Advantage of local hp-adaptivity in FEM simulation of normal zone propagation in a Rebco tape

Alexandre Halbach, Tiina Salmi

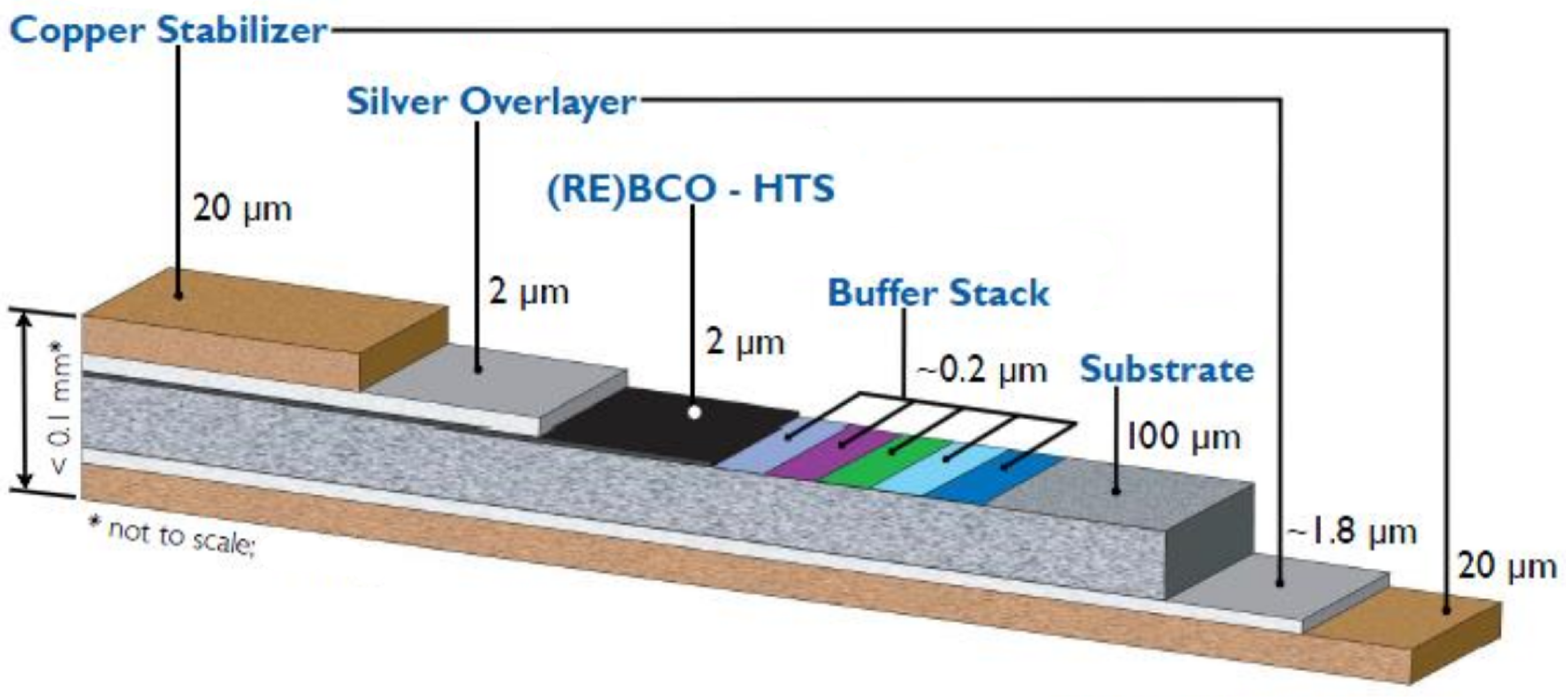
University of Tampere, Department of Superconductivity, Finland

Introduction

Particle accelerator magnets based on HTS tapes can quench during operation. During a quench the thin superconducting layer transitions back to its normal conductor state and the large current redistributes in the surrounding copper and substrate, leading to a sudden heating and a possible quench propagation in the tape. For the magnet safety quenches have to be understood and therefore modeled numerically. Due to the large ratio between tape length and scales of interest this can however lead to heavy computations when the full tape is modeled in 3D. Lumped approximations are typically used.

HP-adaptivity (hpFEM) can be used to refine the tape mesh and adapt the field interpolation orders locally at runtime.

Problem Definition



A 30 cm long YBCO tape is considered (its cross-section is illustrated above). Due to their small thickness the buffer layers are disregarded. The two silver layers could be taken into account but are not considered here due to their small thickness compared to the neighboring thicker copper. The tape is thus made up of a hastelloy substrate layer and a HTS superconducting YBCO layer, sandwiched between copper stabilizer layers. Two coupled physics are considered. The first one is transient heat diffusion:

$$\rho c_p \frac{\partial T}{\partial t} - \nabla \cdot (\kappa \nabla T) = jE$$

with T the temperature [K], j the current density [A/m^2] and E [V/m] the electric field. The right term is the conduction current heating. The second physic considered is conduction current flow:

$$\nabla \cdot (\sigma \nabla v) = 0$$

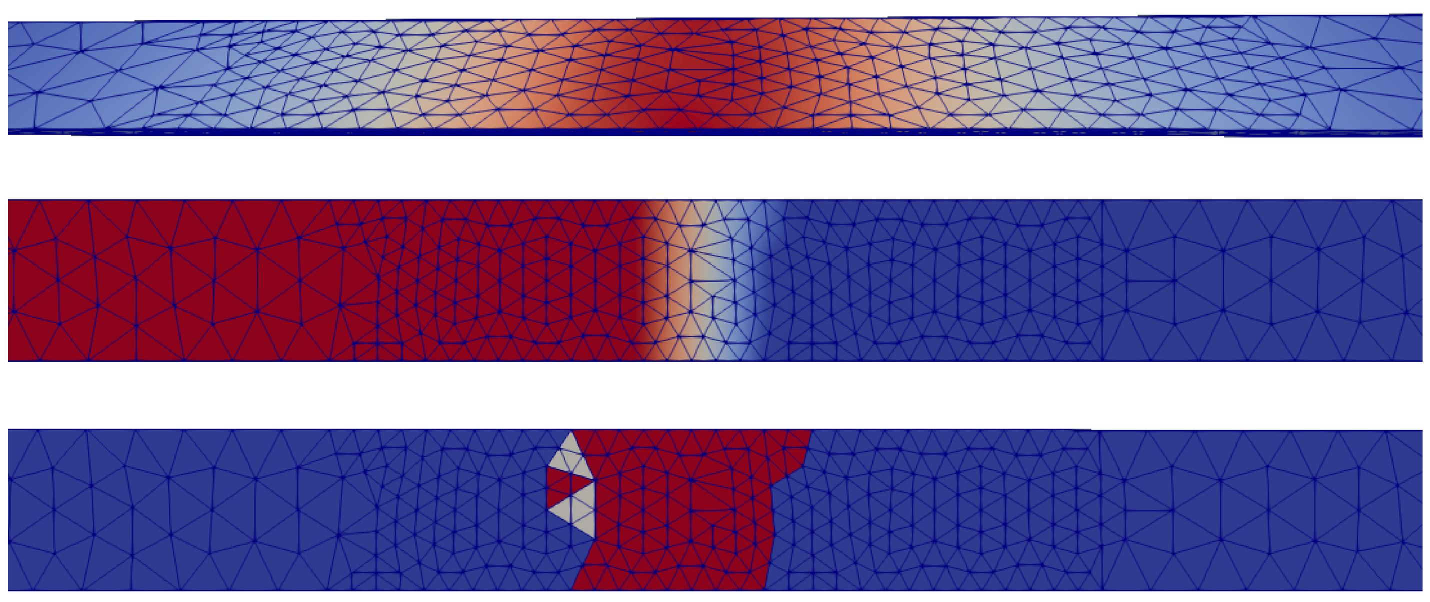
with v the electric potential [V]. For superconductors the conductivity σ follows the usual power law. All material properties are taken from literature. They take into account the dependency on the temperature, on the electric field and on the magnetic field.

HP-adaptivity

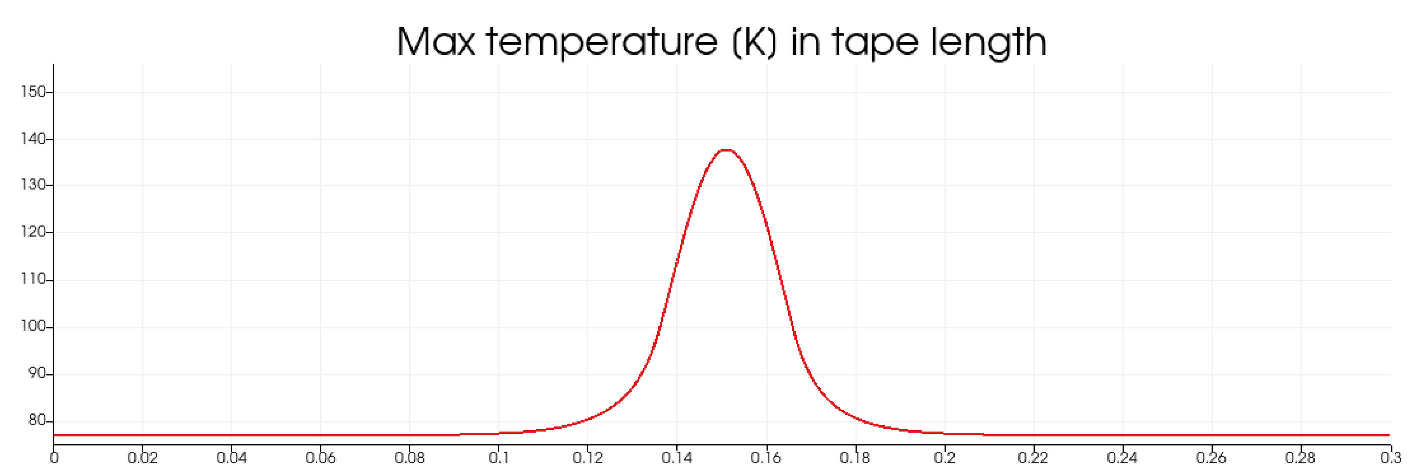
The FEM mesh is adapted locally based on the convergence of the Legendre expansion of the temperature field. The interpolation order of the temperature field is adapted similarly. The interpolation order of the electric potential field is adapted based on the convergence of its own Legendre expansion. The problem can be solved with a coarse approximation where accuracy is not needed.

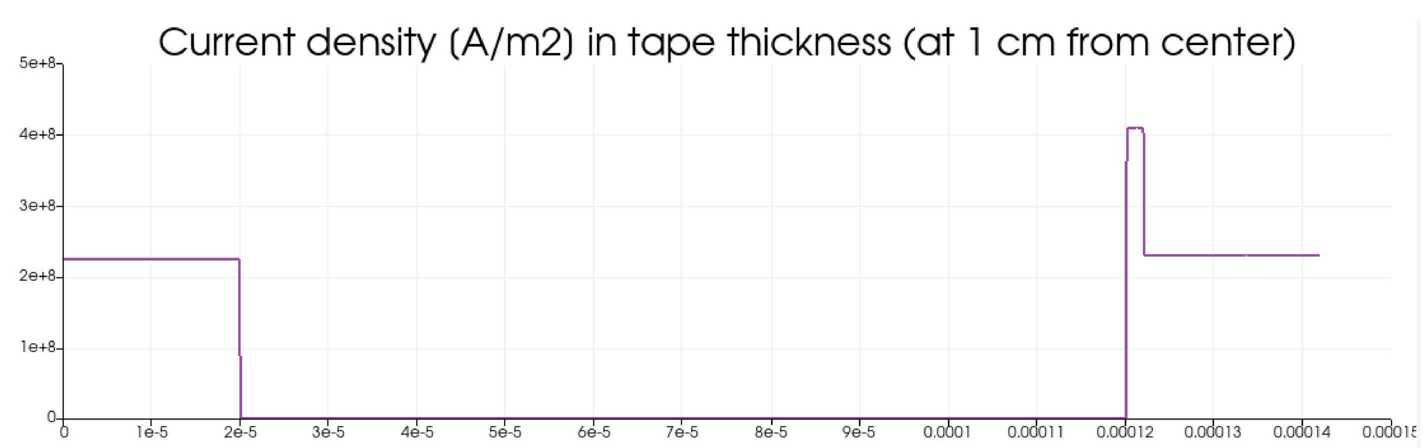
Results

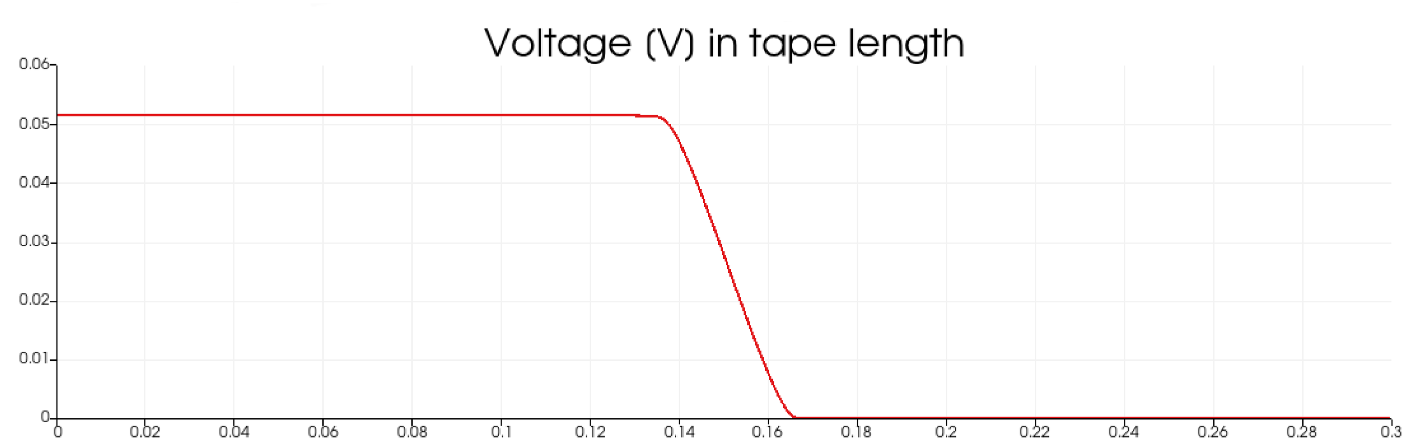
A 30 cm long YBCO tape, initially at 77 K, is considered and the YBCO layer is initially quenched on a 5 mm length. A transient 3D FEM simulation is performed until a 150 K hotspot temperature is reached. Literature values are considered for all material properties and their temperature, electric field and magnetic field dependency are taken into account. The simulation time does not exceed 20 min on a regular laptop and the hp-adaptivity allows to limit the number of unknowns to solve for to less than 100e3 at all times, with an initial count as low as 5700. The field orders are allowed to vary between 1 and 3 and one level of refinement is allowed in the tetrahedral mesh. In the general setting where it is not known a priori where accuracy is needed, the entire 30 cm tape with the finest allowed mesh and highest allowed order would have to be considered. This would lead to about 5e6 unknowns to solve for at every timestep.



The adapted mesh and adapted interpolation order, shortly after quench initiation, is illustrated above (from top to bottom: temperature field, electric potential field and its interpolation order from 1 to 3). As can be seen the mesh is refined only around the quench location and the electric potential field order is highest where the quench causes a current redistribution to the copper and therefore a voltage drop in the tape. The plots below show the main results when a 140 K hotspot temperature is reached. From the middle graph it can be seen that the normal zone has propagated almost 1 cm, since at that location the current has already partially redistributed to the copper layers.







Software used: `sparselizard.org`
Simulation code: `github.com/halbux/sparselizard-users`
Visualization: `https://youtu.be/UV-UyGgua00`