BESSY VSR
Helmholtz-Zentrum Berlin

HZB Helmholtz Zentrum Berlin

HUMBOLDT-UNIVERSITÄT ZU BERLIN

BESSY^{VSR}

The accelerator physics behind

Andreas Jankowiak
on behalf of the BESSY^{VSR} team

BESSY^{VSR} Workshop
Helmholtz-Zentrum Berlin
14.10.2013

The Menue

- **The idea**

  shaping the longitudinal phase space
  by high gradient sc cavity systems

- **Performance parameter**

  fill patterns, bunch lengths, bunch current, emittance

- **Challenges**

  high gradient sc cw cavities, stability requirements,
  coupled bunch instabilities, scaling, lifetime, bunchlength,
  injection process, bunch seperation

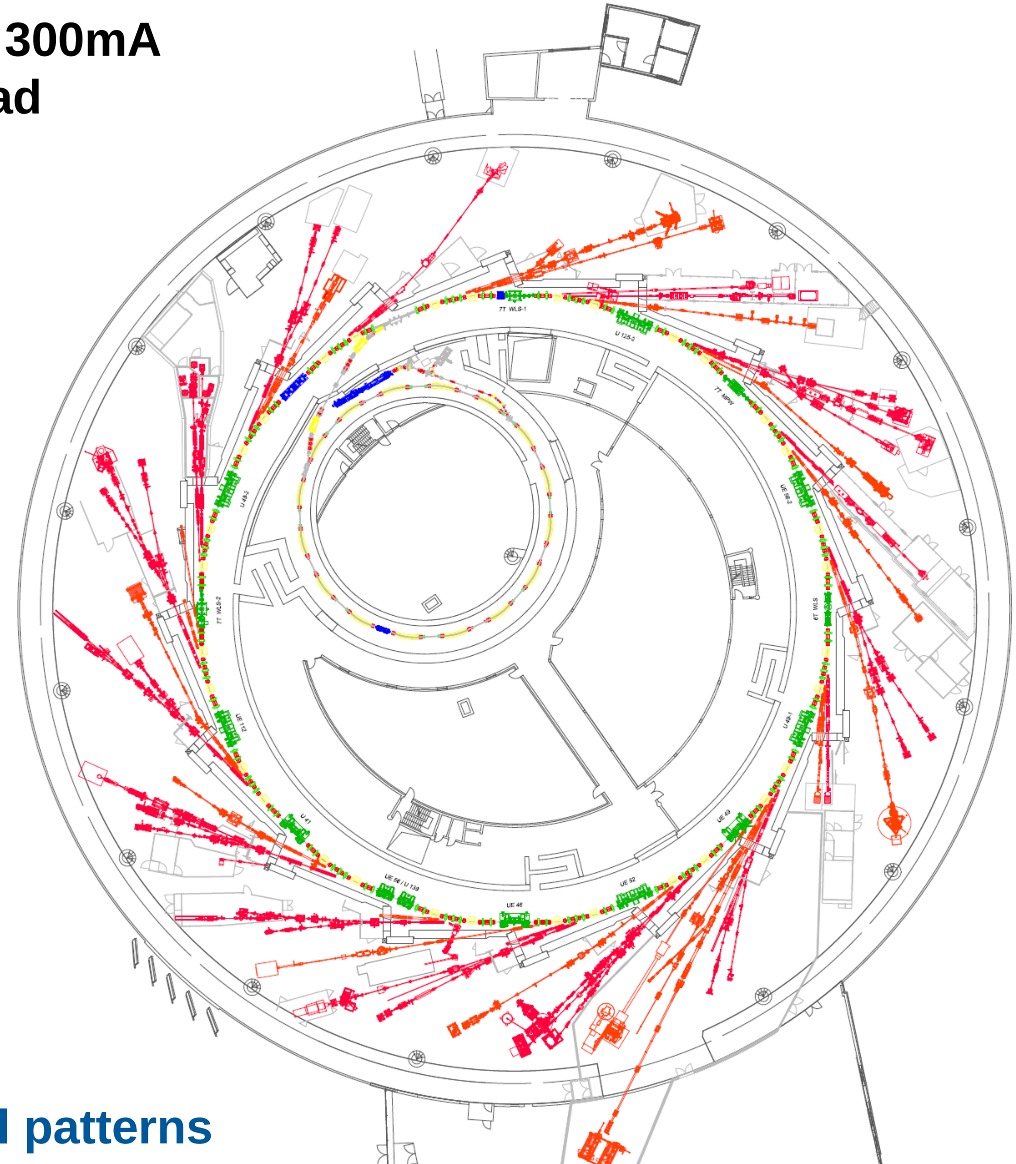
3rd generation light sources: e.g. BESSY II

Energy/current	1.7GeV / 300mA
Emittance	4/6 nm rad
pulse length	15 ps
Straight sections	16
Undulators / MPW+WLS	10 / 1+3
ID / dipole beam lines	32 / 20
end stations (fixed+var)	52

~ 5500 h/a user service
~ 2400 users / a

>> from THz to keV <<

- spectroscopy & scattering
- imaging & lithography
- dynamic studies



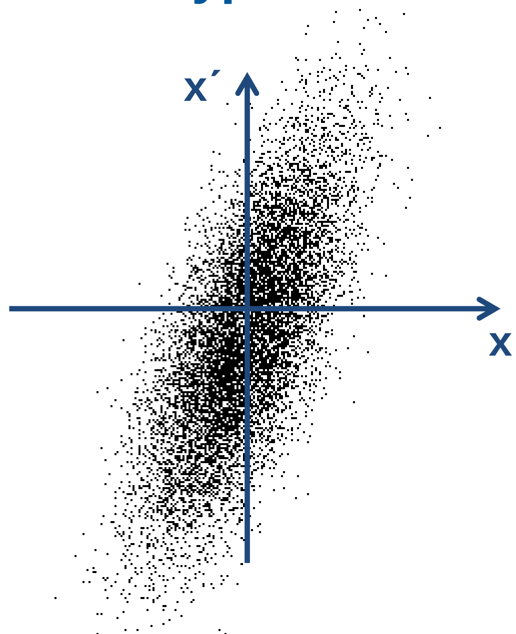
low-α
ps beams, CSR, THz

femto slicing
100fs, polarised x-rays
6kHz and variable
pump probe laser

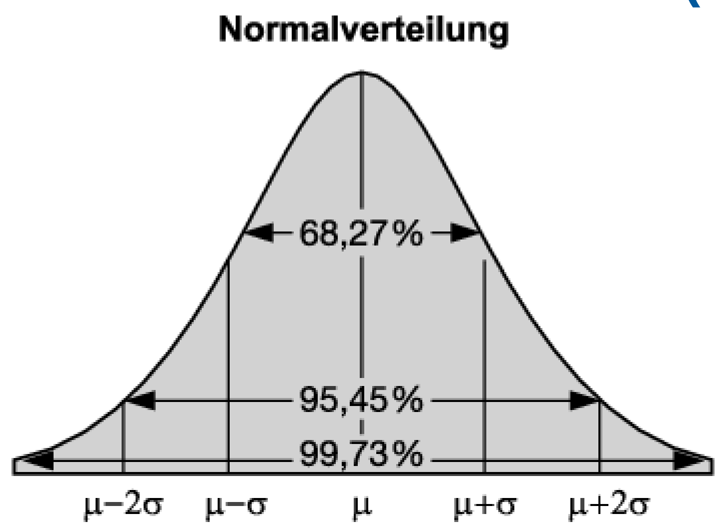
flexible fill patterns
single bunch, camshaft, ...

Beam emittance and pulse length in storage rings (3rd generation)

transversal typical: ~ nm rad



longitudinal typical: ~10mm = 33ps (rms)



equilibrium between (synchrotron) radiation damping and heating (defined by lattice e.g. DBA, TBA, MBA and insertion devices)

$$\varepsilon_x = C_q \gamma^2 \frac{\left\langle \frac{1}{R^3} H(s) \right\rangle}{\left\langle \frac{1}{R^2} \right\rangle} \sim \frac{\gamma^2}{N^3}$$

DLSR = Diffraction Limited Storage Ring (a.k.a. USR = Ultimate Storage Ring) some 100 pm rad down to 10pm !?

$\varepsilon_y \sim 1/100 \cdot \varepsilon_x$ (coupling)

$$\sigma_s \sim \sqrt{\frac{\alpha}{V'}} \cdot \sigma_E$$

low-α operation

BESSY[VSR]

$\alpha = \frac{\delta L / L_0}{\delta p / p_0}$: momentum compaction factor (beam optics)

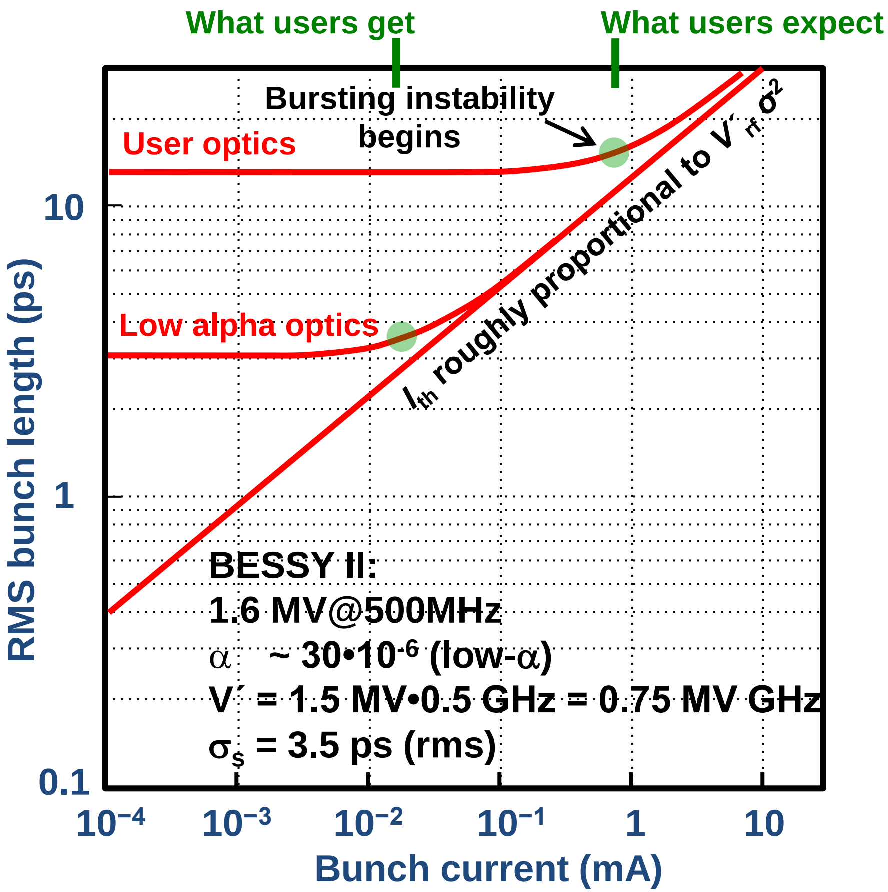
$V' = \frac{dV}{dt}$: gradient of accelerating voltage

Short pulse operation – low-α mode

BESSY II at present

- **Pulse length in storage ring = equilibrium condition** $\sigma \propto \sqrt{\frac{\alpha}{V'}}$ — Machine optics (α), rf-cavities (V')
- **→ easiest: for dynamic experiments change *α***

- **Problem: At certain current beam becomes unstable → lengthening**
- **For ps pulses, flux is reduced by nearly 100**
- **→ All other users are in the dark**
- **Low-*α* shifts only 12 days a year**



G. Wüstefeld et al., HZB

K.L.F. Bane, Y. Cai, and G. Stupakov,
Phys. Rev. ST-AB 13, 104402 (2010).

$$L = L_0\left(1+\alpha\frac{\delta E}{E}\right) \qquad V' = \frac{dV}{dt} = \omega_{rf} V$$

Short pulse operation – ultra high voltage

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

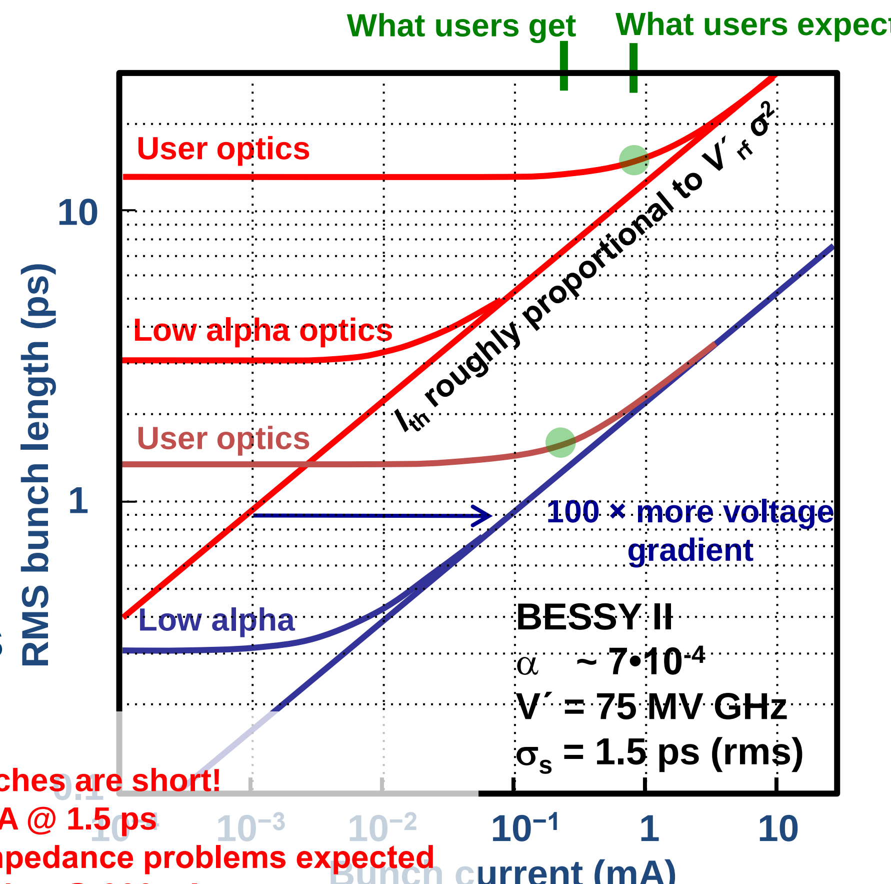
$$I \propto \dot{V} \quad (\sigma = \text{const.})$$

Future: Short pulses, high-flux

- Use the RF voltage as another degree of freedom:
- → Supply additional RF acceleration at higher frequency for overvoltage
- 100x higher gradient

  50 MV @ 1.5GHz = 75 MV GHz

super conducting multi-cell cw cavities (with high current cababilities)



G. Wüstefeld et al., HZB

- Supply short pulses down to 1.5 ps

  in user optic (no low-α)

  @100× more bunch current
- Low *α* permits few 100 fs

But:
now all bunches are short!
350 x 0.86mA @ 1.5 ps
→ severe impedance problems expected
→ no operation @ 300mA average current

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
BESSY low alpha optics and their lengths are m
[1]. The current in these short bunches is limited to
cro Ampere level, to avoid current dependent bunch
ening. An upgrade of the BESSY II rf system
gested to overcome this low current limitation by
of magnitude. Intense, picosecond bunches could
achieved already at the regular user optics. The
ing short and very intense electron bunches are u
generate short X-ray pulses and powerful THz ra
Expected parameters of bunch length and current
cussed.

INTRODUCTION

There is an increasing interest in short electron
in storage rings as sources of synchrotron radiat

Proceedings of IPAC2011, San Sebastian, Spain

Simultaneous Long and Short Electron Bunches in the BESSY II Storage Ring

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

Abstract

We present first ideas of a scheme to develop BESSY II into a variable electron pulse length storage ring. The final goal is, to fill BESSY II with short bunches of 1.5 ps length (rms) and long bunches of 15 ps length simultaneously in the presently applied user optics. All insertion devices are operated as usual, i.e. the helical undulators and 7 T-field insertions. Long bunches of 1.5 mA current per bunch, twice the value of the present user optics, are filled in each second bucket. The other buckets can be filled with short bunches of max. 0.8 mA. The lower current value is required to avoid increase in the bunch length and bunch energy spread, predicted by scaling laws. The total current is e.g. limited by the HOM damping cabailities 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 current cw applications like for the energy recovering linacs (ERLs). These developments seem to make it feasible to install high gradient HOM damped multi-cell cavities in electron storage rings. With an appropriate choice of the frequencies we get a beating pattern of the effective voltage at the different stable fixed points locations, leading to alternating short and long bunches.

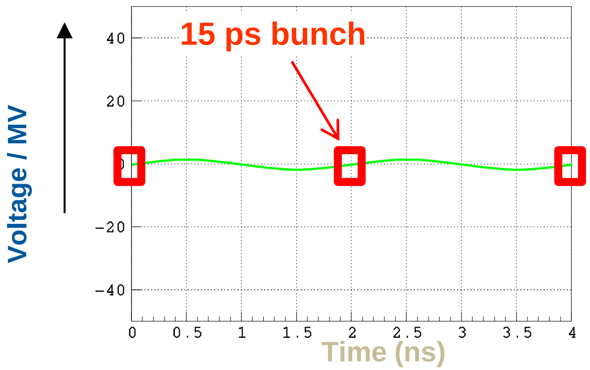
From the well established theory of zero current bunch length we expect 10 times shorter bunches by this rf-focusing. The maximum achievable current is kept just below the bursting instability limit, derived by scaling laws. For a fixed bunch length, the predicted threshold current for bursting is increased 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 rf-cavity parameters, bunch length and the current limit.

ALTERNATING BUNCH LENGTH SCHEME

In case of low currents ("zero current limit") the bunch length σ_0 can be reliably calculated. This length is a function of α and the rf-voltage gradient taken with respect to the longitudinal position $\partial V/\partial z = V' = 2\pi V f_{rf}/c$, given

BESSY^{VSR} – variable pulse length storage ring

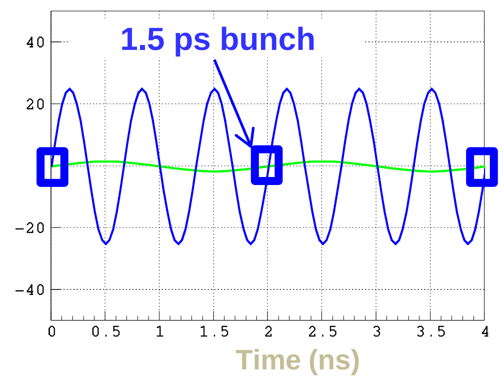
Present



Installed voltage: 1.5 MV at 0.5 GHz

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

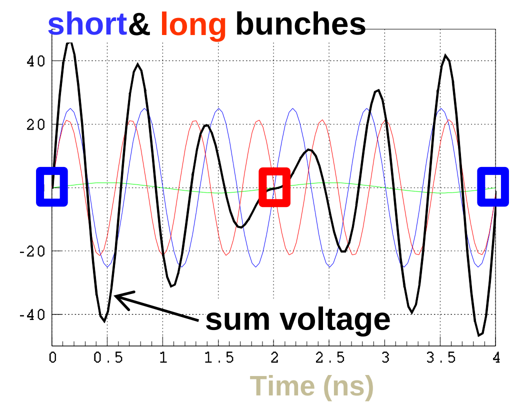
Future I



Installed voltage: 25 MV at 1.5 GHz

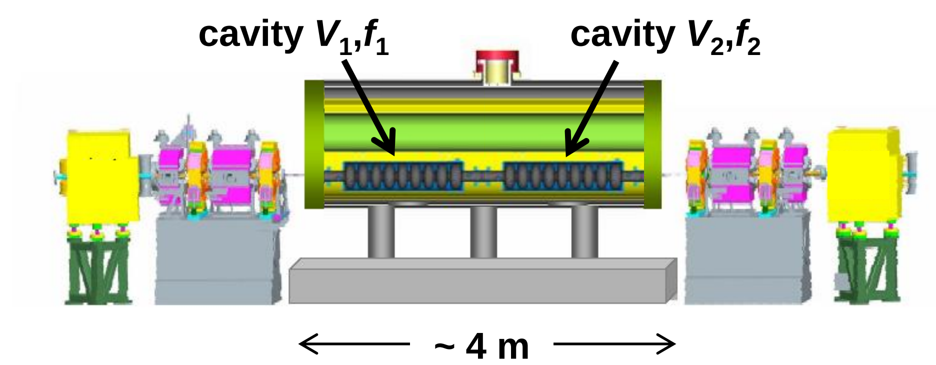
$\dot{V} \propto V \times f_{rf} = 37.5$ MV × GHz

Future II

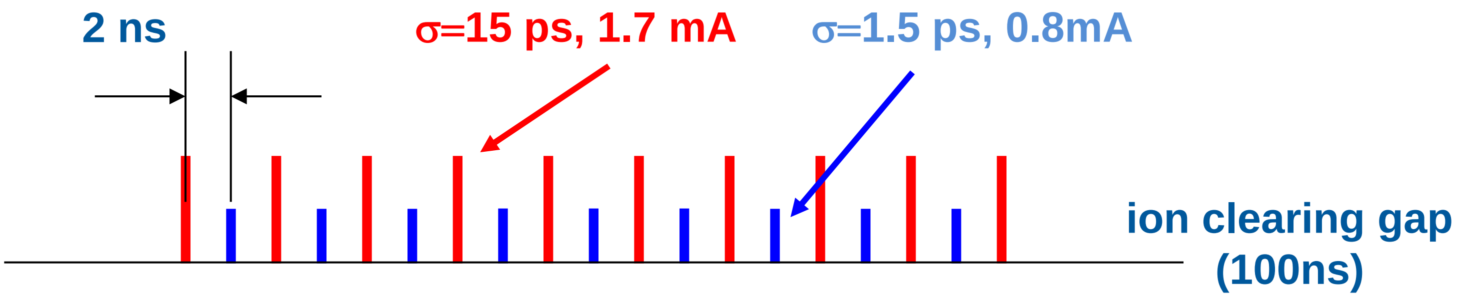


Installed voltage: 25 MV at 1.5 GHz
21.4 MV at 1.75 GHz

$\dot{V} \propto V \times f_{rf} = 75$ MV × GHz



Operation mode I: THz production mode

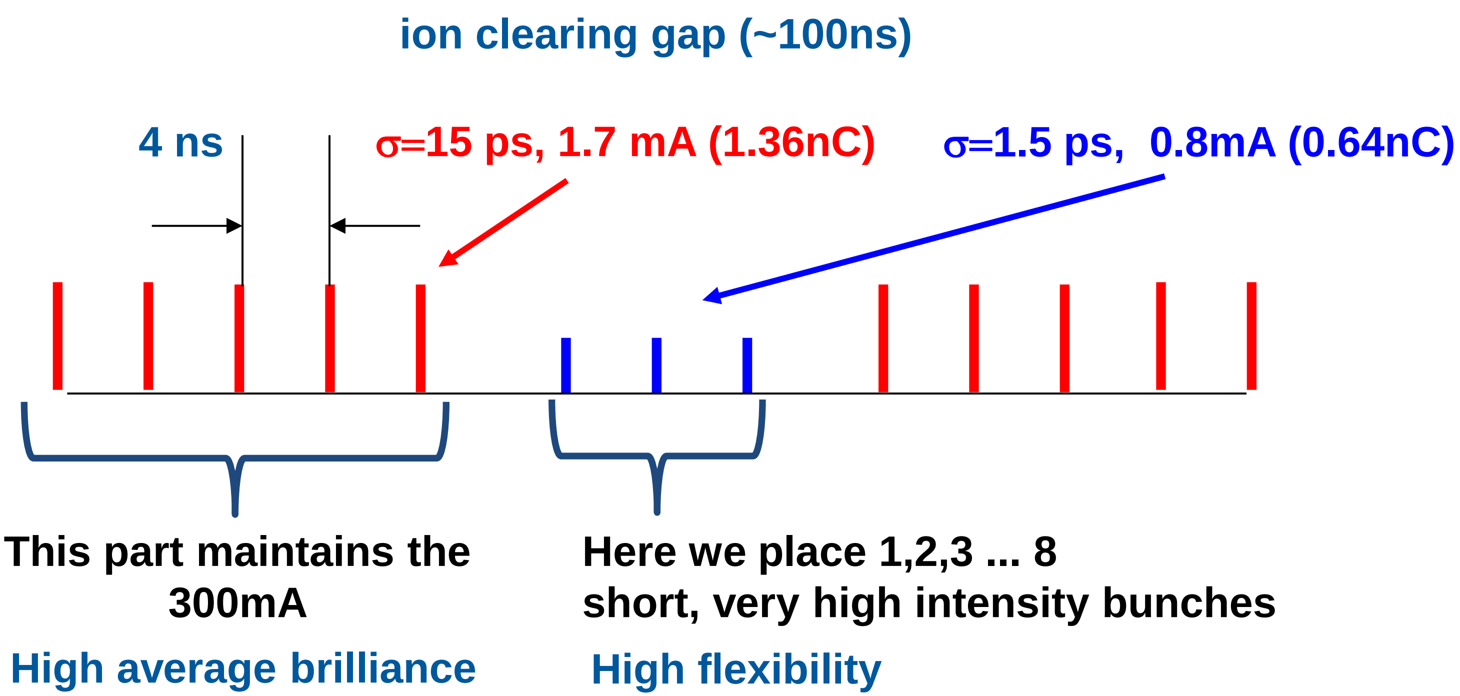


THz / CSR production mode

- 400 times more power per bunch, 2 times broader THz spectrum
- 100 ns ion clearing gap
- max. single bunch currents as shown
- total current to be defined

BESSY II standard optics → emittance as usual (~ 4/6 nm rad)

Operation mode II: Hybrid-Mode with short bunches (main mode)

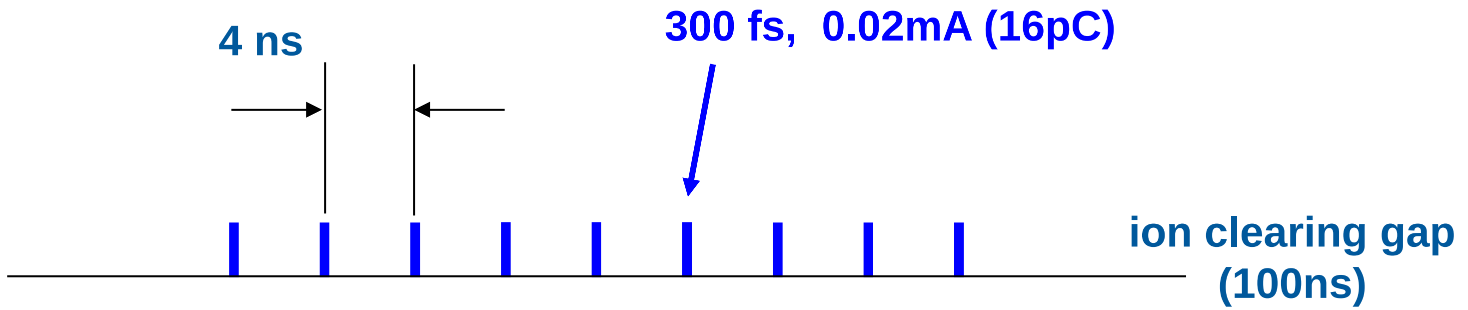


Hybrid-Mode with short bunches

- 700ns bunch train with 18 ps / 1.7 mA, spacing 4 ns
- 100ns ion clearing gap
- some short 1.5ps/0.8mA bunches (1 to 8 (?)) in ion-gap

BESSY II standard optics → emittance as usual (~ 4/6 nm rad)

Operation mode III: Ultra-Short bunches



Ultra-short bunches (low-α mode)

- up to 200 bunches with 300 fs / 0.02 mA, spacing 4 ns
- 100 ns ion clearing gap

BESSY II low-α optics (5 time larger emittance compared to BESSY II user optic)

Will evaluate if new "low emittance" low-alpha optic can be developed?

BESSY^{VSR} – the challenges

SC RF technology
(J. Knobloch, SRF-Science+Technology)

cavity design
- ERL high current multi-cell cavities @ 1.3 GHz (BERLinPro) design
- impedance calculations
- provide mode spectra for beam dynamic studies
- prototyping of cavities and **beam tests**
- scaling 1.3 GHz → 1.5 GHz → 1.7 5GHz

cryo module design
- double cavity module
- integration into storage ring

cryo plant design + integration
- how to integrate 2 K system in BESSY II

cavity parking
- cold/warm, de-tuning

beam dynamics issues
(AJ, Accelerator Physics + Operation)

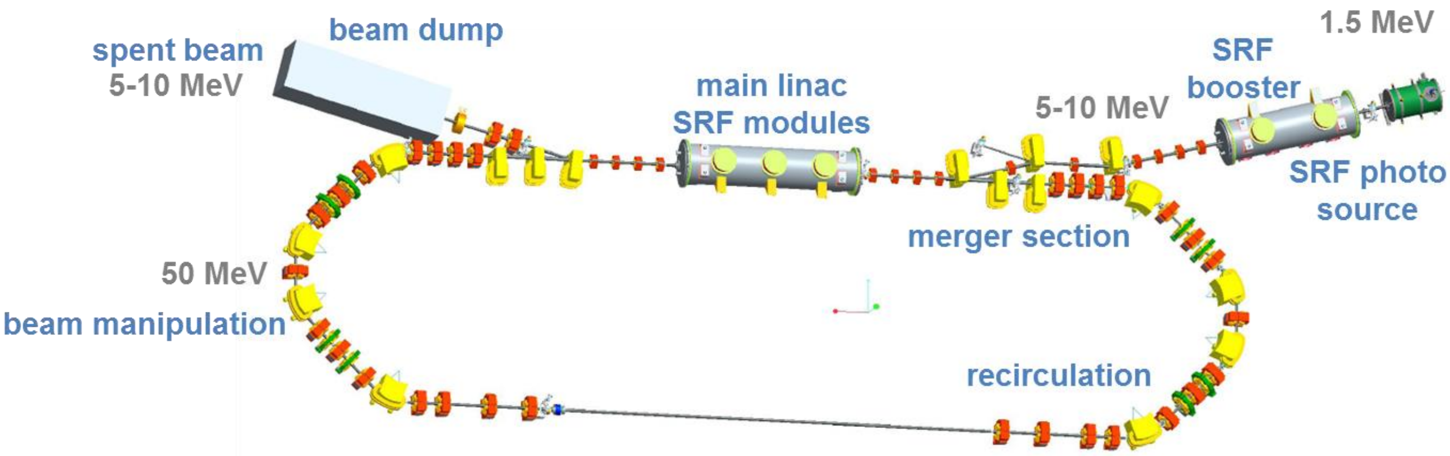
measurements (BESSY+MLS+ ...) + simulations / theory
- low alpha high current tests
- scaling with voltage at lowest bunch lengths
- bunch lengthening and energy spread

single particle dynamics
- jitter studies (defining tolerance reqs.)
- injection process (TopUp, full energy linac)
- low-alpha optics

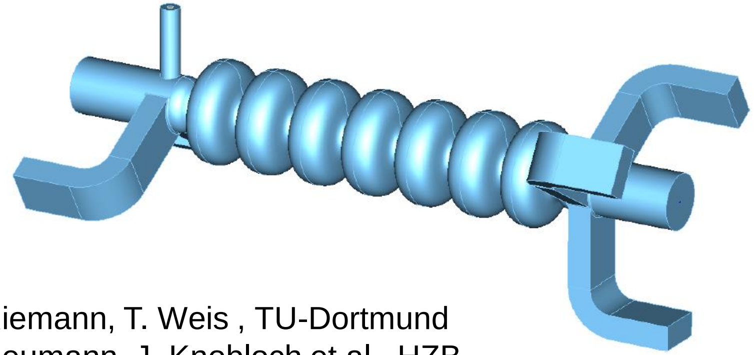
multi particle dynamics (collective effects)
- impedances (beam-cavities-wall interaction)
- coupled-bunch instabilities
- fill pattern dependences
- feedback systems
- intra beam scattering, Touschek lifetime

B*ERL*inPro = Berlin Energy Recovery Linac Project

100mA / low emittance ERL demonstrator

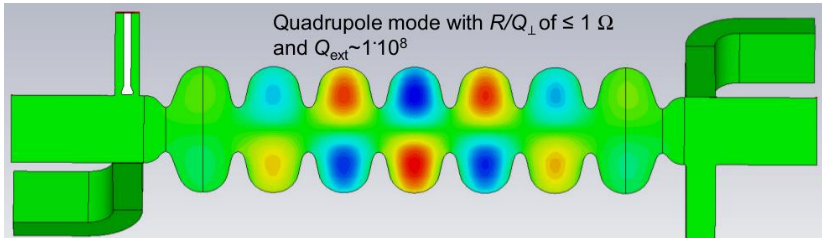


We are developing HOM damped cavities for B*ERL*inPro:



B. Riemann, T. Weis , TU-Dortmund
A. Neumann, J. Knobloch et al., HZB

Higher order mode damped cavities; capable to operate with 100 mA recirculating beam

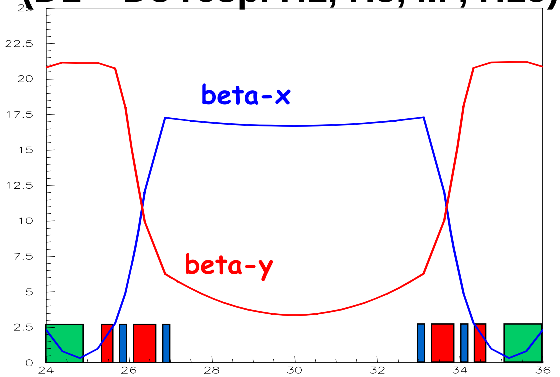


door opener for BESSY^{VSR}

how many cavities / straights do we need ?

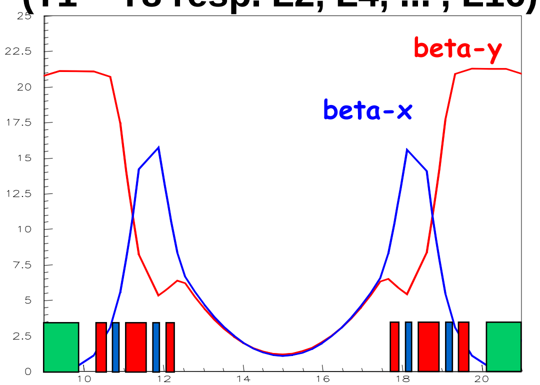
16 straight sections, thereof
8 x H-straight and 8 x L-straight, alternating
2 used for rf-section and injection; 14 available and used for IDs

H-straight (high beta_x)
(D1 – D8 resp. H1, H3, ... , H15)

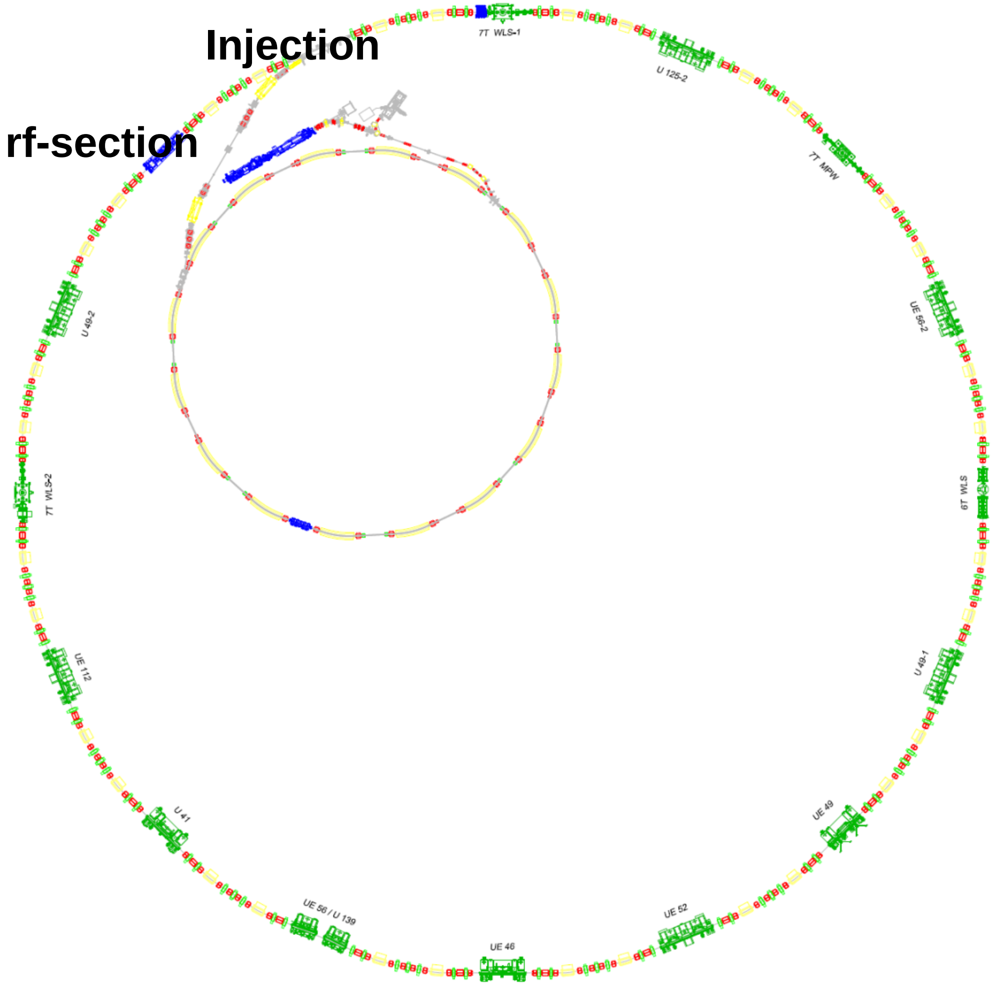


$l_H \sim 4.9$ m

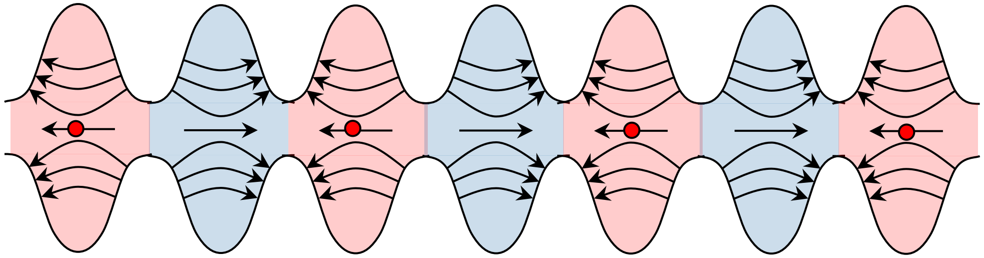
L-straight (low beta_x)
(T1 – T8 resp. L2, L4, ... , L16)



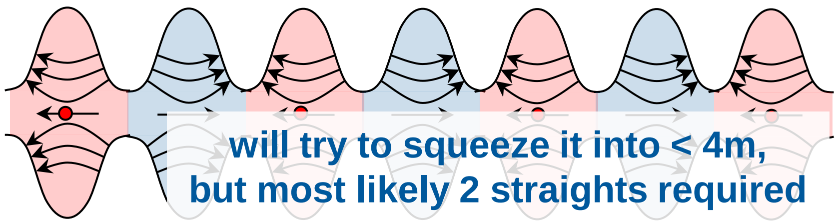
$l_L \sim 4.2$ m



1.5 GHz, λ = 20 cm, 7 cell → l_{eff} = 70cm



1.75 GHz, λ = 17.1 cm, 7 cell → l_{eff} = 60cm

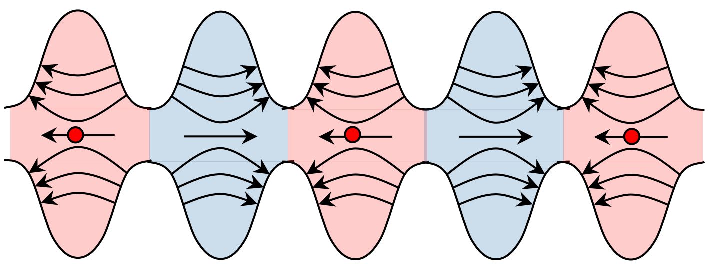


will try to squeeze it into < 4m,
but most likely 2 straights required

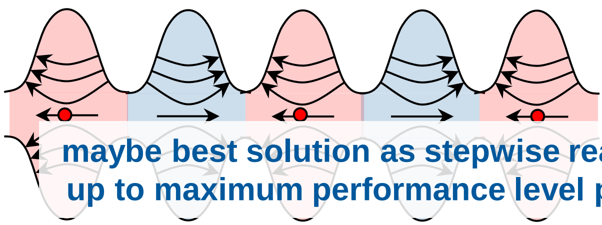
one cavity per frequency: $l_{tot.eff}$ = 1.3 m, V_{grad} = 37.5 MV / m required
→ easily fit in one straight; gradient impossible !

two cavities per frequency: $l_{tot.eff}$ = 2.6 m, V_{grad} = 17.9 MV / m required
→ hardly fit into one straight; gradient ambitious
(JLAB upgrade spec. @ 1.5GHz)

1.5 GHz, λ = 20 cm, 5 cell → l_{eff} = 50cm



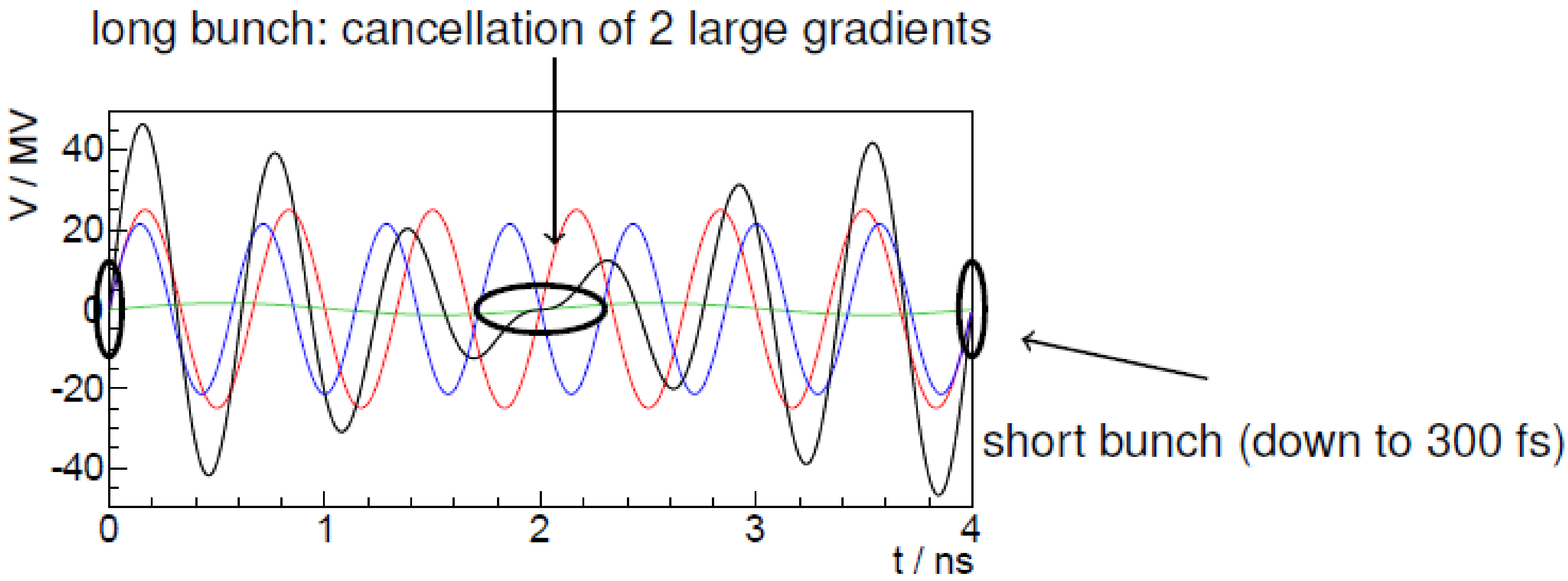
1.75 GHz, λ = 17.1 cm, 5 cell → l_{eff} = 42.8cm



maybe best solution as stepwise realisation
up to maximum performance level possible

three cavities per frequency: $l_{tot.eff}$ = 2.79 m, V_{grad} = 16.6 MV / m required
→ hardly fit into one straight; gradient possible

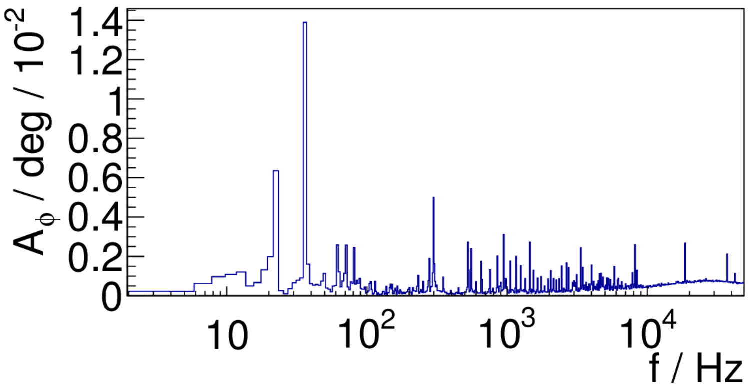
two cavities per frequency: $l_{tot.eff}$ = 1.86 m, V_{grad} = 25 MV / m required
→ could fit into one straight; gradient very challenging



amplitude and phase jitter studies necessary!
expect, that long bunches are most sensitive!

jitter studies – results

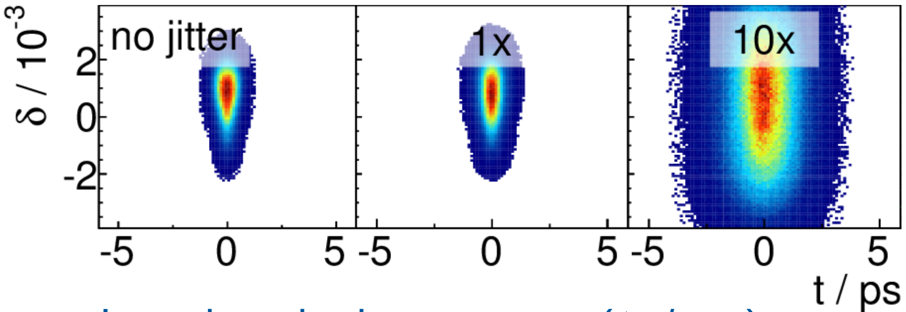
typical phase jitter A_Φ
(HZB measurements of TESLA cavity)



power spectrum of phase jitter A_Φ

(A. Neumann et al., SRF 2011, Chicago, USA, p.262)

simulations with *'elegant'*
300 fs bunches with phase jitter:



long. bunch phase space ($\Delta p/p$, t)

- bunch length blows up if jitter is unrealistic large

Results *

simulation w/o jitter	0.33 ps	1.0 ps	10 ps
simulation incl. expected jitter	0.34 ps	1.0 ps	13 ps
jitter $\times$10	1.0 ps	1.0 ps	31 ps

* all values are zero-current values

(M. Ruprecht et al., IPAC 2013, Shanghai, China, p. 2038)

High-gradient cavities ought to be:

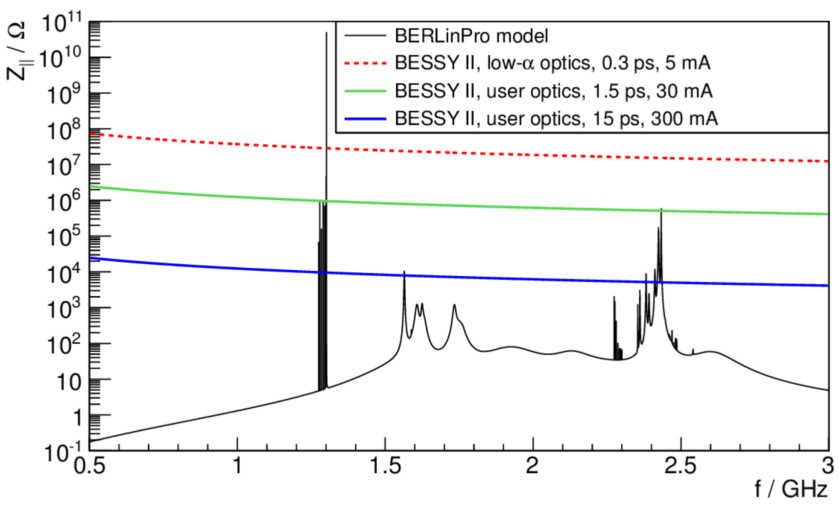
- superconducting
- multi-cell
- high frequency

⇨ unavoidable: higher order cavity modes (HOMs) affecting beam stability

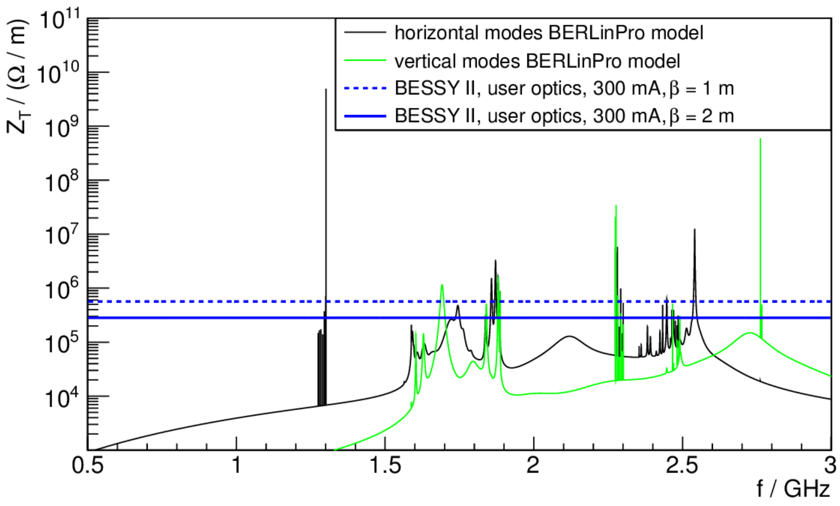
HOMs excite coupled bunch instabilities (CBIs): coherent bunch oscillations in time and energy

Impedance of B*ERL*inPro cavity model + BESSY^{VSR} CBI threshold:

(B. Riemann, TU-Dortmund) **(M. Ruprecht, HZB)**



longitudinal stability diagram



transverse stability diagram

Coupled bunch instabilities and counter measures

- decrease growth rate of oscillations:
  - change cavity design
  - adjust optics parameters (limited!)

- increase damping of oscillations:
  - Landau damping
  - bunch by bunch feedback

MLS-example:
coupled bunch instability threshold at I=10 mA
is shifted by feed back beyond 200 mA.

BESSY^{VSR} low-α is unaffected by CBIs !

Contribution of Touschek lifetime

Beam life time τ is sum of $$\frac{1}{\tau} = \frac{1}{\tau_G} + \frac{1}{\tau_T}$$

τ_G - gas scattering lifetime

τ_T - Touschek lifetime

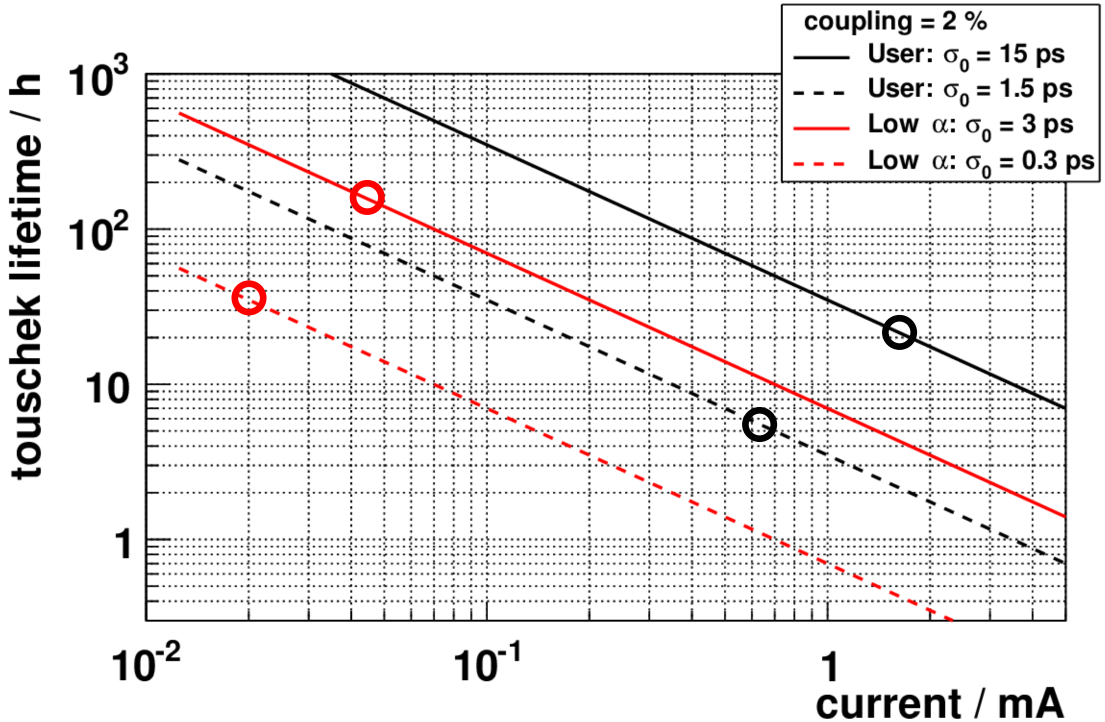
BESSY II : (multi bunch current limit 300 mA → 0.85 mA / bunch)

- **total beam lifetime ≈ 8 h**

BESSY^{VSR} :
Touschek lifetime contribution

O standard optic
- 15 ps, 1.7 mA - 21 h
- 1.5 ps, 0.8 mA - 4.5 h

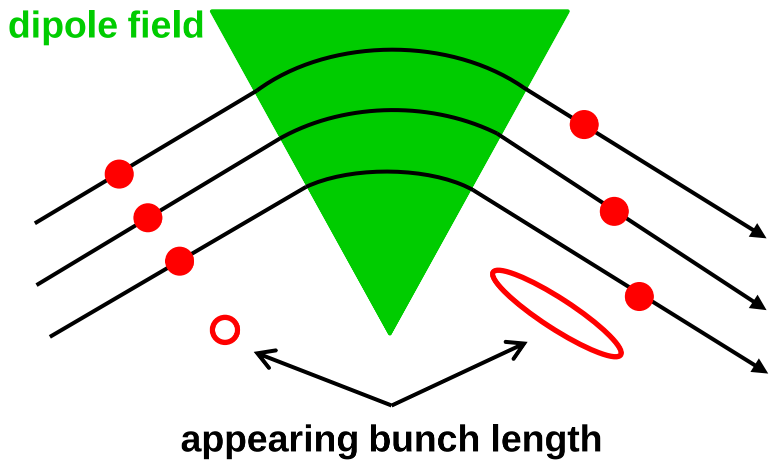
O low α optic (bursting limited)
- 3 ps, 0.043 mA - 150 h
- 0.3 ps, 0.02 mA - 35 h



P . Goslawski, HZB

Length limits for ultra short bunches

basic limit for ultra short bunches: horizontal - longitudinal coupling



The ultimate bunch length limit depends on observation point and applied machine optics

bunch length limits for BESSY^{VSR} low α optics:

- 200 fs inside undulators and wigglers
- 100 fs inside dipoles

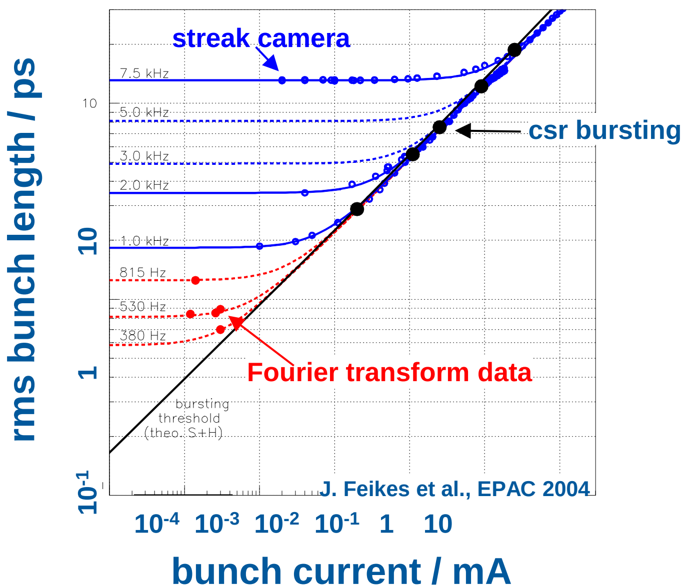
➢ 300 fs (rms) bunch length is a conservative assumption

- bursting limits multi bunch current to 3.5 mA in 300 fs (rms) bunches
- Touschek lifetime no problem because of low charge / current density

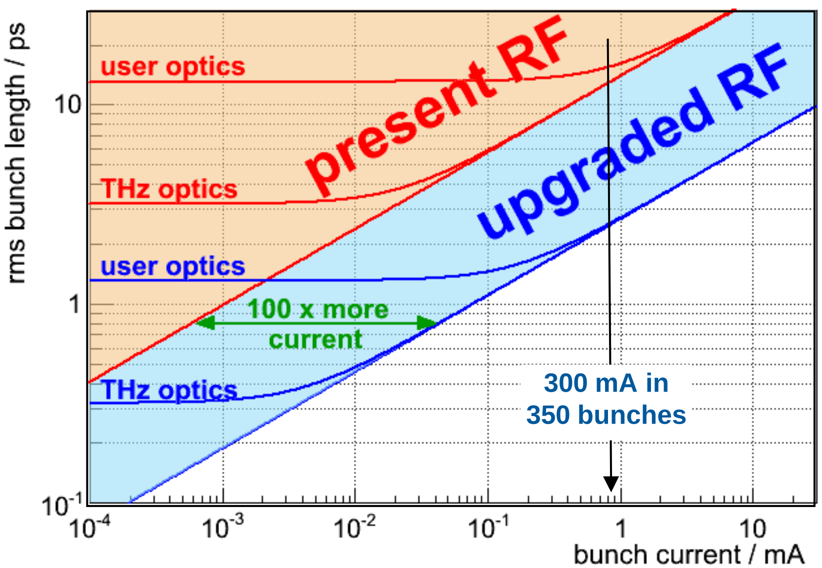
P . Goslawski, HZB

$I \sim \alpha$ and $I \sim V'$ for fixed σ $\rightarrow$ $\sigma \propto \sqrt{\alpha / V'}$

bunch length – current scaling
CSR bursting threshold $\sigma \sim I^{3/7}$



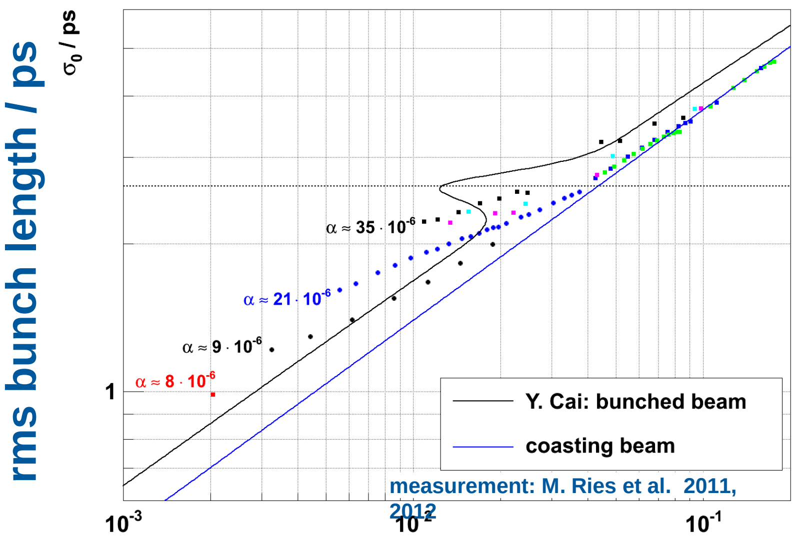
measurements BESSY II



schematic view

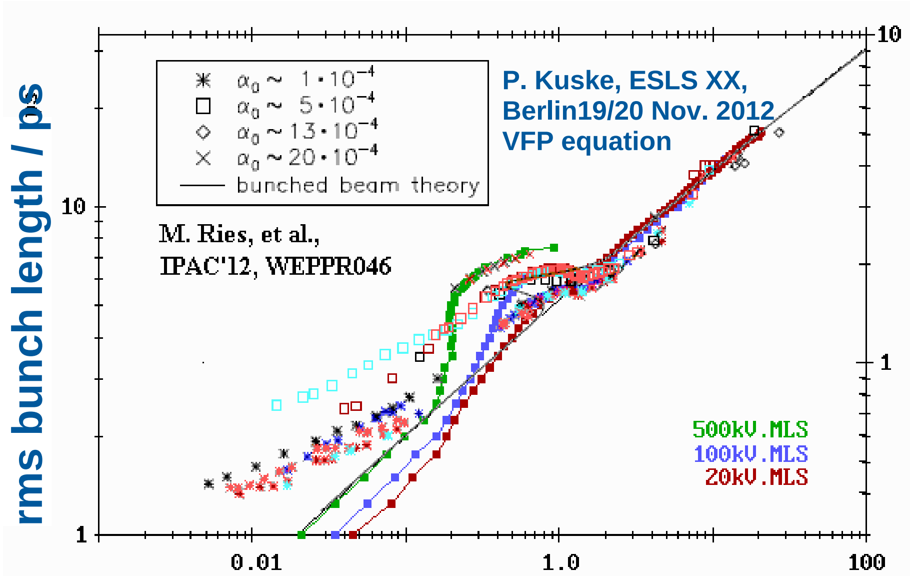
scaled bursting thresholds

BESSY II scaling
measured and simulated data



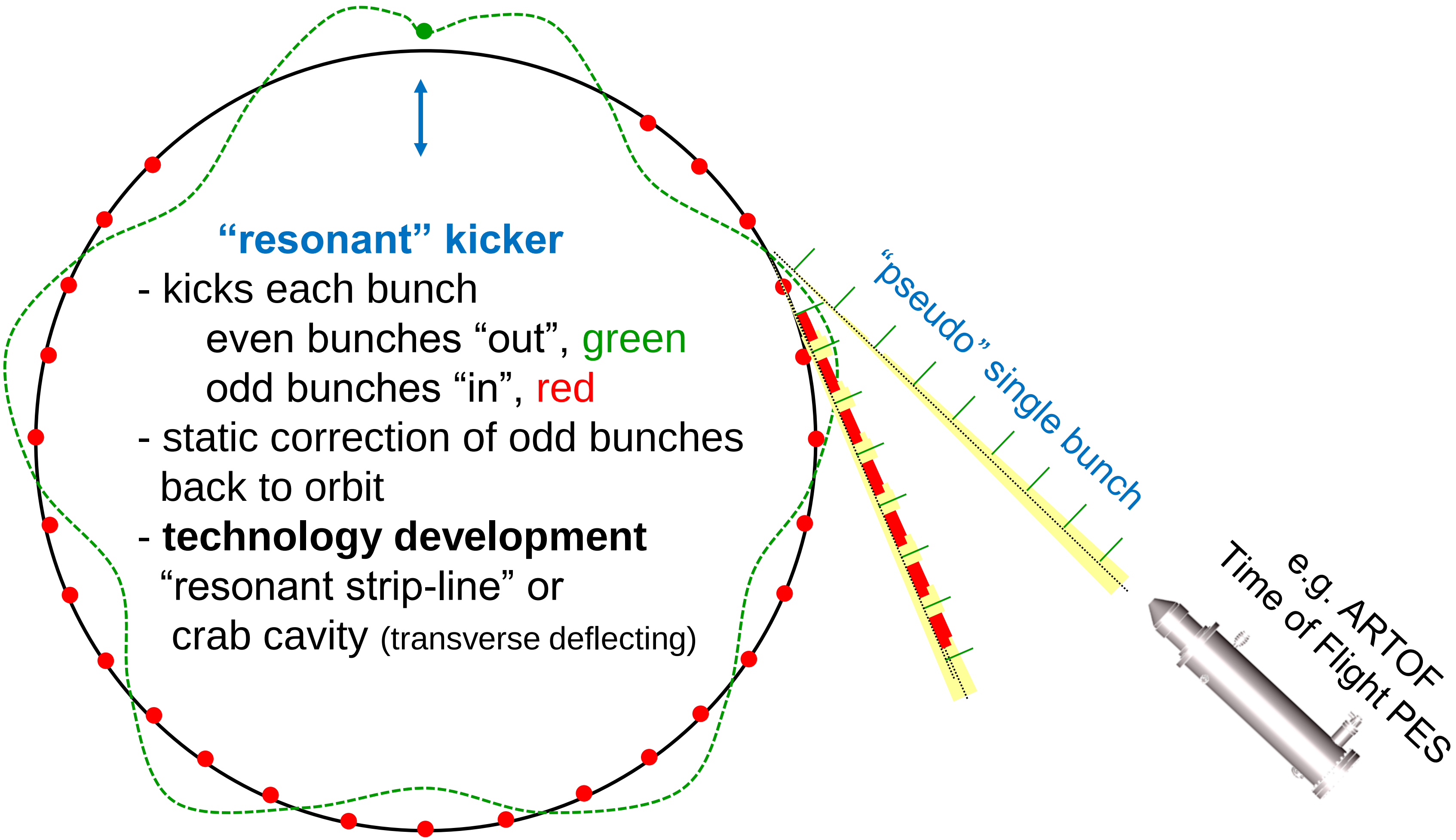
bunch current / rf-voltage in mA/kV

MLS scaling
measured and simulated data



bunch current / rf-voltage in mA/kV

uncertainty to scale threshold at ultra short bunches



“resonant” kicker

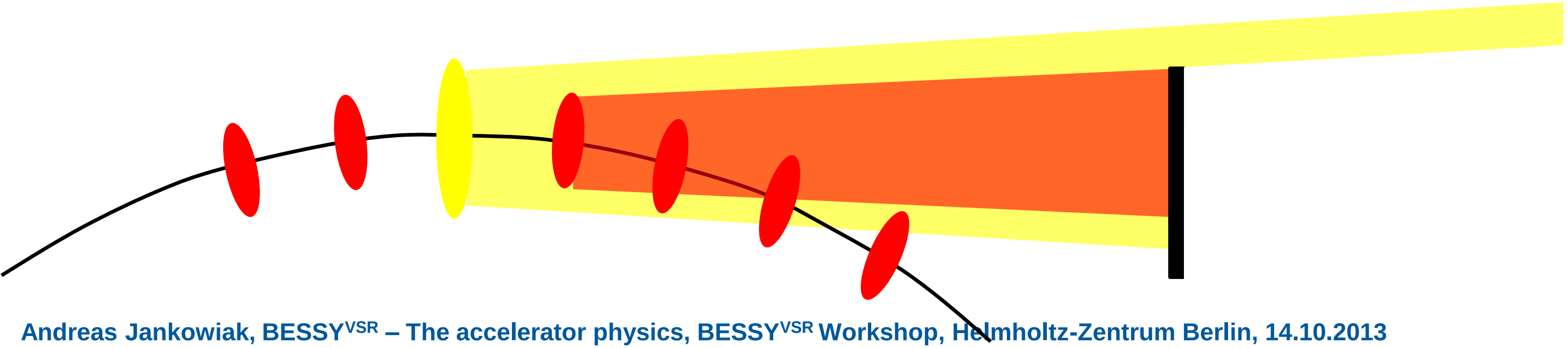
- kicks each bunch
  - even bunches “out”, green
  - odd bunches “in”, red
- static correction of odd bunches back to orbit
- **technology development**
  “resonant strip-line” or
  crab cavity (transverse deflecting)

resonant strip line kicker development is challenging (P. Kuske et al.)

clever, cost effective solution

(K. Holldack, P. Kuske, R. Müller, R. Ovsyannikov, A. Schälicke et al.)

exciting one single bunch horizontally which allows to separate 10^9 photons / s from multi-bunch batch with 10^4 suppression of background!



Summary

high current cw srf-technology necessary for B*ERL*inPro is enabling technology for new concepts for short pulse storage rings → BESSY^{VSR}

BESSY^{VSR} is a concept for a substantial up-grade for 3rd generation light sources
→ combination of standard user operation with short (ps and shorter) pulses

physics design study under way (2013 – 2014)
main challenge: integration of multi-cell sc cavities in storage ring

BESSY^{VSR} is fully supported by management; application to Helmholtz will be prepared; beam tests / finalisation / operation 2017/2018/2019

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