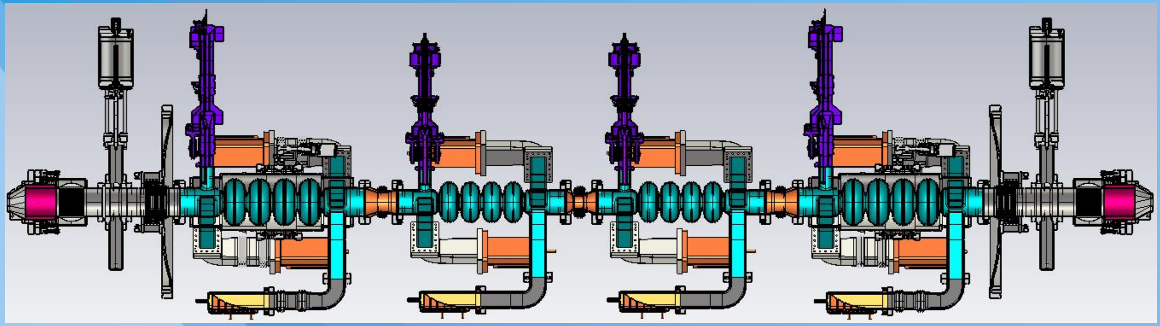
CW LLRF for the BESSY-II Variable Pulse Length Upgrade

Pablo Echevarria, on behalf of LLRF team



LLRF workshop 2017
Barcelona
16-19 Oct. 2017

Outline

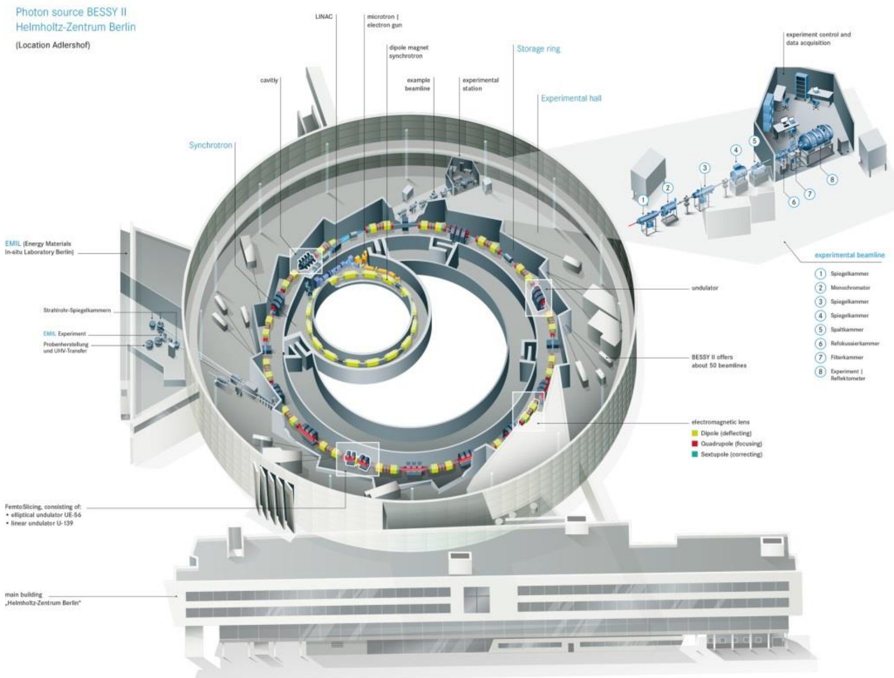
- The BESSY VSR concept
- LLRF challenges
- mTCA.4 single cavity control
- Synergy with bERLinPro

BESSY-II

- The SR BESSY II is a 1.7 GeV synchrotron radiation source operating for 20 years in Berlin

- BESSY II emits extremely brilliant photon pulses ranging from the long wave terahertz region to hard X rays
- Pioneer in offering low α operation with a comunity of users performing dynamic measurements in „functional materials“

In order to remain competitive among the international synchrotron sources a superconducting upgrade is undergoing



Slides courtesy of A. Velez

Upgrading BESSY-II

Third generation light sources move in the direction of minimizing beam emmitance

ESRF (Grenoble), Spring-8 (Japan), MAX IV (Sweden) ⟹ **DLSR by multi-bend achromats (MBA)**

⇓

Long pulses needed ⟸ Lifetime problems (radiation protection) ⟸

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ESRF (Grenoble), Spring-8 (Japan), MAX IV (Sweden) ⟹ **DLSR by multi-bend achromats (MBA)**

⇓

Long pulses needed ⟸ Lifetime problems (radiation protection) ⟸

BUT ...

Short pulse experiments represent one of the strong fields at HZB (low-Alpha, femtoslicing).

Such a pitty to lose!

A complementary approach to DLSRs

BESSY VSR

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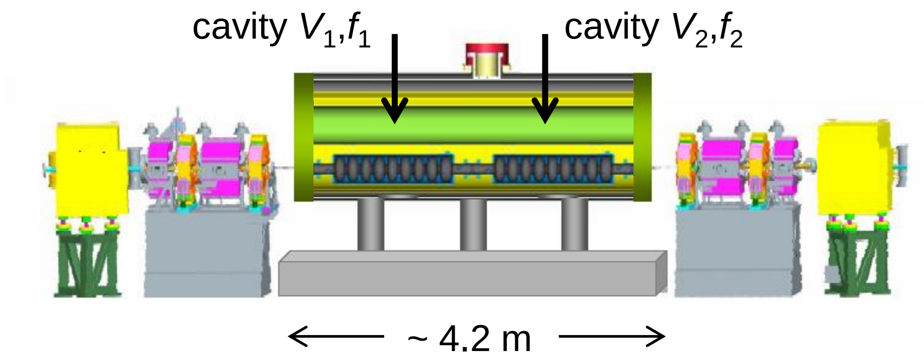
BESSY II , SC Upgrade



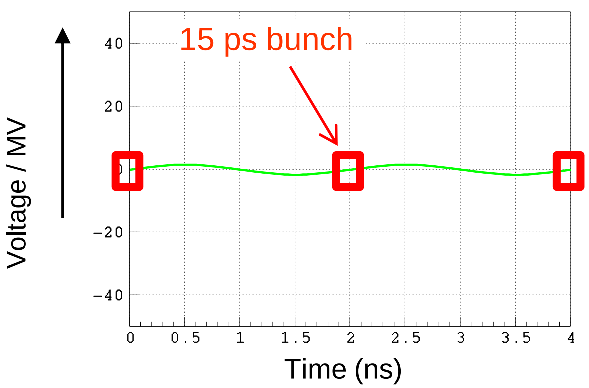
G.Wüstefeld et al.
„Simultaneous long and short electron bunches in the BESSY II storage ring“ IPAC2011

- 1.5GHz and 1.75GHz ---- RF beating
- Odd (voltage cancelation, 15 ps bunches)
- Even (voltage addition, long.focussing, 1.7 ps)

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

← **Machine optics** (α)
← **Hardware (RF cavities)** ($\dot{V}_{rf}$)

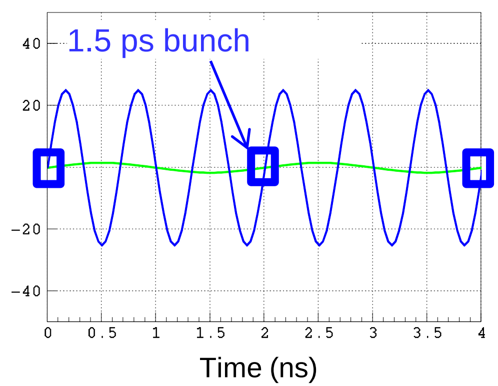
Present



Voltage: 1.5 MV @ 0.5 GHz

$$\dot{V}\,\mu\,V'\;\; f_{rf} = 0.75\ \mathrm{MV}\ '\ \ \mathrm{GHz}$$

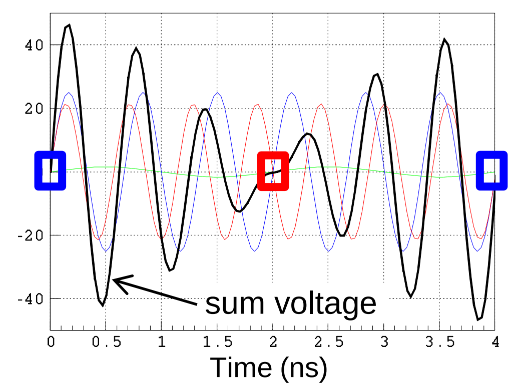
Phase I



Voltage: 20 MV @ 1.5 GHz

$$\dot{V} \propto V \times f_{rf} = 30\ \mathrm{MV} \times \mathrm{GHz}$$

Phase II



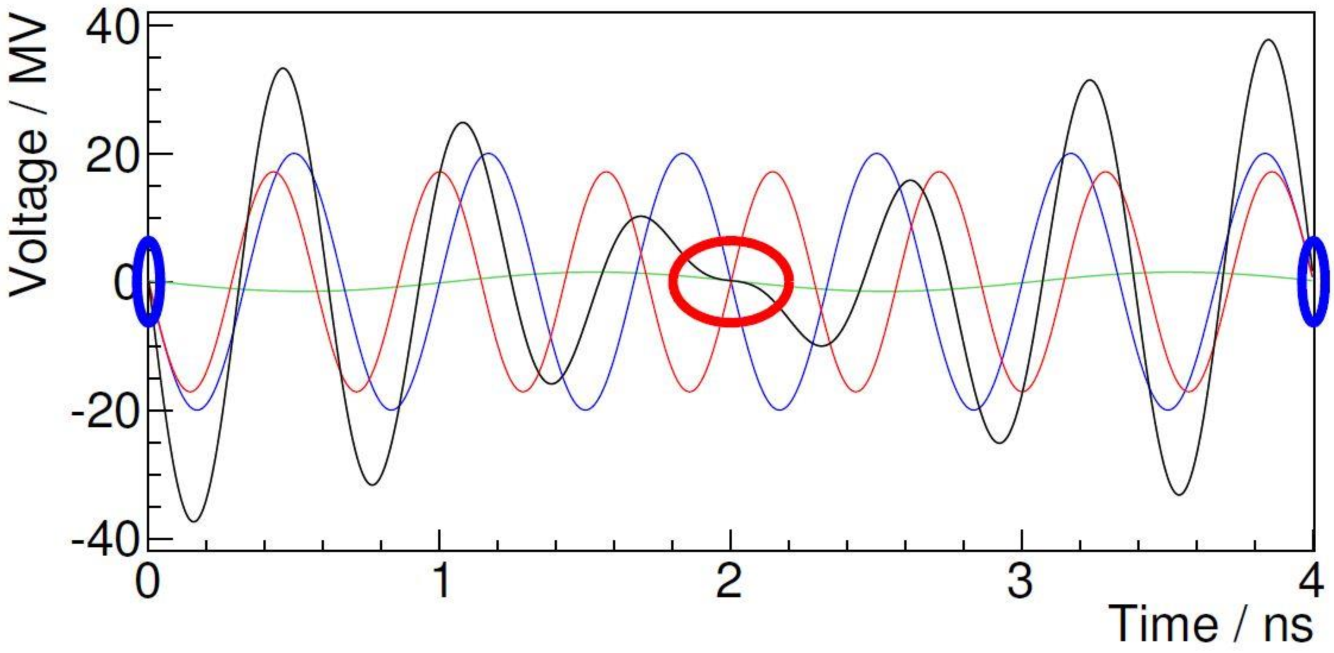
Voltage: 20 MV @ 1.5 GHz
+ 17.1 MV @ 1.75 GHz

$$\dot{V} \propto V \times f_{rf} = 60\ \mathrm{MV} \times \mathrm{GHz}$$

Slides courtesy of A. Velez

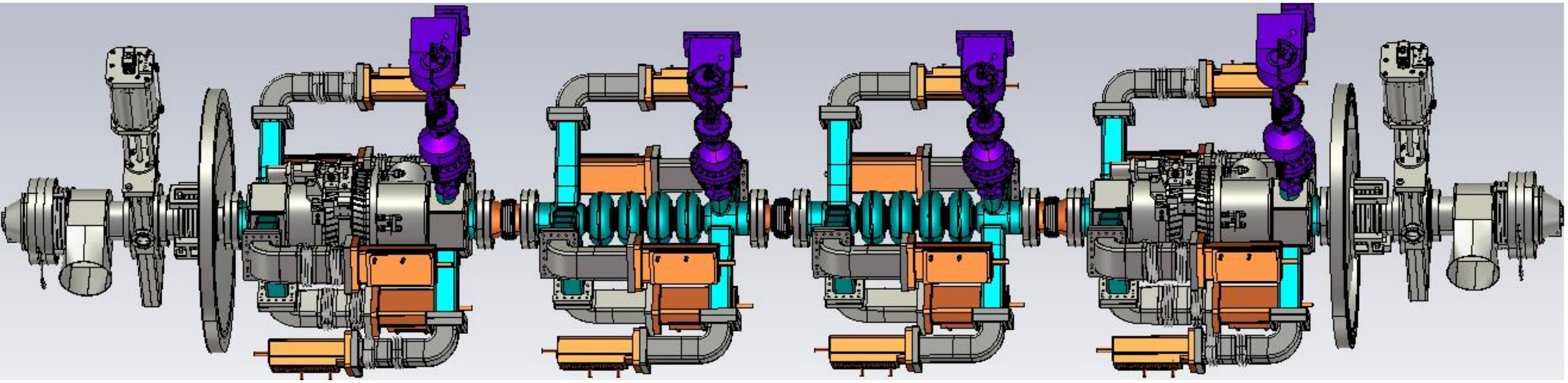
BESSY-VSR's LLRF challenges

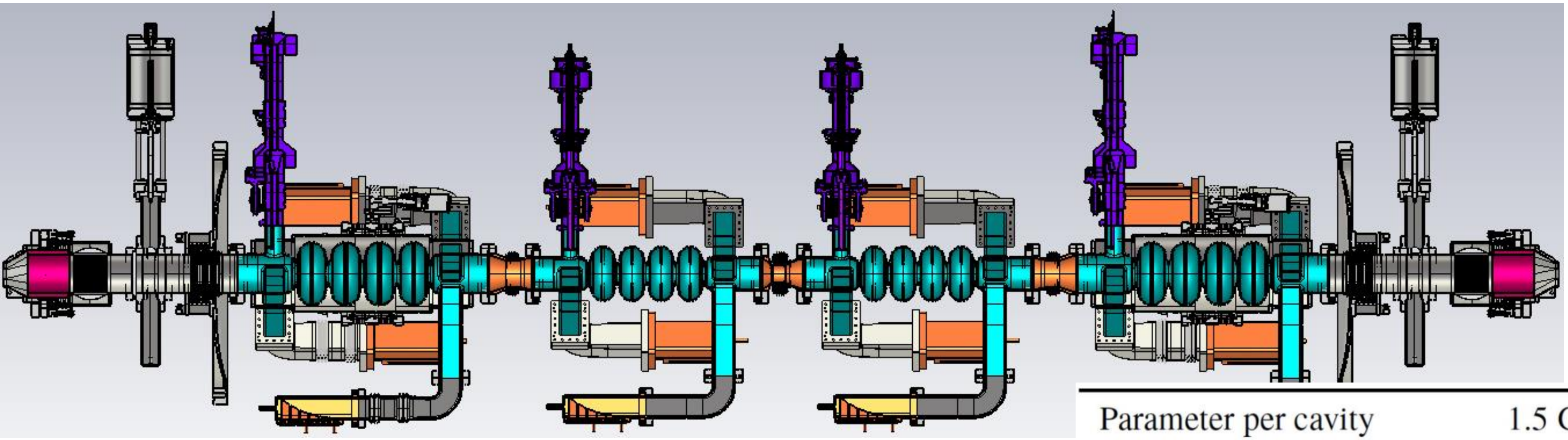
- BESSY-VSR: two superposing voltages at 1,5GHz and 1,75 GHz → Beating of voltage to create RF buckets for long and short bunches
- Zero-crossing operation for focussing/defocussing



Long bunches lay in opposite slopes→ cancellation two large voltages
→ any deviation from nominal is magnified

BESSY-VSR's cavities



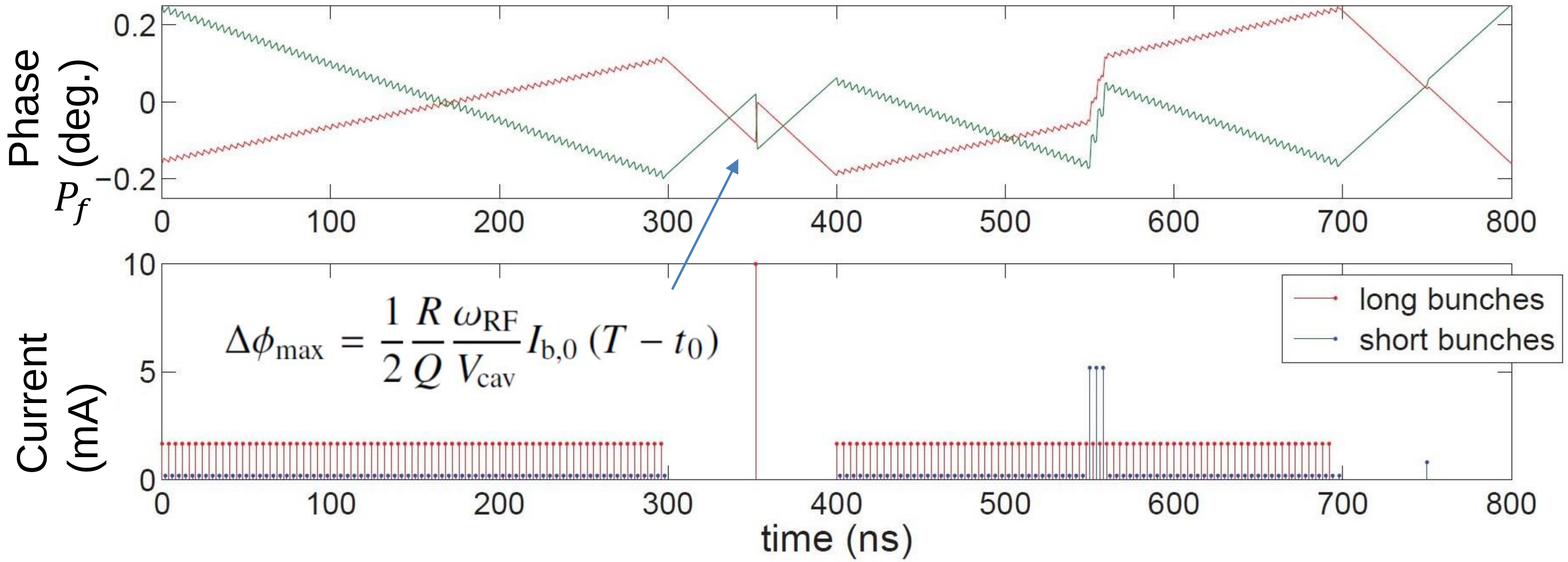


Parameter per cavity	1.5 GHz	1.75 GHz
Voltage (MV)	10	8.7
E_{acc} (MV/m)	20.0	20.0
Q_L	5×10^7	4.3×10^7
R/Q TM_{010}-$\pi(\Omega)$	500	500
ϕ_{acc} (degree)	90	-90
Δf for beam-loading (kHz)	-11.25	15.3
Average $P_f(kW)$	1.49	1.0
Voltage 0.5 GHz	1.5 MV	

- Beam current induces a voltage in the cavity → **Beam loading**

$$V_{beam} = Z_{cav} \cdot I_{beam}$$

- At zero-crossing beam loading is mainly a **phase jump** of the cavity voltage.
- Non uniform bunch train induces a **transient beam loading**



Different zero crossing for each bunch!

Strong phase transient + variation of the focusing gradient → unwanted shorter bunches + lifetime

BESSY-VSR's LLRF challenges

- Low beam-loading allow operation at high Q_L → narrow bandwidth (order of 10s Hz).

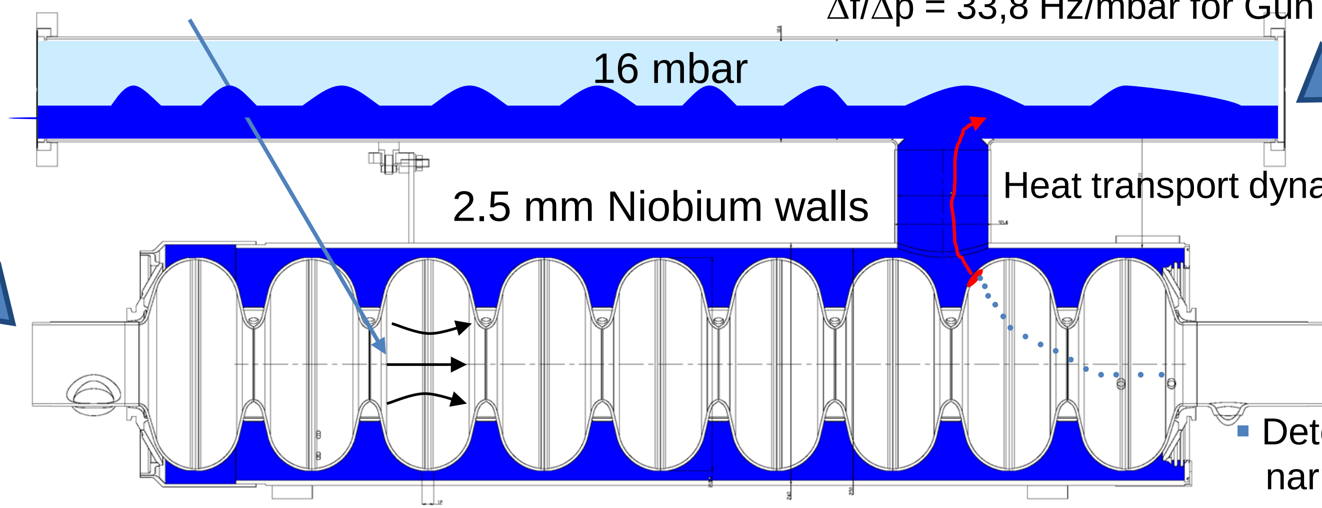
BUT: Field stability is strongly influenced by time varying detuning:

- Helium pressure fluctuations.
- Heat transport dynamics
- Deterministic narrow band sources: vacuum pumps,…
- Stochastic background noise

+ Lorentz force detuning → Ponderomotive instabilities

- Field amplitude variation:
  Dynamic Lorentz force, $\Delta f/\Delta E_{acc}^2 = 1\text{Hz}/(\text{MV/m})^2$

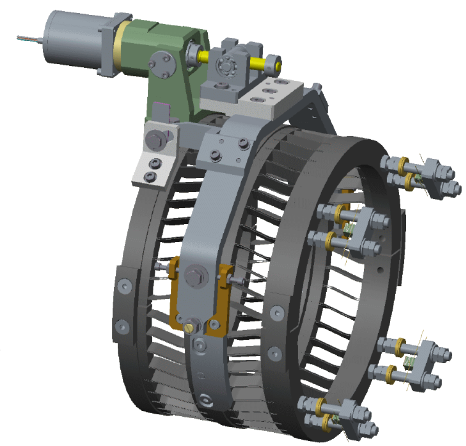
- Helium pressure fluctuations
  $\Delta f/\Delta p$ = 33,8 Hz/mbar for Gun 1.0



- Stochastic background noise

- Deterministic, narrow-band sources: Vacuum pumps

Δl = 1 nm ←→ Δf = 0.6 Hz ←→ $\Delta\Phi$ = 1,14° for BESSY-VSR Cav.



Blade tuner: motor + piezos

Several detuning control strategies:

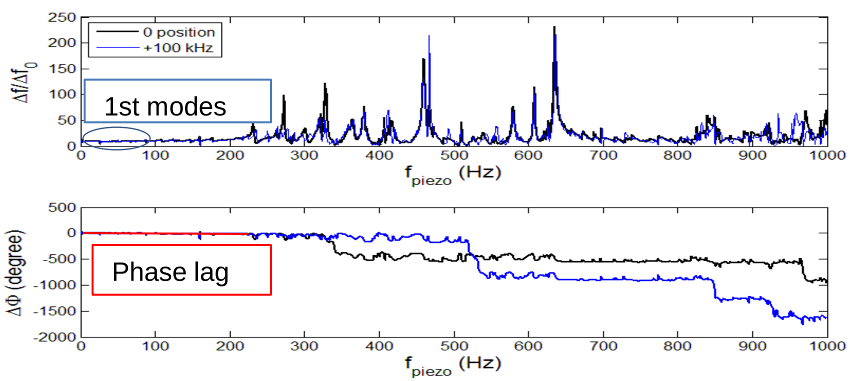
- Classical PID +
- FIR filter + LMS learning algorithm.
- Main vibration tones cancellation
- **Kalman filtering + adaptive control**

A. Neumann, PRST 2010

R. Rybaniec, Real Time Conf. 2016, DESY

A. Ushakov, IPAC 2017

“Iterative process that uses a set of equations and consecutive data inputs to estimate the true value of the object being measured, when the measured values contain unpredicted or random error, uncertainty, noise or variation or when the physical description is not complete”



Measured mechanical response

Poster P-45

Discretized state-space model

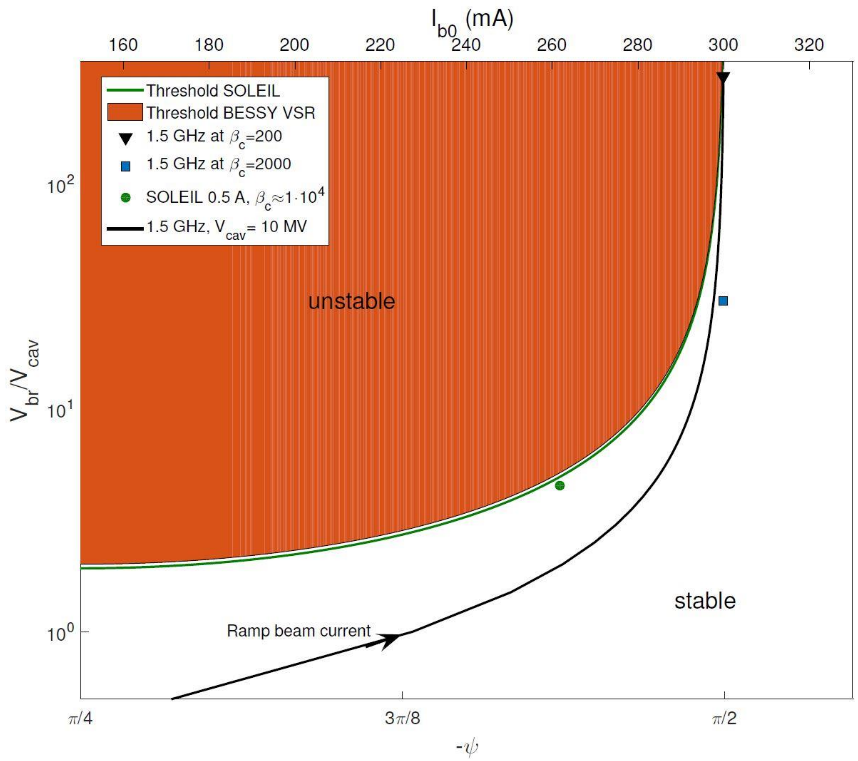
$$\begin{pmatrix}x_1\\x_2\end{pmatrix}_{n+1} = \begin{pmatrix}1 & \Delta t\\ -\omega_m^2\Delta t & 1-\frac{\omega_m}{Q}\Delta t\end{pmatrix}\begin{pmatrix}x_1\\x_2\end{pmatrix}_n + \begin{pmatrix}0\\ \pm k2\pi\cdot\omega_m^2\end{pmatrix}E_{acc}^2(t)$$

BESSY-VSR's LLRF challenges

Robinson instabilities:
Interaction of the beam's synchrotron sidebands with the cavity impedance

- AC instability: $\psi < 0$ with $\tan\psi = {}^{2Q_L\Delta\omega}/_{\omega_r}$
- DC instability or „high intensity limit": $\frac{V_{br}}{V_{cav}} < \frac{\cos\varphi_{acc}}{\sin\psi\cos\psi}$

→ Not fulfilled by 1,75GHz cavities



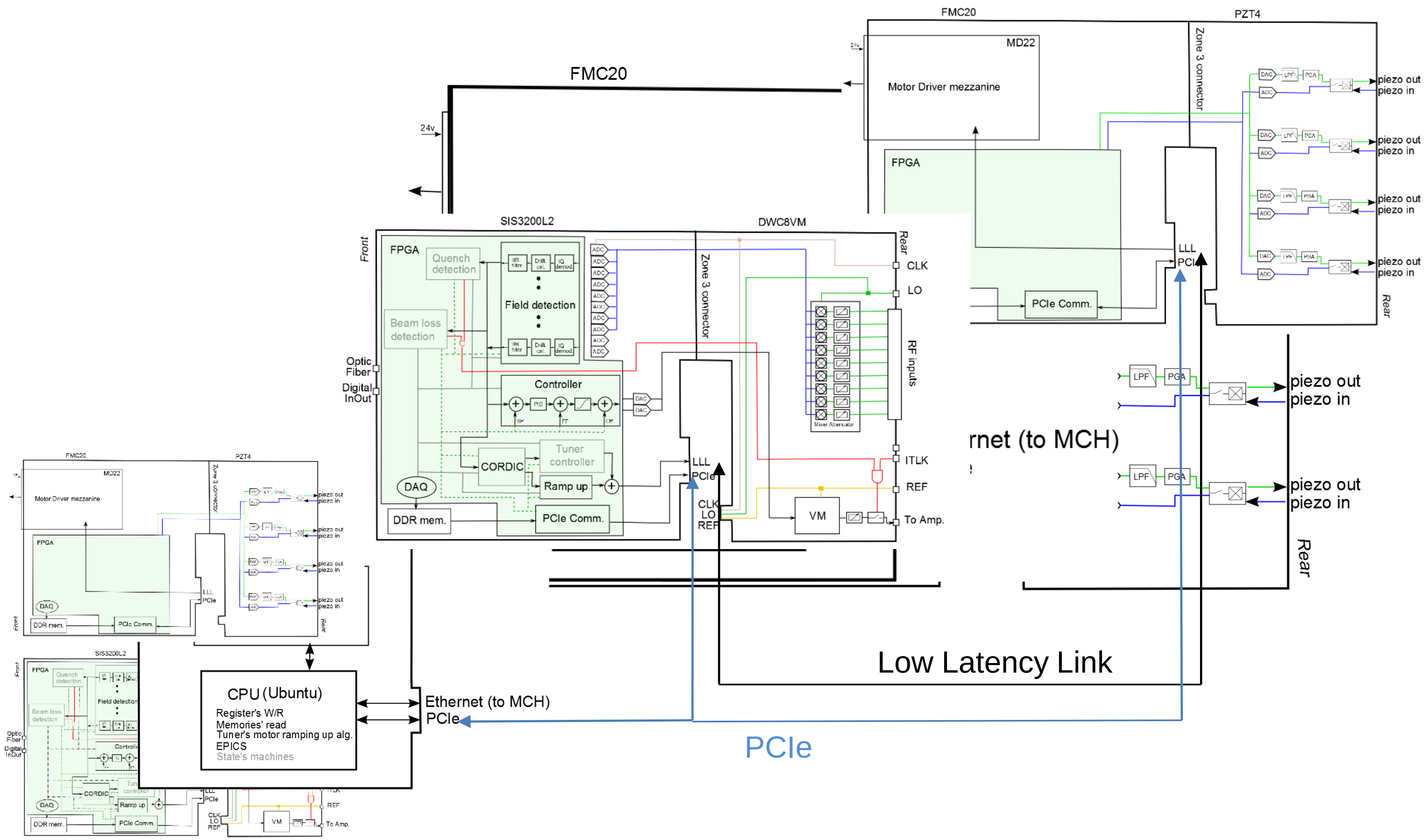
Threshold limit of beam current of the 1,5GHz cavity

- Combined system of all frequencies is labile
- Stability threshold scales with 1+*G*

Poster P-44

mTCA.4 single cavity control

- 1 RF amplifier per cavity → no Vector Sum needed
- Used in EXFEL's gun and ELBE
- Around 600ns of latency (2us in EXFEL's linac setup)



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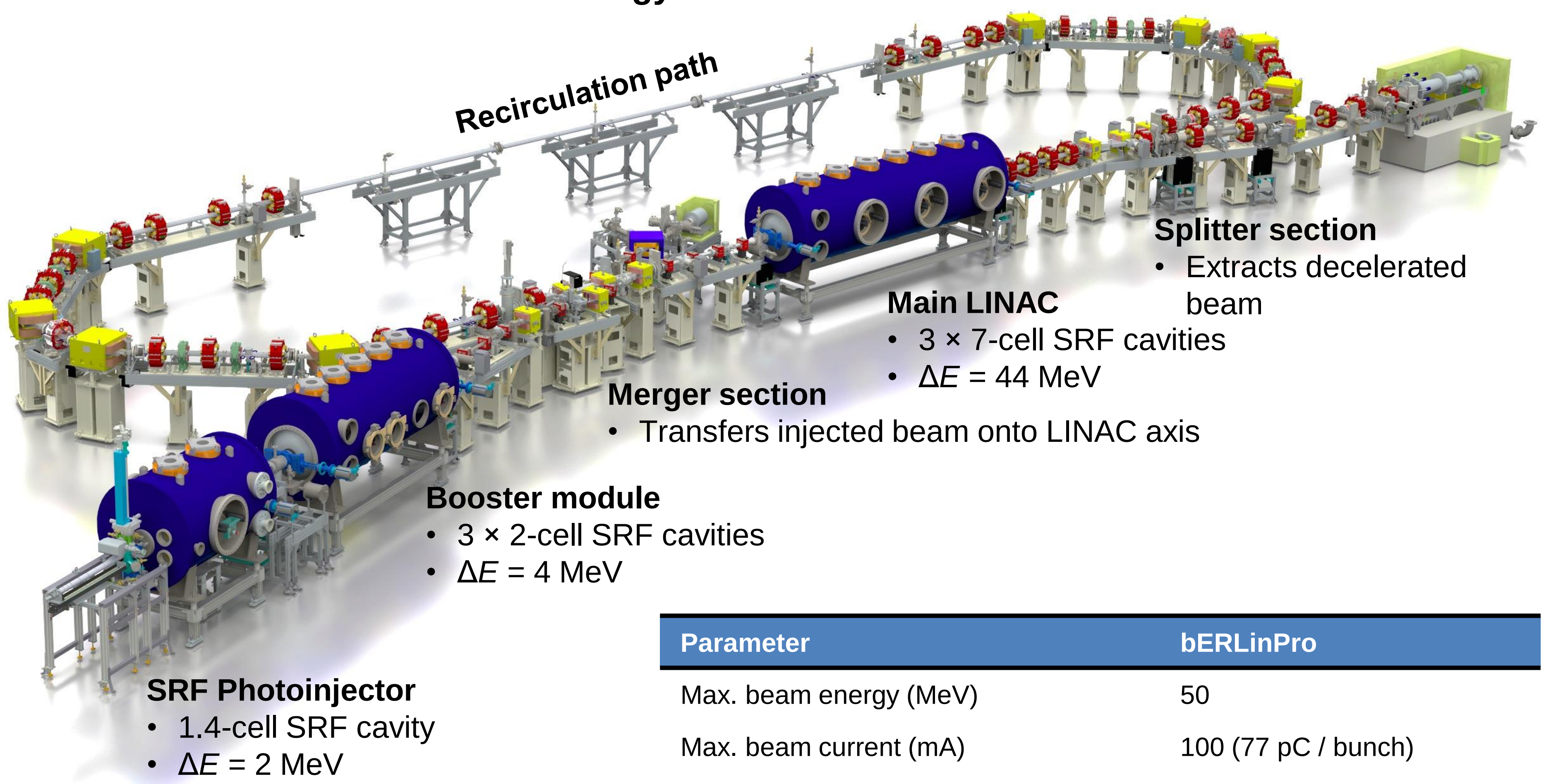
bERLinPro = Berlin Energy Recovery Linac Project

100 mA / low emittance ERL technology demonstrator

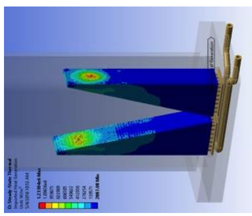
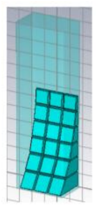
10/2015



Parameter	bERLinPro
Max. beam energy (MeV)	50
Max. beam current (mA)	100 (77 pC / bunch)
Frequency (GHz)	1.3
Normalized emittance (mm mrad)	1 (< 0.5 in simulations)
Bunch length (ps)	< 2 ps (100 fs)
Beam losses	<< 10^{-5} @ 100 mA

BESSY VSR / bERLinPro synergies

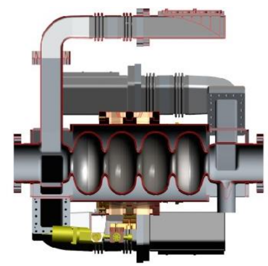
- Joint purchase of all solid state transmitters (SSA, 1.3/1.5/1.75 GHz)
  (call for tender end of 2017)
- One big cavity contract (1.3/1.5/1.75 GHz)
  (call for tender end of 2017)
- Joint development of HOM loads (together with JLAB)

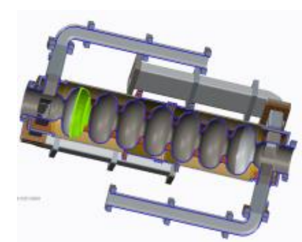
- Cavity development and prototyping

1.5 GHz VSR single cell with waveguide end group
manufactured by RI, tested in small VTA
15 MV/m, no multi-pacting

VSR 1.5 GHz, 4 cell



bPro 1.3 GHz, 7 cell



High similarities with BESSY-VSR in terms of LLRF

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Some similarities with BESSY-VSR:

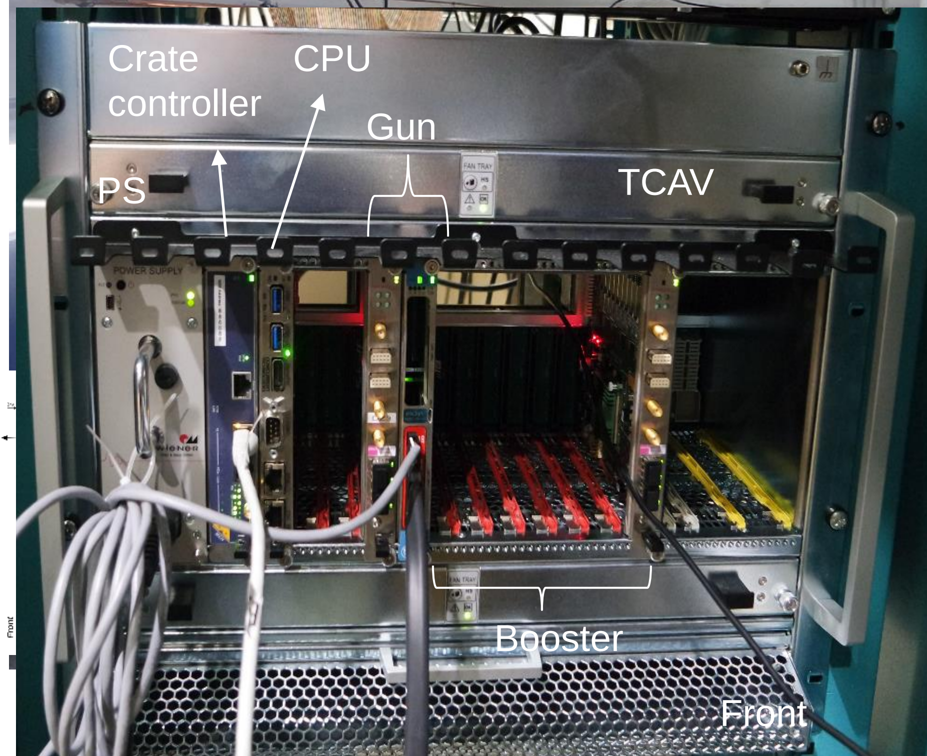
- Linac cavities with high-Q_L → microphonics compensation mandatory
- One booster cavity at zero-crossing → detuning control: V_{cav}, I_{b0}

Some new issues:

- Gun and Booster:
  - High CW power level (230KW) + dual coupler operation
  - Rather low-Q_L
  - Beam loading
- Linac:
  - Detection of beam loss →shut off laser to prevent melting of vacuum chamber → *fastest expected melting time about 10μs*
  - Non-perfect recovery: the beam β is not perfectly matched for the first cavity (~1.5° deviation)
- Gun:
  - Higher Lorentz Force detuning and helium pressure to detuning coefficients→ Ramp-up algorithm mandatory

GunLab

GunLab to test the Gun cavity



bERLinPro's building

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view north-west

THANKS FOR YOUR ATTENTION!

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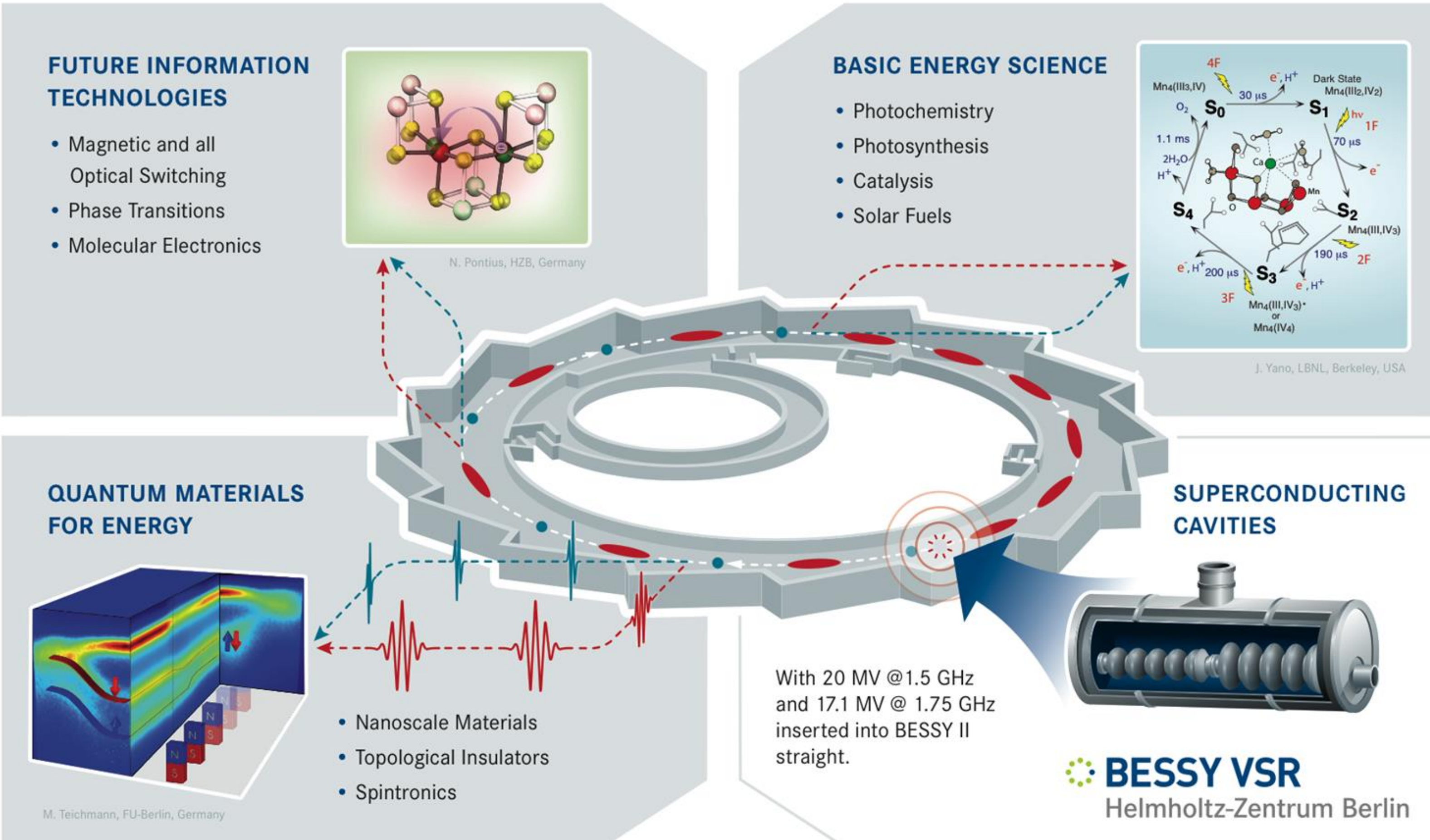

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