Mechanical stress simulation of REBCO tapes using particle methods

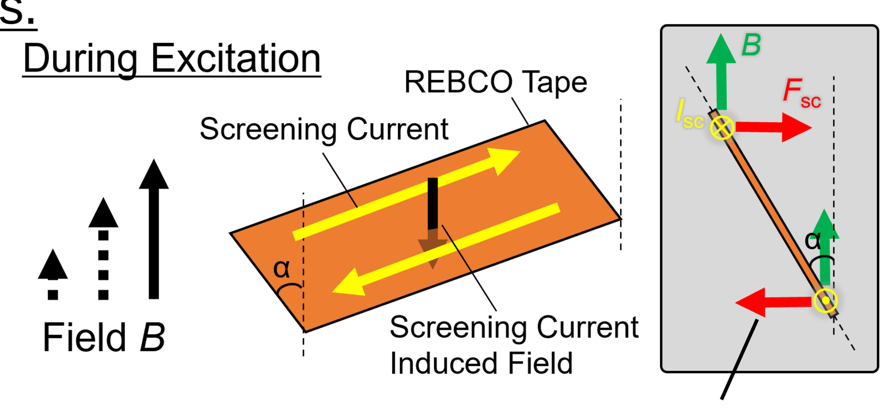
Takanobu Mato(mato@em.ist.hokudai.ac.jp)[1] and So Noguchi[1]
[1]Hokkaido Univ., Japan

Nov. 15-19, 2021
Fukuoka, Japan

INTRODUCTION

On 2017, a world-record high DC magnetic field of 45.5 T was generated with insert no-insulation (NI) Rare-Earth Barium Copper Oxide (REBCO) pancake coils (14.4 T), called "LBC3", and an outsert resistive magnet (31.1 T). NI REBCO pancake coils showed their potential to generate an ultra-high magnetic field. After the 45.5-T generation, plastic deformations of REBCO tapes were observed, although REBCO tapes have great mechanical properties due to a Hastelloy substrate. Similar cases of the damaged REBCO tapes were reported: e.g. the MIT 1.3-GHz NMR insert magnets. The plastic deformation is considered to occur during excitation as shown in the following figure. <u>Towards the development of ultra-high field magnet, it is necessary to clarify the mechanical phenomenon of both REBCO tapes and magnets.</u>

Some journal papers on mechanical simulation on REBCO magnets have been published so far. In these papers, the finite element method (FEM) was employed as a mechanical simulation. In this work, <u>we model REBCO tapes with a particle method, which are able to represent plastic deformation of the material, for mechanical simulation. We show the simulated mechanical behaviors of REBCO tapes under large electromagnetic force.</u>



Large magnetic forces during excitation may damage REBCO tapes.

METHODS AND CONDITIONS

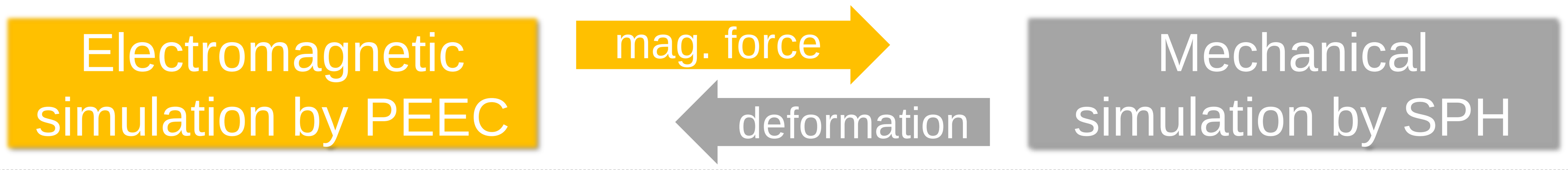
A 3D Partial Element Equivalent Circuit (PEEC) model is employed to simulate the electromagnetic behavior of a REBCO tape. For mechanical computing, a Smoothed Particle Hydrodynamics (SPH) method is used. The SPH method is one of the mesh-free particle methods. A body is modeled with a set of particles. Each particle follows the following conservation equations:

Mass conservation
$$\frac{\mathrm{D}\rho}{\mathrm{D}t} = -\rho\nabla\cdot\boldsymbol{v}$$

Momentum conservation
$$\frac{\mathrm{D}\boldsymbol{v}}{\mathrm{D}t} = \nabla\cdot(-p\boldsymbol{I}+\boldsymbol{\tau}) + \frac{1}{\rho}\boldsymbol{f}_{\mathrm{ex}}$$

Constitutive law
$$\dot{\boldsymbol{\tau}} = G\left(\dot{\boldsymbol{\varepsilon}} - \frac{1}{3}\mathrm{tr}(\boldsymbol{\varepsilon})\boldsymbol{I}\right)$$

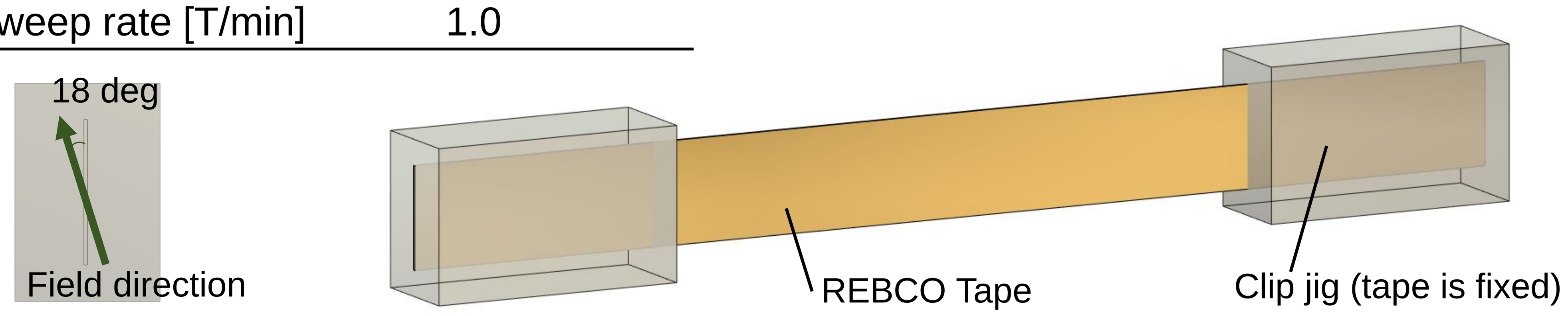
ρ: mass density
$\boldsymbol{v}$: velocity
$\boldsymbol{\tau}$: shear tensor
$\boldsymbol{f}_{\mathrm{ex}}$: external force density
G: shear modulus
$\boldsymbol{\varepsilon}$: strain tensor



Parameters	Values
Tape dimensions [mm]	45 × 4 × 0.05
Clip length (Each edge) [mm]	10
Mass density [kg/m³]	8890
Young's modulus [GPa]	182
Shear modulus [GPa]	68
Yield strength [MPa]	800
Operating temperature [K]	4.2
Field angle [deg]	18
Field sweep rate [T/min]	1.0

We consider a REBCO tape whose ends are clipped. A magnetic field with angle of 18 degrees is applied and ramped from zero up to 2 T in 120 s. No forced current is applied.

We set the composite material properties of Hastelloy and copper as shown in the left table. From the reference [C.C. Clickner, *cryogenics*, 2006], the REBCO tape is modeled as the perfectly plastic material with a yield point of 800 MPa.

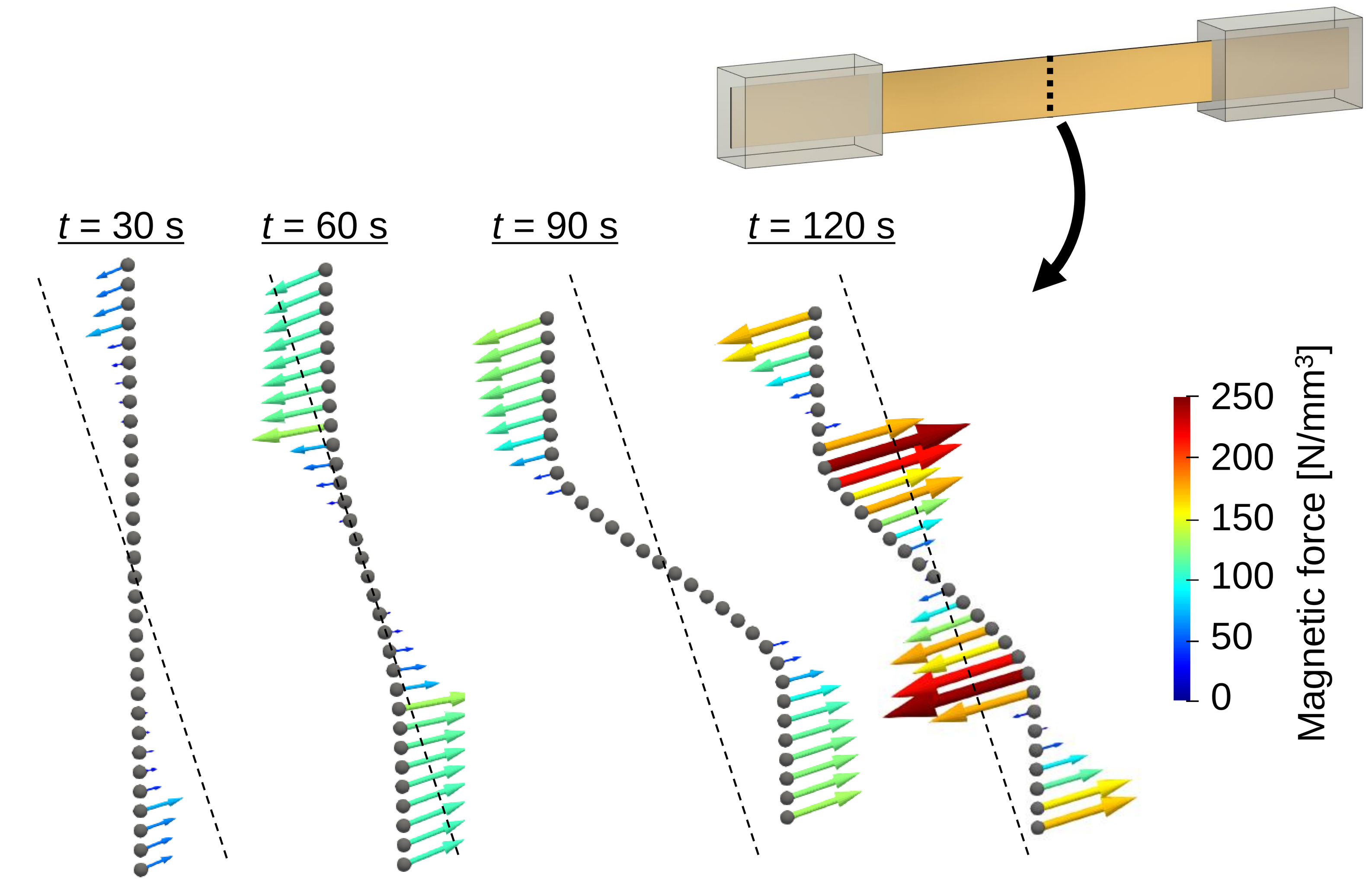


RESULTS

Tape Deformation

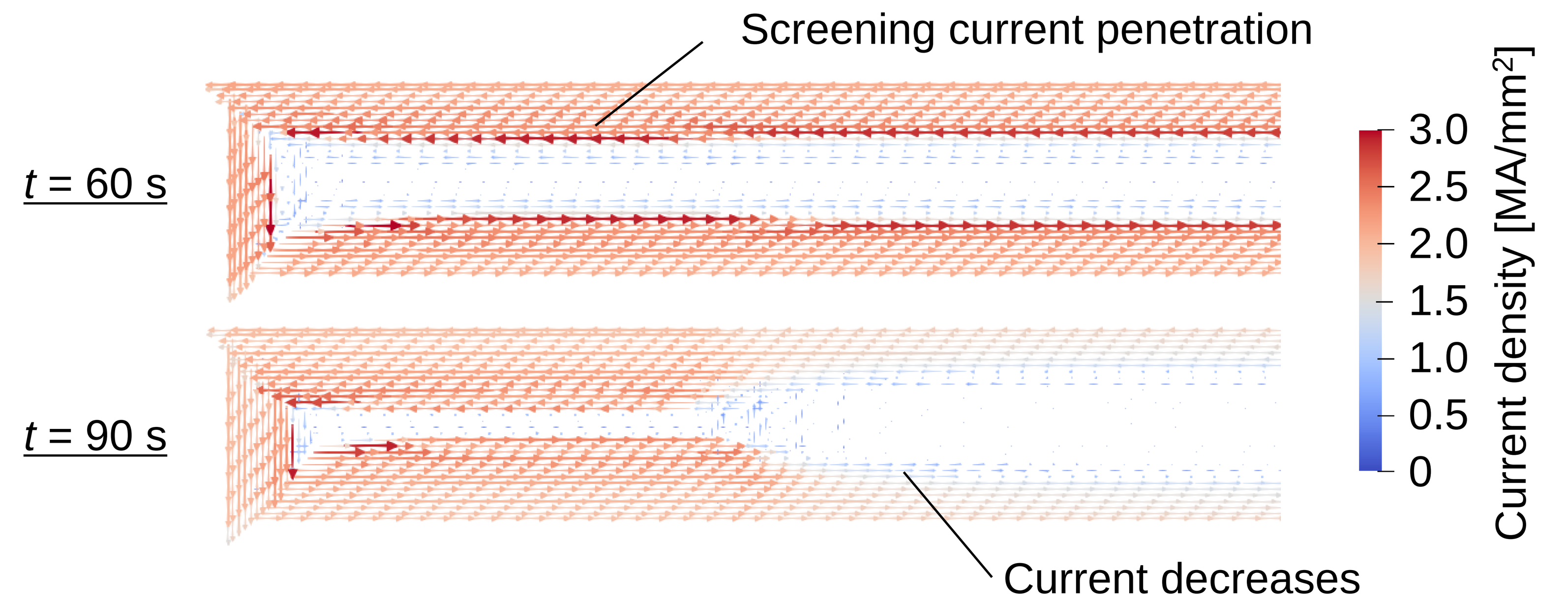
The tape deformation of the center cross section is shown in the right figures.

- At *t* = 30 s, the magnetic forces are not high so that the tape is not twisted at all.
- At *t* = 60 s, the small tape deformation develops due to large magnetic forces.
- At *t* = 90 s, the field reaches 1.5 T. The strain at the tape middle part expands. The magnetic force distribution is narrowed due to deformation.
- At *t* = 120 s, the cross section of the tape has a clear S-shape. The large magnetic force is applied due to the screening current. The width direction of REBCO tape rotates into the orientation of the magnetic field.



Current Distribution

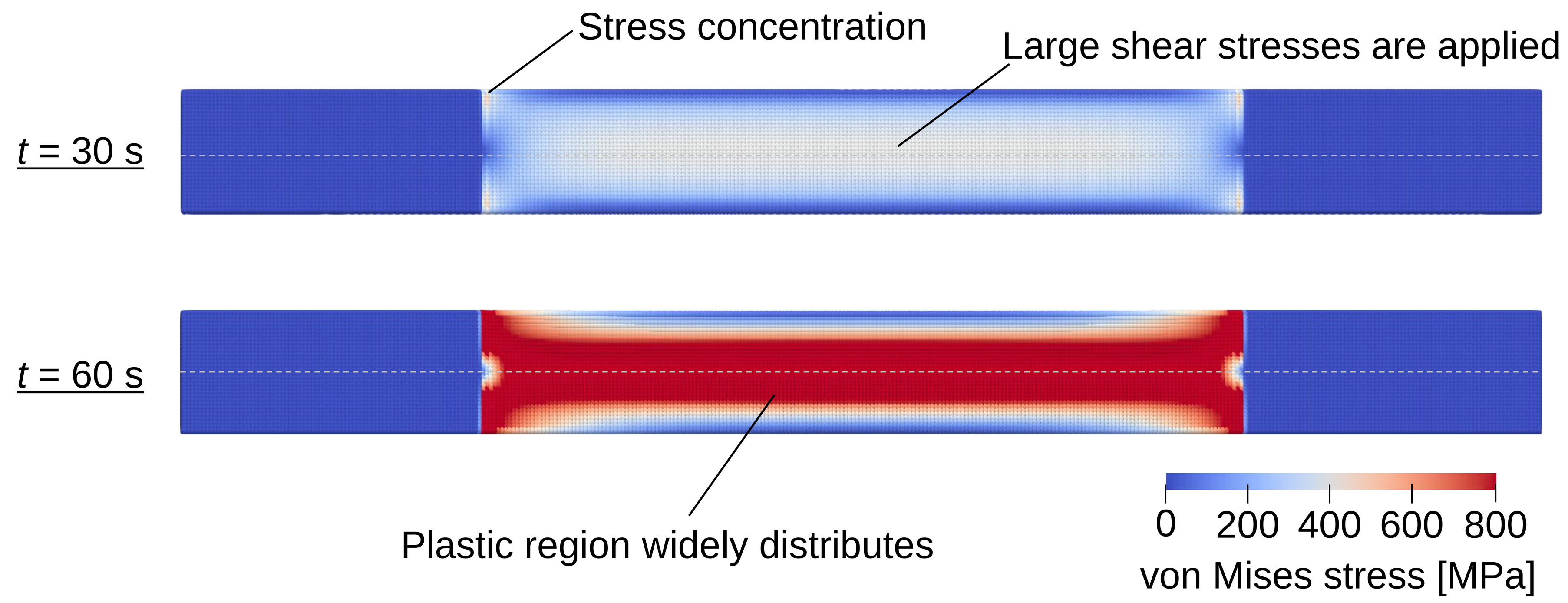
The screening current flows from the end of the tape as shown in the right figure at *t* = 60 s. However, the screening current in the opposite direction can be seen when the tape deformation develops as shown in *t* = 90 s. Thus, the narrow magnetic field distribution is observed.



Stress Distribution

The right figure shows the distribution of the von Mises stress. Here, an area beyond 800 MPa is plastically deformed.

A stress concentration at the tape clipping ends is observed at *t* = 30 s. Large shear is also applied at the center line of the transverse direction of the tape. Then, a wide plastic region can be seen at *t* = 60 s. Mainly, a tape deformation progresses at the transverse center line.



CONCLUSION

In this presentation, we simulated the mechanical behavior of the REBCO tape during field excitation. A Smoothed Particle Hydrodynamics (SPH) method is adopted for plastic deformation simulation, and a 3D Partial Element Equivalent Circuit (PEEC) method for electromagnetic simulation. As a result, the large magnetic force during the excitation leads to large deformations. Since the magnetic forces are applied at top and bottom surfaces in opposite directions, the large shear stresses widely work to the middle of the tape as well as the fixed edge, and the region reached the yield point. Thereafter, the large deformation develops at the plastic regions.