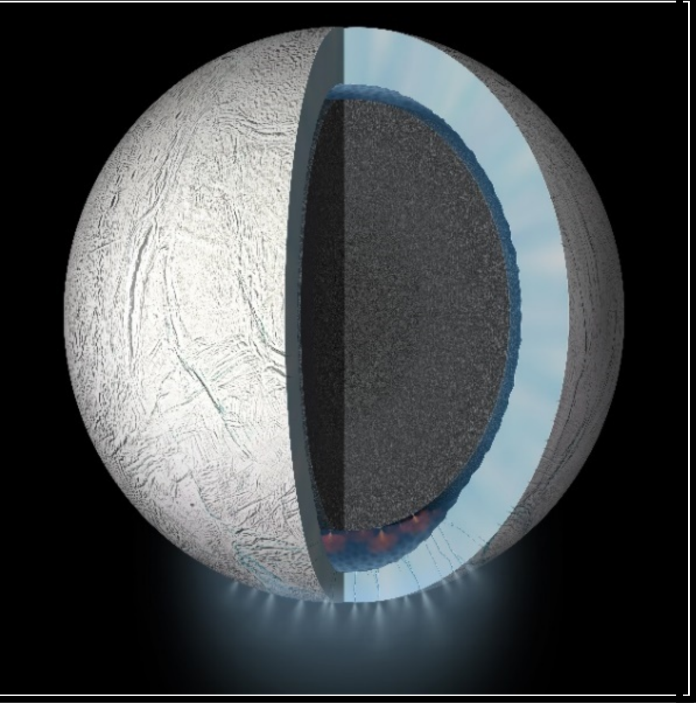

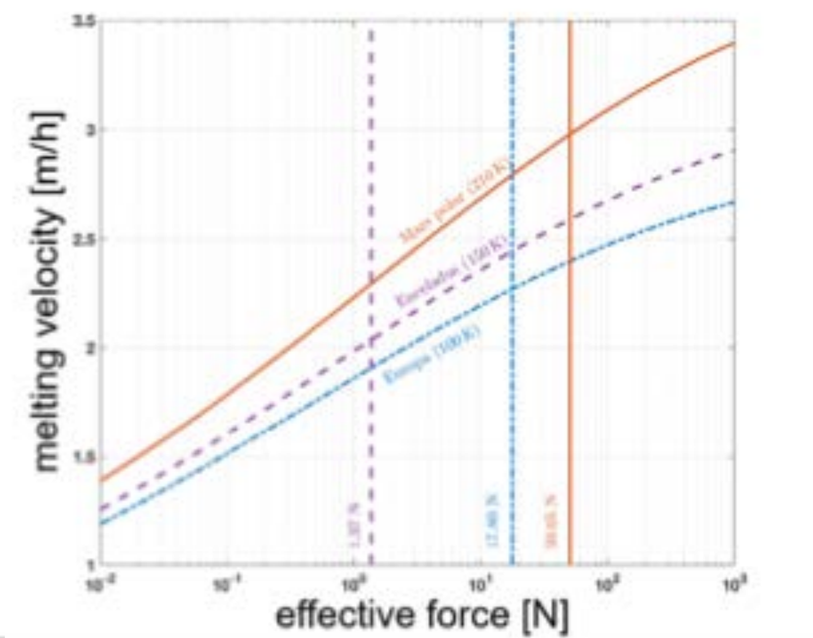

How do gravity and ice temperature affect the performance of thermal melting probes?

June 14th, 2018

Julia Kowalski, Kai Schüller and the EnEx Team

Smead Aerospace
UNIVERSITY OF COLORADO BOULDER

GFD

DLR

Aachen Institute for Advanced Study in Computational Engineering Science

RWTH AACHEN UNIVERSITY

Supported by:
Federal Ministry for Economic Affairs and Energy
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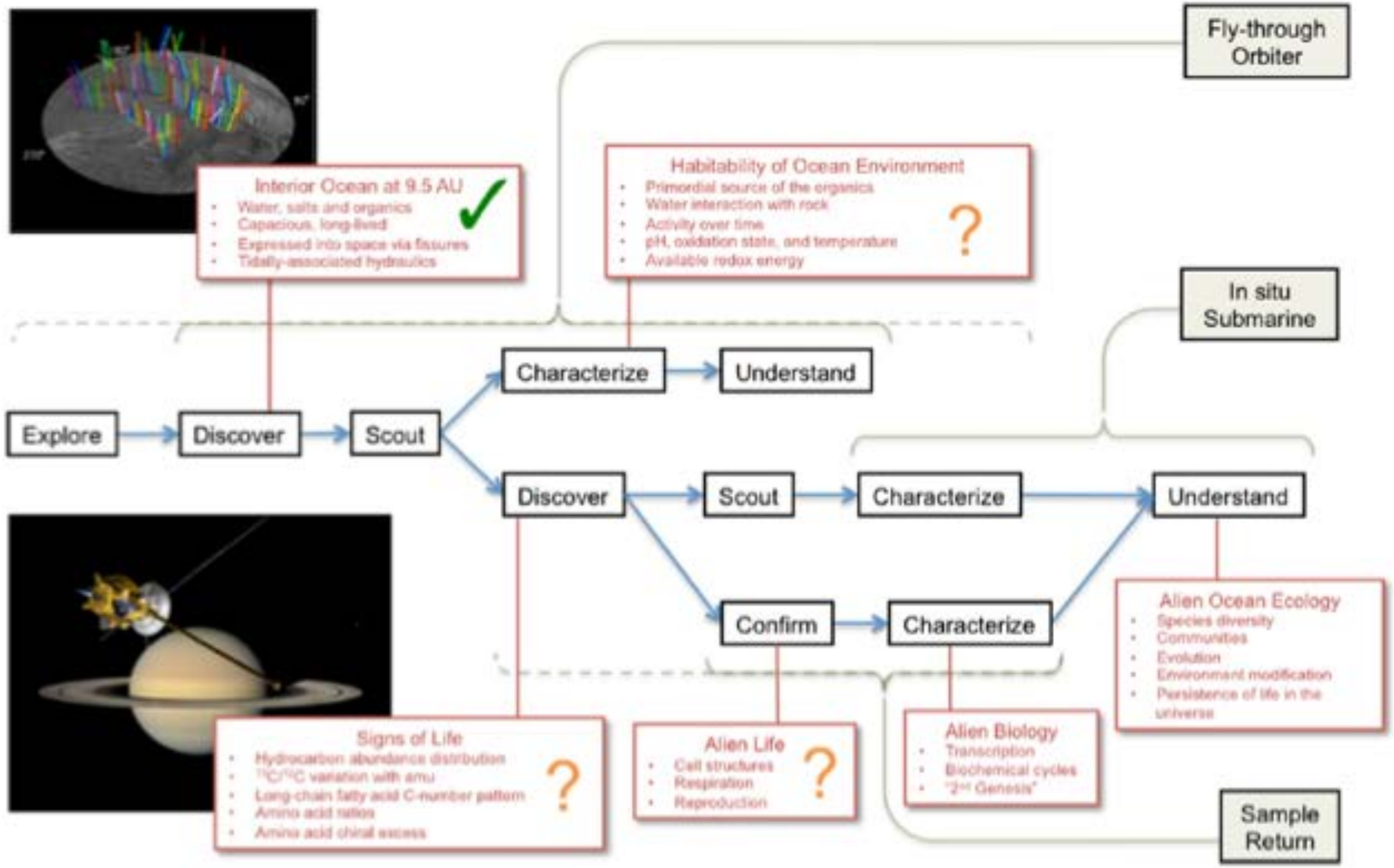
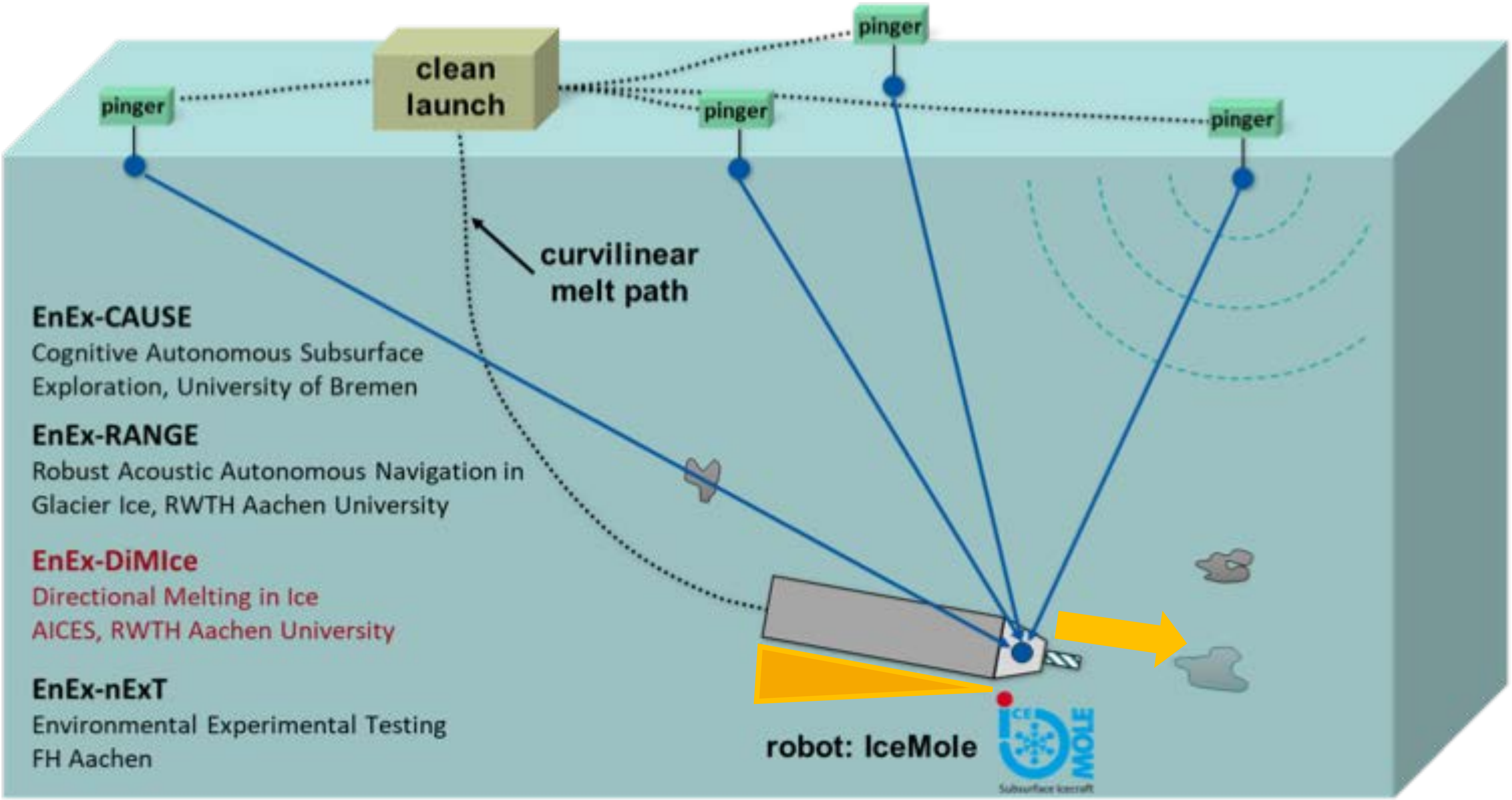
A roadmap to exploring the Ocean World Enceladus



Sherwood, Strategic map for exploring the ocean-world Enceladus. Acta Astronautica, 126: 52/58, 2016.

DLR Enceladus Explorer



EnEx-CAUSE
Cognitive Autonomous Subsurface Exploration, University of Bremen

EnEx-RANGE
Robust Acoustic Autonomous Navigation in Glacier Ice, RWTH Aachen University

EnEx-DiMIce
Directional Melting in Ice
AICES, RWTH Aachen University

EnEx-nExT
Environmental Experimental Testing
FH Aachen

- before 2012
  robotic student project
- 2012 – 2015
  EnEx-MIDGE collaboration - advancing technologies and subglacial sample return in Antarctica
- 2015
  further development of key technologies

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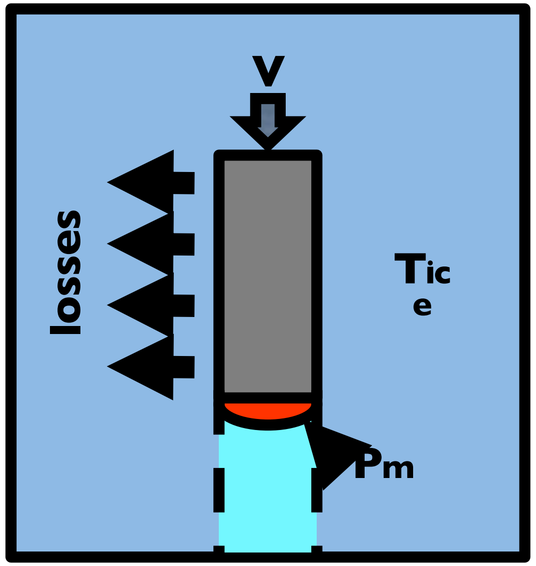
Modeling the dynamics of melting probes – the 0D approach

Engineering model:

Aamot,
CRREL-TR-194. 1967



energy balance yields:

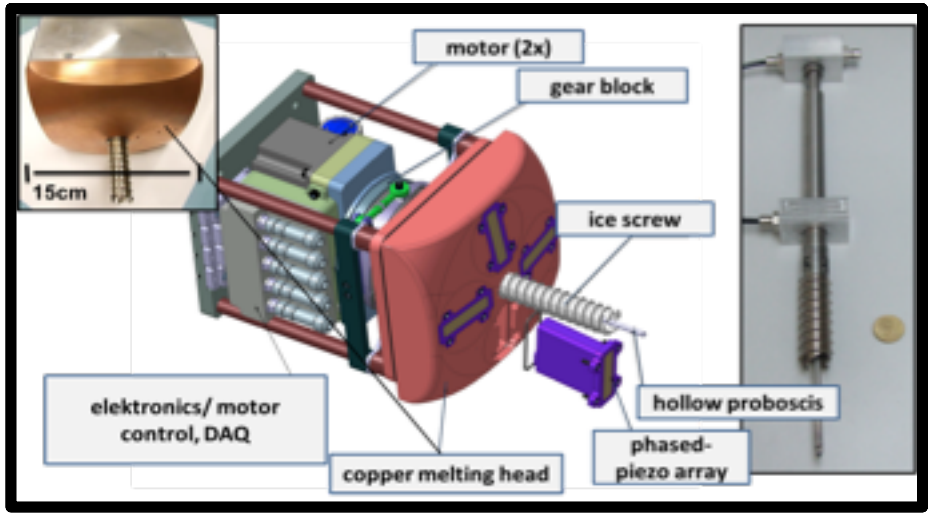
$$\text{melting velocity} = \frac{\text{input power}}{\text{energy needed}}$$

$$V = \frac{P_m}{A\rho\left(h_m + c_p(T_m - T_{ice})\right)}$$

V: melting velocity
P$_m$: input power
A: crosssection of the probe
ρ: density of the ice

c$_p$: specific heat capacity of the ice
T$_m$: melting temperature
T$_{ice}$: ice temperature
h$_m$: melting enthalpy of ice

The IceMole‘s 2015 design:



How do melting probes perform in low gravity conditions?

Modeling the dynamics of melting probes – the 4D approach

Robot motion (concentrated)

The current state of the probe is given by its center-of-mass and its attitude:

$$\xi(t) := \begin{bmatrix} X(t) \\ Q(t) \end{bmatrix}$$

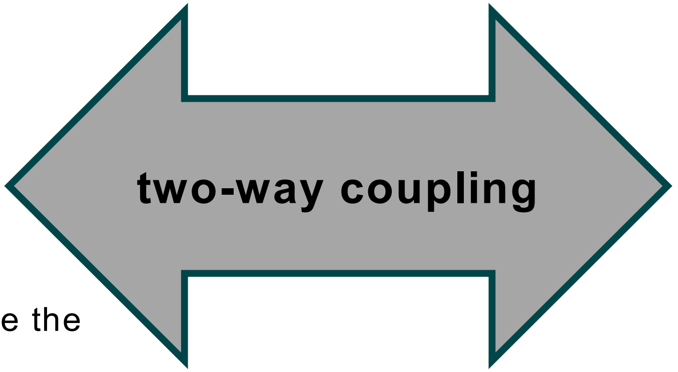
First derivative yields translational and angular velocity:

$$\frac{d}{dt}\xi(t) = \begin{bmatrix} V(t) \\ \omega(t) \end{bmatrix}$$

The **Euler-Newton equations** allow to determine the trajectory based on applied forces:

$$\begin{aligned} m\frac{d}{dt}V(t) &= F(t, u(t)) \\ \mathbf{I}\frac{d}{dt}\omega(t) &= T(t, u(t)) - \omega \times \mathbf{I}\omega \end{aligned}$$

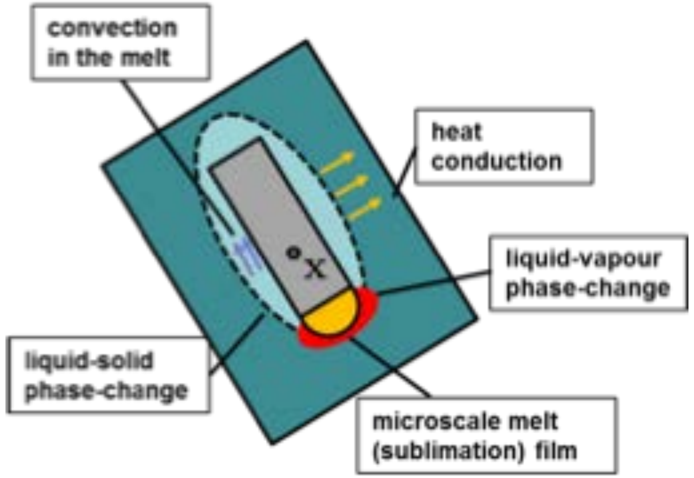
The forces depend on the position of the liquid-solid interface, hence the ambient state *u*.



Cryoenvironment (distributed)

The current ambient state of the ambient is given by temperature, velocity and pressure:

$$u(t, x) := \begin{bmatrix} T(t, x) \\ v(t, x) \\ p(t, x) \end{bmatrix}$$



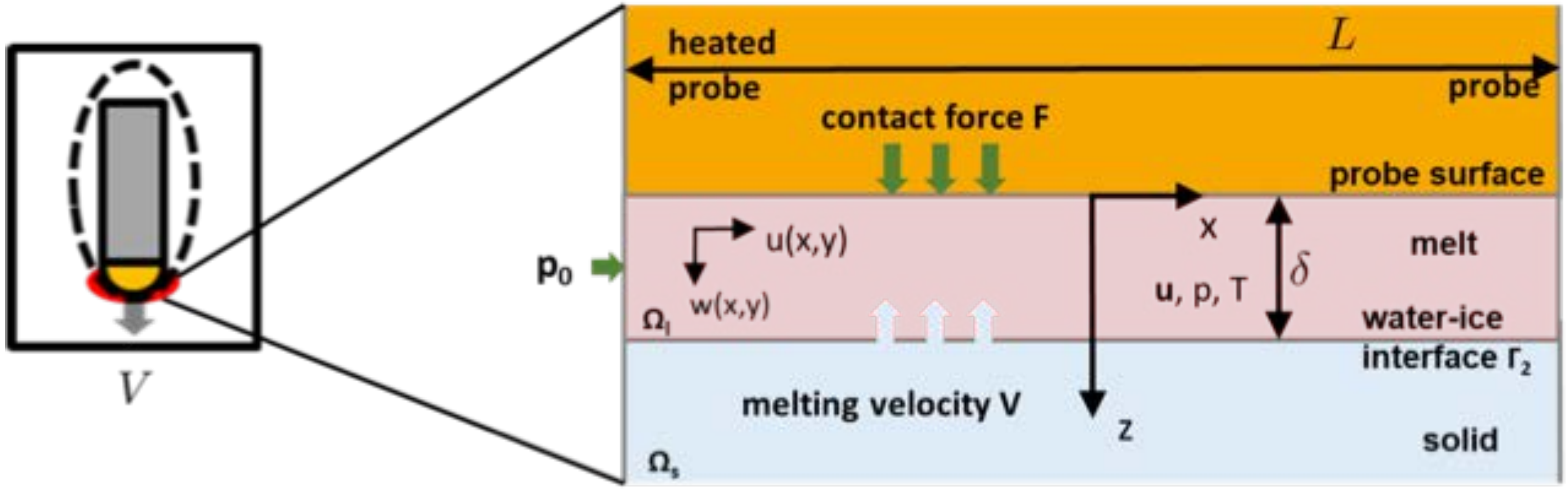
It is subject to a PDE operator

$$\frac{\partial}{\partial t}u(t, x) = \mathcal{L}(u(t, x), \xi(t), \frac{d}{dt}\xi(t))$$

that depends on position and attitude of the probe, as well as its melting velocity.

Modeling the dynamics of melting probes – the smart way

Microscale melt film determines the probe‘s macroscale dynamics



Water-ice interface conditions:

- no-slip
- inflow according to melting rate
- melting temperature
- Stefan condition

Heat source surface:

- no-slip
- no inflow
- temperature or heat flux
- Newton‘s third law:

$$\oint_{\text{surface}} p\, d\sigma = F$$

Ω_l: Mass, momentum and energy balance:

$$\begin{aligned} \nabla \cdot \mathbf{u} &= 0 \\ \partial_t \mathbf{u} + (\mathbf{u} \cdot \nabla)\mathbf{u} &= -\frac{1}{\rho}\nabla p + \nu \triangle \mathbf{u} \\ \partial_t T_l + (\mathbf{u} \cdot \nabla) T_l &= \alpha_l \triangle T_l \end{aligned}$$

Ω_s: Heat equation in the solid ice

$$\partial_t T - (\mathbf{V} \cdot \nabla) T_s = \alpha_s \triangle T_s$$

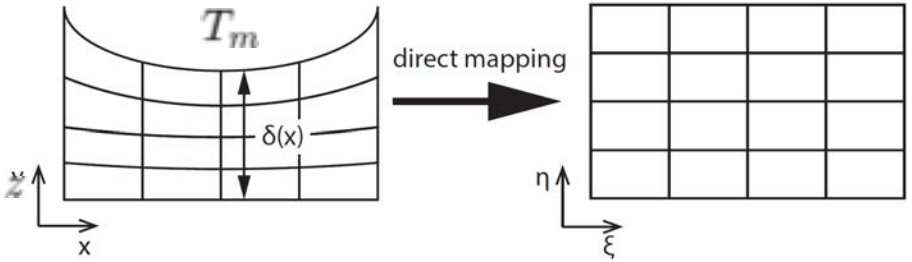
Model reduction based on scaling arguments

Hybridized computational model: SimCoMet – Simulating Contact Melting

Energy balance:

$$\epsilon Pe(u\partial_x T + w\partial_z T) \quad = \quad \partial_z^2 T$$

Transformation:



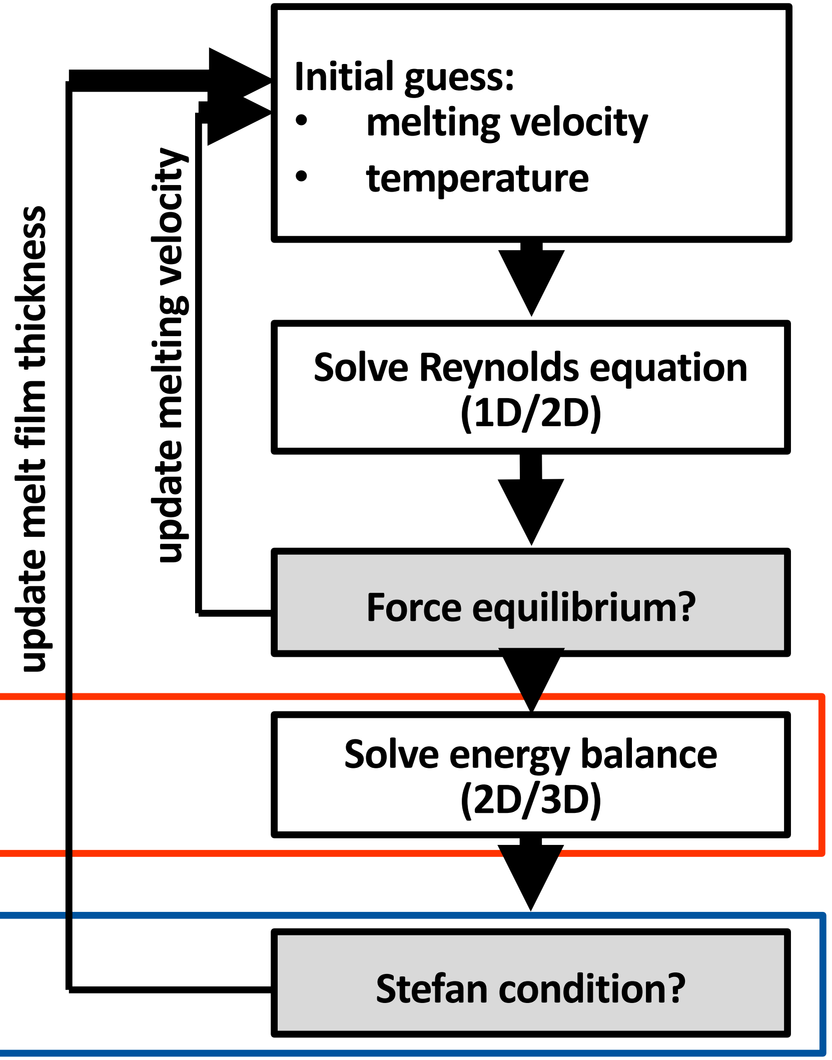
$$\xi = x \qquad \eta = z/\delta(x)$$

$$\begin{aligned} u\partial_x T + w\partial_z T &= u\partial_\xi T + u\partial_\eta T \tfrac{1}{\delta}\left(w - u\eta\partial_\xi \delta\right) \\ \partial_{zz} T &= \partial_{\xi\xi} T \left(\tfrac{d\xi}{dz}\right)^2 + 2\partial_{\xi\eta} T \left(\tfrac{d\xi}{dz}\tfrac{d\eta}{dz}\right) + \\ & \quad \partial_{\eta\eta} T \left(\tfrac{d\eta}{dz}\right)^2 = \tfrac{1}{\delta^2}\partial_{\eta\eta} T \end{aligned}$$

Solved using FDM

Stefan condition (for each x):

$$\partial_z T|_{z=\delta(x)} \quad = \quad \frac{\rho v(x,\delta(x))}{\kappa_l}\left(h_m + c_p(T_m - T_s)\right)$$



Initial guess:
- melting velocity
- temperature

Solve Reynolds equation (1D/2D)

Force equilibrium?

Solve energy balance (2D/3D)

Stefan condition?

Contact melting – some fundamental results

Rotational melting modes

International Journal of Heat and Mass Transfer [illegible]

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journal homepage: www.elsevier.com/locate/ijhmt

Curvilinear melting – A preliminary experimental and numerical study

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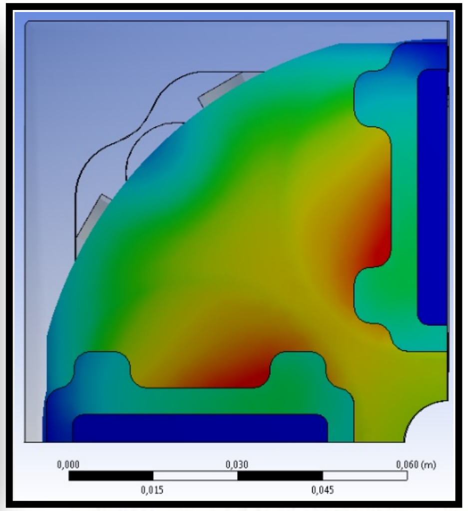
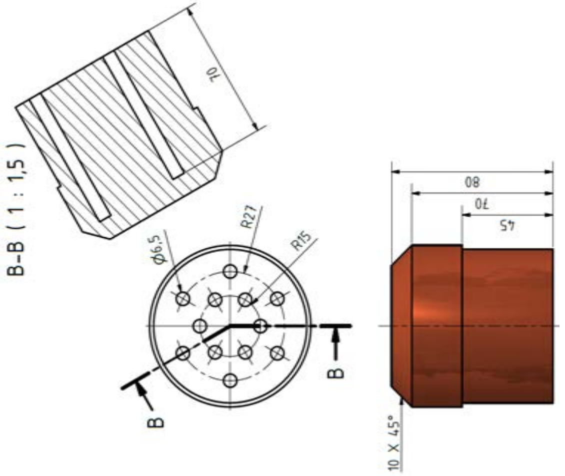
[b] Faculty of Aerospace Engineering, FH Aachen University of Applied Sciences, Germany
[c] CSC – IT Center for Science, Espoo, Finland

Spatially varying heat flux distribution





International Journal of Heat and Mass Transfer 115 (2017) 1276–1287

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journal homepage: www.elsevier.com/locate/ijhmt

Spatially varying heat flux driven close-contact melting – A Lagrangian approach

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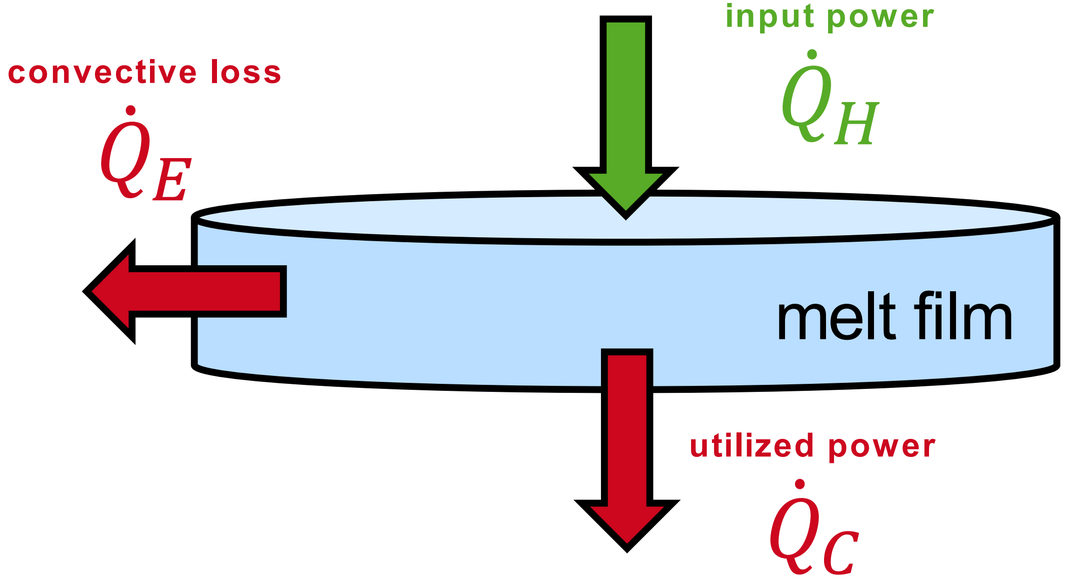
Leverage contact melting theory to study performance in extreme cryoenvironments

Consider melt film (red) as a closed system:



$$\boxed{\dot{Q}_H - \dot{Q}_E - \dot{Q}_C = 0}$$

and apply contact melting theory

Allows us to

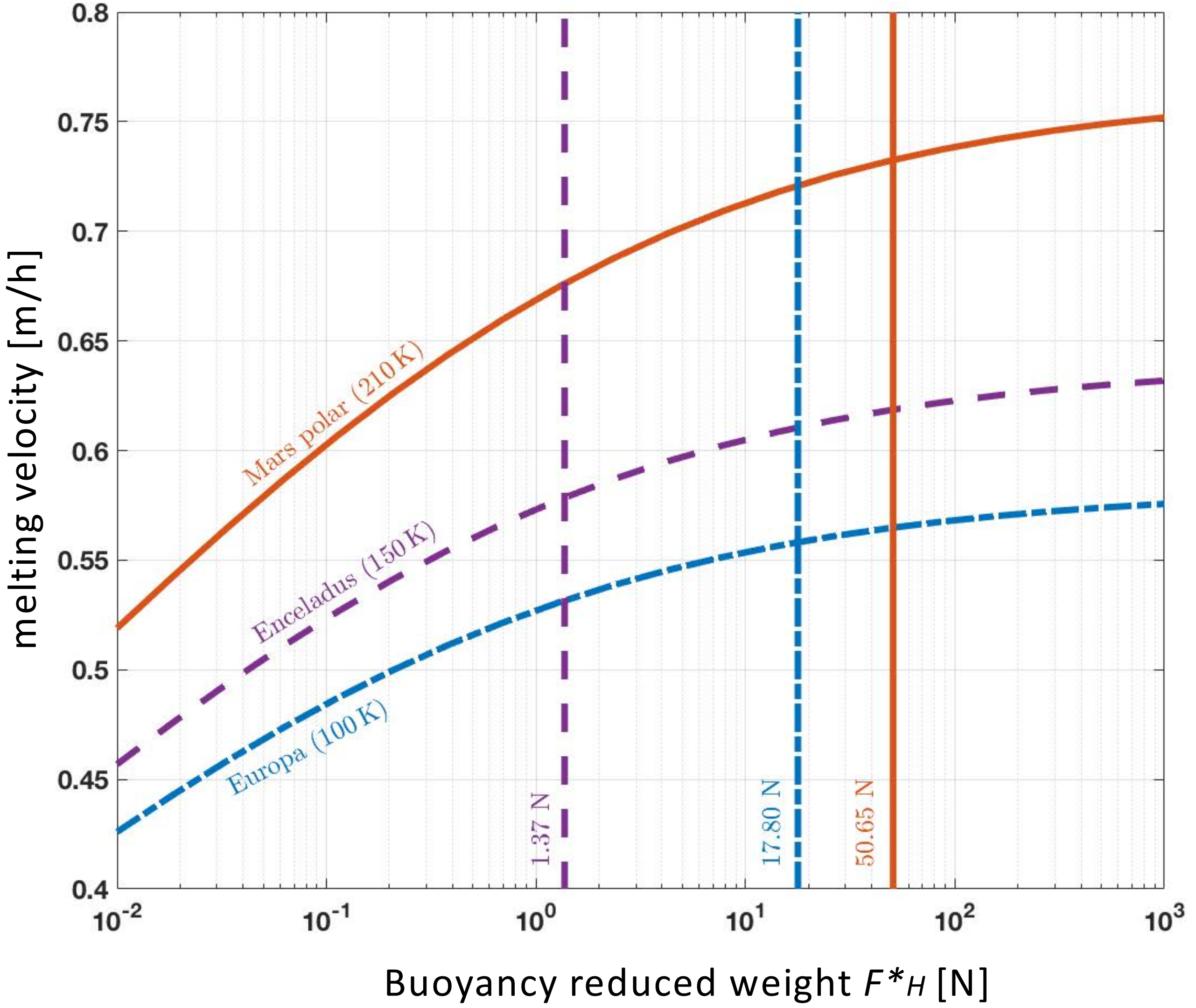
- **study the melting velocity / efficiency**
- **determine the critical refreezing length**

for a reference probe
(1m long / 0.06m radius / 25kg)
in a representative cryoenvironments:

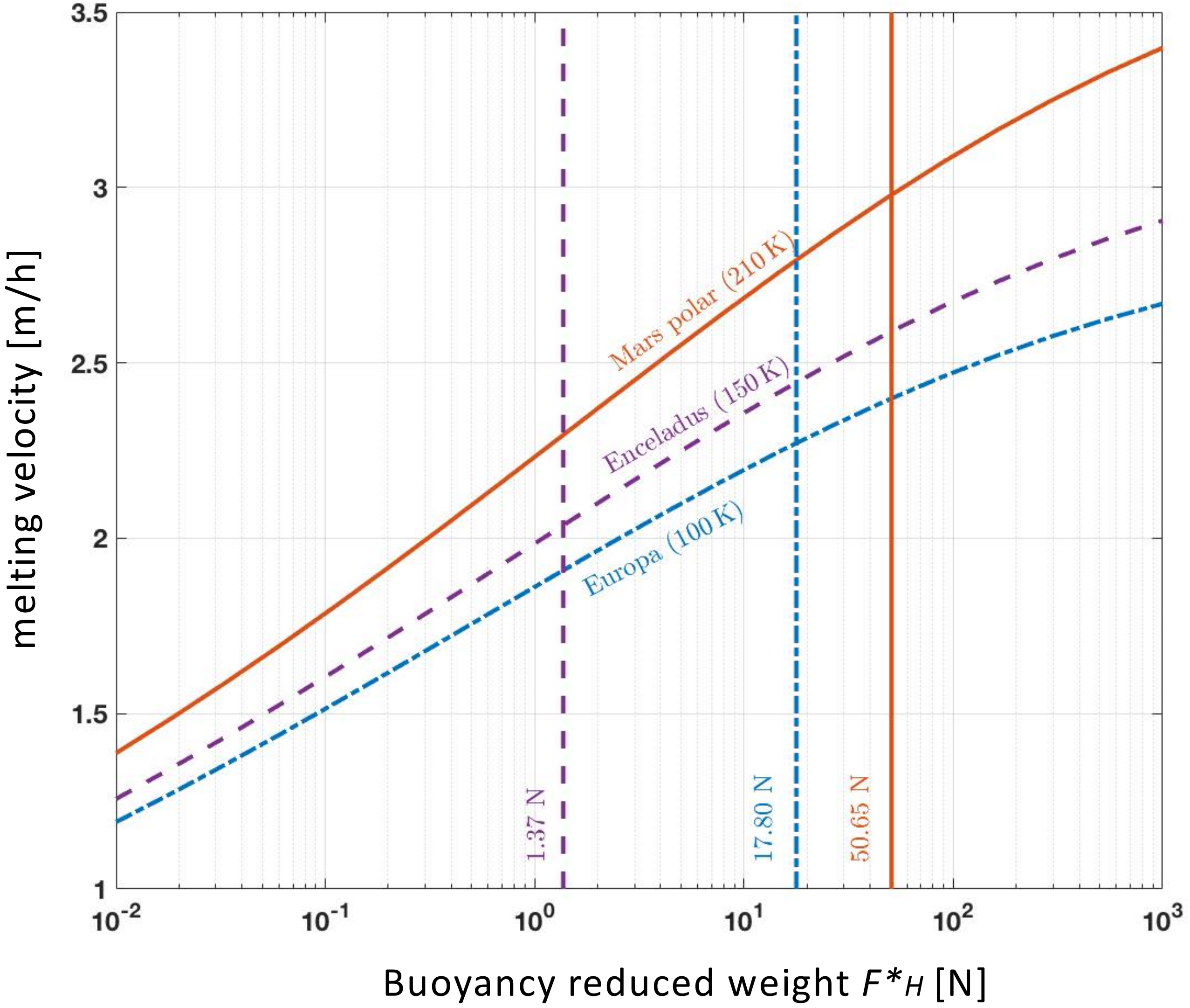
- **Mars: 210 K / 3.7 m/s^2**
- **Enceladus: 150 K / 0.1 m/s^2**
- **Europa: 100 K / 1.3 m/s^2**

Melting velocity over contact force

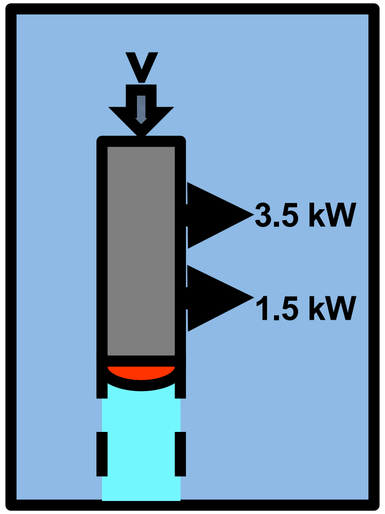
Melting velocity of 1kW probe:

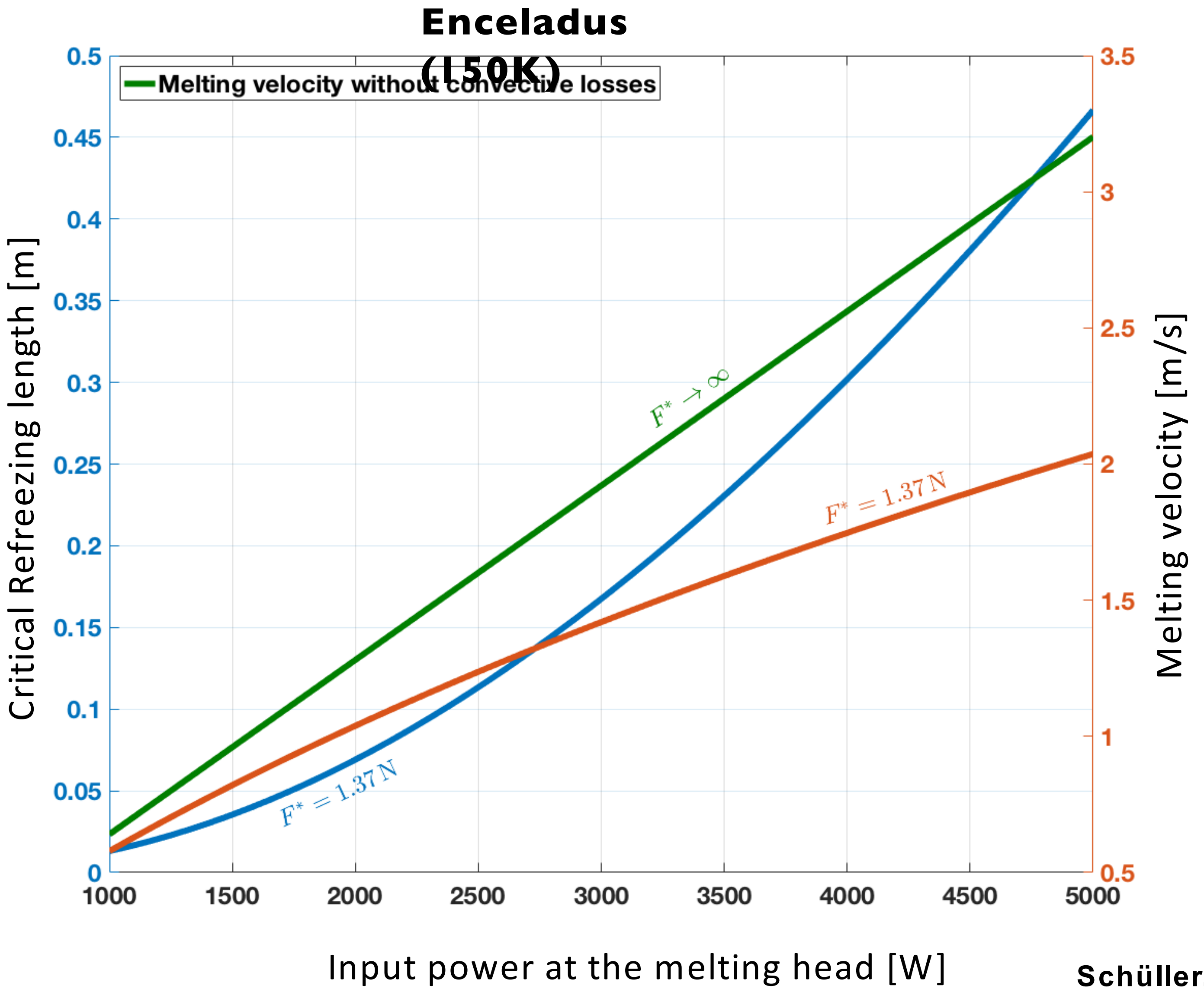


Melting velocity of a 5kW probe:



Implications for the melting probe‘s design





Schüller, Kowalski, Icarus (accepted)

Conclusions and Outlook

Conclusions

- We developed a flexible micro-scale contact melting simulation model
- We gained further insight into the behavior of melting probes in extreme cryoenvironments
- We contributed to the fundamental understanding of contact melting processes
- First validation experiments have been promising

Next steps

- Trajectory model for the IceMole (trajectory control will be tested in 2018 field campaign)
- High altitude rocket and vacuum chamber experiments due soon (VIPER / EnEx- nExT)
- In proposal phase: Smart process model and data integration for ice exploration

Thanks …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