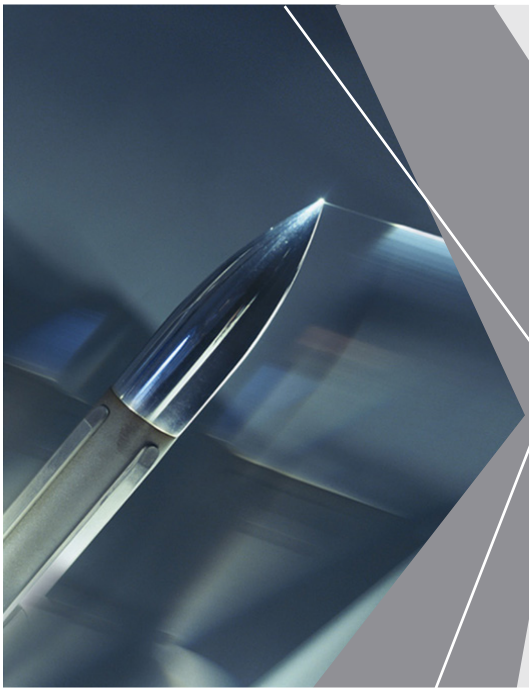

2° Hypersonic.International Symposium- Roma ,
30 June-1 July 2016

Performance Assessment for a Thottleable Ducted Rocket Powered Lower Tier Interceptor

Christoph Bauer, Norman Hopfe and Guido Kurth

CESMA
2nd International Symposion on Hypersonic Flight

BAYERN-CHEMIE
an MBDA company

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- General concept

Performance assessment methodology

- General simulation process

Determination of semi-empirical parameters

- Air intake characteristics
- Combustion efficiency
- Gas generator dynamics

Performance assessment

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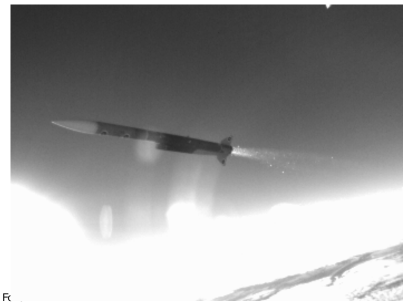
Introduction

Bayern Chemie has brought the throttleable ducted rocket technology:

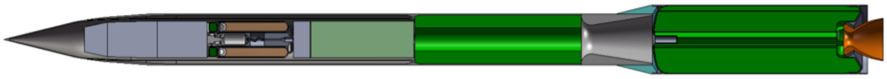
- **highly throttleable airbreathing ramjet**
- **high energy gas generator propellant (boron as energy carrier)**
- **extreme manoeuvres allowing air intake configuration**

with the onset of the METEOR series production to a TRL of 9

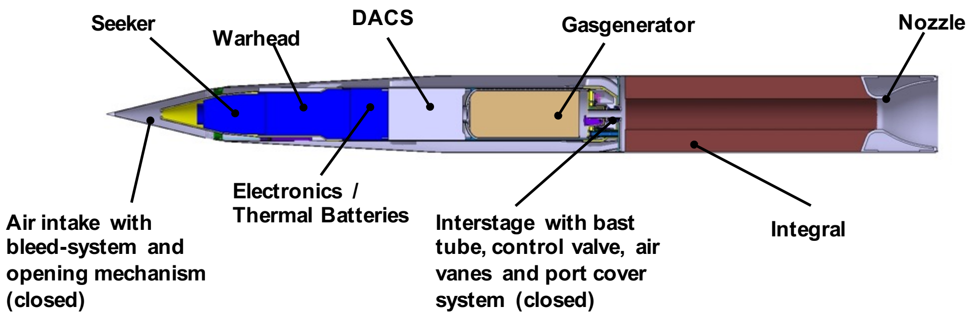


After successful development further applications of this technology have been discussed, leading to

- → **Definition of a concept for a for an airbreathing high super-/ low hypersonic lower tier interceptor**
- → **Ground launched system**
- → **Kinematic range (over ground) 150 km**
- → **Maximum altitude 35 km**
- → **Average flight Mach number: M > 5**



Mach 5+ Lower Tier Interceptor (2nd stage)



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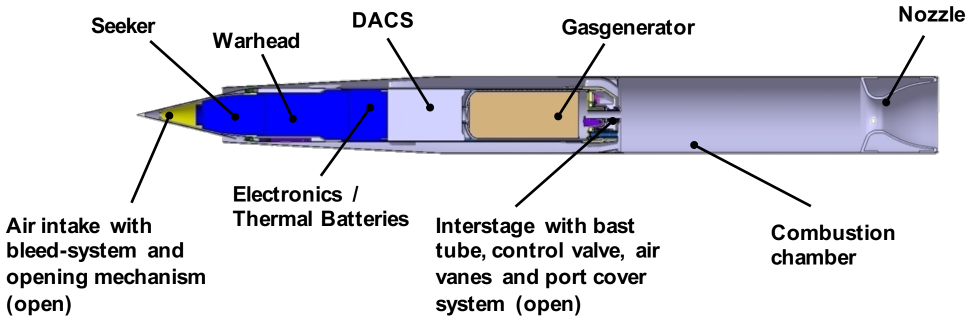
Mach 5+ Lower Tier Interceptor (2nd stage)



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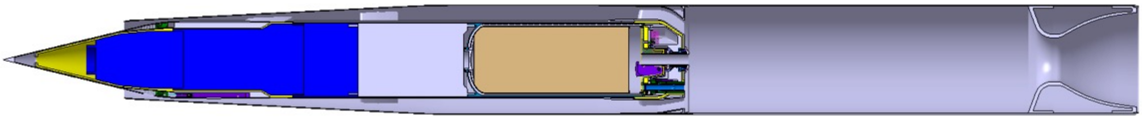
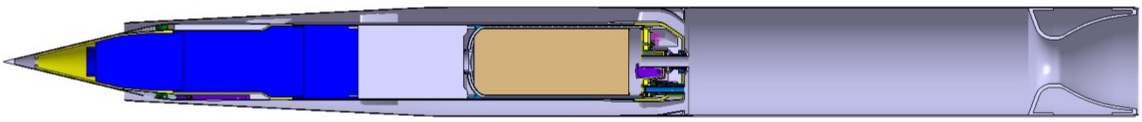
Performance assessment methodology:

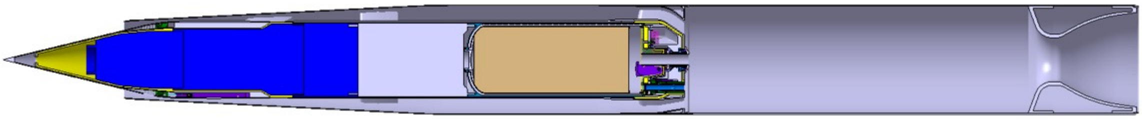


Performance assessment methodology:

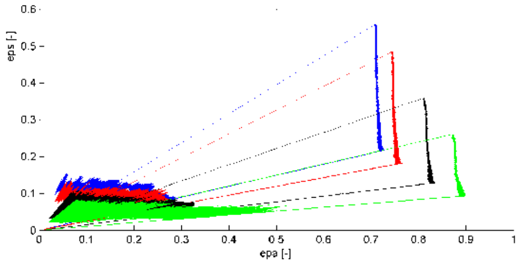


- Flight Mach number
- Altitude
- Ambient pressure & temperature
- Incidence
- Fuel mass flow

Performance assessment methodology:



- Select resp. air intake characteristic



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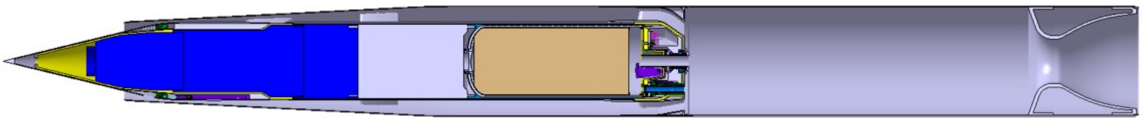
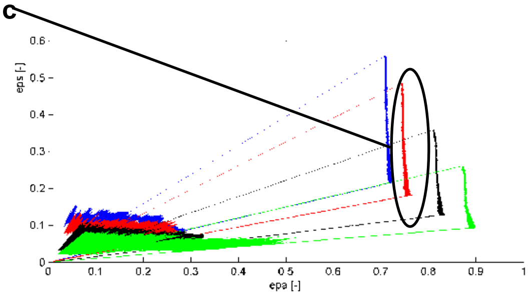
Performance assessment methodology:



- Select resp. air intake characteristic



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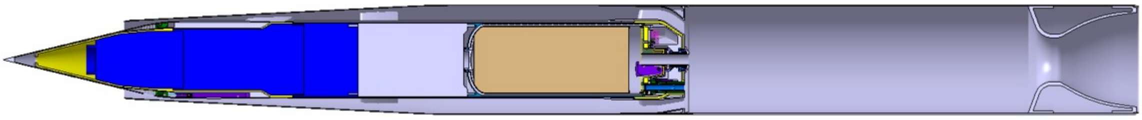
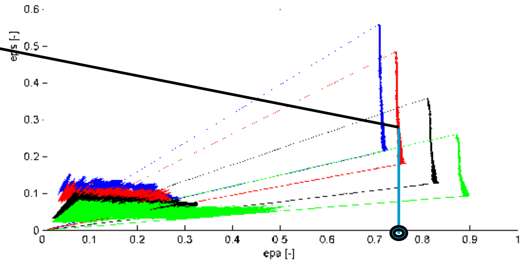
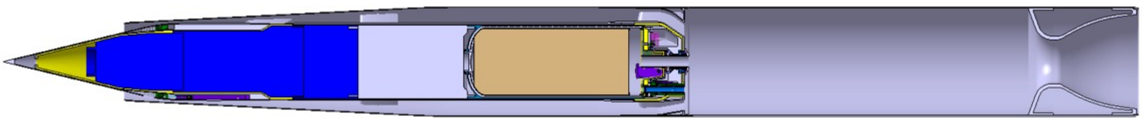
Performance assessment methodology:



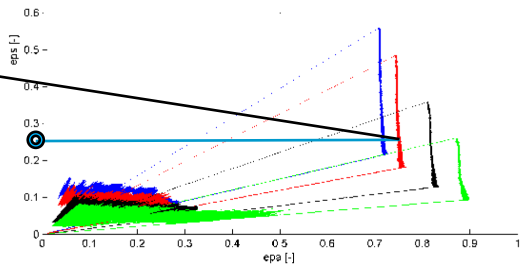
- Select resp. air intake characteristic
- Determine air mass flow



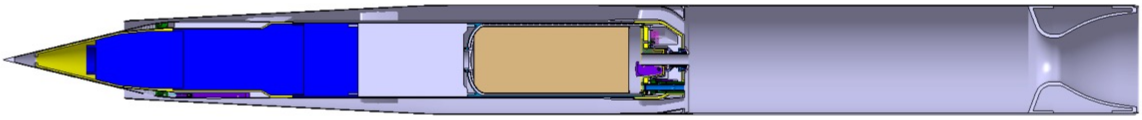
Performance assessment methodology:



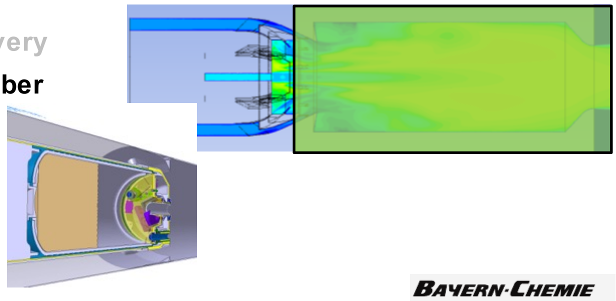
- Select resp. air intake characteristic
- Determine air mass flow
- Assume total pressure recovery



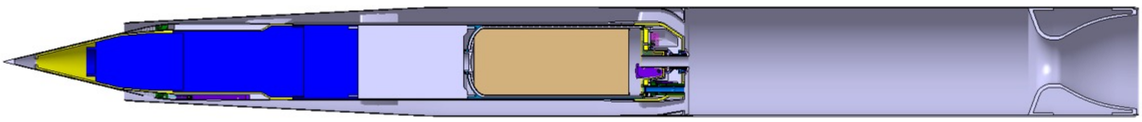
Performance assessment methodology:



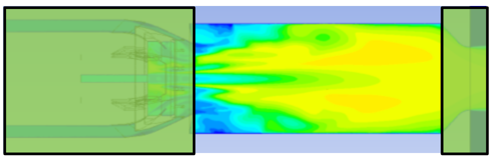
- Select resp. air intake characteristic
- Determine air mass flow
- Assume total pressure recovery
- **Determine combustion chamber entrance conditions (air & fuel)**



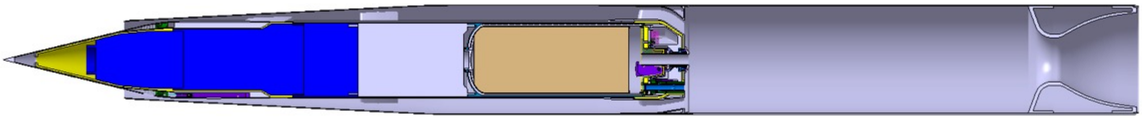
Performance assessment methodology:



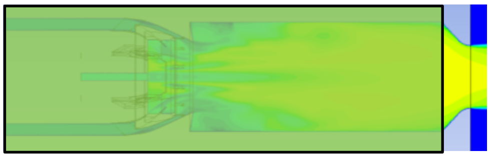
- Select resp. air intake characteristic
- Determine air mass flow
- Assume total pressure recovery
- Determine combustion chamber entrance conditions
- **Determine combustion chamber conditions**



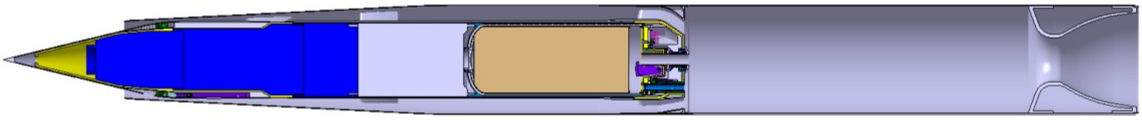
Performance assessment methodology:



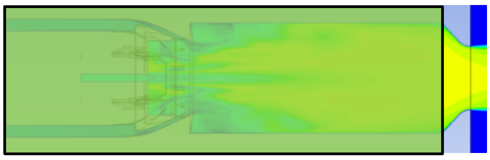
- Select resp. air intake characteristic
- Determine air mass flow
- Assume total pressure recovery
- Determine combustion chamber entrance conditions
- Determine combustion chamber conditions
- **Determine critical area**



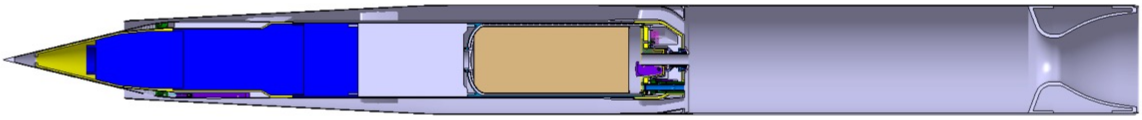
Performance assessment methodology:



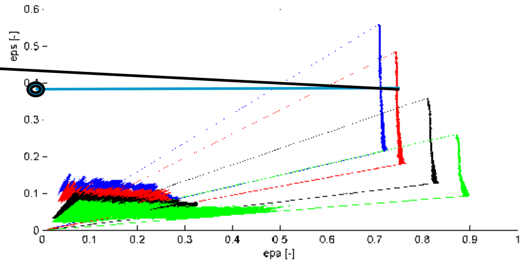
- Select resp. air intake characteristic
- Determine air mass flow
- Assume total pressure recovery
- Determine combustion chamber entrance conditions
- Determine combustion chamber conditions
- Determine **critical area ← does not match geometrical throat**



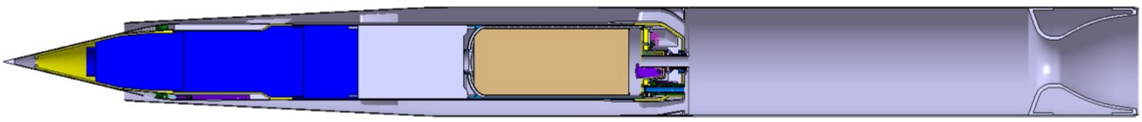
Performance assessment methodology:



- Select resp. air intake charcteristic
- Determine air mass flow
- **Vary total pressure recovery**
- Determine combustion chamber entrance conditions
- Determine combustion chamber co
- Determine critical area ← does not



Performance assessment methodology:

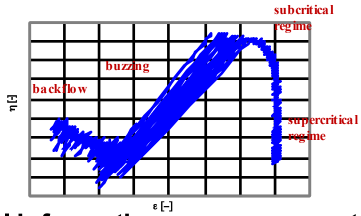


- Select resp. air intake charcteristic
- Determine air mass flow
- Vary total pressure recovery
- Determine combustion chamber entrance conditions
- Determine combustion chamber conditions
- Determine critical area ← does not match geometrical throat

Repeat until match

Performance assessment methodology:

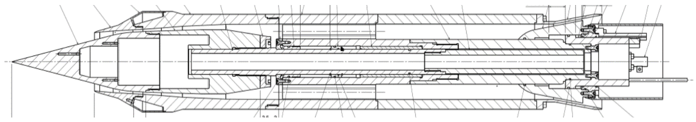
- **Delivers single static performance figures**
  - Requires (semi-)empirical correlations for:
    - Air intake performance
      - Captured air mass flow
      - Total pressure recovery
      - Last stable point
  - Ramjet combustion efficiency



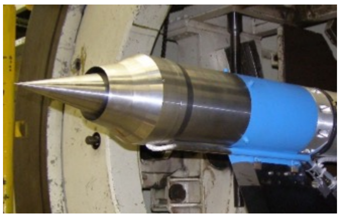
- **Transient performance requires additional information on gas generator dynamics**
  - Propellant burn rate
  - Propellant burn surface
  - Deposit generation
  - Intrinsic delay times

Determination of semi-empirical parameters:

- **Air intake characteristics**
  - **Design and manufacturing of instrumented air-intake wind tunnel model**

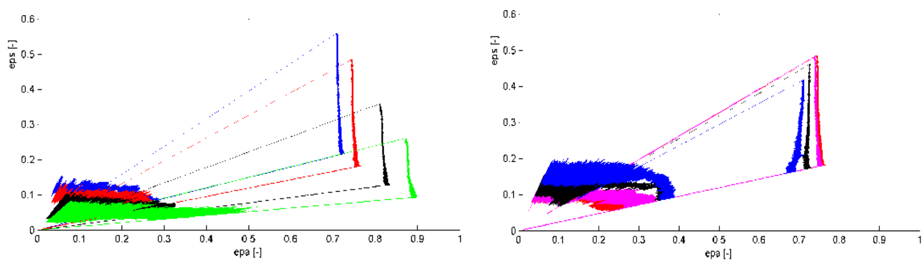


  - **Integration into wind tunnel**



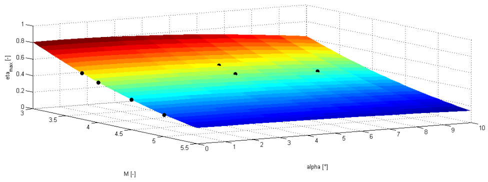
Determination of semi-empirical parameters:

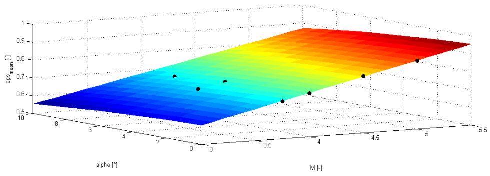
- **Air intake characteristics**
  - **Determination of air intake performance characteristics for selected flight Mach numbers (3.75, 4.0, 4.5, 5.0) and incidences (0°, 5°, 8°)**



Determination of semi-empirical parameters:

- **Air intake characteristics**
  - **Generation of look-up tables**



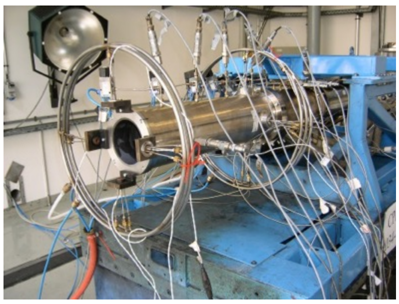


Determination of semi-empirical parameters:

- **Ram combustor efficiency**
  - **Design of fully instrumented test hardware with:**
    - **Individually throttleable air entrance pipes**

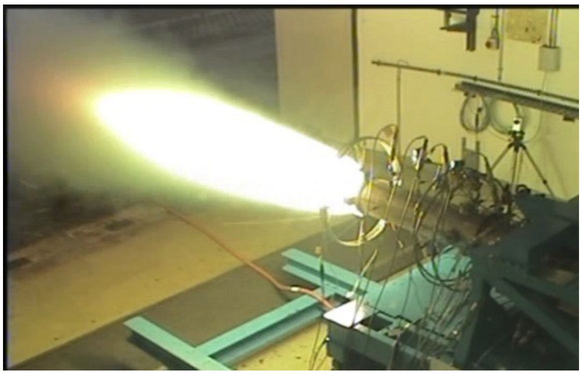
Determination of semi-empirical parameters:

- **Ram combustor efficiency**
  - **Design of fully instrumented test hardware with:**
    - Individually tailored air entrance hoses
    - **Argon flushed pressure and temperature gauges within combustion chamber**
    - **Radiation measurement probes at nozzle exit**



Determination of semi-empirical parameters:

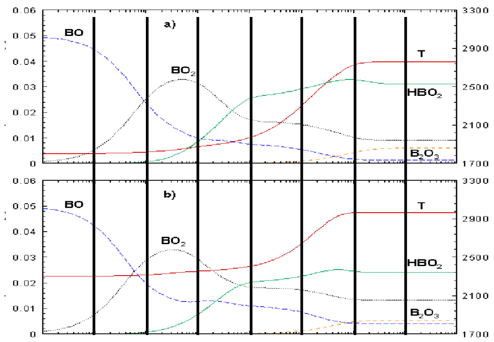
- **Ram combustor efficiency**
  - Instrumented firing, determination of
    - Thrust
    - Combustion chamber
      - Pressure
      - Temperature
    - Gas generator pressure
    - Radiative heat loads



Semi-empirical correlations: combustion efficiency

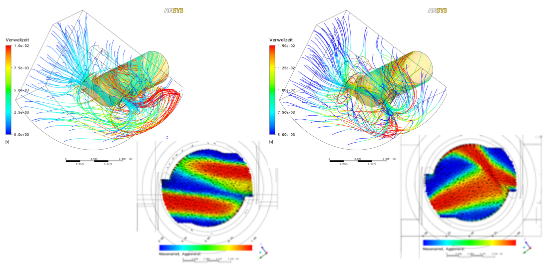
Determination of semi-empirical parameters:

- **Ram combustor efficiency**
  - Computational analysis of internal flow field taking into account
    - Turbulent Boron particle combustion



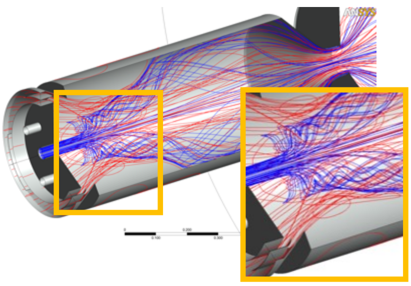
Determination of semi-empirical parameters:

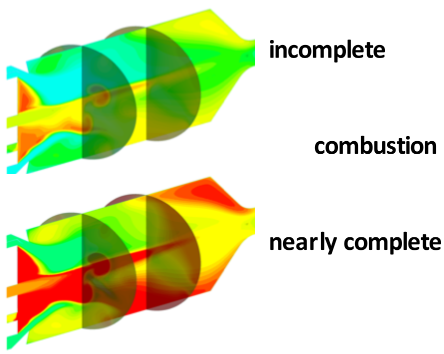
- **Ram combustor efficiency**
  - **Computational analysis of internal flow field taking into account**
    - Turbulent Boron particle combustion
    - **Stochastic particle collisions**



Determination of semi-empirical parameters:

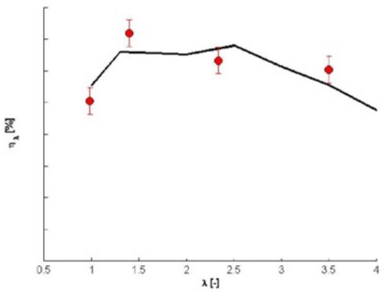
- **Ram combustor efficiency**
  - **Computational analysis of internal flow field**





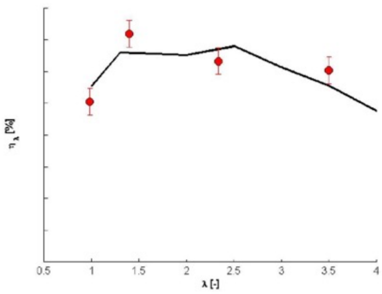
Determination of semi-empirical parameters:

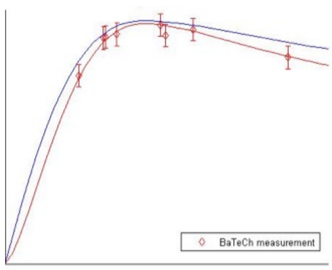
- **Ram combustor efficiency**
  - **Comparison between measurement and simulation → good agreement → validation of simulation**



Determination of semi-empirical parameters:

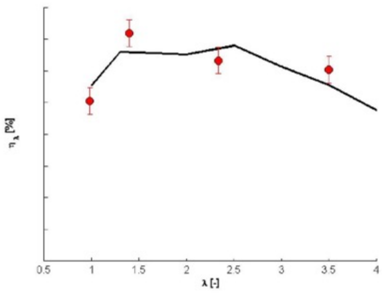
- **Ram combustor efficiency**
  - **Comparison between measurement and simulation → good agreement → validation of simulation → generation of continuous combustion efficiency model**

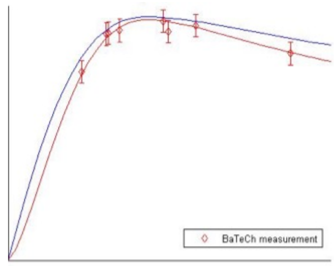


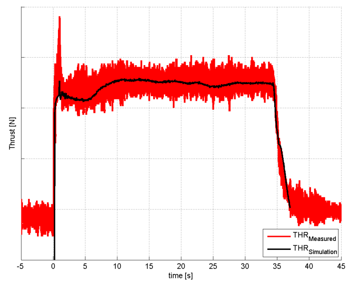


Determination of semi-empirical parameters:

- **Ram combustor efficiency**
  - Comparison between measurement and simulation → good agreement → validation of simulation → generation of continuous combustion efficiency model → validated combustion efficiency for static operational conditions







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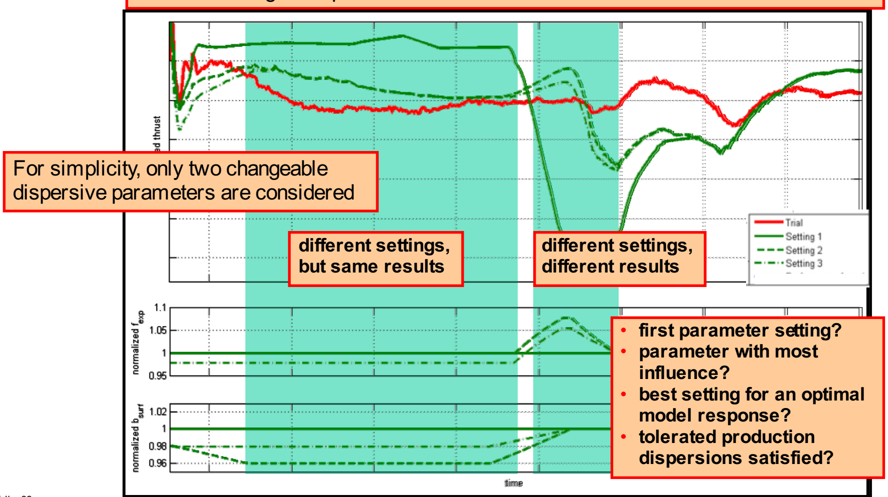
Determination of semi-empirical parameters:

- **Gas generator transient behaviour**
  - **Gas generator is home of a set of inherent dispersion caused by manufacturing tolerances and hostile operational conditions**
    - **Propellant burning surface**
    - **Propellant burn rate**
    - **Control valve position**
    - **Gas generator delay or reaction time**
    - **Expulsion efficiency**

  none of which can be measured during operation.
  - **Measured quantities are:**
    - **Gas generator pressure**
    - **Engine thrust**

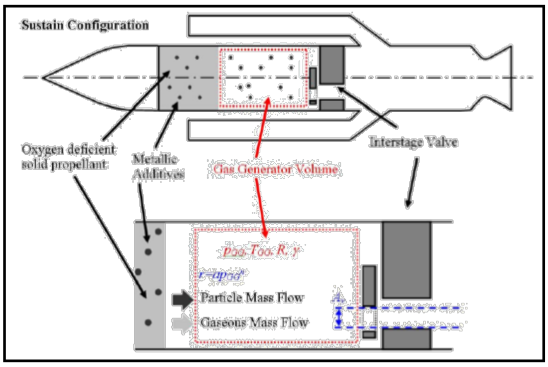
→ Underdetermined system

Problem: changeable parameters have different interactions



Determination of semi-empirical parameters:

- **Gas generator transient behaviour**



Gas generator physical description

$$\dot{m}_{flow} = \frac{p_{GG} \cdot A_v}{c^*}$$

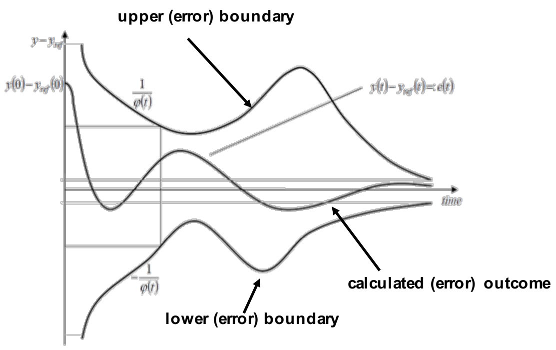
$$\frac{V_{GG}(t) \cdot \dot{P}_{GG}(t)}{R \cdot T_{GG}} = \frac{\rho}{R \cdot T_{GG}} \cdot A_b \, v(t) + \frac{\rho}{R \cdot T_{GG}} \cdot \dot{P}_{GG}(t) - \frac{P_{GG}(t) \cdot A_v}{c^*}$$

Gas generator mathematical description

$$\left.\begin{array}{lll} \dot{x}(t) & = & f_1(x(t), d_1(t)) + g(u(t)) \qquad , x(0) = x^0 \\ y(t) & = & f_2(x(t), d_2(t)), \end{array}\right\}$$

Determination of semi-empirical parameters:

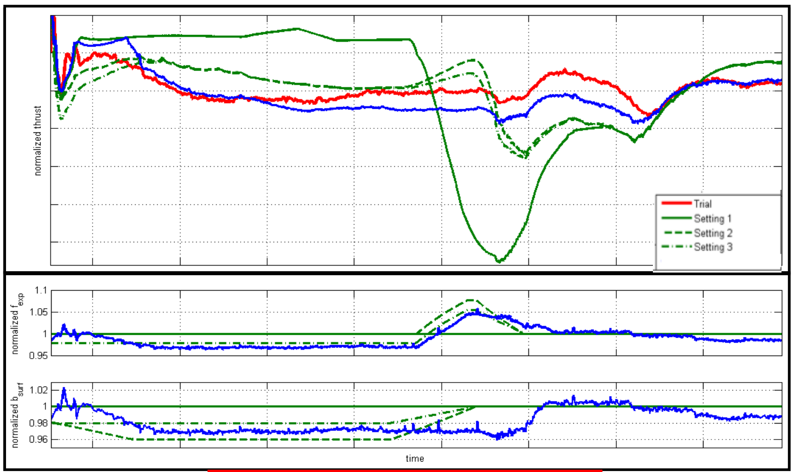
- **Gas generator transient behaviour**



Gas generator mathematical description

$$\left.\begin{array}{lll} \dot{x}(t) & = & f_1(x(t), d_1(t)) + g(u(t)) \qquad , x(0) = x^0 \\ y(t) & = & f_2(x(t), d_2(t)), \end{array}\right\}$$

Performance funnel with predefined error boundaries, such that all parameters are varied in a way that the most probable combination of these parameters leads to best match of measured values



→

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For simplicity, only two changeable dispersive parameters are considered

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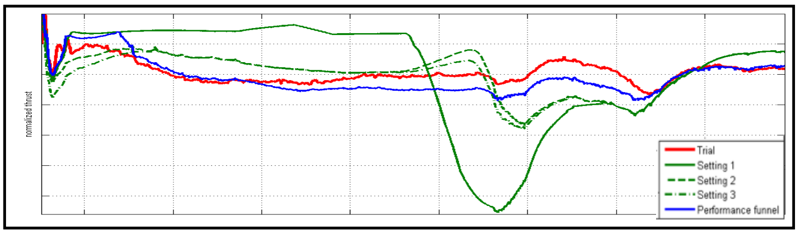
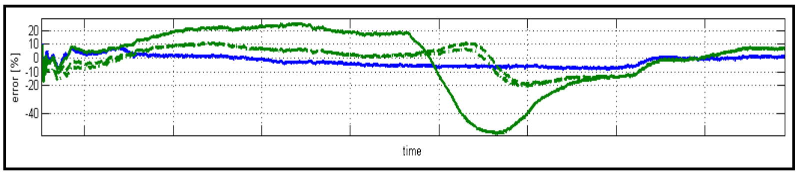


→ fitting error for hand settings more than 30%



→ performance funnel with user-defined error limit of 10% (thrust)

→ thrust match with less than 8% error

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Performance assessment:

- Integration of semi-empirical paarmeters and correlations in existing engine model
- Application of 6 DoF simulation using
  - Missile DatCom
  - Simple LoS Algorithm
- Definition of respective scenarios
  - A: Cooperative target in 150 km distance @ 35 km altitude
  - B: Cooperative target in 30 km distance @ 30 km altitude
  - C: Uncooperative target in 60 km distance @ 29 km altitude
  - D: Uncooperative target in 55 km distance @ 27 km altitude

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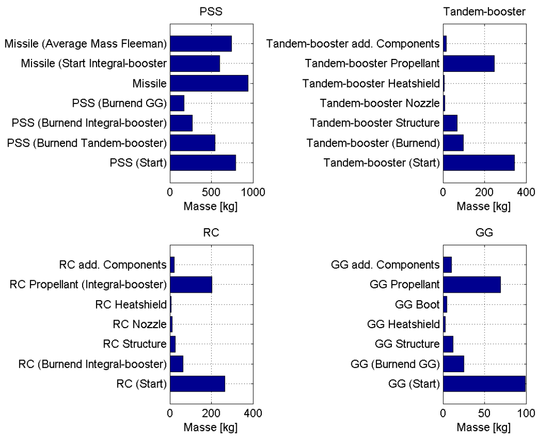
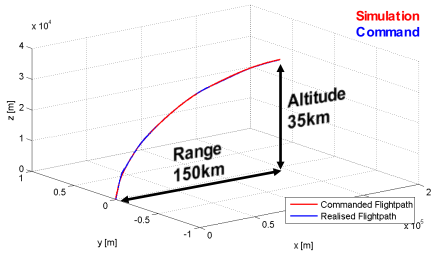
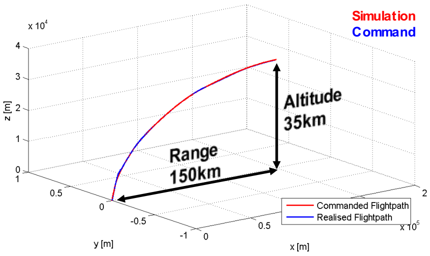
Performance assessment:

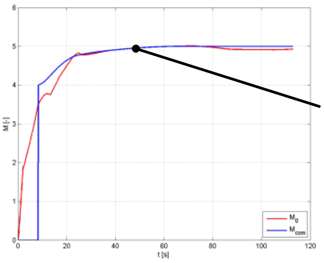
- **Missile mass break down structure**





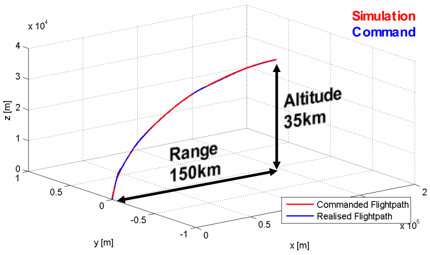
Trajectory A represents target hit in maximum kinematic range of 150km and maximum altitude of 35km

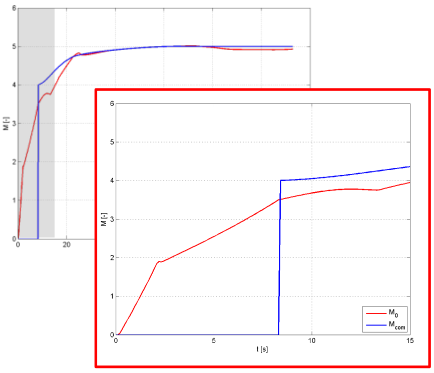




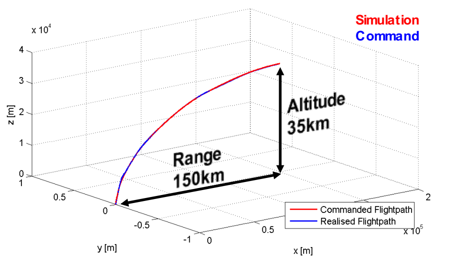
Mach number command and simulated flight Mach number

Trajectory A represents target hit in maximum kinematic range of 150km and maximum altitude of 35km

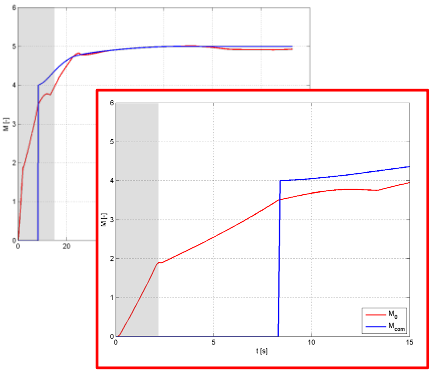




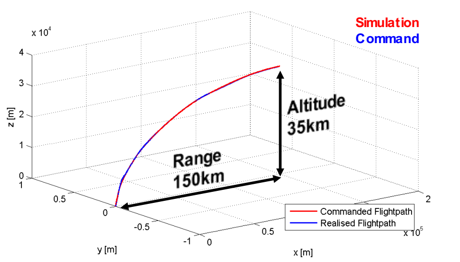
Trajectory A represents target hit in maximum kinematic range of 150km and maximum altitude of 35km



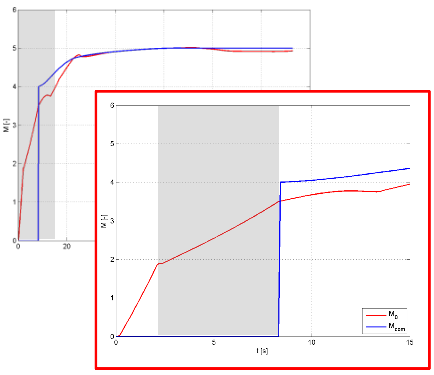
Trajectory A represents target hit in maximum kinematic range of 150km and maximum altitude of 35km



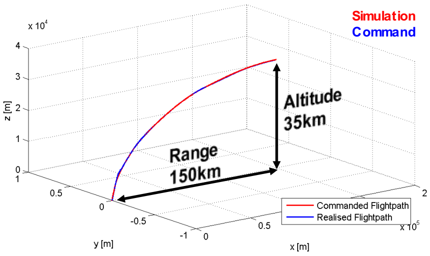
Acceleration after ground launch with start booster



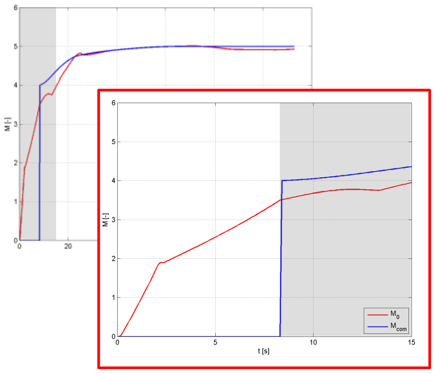
Trajectory A represents target hit in maximum kinematic range of 150km and maximum altitude of 35km



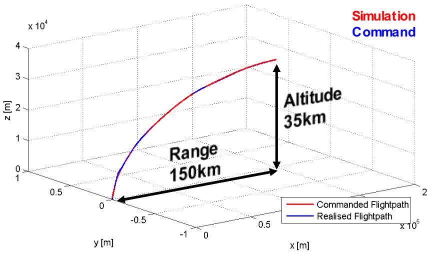
Separation of 1st stage and further acceleration with integral booster (relatively long burn time to reduce static pressure in combustion chamber)



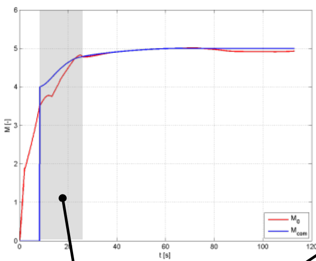
Trajectory A represents target hit in maximum kinematic range of 150km and maximum altitude of 35km

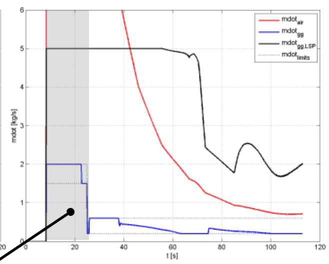


Ramjet mode with active thrust control

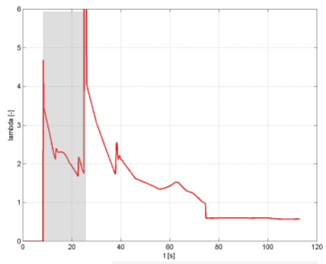


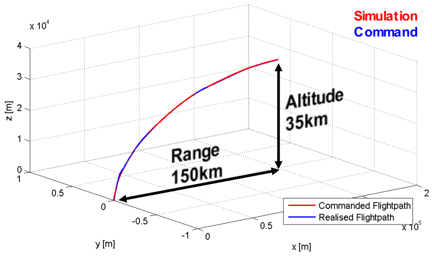
Trajectory A represents target hit in maximum kinematic range of 150km and maximum altitude of 35km

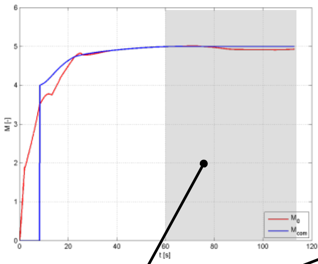


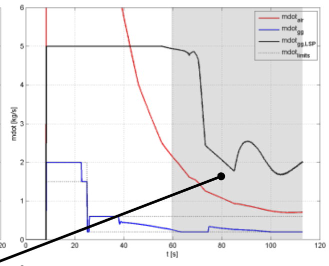


Acceleration phase after transition
→ high fuel flow demand
→ Low altitude
→ high air–fuel equivalence ratio ( )



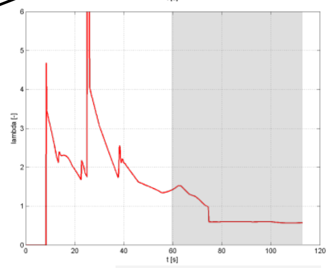


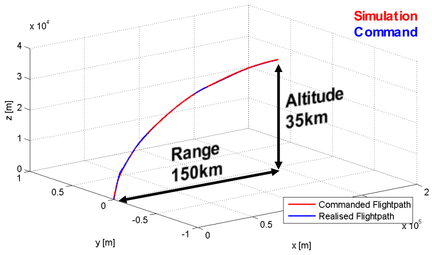


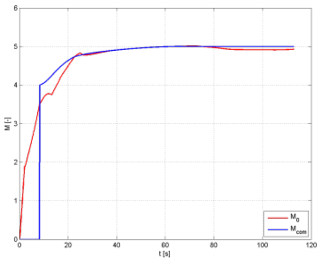


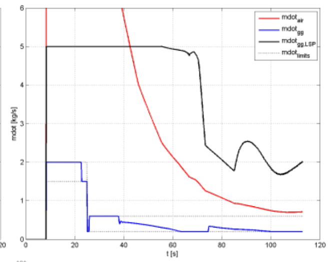
Trajectory A represents target hit in maximum kinematic range of 150km and maximum altitude of 35km

Cruise phase
→ low drag (high altitude)
→ low air–fuel equivalence ratio ( )
→ Limitation of maximum thrust by -limit



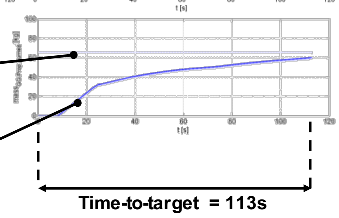






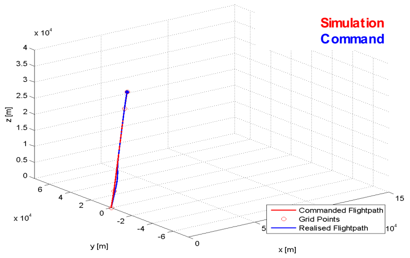
Trajectory A represents target hit in maximum kinematic range of 150km and maximum altitude of 35km

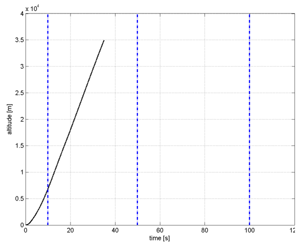
Total gg propellant mass

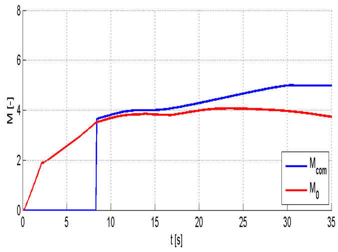


Burned gg propellant mass (11% remaining propellant mass)

Hit could be achieved
Remaining fuel mass sufficient for additional end game manoeuvre or minor acceleration

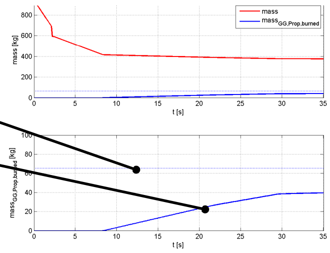






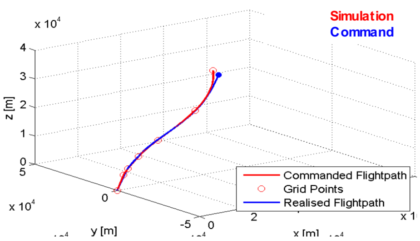
Trajectory B represents target hit in a kinematic range of 12 km and an intercept altitude of 30 km

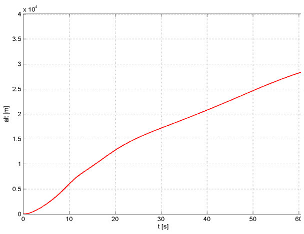
Hit could be achieved
Remaining fuel mass sufficient for additional end game manoeuvre or acceleration

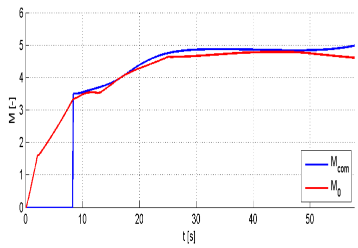


Total gg propellant mass

Burned gg propellant mass (40% remaining propellant mass)

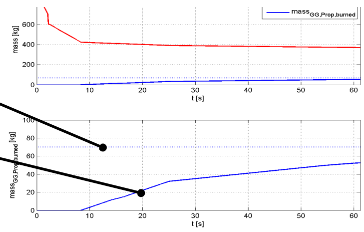






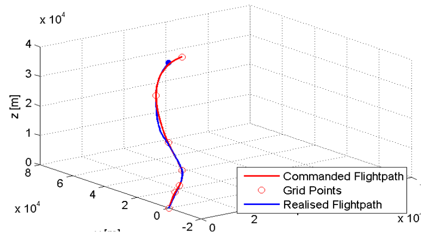
Trajectory C represents target hit in a kinematic range of 60 km and an intercept altitude of 29 km

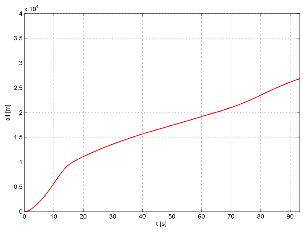
Hit may be achieved
Remaining fuel mass sufficient for additional end game manoeuvre or acceleration

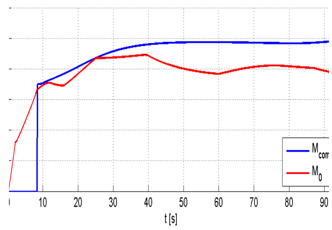


Total gg propellant mass

Burned gg propellant mass (30% remaining propellant mass)







Trajectory D represents target hit in a kinematic range of 55 km and an intercept altitude of 27 km

Hit questionable

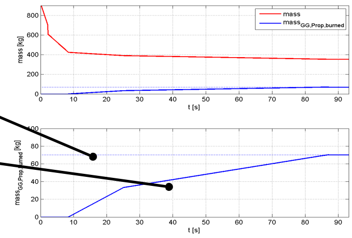
Reduced average flight Mach number due to severe manoeuvring

No remaining fuel due to severe midcourse manoeuvring

→ System improvement necessary

Total gg propellant mass

Burned gg propellant mass (30% remaining propellant mass)



BAYERN-CHEMIE an MBDA company

Ground launched two-stage highly manoeuvrable endo atmospheric lower tier interceptor against air vehicles and ballistic missiles

- **Overall concept defined and partially proven by experimental evidence**
  - **Air intake wind tunnel testing**
  - **Combustion chamber ground testing**
- **Flight trajectory simulations (maximum altitude 35km, maximum kinematic range 150km) show good expected behaviour wrt.**
  - **Kinematic range**
  - **Manoeuvrability**
  - **Maintaining high average intercept velocities**

  for cooperative targets → enhanced endgame capability
- **For targets with evasive manoeuvre capability the system shows performances comparable or better to conventional lower tier interceptors**

BAYERN-CHEMIE an MBDA company

Thank you for your kind interest
Questions are welcome

Contact:
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Technical Director
Bayern Chemie
guido.kurth@mbda-systems.de

BC likes to thank the German BAAINBw for funding the feasibility study on the throttleable ducted rocket powered hypersonic lower tier interceptor

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