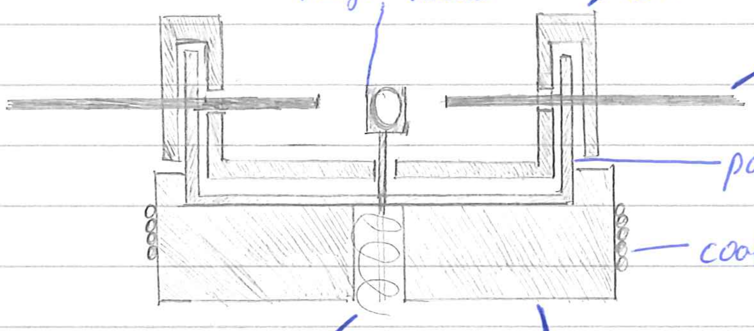
6.10.2014

Salter et. al. 2009

A zero-gravity instrument to study low velocity collisions of fragile particels at low temperatures

Experimental Setup:



Measures:

vacuum chamber	⌀ 250 mm	h 290 mm
particle reservoir	⌀ 180 mm	h 110 mm
- holes for small particles: (180) ⌀ 8 mm	d 9 mm	turn 12,5°
- holes for big particles: (64) ⌀ 16 mm		turn 24°
particle sizes: small: up to 8 mm		
big: up to 15 mm		

Requirements:
- ambient (300 K), low (250 K) and cryogenic (130-180 K) temperatures
- fast and controlled collision reloadability
- safety and size regulations for parabolic flight
- maintain cold and cryogenic temperatures for several uninterupted hours
- no cryogenic liquids and pressurized vessels are allowed aboard flights.

Particle Acceleration:
- original setup: hydraulically driven
- later setup: 2 synchronised electrical dc motors operating in master&slave configuration

- acceleration limit (to avoid compaction): 10 $\frac{m}{s^2}$
- no spikes in acceleration (fragile particles)
- each piston rod extends ~ 0,5 m outside the chamber and passes two seperate vaccum feedthroughs before breaching the internal environment.
- extensions of vacuum chamber build intermediate vacuum environment and can be pumped in parallel (was not necessary so far)
- two 80 mm ~~dy~~ long guiding tubes for particles
- pistons stop abruptley when intended velocity is achieved

? Question: is the acceleration always the same and the pistons stop in different positions for different velocities, or is the acceleration varied and the pistons stop always in the same position? → see Lab Information 15.10.2014

Temperature and Pressure Controll:

- 45 kg copper thermal reservoir
- particle reservoir (copper) moves up and down w.r.t. thermal reservoir by 5 cm when turned
- 10 mm thin U-shaped copper cover → keeps particles confined and works as heat shield
- thermal reservoir sits on the bottom flange of the chamber on insulating PEEK feet
- flexible copper tubing around the thermal reservoir for LN_2
- ≈ 45 L of LN_2 take 50 min to cool the whole thing to 80 K.
- pumps: series of 1 turbomolecular pump and 1 membrane pump

normal turbo pumps survive (mag lev probably would be desastrous)

? Question: Does any of these pumps work during flight?
- warming rate at best vacuum (10^{-6} mbar): 5 $\frac{K}{h}$
- warming rate during flight (10^{-2} mbar): 15 $\frac{K}{h}$

- eight K-type thermocouples monitor temperature

Question: Why does temperature increase linearly? Shouldn't that be exponentially $\left(T_{ambient} - T_{start}\, e^{-\frac{t}{\tau}}\right)$? or is the temperature change in Fig 9 just so small 130 K compared to 170 K) that the curves looks linear? it may be the linear part of an exponential curve, but it also just measures the surface temperature of the big block (T-gradient)

- temperature gradients only a few Kelvin over the whole device
- between end of cooling and start of measurements, temperature increased from 80 to 130 K.

Question: What kind of pressure gauge(s) is (are) used? combi gauge

- heating after experiments, before opening the chamber: heating wire (Ø 3mm, 34 m long, output 840 W) wound around copper block

Camera & Data Acquisition:

Camera:
- high speed, high resolution complementary metal oxide semiconductor camera
- 107 $\frac{frames}{s}$
- 1280 (h) x 1024 (v) pixels
- 8 pixel depth (gray scale)
- pixel size $12 \times 12\,\mu m^2$
- fill factor 40%
- Base/Full CameraLink® interface

Optical System:
- three dimensional optics system (to use only one camera)
- beam splitter above collision space to capture light from two vantage points (seperated either by 48.8° or by 60.0°
- field of view $\approx 24 \times 20\,mm^2$

- focal depth limits vertical range to 5 mm (problematic for ground based checks)

? See Lab Info 15.10.2014 { Question: Are there photos or drawings of the optical system anywhere? No drawings but photos see top flange with window in the lab

? Question: What exactly does the beam splitter do?

Stroboscopic Lights: - ~~Two~~ 4 synchronized Xenon flashlamps now LED
- flash duration $1 \mu s$
- shadow-free illumination
- synchronized with camera via strobe pulse adapter box (reverses and amplifies control pulses from camera)

? Question: Why do the pulses have to be reversed? light switches on when pulse was off → might change (more sensitive to voltage going off than going on)

Computer System: - maximum data rate: 133 $\frac{Mbytes}{s}$
- writes directly to the hard disk for an uninterrupted duration of 33 min

? Question: How long exactly does a single flight campain take? What happens at the end of the 33 min? Is the disk full?
Data acquisition only during collision → 25 s × 31 parabolas ≈ 15 min
- imaging systems with internal memories would not work (insufficent time for readout)
- 2 CPUs (2.66 GHz each)
- PCI-X based frame grabber (2 Gbytes internal memory) Camera bypasses internal storage (SD card etc. and reads pictures to computer immeadiately. Computer needs internal memory to handle the incoming data

? Question: Why do we need internal memory when everything is written to the hard disk immeadiatly?
- 4 SATA-I hard disks (in total 260 GBytes when bundled as RAID 0 array)

* RAID 0 splits data evenly across two or more disks
* PCI-X (Peripheral Component Interconnect eXtended): expansion card, that enhances 32-bit PCI local bus for higher bandwith

Experimental Results:

300 K , 6 mm , 85% porous SiO_2 aggregates
translational velocities from 0,10 to 0,28 $\frac{m}{s}$

particle-particle collisions:
- collisional energies: 1 - 5 μJ
- 10% fragmentation in the collisions

particle-target collisions:
- collisional energies: 0,5 - 2,5 μJ
- 10% sticking in the collisions
- alsmost no fragmentation

all collisions:
- 80 - 90 % semielastic rebounding events (likely due to aggregate compaction)
- angular distribution after collision mostly within ±5°

imperfections: - left hand piston delivers particles at slightly higher speed

9.10.2014

Proposal

Icy Grain Aggregation: Building Comets and Asteroids as a Harbour for Pre-Biotic Chemistry

Theoretical Background:

- N-body simulations and kinetic theories use the coefficient of restitution, ε, to describe the formation of small icy planetessimals (ε = ratio between velocities before and after collision
- Assumption: icy aggregates (radius 1 mm, sub-composed of 10-100 nm particles) quickly grow to cm sizes via collisions at cm/s to few m/s
- Solar nebula: snow line (3 AU), $T \approx 160$ K
  → condensation temperature of crystalline H_2O
- Proto-planetary environments: amorphous H_2O ice
- different H_2O ice phases: differences in sublimation rates, specific surface energies, electrostatics
- Growth of km sized amorphous icy planetessimals: phase transitions on icy bodies will let them grow at ~~at~~ a rate at which they can settle into Kepplerian orbits long before the ices photo-desorb
  → they seed a family of potential comets, Kuiper Belt Objects and asteroids.
- Amorphous H_2O ice may act as crucial glue
  → enhance aggregation process in earliest stages of planetessimal formation
- Growth of weakly aggregated planetessimals via low-velocity collisions only stable in dynamically cold environments

Question: What exactly does "weakly aggregated" mean? Things that are stuck together not very well

- Open question: To what extent do hypo-velocity collisions lead to chemical processing (reactions enhancing chemical complexity / outgassing)?
  → understand potential for life in Solar system
- icy mantles dominated by amorphous water, but ~~th~~ contain huge number of other simple molecules
- Recently observed: hyper-velocity (=fast) impacts increase chemical complexity in ices.
- molecular dynamics simulations of granular cluster collisions suggest that physical, chemical & optical properties of icy grains evolve with their collision history

Earlier Parabolic Flight Measurements:

- Neither aggregate dust nor solid-crystalline ice grains (mm to cm size) can stick under typical cometary nuclei forming conditions.
- Planetary rings and regolith systems: Ice grains may compact on collision, on particle scales over 1 μm, they do not fragment
- Strong evidence, that ice phase and particle size influence collision outcomes
- HGW spheres and fragments of hexagonal ice experiments at 80 K, 1-mm particle Ø, 12 cm/s impact velocity: weak negative correlation between ε and impact velocity ($10 - 15\ \frac{cm}{s}$), upper limit for ε: 0,65
- 85% porous SiO_2 (amorphous), impact velocities $5-22\ \frac{cm}{s}$: weak positive correlation, upper limit $\varepsilon \approx 0{,}85$

Experimental Setup: (What's new / different w.r.t. Salter 2009)

- Laboratory measurements: possible at collision velocities above $20 \frac{cm}{s}$
- camera: $120 \frac{frames}{s}$, 0,4 µm/pixel resolution
- base pressure of the high-vaccum setup: 10^{-8} mbar
- Cu heat sink: weight 70 kg
- Coliseum: name of particle storage
- Heat load keeps experiment at 80 – 130 K (80: beginning, 130: end of flight)
- Room for 124 pairs of small (<5 mm) particles or 34 pairs of larger particles
- 1 collision per parabola for larger particles

? Question: why are there so many differences w.r.t. to Salter 2009? Salter 2009 more reliable numbers

Planned measurements:

- Parameter Space: size, chemical composition, morphology,
? mass, porosity, fractal-dimension (what's that?), radius
with target non-spherical particles, different particlesizes, microscopic surface curvature
? of curvature (for non-spherical particles?), charging,
melting and refreezing processes
sintering (what does that mean in this case?), evaporation
pump on many particles in a bowl and see if gas sticks them together
? (what does that mean here?), condensation (what does
float water vapor over particles → do they stick?)
mixture of different materials and
? that mean here?), outgassing (what's the difference
one comes out of the bubbles where it sits in the other
? to evaporation?)
- Measure: ε, in dependence on:
  * ice phase: HGW, amorphous, crystalline
  * particle size: 500 µm to 1 cm
  * particle porosities: filling factor 50 – 100 %
  * impact velocities: 1 cm/s to $50 \frac{cm}{s}$
  * temperature: 80 – 300 K
  * pressure: ambient to 10^{-6} mBar

  for binary collisions of ice particles
- Dust particles, so porous they can not support their own

weight in the laboratory

Question: How will we produce, handle and store such particles? Maybe at some point we will grow ice during flight, but it ~~is probably to slow → space station~~

- 1 week of parabolic flight experiments

PDRA Tasks and Timeline:

PDRA tasks (except where stated)	Year 1			Year 2			Year 3		
Generation of Amorphous Icy Particles (a)			P						
Laboratory Collisional Studies (b) temperature	80 - 300 K				P				
Laboratory Collisional Studies (b) particle size	500 mm,	1 mm,	5 mm	, 1 cm		P	amorphous		
Laboratory Collisional Studies (b) pressure	ambient to	10^{-6}	mbar				20 -	50 $\frac{cm}{s}$	
Cross correlate parameters laboratory collisions (b)	determine	ε	and	trends	within	ε		P	
Application for Parabolic flight (HJF)									
Flight Preparation (HJF)									
Flight Opportunity – PF collisional Studies (c) + HJF	< 20 cm/s	, most	relevant	ranges			P from (b)		
Generation of Porous Ice Particles (d)									
Laboratory Collisional Studies (e) porosity	20 - 50 $\frac{cm}{s}$	, filling	factors			50 -	100 %		P

P: provisional publications

Besides: Astrochemistry Group meetings, weekly
Individual meetings, weekly
Day to day responsibility for the experiment
5 days of professional development per year
annual review and goal setting process

Expected Collaborations: J. Wright, A. Hagelmann, S. Green
Astrium

2. Question: What do the different blue shades mean?
nothing

22. 10. 2014

Heißelmann et al. 2007

Experimental Studies on the Aggregation Properties of Ice and Dust in Planet-Forming Regions

read! ✓

Theoretical Background: (see also Weidenschilling et al. 1993)

- stars form from gravitational collapse of dense, turbulent, rotating molecular clouds (when gas pressure no longer supports core against gravity)
- after formation of a central protostar, environment cools down → condensation of (sub-) micrometer-sized mineral grains
- dust is accreted along the rotational axis of the system
- accretion disk (rotating, flat) develops perpendicular to that axis
- dust/gas-ratio in protoplanetary disk: ~ 0,01
- inelastic collisions of dust grains combined with adhesive surface forces cause colliding particles to coagulate (hit-and-stick method)
- relative velocities: 1 μm to 100 μm particles → Brownian motion
  larger aggregates → gas turbulence / drift towards center of gravity
- more energetic collisions (increasing rel. velocities with increasing masses) make aggregates more compact by restructuring
- more compact particles decouple from gas motion
- sedimentation to the mid-plane causes runaway-growth-phase
- larger aggregates sweep up smaller ones
- for planetesimals ($\geq$ 1 km) collisions are dominated by gravity
- smaller ~~particles~~ planetesimals are accelerated by gravitational perturbations → high velocity collisions of km-sized bodies → collisional fragmentation
- environment of larger planetesimals is fed with small fragments → capturing → rapid growth (10^5 years) to Mercury size

Numerical Simulations (Dominik & Tielens, 1997):

- two colliding aggregates of fractal structure, consisting of equal-sized, spherical monomers
- key parameters:
  - number of monomer-monomer contacts within aggregate
  - energy required to break up grain-grain contact
  - rolling-friction energy (necessary to roll two neighbouring grains by one quarter of their circumference
- five different regimes (with increasing impact energy):
  1. hit-and-stick (without restructuring)
  2. beginning of restructuring resulting in compaction
  3. state of maximum compaction
  4. break-up of grain-grain bonds
  5. catastrophic disruption of aggregates

Materials:

- Silicates
- Water ices
- condensates of volatiles (flüchtige Substanzen) (e.g. CO, CO_2, NH_3, CH_3OH, CH_4)
  ↳ of great importance in formation of Pluto, comets, Kuiper belt objects, icy moons of giant planets

Earlier measurements:

Blum & Wurm, 1998-2000:

- laboratory experiments, collisions of fluffy fractal aggregates
- fractal dimension $D_f \approx 1{,}91$
- consisting of monodisperse spherical SiO_2 grains (1,9 μm)
- velocity range $0{,}001 \frac{m}{s}$ to $0{,}01 \frac{m}{s}$: sticking probability is unity, no restructuring or compaction occurs
- Tielens & Dominik five regime theory confirmed

Blum, Schräpler et al., 2004-2006:

- large, compact dust aglomerates ($D_f \approx 3$) built from 1,5 μm-sized SiO_2 grains (planetesimal analogue bodies)
- produced by Random Ballistic Deposition (de-agglomerate dust powder to micrometer-sized grains, couple grains to gas flow, deposit them unidirectionally to filter -> "dust cake" (2,5 cm Ø, 2 cm height)
- highly porous structure, volume filling factors $\phi = 0{,}07$ to $0{,}33$.

Langkowski et al., 2007: read!

- microgravity experiments
- 0,1 - 1 mm-sized high-porosity dust aggregates projectile
- target: 2,5 cm, same material
- velocity regime: 0,5 to 3 $\frac{m}{s}$
- near-normal collisions: dominated by sticking
- near-tangential impacts: rebounding behaviour
- for non-sticking collisions, mass transfer from target to projectile was observed (doubling the projectile's mass) why not in other experiments?

Blum & Münch, 1993:

- laboratory collision experiments
- 1 mm aggregates, consisting of 0,2 to 1 μm $ZrSiO_4$ monomers, filling factor $\phi = 0{,}26$
- velocities: 0,15 to 3,9 $\frac{m}{s}$
- arbitrary impact angles
- low velocity encounters: rebounding
- at $v_c \gtrapprox 1 \frac{m}{s}$: transition to fragmentation
- a $v_c > 3 \frac{m}{s}$: complete disruption, number of fragments following a power-law mass distribution
- for bouncing aggregates:
  - central collisions: 10% of translational energy before encounter was conserved afterwards ($\varepsilon_t^2 = 0{,}1$)
  - perfectly grazing encounters: theoretical value of $\varepsilon_t^2 = 0{,}51$ was calculated

Bridges et al., 1984 & Hatzes et al., 1988:

- quasi-2D collision experiments
- icy bodies as found in Saturn's rings (solid ice spheres, several cm Ø)
- low velocities: 0,00015 – 0,02 $\frac{m}{s}$ (v_c)
- coefficient of restitution ε follows power law: $\varepsilon(v_c) = C \cdot e^{-\gamma v_c}$
- ε depends strongly on the properties of contact surfaces (can be lowered up to 30% for roughened / frosted surfaces)
- exept for particles with very smooth surface, ε shows a size dependence

Experimental Setup: (What's new / different w.r.t. Salter 2009)

- particle acceleration with less than 10 g to prevent damage
- 50 kg copper block as thermal reservoir
- dry oil free membrane pump and turbo molecular pump (TMP) → pressure ≤ 10^{-3} mbar
- two sample repositories (1 copper, 1 aluminum) with 180 holes each
- acceleration originally by synchronized hydraulic pistons → now replaced by master-and-slave synchronized electric DC motors (to optimize the separating of projectile from conical piston's head), hard mechanical stop
- pistons pass through ~~a~~ mechanical feedthrough, followed by a guiding PTFE piece
- target screen: • mould of 17 mm Ø and 2 mm depth on each side • made of copper, • mould can be packed with micron-sized dust grains to simulate large protoplanetary bodies' surface, • rotates by 8° per collision, • 0° – 75° collision angles possible, • release mechanism to drop target to fixed position on the bottom of collision volume for particle-particle collisions
- second sample reservoir can be prepared by ground crew while flight crew uses the other reservoir → saves time (2,5 hours)

? Question: How do you prepare the reservoir, which needs to be cooled and under vacuum, when the vacuum chamber and the cooling mechanism are on the aircraft?
How do you keep it cold over night?
Not cold -> dust, not ice experiments

- future: • mount two additional flash lamps at an angle $\alpha = 45°$ to piston's axis and $b = 56°$ to camera axis (to increas quality of images and remove any shadowing effects)
  • install beam splitter optics to record images with an angullar separation of $\Psi = 60°$
  (get three-dimensional collision information)

? Question: for the first flight, there was only one viewing angle? Yes

Experimental Results:

- experiments at room temperature (corresponds to 1 AU distance (=earth distance) from protostar)
- projectiles: • cut from RBD dust aggregates (built from 1,5 µm-sized SiO_2 grains (razor blade)
  • size: 2-5 mm
  ~~porosit~~ • $\phi = 0{,}15$ (at the cutting edges 0,17) (fluffy)
- target: same material, $\phi = 0{,}24$
- velocities: $0{,}1\ \frac{m}{s}$ to $0{,}5\ \frac{m}{s}$
- pressure: $2{,}8 \cdot 10^{-1}$ mbar

Particle-Target collisions: (76)
- 90% bouncing, 10% sticking, negligible fragmentation

Particle - Particle Collisions : (39)

- 90% rebounding , 10% fragmentation , negligible sticking
- central collisions : 5% of translational energy is conserved (value increasing with increasing normalized impact parameter)
- significant amount of energy is transformed to rotational motion

Problems :

- Narrow depth of field -> blurring effects -> rotational velocity cannot be determined
- irregular shape of aggregates -> cannot determine moment of inertia

? Question: When a particle sticks to the target, how do you remove it before the next collision?
Does it fall off between two parabolas?
Yes

5. 11. 2014

Hill et al. 2014a

collisions of small ice particles under microgravity conditions (DLR 11th parabolic flight campaign)

Theory:

- > 1000 exoplanets discovered
- thought to form ~~fr~~ from material of protoplanetary disk (≈ 99% gas, ≈1% dust, by mass)
- turbulence in disk → gravitational instability not sufficient to explain planet formation
- Weidenschilling et al. propose dust aggregation as solution
- relative velocities of particles in protoplanetary disks increase with increasing particle size → larger particles rather bounce than stick (**bouncing barrier**)
- Collisional grain charging proposed to overcome bouncing barrier, but is only possible for small particles → planetesimals are unlikely to form by this mechanism alone
- Mass transfer can lead to growth, counteracted by increasing velocities and erosion → unclear whether this can account for growth beyond centimetre size.
- ice beyond snow line may be able to overcome bouncing barrier (grains coated in icy mantle might stick more efficiently)
- ice condensation could enable dust grains to grow to decimetre size around the snowline and to icy planetesimals if the initial ice grains were sub-micrometre-sized

?. Question: Why do they grow bigger, when they were smaller in the beginning? How does the surface of a decimeter sized thing know, wheter its core was milli or micrometer sized?

→ See paper

- amorphous solid water can form permanent dipoles, which will increase the sticking probability
- particles in protoplanetary disks are assumed to be irregular in shape

- multiple body collisions are likely to occur in protoplanetary disks
- irregular shape is likely to lead to multiple hits in ~~close~~ quick succession

Previous Experiments:

Small Particles at low collision velocities: (dust?)

- sticking due to von-der-Waals forces
- critical velocity for sticking decreases with increasing particle size (1 $\frac{m}{s}$ for micron sized particles)
- direct growth between similar sized particles beyond centimetre sizes has not been demonstrated as van der Waals forces no longer dominate in this size region

Observational:

- icy (water) grains exist around young stellar objects in both crystalline and amorphous ice phases
- warm H_2O gas observed in denser planet forming regions
- C/O ratio in an exoplanetary atmosphere may be intrinsically linked to where the planet aggregated, in relation to the corresponding protoplanetary snow line
- 2013 first direct imaging of CO snow line (using N_2H^+ emission as probe)
- evidence towards presence of icy particles beyond snowline in protoplanetary disks → take their properties into account when considering planet formation

Differences between ice and dust particles:

- ice has larger rolling friction force
- ice has reduced elasticity → increases the threshold velocity for sticking

? Question: Should reduced elasticity not reduce the critical velocity for sticking? →Read Weidenschilling & Zsom papers

Ice collisions using a disk pendulum & ice target:

- coefficient of restitution decreases with increasing impact velocity
- glancing collisions showed very little loss of kinetic energy
- smoth surfaces (original ice)
- presence of frost on the surface reduced COR
- surface melting also reduces COR

Free impacts of ice spheres on ice targets:

- below critical velocity: constant COR
- above critical velocity: ice began to fracture and COR decreased with increasing velocity
- smooth surfaces (original ice)
- frost layer and surface melting, leading to increased surface roughness reduced COR by up to 40%

Parabolic Flight (1,5 cm ice spheres):

- COR spreads from 0 to 0,84
- normalized impact parameter spreads from 0 to 0,6
- relative impact velocities spread between 0,06 and 0,22 $\frac{m}{s}$
- No correlation between COR and impact velocity
  ↳ different to other results, might be due to experimental differences (much closer to reality here than before)

Loss of kinetic energy:

- mostly due to dissipation due to surface fracturing

Fragmentation:

- above certain critical velocity particles will fragment
- 1,24 $\frac{m}{s}$ for 2,8 mm ice spheres $\}$ from impact on target
- 0,702 $\frac{m}{s}$ for 8 mm ice spheres $\}$ experiments

Numerical simulations: - ice particles can loose translational energy into rotation

Experimental Setup & Conditions: (new/different w.r.t. Salter 2009)

- residual pressure: $\approx 10^{-5}$ mbar
- 70 kg copper block (cryopump for remaining water vapour)
- vacum dominated by H_2, CO, N_2 gas
- 22 s weightlessness per parabola (residual acceleration of a few times ~~[illegible]~~ 0,01 g
- temperature range: 130 - 160 K
- T-p-regime well below the range at which surface melting, sublimation or desorption of ice is anticipated (180 - 200 K)
- hydraulic pistons
- piston tips: gold coated copper: large heat capacity and good thermal conductivity
- piston rods: hollow stainless steel: low thermal conductivity
- pistons stop (back) in the outer part of the U shaped heat shield → stay cold → do not induce particle melting
- piston velocity range: 0,1 to 0,3 $\frac{m}{s}$
- relative particle velocities: 0,26 to 0,51 $\frac{m}{s}$
- collision volume: 2,5 x 2,5 x 2,5 cm
- recording volume of camera: 2,4 x 2,0 x 0,5 cm^3
- two viewing angles separated by 60°
- At the end of the flight no particles are found in the vacuum chamber. It is not really known, what happens to them. Some might leave the collision volume and melt in the uncooled parts of the vaccum chamber. However, none are seen to be interfering with later collisions
- Camera and strobe lights are operating only during parabolas
- method of collision and T-p-regime are unique, especially no formation of frost on the particles surfaces, which are not smooth like in other experiments
- temperature is linearly related to time → time dependent effects would show as temperature effects.

- warming rate : first 20 min of flight : $22{,}5 \frac{K}{h}$
  later : $7{,}0 \frac{K}{h}$

? Question: Why is the temperature increasing faster at the beggining? Was the vacuum less good?
Probably

- ice spheres and ice fragments used, 4,7 to 10,8 mm
- ice spheres tended to roll out of their compartments
  -> only six successfull collisions.

? Question: How can we prevent that from happening again?
Have particles a little bit bigger

Sample Preparation:

Ice Spheres (5 mm):

- syringe water droplets into liquid nitrogen (under surface)
- after each droplet wait until surface has quiesced
- polycrystalline ice is produced in this freezing mechanism
  -> cloudy appearance due to significant fraction of grain boundaries within the sample
  -> unisotropic, "rough" surfaces
- only cloudy particles of spherical appearance were chosen (glassy ones would have a different structure)
- the same method will produce hyperquenced glassy water (hexagonal phase, a form of amorphous ice), only if the particles are less than a few microns in diameter

Ice Fragments:

- submerge a spooful of water to liquid Nitrogen
- crash resulting ice with a hammer

Sample Loading:

- conducted in the laboratory, just before the flight
  - Particles stored in liquid N_2 until loading
  - lN_2 bath stood in the centre of the colliseum (precooled to 77K)
  - Used cooled and equilibrated (in l. N_2) tweezers to transfer particles from bath to compartment
  - inner part of U shaped heat shield was removed before this procedure
  - after finishing the loading (a few minutes) heat shield and chamber were closed and pumped out.
  - this procedure minimizes water vapour deposition (frost growth)
  - over the four-hour duration of flight, the icy particles do not accrete additional water vapour to their surfaces nor was additional roughness acquired via sublimation
  - "frost" means that first a crystaline and then an amorphous layer is formed by water ~~wa~~ vapour deposition
  - geometry of experiment means, that first loaded particles are the last to be collided

Data Analysis:

Key Parameters:

- relative velocities before and after encounter: v_b, v_a
- coefficient of restitution: $\varepsilon = \frac{v_a}{v_b}$
- distance between centres of masses: R
- impact parameter: b
- normalised impact parameter: $\frac{b}{R}$

Collisions:

- total observed: 104
- binary collisions suitable for analysis: 52 (6 spheres, 46 fragments)

- other collisions were not suitable for analysis for the following reasons: non-binary (33, spheres rolling out of compartment) poor image quality (7), residual acceleration (4), multiple hit (4) fragmentation (4)
- it would be good to analyse non-binary, multiple-hit, and fragmentation collisions as well, as they are very realistic to protoplanetary disk, but it's not possible with the image quality (frame rate and small collision volume)

Analysis Methodology:

- Extract individual collisions from whole video and view them frame by frame
- track particles manually in both views
- convert positions to three dimensional coordinates
- get particle trajectories from linear fit of positions (not taking into account the encounter time)
  → distance of closest aproach and relative velocities before and after collision
- calculate b, $\frac{b}{R}$, ε
- resolve ε into components tangential and normal to colliding surfaces

Error Analysis:

- v_b, v_a, ε: propagation of errors
- normalised impact parameter: average error, taking into account the geometry of the particles and measurement errors

Test correlation between two ~~values~~ parameters: (x, y)

- linear Pearson correlation coefficient

n data points (x_i, y_i)

mean values $\bar{x}, \bar{y}$

$$r = \frac{\sum_{i=0}^{n} (y_i - \bar{y})(x_i - \bar{x})}{\sqrt{\sum_{i=0}^{n} (y_i - \bar{y})^2} \sqrt{\sum_{i=0}^{n} (x_i - \bar{x})^2}}$$

$r = \pm 1$: perfect positive/negative correlation, $r = 0$ no correlation

Rotation:

- particle must show ~~an~~ some kind of mark and rotate in the field of view
- mark must be tracked across subsequent images
- possible in 10 cases (of 52)

Fragmentation:

- can only be observed when fragments are larger than the observable pixel size of the camera in this case: $39 \times 39\,\mu m^2$

Results:

Parameter ranges:

- impact velocities spread evenly between 0,32 and 0,46 $\frac{m}{s}$ ←
- ε spreads evenly between 0,08 and 0,65
  average: 0,36

? Question: Do the values really spread evenly, or is there something like gaussian distribution? No

- $\frac{b}{R}$ spreads from 0 to 1, with slight favour to head on over glancing collisions
- $\varepsilon_\perp$ spreads from 0 to 0,65
- $\varepsilon_\parallel$ spreads from 0 to 2,1 (> 1 for very glancing collisions, i.e. $b/R \approx 0{,}95$) (velocity transfer between components)
- temperature increase: $22{,}5\ \frac{K}{h}$ (first 20 min)
  $7{,}0\ \frac{K}{h}$ (later)

Parameter correlations:

- no correlation: $\varepsilon - v_b$, $\varepsilon - \frac{b}{R}$, $\varepsilon_\perp - \frac{b}{R}$, $\varepsilon - T$
- slight negative correlation: $\varepsilon_\perp - v_{b\perp}$

Bouncing:

- majority of cases
- if there is a "bouncing barrier" for solid ice particles, this experiment was in that region

→ ε can be calculated to get indication of kinetic energy loss in collision

- components of ε tell that particles rather rebound (normal) than scatter (tangential)
- ε is likely to be dominated by normal component

→ limit for $\varepsilon_\perp$ but not for $\varepsilon_\parallel$

Sticking:

not observed

← 2. Question: Did the hydraulic pistons have more than three settings? For three settings of final velocity, I would expect three peaks instead of an even spread.

Hydraulic Pistons spread evenly, have big hysteresis

→ moved to motor pistons instead

Fragmentation:

- a few cases: one catastrophic, the others small amount of fragmentation
- occured at the same velocities like bouncing, below the critical velocities for fragmentation observed earlier ($0{,}7 - 1{,}2 \frac{m}{s}$)

→ most likely due to prior weakness of the particles (shattered by a hammer for production)

- very small amounts of fragmentation might occur in many more collisions but are not resolveable by the camera

Energy transfer:

- minimum of translational energy loss: 58%   up to 96%
- in most cases some energy is converted to rotation   0.08% to 17%
  (89% of particles do not rotate before collision, 84% rotate after collision, after every collision at least one particle rotated, all particles that rotated before collision continued rotating)
- energy converted to translational energy (rather kept as E_{trans}): 4% to 41%
- unaccounted energy might go into:
  compaction and desorption of material from the surface of particles (heating by friction due to surface roughness), dissipation into surface during contact → all unable to ~~detect~~ detect with this setup

Frost:

- no frosting observed during flight or loading

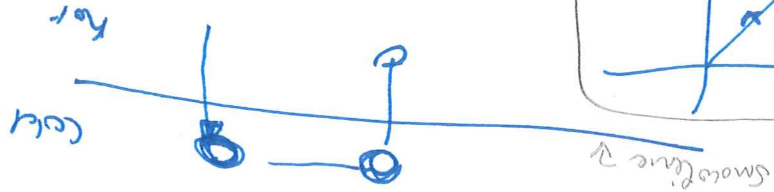
Comparison with other experiments:

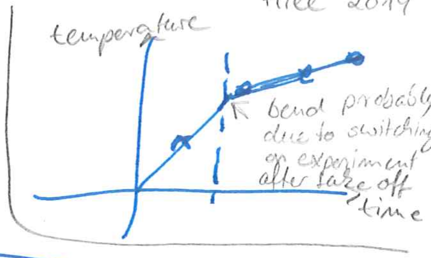
- ε covers range instead of being constant, possible reasons:
  rough & anisotropic surfaces, method of collision (microgravity), same-sized particles instead of particle-target collisions
- limit for ε lower than in Heißelmann 2010:
  ε should decrease with increasing impact velocity, particles not spherical, smaller particles

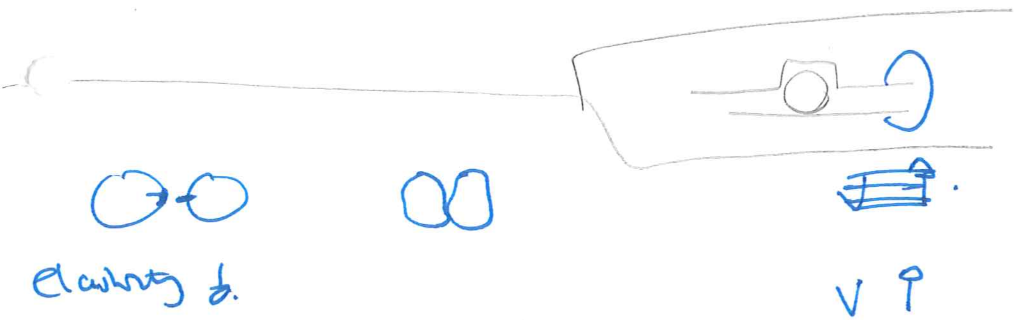
Temperature

- T (and thus time) has no effect on ε: expected because
  ~~***~~ T range too low for surface melting effects

Supervision Meeting 11.11.2014

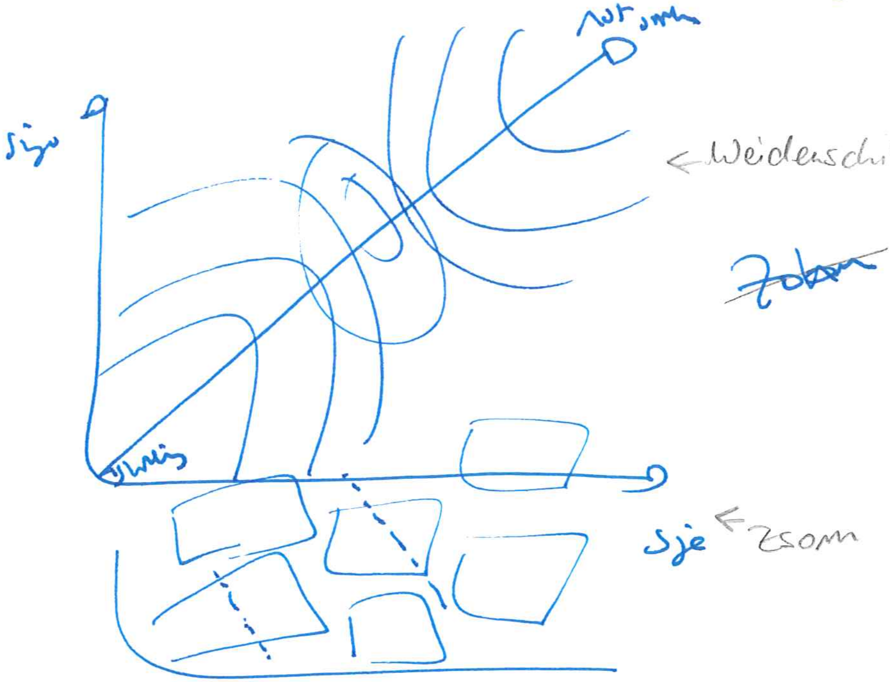






bouncing barrier & elasticity

bouncing barrier



13.11.2014

Hill et al. 2014b

Collisions of small ice particles under microgravity conditions (II): Does the presence of chemical pollutants change the collisional properties?

What's new / different w.r.t. Hill 2014 a and Salter 2009 only.

Theory:

- other simple chemicals than water are known to be present in cold interstellar regions and are likely to pervad into proto-planetary ice particles
- ~~effect of~~ snowlines are molecule specific, with their distance from a protostar increasing with molecular volatility (shown by the indirect detection of CO snow lines
- water snow line is of greatest interest for planet formation, usually between 1 and 10 AU from central protostar
- possible contaminants of water ice: CO, CO_2, CH_3OH (methanol), CH_4, $HCOOH$ (formic acid), NH_3
- methanol and formic acid have been detected in protoplanetary disks in the gas phase, most likely desorbed from icy mantles
- in interstellar ices methanol and formic acid have been detected abundance compared to water ice: methanol: 1-30%, formic acid: 1-5%
- surface melting leads to ice aggregation in atmospheric clouds, (around the melting point of water) but is not possible at temperature-pressure conditions in proto-planetary disks (for crystalline water ice)
- methanol freeze out in protoplanetary disks will happen at lower temperature than in the lab, leading to better mixture of water and methanol in the ice
- surface melting as sticking mechanism might work for amorphous solid water (detected in star forming regions) at conditions in protoplanetary disks
- ASW undergoes glass transition to cubic ice at 137K → restructuring of surface during collisions at that temperature might increase sticking probability

Previous Experiments:

effect of chemical composition not yet studied

Differences between ice and silicate dust:

- ice has larger adhesive force
- ice has higher sticking threshold

Ice sphere on disk pendulum & ice target:

- impact velocities : 0,05 to 1,4 $\frac{cm}{s}$
- temperatures: 85 - 100 K
- pressures : 10^{-4} - 10^{3} mbar

Effect of frost:

- water : · deposition of water vapour at 130 - 150 K leads to cubic frost:
  - ↳ COR reduced by frost
  - · frost grown at 100 K and pressures from a few to 533 mbar:
    - ↳ sticking for porous frost layers
    - ↳ no sticking for dense frost layers
  - → sticking thought to be due to interpenetration of frost layers ("Velcro" effect)
- methanol frost on water ice : · T = ~~100~~ 110 to 150 K, atmospheric p
  - ↳ stronger sticking than water frosts
  - → possibly due to differences in structural and material properties
  - → possibly due to surface melting (melting point of methanol at atmospheric pressure : 176 K)

Free fall impacts of centimetre sized ice spheres of varying porosities:

- particles created by sintering micron sized ice spheres
- impact velocities: 0,44 to 4,12 $\frac{m}{s}$
- T: 263 K , atmospheric pressure
- COR : between 0 and 0,3
- COR depended on porosity , not on velocity
- Sticking observed for high porosities

→ Read Shimaki & Arakawa 2012

Parabolic Flight experiments:

- colliding particles with rough, anisotropic surfaces will produce a broad range of CORs

Experimental Setup & conditions:

- Samples: 1,5 cm ice spheres, pure water, water + 5% methanol, water + 5% formic acid
- Collisions with target at 90° and 60° angle and with each other
  → $\frac{b}{R} = 0$ → $\frac{b}{R} = 0{,}5$
- Target: pure water ice
- velocities: 0,01 to 0,19 $\frac{m}{s}$
- temperatures: 131 to 160 K
- two camera viewing angles, 48,8° apart
- technical problems: no collisions at 30° target angle

? Question: What kind of technical problems?
Target smashed by pistons colliding into it

? Question: How can you fix the target? Earlier papers say, that it is rotating with the coliseum. What version do we have now?
Difference is in coliseum: copper for small particles: target will rotate, aluminum for big particles: target will not rotate

- technical problems: for 60° target angle, only collisions with pure water observed

? Question: What kind of technical problems?
~~expori~~ Residual acceleration (41 cases), anything else?
→ started after water collisions (bad parabolas)

- experimental setup collides (large) particles at low impact parameters

Sample preparation:

- Water or water-mixture was frozen in spherical moulds in a standard kitchen freezer (255 K) ⇝ crystalline water
- after removing from the freezer they were placed in a liquid nitrogen container immeadiately
- loading as discribed in Hill 2014a
- similar procedure for target
- freezing water-methanol mixture at 255 K will probably lead to methanol being at the center of the ice spheres, because it freezes at 176 K → water freezes from the surface inwards and might exclude methanol

? Question: When you break such a particle (before putting it in LN_2), does it have a liquid core?

? Question: Would it help to freeze the samples in liquid nitrogen? That is faster and below the freezing point of methanol. Would also produce other ice structure → maybe closer to protoplanetary disk ice.
→ polycristalline ice if you freeze more than a few mm sized particles → see Hill 2014a

Data Analysis:

Key Parameters:

- θ: angle of the target to the direction of travel
- normalized impact parameter: $\frac{b}{R} = \cos\theta$

Collisions:

- total: 120, suitable for analysis: 58
- not suitable for analysis: 45 residual acceleration, 16 poor image quality, 1 fragmentation

	pure water	5% methanol	5% formic acid	total
target at 90°	7	10	18	35
target at 60°	8	0	0	8
no target	2	8	5	15
total	17	18	23	58

Rotation:

- quantitative analysis not possible due to poor image quality and spherical shape of particles

Results:

Parameter Ranges:

- COR evenly spread between 0,08 and 0,81
- impact velocities target-particle: ≈ 0,05 to 0,10 $\frac{m}{s}$
  particle-particle: ≈ 0,15 to 0,19 $\frac{m}{s}$
- tangential impact velocities are always lower than normal impact velocities (head on collisions)
- log files not recovered due to technical problems
  → heating rate and temperature range not measured, taken from last experiment.

? Question: Does "technical problem" translate as the guy with the data left and we cannot find the files, or were the files really lost on the flight? If so, should we think about a backup mechanism?
→ Portable Hard Drive corrupted while sitting in a cupboard

Correlations:

- no correlations observed for COR with: target angle, chemical composition, impact velocity, target instead of other particle, temperature (i.e. time in this case)

? Question: Fig 3 b & c: In 3c five data points were sufficient for calculating a mean, in 3b eight data points were not sufficient. Why? No points for other chemicals, only one rectangle does not make any sense

? Question: Impact velocities spread evenly. Were there hydraulic or motor pistons used?
Motor

Bouncing:
- only collisional outcome
- if there is a bouncing barrier for ice particles of this size, it will be below 0,01 $\frac{m}{s}$

Energy transfer:
- minimum of ~~trans~~ translational energy loss: 29%
- some energy converted into rotational energy

Rotation:

	rotates (%)	does not rotate (%)	unclear (%)
before	4	89	7
after	71	10	19

rotation cannot account for all the energy loss

Surface melting/wetting:
- not likely at the low pressures in the chamber (250 K and a few mbar would be required)
- if energy is converted into heat, it would lead to desorption of material (not visible)
- surface fracturing also not visible ← (camera resolution)

Structure:
- Formic acid freezes at 282 K → similar to water → probably evenly distributed throughout the ice
- methanol probably trapped in the centre of the particles → pure water surface → no change in COR expected.
- other option: methanol amount too small for influence on structure and COR. Higher amounts would be unrealistic

- for only 5% contaminant : structure probaly dominated by crystalline water -> no effect on COR
- freezing conditions in protoplanetary disks different -> methanol might have larger influence there.

14.10.2014

Heißelmann et al. 2010

Microgravity experiments on the collisional behavior of saturnian ring particles

what is new / different to other papers only

Theory:

- Saturn's rings consist of myriads of particles orbiting Saturn in Keplerian orbits creating a disk only a few meters thick
- spectroscopic observations and radio occultation data: particles of almost pure water ice, size: 1 cm to 10 m
- interactions with moons and moonlets (gravitational perturbation) cause features of rings and work to increase particles orbital eccentricity and ring thickness
- counteracting: frequent inelastic collisions at very low relative velocities ($v \leq 0{,}5 \frac{cm}{s}$) dissipate kinetic energy
  → re-circularize orbits and confine ring height
- glancing collisions are the most frequent ones (simple geometrical considerations)

Theoretical and numerical studies:

- Development of kinetic theories:
  - applicable to thin granular gases of a single species (1978)
  - N-body simulations including particle size distributions (1985-91)
  - visco-elastic collision models (1995)
  - extended to treat fragmentation and coagulation (2004)

  Result: amount of energy that is dissipated through collisions determines stability of homogeneous dense rings
- most N-body simulations and kinetic theories describe inelastic collisional behavior by single parameter: coefficient of restitution (measure of the dissipation of kinetic energy)
- N-body simulations to create model of Saturn's A and C ring:
  - input for numerical light-scattering studies trying to match

photometric properties observed by Cassini
- to reproduce observations, a velocity dependent COR was needed, but dependence 3,5 to 5 times lower than found in disk pendulum studies

- collision model (Brilliantov): COR decreases with decreasing v

Previous Experiments:

Disk pendulum:

- decreasing COR with decreasing v and increasing surface frost
- lower velocities than in this work
- at velocities above ~~1~~ 1 $\frac{cm}{s}$: weak velocity dependence of ε with values between 0,2 and 0,5
- limitation of experiments:
  - treat only impact into large body of infinite mass and infinitesimal surface curvature
  - mass and moment of inertia not realistic (represent whole pendulum instead of individual particle

Ice spheres on larger target:

- COR decreases with increasing particle size / mass
- COR independent of temperature
- COR decreases with increasing v

Investigation of granular cooling and low-velocity binary collisions of mm-sized spherical particles (Grasselli 2009, Sorace 2009)

- COR decreases with decreasing v

Impact of cm-sized spheres into lunar and martian regolith analog material; low-velocity collision experiments of high-porosity dust aggregates:

- If ring particle collisions are dominated by particle's surface properties and not by their icy cores, a regolith layer will clearly reduce the COR considerably (more inelastic behaviour)

Parabolic Flight Experiment: DLR 12th campaign, April 2008

Setup:

- 34 pairs of 15 mm particles
- ≈ 1 collision per parabola
- pistons driven by two synchronized DC ~~motos~~ motors
- free space → truly three dimensional events
- beam splitter optics, angular separation: 48,8°
- setup suitable for pair collisions at relative velocities ≥ 6 $\frac{cm}{s}$ and near-central impact angles

conditions:

- 22 s of weightlessness per parabola
- residual acceleration: a few times 0,01 g
- velocities between 3 and 17 $\frac{cm}{s}$
- predominantly centralized collisions: $\frac{b}{R}$ close to 0

Sample preparation:

- freezing purified water inside silicon moulds in regular kitchen freezer: hexagonal-ice
- store particles in liquid N_2 until storage
- loading as in Hill 2014
- maximum exposure time to humid air: less than 1 min
  ↳ still: some experiments show tiny amounts of surface material (which might be frost) chipped off during collisions

Drop Tower Experiment:

Setup:

- quasi-two-dimensional box (glass) 150 x 150 x 15 mm^3
- 2 cm thick walls (glass → highly elastic with glass particles)
- can hold ≈ 100 cm-sized particles

- two sets of particles stored opposite each other can be accelerated into test chamber
- high speed, high resolution camera: 115 fps
- two overview cameras (25 fps) at an angle of 16,25° relative to chamber
- prototype for future investigations with cryogenic experiments on ice particles
- black marks on the surface of glass beads to track rotation

Conditions:

- 9 s weightlessness
- residual acceleration better than 10^{-5} g
- initial velocity of glass bars that inject particles: 10 $\frac{cm}{s}$ (motor driven)
- 10 mm sperical glass samples
- 32 particles injected from either side, 28 sitting in the chamber at rest → sum: 92 particles
- chamber not evacuated, by air drag on particles ~~neglectable~~ neglectable

- mini drop tower (1,5 m height) available for binary collisions

Data Analysis:

Parabolic Flight:

- 41 image sequences recorded
- treat COR in a statistical way: plot cumulative number of collisions with COR $\leq \varepsilon$ against ε
- analyse normal & tangential components of COR:
  for $\varepsilon_{\parallel}$ only experiments with tangential velocities $v_{\parallel} \gtrsim 5 \frac{mm}{s}$ (36 of 41) were taken into account to avoid $\varepsilon_{\parallel} = \frac{v_{\parallel}'}{v_{\parallel}}$ approaching unrealistic high values while $v_{\parallel}$ approaches zero.
- otherwise like Hill 2014 a+b

Drop Tower:

- images convolved with an image of a single sphere as kernel to yield positions of all particles in all image frames
- -> probability maxima, which determine particle positions can be detected automatically
- track particles over time -> calculate individual particles mean velocity between consecutive images
- resulting particle velocities as a function of time shows that system equilibrates within first 1,5 s
- decay of mean particle velocity:
  - individual particles logarithmically binned
  - mean velocity computed
  - standard deviation of velocity and time measurements
  - assume constant COR ~~ε~~ and simple kinetic theory for granular fluids (Haff) -> read
  - fit temporal rms-velocity ~~dist~~ evolution

$$v(t) = \frac{1}{\frac{1}{v_0} + (1-\varepsilon)\cdot n \cdot \sigma \cdot t}$$

  v_0: initial injection velocity
  n: number density
  to binned velocity data
  $\sigma = 4\pi r^2$: collisional cross-section
- detailed analysis of individual binary collisions among the constituents of the ensemble in the drop tower experiment as well as of binary collisions of identical glass particles (spheres) in the mini drop tower
- two dimensional projection of velocities -> splitting velocities into two ~~..~~ one dimensional components -> discribe distribution by one-dimensional Maxwell-Boltzmann distribution
- Monte Carlo simulation of one-dimensional Maxwell-Boltzmann distribution (plot shows 2σ range)

- smooth glass sphere, 10 mm diameter, Reynolds numbers:
  $v = 4\ \frac{mm}{s} \rightarrow Re \approx 1{,}6$, $v = 10\ \frac{cm}{s} \rightarrow Re \approx 62$
  => relative velocity loss due to air drag $\frac{\Delta v}{v}$ less than a few times 10^{-3}

Results:

Parabolic Flight:

- Parameter Ranges:
  - $\frac{b}{R} = 0$ to $0{,}5$, mean: $0{,}16$ (covers fraction of $\left(\frac{b}{R}\right)^2 = 0{,}25$ of the statistically occuring impacts in Saturn's rings
  - $\varepsilon = 0{,}06$ to $0{,}84$, mean: $0{,}45$
  - $\varepsilon_\perp = 0$ to $0{,}82$, mean: $0{,}41$
    measurement error $\Delta\varepsilon_\perp = 0{,}06$, standard deviation mean $\sigma_{\overline{\varepsilon_\perp}} = 0{,}04$, standard deviation individual value $\sigma_{\varepsilon_\perp} = 0{,}24$
  - $\varepsilon_\parallel$, mean: $1{,}08$
    $\Delta\varepsilon_\parallel = 0{,}38$ $\sigma_{\overline{\varepsilon_\parallel}} = 0{,}19$, $\sigma_{\varepsilon_\parallel} = 1{,}11$
  - $v = 3$ to $17\ \frac{cm}{s}$
  - $v_\perp = 4$ to $22\ \frac{cm}{s}$
  - $v_\parallel = 0{,}5$ to $8\ \frac{cm}{s}$

- Correlations:
  no correlations for:
  COR and $\frac{b}{R}$, COR and v, $\varepsilon_\perp$ or $\varepsilon_\parallel$ with $\frac{b}{R}$ or v, ε with combination of $\frac{b}{R}$ and v
- cumulative number of collisions with COR $\leq \varepsilon$ can be fitted by uniform distribution (fit provided mean $\varepsilon = 0{,}45$)
- large error for $\varepsilon_\parallel$ does not allow secure interpretation
- Values show significant scatter around mean (larger than experimental uncertainty) $\Rightarrow$ model investigations of Saturn's rings should include flat statistical distribution of COR rather than single value
- wide range of ε might reflect anisotropic nature of ice sample's surfaces (roughness, previously slightly melted areas) used in this experiments

Drop Tower:

- Parameter Ranges:
  - injection velocity : 10 $\frac{cm}{s}$
  - median particle velocity in the last 1,5 s : 3,5 $\frac{mm}{s}$
    (50% of particles have velocities between 2 and 5 $\frac{mm}{s}$)
  - $\varepsilon = 0{,}64$ (fit in the time interval 2 to 7 s)
- Mini drop tower parameter Ranges:
  - 12 central collisions
  - velocity range : 1 to 4 $\frac{cm}{s}$
  - ε randomly distributed between 0,35 and 0,95
- drop tower velocity distribution (Maxwell-Boltzmann) can be fitted with a COR of $\bar{\varepsilon} = 0{,}77$, using a range of $\varepsilon = 0{,}2$ to $0{,}9$
- After injection phase kinetic energy is dissipated through inelastic collisions and transformation to rotational motion
- mean particle velocity decays with time, can be described by Haff's law in the intervall 2 to 7 s ($\varepsilon = 0{,}64$)
  before interval: equilibration phase, after interval: change of slope, possible origin: increased COR towards lower velocities, onset of clustering (beyond the scope of this work)
  → clustering more likely, since previous works usually show no increase of ε with decreasing v
- no three dimensional motion information
- velocity dependence of COR found in other experiments could not be reproduced with this setup
- obtained velocities are realistic parameters for simulating collisional processes in Saturn's main rings
- Future experiments:
  - analyse individual collisions, their impact parameters and excitation of rotational motion
  - use cryogenic setup and ensembles of water ice samples
  - use beam splitter optics for three dimensional analysis