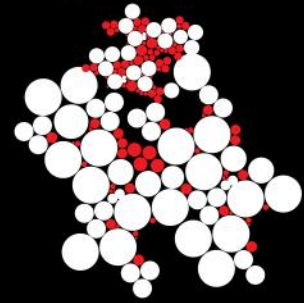


UNIVERSITY OF TWENTE.



HIGH-DYNAMIC SUPERCONDUCTING LINEAR MOTOR

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ASML



PRODRIVE
TECHNOLOGIES

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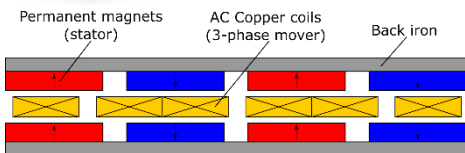
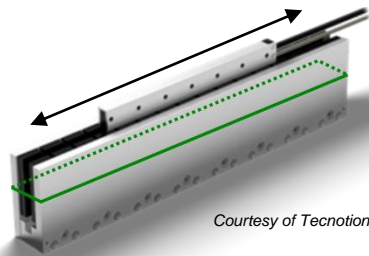


Toegepaste en
Technische Wetenschappen



INTRODUCTION

Conventional linear motor



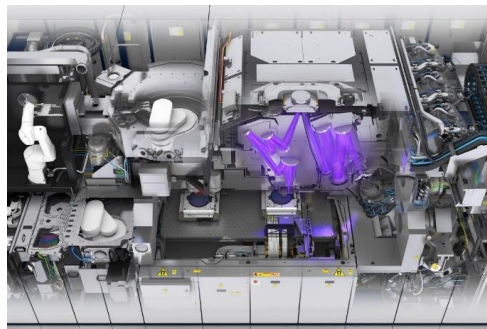
NdFeB magnets and alu racetrack coils
 a_{\max} : 320 m/s² (85 kg payload)

Material limits reached

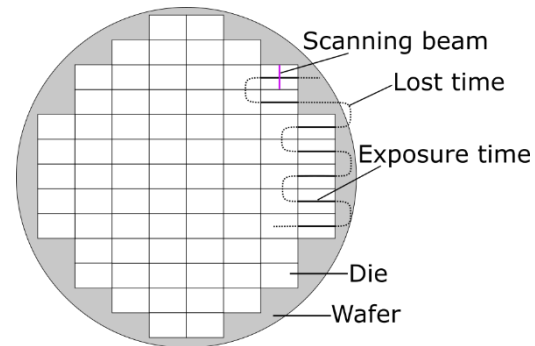
Lithography: still **higher force-density** is desired
Many instances of de-acceleration

Increase stator field by replacing permanent magnets
with DC superconducting electromagnets

Aim for 1000 m/s² in reticle stage

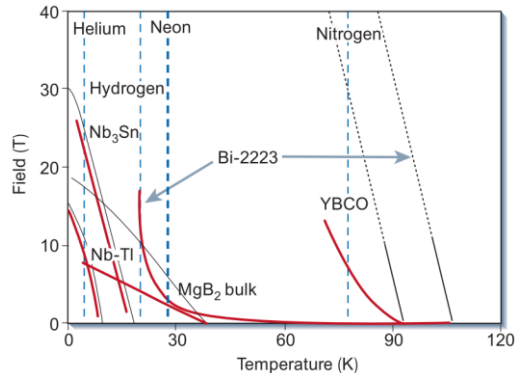


NXE3400, EUV lithography machine, courtesy of ASML

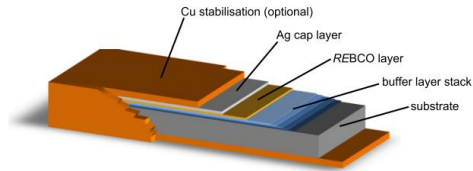


SUPERCONDUCTIVITY

- Higher magnetic field in air gap
- No dissipation
- Allows for larger air gap
- Wide temperature range
- Thermal stability
- Conductor development



Irreversibility field of common superconductors [1]

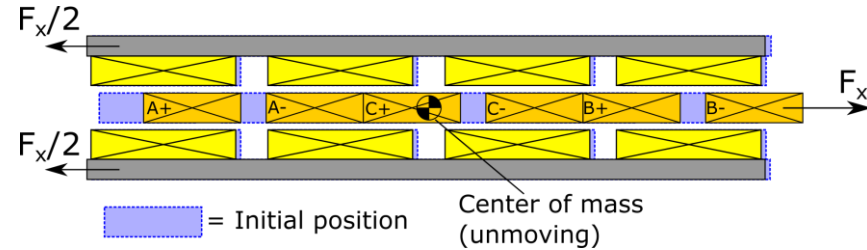


Composition of ReBCO coated conductor [2]




THERMAL CHALLENGE

- DC coils exposed to AC fields
 - Heavy AC loss near I_c
- Forces acting on coils
 - Vibrations disturb process
 - Balance mass is **free to move** (~5g)
- Refrigeration system must carry large heat load from rapidly moving object to cooler, while minimizing impact on motor and machine performance



THANKS FOR YOUR ATTENTION SEE YOU DURING THE POSTER SESSION

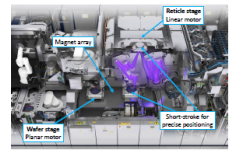


Thermal management of a high-dynamic superconducting linear motor

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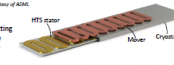
Introduction

Lithography machines employ linear and planar motors to move masks and wafers around. In-between exposure times the reticle must de- and accelerate. During these periods of time no exposure is possible. Reducing this time again increases throughput significantly. High temperature superconducting (HTS) coils are promising, since they can generate very high magnetic fields without dissipation, which are needed to move the reticle rapidly and with high precision.



State-of-the-art:
Fundamental limits of performance reached:
- 520 m/s² on a 85 kg payload [1]
- halfed field strength
- Ohmic heating in resistive primary

x4 magnification factor means reticle must move 4 times as far and fast as before. This is a lot to gain from force-density increase.

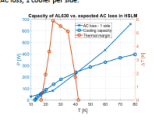


These limits can be overcome with a superconducting material. In this case, the permanent magnets are replaced with DC HTS stator coils. Motor remains unchanged. The aim is set at a motor capable of delivering 2000 m/s² to a 85 kg payload.

The goal of the high-dynamic superconducting linear motor (HSLM) project is to assess the potential of 2G HTS in linear motors, to see where the major challenges lie and determine how they can be overcome.

Case study

is conduction cooling with flexible thermal link between cold head and cold mass a feasible option?
Assumptions: 100120 copper; Cryomech AL80, only AC loss, 1 cooler per side



Find minimum copper load cross-section to sustain given coil temperature

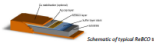
T_{coil} [K]	20	25	30	35	40
$P_{AC} [W/m^2]$	65	80	100	130	200
$A [cm^2]$	140	61	111	184	640

Ideal operating temperature around 25 K, certainly feasible. Area under winding pack > 2000 cm². Other thermal resistances not considered here.

Why choose ReBCO?

Advantage over conventional motors:

- Major increase in stator field
- No DC resistance means no dissipation
- independent on fielded supply



Advantage over other superconductors:

- Possible operation at intermediate (20-40 K) or high (77 K) temperatures
- High J_c high in-plane strength, small bending radius
- Large thermal margin, necessary to sustain heat load
- Many manufacturers driving trend towards higher J_c in ReBCO

Alternative cooling methods

Bath cooling
Open system, venting evaporated liquid.
LHe (20 K) and LHe (27 K) are in the desired operating range. Estimated evaporation is approx. 500 and 150 liter/day, respectively. Very expensive to replenish.

Cryocooler as refrigerant
Closed system. Cryogen carries heat from coils to cooler via convection.
Total cooling power at conduction cooling smaller thermal gradient within stator, resistant to peak loading.

More complex cryostat, large air gap, use of liquids, moving object in liquid may hinder cooling.

Helium gas circulation
Combination of cryocoolers and cryostat that rapidly circulate gaseous helium through a heat exchanger. Hundreds of watts cooling power at 20 K, but very large gas complex system.


Thermal challenge

In addition to a static heat load from current leads etc., the HSLM stator coils will experience a significant dynamic heat load.

The HSLM stator coils carry DC, but are exposed to external AC fields from aluminum mover coils. This will introduce significant hysteresis loss to the windings. Especially when operating near [1, 3].

One finite element model has already been made within the consortium [4]. Using these results, the feasibility of conduction cooling has been investigated.

In order to minimize vibrations, the stator acts as a balance mass and is therefore free to move



Stator will move over a stroke of ~4 cm at 20 Hz. This movement, in combination with the large heat load, makes this a challenging cryogenic system.

Conduction cooling

It is desired to minimize the footprint of the cryogenic system on the lithography process. Conduction cooling has several advantages over other refrigeration schemes, such as:

- Small air gap
- Flexible operating temperature
- Cryogen-free, relatively simple operation
- Compact cryogenic infrastructure
- Commercially available

if conduction cooling is to be implemented, some challenges must be considered:

- Cryocoolers cannot be shaken with the stator (50 m/s²), so must be decoupled
- Low efficiency < 5% Carnot, worse at lower T
- Thermal gradient between cold head and coils

References

[1] De Groot, G., Verbeek, A., de Putter, B. (2016). Submicroning Stage Accelerator. *Journal of Applied Superconductivity*.
 [2] De Groot, G., Verbeek, A., de Putter, B. (2016). Submicroning Stage Accelerator. *Journal of Applied Superconductivity*.
 [3] De Groot, G., Verbeek, A., de Putter, B. (2016). Submicroning Stage Accelerator. *Journal of Applied Superconductivity*.
 [4] De Groot, G., Verbeek, A., de Putter, B. (2016). Submicroning Stage Accelerator. *Journal of Applied Superconductivity*.

Acknowledgements

