Pulse Cable for TESLA Modulators

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1 Introduction

Modulators are used to generate the pulsed power for the klystrons of the superconducting linear accelerator TESLA. The high voltage pulses have a rectangular shape with a voltage up to 120 kV. The electrical power during the pulse is typically 15 MW and can be up to 16.8 MW. The pulse length is 1.7 ms with a repetition rate of 5 Hz, for app. 10 % of the modulators it is 10 Hz. Inside the modulators the switched voltage is at the 10 kV level. Via a pulse transformer the HV is achieved.

Due to the radiation inside the TESLA tunnel and the accessibility of the units the power part of the modulators shall be installed into the service halls. However the transformer tank and the klystrons have to be inside the tunnel near the cavities. The energy has to be transported from the modulator to the transformer via pulse cables.

2 Demands for the cable

The pulse cables have to meet the following specifications:

- The cable shall not generate any stray fields in the tunnel
- The ohmic losses shall be app. 2.0 % in average
- The losses caused by the skin effects need to be low in order to keep the losses low
- There shall only be a low damping of the high frequencies

3 Cable construction

The demand for the low stray fields gives the general design of the cable which is triaxial as shown in Fig. 1. The inner conductor is at the high voltage level (10 kV) of the modulator. The middle conductor carries the return current at the bouncer voltage level of +/- 1 kV. The cross section has to be 300 mm² copper. This is chosen for the inner and outer conductor. The shield is chosen as 16 mm² aluminum or copper foil. As insulator XPE (cross linked Polyethylen) is used.

The rise time of the voltage pulse of the modulator is 10 µs. The current rise time is dependant of the transformer and cable inductance. It is between 140 and 240 µs.

One solid cable having a 300 mm² cross section can not be taken. The occurring skin effect for such a cable does not allow the current to penetrate into the inner part of the conductor. During the pulse the current just flows at the outer rim of the conductor and enters about 2 mm into the material. Additionally the inner inductance of the such a cable leads to a to long rise time of the pulse.

To compensate this effect two solutions are possible:

- The inner conductor of the cable can be built as a tube with a thickness of app. 2 mm. By this the diameter of the entire cable is increased
- There will be several smaller triaxial cables put in parallel. The sum of the cross sections equals to 300 mm².

In discussion with the cable manufacturer the solution with several small cables is preferred for production reasons. A standard cross section of cables is 70 mm² . Therefore only minor changes have to be done to fabricate a cable with 75 mm². This results in a lower price. For TESLA four cables in parallel with a cross section of 75 mm² each are chosen. The impedance of the four cables in parallel is 6.45 Ω. Solutions for the constructions of cable end pieces and cable sleeves are available.

The diameters of the cable are:

Inner conductor Cu bare fine strand	10 mm
Semiconductor layer	10.2 mm
Insulation VPE	19.2 mm
Semiconductor layer	19.4 mm
Outer conductor Cu bare fine strand	21.8 mm
Semiconductor layer	22.0 mm
Insulation	27.2 mm
Semiconductor layer	27.4 mm
Aluminum foil	27.8 mm
Outer sheath	33.8 mm

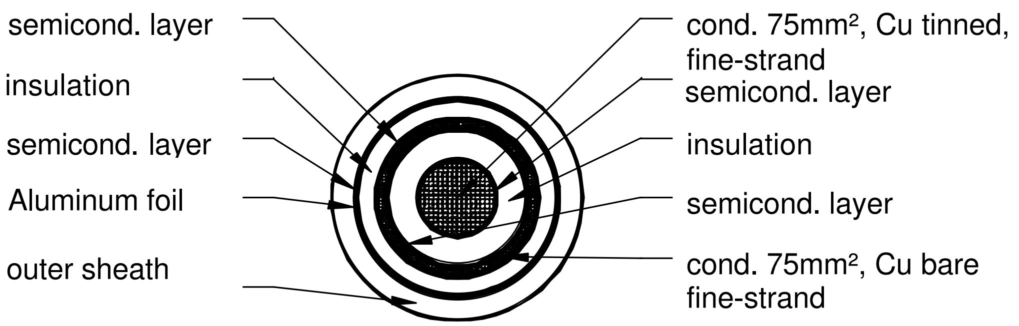

Fig .1: Cross section of the cable

4 Simulation results

The behavior of the cable is simulated in a pSpice model and analytically in [1] in good agreement.
Since the cable impedance is not matched when a transformer is connected to the cable a matching network as shown in Fig. 6 is used.

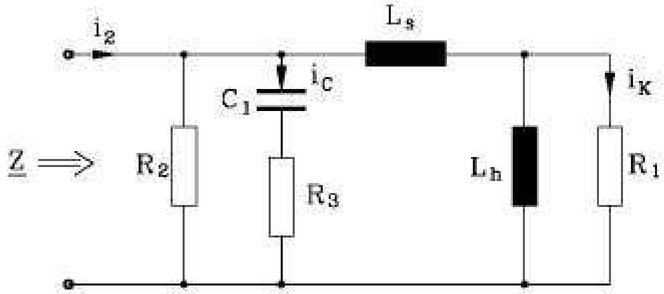

Fig. 6: Impedance matching network

The values for the components are:
R1 = 6 Ω, corresponding to the klystron resistance transformed to the primary side of the transformer. The nonlinear behavior of the klystron is not simulated.
Ls = 200 μ H, transformer leakage inductance
Lh = 2 H, main inductance of the transformer
C1 = 1 μ F, matching network
R2 = 100 kΩ, matching network
R3 = 10 Ω, matching network

The simulation results from [1] are shown for a set of four parallel cables of 100 m length (Fig. 7), 1 km length (Fig. 8), 2.5 km length (Fig. 9) and 3 km length(Fig. 10).

The occurring over shoot of voltage u_2 is at the primary side of the transformer and does not affect the klystron. The klystron voltage corresponds to the current i_k. The rise time delay of the klystron voltage due to the cable is in the order of 90 to 100 μs. The rise time for a 3 km long cable is < 250 μs.

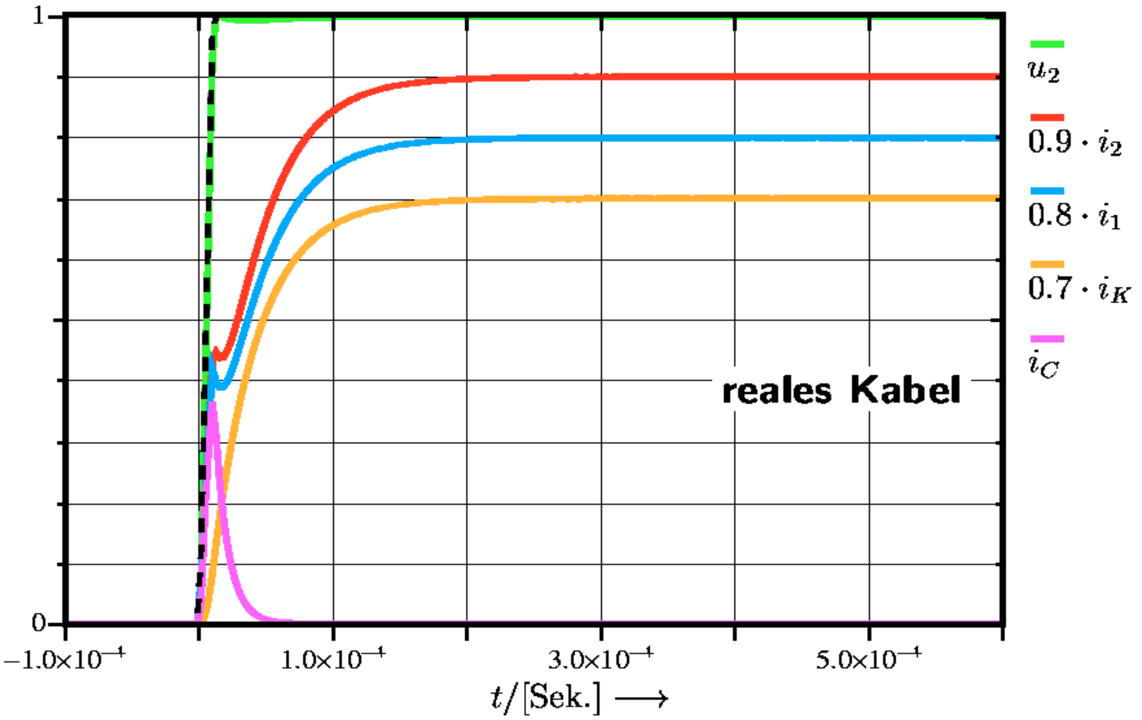

Fig. 7: Simulation result of 4 cables 75 mm² in parallel 100 m

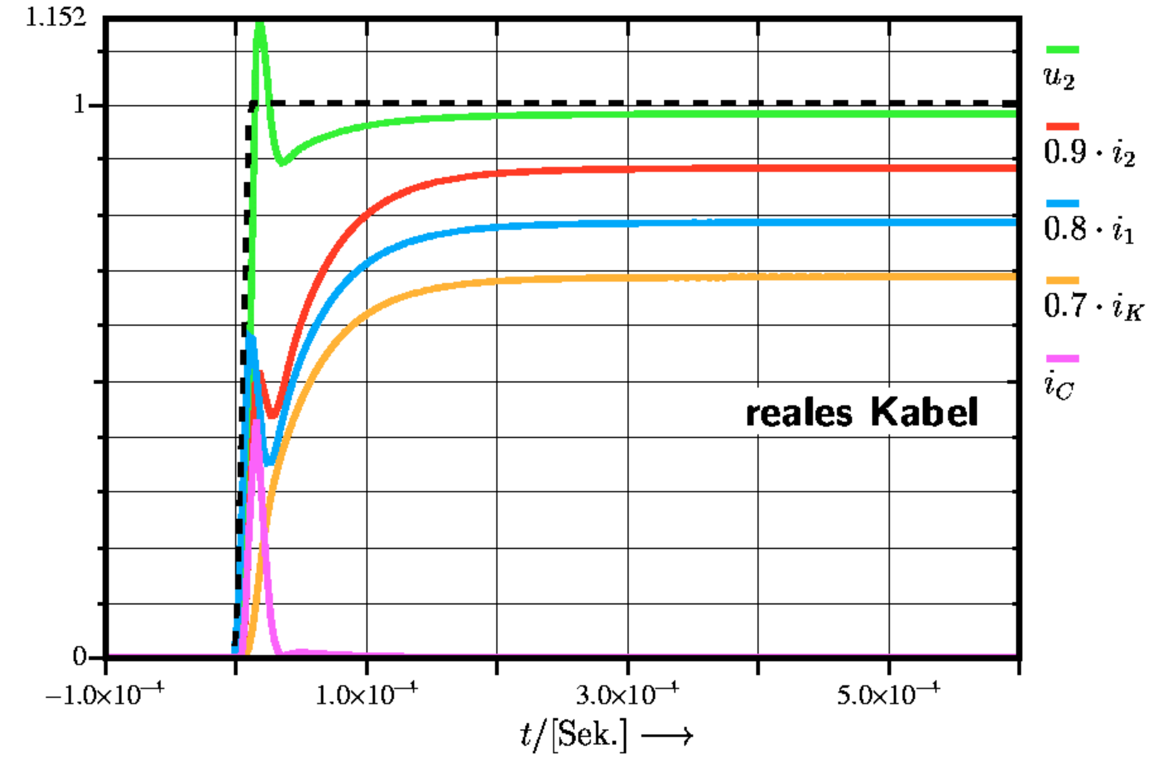

Fig. 8: Simulation result of 4 cables 75 mm² in parallel 1000 m

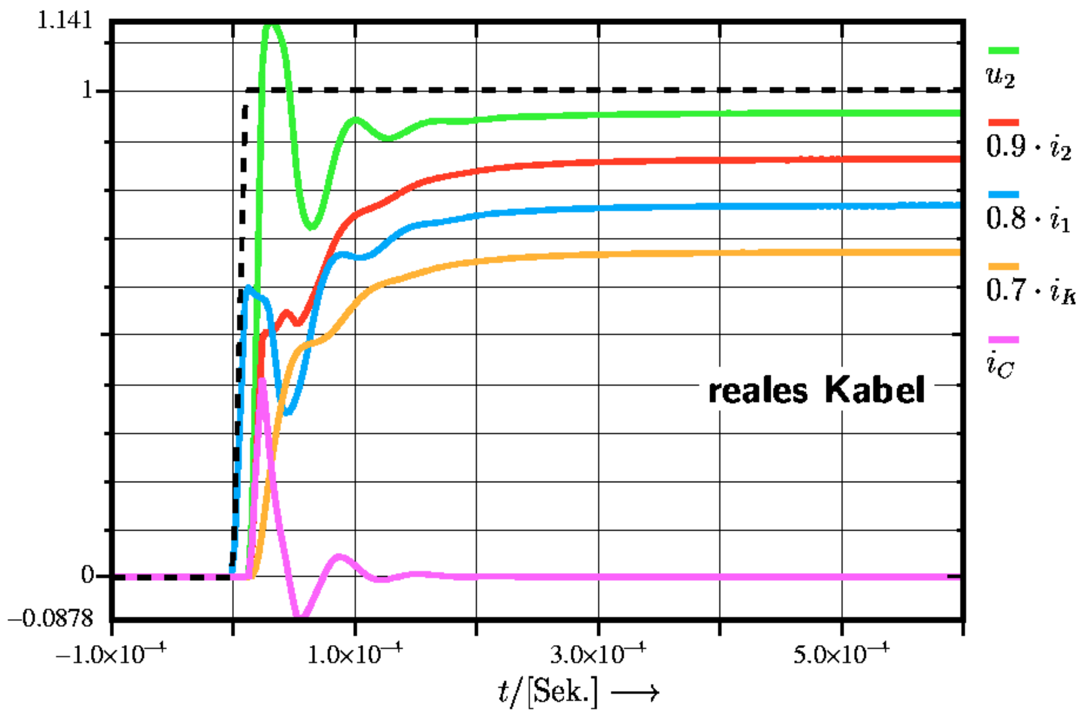

Fig.9: Simulation result of 4 cables 75 mm² in parallel 2500 m

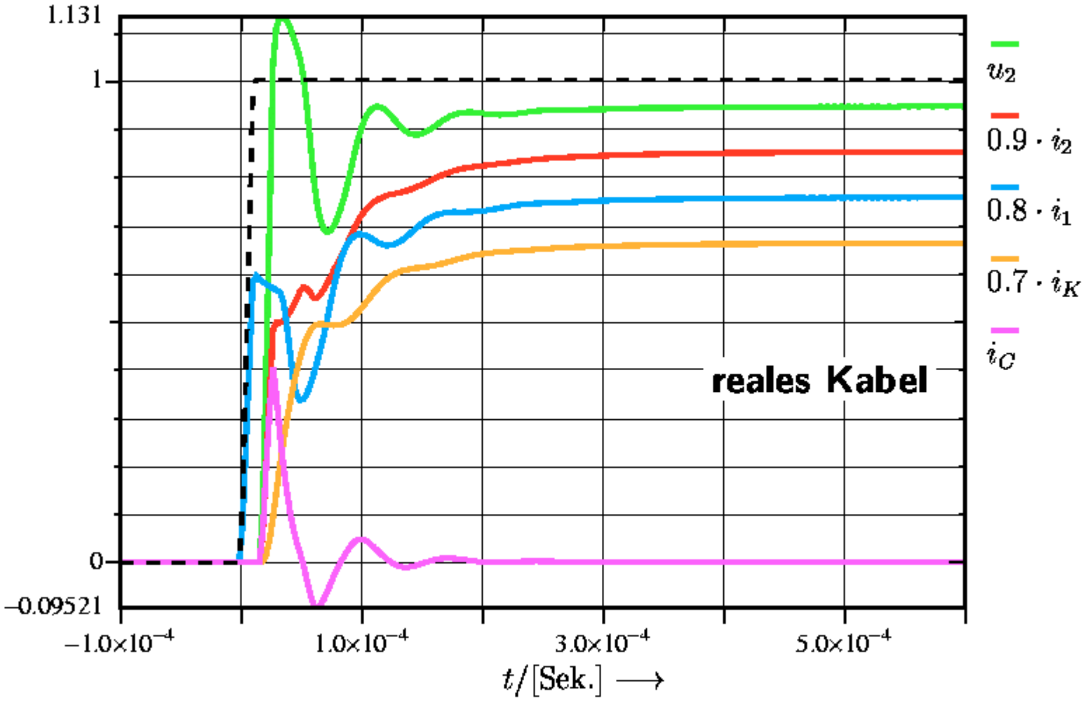

Fig.10: Simulation result of 4 cables 75 mm² in parallel 3000 m

5 Installation

The cables will be installed in a special area inside the tunnel shown in Fig. 11. They will be laid on cable trays that are connected to steel plates which are integrated into the concrete of the tunnel wall.

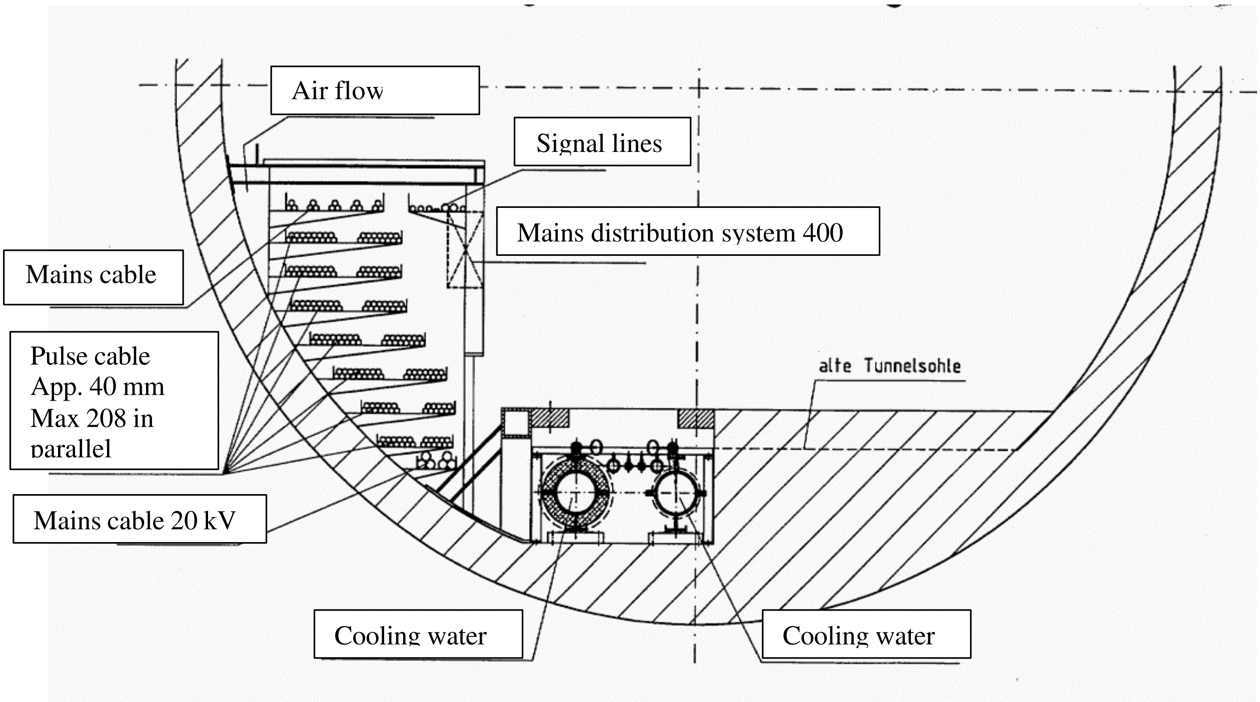

Fig.11. Principle of tunnel installation

6 Cooling

The cable will have a specific loss of 2.8 W/m at 5 Hz respecting 5.5 W/m at 10 Hz repetition rate. Since this value is low the cable shall be natural air cooled. With a proper installation a free air flow is possible as shown in Fig. 11.

7 Specific losses in the tunnel

The cables are a heat load for the tunnel with a maximum of the power near the service halls. At this point all cables are coming in parallel from the service halls. Every 48 m this number is decreased by a set of cables for a modulator. The maximum occurring specific losses are 264 W/m in tunnel near the DESY site where the modulators are operating in 10 Hz repetition rate. In the halls having modulators operating at 5 Hz repetition rate these values are less than 150 W/m.

8 Fire protection

The pulse cables are a fire load in the tunnel. To minimize the risk of a fire for these cables precautions in the construction are made. The outer sheath of the cable will be of halogen free flame retardant material. The outer shield will be constructed of a foil. Therefore in case of a fire the insulation material is kept inside the cable. An outer flame will not have contact with this material. Additionally a fire protective coating will be painted onto the cable. In case a flame heats this coating it will increase in volume avoiding the flame from getting contact to the cable.

A short circuit inside the cable will be detected with the modulator interlock. The main capacitor bank will be short circuited and the modulator will be turned off. By this no further energy will be supplied to heat material .

A slow heating of the cable can occur due to a bad contact in the cable sleeves or cable end piece. In this case smoke will be produced in the hot spot. This has to be detected by smoke detectors which then turn the modulators off.

9 References

[1] M.Filtz, Analytische Berechnungen zu einem Hochspannungskabel, Technische Universität Berlin, Fachgebiet Theoretische Elektrotechnik, Okt. 2000

[2] H. Kaden, Impulse und Schaltvorgänge in der Nachrichtentechnik, R. Oldenburg Verlag, München, 1957

[3] H. Kaden, Wirbelströme und Schirmung in der Nachrichtentechnik, Springer Verlag, 1959