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Temperature Control of the ESS Phase Reference Line

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Introduction and Background



Fig. 1: Phase reference line of copper (left), heating cables and temperature sensors attached (middle), and insulation applied (right).

- **Phase reference signals** for all accelerating components along the 600 [m] linear accelerator.
- Radio-frequency (RF) wave in a rigid coaxial line made of copper. **Temperature changes induce phase instability** because of length variations of the line (17 [ppm/deg C]).
- Phase change $\Delta\varphi$ between x_0 and x_f at time t proportional according to

$$\Delta\varphi \sim \int_{x_0}^{x_f} T(x, t) - T_{cal}(x) dx, \quad (1)$$

with T and T_{cal} the current temperature and the temperature at calibration, respectively.

- Requirement: $\max_{x,t} |T(x, t) - T_{cal}(x)| \leq 0.1$ [deg C] for 600 [m] phase reference line.

Modeling

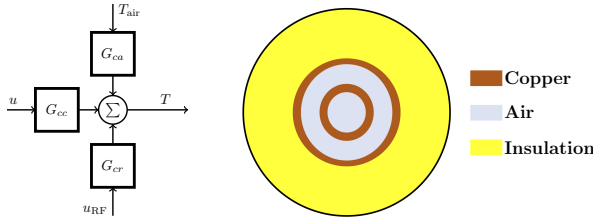


Fig. 2: Block diagram of the process dynamics (left) and schematics of phase reference line cross section with insulation (right).

- **Feedback control** used for temperature stabilization of the line within the requirements.
- **Models of the heat dynamics** developed and simulated using both **analytic and numerical solutions** of the partial differential equation for heat diffusion $\nabla \cdot k \nabla T + Q = \rho c T_t$.
- Inputs and disturbances: Ambient air T_{air} , heat by controller u , and RF heat losses u_{RF} .

Simulation Results

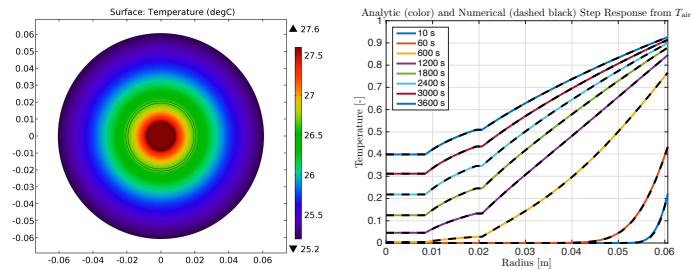


Fig. 3: Stationary temperature in cross section with heat losses in conductors (left) and time & radial temperature dependence (right).

Prototype Setup at Lund University

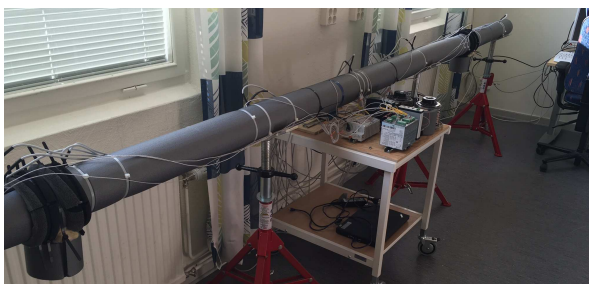


Fig. 4: A 4.5 [m] prototype with two directional couplers was setup and used for controller development and experimental evaluation.

Control Design

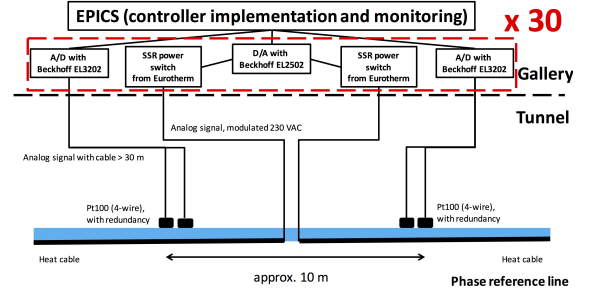


Fig. 5: Control architecture for temperature stabilization with controllers in EPICS (also monitoring and supervision functions).

- **Dynamic models** used for **designing PID controllers** for temperature zones along the phase reference line. Pole placement gives the parameters (K, T_i, T_d) in the control law:

$$u(t) = K \left(e(t) + \frac{1}{T_i} \int_0^t e(\tau) d\tau + T_d \frac{de(t)}{dt} \right), \quad e(t) \text{ control error.} \quad (2)$$

- **Control architecture** based on RTD Pt100 temperature sensors, heating cables, A/D and D/A converters, solid-state relays for power control. **Beckhoff EtherCAT** modules for I/O or **Eurotherm Mini8** controller for both I/O and controller execution.
- **Control hardware** placed in the gallery because of **radiation**. **Special attention for materials** used for temperature sensors and heating cables in the **accelerator tunnel**.

Experimental Results

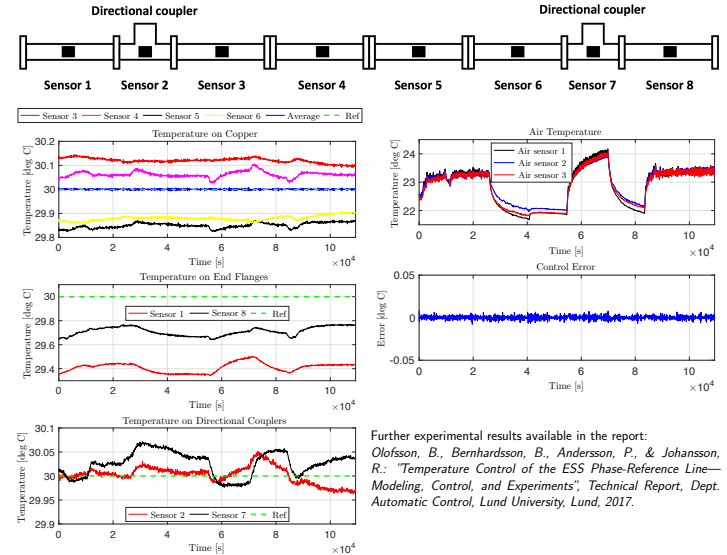


Fig. 6: Sensor placement on phase reference line (upper) and experimental results from prototype setup (lower left and right).

- **Ambient air temperature was increased** with an element with variable power level, while the **feedback control system adjusted the power level in the heating cables** to keep the temperature of the phase reference line stable (one temperature zone for prototype setup).
- The reference value for the control system was chosen as $T_{ref} = 30$ [deg C] in the experiment.
- **All temperature measurements within $T_{cal} \pm 0.1$ [deg C]** during the experiment, where T_{cal} is the temperature at the particular measurement point at the start of the experiment.
- **Temperature of the directional couplers remarkably stable**, even though controlled using the same PID controller loop as the rigid coaxial line sections.

Conclusions

- A prototype control system for **temperature stabilization** of the ESS phase reference line.
- Observed control error variations with respect to the calibrated temperature (also for out-of-loop temperature sensors) **clearly within $\max_{x,t} |T(x, t) - T_{cal}(x)| \leq 0.1$ [deg C]**.