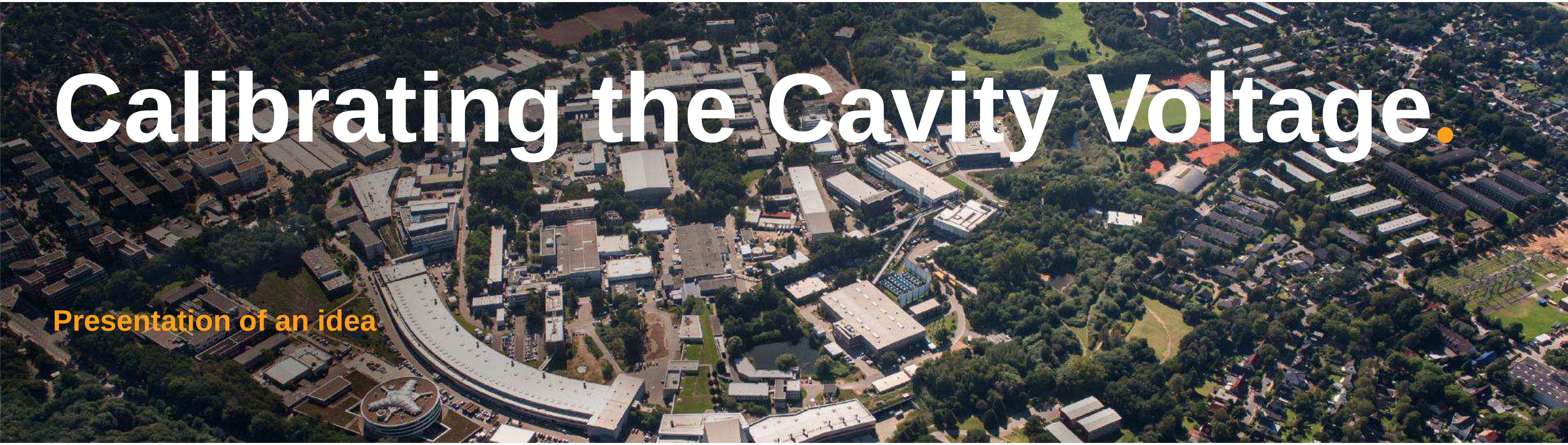
Calibrating the Cavity Voltage.

Presentation of an idea



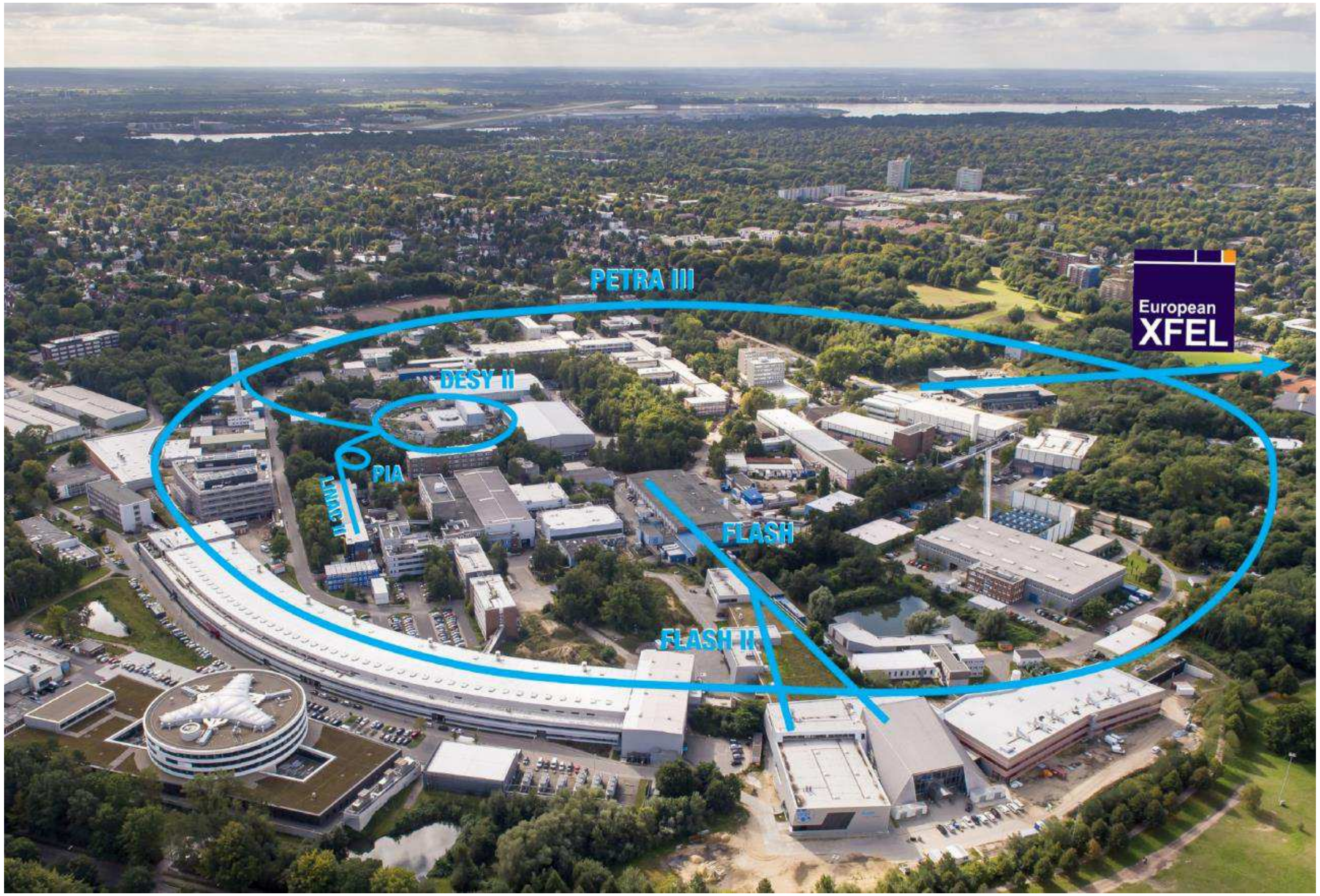
Stefan Wilke, DESY MHF-e
21st ESLS rf meeting Kraków, 15th/16th nov 2017

HELMHOLTZ ASSOCIATION

DESY

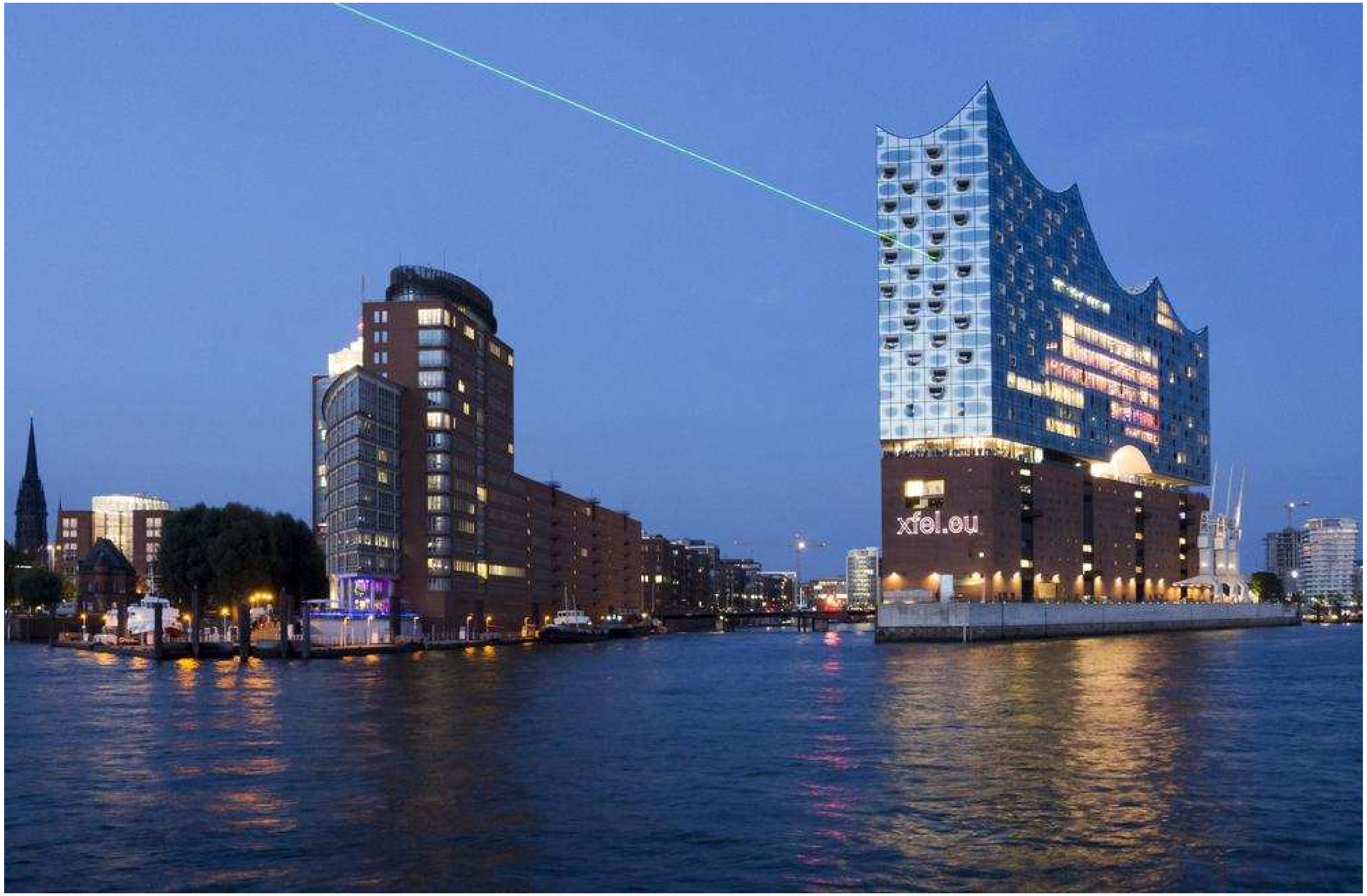
Accelerators at DESY.

linear and circular



Accelerators at DESY.

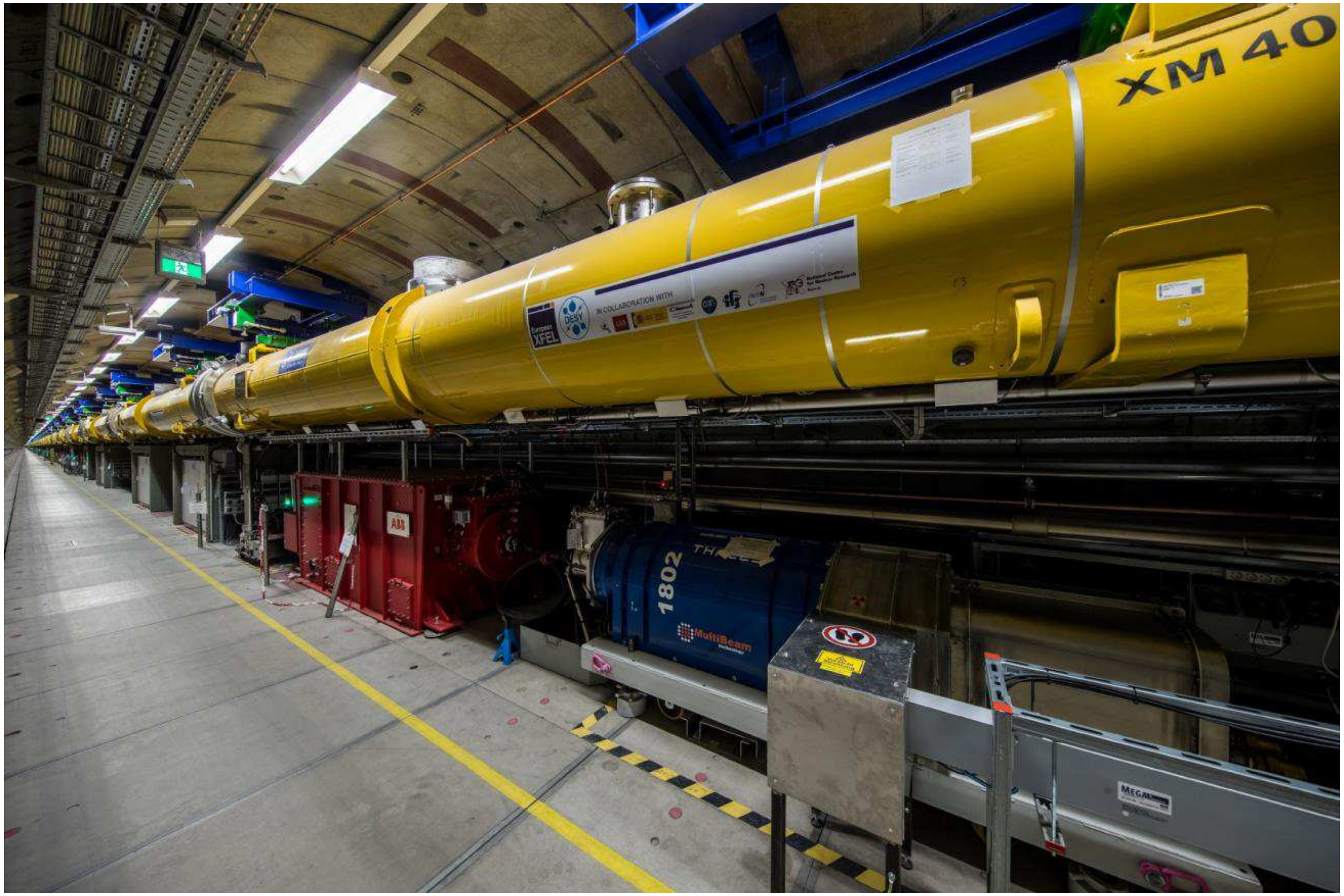
linear and circular



Greetings from
Elbphilharmonie
across the
city of Hamburg to
XFEL in august 2017

Accelerators at DESY.

linear and circular



XFEL

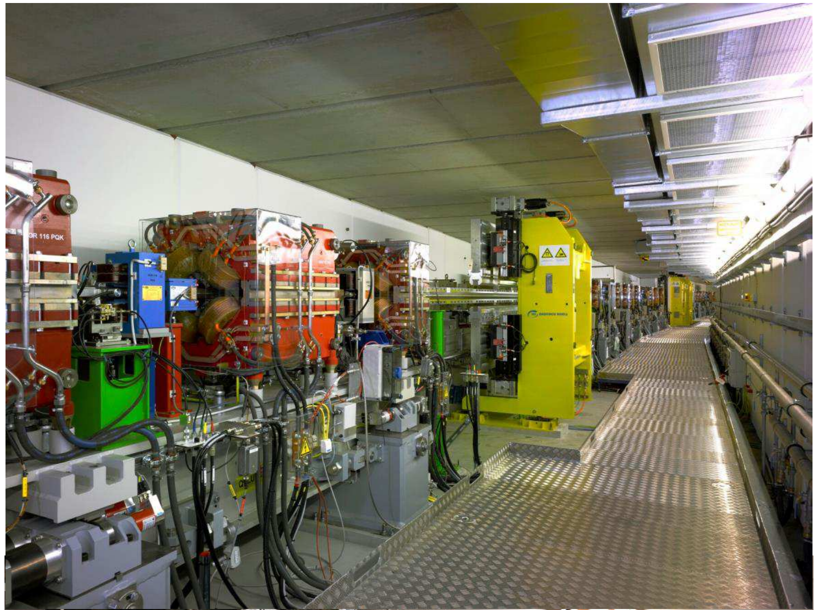
- european project
  11 (12) countries
- ca. 1.22 billion EUR
  (D: 58%, RU: 27%) since 2009
- 3.4 km tunnel length
- 1.3 GHz pulsed rf
  24 klystrons
- 768 sc 9 cell niob cavities
  in 96 cryo modules
  (1.7 km accelerator)
- energy goal: 17.5 GeV
  (now: 14.3 GeV)
- up to 27 000 flashes
  per second
- wavelengths: 4.7 to
  0.05 nm

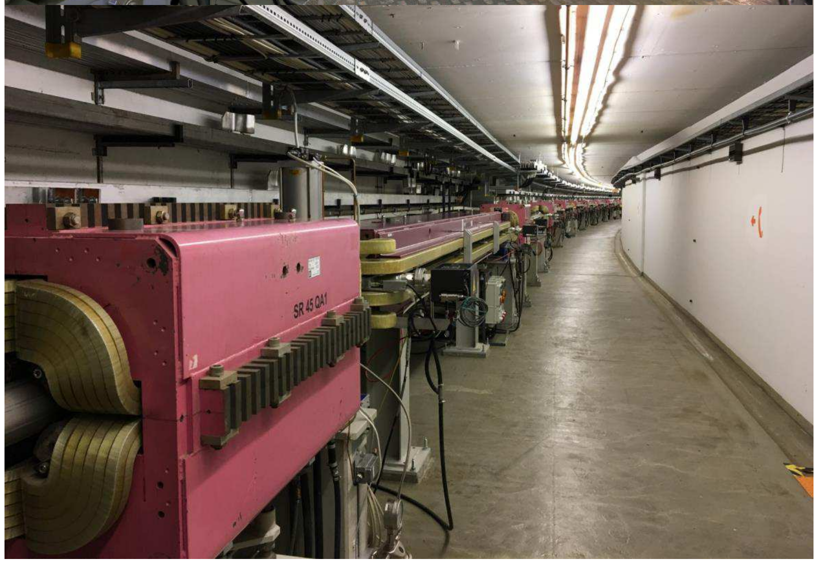
Accelerators at DESY.

PETRA III at DESY, Hamburg

Main parameters:

- l = 2304 m
- beam energy = 6.08 GeV
- beam current: 100 mA (4.8 E12 e^{-}), Top Up
- emittance (hor.) = 1 nmrad
- energy loss: ca. 5 MeV per turn
  (ca. 65 % from damping wigglers)
- 20 undulators
- fill pattern:
  - timing mode :
    - 40 bunches, 192 ns gap, 2.50 mA per bunch
    - 60 bunches, 128 ns gap, 1.66 mA per bunch
  - continuous mode:
    - 480 bunches, 16 ns gap, 0.21 mA per bunch
    - 960 bunches, 8 ns gap, 0.10 mA per bunch
- availability: ca. 97 % (2017), MTBF: ca. 40 h (2017)



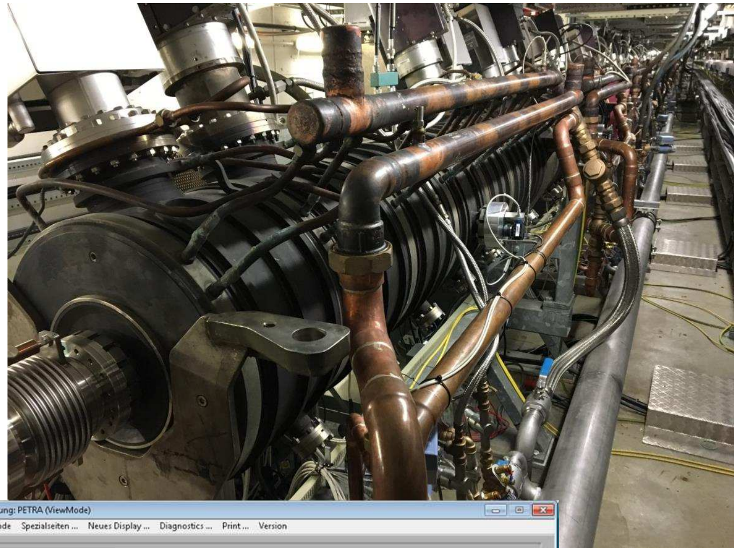


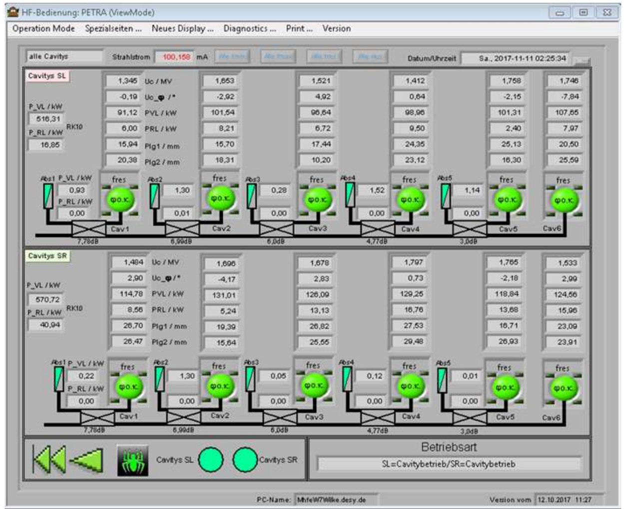
rf system at PETRA III.

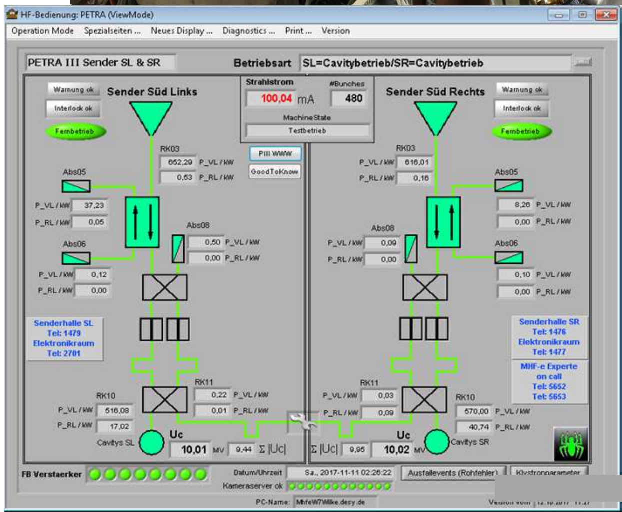
PETRA III at DESY, Hamburg

rf parameters

- frequency: 499.664 MHz
- harmonic number: 3840
- 20 MV cavity voltage
- 12 × 7 cell nc cavities
- rf power: up to 4 × 800 kW
  (2 Thales and 2 Philips klystrons)







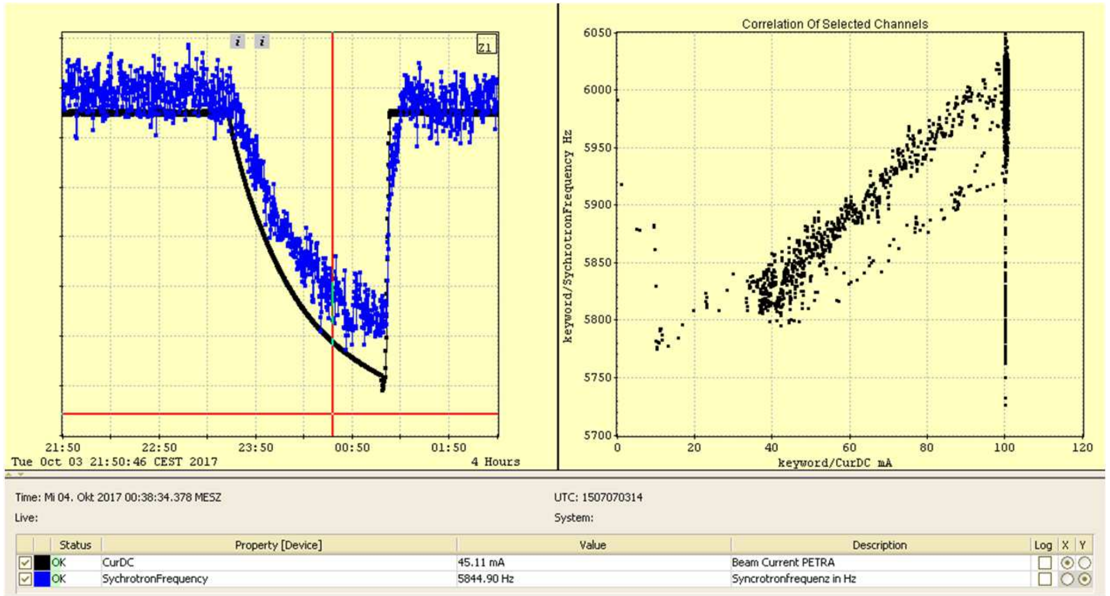
calibrating the voltage.

by using the synchrotron frequency

$$eU_C = \sqrt{\left(\frac{f_s^{\,2} * 2\pi * E}{f_0^{\,2} * \alpha * h}\right)^2 + E_0^{\,2}}$$

U_c / V	sum (geom.) of 12 peak cavity voltage (PETRA: 20 MV)
f_s / Hz	synchrotron frequency (PETRA: ca. 6.1 kHz)
f_0 / Hz	revolution frequency (PETRA: 130120.91 Hz)
h	harmonic number (PETRA: 3840)
α	momentum compaction factor (PETRA: 0.001127)
E_0 / eV	energy loss per turn (PETRA: ca. 5 MeV)
E / eV	beam energy (PETRA: 6.083 GeV)

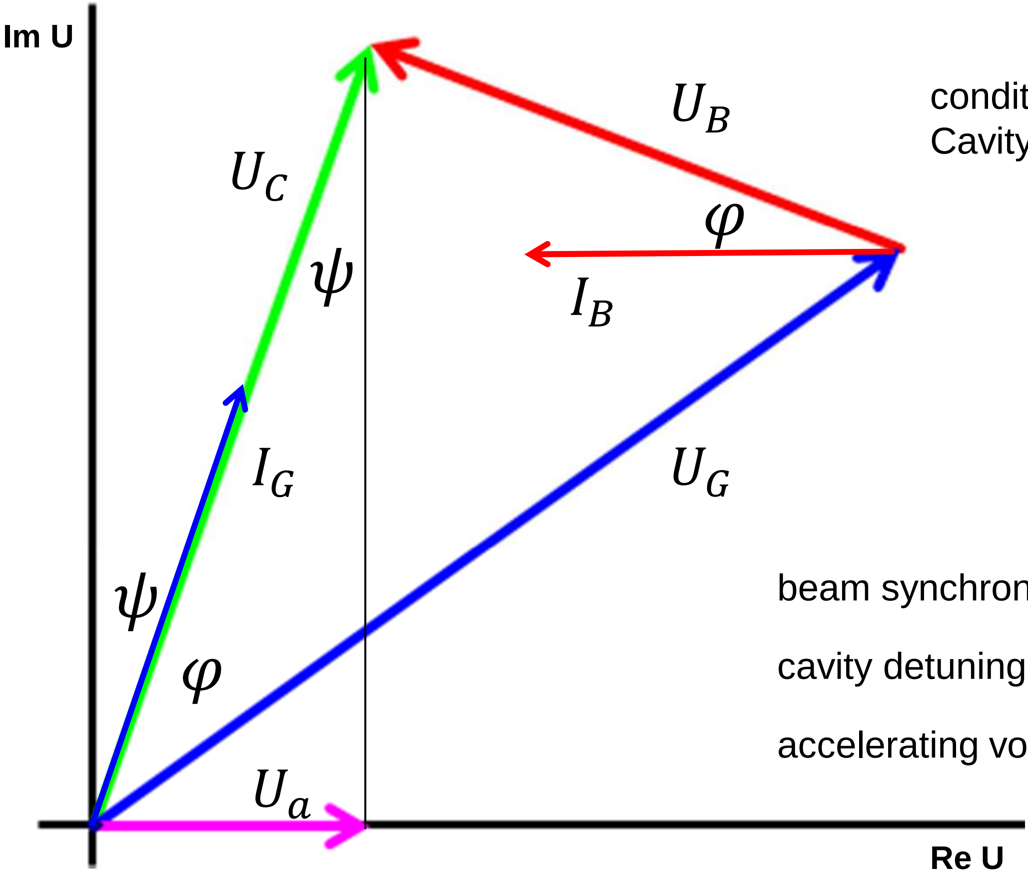
rf frequency (PETRA: 499664310 Hz)
synchronous phase about 14.3 deg



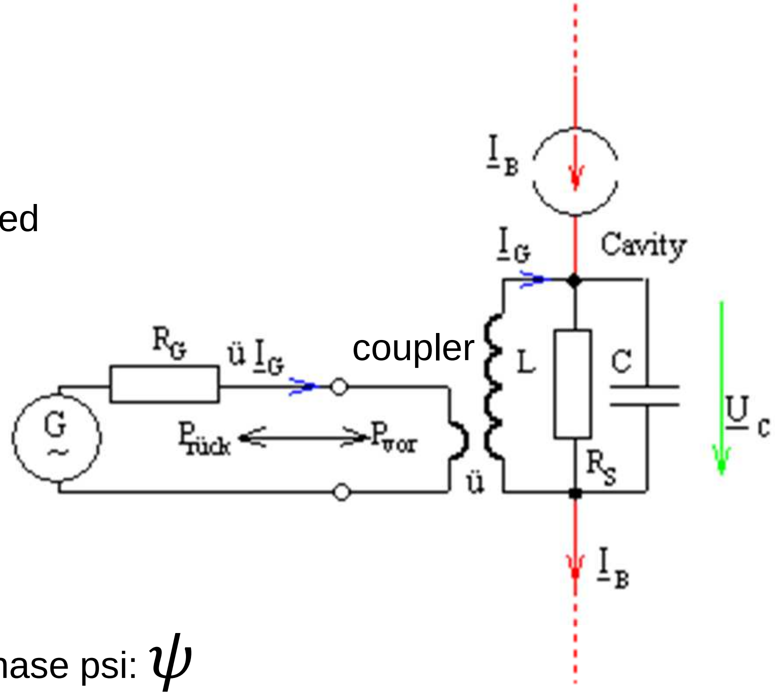
But we observe (here in 40 bunch mode) a big change (5 %) of the synchrotron frequency (blue) when the beam current (black) decreased. Explanation? So we were looking for different methods. And we want to calibrate the voltage of each cavity separated.

the cavity as a triangle.

vector diagram of cavity voltage



conditions:
Cavity is tuned



beam synchronous phase psi: ψ

cavity detuning angle phi: φ

accelerating voltage: U_a

the idea.

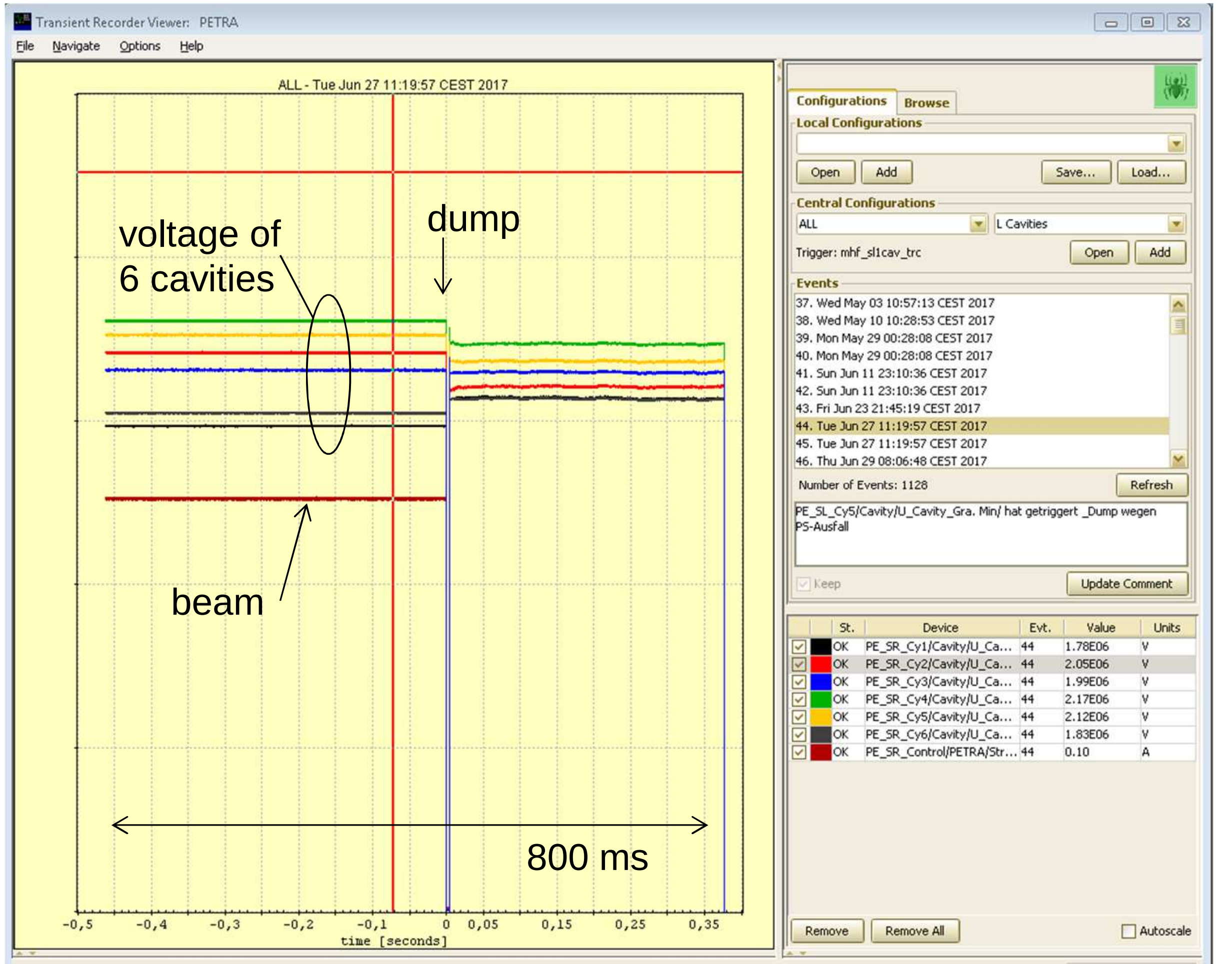
proposed by Michael Ebert (DESY, MHF-e)

- We want to calibrate the cavity voltage without using the generator power to increase the accuracy. This method requires only the knowledge of beam current, shunt impedance and loaded quality factor of the cavity.
- This calibration process makes use of blanking the accelerator rf-power for few milliseconds in order to dump the beam current.
  The transient of the cavity-voltage is measured at three characteristic points:

  1.) Just before the rf-power is blanked (cavity voltage).
  2.) Shortly after the rf is blanked, but the beam current is still unaffected (beam induced voltage).
  3.) Shortly after the beam is lost and the rf is recovered (generator induced voltage).

measure the three sides of the triangle.

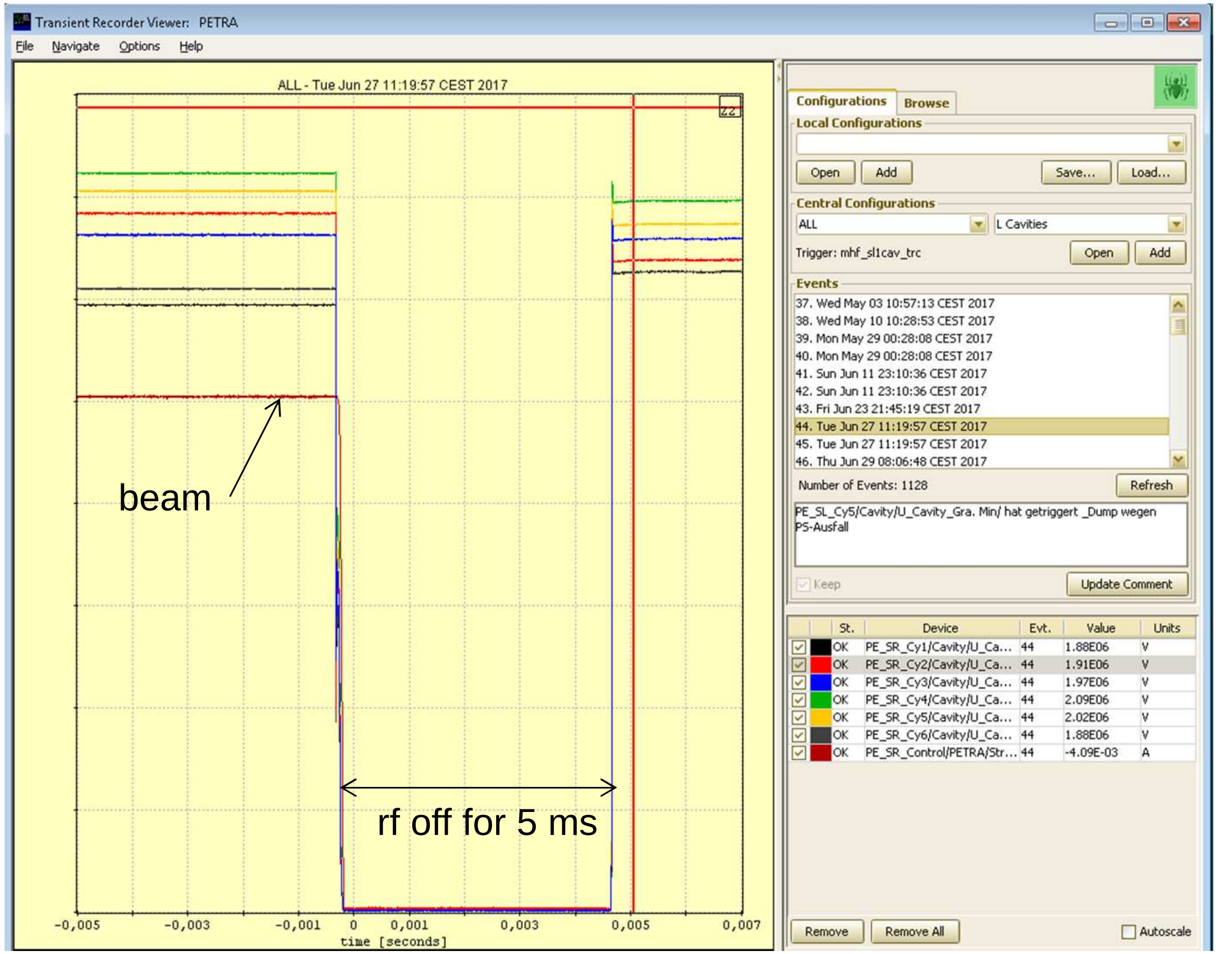
by a transient recorder during a beam dump



The beam is dumped by switching
off the rf for 5 ms.
In this example the reason for the dump
was a trip of a magnet power supply.
A transient recorder saves 800 ms of data.
Here we see the (tentative calibrated)
voltages U_C of 6 cavities (one transmitter)
and the beam current.
The first side of our triangle.
Let´s zoom in...

measure the three sides of the triangle.

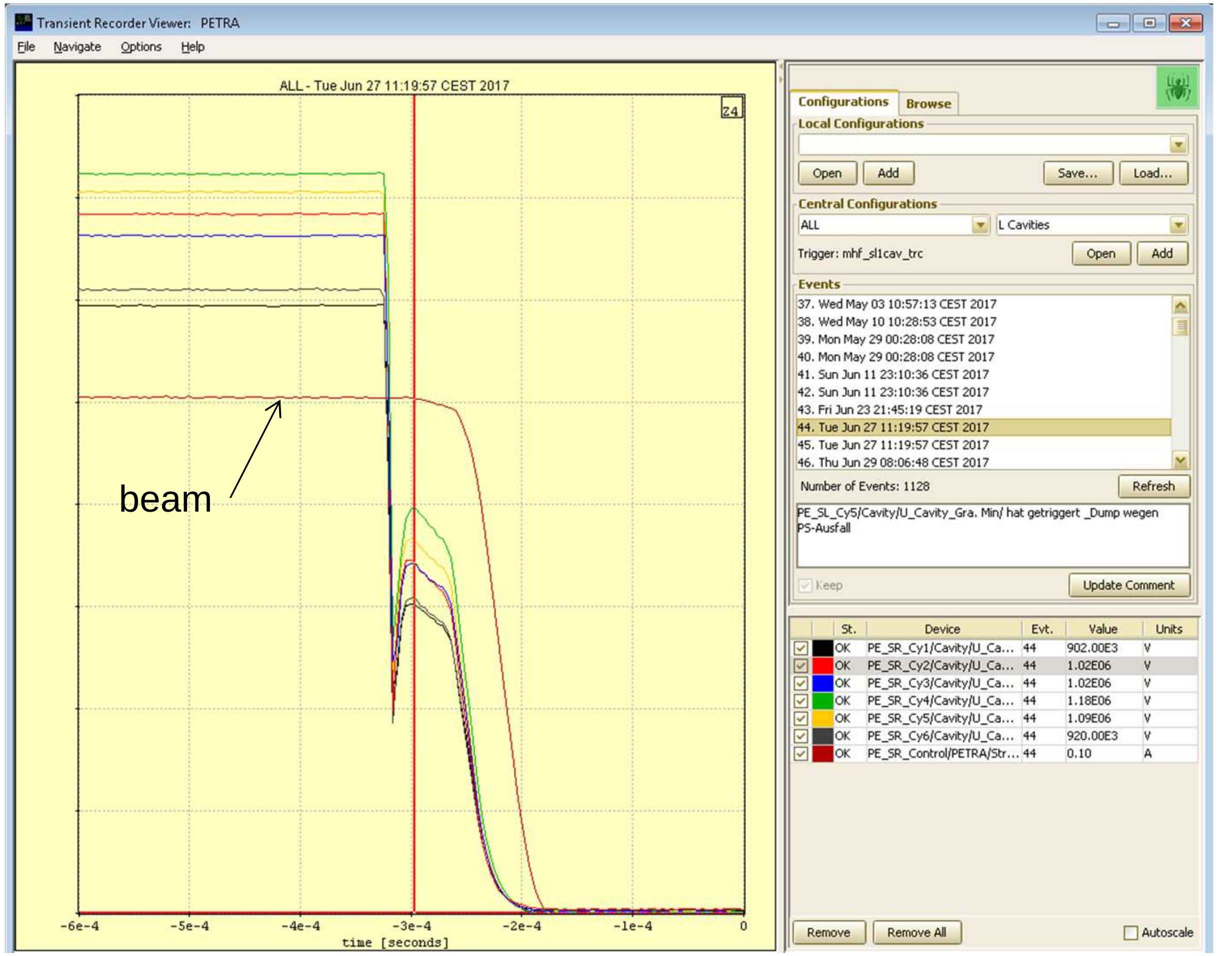
by a transient recorder during a beam dump



Looking on the measurement of the cavity voltage after the beam is gone and the rf ist back again we see the generator induced voltage: U_G
The next side of our triangle.
Let´s zoom in more ...

measure the three sides of the triangle.

by a transient recorder during a beam dump



Looking on the measurement of the cavity voltage during the rf is off but the beam is still in the machine we see in each cavity the beam induced voltage: U_B
We took the maximum after a short time (ca. 30 μs) of changing the charge in the cavity and before the bunch is debunched and lost.
The last side of our triangle.

the next steps.

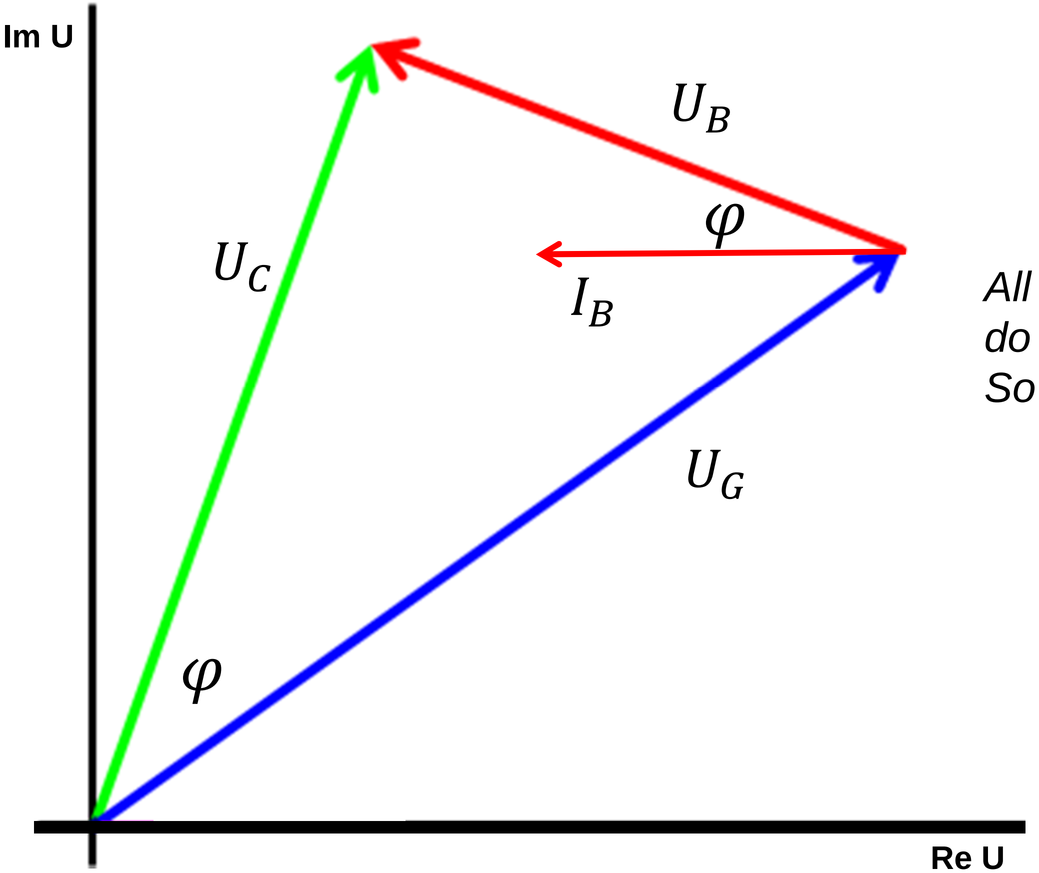
proposed by Michael Ebert (DESY, MHF-e)

- From the arbitrary calibrated measured values a triangle can be constructed and the detuning-angle of the cavity can be calculated.

- By the knowledge of the detuning-angle the beam induced voltage can be calculated. Since the beam-induced voltage forms one side of a triangle, the remaining two sides which represents generator induced voltage and cavity voltage can also be calculated.

constructing the triangle.

calculating and calibrating



1. Calculating the cavity detuning angle phi φ by using the law of cosines:

$$\varphi = \arccos \frac{U_C{}^2 + U_G{}^2 - U_B{}^2}{2 \cdot U_C \cdot U_G}$$

All three sides coming from the same pick up do have the same error.
So there is no effect to phi.

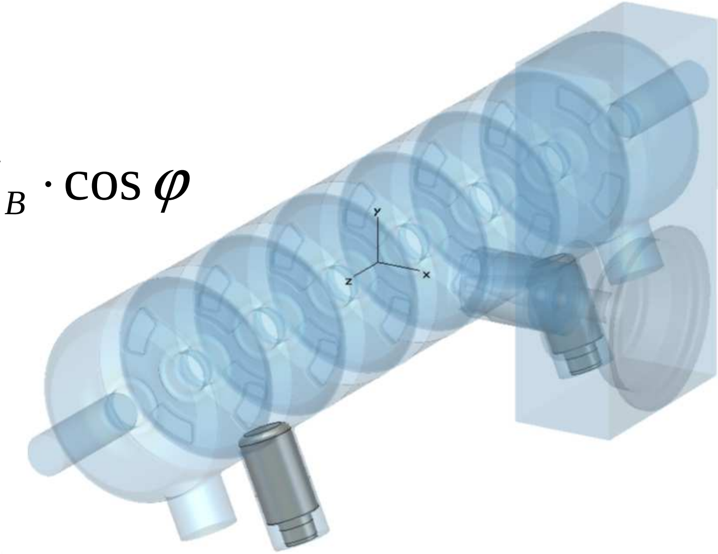
Example (Cavity PE_SR_Cy2):
U_C: 2.051 E06 V
U_G: 1.916 E06 V
U_B: 1.025 E06 V

φ = 29.7 deg

calibrating.

calculating and calibrating

2. Calculating the beam induced voltage: $$U_B = 2\frac{R}{Q}Q_L \cdot I_B \cdot \cos\varphi$$



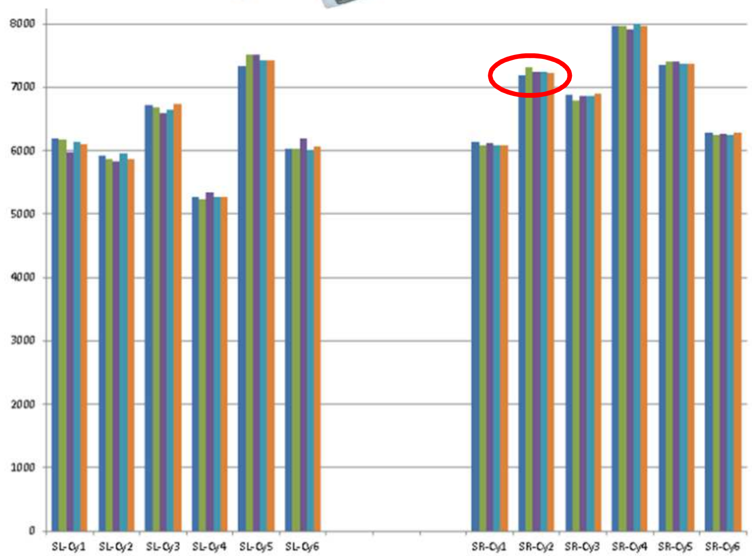
We only need R/Q, beam current and the loaded Q_L:

- *R/Q for our 7-cell cavities was calculated to 845 Ohm at TU-Darmstadt (TEMF) in april 2016 in a high detailed CST-MWS-calculation, including plungers, input coupler and doorknob. Older MAFIA calculations shows 856 Ohm.*
- *Precision of I_B measurement is about 1-2% (less in 40 bunch mode)*
- *Q_L was specified several times by band width measurements*

<u>Example</u> (Cavity PE_SR_Cy2):
Q_L: 7247

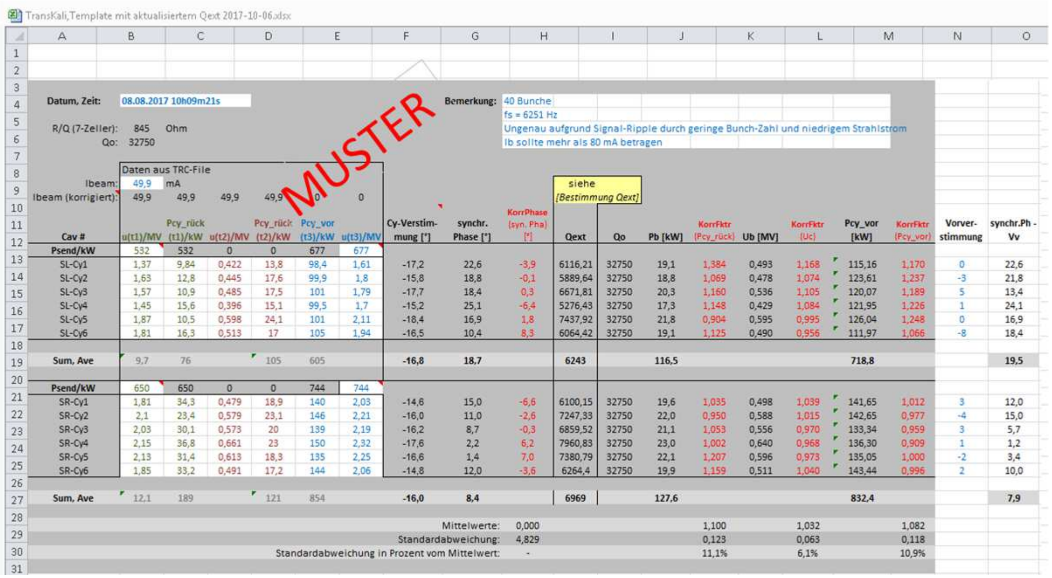
$$U_B = 2 \cdot 845\Omega \cdot 7247 \cdot 100mA \cdot \cos 29.7° = 1.064MV$$

originally $U_B = 1.025$ E06 V, so we had to correct the calibrating factor for that U_C pick up by 1.038



more capabilities.

- It is even possible to calculate the cavity phasing and the forward and reverse coupler power of the cavity.
- The experiences at PETRA-III shows that the accuracy of this calibrating method is comparable to those from directional coupler measurements or calorimetric power measurements.
- By averaging the calibration data of many beam dumps the accuracy can be increased.
- The presented method is potentially well suited for automated calibration.
  For example, calibration data could be generated automatically for each beam dump.



TransKali,Template mit aktualisiertem Qext 2017-10-06.xlsx

Datum, Zeit: 08.08.2017 10h09m21s

R/Q (7-Zeller): 845 Ohm

Qo: 32750

Bemerkung: 40 Bunche
fs = 6251 Hz
Ungenau aufgrund Signal-Ripple durch geringe Bunch-Zahl und niedrigem Strahlstrom
Ib sollte mehr als 80 mA betragen

Daten aus TRC-File

Ibeam: 49,9 mA

siehe [Bestimmung Qext]

MUSTER

Cav #	u(t1)/MV	Pcy_rück (t1)/kW	u(t2)/MV	Pcy_rück (t2)/kW	Pcy_vor (t3)/kW	u(t3)/MV	Cy-Verstim-mung [°]	synchr. Phase [°]	KorrPhase (syn. Pha) [°]	Qext	Qo	Pb [kW]	KorrFktr (Pcy_rück)	Ub [MV]	KorrFktr (Uc)	Pcy_vor [kW]	KorrFktr (Pcy_vor)	Vorver-stimmung	synchr.Ph - Vv
Ibeam (korrigiert):	49,9	49,9	49,9	49,9	0	0													
Psend/kW	532	532	0	0	677	677													
SL-Cy1	1,37	9,84	0,422	13,8	98,4	1,61	-17,2	22,6	-3,9	6116,21	32750	19,1	1,384	0,493	1,168	115,16	1,170	0	22,6
SL-Cy2	1,63	12,8	0,445	17,6	99,9	1,8	-15,8	18,8	-0,1	5889,64	32750	18,8	1,069	0,478	1,074	123,61	1,237	-3	21,8
SL-Cy3	1,57	10,9	0,485	17,5	101	1,79	-17,7	18,4	0,3	6671,81	32750	20,3	1,160	0,536	1,105	120,07	1,189	5	13,4
SL-Cy4	1,45	15,6	0,396	15,1	99,5	1,7	-15,2	25,1	-6,4	5276,43	32750	17,3	1,148	0,429	1,084	121,95	1,226	1	24,1
SL-Cy5	1,87	10,5	0,598	24,1	101	2,11	-18,4	16,9	1,8	7437,92	32750	21,8	0,904	0,595	0,995	126,04	1,248	0	16,9
SL-Cy6	1,81	16,3	0,513	17	105	1,94	-16,5	10,4	8,3	6064,42	32750	19,1	1,125	0,490	0,956	111,97	1,066	-8	18,4
Sum, Ave	9,7	76		105	605		-16,8	18,7		6243		116,5				718,8			19,5
Psend/kW	650	650	0	0	744	744													
SR-Cy1	1,81	34,3	0,479	18,9	140	2,03	-14,6	15,0	-6,6	6100,15	32750	19,6	1,035	0,498	1,039	141,65	1,012	3	12,0
SR-Cy2	2,1	23,4	0,579	23,1	146	2,21	-16,0	11,0	-2,6	7247,33	32750	22,0	0,950	0,588	1,015	142,65	0,977	-4	15,0
SR-Cy3	2,03	30,1	0,573	20	139	2,19	-16,2	8,7	-0,3	6859,52	32750	21,1	1,053	0,556	0,970	133,34	0,959	3	5,7
SR-Cy4	2,15	36,8	0,661	23	150	2,32	-17,6	2,2	6,2	7960,83	32750	23,0	1,002	0,640	0,968	136,30	0,909	1	1,2
SR-Cy5	2,13	31,4	0,613	18,3	135	2,25	-16,6	1,4	7,0	7380,79	32750	22,1	1,207	0,596	0,973	135,05	1,000	-2	3,4
SR-Cy6	1,85	33,2	0,491	17,2	144	2,06	-14,8	12,0	-3,6	6264,4	32750	19,9	1,159	0,511	1,040	143,44	0,996	2	10,0
Sum, Ave	12,1	189		121	854		-16,0	8,4		6969		127,6				832,4			7,9
								Mittelwerte:	0,000				1,100		1,032		1,082		
								Standardabweichung:	4,829				0,123		0,063		0,118		
								Standardabweichung in Prozent vom Mittelwert:	-				11,1%		6,1%		10,9%		

Thank you for your attention.

dziękuję bardzo!