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The IPICS «oldest ice» challenge: a new technology to qualify potential sites

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Among the priorities of the International Partnerships in Ice Core Sciences (IPICS) core project of Past Global Changes (IGBP/PAGES), drilling ice as old as 1.5 million years is probably the most emblematic challenge. The search for a potential site in Antarctica hosting such old ice in good stratigraphic order is under way. Here we propose an innovative way to rapidly qualify potential sites. We plan to build a probe able to drill down to bedrock within one field season. The probe will embed a laser optical instrument measuring in real time key parameters such as the water isotopic composition of the ice and the concentration of one or more greenhouse gases.

Introduction

Understanding past climate variations provides solid physical understanding of the climate response to natural forcings, including the quantification of feedbacks (e.g., between climate and the carbon cycle) and the identification of non-linear responses and thresholds. Ice cores are exceptional archives of past climate and atmospheric composition, providing key information on climate forcing (orbital signal, volcanism, and solar activity), climate feedbacks (atmospheric greenhouse gas concentration, aerosols, dust...), and polar climate history through quantitative reconstructions of past temperature and precipitation accumulation.

Since the 1960s, intensive efforts have been dedicated to the recovery and analysis of ice cores from glaciers and polar ice sheets. In Greenland, the international NorthGRIP project reached 3085 m of depth, covering one full climatic cycle back to the end of the last interglacial period [20]. In Antarctica, the Vostok drilling down to 3300 m of depth – and handled under a unique joint collaboration between Russia, France and the USA – was instrumental to reveal the close relationship between climate and greenhouse gases at glacial-interglacial time scales [22]. The European Project for Ice Coring in Antarctica (EPICA) has completed the Dome C deep drilling, reaching 3260 m of depth and offering an exceptional 800,000 year long archive of climate and atmospheric composition evolution. The oldest part of the EPICA Dome C climatic record revealed surprisingly cool interglacial periods from 800,000 to 400,000 years ago [8, Fig. 1]. A strong imprint of obliquity, increasing from past to present, is found in Antarctic temperature [11], moisture origin [27] and greenhouse gas concentrations [17, 18]. The increased magnitude of interglacials may be attributed to a long-term modulation of the climate response (notably sensitive to the Antarctic water cycle) to obliquity amplitude.

The oldest part of the EPICA Dome C ice core has revealed exceptionally low values of CO_2 from 650,000 to 800,000 years ago [18], questioning the stability of the strong Antarctic temperature – carbon cycle coupling on long time scales, and in contradiction with earlier hypotheses of a long term decreasing trend of CO_2. (e.g., [21]).

The scientific need to extend ice cores records back in time

A key international challenge is now to place the past 800,000 years of climate variability of the EPICA Dome C record in the broader context of the past 2 million years (Myr). Marine records [16] evidence a dramatic reorganisation of the pattern of climate variability taking place around 1 Myr ago, with a shift from the «obliquity world» characterized by 40,000-year weak glacial-interglacial cycles to the «100,000-year world» with longer and stronger glacial-interglacial cycles (Fig. 1). The reasons for this major climate reorganization (the «Mid Pleistocene Transition», MPT) remain unknown and may be intrinsic to the climate – cryosphere – carbon cycle feedbacks. Two major hypotheses have been raised so far (see [12] for a recent review):

1. *A non-linear ice sheet response to a long term cooling trend* [3]. This long term cooling trend would be driven by a progressive long-term decrease in atmospheric CO_2 concentration. The mechanism behind the non-linear ice sheet response itself could involve the Antarctic ice sheet behaviour [23]. Long term cooling gradually drove the East Antarctic ice sheet margin into the sea, changing the behaviour of the Antarctic ice sheet from a terrestrial ice sheet (ablation driven by melt) to a marine ice sheet (ablation driven by calving). Another mechanism could be related with the merging of continental North American ice sheets, below a certain northern hemisphere temperature threshold [4]. Finally, non-linear

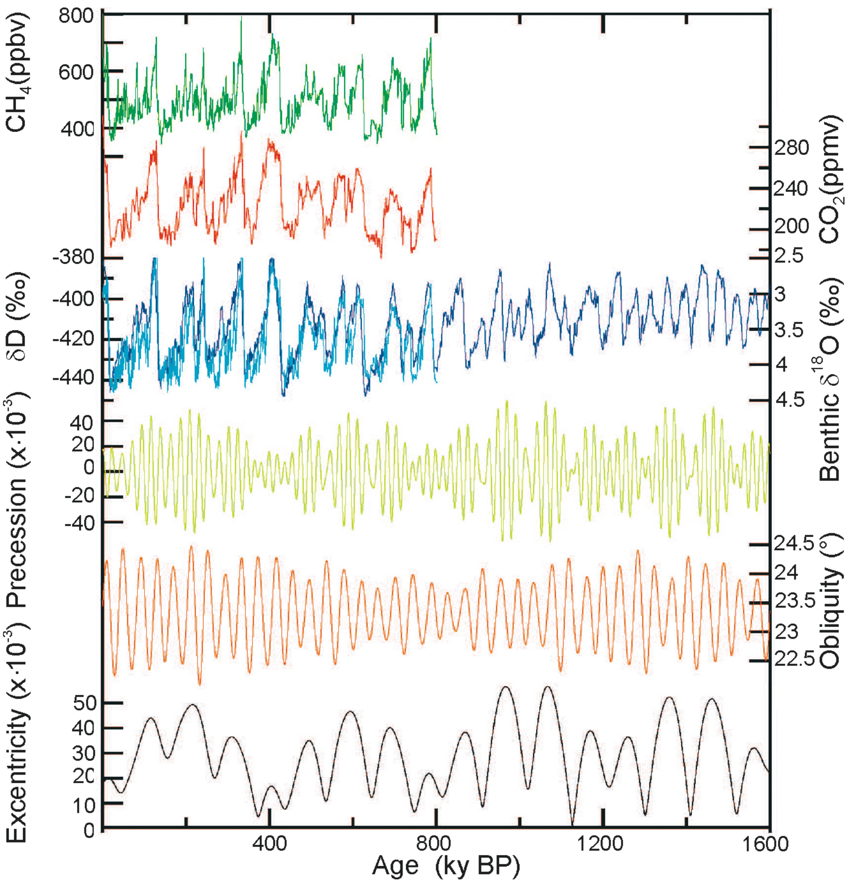

Fig. 1. Antarctic records of the EPICA Dome C δD (light blue, ‰) [11], a proxy of Antarctic temperature, and a stack of Vostok and EPICA Dome C atmospheric CO_2 (red, ppmv) [18–22] and Dome C CH_4 concentrations (green, ppbv) [17] spanning the past 800,000 years.

The horizontal time scale is expressed in thousands of years. While the southern ocean should play a major role on glacial-interglacial CO_2 variations, changes in CH_4 may be mostly controlled by changes in wetlands and therefore northern hemisphere continental climate. For comparison, marine records of changes in benthic $\delta^{18}O$ reflecting variations in global ice volume are displayed (dark blue, ‰) [16] as well as the Earth's orbital parameters (yellow – precession; orange – obliquity, black – eccentricity) [2]. Note the strong similarities between variations in central Antarctic temperature and global ice volume records, and the long-term trend in benthic $\delta^{18}O$ combined with a change of periodicity around 1 Myr ago, shortly before the EPICA record stops.

Рис. 1. Временно́й ряд δD, полученный по керну проекта EPICA на Куполе C (голубая линия, ‰) [11] и отражающий изменение температуры; сводная кривая концентрации атмосферного CO_2, построенная по данным кернов Востока и EPICA (красная линия, 10^{-6} объёмная концентрация) [18–22]; кривая концентрации атмосферного CH_4 по данным керна EPICA (зелёная линия, 10^{-9} объёмная концентрация) [17].

Возраст льда на горизонтальной оси дан в тыс. лет. Изменения CO_2 при переходе от ледниковых к межледниковым периодам во многом контролируются процессами, протекающими в океанах Южного полушария, а изменения CH_4 – процессами на заболоченных территориях и, следовательно, больше связаны с континентальным климатом Северного полушария. Для сравнения показаны: кривая $\delta^{18}O$ по бентосным фораминиферам в морских колонках, отражающая изменение объёма континентального льда (синяя линия, ‰) [16]; изменения орбитальных параметров Земли: (жёлтая линия – прецессия, оранжевая – наклон земной оси, чёрная – эксцентриситет) [2]. Отмечается хорошая согласованность между вариациями температуры в центральных районах Антарктиды и изменениями объёма континентального льда на Земле. Хорошо виден тренд в изменении $\delta^{18}O$ в морских колонках, а также смена характерных периодов вариаций примерно 1 млн лет назад, незадолго до того, как заканчивается палеоклиматический ряд, полученный по керну EPICA

processes in sea ice variations [26], changing the relationship between atmospheric temperature and the rate of accumulation and ablation of continental ice sheets, could also have played a role.

2. *Changes in subglacial conditions that influence ice dynamics* [6]. Geological observations reveal that the earliest northern hemisphere ice sheets had comparable extent but smaller volume before the MPT than after the MPT. Around the MPT, the crystalline Precambrian Shield bedrock became exposed by progressive glacial erosion, providing a higher friction substrate that enabled thicker ice sheet buildup and modified its response to orbital forcing.

The different formulated hypotheses to explain the MPT imply different amplitude and phase lags between orbital parameters, ice volume, climate at different latitudes and atmospheric CO_2 concentrations. Obtaining continuous records of Antarctic temperature and accurate atmospheric composition (with higher resolution and accuracy than estimates from marine core boron isotopes for paleo-CO_2 (e.g., [9]) back to the pre-MPT era is therefore essential to test the existing theories and to develop a data-based understanding of the last major Quaternary climate transition [12]. This urges us to obtain longer ice core records of Antarctic climate and global greenhouse gases.

The International Partnerships in Ice Core Sciences (IPICS), an international strategic programme gathering 25 nations and supported by IGBP/PAGES and SCAR, has identified for the next decade this major challenge: obtaining replicate Antarctic ice core climate and atmospheric composition records at least 1.5 Myr back in time. This requires:

1. To model the ice flow in order to identify the best locations where to find undisturbed records of climate back to 1.5 Myr, i.e. places with very low accumulation rate, simple ice flow regime, and sufficient ice thickness. This goal is currently being addressed by several international teams, using new data obtained during the International Polar Year 2007–2009.

2. To qualify the right location for deep drilling through radar data interpretation and *in situ* depth profiles of key climate variables.

Today, deep drilling operations are heavy and expensive: temporary camps to house ~30 drillers and scientists for several summer field seasons, transportation of tens of tons of drilling equipment including drilling fluids. The progress of deep drilling is at best 1 km/year, therefore requiring at least three drilling seasons plus one preparation season to retrieve ice cores down to bedrock. The logistical costs alone for a Greenland deep drilling (like NEEM) is ~6 to 7 M€, and was ~20 M€ for the Antarctic EPICA Dome C one. Moreover, recent experiences at several deep drilling locations have revealed (i) the importance of local bedrock conditions (local geothermal heat flux, temperature, presence of liquid water) for the preservation of old ice (NGRIP, EDML); (ii) the possibility of disturbed ice stratigraphy near complex subglacial topography (GRIP, GISP2); (iii) the possibility of highly inclined layers preventing the access to very old ice (Dome Fuji).

Despite intense ice flow modelling and improved radar surveys (including with phase-sensitive radars) of basal conditions, uncertainties regarding undisturbed segments (and more importantly their age, hardly accessible with radar profiles for times older than the EPICA ice core) of very old and deep ice remain large, and the selection of the precise deep drilling location is a high risk and costly operation. Therefore, there is a need to invent new, fast and economical approaches for qualifying potential oldest ice sites, before the following steps of deep drilling operations.

Unconventional methodology to probe the oldest ice

Our project relies on inventing, constructing, testing and implementing in Antarctica an *in situ* probe to evaluate, within a single season in Antarctica (instead of four with conventional ice core drilling), the suitability of a target site to recover ice as old as 1.5 Myr. The probe will be a true technological revolution in ice core and ice probing science, at the frontier between laser physics and ice penetrating technologies and system integration. The probe will make its own way into the ice – in an energy efficient manner – and, relying on the innovative OFCEAS laser technology patented by laser physicists at the University of Grenoble, France, it will measure in real time and down to bedrock the depth profiles of the ice δD water isotopic ratio, the trapped gas CH_4 concentration, as well as other gas signals (CO_2, possibly N_2O).

The δD of the melted ice will deliver the baseline climatic signal in the deep ice. Its evolution with depth will allow us to differentiate ice corresponding to interglacial or glacial conditions, to basically «count» the climatic cycles back in time, and to compare them to marine reference records (e.g., [16]). Atmospheric CH_4 shows large changes between glacial and interglacial states (typically from 350 to 800 ppbv). It is an indirect tracer of northern hemisphere climate. Being recorded in trapped bubbles and clathrates, its changes are shifted with depth compared with concomitant climatic changes recorded in δD of H_2O, due to firnification processes. The observation of such a depth shift makes a primary indicator that the ice layers are still in good stratigraphic order [5]. Therefore, with precise measurements of ice δD and CH_4, but also with the CO_2 acquisition, we will already obtain three essential pieces of information during ice probing: (1) the time span of the ice sheet, (2) the integrity of the ice record, and (3) key climate and atmospheric composition signals back to the oldest time ever. The probe accuracy will be sufficient to characterize glacial-interglacial but also millennial-scale variations, and to document the sequence of events.

CO_2 measurements with the probe could be affected by chemical artefacts and solubility effects during gas extraction. However Kawamura et al [13] obtained very good CO_2 results with a wet extraction technique on the Dome Fuji ice core, thanks to the associated very short contact time between gas and water. The CO_2 values obtained with the probe could thus be useful at least on a relative scale. The probe (Fig. 2) requires developing several new unconventional technologies, expressed below as individual tasks.

General design. The drill/probe will be made of (i) an electromechanical drill head, a chip mixing and transfer device, (ii) a thermal head in front of the electromechanical head, linked with a small pump and a pressure resistant casing containing a membrane separation device, and the OFCEAS laser spectrometer and electronics, (iii) an anti-torque device, and (iv) a suspension part, a cable connection and a flexible hosepipe for drill fluid circulation, power, and data communication. The thermal drill will be made of a heated element, extending ~50 cm below the electromechanical component and melting ~10% of the hole diameter. This design will ensure that the very front part of the drill head will not be contaminated with the drilling fluid (water is denser). The produced clean water and extracted gases will then be transferred to a custom-made separation membrane and the OFCEAS system. Approximately 90% of the drill hole will be machined by the electromechanical head above the thermal head, and the produced chips will be mixed with the drilling fluid and released in the borehole for subsequent ascent toward the surface.

Handling the probe chips and fluid. Deep ice drilling operations require filling the borehole with a fluid, in order to compensate the hydrostatic ice pressure at large depths [25]. Using for that purpose the melt water produced from an electrothermal drill requires too much power to keep it above the freezing point. Another option is to produce a film of liquid water around the conductor cable [24]. We also reject this option due to the too high voltages required to dissipate ~150 kW of energy along 4000 m of cable and to bring ~20 kW to the drill head. Our proposed solution (90% electromechanical drilling and 10% thermal drilling) is innovative and energy efficient. The main technical difficulty lies in continuously evacuating the drill chips, and in the associated drilling liquid. Recent European drilling projects used a mixture of an oil product similar to kerosene (density of ~850 kg/m^3 at −30 °C), with HCFC-141b (density of 1325 kg/m^3 at −30 °C), to be close to the mean ice density.

For our project, the drill fluid should (i) easily carry the ice chips (with a typical mixture of 4% chips and 96% fluid)

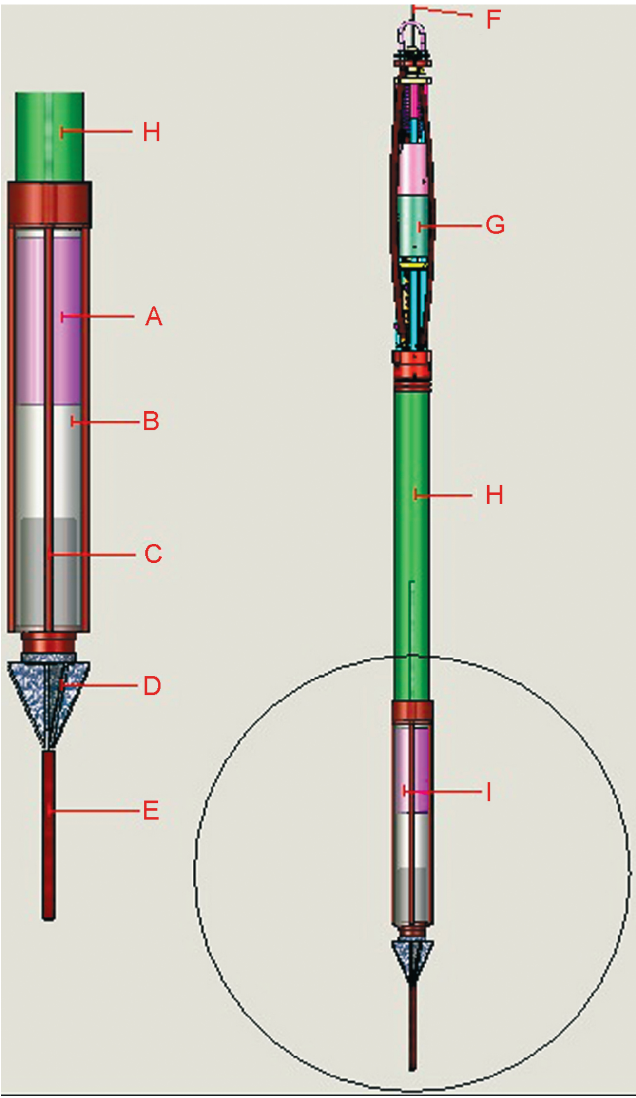

Fig. 2. Structure of the drill/probe (endless screw and chip reservoir not shown here). A – electronic section; B – electric motor and gear box (both including a hollow shaft); C – pipes carrying the drilling fluid on the drill head; D – electromechanical destructive drill head; E – heated pipe melting 10% of the hole diameter (which will be analyzed); F – hosepipe carrying fluid, electric power and data communication between the drill and the surface; G – anti-torque section; H – embedded OFCEAS laser spectrometer; I – pipe carrying the melted ice and released gases to the spectrometer, after membrane separation

Рис. 2. Конструкция бура-зонда (шнек и шламосборник на рисунке не показаны):
A – электронный блок; B – электрический мотор и редуктор с валом, имеющим осевое отверстие; C – трубки, по которым поступает буровая жидкость к коронке снаряда; D – электромеханическая режущая коронка; E – подогреваемая трубка, выплавляющая 10% полного диаметра скважины (талая вода анализируется); F – шланг, по которому доставляется буровая жидкость, передаётся электроэнергия и информация от анализатора на поверхность; G – распор, предотвращающий вращение снаряда в скважине; H – встроенный лазерный анализатор, использующий технологию OFCEAS спектрометрии; I – трубка, по которой талая вода и отсепарированные мембраной газы поступают в анализатор

through the annulus space between the probe and the borehole and then into the borehole, without clogging, (ii) be liquid at −55 °C and have a kinematic viscosity lower than 10^{-6} to 10^{-5} m^2s^{-1} at these low temperatures, for reasonable pressure loss, (iii) compensate at least partly the ice hydrostatic pressure with depth, to prevent borehole closure, (iv) be relatively cheap, as several tens of m^3 will be required during the probing campaign, (v) be in compliance with the Antarctic Treaty Environmental Protection recommendations.

Fluid/chip mixture tests are currently carried out in LGGE cold rooms between −10 °C and −50 °C, following our experience for European drilling operations [1]. Among the tests, we considered the possibility to use an embedded cavity pump technology (Moineau pump), successfully tested by the French petroleum company Schlumberger in light rock drillings. Our preliminary calculations, based on a probe penetration speed of 1 mm/s, showed that a cavity pump of ~1.1 kW could handle a fluid/chip mixture flow of ~1.4 m^3/h and a hydraulic head of 330 m. But, it turns out that the mechanical tolerance between the rotor and stator of such a pump are too tight to accommodate the temperature changes along the ice thickness to be drilled. We will thus use a surface pump, sending clean drilling fluid through a hosepipe connected to the probe in the borehole. The fluid/chip mixture will then raise toward the surface along the borehole and the leak-tight casing in the firn, and it will be recovered at the surface and then sent into a shaker tank where the chips and drilling fluid will be separated, the cleaned drilling fluid then being re-injected into the hosepipe.

Miniaturizing an OFCEAS laser spectrometer. One of the major innovative concepts of the project is to use a ground-breaking technology recently developed by a CNRS research unit in Grenoble (LIPhy): Optical-Feedback Cavity-Enhanced Absorption Spectroscopy (OFCEAS).

Traditionally, water isotopes (the climate signal) in ice cores are measured using isotopic-ratio magnetic-sector mass spectrometers (irMS), a method incompatible with *in situ* measurements due to instrument size. For greenhouse gas measurements, gas chromatography (GC) is the most common method. CO_2 can also be measured by laser spectroscopy (e.g., [18]). Commercial laser detectors based on Cavity Ring Down Spectroscopy (CRDS) present a new way to acquire H_2O isotopes and the mixing ratio of some trace gases in air, within minutes instead of hours of laboratory work. In CRDS, the laser light enters an optical cavity filled with the sample gas and formed by two (sometimes three) highly reflective dielectric mirrors. Following an abrupt switching-off of the laser light, the exponential decay time of the light intensity exiting the cavity is measured. With good mirrors, a decay time of several tens of μs is easily achieved, providing an effective path length of several km. Using a laser diode in the 1.4 to 5 μm spectral region, CRDS provides high molecular selectivity and impressive sensitivity on small samples (tens of cm^3 of air with nmoles of the gas of interest).

Several derivatives of the CRDS technique exist. Off-Axis Integrated Cavity Output Spectroscopy (OA-ICOS), sold by Los Gatos Research (USA), is perhaps the simplest one to implement, and has so far shown the highest sensitivity [7]. But it requires large diameter mirrors, and thus a large volume gas cell (~100 times larger than that of other CRDS techniques). This is not compatible with an ice probe and the small amount of gas trapped in the ice. OA-ICOS also suffers from a low light throughput, requiring highly sensitive detectors and low-noise electronics.

CRDS can also be implemented as Wavelength Scanned CRDS (WS-CRDS). Similar to OA-ICOS, it lacks a built-in wavelength monitor, required to construct a reliable, linear frequency scale with the recorded spectra. This is a must if one wants to make absolute concentration measurements without frequent in-situ calibration with reference gases. The version sold by Picarro (USA) includes a proprietary wavelength monitor, increasing cost and complexity. Danish colleagues have successfully implemented in the field a Picarro instrument downstream from continuous-flow methods on the NEEM ice core, and obtained high-resolution records of $\delta^{18}O$ of H_2O in a less tedious manner than with an irMS. However, both WS-CRDS and OA-ICOS are not compatible with the compact design required for a spectrometer to be integrated in our small diameter ice probe.

The technique that we will use, OFCEAS, provides this and other advantages. It is a derivative of CRDS and a patented development of CNRS/LIPhy [19]. OFCEAS sets itself apart by providing a nearly perfect linear frequency scale (it samples the spectra at frequencies equidistantly spaced by the cavity free spectral range). It also solves the problem of light injection into one of the very narrow cavity transmission modes, a common problem of the other CRDS techniques. Light returning from a cavity mode to the laser source (the «optical feedback»), forces the laser emission to narrow down to below the cavity mode width and to become locked to its frequency even during laser tuning. The cavity has a very small volume (12 cm^3, i.e. 3 (100) times smaller than in a Picarro (Los Gatos Research) instrument. The optical head can be designed to fit in the narrow diameter cylinder of our probe. It provides outstanding sensitivity with less than 50 mbar of absolute sample pressure in the cavity, thus being able to resolve concentration changes on ~0.5 cm^3 STP of gas (the amount trapped in 5 grams of ice) passing through it. OFCEAS has already been field-tested for atmospheric CH_4 concentrations and H_2O isotopic ratios, and for a number of other signals like CO concentration and CO_2 isotopes. The performances of the water isotopologue OFCEAS spectrometer was demonstrated in the extreme case of measurements on-board stratospheric airplanes [10–15].

The cylindrical probe will have an inner probe external diameter of maximum 100 mm (excluding the external endless screw for the chips), leaving 60 to 80 mm of diameter for the laser system. We will build an OFCEAS spectrometer where the laser beams outside the optical cavity (gas cell) are not folded back along the side of the cavity (as in laboratory OFCEAS), but instead remain at their respective ends of the cavity (Fig. 3). This results in a considerable decrease of the lateral dimension of the spectrometer.

The OFCEAS will operate one laser in the 2.4 μm spectral region where CH_4 lines can be selected that absorb one order of magnitude stronger than the line used in previous devices, while suitable H_2O isotopologue lines have also been identified. A similar OFCEAS water vapour isotope ratio spectrometer was successfully operated on the NASA DC-8 research aircraft in 2004 [15], and on the European Geophysica high-altitude airplane. Operating near 1.4 μm and with high H_2O vapour mixing ratios similar to the ice probe configuration, the 1σ precision for δD was better than ~1 ‰ for a 20 s averaging time [10]. Considering the line strengths at the 1.4 and 2.4 μm wavelengths, the same precision for δD can be expected at 2.4 μm. Both the concentration and the isotope ratio measurements are temperature sensitive: a few ‰ per K for the relative precision of the concentration measurement and in the δD value [14]. Therefore, the instrument will be controlled to an absolute temperature stability of better than 0.1 K. We aim at providing a probe precision of typically 1 ppbv over 10 s measure-

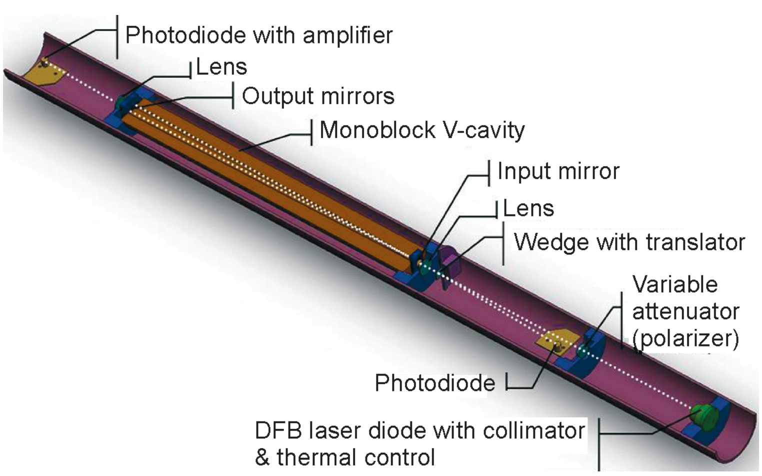

Fig. 3. General layout of the embedded OFCEAS spectrometer.
The overall length will be ~1200 mm, the diameter will be kept below 70 mm

Рис. 3. Общая схема встроенного OFCEAS спектрометра.
Максимальная длина – примерно 1200 мм, диаметр – меньше 70 мм

ment time for CH_4, and of ~1 ‰ for δD of H_2O, i.e. a ratio between the glacial-interglacial signal and the OFCEAS precision of more than 300 for CH_4, and of ~80 for δD of H_2O.

Sample handling from the ice to the instrument. The water and gas fluxes from melted ice must be sampled at a constant flow towards the OFCEAS spectrometer. As water must be introduced in the optical cavity in the form of H_2O vapour for isotopic measurements, an intermediate device is required (i) to separate the gases from bulk water, and (ii) to vaporize part of the water flow before introduction in the cavity. The bulk gas flow will be separated from water by membrane diffusion. Depending on membrane characteristics, a variable amount of water vapour will permeate as well and will directly be used for OFCEAS isotopic measurements. Membrane selection will require to avoid H_2O isotopes and trace-gas fractionation. We plan to use a metal-structured silicone membrane to handle the large pressure gradient (up to 400 bars), similar to those used in commercial instruments for measuring dissolved gases in the oceans (e.g., Los Gatos Research and Contros GmbH).

Instrument integration in the probe. The OFCEAS spectrometer requires very stable temperature conditions (with a target value of ~15 °C) and stable mechanical conditions (no deformation, no vibration). In order to obtain a 1 ‰ accuracy on δD, the gas cell temperature must be stabilized to better than 0.1 K. The OFCEAS outer mechanical support tube (probably in copper alloy for temperature stabilization) will be designed according to structural simulations for mechanical stability, and for handling a constant inner pressure of 10^5 Pa. The relatively high density of copper will provide inertia, to cutoff low frequency (~10 Hz) vibrations produced by mechanical drilling, in addition to the compensation through active stabilization of the laser-cavity distance inside the OFCEAS setup (bandpass at 100 Hz). Calibrated elastomers will stabilize the instrument against the internal probe walls. Together with insulation through cryogel or vacuum (thermal conductivity lower than 0.015 W/m·K), internal heaters providing up to 80 W will be driven by a control loop, to keep the inner tube temperature at 10 °C within a ~1 K variability. This first thermal control will eliminate most of the external temperature variations (from −50 °C to −4 °C). A second thermal control system will be applied on the spectrometer tube, to stabilize it at slightly larger temperature (15 °C) with a precision and long term stability better than 0.1 K.

Discussions

The in-situ probe project clearly belongs to the high gain/high risk category. Several technological constraints must be circumvented. Among them, handling the fluid/chip mixture is probably the most difficult, as failure to do it properly will mean to loose the probe in the borehole due to the risk of chip clogging. Therefore it will be critical to test different fluid/chip mixtures and to determine their behavior not only in cold room conditions but also in the field with tests along a thick firn/ice column. Sample handling will be critical as well from the melt finger to the OFCEAS cavity, as one must avoid contamination of the cavity by the drilling fluid, as well as water vapor saturation, which would result in condensation and loss of mirror reflectivity. Other notable technical difficulties concern (1) the temperature control of the instrument in a large temperature gradient (from −50 °C at the surface to −4 °C at the bottom part of the ice sheet), (2) communication between the probe and the surface, as a large bandwidth is required to provide enough control parameters of the probe behavior and quality of the measurements, (3) the overall weight and season duration for setting up the system at key sites in Antarctica.

Regarding the latter, one aims at reaching bedrock and then recovering the probe at the surface within typically two months maximum in the field in Antarctica. Building and dismantling the camp and setting up the probe system should take two weeks maximum, leading altogether to the full use of the maximum field duration allowable on the East Antarctic plateau during a single season. Although we expect to deploy the probe first at sites in the immediate vicinity of the main inland stations (Concordia, Vostok, South Pole, Kohnen, Dome A, Dome Fuji), the full equipment should be transportable by relatively light traverse means or using standard aircrafts such as a Twin-Otter or a Basler. One of the key parameters defining the logistic constraints of the system is the probe and borehole diameter, the drilling fluid volume being proportional to the borehole squared radius. For instance a 130 mm borehole diameter over 3000 m of thickness requires nearly 40 tons of drilling fluid, i.e. a full sledge of a traverse.

There could be other – possibly simpler – ways to access the deepest part of the East Antarctic ice sheet with hopes to qualify the site for its stratigraphic integrity and time span. Rapid access drilling (hot water for instance), followed by borehole logging with measurements of the ice electric properties or of the dust concentration, belongs to the promising solutions. But there is a major drawback: the succession of maxima and minima in such parameters could either reflect the succession of glacial-interglacial cycles, or the presence of folding. Only by comparing a in-situ measured parameter with comparable signals from, e.g., the marine realm will provide the level of confidence required to setup a multi-year deep ice core drilling operation at the same site afterwards. Our measurements of water isotopes and CH_4 concentration do satisfy this criterion.

In addition, the probe design and implementation are not a «one shot» programme only focusing on the IPICS oldest ice challenge. The probe deployment in critical areas of fast ice stream glaciers could help for instance to provide a depth-age scale and to constrain the glaciological models. Its use in the Southern part of the Greenland ice sheet could help to determine how far the land ice extended during the last interglacial period. Lastly, probing glacier ice will probably prove to be more challenging than probing the world oceans. Therefore, an evolution of the probe design for monitoring dissolved trace gases in marine waters could be one of the major outcomes of our project.

Conclusion and outlook

The IPICS oldest ice challenge requires the ice core community to invent new ways of ensuring that a deep drilling operation will be worth trying at a given pre-selected spot of the East Antarctic plateau. Our project aims at providing such invention, by substituting traditional ice core drilling by in-situ probing of glacier ice and real-time measurements of the water isotopic composition and greenhouse gas concentration. Progresses in laser technology makes now possible to embed a laser spectrometer – based on OFCEAS technology – in a probe making its own way into the ice sheet. Several technical challenges need to be circumvented, notably how to handle the ice chips produced by the electromechanical drill head. We are confident that this high gain / high risk project will lead to several major advances in technologies associated with glaciological investigations. The Antarctic seasons 2015/16 and 2016/17 will tell us if we have been successful.

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Поиск древнейшего льда для палеоклиматических исследований: новая технология верификации перспективности выбранных пунктов бурения

Многочисленные результаты исследований колонок морских донных осадков свидетельствуют, что примерно 1 млн лет назад произошло изменение моды глобальных осцилляций климата, которое заключалось в переходе от 40-тысячелетней периодичности в смене ледниковых и межледниковых эпох к 100-тысячелетней с более амплитудными и продолжительными климатическими колебаниями. Причины, которые в середине плейстоцена привели к перестройке климатической системы планеты (в англоязычной литературе – Mid Pleistocene Transition – MPT), остаются неизвестными и обусловлены природой малоизученных обратных связей между климатом, криосферой и углеродным циклом. Одна из наиболее общепринятых гипотез объясняет MPT нелинейной реакцией ледниковых покровов на медленное продолжительное похолодание климата, вызванное постепенным понижением концентрации CO_2 в атмосфере Земли. Этой гипотезе противоречат данные исследований ледяного керна, полученного в рамках проекта EPICA на Куполе С (Антарктида), которые показали, что, по крайней мере, в период 800–650 тыс. лет назад концентрация CO_2 была ниже, чем в последующую эпоху. С решением проблемы MPT в настоящее время связывают прогресс в понимании роли углеродного цикла в глобальных климатических изменениях. Необходимое условие для решения этой проблемы – получение количественных данных об изменении климата и газового состава атмосферы за последние 1,5–2 млн лет. Такие данные могут быть получены по ледяным кернам Восточной Антарктиды.

Координационный комитет программы Международное партнерство в изучении ледяных кернов (International Partnerships in Ice Core Sciences – IPICS), созданный под эгидой IGBP/PAGES и Научного комитета по исследованию Антарктики (SCAR) и состоящий из представителей 25 стран, назвал наиболее приоритетной на ближайшее десятилетие задачей – получение ледяного керна, который бы позволил реконструировать изменения климата и концентрации парниковых газов за последние 1,5 млн лет. Первый этап этого проекта, который стартовал в период МПГ (2007–2008 гг.), состоит в определении мест, перспективных для бурения с целью получения древнейшего на Земле льда.

В нашей работе предложен новый подход к решению проблемы верификации перспективности выбранных пунктов бурения для получения керна льда необходимого возраста с ненарушенной стратиграфией. Разработана принципиальная схема зонда, способного пройти антарктический ледниковый покров до основания в течение одного летнего полевого сезона, продолжительностью 2–2,5 мес. Зонд имеет встроенный лазерный анализатор, который по мере погружения снаряда измеряет основные характеристики льда, содержащие палеоклиматическую информацию, – изотопный состав (δD), концентрацию метана, а в перспективе – ряд других парниковых газов (CO_2, N_2O). Бурение скважины выполняется механическим и тепловым способами. Тепловая буровая коронка, разрушающая 10% объёма ледяной породы, расположена в 50 см ниже режущей коронки, что обеспечивает чистоту талой воды, которая используется для анализа. Расположенная выше режущая коронка разрушает оставшиеся 90% породы. Шлам, образующийся в результате резания льда, смешивается с буровым раствором, находящимся в скважине, и поднимается к устью скважины помпой, установленной на поверхности. На поверхности шлам отделяется от буровой жидкости, которая затем поступает обратно в скважину. Проектная скорость бурения составляет 1 мм $с^{-1}$. Внешний диаметр зонда – 100 мм, внутренний – 60–80 мм. Внутри зонда размещается лазерный анализатор, принцип действия которого основан на новейшей OFCEAS-технологии (Optical-Feedback Cavity-Enhanced Absorption Spectroscopy). Анализатор измеряет изотопный состав проходящих через него паров воды и концентрацию отделённых от воды газов каждые 10 с, что позволяет получать данные с достаточно высоким разрешением по глубине и возрасту льда. Точность измерения составляет 10^{-9} для объёмной концентрации CH_4 и 1 ‰ для δD, что вполне достаточно для надёжной идентификации не только климатических переходов от ледниковых условий к межледниковым, но и более мелких климатических вариаций. Испытания зонда в полевых условиях планируется провести в летние антарктические сезоны 2015/16 и 2016/17 гг.