SOLEIL SYNCHROTRON

Industrial Partner:

Quantum Technologies

Leipzig, Germany

Hands-on Quantum Sensing – towards Quantum Computer

2nd EPS TIG Hands-on Event for Science, Technology and Interfaces

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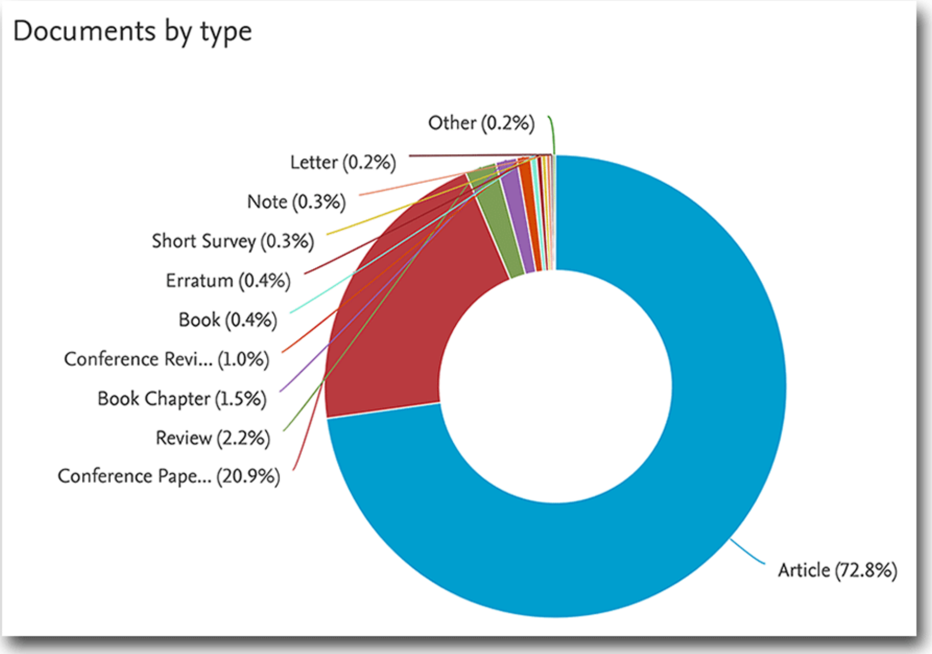
- **What ?**
  - Quantum Computing is revolutionizing the way and the speed with which we « compute ».
  - The potential of a « quantum computer » has been predicted in 1980[1] and the idea pursued by Feynmann and Manin.
  - 1994 Peter Shor found a quantum algorithm for factoring integers, potentially much more powerful than those running on ordinary computers[2]
  - Two basic concepts: Superposition of quantized « states » and entanglement of these systems, called qubits
  - Principle: prepare entangled states, let system work, read out < decoherence time, repeat

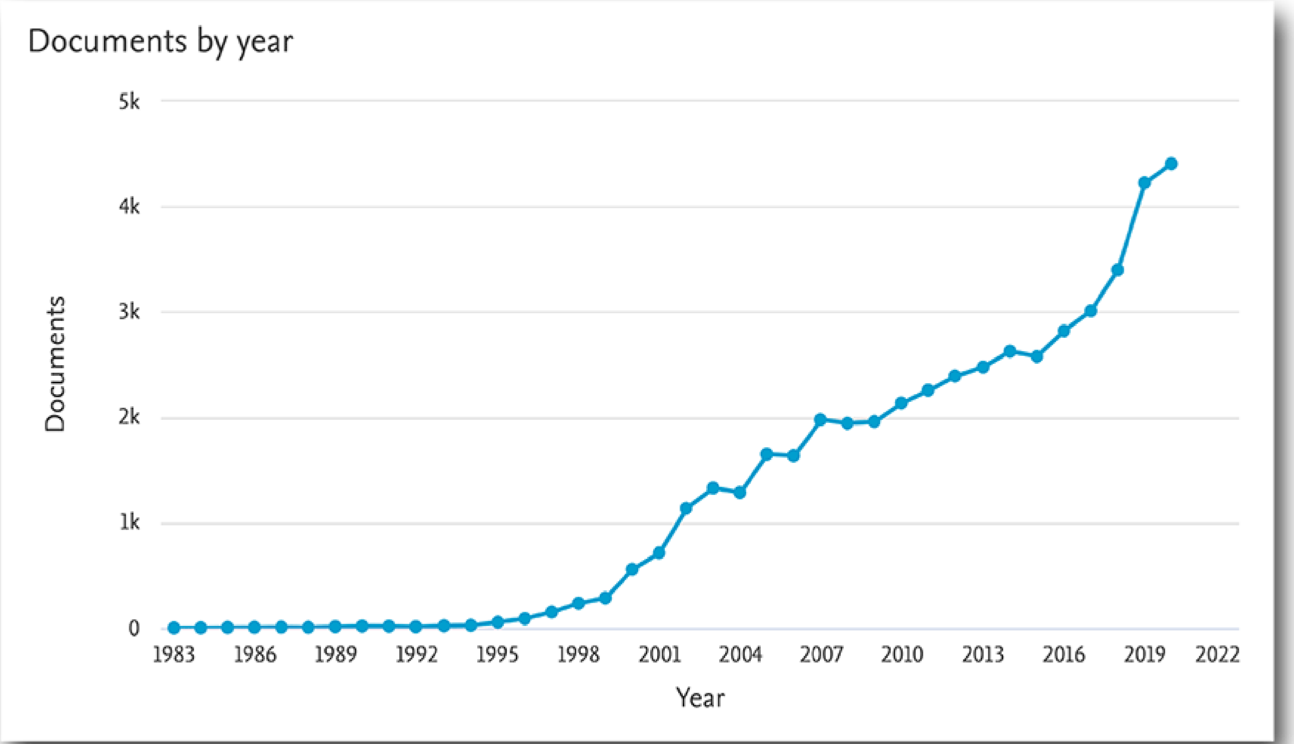
[1]Benioff, Paul (1980). "The computer as a physical system: A microscopic quantum mechanical Hamiltonian model of computers as represented by Turing machines". Journal of Statistical Physics. 22 (5): 563–591. Bibcode:1980JSP....22..563B. doi:10.1007/bf01011339. S2CID 122949592.

[2]Peter Shor, Polynomial-Time Algorithms for Prime Factorization and Discrete Logarithms on a Quantum Computer, arXiv:quant-ph/9508027, 1996

Quantum Computing IS upcoming

- **Why ?**
  - Ultimate computation speed
  - Optimization as a problem class is a key application: financial trading, defense, logistics, cryptography and communication
  - Research on QCs is a globally active field[2]
  - Textbooks are scarce[3]





[2,3] SCOPUS-data, see: https://www.elsevier.com/solutions/scopus/who-uses/research-and-development/quantum-computing-report#Output-international

Quantum Computing

- **How ?**

  – Many physical objects exist, fulfilling the requirements for qubits inside a QC[4], each having advantages and disadvantages, research for appropriate systems is ongoing

  – Key problems for implementation[5]:
    - Physically scalable to increase the number of qubits
    - Qubits that can be initialized to arbitrary values
    - Quantum gates that are faster than decoherence time (typ. between ns and s)
    - Universal gate set
    - Qubits that can be read easily

  – Qubits are very sensitive to their environment. This can also *inversely* be exploited as a feature: **Quantum sensing**

[4] see e.g. https://en.wikipedia.org/wiki/Quantum_computing
[5] DiVincenzo, David P. (13 April 2000). "The Physical Implementation of Quantum Computation". Fortschritte der Physik. 48 (9–11): 771–783. arXiv:quant-ph/0002077. Bibcode:2000ForPh..48..771D. doi:10.1002/1521-3978(200009)48:9/11<771::AID-PROP771>3.0.CO;2-E.

Quantum Technologies - Pillars

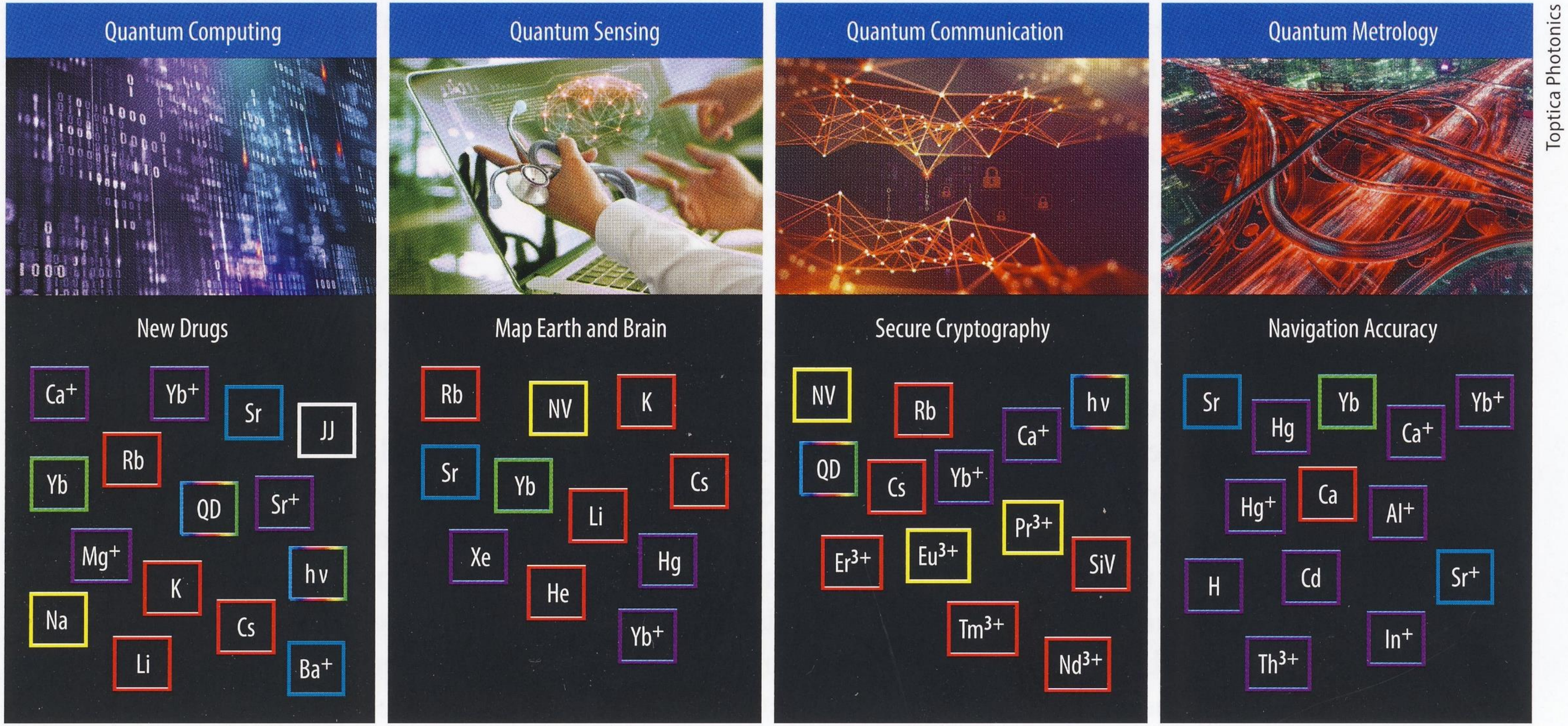
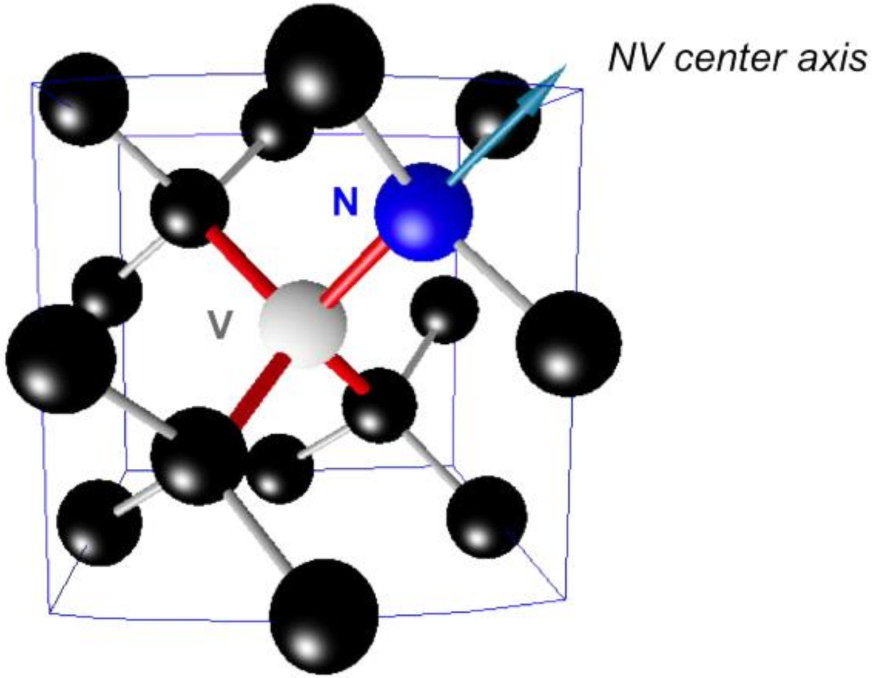


Fig. 1 Four pillars of quantum technologies (top) and a potential application result (below each image). There is a great variety of quantum systems used to implement different applications of quantum technologies. Species of atoms, ions and other quantum systems are shown in the square boxes. The more commonly used elements are at the top, the more exotic ones at the bottom.

From Physics' Best April 2022, p9

Quantum Sensing with NV- centers in Diamond

- NV- centers in Diamond are point defects within the diamond crystal lattice (fcc). One nitrogen atom N is on a lattice position and one adjacent lattice–site is vacant V[6] :

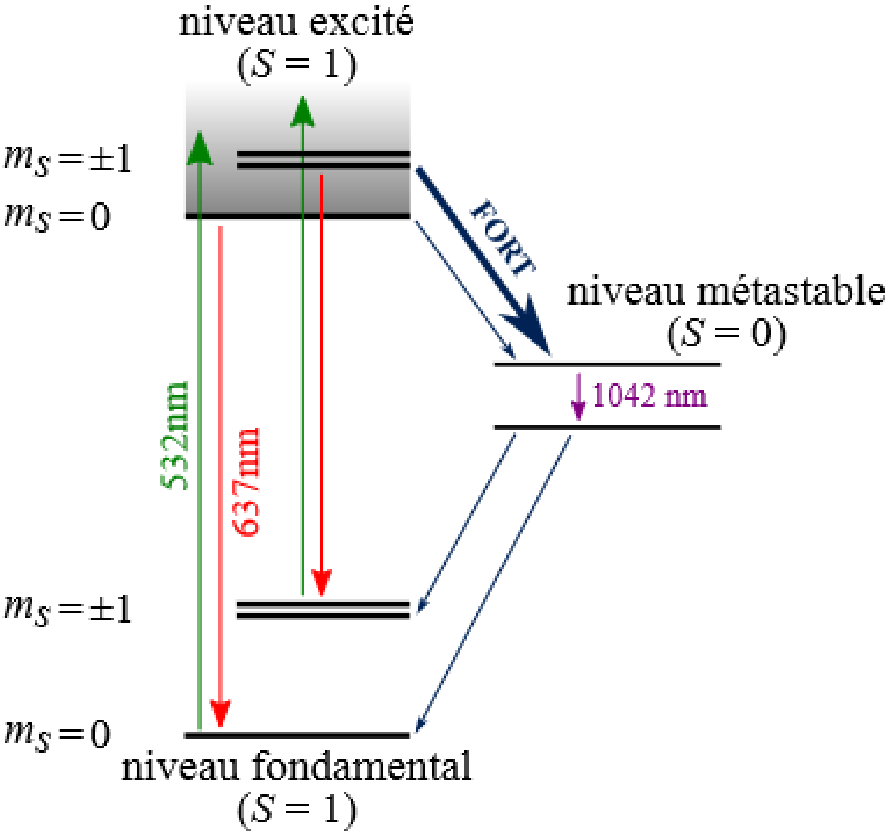


- Two charge states can exist: NV^0 and NV^-. NV^-, has one more electron, the total configuration has a spin of S=1. The NV^- centers are discussed here.

[6] from Margarita Lesik. Engineering of NV color centers in diamond for their applications in quantum information and magnetometry. Quantum Physics [quant-ph]. École normale supérieure de Cachan - ENS Cachan, 2015. English. ffNNT : 2015DENS0008ff. fftel-01158995, https://tel.archives-ouvertes.fr/tel-01158995 and refs therein. Thanks to Prof. J.-F. Roch.

Quantum Sensing with NV- centers in Diamond

- NV- centers' electronic structure[7]



1. Optical pumping from the S=1 ground state triplet populates the excited state.
2. Relaxation occurs optically at 637nm or non radiatively via S=0
3. Optically allowed transitons are spin-conserving, therefore the metastable level is dark.
4. Pump cycling can achieve population of the m_s=0 states, which could be exploited to initialise a quantum state for use within a QC.
5. External magn. Field (=Zeeman splitting on m_s=+-1) does not affect zero spin levels

n.b. : The energy levels and transition-probabilities are furthermore influenced by electrical fields, crystal strain and temperature. Transition energies between these many more levels lie in the Microwave region and permit to prepare and read electrically a population configuration of the NV- center: towards a QC @RT.

[7] From LoicToraille: Utilisation de centres NV comme capteurs de champs magnétiques à haute pression dans des cellules à enclumes de diamant. Physique [physics]. Université Paris Saclay (COmUE), 2019. Français. NNT: 2019SACLN056. tel-02429177v2; https://tel.archives-ouvertes.fr/tel-02429177v2

NV- centers in Diamond: how to make them ?

- Different paths to obtain NV- centers in diamond, from [6]:

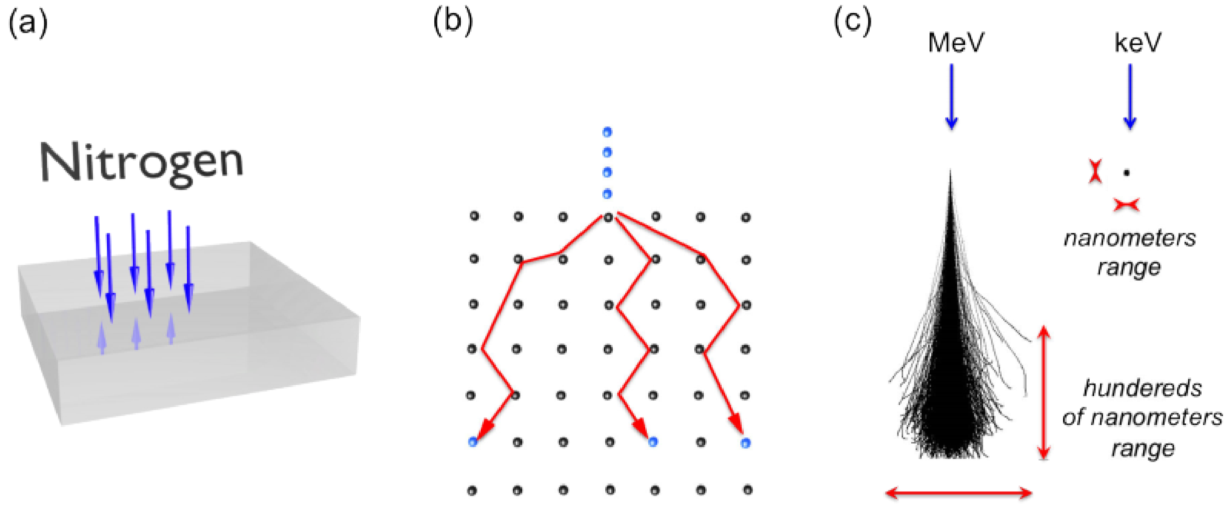


Figure 1.8: (a) Schematic representation of the nitrogen implantation experiment. (b) Ions straggling due to collisions and repulsions. (b) Example of the nitrogen ions penetrating tracks in the diamond sample using SRIM simulation.

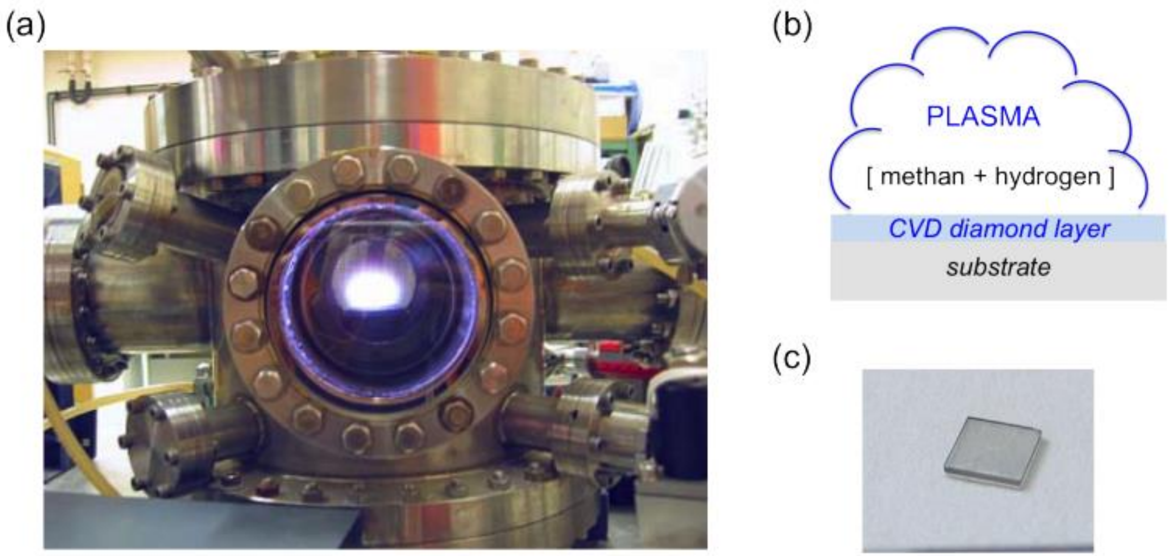


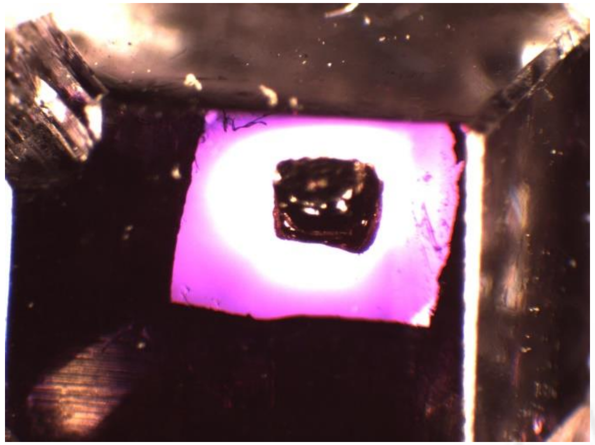
Figure 1.12: (a) Image of a CVD growth reactor used for the deposition of high purity diamond crystal. (b) Schematic representation of the CVD layer deposition process. (c) Image of a standard ultrapure diamond sample.

Spin coherence time is one of the key parameters for quantum computation, surface proximity (<2nm) makes NV- centers spins more fragile to external perturbations. At RT, 2ms have already been reported.

SOLEIL SYNCHROTRON

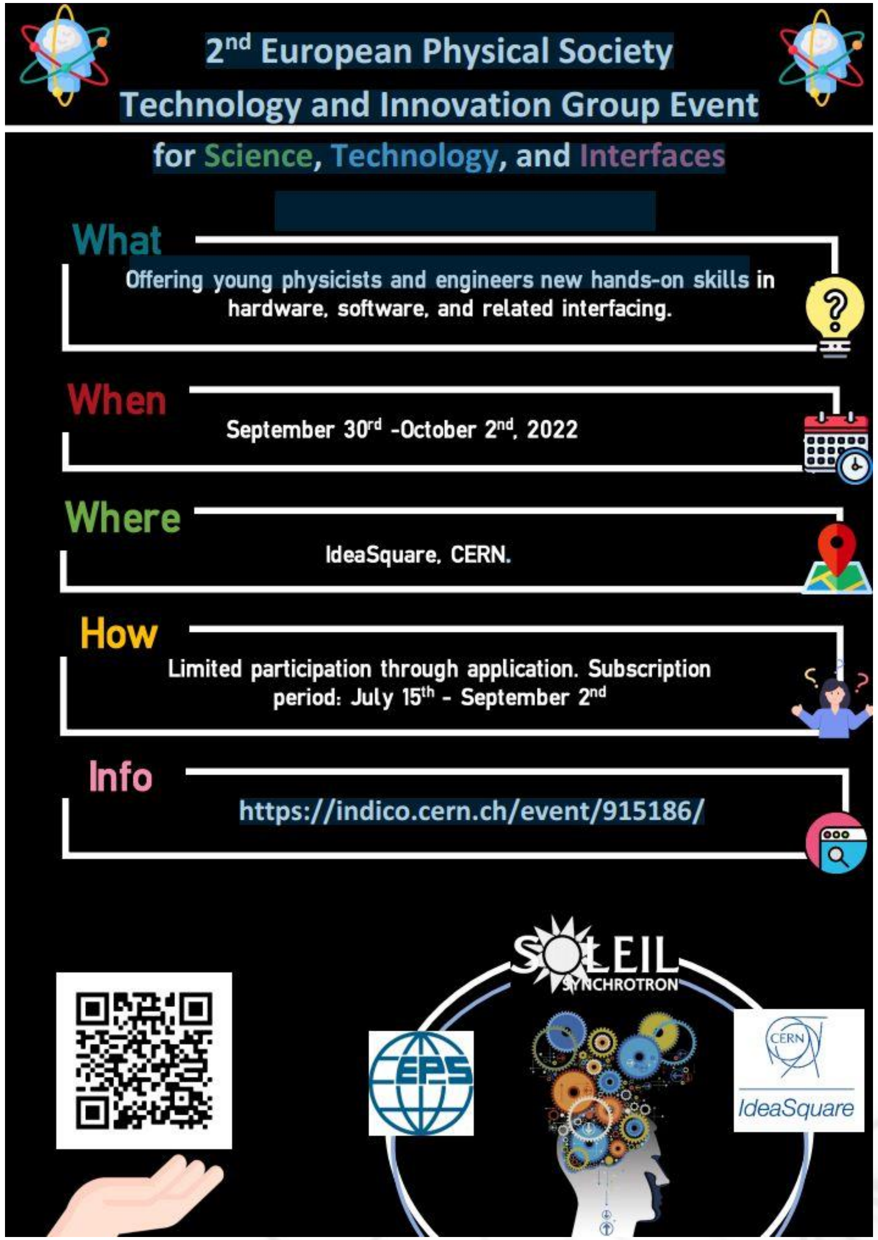
Hands-on quantum magnetometer

- Quantum magnetometer: exploit PL influenced by external magnetic field
- Experimental requirements (your part):
  - Need NV- centers in diamond (by Quantum Technologies, Leipzig)
  - Green light source (532nm)
  - Optical excitation setup
  - Optical read-out concept (consider spectral range versus readout speed)
  - Detector(s)
  - Magnet to produce magnetic field
  - PC and software -> data acquisition and interpretation
  - Ion implantation simulation to obtain NV-Centers
  - Presentation of results



Want More hands-on experience ?

Apply and come to CERN:



More insight into NV- centers in diamond from NATURE[8]:

https://www.youtube.com/watch?v=VCT0wDLyvSs

[8] Link: thanks to Mathieu Chevrot !