19ENG02 FutureEnergy
WP1: UHVDC calibration and testing

Dr. Meisner

Metrology for future energy transmission

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The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

Overview of the Work Package

The aim of this work package is to extend the metrological capabilities for calibration of instrument voltage transformers up to 1200 kV and for testing of system components up to 1600 kV, and if possible, to 2000 kV, to be used in future UHVDC grids with system voltages currently up to 1100 kV.

Work package leader **PTB**

Tasks

1. Extend the existing HVDC reference dividers to two 1200 kV and one 400 kV system
2. Design new UHVDC reference dividers for 1600 kV
3. Validate the UHVDC dividers

Partners

Overview of the WP

Task 1.1 Reference voltage dividers for 1200 kV

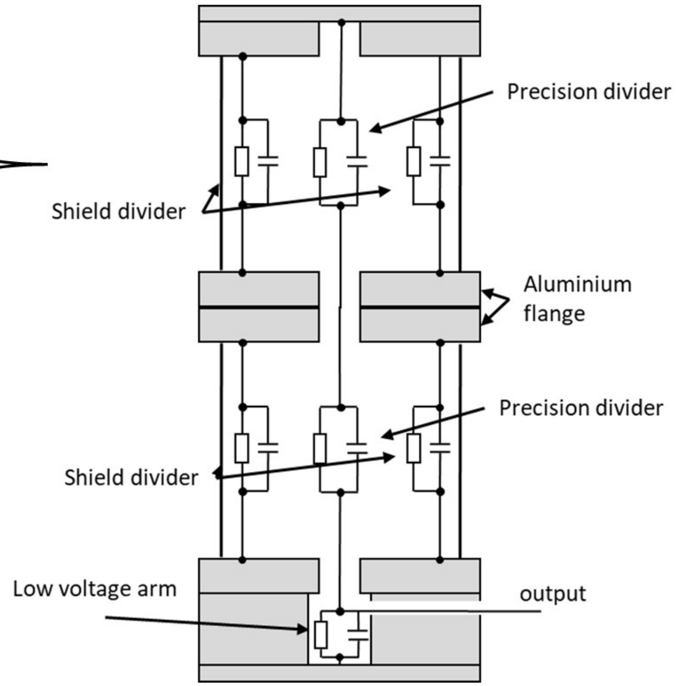
Extend the current 1000 kV HVDC divider to 1200 kV with a target measurement uncertainty better than 40 µV/V


200 kV module


RISE 1000 kV divider

Task 1.2 UHVDC reference divider for 1600 kV

Design of dividers and increase measurement capability to 1600 kV with a target measurement uncertainty better than 200 µV/V

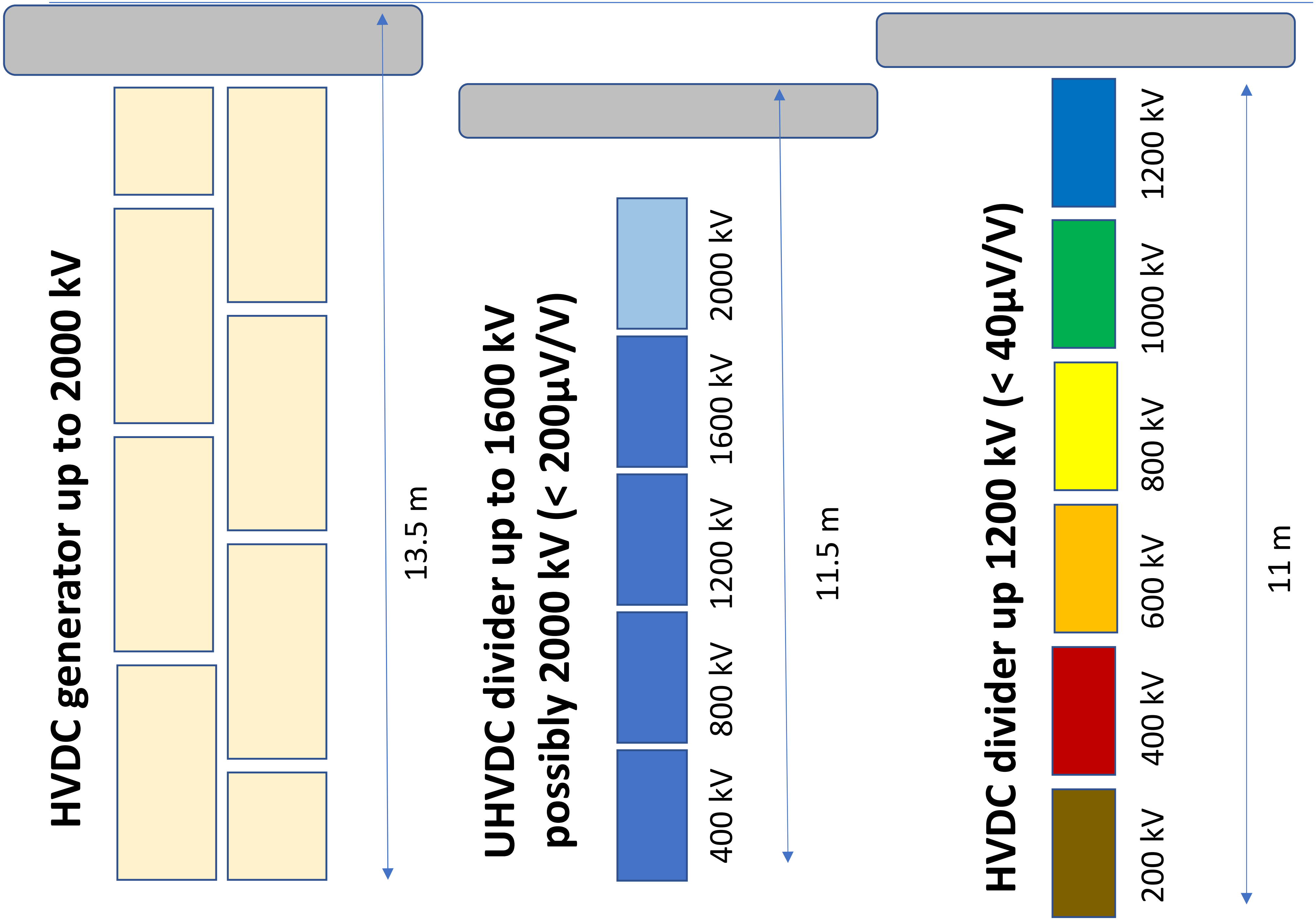


PTB 1600 kV divider design

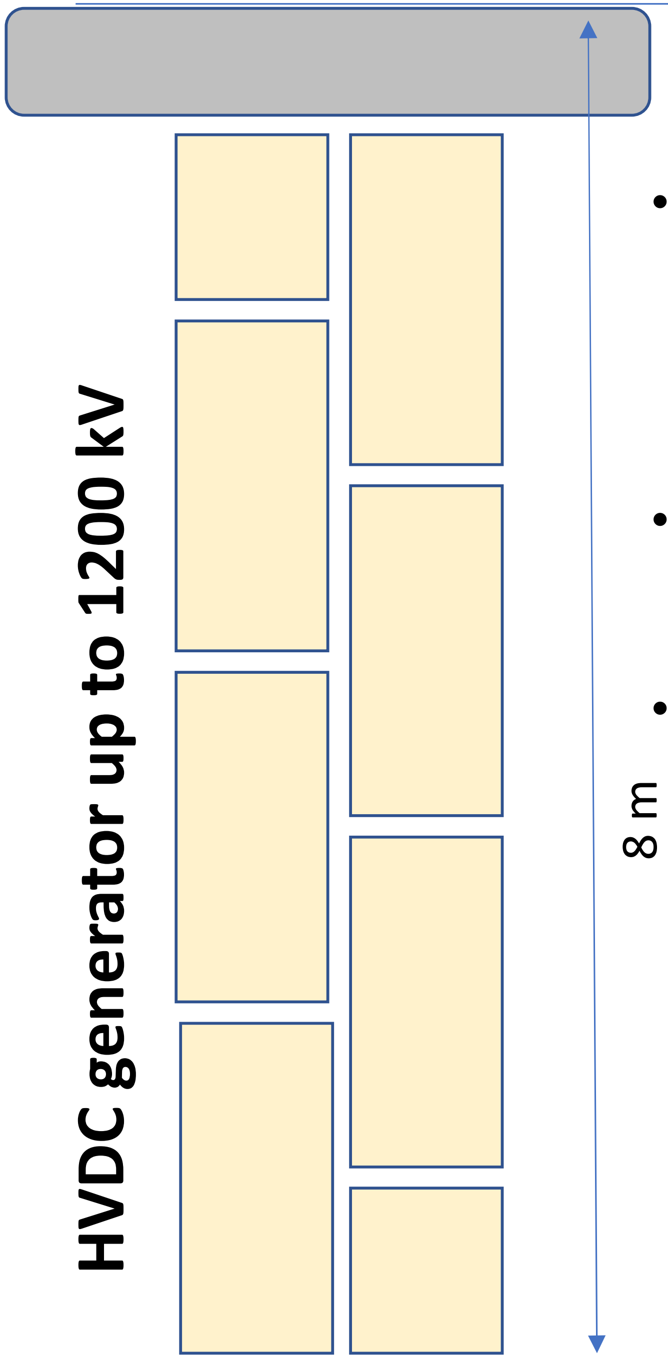
Task 1.3 Validation of UHVDC reference voltage dividers

- Measurement campaign for calibration of UHVDC dividers at RISE up to 1200 kV
- Build a UHVDC generator at PTB for calibration and validation to at least 1600 kV
- Final measurement campaign for calibration of UHVDC dividers at open area test site at PTB

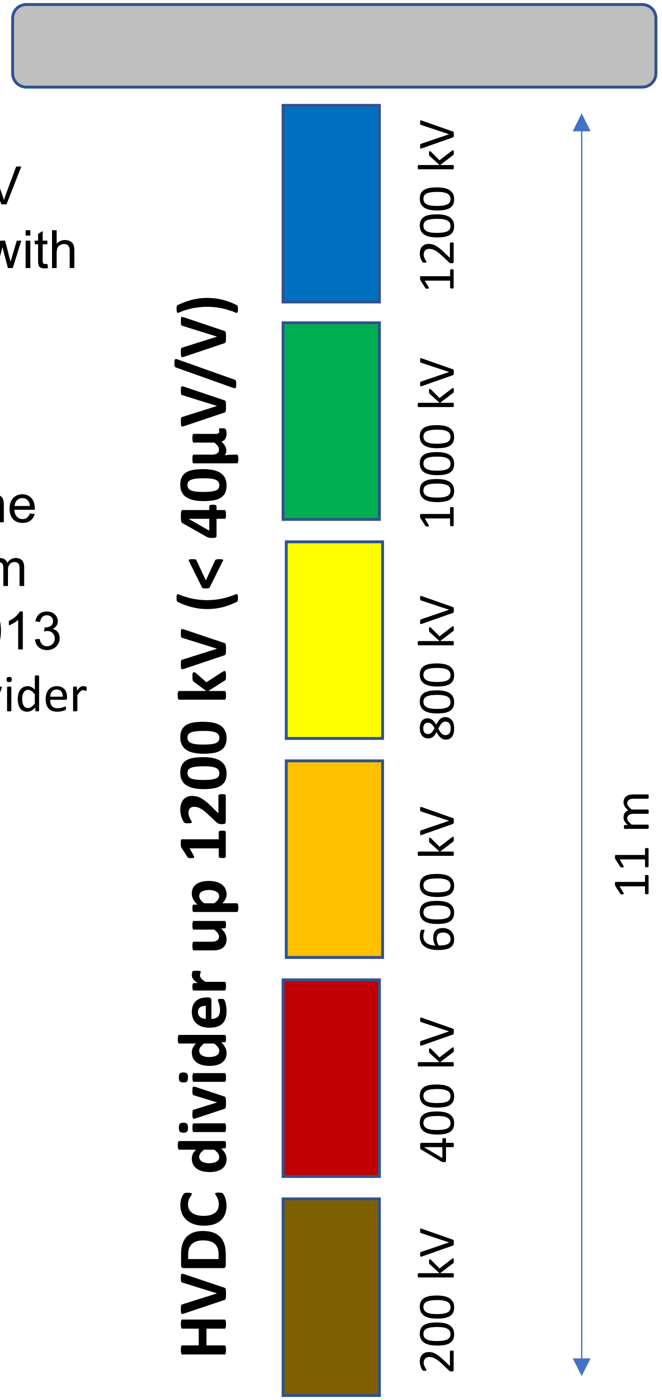
What do we need for WP1?



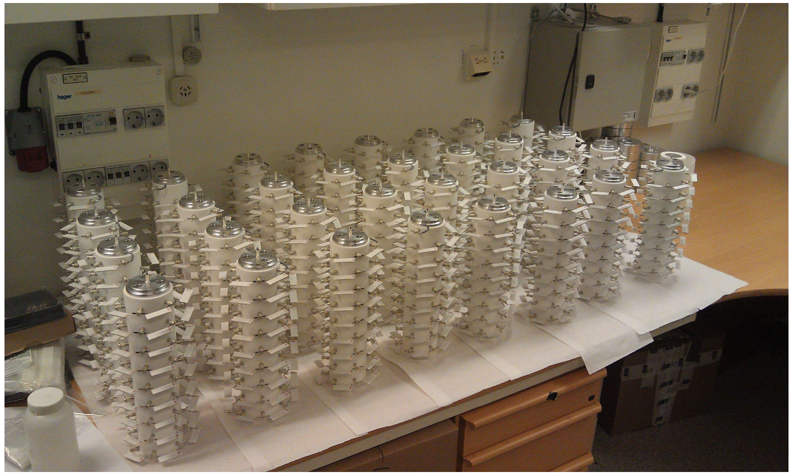
Task 1.1 – Reference voltage dividers for 1200 kV



- Extend the current 1000 kV HVDC divider to 1200 kV with a target measurement uncertainty better than 40 µV/V
- New divider modules for the modular HVDC divider from EMRP ENg07 HVDC in 2013
- Design is a shielded RCRC divider

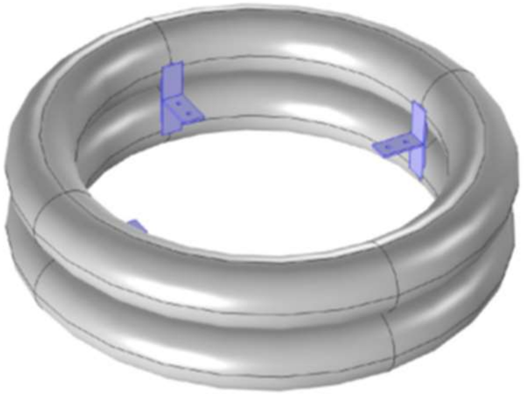


1200 kV HVDC divider

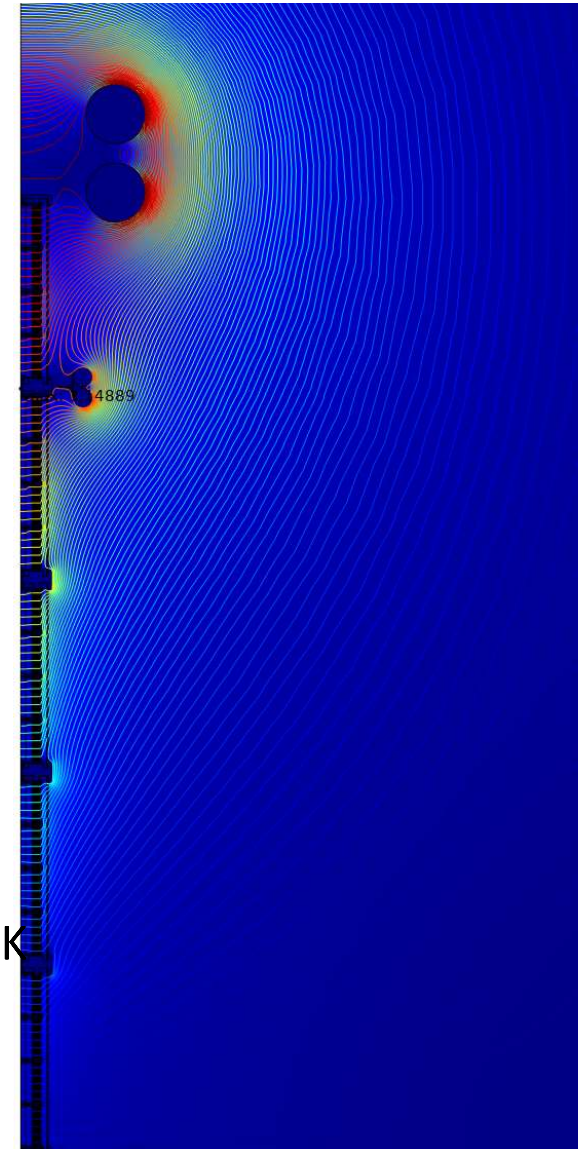


- For the traceability to 1200 kV with the target measurement uncertainty of 40 µV/V, in total seven new 200 kV HV modules are being built.
- The target is to have at least two complete sets of HVDC dividers for traceability to 1200 kV in Europe, by extension of the RISE 1000 kV divider and increase PTB 200 kV capability to 1200 kV.
- The pictures show the precision divider, shield divider and the completed module without housing.

1200 kV HVDC divider



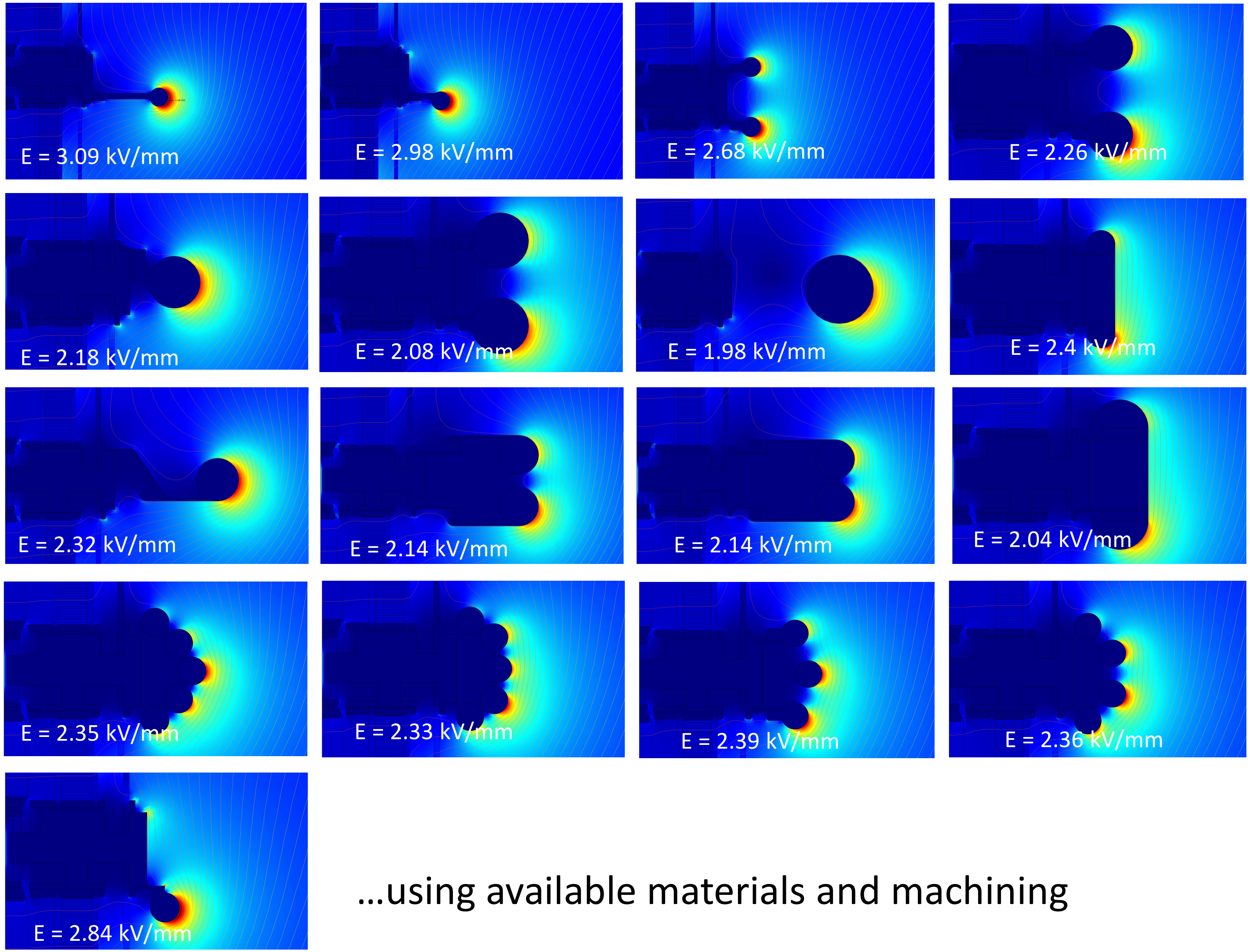
No corona @
+/- 1000 kV

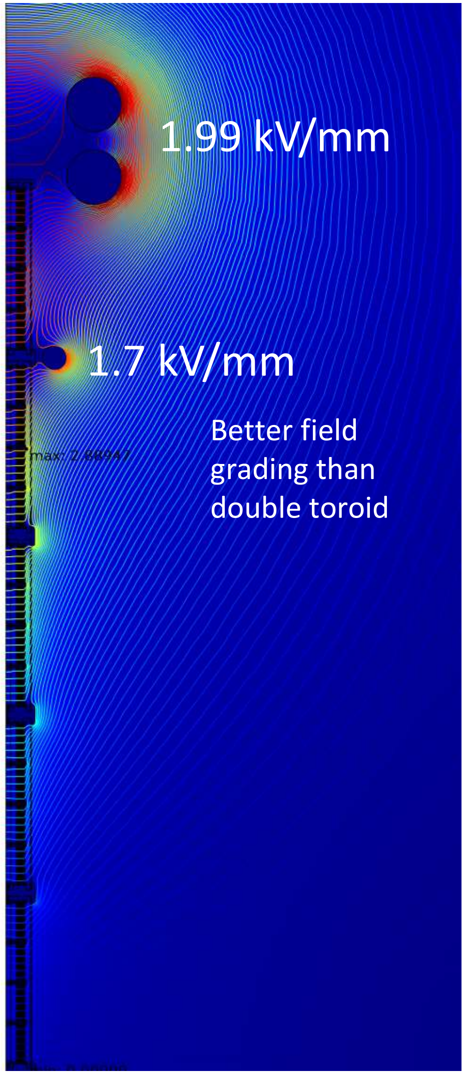


- Field modelling to avoid corona discharge in the 1200 kV divider design has been completed by RISE with input from PTB, TUBITAK and VTT.
- Measurements have been performed by RISE to support the modelling.
- The results show which additional corona rings need to be added to joints between the HV modules.

https://www.ptb.de/empir2020/fileadmin/documents/empir-2020/HV-com2/documents/1200kVbygge.mp4

1200 kV HVDC divider field modeling



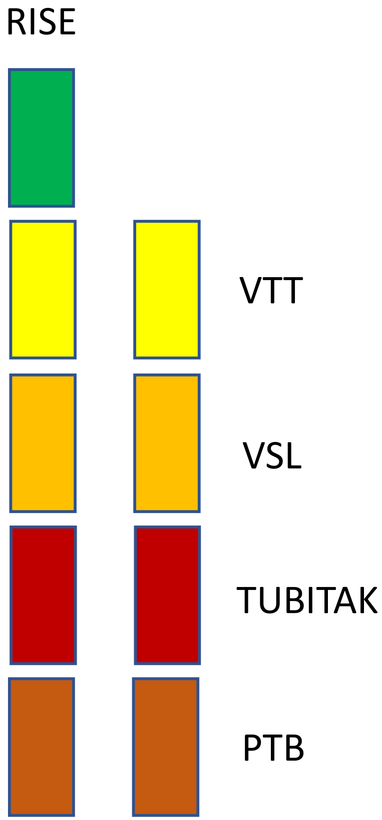


...using available materials and machining

1200 kV HVDC divider

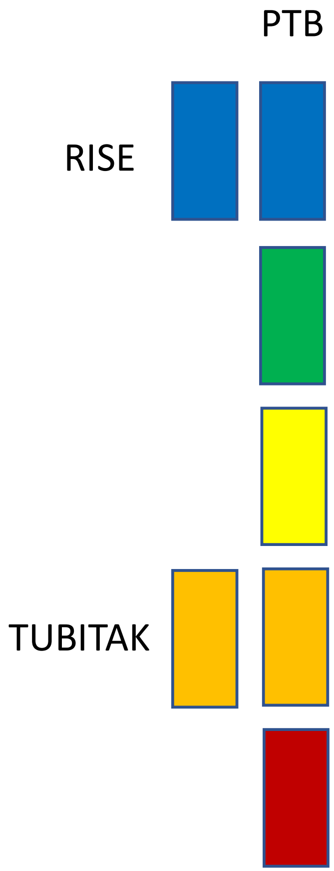
RISE 1000 kV divider at Aalto Finland 2013

9 new 200 kV HV modules 2010-2013

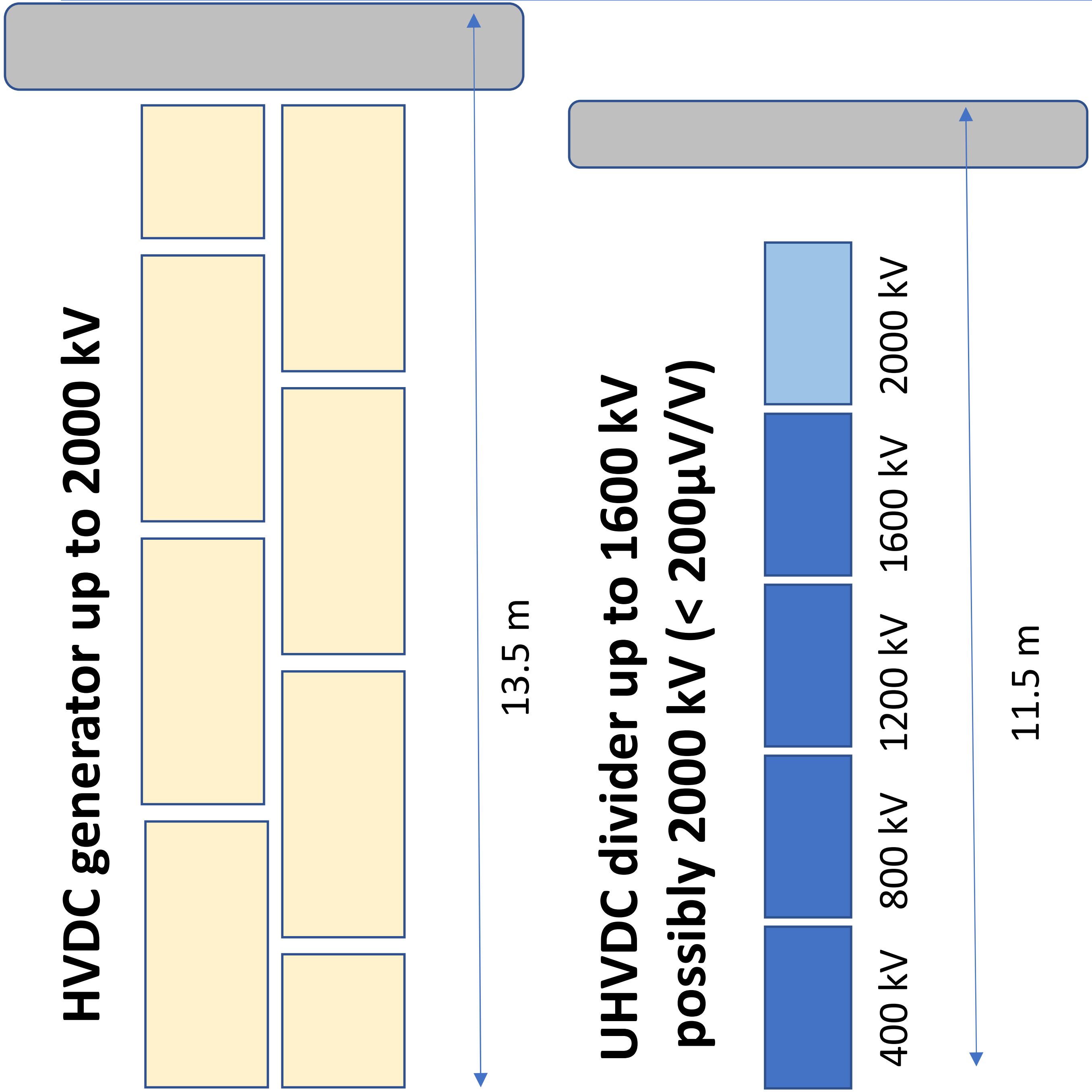


RISE and PTB 1200 kV dividers at RISE 2022

7 new 200 kV HV modules 2020-2022

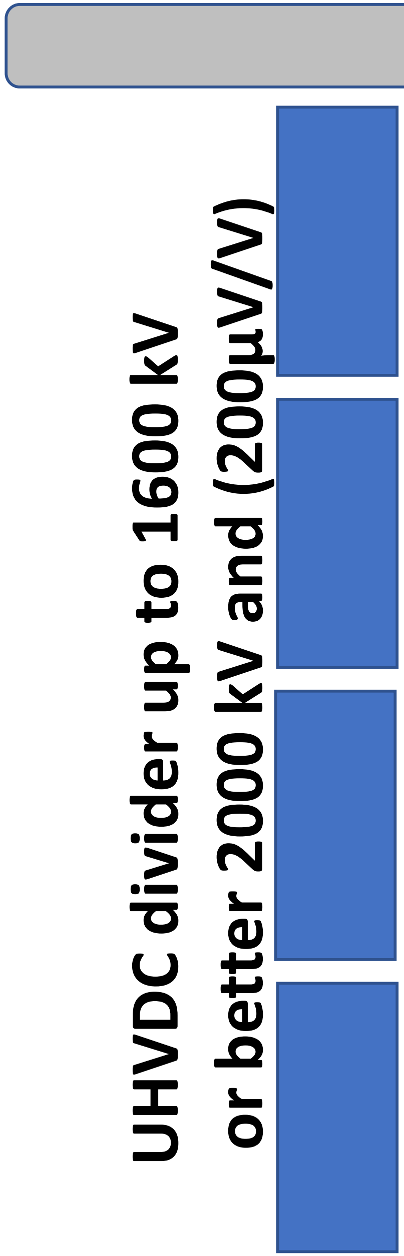


Task 1.2 UHVDC reference dividers for 1600 kV



- Design of new more compact dividers and increase measurement capability to 1600 kV with a target measurement uncertainty better than 200 µV/V
- One modular shielded RCRC divider to full 1600 kV with extension to 2000 kV
- Test a new design of a modular unshielded RCR divider

1600 kV UHVDC divider prototype by PTB



→ PTB designed and setup a prototype of a shielded RCRC modular divider with 400 kV modules (Master Thesis Stephan Passon)

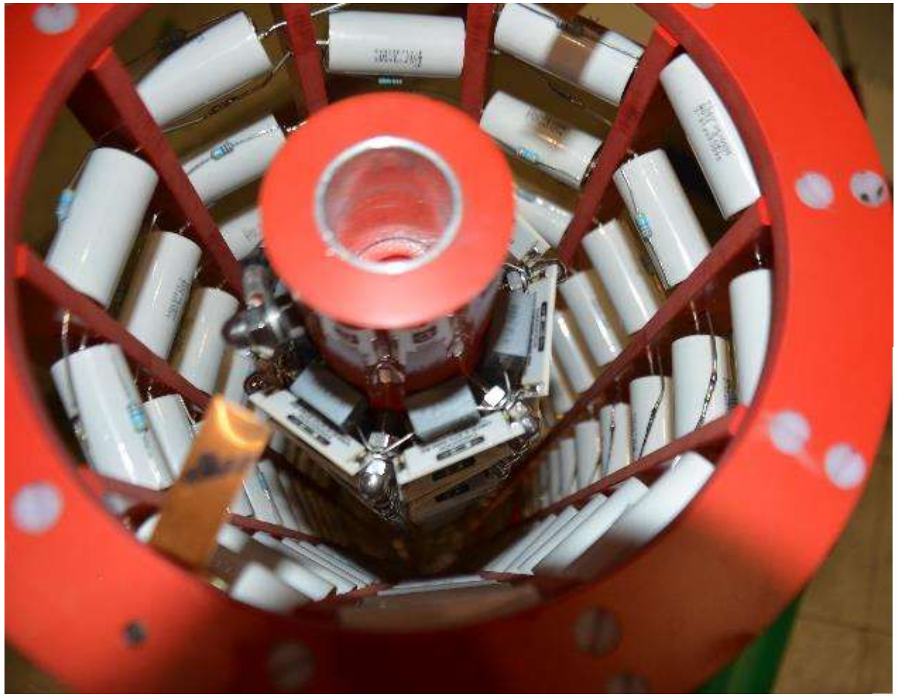
→ It is also the basis for a universal divider (HV-com² and PhD Thesis Stephan Passon)

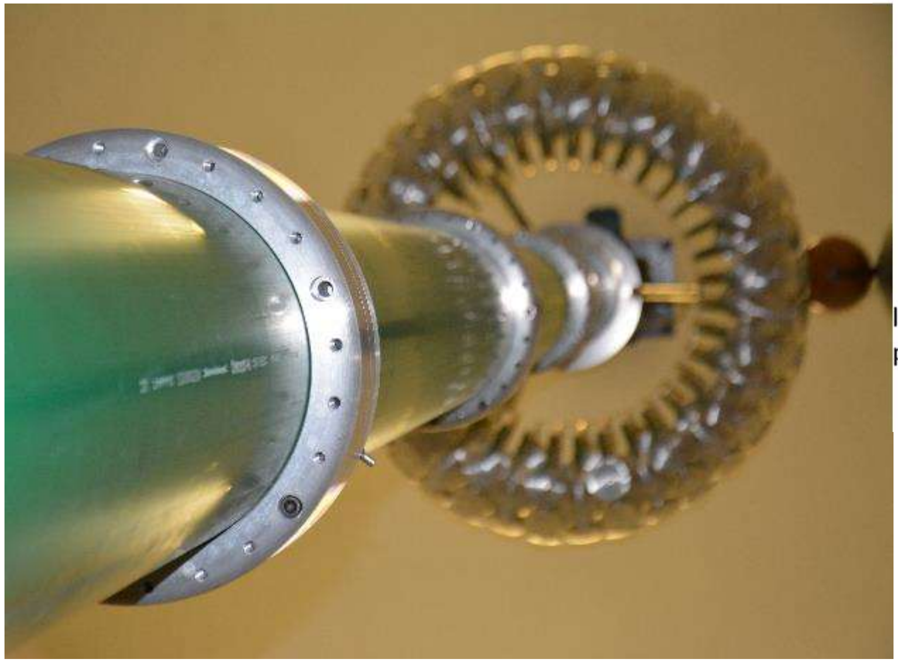
→ PTB did tests for pure HVDC the individual modules are <10ppm dividers (at least up to 200 kV)

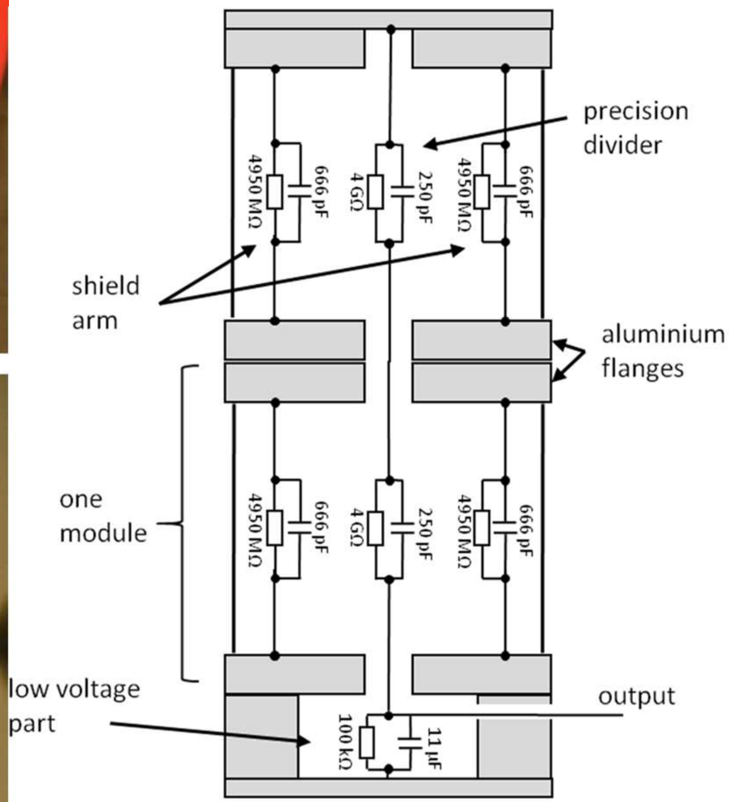
→ Four modules together for 1600 kV
→ Five modules for 2000 kV

→ Multiphysics modelling - size and shape for corona rings to 2000kV

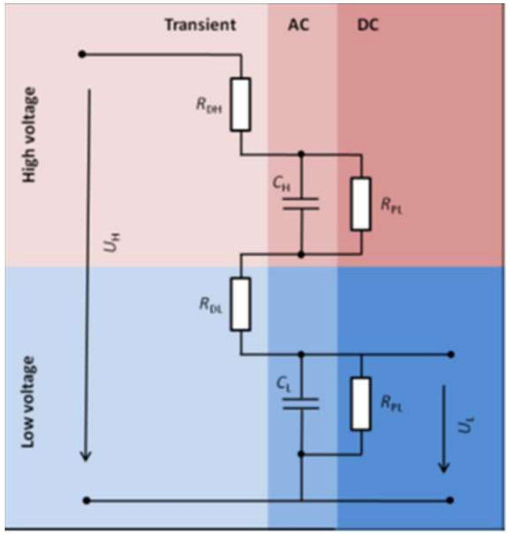
1600 kV UHVDC divider prototype by PTB





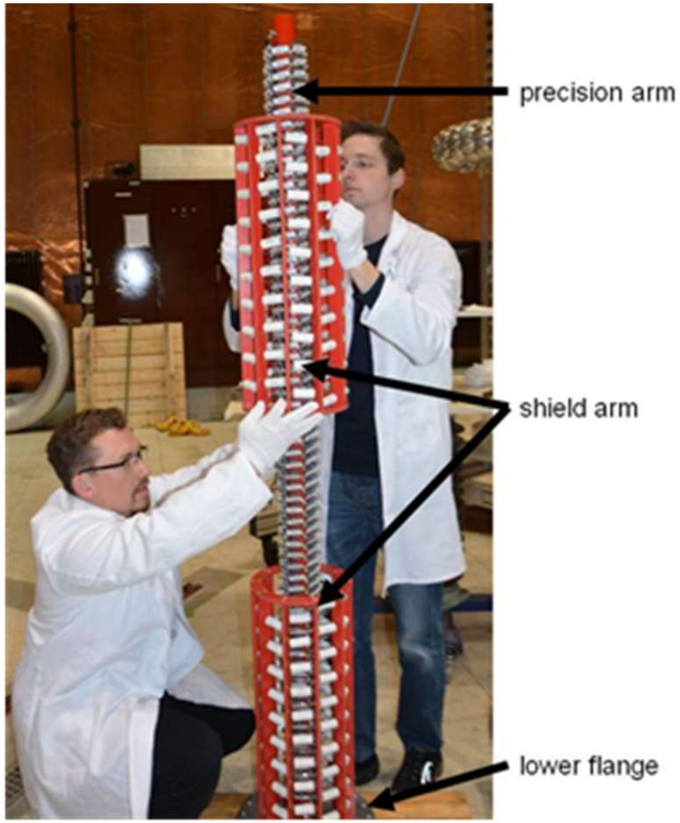


1600 kV UHVDC divider prototype by PTB



- The 10 MΩ precision resistors are in parallel with 100 nF capacitors.
- The schematic diagram of the precision divider is given in the left figure.
- Red colour indicates the high-voltage arm and blue the low voltage arm.
- The pale colours (left) indicate the transient part of the divider, the medium colours (centre) the AC part and the strong colours (right) the DC part.

High voltage divider module PT400	
Nominal scale factor	40.001:1
Nominal voltage	400 kV
Expanded uncertainty (*k*=2)	$1\cdot10^{-5}$ V/V
Resistance of precision arm	4 GΩ
Resistance of shield arm	2475 GΩ
Low voltage arm	100 kΩ



1000 kV UHVDC divider by RISE

→ RISE designed and built two 500 kV (DC) modular damped capacitive RCR universal dividers

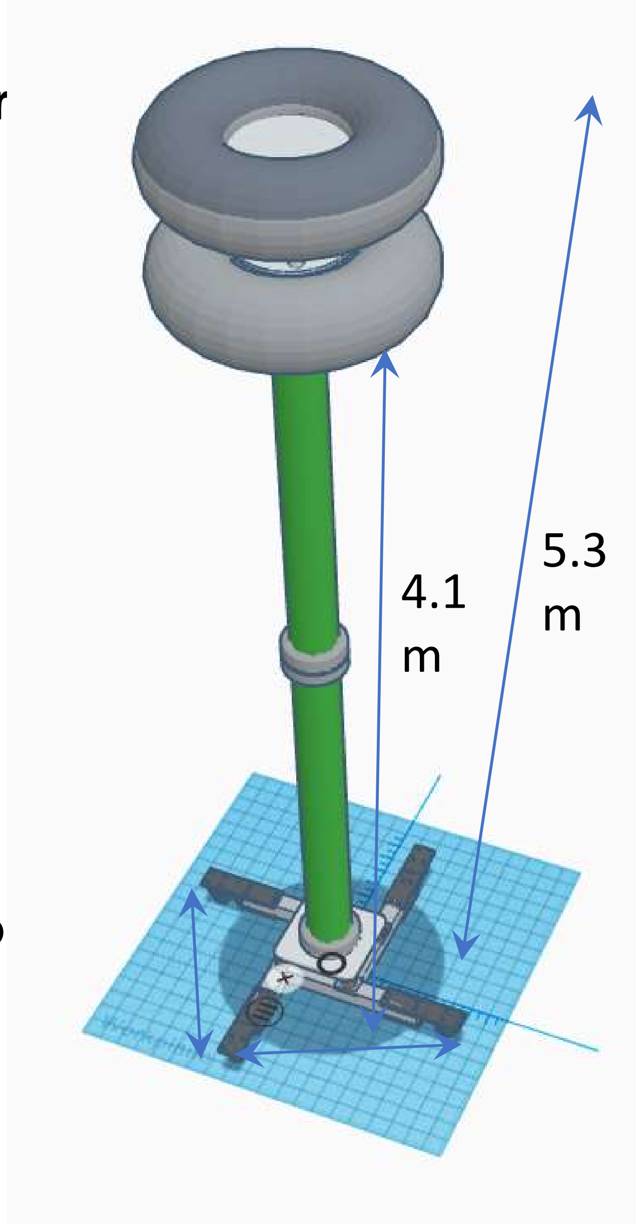
→ The divider is multi-purpose and is also used in the 19NRM07 HV-com^2 project for composite and combined waves – i.e. for DC, AC, SI and LI

→ Multiphysics simulations were used to optimize the corona rings and check the internal stresses

→ The total rating is 500/320/600/700 kV for DC/AC_{rms}/SI/LI

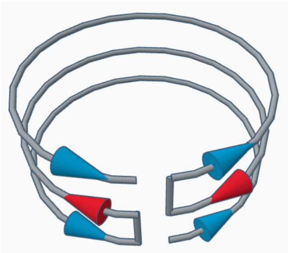
→ Two 500 kV dividers have been built and with two HV modules stacked, reaching 1000 kV for UHVDC calibrartions

→ The divider can be extended to 1500 and 2000 kV

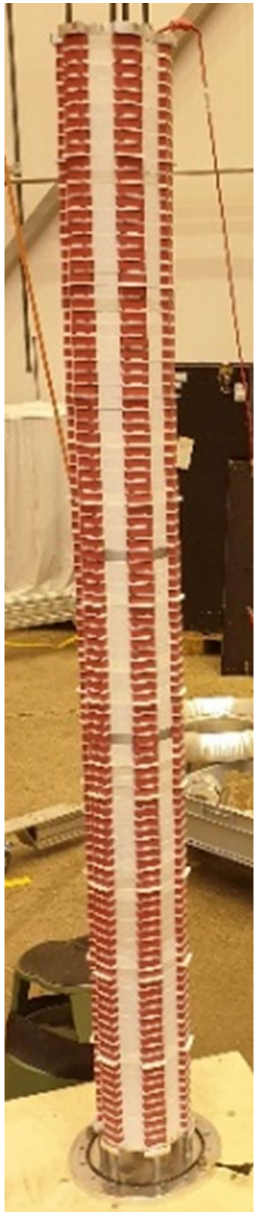


1000 kV UHVDC divider by RISE

Component mounting

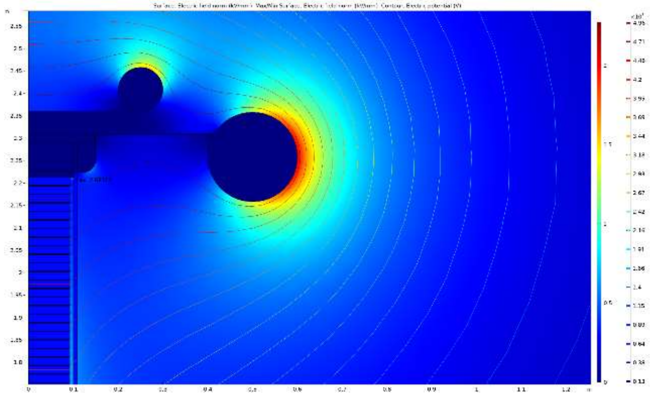


Meandering current path

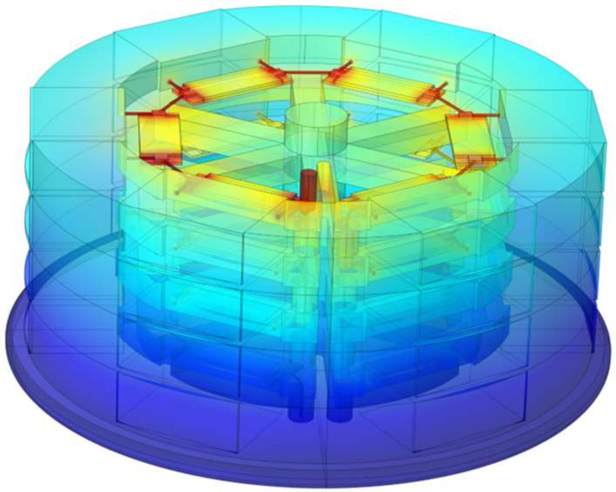


Full 500 kV
100 disc stack

Multiphysics modelling
of field strengths (0 – 4.5 kV/mm)

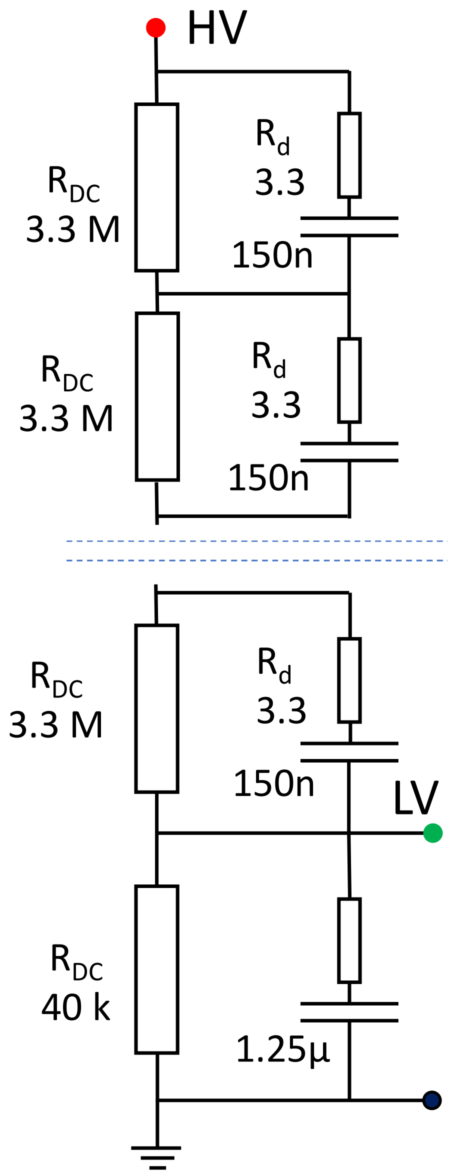


Corona ring for 500 kV system



Internal voltage stresses

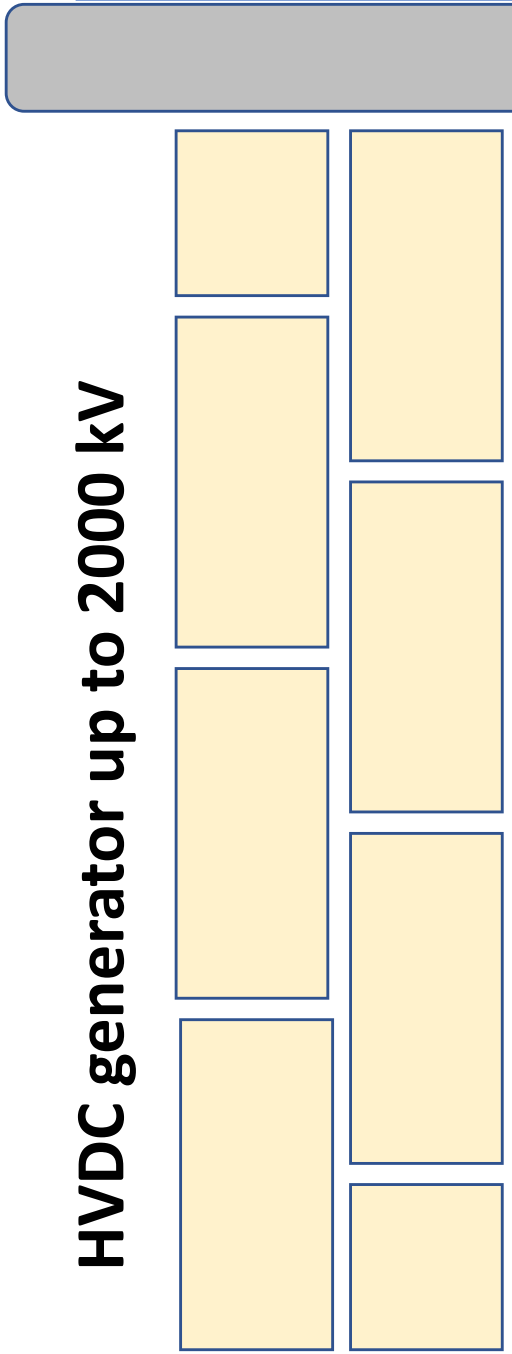
1000 kV UHVDC divider at RISE



- A schematic of DC configuration shown left
- For UHVDC measurements
  - HV arm - 600 pc 3.3 MΩ Caddock type TF050R resistors
- For Composite wave measurements
  - In parallel with the precision resistors 600 pc of 150 nF FKP1 WIMA capacitors.
  - Damping resistors from OHMITE type OX (internal) and OY (front resistor)
- Two LV arms – one for UHVDC measurements and one for AC (composite/combined) wave measurements

Divider parameters for a 1000 kV configuration		
	UHVDC (LV_{DC})	**Composite (LV_{C2} + Attenuator)**
Scale factor	100 000:1	200 000:1
Rated voltage	1000 kV	1000, 640, 1200, 1400 kV
HV resistance	4 GΩ	4 GΩ
HV capacitance	125 pF	125 pF
LV resistance	40 kΩ	1 MΩ (with 50:1 attenuator)
LV capacitance	1.25 µF	500 nF

2000 kV UHVDC generator at PTB

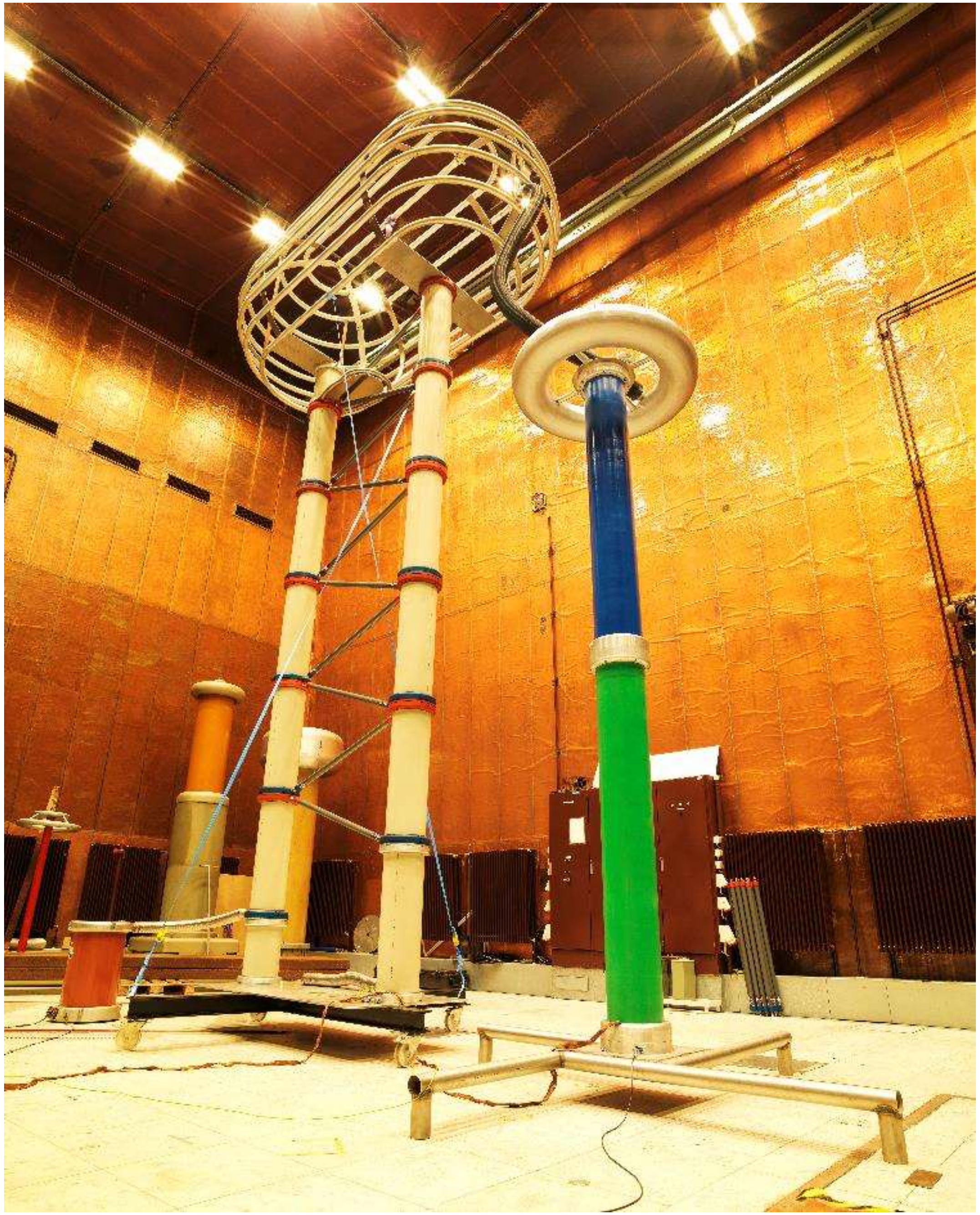


Max nominal voltage
2000 kV (1000 kV in picture)

Ripple factor
< 1·10⁻⁴ V/V

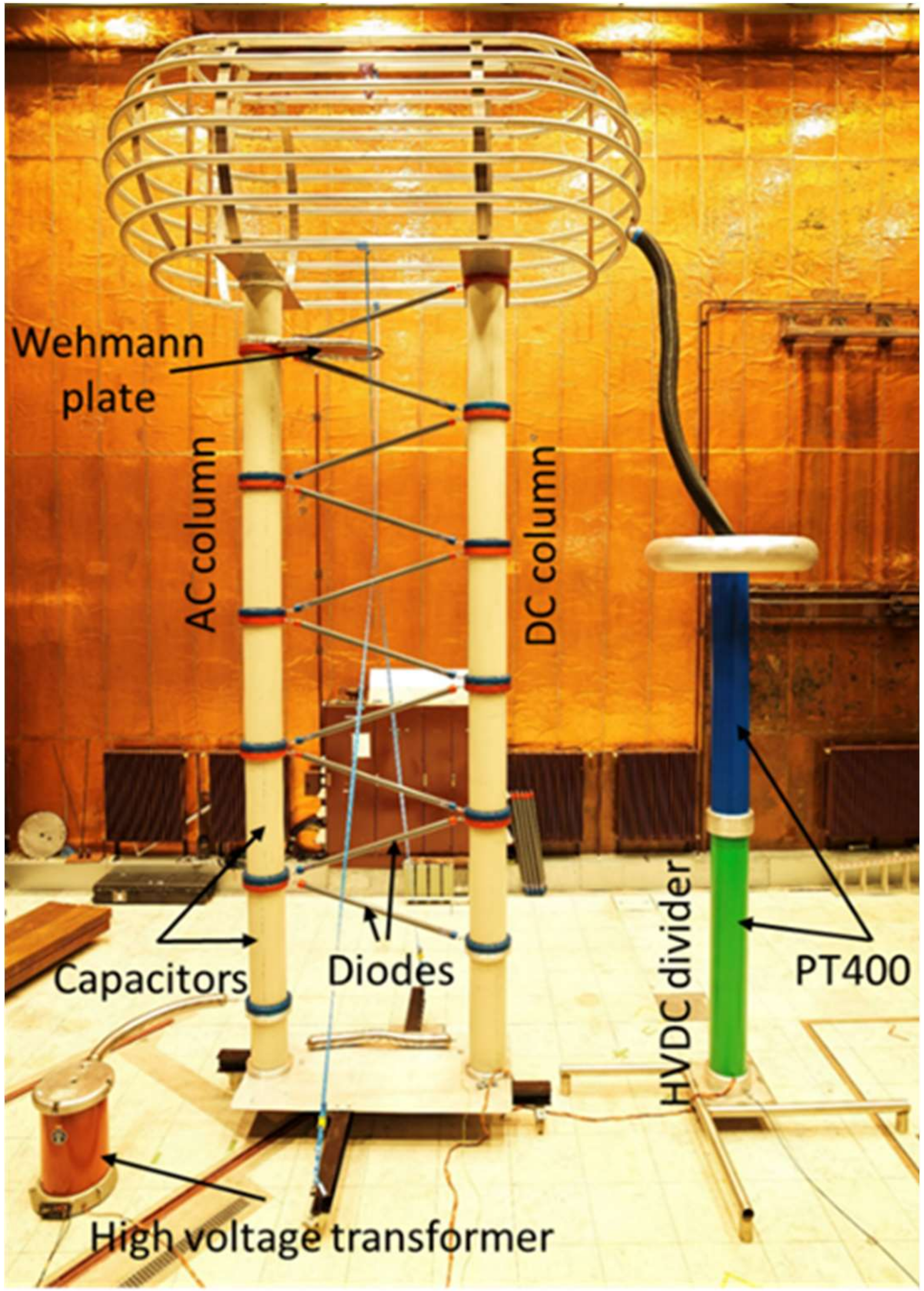
Stability
< 1·10⁻⁵ V/V

Modular design



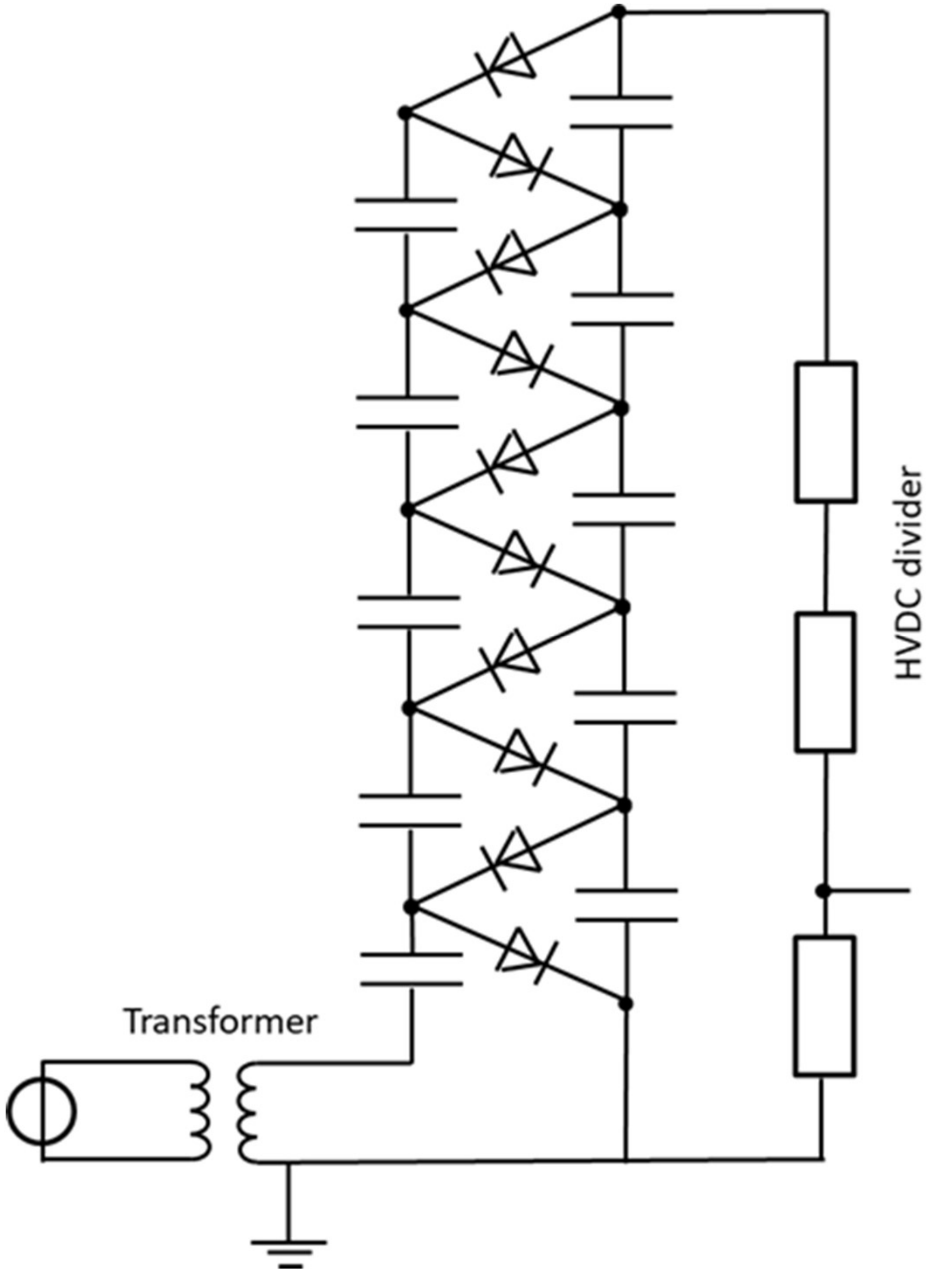
2000 kV UHVDC generator at PTB

- A half-wave voltage multiplier was built.
- The half-wave topology is especially beneficial for the modular design.
- This allows the use of the optimum number of stages to further decrease the ripple factor.
- The optional high frequency switching of the inverter further helps reduce the ripple, as well as the large capacitance of the high voltage capacitors.
- The capacitors have been built by the series connection of 600 individual 47 µF 400 V electrolytic capacitors for every high voltage capacitor.
- The capacitance amounts to 73 nF with a voltage rating of 200 kV and a 40 kV safety margin.

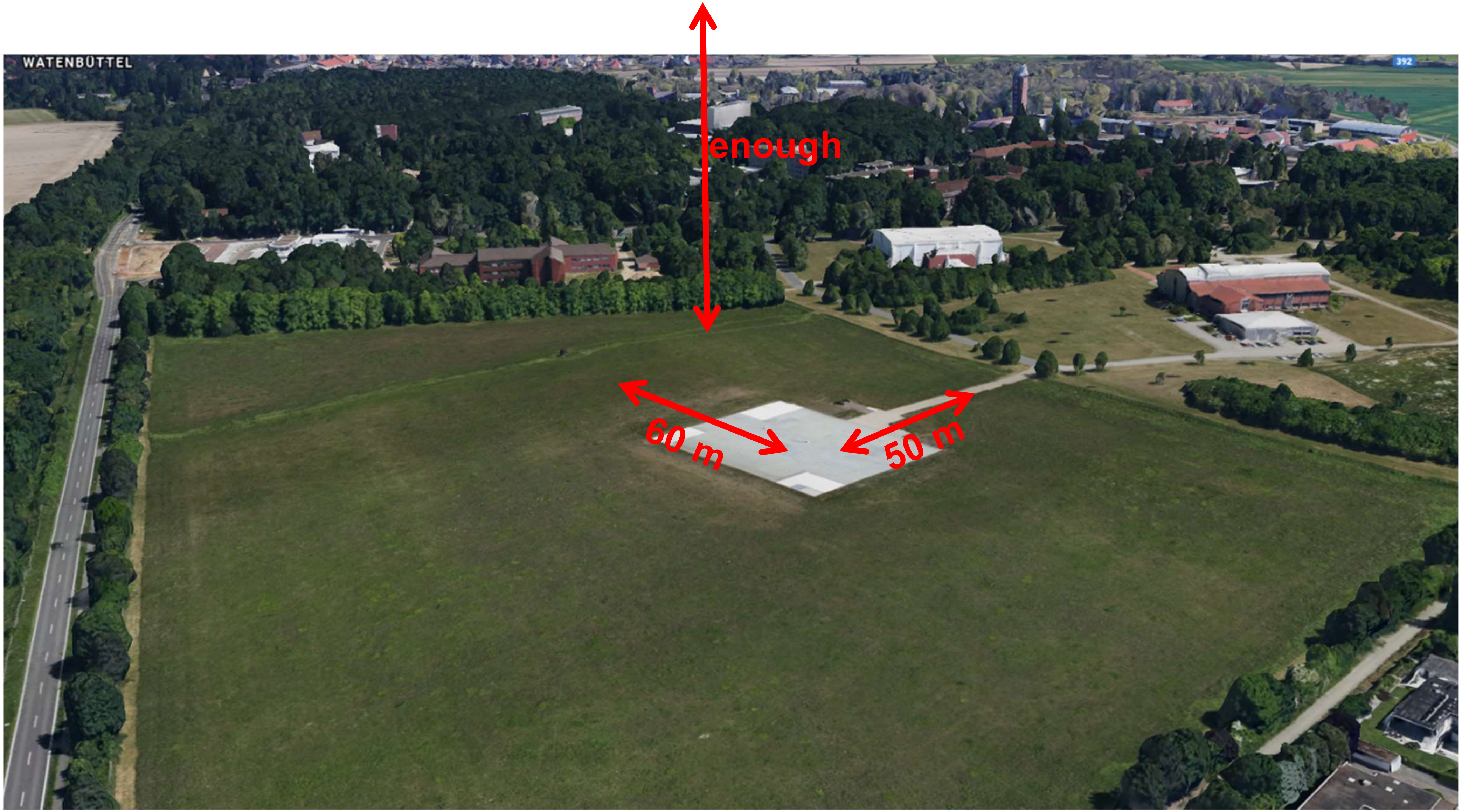


2000 kV UHVDC generator at PTB

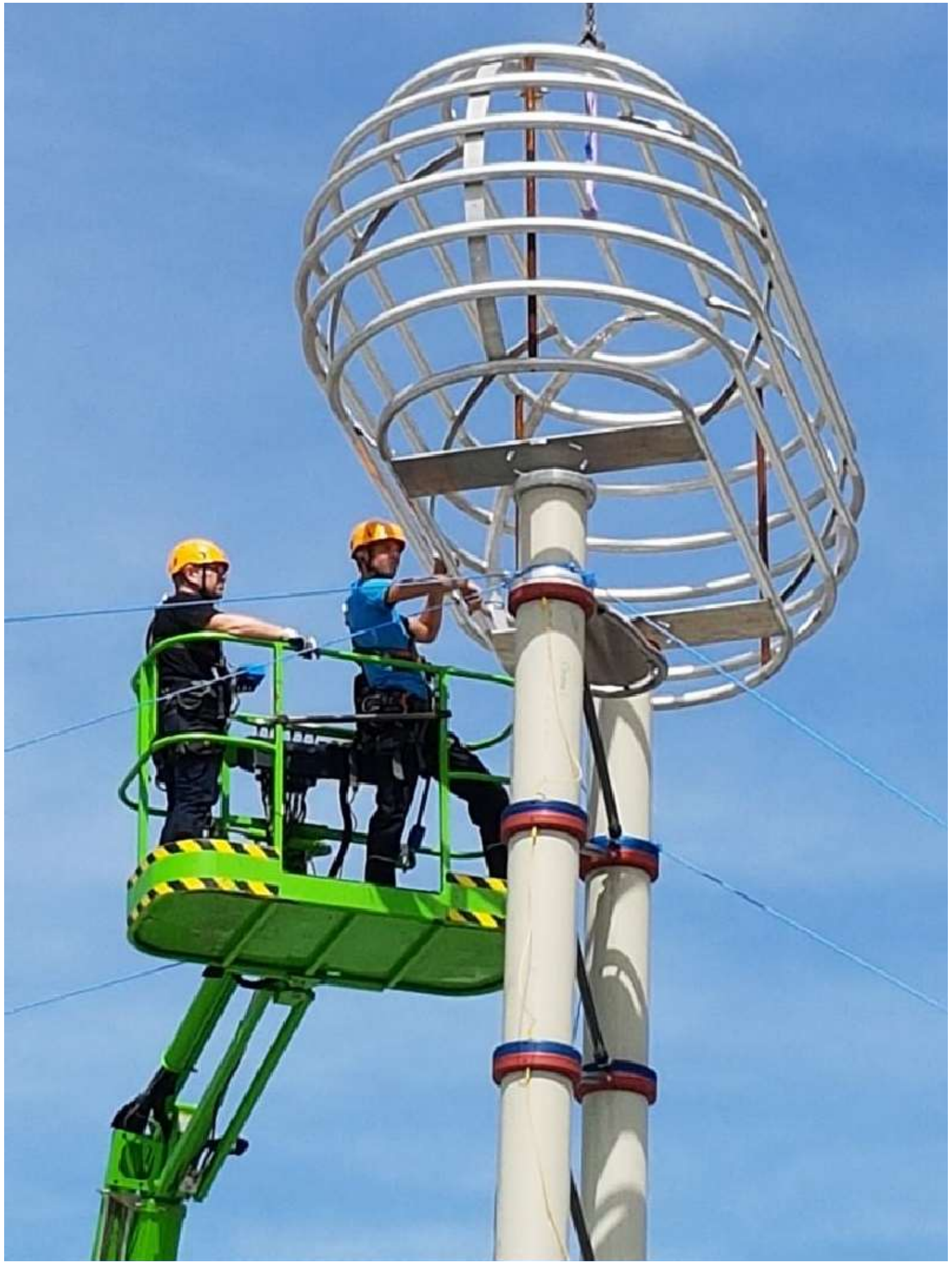
- A symmetrical voltage distribution along each electrolytic capacitor is guaranteed by a 4.7 MΩ resistor.
- The encapsulation in thick-walled polypropylene tubes protects the capacitors and aids the mechanical stability of the entire voltage multiplier.
- The setup of this voltage multiplier is shown in the right figure



Test at the open area test site of the PTB



Test at the open area test site of the PTB 2020



Test at the open area test site of the PTB 2020

Test at the open area test site of the PTB 2020

- Several weeks in summer
- Generator up to 2000 kV and divider up to 1600kV worked!
- Stability target of 100 ppm was reached

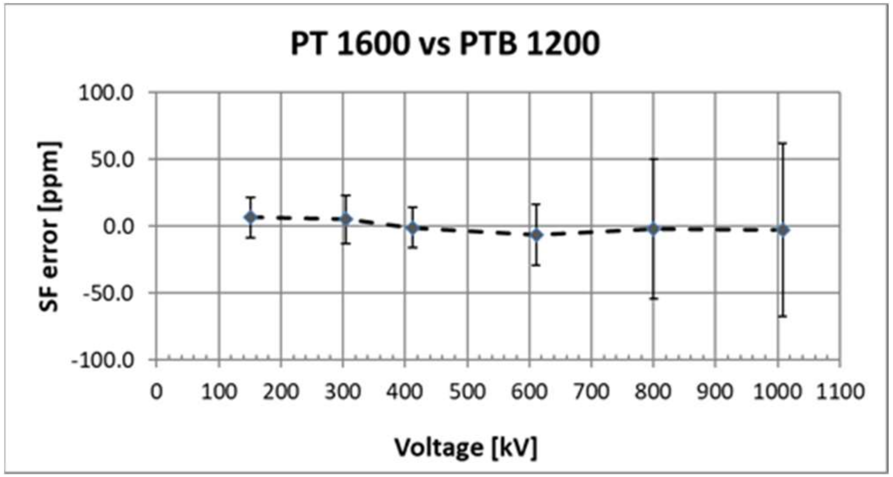
Test at the open area test site of the PTB 2022

Results of the test:

- We had corona at more than 1000 kV on the supply lines
- We need a divider for the generator to use it as a stand alone unit (building in progress – not part of the project)

PTB 1600 kV UHVDC divider calibration results

U [kV]	SF error [µV/V]	k	υ_{eff}	Exp. unc. [±%]
100 kV	6.7	2.0	110	± 0.00149
200 kV	5.1	2.0	190	± 0.00183
400 kV	-0.9	2.0	140	± 0.00150
600 kV	-6.3	2.0	120	± 0.0023
800 kV	-1.9	2.0	100	± 0.0052
1000 kV	-2.6	2.0	60	± 0.0065
Average	-0.5			
Exp. unc. (k=2)	4.0			± 0.0028

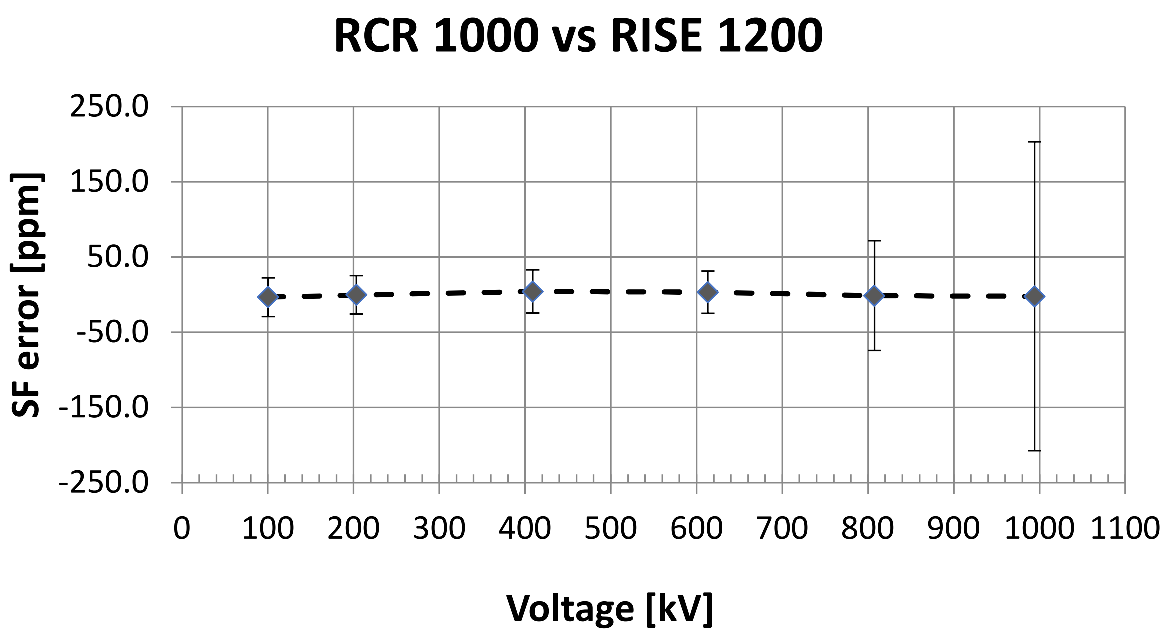


- Using the results from 150 kV to 1000 kV the scale factor (SF) stability is <1 µV/V (Table) with expanded uncertainty of 4.0 µV/V.
- A measurement with the UHVDC up to 1000 kV has an expanded uncertainty of 38 µV/V.
- Omitting the 1000 kV point, suffering from growing corona from the ring cage toroid of the UHVDC divider and the generator above 800 kV, the expanded measurement uncertainty of 28 µV/V.
- The SF stability points to an expanded measurement uncertainty for the **1600 kV UHVDC measurement system of 30 µV/V**.
- However, to hold this limit two new corona rings have been prepared for the UHVDC divider, using a double toroid with larger diameters than the two 1200 kV HVDC dividers

RISE RCR 1000 kV UHVDC divider calibration results

Tab	SF error [µV/V]	k	υ_{eff}	Exp Unc [±%]
100 kV	-3.40	2.0	110	± 0.0026
200 kV	-0.40	2.0	110	± 0.0026
400 kV	4.20	2.0	160	± 0.0029
600 kV	3.30	2.0	150	± 0.0028
800 kV	-1.40	2.0	70	± 0.0073
1000 kV	-2.20	2.0	100	± 0.0205

- The SF stability supports an expanded measurement uncertainty for the UHVDC measurement system of 30 µV/V.
- Further uncertainty analysis gives **an expanded uncertainty of 35 µV/V**



Conclusion

- Through the comparison between the modular PTB HVDC 1200 kV divider and the PTB UHVDC 1600 kV divider it has been shown to have an extremely low scale factor difference between the systems, within 10 µV/V, and an expanded measurement uncertainty of below 30 µV/V at 1200 kV.
- The measurement uncertainty of the RISE and PTB HVDC 1200 kV dividers has been shown to support an expanded measurement uncertainty of 20 µV/V.
- CMC claims for the next revision will be made for both PTB dividers, and the PTB HVDC 1200 kV divider identical to the RISE 1200 kV measurement system which a claimed expanded measurement uncertainty of 20 µV/V.
- The results for the new PTB UHVDC measurement system points toward an expanded measurement uncertainty of 30-40 µV/V at 1600 kV well below the targeted 200 µV/V.
- The results for the RISE RCR measurement system has an expanded measurement uncertainty of 35 µV/V at 1000 kV, with a future uncertainty around 40 µV/V for 1600 kV also well below the targeted 200 µV/V.

https://www.ptb.de/empir2020/fileadmin/documents/empir-2020/FutureEnergy/documents/DJI_0416.MP4

Acknowledgements

This research was performed within the project 19ENG02 FutureEnergy “Metrology for future energy transmission” and 19NRM07 HV com^2 “Support for standardisation of high voltage testing with composite and combined wave shapes”. Both projects 19ENG02 and 19NRM07 received funding from the EMPIR programme co-financed by the Participating States and from the European Union’s Horizon 2020 research and innovation programme.

EMPIR EURAMET

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