Overview of HV Cables and Connectors, Cable Procurement and Future Activities

T. Kramer, A. Ferrero Colomo, L. Ducimetiere, D. Kontelis, L. Sermeus, T. Stadlbauer - CERN

Content

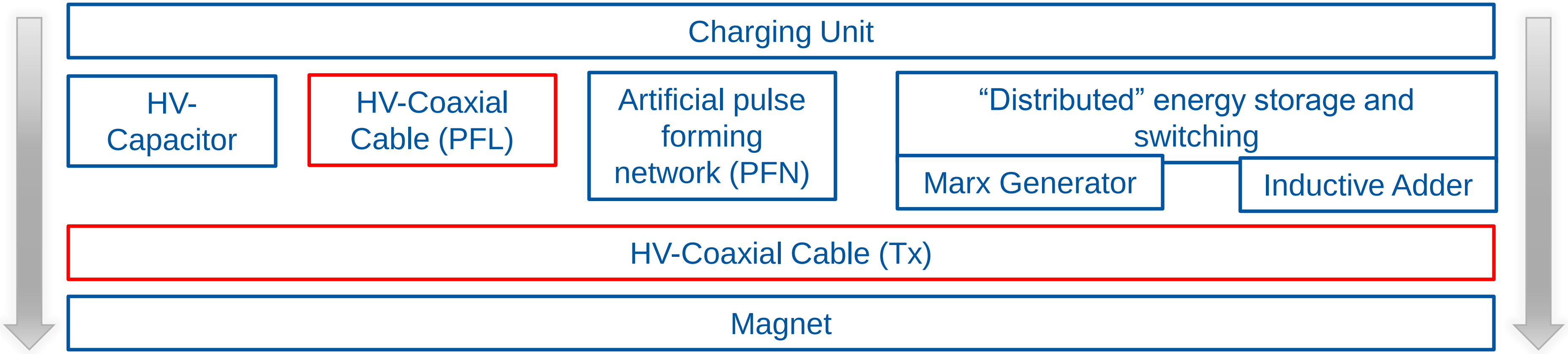
- Introduction
- Overview of CERN HV Kicker Cables and Connectors
- Procurement Activities
- R&D / HV testing / Future Strategies

Coaxial HV-Cable Kicker Applications at CERN

- For **energy storage** and pulse shaping pulse forming lines (**PFL**) or artificial pulse forming networks (**PFN**) can be used.

- A **power switch** is needed to switch the charged “energy storage” to the load. Spark gaps (not anymore at CERN), Thyratrons, Ignitrons, Solid state switches etc. are frequently used.

- **Transmission cables** are used to connect the pulse generator with the magnet.



Charging Unit

HV-Capacitor

HV-Coaxial Cable (PFL)

Artificial pulse forming network (PFN)

“Distributed” energy storage and switching

Marx Generator

Inductive Adder

HV-Coaxial Cable (Tx)

Magnet

Coaxial HV-cables for kicker pulse generation and transmission

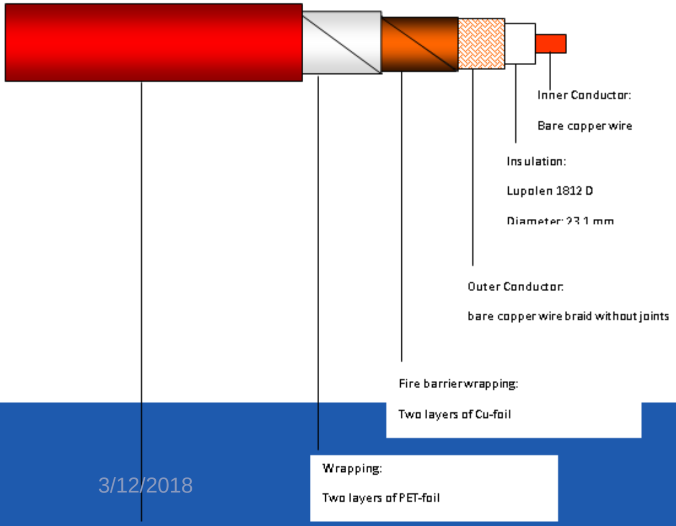
w.r.t. DC HV cables for fast transient events different **requirements** are needed:

- Matched and homogenous **impedance**
  (to avoid a loss of kick strength and reflections along the line)
- Low **attenuation / losses**
  (to avoid droop and pulse distortion)
- High **dielectric strength**
  (to support voltages high enough to drive the required current)

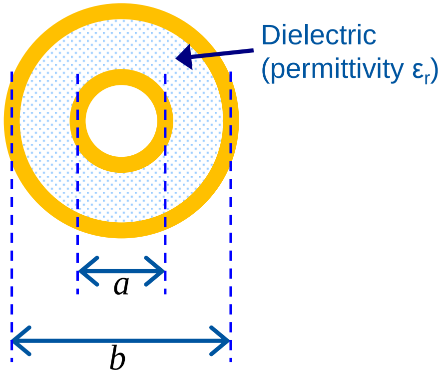
Additional Coaxial Cables Requirements

For use in **accelerator applications** additional requirements might apply:

- **Radiation resistant**
- **Fire resistant**, low smoke, toxicity of gases etc.
- Acceptable **bending radius** for installation
- Velocity of propagation
- …



Coaxial Cable Basics



Cross-section of coaxial cable

Capacitance per metre length (F/m):

$$C = \left(\frac{2\pi\varepsilon_0\varepsilon_r}{ln\left(b/a\right)} \right)$$

Inductance per metre length (H/m):

$$L = 2 \cdot 10^{-7} \cdot ln\left(\frac{b}{a}\right)$$

Characteristic Impedance (Ω):
(typically 20 Ω to 50 Ω).

$$Z_0 = \sqrt{\frac{L}{C}}$$

Delay per metre length:
(~5ns/m for suitable coax cable).

$$\tau = \sqrt{L \cdot C}$$

Where:

a	is the outer diameter of the inner conductor (m);
b	is the inner diameter of the outer conductor (m);
ε_0	is the permittivity of free space ($8.854\text{x}10^{-12}$ F/m).

- Material, diameters and construction type can be selected
    - (b-a) needs to withstand U_{max}
    - Attenuation Losses

Attenuation / Losses (I)

- Resistive losses

  skin effect, proximity effect

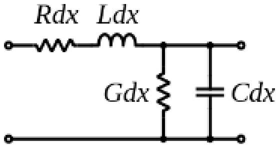
$$\alpha = \alpha_C + \alpha_D + \alpha_G + \alpha_R$$

$\alpha_C = \text{loss due to metal conductivity}$

$\alpha_D = \text{loss due to dielectric loss tangent}$

$\alpha_G = \text{loss due to conductivity of dielectric}$

$\alpha_R = \text{loss due to radiation}$



material conductivity

$$\alpha_{\text{conductors}} = \alpha_c = \frac{11.39}{Z} * \sqrt{f} * \left| \frac{\sqrt{\rho_{rd}}}{d} + \frac{\sqrt{\rho_{rD}}}{D} \right| \quad \frac{\text{dB}}{\text{m}}$$

diameter

- Losses in the dielectric

$$\alpha_D = 92.0216\sqrt{\varepsilon_R}\,\tan\delta \cdot F_{GHz}\,(dB/meter)$$

$$\alpha_G = 8.686 \times \frac{G' \cdot Z_0}{2}\,(dB\,/\,meter)$$

permittivity :

$\varepsilon = \varepsilon' - j\varepsilon''$

loss tangent :

$\tan\delta = \frac{\varepsilon''}{\varepsilon'}$

- Radiated losses

  for high frequencies only

  (less important for our applications)

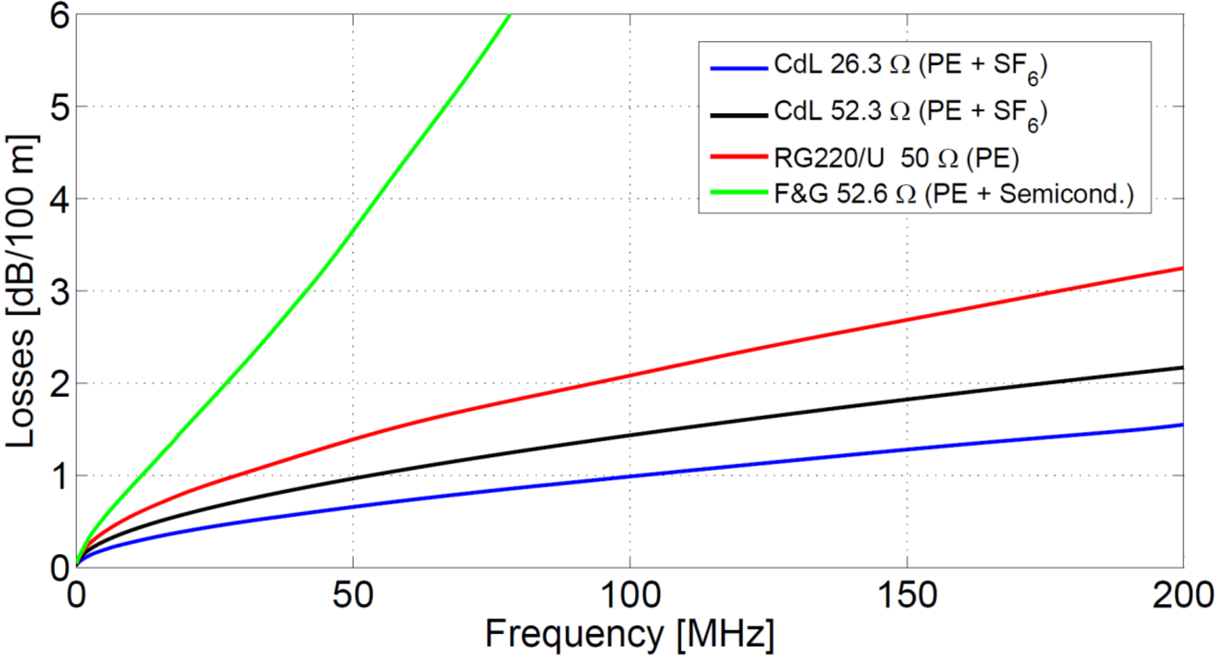
Attenuation / Losses (II)

- At CERN SF6 gas filled cables have the best performance. Their cable construction and dielectric are chosen to minimize losses.

- Solid PE insulated cables show increased losses in the “higher” frequency ranges (RG220/U).

- Semiconducting layers (e.g. F&G 52.6 Ω) dramatically increase the losses following a 2nd order polynomial function.

Courtesy: A. Ferrero Colomo



Cable name	**Outer / Inner cond.** ⌀[mm]	**Impedance**	**Insulation**
CdL	50 / 26.5	26.3 Ω	PE + SF_6
CdL	27 / 7.5	52.6 Ω	PE + SF_6
RG220/U	23 / 6.6	50 Ω	PE
F&G	24.6 / 5.6	52.6 Ω	PE + Semicond.

Cables for Kicker Applications at CERN

Basic requirements:

- Low attenuation
- “High” BDV
- Radiation hard
- LSZH (IS23)

The combination of these requirements is unique

In addition:

- Various operating voltages
- Various Impedances

Consequence:

- Only coaxial cable types in use
- 3 basic cable types (but many “derivatives”):
  - “Classical” PE extruded coaxial (>50km)
  - Multicore coaxial (~2km)
  - SF6 gas filled (~13km)

SF6 gas filled coaxial HV-cable

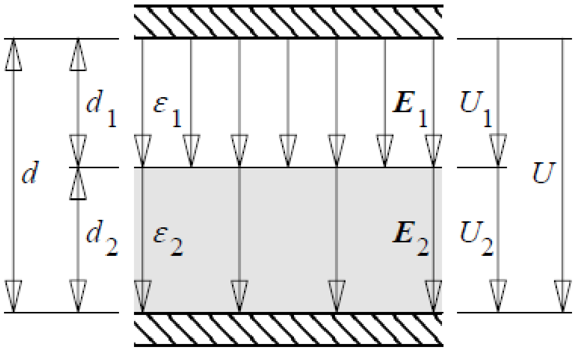
- Dielectric:
  - thin PE foils wrapped around inner conductor,
  - pressurized with SF6 gas - fills all voids.
- Superior dielectric strength.
- Lower velocity factor due to low density PE core.
- No issues with surface discharge of spacers (usually used in large diameter air insulated coax cables).
- Low attenuation/losses (0.3dB/100m @10MHz due to large ID, no semiconducting layers).

- ~13 km in use at CERN (since the seventies, no issues seen so far).
- Nominal voltages up to 80 kV.

Disadvantage:

- Vacuum and SF6 gas systems needed.
- Special gas tight connectors (in house production).
- No quick disconnect.
- Cable relatively stiff and heavy (FAK: 1PFL =2.6 t).
- Not produced anymore!

Remember: Voids / cracks in a dielectric



$$\frac{E_1}{E_2} = \frac{\varepsilon_2}{\varepsilon_1}$$

Dielectric with lower ε_r will take higher stress!

Compare PE with voids (air):

Dielectric constant:

PE = 2.2; Air=1; SF6 =1;

Dielectric strength:

PE = 20-160 MV/m; Air = 3 MV/m; SF6 = 90MV/m @10bar;

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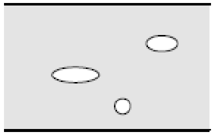
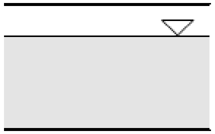
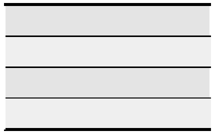


*Hohlräume,
Lunker, Blasen*

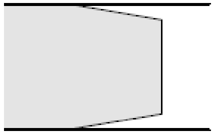
*Risse, Spalte,
unvollkommene
Schichtungen*



*Abgesunkener Öl-spiegel in einem
ölisolierten Gerät*



*Geschichtetes Kon-densatordielektrikum
(Papiere/Folien)*



*Tripel-Punkte
bei Isolierstoff-stützern*

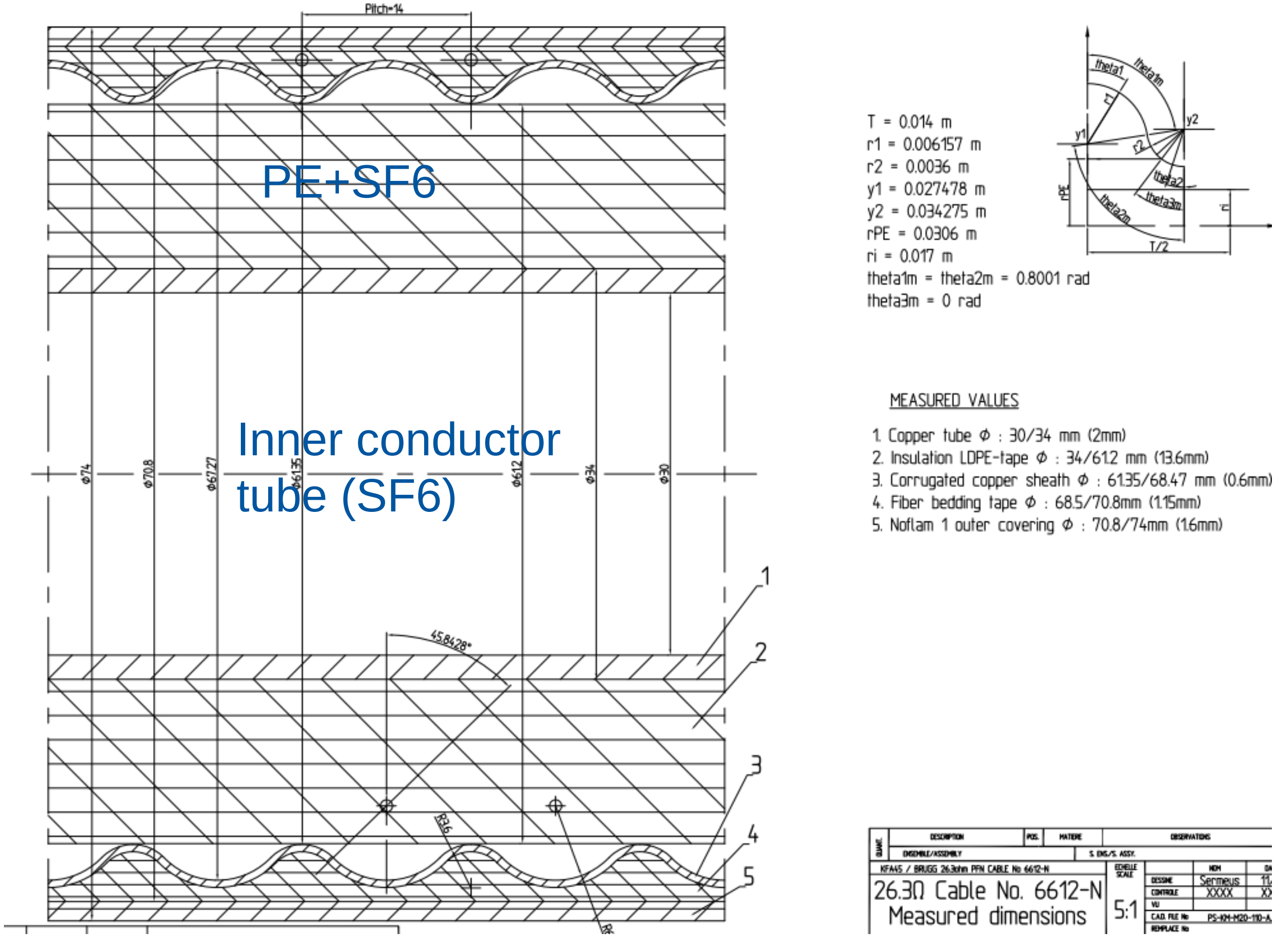
Voids filled with SF6 (instead air)
support an up to 30 times higher stress!

SF6 gas filled coaxial cables at CERN

Impedances:

- 15Ω
- 15.7Ω
- 25Ω
- 26.3Ω
- 30Ω
- 52.6Ω

Build in 1964 – 1978, 1992



PE+SF6

Inner conductor tube (SF6)

T = 0.014 m
r1 = 0.006157 m
r2 = 0.0036 m
y1 = 0.027478 m
y2 = 0.034275 m
rPE = 0.0306 m
ri = 0.017 m
theta1m = theta2m = 0.8001 rad
theta3m = 0 rad

MEASURED VALUES

1. Copper tube ϕ : 30/34 mm (2mm)
2. Insulation LDPE-tape ϕ : 34/61.2 mm (13.6mm)
3. Corrugated copper sheath ϕ : 61.35/68.47 mm (0.6mm)
4. Fiber bedding tape ϕ : 68.5/70.8mm (1.15mm)
5. Noflam 1 outer covering ϕ : 70.8/74mm (1.6mm)

KFA45 / BRUGG 26.3ohm PFN CABLE No 6612-N

26.3Ω Cable No. 6612-N
Measured dimensions

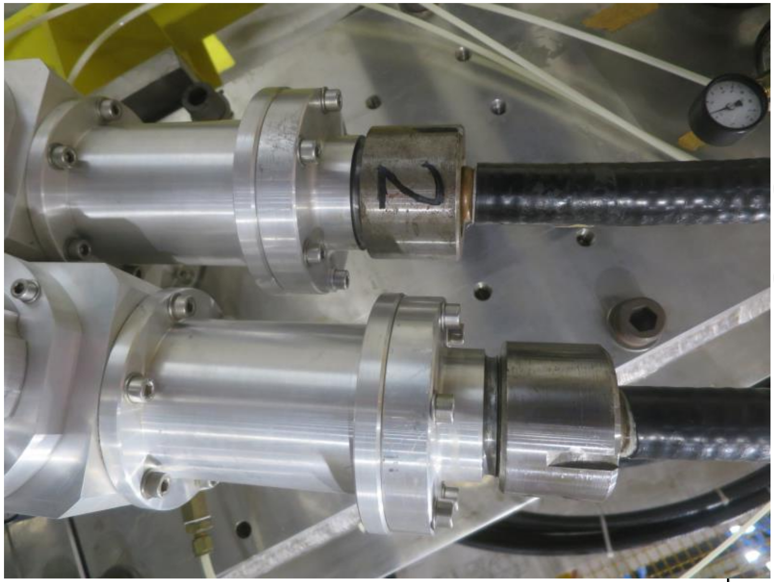
5:1

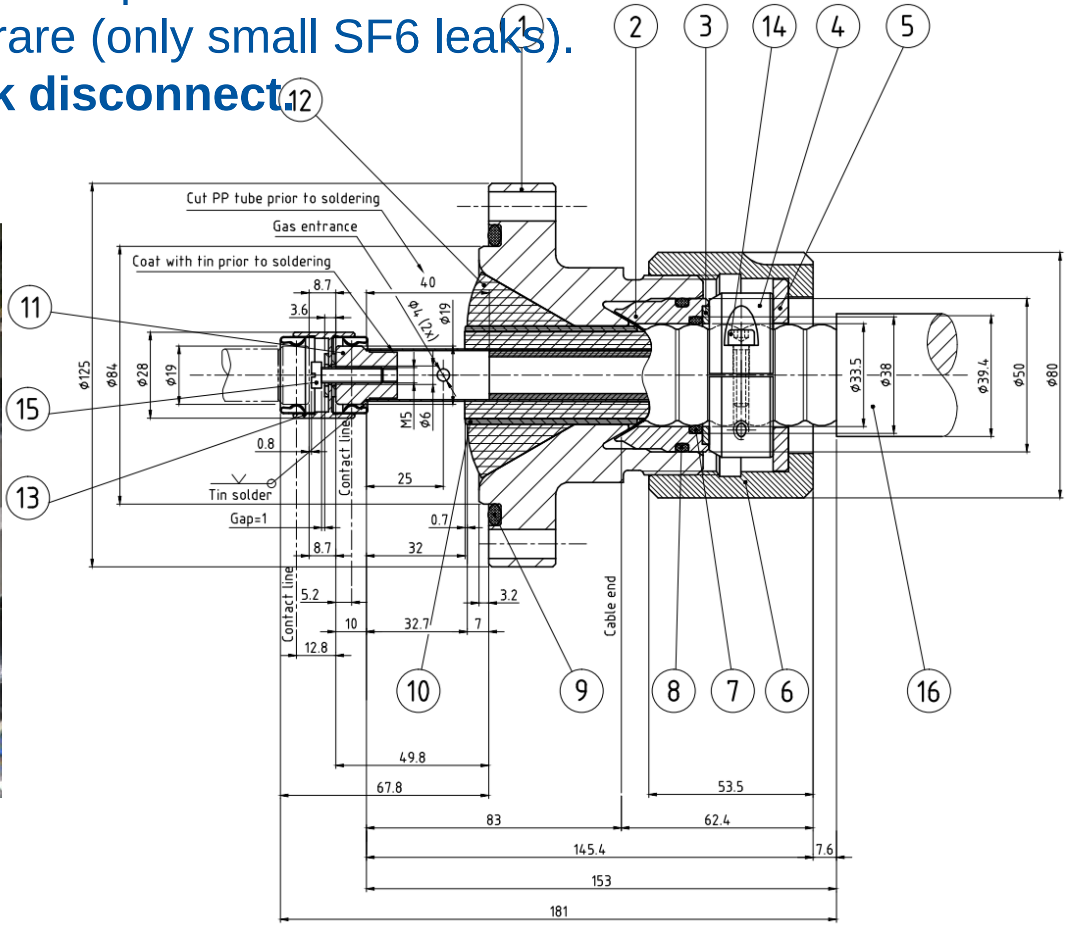
DESSINE Sermeus
CONTROLE XXXX
C.A.D. FILE No PS-KM-M20-110-A

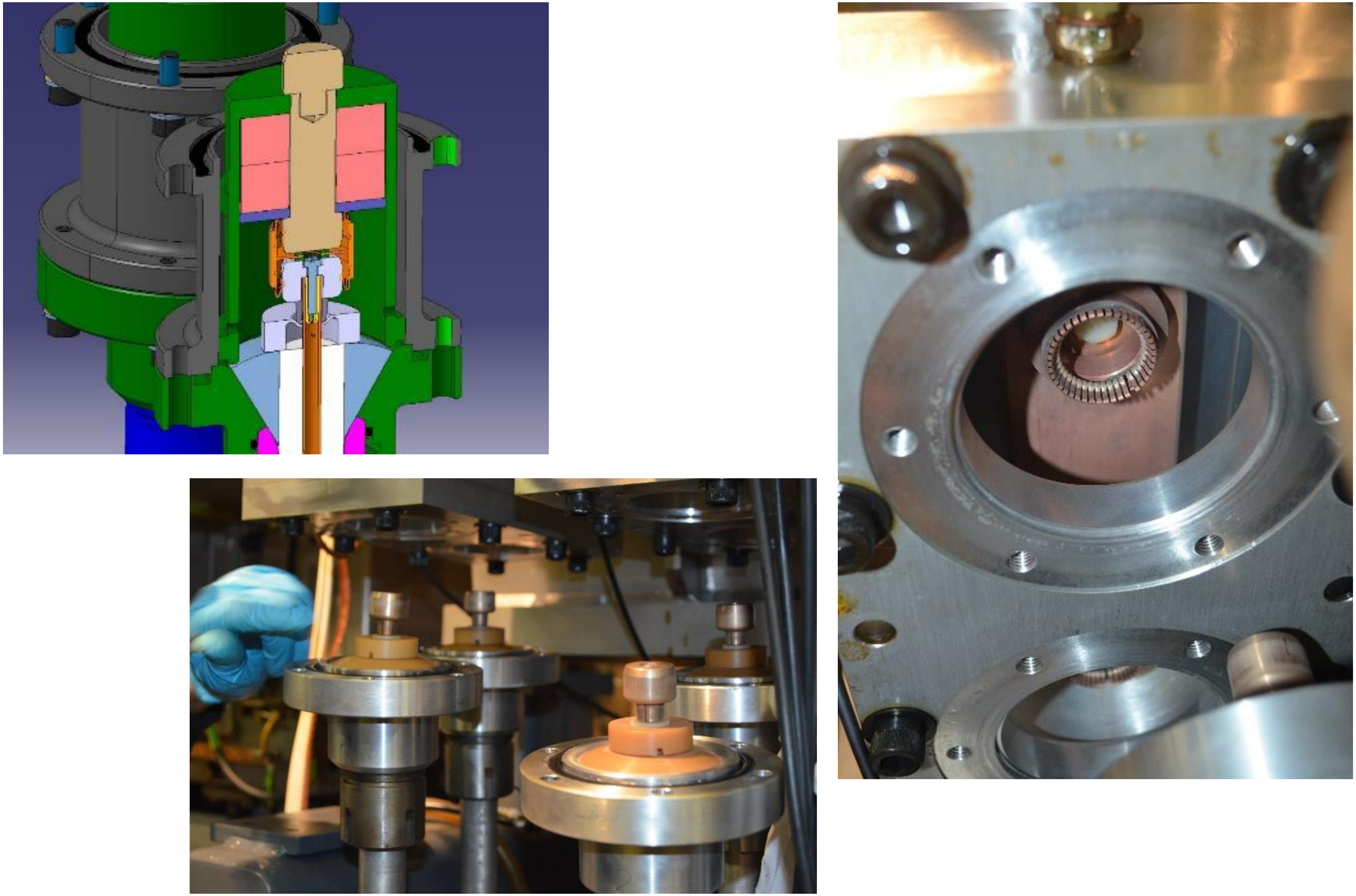
PFL cable cross section

Connectors for SF6 gas filled coaxial cables

- **Robust design** developed in house.
- Usually connection box is SF6 gas filled too.
- Many variants **up to 80kV, 5kA** in operation.
- **Reliable** - operational issues rare (only small SF6 leaks).
- **Maintenance effort, no quick disconnect.**



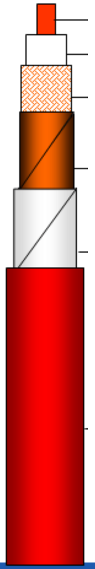




RG-220 like cables

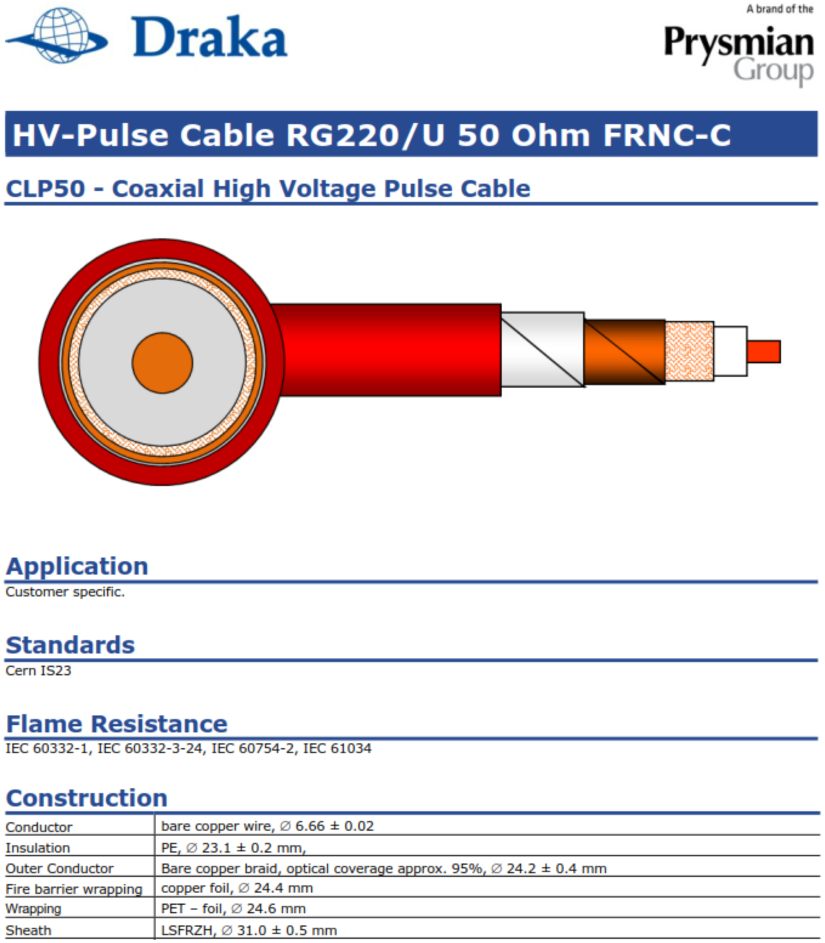
- Workhorse at CERN (>50km in operation).
- RG-220 initially a US military standard (MIL-C-17).
  - Not many “real” RG-220/U cables remaining… (as PVC jacket not accepted anymore at CERN for new cable deliveries)
  - …but many derivatives.
  - RG-220 often (wrongly?) used as generalized expression.

- Many impedances: 18, 20, 50, 30, 52.6, 60 Ω
- From different suppliers: Draka, F&G, PKI, Sterling…
- …and each with different connectors.



CLP50

- Improved RG-220/U.
- 50Ω coaxial cable without semiconductor.
- Compliant with CERN IS23.
- Factory tested, 35kV RMS.
- At CERN used for operational voltages up to 40kV pulsed.
- Used with LEMO and in house made connectors.
- “Regular” consumption due to exchange of irradiated cables in critical systems.



Draka

A brand of the Prysmian Group

HV-Pulse Cable RG220/U 50 Ohm FRNC-C

CLP50 - Coaxial High Voltage Pulse Cable

Application

Customer specific.

Standards

Cern IS23

Flame Resistance

IEC 60332-1, IEC 60332-3-24, IEC 60754-2, IEC 61034

Construction

Conductor	bare copper wire, ∅ 6.66 ± 0.02
Insulation	PE, ∅ 23.1 ± 0.2 mm,
Outer Conductor	Bare copper braid, optical coverage approx. 95%, ∅ 24.2 ± 0.4 mm
Fire barrier wrapping	copper foil, ∅ 24.4 mm
Wrapping	PET – foil, ∅ 24.6 mm
Sheath	LSFRZH, ∅ 31.0 ± 0.5 mm

Quantities in Operation

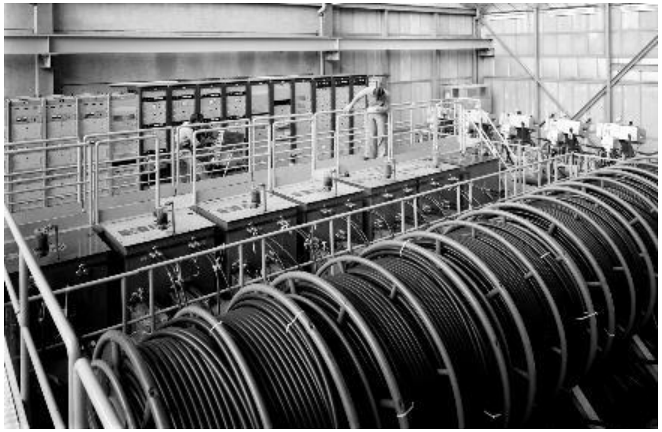
Top 3:

~20 km PS extraction (PFL)

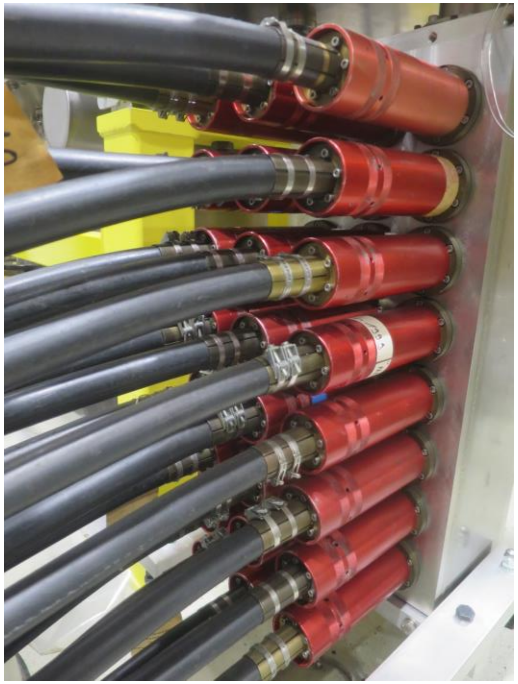
~12 km for SPS injection (Tx)

~10 km for SPS beam dump kickers (Tx)

….



Reels of PFL used at the PS complex (as old as the photograph!)



D. Kontelis

(Incomplete) Overview of Extruded Cables

Name	CERN type	Inner Conductor		Outer Conductor	Max. attenuation (dB/km)					C (1kHz, pF/m)	Test voltage (50 Hz, r.m.s., kV)	Zo (Ω)	Comment
		Type	Diameter (mm)	Diameter (mm)	100 kHz	250 kHz	500 kHz	1 MHz	10 MHz				
Draka 18 Ohm IK	CPP18	Al-tube	14.5	27.2	1	1.6	2.5	3.5		326	45	18	semiconducting layer
Draka 20 Ohm	CPP20	Cu-tube	15	26.4	0.9	1.5	2.1			350	35	18	semiconducting layer
Draka 30Ω cable 9.3/21	-	Cu-tube (0.25)	9.3	21.0					23	183	30	30	semiconducting layer
Cable 40 kV DC IKD	CMP48	Bare Cu wire, E - Cu 58	2	10.9						165	60	45	
Cable 40 Ohm MKB	CLPS40	Bare Cu wire, E - Cu 58	6.66	17.8	0.9			3		140	30	39	
F&G 50 Ohm 60 kV MKA	SPS/ABT/GS/D5-146	solid Cu wire	10.4	40.7	0.4	0.7	1	1.5			60	50	obsolete
RG220 50Ω	CLP50	Bare Cu wire	6.66	24.2	0.5			1.7	5.7	100	35	50	
RG220 52.6Ω	CLP52	Bare Cu wire	6.2	24.1	0.5			1.7	5.7	96	35	52.6	
PKI 60Ω		Bare Cu wire	5.16	23.1						84	35	60	obsolete
Multicore 4x7.0L	-	Stranded Cu wires 12x1.3	6.65	11.65	2.6			9.2	31	400000	18kV	17	semiconducting layer

Connectors: LEMO

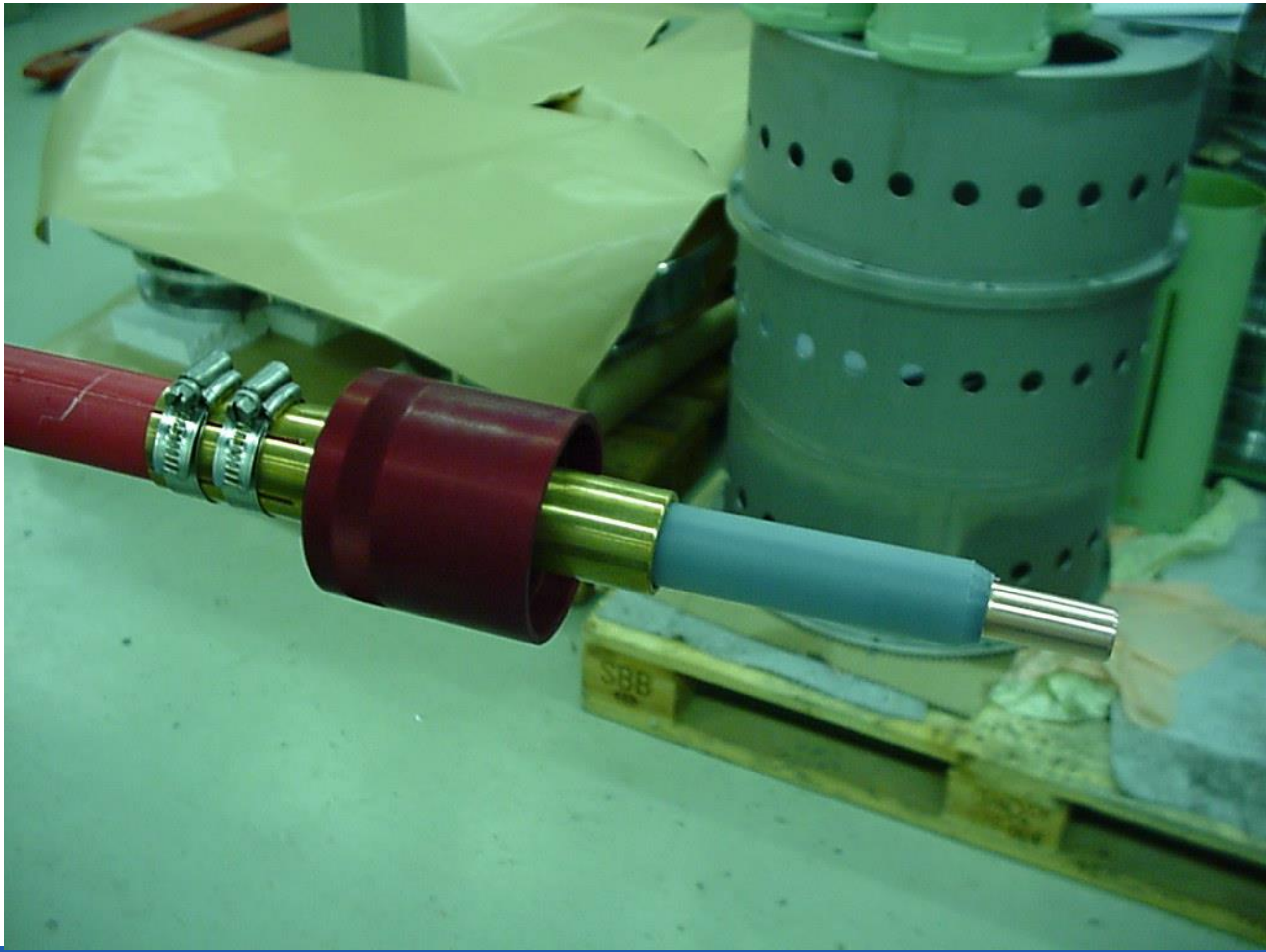
- LEMO HT50
- Commercially available
- Relatively easy to mount (still requires cable machining but no moulding process).
- Quick disconnect.
- In use for system voltages up to 40kV.
- With regular maintenance (greasing) no major operational issues.

Connectors: LEMO (II)

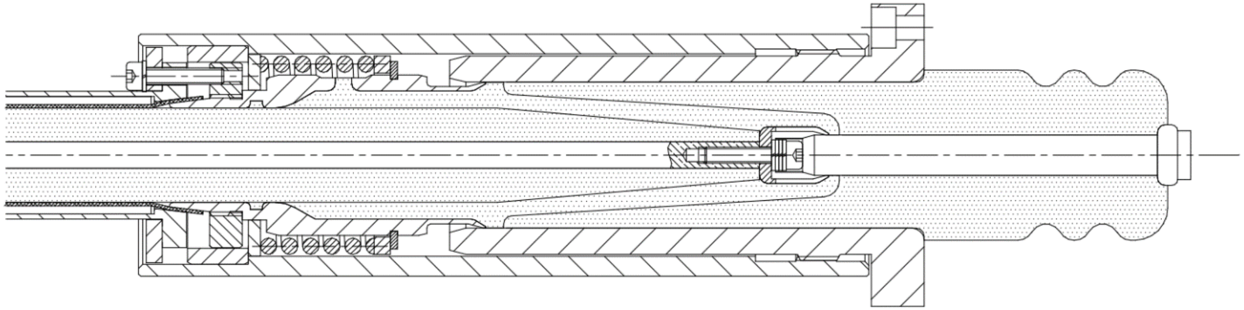
- Several smaller LEMO types will be used in the future (e.g. new BI-DIS, 15kV).

Connectors: Made in house (I)

- Different designs available.
- Mechanical assembly process without moulding.
- Screws to receptacle (needs tool). Takes longer to disconnect w.r.t. LEMO.



Connectors: Made in house (II)



- Moulded version (Scotchcast 815).
- Better HV performance than HT50.
- Used for critical systems.
- Cable machining, moulding and assembly takes some time.


FEVRIE
FEVRIER

60 kV version (obsolete)

70 kV version

- Used for short distances only (PFN to switch).
- Difficult to machine (large diameter, tolerance)

Other…

Several other cables and connectors in use mainly for connection of HV power supplies to charging units.

Not part of this presentation.

Connectors – main issues

- Almost no issues concerning BDV.
- Some contact erosion seen for high currents (5-6kA) and corrected by using a self centering multicontact design.
- Most of the issues are of mechanical nature (damage while connecting / disconnecting).

Procurement and Future Activities

- SF6 gas filled cable replacement.
- Continuous replacement of irradiated cables.
- R&D on new cables and connectors.

SF6 gas filled cable replacement (I)

- Initally tried to replace cables 1:1.
- **Very limited market** for SF6 gas filled cables (only CERN ?).
- Also CERN only needs **small quantities** (~2-3km per system).
- **Demanding specification** (85kV, low attenuation, tolerances (must match existing system!)).
- **Long and difficult procurement process.**
- Finally found one manufacturer:
  - Setting up the production, prototyping, pre-series and series production however **very expensive**.
  - Reengineering and production **risks**.
  - Would still be the same **“old” technology**.
  - **SF6 gas handling** getting more and more restricted.

SF6 gas filled cable replacement (II)

Updated strategy: No 1:1 replacement.

Alternatives to SF6 gas filled cables

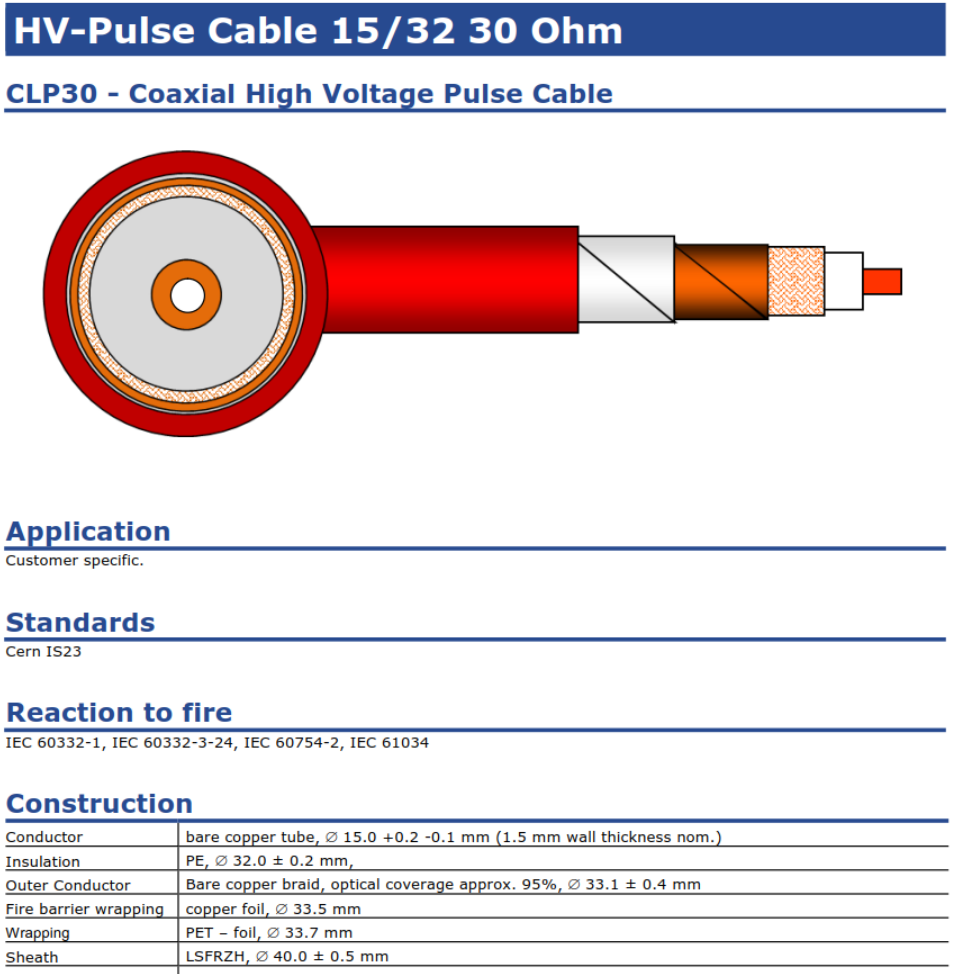
- **New generator technologies**
  - 80kV, 3kA, tr<100ns still challenging

- **Improved PE extruded cables**
  - No manufacturer so far willing to develop, produce (and guarantee) 80kV cable without semiconducting layer.
  - Started initiatives together with manufacturer

New CLP30 Prototype from Draka

- 30Ω, no semiconducting layer
- Low attenuation
- Good BDV w.r.t. RG220
- Potential for future optimization towards higher operational voltages.

- CERN will profit from low attenuation (SF6 Tx cable replacement) and higher BDV.



HV-Pulse Cable 15/32 30 Ohm

CLP30 - Coaxial High Voltage Pulse Cable

Application

Customer specific.

Standards

Cern IS23

Reaction to fire

IEC 60332-1, IEC 60332-3-24, IEC 60754-2, IEC 61034

Construction

Conductor	bare copper tube, ∅ 15.0 +0.2 -0.1 mm (1.5 mm wall thickness nom.)
Insulation	PE, ∅ 32.0 ± 0.2 mm,
Outer Conductor	Bare copper braid, optical coverage approx. 95%, ∅ 33.1 ± 0.4 mm
Fire barrier wrapping	copper foil, ∅ 33.5 mm
Wrapping	PET – foil, ∅ 33.7 mm
Sheath	LSFRZH, ∅ 40.0 ± 0.5 mm

Alternatives: Modified Heliflex cable

Basic Idea: Take OTS Heliflex cables and modify the dielectric

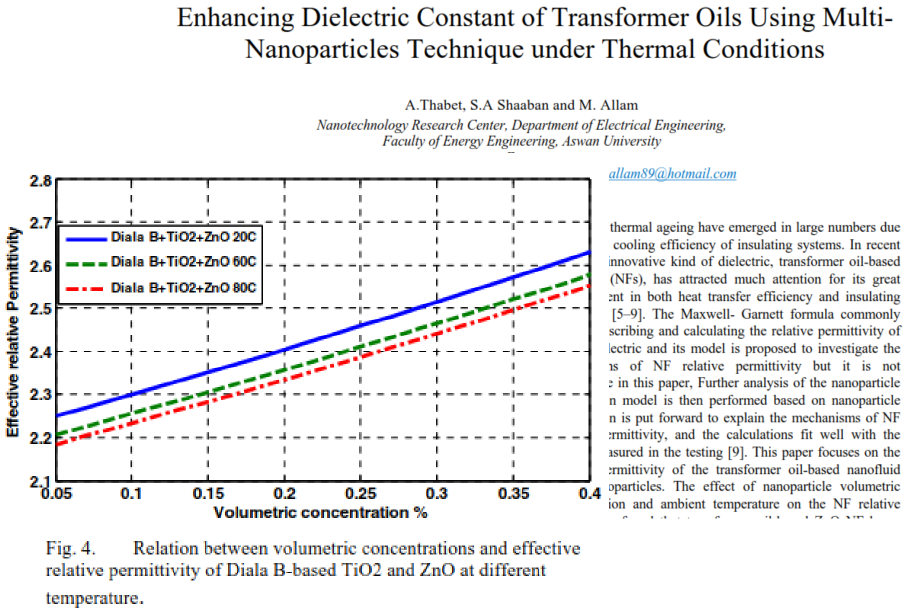
e.g. fill with oil: Diala (Er 2.2, Midel 7131 (Er 3.2) or Theso (Er 15)
Adjust Er (hence impedance!) with Nanoparticle additives?

Advantage:

- OTS,
- Versatile (one fits all),
- Perfect impedance match possible!

Disadvantage:

- Oil needed, bulky
- Complex? (Control impedance)
- BDV?



Enhancing Dielectric Constant of Transformer Oils Using Multi-
Nanoparticles Technique under Thermal Conditions

A.Thabet, S.A Shaaban and M. Allam
Nanotechnology Research Center, Department of Electrical Engineering,
Faculty of Energy Engineering, Aswan University
allam89@hotmail.com

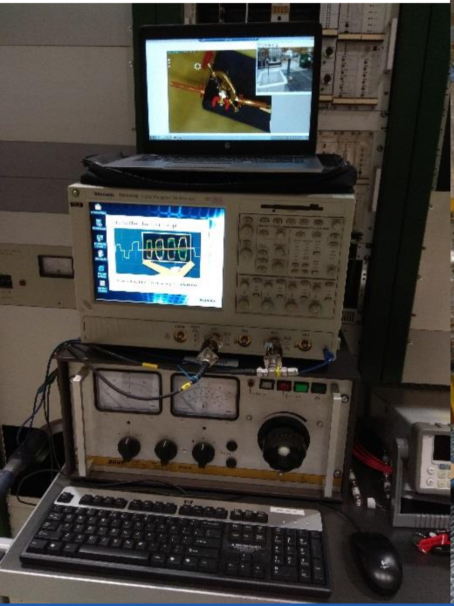
thermal ageing have emerged in large numbers due
cooling efficiency of insulating systems. In recent
innovative kind of dielectric, transformer oil-based
(NFs), has attracted much attention for its great
ent in both heat transfer efficiency and insulating
[5–9]. The Maxwell- Garnett formula commonly
scribing and calculating the relative permittivity of
lectric and its model is proposed to investigate the
ns of NF relative permittivity but it is not
e in this paper, Further analysis of the nanoparticle
n model is then performed based on nanoparticle
n is put forward to explain the mechanisms of NF
ermittivity, and the calculations fit well with the
asured in the testing [9]. This paper focuses on the
ermittivity of the transformer oil-based nanofluid
oparticles. The effect of nanoparticle volumetric
ion and ambient temperature on the NF relative

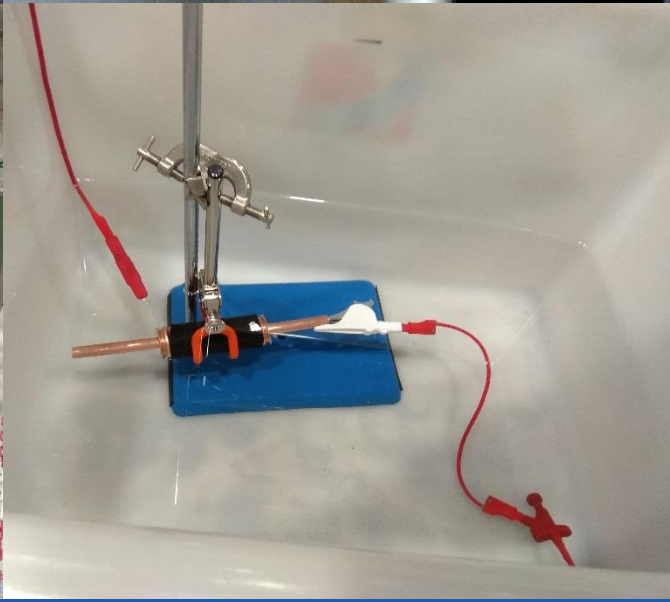
Fig. 4. Relation between volumetric concentrations and effective relative permittivity of Diala B-based TiO2 and ZnO at different temperature.

Testing ongoing

- Low cost PD test place
- Small scale prototype (1-1/8”)
- 1st measurements BDV air ~21kV / oil ~60kV (terminations?)

Courtesy: T. Stadlbauer, D. Kontelis





Summary

- **Coaxial HV cables** are still a **central part** of pulsed power activities for kicker systems at CERN.
- Various coaxial cables and connectors in operation at CERN.
- Only operational issues seen belongs to cable/connector handling during connection/disconnection activities.
- Activities ongoing to **replace SF6 gas** filled cables.
- Recent R&D efforts in **new pulse generator technologies** show already promising alternatives (e.g. Inductive adder, Marx-Generator etc..).

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