MATTER AND TECHNOLOGIES

Matter and Technologies

Highlights and PoF V Strategy

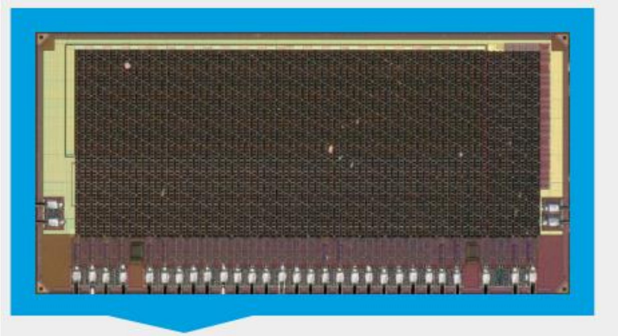
Friederike Januschek

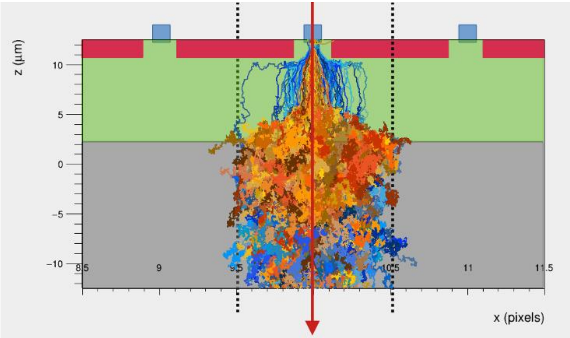
PRC 100 Open Session, 11.11.2025

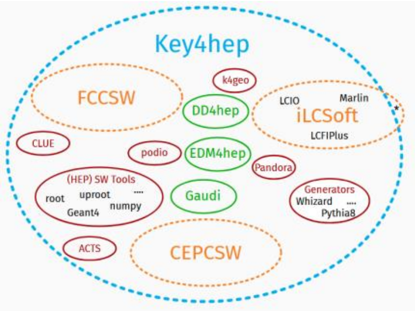
HELMHOLTZ

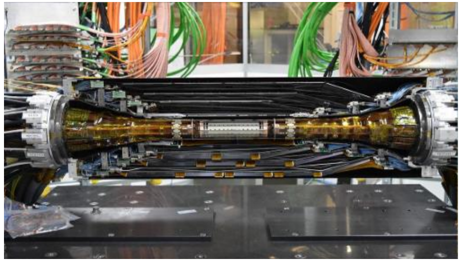
Particle Physics needs cutting-edge technologies

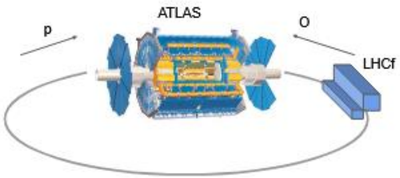
All pictures from the Open Session of the last PRC

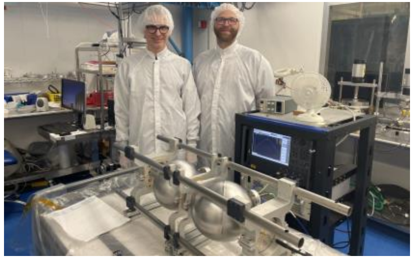


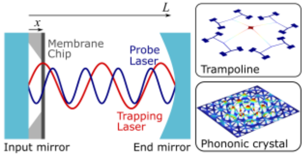












New technologies enable new insights!

Fundamental research in technologies

MATTER AND TECHNOLOGIES MT DESY.

We have identified three key technological areas

- New concepts in acceleration and accelerators – from largest to smallest systems.
- New concepts in sensing and detection – make the invisible visible.
- New disruptive concepts in data-driven research and data science.

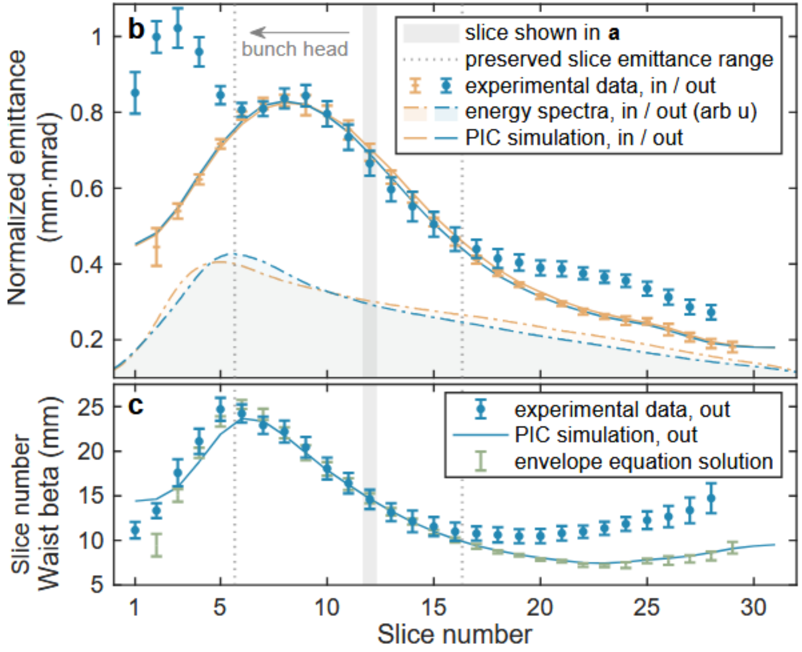
Matter and Technologies – the program for technology research.

We research new and leverage emergent technologies to find solutions for current challenges and create new opportunities with accelerators, detectors and data for the science of today and tomorrow.

Driven by science and driving science.

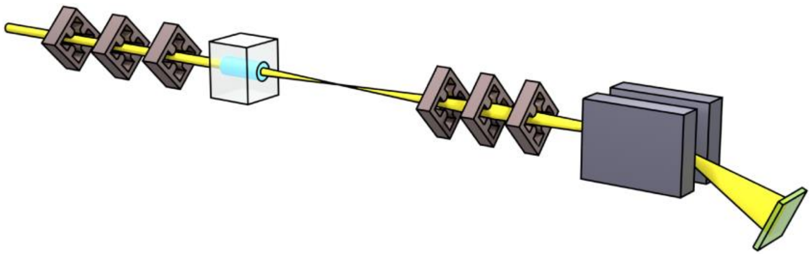
Preserving emittance while focussing

FLASHForward results at arXiv:2509.08420



Emittance preservation with a plasma lens

- Symmetric focussing at kT-MT/m with a plasma lens
- Shown: can be done whilst preserving emittance for many beam slices
- Important to enable staging ➔ crucial step on the road to Plasma Wakefield Acceleration applications



Speeding up MC generation

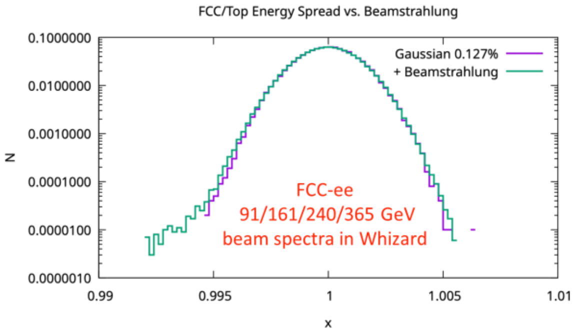
Whizard 3: arXiv: 2507.19285

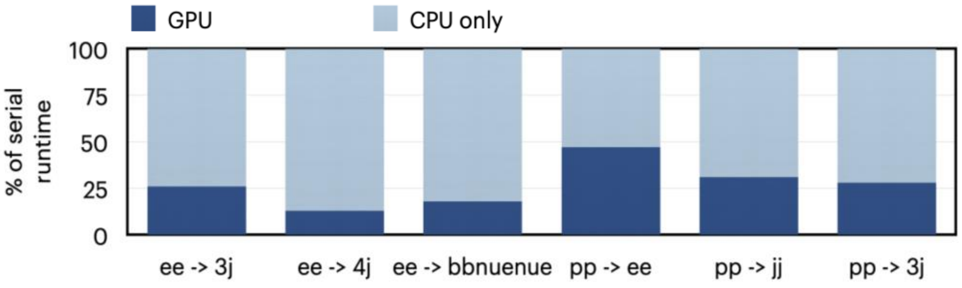
Whizard 3: Complete MC generator for all colliders @ LO/NLO (e.g. NLO QCD+EW for LHC + MuC, EWPDFs, FCC-ee beam simul.)

Fully modular framework of test-driven research software development

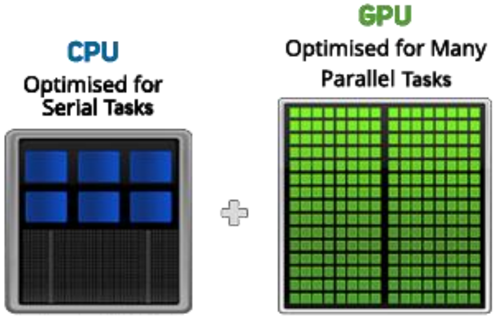
- Performance boosting via GPU offloading, MPI parallelization, ML phase space sampling
- Matrix elements + phase space integration + event generation on GPU e.g. MPI brings complex phase-space integration down from weeks to hours

Lepton collider beam simulations (Gaussian spread, parametrized fit)





Benchmarking of LO integration on CPU vs. GPU

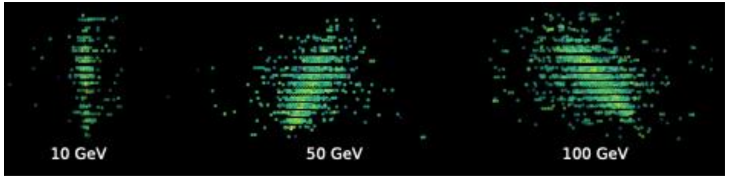


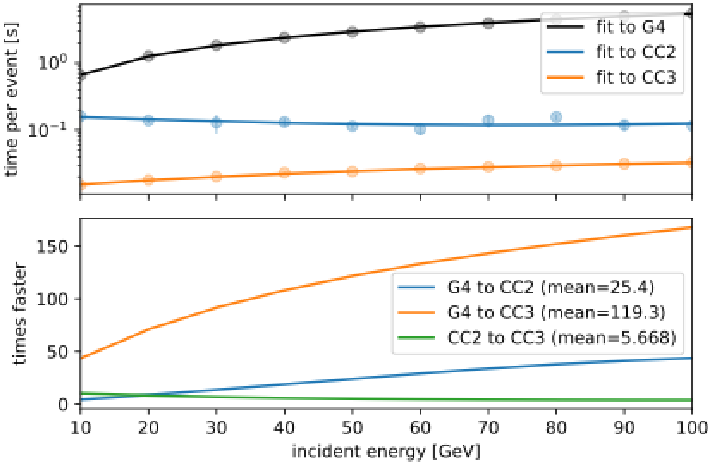
Using AI to simulate EM-showers much faster

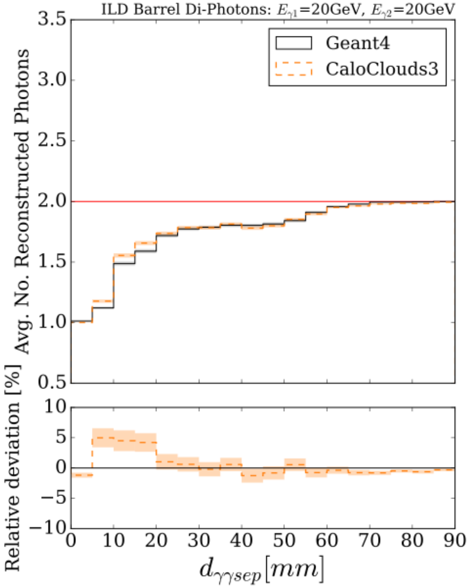
… but with (nearly) the same precision **arXiv:2511.01460**

- CaloClouds3: **50** times (10 GeV) – **150** times (100 GeV) faster than Geant4 on single CPU

- Agreement with Geant4 – after **full reconstruction** – on **physics observables** (di-photon separation, π^0 eff. in $\tau^+\tau^-$ events)

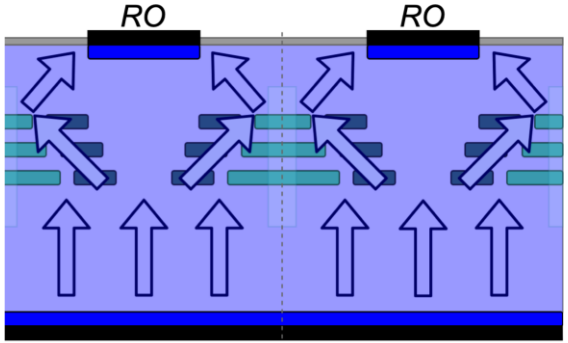






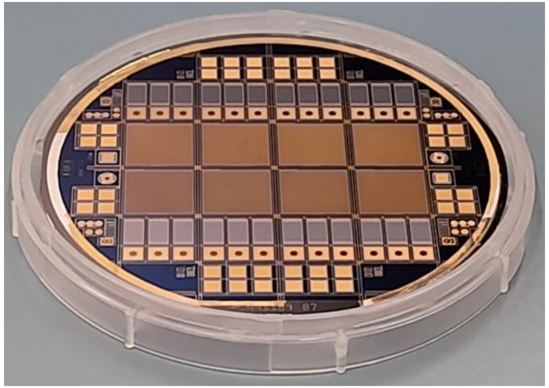
Improving Spatial Resolution by Charge Sharing

The Enhanced Lateral Drift (ELAD) Sensor Prototype has arrived

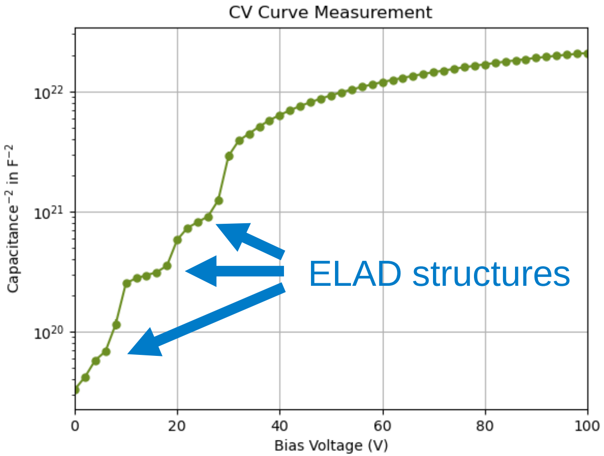


Silicon sensor design developed at DESY

- Featuring **deep implant layers** (regions of additional doping) to locally engineer the electric field inside the sensor bulk
- Modified drift path of charge carriers results in increased charge sharing and thus an **improved spatial resolution**
- Potential application: tracking detectors for future lepton colliders

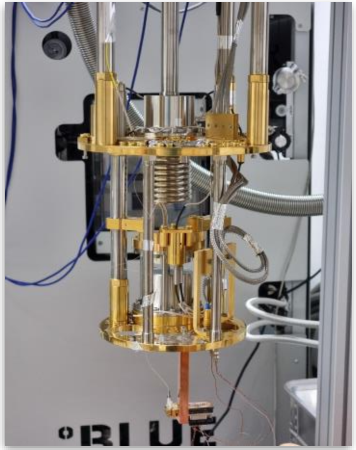


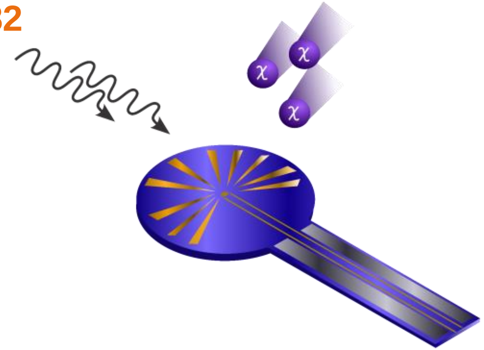
Prototypes have arrived and are being tested. First results look promising.



Searching for dark matter with a 0.2 ng detector

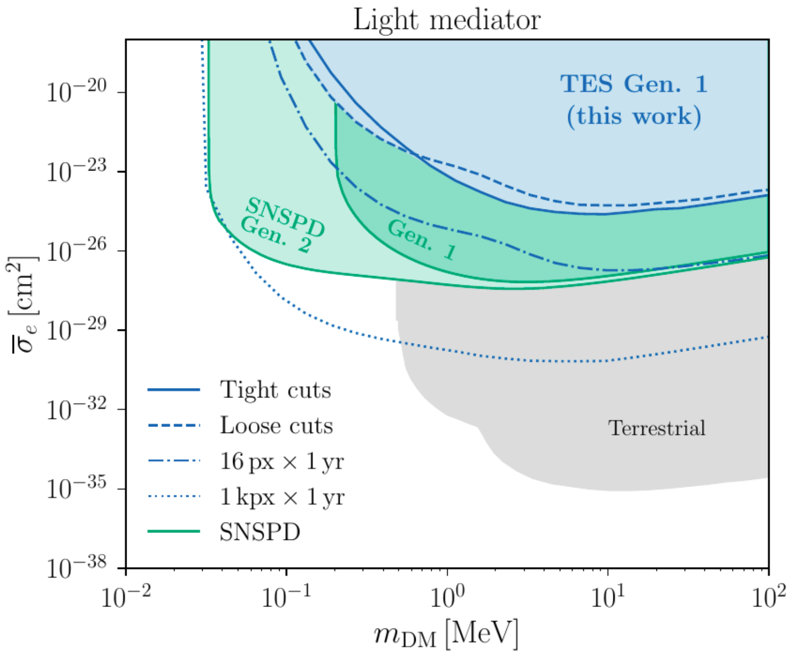
First results: arXiv:2506.18982





Superconducting detectors are promising for sub-MeV dark matter searches

First direct search for light dark matter interactions in a **transition-edge sensor** (use of the TES as target and sensor simultaneously) ➔ Successful proof-of-concept study



Overburden effects need to be considered above approximately the order of 10^{-24} cm^2

Helmholtz *Matter*

MATTER AND THE UNIVERSE MU

Topic **MU-FPF**
Fundamental Particles and Forces

Fundamental Interactions
Pushing the limits of our under-standing of fundamental interactions

- EW precision and Higgs physics (HH, H potential)
- SF QED
- QCD (incl. lattice and QC)
- Probing SM extensions

The Origin of Mass
Covering the puzzle of the origin of mass and of flavour, and the imbalance between matter and ant-matter in the universe

- EWSB
- Higgs portal
- Top, beauty, tau physics
- CPV
- LFU

The Early Universe
Exploring the evolution of the early universe and the nature of the dark sector

- Cosmology (inflation, …)
- DM searches (WIMPs, axions, ALPs, …)
- GW
- EW phase transitions

MATTER AND TECHNOLOGIES MT

Accelerator R&D (ARD)
Accelerator Science and Technology for highest performance and sustainability

- SRF systems
- Hadron & electron acc.
- Beam control, diagnostics, dynamics
- Plasma accelerators

Detector Technologies and Systems (DTS)
Advancing discovery through world-leading detector innovation

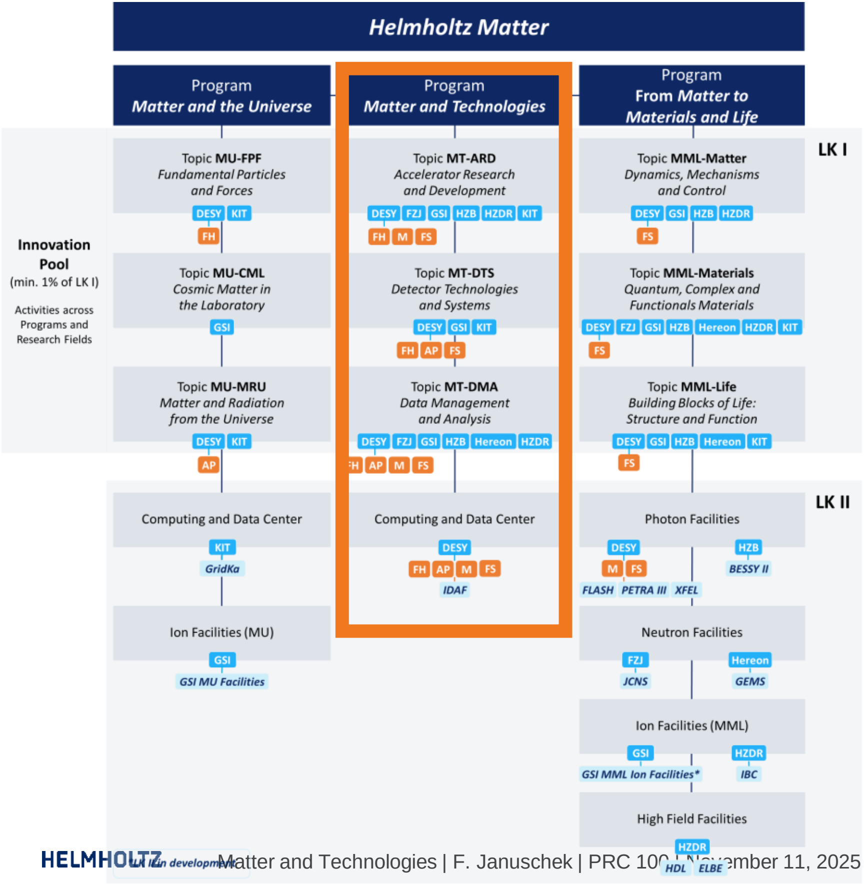
- Sensing and detecting
- Quantum technologies
- Systems and systems technologies
- Detection methods

Data Management and Analysis (DMA)
Enabling and accelerating MATTER science with frontier digital solutions

- Frontier methods in computational and data science
- Sustainable solutions
- Innovation for research infrastructures

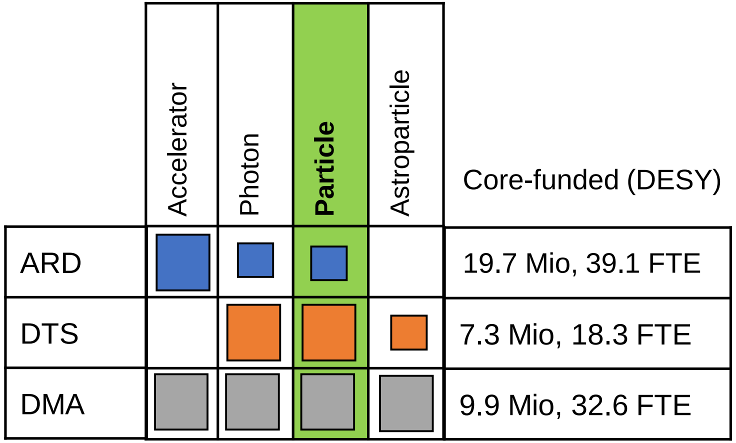
Technologies cross borders

MT as a program in our research field is cross-center, but also cross-division at DESY



PoF IV

Mapping to DESY divisions



DESY-FH has large contributions in MT-DTS and MT-DMA and a smaller, but important contribution in ARD.

FH: Technology-Platforms

- Technology development within MT strongly linked to the other two programs MML and MU (Matter and the Universe, which includes particle physics)
- Within FH: detector physicists and scientific computing experts are part of experiment groups/IT
- **Detector R&D** and **Scientific Computing platforms:** horizontal to this group structure ➔ bring people together and link between MT and MU.
- Steering groups with experts from the FH groups.
- No regular personnel
- But: two postdoc positions (2+1 y) for cross-group scientific computing projects per year.
- Organise seminars, meetings, strategy discussions etc.

Selection of key technological goals within FH

Our strategy for the next funding period

Beam-driven plasma accelerator stage with high quality, high efficiency and high average power at 1GV/m

Going to higher energies, staging

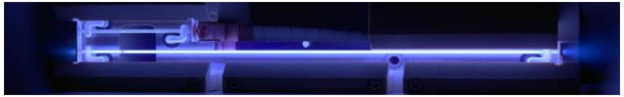
Move towards a full 5D-tracking/calorimeter system

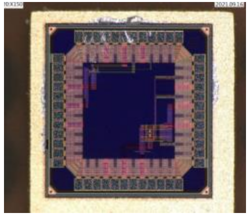
Enable quantum detectors

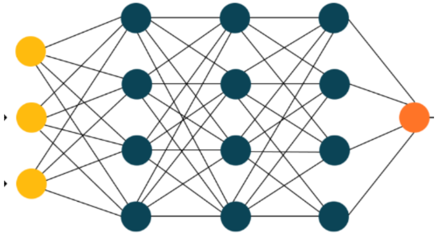
Maximising data processing on the detector

AI for autonomous beamlines, autonomous experiments, monitoring and digital twin technology

Develop quantum computing solutions and algorithms







Accelerators: Mid-term future

Develop a self-consistent plasma-accelerator stage

with high quality, high efficiency and high average power at 1 GV/m

High beam quality

Low energy spread

Emittance preservation

High efficiency

Driver depletion

Plasma-to-witness efficiency

High average power

Rapid recovery time

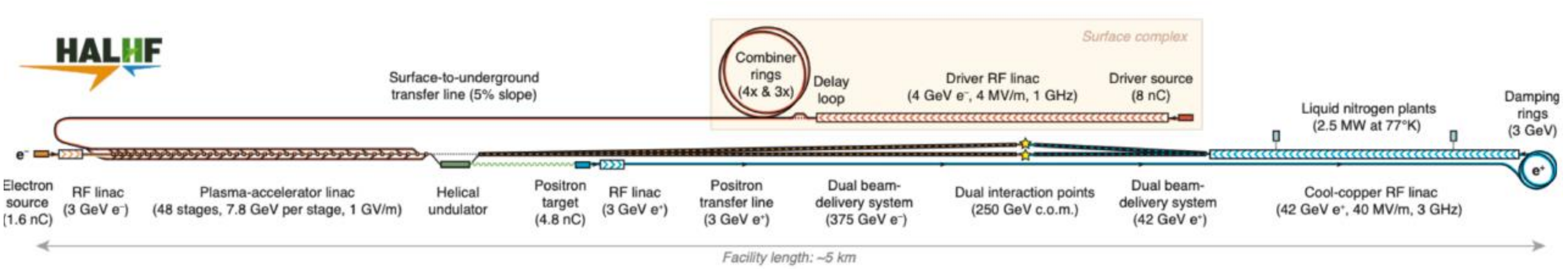
High repetition rate

All combined with >1 GV/m with energy gain as large as possible and as stable as possible.

Accelerators: Longer-term goals

Going to higher energies

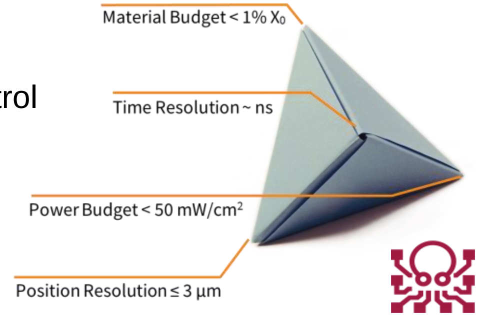
- Possible high energy gain experiments at ELBEX / EuXFEL
- Stacking of multiple plasma modules to get to very high energy

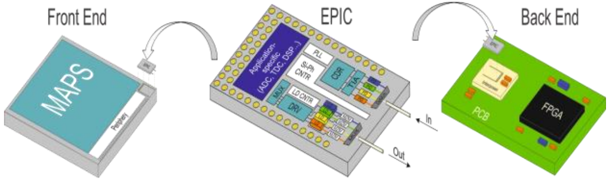


Any staging requires energy doubling, beam quality and probably high repetition rate – all being studied at FLASHForward .

Detector strategy

- Next generation **trackers** and **calorimeters** are required to provide **high resolution**, additional measurements such as **timing** and **energy**, while consuming **little power** at **reduced non-detection related mass**.
- Maximising **data processing on the detector** is paramount to achieve performance targets and to keep the needed data transfer under control.
- Strategy:
  - High level of integration allows for scalability while keeping system complexity under control
  - High bandwidth data transfer at low power consumption
- Key technologies to address these challenges
  - CMOS based sensors
  - Photonic transceivers
  - Advanced interconnects and wafer bonding
  - Advanced cooling techniques

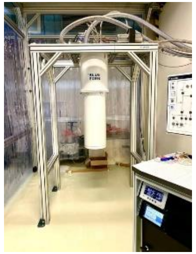




Detector strategy: Infrastructures

Infrastructures play a key role for detector development and its strategy at DESY

- Test beam: Essential work horse for detector development in particle and nuclear physics.
- Detector Assembly facility (DAF): Large clean rooms
- Smaller detector labs
- Workshops

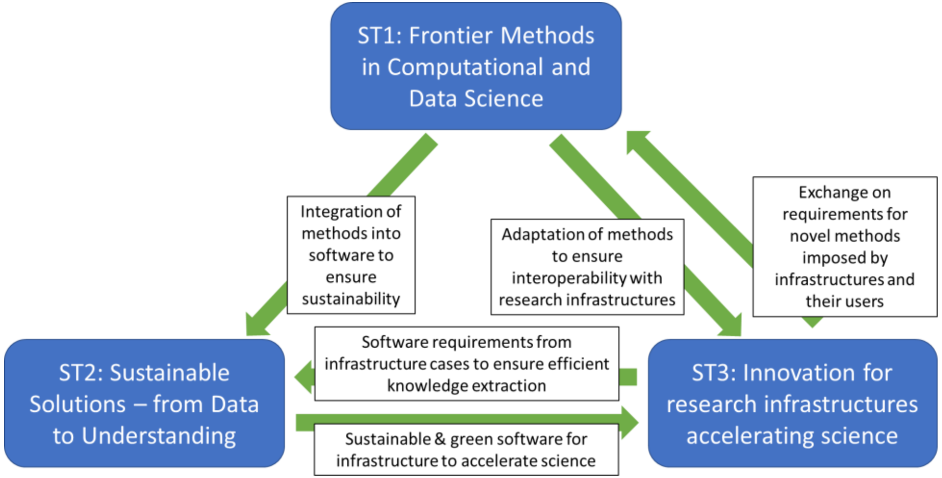


Data/Scientific Computing strategy

DMA in PoF V: Novel Methods, Sustainability, Infrastructures

➔ AI as a cross-cutting theme

- Key DESY-FH topics:
  - Data- and Metadata storage (e.g. dCache, MDC for on-site)
  - Research software engineering (e.g. key4HEP)
  - Autonomous experiments (autonomous beamlines a key topic within DESY, might profit)
  - Sustainable dynamic energy use and resource provision for large infrastructures
  - AI-based procedures for monitoring and digital twin technology for distributed computing infrastructures (IDAF)
  - Quantum computing applications
- IDAF as key Matter infrastructure



Summary

- Technology development is an important and successful part of FH science activities
  - Accelerator development
  - Detector development
  - Data science
- Matter and Technologies is a unique program for technology research, that is cross-center and cross-division at DESY
- For FH, the technology platforms play an important role
- MT at DESY-FH is very well positioned for PoF V
- Strategy focus for the next funding period:
  - ARD: Plasma (FLASHForward)
  - DTS: Systems, Pixel detectors, Data
  - DMA: Novel Methods, Sustainability, Infrastructures

Backup

MATTER AND TECHNOLOGIES

MT IDAF

Interdisciplinary → Photon science MML Accelerator R&D MT (Astro-)particle physics MU

Data and → Data centric concepts and implementation

Analysis → Designed for the diversity of analyses

Facility. → Supporting the complete data lifecycle

- Key goals for PoF V
  - Enabling the large, PoF V data sources (HL-LHC, PETRA IV, BELLE, CTAO, XFEL)
  - Serving the smaller onsite experiments
  - Digital twin for sustainable data center
  - Integration of AI at all levels of user interaction
  - Support novel analysis techniques (e.g. columnar analysis): Interplay Users<==>IDAF
  - TIER Upgrade

MT-ARD

MATTER AND TECHNOLOGIES

Continuous development of the very successful ARD sub-topic structure

	2021 – 2027 PoF IV	2028 – 2034 PoF V
ST1	Advanced CW SRF-Systems	SRF systems for sustainable applications
ST2	New Concepts and Prototypes for Maximizing the Performance of Hadron & Electron Accelerators	Efficient and High-Performance Hadron & Electron Accelerators
ST3	Advanced Beam Control, Diagnostics and Dynamics	Tailored 6D Beam Dynamics, Diagnostics, and Intelligent *(Beam)* Control
ST4	Ultra Compact, Novel Accelerators and their Applications	Plasma Accelerators and their Applications

5 centres & 2 Institutes

DESY. GSI HI JENA HIM HZB KIT HZDR

R&D for outstanding science & technologies

& disruption

Within PoF V DESY will contribute to all subtopics, with a clear focus on ST3 (Beam Control) and ST4 (Plasma)

Contribution to Competence Team Optical Technologies (OPT)

MT-DTS @ PoF V

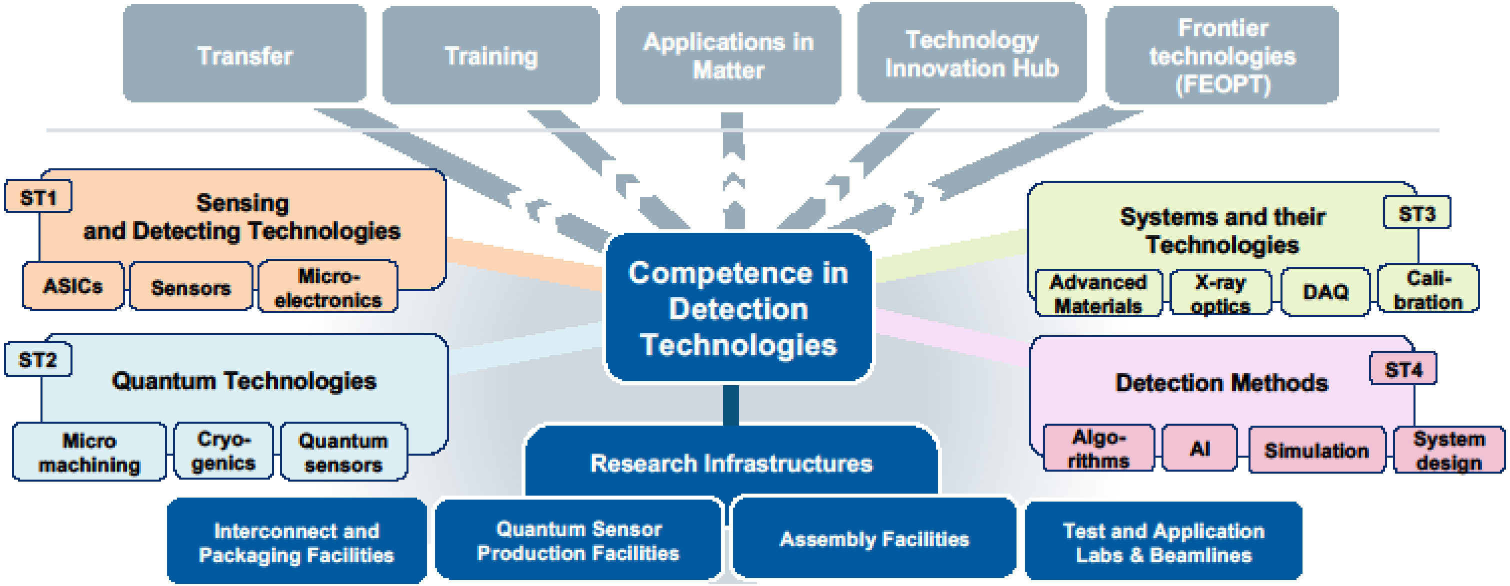
Preliminary structure

Detector Technology and Systems (DTS)

ST1	ST2	ST3	ST4
Sensing and Detecting Technologies	**Quantum Technologies**	**System Technologies**	**Detection Methods**
“Realize intelligent and compact granular detectors with high space and time resolution”	“Establish highly pixelated quantum sensors with ultimate energy resolution”	*“Build sustainable detector systems and cope with drastically increasing data rates”*	“Integrate advanced detector systems into multidimensional modalities for scientific discovery”

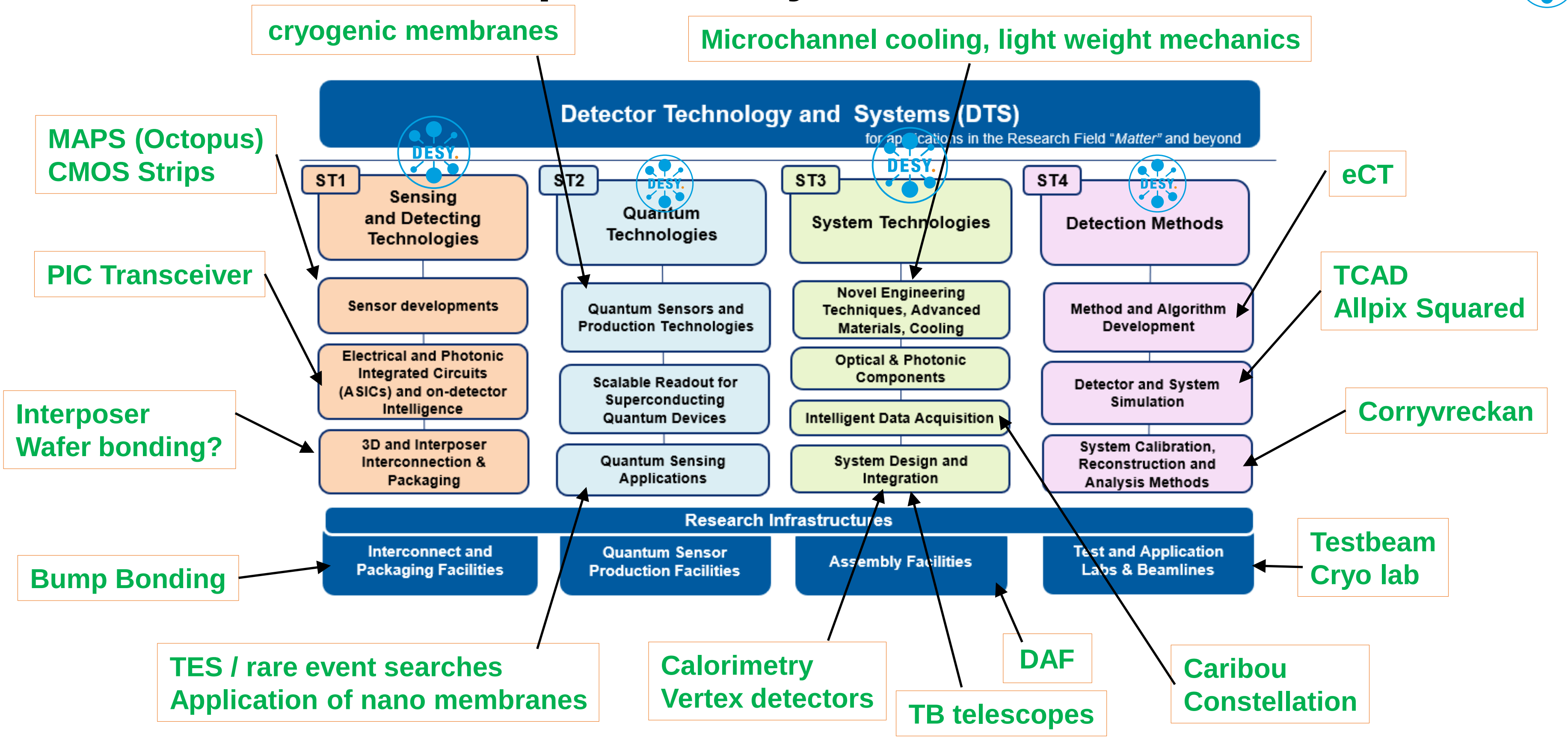
MT-DTS @ PoF V

Structure



- New sub-topics: Quantum, Detection Methods
- DESY-FH subtopic conveners: Simon Spannagel (ST1), Steven Worm (ST2), Moritz Guthoff (ST3)

DTS FH activities in preliminary PoF V structure



MT-DMA

Refining the PoF IV structure for a sustainable future of data-driven science

	2021 – 2027 PoF IV	2028 – 2034 PoF V
ST1	The Matter Information Fabric: F.A.I.R. Data Management	Frontier Methods in Computational and Data Science
ST2	The Digital Scientific Method: Exascale, AI, Quantum	Sustainable Solutions – from Data to Understanding
ST3	The Digital Experiment & Machine Fast feedback, online analysis	Innovation for research infrastructures accelerating science

Contributions to OPT-FE visible in all subtopics, highlighting synergies

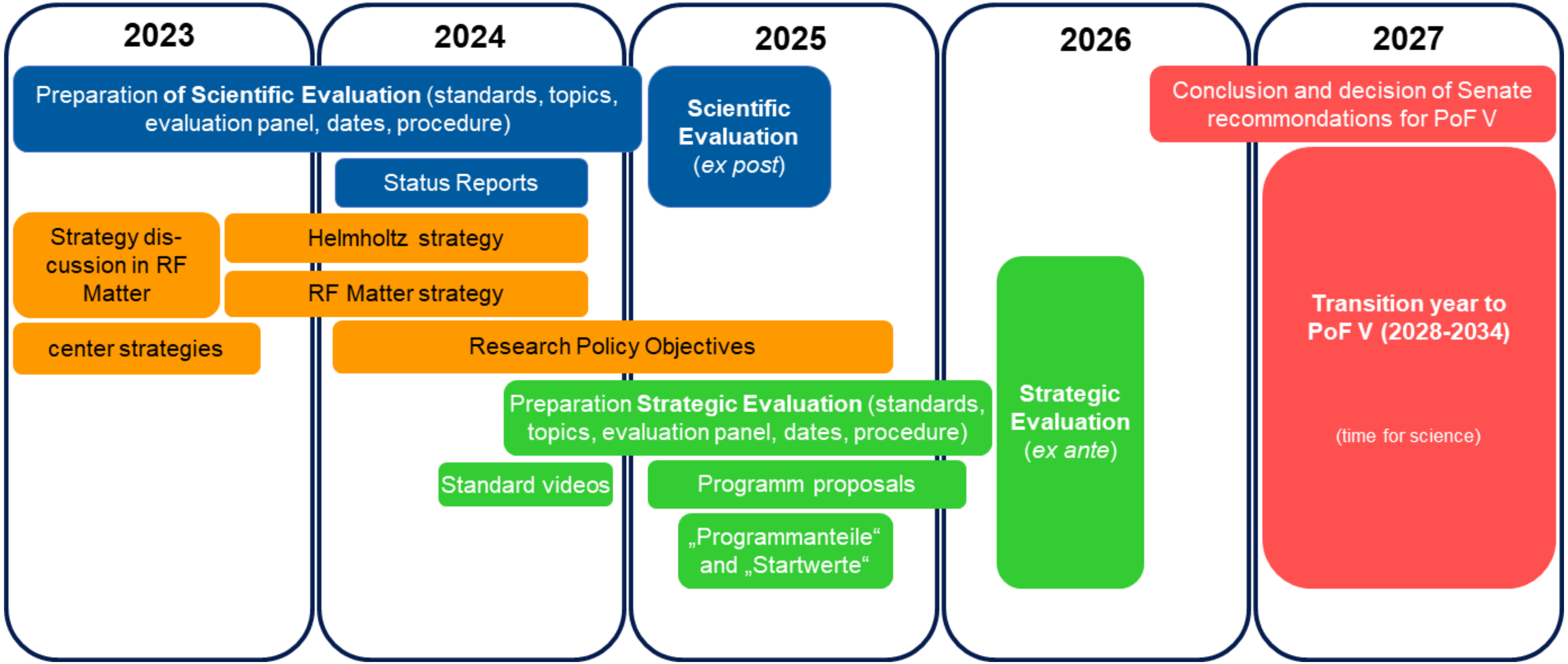
5 centres & 3 Institutes

The focal point of Helmholtz Matter **digitalization**

Timeline for PoF V

MATTER AND TECHNOLOGIES MT DESY.

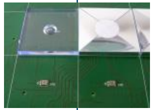
Preparations for PoF V in full swing



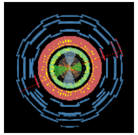
Topics of Interest & Connections to DRDs

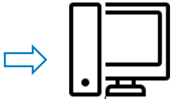
Silicon detector development is a strong focus of our interest
- Monolithic CMOS
- Novel sensors (ELAD, digital SiPM, …)
- Software tool developments
- Involvement in DRD3 (Silicon)

Calorimeter developments
- Highly granular SiPM on tile calorimeter
- Involvement in DRD6 (Calo)



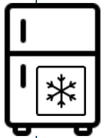
Data transfer
- Silicon photonics
- Advanced interconnects
- Involvement in DRD7 (Electronics)





Integration
- Detector integration center
- R&D on light weight mechanics, local cooling and cooling systems
- Involvement in DRD8 (Integration)

Cryogenic detectors
- Transition Edge Sensors
- Developments for axion/dark matter experiments
- Involvement in DRD5 (Quantum sensors)



Infrastructure
- Detector Assembly Facility
- Test beam

Cross topic goal: Build a demonstrator vertex detector based on CMOS technologies

Technologies for Fusion Energy and Frontiers of Optics

Key technology areas

- High energy and high-P_{av}- pulsed lasers
- Ultrafast laser systems
- Laser and particle diagnostics and sensors
- Silicon photonics
- Modern X-ray optics
- Tritium technologies
- Magnet development
- Data, KI, controls and simulations

These innovation areas will have major impact on our facilities and Germany's technological sovereignty in research and innovation.