IPPW-9 Short Course 2012

Entry Phase Plasma Study
(Non-equilibrium Instrumentations for Entry)

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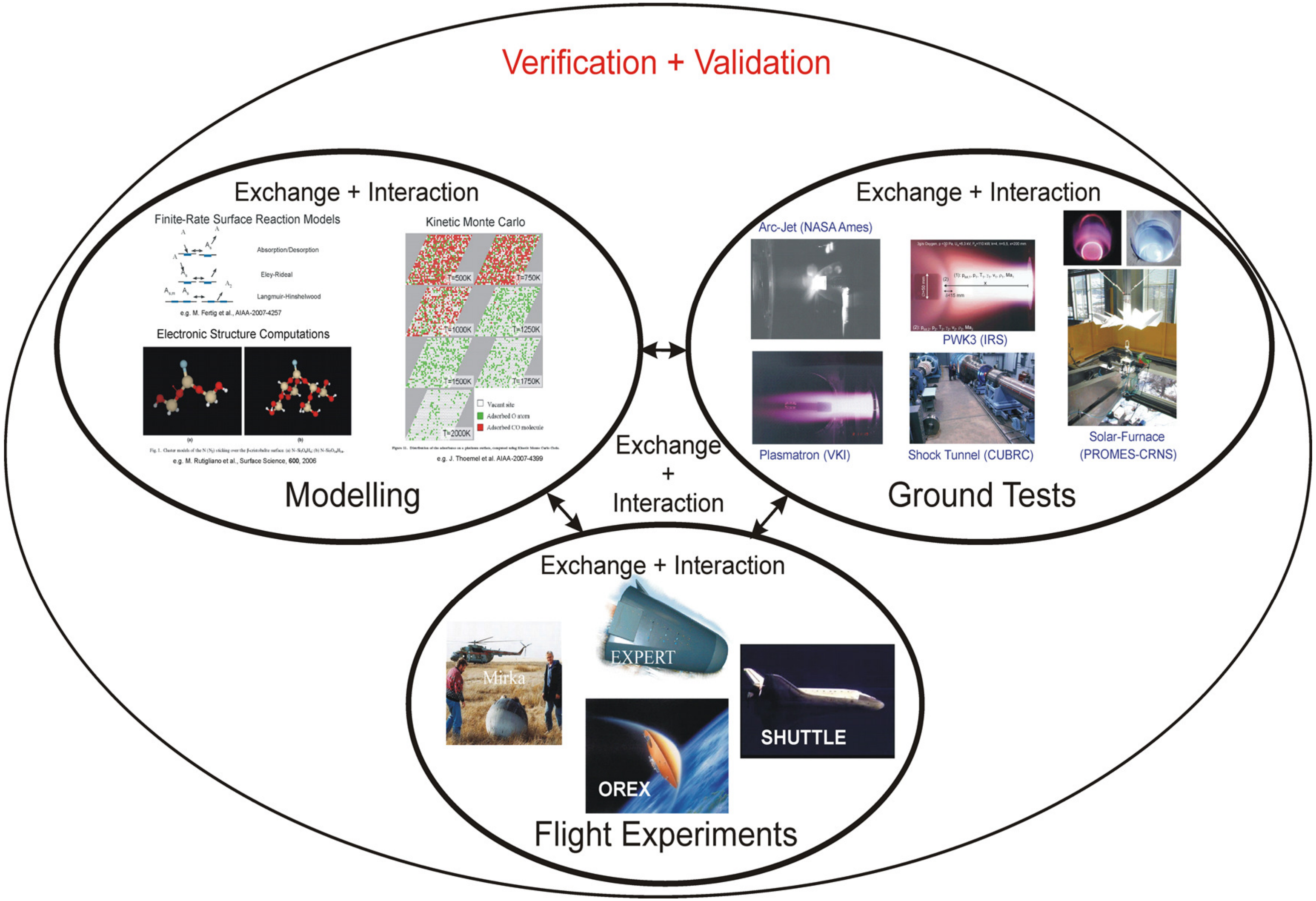
Content

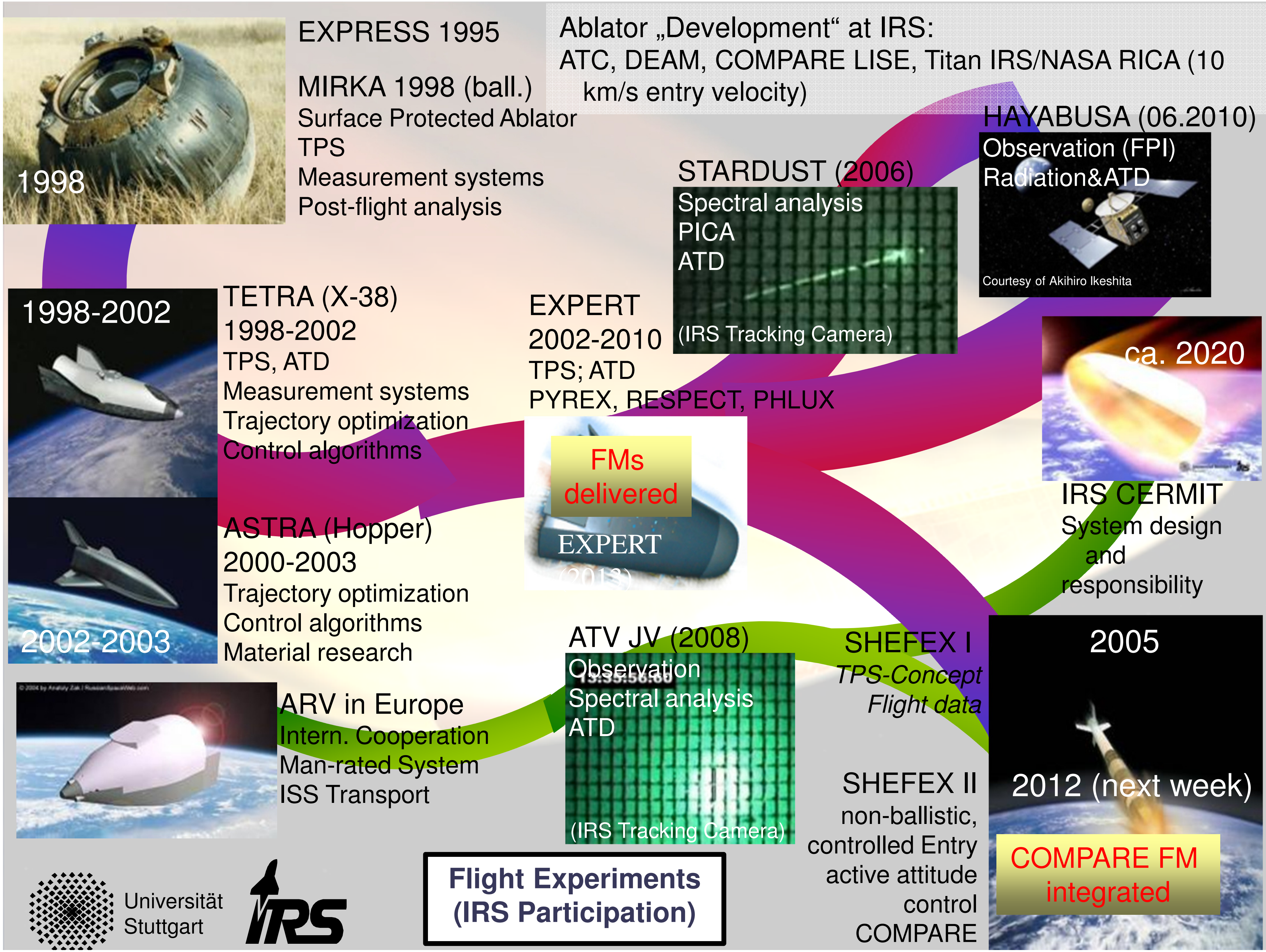
- What is needed
  - Flight experiments
  - Ground-based experiments
  - Modeling

  → Verification and Validation
- Examples for advanced instrumentations with relevance to non-equilibrium effects
  - Radiation (Thermopiles, Emission spectroscopy)
    - RESPECT aboard of ESA capsule EXPERT
    - Radiometers e.g. for SHEFEX2 (as technology demonstration e.g. for EXOMARS)
  - Thermochemistry (e.g. catalysis)
    - PHLUX: Catalysis based pyrometric sensor system for EXPERT
  - Boundary-Layer sensors (such as e.g. COMPARE)
    - Combination of several sensors: Heat Flux, pressure, radiation

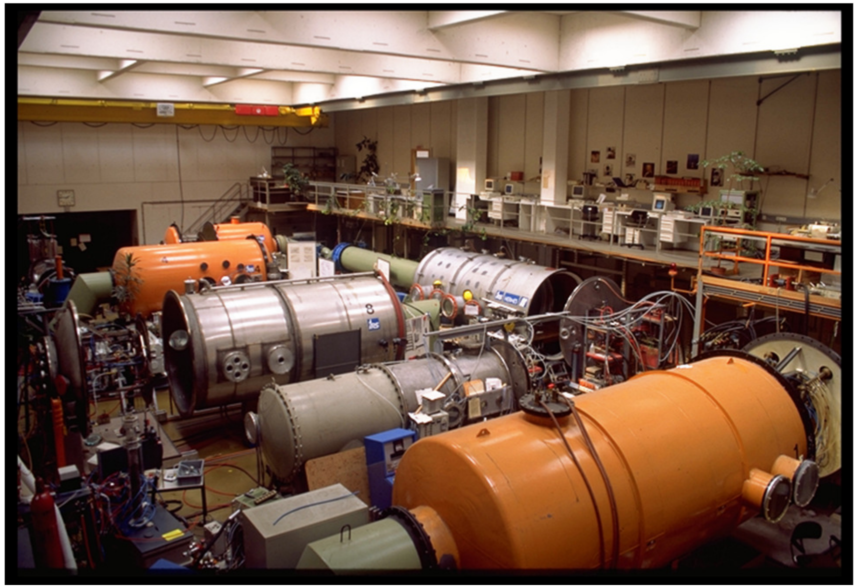
    → separation of radiative and convective HF, assessment of enthalpy

Assessment of Gas-Surface-Interactions/ Non-Equilibrium: What do we need?

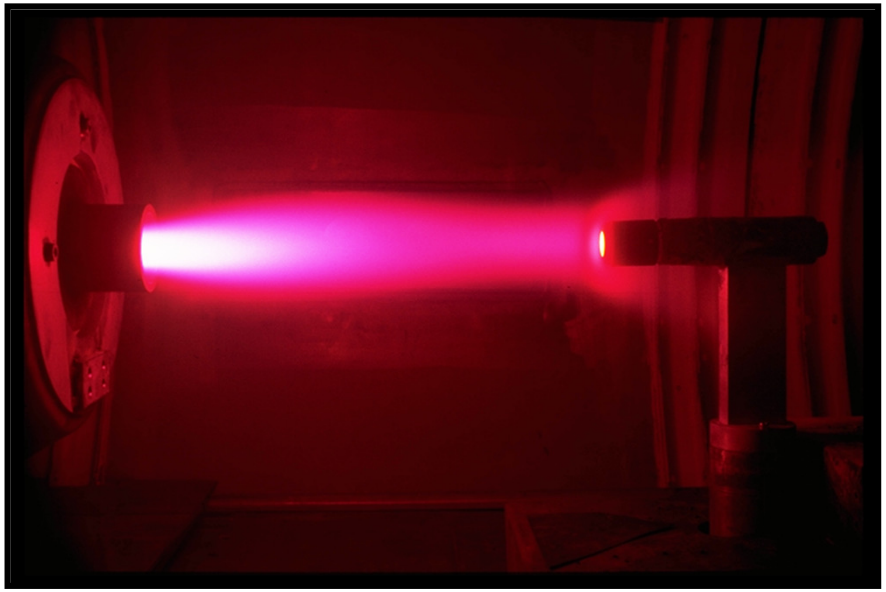



1998
EXPRESS 1995
MIRKA 1998 (ball.)
Surface Protected Ablator
TPS
Measurement systems
Post-flight analysis
Ablator „Development“ at IRS:
ATC, DEAM, COMPARE LISE, Titan IRS/NASA RICA (10 km/s entry velocity)
HAYABUSA (06.2010)
Observation (FPI)
Radiation&ATD
Courtesy of Akihiro Ikeshita
STARDUST (2006)
Spectral analysis
PICA
ATD
(IRS Tracking Camera)
1998-2002
TETRA (X-38)
1998-2002
TPS, ATD
Measurement systems
Trajectory optimization
Control algorithms
EXPERT
2002-2010
TPS; ATD
PYREX, RESPECT, PHLUX
FMs delivered
EXPERT
(2013)
ca. 2020
IRS CERMIT
System design and responsibility
ASTRA (Hopper)
2000-2003
Trajectory optimization
Control algorithms
Material research
2002-2003
ATV JV (2008)
Observation
Spectral analysis
ATD
(IRS Tracking Camera)
SHEFEX I
TPS-Concept
Flight data
2005
ARV in Europe
Intern. Cooperation
Man-rated System
ISS Transport
SHEFEX II
non-ballistic, controlled Entry
active attitude control
COMPARE
2012 (next week)
COMPARE FM integrated
Universität Stuttgart
IRS
Flight Experiments (IRS Participation)

Ground-based Experiments: Facilities at IRS



4 Plasma wind tunnels
in 2 laboratory halls



Material sample in plasma wind tunnel,
Atmospheres of different planets

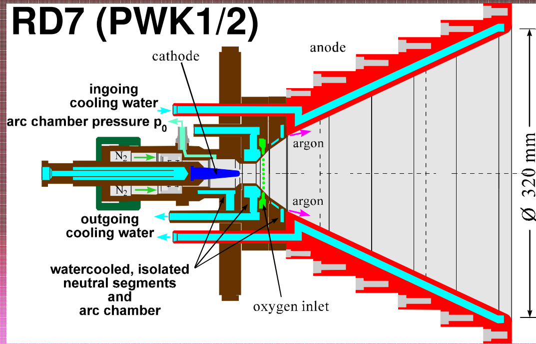
(Main) vacuum system: > 250.000 m^3/h
Electric power systems:
6 MW DC (48 kA max.)
> 150 kW RF (500-1500 kHz)

Specific enthalpies: 10 – 150 MJ/kg
Total pressures: 10 – 8.000 Pa
Simulated Atmospheres:
Earth, Mars, Titan...

IRS Plasma Wind Tunnels

MPG driven PWK1 / PWK2

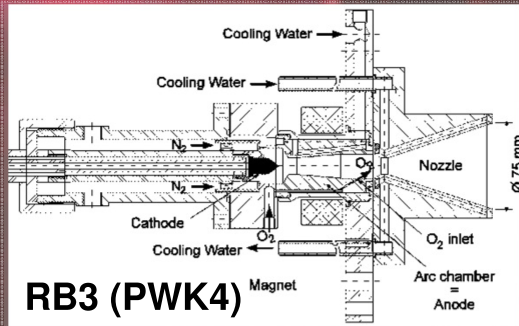
- length 6m, ø 2m
- specific Enthalpies: 2-150 MJ/kg (Air)
- total pressures: 1-100 hPa
- Working gases: N_2+O_2, Ar, Ar+O_2, N_2, H_2, N_2+CH_4, Ar+CO_2, He
- RD5 nozzle exit ø125mm,RD7 nozzle exit ø 320mm



RD7 (PWK1/2)

TPG driven PWK4

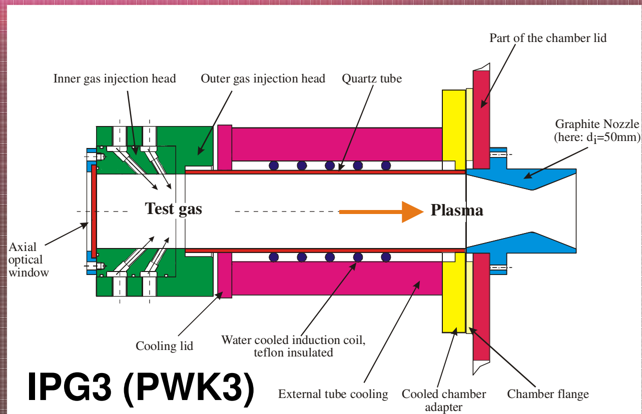
- length 2m, ø 1.6m
- specific Enthalpies: 1-30 MJ/kg (Air)
- Total pressure: 1-1000 hPa
- Working gases: N_2+O_2, Ar, Ar+O_2, N_2, H_2, N_2+CH_4,Ar+CO_2,H_2+O_2,He



RB3 (PWK4)

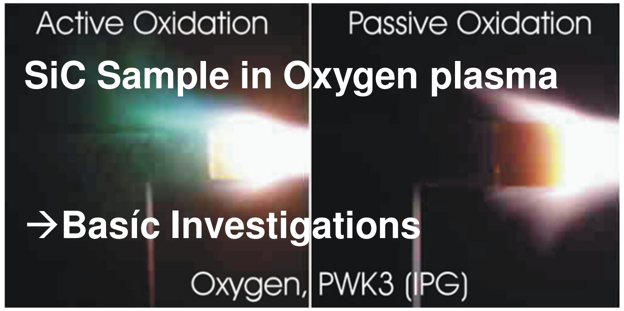
IPG driven PWK3

- length 6m, ø 2m
- specific Enthalpies: 1-80 MJ/kg (Air/Oxygen)
- Total pressures: 1-15 hPa (air) / 50 hPa (O_2)
- Working gases: any, e.g. N_2, O_2, Ar, H_2, CO_2 or combinations



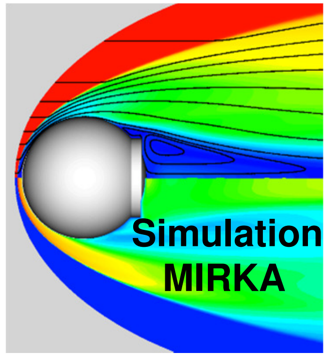
IPG3 (PWK3)

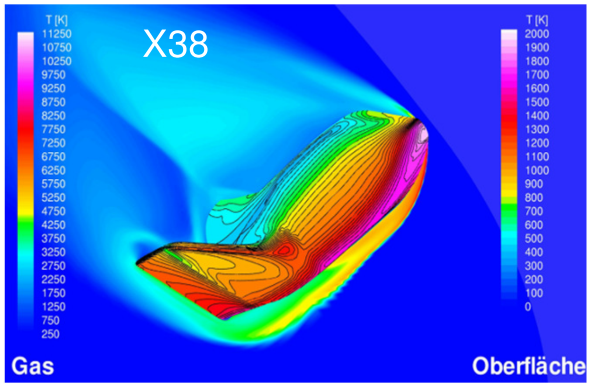
Ground-based Experiments: Examples



- Investigation and Qualification of Thermal Protection Systems (TPS) and Instrumentation
- Modelling and numerical Simulation

  → Earth, Mars, Titan….





Overview of available codes at IRS: Modelling

URANUS	SAMSA	SINA / ARCHE	PICLas	LasVegas
Navier-Stokes			Particle Method / Boltzmann Equation	
continuum flow, thermal and chemical non-equilibrium			rarefied *plasmas*, strong non-equil.	Rarefied *gases*, strong non-equil.
re-entry	MPD (self and applied field)	TLT, IPG, PWK	PPT, Ion thruster,…	Re-entry
2D rotational symm. / 3D	2D rotational symmetric	3D (rotational symmetric)	3D	2D rotational symmetric
fully implicit	explicit			
fully coupled		loosely, iteratively coupled		single
structured multiblock grids	unstructured, adaptive grids	structured multiblock grids	Unstructured grids	unstructured, adaptive grids
Air, CO_2	Argon	Air, N_2, H_2, CO_2	any	any
PARADE/HERTA gas-radiation coupling		**HERTA** gas-radiation coupling		
Gas kinetic gas-surface interaction model with catalytic reaction schemes. CVCV mult. temperature gas-phase model		changeable chemical modules		Gas kinetic gas-surface interaction model with catalytic reaction schemes.

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Content: Spectroscopic Instrumentations for Entry

- Emission spectroscopy based instrumentations
  - Basics of emission spectroscopy
  - Overview of past emission spectroscopic experiments
  - Payload design example: RESPECT/EXPERT
    - Payload design
    - Metrological layout
  - Outlook on EUV/VUV spectroscopy
  - Scientific objectives/results

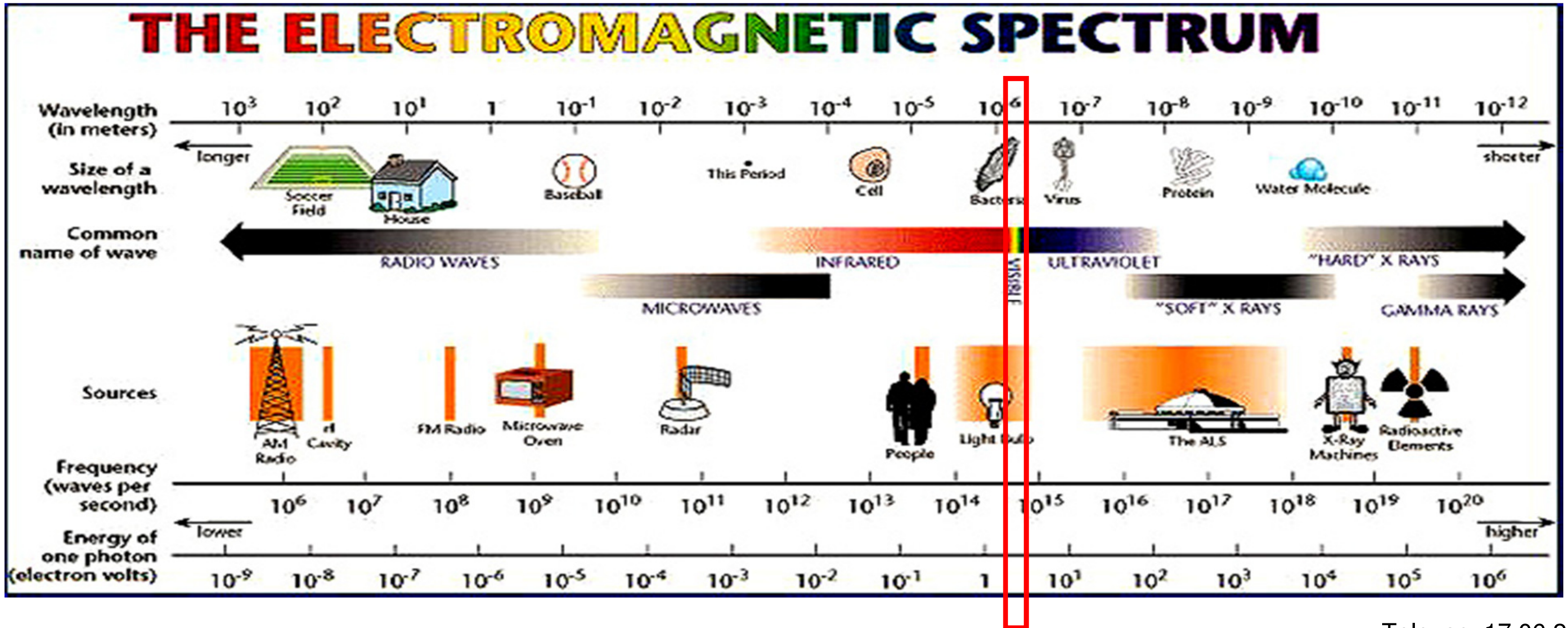
What is Emission Spectroscopy?

- Measurement principle:

  Analysis of electromagnetic radiation emitted by measurement object under consideration of spectral radiation intensity distribution.

➔ Qualitative and quantitative analysis of the chemical composition.

➔ Determination of thermodynamic properties (e.g. excitation temperatures).



Why Emission Spectroscopic In-Flight Measurements

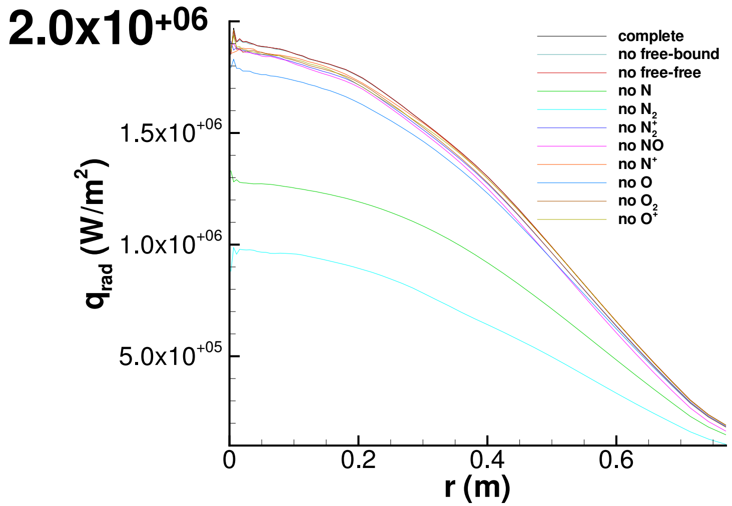
- TPS are exposed to significant mechanical and thermal loads
  ➔ Loads are defined by the plasma state of post shock regime and boundary layer

- Emission spectroscopic in-flight experiments provide data for validation of chemical/radiation models employed to simulate the loads on TPS systems
  - Validation of design tools

- Suitability of ground test facilities is limited
  - Multitude of relevant parameters can not be reproduced at the same time

➔ In-flight experiments required

EXAMPLE: Contribution of different species to heat flux onto FIRE II versus vehicle radius (80 nm≤λ≤800 nm)



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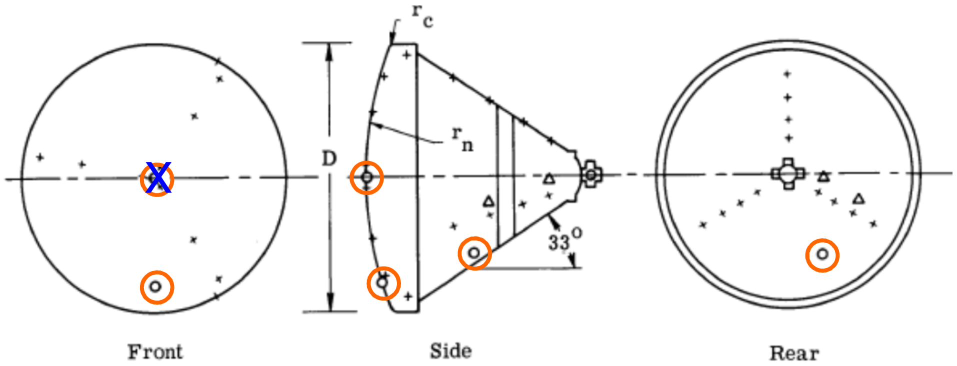
FIRE - Flight Investigation of the Reentry Environment

- 2 re-entry flights in 1964/1965 in preparation of the Apollo program
- Blunt, Apollo like shaped capsule
  - Nose radius: 0.935m, diameter: 0.672m / 0.630m / 0.587m
- Hyperbolic re-entry
  - FIRE I: v = 11.57 km/s, γ = -14.6°
  - FIRE II: v = 11.35 km/s, γ = -14.7°
- Instrumentation for radiation heat flux
  - 1 spectrometer system x
    - 200nm – 600nm (FIRE II: limited to 300nm – 600nm due to blocked mechanism
    - 4nm spectral resolution
  - 3 radiometer systems ○
    - 200nm – 4000nm



Cauchon, D. L., Radiative Heating Results from the FIRE II Flight Experiment at a Re-entry Velocity of 11.4 Kilometers per Second, TM X-1402, NASA, 1967.

FIRE - Flight Investigation of the Reentry Environment

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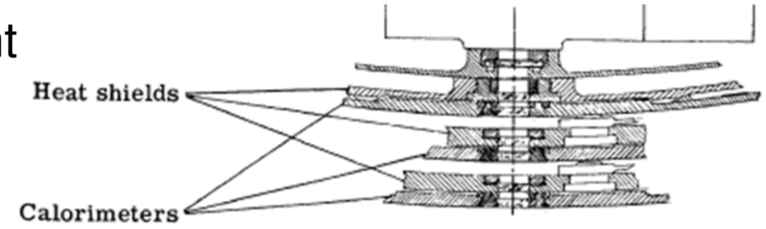
- Layered heat shield
  - → Measurement periods in clean environment
  - flow undisturbed from erosion products
  - realized by 3 calorimeter layers



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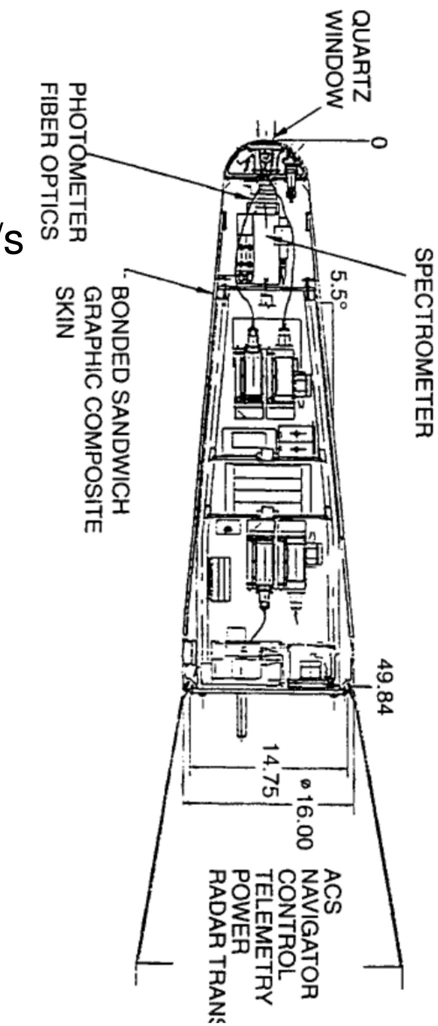
- Test case for coupled flow field/radiation simulation (Park, Merrifield/Fertig)
  - Rebuilding of total heat flux is rather successful, but limitations apply:
    - simulations show up to 90% of total radiation heat flux in VUV
    - →VUV measurements recommended
    - Absorption in boundary layer extremely sensitive to chemical composition
    - →TPS material characterization/ consideration of gas surface interaction (catalysis) required

Data Period	Altitude / km	Velocity / km/s
Fire I		
1	89.01 – 70.00	11.63 – 11.53
Fire II		
1	83.75 – 69.80	11.37 – 11.30
2	54.34 – 53.23	10.61 – 10.51
3	41.80 – 40.75	8.20 – 7.74

- FIRE II is considered one of most significant in-flight experiments

Bow Shock UV & UV Diagnostics Experiment

- Flight regime different to the hyperbolic conditions of FIRE
- Bow Shock UV (BSUV), 1990
  - measurement during ascent from 38km – 70km, v = 3.5km/s
- UV Diagnostics Experiment (UVDE), 1991
  - measurement during re-entry, structural failure at 62km, v = 5.1km/s
- Instrumentation (BSUV & UVDE)
  - Upper stage with nose radius of 0.1016m instrumented with:
    - 8 radiometers (different viewing angles, 0°, 30°, 50°)
      - NO γ, OH A-X and N_2^+ 1st. neg. band systems
    - NO filled CaF_2 window acting as VUV detector (O I 130.4nm + H I 121.5nm (only UVDE))
    - 1 spectrometer (stagnation point)
      - 200nm – 400nm
      - 1nm spectral resolution
- Numerical rebuilding successful for lower altitudes
- Triggered improvements (Kanne):
  - NO reaction rates
  - electronic excitation due to heavy particle collisions
- Allowed for validation of numerical models originally developed for hyperbolic entry



Erdman, et al, Measurement of Ultraviolet Radiation from a 5-km/s Bow Shock, *Journal of Thermo-physics and Heat Transfer*, Vol. 8, No. 3, 1994

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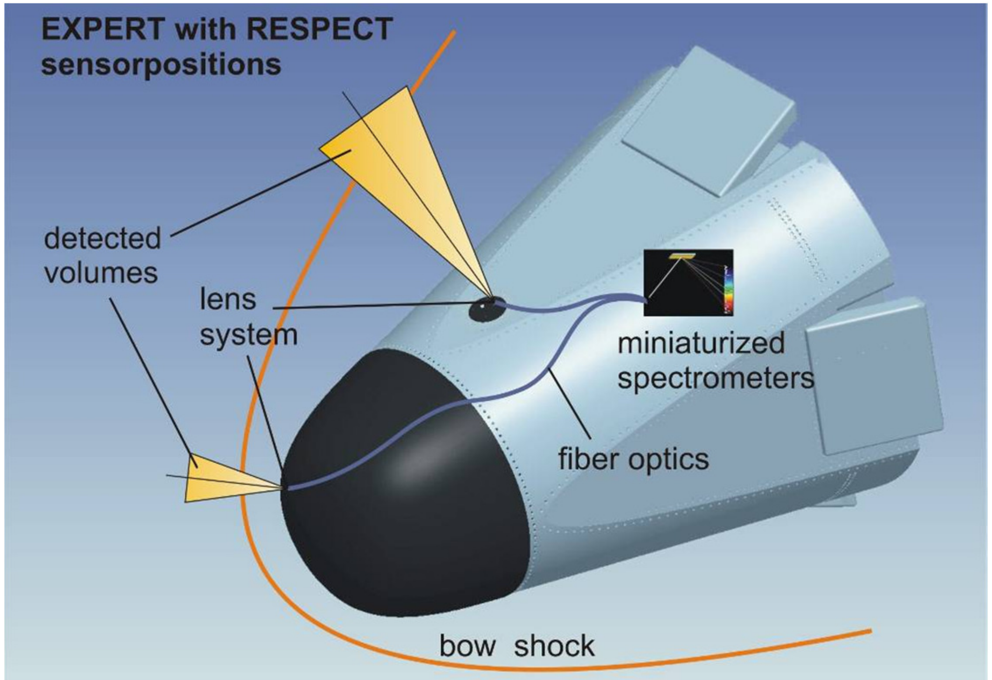
RESPECT - Re-Entry SPECTrometer

- Goal: Build a database on **spectrally resolved emission** during re-entry
- **Comparison with coupled flow field/radiation codes** → achieve information about chemical models used (validation)
- Both for design and post flight analysis a strong coupling to numerical simulation is needed.



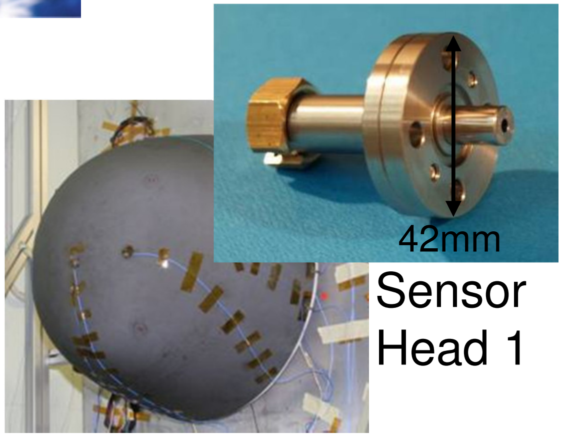
Sensor Head 1 (C/C-SiC nose):

- Higher temperatures in the stagnation region
  → **more species observed**
  → more accurate statements on chemical models possible
- Detection of erosion **products possible. (i.e. active/passive oxidation)**

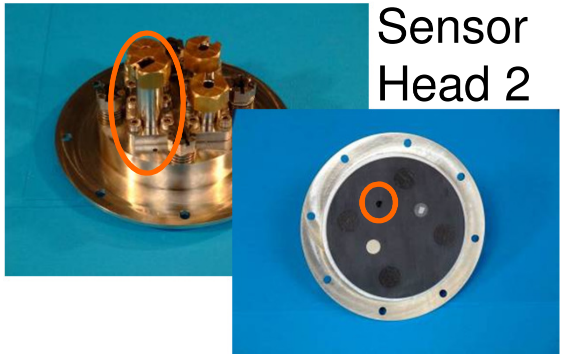
Sensor Head 2 (PM1000 panels):

- Examination of relaxation

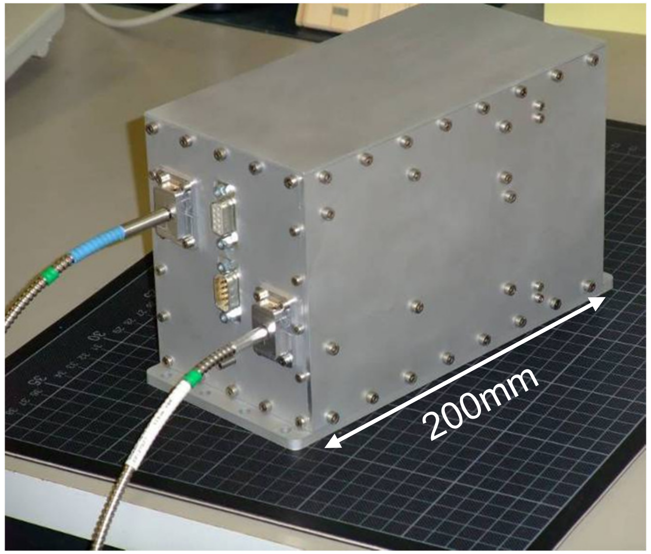
RESPECT sensor system



Sensor Head 1



Sensor Head 2



Fiber Optics & Sensor Unit

- sensor system developed at IRS on basis of miniaturized spectrometer (OceanOptics S2000)
- electronics (spectrometer control, power supply, data storage & transfer) designed at IRS

<u>system parameters:</u>

mass: ≈2.8kg
- ≈ 2.0kg SU
- ≈ 0.2kg SH1
- ≈ 0.1kg SH2
- ≈ 0.5kg harness (tbc)

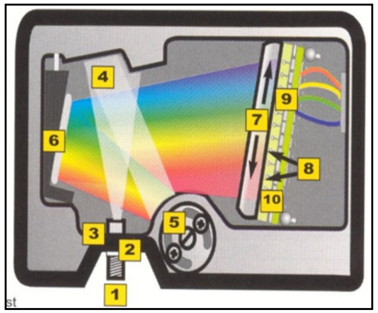
measurement spec.:
- ≈ 200 - 850nm
- FWHM ≈ 1.5nm
- exposure: 1-242ms
- sampling rate up to 8.5Hz

power consumption:
- ≈ 3.5 W

data interface:
- RS422 @115kbps
- 3 Kbyte/spectrum

Commercially Availabel Miniaturized Spectrometers (selection of models considered for RESPECT)

	S 2000	**HR 4000**	**MCS 55**
Supplier	Ocean Optics	Ocean Optics	Zeiss
Dimensions (mm)	90 x 64 x 35 (70)	150 x 105 x 46	140 x 105 x 75
Weight	190 (380) g (electronics : 230 g)	570 g	1750 g (w/o electronics)
Power	110 (170) mA @ 5 VDC	450 mA @ 5 VDC	
Detector	2048, CCD Array	3648, CCD Array	1024, diode array
Wavelength Range	200 – 850 nm	200 – 1100 nm	215 – 1015 nm
Pixel Resolution	0,35 nm	0,25 nm	0,8 nm
Optical Resolution	1,5 nm	0,75 nm	3 nm

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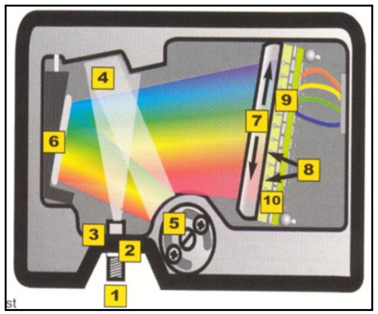
Detector	2048, CCD Array
Wavelength Range	200 – 850 nm
Pixel Resolution	0,35 nm
Optical Resolution	1,5 nm

OceanOptics S2000 selected

- small
- light weight
- low power consumption
- reasonable resolution for miniaturized spectrometer
- no movable parts → robust design



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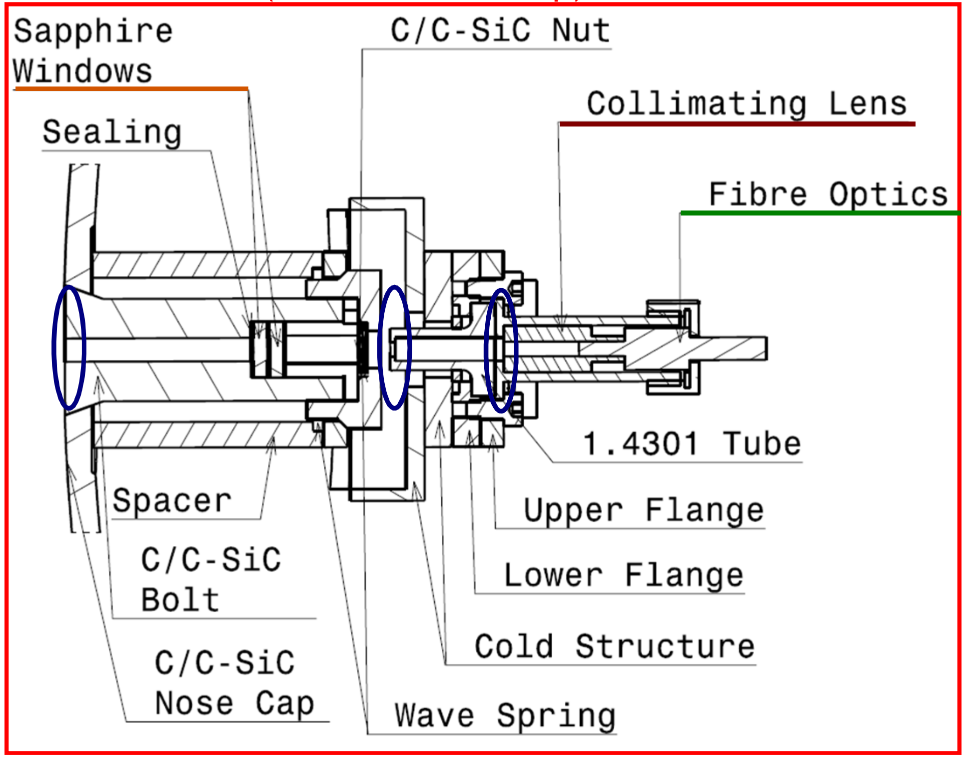
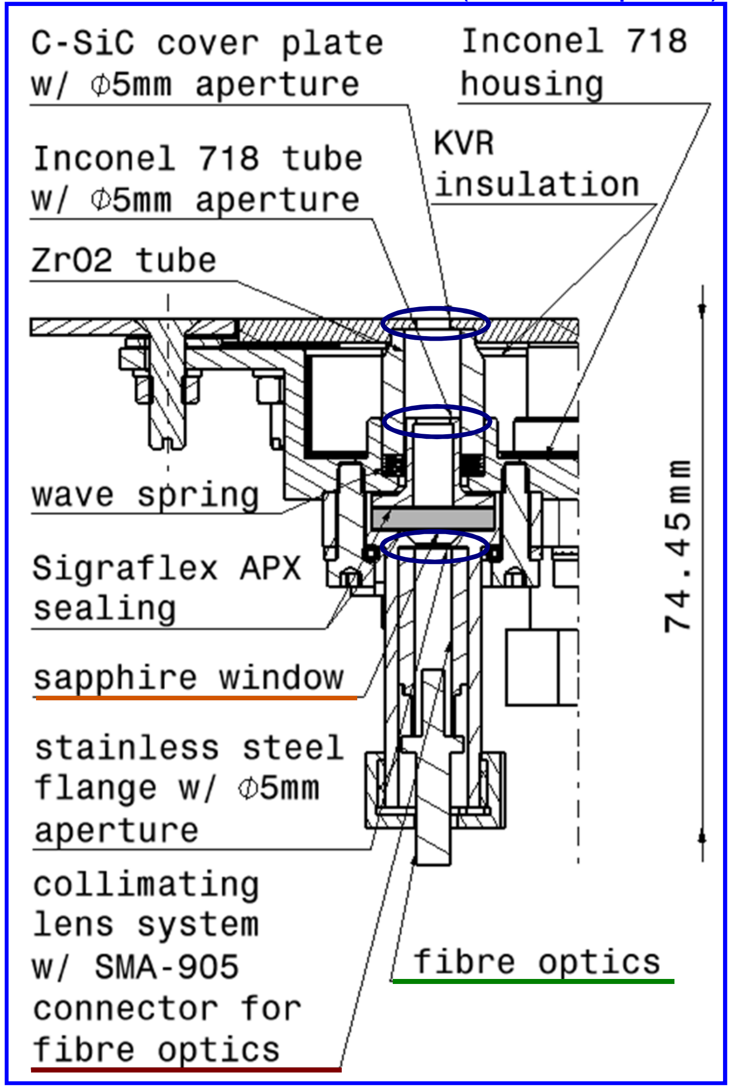
Sensor Head Design

Sensor Head 1 (C/C-SiC nose cap)



Sensor Head 2 (PM1000 panel)

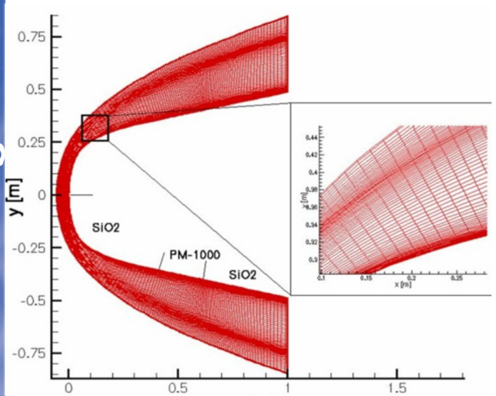


apertures sapphire windows lens fiber optics

- lens design used to benefit from chromatic aberration, i.e. weakening of UV signal
- aperture design primarily used to adjust signal strength

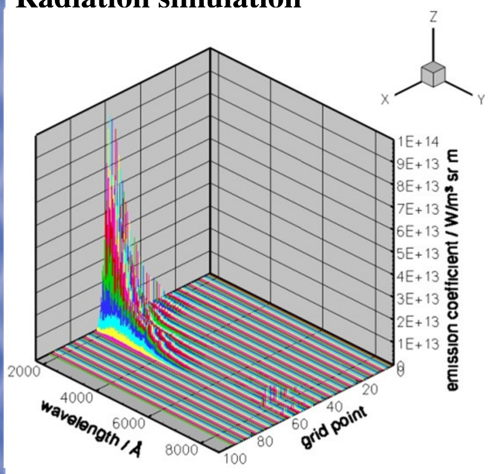
Metrological Layout

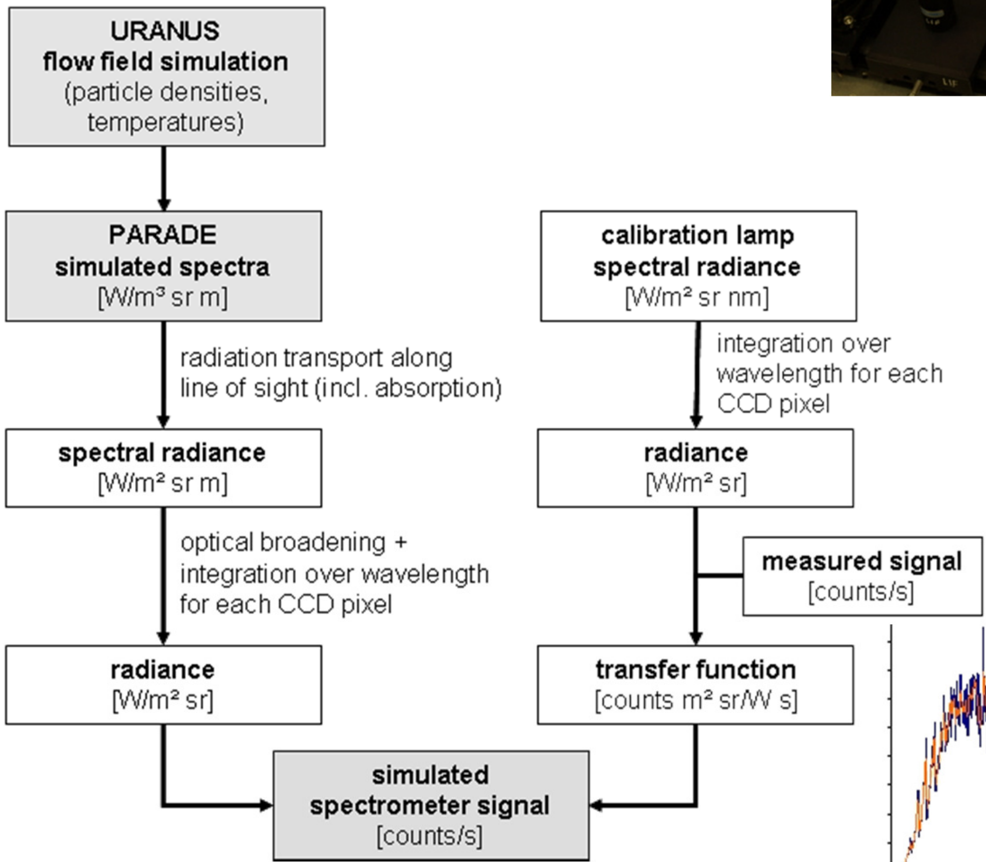
Metrological layout is based on complex numerical simulations and experiments to determine the sensor system characteristics by means of calibration measurements.

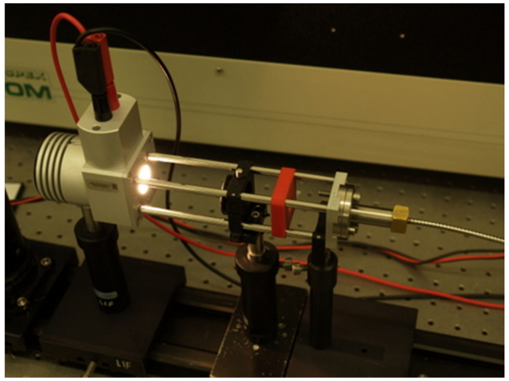


URANUS
Flow field simulation

PARADE
Radiation simulation

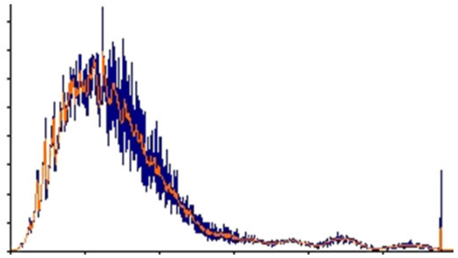






Calibration

Simulated signals

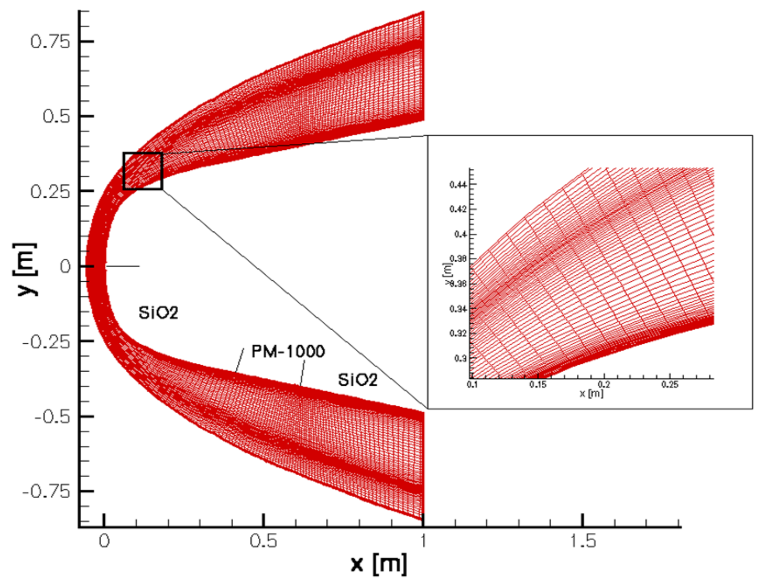


URANUS Flow Field Simulation

Upwind Relaxation Algorithm for Non-equilibrium Flows of the Universität Stuttgart

<table>
<tr><th>URANUS
axisymmetric</th><th colspan="2">URANUS
3D</th></tr>
<tr><td colspan="3">Navier-Stokes code (Euler or ideal gas optional)</td></tr>
<tr><td colspan="3">Fully implicit (explicit optional)</td></tr>
<tr><td colspan="3">Non-equilibrium thermo-chemical air models:</td></tr>
<tr><td>- 11 species: N_2, O_2, NO, N, O, N_2^+, O_2^+, NO^+, N^+, O^+, e^-
- 6 temperatures: T_{transl}, $T_{vib,N2}$, $T_{vib,O2}$, $T_{vib,NO}$, $T_{rot,mol}$, T_e</td><td>- 5 species: N_2, O_2, NO, N, O
- 4 temperatures T_{tr}, $T_{vib,N2}$, $T_{vib,O2}$, $T_{vib,NO}$</td><td>- Variable use of different thermo-chemical models (under development)</td></tr>
<tr><td colspan="3">Influence of thermal nonequilibrium on reaction rates: CVCV, (TTv)</td></tr>
<tr><td colspan="3">Transport coefficient model: Chapman-Cowling, (Gupta-Yos)</td></tr>
<tr><td colspan="3">Gaskinetic Gas-Surface model including surface reaction models</td></tr>
<tr><td>Structured grids</td><td colspan="2">Structured grids, multiblock optional</td></tr>
</table>

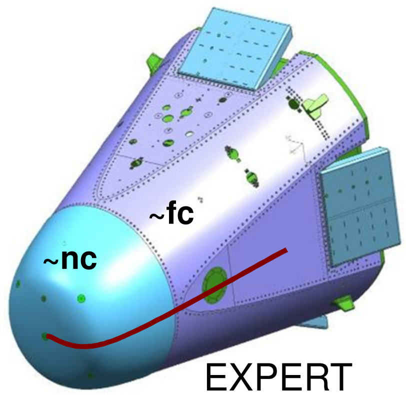
URANUS simulation grid for EXPERT



- Structured 116 x 90 cells and shock adapted grid
- Grid spacing at the surface: order of local mean free path (40 mesh points)
- Multiple surface modeling with different catalytic properties, detailed catalysis modeling SiC (SiO2), global recombination coefficient PM1000

URANUS Results (Required for Radiation Simulation)

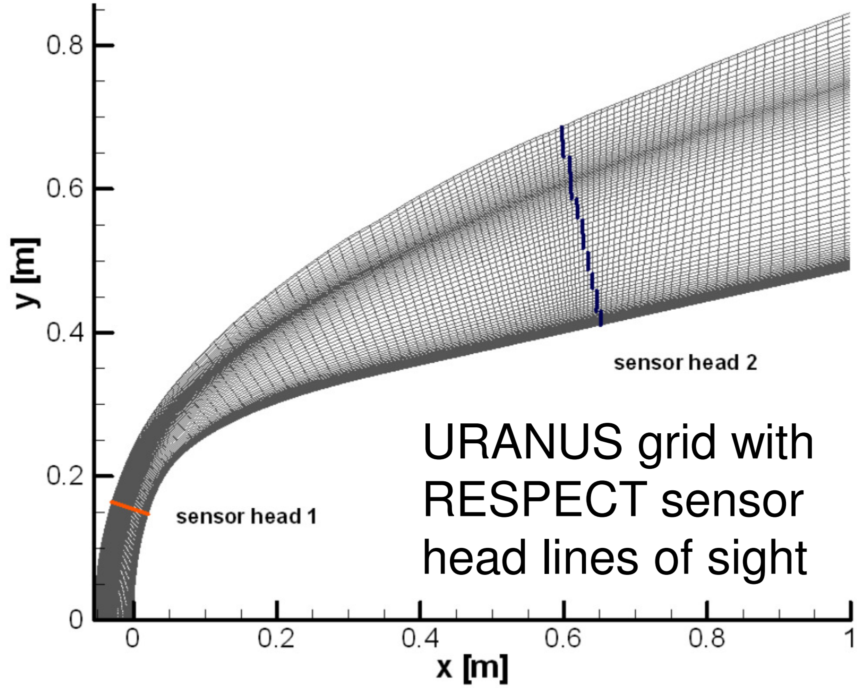
- Excitation temperatures along RESPECT sensor head lines of sight
  - T_{trans}, T_{vib_NO}, T_{vib_N2}, T_{vib_O2}, T_{rot}, T_{el}
- Mole fractions along lines of sight
  - N_2, O_2, NO, N, O, N_2^+, O_2^+, NO^+, N^+, O^+, e^- (11 components)
- Total pressure to calculate particle densities



EXPERT

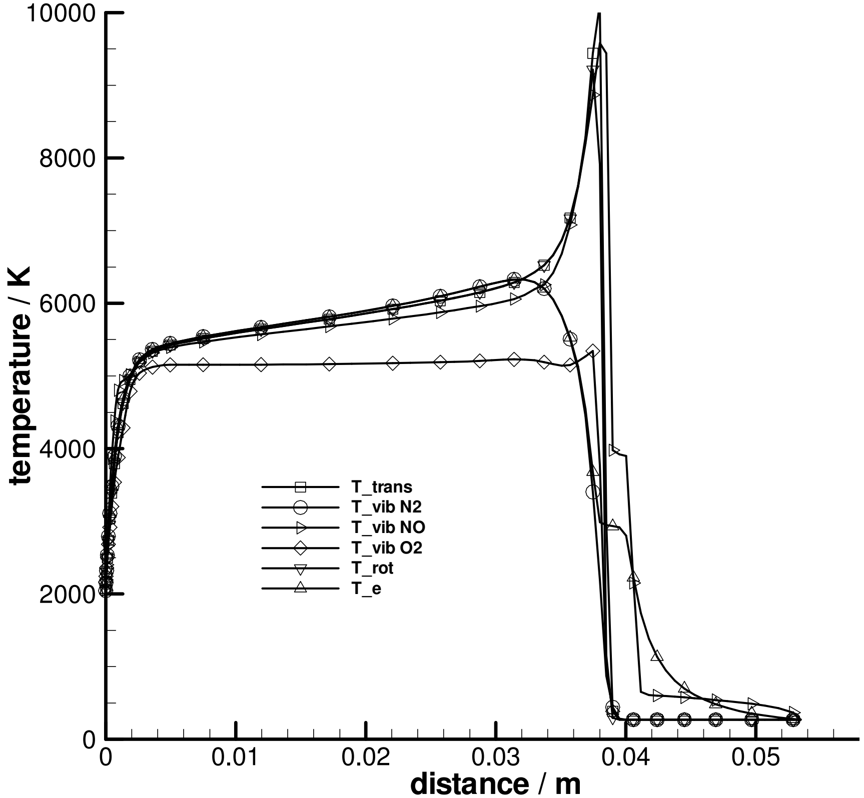
Simulated trajectory points

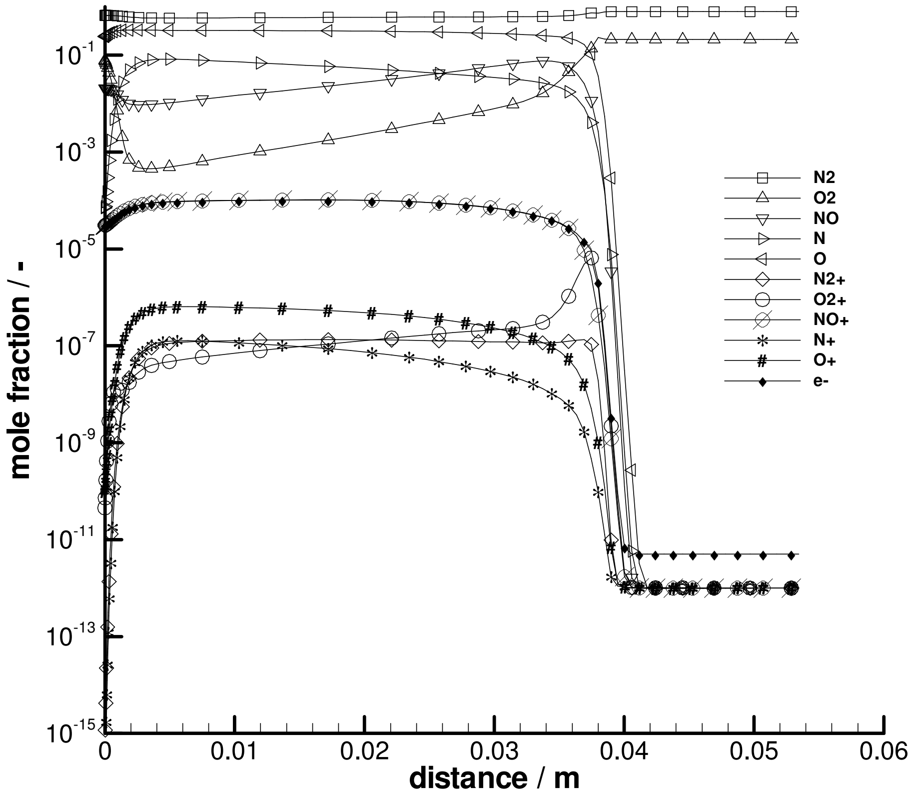
h [km]	v_∞ [km/s]	Ma_∞ [-]
34.14	4.27	13.75
49,93	4.97	14.99
70,39	5.05	17.13
79.95	5.04	17.97



URANUS grid with RESPECT sensor head lines of sight

URANUS Results – Sensor Head 1





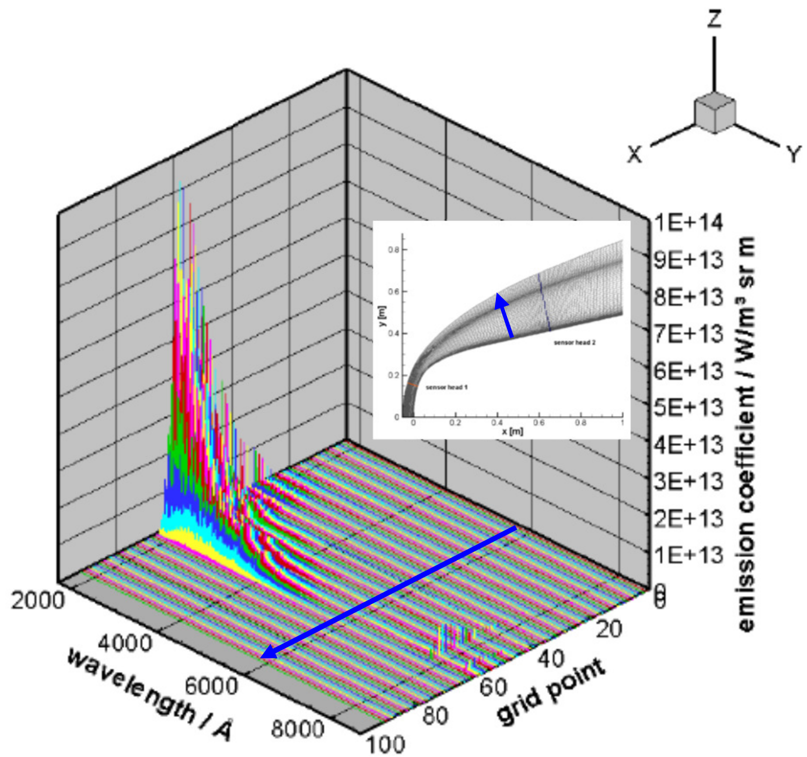
- Exemplary trajectory point: h=49.93 km, v∞= 4.97 km/s, Ma∞= 14.99
- Bow shock distance about 4-5 cm
- Excitation temperatures (T_{trans}, T_{rot}, T_{vib_NO}) up to 13000K
- mole fractions
    - Dissociation of N_2 and O_2
    - Formation of new species in post shock regime, mainly NO
    - NO^+ is main source of electrons in post shock regime

Radiation Simulation – PARADE (Plasma Radiation Data Base)

- calculation of spectrally resolved emission and absorption coefficients
  - calculations include physical effects, e.g. Stark effect or Doppler effect
  - continuum radiation
  - simulated species:
    - atoms: N, N^+, O, O^+
    - molecules: N_2, N_2^+, NO, O_2
  - resolution: 0.01 nm
- optical broadening is considered by a separate C-program
- 1D radiation transport calculated on basis of radiation transport equation

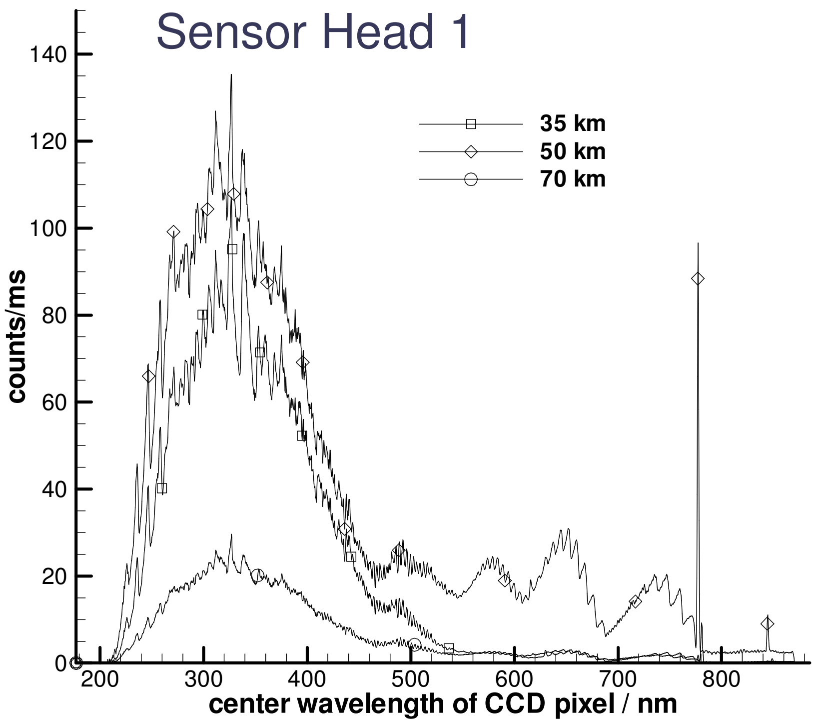
$$I_n(\lambda) = \frac{\varepsilon_n(\lambda)}{k'_n(\lambda)}\left[1 - \exp\left(-k'_n(\lambda)x\right)\right] + I_{n-1}(\lambda)\exp\left(-k'_n(\lambda)x\right)$$

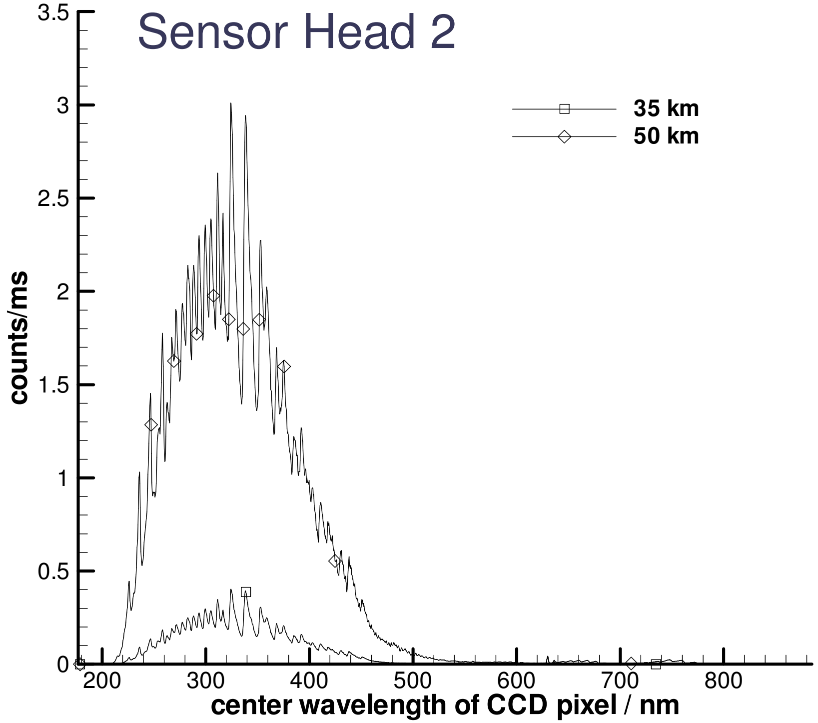
ε….emission coefficient
κ'…absorption coefficient corrected for stimulated emission



PARADE output along the optical path of sensor head 1, altitude 50km

Simulated Spectrometer Signals





- Contribution of simulated species to predicted spectra:
  - spectra of both sensor heads dominated by O_2 and NO
  - 70km altitude spectrum for SH1 shows N_2 molecule bands
  - spectra of SH1 show 777nm oxygen emission line triplet
- Altitude range for measurements:
  - dynamic range of 3000 counts (4096 w/o margin), 1ms – 242ms exposure time
  - SH1: 70km – 35km
  - SH2: around 50km, apertures already designed with max. allowed diameter

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Content: Spectroscopic Instrumentations for Entry

- Emission spectroscopy based instrumentations
  - Basics of emission spectroscopy
  - Overview of past emission spectroscopic experiments
  - Payload design example: RESPECT/EXPERT
    - Payload design
    - Metrological layout
  - **Outlook on EUV/VUV spectroscopy**
  - Scientific objectives/results

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Outlook on EUV/VUV spectroscopy

- EUV/VUV radiation dominates the radiation heat flux for fast Earth re-entries

- So far no EUV/VUV emissions spectroscopic experiments flown
  - Availability of detectors/spectrometers problematic
  - Radiation transport to spectrometer/sensor is difficult
    - No EUV/VUV optical fiber (and viable window) materials available
    - Spectrometer/Sensor must be mounted with immediate access to TPS optical feed through

- Planned for ESA capsule PHOEBUS

➔ Several key challenges must be solved in order to fly a EUV/VUV spectrometer payload

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Content: Spectroscopic Instrumentations for Entry

- Emission spectroscopy based instrumentations
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  - Payload design example: RESPECT/EXPERT
    - Payload design
    - Metrological layout
  - Outlook on EUV/VUV spectroscopy
  - **Scientific objectives/results**

RESPECT – Post Flight Analysis

Calibration check & Sensor system inspection

Post processing of measured spectra

Measured spectra

Link to EXPERT PLs and trajectory data

COMPARISON

URANUS flow field simulation

PARADE radiation simulation

Rebuilt spectra

Results:
- Species Identification incl. Erosion Products (if existent)
- Determination of excitation temperatures
- Detection of PAT – APT
- Analysis of relaxation

<u>Improvement/Validation of Numerical Models</u>
- Statement on accuracy of current numerical models
  - Chemistry modeling (emphasis on O_2)
  - Radiation modeling (required improvements in QSS modeling expected)
- Diffusion, chemistry and radiation modeling of erosion products (if present)
- Test case definition for improved/future numerical tools

Results:
- Extraction of locally resolved plasma composition (e.g. particle densities, excitation temperatures, …)
- Analysis of relaxation

Further research (e.g. QSS modeling)

Immediate impact on future re-entry vehicle design by increased reliability of design basis (numerics).

Motivation for Catalysis Assessment (Example Earth)

- Earth peak heating conditions (below 80 km, depending on β and lift): V_{PH} of vehicle from LEO is about 6 km/s→ Shock temperature rise by a factor of about 80 leading to post shock temperature of about 16.000K
- Relaxation of internal degrees of freedom and chemistry much slower than translational relaxation→ Relaxation zone downstream of the shock
- Chemical relaxation: About two thirds of total enthalpy transferred into chemical energy → Temperature decrease to about 6000K
- Radiation cooled TPS: Wall temperatures usually below 2000K → Dissociation degree of equilibrium air negligible. But under peak heating conditions collision frequency between gas particles too low → Chemical non-equilibrium in boundary layer → Significant amount of atoms formed downstream of shock pass boundary layer and reach surface
- Depending on surface material, recombination of atoms may be catalyzed. → Formation enthalpy of atoms become released at surface

→ Heat flux increase by a factor of three!

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Motivation for Catalysis Assessment (Example Earth)

→ Importance of getting rid of conservative assessments for heat shield design as this leads to

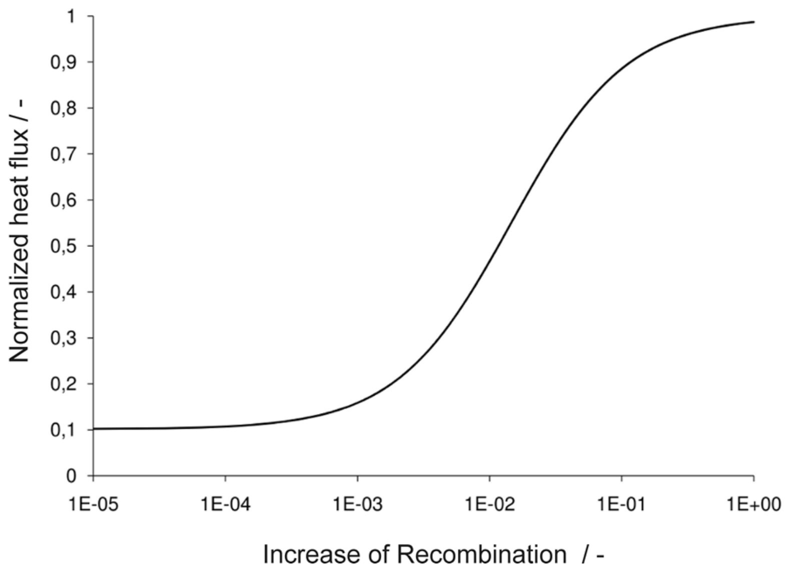
- Too high TPS masses and (, therefore,) a
- Too high vehicle mass and/or a
- Loss of (potential) scientific payload mass and/or
- Too high overall costs

→ Design tools to optimize TPS masses taking into account surface reaction models are a need!

Motivation for Catalysis Assessment (Example Earth)

- At least two fractions of heat flux have to be considered:
  - Convective heat flux which does not directly depend on the material and
  - Recombination heat flux which results from the chemical recombination of atoms, a process, which directly depends on the material of the space vehicle surface
- Increase in heat flux can be as much as 3 times for an air system, comparing a non-catalytic to a fully catalytic material[1, 2]
- Experimental conditions have to be known precisely
- If the ratio of the variable recombination and convective heat flux to a fully catalytic heat flux is taken a trend is obtained
- Steep slope regime is of interests as the potential to manipulate the heat flux is most significant

→ Very high potential to save mass



heat flux depending on increase of recombination (as an example)

Catalysis - Basics

- Definition of recombination coefficient γ_i as

$$\gamma_i = \frac{\dot{N}_{Ai,recom}}{\dot{N}_{Ai,tot}}$$

- Gas-specific parameter. Index recom is assigned to respective number of recombining species while index tot is assigned to the total number of particles that flow to the surface per second
  → γ is always between 0 (non-catalytic) and 1 (fully catalytic)

- In consistence with the gradients (remember figure), the following regimes can be defined:
  - $\gamma < 1$: materials of low catalysis
  - $0.01 < \gamma < 0.1$: materials in with medium catalysis
  - $\gamma > 0.1$: materials of high catalysis

- However, aspect of energy accommodation still ignored i.e. the answer to the question which fraction of the heat flux derived from the recombination processes is experienced by the surface (other fraction could stay with the molecule that is not necessarily in equilibrium with the surface)

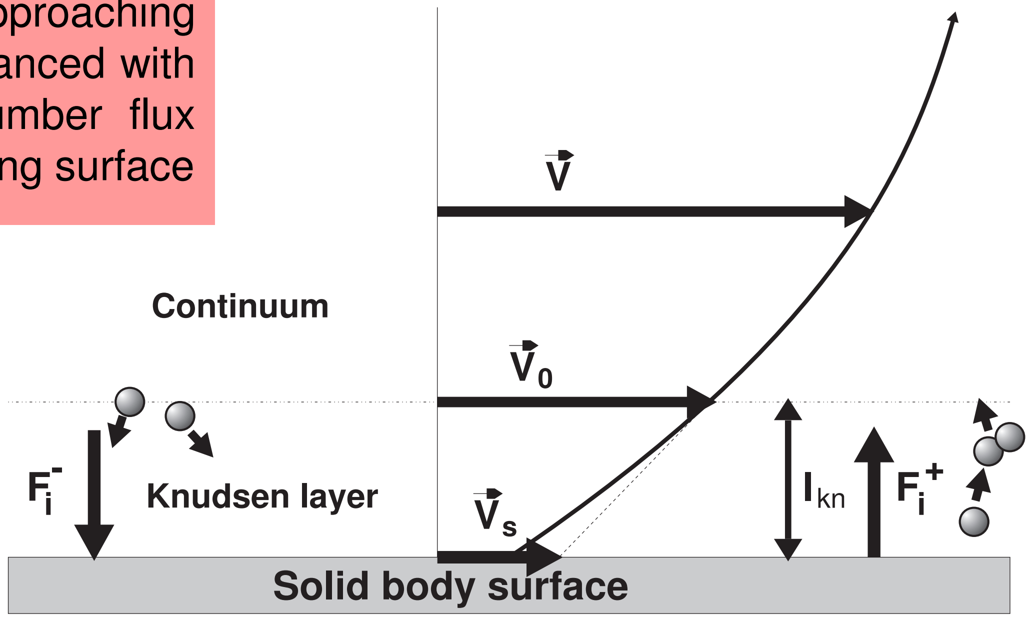
- Energy accommodation coefficient β defined as

$$\beta = \frac{\dot{q}_{surface,recom}}{\dot{q}_{tot,recom}}$$

The product of both β and γ may has to be taken into account

Gaskinetic Gas-Surface Interaction Model

Energy and number flux of species approaching the surface balanced with energy and number flux of species leaving surface



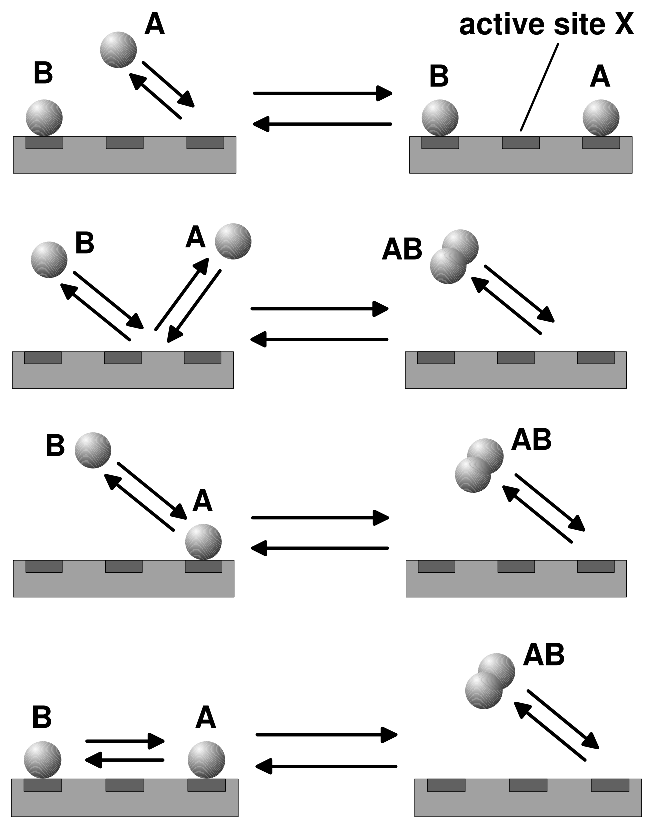
The gaskinetic modeling of the gas-surface interaction allows to compute the fluxes at the surface exactly and is able to describe thermal nonequilibrium effects.

- Simple formulation of reactive boundary conditions based on fluxes
- Valid in the slip flow regime as well as in the continuum regime

Catalytic Surface Reactions

Heterogeneous Catalysis:

- Adsorption/Desorption
- Recombination / Dissociation
- Eley-Rideal Mechanism
- Langmuir-Hinshelwood Mechanism

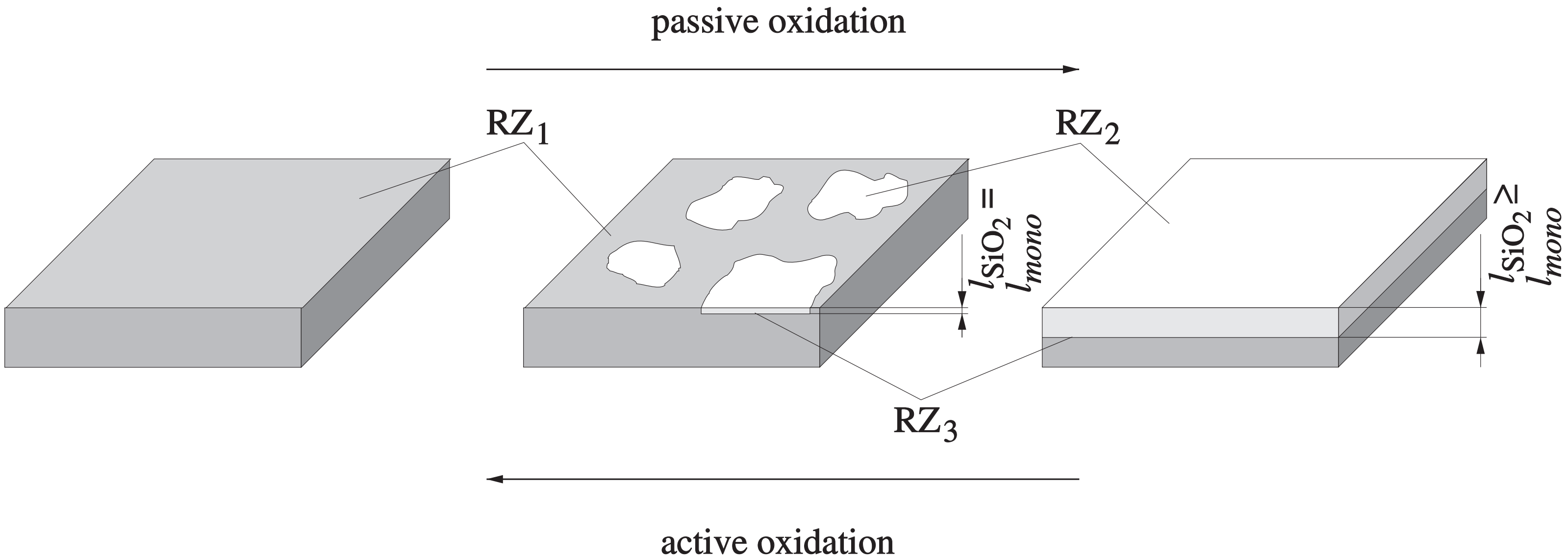


Detailed description of surface processes required

Oxidation Regimes

- Chemical reactions of SiC with oxygen: formation of SiO, SiO_2, CO and CO_2. (latter negligible at expected temperatures)
- SiO and CO are gaseous at those temperatures, leading to erosion and rapid material loss.
- SiO_2 is liquid or solid at the lower temperatures. ⇨ Layer formation on top of SiC. ⇨ Diffusion barrier, can be considered as self protection mechanism (oxygen flux to the surface hindered).
- Mass loss rate under these so called ‘passive oxidation conditions’ much lower.
- Higher temperatures and lower oxygen pressures: SiO_2-layer is removed and SiO formation more likely. ⇨ ‘active oxidation’.

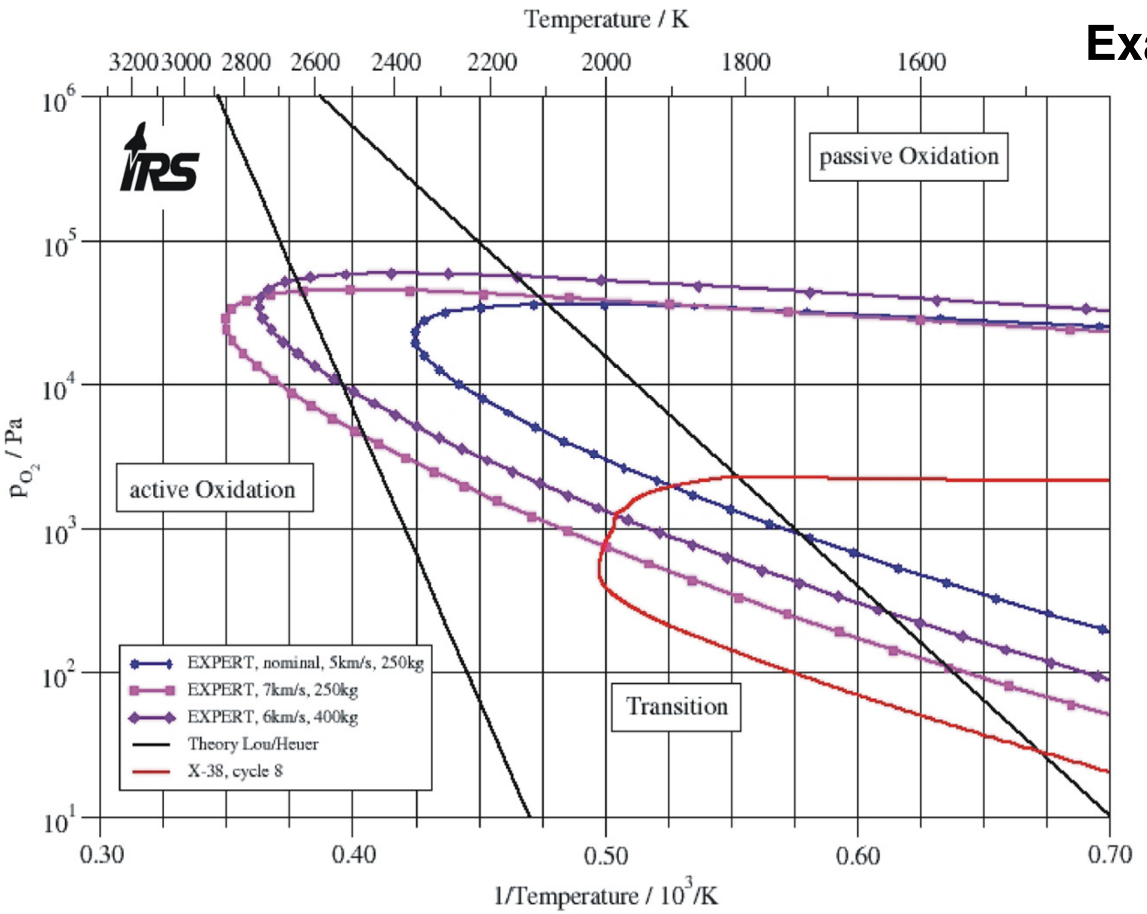
Active / Passive Oxidation of SiC



The transition from active to passive oxidation is modeled by three reaction zones:

- Interface between SiC and gas (RZ_1)
- Interface between SiO_2 and gas (RZ_2)
- SiO_2 layer on top of the SiC including the interface (RZ_3)

Assessment of Oxidation Regime based on Equ. Model



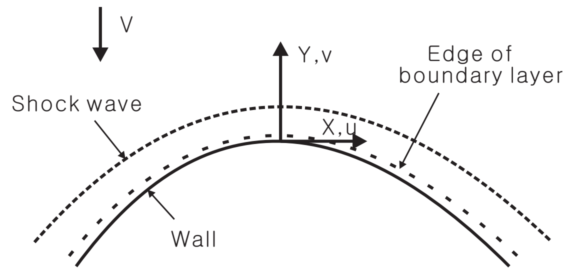
Examples: EXPERT and X-38

Heuer and Lou equilibrium theory

<u>Laux PhD</u>: all measured PAT are in the transition regime calculated by Lou et al.

Active Oxidation may occur for both vehicles. However, equilibrium models are not able to predict transition during re-entry properly, since boundary layer around vehicles is in chemical non-equilibrium.

Catalysis (Goulard)



Axiom 1

$$\frac{q\ to\ fully\ catalytic\ wall}{q\ to\ noncatalytic\ wall} \approx \frac{CpT + energy\ contained\ in\ dissociation}{CpT}$$

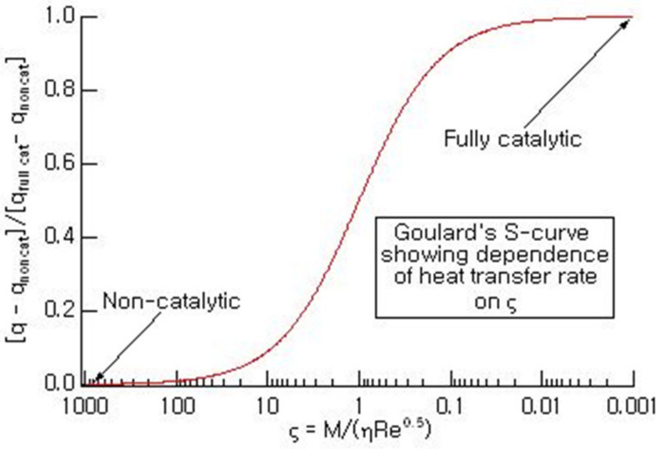
Axiom 2

$$q\ to\ a\ fully\ catalytic\ wall \approx q\ in\ a\ nonreacting\ gas.$$

Axiom 3

Transition from noncatalytic to catalytic wall occurs where ζ = 1

$$\zeta = \frac{0.47}{Sc^{2/3}} \frac{1}{\rho_w k_w} \sqrt{2\rho_e \mu_e (\frac{du_e}{dx})}$$



(source: Chul Park)

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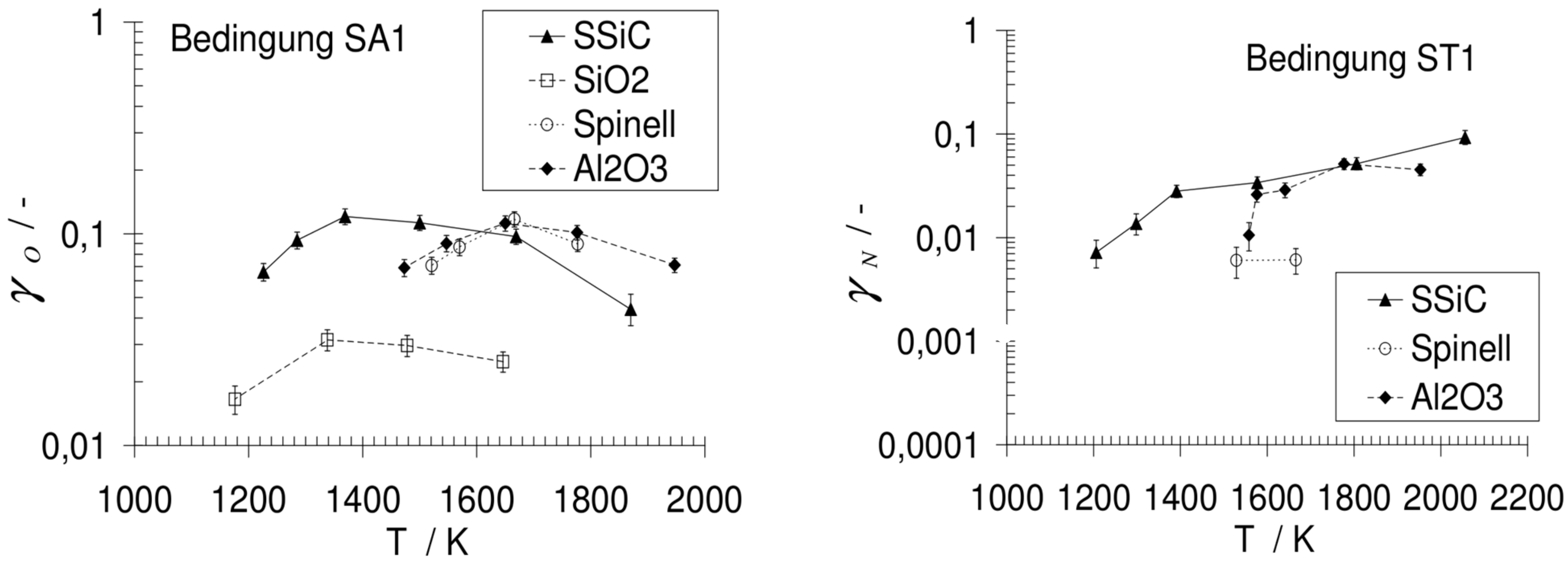
Gas-specific Catalysis Properties for SiC and SiO_2



Source: Pidan et al.

Interpretation

- Oxygen related recombination coefficient for SiO_2 has its maximum around 1400K (similar to SiC such that a SiC layer before passivating the sample would even have the same qualitative behaviour)
- PAT: SiO_2 layer vanishes, now SiC layer relevant
- Nitrogen related recombination coefficient for SiC strongly increasing within the regime of high catalysis
- Behaviour confirmed by measurements of Steward

→ Additional energy contribution due to increased recombination of atomic Nitrogen

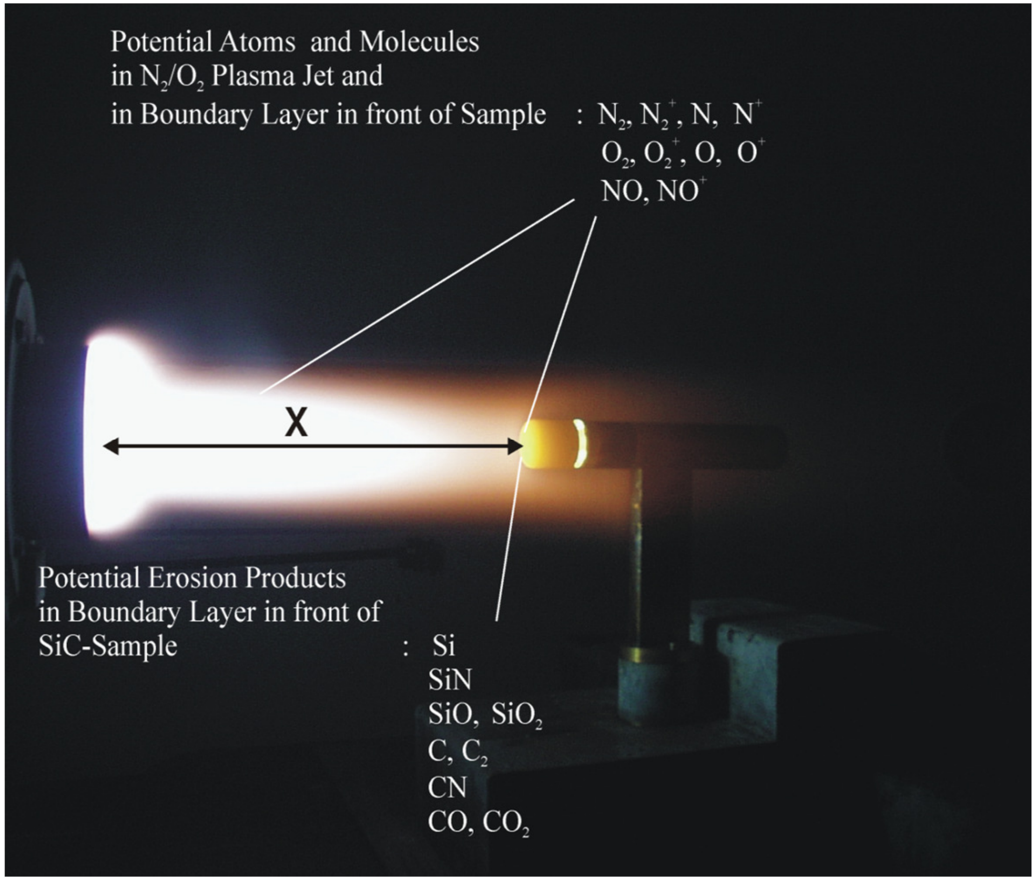
Probe Techniques

European Standard

Transition (PAT, APT) to be investigated

- Active Oxidation leads to increased heat load
- Necessity of better thermal insulation
- Thicker heat shield (e.g. X-38)
- Heavier TPS
- Reduced re-usability (higher erosion rates)

- Complexity of thermo-chemical situation and reaction schemes (rarely accessible with standard measurement techniques)



Species expected in plasma / boundary layer using SiC-based material sample in air plasma, here: magneto-plasmadynamically driven PWK2-RD5, x-position shown

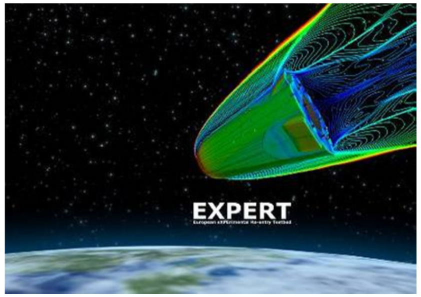

Cassini-Huygens
Saturn
Stardust
Re-entry ATV
56:60
Mirka
Express
IRDT
X-38
Hopper
HOPE-X
Sänger
Hermes
SHEFEX II
EXPERT
1. NC heating (PYREX)
2. PHLUX Catalysis
3. RESPECT

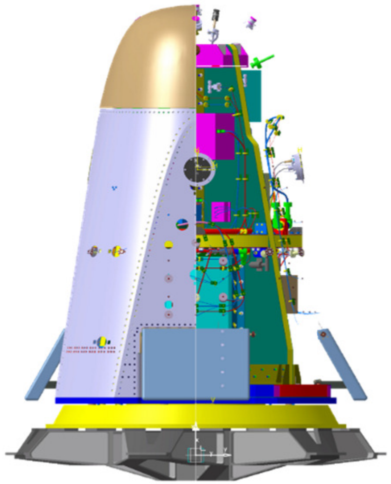
In-Flight Measurement Technology

EXPERT European eXPErimental Re-entry Testbed (ESA)

- ESA project for investigation of numerous phenomena in atmospheric reentries:
  - Real gas effects
  - Transition (APT-PAT, LTT)
  - Plasma (Composition, …)
  - Catalytic Effects
- Realization:
  - Ballistic capsule with several onboard sensor systems

  → **Validation of numerical tools (Chemistry-, Radiation-Modeling, …)**





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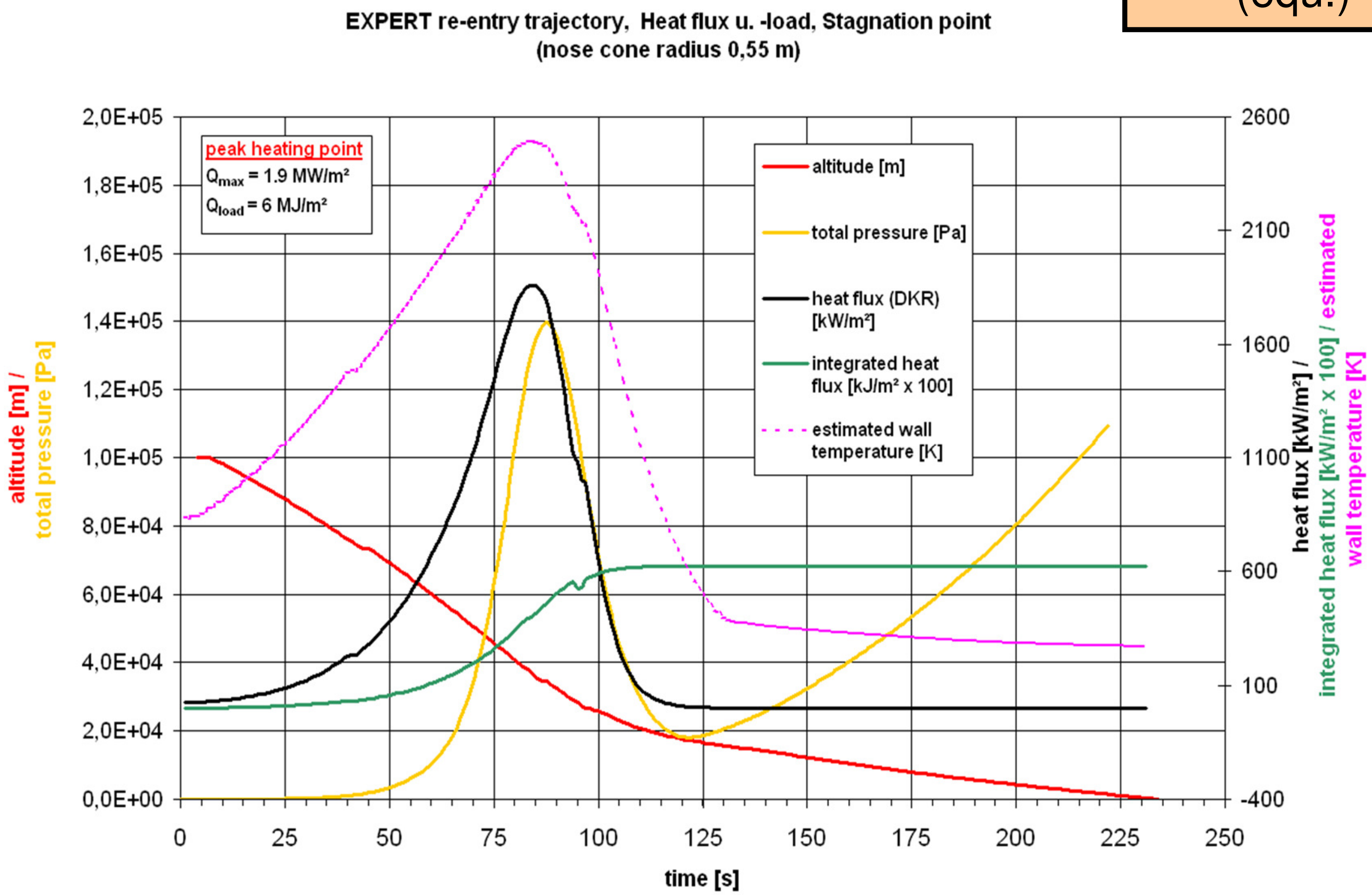
Trajectory EXPERT

… very high maximum heat fluxes expected …

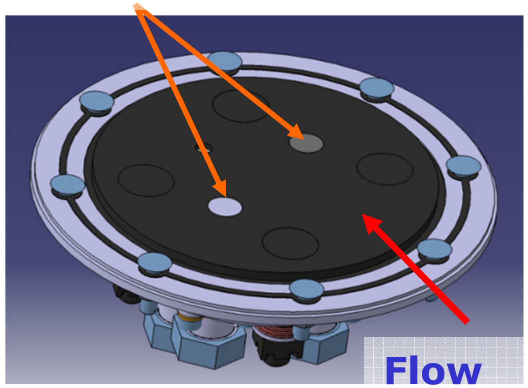
$T_{Wall,max}$=2490K (equ.)

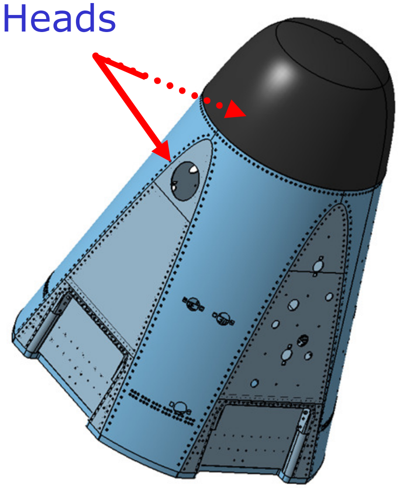


PHLUX – Pyrometric Heat fLUx eXperiment

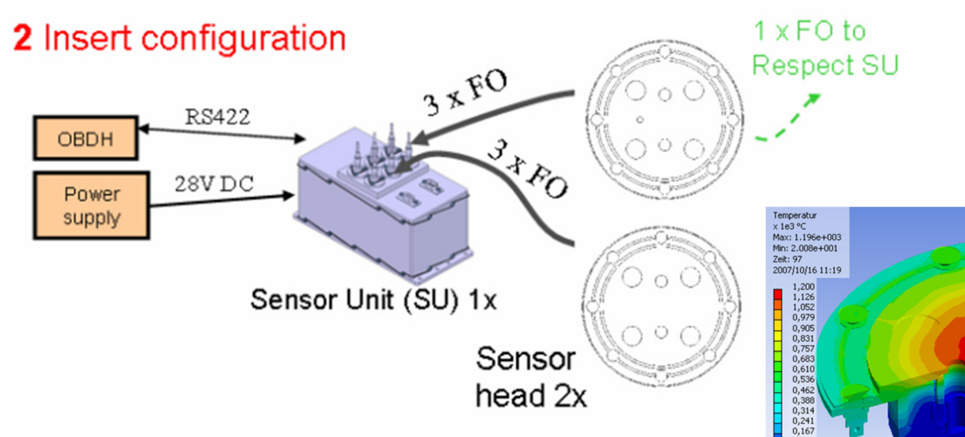
Scientific Goal:

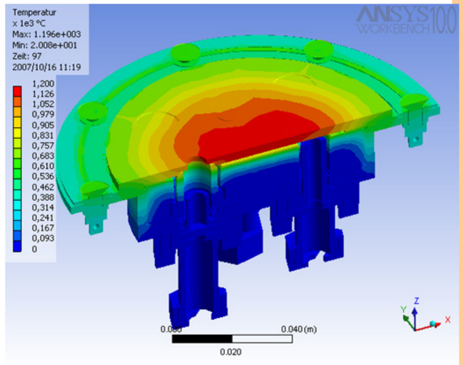
- Determination of the Dissociation Degree near the Surface during Re-Entry
    - Measurement of Backside Temperature of two different material samples
    - Determination of heat flux from temperature measurement
    - Investigation of dissociation degree from different but known catalytic behaviour and numerical tools
- Investigation of relaxation processes
- Comparison with numerical calculation
    - Validation and Improvement of numerical Tools
    - Development of efficient TPS systems



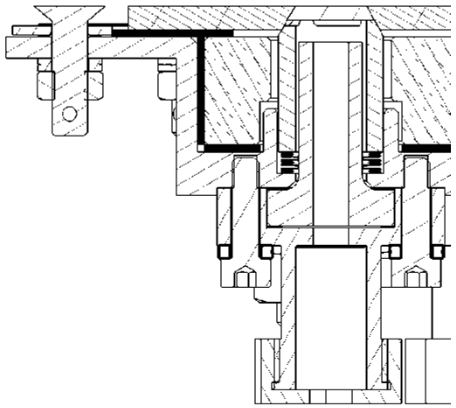


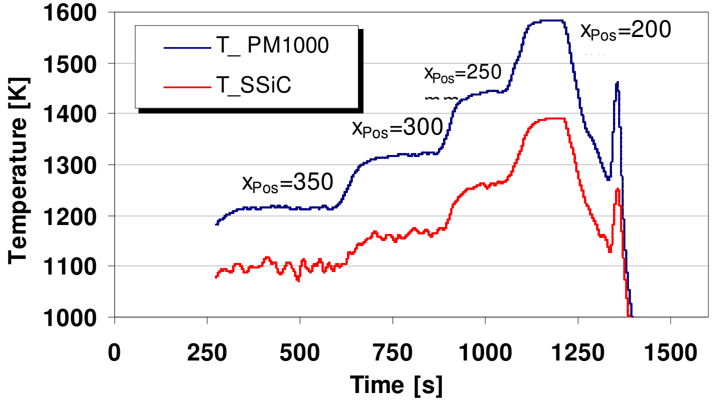
PHLUX - Configuration





1 Sample Temp. Measurement





Key Data:

Mass: 3,8 kg
- 2,4 kg SU
- 1,1 kg SH
- 0,3 kg Kabel

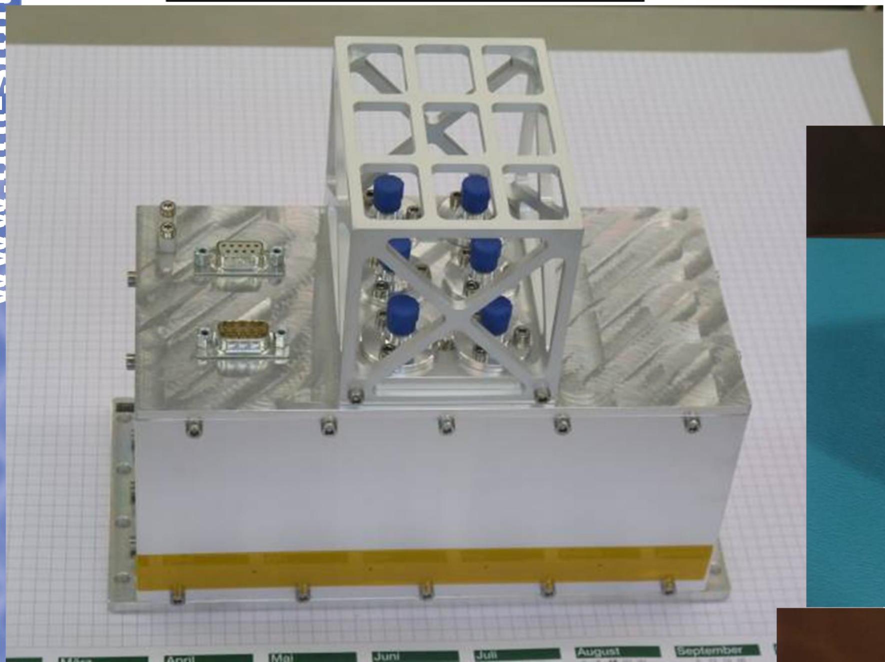
Measurement Range:
- 1200-1800nm
- 420℃ – 1430℃

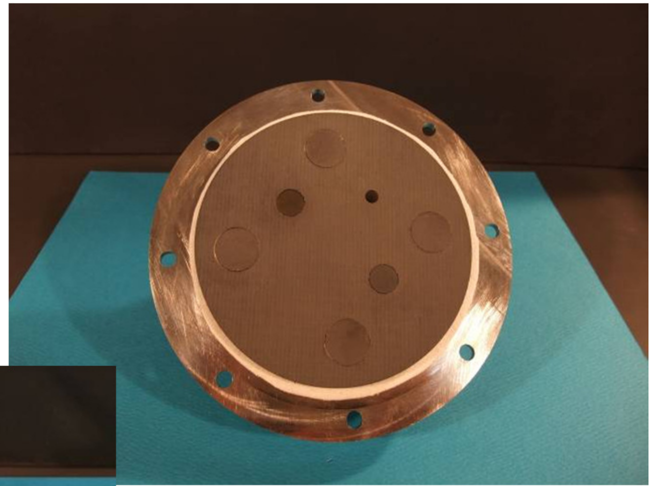
Power:
- ≈ 6 W

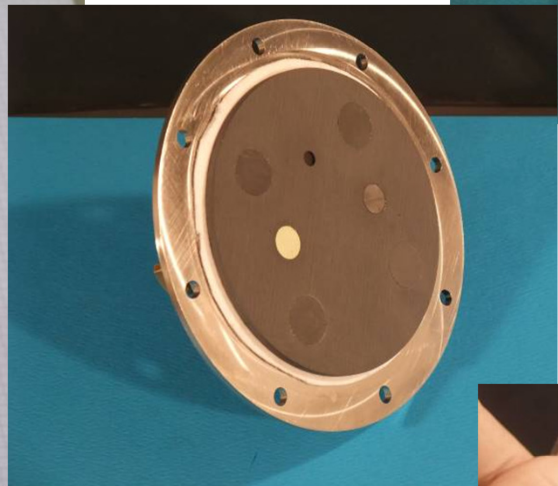
Data Aquisition:
- RS422@115kbps
- Interval 100Hz
- 23 Bytes per second

PHLUX FM

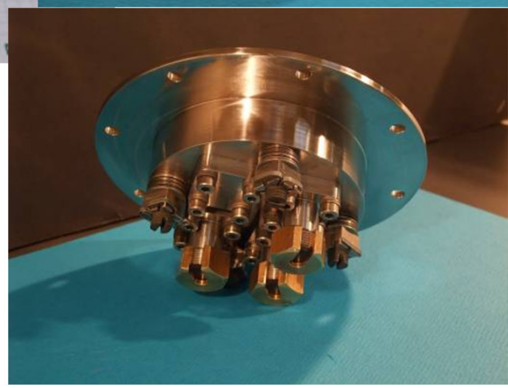
Sensor Unit







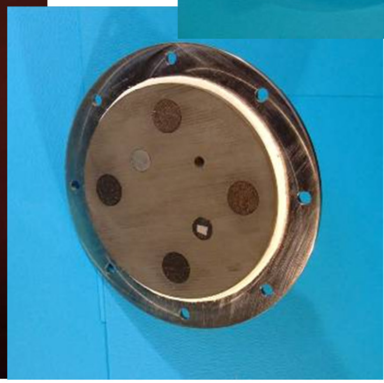
2 x Sensor Heads



PHLUX Qualification

PWT + Functional

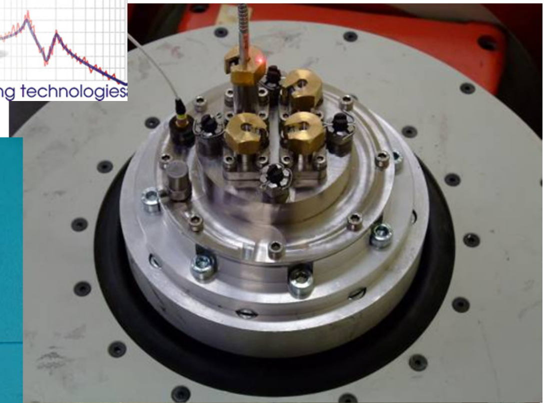
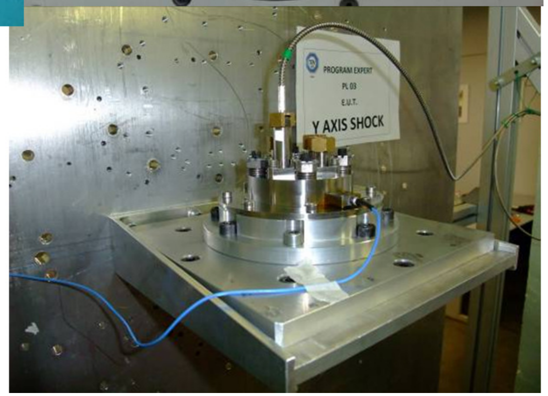


Electronics qualified in PYREX SU Qualification Test Campaign

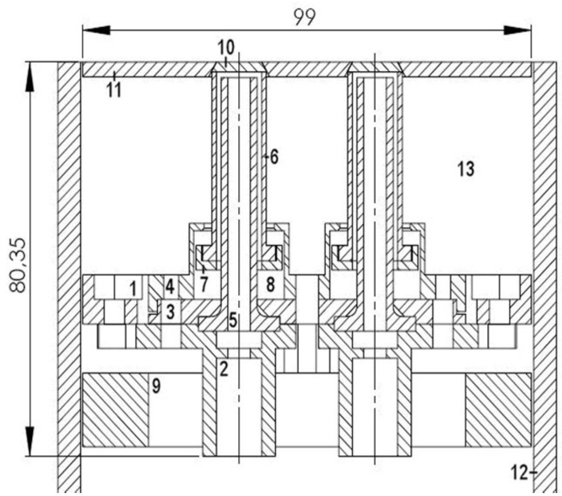
Mechanical + Shock

∂t² dynamic testing technologies

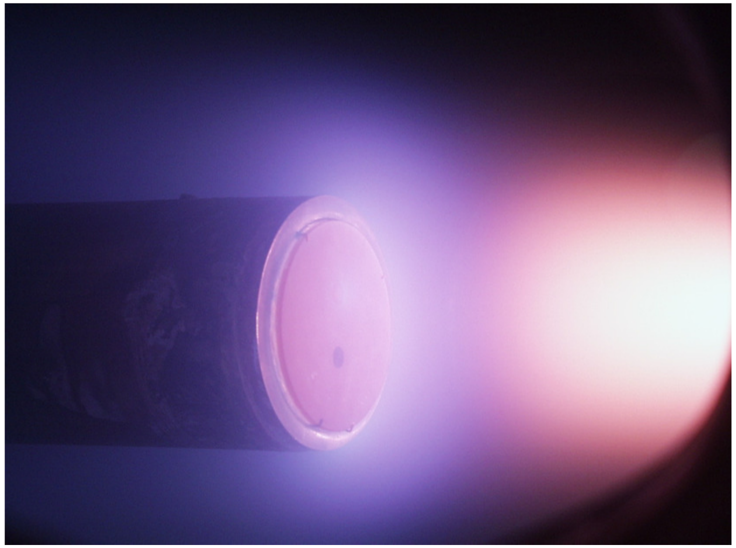




PHLUX Breadboard/EM – PWT Functional Qualification

For ground testing a laboratory model (PHLUX-LM) has been developed and tested in the inductively heated plasma wind tunnel PWK3 at IRS



Schematic of Sensor PHLUX-Breadboard



PHLUX-LM in PWK3, O_2, $p_\infty = 40$ Pa, PM1000 & SSiC

Tested candidate materials:

- *SSiC*
- *Al_2O_3*
- *SiO_2*
- *ZrO_2*
- *Yt_2O_3*
- *Spinell*
- *MgO*
- *PM1000*

Test Gases:

- *Oxygen*
- *Nitrogen*
- *Air*

Same function principle using relevant functional design (subsystems and parts)

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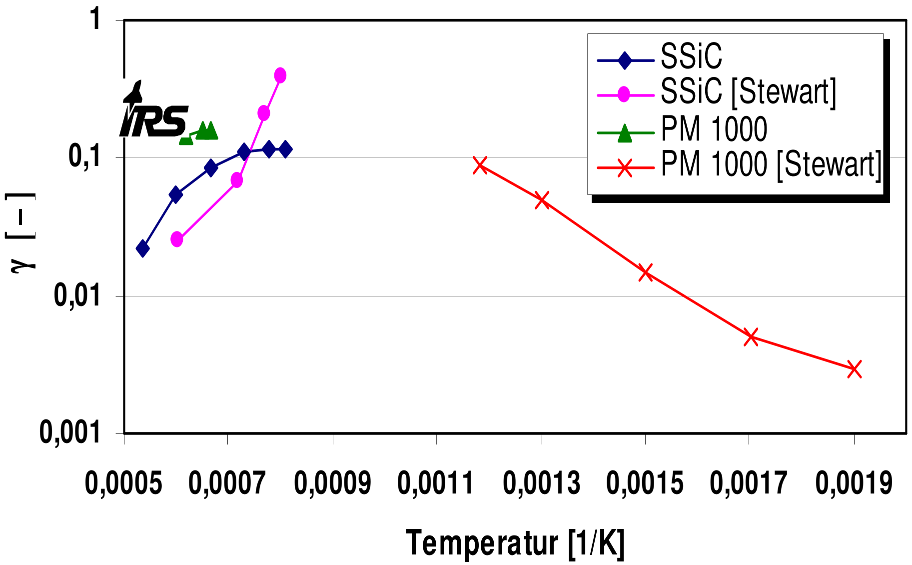
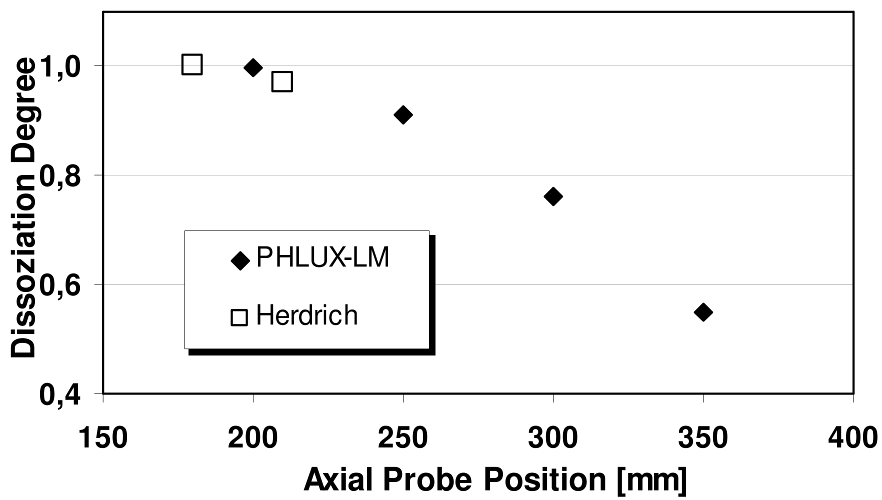
PHLUX EM - Ground Testing- Evaluation





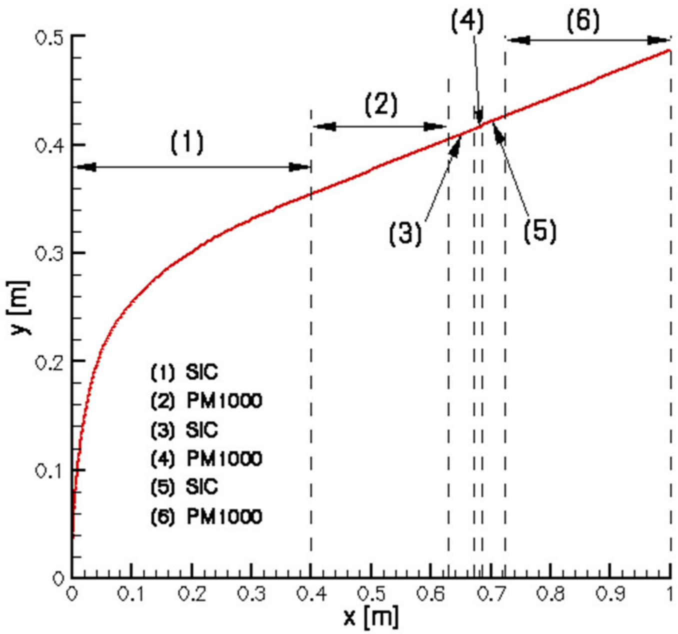
URANUS Flow Simulation

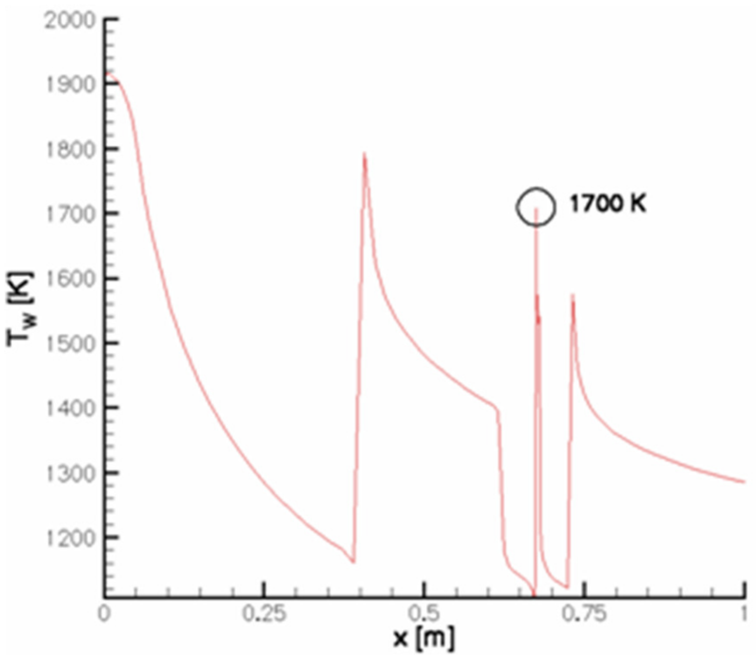
Upwind Relaxation Algorithm for Non-equilibrium Flows of the Universität Stuttgart

Surface modelling of EXPERT:

Oberflächenstück	Simulation S5.	Simulation S6.
(1)	$\gamma = 10^{-3}$	$\gamma = 10^{-3}$
(2)	$\gamma = 0$ (non catalytic)	$\gamma = 1$ (fully catalytic)
(3)	$\gamma = 10^{-3}$	$\gamma = 10^{-3}$
(4)	$\gamma = 1$ (fully catalytic)	$\gamma = 1$ (fully catalytic)
(5)	$\gamma = 10^{-3}$	$\gamma = 10^{-3}$
(6)	$\gamma = 0$ (non catalytic)	$\gamma = 1$ (fully catalytic)

- Investigation of further effects like catalytic jumps occuring on material samples





URANUS CFD Simulations

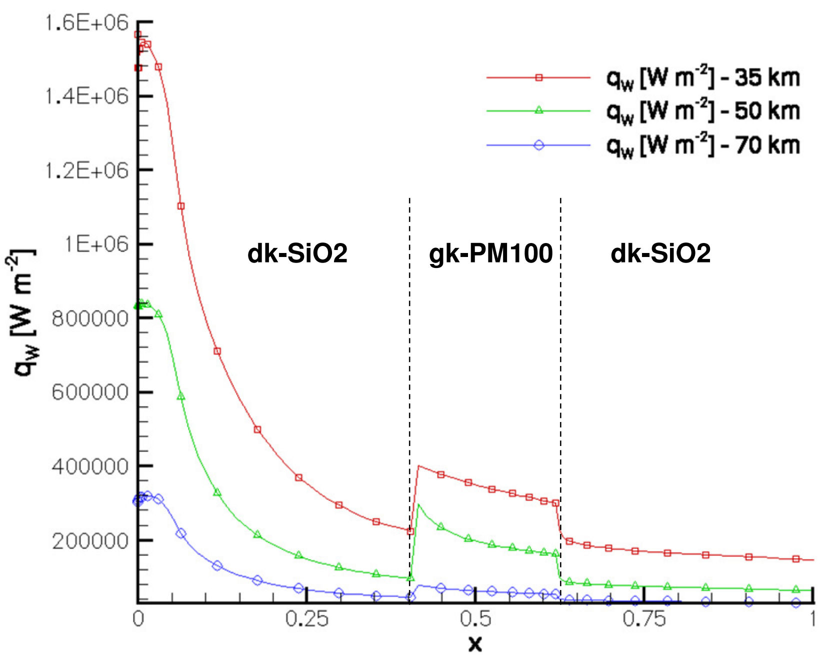
Upwind Relaxation Algorithm for Non-equilibrium Flows of the Universität Stuttgart

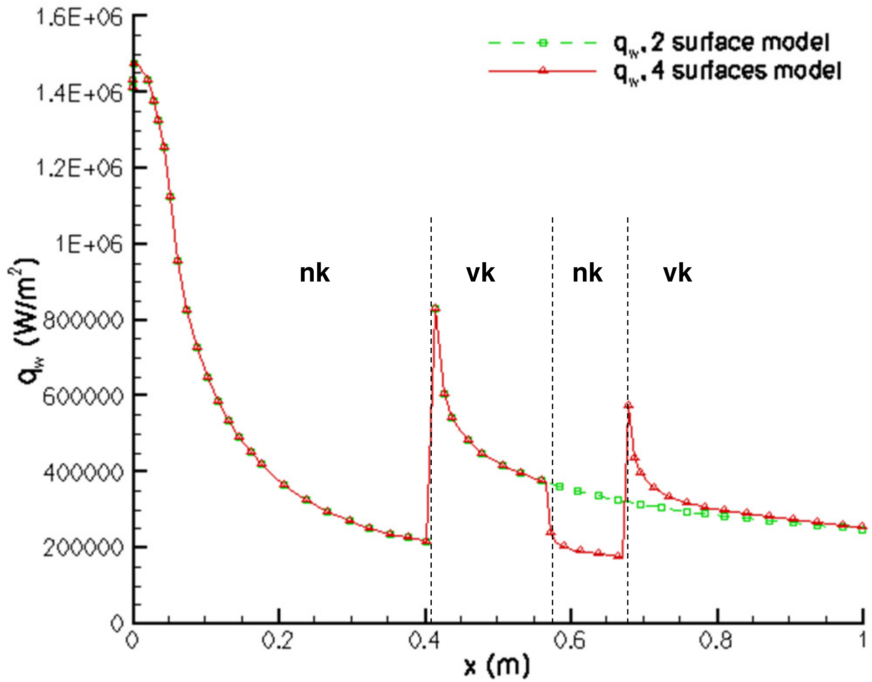
Simulated trajectory points:

Simulation	h [km]	v_∞ [km/s]	Ma_∞ [-]
S1.	34.14	4.27	13.75
S2.	49.93	4.97	14.99
S3.	70.39	5.05	17.13
S4.	79.95	5.04	17.97

- Comparison of numerical calculation with measured flight data with detailed catalysis models derived in PWT tests
- Determination of dissociation degree from data evaluation in combination with CFD simulations

Heat flux distribution:





COMPARE - Motivation

- Several entry, re-entry or sample return missions are envisaged for the near future exploration (e.g. ExoMars)
- Atmospheric entry maneuvers are a crucial phase for the success of a mission and still not completely controllable
- Many phenomena during the entry phase need to estimated conservatively in the course of design and layout of TPS
- Space missions have very restricted mass budget and mostly no possibility of applying scientific sensor systems (e.g. spectrometer sensor system weighs approx. 3kg, see RESPECT for EXPERT)
- Measurement techniques and relevant lightweight sensors to assess the interaction between the aerothermodynamic flow and the response of the TPS need to be developed

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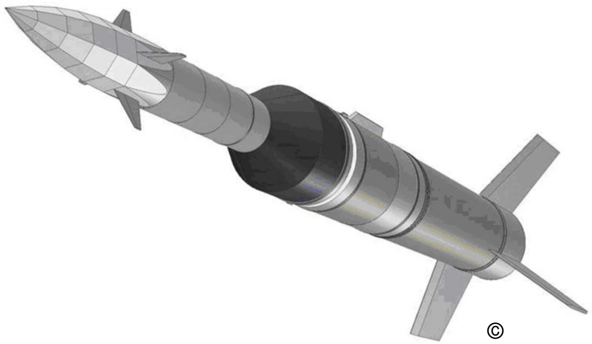
COMPARE - SHEFEX II

- Sharp Edge Flight Experiment II (SHEFEX II):
  - Testing new TPS concepts, feasibility of facetted geometries for entry vehicles and aerodynamic control
  - Entry conditions: m_e=350kg, γ_e=-25°, v_{max}=3.5km/s at h=35km, Ma_{max}=12.6 at h=80km
  - Launch: September 2011, Andøya Rocket Range, Norway
  - Experiment time: 60 s



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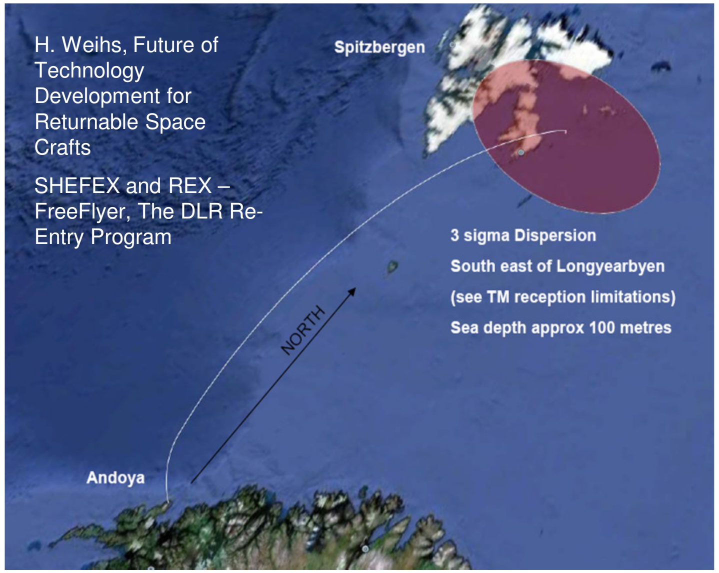
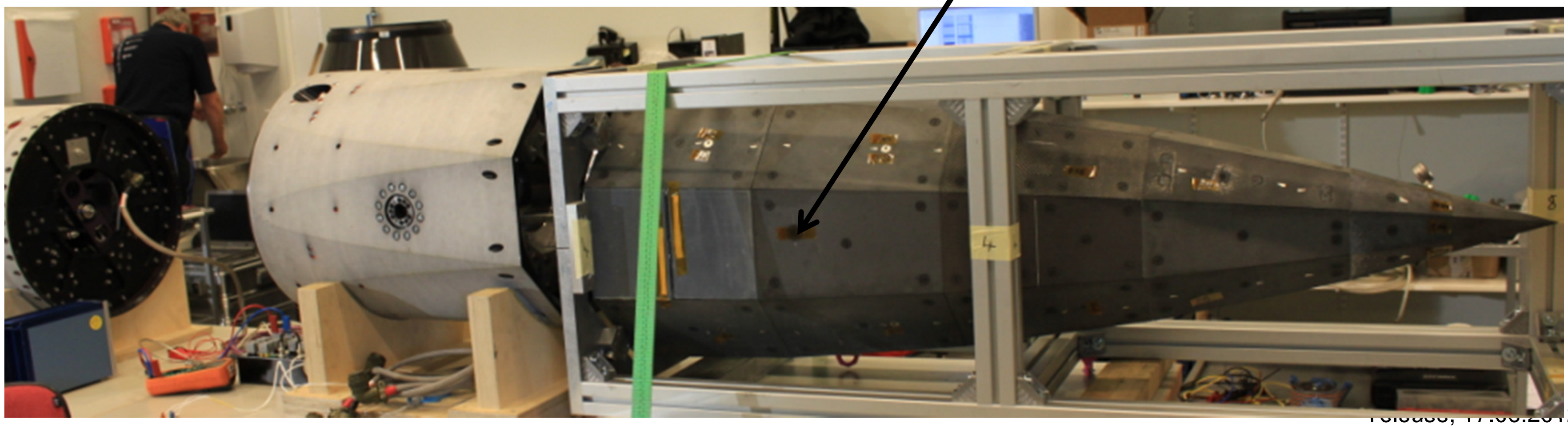


H. Weihs, Future of Technology Development for Returnable Space Crafts

SHEFEX and REX – FreeFlyer, The DLR Re-Entry Program

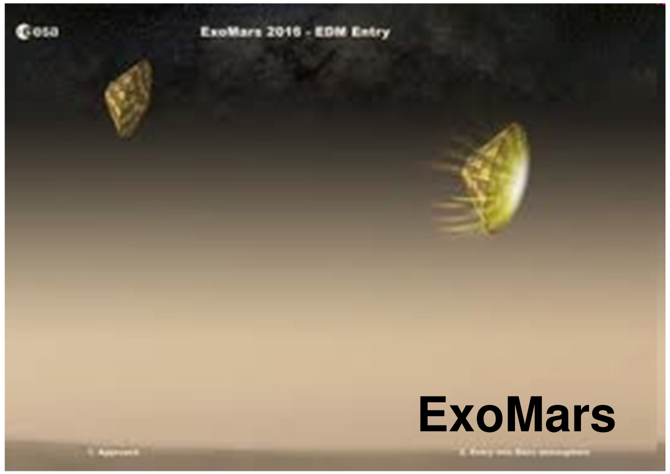
COMPARE on SHEFEX II

- Combined Pyrometric and Radiometric Trajectory Rebuilding Experiment COMPARE:
  - Pyrometric measurement of the TPS backside temperature and determination of the TPS temperature
  - Pressure measurement
  - Radiometric measurement of the surrounding plasma
- Goals:
  - Determination of the enthalpy → trajectory parameters
  - Information on the dynamic behavior of the vehicle
  - Increase of the TRL, qualification step



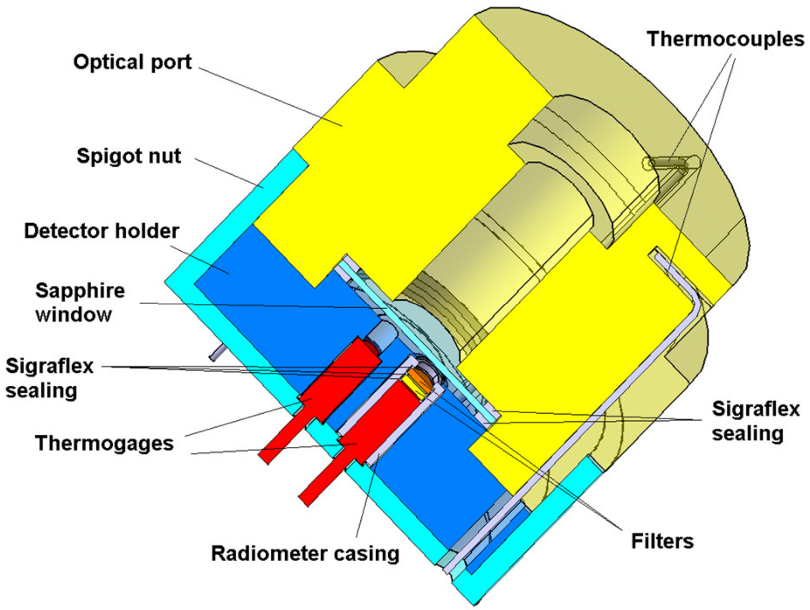
LISE - Motivation

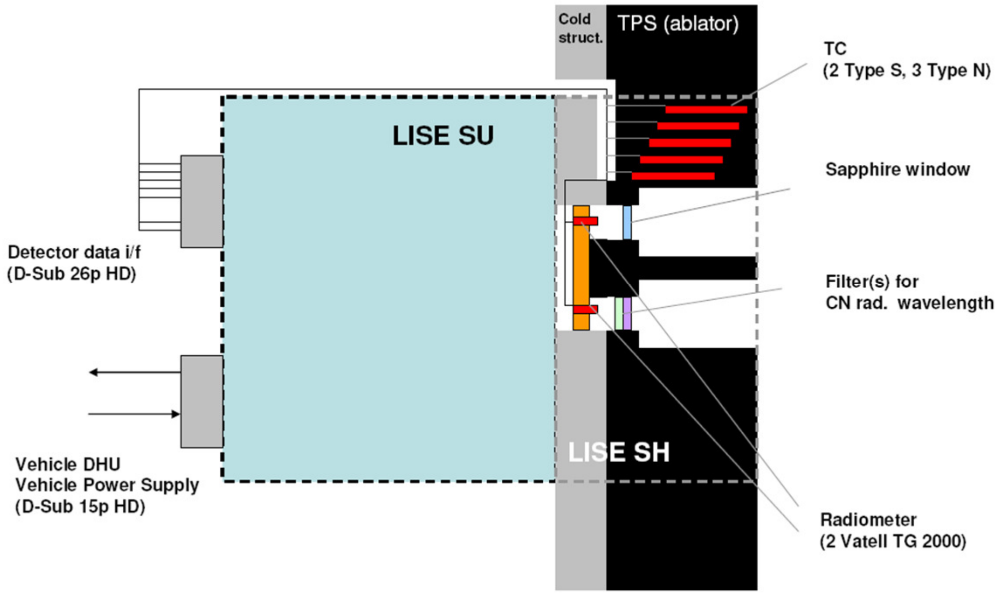
- Upcoming high speed atmospheric entry missions: ExoMars, Mars Sample Return and other ample return missions
- Heat shield of planetary entry probes is a critical component
- Uncertainties in the modeling of the aerothermodynamic environment for TPS sizing relative high, due to lack of in-flight data, e.g. convective and radiative heat flux, plasma composition
- Measurement techniques and relevant lightweight sensors for flight missions need to be developed



LISE - Sensor System Design

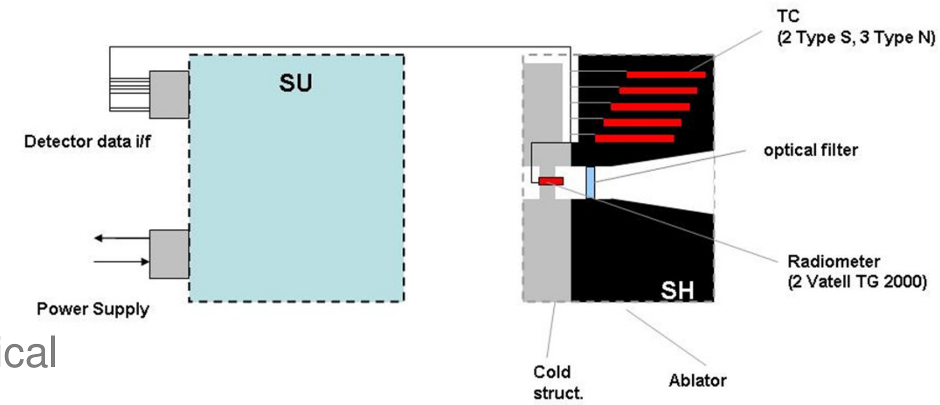
- Aim: To measure simultaneously the temperature in the thermal protection shield by using thermocouples and the radiative heat flux by using suitable radiometers
- Objective: Determination of the total heat flux, determination of radiative heat flux and detection of specific species in the plasma
- Budgets: 1.19 kg w. E-Box (0.65 kg w.out E-Box), 3W, 28 V DC, 24 byte data word length

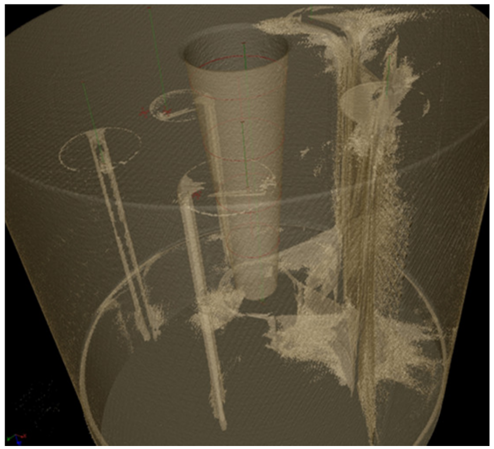




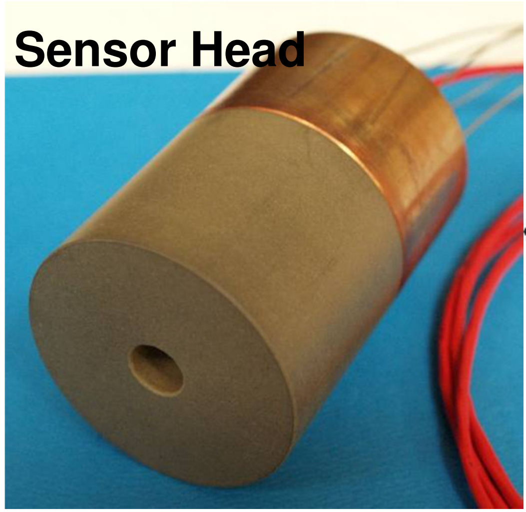
LISE - Breadboard Design

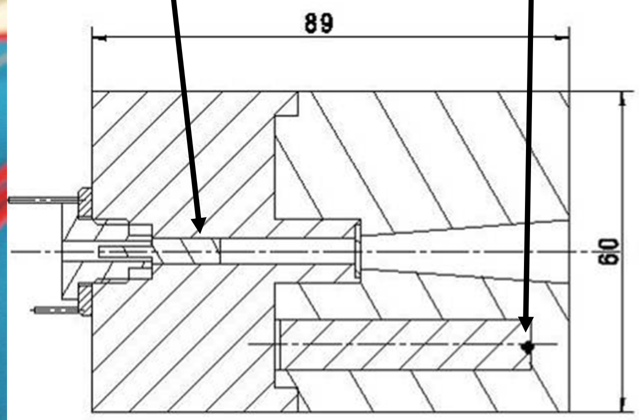
- Ablator material: S5000
- cold structure: copper
- Thermocouples & radiometer to measure total & radiative heat flux
- Two breadboards for two different optical ranges (especially CN) with different optical filters
- SU identically equal to sensor system sensor unit





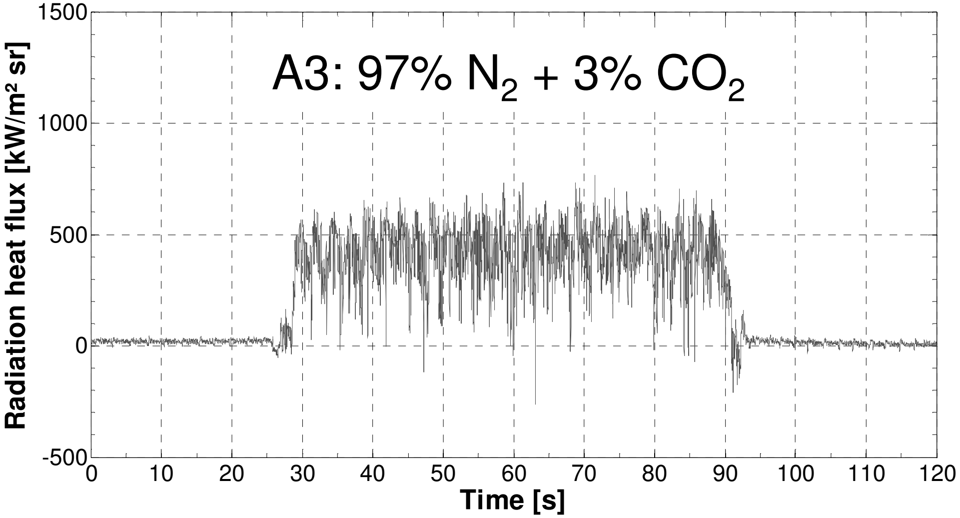
Sensor Head





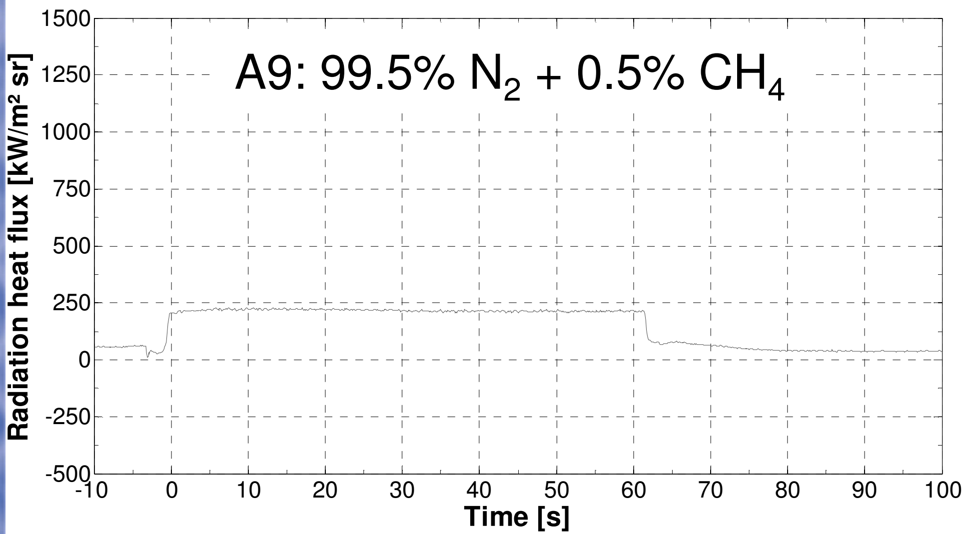
LISE - Test Results: Radiation Measurement LISE_A

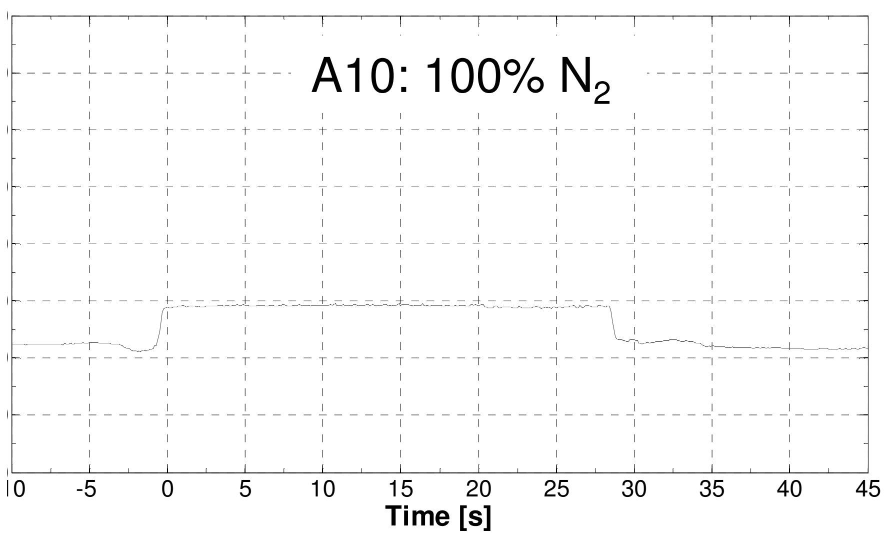
- Total radiative heat flux measurement
- Test A3: data recorded via LISE E-Box
  - significant radiation measured



LISE - Test Results: Radiation Measurement LISE_A

- Total radiative heat flux measurement
- Test A3: data recorded via LISE E-Box
  - significant radiation measured
- Tests A9 and A10: data recorded via Vatell Amplifier available at DLR
  - radiation has the same level (CN molecules not existent?)
  - ➢ window contamination increased after each test





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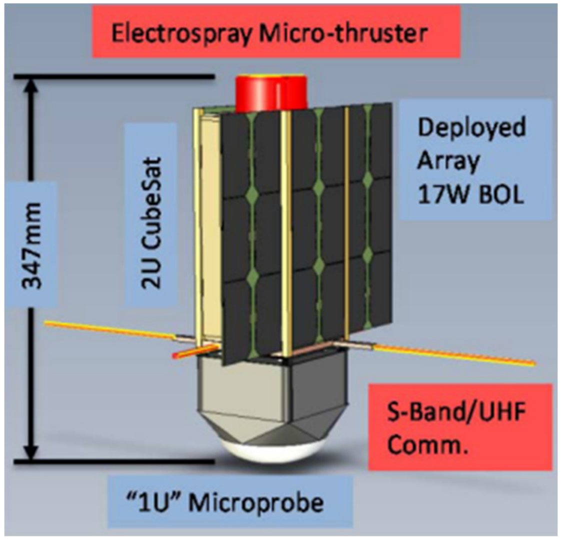
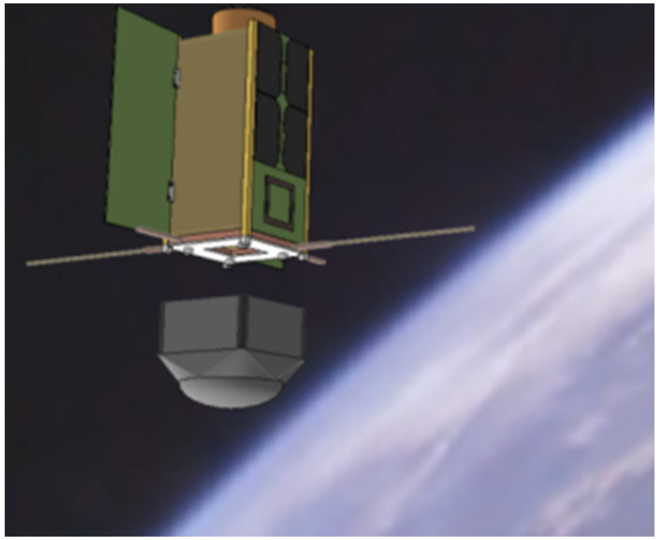
MIRKA2 - Objectives

- Demonstrate micro-propulsion for atmospheric entry of small planetary probes and Earth de-orbit applications (including cubesats)
- Demonstrate communications technology and architectures supporting small spacecraft and Earth re-entry probes
- Flight qualification of the RICA material developed by IRS and NASA Goddard
- Technology demonstration: Small scale, low cost spacecraft, CoTS products
- Validation of existing numerical atmospheric re-entry models, potential atmospheric research





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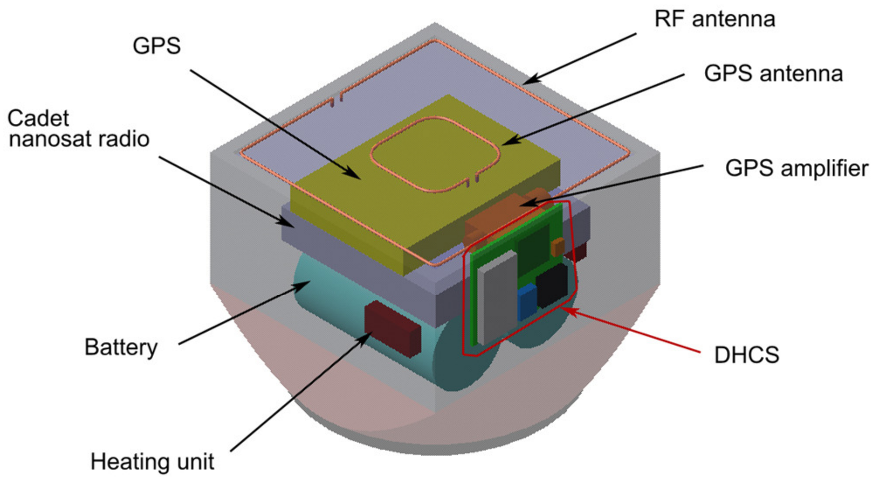
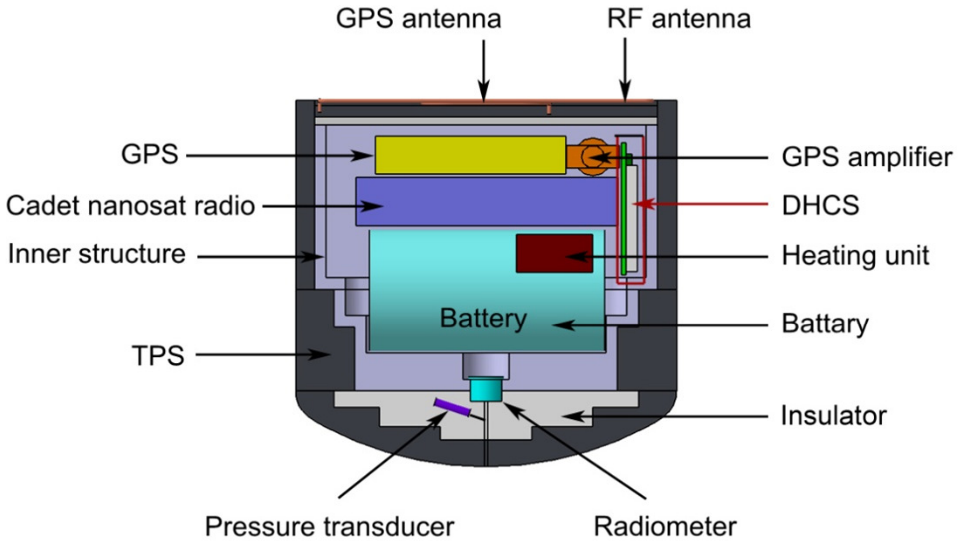
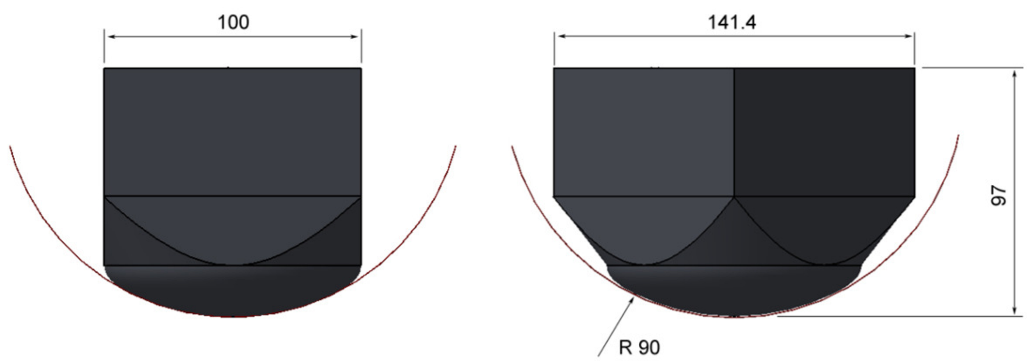
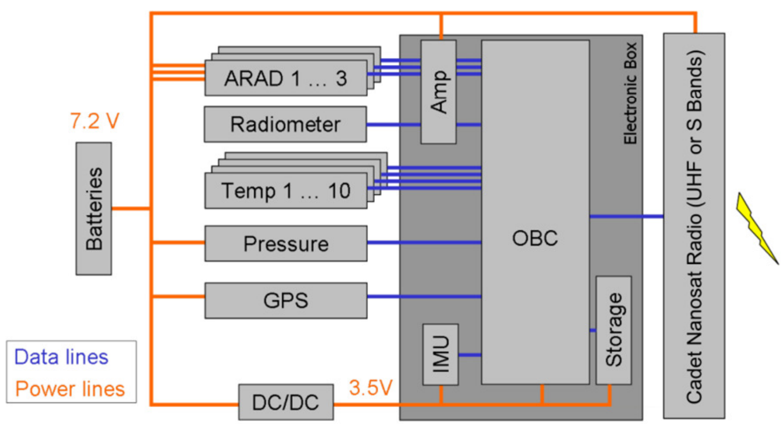
MIRKA2 – Design and Payload









Assessment of Gas-Surface-Interactions/ Non-Equilibrium