

A Pilot Project on Digital Twin Technology for Advancing Ionizing Radiation Metrology

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1. Introduction

Digital Twin (DT) technology, a hallmark of Metrology 4.0, offers a transformative approach to ionizing radiation metrology by enhancing reliability, enabling real-time data synchronization, and facilitating innovative applications. This pilot project focuses on developing and validating a DT framework that mirrors the processes and parameters of a physical calibration laboratory for air kerma measurements. The long-term vision is to support interlaboratory comparisons (ILCs) with virtual comparisons (vComparison) and other metrological applications.

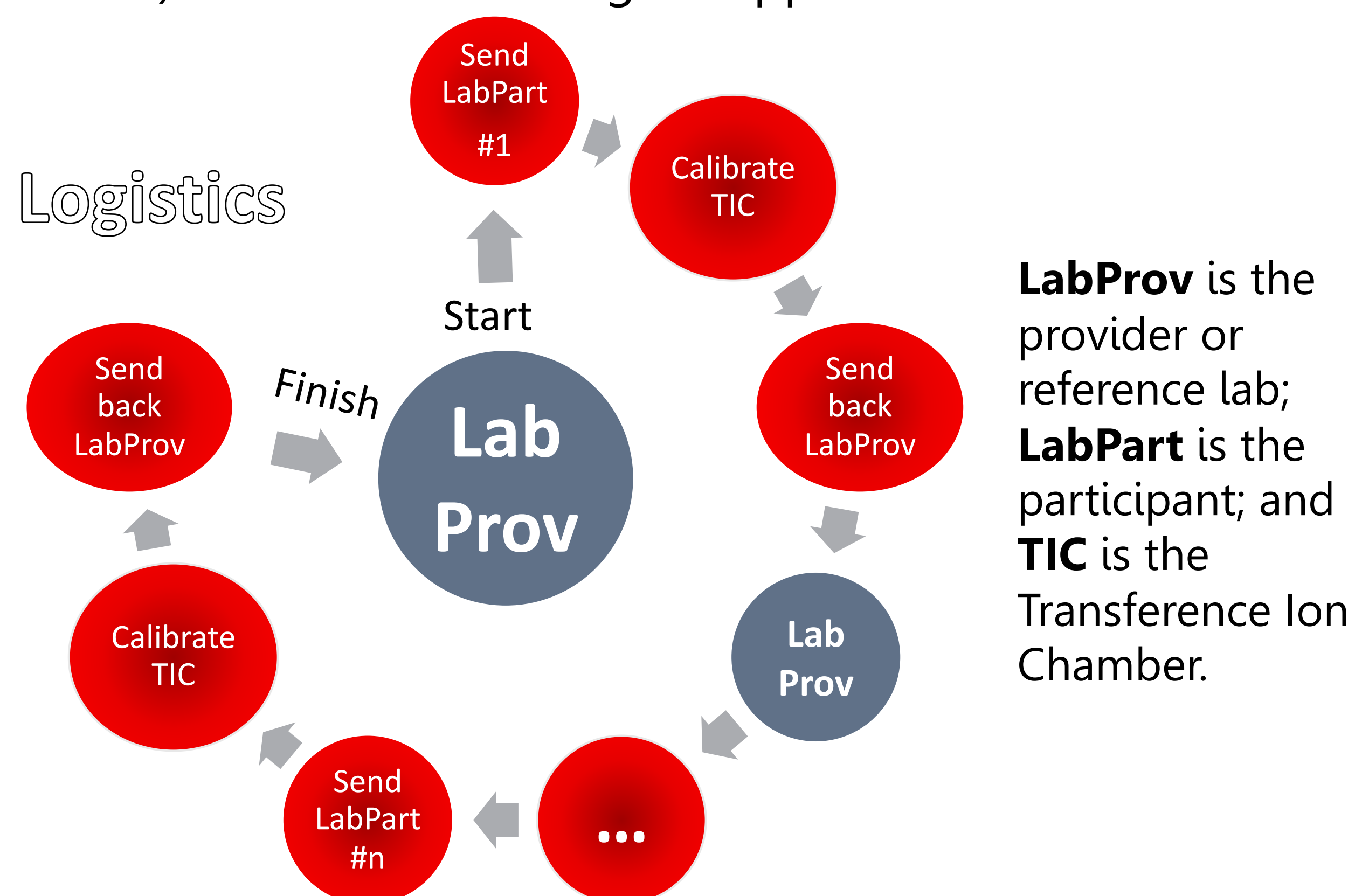


Figure 1. Traditional Comparison "serial" Workflow.

The idea is to create Digital Twins of Laboratories aiming, instead of traditional comparison (figure 1), virtual comparison (**vComparison**) based on **Monte Carlo Simulation**, **Beam Dosimetry**, and **Beam Spectrometry**.

2. Materials and Methods

The project involved the creation of a virtual counterpart of a calibration laboratory using EGSnrc Monte Carlo (MC) simulations. For spectrometry and air kerma simulations, the applications used were `egs_phd` and `egs_kerma` applications, respectively. The DT replicates physical processes and parameters related to air kerma measurements, including energy spectra and radiation field characteristics.

The apparatus for air kerma measurement under ISO N 60 quality, according to ISO 4037 [1], for physical and virtual environment was established with a good agreement [2] for both LabProv and LabPart. See table 1 and figure 2.

Table 1. Result of N 60 spectra variables.

	Mean Energy (keV)	Resolution
ISO 4037-1	48	36 %
Tolerance	45.6 - 50.4	30.6 - 41.4 %
Experimental	47.3	33 %
Simulated	47.2	32 %

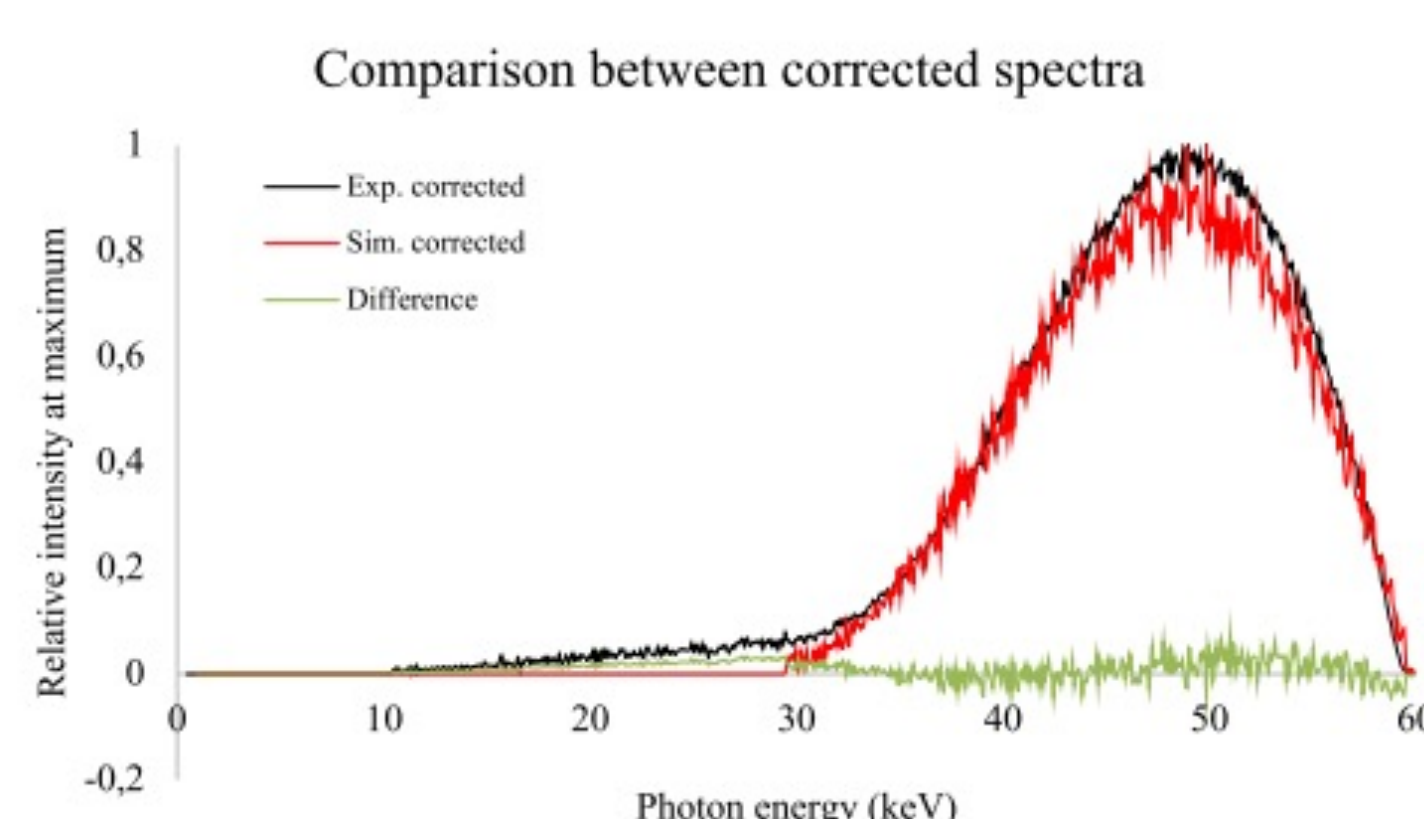


Figure 2. Spectra of the N 60 established.

4. Results and Discussion

Despite the limitations of air kerma MC simulations, such as the inability of EGSnrc to model exposure in mAs and the resulting photon generation accurately [3], the relational nature of ILCs mitigates this issue by using calibration factors and their uncertainties in result evaluation.

The proposed scenario was the LabProv being responsible for the physical-to-virtual characterization of the TIC performing all physical measurements and its virtualization, giving the calibration factor at the end, as shown in figure 3 [4].

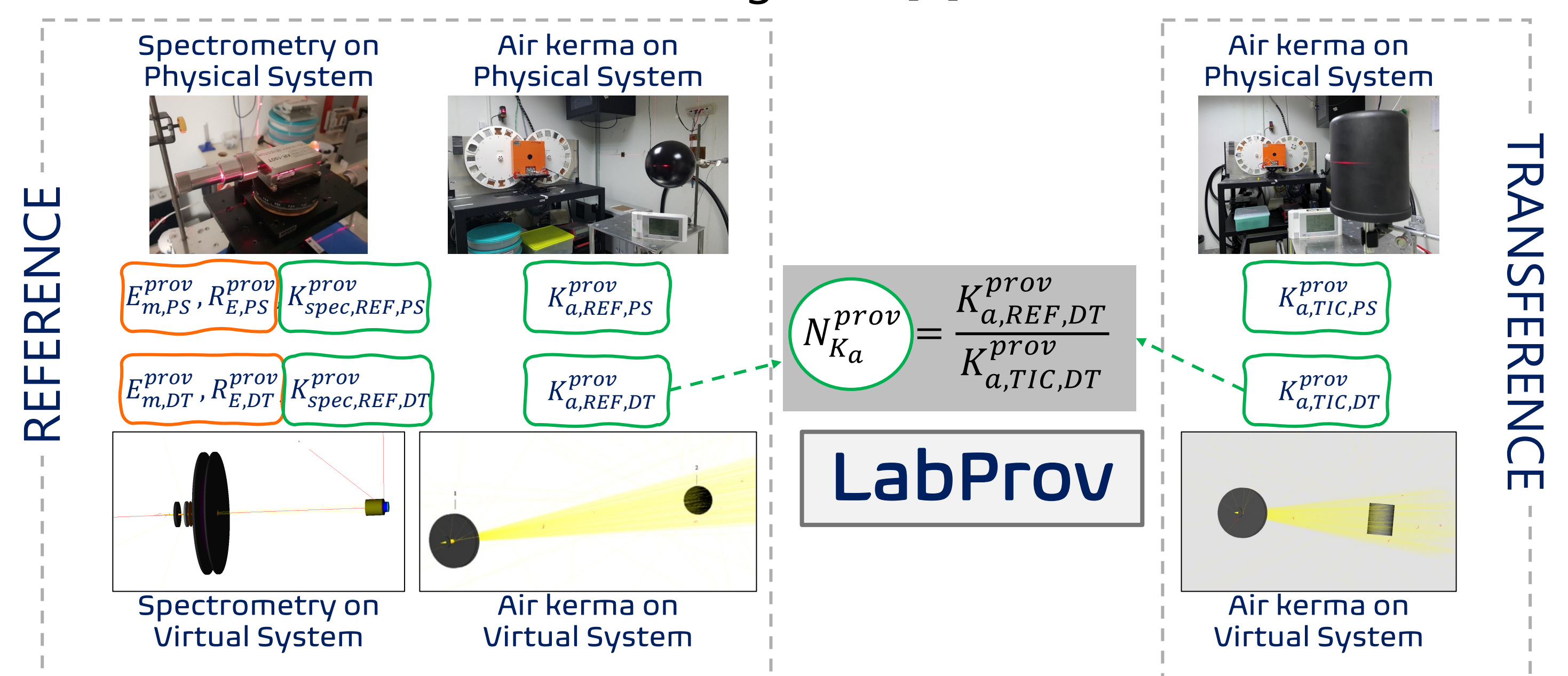


Figure 3. LabProv steps for the ILC.

The LabPart (one or many) has to perform the same measurements and tests in the REFERENCE part (figure 3). But only the virtual measurements of the TRANSFERENCE part once the TIC is already virtualized and the Lab receives only a MC code with the virtual transference chamber (vTIC), see figure 4.

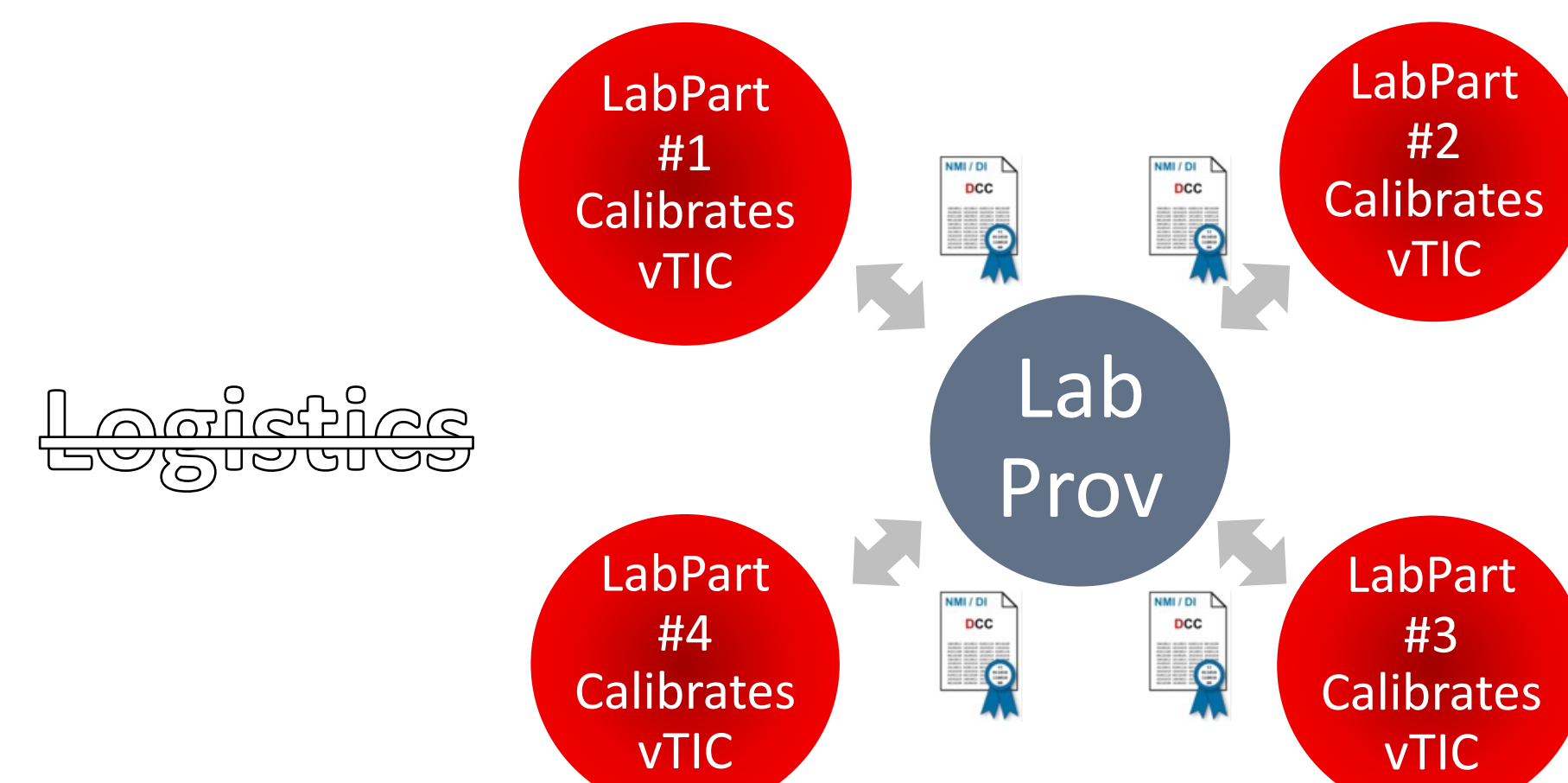


Figure 4. Proposed vComparison with "parallel" Workflow.

Firsts bilateral tests showed normalized errors around 0,35 – 0,50.

5. Conclusion

This pilot project introduces DT technology in ionizing radiation metrology, aiming to reduce logistical challenges, enhance reliability, and enable future applications like virtual ILCs within Metrology 4.0.

Project limitations include the need to refine the modeling of specific laboratory phenomena, perform more validation studies, improve uncertainty evaluation, use smart sensors, and extend the methodology to include additional calibration setups and measurement quantities.

This project aligns with the needs of the metrology community and matches with the BIPM's focus on innovation in the 150th Anniversary Poster Competition.

REFERENCES

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- [2] Macedo, E. M. et al. (2023). Virtual Laboratory of Ionizing Radiation Metrology: Validation by spectrometry. *Journal of Physics: Conference Series*, 2606(1), 012023. <https://doi.org/10.1088/1742-6596/2606/1/012023>
- [3] Worrall, M., & Sutton, D. G. (2019). Validation of a beamnrc monte carlo simulation of a broad beam diagnostic x-ray unit. *Radiation Protection Dosimetry*, 185(4), 440–451. <https://doi.org/10.1093/RPD/NCZ032>.
- [4] Macedo, E. M. (2024). Desenvolvimento de um Sistema Digital Twin na Comparação Interlaboratorial para a Grandeza Kerma no ar. Ph.D. thesis. Instituto de Radioproteção e Dosimetria, Rio de Janeiro (p. 107).