ACCELERATORS VALIDATING ANTIMATTER PHYSICS

A Marie Skłodowska-Curie European Training Network

THE GIRL BEHIND THE NAME

Ava Scott loved Build-a-Bears, zip wires, climbing in the park and playing with her friends. She always had a smile on her face and happiness in her eyes.

But in July 2012 her world changed forever. Ava was diagnosed with Ewing's Sarcoma, a cancerous tumour in her leg. Ewing's Sarcoma can develop anywhere in the body, although it most often starts in the bone. Fewer than 30 children in the UK develop Ewing's sarcoma each year.

Ava undertook six rounds of VIDE chemotherapy, removal of her femur and over fifty sessions of radiotherapy. So much time was spent in hospital that it caused her to constantly pick up infections.

She battled her illness with dignity and never complained about the treatment. Sadly, on 21st September 2013, Ava lost her battle. She was only 8 years old.

This project was named after Ava to honour the life of an inspiring little girl who touched our hearts.

CONTENTS

ACCELERATORS VALIDATING ANTIMATTER PHYSICS

The AVA (Accelerators Validating Antimatter physics) project is an Innovative Training Network that has received 4 Million Euro of funding within the H2020 Marie Skłodowska-Curie Actions.

The project enables an interdisciplinary and cross-sector program on antimatter research and development. The network partners include most of the European expertise in antimatter research and joins four universities, eight national and international research centers and thirteen partners from industry and government.

Within the AVA R&D project, partners carry out research across three linked scientific work packages. These cover facility design and optimization, advanced beam diagnostics and novel low energy antimatter experiments.

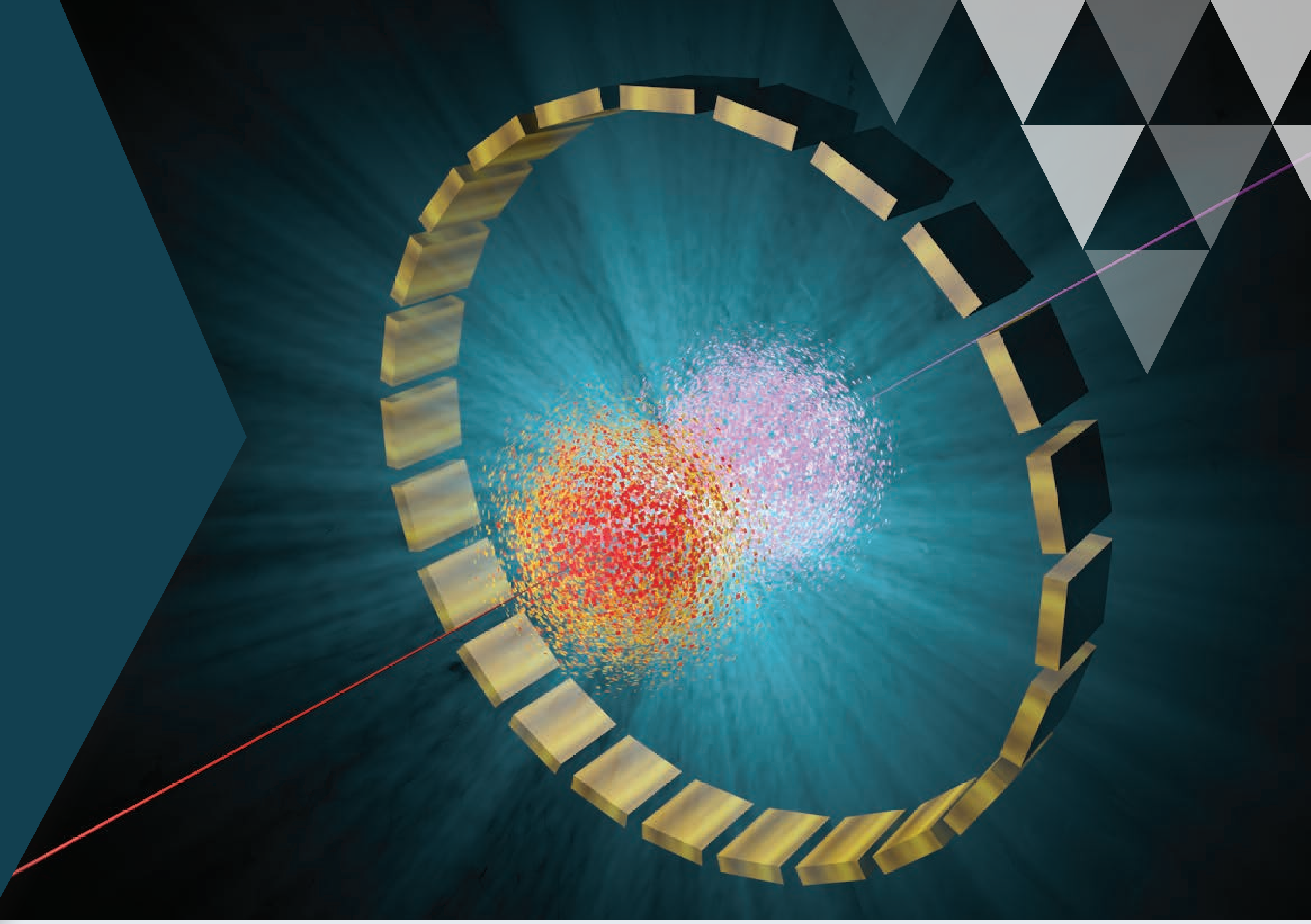
Fifteen early stage researchers have been recruited to established scientific teams. A structured combination of local and network-wide training is offered within AVA. This includes hands-on training with state-of-the-art accelerator facilities, as well as an international training programme consisting of schools, topical workshops and conferences that is open to all AVA Fellows, as well as the wider scientific community.

The AVA project is managed by a Supervisory Board made up of project partner representatives. A smaller Steering Committee comprising selected senior scientists from the partners oversees the Fellows' training and the overall project management.

During the first moments of the Big Bang, both matter and antimatter should have been created in equal amounts. But the observable universe is mainly matter and there remains a fundamental question to be answered by physicists:

Where has all the antimatter gone ?

ANTIMATTER PHYSICS

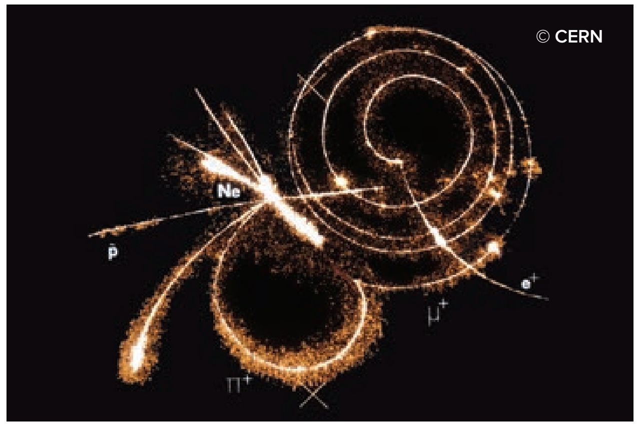


Antimatter was predicted in 1928 by Paul Dirac and its existence was confirmed in 1932 when Carl Anderson discovered the positron.

Antiprotons were first created artificially in 1955 at Berkeley. Antiparticles are created naturally in extreme environments where high energy particle collisions take place, such as thunderstorms or when cosmic rays enter the earth's atmosphere. Antimatter is created in minute amounts and is immediately annihilated on contact with matter; the collision between a particle and its antiparticle leads to an annihilation event with energy released according to $E=mc^2$.

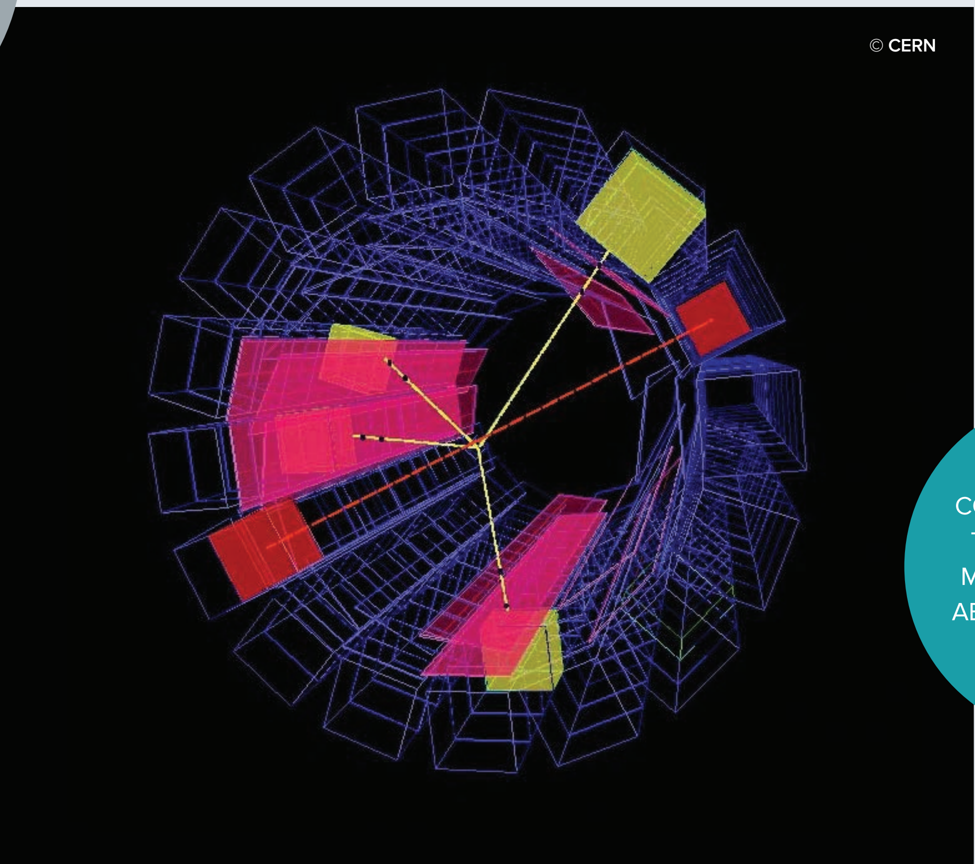
The less energy antiprotons have, the easier it is to study and manipulate them. Reducing the energy of antimatter (a process often referred to as decelerating or cooling) is one of the major aims of the AVA project.

CERN is currently the only place in the world where scientists routinely create and study antiprotons. The process begins with a beam of extremely high energy protons being fired onto a metal target. In particle accelerators, matter and antimatter particles are always produced as a pair and they have extremely high energies. One of the major scientific achievements at CERN is the ability to isolate and trap antiprotons before they annihilate, and to reduce their energy to a level at which meaningful measurements may be made.



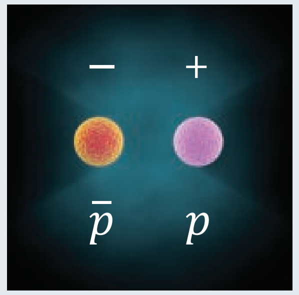
ANTIMATTER WAS PREDICTED IN 1928 BY PAUL DIRAC AND ITS EXISTENCE WAS CONFIRMED IN 1932 BY CARL ANDERSON. ANTIPROTONS WERE FIRST CREATED ARTIFICIALLY IN 1955 AT BERKELEY.

Pictured below: Matter-antimatter annihilation in the ATHENA experiment at CERN. The antiproton produces four charged pions (yellow) whose positions are given by silicon microstrips (pink) before depositing energy in CsI crystals (yellow cubes). The positron also annihilates to produce back-to-back gamma rays (red).



Antimatter particles have the same mass as their matter counterparts, but properties such as electric charge and magnetic moment are opposite.

The antiproton $\bar{p}$ has the same mass and spin as a proton (p) but carries a negative charge.



WE ARE ALL CONCERNED ABOUT THE THINGS THAT MATTER, BUT WHAT ABOUT THINGS THAT ANTIMATTER?

The Antiproton Decelerator **(AD)** and the Extra Low ENergy Antiproton **(ELENA)** rings are facilities at CERN designed to trap, store and facilitate antimatter research. They help scientists understand fundamental properties of antimatter and to advance fundamental scientific knowledge.

ANTIPROTON DECELERATOR (AD)

Photograph of the AD storage ring © CERN.

Accelerator science is still a new academic area where only limited targeted training is provided around the world. The institutions behind AVA have pioneered a number of training initiatives in this area.

Accelerator science covers the design and optimization of machines that can bring charged particles to high energies. These **particle accelerators** are a key underpinning technology for fundamental science and numerous society applications. Amongst others, they allow creating antimatter particles, as well as slowing down these exotic and short-lived particles, so that meaningful measurements can be made with them.

The AD began operations in 2000. Antiprotons are decelerated to an energy of 5.3 MeV and are ejected to one of several connected experiments including:

- **AEgIS** (Antimatter Experiment: gravity, Interferometry, Spectroscopy) which compares the effects of gravity on antimatter and matter
- **GBAR** (Gravitational Behaviour of Antihydrogen at Rest) will measure the free fall acceleration of ultracold, neutral antihydrogen atoms
- **ASACUSA** (Atomic Spectroscopy And Collisions Using Slow Antiprotons) will precisely measure the hyperfine structure of antihydrogen and compare it to the well-known value for hydrogen
- **BASE** (Baryon Antibaryon Symmetry Experiment) will measure the charge-to-mass ratio and the magnetic moment of antiprotons
- **ALPHA** makes, captures and studies antihydrogen atoms and compares them with hydrogen atoms

ELENA © CERN

THE ELENA RING HAS BEEN DESIGNED TO REDUCE ANTIPROTON ENERGIES TO BELOW 0.1 MEV

EXTRA-LOW ENERGY ANTIPROTON RING (ELENA)

ELENA is a small, 30 m synchrotron ring designed to cool the 5.3 MeV antiprotons from the AD even further. Following successful trials ELENA is expected to be fully operational in 2018.

ELENA will improve the conditions for antimatter experiments dramatically. The less energy antiprotons have, the easier it is to study and manipulate them. The ELENA ring has been designed to reduce antiproton energies to below 0.1 MeV. In addition, the beam density will be improved, increasing antiproton trapping efficiency between 10 and 100 times. ELENA will also enable different experiments to receive antiproton beams simultaneously.

Physicists have already used the AD to measure the magnetic moment of the antiproton with more precision than for the proton, an extraordinary achievement.

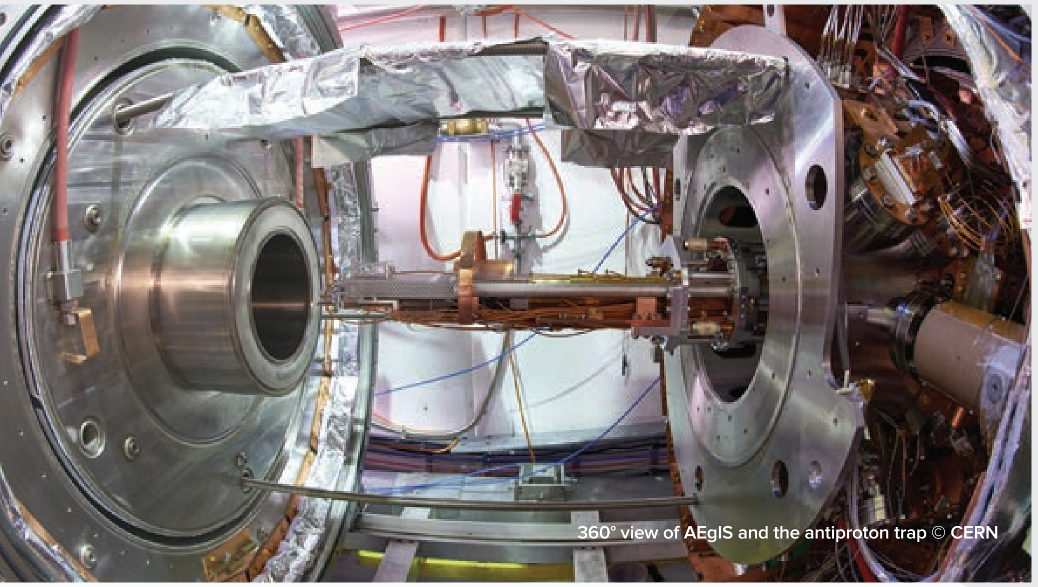
ELENA will allow new experiments into the fundamental properties of antimatter, such as GBAR, to be undertaken.

The new FAIR complex and large accelerator ring in the forest © FAIR

AVA research that contributes to ELENA will also contribute to **FLAIR**, a proposed Facility for Low-energy Antiproton and Ion Research currently in development at Darmstadt, Germany. ELENA and FLAIR both aim at providing cooled beams of antiprotons at lower energies than achievable anywhere in the world today.

WORK PACKAGE DESIGN AND OPTIMIZATION

The Design and Optimization work package targets improvements in the performance of the ELENA and FLAIR low energy antimatter facilities, addressing keV antiproton beam lifetimes and achievable stability in storage rings, deceleration and extraction through simulation and experimental studies, and new control systems. The Fellows work closely together in order to boost the performance of the accelerators and enable new experiments.



360° view of AEgIS and the antiproton trap © CERN

This work is closely connected to the studies of **Bruno Galante** at CERN who works on the *Generation of Cold Electrons for an eV Electron Cooler.* Electron cooling of the antiproton beam will be essential to reduce or eliminate any **emittance** growth caused by the deceleration process. An antiproton beam with a small **emittance** will be needed for further deceleration and extraction to the trap experiments. Different options for a cold electron source are under investigation, including expected performance and limitations, to improve the understanding of cold electron beam generation. This project involves simulations into the electron source performance, as well as experimental studies for a full characterization of the emitted electron beam.

Electron Cooler at ELENA © CERN.

Existing low energy storage rings have limitations on beam intensity. Amongst others, this can result in a reduced beam lifetime, as observed in experimental studies. The nature of these effects is not fully understood.

Bianca Veglia at the University of Liverpool/Cockcroft Institute works closely with Tech-X and other Fellows studying antimatter experiments on *Beam Stability and Lifetime in low energy Storage Rings.* She develops realistic models for beam transport, storage, deceleration and cooling from storage rings through beam lines to experiments. These allow investigating the effects impacting on beam stability and **emittance**. They also help establish realistic models of beam storage and cooling. Simulation tools developed by her enable start-to-end simulations of antiproton pulses through electrostatic low energy beam lines. She uses these to optimize beam handling by the AVA experiments.

INFO BOX

Emittance is a property of a charged particle beam in a particle accelerator. It is a measure for the average spread of particle coordinates in position-and-momentum phase space. The smaller the emittance, the higher the quality of the beam.

Aerial view of CERN © CERN

A powerful control system which efficiently integrates all experiments, beam handling and transport systems, and diagnostics is crucial for any accelerator based research facility. It should include online capability, fast data exchange, history and error logging, as well as device access across the entire accelerator facility and the experiments. A project based at COSYALB focuses on the *Development of a Versatile Control System* to link all technical and experiment developments within AVA. The primary goal is to enable enhanced communication between all essential devices to enhance accelerator and experiment performance. This includes a flexible machine control system, real-time feedback and development of a precise timing system.

Power supply for accelerators and beam lines © FOTON

INDRAJEET PRASAD IS BASED AT FOTON WHERE HE DESIGNS, BUILDS AND TESTS HIGH PRECISION POWER SUPPLIES FOR USE IN ALL BEAM LINES AND RINGS WITHIN AVA

Critical for beam storage and energy ramping in a storage ring and efficient beam transport from a ring to the experiments, are power supplies that have a stability of better than 10^{-4}, can be ramped over more than one order of magnitude in output voltage in 1 s over a linear ramp and that can be smoothly integrated into the accelerator control system. **Indrajeet Prasad** is based at FOTON where he designs, builds and tests *High Precision Power Supplies* for use in all beam lines and rings within AVA. He is in the process of developing a comprehensive database of the power supply requirements which will be used to define a suitable interface for their seamless integration into the respective accelerator control system. In a next step, he will design prototypes and test them in collaboration with Fellows from across the network.

AVA **FELLOWS**

Bianca Veglia

studied Physics at the University of Turin. During her Bachelor's Degree she had the opportunity to spend a year at the Rheinische Friedrich-Wilhelms-Universität in Bonn joining their Erasmus program. After obtaining her Master's Degree in Theoretical Physics in 2015 she subsequently worked as a credit risk management analyst for a big consulting company. Bianca Veglia is based at the University of Liverpool/Cockcroft Institute where she studies *Beam Stability and Life Time in Low Energy Storage Rings*.

Bruno Galante

obtained his Bachelor's Degree in Physics from The University of Parma in 2014. He continued his studies until October 2016, when he graduated with a Master's Degree and specialization in Physics of matter and Physics of functional materials. During his thesis, he worked on an experimental project called *"Carbon nanostructures for symmetric Supercapacitors"*, testing and , testing and functionalising new nanostructured materials for supercapacitors electrodes. He went on to work for a consulting company as a business analyst and blockchain developer in Dublin and Milan. Bruno Galante is based at CERN and is undertaking his PhD studies on the *Generation of Cold Electrons for an eV Electron Cooler* at the University of Liverpool.

Indrajeet Prasad

graduated with Electronics and Instrumentation engineering from West Bengal University of Technology, India in 2011. His Master's Degree in Control in Electrical Engineering from Wrocław University of Technology, Poland focused on *"Line differential protection insensitive to CT saturation"*. During his Master's Degree, he also undertook an apprenticeship at ABB, Polska for 1 year with a focus on control and automation engineering. He has worked as an Assistant Researcher at Transilvania University of Brașov, Romania on the FP7 Marie Curie Research project EMVeM. Later he joined AGH University of Science and Technology, Poland as a Scientific and Technical Specialist. Indrajeet Prasad is based at FOTON in Czech Republic, working on *High Stability, Rampable Power Supplies for keV Ion Beams.*

DESIGN AND **OPTIMIZATION**

Above:
The Globe of Science and Innovation, CERN. CERN is the only place where antiprotons are routinely produced.

© CERN

ELENA ring © CERN

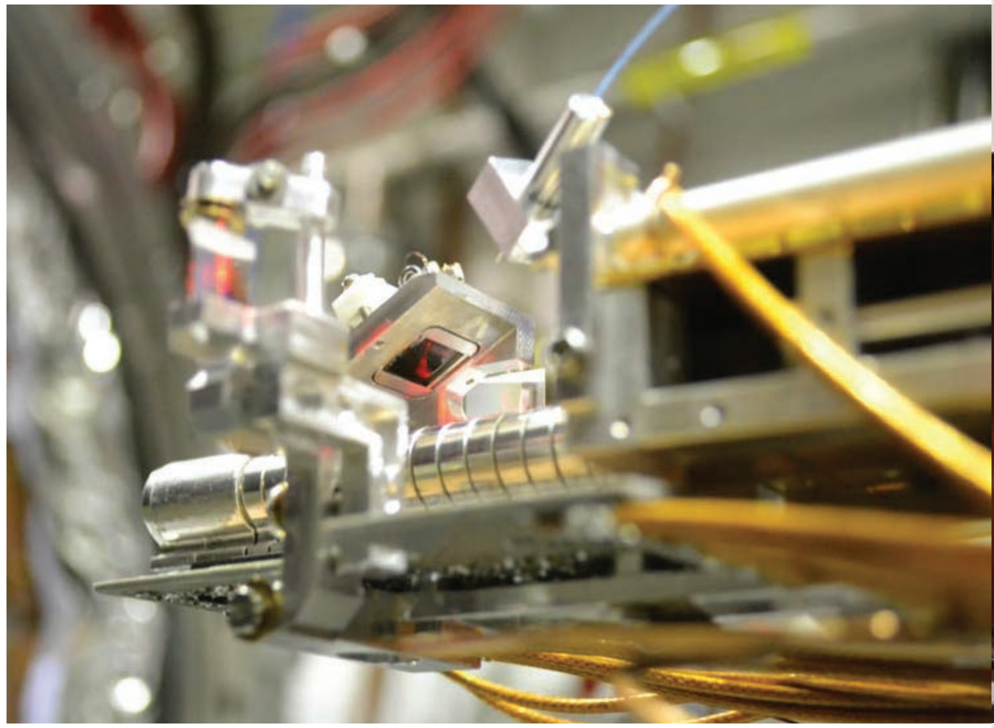
WORK PACKAGE BEAM DIAGNOSTICS

The improvements in simulations of beam storage, handling and control that are being developed in AVA's first work package need to be accompanied by R&D into enhanced Beam Diagnostics that can monitor the properties of a low energy antiproton beam and help verify simulation models experimentally. The research complements work on facility design and optimization and at the same time provides vital information about the beam for detailed studies in the last remaining work package, antimatter experiments. R&D is carried out into beam profile, position and intensity measurement, as well as detector tests with the aim to provide significant improvements in detection resolution and sensitivity.

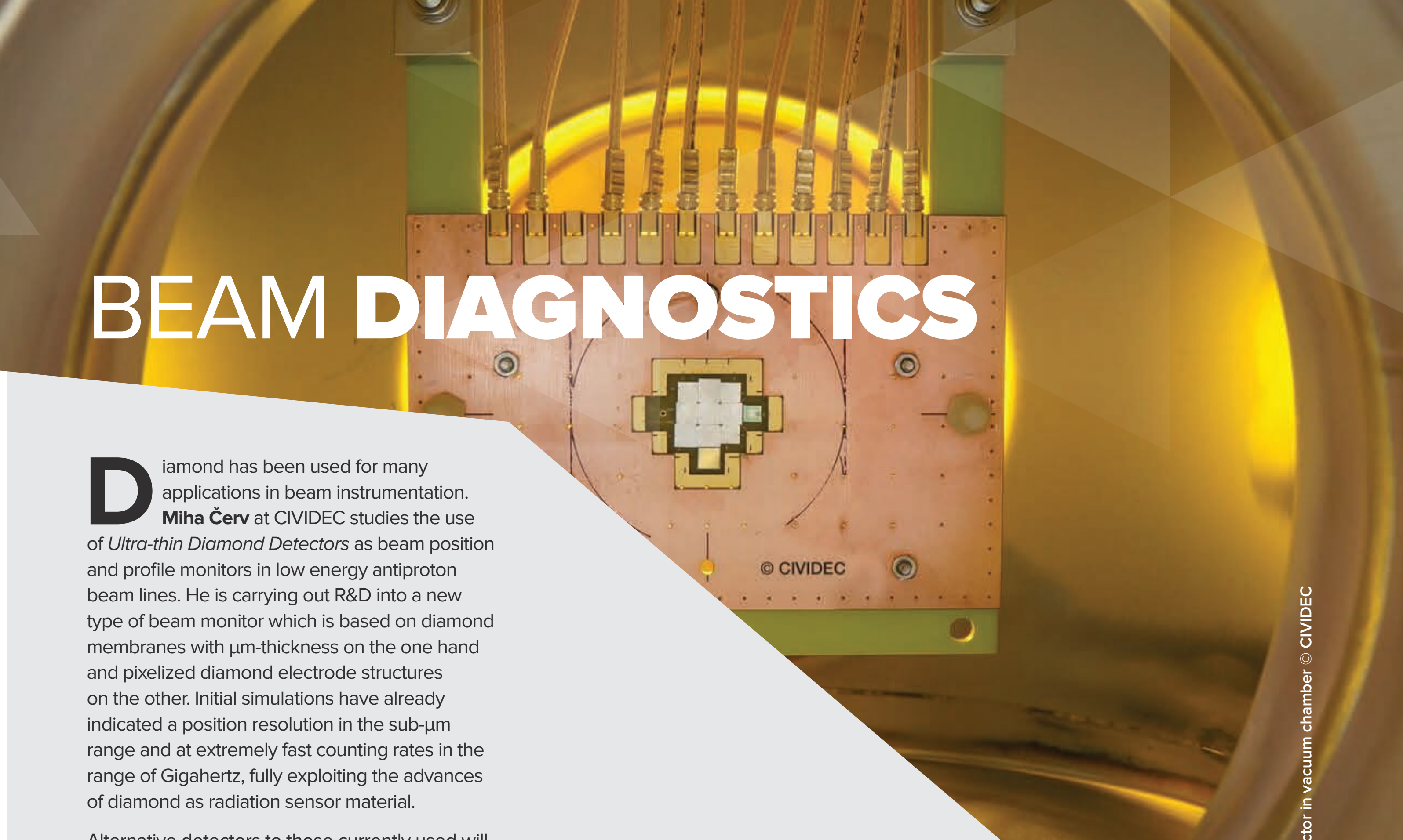
The exact measurement of the beam profile in any accelerator is of great importance for a full understanding of the physical processes happening in the beam. Of particular relevance is the detection of particles in the tail distribution of a beam, the so-called 'beam halo'. This requires the detection of small quantities of light which is often difficult because other parts of the beam yield much higher signal levels. A (digital micro mirror device) *DMD-based Beam Halo Monitor* allows to restrict any measurement to specific 'regions of interest' and is hence a promising tool for imaging of beam parts. At the University of Liverpool/ Cockcroft Institute **Milena Vujanovic** adapts this imaging method for advanced measurements that cannot presently be achieved with any other technique. Working with ViALUX, measurements shall be extended towards emittance and general 6D phase space diagnostics.

For the optimization of any detection techniques it is essential that detailed tests into the monitor characteristics can be carried out on an ongoing basis. As experiments mature, however, opportunities for detector testing decreases. **Mattia Fanì** at CERN is designing an *Instrumentation and Detector Test Stand* to carry out investigations using diamond, liquid and cryogenic detectors developed across this work package over a wide range of beam energies and intensities. Simulations and technical design considerations such as space limitations and vacuum requirements will help make the final stand a polyvalent facility for evaluating the performance of beam instrumentation, adaptable for any low-energy antiproton and ion facility. This work is complemented by the development of a low energy antihydrogen beam.

In any accelerator, non-destructive beam current measurements are required for the optimization of machine performance, as well as for experiments with the beam. The intensity of low energy antiproton beams is typically low, requiring sensitive devices with a detection threshold below 1 nA. Such thresholds can be reached by a SQUID-based measurement of the beam's magnetic field, however this type of advanced monitor still requires a second instrument to provide a meaningful dynamic range. *Ultra-sensitive Beam Intensity Monitors* are not commercially available and are now being developed by **David Haider** at GSI in collaboration with other researchers within this work package.



Above: AEgIS antihydrogen production region © M Doser



Photograph of diamond detector in vacuum chamber © CIVIDEC

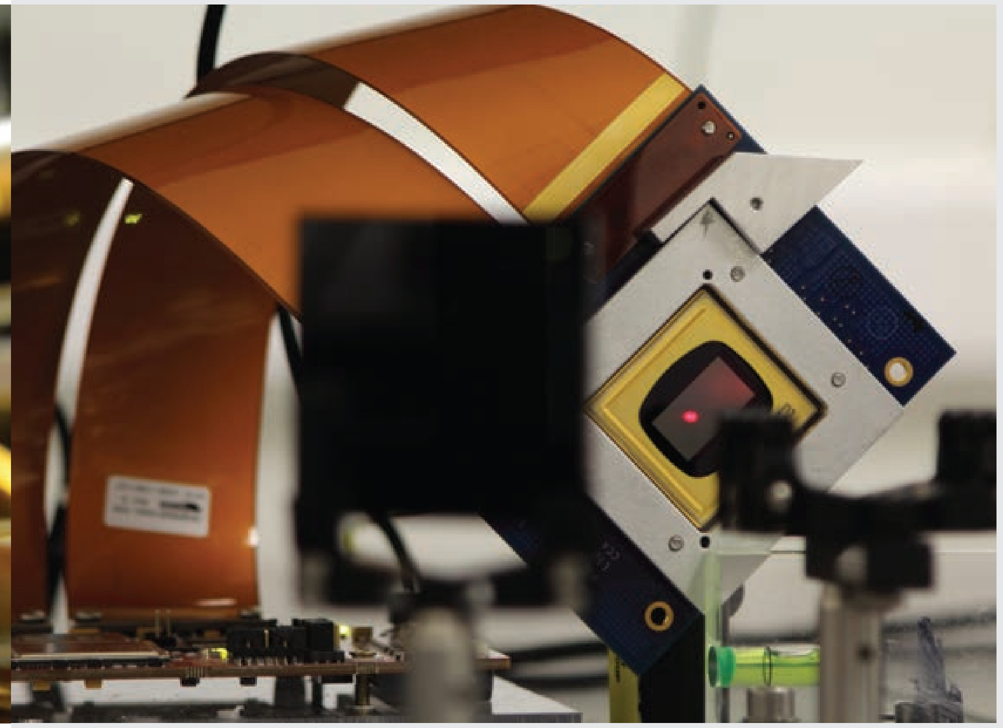
Diamond has been used for many applications in beam instrumentation. **Miha Červ** at CIVIDEC studies the use of *Ultra-thin Diamond Detectors* as beam position and profile monitors in low energy antiproton beam lines. He is carrying out R&D into a new type of beam monitor which is based on diamond membranes with µm-thickness on the one hand and pixelized diamond electrode structures on the other. Initial simulations have already indicated a position resolution in the sub-µm range and at extremely fast counting rates in the range of Gigahertz, fully exploiting the advances of diamond as radiation sensor material.

Alternative detectors to those currently used will be required for beam energies below 100 keV. **Dominika Alfs** works at Forschungszentrum Jülich to identify suitable alternatives, including *Liquid Target-based Antiproton Detectors.* These will trigger annihilation events and shall be used to monitor the beam track via straw tubes or scintillators. Monte Carlo simulation studies have already been carried out to understand the performance limits and key requirements of this detector. A prototype detector is being designed and built for experimental studies and will be the basis for a final design.

CryoAmplifier © Stahl Electronics

AVA BEAM DIAGNOSTICS R&D PUSHES THE BOUNDARIES OF EXISTING TECHNOLOGIES.

The trap experiments at the AD and FLAIR used for precision determination of the antiproton magnetic moment require amplifier technologies with exceptional sensitivity and ruggedness. **Ilya Blinov** is based at Stahl Electronics and links between the company and experts at GSI in Darmstadt to develop single particle *Cryogenic Detectors*. The R&D targets a novel detection system which will be easier to operate, rugged under the adverse conditions found at ELENA and FLAIR, and feature much higher detection sensitivity by using latest generation electronic detectors.



Above: Photograph of DMD-based beam halo monitor

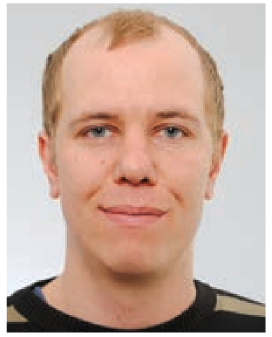
AVA FELLOWS

Milena Vujanovic

received her Bachelor's Degree in Physics from the Faculty of Natural Sciences and Mathematics at the University of Montenegro. After spending three months as a CERN summer student with the Radiation Protection group, she enrolled at the University of Belgrade, Department of Theoretical and Experimental Physics. Milena was part of the AEgIS experiment at CERN for 15 months were she gained expertise in positronium physics, magnetic and electrostatic positron transport, ultra-high vacuums, cryogenic operations, screening of magnetic fields and gamma radiation. Milena Vujanovic is based at the University of Liverpool/ Cockcroft Institute and develops an *Advanced Optical Beam Halo and Emittance Monitor.*

Mattia Fanì

earned his Master's Degree in physics at the University of Bologna with a specialization in nuclear and sub-nuclear physics. During his thesis work he took part in the ALICE Collaboration at CERN, fine tuning existing hardware for the LS2 upgrade. This will allow the time-of-flight detector to register four times more data in *pp* collisions than that initially expected and without any additional cost. He also worked at the LNGS developing a high collection efficiency detector for dark matter experiments. Mattia Fanì is based at CERN, working towards an *Instrumentation and Detector Beam Line and Test Stand.*



Miha Černv

studied electrical engineering at the University of Ljubljana and obtained his Bachelor's Degree in 2012. He went on to work at the Jožef Stefan Institute where he designed devices for use both at the Institute and at CERN. He turned one of the projects into his Master's thesis, which he completed in 2017. During his studies, he did an internship at CERN working with FPGA chips and diamond detectors. Miha Černv is based at CIVIDEC, Vienna, where he develops *Novel Diamond-based Detectors for Beam Characterization.*

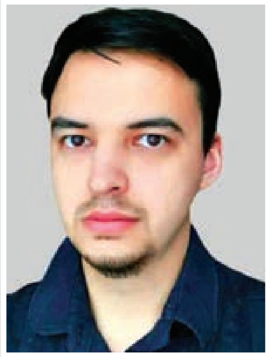
BEAM DIAGNOSTICS

David Haider

undertook his Master's Degree at the Faculty of Physics of the TU Wien, Austria. During his studies, he worked at the Institute of High Energy Physics (HEPHY) in Vienna on the analysis of weak particle decays within the data of the BELLE experiment at KEK, Japan. He worked at the Stefan Meyer Institute for Subatomic Physics (SMI) building a sub-Kelvin refrigerator platform to measure the kaon mass with a calorimetric particle detector. For his diploma thesis, he once again joined SMI, where he refined a scintillating fibre detector and characterized the associated Multi Pixel Photon Counters to verify the production of antihydrogen within the AEgIS experiment. David Haider is based at the Beam Instrumentation Group at GSI, Darmstadt, carrying out *Ultra-sensitive Beam Intensity Measurements.*

Dominika Alfs

graduated from the Faculty of Physics, Astronomy and Applied Computer Science of the Jagiellonian University in Kraków, Poland. Her Bachelor's thesis investigated the impact of introducing small light guides into a single detector module on the time resolution. She joined the P349 antiproton polarization experiment to determine the polarization degree of antiprotons and has worked on data analysis, software development and detectors calibration. For her Master's thesis she performed the drift chamber calibration and prepared methods for 3D track reconstruction and was awarded her degree with distinction. Dominika Alfs is based at Forschungszentrum Jülich, developing *Liquid Target-based Antiproton Detectors.*



Ilya Blinov

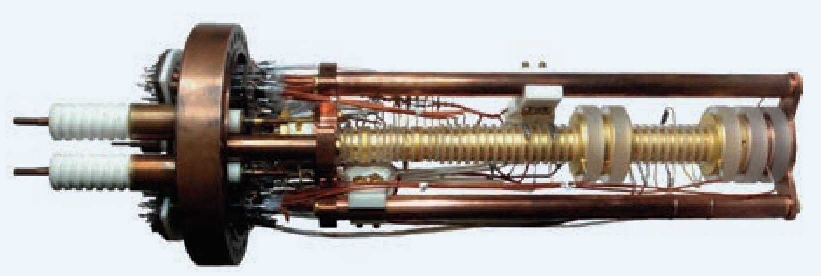
graduated from the Volga State University of Technology (Russian Federation) with a Master's Degree in Design and Technology in Electronics Engineering. For his master's project he designed wireless environment monitoring equipment with low power consumption. After obtaining his degree, he co-founded electronics design company Pharad LLC, where he designed wireless telemetry devices, smart meters and motion control systems. Ilya Blinov is based at Stahl-Electronics and develops *Novel Super-sensitive Charge Sensors for use in Ion and Antimatter Research.*

WORK PACKAGE ANTIMATTER EXPERIMENTS

R&D from the Design and Optimization and Beam Diagnostic work packages paves the way for entirely new low energy Antimatter Experiments. This can include studies into the collision dynamics of correlated quantum systems, experiments into the effects of gravity on antimatter, as well as spectroscopic measurements that give an insight into the structure of antiparticles. A lot of progress has been made in this area and this work package aims at improving measurement precision further still.

The study of the *Collision Dynamics of Correlated Quantum Systems* can be undertaken by crossing a gas jet target with a beam of low energy antiprotons. However, this requires beam compression to a diameter of around 1 mm and a pulse length of 1-2 ns. At the University of Liverpool/Cockcroft Institute, **Volodymyr Rodin** develops a comprehensive simulation framework which shall enable these studies under both ELENA and FLAIR conditions. Compression of the beam is based on higher order harmonic bunching and phase space 'gymnastics' and, for the first time, extended to a full 3D description of bunches motion. He considers all relevant effects on the beam, such as intra-beam scattering, phase space rotation, scattering and cooling. Studies of in-ring schemes are being done along (quasi) single-pass setups where the spectrometer would be installed in an external beam line or a dedicated small storage ring.

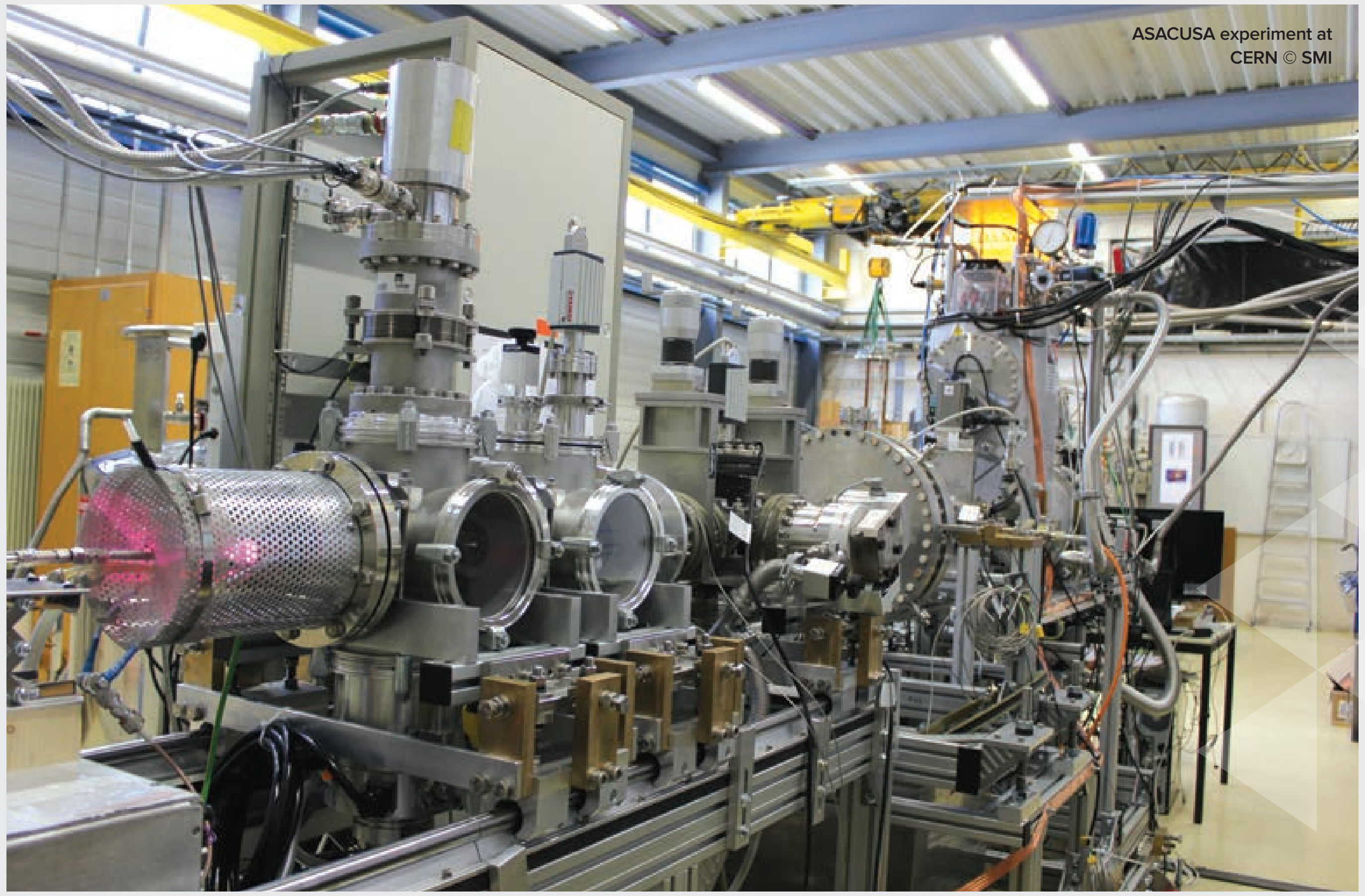
Reservoir trap as used in the BASE experiment © CERN.



In order to make experiments independent of accelerator-beam time cycles and shut-down periods it would be highly desirable to have an additional controllable source of antiprotons. At GSI, **Jeffrey Klimes** develops, builds and tests a *Reservoir Trap* to deliver a well-defined number of antiprotons, and even a single particle, into adjacent precision traps for periodic measurement cycles over extended periods of time. This special setup will help to make all experiments independent of accelerator beam-times and shut-down periods and will provide beams at different energies.

AEgIS scintillating fibre detector. © M Doser

The advances in laser cooling of trapped ions with precision (anti)proton spectroscopy and antihydrogen ground state hyperfine splitting spectroscopy are being combined by **Markus Wiesinger** who is based at the Max Planck Institute for Nuclear Physics to perform stringent tests of CPT invariance. He carries out R&D into *Sympathetic Cooling of Antiprotons* which shall be achieved by coupling them to laser-cooled ions. Working closely with CERN and RIKEN, this is expected to provide the coldest antiprotons ever observed and improve both, sampling rate and precision in single antiproton spectroscopy by orders of magnitude. His work will constitute a considerable upgrade of the BASE experiment.



ASACUSA experiment at CERN © SMI

INFO BOX

Charge, parity, and time, or so-called **CPT** Symmetry is a fundamental symmetry of physical laws under simultaneous transformation of charge conjugation (C), parity transformation (P), and time reversal (T). All experiments to date suggest that CPT symmetry holds for all physical phenomena. Antimatter experiments test and challenge this theorem.

A *Ramsey technique to measure the Ground-state Hyperfine Structure of Antihydrogen* shall be integrated into an existing setup at the AD by **Amit Nanda** who is based at SMI in Vienna. He will use this approach to measure the ground-state hyperfine structure of antihydrogen. It is predicted that this will improve the precision of this measurement by a factor of 10 and thus provide one of the most sensitive tests of CPT invariance ever performed. For this purpose, he is working on the optimization of a hyperfine spectrometer line with two cavities through simulations in collaboration with other AVA Fellows. This setup will then be tested using a polarized hydrogen source.

A particular challenge in trap experiments is the transition of the beam from the beam line to the experiment. *Optimization of Beam Transport and Injection* will be studied by **Siara Fabbri** at the University of Manchester/ Cockcroft Institute. Her work will allow antihydrogen experiments to be performed with significantly higher efficiency and thus benefit all trap-based developments within AVA. She is also prototyping a non-destructive beam counter for quantifying antiprotons extracted from the ALPHA catching trap. Non-destructive diagnostics for trapped plasma modes will be used to characterize particle temperature and perform *in situ* measurements of magnetic field critical to precision microwave and optical spectroscopy.

AVA **FELLOWS**

Volodymyr Rodin

started his physics career at Taras Shevchenko University of Kyiv (Ukraine). He obtained his Master's Degree in 2017 with a thesis *"Development of Wavelength-shifting Optical Module (WOM) simulation model in GEANT4 for SHiP experiment"*, in collaboration with a group in Berlin. The work consisted of creating a comprehensive simulation of WOM and its verification with experimental data. Volodymyr Rodin is based at the University of Liverpool/Cockcroft Institute and carries out *6-D Studies into Beam Motion in Low Energy Storage Rings.*

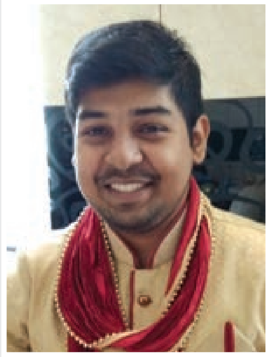
Jeffrey Klimes

earned his Bachelor's Degree from Purdue University in Physics and Nuclear Engineering. He then went to the University of Chicago where he earned his Master's Degree from the Physical Sciences Division in 2016 in collaboration with the Beta Paul Trap experiment at Argonne National Laboratory. He continued to work at Argonne as a Research Associate for the University of Notre Dame, building a beam line source used for precision mass measurements at the Canadian Penning Trap. Jeffrey Klimes is based at GSI and registered for a PhD on a *Reservoir Trap for Penning Trap Experiments* at the University of Heidelberg.

Markus Wiesinger

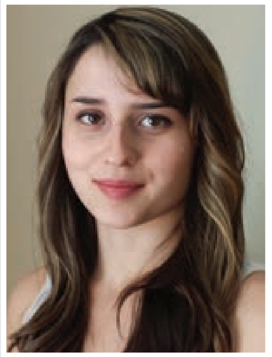
studied physics at the Vienna University of Technology (TU Wien), where he received his Bachelor's and Master's Degrees in Physics, both with distinction. During his studies he spent time at the Max Planck Institute for Plasma Physics in Munich, and at the ETH in Zurich working on a scintillating fibre detector for the Mu3e experiment. For his Master's thesis, he worked at the Stefan Meyer Institute and at CERN on the Hbar-HFS experiment to determine hyperfine splitting in antihydrogen. His work primarily focused on tests of the hyperfine spectroscopy apparatus for antihydrogen atoms with hydrogen atoms. Markus Weisinger is based at the Max Planck Institute for Nuclear Physics in Heidelberg, working on *Sympathetic Cooling of Antiprotons.*

ANTIMATTER **EXPERIMENTS**



Amit Nanda

obtained his Master's Degree in Physics from the National Institute of Science Education and Research, India. His thesis focused on the measurement of ϕ meson production at the ALICE detector at CERN. He has worked on the quality control and quality assurance of the MICROMEGAS readout boards for the ATLAS New Small Wheel and the design for an automated tool to measure electrical properties of the readout anode boards. Amit has published research in optimizing the gas flow rate, characterizing and performing the long term stability tests of a triple-GEM detector prototype for ALICE. He has also worked on dissipative coefficients of hadronic matter. Amit Nanda is based at the Stefan Meyer Institute and studies a *Ramsey Technique to Measure Ground-state Hyperfine Structure of Antihydrogen.*



Siara Fabbri

graduated from the Department of Physics and Astronomy at the University of California Los Angeles (UCLA). She has conducted several research projects in the Particle Beam Physics Laboratory, designing and constructing an RF deflecting cavity with the purpose of streaking ultrafast diffracted electron beams and performing beam diagnostics. She worked on an experiment which demonstrated a guided-THz inverse free-electron-laser technique to compress a 6 MeV 100 fs electron beam by nearly an order of magnitude and develop a longitudinal profile diagnostic. She has performed research on efficient energy extraction from a relativistic electron beam in a strongly tapered undulator and has investigated ultrafast electron diffraction microscopy at Lawrence Berkeley National Laboratory. Siara Fabbri is based at the University of Manchester/Cockcroft Institute and works on *Optimization of Degrader Integration, Beam Injection and Magnetic Field Measurements* for the ALPHA Experiment at CERN.

FOCUS ON
SKILLS AND TRAINING

At the very heart of the AVA network is a dedicated, cutting-edge research project for each Fellow at their host institution.

In addition to the pure research element, the network provides a series of established and bespoke training events. These build on the highly successful training schemes developed within earlier training networks coordinated by the University of Liverpool, including DITANET, oPAC, LA^{3}NET and OMA.

The AVA Fellows have already attended a Researcher Skills School and bespoke Media Workshop. The network partners will support a series of Topical Workshops and training events throughout the project. The contribution of industry partners to the AVA training programme ensures that the transfer of industry-relevant skills is an integral part of all individual projects, and the Fellows gain a broad insight into both academic and industrial aspects associated with antimatter research. A network-wide secondment scheme enables Fellows to spend time working at other institutions within the network, receiving hands-on training in specific techniques and a broader experience.

Wherever possible, these events are held together with other training networks. Such a collegiate approach has two distinct advantages: the advantages of scale bring training opportunities to more Fellows, and it brings together Fellows from a variety of disciplines helping to develop personal networks and start lifelong collaborations.

The training events culminate at the end of the AVA project with an outreach symposium at which the Fellows will showcase their research both to their peers and the general public. An international conference on antimatter research will also be organized by the network.

AVA TRAINING PROGRAMME ENSURES THAT THE TRANSFER OF INDUSTRY RELEVANT SKILLS IS AN INTEGRAL PART OF ALL INDIVIDUAL PROJECTS

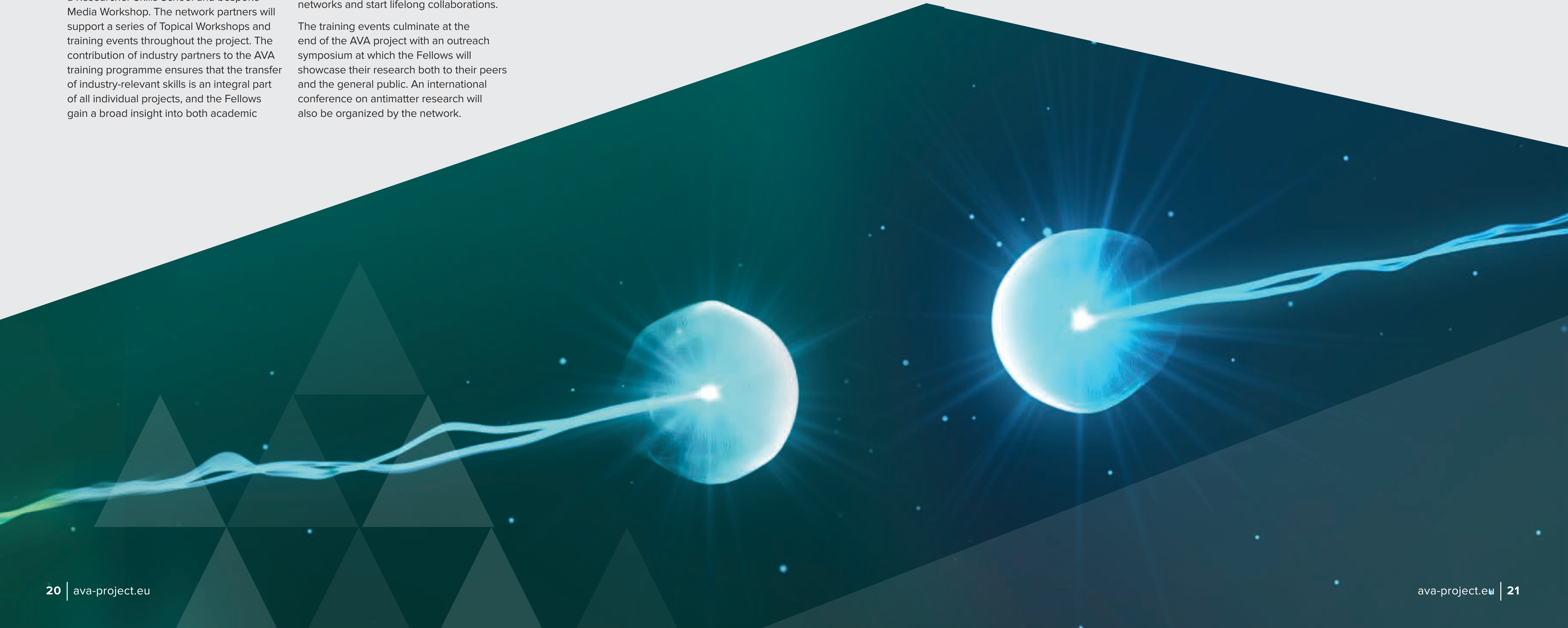
TOPICAL WORKSHOPS

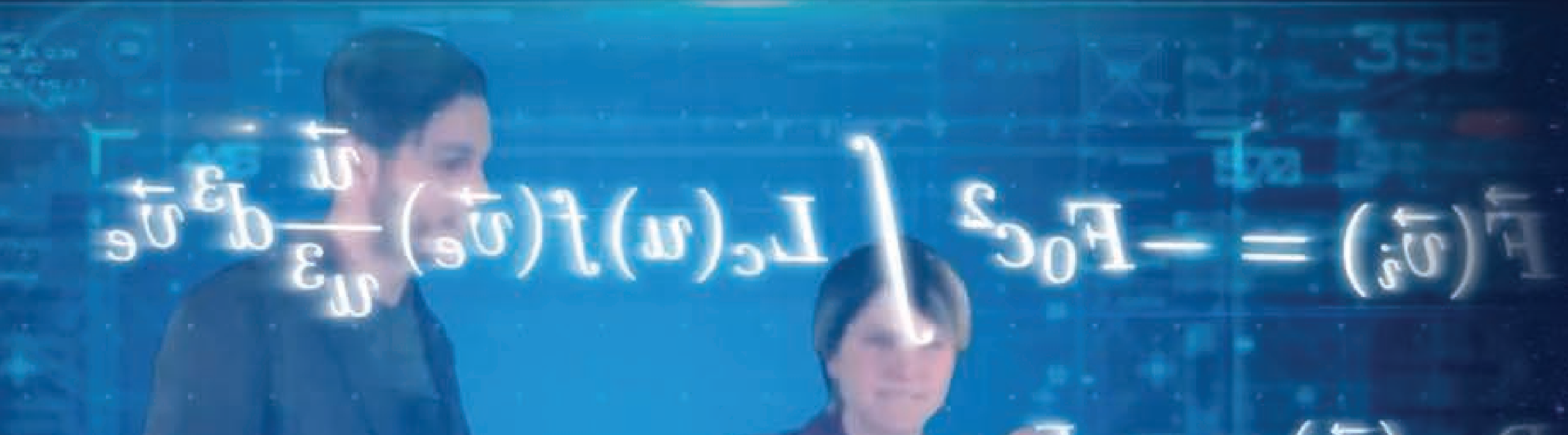
Throughout the project, network partners will organize and host Topical Workshops, covering all research areas of the AVA project. A typical workshop will last two or three days and external participants are encouraged to attend. Each workshop will be split in sessions and each of the session topics will be led by a renowned invited speaker who will give a keynote talk.

The 1st workshop will be held in Vienna and organized by CIVIDEC. It will tackle the use of diagnostics and detectors in storage rings, beam lines and experiments. It will address current challenges in characterizing antiparticle beams in detail. The event will also promote technology transfer between different applications.

The 2nd workshop will be organized by GSI and cover the optimization of antiproton facility design and operation with the help of diagnostics. It will cover integration of individual monitors into the overall accelerator control system, as well as using diagnostics output data as input for beam dynamics simulations and accelerator performance optimization.

The 3rd workshop will cover the machine-experiment interface and be organized by COSYLAB. This event will consider efficient diagnostics integration in an accelerator and how the readout from monitors can be linked to lattice design codes via online control systems.





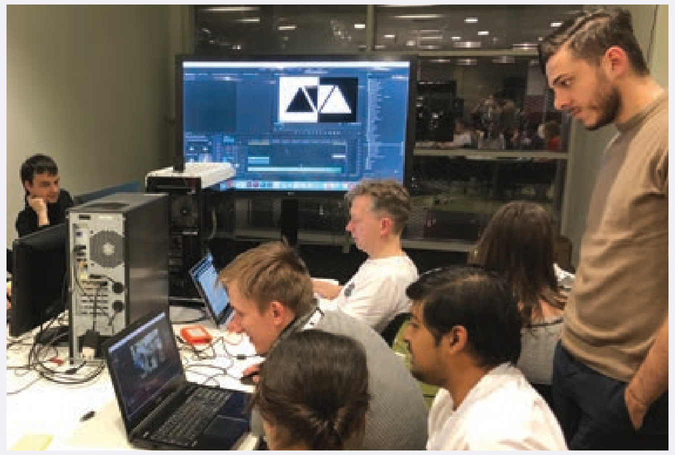
MEDIA **TRAINING**

AVA Fellows benefitted from unique media training, delivered by project partner Carbon Digital at one of the UK's premium creative hubs, MediaCityUK in Manchester. The Fellows developed and honed the skills required to produce their very own project film.

Search for "AVA - Nature (anti)matters"

The training began with an overview of the creative process and a description of how media production is structured. Storyboards and scripts were created and the overall 'look and feel' of the film decided in pre-production. Green screen filming gave everyone the opportunity to participate in the film and the Fellows recorded sections of the script relating to their specific work package and decided who would star in the final version.

Throughout their career, researchers are expected to promote and advertise their research using professional media techniques and this unique training was designed to meet these needs.



SKILLS **TRAINING**

At the start of the AVA project the Fellows attended an established 'Researcher Skills School' at the University of Liverpool. Non-technical skills such as presentation skills, science communication, project management, IPR and team working were developed. This School model has been recognized by the European Commission as 'best practice' for providing future generations of scientists and engineers with skills invaluable for their future careers, whether in academia or industry.

Towards the end of the project in 2020, an Advanced Researcher Skills School will be organized by the University of Liverpool. This will cover topics such as research commercialization, entrepreneurship, patent regulations and technology transfer. The Fellows will also receive training in skills for the labour market, such as CV writing and job interviews, and will be made aware of different career pathways open to them.

SECONDMENTS

In addition to the network-wide training events, AVA provides a secondment scheme which allows Fellows to train with the other partners involved in the network. This will provide training in research areas not directly linked to their research projects, broadening the expert knowledge of each Fellow substantially. Secondments also help to facilitate knowledge exchange across institutional and national boundaries and help develop and maintain working relationships within the wider research community.

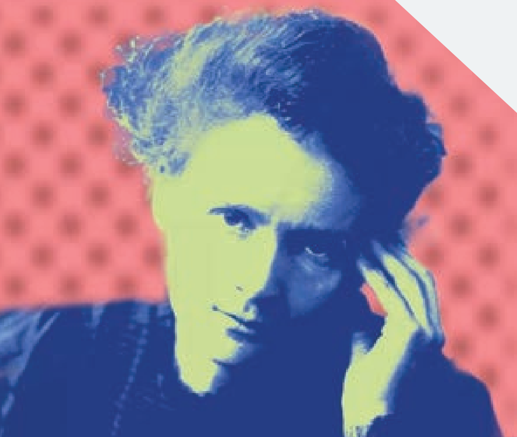
FINAL CONFERENCE

The AVA final conference will take place at the end of the project in autumn 2020 to summarize and present the main research findings to the general public and discuss the further challenges in antimatter research. The project will also host a large outreach symposium in summer 2019 to showcase the research carried out by the Fellows to a general audience.

OUTREACH AND COMMUNICATION

COMMUNICATING SCIENCE

AVA Fellows are required to complete science outreach activities during their Fellowship. This could be as science ambassadors, undertaking school visits and creating or contributing to science resources such as videos. The Fellows are also expected to organize their own outreach and scientific events. The ability to effectively communicate research to a broad audience will have a tremendous impact on the trajectory of their career and the network supports its Fellows in this.



SCIENCE COMMUNICATION IS ABOUT THE FUTURE OF SCIENCE.

IT INFLUENCES WHAT RESEARCH IS FUNDED, NEW LAWS AND REGULATIONS AND CAN CHANGE PEOPLE'S LIVES.

MARIE CURIE DAY

AVA Fellows at Liverpool, CERN and LMU in Munich celebrated the life and achievements of Marie Skłodowska Curie on the 150th anniversary of her birth. Hundreds of schoolchildren, postgraduate students and staff participated across the three sites. They took part in poster competitions, hands-on activities, and live-streamed presentations, including a contribution from European Commission's Director General of Education and Culture, Martine Reicherts. The events and associated press coverage reached over half a million people. All information can be accessed via **marie-curie-day-2017.org.**

GOOD COMMUNICATION CAN INSPIRE FUTURE GENERATIONS OF SCIENTISTS.

PHYSICS OF STAR WARS

To coincide with the 40th anniversary of the original Star Wars film, the AVA Fellows introduced their own cutting-edge research to hundreds of invited school children. Real world physics was related to movie concepts, for example matter-antimatter interactions and the light and dark side of The Force. Events such as this are an ideal opportunity for Fellows to develop their own presentation skills and to inspire the next generation of researchers. This event alone had a media reach of more than a million people.

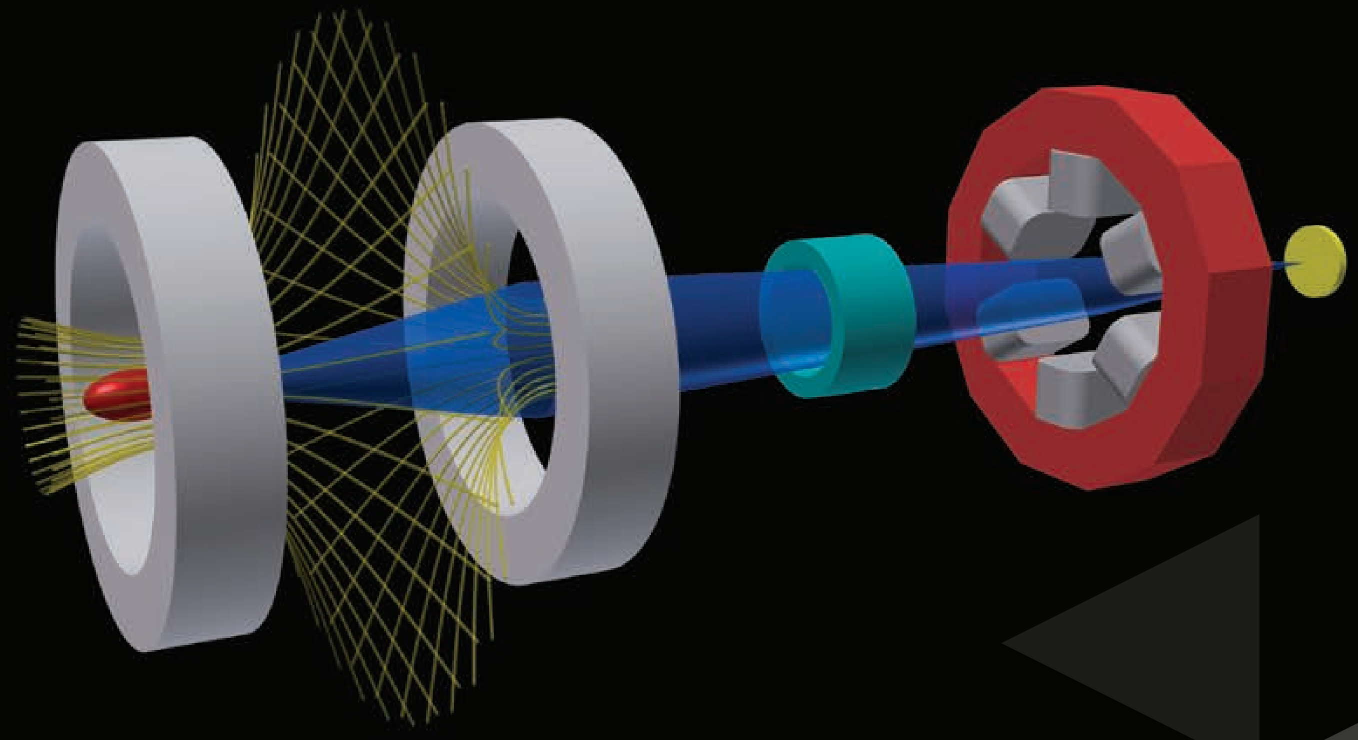
The AVA project promotes and disseminates the activities of its Fellows and partners through social media platforms. This is an important way to engage the public, broaden scientific thinking and inform the scientific community of our research successes.

/TheQUASARGroup

@Quasar_6roup **#AVA**

The Steering Committee is a small body of senior scientists chaired by the Coordinator. It includes three partner representatives and one AVA Fellow who collects input from all Fellows regarding training, general queries or problems prior to all meetings. The Steering Committee is responsible for the overall network strategy and makes decisions on running the AVA project, coordinating the wide range of training activities, and monitoring network activities including R&D results, communication, dissemination and intellectual property arising from the research.

PROJECT **MANAGEMENT**



Every partner in the network is represented on the Supervisory Board. The board meets annually to monitor the progress of the Fellows and the quality of their training. Feedback from industry partners ensures that the AVA training remains relevant to the international job market. A dedicated project T.E.A.M (Training, Education, Administration, Management) supports the Coordinator in project implementation and is based at the University of Liverpool/Cockcroft Institute. It comprises a project manager, web specialist, and administrative assistant. The T.E.A.M. is responsible for the day-to-day management of AVA, partner contacts and communication.

Professor Carsten P Welsch

is Head of the Department of Physics at the University of Liverpool. He is scientific coordinator of AVA with over 20 years' experience in accelerator design and beam diagnostics R&D. His research focuses on frontier accelerators & underpinning technologies, novel high gradient accelerators, as well as applications of accelerators in addressing global challenges. He is one of the most experienced coordinators of Marie Curie Actions and has led five European networks and four Individual Fellowships to date.

Professor Eberhard Widmann

has been the director of the Stefan Mayer Institute (SMI) for over ten years. He has worked with exotic atoms containing antiprotons since 1990, using laser and microwave spectroscopy to determine fundamental properties of antiprotons and to study the fundamental matter-antimatter symmetry. He is also interested in the strong interaction, which can be investigated using exotic atom X-ray spectroscopy and hadron physics. He was head of the spectroscopy group of the ASACUSA collaboration at the AD and recently became one of two co-spokespersons of ASACUSA.

Professor Erich Griesmayer

is the founder and CEO of CIVIDEC Instrumentation. He is Associated Professor at the Vienna University of Technology in electronic instrumentation. He has been a Scientific Associate at CERN for more than 20 years and has a broad knowledge and experience in accelerator technology. He is experienced in technology transfer and in generating innovative technologies. His professional background is in electronic measurement technology with a focus on diamond detectors and ultra-fast electronics.

Dr Michael Doser

is a senior research physicist and former deputy head of CERN's physics department. He has 30 years of experience in the field of antimatter using it either as a tool (to study the strong interaction), or as an object of study itself. His current focus is on the formation of anti-atoms, the search for an explanation of the matter-antimatter asymmetry, and the measurement of the gravitational interaction between matter and antimatter. He is editor of *Physics Letters B* and the *Review of Particle Properties*. He has been involved in numerous international outreach activities, speaking to a wide range of non-specialist audiences, from school children to decision makers, often at art-related events.

PROJECT **PARTNERS**

The beneficiary partners on these two pages have received part of the 4 Million Euro of funding from the European Union to host the AVA Fellows. They allow them to carry out their own specific research projects. The associate partners listed on the following pages play a distinct role within the network training. They either contribute to specific training events, such as Schools, or provide secondment opportunities to broaden the Fellows' skills and boost their employability.

UNIVERSITY OF LIVERPOOL

The University of Liverpool is a member of the Russell Group of major UK research-intensive universities. It has an enviable international reputation for innovative research in particle, nuclear and condensed matter physics. Liverpool is also a key contributor to the Cockcroft Institute, an international centre of excellence in accelerator science and technology.

CERN, the European Organisation for Nuclear Research, is the world's largest particle physics laboratory. CERN acts as a focal point for European physics and technology collaborations and hosts over 6,000 visitors from more than 300 external institutes annually. CERN has world-class accelerator facilities, promotes communication and public education and has an enviable track record as a European training centre.

GSI is the German national centre for heavy ion research and hosts the Facility for Antiproton and Ion Research, FAIR. The laboratory undertakes research in nuclear and atomic physics, plasma physics, materials research, biophysics and cancer treatment with heavy ion beams. GSI is most famous for their research of heavy elements which have led to the discovery of six new elements. GSI is a member of the Helmholtz Association of German Research Centres.

COSYLAB
CONTROL SYSTEM LABORATORY

Cosylab d.d. started at the Jožef Stefan Institute, the largest Slovenian research institute and is the worldwide leader in control system integration for particle accelerators and other large physics facilities. They specialize in both, hardware and software solutions. They also provide value services such as customization and integration of already existing solutions, custom development, consulting and tutoring.

JÜLICH
FORSCHUNGSZENTRUM

Forschungszentrum Jülich (FZJ) is one of the largest interdisciplinary research institutions in Europe. It comprises nine research institutes including the Institut für Kernphysik (IKP) which operates the Cooler Synchrotron (COSY) and is responsible for the design and construction of the High Energy Storage Ring of FAIR. FZJ is also a member of the Helmholtz Association of German Research Centres.

stahl-electronics
Cryogenic and Precision Electronics

Stahl-Electronics was founded as a spin off from the University of Mainz in 2002. The company specializes in the development of scientific equipment and detection systems for charged particles. They are particularly experiences in cryogenic detectors.

cividec
Instrumentation

CIVIDEC is an international R&D company born from the cutting-edge technology of CERN, specialized in diamond detectors and ultra-fast electronics. The company focuses on technological solutions for particle accelerator beam diagnostics and on neutron detection.

MANCHESTER 1824
The University of Manchester

A member of the Russell Group, the University of Manchester is one of the largest in the UK. In accelerator science, Manchester has international research expertise in the physics of particle accelerators, dynamics of charged particles and RF accelerating structures. In antimatter research, Manchester is a key member of the ALPHA experiment at CERN, as well as the Cockcroft Institute.

The Austrian Academy of Sciences runs 29 institutes in all fields of science and humanities, which are among the leading institutes in Austria and abroad.

The Stefan Meyer Institute (SMI) is one of two institutes of ÖAW in the field of subatomic physics and is well-known for studies of fundamental symmetries and interactions using precision spectroscopy of exotic atoms and has a strong program on hadron physics in the strange and charm sector.

FOTON
joy of technology

FOTON, s.r.o. is a Czech company specializing in the design and manufacture of advanced scientific instrumentation including high voltage power supplies, optoelectronics, micropositioning automation, plasma diagnostics, vacuum control technology and precision instrument engineering.

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

The Max Planck Institute for Nuclear Physics is part of the German Max Planck Society. Research fields at the institute include high precision physics using stored ions, particle astrophysics, theoretical quantum dynamics and quantum dynamics and control.

ASSOCIATE **PARTNERS**

Associate partners contribute significantly to the training of the AVA Fellows. They are actively encouraged, through membership of the Supervisory Board, to improve training strategies and help ensure the highest possible standards of training are met, particularly with regard to industry-relevant skills. They also provide scientific and R&D support, contribute to Schools and Topical Workshops and offer secondment opportunities for the AVA Fellows.

Science & Technology Facilities Council

STFC is the UK organization responsible for providing large scale accelerator facilities within the UK, and supporting UK involvement in international accelerator programs. The Accelerator Science and Technology Centre (ASTeC) contributes advanced R&D to new and future accelerators and is a core member of the Cockcroft Institute.

Intellectual Property Office

The Intellectual Property Office is the UK Government's official body responsible for Intellectual Property (IP) rights.

Fistral Training and Consultancy Ltd.

Fistral Training and Consultancy Ltd deliver training courses in Project and Risk Management, Team Working, Communication, Collaboration, Influencing, Personal Effectiveness and Leadership.

Holdsworth Associates

Holdsworth Associates is an award-winning public relations consultancy with a creative approach to communications.

edgewave

Edgewave provide high-end laser beam sources, working with end users to deliver application-specific, tailor-made laser solutions.

University of Sussex

The University of Sussex is a leading UK research university. The Experimental Particle Physics research group aims to answer fundamental questions posed by modern physics and they contribute to a number of large scale experiments at CERN and around the world.

bergoz INSTRUMENTATION

Bergoz instrumentation specializes in ultra-low-noise analogue electronics design, developing and manufacturing transformers, transducers, monitoring devices and electronic instrumentation for non-destructive current measurement and elementary particle beams diagnostics.

INVENTYA – Your success. Our commitment.

As a leading innovation management consultancy, Inventya provide proof-of-market research, product-service commercialization and market-oriented due diligence services.

ViALUX

ViALUX GmbH is a highly innovative company with a continuing focus on the latest technology developments. The company has extensive experience developing, producing and distributing electro-optical components and optical measurement systems for 3D-shape and deformation analysis.

RIKEN

As Japan's largest research institution, RIKEN is renowned for high-quality research in a range of scientific disciplines including physics, chemistry, biomedical sciences, engineering and computational sciences.

Aarhus University

Aarhus University is a major Danish research university ranked in the top 100 universities worldwide. They are leading participants in many large scale experiments and are a lead partner in the ALPHA experiment at CERN.

Wigner

Wigner RCP is the largest academic research centre in Hungary and hosts the Institute for Solid State Physics and Optics and the Institute for Particle and Nuclear Physics.

TECH-X

Tech-X support research in academic, government and commercial sectors, providing unique simulation software that uses high performance and heterogeneous computing techniques.

CARBON DIGITAL

Carbon Digital are a visual effects agency delivering world class content for corporate, television commercials, broadcast and game trailers.

CONTACT

Professor Carsten P Welsch
AVA Coordinator

Department of Physics
University of Liverpool
Liverpool L69 7ZE
United Kingdom

www.ava-project.eu

/TheQUASARGroup

@Quasar_6roup **#AVA**

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement no. 721559.