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Design Details of FOCS-2, an Improved Continuous Cesium Fountain Frequency Standard

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Abstract—We report on the design, construction and current status of FOCS-2, the second continuous fountain microwave cesium frequency standard after FOCS-1. Both incorporate velocity-selective light traps driven by an electrostatic motor. FOCS-2 will take fuller advantage of the continuous fountain approach to gain in shot-noise-limited stability without loss of accuracy via the use of a higher flux. This is obtained via the implementation of a novel slow-atom pre-source and better collimation of the atomic beam. A detailed description of the apparatus is provided and compared with FOCS-1 to highlight improvements. In addition, we present results from related experiments on collimation in a 2D optical lattice. The goals for this new standard are a short-term stability of $< 4 \times 10^{-14} \tau^{-1/2}$ and a relative frequency uncertainty of $< 1 \times 10^{-15}$.

I. INTRODUCTION

The best current realizations of the S.I. second are atomic fountain clocks [1] about a dozen of which are in operation world wide with a similar number under construction. They can yield long-term stabilities characterized by a relative Allan deviation of typically a few times 10^{-16} while the accuracy frequently reported is better than 1×10^{-15} . Indeed, the accuracy of some cesium fountain clocks might one day reach $(1 \text{ to } 2) \times 10^{-16}$ [2].

A. Why use a continuous fountain?

Though their designs and the methods of metrological evaluation employed vary somewhat, all but two of existing fountain clocks are based on an identical principle of sequential capture, launch, interrogation and detection of atoms in a vertical flight. The use of dense packets of atoms ($\approx 10^8 \text{ cm}^{-3}$) leads to a trade-off between stability and accuracy, as a result of a collisional frequency shift ($-2 \times 10^{-21} (\text{at}/\text{cm}^{-3})^{-1}$) [3], [4], [5]. The pulsed nature of the microwave interrogation process usually degrades the stability due to the intermodulation (or Dick) effect resulting from down-conversion of the local oscillator phase noise in the modulation-demodulation scheme used to generate the servo error signal [6], [7], [8]. This limitation can be overcome if one employs a very low noise local oscillator such as a cryogenic compensated sapphire resonator [9] though these lie beyond the resources of most standards laboratories. Juggling or multi-ball fountains [10], [11] are an intermediate alternative between pulsed and continuous standards both in

terms of intermodulation and density-related frequency shifts. As predicted several years ago [7] and demonstrated recently by our group [12], [13], continuous fountains, allow almost complete suppression of intermodulation effects even when one uses a commercial quartz local oscillator. At the same time, because one requires a hundred-fold lower atomic flux to obtain the same signal-to-noise ratio as in pulsed fountains, collisional frequency shifts are much smaller. Indeed, they might even be 1000 times less owing to the higher longitudinal temperature inherent to continuous fountains ($75 \mu\text{K}$ instead of $\approx 2 \mu\text{K}$) that provides an extra suppression factor [14]. This leaves scope for one to increase the atomic flux and therefore gain in stability without notable loss of accuracy. Equally important from a metrological standpoint is the different relative weight of contributions to the uncertainty budget for a continuous fountain clock [15] compared with a pulsed one.

B. Challenges

Continuous fountain clocks provide more of a challenge to experimentalists than do their pulsed counterparts, for several reasons. Because of the need for simultaneous capture, cooling and launch of atoms, there is a compromise between flux and transverse temperature of the moving optical molasses, typically $60 \mu\text{K}$, so additional transverse cooling is required. The atomic trajectory must be parabolic so that the launch and detection phases are isolated from each other. This requires a different design of microwave resonator and imposes a tight geometrical constraint on the range of heights to which atoms can be launched without loss of flux. Consequently, one cannot map the magnetic field present in the interaction region in a straightforward way. It is however possible to use the symmetry and contrast of the Ramsey pattern of the linearly field dependent transitions ($m_F \neq 0$) to extract a value for B and B^2 , both averaged over the atomic trajectory to correct for the quadratic Zeeman shift at the $10 - -16$ level [15]. Selection of an initial population of atoms in $F=3, m_F=0$ or $F=4, m_F=0$ is harder to achieve, which often leads to a background on the signal of detected atoms after Ramsey interrogation. Finally, in a continuous fountain, atoms undergoing microwave interrogation must be shielded from fluorescence from the source which is necessarily ever present.

C. Swiss continuous fountain clocks

Over the past decade, our group has pioneered the continuous fountain approach. This work was initiated in a collaboration between the Federal Office of Metrology METAS and the Observatoire cantonal de Neuchâtel, Switzerland. It continues as a joint effort between METAS and the Laboratoire Temps et Fréquence of the University of Neuchâtel (LTF-IMT). The design and construction of the continuous cesium fountain clock FOCS-1 was first described at EFTF1999 [16]. In 2003, this standard was transferred to METAS where its metrological evaluation is still in progress. At the same time, the construction of a second, improved clock FOCS-2 was begun in Neuchâtel. Its aim is to take fuller advantage of the continuous fountain approach by using an atomic flux in the $m_F=0$ state 40-1000 times higher. To achieve this, more atoms are launched to begin with thanks to a slow beam pre-source that loads the optical molasses [17], [18]. In addition, improved collimation based on optical lattices [19], [20], [21] means more atoms reach the detection zone after microwave interrogation. The design of FOCS-2 was inspired by experience acquired with FOCS-1 as well as input from auxiliary measurements performed on an experimental fountain dubbed FOCS-X that demonstrated an achievable gain in flux of at least 40. Given the shot-noise-limited stability of FOCS-1 is $2 \times 10^{-13} \tau^{-1/2}$ [12], that of FOCS-2 should be $< 4 \times 10^{-14} \tau^{-1/2}$. Since March 2006, FOCS-2 has been installed at METAS. The present article describes it in detail for the first time and includes results from pilot experiments.

II. OVERVIEW OF FOCS-2

A section through the apparatus is shown in Fig. 1. The vacuum chamber consists of two regions, a lower section for the capture, launch and detection of atoms, and an upper cylindrical volume containing the microwave cavity. Both are evacuated to $\leq 2 \times 10^{-9}$ mbar by a 75 l/s ion pump located at the bottom of the apparatus (absent from the figure). The chambers are made from aluminium alloy and to save space, window and ports are attached using indium seals. A slow (20 ms^{-1}) atomic beam from a pre-source is used to load a 3D optical molasses formed by three pairs of counter-propagating laser beams. The horizontal beam (x -direction) is reflected from a gold-coated prism that acts as a half-wave plate (for the definition of the axes *cf.* Fig. 4. Its frequency lies 12 MHz below resonance with the $6s \ ^2S_{1/2} \ F=4 \rightarrow 6p \ ^2P_{3/2} \ F'=5$ component of the D2 line (hereafter 45'). The other four beams lie in the yz plane and are inclined at $\pm 45^\circ$ to the vertical. In this way, no laser beam propagates vertically to perturb the atoms during their flight. We currently use 10 mW per 25 mm diameter beam. A re-pumping laser necessary to maintain the cooling process is tuned to the 34' component of the D2 line. Typically 100 μW are used and the beam is usually superimposed on the $\pm x$ source beams though provision is made for a repumper along the y -axis which is more efficient as demonstrated elsewhere [18]. The atoms are launched by the use of a moving optical molasses whereby the upward-directed beams are de-tuned

by $\Delta\nu \approx 3.2$ MHz above the frequency of the horizontal beam and the downward facing beams the same frequency increment below. In this way the mean vertical velocity of the laser-cooled atoms is $1.2 (\text{ms}^{-1}/\text{MHz}) \Delta\nu = 3.85 \text{ ms}^{-1}$. Previous experiments indicate the isotropic temperature of this source should be 60 μK . To reduce divergence of the atomic beam, a collimation stage is located several centimetres above the source region. Whereas in FOCS-1 an orthogonal pair of 1D optical molasses is employed, FOCS-2 will make use of one or two 2D optical lattices to give a lower transverse temperature ($\leq 3.5 \mu\text{K}$ measured with an experimental fountain (FOCS-X) [20], [21] instead of the 7 μK of FOCS-1) and hence a higher atomic flux. The longitudinal temperature after collimation is estimated to be 75 μK , by comparison with the other continuous fountains. About 1 cm above the second lattice, there is provision for a beam along the y -direction, for instance a "de-pumper" tuned to the 44' component or else a probe tuned to 45' for diagnostics. A rotating light trap [22] (Fig. 6) will be located between the de-pumping and Ramsey interrogation regions. Such a device transmits about 90 % of the atomic flux while attenuating the source light by a factor $\geq 10^4$. The atoms enter the cylindrical volume of the C -field region where they pass twice through the Ramsey microwave cavity in a parabolic flight of height 310 mm, crossing regions separated horizontally by 57 mm in a time of 0.51 s. Three layers of mu-metal around the upper chamber reduce stray magnetic fields to about 1 nT. The atoms re-enter the lower chamber where they are detected by laser-induced fluorescence on the 45' transition. Source and detection regions are separated by a light-tight panel and graphite is used to prevent cesium atoms and light from entering the detection region. In the lower chamber, stray magnetic fields are at present compensated by pairs of Helmholtz coils, later to be reinforced by an outermost mu-metal layer surrounding the whole fountain. More details of various parts of the apparatus are provided below.

III. DETAILED DESCRIPTION OF FOCS-2

While the operating principle of FOCS-1 and FOCS-2 is identical, the fountains differ in many aspects of their detailed design. Because FOCS-2 is a more complex machine, efforts have been made to increase reliability and ease of operation *e.g.* a simpler scheme for generating the laser frequencies, reduced vibrations around the optical table, improved pumping speed of the vacuum chamber and easier access to the rotating light trap.

A. Lasers and optics

All lasers for the experiment are located on a single air-cushioned optical table. Beams are transported to the adjacent fountain via polarization-preserving single-mode optical fibres. The frequency ν_{master} of a master extended-cavity laser diode (ECLD) is locked 160 MHz above the hyperfine component 44' of the D2 line. For this we use a double-pass acousto-optic modulator (AOM) at ν_{AOM} . The RF ν_{AOM} is frequency modulated at 50 kHz. The frequency modulated, shifted optical

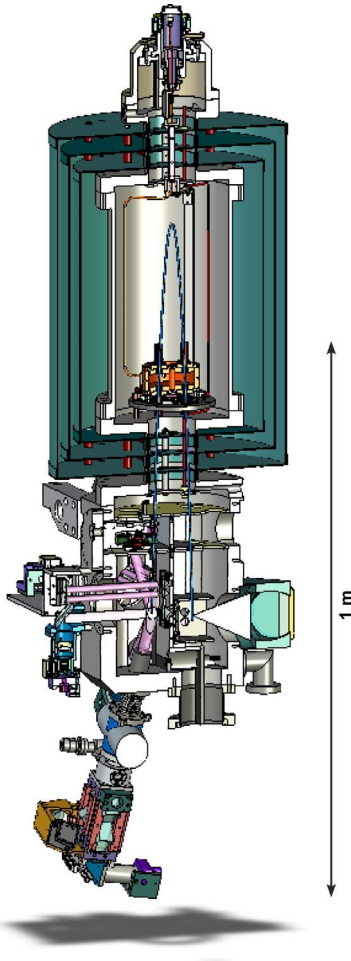


Fig. 1. Cut-away view of the FOCS-2 continuous cesium fountain clock showing the pre-source, the launch collimation and detection module, the parabolic flight of atoms through the microwave cavity (Fig. 8) and the location of the velocity-selective light trap (Fig. 6).

radiation at $\nu_{\text{master}} - 2\nu_{\text{AOM}}$ is sent into a saturated absorption cell to provide an error signal for locking the laser 160 MHz above the $44'$ component, *i.e.* 92 MHz below $45'$.

The main, unmodulated beam of the master laser injects a first tapered amplifier (MOPA1) with about 13 mW giving typically 300 mW at the output. This beam is then trisected, each fraction crossing thereafter a separate AOM. One of these, at 80 MHz, transmits the x -beam shifting its frequency to lie 12 MHz ($2.3 \cdot \Gamma$) below that of the $45'$ transition. A fraction of this beam is split off to seed a second tapered amplifier (MOPA2) that feeds the pre-source. The two remaining AOM's shift the optical frequencies by $80 \text{ MHz} \pm \Delta\nu$. The value of $\Delta\nu$ is selected to produce the launch velocity of $1.2 (\text{ms}^{-1}/\text{MHz}) \Delta\nu$. The re-pumping beams essential to the pre-source and 3D optical molasses are produced by a single Distributed Bragg Reflector (DBR) laser diode whose frequency is servo-locked to the $34'$ component in an optical set-up identical with that of the maser and all other laser diodes. Here, however, the laser current is modulated at 50 kHz to provide the error signal. The probe laser is an ECLD, of

identical design to the master laser. Since, for detection, we wish the laser frequency to lie about $\Gamma/2 \approx 2.7$ MHz below the $45'$ hyperfine component of the D2 line, we use the Zeeman effect of a solenoid wound around the absorption cell. The current in this coil is modulated at 45 kHz to provide a dither (50 kHz is avoided to reduce pick-up in neighbouring servo-electronics). As with FOCS-1, the laboratory temperature is controlled to $(20 \pm 0.1)^\circ \text{C}$ and the optics are protected by a perspex box to minimize draughts.

B. Two-dimensional pre-source

One of the key improvements in FOCS-2 is the use of a 2D magneto-optical trap, slow beam pre-source [17], [18] whose capture in the 3D optical molasses is more efficient than vapour loading. The upshot is a launched atomic flux about 20-fold higher than in FOCS-1. Provided there is no additional technical noise (*e.g.* from frequency fluctuations of the laser used for the pre-source), this flux increase should enable a $\sqrt{20}$ improvement in the shot-noise-limited stability of the fountain clock. The use of a pre-source also minimizes background cesium vapour that degrades under-vacuum optics over time. In the pilot studies performed on the fountain FOCS-X, the pre-source lay in the xz plane and was inclined at 45° . FOCS-2 has been designed to increase the velocity capture range by the use of a more vertical slow beam; the pre-source is attached to a corner of the lower vacuum chamber and the exit beam is inclined at 18° to the plane of the parabola (xz) and at 25° to the yz plane (Fig. 2). This brings the pre-source adjacent to the ion pump that has to be shielded by a 1 mm thick layer of mu-metal to reduce unwanted field gradients below 0.1 G/cm.

C. Three-dimensional moving optical molasses

The geometry of the source from which the fountain is launched is similar to that of FOCS-1 but uses lasers in a $\text{lin} \perp \text{lin}$ polarization rather than $\sigma^+ - \sigma^-$ since this gives about 10 % higher flux. In addition, the collimators contain beam splitters and photodiodes for monitoring of power. The absence of background cesium vapour thanks to the use of the pre-source is evidenced by the loading time of about 1 s where the vacuum is $< 2 \times 10^{-9}$ mbar (Fig 3).

D. Collimation of the atomic beam

In a first instance, the 2D collimation will be achieved by Sisyphus cooling in a single, power-recycling, phase-stable 2D optical lattice [20] (Fig. 4). The laser frequency tuned 160 MHz above the $44'$ component is derived by injection locking a laser diode with a fraction of the output from MOPA1. This scheme has been tested successfully with FOCS-X to form the pre-cooling lattice "A" described shortly below. Other schemes studied with the same apparatus including grey molasses on the $32'$ component [21] and Zeeman-induced degenerate Raman sideband cooling (ZIDRSC) [19], [23]. We also demonstrated the use of 2D magnetically-induced laser cooling as a means to compensate transverse magnetic fields *in situ* [24]. With a single optical lattice "B", ZIDRSC provides temperatures as low as 1.6 μK but only

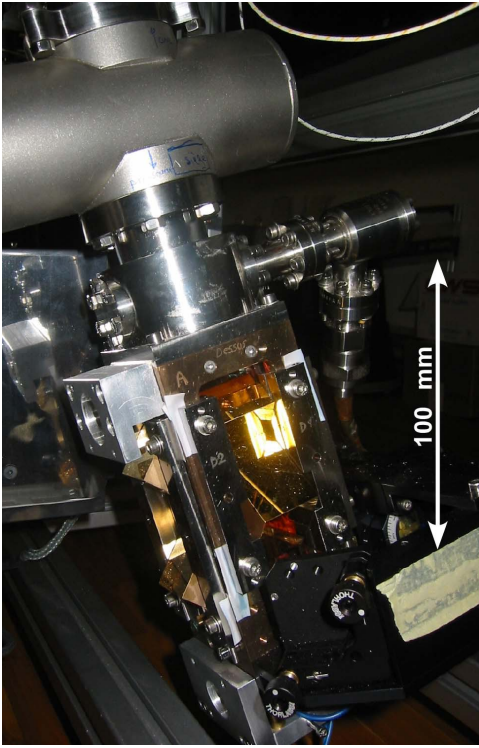


Fig. 2. Photo of the pre-source installed at the base of the FOCS-2 fountain adjacent to the ion pump(left). The gold-coated prisms used to reflect the criss-cross laser beams are clearly visible. The cesium reservoir can be seen on the right of the image. The upper part shows the isolation valve between pre-source and main fountain chamber.

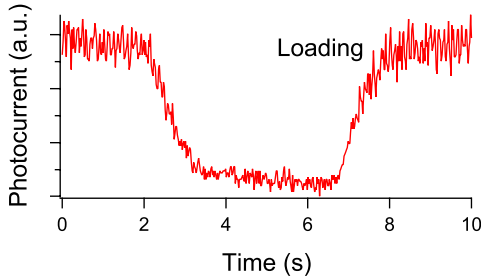


Fig. 3. Absorption of a probe laser beam along y by a static optical molasses in the FOCS-2 source as a function of time following interruption of the pre-source beams. Span=10 s. The loading time constant of about 1 s is compatible with a background pressure of $<2 \times 10^{-9}$ mbar.

$< 10\%$ of the flux is cooled. The addition of a Sisyphus pre-cooling lattice A yields increased flux but a higher temperature ($2.2 \mu\text{K}$) (Fig 5). Whatever the result, however, the atoms are pumped into a magnetically sensitive Zeeman sub-level so efficient transfer to $m_F=0$ would be required [25]. In fact, the proximity of source and collimation stages in FOCS-2 precludes in any case the use of ZIDRSC but the apparatus has been designed with its Stark-induced counterpart [26] in mind. This technique, which works in zero magnetic field, uses the light shift of a near-resonant laser both to create degeneracy of vibrational levels and optical pumping to $F=3$, $m_F=0$. Were the method to be applied successfully so as to cool all the

atoms, it would give a 7-fold flux increase compared with Sisyphus cooling as a result of the optical pumping and a further factor of between 4 and 8 resulting from a lower transverse temperature ($\leq 1.6 \mu\text{K}$ cf. $7 \mu\text{K}$ with FOCS-1). Research to this end remains one of our goals.

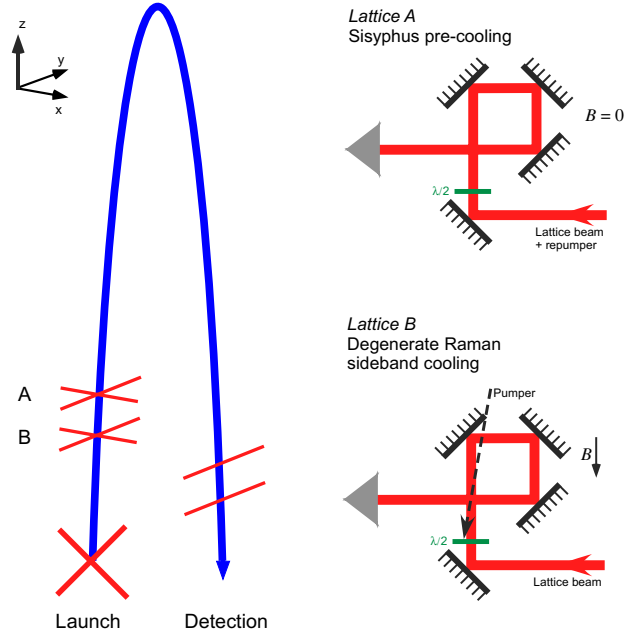


Fig. 4. Left: parabolic flight of cesium atoms and positions of different laser beams. Right: layout of the phase-stable, power-recycling 2D lattices for collimation of the atomic beam. Lattice A (10 mW) produces Sisyphus cooling using a lin \perp lin configuration with frequency 90 MHz below the $45'$ component of the D2 line. The repumper ($50 \mu\text{W}$) is tuned to 34 and injected into the lattice. Lattice B, located above it, is used for degenerate Raman sideband cooling. The lattice beam (155 mW) is tuned to the 44-45 crossover and the polarization is lin \perp lin. Here the circularly-polarized pumper beam is resonant with the $32'$ transition

E. Rotary light trap

One of the major issues concerning the implementation of a working continuous fountain clock has been the velocity-selective light trap. In the fountain FOCS-1, if fluorescence from the 3D moving optical molasses source is allowed to reach the Ramsey region, it produces a measured light shift of the clock transition frequency of $1.4 \cdot 10^{-12}$. It is thus imperative to attenuate this radiation if the clock is to be accurate. The perturbation would be even greater for FOCS-2 where a ≥ 40 -fold higher atomic flux is anticipated. In fact, were the flux increased by a further factor of 25, one might need to shield atoms from fluorescence in the detection region too. Provision for this has been made in the vacuum chamber of FOCS-2. The efficiency of an appropriate light trap, based on a turbine with glass blades rotating at 17 Hz, was verified several years ago [15]. The blades turning at the same average speed as the upward moving atoms absorb most of the light and specularly reflect the rest into a graphite trap, the attenuation in the region of the microwave cavity being $>10^4$. For a long time, however, experiments were hampered by frequent failures of magnetic stepper motors used to drive

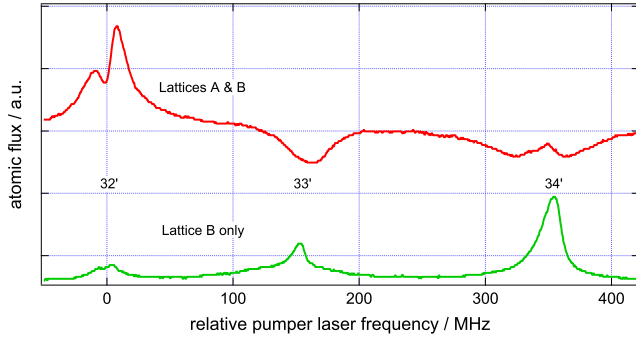


Fig. 5. 2D collimation of an atomic cesium fountain using stacked optical lattices. The first lattice A provides pre-cooling. The second, B, uses a magnetic field of 80 mG along y and a pumper laser tuned near the $32'$ hyperfine component of the D2 line to induce degenerate Raman sideband cooling [19]. The figure shows atomic flux detected at the end of a fountain as a function of pumper laser frequency crossing lattice B horizontally almost along the y axis. Lattice A: laser tuned 160 MHz above the $44'$ hyperfine component of the D2 line (4.5 mW). Polarization $\text{lin} \perp \text{lin}$. Repumper (0.05 mW) tuned to $34'$ injected in the same lattice, polarization orthogonal to the cooling laser. Lattice B: laser tuned to the $44'$ - $45'$ crossover, (155 mW). Polarization linear inclined at $??^\circ$ to the vertical.

the turbine under UHV. A recent breakthrough has been in the implementation in FOCS-1 of a reliable electrostatic motor [22]. This novel device, developed in collaboration with colleagues from the École Polytechnique Fédérale de Lausanne, is based on dielectric properties of glass (Figs. 6 and 7). It provides continuous, intrinsically smooth rotation, is non-magnetic and does not outgas.

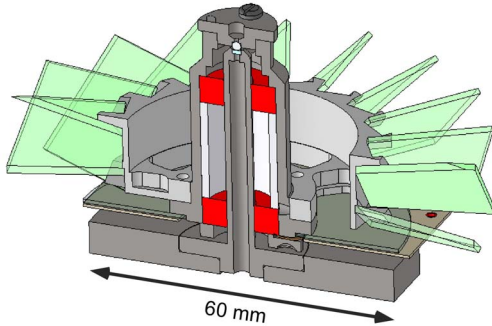


Fig. 6. Section through the velocity-selective light trap. Rotor, stator with 180 electrodes, turbine, glass blade, ball race, bearing, sapphire flat.

F. Microwave interrogation

The cylindrical, coaxial microwave cavity oscillating in a TE 021 mode, is identical with that of FOCS-1 [27] aside from the higher operating temperature of $35(1)^\circ\text{C}$ instead of $32(1)^\circ\text{C}$. It can be rotated by exactly 180° to allow measurement and cancelation of any end-to-end phase shift. The high quality factor $Q=15\,000$ is necessary to minimize the distributed phase shift. Fig. 8 shows the cavity installed on its turntable in the fountain.

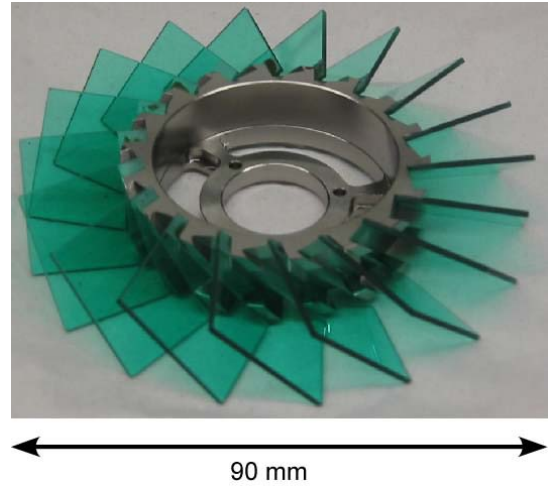


Fig. 7. Photo of the titanium turbine of the light trap and glass blades.

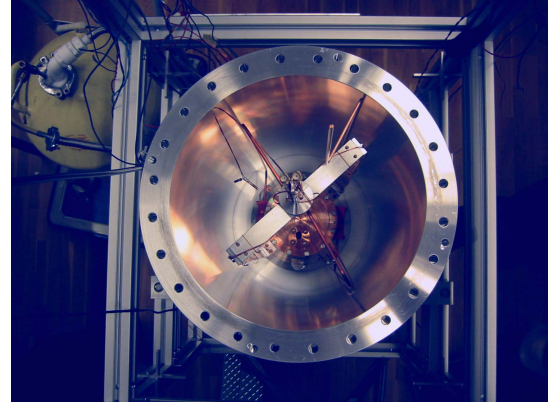


Fig. 8. Bird's eye view of the microwave cavity of FOCS-2 installed on its turntable in the vacuum chamber showing the cut-off tubes and the arms used to rotate the ensemble by exactly 180° .

G. Detection of atoms

Atoms can be detected at different stages of the trajectory. At the level of the 3D source optical molasses, a probe beam along the y -axis, perpendicular to the plane of the parabolic flight, is used to perform absorption measurements for diagnostics. For a static optical molasses, typical single-pass absorption of 25 % corresponds to about 2×10^9 atoms in the source. An extra collimator located 7 cm above the launch position, can be used for absorption measurements to verify that, with a moving molasses, atoms are indeed being launched. At the end of the parabola, there are two regions where either the atoms in $F=4$ or, with the addition of a re-pumping laser, the total number in $F=3$ and $F=4$ can be detected by laser-induced fluorescence. For diagnostics, we employ phase sensitive detection in which the x -beam of the source molasses is modulated at about 5 Hz by a mechanical chopper wheel. For operation of FOCS-2 as a clock, the microwave transition will provide modulation of the $F=3$ and $F=4$ populations instead.

IV. CONCLUSION

The continuous atomic fountain clock FOCS-2 has been fully assembled at METAS. A parabolic flight of atoms has been observed since when the microwave cavity has been installed in the apparatus. A.c. Stark shifts due to light from the source will be eliminated via the use of a velocity-selective light trap driven by a novel electrostatic motor. The standard should benefit from a ≥ 40 -fold greater atomic flux than its predecessor due to the implementation of a pre-source and improved collimation via optical lattices. This in turn should lead to an improved shot-noise-limited short-term stability of $\leq 4 \times 10^{-14} \tau^{-1/2}$.

V. ACKNOWLEDGMENTS

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