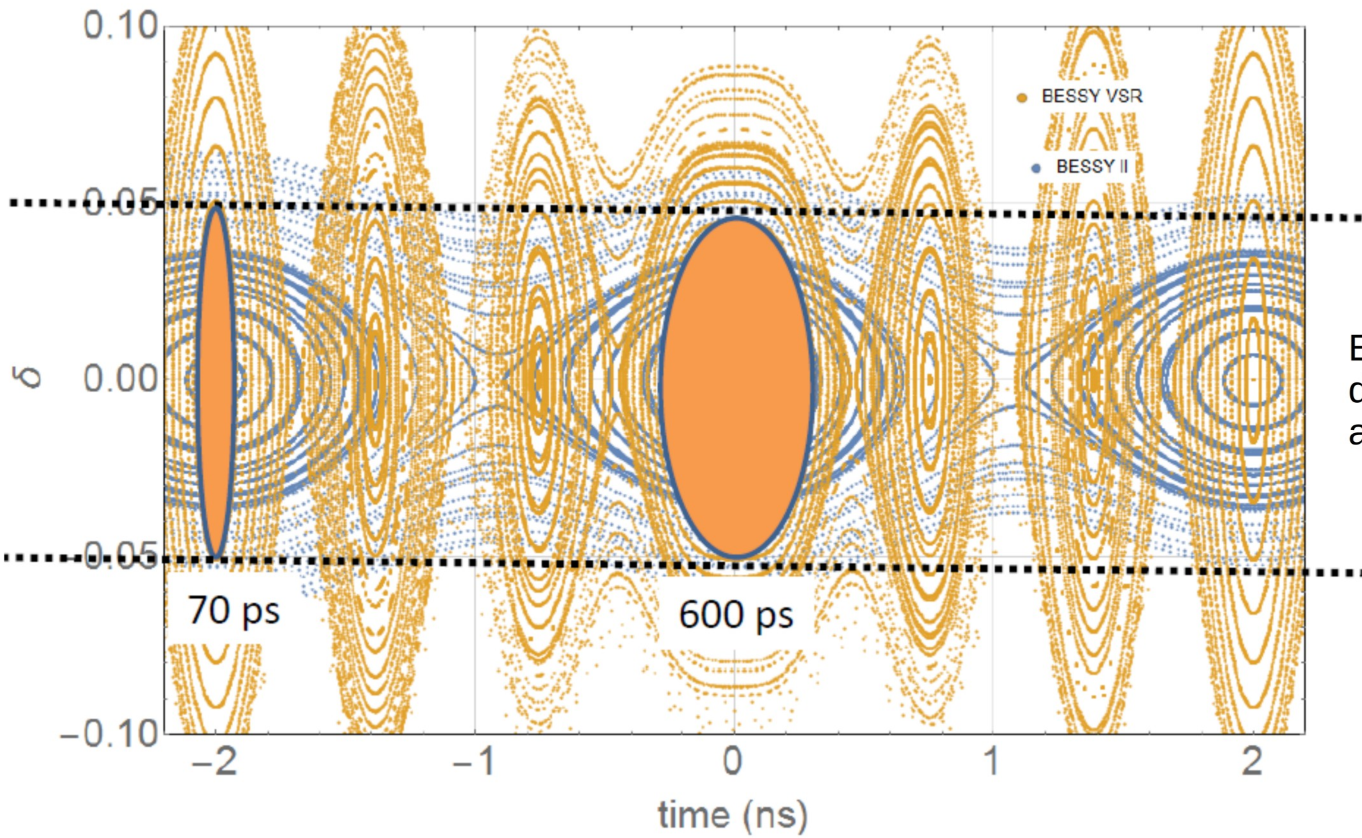


BESSY VSR: injection into short bunches

T. Atkinson et al.

TopUp injection into the BESSY VSR longitudinal phase space

- TopUp radiation safety requirements:
  - 4-h average injection efficiency > 90% mandatory
  - Single shot injection efficiency > 60% mandatory
- Strong gradient reduces phase acceptance of injected bunch (70 ps long)



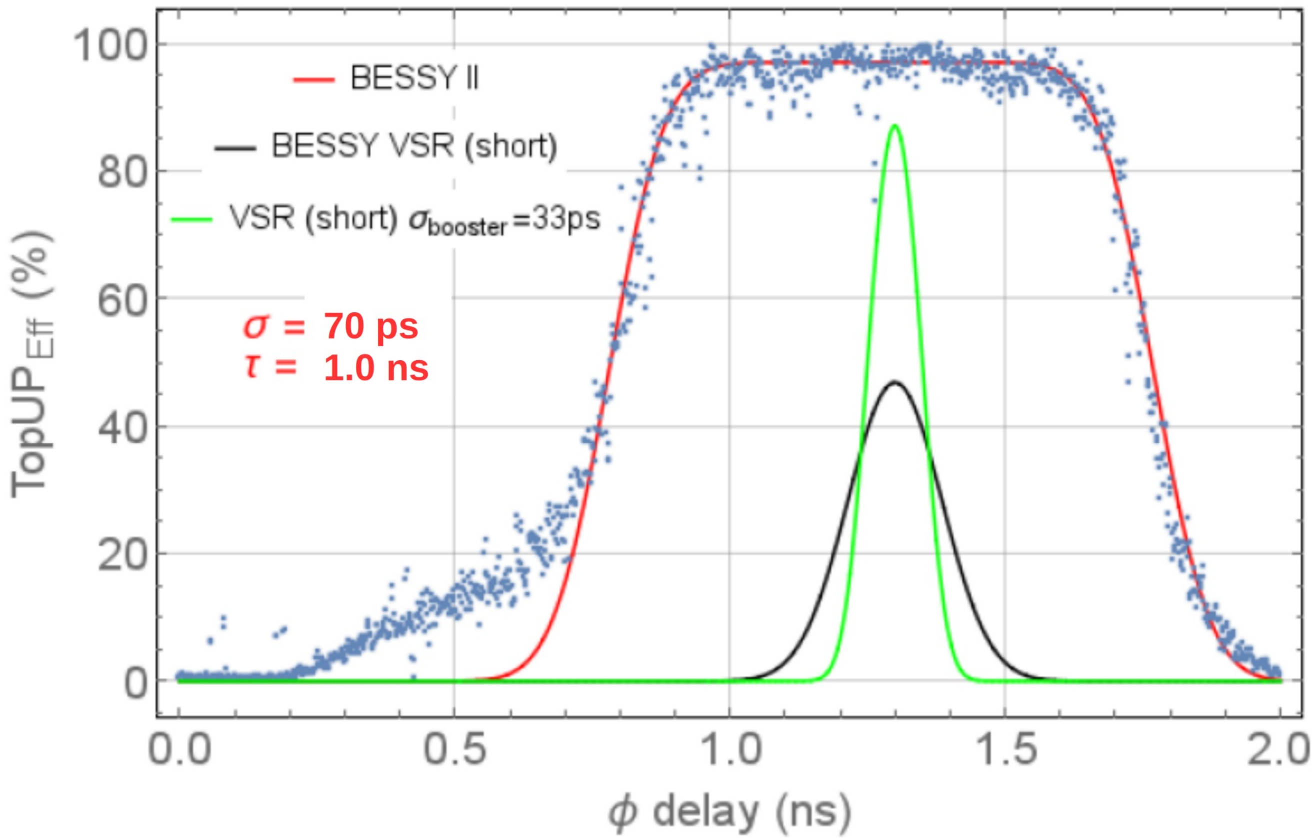
Energy acceptance defined by DA and ID gaps

T. Atkinson et al.

Measurements at BESSY II show

- To maintain 90% injection efficiency into short VSR bucket requires a reduction of the bunch length in booster by factor 2 (70 ps -> 35 ps)
- Modification of Booster: low alpha, 6D emittance exchange, bunch shortening in booster by 2 additional 5cell PETRA cavities

Phase Acceptance Scan and PSO to improve Dynamic Aperture



BESSY VSR: time line

doi:10.5442/R0001

Since 2013	VSR Science Workshops @ HZB
2015	Technical Desgin Study ready Application to Helmholtz Association submitted (strategic investement, 19 M€ + 10 M€ HZB) Scientific evalutaion of application: “Outstanding project” Full support by German Committee for Research with SR
2016	BESSY VSR not prioritised, application maintained Support of Berlin and local Administration: start of 2 R&D projects for SRF cavity developement and BunchByBunch diagnostics (3 M€) Diamond & Soleil study implementation of VSR scheme in their upgrade
2017	Successful applied for EFRE funding (via State of Berlin, 7.5 M€) 11.8 M€ granted by Helmholtz Association (from 2018 on) **BESSY VSR fully funded !**
2020/2021	**Preparatory Phase:** 2 x 4 cell 1.5 GHz cryo module in operation with 20 MV/m @ BESSY II (only short bunches – landau cavity)
2021/2022	**Start of user operation with full VSR** (ca. 22 weeks dark-time for installation and commissioning, distributed over 2-3 shutdowns)

Conclusions, Summary

The BESSY VSR project

- combines high brilliance with short intense pulses
  -> Simultaneously long and short bunches
  -> Shorter bunch than in low α, but bunch current as in standard user
  -> Structure and Dynamics

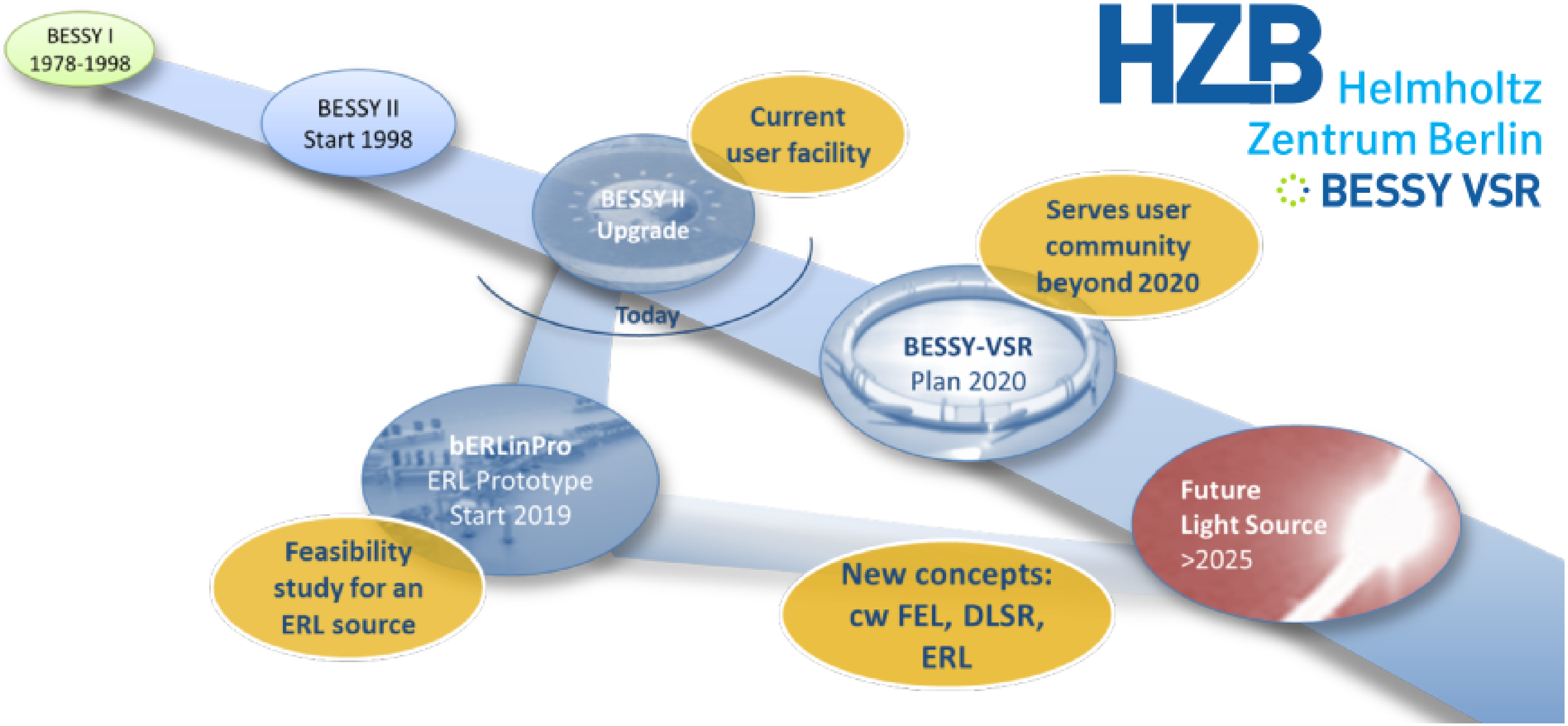
  -> Introducing strong focusing and strong HOM damped
  sc cavities in cw operation

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

- opens a new regime of storage ring operation
  -> future combination of DLSR + VSR? (in a certain energy range)

- is the ideal upgrade path of BESSY II
  -> addressing the needs of the existing user community (timing experiments)
  -> attracting new users

Thank you for your attention



Thanks to all Colleagues contributing to BESSY VSR:

Institute for Accelerator Physics, SRF Science and Technology, Instrumentation and Methods
Undulator, Operation Departement