EASITrain Final Event
WP4 Summary

Francois MILLET

September 21st, 2021

Contributions from Andrea Vitrano, Jakub Tkaczuk, Sofiya Savelyeva, Maxime Podeur

The European Advanced Superconductivity Innovation and Training (EASITrain) project receives funding from the European Union's Horizon 2020 research and innovation programme under grant No 764879. The information herein only reflects the views of its authors and the European Commission is not responsible for any use that may be made of the information.

WP4 Objectives

- Assess the merits of different magnet refrigeration architectures and optimise superconducting magnet cooling at ~4 K
- Develop an optimised Nelium-based refrigeration system for the 40–60 K temperature range

WP4 Deliverables

- D4.1: Architectures and models for superconducting magnet cooling
- D4.2: Specification for Nelium refrigeration system
- D4.3: Specification for optimised heat extraction for magnet coils
- D6.4: EASISchool2 on Cryogenic Applications

Job done

WP4 Dream Team

ESR3

Andrea Vitrano

CEA-Saclay

Supervisor: Bertrand Baudouy

ESR4

Jakub Tkaczuk

CEA-Grenoble

Supervisor: Francois Millet

ESR11

Sofiya Savelyeva

Tech. Univ. Dresden

Supervisor: Christoph Haberstroh

ESR15

Maxime Podeur

Univ. Stuttgart

Supervisor: Damian Vogt

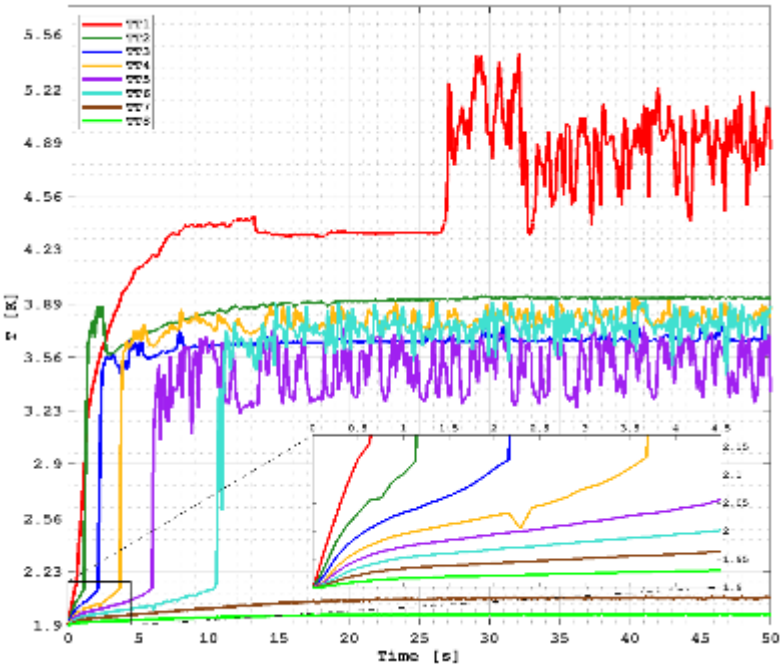
WP4 partners

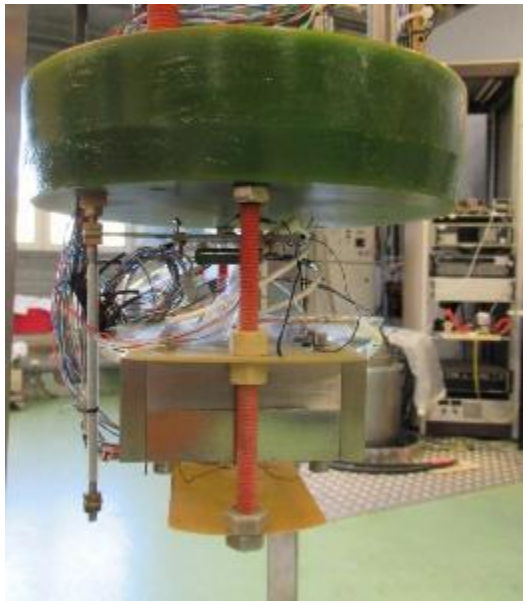
CEA: Andrea Vitrano 1/2

Experimental heat transfer study

- Construction of an experimental model to study transient heat transfer and phase change in superfluid helium in confined geometry
- Realization of numerous tests at different temperatures, heat loads and orientations with different channel's heights
- Typical test result for the 200 µm-high channel in horizontal orientation below

Temperature evolution of all sensors as a function of time at 1.9 K and for 59.9 kW/m^2



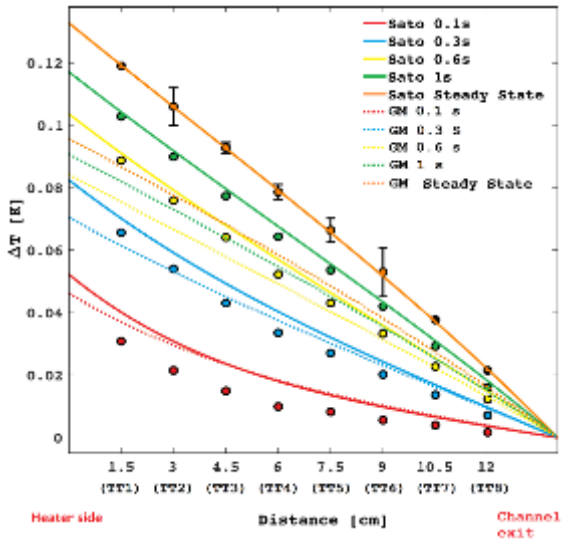


Picture of the 200 µm high channel installed below the λ-plate of the cryostat in the horizontal position.

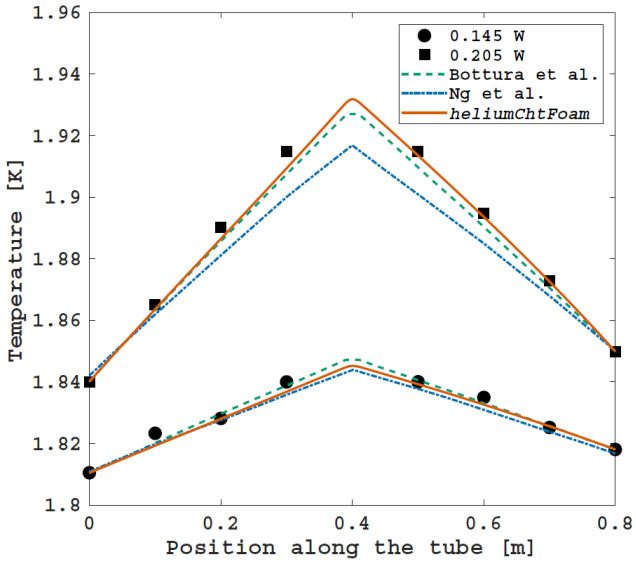
CEA: Andrea Vitrano 2/2

Numerical heat transfer study

- Development of a numerical code for transient heat transfer and phase change in superfluid helium in confined geometry
- Validation of the model against other codes and results
- Validation of the model against our own experimental results in single phase and two-phase helium (below)



Comparison of the temperature increase for the 1 mm channel between simulation (line) and measurement (markers) for 22 kW/m2 at 1.81 K. Plain lines: Computation with the Sato's law. Dotted lines: Computation with Gorter-Mellink's law indicated as GM.

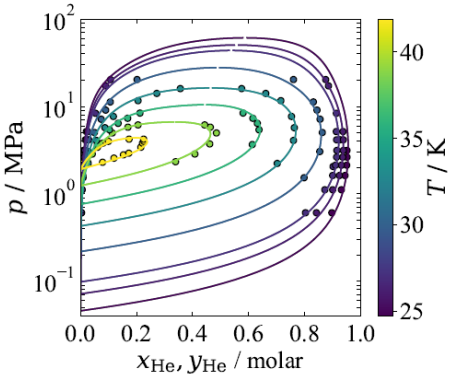


He II temperature profiles comparison between our code (red solid line) and data from Srinivasan and Hoffman's tube experiment (markers). The simulations by Bottura and Rosso, and Ng et al. are also shown as dashed and dash-dotted line respectively.

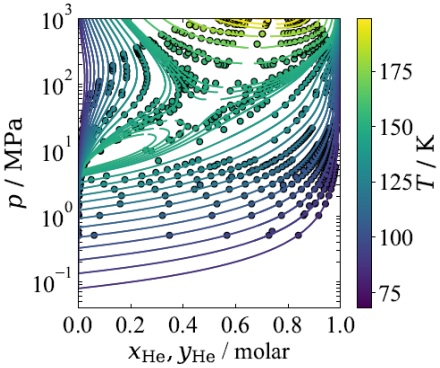
CEA: Jakub Tkaczuk 1/2

Numerical models for cryogenic mixture properties

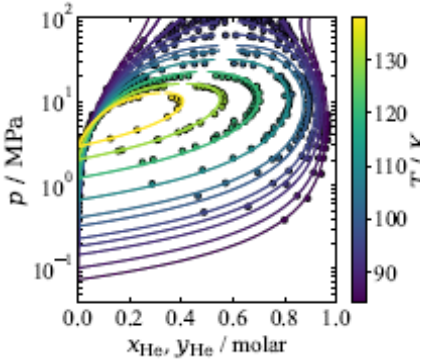
- Developing the multi-parameter Equations of State for thermodynamic properties of cryogenic binary mixtures: helium-neon, helium-argon, neon-argon and helium-nitrogen
- Review of the Equations of state (ideal gas, Van der Waals, virial, Helmholtz energy)
- Validation of the developed model against existing experimental results
- **Industrial secondment** at Air Liquide Advanced Technologies for process cycle calculations



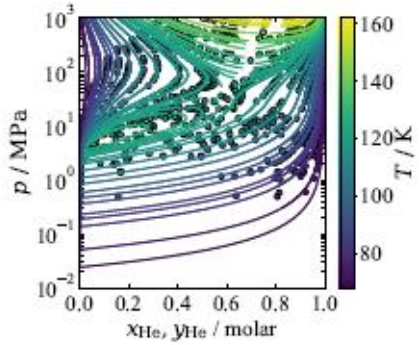
Vapor-liquid equilibrium of helium-neon



Vapor-liquid and gas-gas equilibria of helium-argon



Vapor-liquid equilibrium of neon-argon



Vapor-liquid and gas-gas equilibria of helium-nitrogen

CEA: Jakub Tkaczuk 2/2

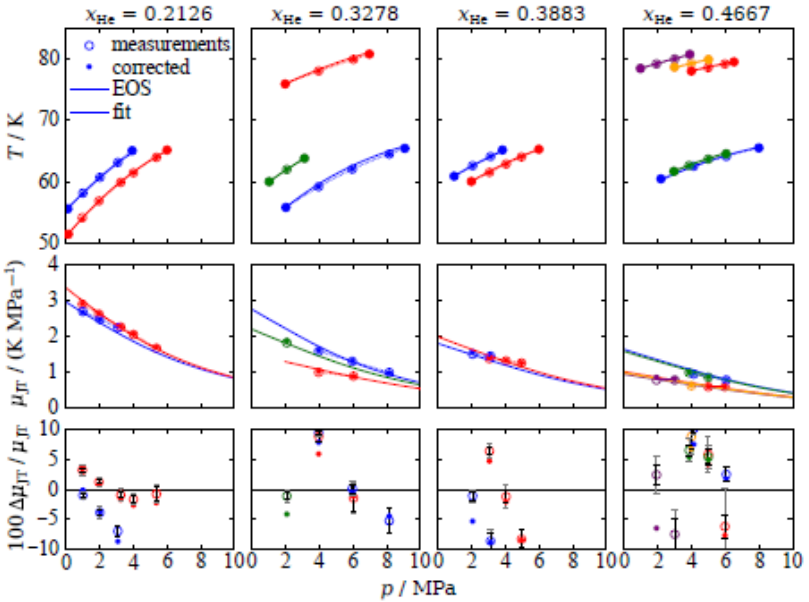
Experimental study for cryogenic mixture properties

- Measurements of the Joule-Thomson coefficient of cryogenic binary mixtures: helium-neon, helium-argon, neon-argon and helium-nitrogen

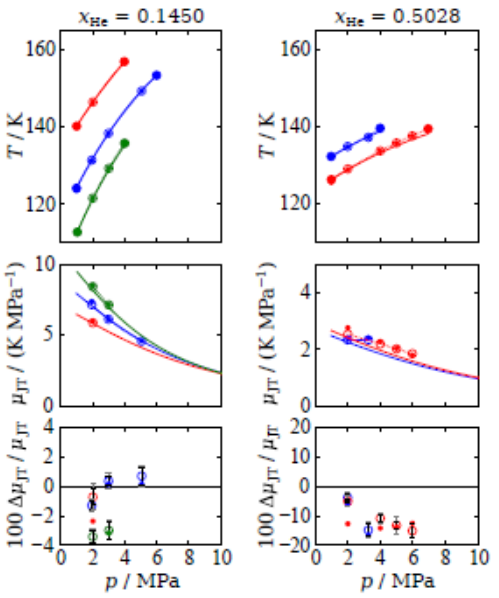
$$\mu_{JT} = \left.\frac{\partial T}{\partial p}\right|_h$$

- Test bench design and construction and qualification of the test bench with pure fluids
- Validation of the developed mixture model against our own experimental results for helium-neon

Test bench for JT coefficient measurements at cryogenic temperatures



helium-neon



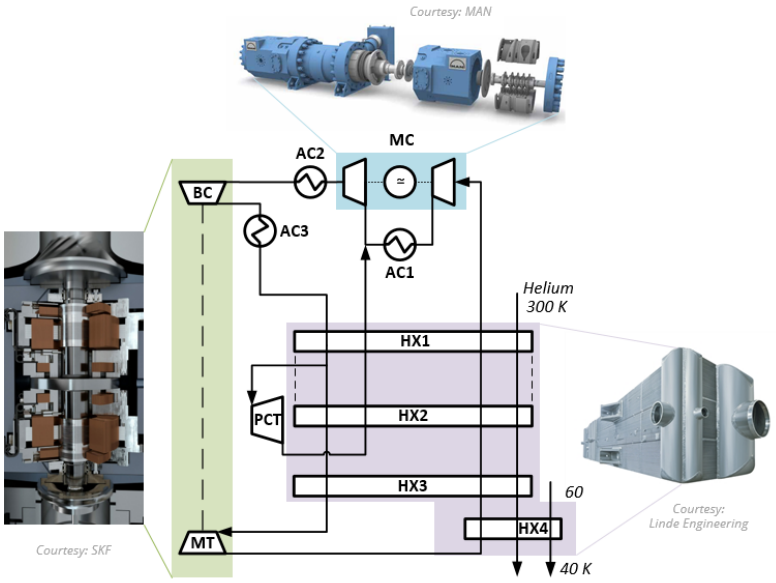
helium-nitrogen

Comparison between EOS model and measurements

TUD: Sofiya Savelyeva 1/2

Design study for Nelium Turbo-Brayton refrigerators

- A Nelium Turbo-Brayton cryogenic refrigerator for the FCC-hh was designed including main cycle components;
- The improved design provides **0.5 MW of power savings** compared to the baseline cycle (20 MW); achieved Carnot efficiency with currently developed turbo-compressor (MAN) at 60% neon content: **39%**;
- The refrigerator concept was economically and thermodynamically evaluated against existing cooling concepts;
- ***Part-load*** mode and refrigerator operation at magnet ***cool-down*** were investigated in details and the efficient control strategies were offered;
- The production process of the neon-helium mixture was reviewed, concepts of an industrial production of the ***Natural Nelium mixture*** studied in cooperation with Linde AG;
- An **open library for cryogenic cycle simulations** was developed in Python (CryoSolver);



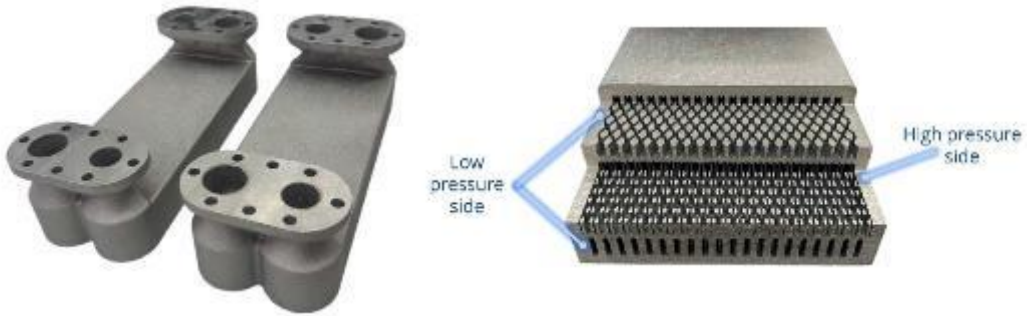
Flow diagram and components of the offered cycle arrangement.

TUD: Sofiya Savelyeva 2/2

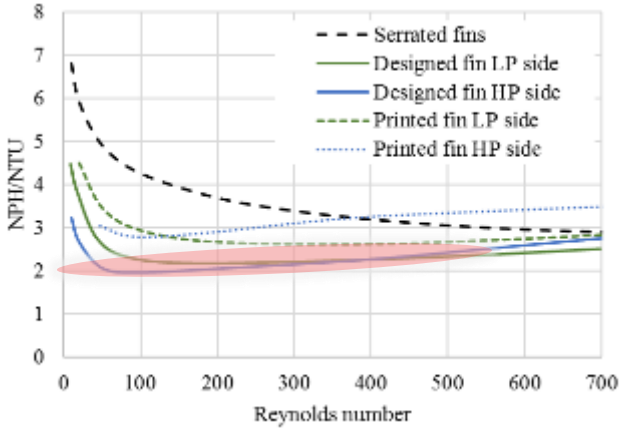
Application study for Nelium Turbo-Brayton refrigerators

- Possibilities to scale down the cycle for industrial applications were studied and evaluated within the **industrial secondment** at Linde Kryotechnik AG;

- A concept for compact ***3D-printed cryogenic heat exchangers*** was evaluated for small-scale Turbo-Brayton cycle applications; heat exchanger prototypes were successfully studied numerically and experimentally; ***optimal ratio of the pressure drop and heat transfer*** found were compared to state-of-the-art geometries in the laminar flow range.



3D-printed cryogenic heat exchanger prototypes.

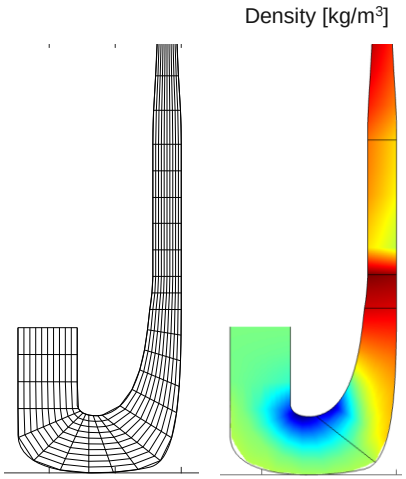


Characteristics of the 3D printed heat exchanger geometry compared to the state-of-the-art geometry (NPH/NTU ratio).

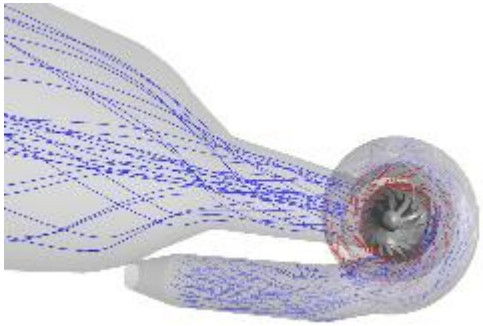
USTUTT: Maxime Podeur 1/2

Modeling study of multi-stage turbocompressors

- Various models and tools have been derived for the design of turbocompressor stages including: a blade modeler, a 0D/1D solver and 2D through flow solver
- Different optimization algorithms have been developed as well as a surrogate model generation tool
- A model predicting the multi-stage turbocompressor performance has been derived to obtain the optimal architecture depending on the operating gas
- A model has been developed to validate the rotordynamic criteria of any multi-stage architecture operating with light gases



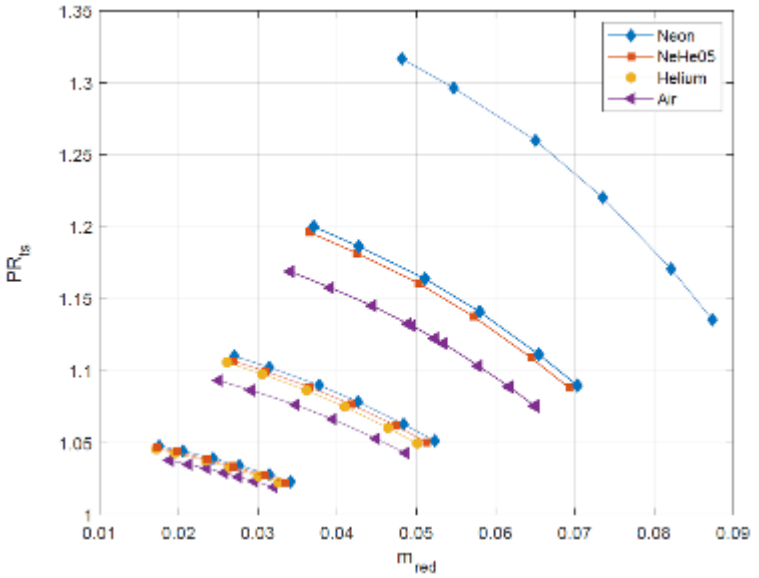
- **3 Turbocompressor stages** have been designed and optimised for aerodynamic performance using CFD and their structural integrity during operation has been validated using FE analysis



USTUTT: Maxime Podeur 2/2

Application study for turbocompressor stages

- **An experimental test facility** has been designed, built and is now used for the validation of turbocompressor performance operating with light gases (Any mixture from pure helium to pure neon) and air
- Experimental results have been used to assess the effect of gases with various molecular weights on compressor performance

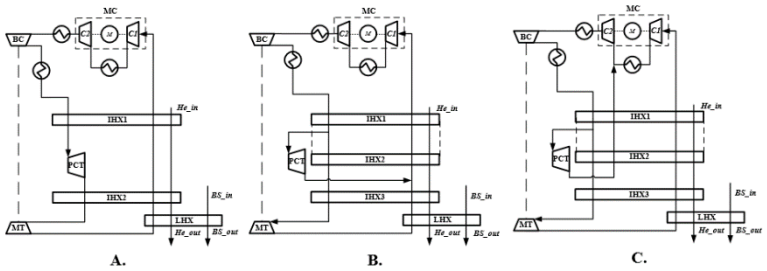


- A model has been derived to retrieve the adiabatic compressor efficiency by estimating the heat transfer due to the coolant flowing inside the motor housing
- **Industrial secondment** at MAN and continuous consulting with engineers at MAN Energy Solutions for the design of the second compressor stage

Common WP4 actions

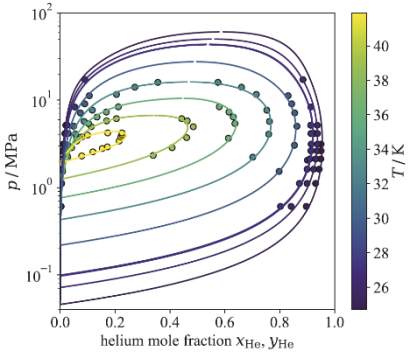
1. Cooperation between TU Dresden (ESR11) and University of Stuttgart (ESR15):

- Iterative common work on the optimal design for refrigerator and turbo-compressor;
- Cooperation on the turbo-compressor test rig setup.



2. Cooperation between CEA-Grenoble (ESR4) and TU Dresden (ESR11):

- The neon-helium mixture properties model (CEA) used for the cryogenic cycle simulation and component design (TUD).



WP4 Publications

+ Presentations at different conferences and workshops in Cryogenics or Turbomachinery

- J.Tkaczuk et al. Equations of State for the Thermodynamic Properties of Binary Mixtures for Helium-4, Neon, and Argon. *Journal of Physical and Chemical Reference Data, 49*(2), 023101. (2020) doi:10.1063/1.5142275
- S. Savelyeva et al. Natural neon-helium mixture as working fluid for 40-80 K cryogenic refrigerators. In Conference Proceedings: Cryogenics 2019. The 15th IIR International Conference, 2019, DOI: 10.18462/iir.cryo.2019.0076;
- S. Savelyeva et al. Thermodynamic and economic aspects of the Nelium Turbo-Brayton refrigerator development for the FCC-hh. IOP Conference Series Materials Science and Engineering 755:012069, 2020, DOI: 10.1088/1757-899X/755/1/012069;
- S. Savelyeva et al. “Experimental and numerical study of a 3D-printed aluminium cryogenic heat exchanger for compact Brayton refrigerators”, *Cryogenics* (submitted 17.05.2021);
- S. Savelyeva, S. Klöppel, Ch. Haberstroh. “CryoSolver. Package for cryogenic cycle simulation in Python. Documentation”, 2020. https://doi.org/10.5281/zenodo.4001668.
- M. Podeur et al. Impeller design and multi-stage architecture optimisation for turbocompressors operating with a helium-neon gas mixture. In Conference Proceedings: IGTC, 2019
- M. Podeur et al. Impeller design and multi-stage architecture optimisation for turbocompressors operating with a helium-neon gas mixture. International Journal of Gas Turbine , Propulsion and Power Systems, Volume 11, Number4
- M. Podeur, D. Vogt. Experimental and numerical similitude study using a novel turbocompressor test facility operating with helium-neon gas mixtures. In Conference Proceedings: Turbo Expo, 2020
- M. Podeur, D. Vogt. Experimental and numerical similitude study using a novel turbocompressor test facility operating with helium-neon gas mixtures. Journal of Turbomachinery (waiting for publication)
- In preparation: M. Podeur, D. Vogt. Development of a Surrogate model for the prediction of critical frequencies and static loads in multi-stage turbocompressor
- In preparation: M. Podeur, D. Vogt. Experimental evaluation of heat transfer effect on turbocompressor performance operating with helium-neon gas mixtures. EPJ Techniques & Instrumentation

WP4 Researcher status

Andrea Vitrano:

- PhD defended and obtained on July 23 2021
- Postdoctoral position at CERN for 2 years since September 2021
- Paper submitted to Computer Physics Communications + 2 papers in preparation

Jakub Tkaczuk:

- Job search
- Thesis writing finished and PhD to be defended in December 2021
- Paper in preparation for JT coefficient measurements for cryogenic binary mixtures

Sofiya Savelyeva:

- EASITrain contract ended 31.01.2021, TUD contract extended until 30.09.2021;
- Thesis writing at the final stage.

Maxime Podeur:

- Employed at University of Stuttgart until 31.12.2021;
- Next: thesis writing

Thanks !

- To the ESRs for their works and results
- To the hosting institutes for the permanent support
- To the project office for the network organization
- To the partners for the secondements and case studies
- To the European Union funding H2020-MSCA-ITN