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EMS

Feasibility analysis of the cryogenic system for a High-dynamic Superconducting Linear Motor

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Part of the High-dynamic Superconducting Linear Motor (HSLM) project
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NWO Toegepaste en Technische Wetenschappen TU/e ASML VDL PRODRIVE TECHNOLOGIES

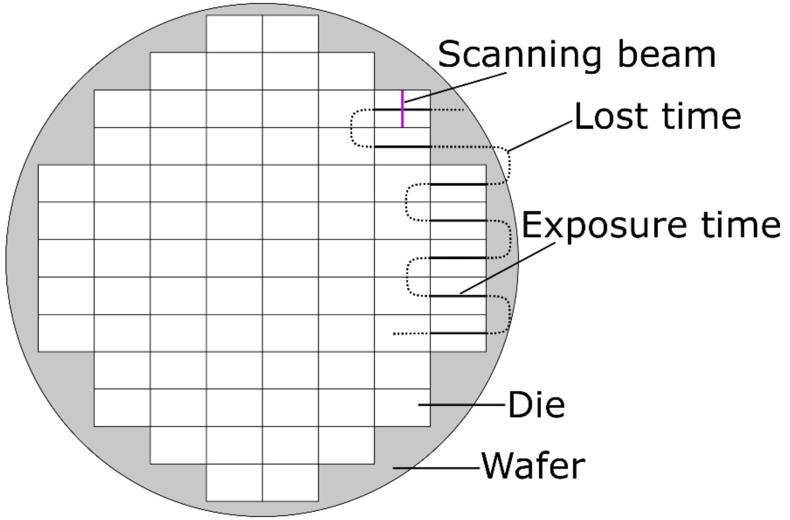
1.1 Motivation

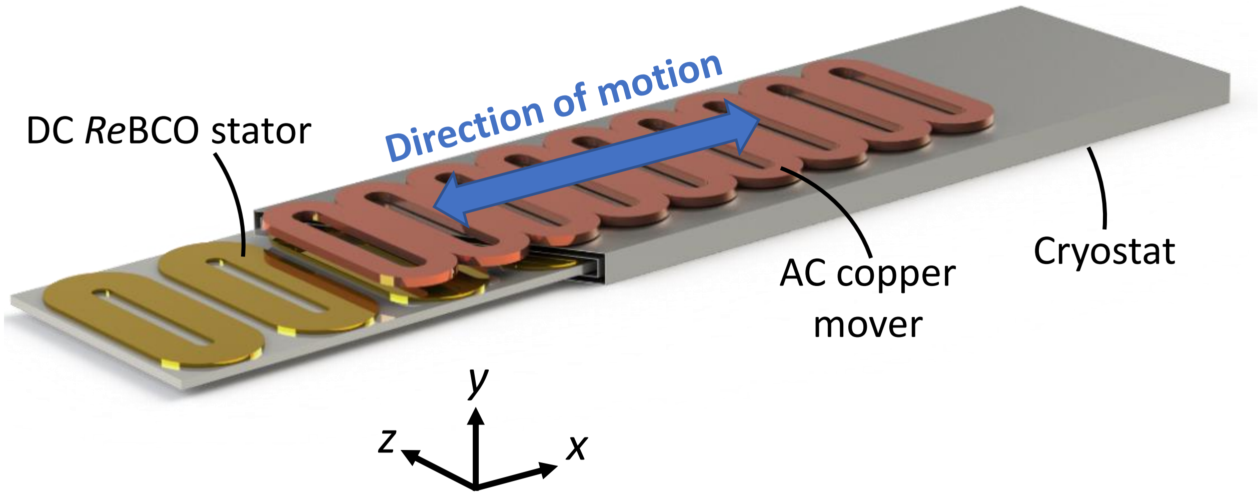
Linear motor for lithography application

- Reticle stage
- Long stroke
- Improve throughput by rapid acceleration

Design target

- DC *Re*BCO stator / AC copper mover
- Increase air gap magnetic field by order of magnitude
  - Higher force-density
  - Acceleration: 100g
    Payload mass: 100kg





1.2 Benchmark

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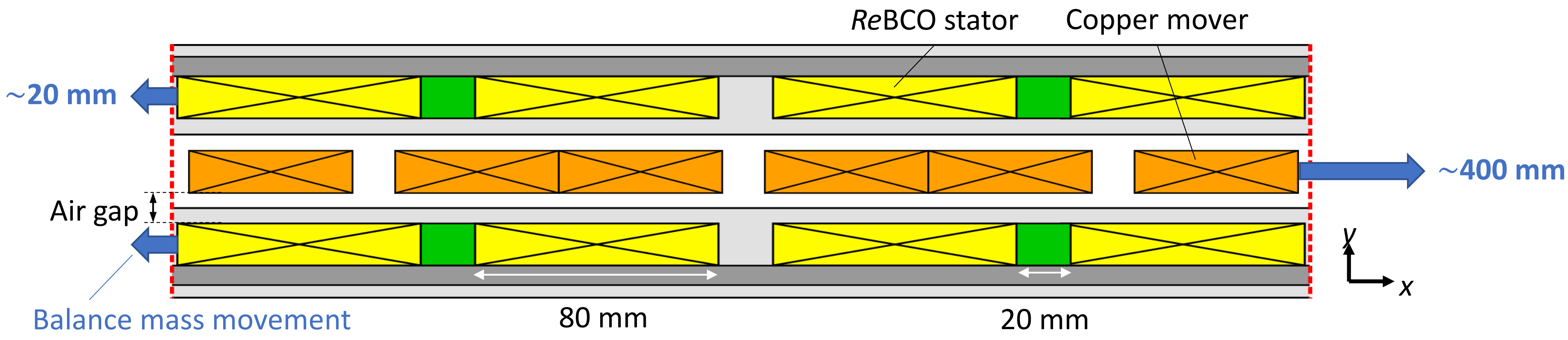


Benchmark dimensions (may change)	
Air gap height	12 mm
Winding pack dimensions	4 x 80 mm
Coil length (straight)	0.5 m
Stator magnetic field on mover	~ 1.5 T
Mover magnetic field on stator	~ 0.2 T
Stator coil current	280 A

- Air gap / cryostat wall
  - Minimize for high force-density
- Significant heat load
  - AC loss major contributor
- Moving cold mass
  - ~20 mm at ~10 Hz
- **Goal: assess feasibility of cryogenic options**

1.3 Operating temperature

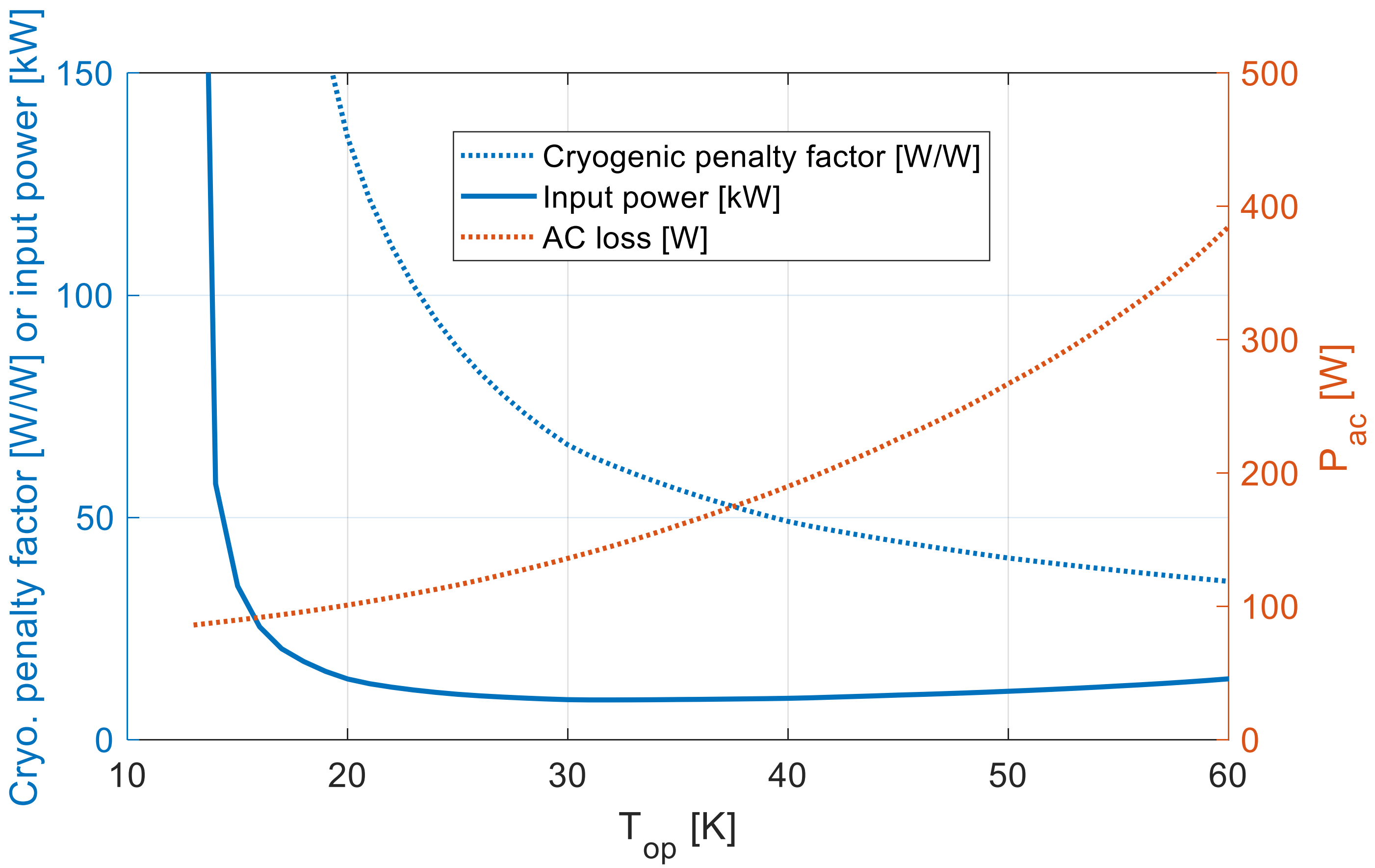
Most efficient operating point is between **20 and 50 K**

- Benchmark FEM 40 K
- Scale AC loss to operating temperature T_{op}

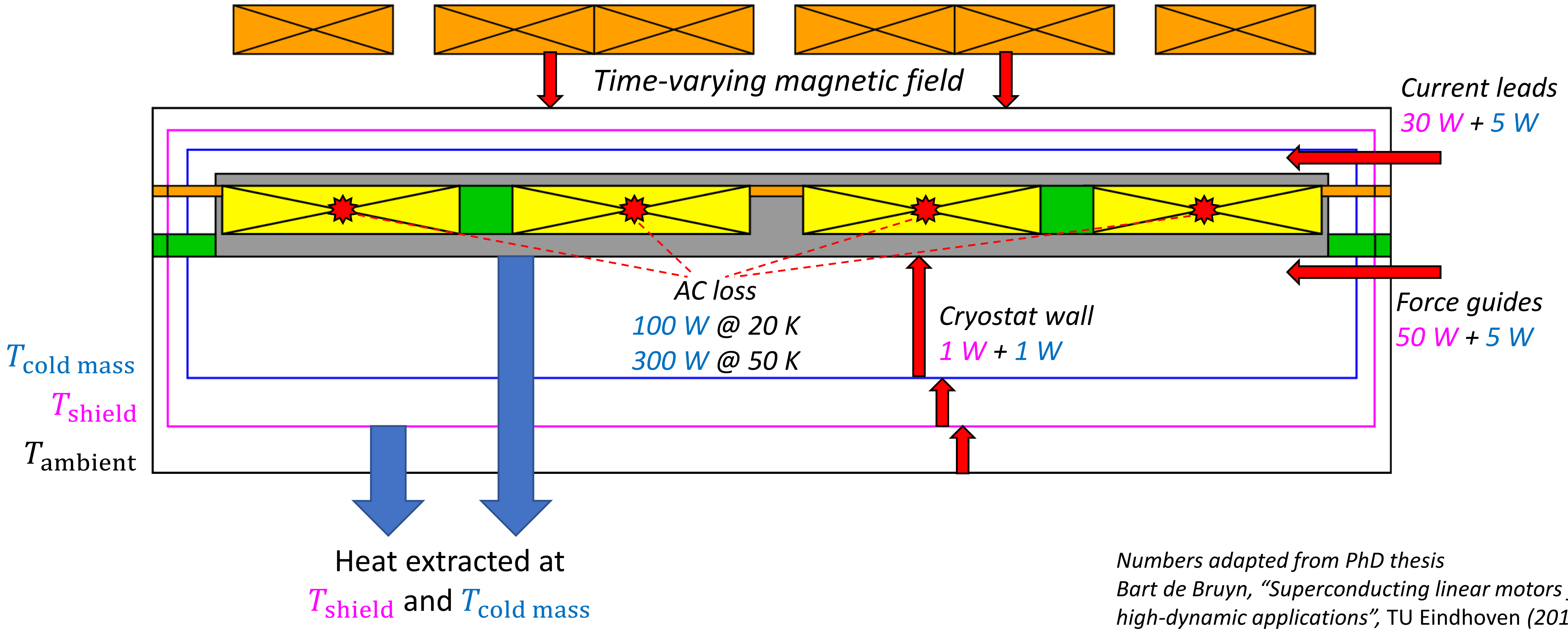
$$P_{\mathrm{AC}}(T_{\mathrm{op}}) = P_{\mathrm{AC}}(40K)\frac{I_{\mathrm{c}}(40K)}{I_{\mathrm{c}}(T_{\mathrm{op}})}$$

- CPF of 20 K-single stage-GM cryocooler

$$P_{\mathrm{in}} = \mathrm{CPF} * P_{\mathrm{AC}}$$



1.4 Estimated heat load



Numbers adapted from PhD thesis Bart de Bruyn, "Superconducting linear motors for high-dynamic applications", TU Eindhoven *(2018)*

2.1 Systematic review; cryostat options

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Gather concept cryostat designs (N=24)

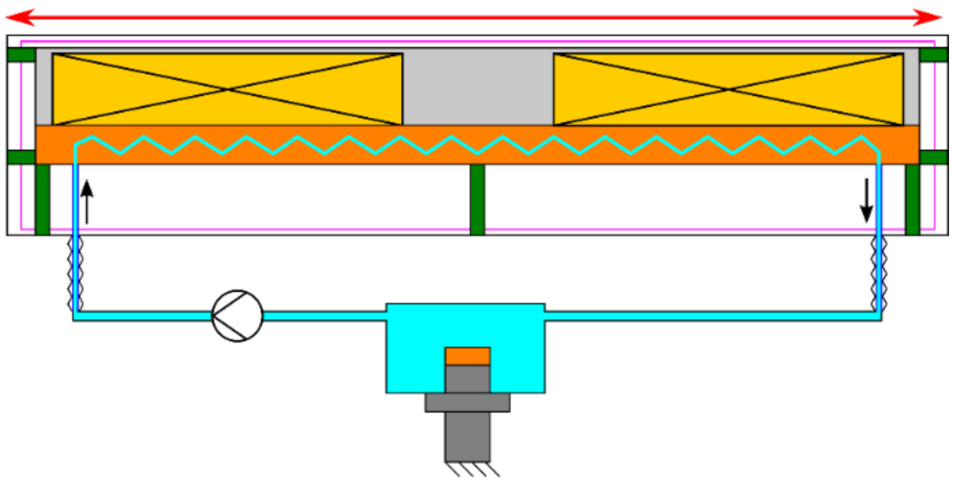
Define assessment criteria (N=7)

Assess the performance of each concept at each of the criteria

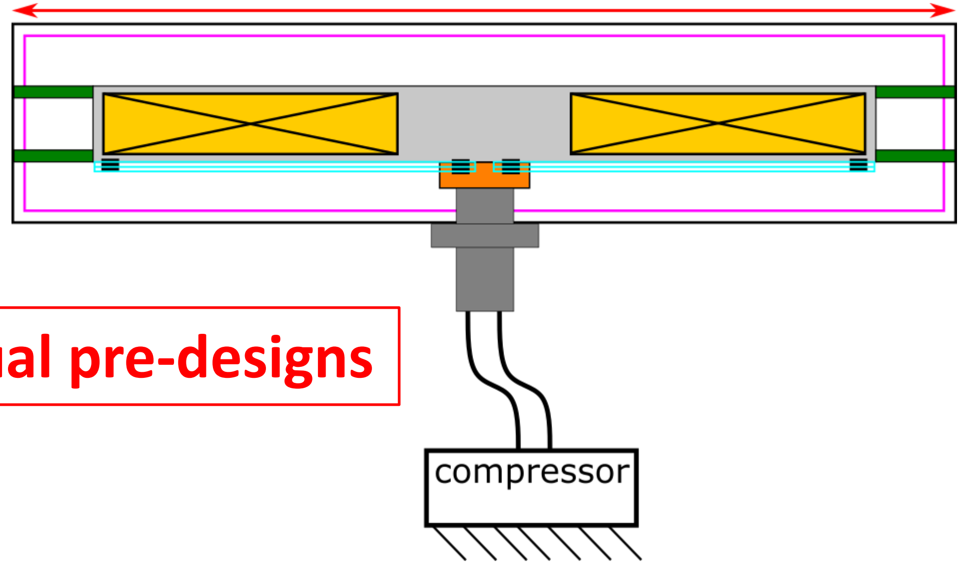
Quantitatively where possible

Conclusion

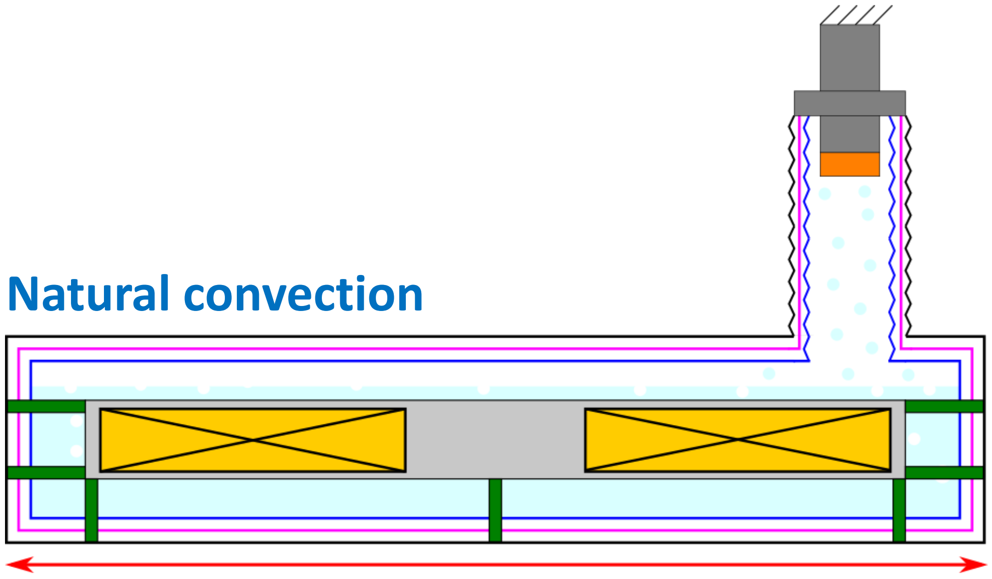
Forced convection – cooling channels



Cryogenic heat pipes - conduction



Natural convection

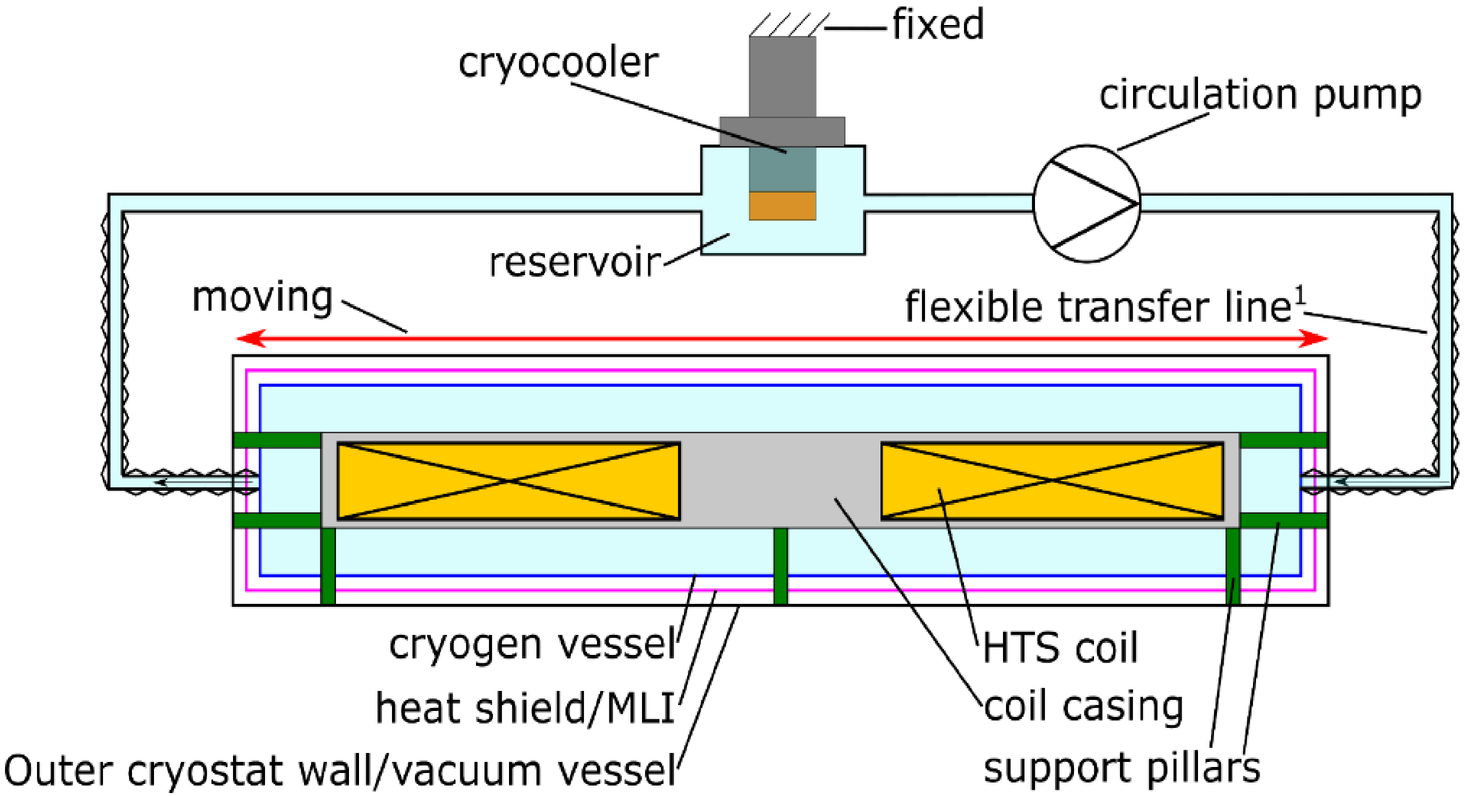


Conceptual pre-designs

2.2 Systematic review criteria

Fundamental characteristics
• Temperature gradient between cold mass and cryocooler/reservoir
• Contact area between coil and heat sink
• Thermal reservoir in case of quench
• Cryostat wall thickness

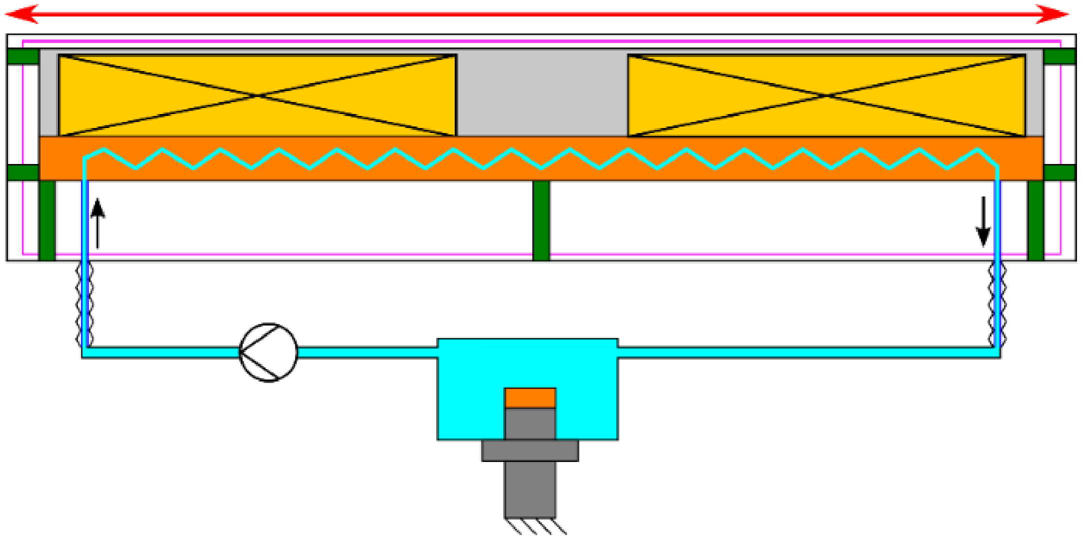
Engineering challenges
• Retaining cooling power under rapid acceleration
• Cable slab size
• Maturity/reliability



[1] line consists of: inner cryogen vessel, vacuum space with MLI, outer cryostat

2.3 Systematic review results – summary

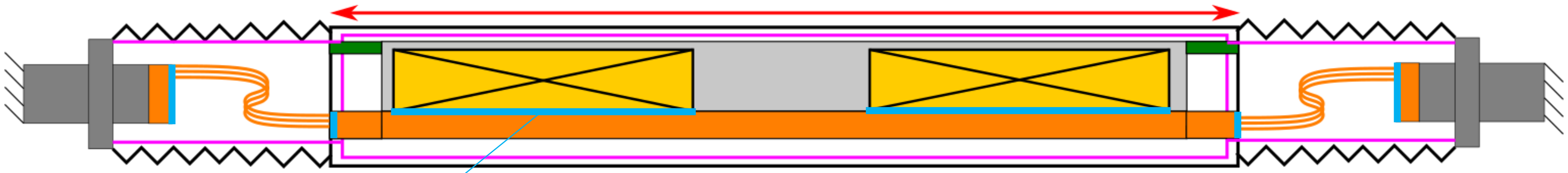
Forced convection of **saturated liquid**, via **cooling channels**, heat extracted by stationary cryocooler



Conduction cooling through **base plate** and **flexible** medium, heat extracted by stationary cryocooler

Conceptual pre-designs

3.1 Case study - conduction cooling



- Thermal interface resistances
  - Epoxy, thermal grease, indium
- Flexible thermal link
  - Copper braids
  - Add cross-section until sufficient
- Eddy current loss
  - Balance eddy current loss versus thermal resistance

Image: Technology Applications Inc.

Duty cycle

$$\boldsymbol{P_{eddy}} = 0.5 * V * \frac{(\pi f B_a d)^2}{6\rho}$$

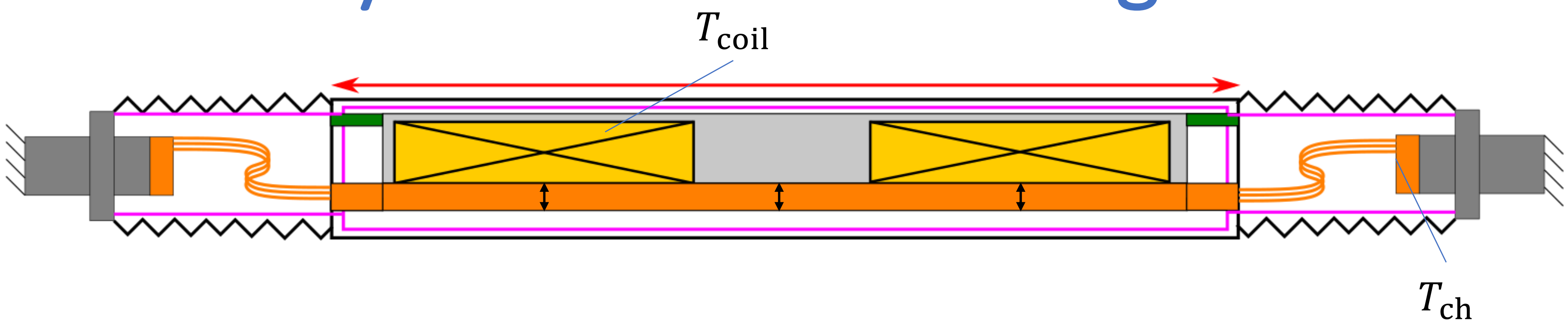
Estimated eddy current loss in laminated (1 mm) RRR100 copper cooling plate:

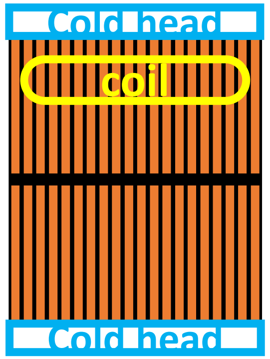
T_{op} [K]	P_{eddy} [W]
40	**70**
25	**130**

Recall $P_{hyst} \approx$ 100 W

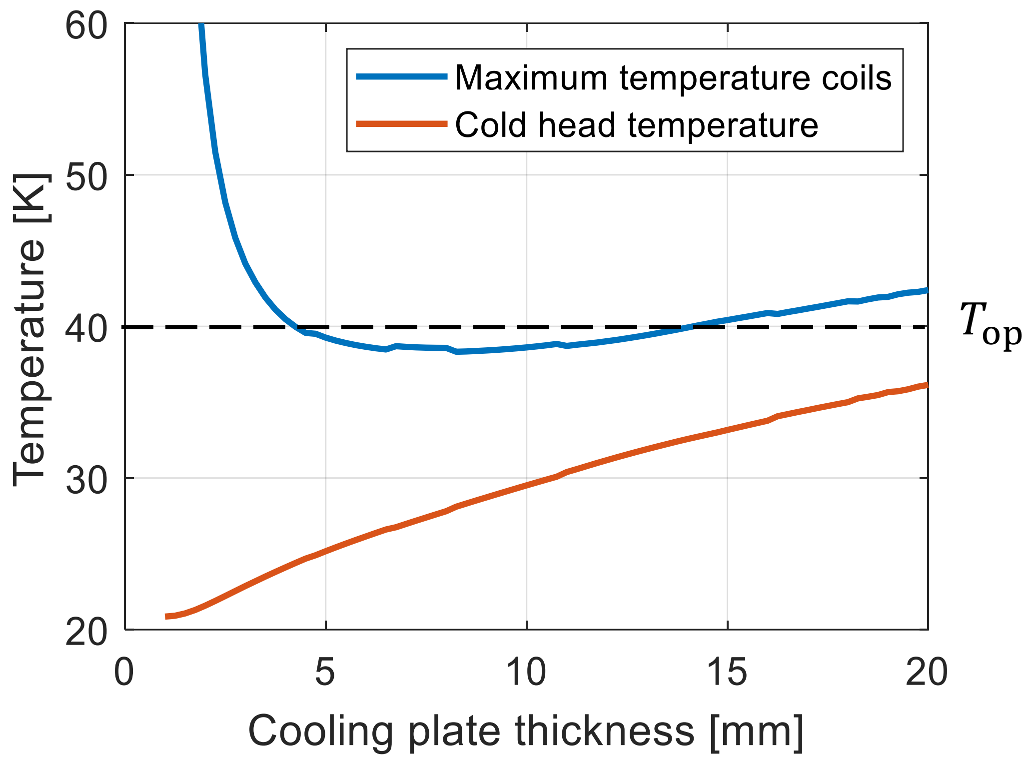
P_{eddy} significant, requires attention

3.2 Case study - conduction cooling



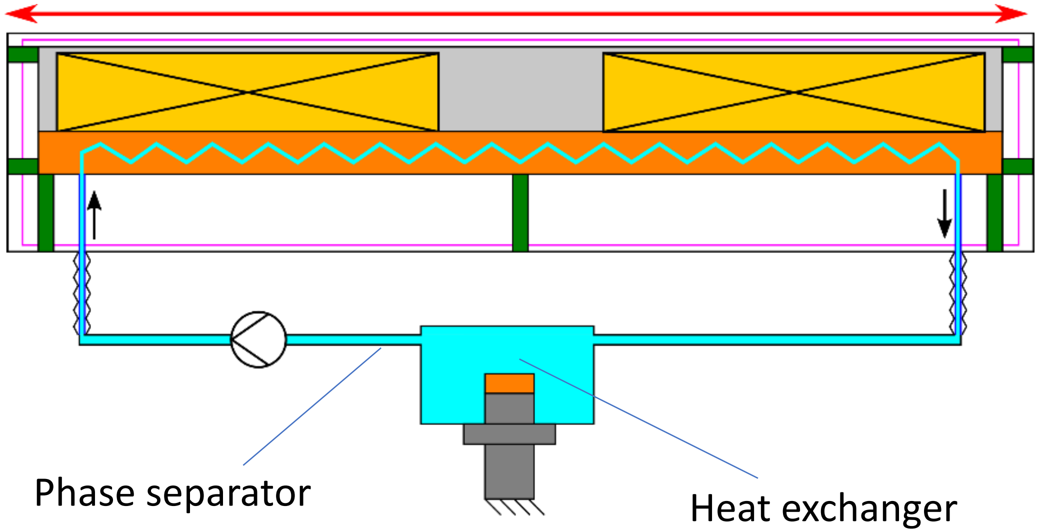


- Thermal resistance ($\propto 1/h$) and eddy current loss ($\propto h$) in conflict
  - Optimum can be found
- Combined copper plate + braids can maintain T_{op}
  - P_{eddy} not necessarily a showstopper, but needs careful consideration
- **Conduction cooling can be a viable cooling strategy for the HSLM**



3.3 Case study - force-flow cooling

- Liquid at T_{sat} close to stator
  - Resistive cooling plate, reduces eddy currents 2-3 orders of magnitude with respect to OFHC copper
  - T_{coils} homogeneous
- Limited 'sloshing' effect in channels
- Off-the-shelf components
- 2 fluids (LH_2, LNe) within optimal T-range

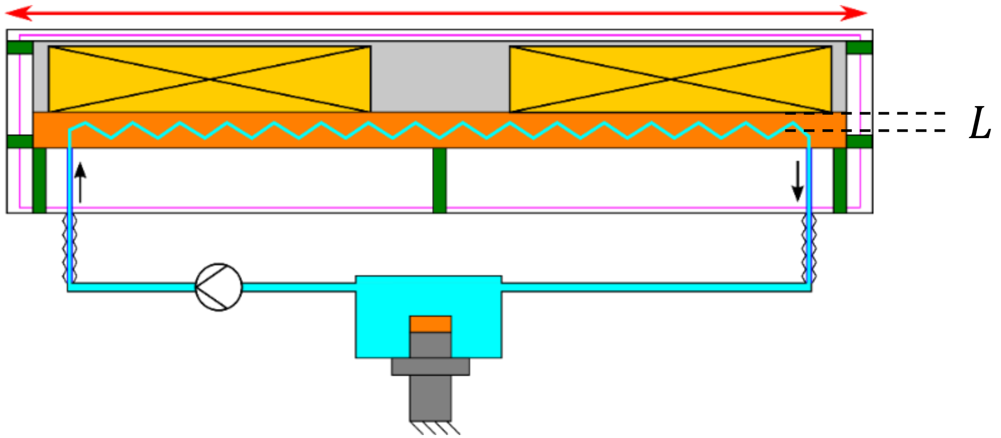


Cryogen	H_2	Ne	N_2
Boiling point [K]	20.3	27.1	77.3
P_{AC} [W] (est.)	102	124	1103
Latent heat [kJ/kg]	448	85.7	199
dm/dt [g/s]	0.2	1.4	5.5
dV/dt [mL/s]	3.2	1.2	6.9

Very doable →

Evaporation rate

3.4 Case study - force-flow cooling



Temperature difference between coil and cooling channel per unit length for select materials ***at 20 K****. Eddy current loss scales with* $1/\rho$*.*

Material	ρ [μΩ·cm]	k [W/m·K]	$\frac{\Delta T}{L} = \frac{P}{Ak}$ [K/cm]
OFHC copper (RRR=100)	0.017	2430	**2e-3**
Stainless steel 304	49.4	2.2	**2.3**
Brass	4.2	22	**0.23**
Al 6061	1.4	28	**0.18**

Material data from: Ekin (2006)

- Potential down sides
  - Risk of leak
  - ΔT in heat exchanger (gas)
  - Heat in-leak flexible cryostat

- Eddy currents in the cooling plate strongly reduced while maintaining operable ΔT
- **Force-flow evaporative cooling can be a viable cooling strategy for the HSLM**

4. Outlook

- We have conducted a systematic review assessing the feasibility of a wide range of cooling strategies for application in a High-dynamic Superconducting Linear Motor

- **Conduction cooling** cryostats and **force-flow** cooling cryostats are selected to best meet the demanding conditions imposed by the system
  - Additional complications: no showstoppers

- Further investigation into feasibility of the 2 systems is underway