The MVM ventilator and 3Dπ PET scanner development arising from basic science work

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Abstract During the COVID-19 pandemic, members of the DarkSide-20k (DS) Dark Matter international experimental collaboration together with engineers, scientists and manufacturers in Italy, Canada, the USA and eight other countries diverted their research efforts to develop MVM, a new readily manufactured, relatively low-cost ventilator tailored to the most severe intubated patients. Using expertise developed for DS, they produced and received authorization for 7300 units delivered to the Canadian government for its stockpile, now being considered for donation to other countries in urgent need. Other members of DS are using photo-electronics innovation to develop 3Dπ a more sensitive positron emission tomography (PET) scanner that can provide better resolution and reduce doses, of particular value for providing access for pediatric patients.

1 The MVM ventilator

In late March 2020, the leader of the DarkSide-20k international collaboration, Prof. Cristiano Galbiati was locked down in Milano by one of the original surges of the COVID-19 pandemic. He realized that the technical expertise that had been developed within the experimental collaboration for a very basic science objective could be applied to develop a simplified, low-cost ventilator aimed at the most extreme COVID patients who have been intubated.

He enlisted the collaboration of collaboration members, industrial partners, medical consultants and others for a rapid response to this urgent need. This included myself, and I found that members of Canadian industry, National laboratories and academics were very pleased to participate, being able to use their existing expertise to help in this crippling pandemic. The DarkSide-20k collaboration’s primary scientific objective is the use of up to 100 tonnes of liquid argon in a low-radioactivity underground location at the LNGS laboratory in Gran Sasso, Italy, to perform a sensitive search for Dark Matter particles.

The DS experiment requires the use of sophisticated techniques for handling argon gas, including systems for the extraction of low-radioactivity argon from underground locations. Such techniques including the control systems were able to be adapted to develop a prototype ventilator that worked on the bench in about 10 days. That design was the basis for a first paper placed on the archive on March 23, 2020, followed by updates on March 31 and April 10 \cite{1}.

The final, complete paper describing the Mechanical Ventilator Milano (MVM) was published in Physics of Fluids in March 2021 \cite{2}. Reference 2 provides the detailed account of the MVM, and the present paper will be only a qualitative overview of the device, emphasizing the more historic aspects of the development. The full membership of the collaboration is represented in the author list for this paper.

From the outset, the collaboration was committed to open access to the basic design that was published under a CERN Open Access licence enabling it to be used in countries in need. In Canada, the collaboration worked with companies Vexos and JMP Solutions and was successful in obtaining a contract for the supply of ventilators for the Canadian stockpile and possible international donation. This provided a strong impetus and was extensively supported by industrial partner, Elemaster that had been involved strongly since the very early days, as well as all international collaboration members working on many aspects of the development. It is worth emphasizing that the long experience of collaboration members working in large collaborations remotely and internationally over the internet was very valuable in providing a rapid and comprehensive response in this case.

The final design for the MVM is shown in Fig. 1. Figures 1, 2 and 3 are taken from Reference 2. In essence, the device requires the timed control of an inlet and an outlet valve to provide air with enhanced oxygen content to match patient requirements. However, in practice, it requires the full set of valves, monitoring and control computers and safety equipment that are shown in the figure. The monitoring and control is done by a computer system that also supports the display screen and accepts commands from the doctor or respiratory therapist assisting the patient. There are pressure monitors, flow meters, pressure relief valves for safety, alarm signals and an independent computer unit that oversees the entire system to ensure safety. The entire system underwent extensive testing to...
Fig. 1 A schematic of the MVM ventilator system (light blue box) with the connection to the patient. Dashed lines indicate electrical connections, and solid lines indicate gas connections. Thick black lines represent the breathing circuit, thin red lines are connections to pressure measurements, and the green line is the gas connection to drive the pneumatic valve at the end of the expiratory line. The direction of gas flow is indicated by the blue (inspiratory phase) and red (expiratory phase) arrows. The lines in gray indicate the breathing circuit relief lines. The breathing circuit shown has check valves in the inspiratory and expiratory lines. The beige rectangle represents the main electronics and control board, and the yellow square represents the supervisory board, which provides a redundant monitor and control.

meet the ISO requirements for devices of this type and received FDA Emergency Use Authorization, Health Canada Interim Order authorization, as well as CSA and CE certification. Following this authorization, final production in Canada began on November 30, 2020, and 7300 units were produced, delivered and accepted after extensive quality assurance testing by the end of February 2021.

The final internal layout is shown in Fig. 2. The front display in Fig. 3 shows the touch screen that enables the therapist to see pressure profile and other data while adjusting the parameters.

The MVM ventilator provides two modes:

1. **Pressure-controlled ventilation (PCV)** is used for patients who are unable to breathe on their own and provides a regular pattern of breaths with pressure profile and rate tuned to the patient needs. A new breath starts at the end of the preset breath cycle or if the patient attempts to initiate a breath. The software is able to provide an appropriate response for unusual events such as coughs, sighs or other events that require an alarm to be rung to summon supervisory personnel.

2. **Pressure support ventilation** is provided when the patient is able to breathe weakly so the machine is supporting their efforts. The settings then provide a regular pattern for each breath when the ventilator senses the initiation by the patient. This mode can be used when patients are being weaned off the ventilator to regain full control of their own breathing. The ventilator needs to recognize if breathing stops and then switches back to PCV and rings an alarm.
The evolution of the design to meet medical requirements, the industrialization of the device, the simplification of the components to meet available supply, the testing and the overall administration of the project required an extensive collaboration with a wide variety of skills. In spite of the extensive restrictions imposed by the pandemic, collaboration members worked very long hours on all aspects, sometimes taking advantage of the nine time zones to broaden the time availability to our advantage. We had participation by medical experts, starting in the first days when the experts in Milan had some of the best experience on the treatment of COVID and expanding across our time zones to include respiratory consultants who helped with the definition of the device’s capabilities and later the writing of the manuals and training information. It was of great value to work directly with manufacturers from the start, providing experience in developing a product which would be reliable and fully compliant with regulatory requirements. Their expertise and international connections in supply chains were also essential in identifying suppliers who could provide the required parts in a timely and economic way in spite of the pandemic. We also had assistance from private philanthropic donors who provided funds to lock in orders that were essential for the timely execution of the project amid substantial international demand for parts. Our hard-working technical team that included physicists, engineers, technicians and other supporting staff were a central element in our success and included specialists in gaseous systems, electronics, computing, certified safety software, ISO standards and quality assurance testing.

2 The 3Dπ PET scanner

A different subset of the DarkSide-20k collaboration, also led by Prof. Cristiano Galbiati, has been developing a new type of positron emission tomography (PET) scanner based on liquid argon technology known as the 3Dπ. The use of liquid argon doped with xenon, together with the latest cryogenic silicon photomultipliers (SiPMs), provides timing improved by up to a factor of four and improved detection efficiency compared with presently available commercial scanners. This development is based on a patent by Princeton University in the USA and Instituto Nazionale di Fisica Nucleare in Italy [3] and uses SiPMs developed for the DarkSide experiment. A subset of the collaborators are funded for prototype development.
in Sicily. An artist picture of the scanner is shown in Figure 4. The blue color represents the liquid argon region. More detailed specifications are contained in reference 4 [4].

This technology can allow a reduction of radioactive dose and thereby a reduction of cancer risk. This provides enhanced opportunities for more frequent screening in adult patients, or for pediatric oncology or tracing of the dose in real time. Figure 5 shows a comparison of resolution and corresponding count rates for the 3Dπ in comparison with two GE commercial scanners and a scanner using LYSO detectors at UC Davis.

**Data Availability Statement**  No Data associated in the manuscript.
References

1. C. Galbiati et al, ArXiv physics.med-ph 2003.10405v3 (2020)
2. A. Abba et al., Phys. Fluids 33, 037122 (2021)
3. C. Galbiati, US Patent 10,314,551 B2 (2019)
4. M. Lai et al. European Physical Society Conference on High Energy Physics 2021, Jul 2021, Online, Germany. pp.778, available at https://doi.org/10.22323/1.398.0778

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