AGILENT SPUTTER ION PUMPS
A 60 YEAR HISTORY

THE ION PUMP
60
YEARS OF INNOVATION

INVENTOR

1957 - 2017

The Invention that Made UHV Possible

Agilent celebrates the 60 Year anniversary of the Ion Pump invention at Varian Associates by Jepsen, Helmer and Hall, a milestone that made UHV possible. Agilent Technologies inherited an unequalled wealth of experience in the field of high- and ultra-high vacuum technology with its acquisition of Varian, Inc. in 2010. The development of this critical enabling foundation technology has provided clean high- and ultra-high vacuum for many applications in science and technology, from particle accelerators and analytical instruments to semiconductors and coatings.

The Early History

The original activity of Varian, co-founded in 1948 by Russell Varian, the inventor of the Klystron, and his brother Sigurd, was in the field of microwave electron tubes. Robert Jepsen joined the company in 1951 and soon became director of the Klystron research group. His investigation about electronic vacuum pumping led in 1957 (see Fig. 1) to the realization of the first sputter ion pump (SIP), later named VacIon pump, of which he was co-inventor [1].

Fig. 1 - The first VacIon, sputter ion pump was invented by Varian in 1957.
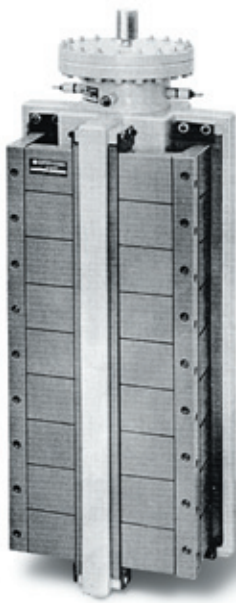
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Fig. 2 - The first series of Varian sputter ion pumps.

The pump was developed as an appendage pump for maintaining Ultra High Vacuum (UHV) in microwave power tubes after processing, but soon after honeycomb-shaped anodes and commercial VacIon pumps (see Fig. 2) with speeds of thousands of liters per second were produced.

Lewis Hall and John Helmer were members of the research team, involved in the choice of the most suitable cathode material and in the optimization of the ion pump design. Sherm Rutherford joined Varian in February 1959 in the Central Research Department (which, soon after, spun off the Vacuum Division). His activity, working for Robert Jepsen, was to study the behavior of the sputter ion pump (in terms of pumping speed and discharge intensity I/P) over a wide range of parameters, such as magnetic field, voltage, anode cell diameter, anode cell length and pressure [2,3]. Renn Zaphiropoulos joined the Vacuum Division in 1959 and was engaged in scaling up the ion pump from the original appendage pump to a full range of large pumps up to 5000 l/s [4], as shown in Fig. 3. His group worked on high voltage feedthroughs, magnets, control units, systems, flanges, valves, sorption pumps and Titanium Sublimation Pumps (TSP).

In 1960 the "slotted" titanium cathode [5], named "Super VacIon Pump", was introduced on the basis of observations about noble gas pumping mechanism [6] and unstable Argon pumping phenomena.

In the same years triode pumps were invented by W.M. Brubaker (Consolidated Electrodynamics Corporation) [7,8] and Varian began to sell them in the late '60s under the name "Noble Ion Pumps", then changed the name to "Triode Ion Pumps" in the early '70s.
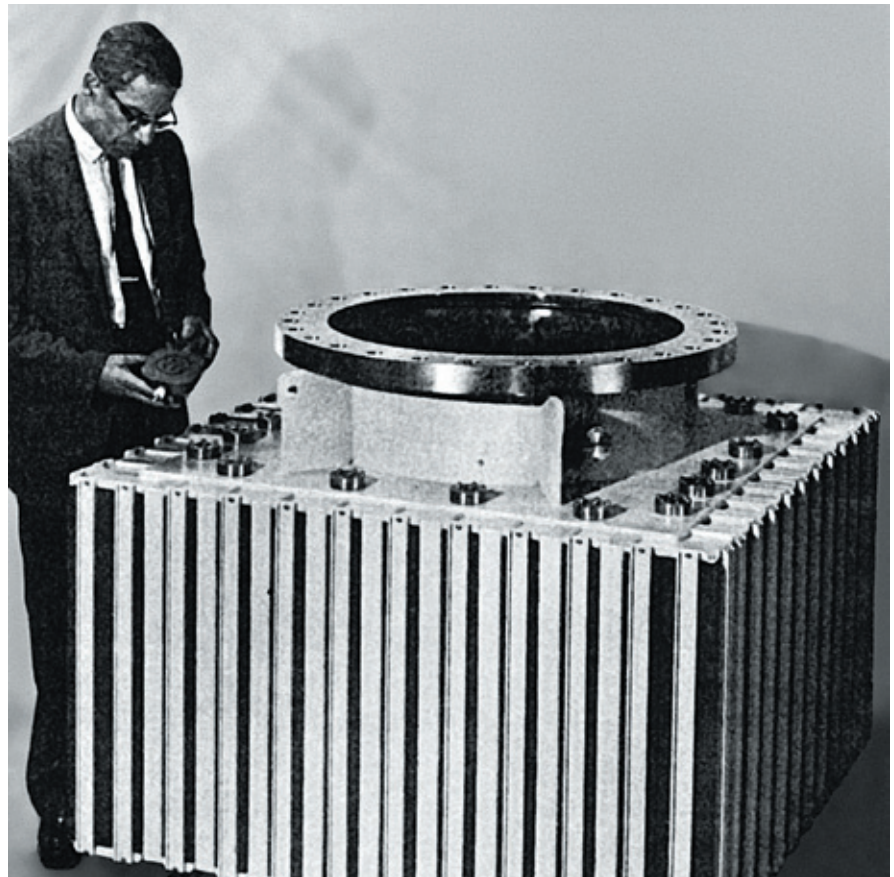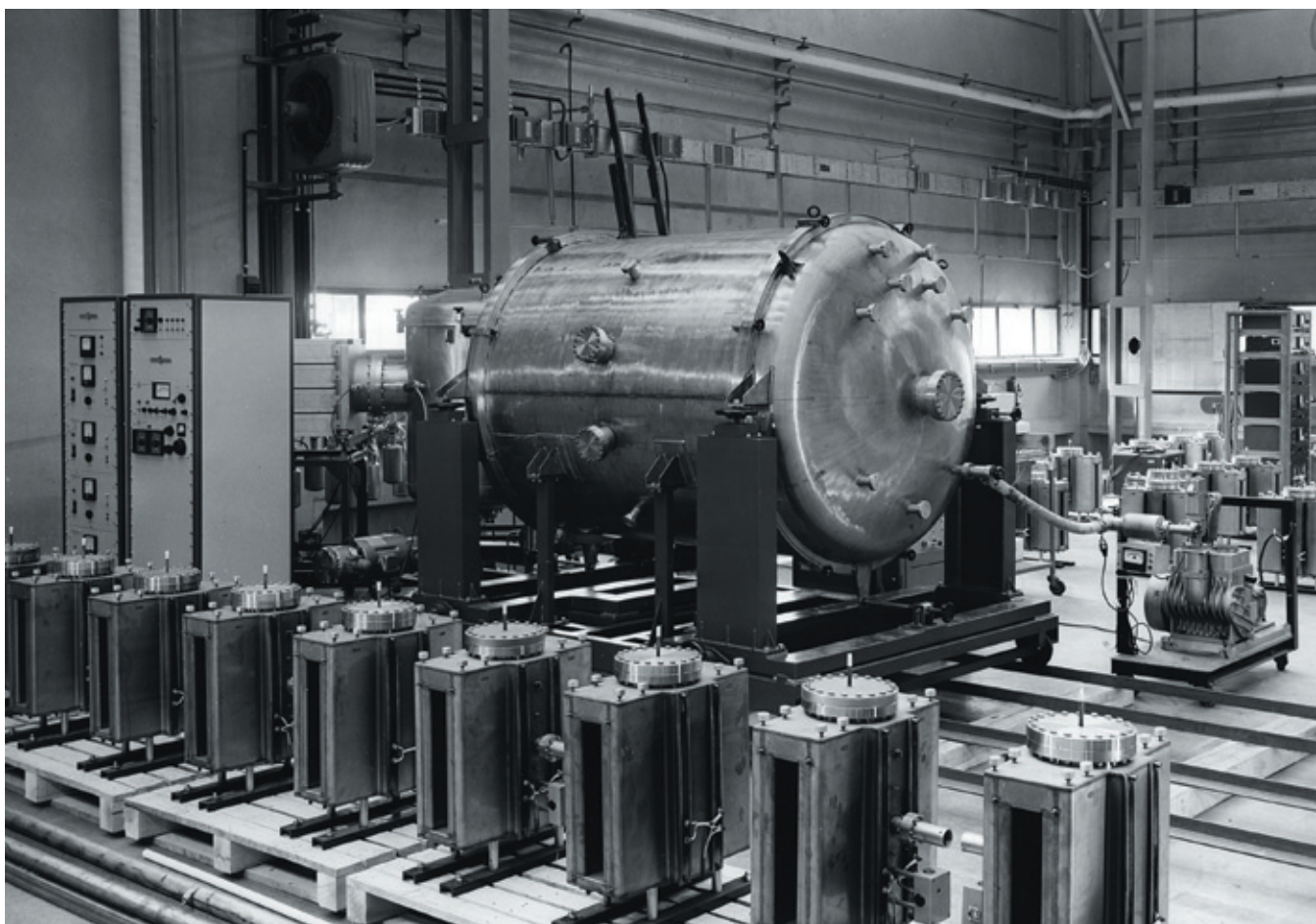

Fig. 3 - 5000 liter per second VacIon, pump.

Fig. 4 - Sputter ion pump production in Torino plant, built in 1967.

Ultra High Vacuum Technology

As we know today, the Ultra High Vacuum (UHV) technology in applications such as high energy physics, medical particle accelerators and surface science experiments is based on the use of all-metal bakeable vacuum systems. This technology was developed together with the application of the VacIon, pump, using stainless steel forms and tubing, copper-sealed "Wheeler" flanges, and metal-ceramic feedthroughs. Previous UHV research required in fact glass chambers,

a solution that proved to be commercially impractical. Varian showed that stainless-steel vacuum systems had equally low outgassing rates and the use of glass was not necessary. For example, low UHV pressure gauges (often referred to as Helmer gauges) were evaluated for the first time in a stainless-steel enclosure.

One of the first large installations of sputter ion pumps was the hadron collider ISR (Intersecting Storage Rings), that ran at the European Organization for Nuclear Research (CERN) in Geneva from 1971 to 1984. For the manufacture of ion pumps to equip CERN, a new Varian factory was opened in 1967 near Torino (see

Fig. 4). This plant is still today the hub of production of sputter ion pumps, commonly referred to in Europe as "ion getter pumps".

It was soon understood that the combination of sputter ion pumps and titanium sublimation pumps (TSP) could in principle lead to pressures as low as 10^{-12} Pa [9], but there were important limitations in starting and operating SIPs at high pressures.

Operation at High Pressure

At that time SIPs were the only existing oil-free pumps for the vacuum range below 10^{-4} Pa, but there were many problems involved in their operation at higher pressure, including high power dissipated with consequent high temperature and outgassing, Argon instability, short circuits and arcing, and overall limited pump life. Since zeolite (sorption) pumps, able to operate from atmosphere down to 1 Pa, were typically used as roughing pumps for SIP, starting a sputter ion pump was an unreliable process. During the '60s and '70s most of R&D activities were then focused in extending the operation of SIPs towards high pressure, with the contribution of Kimo Welch [10] and Dave Harra [11,12]. By combining high evaporation rate sublimators with SIP pumping, systems were designed for operation at 10^{-2} Pa with speeds of thousands of liters per second (see Fig. 5) [13, 14].

A new era began with the advent of oil free turbomolecular pumps and their corresponding oil free roughing pumps (e.g. Scroll), which soon became the ideal complement to SIPs in the higher range of pressure. As a consequence, the application range for ion pumps became more clearly identified as UHV.
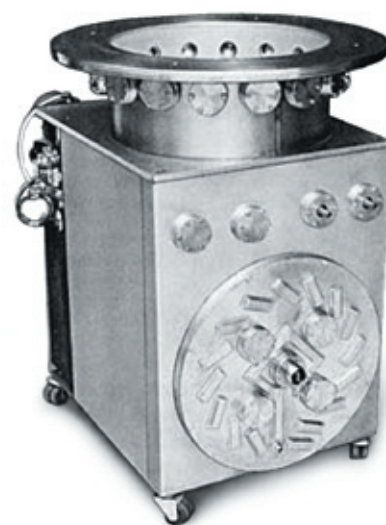
Fig. 5 - Pumping module with demountable sublimation pumping array installed. Overall height of the module was 33" and the baseplate diameter was 26".

Optimization of Sputter Ion Pumps

One of the main issues in the use of sputter ion pumps has always been instability when pumping noble gases at high pressure, or at low pressure for a long period of time. To overcome this limitation, several attempts were made to develop elements devoted to the pumping of noble gases: the slotted cathode and the triode, both already mentioned, and the differential ion (DI), proposed in 1967 by T. Tom and B.D. James and introduced by Ultek [15]. In differential ion pumps one cathode is made of Tantalum, the other of Titanium. The choice of one cathode of heavier material was made to increase the number of elastic collisions of the noble gas ions with the cathodes. A stable pumping action occurs in fact when the gas ions bounce back as energetic neutrals and implant into the anode or the walls, where they are permanently buried by the continuously sputtered titanium. With such a solution, the pumping speed for noble gases is higher (about 20% of the nominal pumping speed for nitrogen). On the other hand, Hydrogen pumping speed is reduced due to the low solubility of Hydrogen in Tantalum.
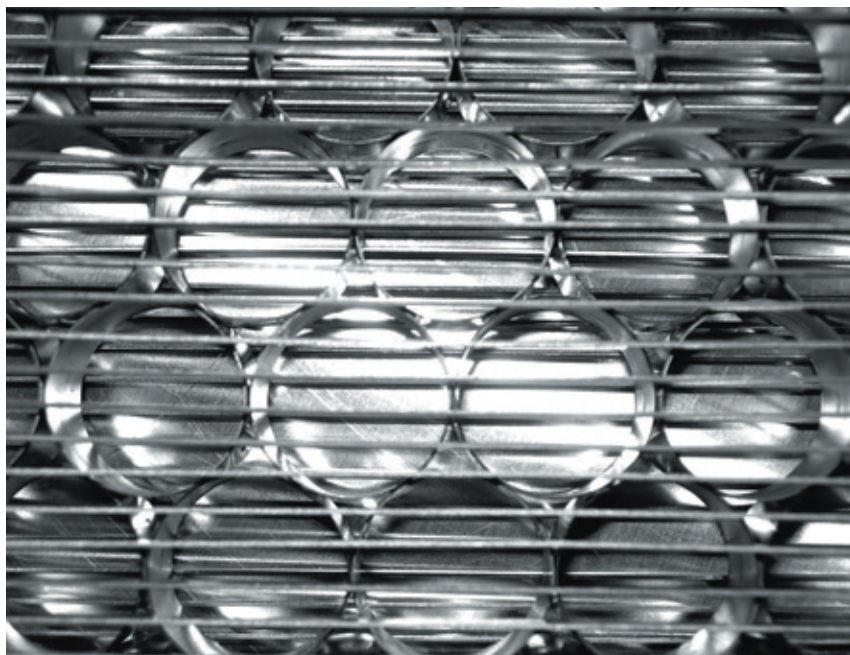
A second approach is used in the triode pump, where the cathodes were originally made of several Titanium strips (see Fig. 6a). In this configuration, cathodes are transparent to ions and the whole pump envelope becomes available as an additional pumping surface, from which no re-sputtering of the pumped molecules occurs. This is obtained by maintaining the same relative voltage potentials between anode and cathodes of the diode, but with the cathodes operated at a negative voltage while the anode and the pump walls are grounded. Triode pumps have a lower capacity for Hydrogen than standard

Fig. 6a - Triode pump cathode formed by Titanium strips.

pumps, due to cathode distortion and to Ti embrittlement phenomena, leading to undesired breaking, short circuits and high leakage current. On the other hand, the triode principle is the only known configuration also able to pump noble gases even heavier than Argon in a stable manner [16].

On the basis of the experience acquired in two decades with triode pumps, in 1983 Varian completely redesigned the triode, developing a new cathode structure known as StarCell® (see Fig. 6b). The StarCell® cathode plates show a cell structure with sharp, radially arrayed titanium fins which, following the Penning cell electric field symmetry, significantly enhance the probability of grazing collisions and the production of energetic neutrals [17].

The reflection probability is in fact also a function of the incidence angle. This most advanced solution provides the best behaviour: noble gases are pumped more stably and with enhanced pumping speed. At the same time the StarCell provides pumping speed and capacity for Hydrogen comparable to diodes, much higher than the ones of a noble diode. Also, the high-pressure operation is more stable than in standard triode pumps; distortion of the cathode is avoided and element life is increased due to the controlled erosion of the cathode cells from the center towards the periphery. Apart from the issue of noble gas pumping, the performance of sputter ion pumps depends on several factors, such as the magnetic field, the applied voltage and the element shape. For this reason the activity of Varian R&D was, and continues to be, focused on the optimization of the main parameters influencing the Penning cell operation. The main results obtained are briefly summarized here.

With regard to the magnetic field, it was shown that maximum efficiency at low pressure is obtained when it is high and aligned with the axis of the cells. This condition can be achieved, by designing circuits with enhanced homogeneity, rather than by increasing the magnetic circuit dimensions. One possibility is
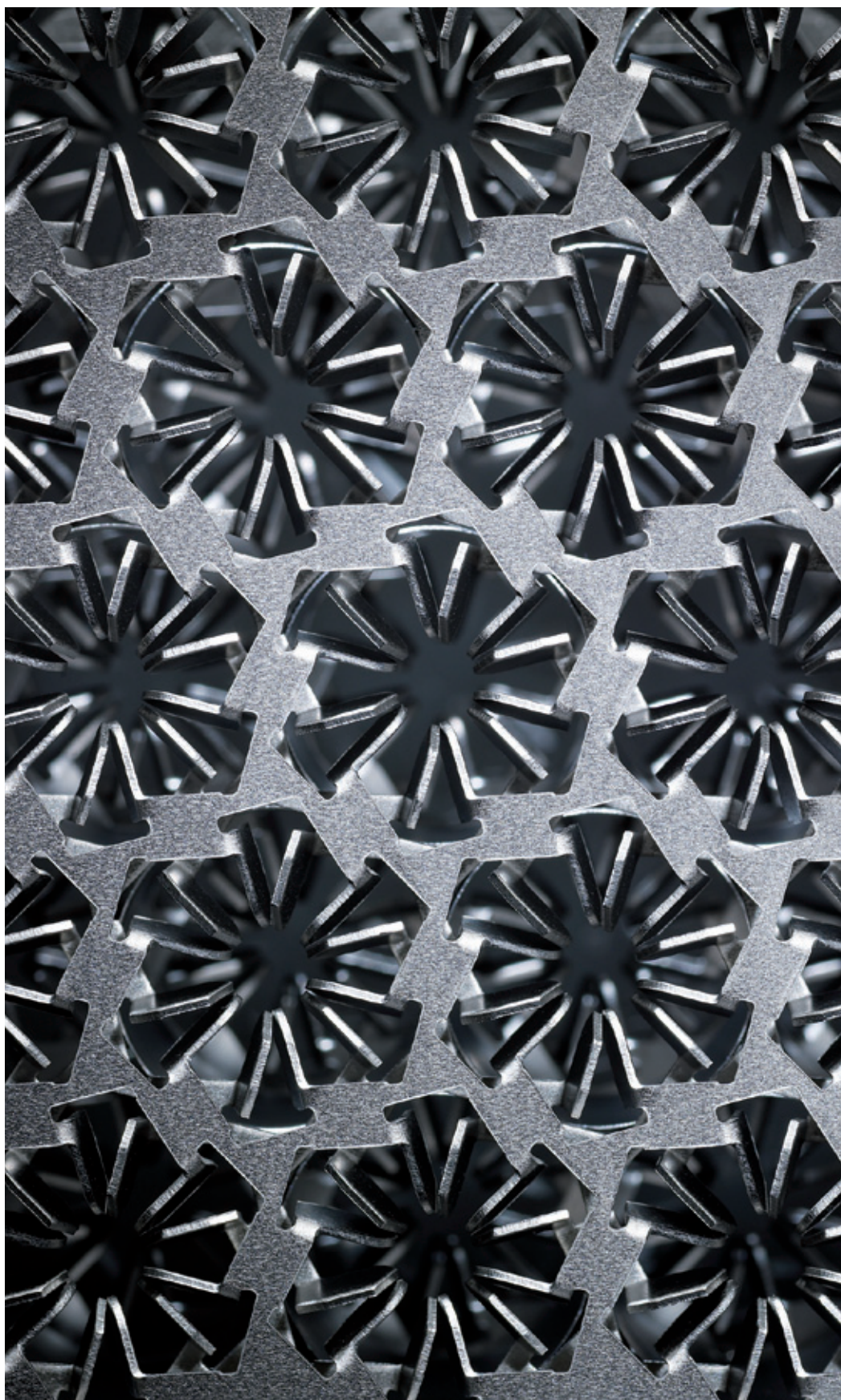

Fig. 6b - StarCell, structure.

Fig. 7 - Example of sputter ion pump whose magnetic circuit was optimized by placing additional magnets in the boundary regions to improve homogeneity.

optimization of the existing rectangular elements by deviating the magnetic flux lines through the use of additional magnets placed in the boundary regions (see Fig. 7) [18, 19]. Another solution adopted is the design of axially symmetric pumps with cells of different diameter in order to better fill the available cathode surface and use equal magnetic field for all the cells of the same diameter (see Fig. 8) [20].

The voltage [21] applied between cathode and anode and its influence on the sputtering yield, and therefore on the pumping speed, was investigated and tested in the late '80s [22]. This testing demonstrated that the maximum pumping speed increases with increasing voltage, while the pumping speed in the lower pressure range is higher at lower voltage,

Fig. 9 - Anode structure known as "SEM" element.

when the current is lower also. This pressure dependence is due to the space charge effect that depresses the voltage in the central zone of the Penning cell. On the basis of these observations, Varian developed in the '90s a new High Voltage controller for SIP that was able to change the voltage according to the pressure (read through the ion current). Thanks to this operating mode, the pumping speed is optimized in the whole operating pressure

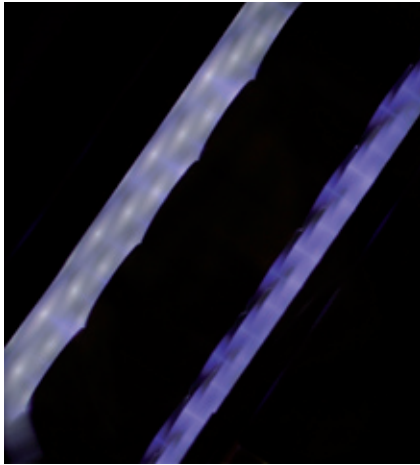Fig. 8 - Axial symmetric anode with cells of different diameter.

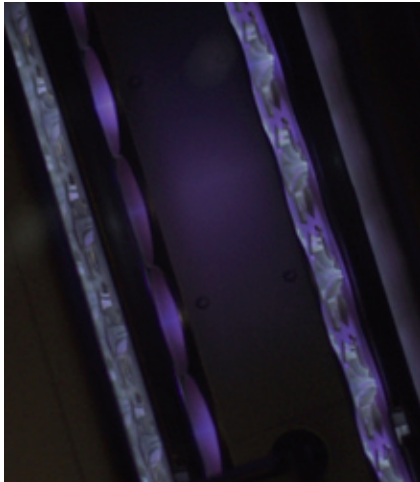Fig. 10 - Plasma at diode element during operation at $7*10^{-5}$ Pa.

Fig. 11 - Plasma at StarCell element during operation at $5*10^{-5}$ Pa.

range. This provides advantages at low pressures, not only in terms of higher pumping speed, but also in reducing the leakage current. Leakage current, due mainly to field emission, is exponentially proportional to the voltage (according to the Fowler-Nordheim equation) and is greatly reduced if the pump is operated at voltage as low as 3kV, allowing a more reliable ion current reading and therefore a better pressure conversion.

Finally, in order to reduce leakage current, a new anode structure was developed, in which interstitial cavities between contiguous cells were eliminated, as shown in Fig. 9. In fact the dendrites (whiskers) that are formed on the cathode surface during high-pressure operation are recognized sources of field emission and of leakage current. Studies [23] have shown that the greater number of them is created in the interstitial areas between the cells. This new element is usually called "SEM element" since it is very often employed in scanning electron microscope applications, where the ion pump current is used as a pressure set point to protect the microscope gun (filament or microtip electron emitters) in case of overpressure. It allows a reliable pressure indication (read from the ion pump current) down to 10^{-8} Pa.

Fig. 12 - Agilent VacIon Plus Pump.

Technology Innovation in UHV

Besides having been pioneer in vacuum technology, we continue to study and develop new vacuum solutions and technologies, partnering both with our customers and the major research centers worldwide.

The inline ion getter pump with optimized magnetic field is among the many products that we custom designed in these last 10 years. This pump was developed in collaboration with "Deutsches Elektronen Synchrotron" (DESY) (see Fig. 13). Using the innovative inline concept (protected by 2010 patent EP 2 431 996 A1), ion pumps installed on the XFEL system [24] (see Fig. 14) have become an integral part of the beam tube, without the need of being connected to it through T-pieces. The arrangement of the magnets, symmetrically located around the axis of the tube, and the geometry of the pole piece, used to guide the magnetic field lines, were designed to minimize any disturbance on the beam trajectory.
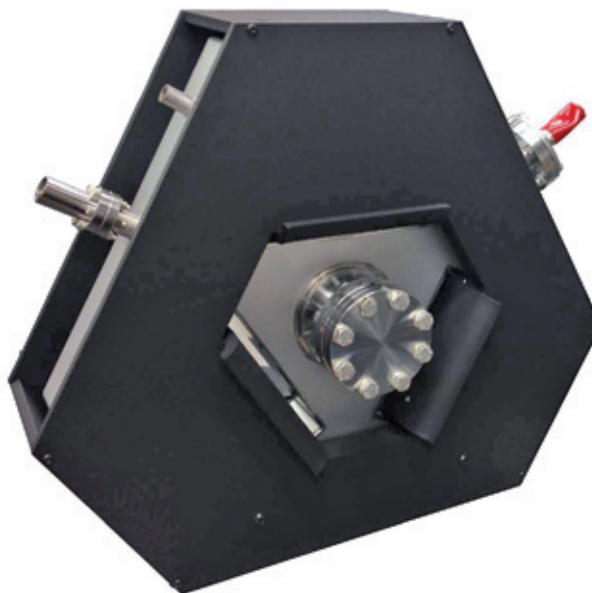

Fig. 13 - The in-line ion getter pump.

Fig. 14 - Agilent In-line Ion pumps integrated into a transport beam-line at X-FEL/Desy.

Fig. 15 - Ion VacIon Plus 1000 Pump.

Fig. 16 - Agilent Ion Pumps mounted on LIGO Gravitational Waves Detector and at MIRAPRO for KAGRA Gravitational Wave Interferometer.
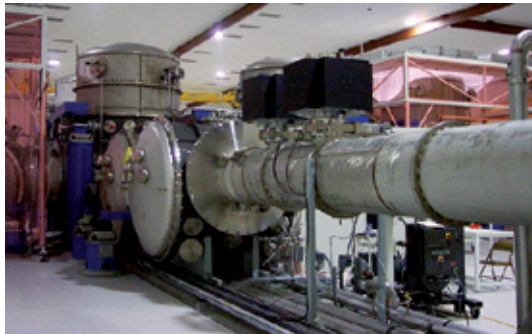

Fig. 17 - The Gravitational Waves Detection by the Laser Interferometer Gravitational-Wave Observatory (LIGO).

Furthermore, the element location inside the ion pump has been optimized to "self-shield" the beam, without requiring the addition of expensive and complex optical shields.

Another ion pump that was engineered to satisfy a specific application requirement was the large 2500 L/s ion pump, designed to equip the Laser Interferometer Gravitational-Wave Observatory (LIGO) [25] (see Fig. 17) in US, where the Gravitational Waves were recently detected. These gravitational waves were detected by LIGO's multikilometer-scale detectors 100 years after Einstein's prediction in the general theory of relativity. These detectors use laser interferometry to measure the minute ripples in space-time caused by passing gravitational waves from cataclysmic cosmic sources, such as the mergers of pairs of neutron stars, black holes, or supernovae. LIGO's vacuum system was equipped with the 2500 L/s ion pumps designed and produced by Agilent.

After the success of the LIGO experiment, Agilent developed a new VacIon Plus 1000 pump (see Fig. 15) to be used in the same field of application; this pump was already produced in the past, but has been completely restyled in 2016, with new welding techniques and the use of finite element method simulations.
The VacIon Plus 1000 will be installed in the new Kamioka Gravitational Wave Detector (KAGRA) (see Fig. 16), another large interferometer under construction in Japan (pumps will be assembled and tested by MIRAPRO). Creating ultraclean and stable high vacuum in these multikilometer detectors is instrumental to the operation of the entire system. Furthermore, uptime, reliability, and vibrationless operation are absolute requirements for such detectors. Agilent designed and built customized ion pumps to fulfill all these stringent criteria, providing the ideal vacuum conditions for the success of the experiment.
A further innovation related to the world of ion pumps was the introduction in 2011 of the 4UHV (see Fig. 18), which was the first true four-channel ion pump controller

Fig. 18 - 4UHV Ion Pump Controller.

Fig. 19 - Agilent Ion Pump 200.

for Ultra High Vacuum (UHV) applications. The 4UHV is available in different configurations, to independently power, control, and monitor combinations of multiple pumps of different sizes, from one to four pumps, allowing greater flexibility of use. The 4UHV is factory preprogrammed to automatically convert the current reading of any VacIon Plus pump into pressure. To ensure reliable pressure reading down to the UHV region, the 4UHV optimizes the applied high voltage as a function of pressure, thus eliminating the misleading influence of leakage currents.

Finally, in 2016 the VacIon Plus 200 was introduced. This ion pump is tailored for XHV (eXtreme High Vacuum) and UHV applications, such as research centers, universities, particle accelerators, and beamlines. The new VacIon Plus 200 (see Fig. 19) is the first ion pump in the market with maximum pumping speed at low pressure. Besides being the most compact pump in its category, the VIP200 achieves peak pumping speed in the 1 × 10-8 mbar range. This range is the usual operating range for ion pumps, while conventional ion pumps have the peak at higher pressure (typically in the 1 × 10-6 mbar range). This is possible thanks to the

special element design and to the optimized magnetic field distribution. Furthermore, the VIP200 is currently the unique pump completely vacuum fired: This means that all the surfaces exposed to vacuum are vacuum fired in a vacuum furnace before the pump assembly. This thermal treatment effectively reduces (up to 90%) [26] the hydrogen outgassing rate, allowing a faster pump-down to the ultimate pressure. operating range for ion pumps, while conventional ion pumps have the peak at higher pressure (typically in the 1 × 10-6 mbar range). This is possible thanks to the special element design and to the optimized magnetic field distribution. Furthermore, the VIP200 is currently the unique pump completely vacuum fired: This means that all the surfaces exposed to vacuum are vacuum fired in a vacuum furnace before the pump assembly. This thermal treatment effectively reduces (up to 90%) [26] the hydrogen outgassing rate, allowing a faster pump-down to the ultimate pressure.

Pumping Speed vs Pressure

Nitrogen unsaturated Diode   Nitrogen saturated Diode   Argon saturated Starcell
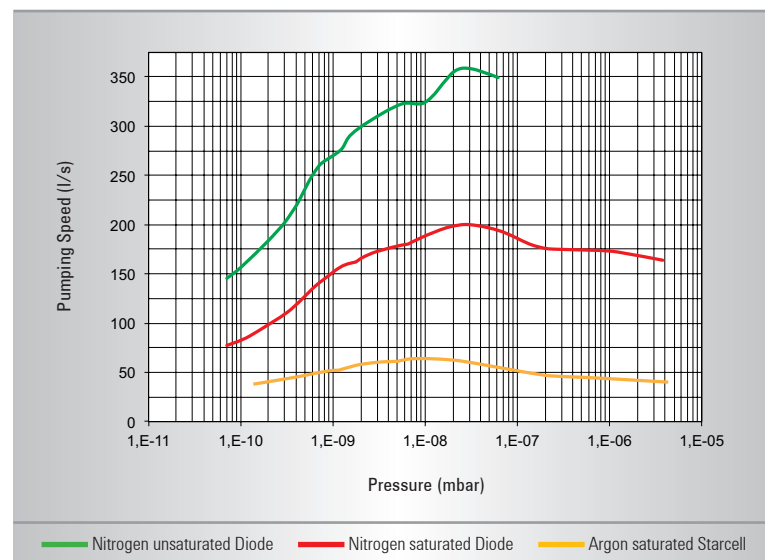
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[24] DESY's XFEL is a groundbreaking X-ray research site based in Hamburg (Germany). It will generate X-ray flashes with brilliance 1 billion times higher than that of the best conventional X-ray radiation sources.

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Acknowledgements

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A 60 year history

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