Variable pulse length Storage Ring BESSY-VSR

Opportunities and Challenges

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on behalf of the BESSY VSR team

Helmholtz-Zentrum Berlin / BESSY II

7th LER workshop, CERN
15. – 17.02.2018

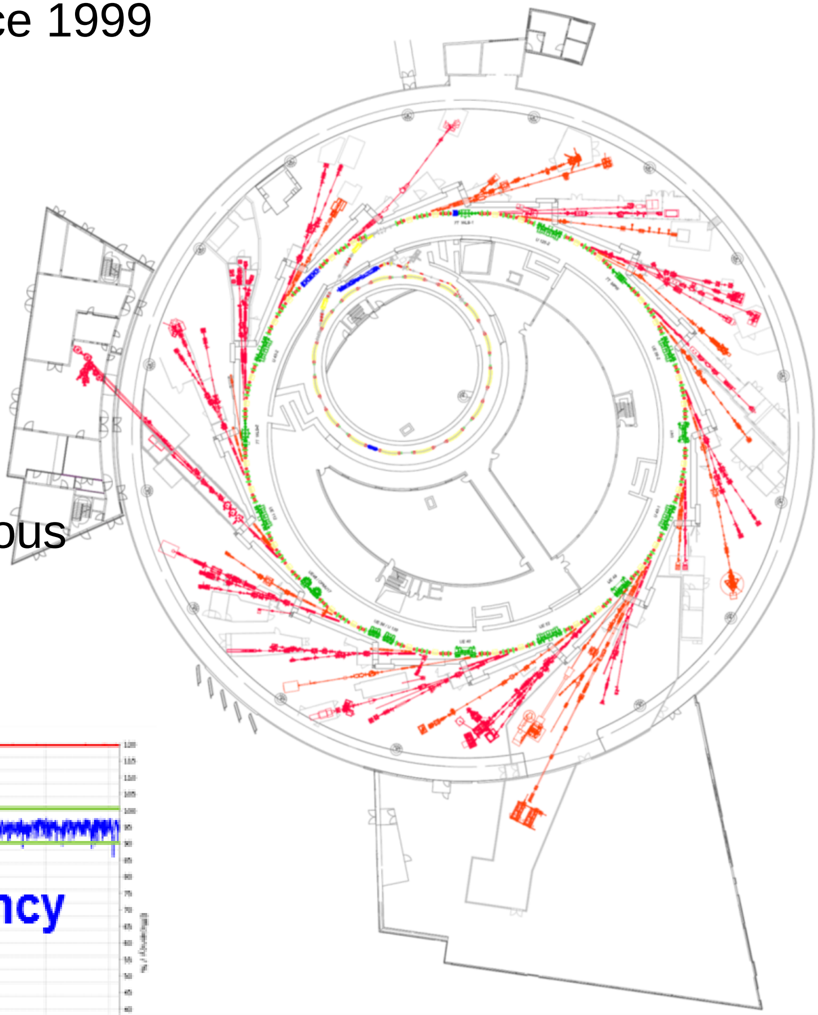
The menu

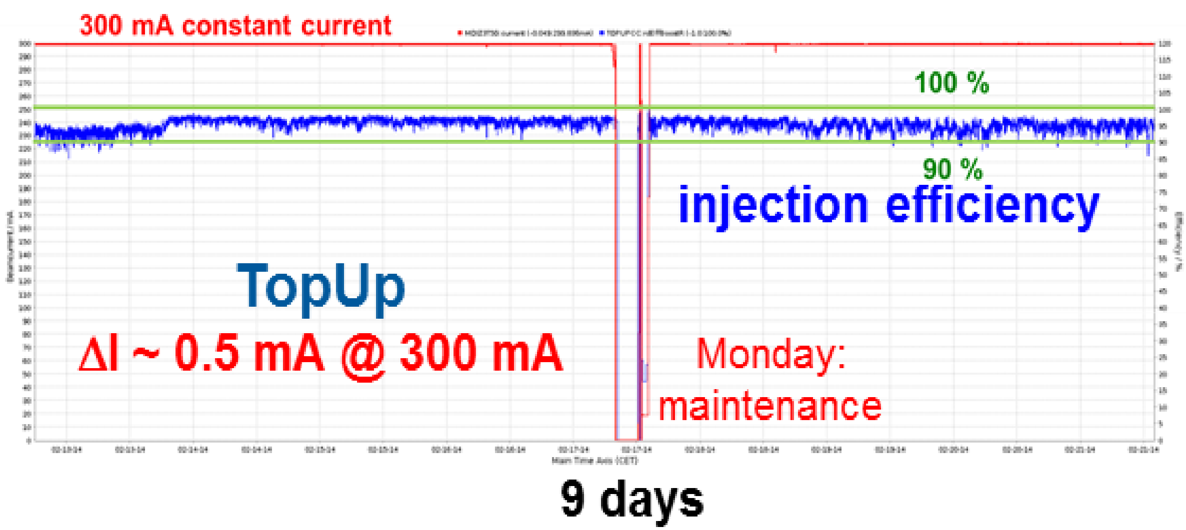
- BESSY II
  - strong support for timing experiments
- Upgrading BESSY II to BESSY VSR
  - variable pulse length storage ring
    increasing the phase space density orthogonal to DLSR / LER
- The BESSY VSR project
  - funding, status, timeline
- The challenges
  - bunch length versus bunch charge
  - high current, HOM damped cw SRF cavities
  - module integration
    reducing dirt, avoiding synchrotron radiation hitting cavities, …

Construction 1992 – 1998, in user operation since 1999

Energy/current	1.7GeV / 300mA
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

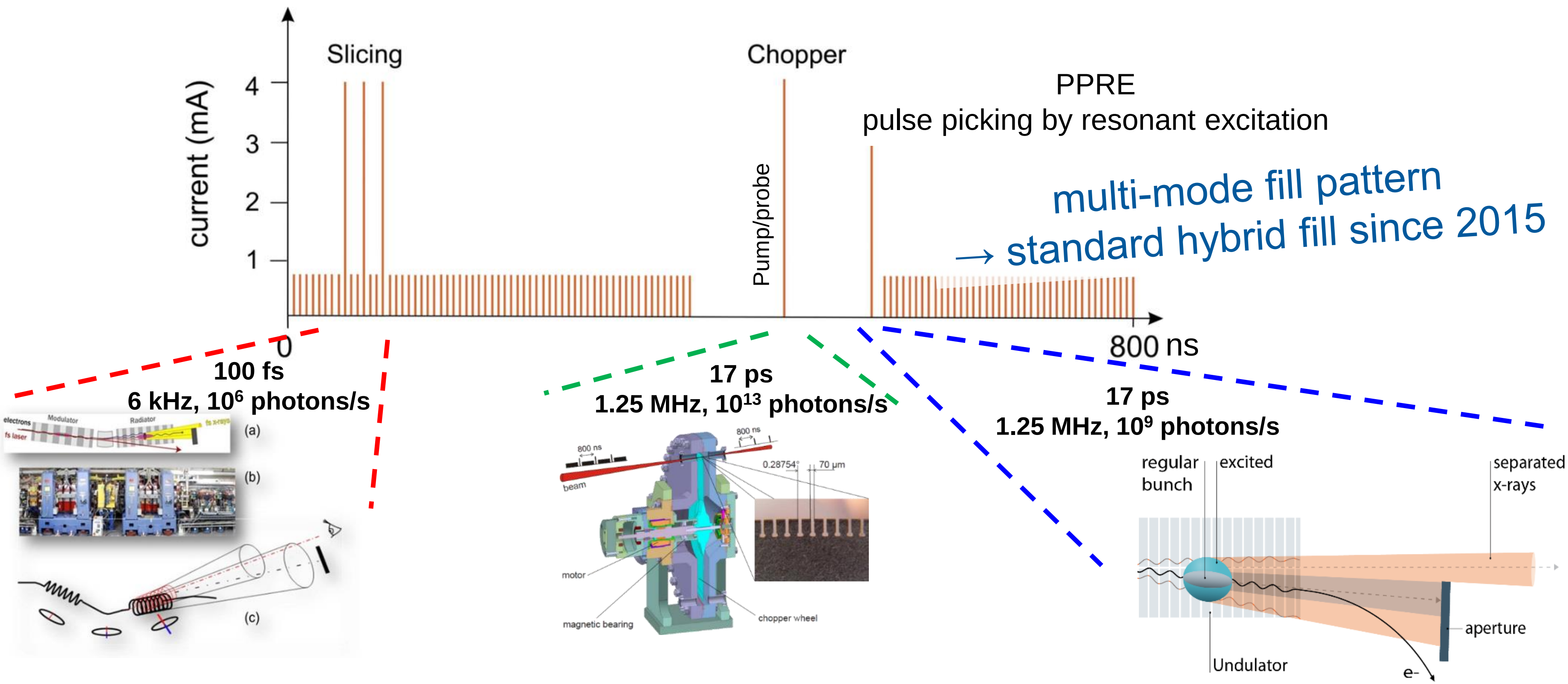




Timing Experiments well supported @ BESSY II

~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, ELETRRA 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**

$$\underbrace{\sigma \propto \sqrt{\frac{\alpha}{\dot{V}_{rf}}} \qquad I \propto \alpha}_{I \propto \dot{V} \; (\sigma = \text{const.})}$$

Today: short pulses, low flux

1.5 MV @ 500 MHz rf-systems = 2π 0.75 MV GHz

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

→ limited average current (~ 1/100)

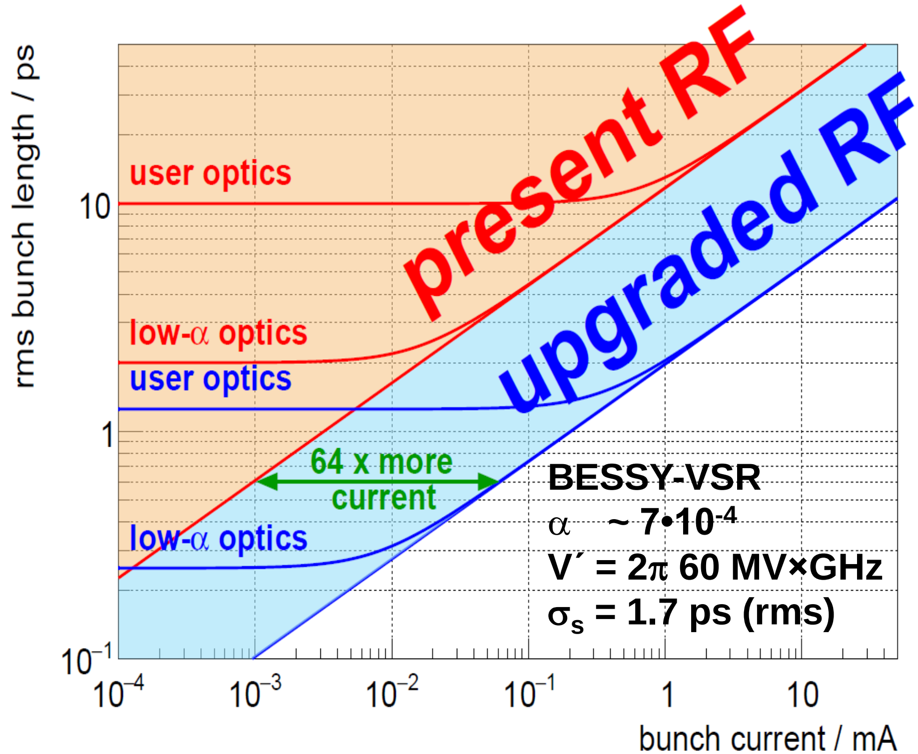
→ rather “dark” operation mode

Future: short pulses, high flux

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

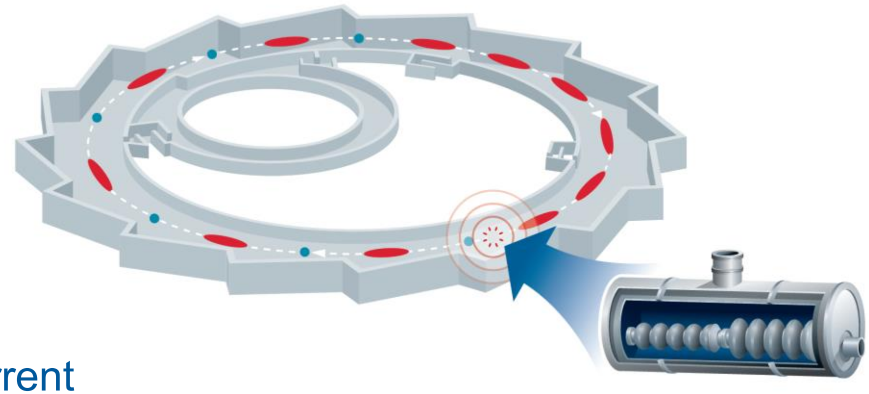
→ short 1.9 ps pulses with same current as in standard user op.

→ forced low-alpha mode permits even ~ 400 fs



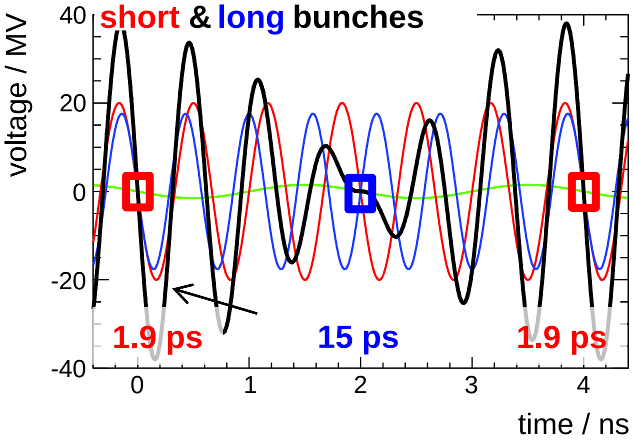
BESSY-VSR – A smart idea

$$\sigma \propto \delta_0 \sqrt{\frac{E_0}{\omega_0} \cdot \frac{\alpha}{\omega_{rf} V_{rf}}} \qquad I \propto \alpha$$



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

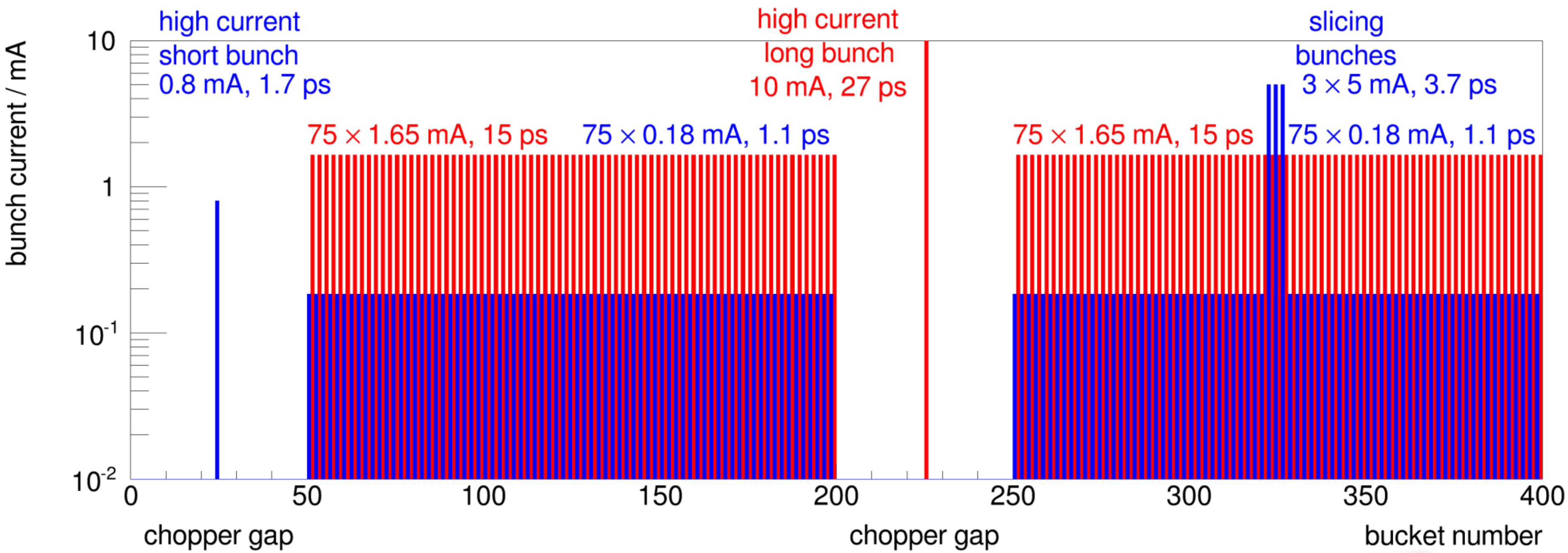
Combining two RF systems with different frequencies (1.5 GHz & 1.75 GHz) generates long and short buckets, which can be filled individually to generate optimized fill pattern.



1.5 MV @ 0.5 GHz
16 MV @ 1.5 GHz
14 MV @ 1.75 GHz

J. Feikes, P. Kuske, G. Wüstefeld EPAC 2006
G. Wüstefeld, A. Jankowiak, J. Knobloch, M. Ries, IPAC 2011

BESSY-VSR – Fill pattern



- 300 mA average current
- camshaft single bunches (short and long) in gaps
- 100 ns gaps → for single bunch separation by chopper

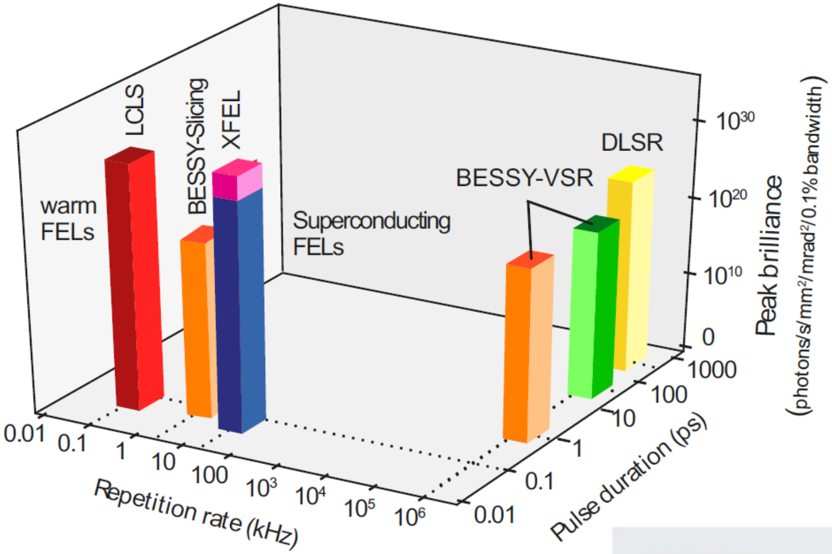
in low alpha mode
400 fs @ 0.04 mA / bunch

multi functional / multi user hybrid mode

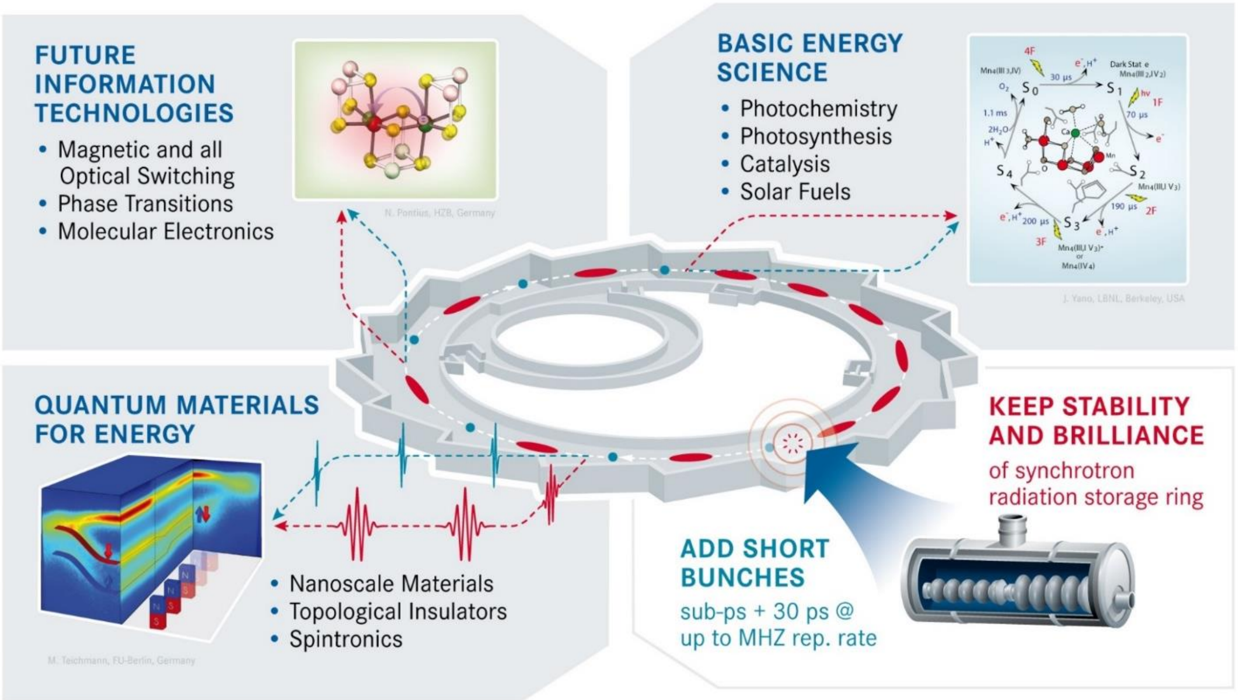
ps short single bunch, high current single bunch, slicing bunches, high average brilliance, background of intense CSR/THz radiation

preserving BESSY II emittance and TopUp
→ 5 nm rad, lifetime > 5h, average inj. eff. > 90%

BESSY-VSR – Adding the dimension of time (high rep. rate ps pulses)



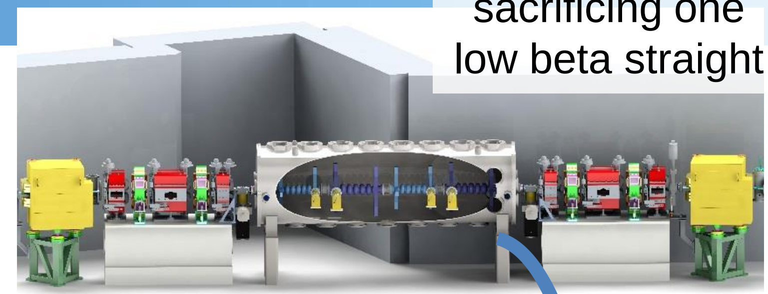
"Beating the complexity of matter through the selectivity of soft X-rays"



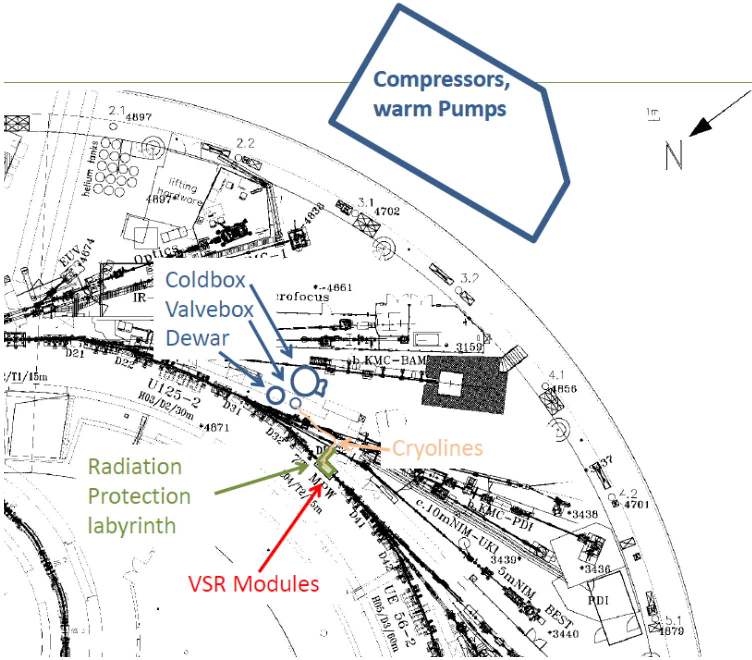
BESSY-VSR – Technical realisation

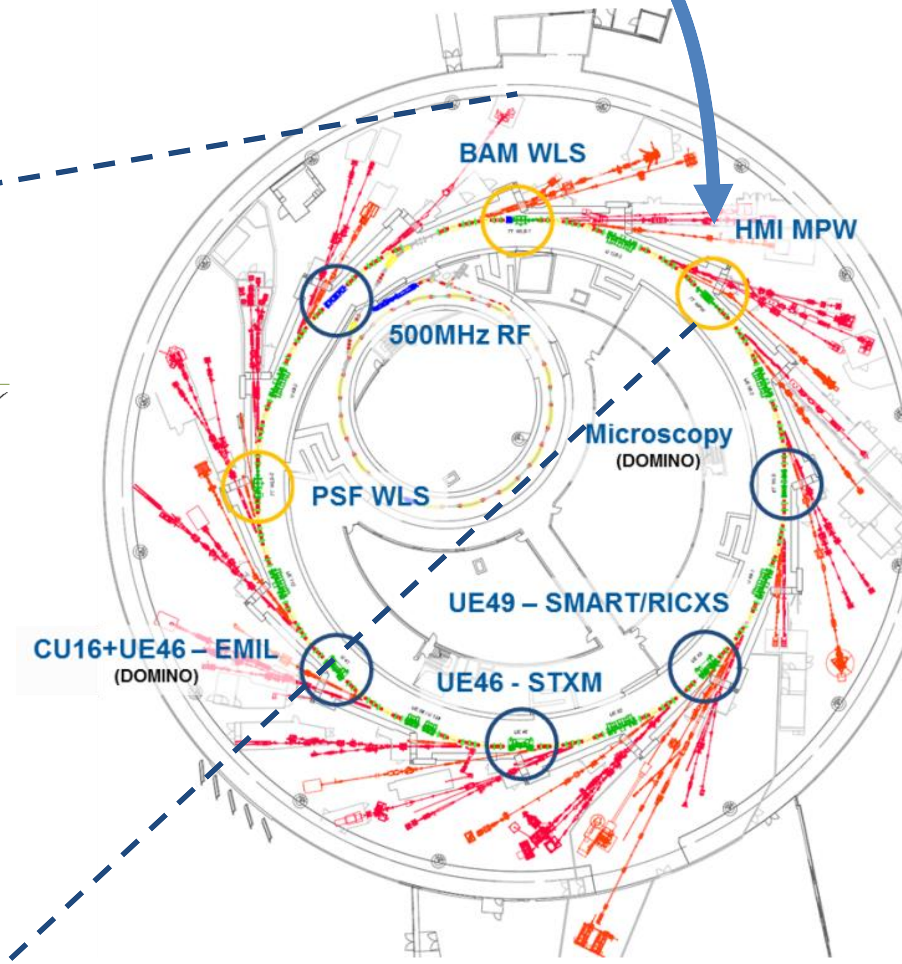
One cryo-module with:
2 x 4 cell @ 1.5 GHz & 2 x 4 cell @ 1.75 GHz
operating at **1.8 K LHe** temperature
active length: **1.50 m** with **20 MV/m**
total gradient: **2π 50 MV×GHz (x 60 increase)**

sacrificing one low beta straight



Installation of 1.8 K Cryo-System





BESSY-VSR – Time line

doi:10.5442/R0001

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	2019	2020	2021	2022
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**

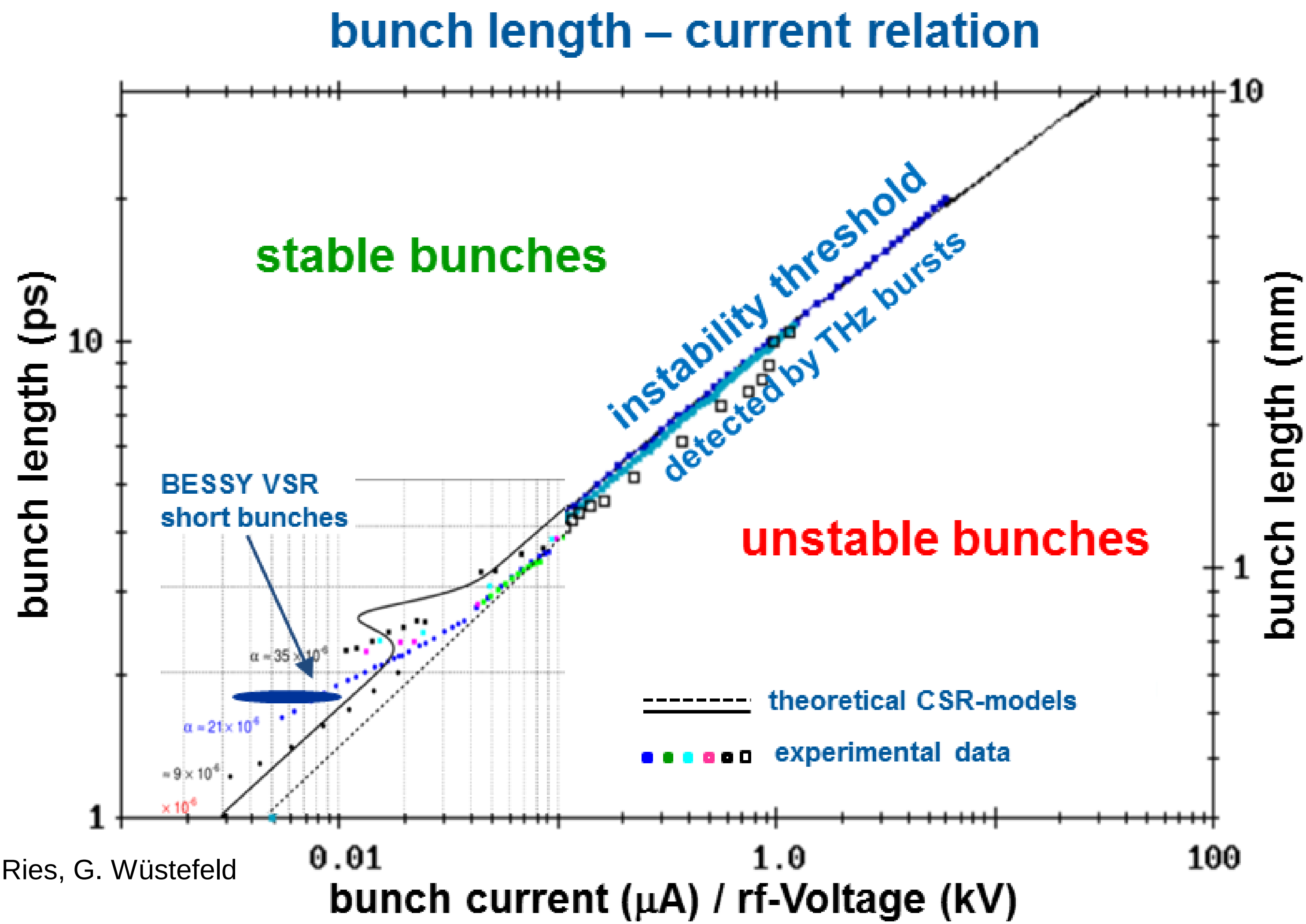
  bunch length in booster 60 ps, injection efficiency > 90%

  → bunch “compression” in booster at least by factor 2 needed

Bunch length / current scaling

Highly charged short bunches are limited by the CSR bursting instability

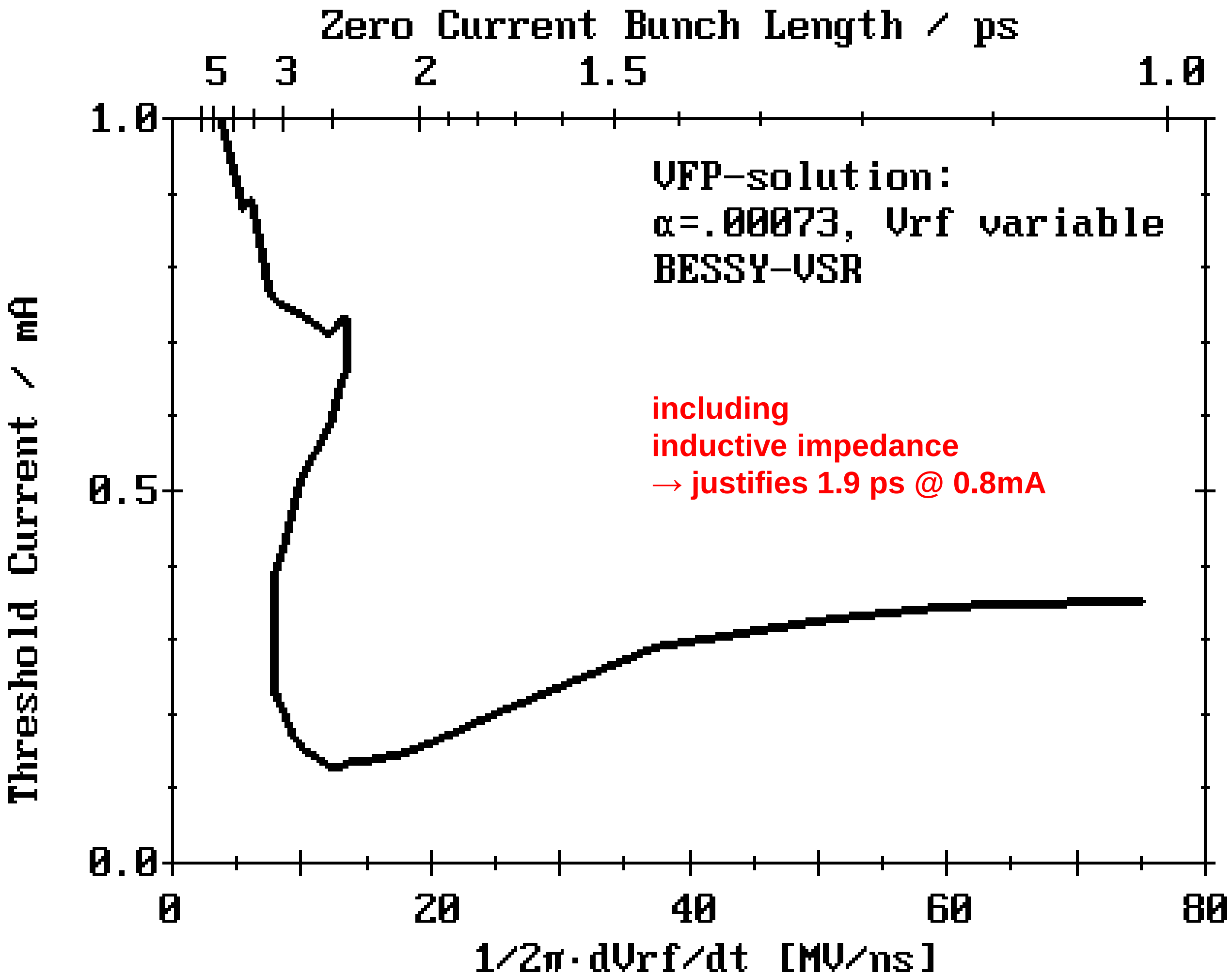
⇨ unstable bunches are not lost, they blow up in energy spread and length



P. Kuske, M. Ries, G. Wüstefeld

P. Kuske, Proceedings of IPAC2017, Copenhagen, Denmark, thpab007
P. Kuske, Proceedings of IPAC2013, Shanghai, China, WEOAB102

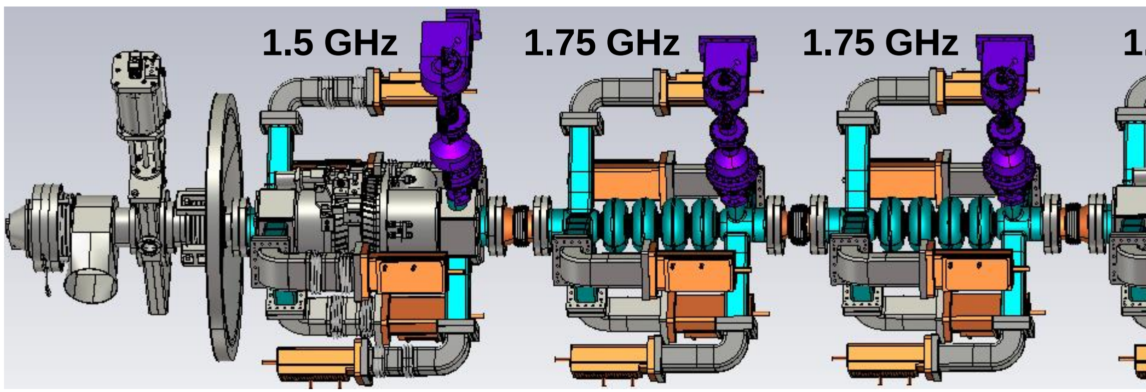
CSR-driven longitudinal instability of short bunches – predictions of VFP-solver with parallel plate model for BESSY VSR (in black)

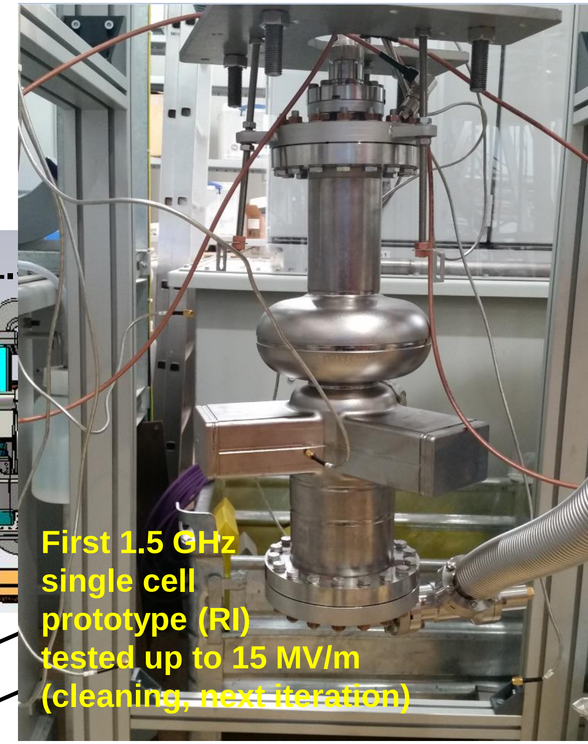


BESSY VSR – Cavity design / HOM damping concept

Due to space restrictions (4,3m free length in straight) number of cells per cavity = 4

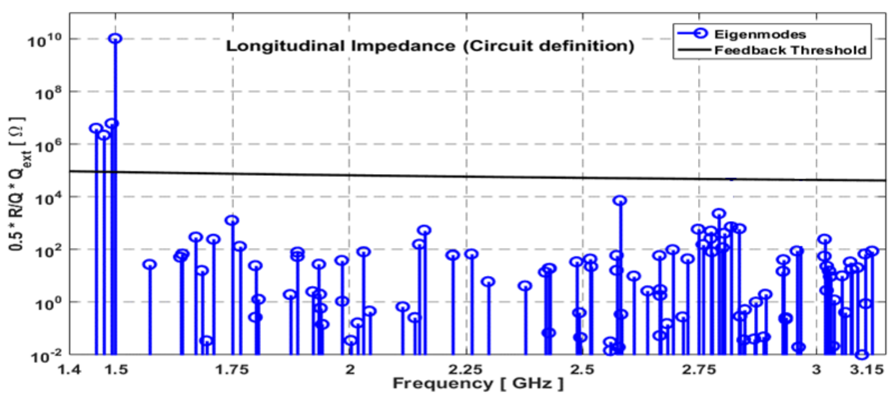
- 4-cell design is validated and closed.
- Total module Voltage 29.7 MV (@20 MV/m)
- Bunch length 1.9 ps @ 0.8 mA (zero current = 1.2 ps)

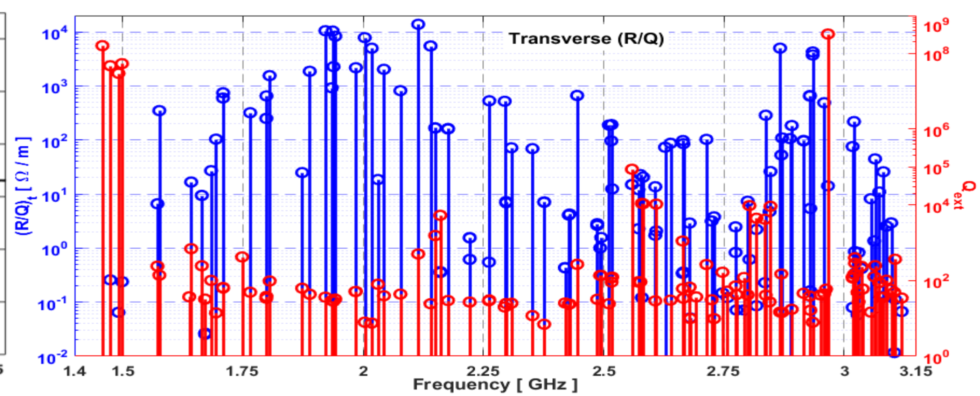




A. Velez, A. Neumann, F. Glöckner, et al.

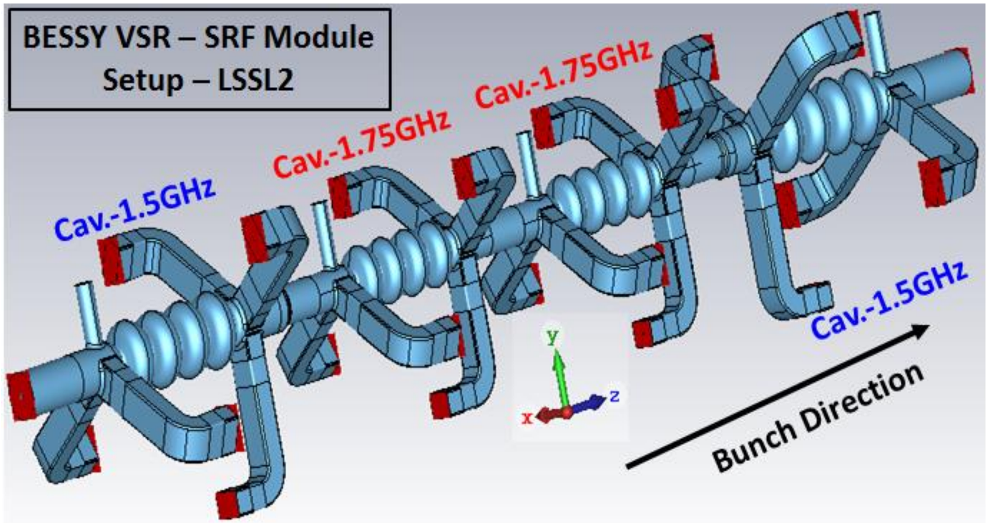
Calculated impedance budget for single cavity (eigenmode analysis)

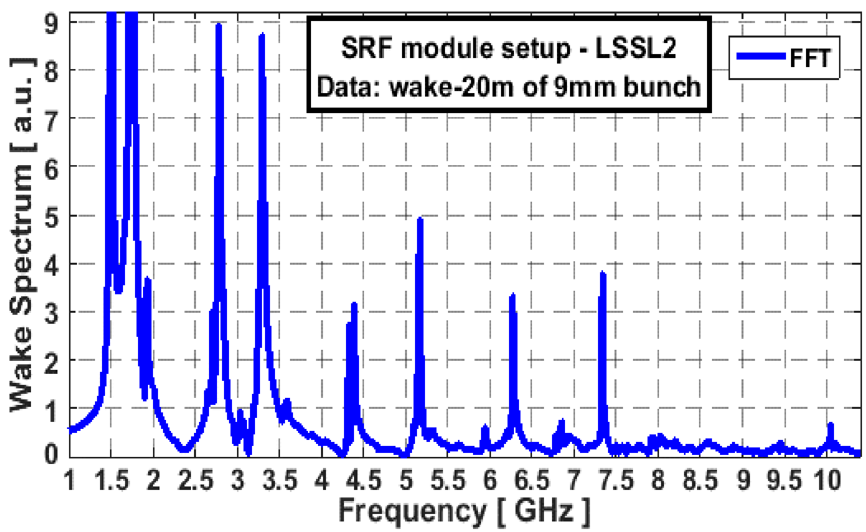




Full Module Long Range Wakefield Simulation

(Off-axis XY = 2.1 mm, 9 mm bunch, 20 m wake length)





VSR Module Power Levels: Baseline Filling Patern

HOM Power [W]

Port	LSSL1	LSSL2	SSLL1	SSLL2
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
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
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
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

1.5 GHz (ports 1–6)

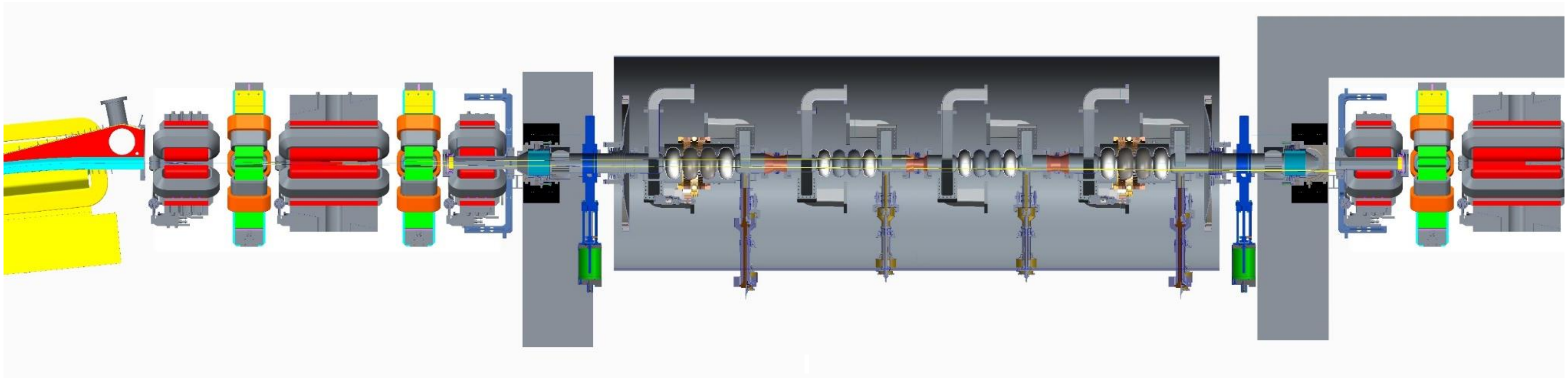
1.75 GHz Cavities (ports 7–18)

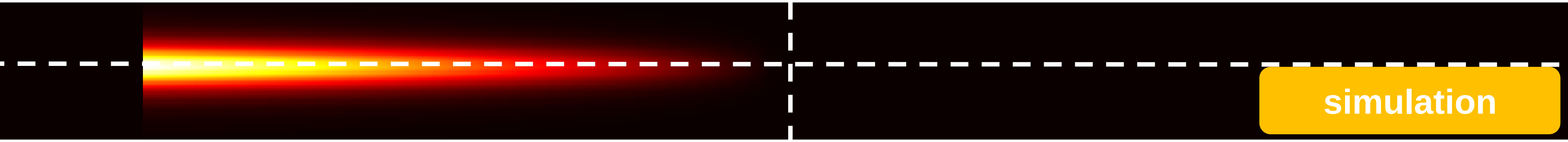
1.5 GHz (ports 19–24)

Beam pipes (ports 25–26)

18

BESSY VSR module - Synchrotron Radiation in SRF Cavity Straight





power density distribution at module entrance

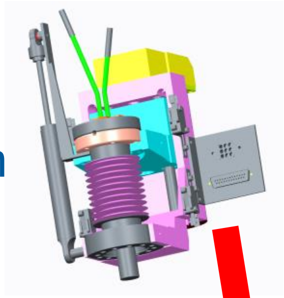
integrated power inside module ~ 67 W @ 1.8 K

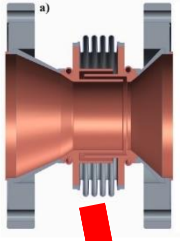
maximum power density on iris ~ 230 W / cm^2

M. Ries et al.

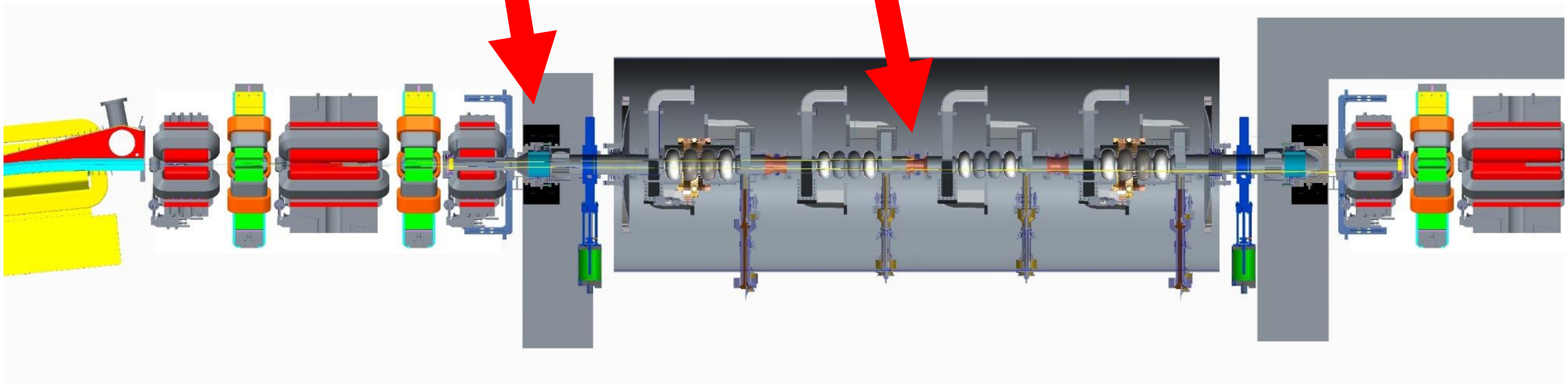
integration of one “warm”=outside and one “cold”=inside module collimator

16 mm





Ø 24 mm

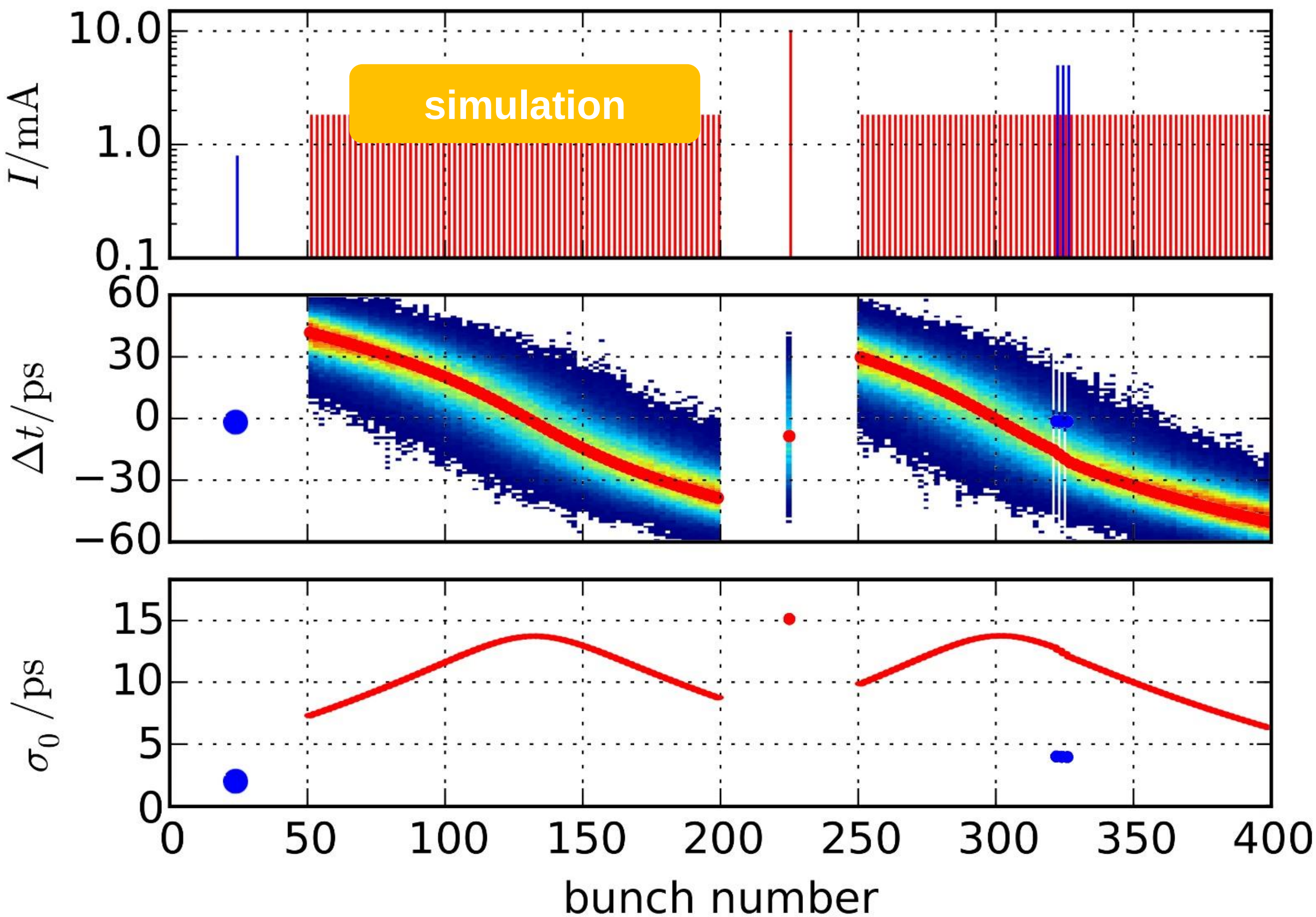


integrated power inside module ~ 0 W @ 1.8 K
integrated power inside module ~ 11 W @ 5 K

2do: orbit stability margins, MPS

M. Ries et al.

BESSY VSR three frequency nc/sc RF system – Beam loading



M. Ruprecht, PhD thesis and Proc. IPAC

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

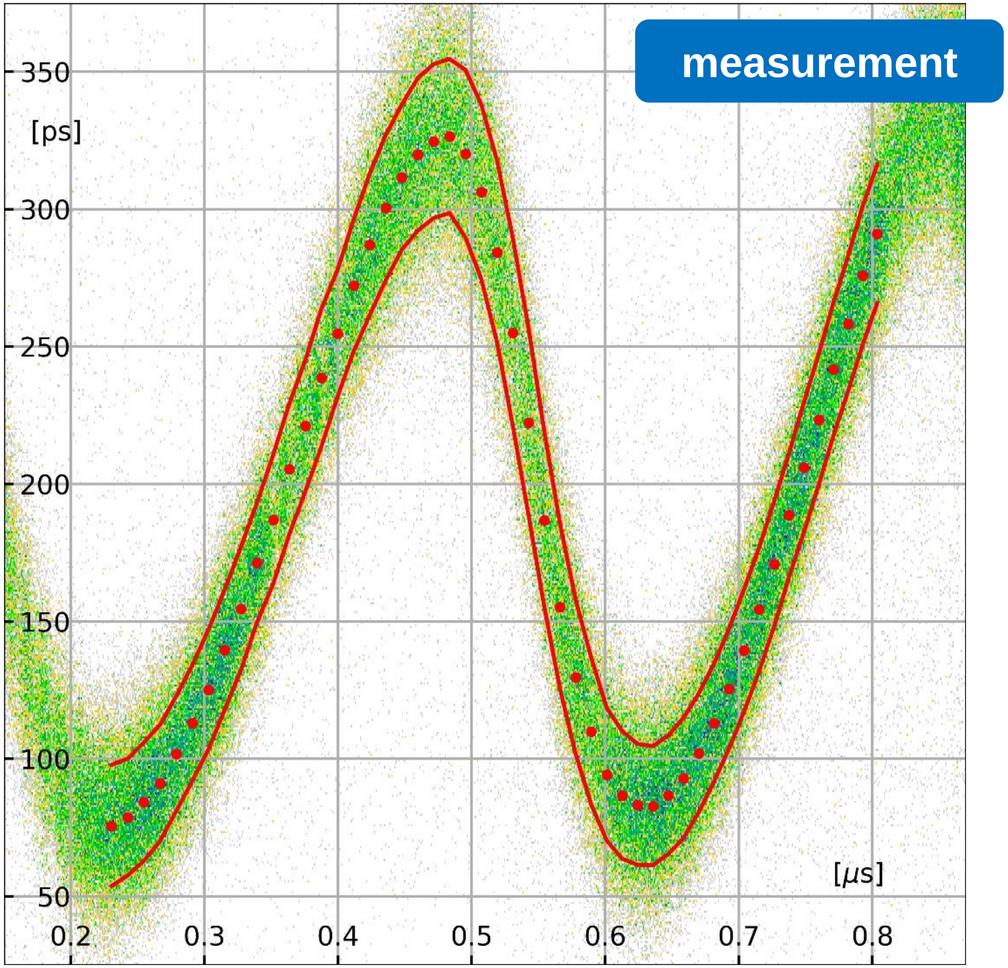
long bunches are affected most as the delicate balance of canceling gradients is disturbed

affected quantities:

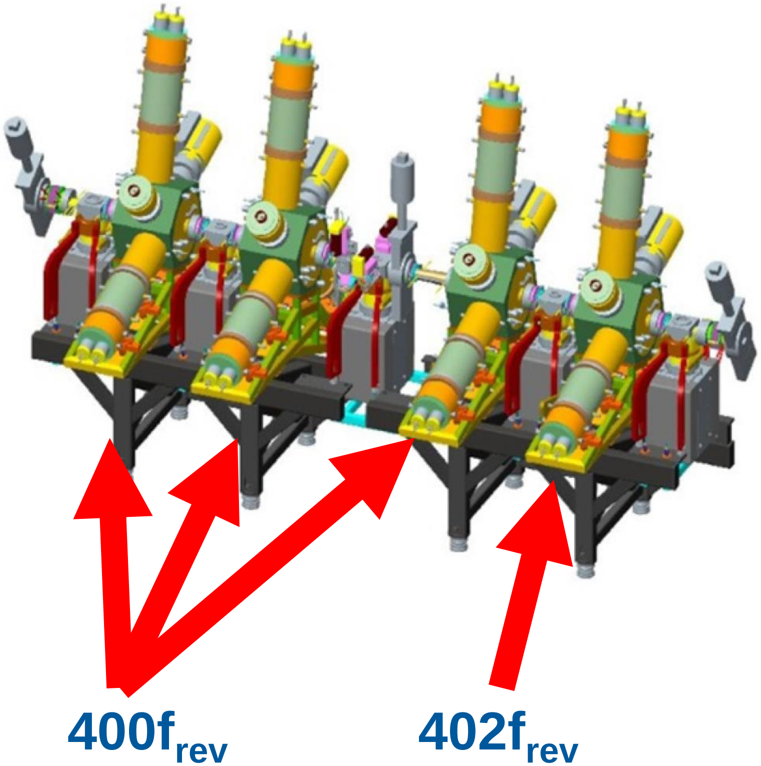
- arrival time (phase transient)
- focusing gradient (bunch length transient) → Touschek lifetime reduced by up to 50%

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

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



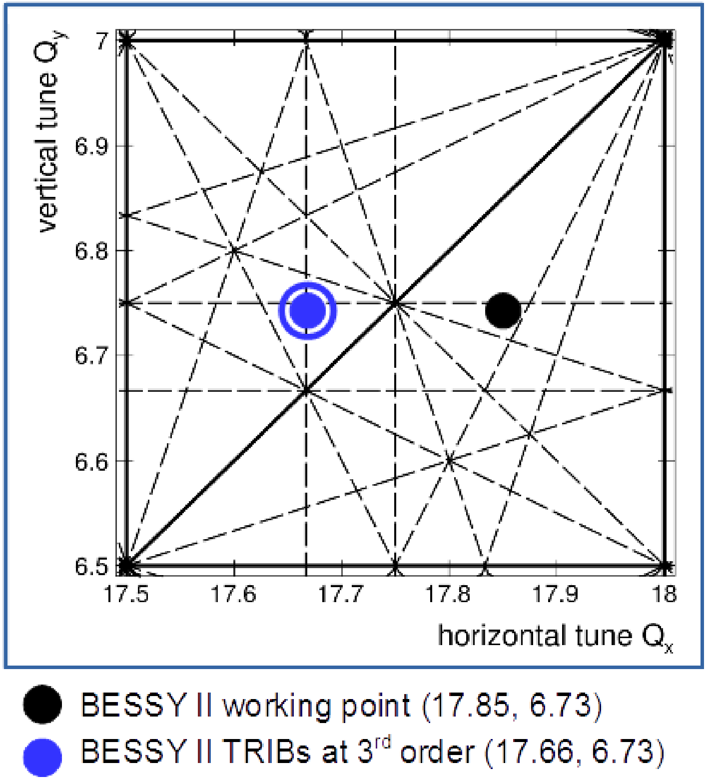
potential Touschek lifetime increase for BESSY VSR ~ 50%

TRIBs – A way to overcome the transient beam loading issues?

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

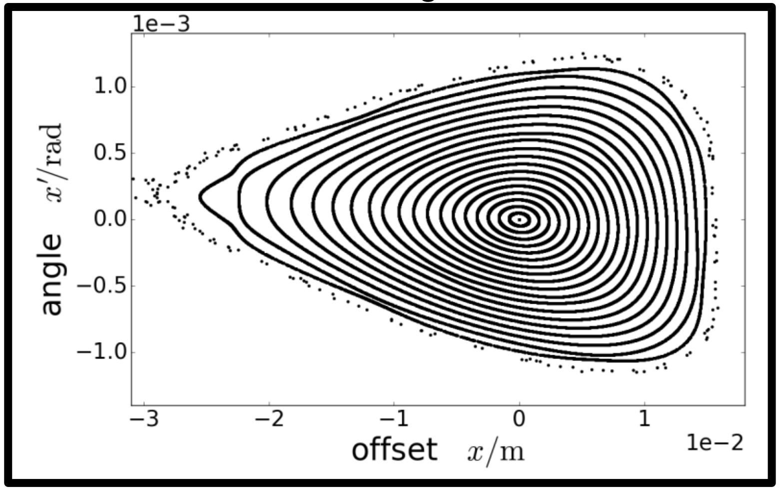
TRIBs at BESSY II
A new Bunch Separation Scheme

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

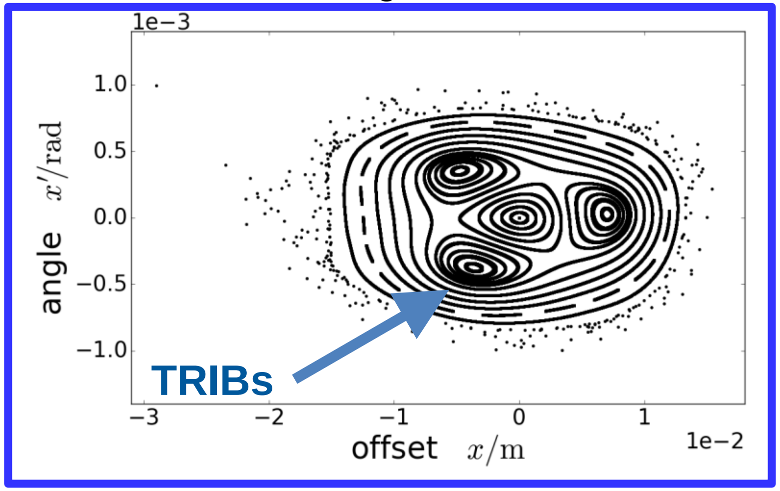


2nd stable fix point & orbit

BESSY II standard setting



BESSY II TRIBs setting at 3rd order resonance



TRIBs – It is real (@BESSY II and @MLS)

TRIBs at BESSY II
Proof of Principles Studies:

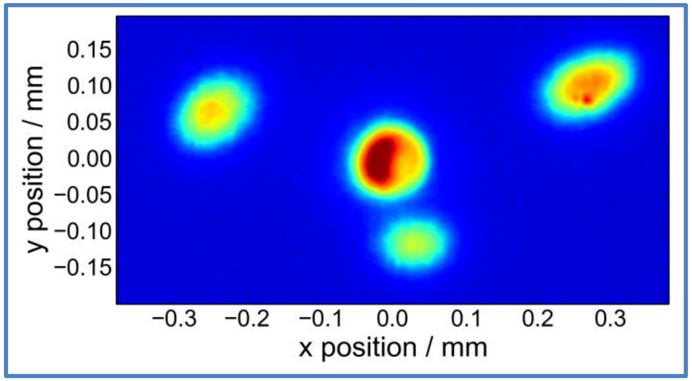
- Current can be shuffled between both orbits without losses
- Separation at user beamlines is promising
- TopUp injection is possible (if all current is stored on core orbit)

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

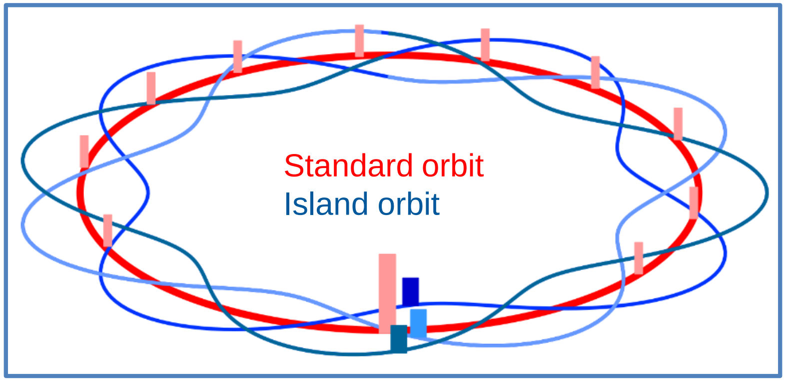
TRIBs - the long term objective:

- 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: 2nd fill pattern, tailored for timing experiments stored on 2nd orbit

Bending magnet beamline, source point image



TRIBs Scheme, 2nd fill pattern stored on 2nd orbits

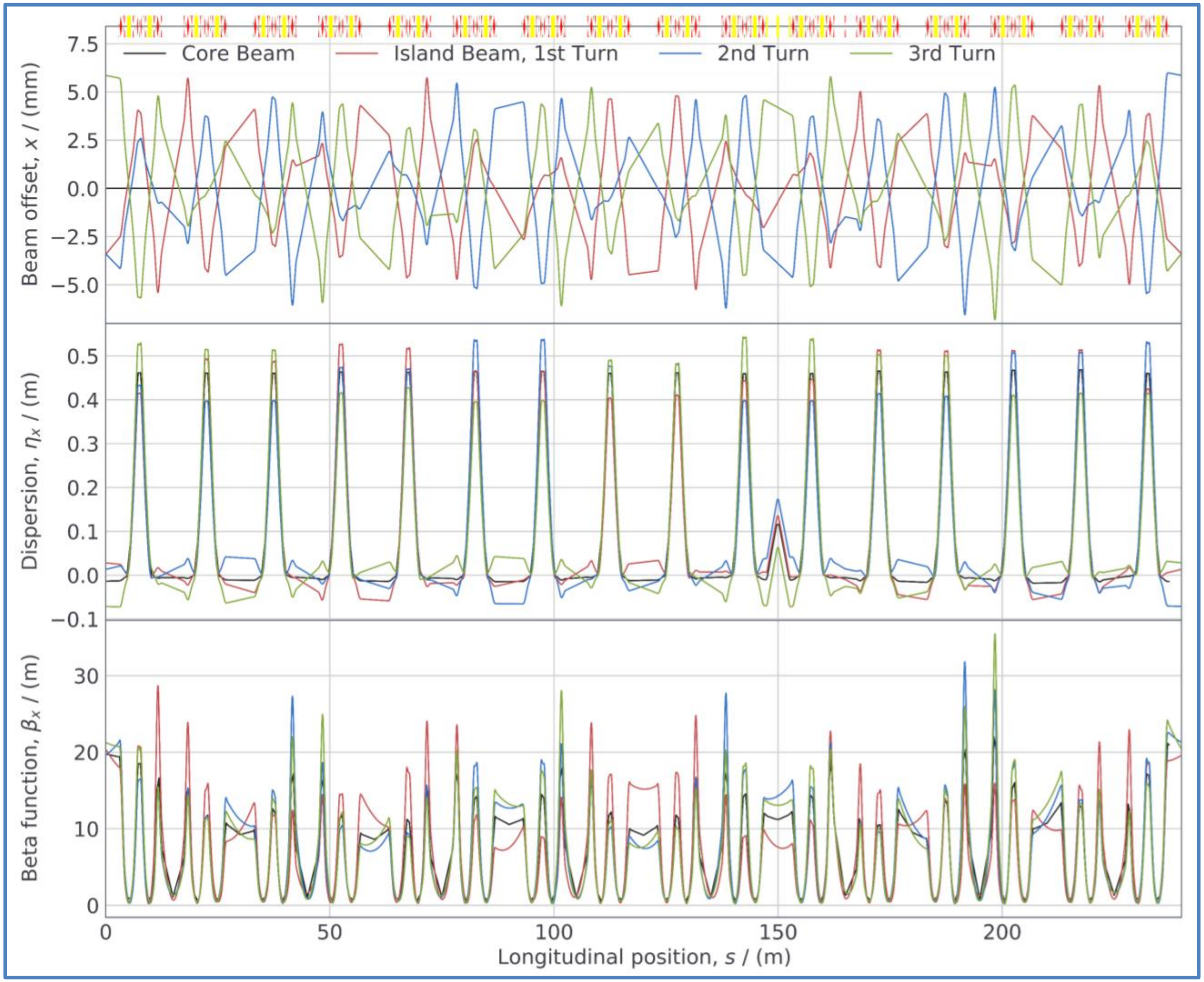


TRIBs – Optics parameter

TRIBs at BESSY II – Separation and Twiss Parameters of TRIBs orbit

F. Kramer, PhD thesis in preparation

Horizontal beam offset
Dispersion function
Beta function

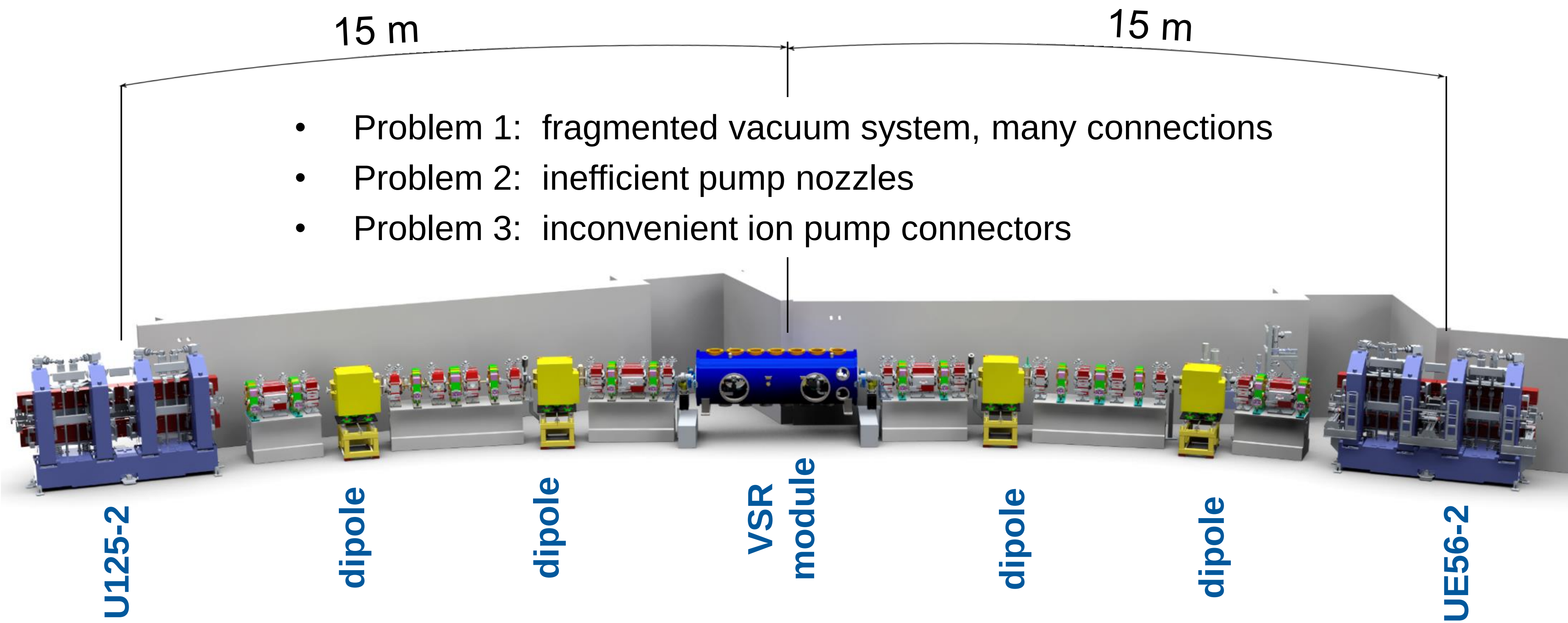


Equilibrium Emittance:

BESSY II std. :	7 nm rad
TRIBs core orbit:	8 nm rad
TRIBs island orbit:	9 nm rad

BESSY VSR vacuum system – BESSY II as it is

Ring section for BESSY VSR module installation



- Problem 1: fragmented vacuum system, many connections
- Problem 2: inefficient pump nozzles
- Problem 3: inconvenient ion pump connectors

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

BESSY VSR vacuum system – Redesign

approach re-design

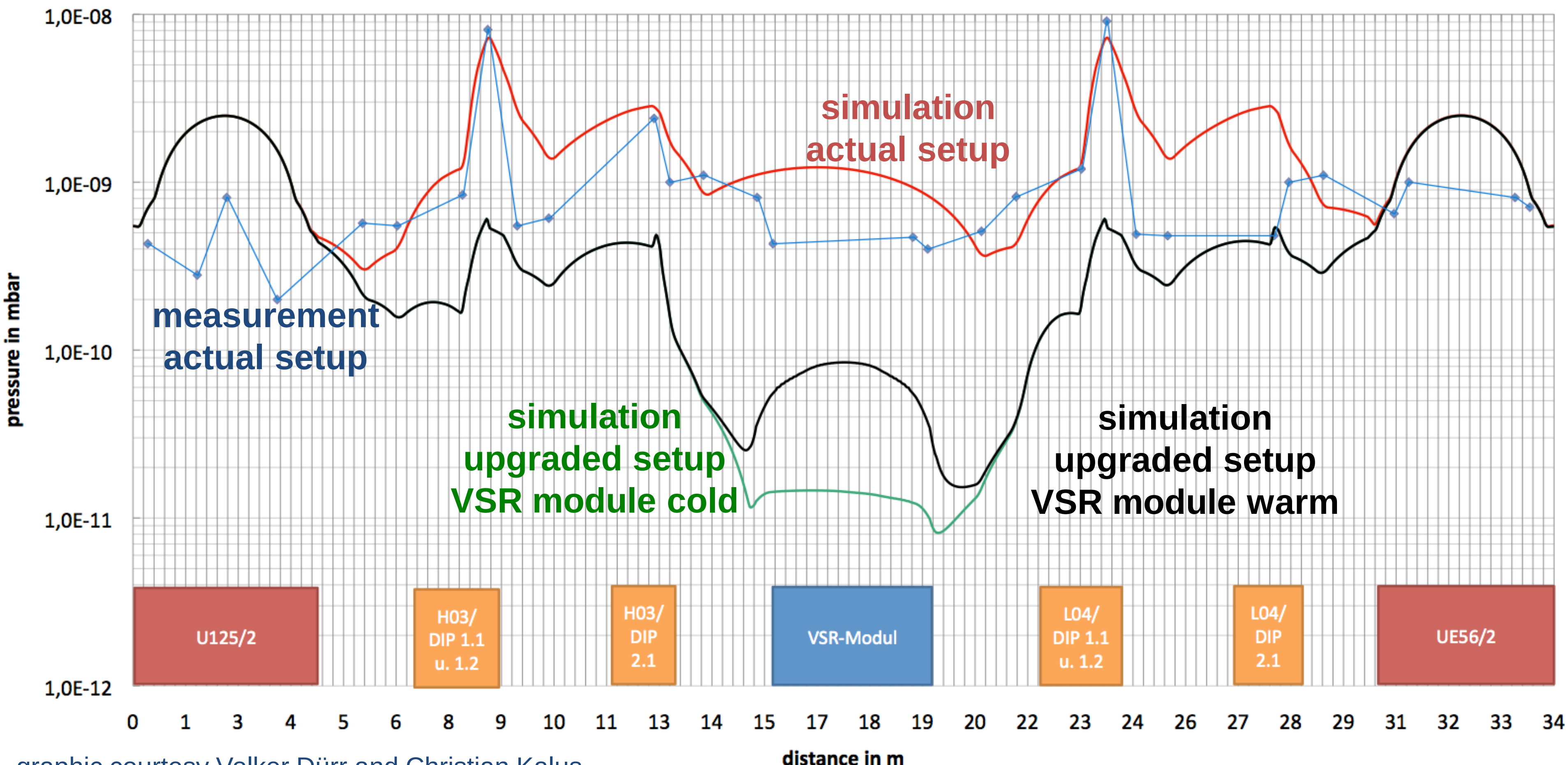
- fewer, longer vacuum chambers
  → less fragmentation, fewer connections, easier pre-assembly
- NEG coated chambers
- improved ion pump nozzles with smaller ion pumps
- new dipole supports
- additional gate valves
- new BMPs
- new synchrotron radiation absorbers

approach installation (particle free installation)

- pre-assembly in cleanroom
- “portable” clean enclosure (laminar flow boxes) to assemble remaining connections

BESSY VSR vacuum system – Expected performance

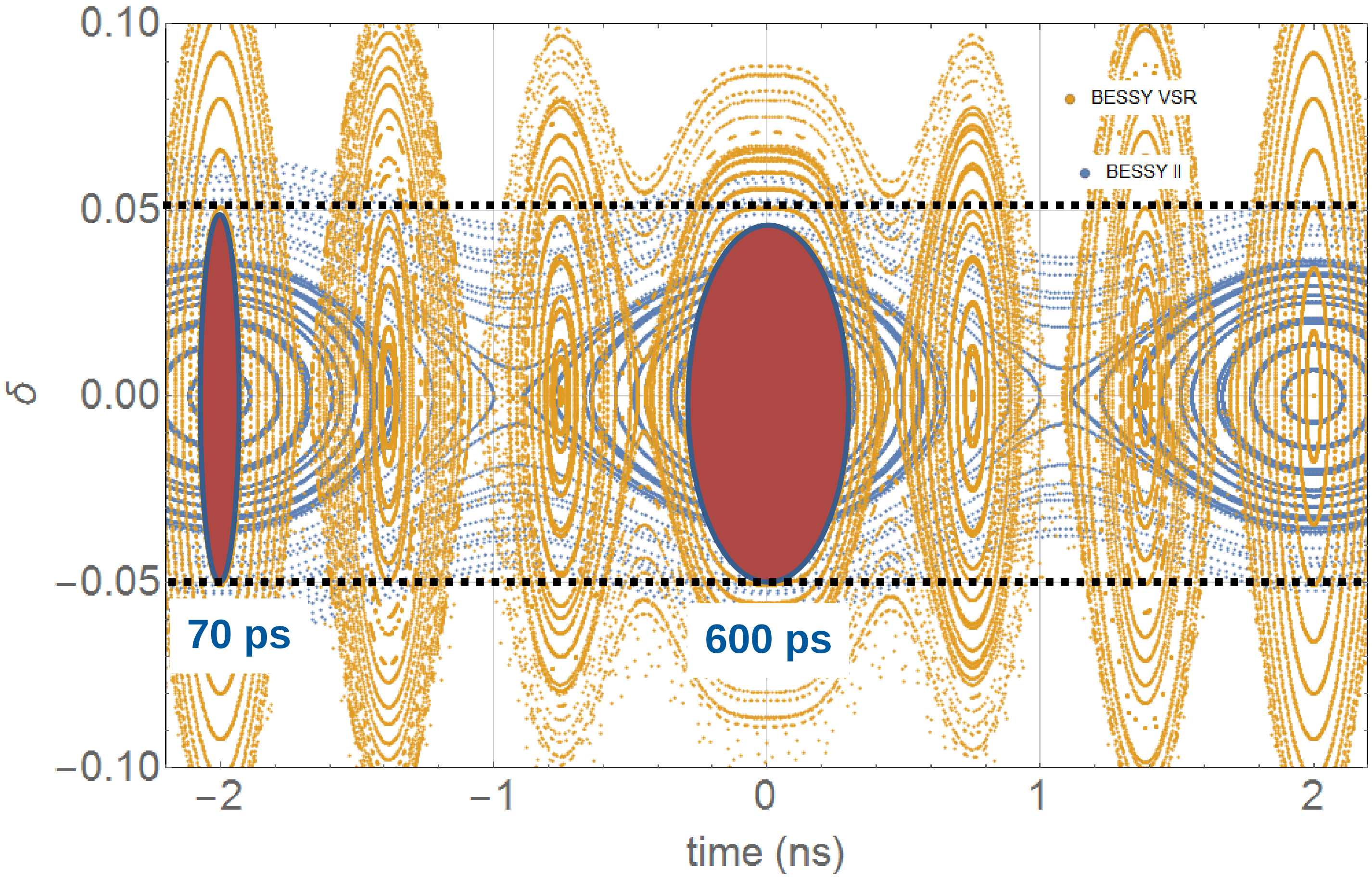
Pressure profile - currently and with planned improvements



graphic courtesy Volker Dürr and Christian Kalus

BESSY VSR – Injecting in short bunches

The “beating” principle of the BESSY VSR scheme with its short bunches leads to a reduction in phase acceptance compared with todays BESSY II standard bucket
→ “shooting a camel through the eye of an needle” = bunch length booster needs to be reduced

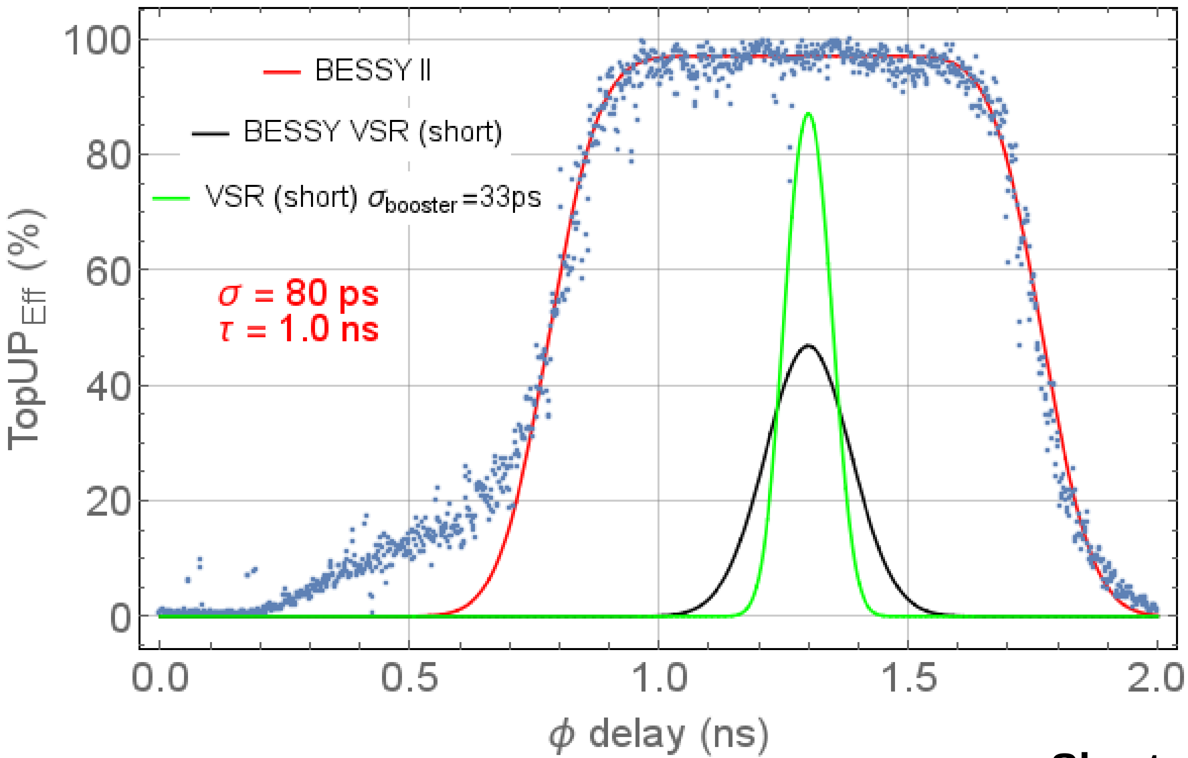


acceptance defined by machine and IDs

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%

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



τ = 1 ns → 3% energy acceptance

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.

P. Kuske, J. Li, T. Atkinson, A. Matveenko, F. Kramer, et al.

Summary BESSY-VSR

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