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Superconducting stage actuation

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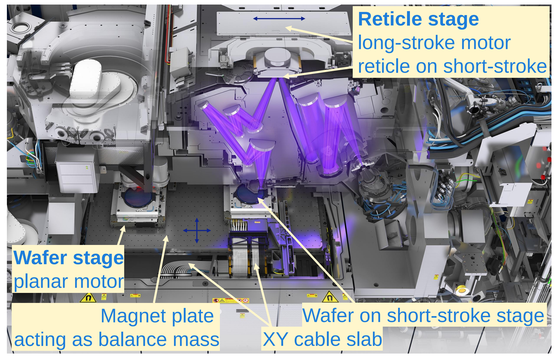
PRODRIVE TECHNOLOGIES

Context

In litho equipment, **high productivity** and **sub-nanometer precision** of motion stages are combined to enable shrink in chip production at reasonable cost. Superconducting motors are an option for long-stroke motion, driving large masses at a precision of a single micrometer.



Reticle (mask) stages

- Linear synchronous motor
- Highest accelerations: 160-320 m/s^2
- Moving mass payload/motor: ~85/40 kg

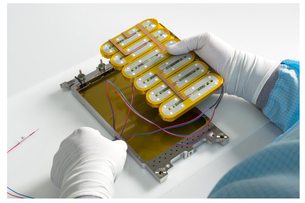
Wafer stages

- Planar XY synchronous motor
- 40-100 m/s^2 + Levitation
- Moving mass payload/motor: ~100/40 kg

Challenges

Manufacturing tolerances

- Magnet-to-magnet in-plane tolerance <150 μm
- Tolerances at cryogenic temperature → shrink and shrink repeatability



Picture source VDL ETG

Static & dynamic loads

- HTS cable stability
- kN interaction forces
- Positioning stability under dynamic loads
- Cryostat moving ~50m/s2
- Fatigue for >1e9 cycles

Cleanliness

- Ultra-clean vacuum
- No particles to be shed from motor

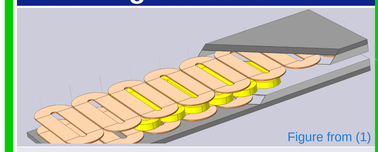
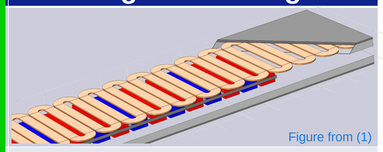
Efficiency

- Thin cryostat wall in actuator gap
- Reduce AC loss
- Cooling efficiency

Availability

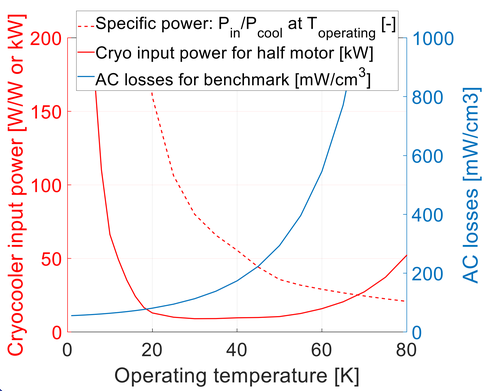
- In-situ serviceability
- Spare part within reasonable cost
- Minimize quench (propagation) & cooldown time
- Tens (hundreds) HTS coils → < 0.0001/coil/yr failure

Concept

DC HTS magnet array + moving Alu coils	AC HTS coil array + moving NdFeB magnets
 Figure from (1)	 Figure from (1)
3.5x higher force/volume for same cooling power w.r.t. conventional (1)	2x higher force/volume (1), and moving NdFeB 3x heavier than Alu → less acceleration
Losses from AC field over DC-HTS	Losses from AC current in HTS + AC field from mover
Accuracy by current steering Alu coils: well known	High-accuracy AC steering of HTS coils required

(1) de Bruyn, B. J. H. (2018). *Superconducting linear motors for high-dynamic applications,* PhD Dissertation, Eindhoven: Technische Universiteit Eindhoven

Expected HTS coil loads

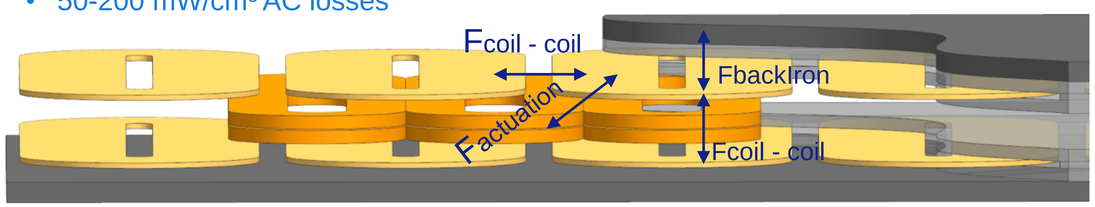


AC losses

- Moving coils induce AC field in DC-steered HTS coils
- 20-50K operating temperature for cooling efficiency
- 50-200 mW/cm^3 AC losses

Forces on HTS coil

- $F_{coil-coil}$ XY >150 kN/m^2, Z >200 kN/m^2, static
- $F_{actuation}$ >250kN/m^2, dynamic ∈ [10-1000]Hz
- $F_{HTS-to-backIron}$ >450 kN/m^2, static
- Quench/emergencies: to be determined



Target HTS linear stage

3x faster → Justify the risk and effort
- 10 m/s, **1000m/s²** for 85 kg payload
- +30% force for damping and servo control

<1μm positioning performance
- Force variation < 10%, unrepeatable error < 1%

Energy efficiency higher than conventional

Mature for usage in semiconductor industry
- Downtime budget incl. recovery to full production < 20 min/machine/year

Conclusions

- Superconducting motors can offer higher cost efficiency for lithographic equipment
- High accuracy specs induce challenges to manufacturing tolerances and dynamic stability
- Dynamic loads challenge the mechanical design and fatigue strength in cryogenic conditions
- Dynamic loads induce AC losses and require adequate cooling techniques to maintain cost efficiency