

TECHNICAL ANNEX

1. S&T EXCELLENCE

1.1. SOUNDNESS OF THE CHALLENGE

1.1.1. DESCRIPTION OF THE STATE OF THE ART

Charged particle accelerators are widely spread across Europe and throughout the world. The largest facilities are synchrotron radiation light sources (storage rings or free electron lasers), high energy physics colliders, nuclear physics research facilities and synchrotrons for hadron therapy.

These accelerators are used for both fundamental and applied science and are crucial instruments for scientists to be able to understand the world around us and to find technical solutions to the societal challenges of now and of the future. These facilities are capital and operationally intensive with significant national and international investments having been made. It is therefore essential that reliable operation is ensured as well as smooth commissioning of the new and upgraded facilities that are planned to come online in the coming years.

The process of commissioning an accelerator consists of determining the correct configuration of the magnets, radio frequency (RF) structures and diagnostics that will allow operators to achieve the design parameters for the particle beam. This process will eventually deliver the performance required by the facility users in terms of beam properties and will allow the machine to be operated over long periods of time with high reliability and availability. The most important quantities to correct are generally the beam closed orbit or trajectory (representing the average position of the beam throughout the accelerator) and the accelerator linear and non-linear optics that will, for example, impact the beam size, Touschek lifetime [1] and the ability to inject particles into the accelerator [2]. Other aspects such as beam stability are critical for operation and require active correction algorithms implemented in high-speed feedback loops. Advanced experimental methods and algorithms have been and still are being developed to optimise this process and to operate accelerators in the most efficient way.

While these methods and algorithms can be applied and are used with some small variations by all the particle accelerators in the world, the software applications to implement them are generally facility specific. The physicists and software engineers who develop them have to adapt to different control systems and hardware configurations. In addition, the same tools need to be developed again for simulations at the design phase of accelerators in order to specify alignment and magnetic field tolerances as well as hardware and diagnostics specifications. This constant re-implementation and adaptation of existing numerical tools represents a large use of highly specialised resources to simply repeat what has already been done before, elsewhere, multiple times. It is therefore desirable to instead develop these tools in a collaboration between many facilities.

In 1993, a world-wide collaboration effort on commissioning and operation tools for synchrotron light sources was started by the development of the software called “Matlab Middle Layer” (MML) [3], originally initiated at SLAC National Accelerator Laboratory/Lawrence Berkeley National Laboratory (LBNL). MML gave smaller facilities easy access to the same tools and algorithms as used by the large laboratories. One example is Linear Optics from Closed Orbit (LOCO) [4] which is used for linear optics corrections. Since its creation, the MML software has provided: 1) independence from the underlying control system, 2) abstracted element naming conventions, 3) graphical interfaces for common tuning and design tools and 4) the possibility to run the measurements and control loops in “simulation mode”, thus allowing software tool testing without the need for costly beam time, or in the absence of the accelerator for new projects. The beam simulations were done using the Accelerator Toolbox (AT) [5] software, which is a set of Matlab [6] functions dedicated to the simulation of beam dynamics for high energy particle accelerators.

Presently, the MML software is used by most synchrotron light source laboratories to link the beam dynamics simulations with commissioning and operation activities. In many aspects, it acts as a **digital twin**. All required high-level software applications (from magnet calibrations to optics tuning) can be developed based on beam dynamics simulations in AT. The same software code (including user interfaces) is used directly with the real beam by simply switching global flags ("physics"/"hardware" for units and "simulator/online" for control). This tool has tremendous advantages for the development of new storage rings and for their commissioning and operation. Moreover, the tools developed in one laboratory with MML are immediately usable by all other laboratories using MML, thus fostering exchanges and collaboration between accelerator physicists around the world.

However, the MML software has branched into many versions and become fragmented in order to implement more modern tools that go beyond the scope of the original project. As a result, it has become impossible to maintain it in a collaborative and efficient way. The last non-laboratory specific version update was released in 2017. Since the software does not implement modern coding practices, libraries and scientific open data management are becoming obsolete and this puts accelerator-based facilities at risk. Updating MML would require an entire re-writing of its core and user interfaces in Matlab, a proprietary software poorly known among students and young professionals entering the field of particle accelerators today. Matlab is therefore not the best suited option for such heavy development effort. MML nevertheless remains a most valuable tool that can serve as a reference for the present project proposal and can temporarily be used in its present frozen state to maintain operations until a better and sustainable alternative is available.

Python [7], on the other hand, is open-source, is among the most widely used programming languages, and benefits from extensive open-source scientific libraries which integrate modern algorithms. Available Python packages allow modern computing techniques to be integrated such as heavy parallelisation (CPU/GPU), or to interface to modern scientific libraries involving advanced data analysis, optimisation algorithms or machine learning algorithms that are now a critical aspect of accelerator design and operation. Selecting Python as the software language for the replacement of MML allows to reach a much wider user base, simplifies interfaces to many other software libraries used by our community and will help in future developments critical for the new, more complex, generation of accelerators.

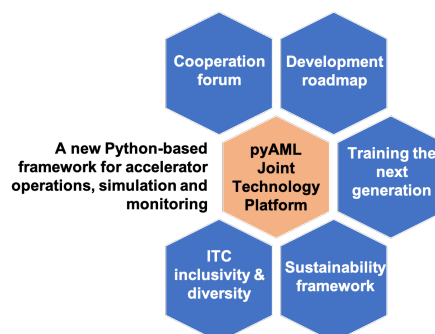
As highlighted by the LEAPS initiative (League of European Accelerator-based Photon Sources) there is a strong need for all next generation light sources in Europe and worldwide to obtain a modern python based middle layer.

1.1.2. DESCRIPTION OF THE CHALLENGE (MAIN AIM)

This Action therefore addresses the development of a new, modern and open-source **Python Accelerator Middle Layer (PyAML)** as a joint technology platform. The Action activity will draw together the critical mass of partners from all relevant accelerator facilities in order to define a new common framework to operate, simulate and monitor charged particles accelerators through PyAML. This will become a new and sustainable standard for the whole international community of stakeholders. The structured coordination and empowered networking given by the Action will be of critical benefit to the definition, frameworking and collaborative development of the project and will result in a significant gain in time and efficiency.

The key aims (details provided later) of the **PyAML-Net** (PyAML Network) Action are to:

- Create a forum and cooperation network for the new PyAML joint technology platform to be specified and developed
- Assure a sustainable framework for long-term development and maintenance of PyAML
- Train a new generation of physicists and software engineers in exploiting and developing PyAML
- Actively involve Inclusiveness Target Countries (ITCs) Action partners in the development of PyAML
- Create a strong link and exchange among different types of expertise needed for the development of a PyAML: charged particle beam dynamics, software engineering, accelerator operation etc.



The development of a new, modern and open-source PyAML will draw from the expertise recently gained by the accelerator community while collaboratively developing and maintaining the Python Accelerator Toolbox (pyAT) software toolkit for simulations of high energy charged particle beam dynamics. It will also build upon already existing implementations of Python interfaces to control systems developed at several world-wide laboratories as independent local projects such as (but not limited to) *aphla* (NSLS-II, Brookhaven National Laboratory) [8], *sirius-py* (at the SIRIUS Light source, Brazil) [9], *python virtual accelerator* (PSI, Switzerland) and *pytac* (Diamond Light Source, UK). These success cases will provide the seeds to build an accelerator-oriented software library reproducing the features of MML in Python, but will also extend further to include new requirements while keeping the independence from the specific accelerator control system (for example the commonly used TANGO [10] or EPICS [11]), thus fostering collaboration.

Most building blocks for a new Python version of MML have already been started independently in several laboratories. For example, joint efforts have recently progressed towards the translation of error setting and correction functions from the Simulated Commissioning package (SC, based on Matlab AT, [13]) to Python, extending the tuning possibilities presently available in MML and in particular reproducing the features of LOCO optics correction in Python.

The newly designed **PyAML** will be a common work among all participating institutes and companies to put together existing tools and create the missing components (such as graphical interfaces, CPU or GPU parallelisation and Machine Learning support) to form a common library that can be used by all. The PyAML joint technology platform will include the following required features already available in the MML software:

1. Control system agnostic (abstracted interaction with different control systems)
2. Accelerator/facility agnostic (abstracted naming conventions for all devices)
3. Work for transfer-lines, linear and circular accelerators, ramped accelerators
4. Digital twin (allows testing of tuning tools in real life conditions without the need for expensive and limited beam time)
5. Tools for orbit, trajectory, linear and non-linear optics corrections

It would also feature, thanks in part to existing Python packages:

6. Fully open source code (with an open software license to be defined, such as Apache 2.0)
7. Include the possibility to be used on large High Performance Computing (HPC) clusters for automated commissioning simulations
8. Profit from recent beam dynamics developments to be faster and more precise than the existing MML (e.g. GPUs and analytic Jacobians) by using state-of-the-art programming techniques and state-of-the-art accelerator-oriented libraries
9. Enable easy and user-friendly connection to any control system (for example EPICS and TANGO), starting from the simple set/get abstractions to include more advanced features such as control system commands, properties and timing features
10. Make use of most modern OPENDATA, OPENSCIENCE and FAIR (Findable, Accessible, Interoperable, Reusable) principles [13] and data labelling for machine learning and artificial intelligence algorithms [14] (following the EU guidelines [15])
11. Include off-line digital twin for tuning tools development and on-line digital shadow for monitoring of indirect observables and anomaly detection
12. Enable straightforward implementation of available Python based Artificial Intelligence and Machine Learning tools (e.g.: pytorch [16], Badger/Xopt [17])
13. Enforce thorough documentation and easier/shared maintenance (GitHub [18])
14. Provide a virtual accelerator environment to train students or newcomers to the field

PyAML also represents a virtual machine which could be set up to simulate the accelerator in real-time. Its use could then be extended (compared to MML) to continuously monitor characteristic quantities (orbit, tunes, optics, etc..) and their drift with respect to the expected values. Training Artificial Intelligence (AI) models with this information could support accelerators operation by an efficient detection and prediction of failures (anomaly detection). The operation of accelerators will strongly benefit from such modern numerical tools.

PyAML will set a common language for tuning and development of accelerator-based infrastructures. The training of students and Young Researchers and Innovators (YRIs) will become independent of the laboratories leading to a faster and collaborative exchange of software development and accelerator tuning skills. PyAML will also provide a platform to raise the level of software skills in the accelerator

physics field in general, which is essential for the future of the field and to maintain the interdisciplinary nature as a strong computational physics field.

1.2. PROGRESS BEYOND THE STATE OF THE ART

1.2.1. APPROACH TO THE CHALLENGE AND PROGRESS BEYOND THE STATE OF THE ART

The PyAML-Net Action members will define a **new architecture** for the code, taking inspiration from existing tools and operational experience. The new architecture will be designed so as to be **easy to setup, easy to maintain and easy to extend**. Each component will have detailed specifications, documentation and dependencies. Unit tests will be designed to guarantee code durability and run on a Continuous Integration/Continuous Deployment (CI/CD) platform.

The preliminary schematic structure of the PyAML joint technology platform software is depicted in Figure 1. The green dashed boxes highlight the novelties introduced by this project. These are either based on existing separate projects or totally new features to be enabled by the new code architecture.

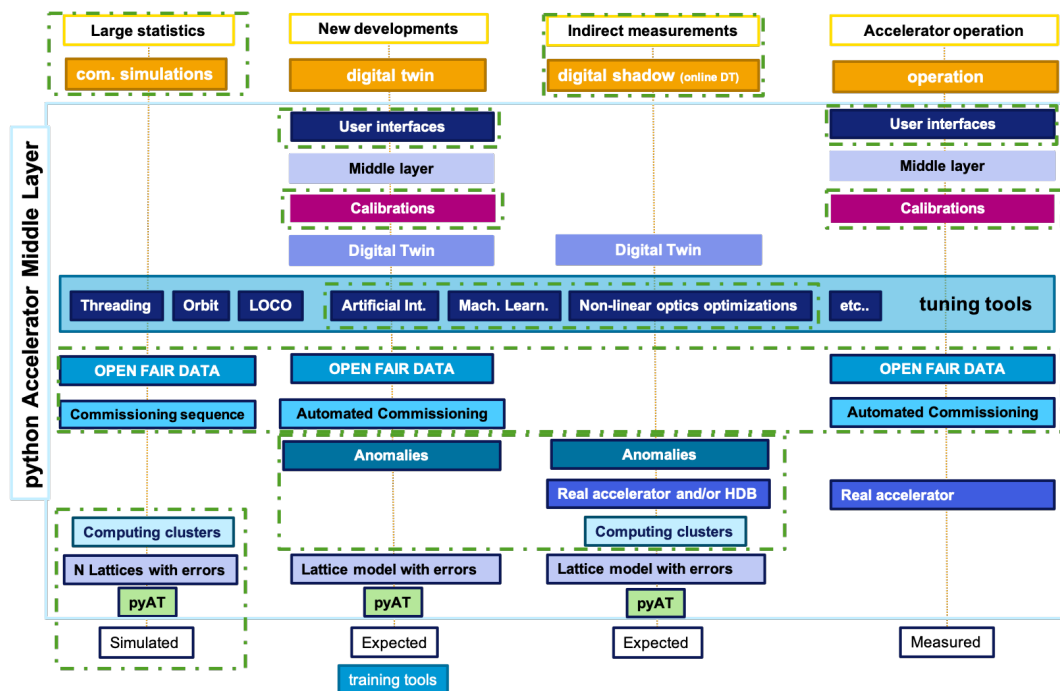


Figure 1: Preliminary schematic structure of the PyAML joint technology platform software. Green dashed boxes represent the progress beyond the state-of-the-art introduced by the PyAML joint technology platform developed by the Action.

This PyAML architecture will follow “Agile software development” approaches when needed in order to meet the requirements of all presently existing use cases. It will also allow to expand towards **automation, anomaly detection** and use of **artificial intelligence** and **machine learning** for **non-linear optics optimisations**.

Compared to MML, the graphical interfaces will be separated from the computational aspects to allow a **fluid and customisable user interface design**.

The data structures used within PyAML will implement **open FAIR data** principles where relevant. In addition to the benefits to the wider accelerator community, this will also provide improvements for the immediate user, with extensive metadata in a clear human-readable format. This will greatly assist in problem-solving during accelerator commissioning and troubleshooting.

The **digital twin** mode of PyAML will be invaluable for off-line development but also for training of the next generation of accelerator operators, scientists and engineers. They will be able to learn beam dynamics, use real charged particle accelerator control tools and gain experience in practical actions which will be the daily activity of their career without the need for access to a real accelerator.

The digital twin will be updated either based on a simulated accelerator or on realistic data. The realistic data could be the current accelerator settings themselves or archived data. The continuous update of the PyAML digital twin with data coming from the real accelerator settings will enable a **digital shadow** showing the expected machine behaviour in terms of beam dynamics as settings are changed. This will in turn provide the possibility of comparing, at a high frequency, the expected and measured performances, paving the way to **anomaly detection** systems, potentially improving efficiency during operations.

The two distinct branches of research on **commissioning simulations** and real accelerator tuning will be unified, making the PyAML based software able to run the same algorithm (ex: orbit correction): 1) on the accelerator itself, 2) on the digital twin simulation or 3) on a **large number of simulated accelerator lattice realisations** with random errors defined by the users and distributed on a computing cluster for their evaluation. The first two options were already available in MML while the third is currently available in a separate software package. Thanks to PyAML, the commissioning simulations features will be integrated in the same infrastructure, once again avoiding repetition of the same tools and bridging the gap between simulations and measurements. This development will also open the way to the possibility of running **automated commissioning** of accelerators.

1.2.2. OBJECTIVES

1.2.2.1. Research Coordination Objectives

Build a pan-European research network with diverse stakeholders including researchers, software engineers, students, PhDs, post docs, engineers, accelerator operators, and private companies across disciplines and countries. The objective is to support increased collaboration and coordinated action in the development and maintenance of PyAML, for both short and long-term.

Combine efforts in the development of existing and new accelerator control and modelling tools.

The existing and new algorithms, procedures and software tools developed based on PyAML will be readily available to any other stakeholder independently from the diverse control systems, geographical locations and kind of accelerator. This will build on the existing work of Action members and world-wide published results.

Support the development of the PyAML joint technology platform. This objective is necessary to: 1) maximise the impact of modern tuning algorithms; 2) enable the re-use, comparison and analysis of large data sets; and 3) enable worldwide access to state-of-the-art accelerator tuning tools.

Develop a coordinated research agenda for accelerator tuning tools development that addresses key challenges such as anomaly detection and non-linear magnetic elements (optics) optimisations. The Action will list the most demanded tools and plan for their integration in the PyAML platform, eventually expanding beyond the end of this Action.

Support YRIs, and researchers from ITCs by ensuring their involvement and active participation throughout the project and full representation in all activities, including Action leadership. The objective is to develop a new generation of accelerator experts, who will have a solid network of collaborators and mentors, and the expertise needed to drive future research in particle accelerator commissioning, tuning, optimisation and operation.

1.2.2.2. Capacity-building Objectives

Building capacity in all Action countries is a central goal of this COST Action. While focused on young researchers, this also includes more senior researchers new to this research field and laboratories/industry that do not yet have access to a charged particle accelerator. Particle accelerator operators will also be strongly involved. The Action focuses on providing access to state-of-the-art knowledge on accelerator control operation and tuning across Action members. Specific capacity-building objectives of the PyAML Action include:

- **Fostering communication, networking and collaboration among Action members from diverse backgrounds**, in particular experts of high energy charged particles beam dynamics working at different accelerators, with software engineers, operators and private companies. The network will actively grow and address gaps over the course of four years through online and in-person networking activities, including Working Group meetings and Training Schools. It will take concrete action to promote diversity, equality and inclusion and ensuring active involvement of YRI and participants from ITCs (see Working Group 1 below).

- Facilitating the **transfer and exchange of knowledge** between: 1) research areas like accelerator commissioning simulations, accelerator operation and accelerator control system design and 2) laboratories and private companies.
- Enable **collaborative workshops** including **contributions from various research fields**, including computer sciences, beam dynamics, control systems, data acquisition, AI/ML and functional mock-ups. **Enabling conference participation** by participants targeted by the COST Excellence and Inclusiveness policy.
- **Short-Term Scientific Missions** (STSMs) to test the software tools developed in real accelerator scenarios and to expand the skills and widen the knowledge level of participants.
- **Build on existing accelerator middle layer initiatives**, at national and international laboratories, drawing on their experience and expanding our ability to effectively commission, correct, optimise and operate particle accelerators.
- **Empower collaborations** in European research projects in the following ways: 1) encourage network members to collaboratively write funding applications, 2) continue the link established among researchers after the duration of the Action by developing a roadmap for collaborative research, 3) organise online events, provide newsletters and promote research through social media, 4) maintain the Action website as an ongoing, open access resource for researchers, operators and private companies.
- **Support to YRIs** by giving them prominent roles in the development and management of the Action. Short-Term Scientific Missions will be hosted by home institutions of Action members and by excellence centres world-wide. Early-stage researchers and practitioners will derive considerable benefit from the broader activities offered by a COST network, such as participation in WG activities, Training Schools and conferences, and from the opportunity to develop collaborative partnerships. The network will organise at least three Training Schools. YRIs and early career participants will be given the opportunity to lead these activities and decide the most relevant subjects.

All these capacity-building objectives will be pursued considering the COST inspiring principles of inclusivity and excellence. YRIs will be strongly encouraged to actively take part in the implementation of the Action activities. The involvement of ITC partners in the knowledge sharing and community achievements will be one of the Action priorities.

PyAML aims at merging the research efforts of laboratories, which have so far operated separately. Barriers in terms of scientific language and culture among the communities must be overcome for PyAML to be successful. The Action will thus organise regular informal virtual meetings (Zoom) for members of PyAML, thematically separated in terms of the Working Groups.

2. NETWORKING EXCELLENCE

2.1. ADDED VALUE OF NETWORKING IN S&T EXCELLENCE

2.1.1. ADDED VALUE IN RELATION TO EXISTING EFFORTS AT EUROPEAN AND/OR INTERNATIONAL LEVEL

PyAML-Net is the second large-scale effort in the accelerator community directed towards the creation of a software middle layer to share modelling and operational correction tools developments among laboratories. The first such effort (MML) was initially very successful but has slowly lost momentum to become finally frozen (or lab-specific) since several years now. The software developed within the PyAML joint technology platform will be able to replace and extend the features available within MML. It will also restart the collaborative development in the particle accelerators community in a more shared and organised manner, thus making it more likely to last over time. Some individual laboratories have already started to transfer their MML based accelerator tuning tools to their own operational ecosystem, but without the aim of making a tool usable and expandable to all other laboratories. This is too much effort for a single laboratory, university or company, but becomes feasible in the framework of a COST Action.

The vision of the PyAML-Net Action calls for a truly interdisciplinary approach and coordination of these efforts, to achieve breakthroughs in various fields (open FAIR data, HPC clusters exploitation, non-linear optics optimisations, calibration cross-talks, among others). It is thus crucial that these efforts are linked together, not only to advance the field of particle accelerator tuning and operation, but also to identify knowledge gaps and harmonise the portability of scientific knowledge among contributors within PyAML. As such, a COST Action is uniquely placed to provide support for networks on such a scale. In particular, it will provide mobility of researchers, access to large facilities, intensive information exchange, and an

in-depth educational program for young researchers that would be impossible under any other type of research network. Moreover, the open nature of the Action will ensure the timely addition of new partners with new ideas, which will also be actively sought by the PyAML consortium.

2.2. ADDED VALUE OF NETWORKING IN IMPACT

2.2.1. SECURING THE CRITICAL MASS, EXPERTISE AND GEOGRAPHICAL BALANCE WITHIN THE COST MEMBERS AND BEYOND

PyAML-Net will build on particle accelerator laboratories and companies across member countries. The network of proposers consists of a large number of top researchers, software engineers and private company experts, balanced by discipline, geography, gender and age. It will also connect with international laboratories including SLAC (USA), LBNL (USA), BNL (USA), LNLS (Brazil), ANSTO (Australia) and PAL (South Korea), all devoted to particle accelerator physics. Initiators of this Action have already reached out to these organisations and other stakeholders and will actively broaden this network throughout the Action. Further participation will be ensured through outreach at all major PyAML-Net events. The network will include academics, software engineers and representatives from industry. Together they represent **a critical mass of stakeholders** that is truly **inter-disciplinary** (e.g. physics, software, computer science, control systems, web interfaces for applications), **inter-cultural** and **inter-connected** (e.g. representing a wide range of European countries and cultures). The network will be **inter-sectoral** and will bridge the gap between research and practical applications.

The international reach of the network will be ensured through participation at international conferences targeting both researchers and engineers. Alongside knowledge sharing, these activities will help to grow the network by engaging new partners and providing greater opportunity for future collaborations.

PyAML-Net will also be **inclusive** and **inter-generational**. The project includes a Working Group (WG1) dedicated to supporting interdisciplinarity and inclusion. PyAML-Net will involve members at all career stages including early-career participants, YRIs and senior researchers. The network will ensure a critical mass and active participation through social networking and dissemination activities at local, regional and national levels.

The need to test the software developed by PyAML-Net will encourage the Action members to spend time (STSMs) in different laboratories, industries and facilities, creating new links and eventually expanding the participation in PyAML-Net.

The criteria of PyAML to be control system and machine independent will increase the expertise level and critical mass of individuals involved in the Action.

2.2.2. INVOLVEMENT OF STAKEHOLDERS

Charged particle accelerator laboratories and related companies are the primary stakeholders of this Action. Further involvement of stakeholders benefiting from an efficient and comprehensive set of tools for commissioning and operation of their accelerators will be sought when the COST Action is granted. As this Action aims to draw knowledge from stakeholders on well-established accelerator tuning techniques and well-known charged particle accelerator beam dynamics, further integration of valuable chain partners is likely.

All Action members will participate in: 1) consolidation of mutual collaborations and the creation of new ones, 2) knowledge exchange with local and international scientists, 3) increased awareness about PyAML and its features through sharing of the Action's contents, objectives and results.

YRIs shall primarily be involved and shall benefit from the activities by networking, internationalisation and communications, such as meetings, conferences and workshops aimed towards: 1) the development of their comprehensive professional profile and skills, 2) promoting the participation of women in research and reducing their under-representation at higher levels on the career ladder, and 3) encouraging the integration of multiculturalism and diversity in research.

The presence of Action partners at key sector events, including IPAC2025 (Taiwan), IBIC2025 (Liverpool, UK), ICALEPCS2025 (Chicago, USA) and future similar events, will facilitate further stakeholder involvement. Moreover, targeting these established events will foster a dialogue between current COST Action participants and newcomers to the field.

Ultimately, PyAML-Net will act as a unique focal point for a diverse network of stakeholders, supporting coordinated action and allowing us to develop a long-term roadmap for research on tuning tools for commissioning, operation and enhancement of charged particle accelerators.

3. IMPACT

3.1. IMPACT TO SCIENCE, SOCIETY AND COMPETITIVENESS, AND POTENTIAL FOR INNOVATION/BREAKTHROUGHS

3.1.1. SCIENTIFIC, TECHNOLOGICAL, AND/OR SOCIOECONOMIC IMPACTS (INCLUDING POTENTIAL INNOVATIONS AND/OR BREAKTHROUGHS)

The PyAML joint technology platform will make the design, commissioning and operation of existing and future charged particle accelerators, faster and collaborative. The proposers of this Action (and those partners that will likely join after the Action is approved), will share experiences and tools. By joining resources, increased time will become available for new developments and tests of new ideas. Also, new facilities deciding to use the software developed by PyAML-Net will not have to start from zero, but will benefit from tested, reliable and continuously maintained tools for their development representing an enormous gain in time and resources for future projects. Table 1 lists the foreseen short- and long-term impacts of the PyAML-Net network actions.

Short term impact	Long term impact
Scientific impact	
An interdisciplinary network of scientists collaborating on advancing accelerator tuning tools through a common middle layer software.	A sustainable network that supports long-term, high-impact accelerator tuning tools development, research and maintenance.
A roadmap for the development of accelerator tuning tools that leverages scientific and technical advances.	Collaborative research projects and coordinated actions that address key challenges for accelerator design, commissioning and operation.
A new architecture for accelerator tuning software, easy to expand, update, maintain and setup.	More efficient commissioning of new accelerators and improvement of the performance of existing machines.
Mentorship and increased opportunity for YRIs working in particle accelerator physics.	A new generation of scientists, researchers and innovators who will drive the future of charged particle accelerator design, commissioning and operation.
Technical impact	
Shared case studies of middle layer software implementation.	A common platform for the development and operation of advanced tuning tools for particle accelerators independent of the specific control system and of the layout and naming conventions of a specific accelerator allowing easy sharing and integration of new tools.
Guidelines for the implementation of AI and machine learning for particle accelerators.	AI technologies that are able to improve accelerators performance criteria such as: beam lifetime, injection efficiency, beam transmission, beam size, beam stability, etc.
Software services for accelerator tuning, usable from a command line for common tasks such as tune, orbit, beam based alignment, chromaticity and optics correction which are applicable to any accelerator (linear/circular, ramped/fixed energy, etc.).	Software services for as many accelerator tuning procedures and algorithms as possible, usable from a command line or as parts of a sequence of tuning actions in large statistics simulations run on computing clusters.
User friendly and documented accelerator tuning tools.	Graphical interfaces with no need for computations (performed in separate processes).

Case studies of successful implementation of middle layer technologies for particle accelerator tuning.	Consistent sharing, re-use and adoption of tools developed for particle accelerator tuning, with minimal or absent adaptations.
Timestamped and fully detailed metadata easy to access, analyse and store.	OPEN and FAIR Scientific open data management, for durability and easier sharing (where relevant).
Socio-economic impact	
Allow quick build-up of experience to design and operate new accelerator-based facilities in countries that presently do not have them.	New facilities rapidly become contributors to the scientific work, expanding the access to accelerator based science around the world.
Greater interaction between researchers, software engineers and companies in the field of particle accelerator tuning.	Reciprocal communication that increases the capacity for research to be fast and effective in bringing particle accelerators performance to unprecedented levels and expand the number of laboratories and companies which can operate accelerators.
Increased emphasis on diversity, inclusion and equality in particle accelerator research at the European level.	Less differentiation of software for the same tasks, with the provision of online documentation which meets the needs of diverse groups in an inclusive and equitable manner.
Faster commissioning and accelerator tuning. Faster application of development done in other sites to improve beam quality.	Better beam parameters for users, thus more/better/faster experiments with their existing infrastructures.
Greater collaboration and knowledge exchange between participants from different countries.	More time and resources available for new developments thanks to the PyAML platform that drastically reduces the time and resources needed for re-implementation of the software required for accelerator tuning.

Table 1: Short and long-term Impacts of the PyAML-Net Action

3.2. MEASURES TO MAXIMISE IMPACT

3.2.1. KNOWLEDGE CREATION, TRANSFER OF KNOWLEDGE AND CAREER DEVELOPMENT

PyAML-Net will achieve its scientific objectives through four interdisciplinary Working Groups (WGs) (described in section 4) that will coordinate and meet regularly to work on specific themes that will fuel the global networking Action activities. This will be done by exploiting the available networking tools of COST in order to bring together target groups of experts and YRIs from the different communities relevant for this Action.

One of the key pillars of the Action will be tests of the software releases at several laboratories, which will mainly take place via STSM. These are an effective way to ensure knowledge transfer with direct human contact and training through common research. For this, PyAML-Net will launch STSMs among the members of the different WGs, giving priority to establish new collaborations between YRIs and experts in the field as well as between experienced researchers and ITCs or underrepresented groups. Besides boosting the research output of the Action participants, these tools will help to increase the global capabilities of the community and strengthen efforts to achieve the Action objectives.

Another pivotal element that PyAML-Net will use to transfer and communicate knowledge through the network will consist of different types of meetings, namely:

International Conference: an annual international conference will be organised. This event will aim to bring together experts in the different topics of interest for the Action and help the rest of the community, especially YRIs and ITC researchers, to interact with them and other experts. These events should act as a catalyst for new collaborations that could be implemented via STSMs. In addition, these conferences will also be useful to highlight relevant results from STSMs and the work of underrepresented groups, ITC researchers, and YRIs.

Workshops: PyAML-Net will also feature regular short (half day) workshops for more focused research areas and WG interfaces which will accelerate many of the Action's objectives.

Finally, PyAML-Net will train and promote YRIs by complementing their career development with several Action activities, which will be:

Training schools: PyAML-Net aims to organise one training school per year that will equip the next generation of researchers with new skills for the development of PyAML software tools and to broaden their accelerator physics, software engineering and operation knowledge. The schools will be open to participants outside of the Action's network. These will be interdisciplinary in nature and will host leading researchers as instructors who will be crucial in achieving the highest standards. Schools will adopt inclusive approaches for selecting participants and strive for diversity amongst speakers and tutors. Schools will equip the students with the technical know-how to excel in the field as well as the general skills in communication, presentation, and networking to succeed inside or outside the particle accelerator community.

To extend the impact of the schools and to provide long-lasting support to PyAML-Net members and the international community at large, the **Action website** will include all training materials and will link to the specific page created for each conference, workshop or seminar event organised by the Action, as well as news and links of relevant talks. Materials such as software code, examples, presentations, and links to the Action publications and related works will also be available in the PyAML GitHub software repository.

Transfer of knowledge: Section 3.2.2 below describes the channels that will be used to disseminate knowledge to the general public. Here the Action will focus on knowledge transfer within the network, between particle accelerator experts and others, and to the wider community of stakeholders, including researchers, engineers, software engineers, particle accelerator operators and private companies. All PyAML-Net organised conferences and workshops will include events that are open to these groups. The Action partners will also submit papers to international conferences and journals, alongside more specific conferences and professional journals/newsletters. Papers will be published under open access conditions. To strengthen the long-term impact, WG1 will take specific steps to support knowledge transfer between 1) younger and experienced researchers, and 2) research and practice (operation of particle accelerators). PyAML-Net will also develop specific channels to ensure intergenerational knowledge transfer. This will include mentorship for young researchers, including doctoral students, post-doctoral researchers and innovators. It will also include research visits across the network and co-leadership of WGs by experienced and young researchers, engineers, computing scientists, software engineers, private company experts or particle accelerator operators.

Knowledge transfer to other sectors: to support long-term knowledge transfer between research and practice, PyAML-Net will develop training materials for educational organisations (e.g., universities) and online training materials that can be directly and freely accessed by stakeholders and the general public.

Career Development: The Action will facilitate career development and enhance the personal competencies for participants, particularly YRIs and early-career participants. It will also ensure that participants from ICT countries benefit from increased involvement in EU funded research. The Action will cultivate interdisciplinary research skills and help participants connect with audiences and networks beyond their usual domains. By fostering collaboration among peers within a robust network of experts, the Action will pave the way for future joint funding applications beyond the duration of the Action. YRIs will have the chance to develop their leadership skills by leading and co-leading WGs and specific activities. In addition, YRIs will be strongly encouraged to undertake STSMs, and present at conferences and dissemination events.

3.2.2. PLAN FOR DISSEMINATION AND/OR EXPLOITATION AND DIALOGUE WITH THE GENERAL PUBLIC OR POLICY

The main methods used for dissemination will include: 1) electronic communication, 2) face-to-face events, 3) code releases, 4) publications and 5) trainings. These plans will be regularly reviewed.

1) Electronic communication:

- The Action will create a **public website** as a central hub for information and resources created through the Action.

- Social media channels will be used to publicise events to potential stakeholders, encouraging participation in WGs, workshops, stakeholder conferences, meetings and training schools.
- Social media will also be used to maximise dissemination of knowledge and results. The platforms used will be actively reviewed. The Action will use GitHub, Mattermost, LinkedIn and email mailing lists as they are most widely used by the involved stakeholders.
- Public awareness will be achieved through media communication and announcements from the Action members. Newsletters on the action website will also support this aim.

2) Face-to-face events

- Yearly WG conferences will be organised to discuss the progress of the developments and the test results at accelerator facilities. A Final Conference will present the results of the PyAML-Net Action. These conferences will be in-person meetings and will have an option to attend virtually and follow via online live streaming (Zoom meetings).
- Annual meetings and participation in international conferences (both academic and based on particle accelerator operations) will facilitate further exchange of knowledge among Action members and a wider audience.
- WG meetings will take place twice per year and serve to enhance communication among the members of the Action and local audiences.
- Several half-day workshops, connected to STSMs, about every 6 months, will be organised in different geographical regions and online with stakeholders. The workshops will present and discuss the ongoing work of the WGs.

3) Code releases

- Specific open source software releases will be scheduled to distribute stable and tested software.
- Documentation and training will be available online (via the Action website or the Action code repository) at each release.

4) Publications

- The WGs will produce reports on the state-of-the-art, recommendations on technology to develop accelerator tuning tools based on common accelerator middle layer software and strategies/research methodologies for effective implementation of these software tools.
- To ensure broad awareness within the scientific community, the Action partners will publish open-access peer-reviewed articles. The articles will be shared on the website and in open-access journals and published through social media, electronic newsletters, and traditional media.
- To increase the reach of our publications with the public the Action will also create executive summaries, press releases, infographics, and media output in collaboration with the communication experts of the Action members institutions.

5) Training

- The Training Schools will produce materials that will be made available to the public via the web site of the Action and on the Action's GitHub code repository.

In addition to the above online dissemination activities, PyAML-Net will also endeavour to set up other types of live activities to engage with the general public in different scenarios such as **School visits, open days and educational events**. The Action will promote among members the need to interact with school/high school teachers and pupils to inspire the next generation of educators and scientists. To this end, the Action will encourage dissemination talks in schools, participation in online "Play with a synchrotron" events (enabled by the PyAML digital twin technology), and the development of educational resources with up-to-date information on the Action's activities. Resources will be made available at these events for direct interaction with the PyAML software. When needed the Action will look for support from the communication experts of the Action's partner institutes, in order to maximise the impact of the above dissemination plan.

4. IMPLEMENTATION

4.1. COHERENCE AND EFFECTIVENESS OF THE WORK PLAN

4.1.1. DESCRIPTION OF WORKING GROUPS, TASKS AND ACTIVITIES

The primary activities of the PyAML-Net Action will be carried out through the establishment of four WGs. Three thematic Working Groups (WGs 2-4 below) will support progress beyond the state of the

art in key technical areas: WG2 middle layer, calibrations and digital twin; WG3 tuning tools and commissioning simulations; WG4 operational aspects. Bridging and connecting each of these thematic groups, the Action will include a Core Group (WG1) which will foster collaboration and drive the core principles embodied by the network. STSMs and Training Schools will be organised throughout the Action, with the objective of promoting collaborations, enhancing capacity, and the development of YRIs and other stakeholders.

Working Group 1: Inclusion, YRI engagement, inter-disciplinary innovation, impact and dissemination

WG1 will maintain the core objectives of PyAML-Net and ensure that they are enacted in all WGs, activities and STSMs. It will include representatives of all other WGs and members of the Management Committee (MC). It will also include YRIs and representatives of diverse stakeholders in the particle accelerators research ecosystem. The core activities which will be enacted and supported by WG1 are:

Task 1.1: Involvement and co-design by YRIs: reviews of prior work on particle accelerator tools development highlight a fair representation of YRIs in the research and development processes, often pursued by PhD and PostDoc research activities. YRI-involvement will remain central to PyAML-Net. YRI-led hackathons and design sprints (D1.1) will be employed to support this objective.

Task 1.2: The objectives of the PyAML-Net network are ambitious. To achieve them WG1 will bring together a pan-European network during Training Schools and Annual Meetings (M1.1, M1.2, M1.3, D1.2) that is interdisciplinary and intersectoral, balanced in skills, experience and perspectives, and including a wide range of stakeholders. The WG1 will also nominate a Technical Advisory Committee composed of experts responsible for managing code development and repositories (hosted on GitHub), taking final decision in case of disagreement on technical aspects of the project throughout WG2, WG3, and WG4.

Task1.3: WG1 will also focus on disseminating the findings and recommendations of the network and ensuring that it achieves the desired short and long-term impacts. It will be responsible for managing the overall impact and dissemination program, ensuring that stakeholders across Europe have the opportunity to benefit from our knowledge exchange and network building initiatives. Key outputs of WG1 in this sense will be the creation of the Action website (D1.3) and a set of training materials that can be used by educational organisations spanning multiple disciplines, including physics and software engineering.

Task1.4: During the lifetime of the COST Action, WG1 in collaboration with other WGs will promote collaborative funding applications (D1.4). The Action website will include a space dedicated to sharing opportunities across countries, including opportunities focusing on career development of early-career participants and YRIs. This will ensure a strategy oriented to the future that allows for the introduction of new initiatives throughout the life of the Action, also paving the way for future implementation with the involvement of early-career participants, young researcher innovators, and entrepreneurs, fostering the long-term impact of the network.

Working Group 2: Middle Layer, calibrations and digital twin

This working group will be devoted to the central activity of PyAML-Net: creating **middle layer** software that will make an abstraction of the specific control system (TANGO, EPICS, DOOCS, etc.), of the specific particle accelerator (linear, circular, ramped, fixed energy, etc.) and of the naming convention of components. It will also provide access to a digital twin and the possibility to operate in physics or hardware units.

Task 2.1: WG2 will define a Python accelerator middle layer software for all subsequent developments. WG2 will be responsible for all updates to the main core of the PyAML software libraries. The first version will be shared as soon as possible for tests and feedbacks (D2.1) after a common definition of the specifications list (M2.1) and will include digital twin mode as a feature. The code will be enhanced, reviewed and possibly totally changed if needed in later stages. A new release will be done approximately every 12 months (M2.1, M2.2, M2.3, D2.4) including the changes and improvements requested by the other WGs.

Task 2.2: Initially the middle layer will be assumed to work in physics units. As early as possible a preliminary simplified software package for **calibrations** will be made available (M2.4). An additional **calibrations** package will be designed to translate physics units (Tesla, meter, electron-Volt, etc.) to

hardware units (Amperes, Volts, etc.). This calibration package will enable conversion algorithm from simple linear calibrations up to complex combined function magnets calibrations that involve multiple fields for multiple power supply inputs (D2.2). A new release will be done approximately every 12 months (M2.5).

Task 2.3: The middle layer will also enable a **digital twin** mode. The WG will assess the possibility to provide a way to choose the simulation engine behind the digital twin (D2.3). pyAT will be an obvious choice for storage rings, but Elegant [19] or OPAL [20] could be a better solution for linear accelerators.

WG2 will keep focus on **documentation** and **maintenance** during the whole development. **CI/CD** features will be fully in place by the end of the action for all the code source of the above components (D2.4). It will also do all necessary **updates** to the code as requested and agreed with the other WGs.

Working Group 3: Tuning tools and commissioning simulations

The WG3 will be responsible for building the tools that users will interact with for real experiments, measurements and tuning of the accelerators. Initially the middle layer software will not be available, but commissioning simulations tuning scripts will be developed such that they can be used with the middle layer software developed by WG1. This group is also in charge of providing a **commissioning-simulation mode** for the PyAML joint technology platform. During the development, feedback and exchange with WG2 will be necessary.

Task 3.1 (tuning tools): Develop a preliminary version of basic tuning tools such as (but not limited to): tune correction, orbit correction and chromaticity correction (D3.1). Ensure that this software may be used within the PyAML middle layer software (M3.1). Test the individual actions for at least one case of circular accelerator or linear accelerator or ramped energy accelerator or a transfer line (if applicable) by using the digital twin mode of the PyAML middle layer software (M3.2). Include the basic tuning tools in the main code repository (D3.2). Develop at least one more advanced tuning tool such as (but not limited to): Beam Based Alignment (BBA), Linear Optics from Closed Orbit (LOCO), Badger/Xopt optimisations (Machine learning and Artificial intelligence) (M3.7). Test using the PyAML middle layer in digital twin mode and in commissioning simulations mode (M3.8). Include the advanced tuning tools in the main code repository (D3.4).

Task 3.2 (PyAML tuning tools sequencing and commissioning-simulation mode): develop or choose a sequencer software to perform the above corrections in a sequence (M3.3). Test the sequence of actions for a circular accelerator, linear accelerator, ramped energy accelerator and a transfer line (if applicable), using the digital twin mode of the PyAML middle layer software (M3.4). Define how to interact with HPC clusters (M3.5). Enable commissioning simulations mode: use the tools developed in Task 3.1 in a sequence to run commissioning simulations on a large number of alignment gradient and diagnostic errors scenarios (D3.3). Save all instances of corrected lattices such that their performance in terms of lifetime, injection efficiency, transmission efficiency, etc. may be evaluated (M3.9). Add sequencing of tuning tools to main code repository (D3.5).

Working Group 4: Operational aspects

WG4 will be responsible for testing the software on real machines and looking at the most operational aspects of the PyAML software. It will be in charge of testing the tools defined by WG3, of the design of corresponding user interfaces, of data formats, of archiving, of anomaly detection and of the tools for the setup of different optics for a given accelerator.

Task 4.1: Test the code developed by WG3 within the infrastructure provided by WG2 at different laboratories (YRIs in STSMs for this scope). Test in at least 3 facilities at most 6 months after every release (M4.1, M4.2, D4.1).

Task 4.2: Design at least one basic “thin” (no beam dynamics computations within the interface) user interface. Compare different possible options for graphical interfaces. Evaluate if graphical interfaces should be provided with the PyAML software or not (D4.2).

Task 4.3: Evaluate available software for data archiving and access (for example Tiled [21]) and propose modifications to the data formats generated by WG3 for saved data. Evaluate if FAIR principles are enforced in data formats (D4.3) when needed. Contribute to WG2 developments to obtain this result.

Task 4.4: Set up software to perform slow and fast feedbacks for orbit correction. Evaluate speed rates and provide feedback to WG2 for potential bottlenecks (D4.4).

Task 4.5: Compare the data collected from Task 4.1 during real experiments with data obtained from the digital twin mode of the PyAML software to determine if they are usable for anomaly detection. Provide feedback to WG2. (D4.5)

4.1.2. DESCRIPTION OF DELIVERABLES AND TIMEFRAME

Table 4 below lists the deliverables and milestones in chronological order. Several deliverables of WG3 and WG4 are made possible by milestones of WG2 (see GANTT chart in Sec 4.1.4).

Description (D=deliverable, M=Milestones)		Month
D1.3	Website	3
M2.1	Middle layer software specifications	3
D2.1	First version of Python accelerator middle layer (PyAML) software + license	6
M2.4	Preliminary simplified calibration package	6
M3.1	Ensure that basic tuning tools may be interfaced with D2.1	6
D3.1	At least one among the basic tuning tools is developed: orbit, tune, chromaticity	9
M1.1	Annual meeting + training school + report/minutes/training materials	9
D1.1	YRI-led hackathons and design sprints	12
M3.2	Test basic tuning tools in digital-twin mode	12
M4.1	Test D2.1 in at least 3 laboratories	12
D3.2	Include an initial version of basic tuning tools in main code repository	15
M3.3	Develop/choose a preliminary version of sequencer for tuning actions	15
D4.3	Provide first examples of data formats using FAIR principles	18
M2.1	Middle layer software update release	18
M3.4	Test sequence of tuning actions for several accelerators	21
M1.2	Annual meeting + training school + report/minutes/training materials	21
D2.2	First version of a calibrations software	24
D3.3	Run D3.2 tools as a commissioning sequence on cluster	24
M4.2	Test M2.1 in at least 3 labs	24
M3.5	Define how to interact with a computing cluster	27
D4.2	Test of at least one GUI, decision to use GUIs or not	30
M2.2	Middle layer + calibration software update release	30
M3.7	At least one advanced tuning tool is developed: BBA, LOCO, Badger	30
M1.3	Annual meeting + training school	33
M3.8	Test at least one advanced tuning tool: BBA, LOCO, Badger in digital-twin and commissioning-simulations mode	33
D2.3	Evaluation version of a variable engine digital twin	36
D3.5	Include an initial version of advanced tuning tools in main code repository	36
D4.4	First examples of slow and/or fast orbit feedbacks	36
M4.3	Test M2.2 in at least 3 labs	36
M3.9	Run sequence of tuning actions (basic and advanced) in commissioning-simulations mode, store files for evaluation	39
D3.4	Add sequencing and commissioning-sequence mode to main repository	42
M2.3	Middle layer + calibration + digital twin software update release	42
D4.5	Evaluate feasibility of anomaly detection	42
D4.1	At least 3 labs have PyAML software installed and available for use	45
D1.2	Final meeting	48
D1.4	Promote, organise and eventually submit collaborative funding applications	48
D2.4	PyAML software update major release, including doc, CI/CD, tests, examples	48

Table 4: Deliverables and Timeframe of the PyAML network

4.1.3. RISK ANALYSIS AND CONTINGENCY PLANS

Considering a probability score going from 1 (unlikely) to 3 (likely) and an impact going from 1 (minor) to 3 (major), Table 2 lists risks and corresponding contingency plans. The risk score is given by Impact + Probability.

Risk (Imp. + Prob.)	Contingency plans
Lack of understanding between disciplines or sectors (3+1)	The Action Chair, Vice-Chair, MC members, and WG leaders will leverage their expertise to support communication and shared understanding. WG leaders have experience of fostering multidisciplinary work and connecting researchers from different backgrounds.
Low quality deliverables and outputs (3+1)	Best practice in software development procedures will be enforced, such as peer-reviewed pull-requests and CI/CD tests. Should this problem appear, participants will be asked to improve the deliverable, if needed with the help of other WG members and eventually external experts.
Delay in the production of deliverables (3+1)	Agree due dates in advance. Provide reminders and propose solutions. The WG leaders and MC will ensure that deadlines are respected. Should delays continue to occur a substitute within the Action will be assigned to the task.
Disruption to knowledge sharing and the exchange of information (2+1)	The diverse range of activities may lead to interruptions in the network's knowledge and information flow. To prevent this, the MC will maintain communication among members, ensuring regular meetings and clear communication of objectives and timelines.
Conflicts (2+1)	Should a conflict emerge among two or more partners, the MC will act to mediate and to find a solution. In case the conflict persists, an ad-hoc crisis committee will be established with the support of the COST Association, possibly involving external expert to reach a solution
Low participation in WG meetings, conferences (2+1)	Given the response to the invitation to join the COST Action proposal, the likelihood of this risk is low. Should it happen, the MC will foster targeted engagement efforts. Scheduled meetings will take place involving WG leaders and participants, with the purpose of strengthening or modifying the project plan as needed to ensure that all participants can make meaningful contributions.
Low involvement of PhD students and YRIs (2+1)	COST Action members will clarify the benefits of involvement, emphasising networking and mentorship opportunities. All MC members are encouraged to involve early-career participants and YRIs.
Partners leave the network (2+1)	When members leave, a replacement will be identified promptly from MC or MC Substitution List, while considering geographical, gender and age balance.

Table 2: Risks and contingency plans of the PyAML network

4.1.4. GANTT DIAGRAM

