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

$$\Delta\varphi \sim \int_{x_0}^{x_f} T(x,t) - T_{\text{cal}}(x)\, \mathrm{d}x, \tag{1}$$

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

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

Modeling

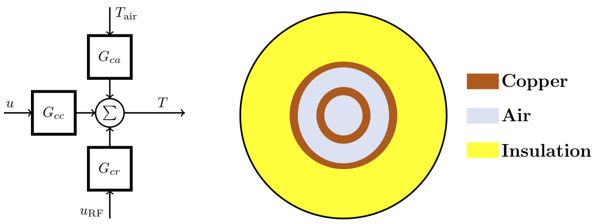


Fig. 2: Block diagram of the process dynamics (left) and schematics of phase reference line cross section with insulation (right).

- 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

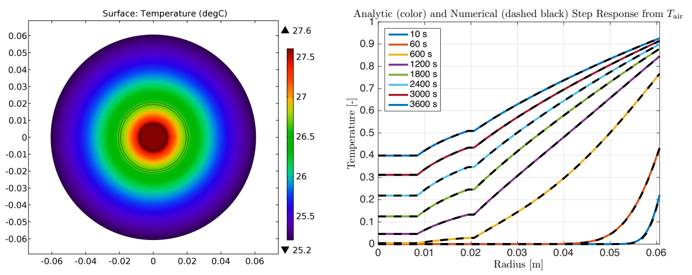


Fig. 3: Stationary temperature in cross section with heat losses in conductors (left) and time & radial temperature dependence (right).

Prototype Setup at Lund University

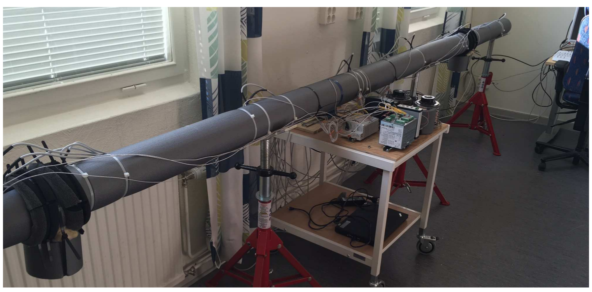


Fig. 4: A 4.5 [m] prototype with two directional couplers was setup and used for controller development and experimental evaluation.

Control Design

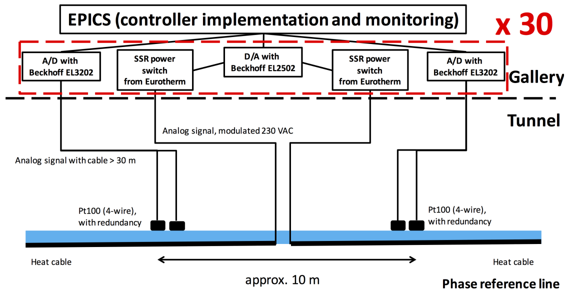


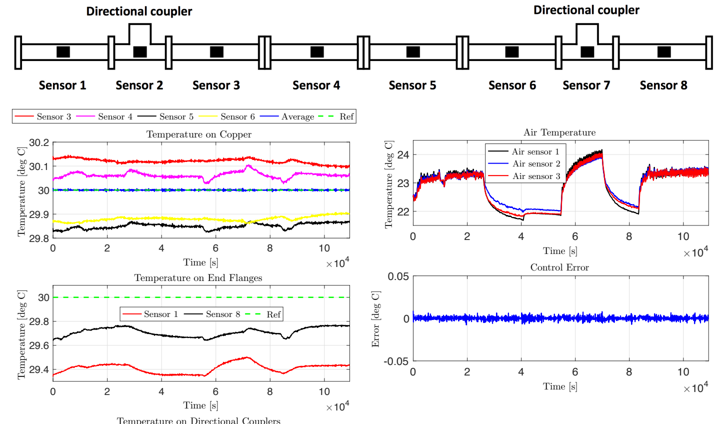
Fig. 5: Control architecture for temperature stabilization with controllers in EPICS (also monitoring and supervision functions).

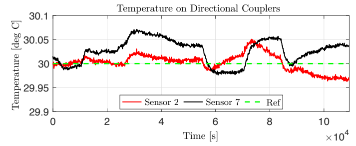
- Dynamic models used for designing PID controllers for temperature zones along the phase reference line. Pole placement gives the parameters (K, T_i, T_d) in the control law:

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

- 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





Further experimental results available in the report: *Olofsson, B., Bernhardsson, B., Andersson, P., & Johansson, R.: "Temperature Control of the ESS Phase-Reference Line—Modeling, Control, and Experiments", Technical Report, Dept. Automatic Control, Lund University, Lund, 2017.*

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 $T_{\text{ref}} = 30$ [deg C] in the experiment.
- All temperature measurements within $T_{\text{cal}} \pm 0.1$ [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 $\max_{x,t} |T(x,t) - T_{\text{cal}}(x)| \leq 0.1$ [deg C].