Technology Development Programme

Technology Mapping
2026 Series

Metrology and Reverse Engineering

FUSION FOR ENERGY



Version history

VERSION	DATE	CHANGES
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Contents

Table of Figure and tables ... 4
Table of Proposals ... 4
Foreword ... 5
Executive Summary ... 6
1 Introduction ... 7
1.1 Context ... 7
1.2 Metrology and Reverse Engineering technology mapping ... 7
2 Technology mapping process ... 8
2.1 Topic proposal ... 8
2.2 Online workshop ... 8
2.3 In person workshop ... 9
2.4 Final report ... 9
3 Metrology and Reverse Engineering technology Breakdown ... 10
3.1 Metrology and Reverse Engineering overview ... 10
3.2 Technical breakdown of technologies ... 10
3.3 Map of development areas ... 11
3.3.1 Advanced Metrology Tools & Techniques ... 12
3.3.2 Integrated Engineering & Dimensional Management ... 13
Design for Tolerance: Integrating Tolerancing Requirements (J.J. Cordier and J. Fuentes) ... 14
3.3.3 Core Metrology & Reverse Engineering Practices ... 15
Advanced Reconstruction: Creating the As-Built Model (M. Biancolini - UNIROMA 2) ... 15
4 Summary of the workshop ... 17
5 Outcome: technology road-mapping ... 18
5.1 Technology dashboards ... 18
5.2 Overview of the in-person session development proposals ... 19
5.2.1 Advanced Metrology Tools & Techniques ... 19
5.2.2 Integrated Engineering & Dimensional Management ... 19
Business intelligence from design to operation for large complex assemblies ISO GPS based ... 19
5.2.3 Core Metrology & Reverse Engineering Practices ... 19
Tool for a quantitative assessment of process uncertainty ... 19
Measurement Filtering Tool of External Deformation Effects ... 20
Integrated tool for managing As-Built reconstruction ... 20
Management of simplified tolerance stack-up hybrid models for big assemblies ... 20
6 Conclusion ... 28
Appendix 1: Technology Readiness Levels ... 29
Appendix 2: Technology assessment ... 30

Table of Figure and tables

Figure 1: Technology Mapping Process 8
Figure 2: Overview of the Development Areas 11
Figure 3: Logos of participating entities 17
Figure 4: Typical technology dashboard 18
Table 1: TRLs 29
Table 2: Technology Assessment 30

Table of Proposals

Proposal 1: Ad-hoc system for milling machine calibration 21
Proposal 2: Compact metrology tool for in-process control within CNC 22
Proposal 3: Business intelligence from design to operation for large complex assemblies ISO GPS based 23
Proposal 4: Tool for a quantitative assessment of process uncertainty 24
Proposal 5: Measurement Filtering Tool of External Deformation Effects 25
Proposal 6: Integrated tool for managing As-Built reconstruction 26
Proposal 7: Management of simplified tolerance stack-up hybrid models for big assemblies 27

Foreword

The fusion sector is entering a transformative era, characterized by a rapid acceleration in technological advancement. It is now imperative for academia, public research organizations, and private stakeholders to rise to this challenge by synchronizing their efforts. Only through a unified technology roadmap can the community clearly chart the progression of critical fusion technologies from foundational research to large-scale industrial application.

As a European hub for fusion technology, F4E is uniquely positioned at the core of this ecosystem. We are committed to identifying vital R&D opportunities for future power plants, facilitating the seamless exchange of specialized knowledge, and fostering strategic partnerships across the entire fusion landscape.

Driven by this ambitious objective, F4E convened the inaugural technology mapping workshop focused on Metrology and Reverse Engineering technologies, bringing together over 150 experts from 22 public and private entities in a collaborative effort to share knowledge and align on common priorities. We are now pleased to present the resulting report, which aims to serve as a reference for economic operators navigating the complexities of national, international, and private funding landscapes.

The insights gathered during the workshop have enabled the development of a solid basis for strategic planning, and we intend to build on this approach by extending it to other key technology domains to sustain progress across the fusion sector.
However, these efforts cannot rely on internal activities alone, and active engagement from all stakeholders will be essential. We therefore invite the community to contribute to this process and work together to accelerate the development of fusion technologies.

Dr. Enrique García-Vidorreta
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Metrology & Reverse Engineering Group Leader

Executive Summary

Metrology is not a peripheral task but a transversal topic that must fully integrate geometrical requirements from the initial design phase right through to system operation. The 2026 Metrology and Reverse Engineering Mapping exercise is a groundbreaking initiative to accelerate their development across Europe. This comprehensive assessment, involving over 150 participants from several public and private organizations, focused on highlighting the critical areas where Metrology and Reverse Engineering activities shall play a role. The output of the exercise is intended to be used by the public and private European fusion Metrology and Reverse Engineering community as a reference document to guide current and future investment.

Technology mapping

The mapping exercise identified and characterized 6 technologies across 3 primary domains:

- ***Advanced Metrology Tools and Techniques***, dedicated to the investigation and deployment of state-of-the-art measurement systems and emerging methodologies, with particular emphasis on their integration within manufacturing and assembly workflows, as well as their application to in-process and in-operation monitoring for performance verification and control.
- ***Core Metrology & Reverse Engineering Practices***, focused on the essential activities performed both before and after the actual physical measurement process, including detailed discussions on uncertainties estimation, the crucial management of as-built data, and the rigorous definition of tolerances through comprehensive stack-up analyses
- ***Integrated Engineering & Dimensional Management***, addressed to the definition of top-level geometrical requirements, their systematic propagation throughout the design and development lifecycle, and the consequent impact on metrology strategies, verification methodologies, and overall dimensional control.

Each technology was evaluated against a defined set of criteria, including Technology Readiness Level (TRL), applicability to other sectors, criticality, development needs, and European capabilities. This data was consolidated conveniently in a visual dashboard for each technology for reference and regular updates.

The report points out key opportunities to strengthen European capability in the metrology & reverse engineering fields:

- Develop specific metrology tools to integrate better dimensional control during critical phases of the manufacturing process
- Provide a more in-depth traceability of the as-built data acquired during the several phases of the product's life cycle
- Improving how uncertainty of the measurement process is estimated according to standard
- Integrate measurability aspects in the definition of geometrical requirements, already from the design phase

Investment Implications

Whilst geometrical requirements and metrology practices are cross-sector and globally established disciplines, Europe has a strong opportunity to play a leading role in defining a common framework for their management, creating a tangible competitive advantage.
Europe also benefits from a wide range of funding sources, including European and national public programmes, private investments, and international collaborations. Ensuring better coordination across these instruments, together with a more fluid exchange of knowledge and information, will be key to effectively developing a strong and consistent metrology culture for fusion in Europe.

1 Introduction

1.1 Context

In 2024, Fusion for Energy launched a Technology Development Programme (TDP) as part of the implementation actions of its Industrial Policy. This TDP is dedicated to building and reinforcing European Fusion Supply chain capabilities for technologies that are deemed to be critical for the future of commercial fusion. The programme requires the identification of key technologies to direct R&D contracts to European contractors.

Prioritizing and allocating funding opportunities across both organizations requires a comprehensive review of the involved technologies on each major fusion technical domain. Doing this exercise in a collaborative way will enable stakeholders to identify which technologies are fundamentally needed (technology mapping). A map built through consensus of key stakeholders in the field can also serve as a powerful argument when seeking additional funding from national and international public and private investors.

To coordinate these efforts, Fusion for Energy has launched a technology mapping initiative uniting academia, research laboratories, industry, start-ups and the ITER Organization to develop a comprehensive technology development roadmap for Metrology and Reverse Engineering domain.

The outcome of this exercise will serve all stakeholders to guide their action in their respective domains, allowing an effective investment of resources. Given the fast evolution of technology, a periodical follow-up of the workshop outcome shall be assured in subsequent technology mapping exercises.

1.2 Metrology and Reverse Engineering technology mapping

Metrology tools and techniques, Reverse Engineering practices, and the management of dimensional and geometrical requirements are key elements in the design, manufacturing, and assembly of any product, both in fusion and non-fusion contexts. From a technical perspective, these disciplines have a direct impact on system schedule and cost.
A common practice among high-performing manufacturers is the effective integration of Metrology and Reverse Engineering within manufacturing processes. Access to reliable as-built data for parts and components, both during production and prior to assembly, is essential to detect non-conformities at an early stage and to anticipate and plan corrective actions.
In addition, measurability must be considered already during the design phase, as it plays a key role in the correct translation of functional requirements into dimensional and geometrical specifications.

The scope of this mapping exercise covers metrology tools and techniques, reverse engineering practices, and dimensional and geometrical management.

The main associated activity was a workshop structured in two phases, held in November 2025 and January 2026, aimed at collecting the majority of the relevant inputs while also providing a platform for participants to exchange knowledge and strengthen networking.

This document provides a complete overview of the exercise, detailing the process and scope through a comprehensive technology breakdown, summarizing the meetings held and providing the resulting proposed technology development roadmap.

2 Technology mapping process

The technology mapping process consists of 4 stages.

Figure 1: Technology Mapping Process

2.1 Topic proposal

In preparation of the exercise, staff from Fusion for Energy prepared a draft technology breakdown with some input from ITER Organization colleagues, listing technologies of interest and grouping them functionally.
This breakdown, together with a brief description of each selected technology, was included in a proposal of topics (see section 3) for consultation by participants ahead of the first meeting (the online workshop).

2.2 Online workshop

The online workshop provided an opportunity for all participants involved in the technology mapping exercise to come together. It lasted approximately 8 hours and was structured according to the following agenda:

- Welcome and introductory remarks
- The technology mapping process
- Short introductory presentations about the field of interest
- Brief overview of technology breakdown
- Presentation about the technology domains by F4E staff
- Presentation about each topic by invited presenters
- Explanation of the next step (in person workshop)
- Survey feedback and wrap-up

The main outcome of the online workshop was a consolidated list of industry needs and key development areas, agreed upon by all participants. This breakdown formed the basis of the technology mapping, representing the primary output of the initial phase of the exercise.
An online session report, including the updated technology breakdown (see Section 3), was shared with participants ahead of the in-person workshop.

2.3 In person workshop

The in-person workshop aimed to develop detailed proposals for technology development, building on the industry needs identified and agreed during the online workshop.

The characterization of each technology followed a structured four-step approach:

- Agreement on current Technology Readiness Level (see Appendix 1 for definitions)
- Definition of the next step (e.g. analysis, prototype, testing, industrialization plan, etc.) including, where possible, a view on medium- to long-term developments
- Evaluation of key technology characteristics (see Appendix 2 for the full list of assessed parameters).
- Development of indicative timelines, defining short-, medium-, and long-term needs for the technologies included in the mapping

The workshop was highly collaborative, with sessions designed for participants to exchange, build consensus and provide feedback on specific interests and the mapping process itself.
It also provided opportunities for knowledge exchange and the establishment of collaborations over its one-and-a-half-day duration, including both formal sessions and informal networking moments.

2.4 Final report

After the in-person workshop, the outcome was compiled into this final report. The report includes an overview of capabilities in the field as well as the proposed technology roadmap detailing and prioritizing possible actions for the period until the next review (typically 2 to 3 years). This report is the result of a collective effort, with many participants providing valuable comments before the final version of the report was published.

3 Metrology and Reverse Engineering technology Breakdown

3.1 Metrology and Reverse Engineering overview

Metrology and reverse engineering are disciplines integral to the entire product lifecycle. They provide useful inputs for the completion of every step of product design, manufacturing, and assembly.
In a typical product life cycle, the design phase aims at defining a product compliance with top-level functional requirements. To achieve this goal, 3D CAD models, detailed drawings and geometrical requirements are defined.
In manufacturing, these geometrical requirements shall be thoroughly monitored and verified.
During manufacturing steps intermediate checks on geometrical requirements are performed by means of metrology dimensional inspections. At the end of manufacturing, the final assessment of all the geometrical requirements is performed, and an as-built representation of the component geometrical requirements is produced and used as main input for the assembly and commissioning the component.
Geometrical requirements are the main drivers not only of the manufacturing process but also of the metrology and reverse engineering activities, which shall be effectively considered part of the process.
As a direct consequence, the level of tolerance associated to each specific requirement could have a significant impact on the manufacturing and metrology processes (e.g. the process for assessing geometrical requirements), It is crucial to proper take into account manufacturability, measurability, functionality and assembly aspects while specifying the requirements.
The more stringent is the tolerance value, the higher is the cost of metrology, usually impacted by the need of a more resource demanding metrology process to be deployed (stable environment, scope specific cutting-edge measurement tools, novel techniques for alignment and verification). Similarly, reverse engineering activities are more sophisticated and demanding (in terms of final reconstruction error) the more stringent assembly requirements are.

The workshop provided a platform to directly address these challenges, fostering consensus among attendees while identifying key development areas and brainstorming innovative solutions.

3.2 Technical breakdown of technologies

The technologies can be split into three main domains:

- **Advanced Metrology Tools & Techniques, covering** measurement instruments, novel techniques, and their integration into the manufacturing and assembly processes, as well as the monitoring of systems during operation.

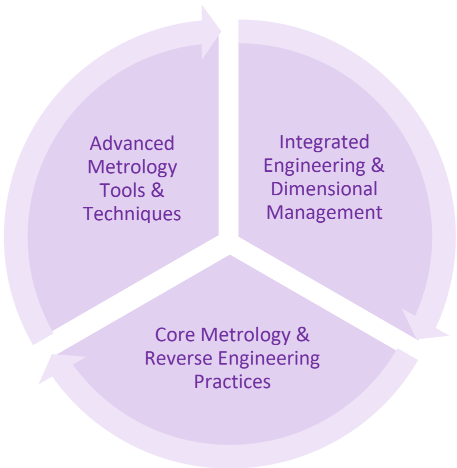
- **Integrated Engineering & Dimensional Management,** addressing the highest level of geometrical requirements, their definition, their subsequent propagation throughout the design process, and the significant impact these top-level requirements have on the overall metrology process.

- **Core Metrology & Reverse Engineering Practices,** focusing on the essential activities performed both before and after the actual physical measurement process. This included detailed discussions on uncertainties estimation, the crucial management of as-built data, and the rigorous definition of tolerances through comprehensive stack-up analyses.

3.3 Map of development areas

The purpose of this section is to provide a brief overview of the needs of the industry and main development areas identified at the end of the online session and categorized in metrology, reverse engineering and dimensional and geometrical management. In the following subsections, the content of the presentations held during the online session is detailed.

Overview



Advanced Metrology Tools & Techniques

- Development of methods for calibration of machining tool with metrology instruments
- Integration of metrology instruments in machining tools
- Development of solutions for 6DoF tracking for large-scale components.
- Development of solutions combining laser trackers and AI to identify scan zones and support remote operations.
- Development of double-wavelength instruments to correct for refraction effects in both distance and angular measurements
- Development of robust industrial monitoring solutions capable of withstanding harsh conditions (high magnetic fields, significant radiation and cryogenic temperatures)
- Development of AI-assisted alignment tools to speed up and refine setups of tomography and Non-destructive methods for scanning internal surfaces.

Integrated Engineering & Dimensional Management

- Development of supporting tools and software for the effective definition and management of geometrical requirements
- Development of supporting tools and software for requirements mapping to ensure robust traceability of all system needs.
- Development of centralized platform connecting design, simulation, machining and metrology

Core Metrology & Reverse Engineering Practices

- Development of tools for semi-automatic or AI-based point-cloud classification
- Development of tools based on data fusion techniques to improve reconstruction combining scans
- Development of tools for or AI-assisted reconstruction of CAD models
- Development of environments for standardized, large-scale uncertainty estimation
- Development of detailed models for thermal scaling to maintain a valid uncertainty budget.
- Development of standardized tools for assessing compliance of measurement instruments with uncertainty
- Incorporation of as-built information into tolerance stack-up models
- Detailed modelling of tolerance stack-ups for full-system representation

Figure 2: Overview of the Development Areas

3.3.1 Advanced Metrology Tools & Techniques

Metrology for In-Process Quality Control (U. Mutilba – TEKNIKER)

The discussion focused on how metrology can support manufacturing directly in-process, using tools such as laser trackers, calibrated scanners and even CNC machines for intermediate checks. Speakers stressed the importance of understanding uncertainty, environmental effects and the risks of false acceptance or false rejection.

Several questions shaped the debate. Discussions first addressed Tool Calibration, specifically exploring how high-precision metrology instruments could be used to accurately calibrate machining equipment. Attention then shifted to establishing Common Reference Frames, determining the optimal method for creating shared coordinate systems verifiable by both the machining and measurement tools. Finally, the group examined the Direct Incorporation of metrology systems, assessing the technical requirements and advantages of embedding these instruments directly within the operational structure of the machining tools.

Main Hot Points, Highlights and Challenges

- Difficulty in proving that the instrument's reported uncertainty reflects real accuracy under operating conditions.
- A substantial effort is necessary for the proper qualification and calibration of machining tools.
- Considerable work is needed to successfully establish a common reference system shared between machining tools and metrology instruments.

Guidance & Monitoring for Precision Assembly (D. Mergelkuhl – CERN)

The presentation showed how metrology assists assembly through short-term feedback and monitoring, especially in demanding environments. The presentation identified areas for improvement within the management of ambient environmental conditions. To substantially enhance the accuracy of complex assembly processes, the speaker proposed the development of double-wavelength instrumentation capable of applying critical corrections for refractive effects affecting both linear distance and angular measurements. The speaker also emphasized the necessity for monitoring systems robust enough to endure harsh operating environments, such as high magnetic fields, significant radiation, and cryogenic temperatures. Currently, suitable industrial sensor solutions are limited.

Questions addressed potential improvement using metrology scans: the speaker noted that acquisitions exist, but the challenge is turning them into reliable guidance. On 6DoF tracking, it was explained that tools for small objects work well, while large-scale solutions are still not ready. Participants also asked about remotization and safety: the answer highlighted approaches combining laser trackers, fiducials and AI to identify scan zones. On dynamic accuracy, it was noted that sectors like aerospace combine multiple 6DoF strategies to enable fast and precise positioning.

Main Hot Points, Highlights and Challenges

- Need for better solutions for 6DoF tracking, especially for large-scale components.
- Potential in combining laser trackers + AI to identify scan zones and support remote operations.
- Development of double-wavelength instruments to correct for refraction effects in both distance and angular measurements
- Development of robust industrial monitoring solutions capable of withstanding harsh conditions (high magnetic fields, significant radiation and cryogenic temperatures)

Maintaining the Digital Twin: Real-Time Geometric Status (S. Sablerolle – ESA)

The presentation addressed how geometric information can support operational digital twins. The speaker outlined the difficulty of assessing geometry under varying test conditions and the distinction between continuous measurements and spot checks processed in real time.

Questions focused on temperature management: maintaining uniform conditions over large areas is difficult and requires dedicated solutions. On calibration through thermal cycles, the answer stressed that each step requires its own validated thermal model and uncertainty. The speaker noted that deformation modelling and uncertainty remain strong limiting factors in the usage of digital twins during operation. The link between measurement, deformation and analysis is still hindered by the uncertainty of the analysis itself.

Main Hot Points, Highlights and Challenges

- Thermal control in large environments is one of the main challenges.
- Calibration across thermal cycles requires careful modelling to maintain a valid uncertainty budget.
- Difficulty in building a reliable digital twin for production lines due to the complexity of uncertainty propagation.
- Uncertainty in analysis and deformation models is still an open debate.

3.3.2 Integrated Engineering & Dimensional Management

Product Lifecycle Management of Dimensional Requirements (G. Concheri – UNIPD)

The presentation primarily focused on the critical topic of defining and managing geometrical requirements throughout the project lifecycle. Three main domains were identified as central to where these requirements are established, debated, and communicated: Design, Manufacturing, and Quality Control.

The speaker highlighted the inherent complexity involved in managing these geometrical requirements, particularly due to the multiple actors and diverse phases involved in the product life cycle. A significant point raised was the observation that a shared awareness and deep understanding of the ISO Geometrical Product Specification (GPS) standards is often lacking across teams. This gap in knowledge frequently leads to major difficulties in clear and effective communication.

Reactions and questions from the audience directly reflected these challenges, addressing the widespread difficulty encountered when attempting to define geometrical specifications accurately within the framework of the established ISO GPS standards, and underscoring the pressing need for effective supporting tools.

Main Hot Points, Highlights and Challenges

- ISO GPS is a language, not a methodology; its effectiveness depends on user understanding and correct application in design.
- Supporting tools and software are key necessities for the effective definition and management of geometrical requirements

Design for Tolerance: Integrating Tolerancing Requirements (J.J. Cordier and J. Fuentes)

The presentation detailed the definition and subsequent management of both functional and interface requirements specifically within the context of the ITER project. Central to the effective handling of these requirements are essential tools and studies, notably tolerance stack-up analysis tools and comprehensive design studies. Furthermore, the monitoring of these requirements is maintained throughout the assembly phase, which critically includes the rigorous management of as-built information.

A primary challenge highlighted by the presenter was the notable lack of an integrated approach spanning the different technical environments and analytical studies. This absence of integration effectively delegates the complex task of synthesizing all the various aspects of the product specification to the individual teams working on the project, creating a demanding layer of manual coordination.

Main Hot Points, Highlights and Challenges

- The necessity for all project actors to stay aligned on geometrical requirements as they evolve throughout the entire product life cycle.
- The imperative to establish clear requirements mapping to ensure robust traceability of all system needs.

Integrated Metrology Design (M. Narduzzi – FERMILAB)

The speaker demonstrated the essential aspects of integrating metrology directly into the product design and manufacturing process. Using examples of stringent system requirements, it was clearly illustrated how project stakeholders must consider various aspects of measurability as early as the initial design phases to ensure that future assessments and quality checks remain feasible.

Early design studies must involve detailed planning regarding the accessibility of features, determining the necessity for extra material to aid in metrology, and defining the critical steps for alignment of subassemblies before major manufacturing steps are executed.

The audience reiterated several key points already highlighted in earlier presentations, reinforcing the importance of effective integration and robust requirements management. In conclusion, the speaker suggested to develop software tools specifically capable of supporting the measurement strategy definition in conjunction with all other technical aspects of the product design. On a related technical note concerning the measurement process, the speaker highlighted an interesting possibility for advanced inspection. Specifically, they suggested the integration of tomography or other non-destructive examination methods with systems used for global alignment. This combination could be leveraged to precisely measure the thicknesses of components.

Main Hot Points, Highlights and Challenges

- Highlighted the need for centralized platform connecting design, simulation, machining and metrology, Agile and iterative approaches may help handle changing requirements.
- AI-assisted alignment to speed up and refine setups of tomography and Non-destructive methods for scanning internal surfaces.

3.3.3 Core Metrology & Reverse Engineering Practices

Advanced Reconstruction: Creating the As-Built Model (M. Biancolini - UNIROMA 2)

The presentation primarily concentrated on the algorithms employed for updating the As-Built representation of CAD/CAE models. This process utilizes metrology information—measurement data collected from the physical component—to automatically refine the digital twin. This methodology is critical for streamlining as-built information directly into the established process for managing component requirements.

Furthermore, other contributions addressed the complex challenge of managing large volumes of scan data. Specifically, there was a recognized need to leverage advanced technology, such as Artificial Intelligence (AI) solutions, to automate the time-consuming process of feature recognition within this collected data.

The discussion also addressed the specific challenge of managing multiple scans of the same feature, particularly when these scans are captured at different moments in time and utilize varying resolutions. Potential solutions were explored, aiming to effectively integrate information derived from these diverse sources and ultimately improve the consistency and accuracy of the resulting data.

Main Hot Points, Highlights and Challenges

- Need to accelerate point-cloud → CAD workflows through semi-automatic or AI-based classification.
- Data fusion techniques can combine dense but lower-quality scans with sparse high-accuracy measurements to improve reconstruction.
- Importance of preserving design intent: many CAD details are lost after manufacturing; updated CAD models or AI-assisted reconstruction could bridge this gap.

Quantifying Trust: Evaluating Measurement Uncertainty (D. Heisselmann – PTB)

The presentation aimed at giving an overview and showing the main challenges in the estimation of the uncertainty of a metrology process following the standards. The discussion revisited the need for reliable uncertainty estimation, taking into account not only the instruments specifications, but contributors coming from all sources (environmental conditions, alignment, feature definition). The difficulty in having a non-ambiguous way to comply with standards create difficulties in assessing the compliance with a geometrical requirement. In response to questions, speakers underlined that many uncertainty issues originate from design: poor ISO GPS usage, unsuitable datums, and missing functional tolerances.

Main Hot Points, Highlights and Challenges

- Lack of standardized, traceable procedures for large-scale uncertainty estimation.
- Need for having a standardized way to assess compliance of measurement instruments with uncertainty

Tolerance Stack-Up Analysis and Definition (P. Leonard – ITER)

The presentation addressed the application of tolerance stack up analysis in the management of ITER geometrical requirements. The presenter gave an overview of typical usage of tolerance stack up models in industry, before entering into the details on how the methodology has been applied in the tokamak design and manufacturing.

The ITER example showed the difficulty of managing tolerances without centralized data. Modern 3D statistical tools improve analysis, but only if requirements and documentation are consistent.

Questions addressed integrating as-built data: simplified models can update some components, but full integration remains difficult. Regarding tracing which tolerances impact which requirements, speakers pointed to engineering judgement supported by statistical tools. Comments stressed that analyses are often run before geometric definitions are complete, reducing reliability.

Main Hot Points, Highlights and Challenges

- Inclusion of as-built data: simplified models can be updated with actual measurements to compute more realistic tolerances.
- Integration of tolerance stack up analyses with requirement databases and 3D design models

4 Summary of the workshop

In total, 150 participants registered for the 2025 Metrology and Reverse Engineering Technology Mapping workshop, with the online session reaching a peak attendance of 150 participants and 40 participants attending the in-person workshop. Overall, 22 public and private entities were represented. Fusion for Energy would like to thank all participants for their valuable contributions throughout the workshop and in the follow-up activities.

Figure 3: Logos of participating entities (excluding F4E and IO)

5 Outcome: technology road-mapping

5.1 Technology dashboards

During the in-person workshop, and throughout the preparation of this report, a significant amount of valuable data was collected and consolidated into a dedicated database. For each technology, the following information is currently available:

- TRL
- Criticality
- Other fields of application
- Alternative technologies
- Potential showstoppers
- Existing and needed test facilities
- European entities involved
- Technology development actions

This data has been structured into individual dashboards for each technology, providing a clear and accessible snapshot of the current state of the database:

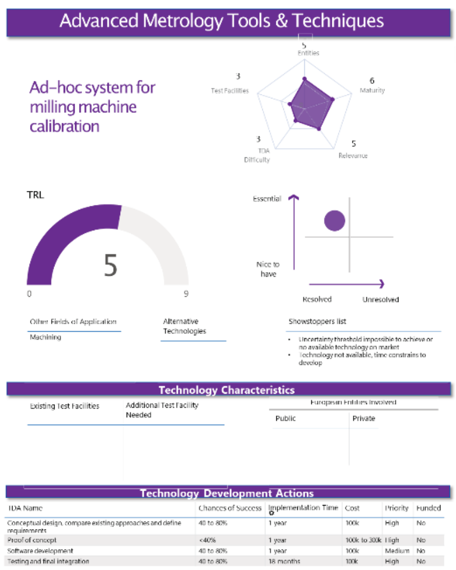


Figure 4: Typical technology dashboard

Note that the spider diagram (scores out of 9) has been arranged in such a way that the more the colored area, the more development is needed.

The dashboards reflect the status of the data at the time of publication of this document, while the underlying database will be regularly updated and the dashboards revised and re-issued as needed. The community is encouraged to share any relevant updates through their Fusion for Energy contact, with a view to keeping the information as accurate and up to date as possible, and in the future this data may also be made available for interactive consultation via the Fusion for Energy website.

5.2 Overview of the in-person session development proposals

5.2.1 Advanced Metrology Tools & Techniques

Ad-hoc system for milling machine calibration

The main aim of this TDP proposal is to develop a solution to enable an integrated milling machines' calibration guided by metrology tools, with the following sub-objectives:

- Volume of machine: 12x7x5m
- Uncertainty 0.01 mm
- Compatible with existing manufacturing hardware/software

This solution will allow a substantial reduction of the time needed for potential re-machining, with a consequent impact on costs.

Compact metrology tool for in-process control within CNC

The main aim of this TDP proposal is to develop metrology tools for integrated dimensional controls within the CNC environment, with the following sub-objectives:

- Size of parts: up to 1-2m
- Uncertainty 0.01 mm
- Compatible with existing manufacturing hardware/software

This solution will allow a substantial reduction of the schedule time needed for dimensional control, handling and alignment activities, with a consequent impact on costs.

5.2.2 Integrated Engineering & Dimensional Management

Business intelligence from design to operation for large complex assemblies ISO GPS based

The main aim of this TDP proposal is to develop a standard framework and related shared open-source tools with the following two sub-objectives:

- To enable the management of functional and geometrical requirements for large and complex assemblies
- To allow an effective interplay among designers, manufacturers, metrologists, end users

This solution enables a better definition, management and verification of geometrical requirements throughout the product lifecycle, incorporating a systems engineering perspective. In addition, it is proposed that the solution developed becomes an assistant that helps bridge the knowledge gap between the design, manufacturing and metrological control phases.

5.2.3 Core Metrology & Reverse Engineering Practices

Tool for a quantitative assessment of process uncertainty

The main aim of this TDP proposal is to develop software to automatically assess the uncertainty of a measurement process, with the following sub-objectives:

- The tool shall be universal and contemplate a wide diversity of instruments and uncertainty sources
- Simulation and traceability shall be ensured

This solution enables a better definition and management of process uncertainty throughout the manufacturing. In addition, the tool will help in the decision-making process of the metrology strategy.

Measurement Filtering Tool of External Deformation Effects

The main aim of this TDP proposal is to develop a tool which will allow to filter and compensate measurements based on the creation of high-fidelity FEA model and morphing back the measured points, with the following sub-objectives:

- The tool shall feed by environmental data of relevance along time
- The tool shall allow to estimate uncertainty due to the compensation

This solution enables a better definition, management and traceability of process uncertainty throughout the manufacturing.

Integrated tool for managing As-Built reconstruction

The main aim of this TDP proposal is to develop a stand-alone application which integrate already existing solutions in as-built reconstruction and management or introduce new software features and code, with the following sub-objectives:

- The tool shall allow the integration of nominal and as-built data, ensuring traceability
- The tool shall report on the error introduced by each assumption of the reconstruction process (alignment, filtering, segmentation)

This solution enables a better management and traceability of the as-built, allowing an effective interplay within manufacturing and engineering departments.

Management of simplified tolerance stack-up hybrid models for big assemblies

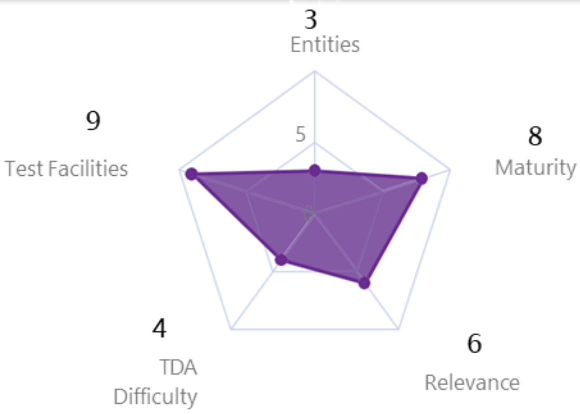
The main aim of this TDP proposal is to develop a framework for streamline simplified tolerance stack-up models of big assembly including as-built data, with the following sub-objectives:

- Define and validate an architecture for simplification of full hybrid models, including reporting on the assumptions made
- The tool shall integrate as-built information coming from manufacturing, possibly leveraging AI

This solution enables a better management and traceability of the impact of components as-built deviation within system assembly.

Advanced Metrology Tools & Techniques

Ad-hoc system for milling machine calibration



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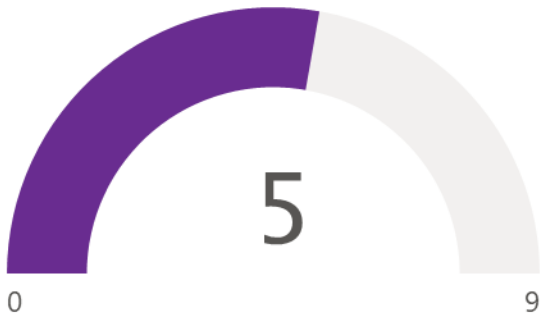
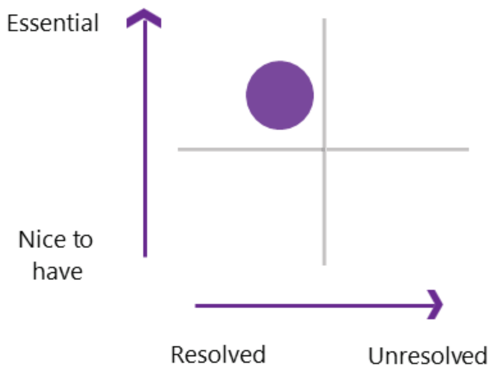




Other Fields of Application

Machining

Alternative Technologies

Showstoppers list

- Uncertainty threshold impossible to achieve or no available technology on market
- Technology not available, time constrains for development

Technology Characteristics

Existing Test Facilities	Additional Test Facility Needed

European Entities Involved

Public	Private

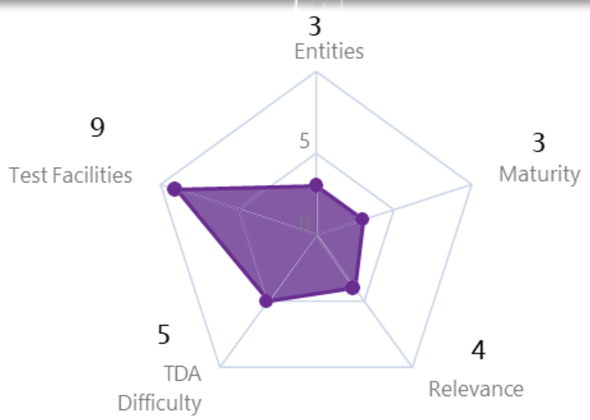
Technology Development Actions

TDA Name	Chances of Success	Implementation Time	Cost	Priority	Funded
Conceptual design, compare existing approaches and define requirements	40 to 80%	1 year	100k	High	No
Proof of concept	<40%	1 year	100k to 300k	High	No
Software development	40 to 80%	1 year	100k	Medium	No
Testing and final integration	40 to 80%	18 months	100k	High	No

Proposal 1: Ad-hoc system for milling machine calibration

Advanced Metrology Tools & Techniques

Compact metrology tool for in-process control within CNC



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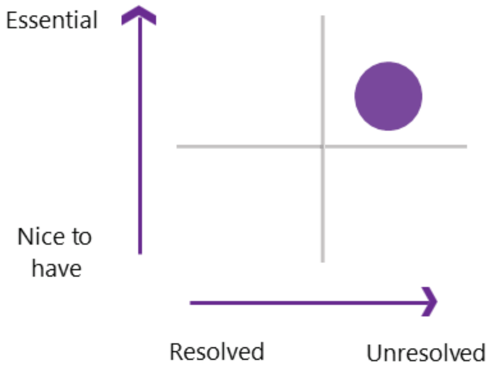


Other Fields of Application

Machining

Alternative Technologies

Showstoppers list

- Uncertainty threshold impossible to achieve or no available technology on market
- Technology not available, time constrains for development
- Compensation not achievable compared to size of the machine

Technology Characteristics

Existing Test Facilities	Additional Test Facility Needed

European Entities Involved

Public	Private

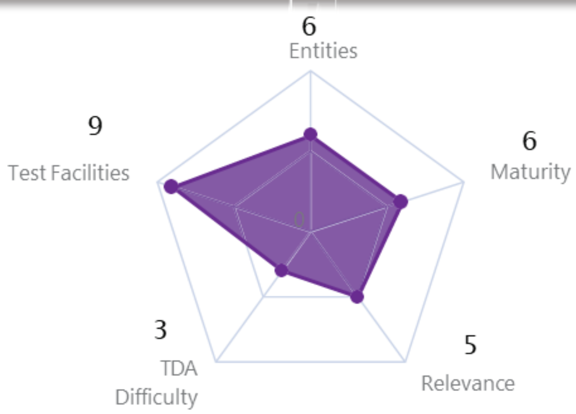
Technology Development Actions

TDA Name	Chances of Success	Implementation Time	Cost	Priority	Funded
Artefact Design and manufacturing	40 to 80%	6 month	60k	High	No
Definition of measurement techniques and self calibration	<40%	1 year	100k	High	No
Uncertainty budget estimation	>80%	6 months	70k	Medium	No
Software/GUI development	>80%	18 months	150k	Low	No
Proof of Concept	40 to 80%	6 months	50k	High	No
Prototype, testing	40 to 80%	18 months	200k	High	No
Integration	<40%	1 year	100k	Medium	No

Proposal 2: Compact metrology tool for in-process control within CNC

Integrated Engineering & Dimensional Mngmt

Business intelligence from design to operation for large complex assemblies ISO GPS based



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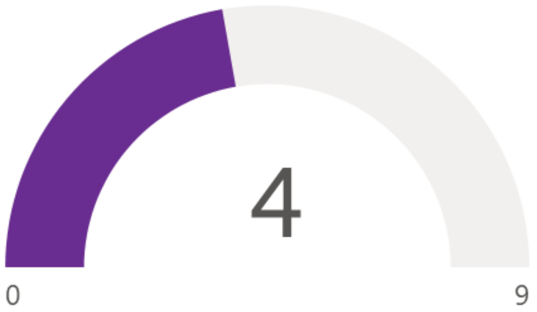
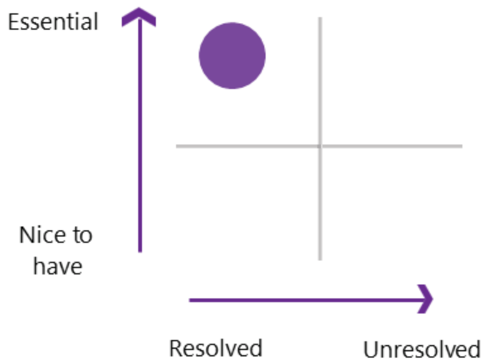




Other Fields of Application

Engineering
Design
Supply Chain

Alternative Technologies

Showstoppers list

- Resistance to change from users and stakeholders - Mitigation: stakeholders management plan
- Time and cost required to scale the platform to other projects/users – Mitigation: phased toll-out strategy

Technology Characteristics

Existing Test Facilities	Additional Test Facility Needed

European Entities Involved

Public	Private

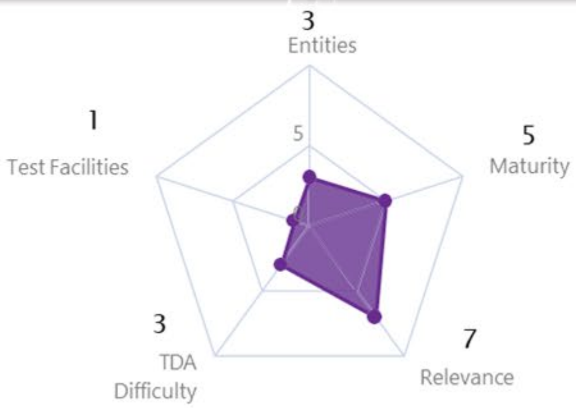
Technology Development Actions

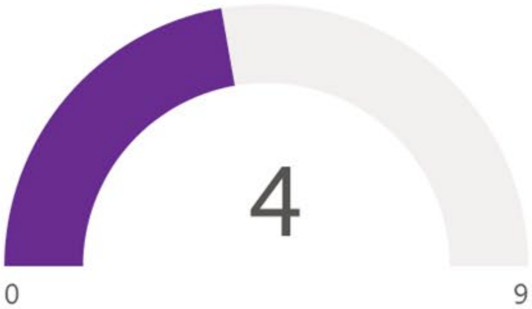
TDA Name	Chances of Success	Implementation Time	Cost	Priority	Funded
Macro definition of the standardized framework and database structure	>80%	5 months	50k	High	No
Definition, collection, and processing of the product geometrical requirements	>80%	5 months	50k	High	No
Control, collection, and processing of the product metrology data	>80%	5 months	50k	High	No
Reverse engineering	>80%	5 months	50k	High	No
Consistency and traceability checks of geometrical requirements	>80%	5 months	50k	High	No

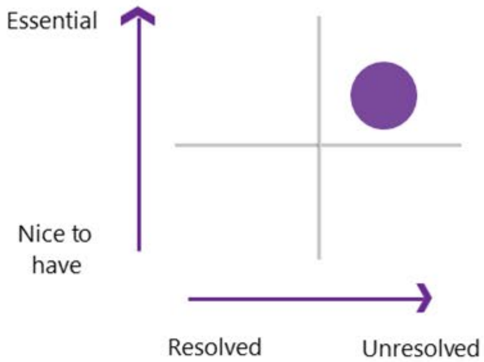
Proposal 3: Business intelligence from design to operation for large complex assemblies ISO GPS based

Core Metrology & Reverse Engineering Practices

Tool for a quantitative assessment of process uncertainty







Other Fields of Application

Design
Manufacturing
Supply Chain

Alternative Technologies

Showstoppers list

- No available technology on market
- Time constrains for development
- Resistance from stakeholders

Technology Characteristics

Existing Test Facilities	Additional Test Facility Needed

European Entities Involved

Public	Private

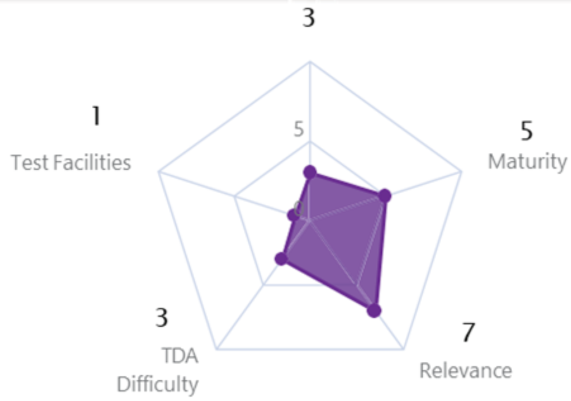
Technology Development Actions

TDA Name	Chances of Success	Implementation Time	Cost	Priority	Funded
Streamline actual processes of uncertainty assessment	40 to 80%	6 month	30k	High	No
Validation of the standard process	<40%	1 year	50k	High	No
Identify which measurement systems can be implemented	>80%	3 months	70k	Medium	No
Integration and programming of the development	>80%	1 year	100k	Low	No
Validation of the tool	40 to 80%	3 months	20k	High	No

Proposal 4: Tool for a quantitative assessment of process uncertainty

Core Metrology & Reverse Engineering Practices

Measurement Filtering Tool of External Deformation Effects



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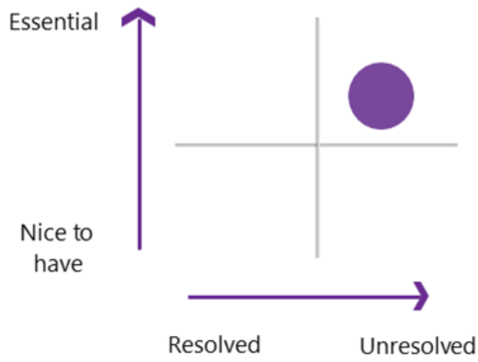


Other Fields of Application

Design
Manufacturing
Supply Chain

Alternative Technologies

Showstoppers list

- No available technology on market
- Time constrains for development
- Resistance from stakeholders

Technology Characteristics

Existing Test Facilities	Additional Test Facility Needed

European Entities Involved

Public	Private

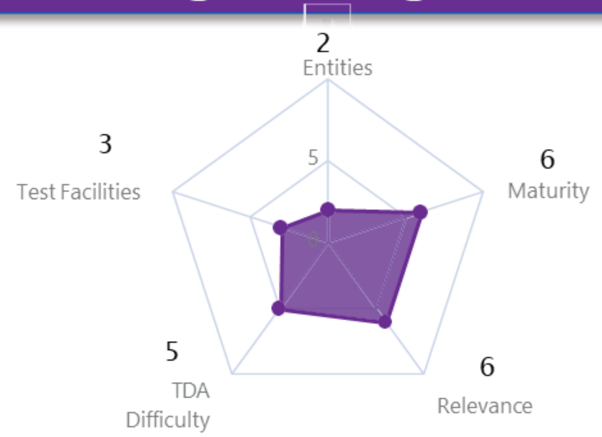
Technology Development Actions

TDA Name	Chances of Success	Implementation Time	Cost	Priority	Funded
Identification of scenarios to implement	>80%	6 months	30k	High	No
Evaluation of FEA capabilities in the selected scenarios	40 to 80%	6 months	70k	High	No
Validation of FEA capabilities in the selected scenarios	<40%	3 months	30k	High	No
Design of specific tooling for part monitoring	40 to 80%	1 year	150k	High	No
Standardization of measurement compensation	40 to 80%	6 months	20k	High	No
Validation of measurement compensation	<40%	3 months	30k	High	No
Code development and integration	>80%	1 year	100k	Medium	No
Proof of Concept	40 to 80%	6 months	30k	High	No

Proposal 5: Measurement Filtering Tool of External Deformation Effects

Core Metrology & Reverse Engineering Practices

Integrated tool for managing As–Built reconstruction



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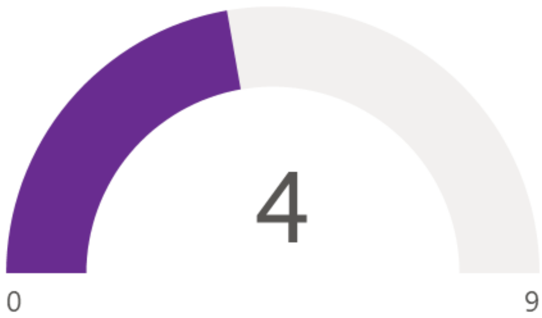
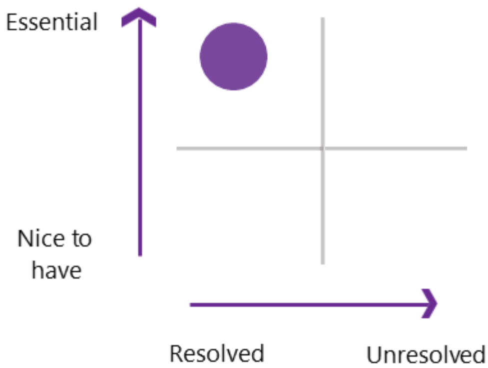




Other Fields of Application

Engineering
Manufacturing

Alternative Technologies

Showstoppers list

- Resistance to change from users and stakeholders - Mitigation: stakeholders management plan
- Technology not available, time constrains for development

Technology Characteristics

Existing Test Facilities	Additional Test Facility Needed

European Entities Involved

Public	Private

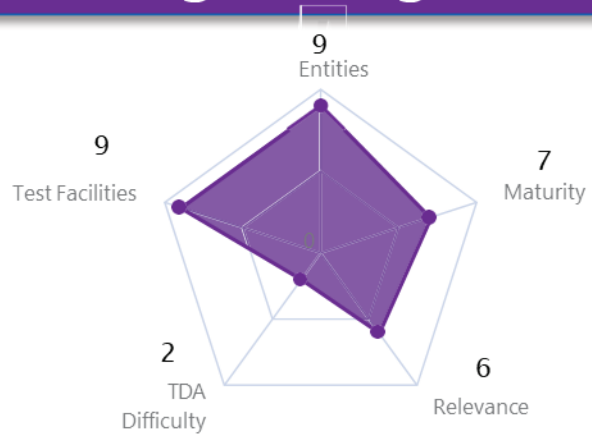
Technology Development Actions

TDA Name	Chances of Success	Implementation Time	Cost	Priority	Funded
Survey of market/academic/research solutions	>80%	5 months	50k	High	No
Code development for specific tasks	>80%	5 months	50k	High	No
Integration	>80%	5 months	50k	High	No
Proof of Concept	>80%	5 months	50k	High	No

Proposal 6: Integrated tool for managing As-Built reconstruction

Core Metrology & Reverse Engineering Practices

Management of simplified tolerance stack-up hybrid models for big assemblies



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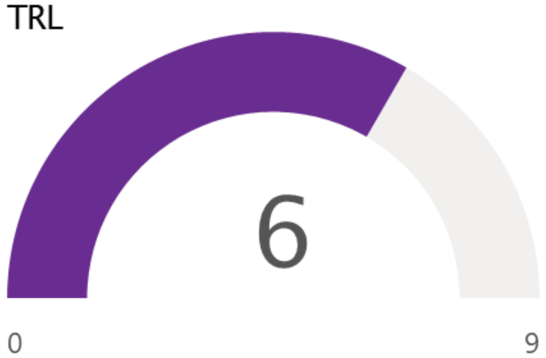

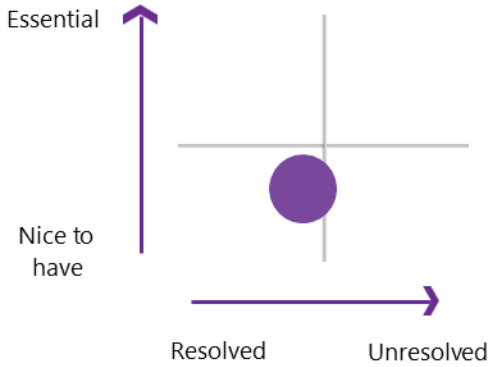

Other Fields of Application

Engineering
Manufacturing

Alternative Technologies

Showstoppers list

- Resistance to change from users and stakeholders - Mitigation: stakeholders management plan
- Technology not available, time constrains for development

Technology Characteristics

Existing Test Facilities	Additional Test Facility Needed

European Entities Involved

Public	Private

Technology Development Actions

TDA Name	Chances of Success	Implementation Time	Cost	Priority	Funded
Code development for integration of full and reduced models	40 to 80%	1 year	40k	Low	No
Development of AI assisted as-built implementation	<40%	6 months	70k	Low	No
Code development for as-built implementation	>80%	6 months	30k	Low	No
Proof of Concept	>80%	3 months	20k	Low	No

Proposal 7: Management of simplified tolerance stack-up hybrid models for big assemblies

6 Conclusion

The first Metrology and Reverse Engineering Mapping exercise represents **a significant first step towards the acceleration of the development of technologies in Europe**. It brought together academia, research institutions, startups and industry to provide an evaluation of current capabilities in Europe and a clear path forward to develop the required technologies in support of fusion as a viable energy source.

Workshop outcome

The work carried out highlighted that the modern manufacturing landscape shall address concretely the gap between theoretical design intent and the realities of shop-floor operations. To maintain global competitiveness, the industry must evolve beyond viewing metrology and reverse engineering as isolated disciplines, moving instead toward a dynamic, integrated digital thread. This transition, however, introduces several foundational challenges that must be addressed systematically.

Starting from the requirements management, the industry is recognizing that ISO GPS is a language, not a rigid methodology. Its success depends entirely on how well users apply it during the design phase. To support this, there is an urgent need for software tools that manage geometrical requirements throughout the entire product lifecycle. Maintaining alignment between all project actors as requirements evolve is essential, requiring clear requirements mapping and agile iterations to ensure robust traceability from start to finish.

Guided by these geometrical mandates, the participants addressed the need for a centralized platform that unifies design, simulation, manufacturing, and reverse engineering. The goal is to preserve design intent; currently, too many information related to as-built are not traced post-manufacturing, with an high impact in time and cost to the following assembly and integration activities. By integrating requirement databases with nominal, as-built 3D models and tolerance stack-up analysis, companies can compute more realistic tolerances and maintain a true record of the components produced.

Furthermore, geometrical requirements must be developed in tandem with appropriate measurement processes defined at the design stage. The correct balance between measurement uncertainty and dimensional tolerances is an aspect often overlooked during design. The industry would benefit significantly from standardized tools that assist in defining metrology processes specifically tailored to satisfy complex geometrical requirements.

Finally, in relation to measurement tools and techniques, there is clear value in integrating dimensional controls directly into manufacturing workflows—most notably within CNC machining. The advancement of calibrated instrumentation embedded within machine tools represents a major opportunity to optimize both production timelines and operational costs.

Path Forward

This mapping exercise represents more than a technical assessment, it provides a clear framework for coordinated action. Success will require **a coordinated investment strategy across multiple funding sources**, public and private, national, European and international.

It constitutes a **call to action** for the European Metrology and Reverse Engineering community and the fusion energy leadership in general. Funding and resources must now be allocated to the identified technology development actions in a coordinated manner. The proposal to regularly update the technology dashboards, identifying actions that have been funded and gaps that have been filled goes into that direction. **A European Metrology and Reverse Engineering community has been established. With adequate resources, it will deliver world class capabilities for Europe.**

Appendix 1: Technology Readiness Levels

For this workshop, a TRL scale from 1 to 9 will be used, in line with the IAEA definitions[2].
It considers the different criteria for different streams as illustrated in the table below extracted from the document in reference. By default, the "System" stream will be used. For more details, please refer to the TECDOC 2047 itself[1].

TRL	Systems	Materials	Software	Manufacturing	Instrumentation
1	Basic principles	Evidence from literature	Mathematical formulation	Process concept proposed	Understand the physics
2	Technology concept	Agreed property targets, cost & timescales	Algorithm implementation documented	Validity of concept described	Concept designed
3	Proof of concept	Materials' capability based on lab scale samples.	Prototype architectural design of important functions is documented	Experimental proof of concept completed	Lab test to prove the concept works.
4	Validation in a laboratory environment	Design curves produced.	ALPHA version with most functionalities implemented with User Manual and Design File available	Process validated in lab	Lab demonstration of highest risk components
5	Partial system validation in a relevant environment	Methods for material processing and component manufacture	BETA version with complete software functionalities, documentation, test reports and application examples available	Basic capability demonstrated using production equipment	Requiring specialist support
6	Prototype demo in a relevant environment	Validated via component and/or sub-element testing.	Product release ready for operational use	Process optimised for capability and rate using production equipment	Applied to realistic location/environment with low level of specialist support.
7	Prototype demo in an operational environment	Evaluated in development rig tests	Early adopter version qualified for a particular purpose	Economic run lengths on production parts	Successful demonstration in test.
8	Test and demonstration	Full operational test	General product ready to be applied in a real application	Significant run lengths	Demonstrated productionised system
9	Successful mission operation	Production ready material	Live product with full documentation and track record available	Demonstrated over an extended period	Service proven

Table 1: TRLs

[2] IAEA TECDOC 2047 Considerations of TRL for Fusion Technology Components available from: https://www-pub.iaea.org/MTCD/Publications/PDF/TE-2047web.pdf

Appendix 2: Technology assessment

1. Added-Value Towards Nuclear Fusion		
Criterion	*Scale*	*Explanation*
Need for and potential benefit	Major / Medium / Minor	Does this technology address a critical and unresolved challenge in nuclear fusion?
Availability of alternative solutions	Yes/No (EU) Yes/No (Outside EU)	Are there competing solutions in Europe or globally?
Differentiation / Competitive Advantage	Yes / No	Does this technology offer a unique advantage over existing solutions?
2. Maturity & Feasibility		
Criterion	*Scale*	*Explanation*
Technology Readiness Level (TRL)	1 to 9	Standard TRL scale (see Appendix).
Expected time to TRL 9 (full maturity)	<5 years / 5–15 years / >15 years	How long until the technology is commercially viable?
Availability of test facilities	Yes / No	Are there existing facilities in Europe to validate the technology?
3. Interest from the Innovation Ecosystem		
Criterion	*Scale*	*Explanation*
Interest from start-ups	None / 1–3 interested parties / >3 interested parties	Level of engagement from early-stage companies.
Interest from industry	None / 1–3 interested parties / >3 interested parties	Level of interest from established industry players.
Interest from research institutions	None / 1–3 interested parties / >3 interested parties	Interest from universities, national labs, and research centers.
4. Other Investment Decision-Making Factors		
Criterion	*Scale*	*Explanation*
Market potential	Nuclear fusion-specific / Wider market potential	Is the technology limited to fusion, or does it have broader applications?
Competences & skills development	Yes / No	Will this technology enhance European expertise in fusion?
Regulatory impact	Yes / No	Does the technology pose significant regulatory challenges?
5. Risk, Cost, and Implementation Timeline of Next Step on Roadmap		
Criterion	*Scale*	*Explanation*
Outcome predictability & risks	Low risk / Medium risk / High risk	How uncertain are the results of the next development?
Estimated development cost	0–500k EUR / 501k–2M EUR / >2M EUR	Rough cost estimate for next development step.
Time to first output (once funded)	<1 year / 1–2 years / >2 years	Timeframe for delivering tangible results.

Table 2: Technology Assessment

Fusion for Energy

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