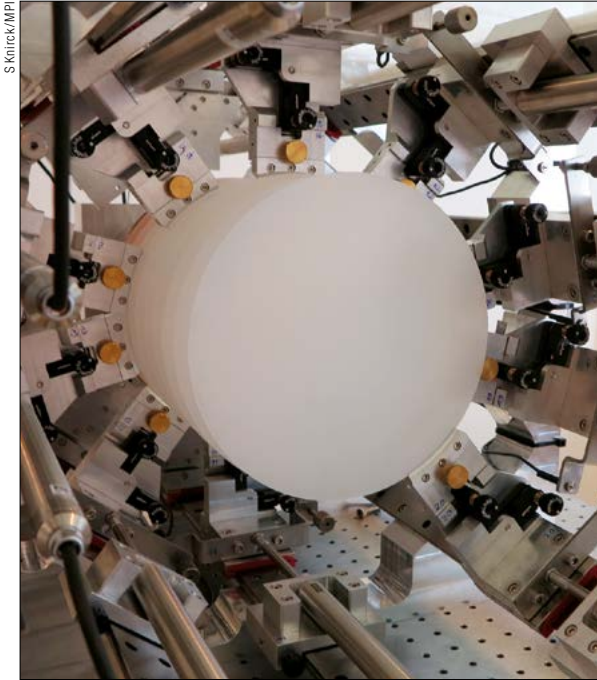




S. Klotz/MPI

Search for WISPs gains momentum

Despite tremendous efforts, the search for the constituents of dark matter has so far been unsuccessful. Interest is therefore growing in new experiments that probe dark-matter candidates such as axions and other very weakly interacting sub-eV particles.

Understanding the nature of dark matter is one of the most pressing problems in physics. This strangely nonreactive material is estimated, from astronomical observations, to make up 85% of all matter in the universe. The known particles of the Standard Model (SM) of particle physics, on the other hand, account for a paltry 15%.

Physicists have proposed many dark-matter candidates. Two in particular stand out because they arise in extensions of the SM that solve other fundamental puzzles, and because there are a variety of experimental opportunities to search for them. The first is the neutralino, which is the lightest supersymmetric partner of the SM neutral bosons. The second is the axion, postulated 40 years ago to solve the strong CP problem in quantum chromodynamics (QCD). While the neutralino belongs to the category of weakly interacting massive particles (WIMPs), the axion is the prime example of a very weakly interacting sub-eV particle (WISP).

Neutralinos as WIMPs have dominated the search for cold dark matter since the mid-1980s, when it was realised that massive particles with a cross section of the order of the weak interaction would result in precisely the right density to explain dark matter. There have been tremendous efforts to hunt for WIMPs both at hadron colliders, especially now at CERN's Large Hadron Collider (LHC), and in large underground detectors, such as CDMS, CRESST, DARKSIDE, LUX, PandaX and XENON. However, up to now, no WIMP has been observed (*CERN Courier* July/August 2018 p9).

Very light bosons as WISPs are a firm prediction of models that solve problems of the SM by the postulation of a new symmetry

which is broken spontaneously in the vacuum. Such extensions contain an additional scalar field with a potential shaped like a Mexican hat – similar to the Higgs potential in the SM (figure 1). This leads to spontaneous breaking of symmetry at a scale corresponding to the radius of the trough of the hat: excitations in the direction along the trough correspond to a light Nambu–Goldstone (NG) boson, while the excitation in the radial direction perpendicular to the trough corresponds to a heavy particle with a mass determined by the symmetry-breaking scale. The strengths of the interactions between such light bosons and regular SM particles are inversely proportional to the symmetry-breaking energy scale and are therefore very weak. Being light, very weakly interacting and cold due to their non-thermal production history, these particles qualify as natural WISP cold dark-matter candidates.

Primordial production

In fact, WISP dark matter is inevitably produced in the early universe. When the temperature in the primordial plasma drops below the symmetry-breaking scale, the boson fields are frozen at a random initial value in each causally-connected region. Later, they relax towards the minimum of their potential at zero fields and oscillate around it. Since there is no significant damping of these field oscillations via decays or interactions, the bosons behave as a very cold dark-matter fluid. If symmetry breaking occurs after the likely inflationary-expansion epoch of the universe (corresponding to a post-inflationary symmetry-breaking scenario), WISP dark matter would also be produced by the decay of topological defects from the realignment of patches of the universe with random initial conditions. A huge region in parameter space spanned by WISP masses and their symmetry-breaking scales can give rise to the

Image above: test setup of the MADMAX experiment with sapphire plates to allow the detection of axion–photon conversion.

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Dark matter

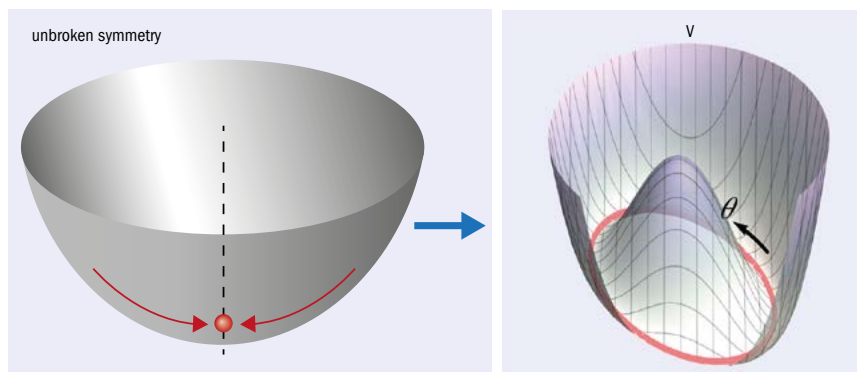


Fig. 1. The potential of a complex scalar field in primordial plasma in the very early universe (left) takes the form of a Sombrero (right) once the temperature drops below the symmetry-breaking scale. The energy-breaking scale corresponds to the radius of the valley from the centre, while the axion represents oscillations around one of the minima, which arise due to QCD gluon-field fluctuations.

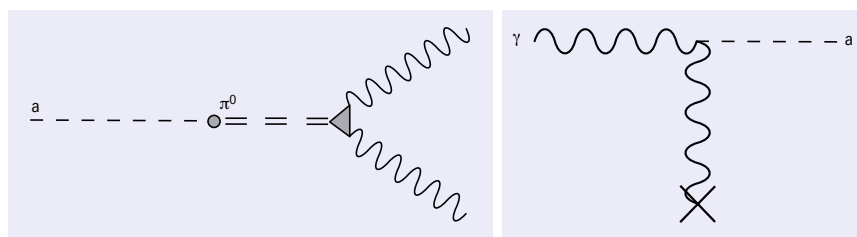


Fig. 2. Left: diagram showing axion–photon coupling via axion–pion oscillation. Right: via the Primakoff effect, a virtual photon can be borrowed from a static magnetic field (denoted by the cross) to induce photons to convert into axions or vice versa, as first suggested by P Sikivie.

observed dark-matter distribution.

The axion is a particularly well-motivated example of a WISP. It was proposed to explain the results of searches for a static electric dipole moment of the neutron, which would constitute a CP-violating effect of QCD. The size of this CP-violation, parameterised by the angle θ , is predicted to have an arbitrary value between $-\pi$ and π , yet experiments show its absolute value to be less than 10^{-10} . If θ is replaced by a dynamical field, $\theta(x)$, as proposed by Peccei and Quinn in 1977, QCD dynamics ensures that the low-energy effective potential of the axion field has an absolute minimum at $\theta=0$. Therefore, in vacuum, the CP violating effects due to the θ angle in QCD disappear – providing an elegant solution to the strong CP problem. The axion is the inevitable particle excitation of $\theta(x)$, and its mass is determined by the unknown breaking scale of the global symmetry.

Lattice-QCD calculations performed last year precisely determined the temperature and corresponding time after the Big Bang when axion cold dark-matter could have formed as a function of the axion mass. It was found that, in the post-inflationary symmetry breaking scenario, the axion mass has to exceed $28 \mu\text{eV}$; otherwise, the predicted amount of dark matter overshoots the observed amount. Taking into account the additional production of axion dark-matter from the decay of topological defects, an axion with

a mass between $30 \mu\text{eV}$ and 10meV may account for all of the dark matter in the universe. In the pre-inflationary symmetry breaking scenario, smaller masses are also possible.

Axions are not the only WISP species that could account for dark matter. There could be

axion-like particles (ALPs), which are very similar to axions but do not solve the CP problem of QCD, or lightweight, weakly interacting, so-called hidden photons, for example. String theory suggests a plenitude of ALPs, which could have couplings to photons, leptons or light quarks.

Due to their tiny masses, WISPs might also be produced inside stars or alter the propagation of photons in the universe. Observations of stellar evolutions hint at such signals: red giants, helium-burning stars and white dwarfs seem to be experiencing unseen energy losses exceeding those expected from neutrino emission. Intriguingly, these anomalies can be explained in a unified manner by the existence of a sub-keV-mass axion or ALP with a coupling both to electrons and photons. Additionally, observations suggest that the propagation of TeV photons in the universe suffers less than expected from interactions with the extragalactic background light. This, in turn, could be explained by the conversion of photons into ALPs and back in astrophysical magnetic fields, interestingly with about the same axion–photon coupling strength as indicated by the observed stellar anomalies. Both effects have been known for almost 10 years. They are scientifically disputed, but a WISP explanation has not yet been excluded.

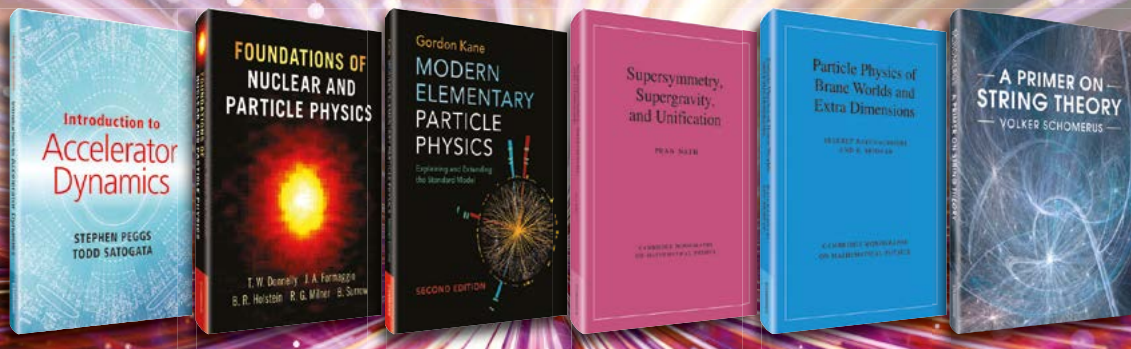
Experimental landscape

Most experiments searching for WISPs exploit their possible mixing with photons. Given the small masses and feeble interactions of axions and ALPs, however, building experiments that are sensitive enough to detect them is a considerable challenge. In the 1980s, Pierre Sikivie of the University of Florida in the US suggested a way forward based on the conversion of axions to photons: in a static magnetic field, the axion can “borrow” a virtual photon from the field and turn into a real photon (figure 2). Most experiments search

Thrilling data runs are expected to start in the early 2020s.

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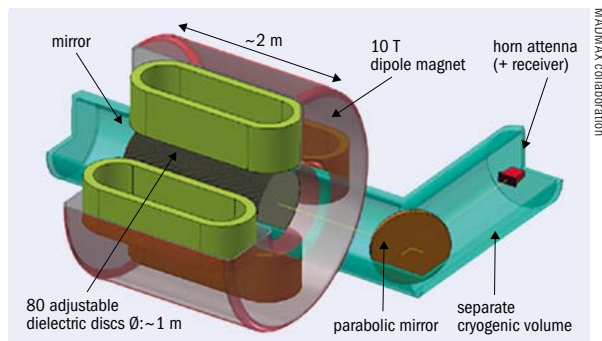
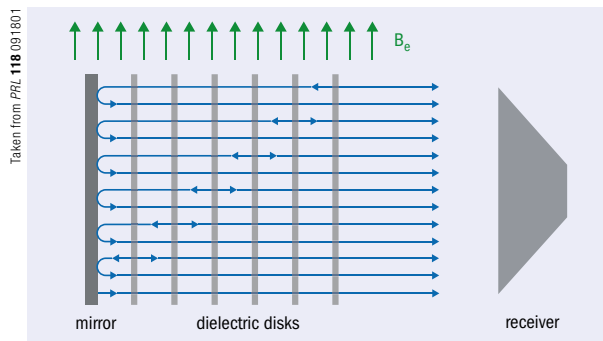


Fig. 3. The principle of a dielectric haloscope (left) and a schematic of the proposed MADMAX setup (right).

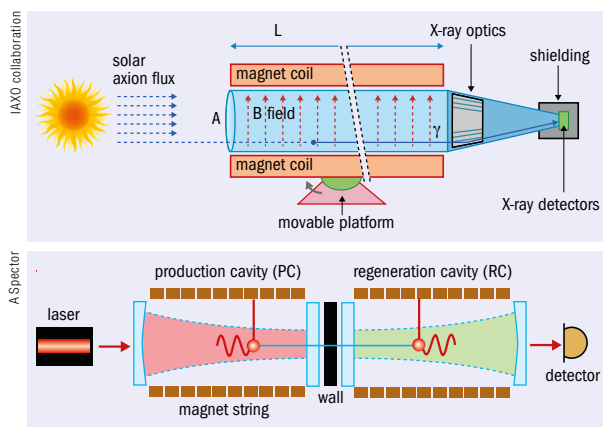


Fig. 4. Schematic principle of a helioscope (top) and light-shining-through-walls experiment (bottom).

for axions and ALPs in this way, with three main approaches being pursued: haloscopes, which look directly for dark-matter WISPs in the galactic halo of our Milky Way; helioscopes, which search for ALPs or axions emitted by the Sun; and laboratory experiments, which aim to generate and detect ALPs in a single setup.

Direct axion dark-matter searches differ in two aspects from WIMP dark-matter searches. First, axion dark matter would convert to photons, while WIMPs are scattered off matter. Second, the particle-number density for axion dark-matter, due to its low mass, is about 15 orders of magnitude larger than it is for WIMP dark matter. In fact, cold dark-matter axions and ALPs behave like a highly degenerate Bose–Einstein condensate with a de Broglie wavelength of the order of metres or kilometres for μeV and neV masses, respectively. Dark-matter axions and ALPs are thus much better pictured as a classical-field oscillation. In a magnetic field, they induce tiny electric-field oscillations with a frequency determined by the axion mass. If the de Broglie wavelength of the dark-matter axion is larger than the experimental setup, the tiny oscillations are spatially coherent in the experiment and can, in principle, be “easily” detected using a resonant microwave cavity tuned to the correct but unknown frequency. The sensitivity of such an experiment increases with the magnetic field strength squared,

the volume of the cavity and its quality factor. Unfortunately, since the range of axion mass predicted by theories is huge, methods are required to tune the cavity to the frequency range corresponding to the respective axion masses.

This cavity approach has been the basis of most searches for axion dark-matter in the past decades, in particular the Axion Dark Matter Experiment (ADMX) at the University of Washington, US. Using a tuning rod inside the cavity to change the resonance frequency and, recently, by reducing noise in its detector system, the ADMX team has shown that it can reach axion dark-matter sensitivity. ADMX, which has been pioneering the field for two decades, is currently taking data and could find dark-matter axions at any time, provided the axion mass lies in the range 2–10 μeV . Meanwhile, the HAYSTAC collaboration at Yale University has very recently demonstrated that the same experimental approach can be expanded up to an axion mass of around 30 μeV . Since smaller-volume cavities (usually with lower quality factors) are needed to probe higher frequencies, however, the single-cavity approach is limited to axion masses below about 40 μeV . One novel method to probe higher masses is to use multiple matched cavities, as for example followed by the ADMX and the South Korean Center for Axion and Precision Physics.

Transitions

A different way to exploit the tiny electric-field oscillations from dark-matter axions in a strong magnetic field is to use transitions between materials with different dielectric constants: at surfaces, the axion-induced electromagnetic oscillations have a discontinuity, which is to be balanced by radiation from the surface. For a mirror with a surface area of 1 m^2 in a 10 T field, this would lead to an undetectable emission of around 10^{-27} W if axions make up all of the dark matter. Furthermore, the emission power does not depend on the axion mass. In principle, if a parabolic mirror with a surface area of 10,000 m^2 could be magnetised with a 10 T field, the predicted radiation power (10^{-23} W) could be focused and detected using state-of-the-art amplification techniques, but such an experiment seems impractical at present.

The axion is a particularly well-motivated WISP.



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Fig. 5. The CAST experiment at CERN, which reuses a prototype dipole magnet from the LHC, photographed in December 2016.

Alternatively, many magnetised dielectric discs in parallel can be placed in front of a mirror (figure 3): since the emission from all surfaces is coherent, constructive interference can boost the signal sensitivity for a given frequency range determined by the spacing between the discs. First studies performed in the past years at the Max Planck Institute for Physics in Munich have revealed that, for axion masses around $100 \mu\text{eV}$, the sensitivity could be good enough to cover the predicted dark-matter axion mass range. The MAD-MAX (Magnetized Disc and Mirror Axion Experiment) collaboration, formed in October 2017, aims to use this approach to close the sensitivity gap in the well-motivated range for dark-matter axions with masses around $100 \mu\text{eV}$. First design studies indicate that it is feasible to build a dipole magnet with the required properties using established niobium-titanium superconductor technology. As a first step, a prototype experiment is planned consisting of a booster with a reduced number of discs installed inside a prototype magnet. The experiment will be located at DESY in Hamburg, and first measurements sensitive to new ALPs parameter ranges are planned within the next few years.

Model independent searches

These direct searches for axion dark matter are very promising, but they are hampered at present by the unknown axion mass and rely on cosmological assumptions. Other, less-model dependent, experiments are required to further probe the existence of ALPs.

ALPs with energies of the order of a few keV could be produced in the solar centre, and could be detected on Earth by pointing a strong dipole magnet at the Sun: axions entering the magnet could be converted into photons in the same way they are in cavity experiments. The difference is that the Sun would emit relativistic axions with an energy spectrum very similar to the thermal spectrum in its core, so experiments need to detect X-ray photons and are sensitive to axion masses up to a maximum depending on the length of the apparatus (figure 4, top). This helioscope technique was brought to the fore by the CERN Axion Solar Telescope (CAST), shown in figure 5, which began operations in 2002 and has excluded axion masses above 0.02 eV . As a successor, the International Axion Observatory (IAXO) was formally founded in July 2017 and

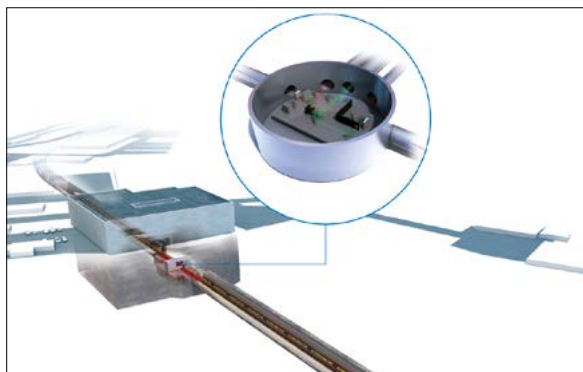


Fig. 6. Schematic of the ALPS II experiment's final stage, which will re-use 20 HERA straightened dipoles in a section of the tunnel at DESY.

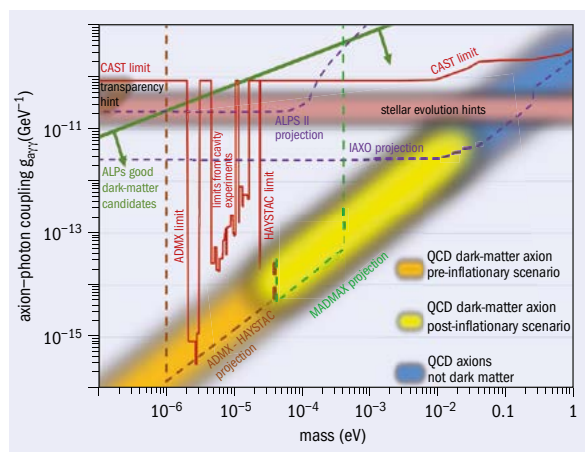


Fig. 7. Axion mass versus axion–photon coupling parameter space showing sensitivities and regions that could explain dark matter, stellar anomalies and TeV-transparency hints.

received an advanced grant from the European Research Council earlier this year. The near-term goal of the collaboration is to build a scaled-down prototype version of the experiment, called baby-IAXO, which is under discussion for possible location at DESY.

The third, laboratory-based, approach to search for WISPs also aims to generate and detect ALPs without any model assumption. In the first section of such an experiment, laser light is sent through a strong magnetic field so that ALPs might be generated via interactions of optical photons with the magnetic field. The second section is separated from the first one by a light-tight wall that can only be penetrated by ALPs. These would stream through a strong magnetic field behind the wall, allowing them to be re-converted into photons and giving the impression of light shining through a wall (figure 4, bottom).

Such experiments have been performed since the early 1990s, but no hint for any ALP has shown up. Today, the most advanced project in this laboratory-based category is ALPS II, currently being set up

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at DESY (figure 6). This experiment will use two optical resonators implemented into the apparatus to “recycle” the light before and increase the re-conversion probability of ALPs into photons behind the wall, allowing ALPS II to reach sensitivities beyond ALP–photon coupling limits from helioscopes. It also plans to use 20 dipoles from the former HERA collider, each of which has to be mechanically straightened, to generate the magnetic field.

Gaining momentum

Searches for very lightweight axions and ALPs, potentially explaining all of the dark matter around us, are strongly gaining momentum. CERN has been supporting such activities in the past (with solar-axion and dark-matter searches at CAST, and the OSQAR and CROWS experiments using the shining-light-through-walls approach) and is also involved in the R&D phase for next-generation experiments such as IAXO (*CERN Courier* September 2014 p17). With the new initiatives of MADMAX and IAXO, both of which could be located at DESY, and the ALPS II experiment under construction there, experimental axion physics in Europe is set to probe a large fraction of a well-motivated parameter space (figure 7). In addition to complementary experiments worldwide, the next 10 years or so should shine a bright light on WISPs as the solution to the dark-matter riddle, with thrilling data runs expected to start in the early 2020s.

• Further reading

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Résumé

La quête des WISP prend de la vitesse

La nature de la matière noire demeure à ce jour l'une des grandes énigmes de la physique. Les recherches portant sur des constituants de la matière noire semblables à des WIMP ayant jusqu'ici été infructueuses, l'intérêt se porte de plus en plus sur d'autres candidats à la matière noire, notamment les axions ou des particules semblables à ceux-ci. De nouvelles expériences, qui cherchent des particules de ce type – soit émises par le soleil soit produites en laboratoire – passent à présent à la vitesse supérieure. Parmi celles qui fleurissent en Europe, on peut citer IAXO, MADMAX et ALPS II. Ensemble, elles sonderont une grande partie d'un espace de paramètres bien déterminé.

Axel Lindner and **Andreas Ringwald**, DESY, Hamburg; and **Béla Majorovits**, Max Planck Institute for Physics, Munich.

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UHV Design advances bellows-free drive for critical beamline applications at CERN

Spring-loaded magnetically-coupled device provides a fail-safe solution that could reduce unscheduled downtime due to loss of ultra-high vacuum.

Innovative design

A customer enquiry for a linear power probe – a magnetically-coupled actuator that can operate remotely in vacuum – has led to a new fail-safe design that could improve the operability of beamlines around the world.

“CERN explained that they were looking for a product that would avoid using bellows”, says Jonty Eyres, engineering director at UHV Design. The UK-based firm specializes in the design, manufacture and supply of motion and heating products specified for use in high- and ultra-high vacuum conditions.

“Bellows-sealed devices have been the go-to space for moving things in and out in a clean manner and with minimal outgassing”, Eyres explains. Depending on the type of bellows used, and their application, their service life can reportedly range from 10 000 up to as many as 2 million actuations. But they won’t last forever. And when they fail it can lead to an unexpected loss of vacuum and costly delays.

The challenge for Eyres and his colleagues was to come up with a solution that reproduced the clean operation of a bellows-sealed device, but in a fail-safe manner.

Over the past 20 years, the firm has developed considerable expertise in magnetically-coupled devices. Their bellows-free approach features an arrangement of magnets located inside and outside a rigid tubular vacuum envelope. Moving the magnetic housing on the outside advances and retracts an actuation shaft held centrally inside the device.

The team used specialized software to optimize both the magnetic coupling between the inside and the outside, and the screening of the device.

Online meetings allowed the client – in this case CERN – to voice the product criteria that were important to them.

“We used the sessions to discover their feedback, the pros and cons and where we think the scope is in terms of performance”, Eyres explains.



Compact, bellows-free actuator.

“Once we are confident in a prototype, the next stage is to put it on a vacuum rig and start running rigorous tests on performance and precision”, says Eyres. This includes carrying out residual gas analysis using a mass quadrupole device to examine how the mechanism affects the vacuum pressure. A major benefit of the firm’s design is that there are no bellows to fail. But instead the team has to contend with moving parts in vacuum.

The engineers tackled this by keeping the contact areas to a minimum and using rolling parts, not sliding parts, to limit any pressure rise during operation. Preserving ultra-high vacuum conditions is critical.

Designed for cleanliness

But having rolling contacts isn’t the end of the story. In addition, the materials combination must be inert to prevent the mechanism from bonding or sticking over time. And the requirement for absolute cleanliness means that all of the bearings have to be designed to operate without lubrication.

The company’s solution was to use silicon nitride (a hard ceramic) ball races that pressed against two extremely tough shafts made out of tungsten carbide. This arrangement keeps the internal push-rod centrally supported, paving the way for precise movement into and out of the beamline. Furthermore, external constant force springs retract the in vacuum mechanism should any failure occur in the pneumatics driving the unit. In this fail-

safe position, the linear actuator has no effect on the beam.

A system of flexures ensures that no undue stresses are placed on any of the critical parts during bake out as they expand at different rates according to their composition.

The firm’s bellows-free solution brings together creative design, smart materials selection and precision operation. Now that the linear drive is in its final prototype phase the team is working towards fulfilling multiple orders from CERN for what will be a bolt-on solution pre-wired with all of the necessary cables and switches.

“Every beamline in the world needs beam diagnostics,” Eyres comments. “And off the back of this project we’re ready to work with more clients who are also looking to move away from bellows in critical areas.”

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