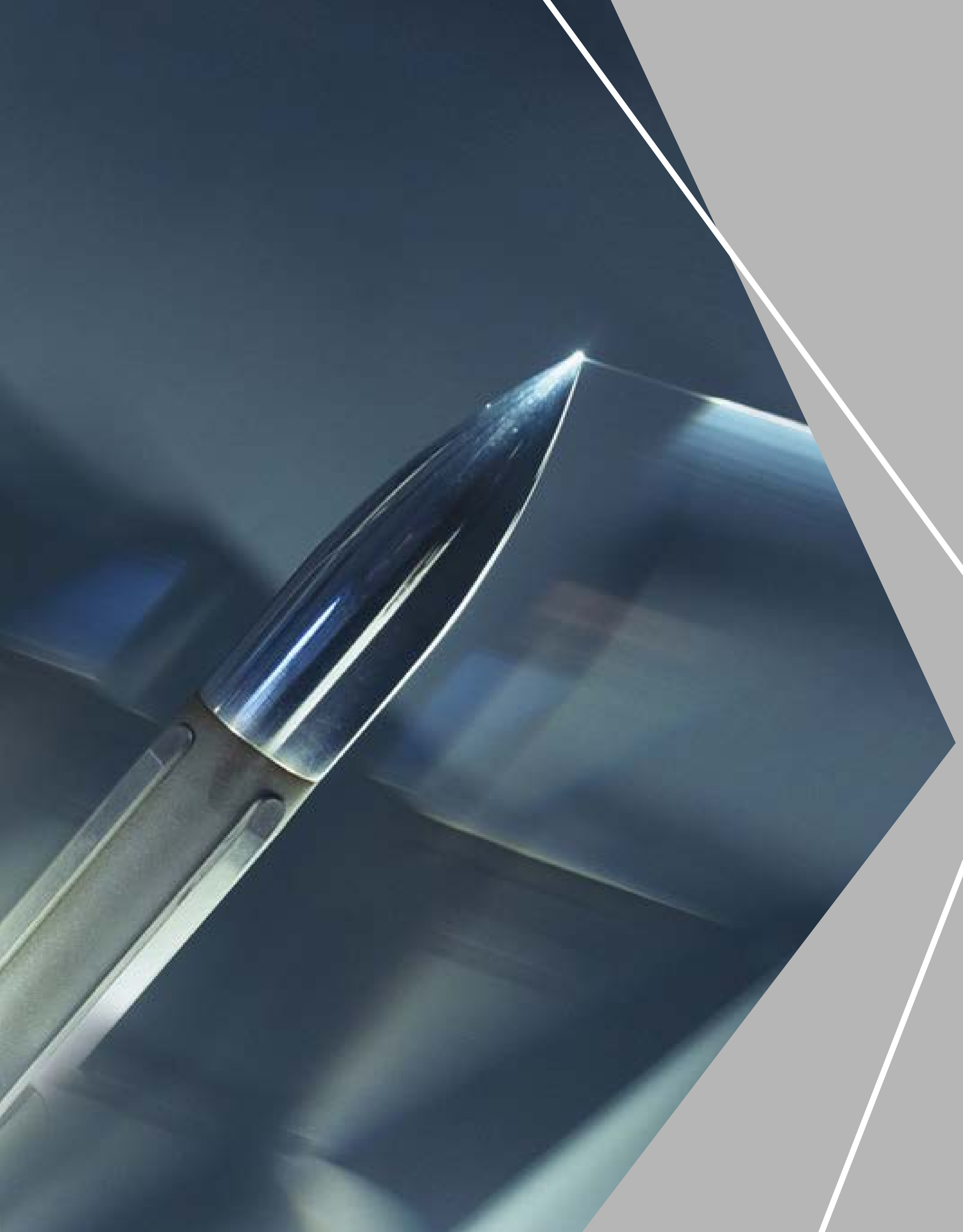

Propulsion Technologies for De-/Re-Orbiting and Active Debris Removal

K. W. Naumann, P. Caldas Pinto, A. Weigand, A. Ringeisen

ESA/ESTEC CLEAN SPACE INDUSTRIAL DAYS

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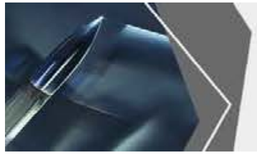
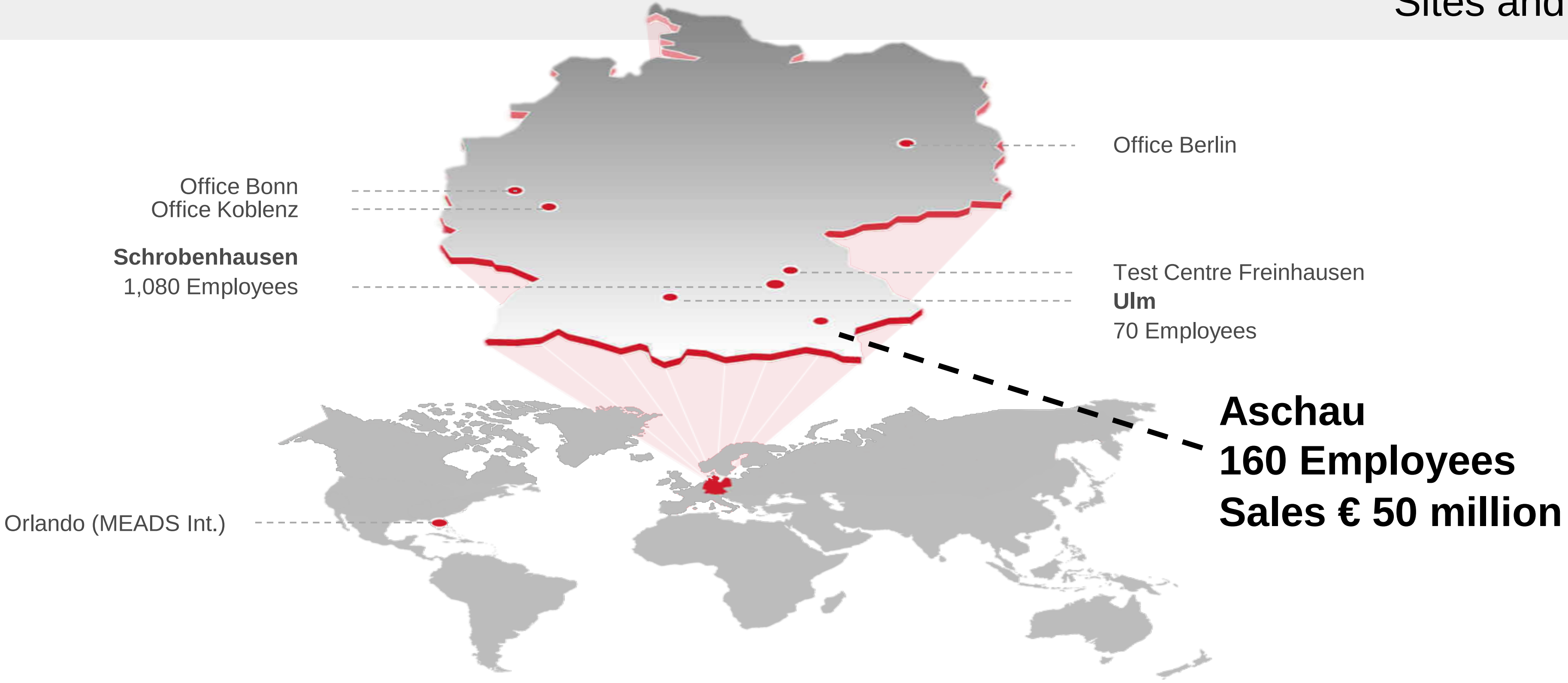


MBDA Germany and Bayern-Chemie

Sites and Offices



Bayern–Chemie is the Competence Center for Missile Propulsion Systems within MBDA and for the German MoD

Bayern-Chemie owns the full capabilities from R&D to production and to life cycle management

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Outline

- Existing and emerging space propulsion technologies for De- and Re-Orbiting Missions
- Mission scenarii and appropriate technical solutions
    - Technical / physical limits and feasibility
    - Complexity of the design and interaction of functions
- Maturity aspects and development roadmaps
- Summary and outlook

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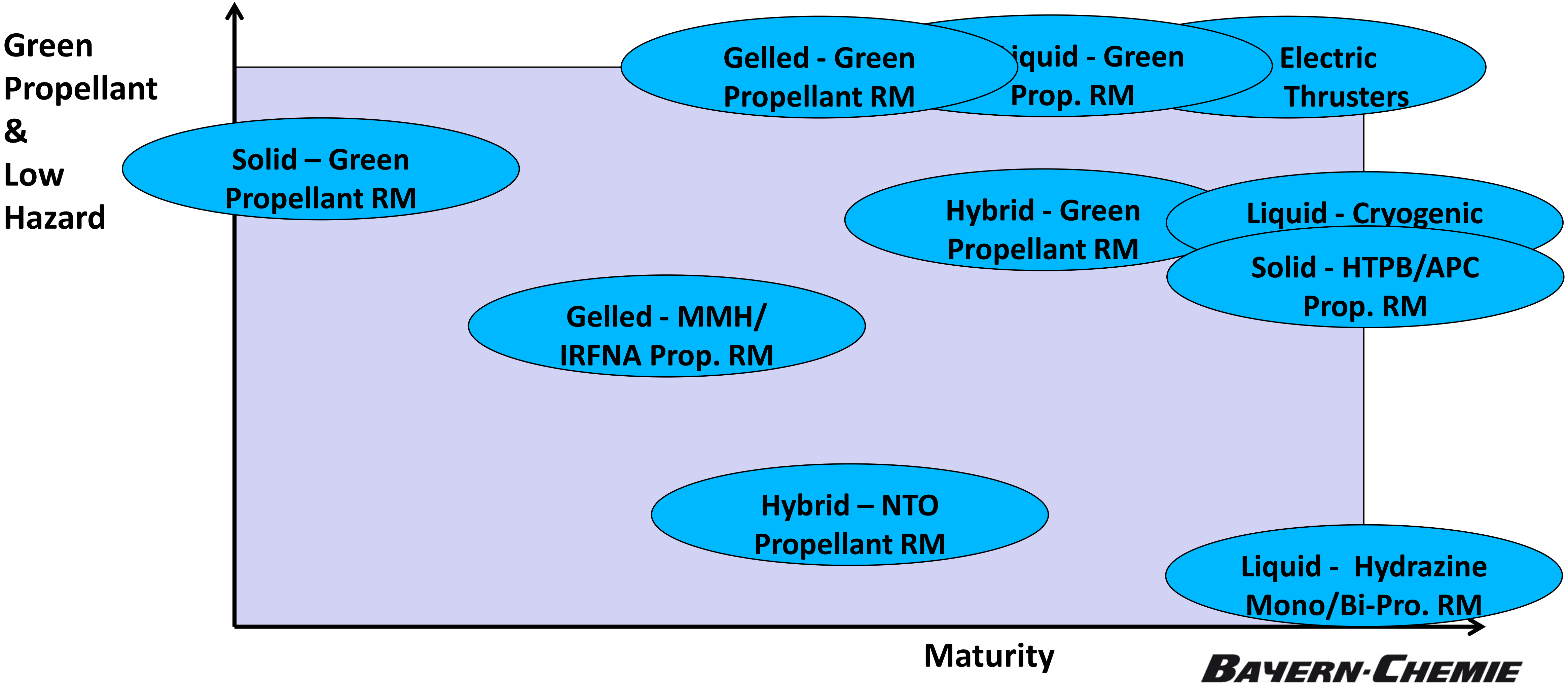
Mature and emerging propulsion technologies with storable propellants (1/5)



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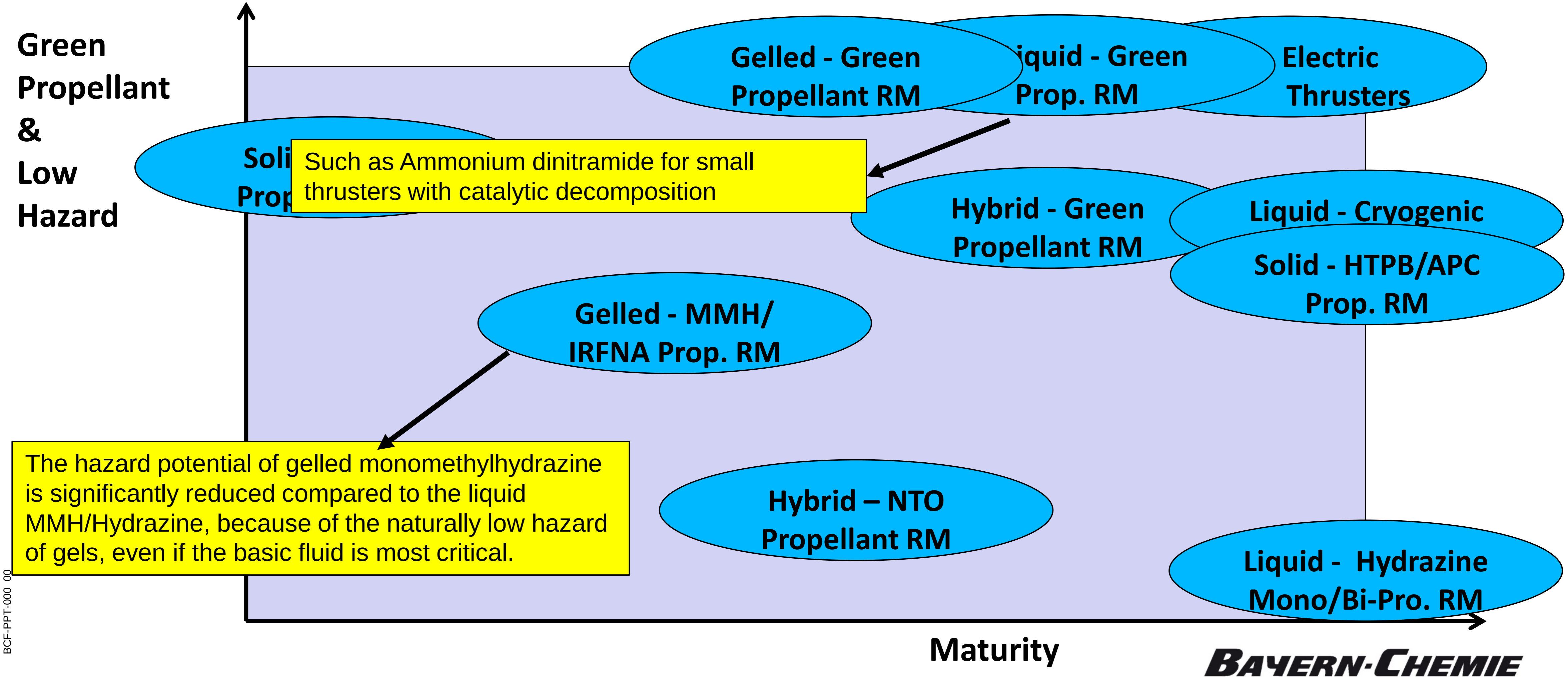
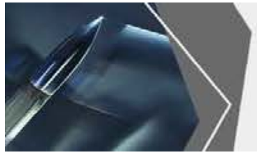
Mature and emerging propulsion technologies with storable propellants (1/5)



Mature and emerging propulsion technologies with storable propellants (2/5)

Operational Performance	APC Solid	Green Solid	Cryo-genic	Liq. Hy-drazine	Green Liquid	Hybrid NTO	Green Hybrid	Gelled Hydr.	Green Gelled	Electr. Thrust.
Throttleability (Proportional / Intermittent)	—	—	✓	✓	✓	✓	✓	✓	✓	✓
Defined engine shut-off	—	—	✓	✓	✓	✓	✓	✓	✓	✓
Reignitability (Solid: Bi-Pulse or Multipulse)	±	±	✓	✓	✓	✓	✓	✓	✓	✓
Simple handling	✓	✓	—	—	✓	—	±	—	✓	✓
Simple storability	✓	✓	(✓)	—	✓	—	±	✓	✓	✓
Long storage	✓	✓	—	✓	✓	✓	±	✓	✓	✓
Increase energy content by energetic particles (w/o sedim.)	✓	✓	—	—	—	—	—	✓	✓	N/A
Energetic Autonomy	✓	✓	✓	(✓)	(✓)	✓	✓	✓	✓	—
Fuel movement, sloshing	✓	✓	—	—	—	—	—	✓	✓	✓
Thrust Level (XL-L-M-H-XH)	L - XH	L - XH	M-XH	L-M	L	L-H	L-H	L-M	L-H	XL



Mature and emerging propulsion technologies with storable propellants (3/5)

Green Performance	APC Solid	Green Solid	Cryogenic	Liquid Hydrazine	Green Liquid	Hybrid NTO	Green Hybrid	Gelled Hydrazine	Green Gelled	Electr. Thrusters
REACH regulation	±	✓	✓	—	✓	—	✓	—	✓	✓
Exhaust gas	—	✓	✓	✓	✓	✓	✓	✓	✓	✓
Exhaust particles from propellant or other sources (thermal insulation)	±	±	✓	✓	✓	±	±	✓	✓	✓
Production	±	±	✓	± —	✓	—	±	—	✓	✓
Storage (Environmental safety procedures)	✓	✓	✓	—	✓	—	✓	±	✓	✓
Transport (Environmental safety procedures)	✓	✓	✓	—	✓	—	✓	±	✓	✓
Effect of leakages (Environmental)	✓	✓	✓	—	✓	—	✓	±	✓	✓
Disposal	±	✓	✓	—	✓	—	✓	—	✓	±

Mature and emerging propulsion technologies with storable propellants (4/5)

Hazard Performance Not sensitive against:	APC Solid	Green Solid	Cryogenic	Liquid Hydrazine	Green Liquid	Hybrid NTO	Hybrid H_2O_2, N_2O	Gelled Hydrazine	Green Gelled	Electric Thrusters
Accidental ignition of the rocket motor	—	—	✓	✓	✓	✓	✓	✓	✓	✓
Impact, friction, electric discharge (on propellant or oxidizer)	—	—	✓	—	✓	—	—	✓	✓	✓
Cracks (Propellant grain)	—	—	✓	✓	✓	±	±	✓	✓	✓
Fire hazard from leakage	✓	✓	—	—	±	—	—	✓	✓	✓
Fire / explosion hazard from impact / destruction	—	—	—	—	±	—	—	✓	✓	✓
Fire / explosion hazard at handling / fuelling	✓	✓	—	—	✓	—	±	✓	✓	✓
Hazard from external fire, heating	—	—	—	—	±	—	—	✓	✓	✓
Boil-off	✓	✓	—	—	±	—	—	✓	✓	✓

Mature and emerging propulsion technologies with storable propellants (5/5)

	APC Solid	Green Solid	Cryo-genic	Liquid Hydra-zine	Green Liquid	Hybrid NTO	Hybrid H_2O_2, N_2O	Gelled Hydra-zine	Green Gelled	Electric Thrus-ters
Throttleability (Proportional / Intermittent)	—	—	✓	✓	✓	✓	✓	✓	✓	✓
Defined engine shut-off	—	—	✓	✓	✓	✓	✓	✓	✓	✓
Reignitability (Solid: Bi-Pulse or Multipulse)	±	±	✓	✓	✓	✓	✓	✓	✓	✓
Simple handling	✓	✓	—	—	✓	—	±	—	✓	✓
Simple storability	✓	✓	(✓)	—	✓	—	±	✓	✓	✓
Long storage	✓	✓	—	✓	✓	✓	±	✓	✓	✓
Increase energy content by energetic particles (w/o sedim.)	✓	✓	—	—	—	—	—	✓	✓	N/A
Energetic Autonomy	✓	✓	✓	(✓)	(✓)	✓	✓	✓	✓	—
Fuel movement, sloshing	✓	✓	—	—	—	—	—	✓	✓	✓
Thrust Level (XL-L-M-H-XH)	L - XH	L - XH	M-XH	L-M	L	L-H	L-H	L-M	L-H	XL
REACh	±	✓	✓	—	✓	—	✓	—	✓	✓
Exhaust gas	—	✓	✓	✓	✓	✓	✓	✓	✓	✓
Exhaust particles from propell-ant or other sources (thermal insulation)	±	±	✓	✓	✓	±	±	✓	✓	✓
Production	±	±	✓	—	✓	—	±	—	✓	✓
Storage (Environmental safety procedures)	✓	✓	✓	—	✓	—	✓	±	✓	✓
Transport (Environmental safety procedures)	✓	✓	✓	—	✓	—	✓	±	✓	✓
Effect of leakages (Environmental)	✓	✓	✓	—	✓	—	✓	±	✓	✓
Disposal	±	✓	✓	—	✓	—	✓	—	✓	±
Accidental ignition of rocket motor	—	—	✓	✓	✓	✓	✓	✓	✓	✓
Impact, friction, electr. discharge (on propellant)	—	—	✓	—	✓	—	—	✓	✓	✓
Cracks (Propellant grain)	—	—	✓	✓	✓	±	±	✓	✓	✓
Fire hazard from leakage	✓	✓	—	—	±	—	—	✓	✓	✓
Fire / explosion hazard from impact / destruction	—	—	—	—	±	—	—	✓	✓	✓
Fire / explosion hazard at handling / fuelling	✓	✓	—	—	✓	—	±	✓	✓	✓
Hazard from external fire, heating	—	—	—	—	±	—	—	✓		
Boil-off	✓	✓	—	—	±	—	—	✓	✓	✓

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Mission scenarii and appropriate green technical solutions (1/5)

De-Orbiting kit for end-of-life (natural or accidental) de-orbiting of LEO satellites

- Complex and delicate structures:
  - $\Rightarrow$ Low acceleration (< 0.4 m/s^2)
  - $\Rightarrow$ Low thrust level (≤ 400 N/ton)
  - $\Rightarrow$ Long operation times (10^2 s – 10^3 s)

Specific Impulse is currently no major discriminator between green chemical propulsion technologies

Only long-time storable propellants considered

- Solid RM: Few components but challenging thermal management; low burning rate propellant, particle-free propellant, double-pulse motors (available @ BC)
- Green Liquid RM: Low thrust level acceptable
- Green Hybrid RM: Challenging: Long-time storage of oxidizer, lightweight design
- Green Gelled Prop. RM: Mission-adaptable thrust, lightweight design incl. uncooled CMC combustion chamber (@ BC)
- Electric RM: Needs operating electric system incl. sun paddles

Mission scenarii and appropriate technical solutions (2/5)

Re-Orbiting kit for end-of-life (natural or accidental) re-orbiting of MEO/GEO satellites

- Complex and delicate structures:
  - ⇒ Low acceleration (< 0.4 m/s^2)
  - ⇒ Low thrust level (≤ 400 N/ton)

Little Δv needed

Only long-time storable propellants considered

- Solid RM: Few components but challenging thermal management; low burning rate propellant, particle-free propellant (available @ BC)
- Green Liquid RM: Low thrust level acceptable
- Green Hybrid RM: Challenging: Long-time storage of oxidizer, lightweight design
- Green Gelled Prop. RM: Mission-adaptable thrust, lightweight design incl. uncooled CMC combustion chamber (@ BC)
- Electric RM: Needs operating sun paddles and electric system = operational satellite

Mission scenarii and appropriate technical solutions (3/5)

De-Orbiting kit for orbit insertion stages / apogaeum motors

- Robust structures allow high thrust, high acceleration, „short“ time of operation

• Solid RM:	Simple function, high thrust facititates thermal management, particle-free propellant, double-pulse motors (available @ BC)	
• Green Liquid RM:	Storable:	Thrust level too low
	Cryogenic:	Possible
• Green Hybrid RM:	Challenging:	lightweight design if high thrust requirement
• Green Gelled Prop. RM:	Mission-adaptable thrust, lightweight design if high thrust requirement	
• Electric RM:	Not sufficient electricity available	

Mission scenarii and appropriate technical solutions (4/5)

Propulsion system for tug vehicle for Active Debris Removal – rigid connection

- Complex and delicate structures:

  $\Rightarrow$ Low acceleration (< 0.4 m/s^2) $\Rightarrow$ Low thrust level ($\leq$ 400 N/ton) $\Rightarrow$ Long oper. times (10^2 s – 10^3 s)

  Medium-time storability of propellants required

• Solid RM:	Few components but challenging thermal management; low burning rate propellant, particle-free propellant, double-pulse motors (available @ BC)
• Green Liquid RM:	Challenging: Thrust level > 200 N
• Green Hybrid RM:	Challenging: Lightweight design
• Green Gelled Prop. RM:	Mission-adaptable thrust, lightweight design incl. uncooled CMC combustion chamber (@ BC)
• Electric RM:	Needs electric power system (sun paddles)

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Mission scenarii and appropriate technical solutions (5/5)

Propulsion system for tug vehicle for Active Debris Removal – slack connection (tether)

- Complex and delicate structures:

  $\Rightarrow$ Low acceleration (< 0.4 m/s^2) $\Rightarrow$ Low thrust level ($\leq$ 400 N/ton) $\Rightarrow$ Long oper. times (10^2 s – 10^3 s)

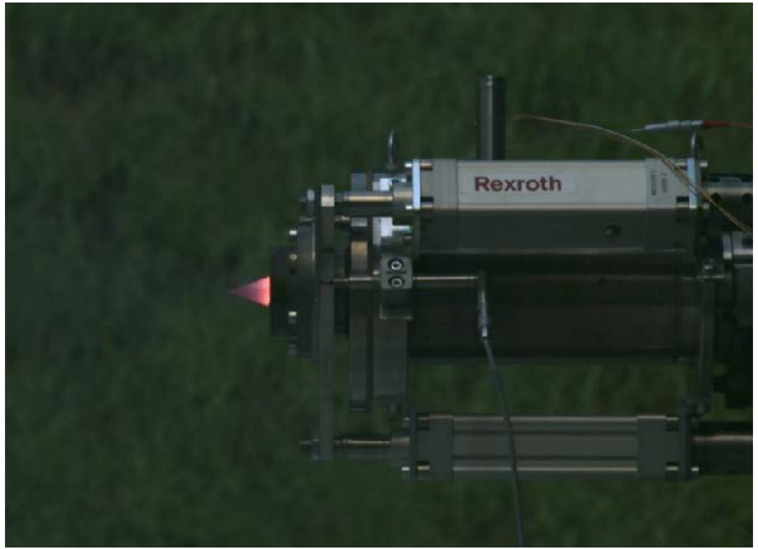
  Medium-time storability of propellants required

  Adaptable thrust needed in order to eliminate slack/elastic tether reaction on stepwise thrust variations
- Solid RM: No thrust variation, few components but challenging thermal management; low burning rate propellant, particle-free propellant, double-pulse motors (available @ BC)
- Green Liquid RM: Challenging: Thrust level > 200 N
- Green Hybrid RM: Mission-adaptable thrust to straighten tether and compensate tether move-ment, Challenging: Lightweight design
- Green Gelled Prop. RM: Mission-adaptable thrust to straighten tether and compensate tether move-ment, lightweight design incl. uncooled CMC combustion chamber (@ BC)
- Electric RM: Needs electric power system (sun paddles)

Summary and outlook:

- SRM technology is mature and ready for space applications
- Next step: Demonstration with nano-Sat (2016)

- Green GRM / GGG technology has reached a degree of maturity that allows to enter into specific developments for a number of space applications and provides unique capabilities in terms of thrust variation, safety, handling affordability and environmental compatibility:
  - Thrust adaptable rocket motors with high thrust turn-down ratio verified
  - Good scalability from 300 N to 20 kN
  - Lightweight design possible, CMC combustion chamber promising



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Thank you for your kind interest

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- Bundeswehr Technical Center for Weapons and Ammunition (WTD 91)
- DLR Institute of Structures and Design

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