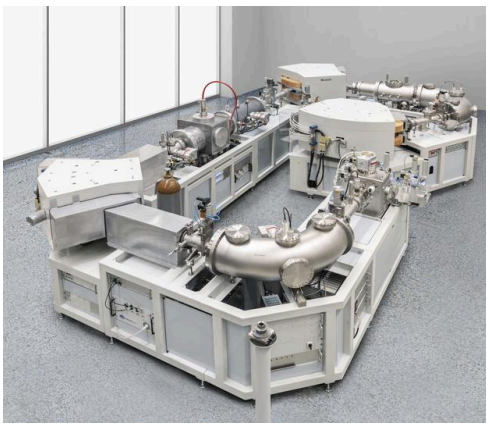
Comparison of currently available ^{14}C measurement technologies

Radiocarbon (^{14}C) measurement requires determining the fraction of modern carbon in a sample in a **fast, economical, and precise** manner across various industrial, environmental, and analytical applications: bio-based content of materials, biogenic share of fuels, fossil CO2 in emissions and air, ^{14}C-labelled compounds in pharmaceutical studies, and ^{14}C monitoring around nuclear facilities. The pros and cons of the currently available technologies are analyzed below:

	SCAR Saturated-absorption CAvity Ring-down	**AMS** Accelerator Mass Spectrometry	**LSC** Liquid Scintillation Counting
Weight	✓ KG	✗ KG KG KG KG KG	✓ KG
Minimum sample needs	✓ 1	✓ 1	✗ 6
Measurement precision	✓ **HIGH**	✓ HIGH	✗ LOW
Dynamic range	✓ **VERY HIGH**	✗ LOW	✓ HIGH
Cost (€)	✓ **< 600 k**	✗ 1.5 – 5 M	✓ 150 k
Sample handling and preparation	✓ **Fully automatic**	✓ Automatic	✗ Manual







LSC



Principle:

counting individual radioactive decay events by detecting weak flashes of light (scintillations) produced when a ^{14}C atom of the sample under examination decays within a special liquid in which the sample itself is dissolved.

Advantages:

- **Economical technology:** the cost of an LSC machine varies in the range of €100-200k. The equipment is fairly compact (footprint <1 m2) but not particularly light (up to 800 kg), due to the massive use of lead shielding necessary to minimize the instrumental background.

- **Established for high-activity samples:** LSC is the long-standing method for ^{14}C-labelled studies and for monitoring ^{14}C discharges from nuclear facilities, where ^{14}C levels are well above natural.

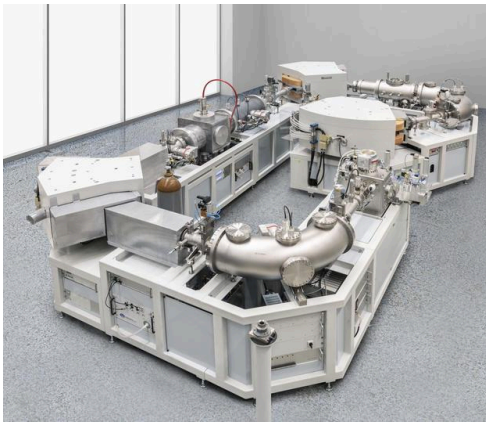
Limits:

- **Low sensitivity:** when the biogenic fraction of the sample is very low (< 20%), the measurement uncertainty, which is typically around 5% (absolute), becomes comparable to the measured value. It is possible to achieve lower uncertainties, but only for certain types of samples (colorless matrices) and by significantly extending the measurement times (see next point).

- **Long analysis times:** to compensate for the low sensitivity and accumulate a sufficient number of "scintillation" events to guarantee a statistically valid data point, a single measurement can last from a few hours to several days.

- **Disposal costs for toxic materials:** the scintillation liquids in which the sample is diluted are often toxic. In some cases, it is necessary to synthesize the sample in benzene (highly flammable and carcinogenic). In any case, the disposal of products after measurement requires compliance with complex protocols and entails non-negligible costs, estimated at approximately €50-100k / year.

AMS



Principle:

counting individual 14C atoms contained in the starting sample, after converting the carbon contained therein into graphite. The discrimination between isotopes of ^{12}C, ^{13}C, and ^{14}C is conducted within a particle accelerator, utilizing the principle that in a magnetic field, the heavier ^{14}C nuclei are deflected less than the lighter ones (^{12}C and ^{13}C), making it possible to separate and count them selectively.
AMS is considered the reference technique for radiocarbon detection, primarily thanks to the excellent levels of precision it can reach even for samples with low 14C content.

Advantages:

- **High precision:** with AMS, it is fairly easy to obtain a measurement uncertainty of 1% (relative) regardless of the level of ^{14}C present in the sample, with measurement times ranging from approximately 20 to 120 minutes per sample.

- **Reduced measurement times:** the measurement time per single sample is usually less than 1 h.

Limits:

- **High price:** the cost of an AMS machine varies from €2 to 10M, depending on the type of instrument and the energy reachable by the ion beam. To this is added the cost of setting up the laboratory, which must necessarily be a dedicated room, with an available surface area that can vary from 30 m^2 to 200 m^2, suitable for supporting a weight of several tons.

- **High operating costs:** an AMS machine requires dedicated and specialized personnel for both normal daily use routines and periodic maintenance. This typically involves a shutdown every 1-2 months for cathode cleaning operations, replacement of the Cesium reserve, or checks of the ultra-high vacuum system (UHV).

- **High turnaround times:** measurement is not performed on one sample at a time; instead, a "carousel" of several dozen unknown samples and standard samples (for calibration) is prepared, and a complete, uninterrupted measurement is launched on the entire "carousel". Although the measurement time per sample is less than 1 h, the final results for the entire measurement cycle are returned approximately 48 h after the measurement starts.

- **Complex sample preparation procedures:** the carbon present in the sample to be analyzed is first converted into CO_2 and then transformed into graphite to make the "pellets" to be inserted into the accelerator. This process requires several hours for each sample, which are added to the time required for measurement. Some modern AMS systems can directly process the CO_2 sample, bypassing the graphitization phase, but at the expense of sensitivity, which entails a significant lengthening of measurement times.

SCAR



Principle:

Instead of counting individual decays (LSC) or individual ^{14}C atoms (AMS), the laser-based SCAR technique utilizes a precise measurement of the selective absorption of laser light by $^{14}CO_2$ molecules. The sample is combusted in an elemental analyzer upstream to produce carbon dioxide (CO_2), which is sent to the instrument to be trapped, purified and measured. $^{14}CO_2$ molecules absorb laser light at a slightly different wavelength than those formed of $^{12}CO_2$ and $^{13}CO_2$. By measuring this absorption with the ultra-high sensitivity technique called "Saturated-Absorption Cavity Ringdown Spectroscopy", the molar fraction of $^{14}CO_2$ relative to $^{12}CO_2$ is derived.

Advantages:

- **Overall cost-effectiveness:** the price of a SCAR instrument is below €600k. Considering the practically zero operating costs (see next point) and the significantly higher throughput, the cost per sample of the SCAR solution is comparable to that of LSC over a 1-year period and significantly lower over longer amortization periods.
- **Low operating costs:** the SCAR instrumentation is compact (150 × 79 cm footprint, ~1.2 m^2) and lightweight (380 kg), fits through a standard laboratory door and can be installed in a normal laboratory. It does not require special maintenance and can operate for months or years without interruption. It does not require dedicated or particularly specialized personnel.
- **Good precision:** with SCAR, the typical measurement uncertainty is 2 pMC (absolute) at 15 minutes, 1 pMC at 60 minutes and 0.5 pMC at 240 minutes of averaging, with a best overall accuracy of 0.2 pMC in a laboratory with temperature stability better than ±0.5 °C/day. Except for samples with very low ^{14}C content (< 5 pMC), this results in relative measurement errors from very good to acceptable (from 0.5% to 10%).
- **Wide measurement range:** from 0.1 to 10^4 pMC, covering fossil-dominated samples as well as moderately enriched ones, such as labelled compounds and environmental samples from around nuclear facilities.
- **Reduced measurement times:** the measurement time for a single sample starts from 15 minutes, which allows about 30 samples per 8-hour day at 1-2 pMC precision; longer averaging (typically up to 1 h) is used when higher precision is needed.
- **Ease of sample preparation:** the CO_2 gas into which the sample carbon is converted via combustion is injected directly into the machine for measurement. This significantly speeds up the entire process, allowing for complete automation.
- **Short turnaround times:** combining the features mentioned above with the ability to process single samples results in turnaround times from sample receipt that can be less than 1 h.

Limits:

- **Minimum Carbon limit required for measurement:** to perform the measurement, a Carbon quantity of at least 1.5 mg (typically 2 mg) is required. Applications for which this requirement constitutes a real limit are, however, very rare.
- **Highly enriched samples:** samples above 10^4 pMC, such as some nuclear effluents or high-dose labelled samples, must be diluted before measurement.

In terms of performance, a concise comparison between the three technologies has been included in the revision of the European standard *"EN 16640 - Bio-based products - Bio-based carbon content - Determination of the bio-based carbon content using the radiocarbon 14C method"*, currently under adoption. The table below reports this comparison, referring to a standard measurement, lasting 1 h, on a 100% biogenic sample:

Table 1 — Advantages and disadvantages of the methods

Method	Additional requests	ASD	RSD	Duration needed for measurement	Typical carbon mass needed	Equipment costs
Method A (LSC)	- Normal laboratory	5 pMC $\propto \sqrt{F}$	10 % $\propto 1/\sqrt{F}$	2 h to 24 h	> 1g	Low
Method B (AMS)	- Large installation - Graphite conversion device [a]	0,3 pMC $\propto \sqrt{F}$	0,3 % $\propto 1/\sqrt{F}$	10 min to 30 min	< 1 mg	High
Method C (SCAR)	- Normal laboratory - Gas purification device	1 pMC constant	1 % $\propto 1/F$	10 min to 6 h	1 mg to 10 mg	Intermediate

[a] A few years ago, compact new AMS equipment became available. In a number of cases, no graphite conversion is required anymore.

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