# Analysis of hydrodynamic effects using ultrafast X-ray tomography with GPU accelerated data acquisition

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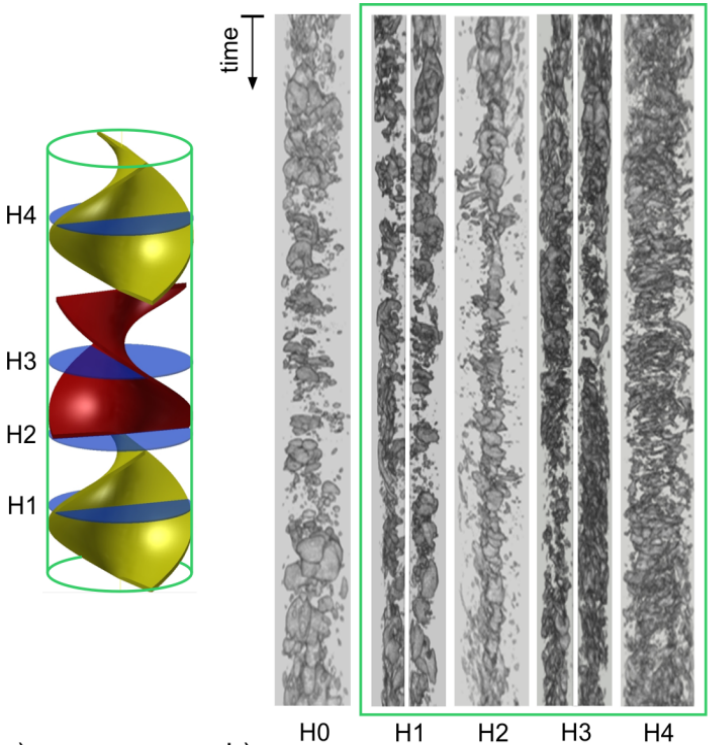
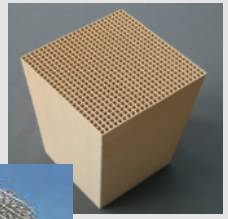
## Outline

- Motivation
- Ultrafast X-ray CT scanner
- Data processing
  - ✓ Previous
  - ✓ Current
  - ✓ Further strategy
- Further concepts
- Conclusion

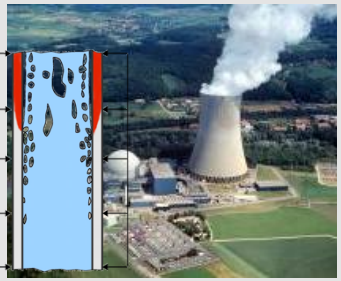


# *Motivation*

Experimental investigations for chemical engineering,

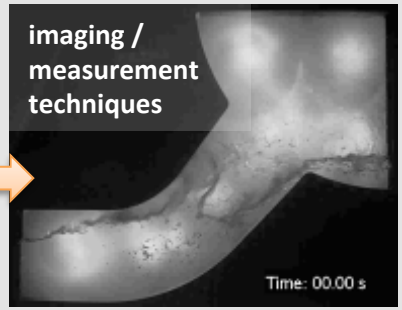


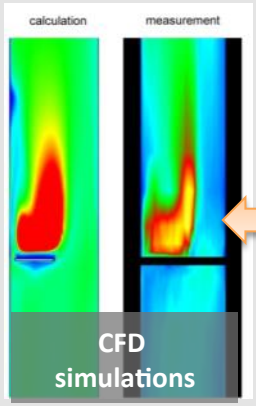
power engineering,

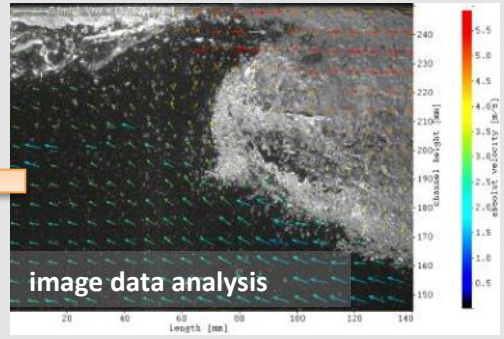


mineral oil processing

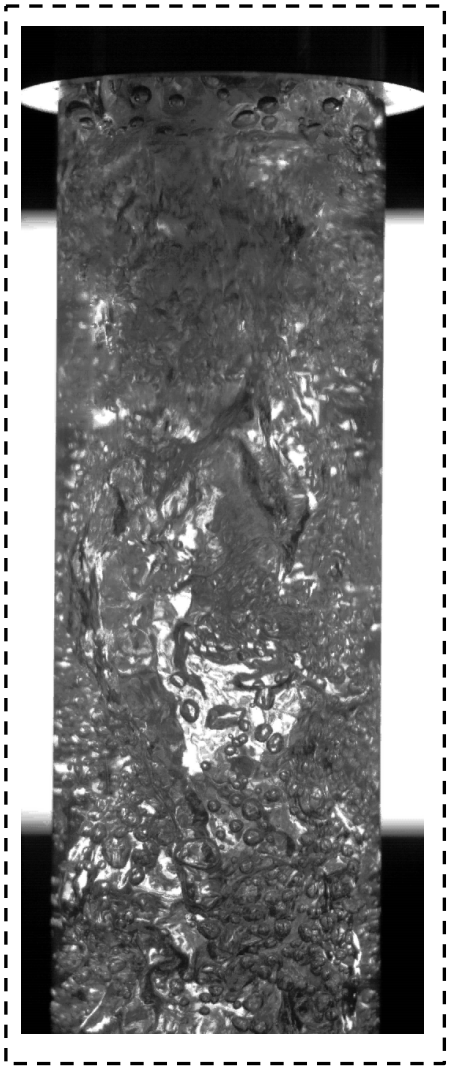
Fluid mechanics and multiphase CFD modeling and simulation

# *Motivation*

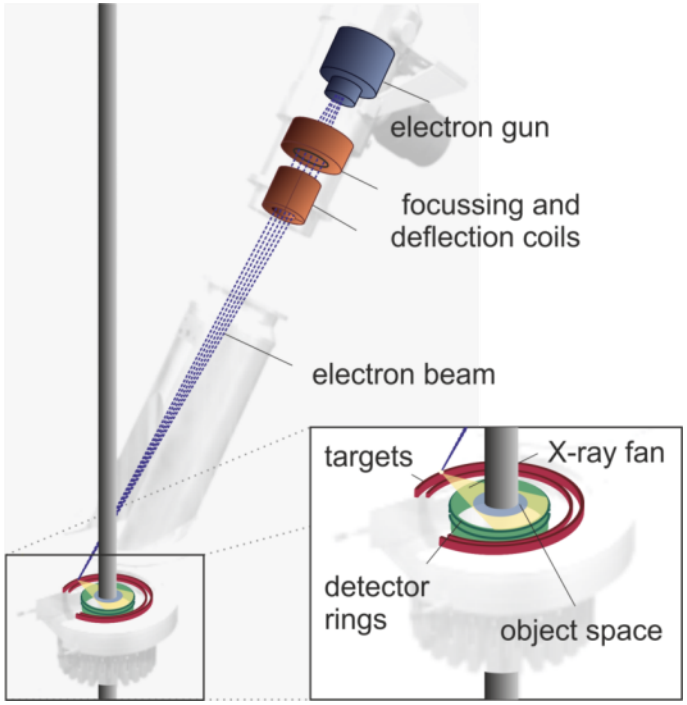


## Optimal measurement technique

- high spatial resolution (in 3D)
- high temporal resolution
- non-intrusive measurement
- non-superimposed information
- suitable for opaque systems
- suitable for any geometry (including internals)

# ROFEX - Parameters

## Principle




| | |
|---|---|
| **frame rate:** | up to 8000 $s^{-1}$ |
| **spatial resolution:** | down to 1 mm |
| **acceleration voltage:** | 150 kV |
| **max. beam power:** | 10 kW |
| **no. of detector elements:** | 2 x 288 |
| **detector frequency:** | 1 MHz |

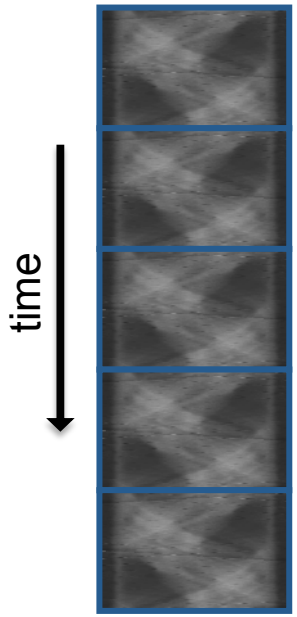
## Setup

## Setup with housing and elevator unit

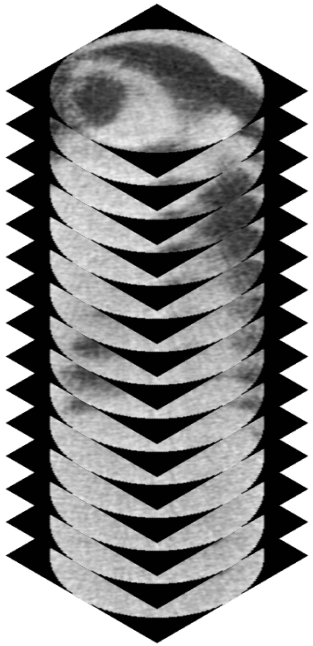
📖 F. Fischer et al., Nucl. Eng. Des. 2010

# *ROFEX – Data processing (theory)*

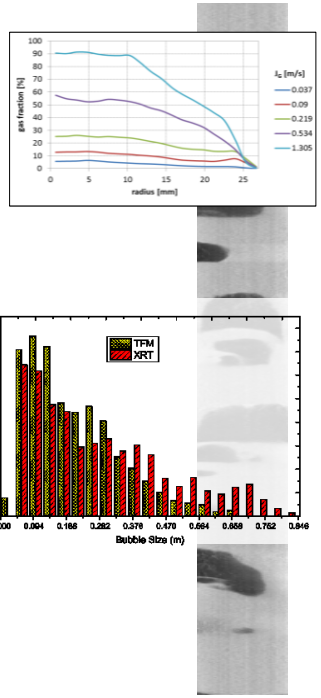
**raw data sinograms** → image reconstruction → **image sequence** → feature extraction → **parameter distribution**




- filtered back-projection
- algebraic reconstruction (ART, SIRT, MART)
- …



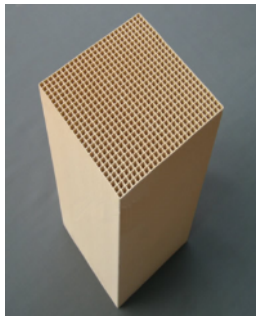
- hold-up distribution
- bubble size distribution
- axial velocities
- …

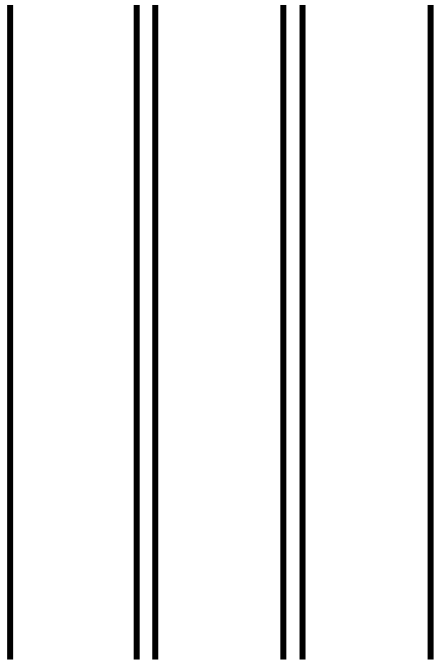


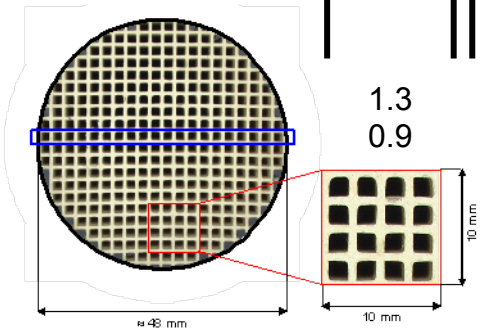

📖 M. Bieberle et al., Exp. Fluids 2009
📖 M. Bieberle et al., Philos. T. Roy. Soc. A 2015

# *ROFEX – Applications*

## Monolith structures

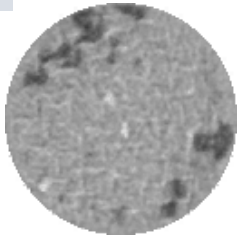






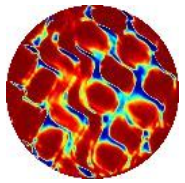

1.3 0.43 1.3 $v_L$ (m/s)
0.9 0.17 0.17 $v_G$ (m/s)

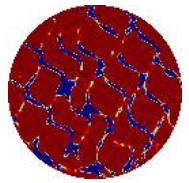
## Metallic structures



**Flood and deflood**
1 second
1000 fps
(30 x slow motion)

**Flooding point**
1000 fps
(10 x slow motion)





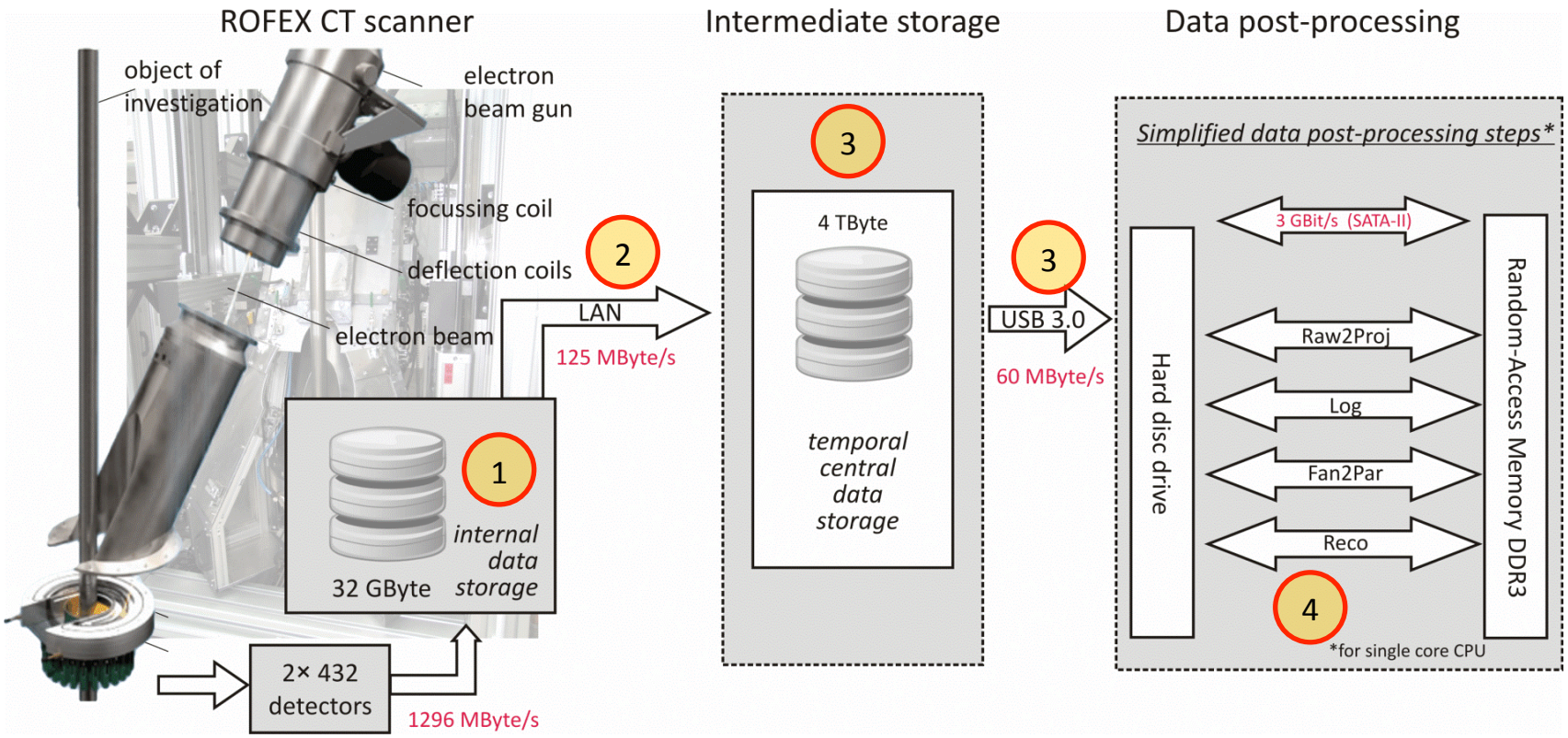
## Foam structures

# *ROFEX – Systems*

time

| | ROFEX-I | ROFEX-III | ROFEX-III+ | ROFEX-II | HECToR |
|---|---|---|---|---|---|
| Start-up date | 2010 | 2012 | 2016 | 2017 | 2018 |
| Maximal photon energy [keV] | 150 | 150 | 150 | 150 | 998 |
| Measuring planes | 2 (8) | 2 | 2 | 2 | 2 |
| Measuring diameter [mm] | 120 | 180 | 160 | 60 | 420 |
| Sampling frequency [MHz] | 1 | 1 | 2 | 1 | 2 |
| Data volume [GByte / s] | 0.80 | 1.21 | 1.97 | 1.34 | ?? |

# *Data acquisition & data processing (until 2014)*




1 - limited data acquisition time
2 - slow data transfer
3 - slow and decentral intermediate data storage
4 - very slow data reconstruction (without parameter extraction)
5 - improvable data management

- No online analysis
- Long waiting for validity of measuring data limits the availability of the scanner
- no scientific „play around“
- ...

# *Concept for an enhanced data acquisition & processing (2014)*

## Main problems

### Data transfer

**Priority 3**

- New detector hardware
- Sufficiently fast (& commercially available) data interface

| | |
|---|---|
| 10 GBit/s | 1280 MByte/s |
| 40 Gbit/s | 5120 Mbyte/s |

### Data processing

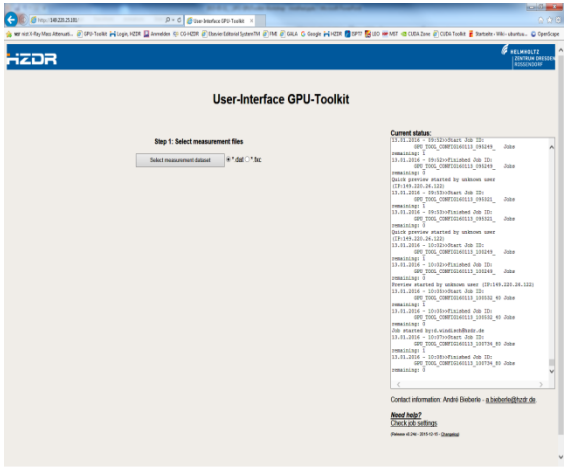
**Priority 2**

- Enhanced data processing hardware
- Massive data processing algorithms

### Data management

**Priority 1**

- Central and web-based data processing and management



# *Concept for an enhanced data acquisition & processing (2014)*

**Priority 1 & 2**

## *Basis for data processing*

UFO
frame work

| | Advanced performance PC |
|---|---|
| **Processor** | Intel Xeon E5-1650 v3<br>(6 cores / 12 threads) |
| **Processor clock** | 3.5 GHz / 10 MB<br>(Turbo: 3.8 GHz) |
| **RAM** | 128 GByte<br>DDR4 / 2133 MHz |
| **HDD** | SSD Samsung SATA III 256GB<br>(500 MByte read / 410 MByte write) |
| **Multi-core GPU** | 2x Tesla K20<br>(NVIDIA®, 4.8 GByte DDR5) |
| **Ethernet interface** | 2x 10GbE/40GbE<br>(Intel XL710QDA2BLK) |
| **System software** | Ubuntu 14.02 LTS (64 Bit) |
| **Developer KIT** | NVIDIA NSight / Eclipse |
| **Compiler** | GCC 4.8.1 & NVCC |
| **Special libraries** | OpenMP, CUDA 7.5 |

central
server

10 GbE

# *Concept for an enhanced data acquisition & processing (2014)*

**Priority 1**

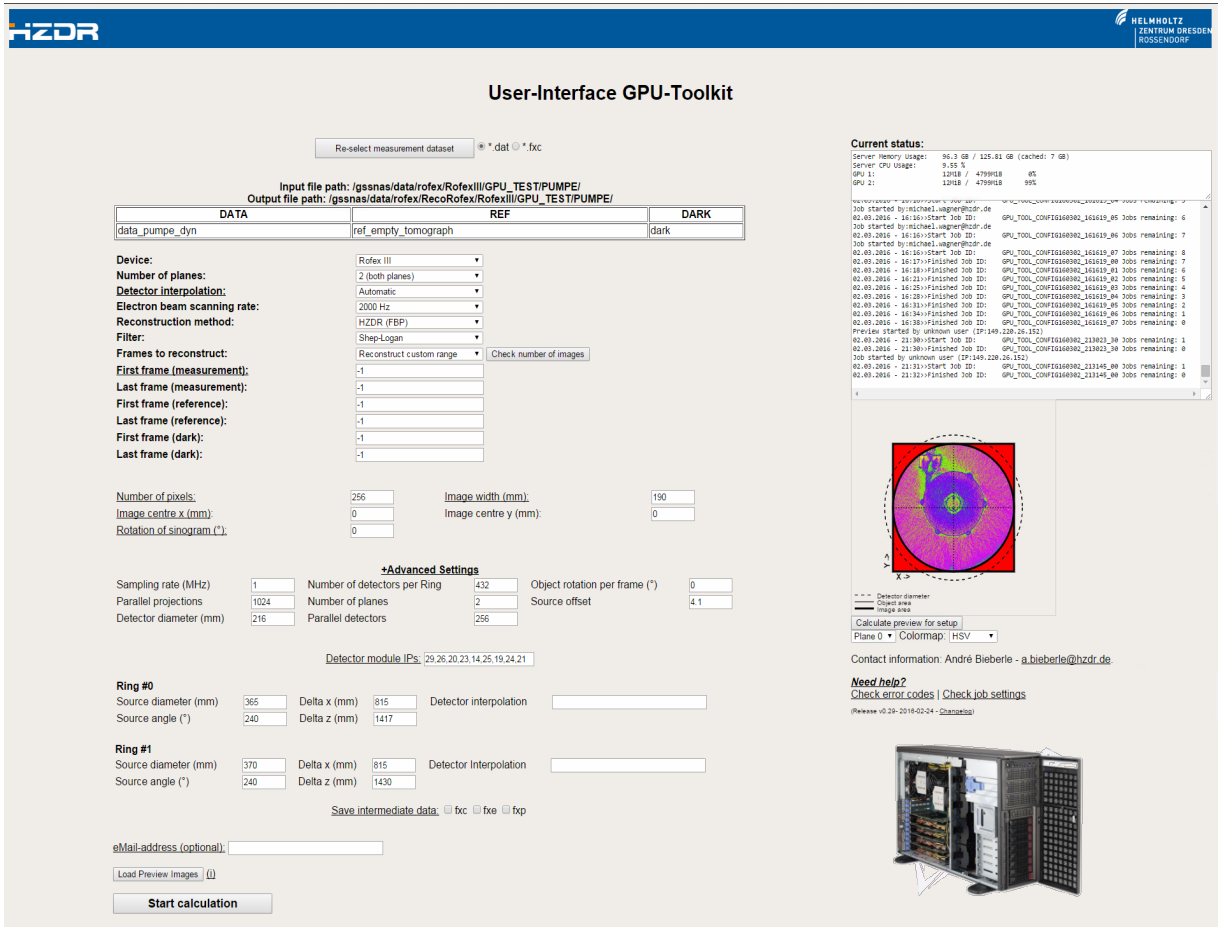
## *Processing concept*

### Requirements

- OS independent
- Uniform software versions
- (Hidden and) central data storage
- Integrated data management

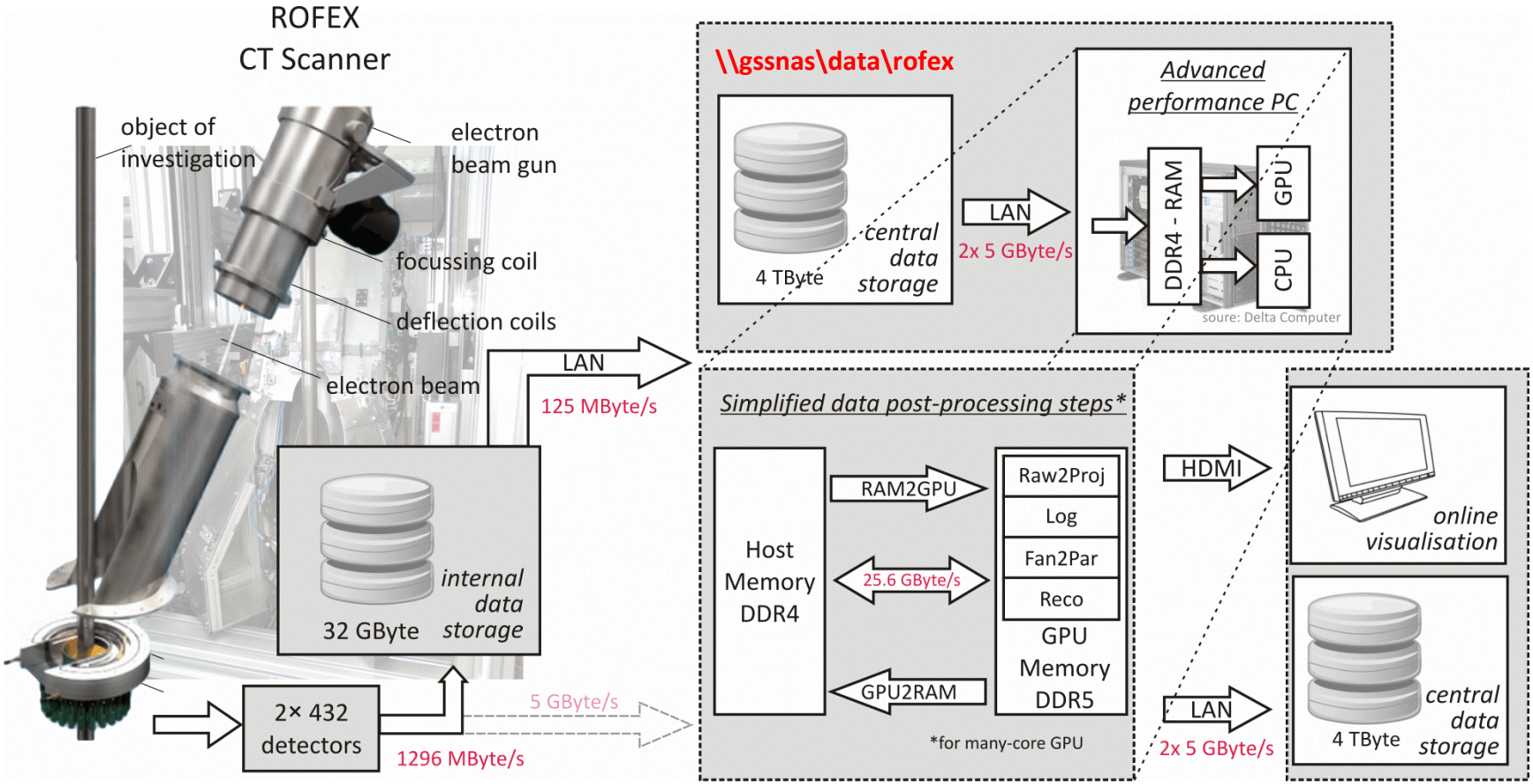
### Web based solution

- Homepage as input media (mobile access with Laptops, Smartphones, etc.)
- Job server (collecting all job requests)
- OS behind (Linux) is regardless
- No decentral data transfer
- Comfortable notification via email …..



# *Concept for an enhanced data acquisition & processing (2014)*

**Priority 2**



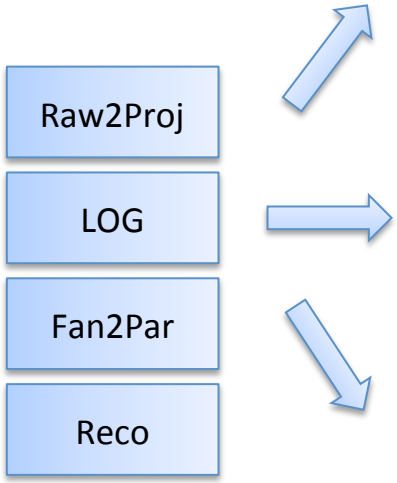

**\\gssnas\data\rofex\reco**

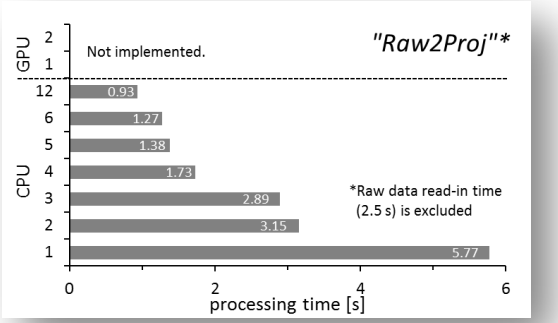
# *Enhanced processing – Results - I*

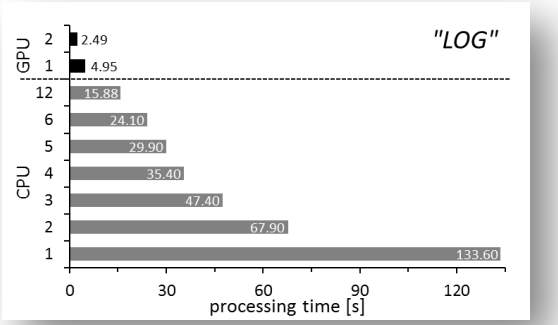
**Priority 2**

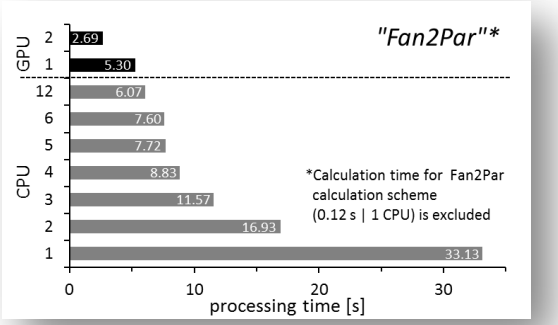
## *Data pre-processing*

*(Raw2Proj, LOG, Fan2Par)*



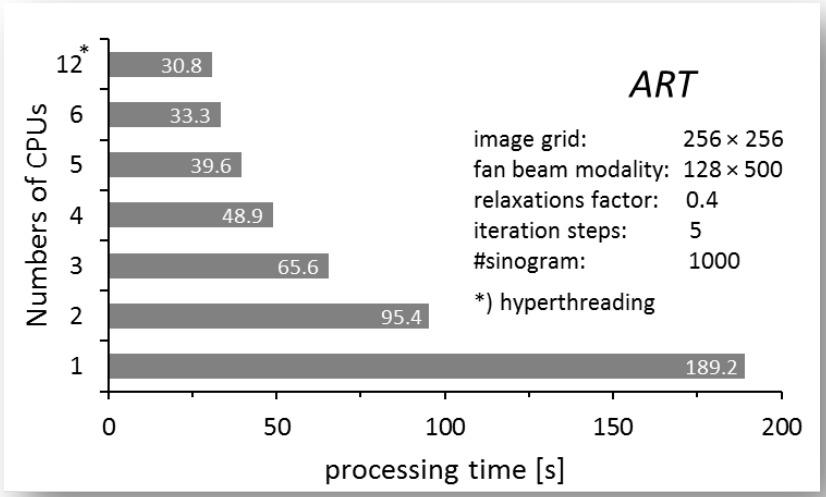



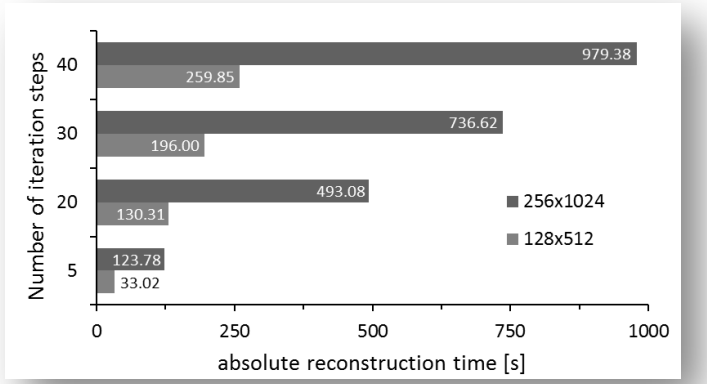
# *Enhanced processing – Results - II*

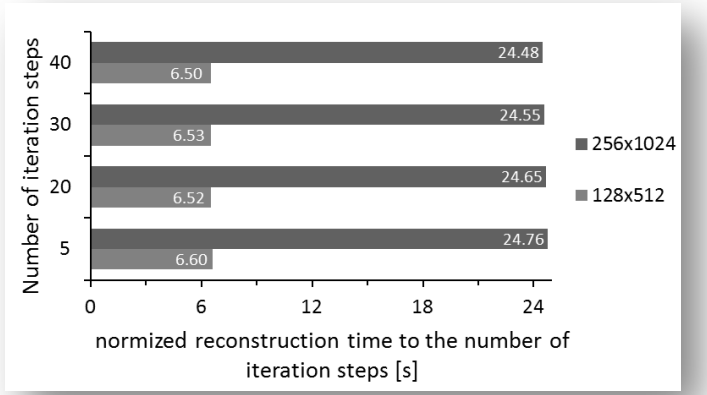
**Priority 2**

## *Data reconstruction*

*(Algebraic Reconstruction Technique)*



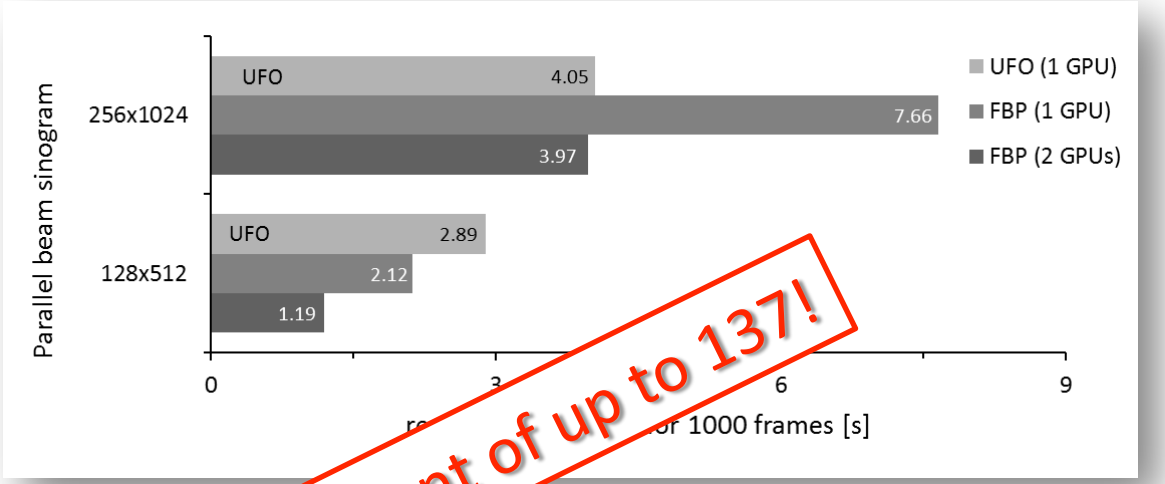



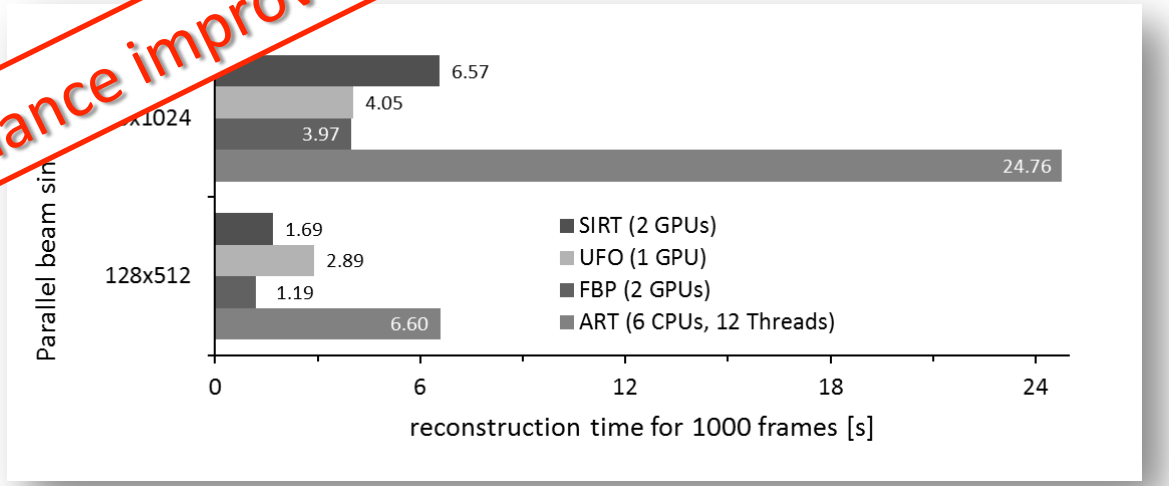
# *Enhanced processing – Results - III*

Priority 2

## *Data reconstruction*
*(Filtered Backprojection)*



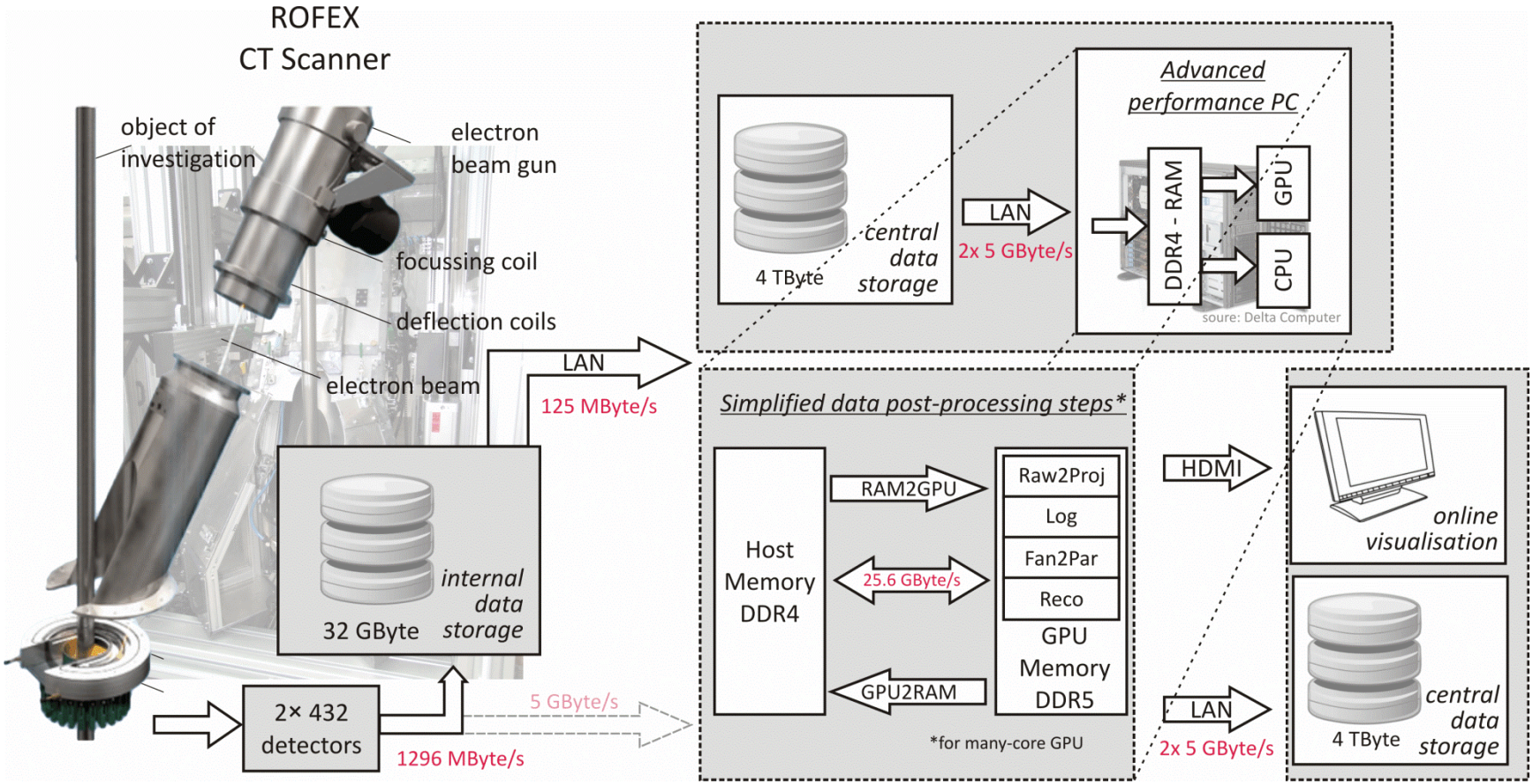

## *Data reconstruction*
*(Comparison)*




Performance improvement of up to 137!

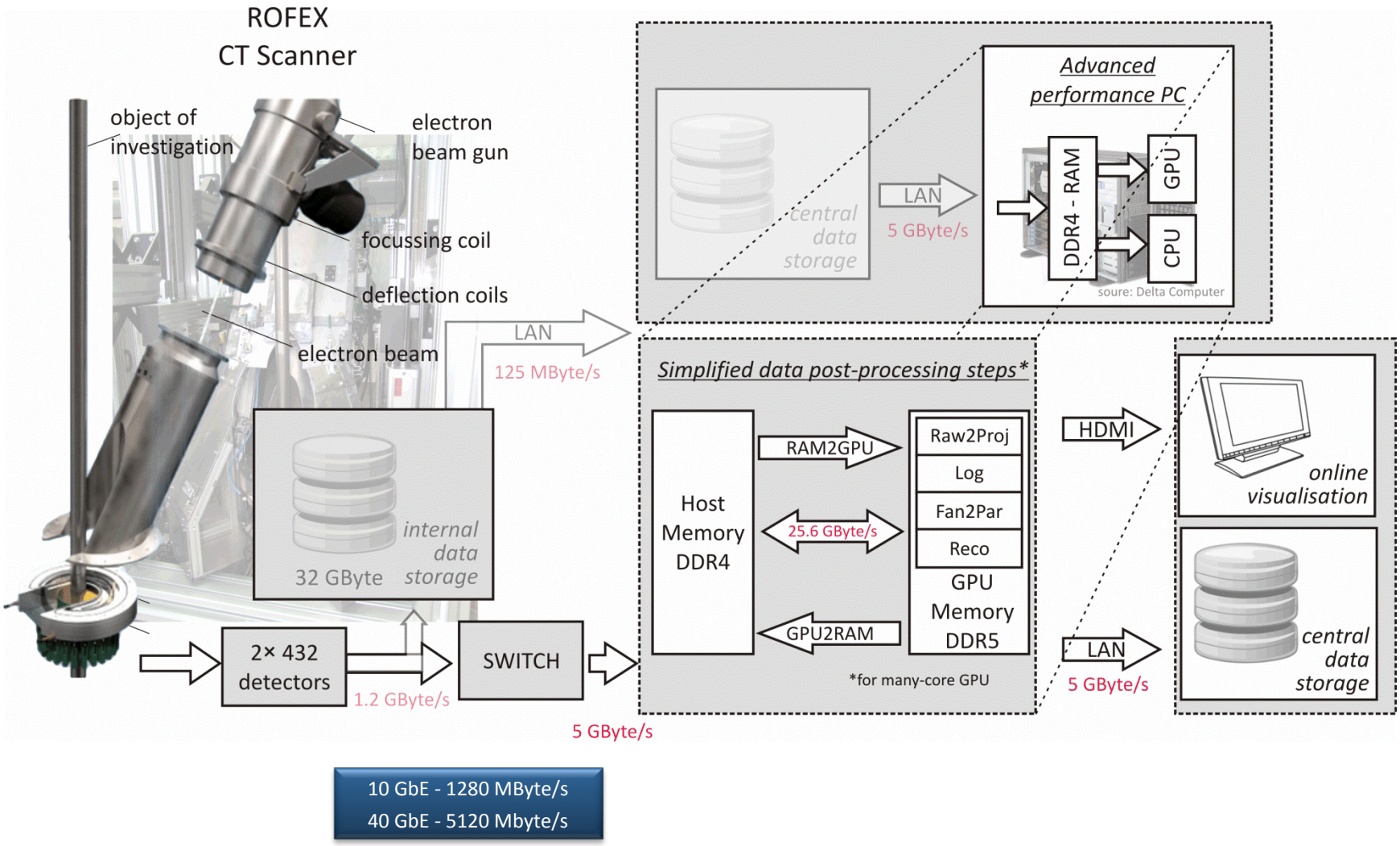
# *Further concepts*

**Priority 3**



# *Further concepts*

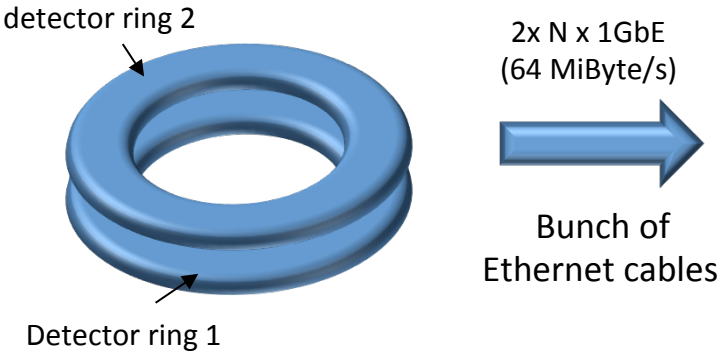
**Priority 3**




10 GbE - 1280 MByte/s
40 GbE - 5120 Mbyte/s

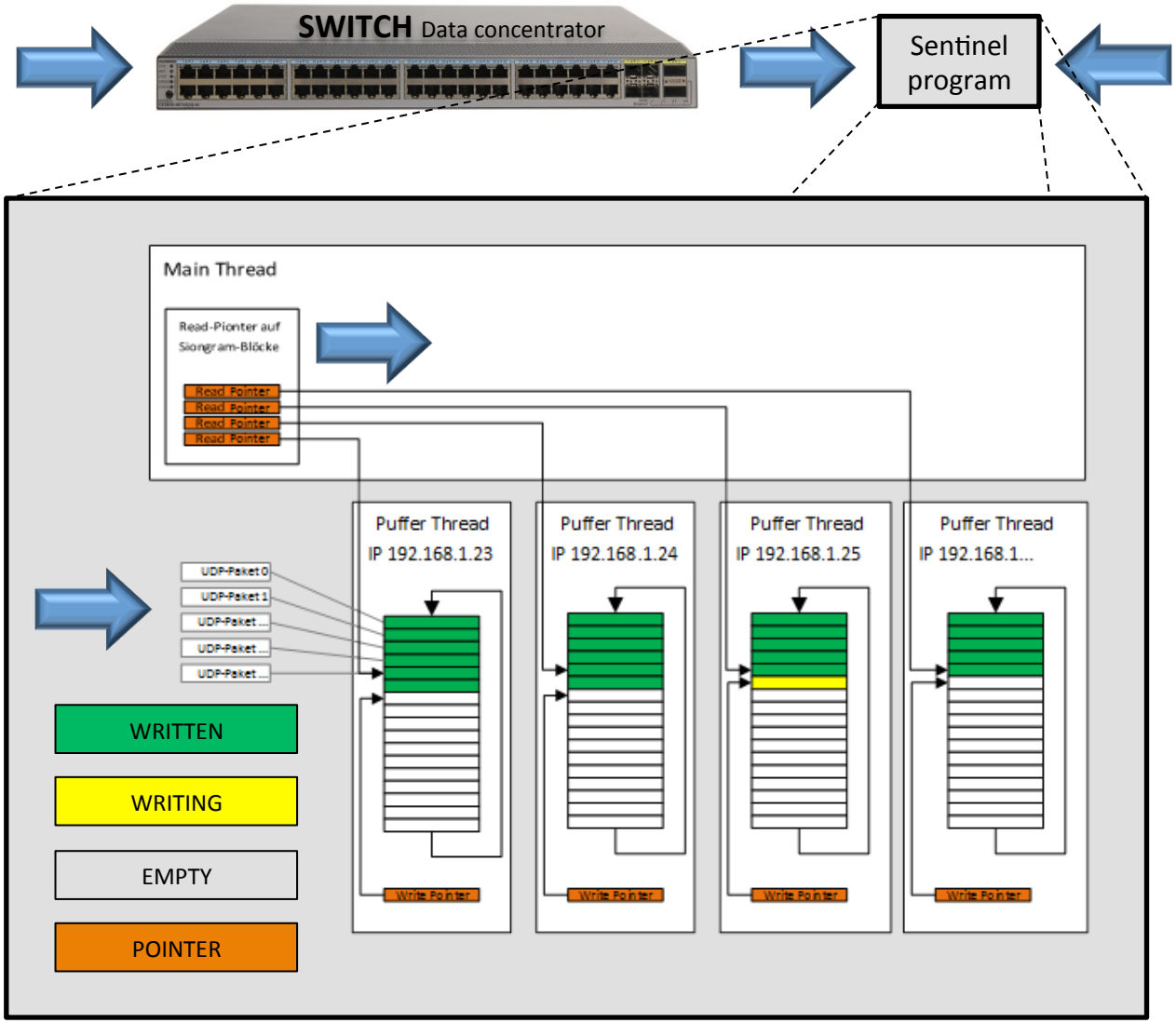
# *Further concepts - Hardware*

Priority 3

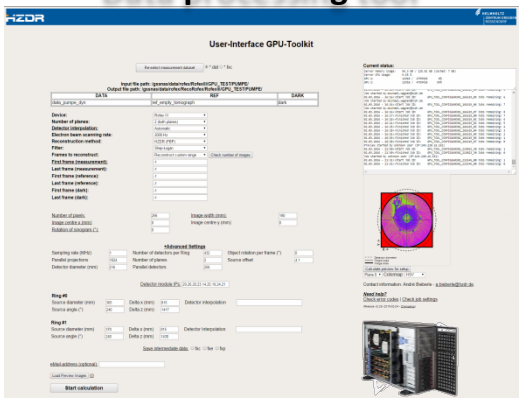


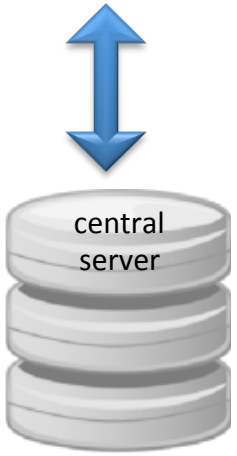
# *Further concepts - Software*

Priority 3




## Data processing tool



# *Conclusion*

- The ultrafast electron beam X-ray CT scanner is very suitable for contact-free multi-phase flow investigations in technical devices. The X-ray CT scanners deliver up to 8,000 frames/s with a spatial resolution of approximately 2 mm.
- Each scanner produces more or less 1 GByte/s of measuring raw data (reconstructed data excluded!). Thus, there is an immense amount of data to be handled.
- A new data processing tool is established that is server-based. Thus, it can be (internally or even externally) used via web browser (OS independent). A job server lists all incoming reconstruction requests. Data is centrally stored (and archived).
- The new data processing tool uses multi core CPU and many core GPU architectures to perform massive data processing. This increases data reconstruction time by a factor of up to 137.
- Because of the strongly reduced data processing time new reconstruction algorithms and other post-processing algorithms (interpolation, image processing, parameter extraction, etc.) can be applied to enhance scientific work.
- A new detector hardware concept is developed and to be installed in the 2$^{nd}$ quarter of 2016. Thus, online analysis will be possible and therefore online process controlling.

## *Acknowledgment*

### Students

- Sebastian Vogt (Practical training & Bachelor student)
- Tobias Frust (Student research project & Diploma thesis)
- Dominic Windisch (Research assistant)
- Jan Stephan (Student assistant)

### Academics

- Michael Wagner (HZDR)
- Matthias Vogelgesang (KIT)
- Michael Bussmann (HZDR)
- Andreas Kopmann (KIT)
- Peter Kaever (HZDR)
- Guido Juckeland (HZDR / TU Dresden)

### Engineers

- Bert Lange (HZDR)
- Torsten Berger (HZDR)
- IT group of HZDR

Thanks for
your attention!