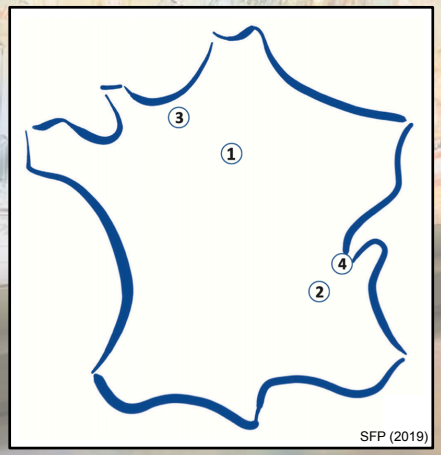
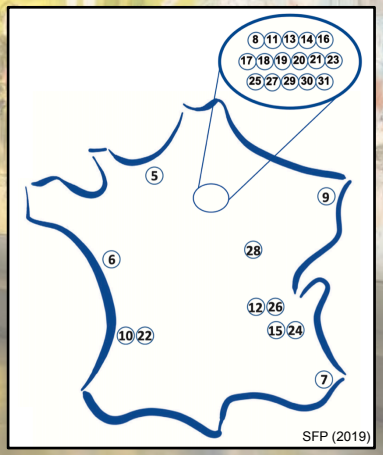
Overview of French Accelerator Facilities for Applications (outside Nuclear and Particle Physics)

E. Métral (CERN and JUAS director)





Many thanks to M. Baylac, F. Bouly, P. Lebrun and L. Rinolfi

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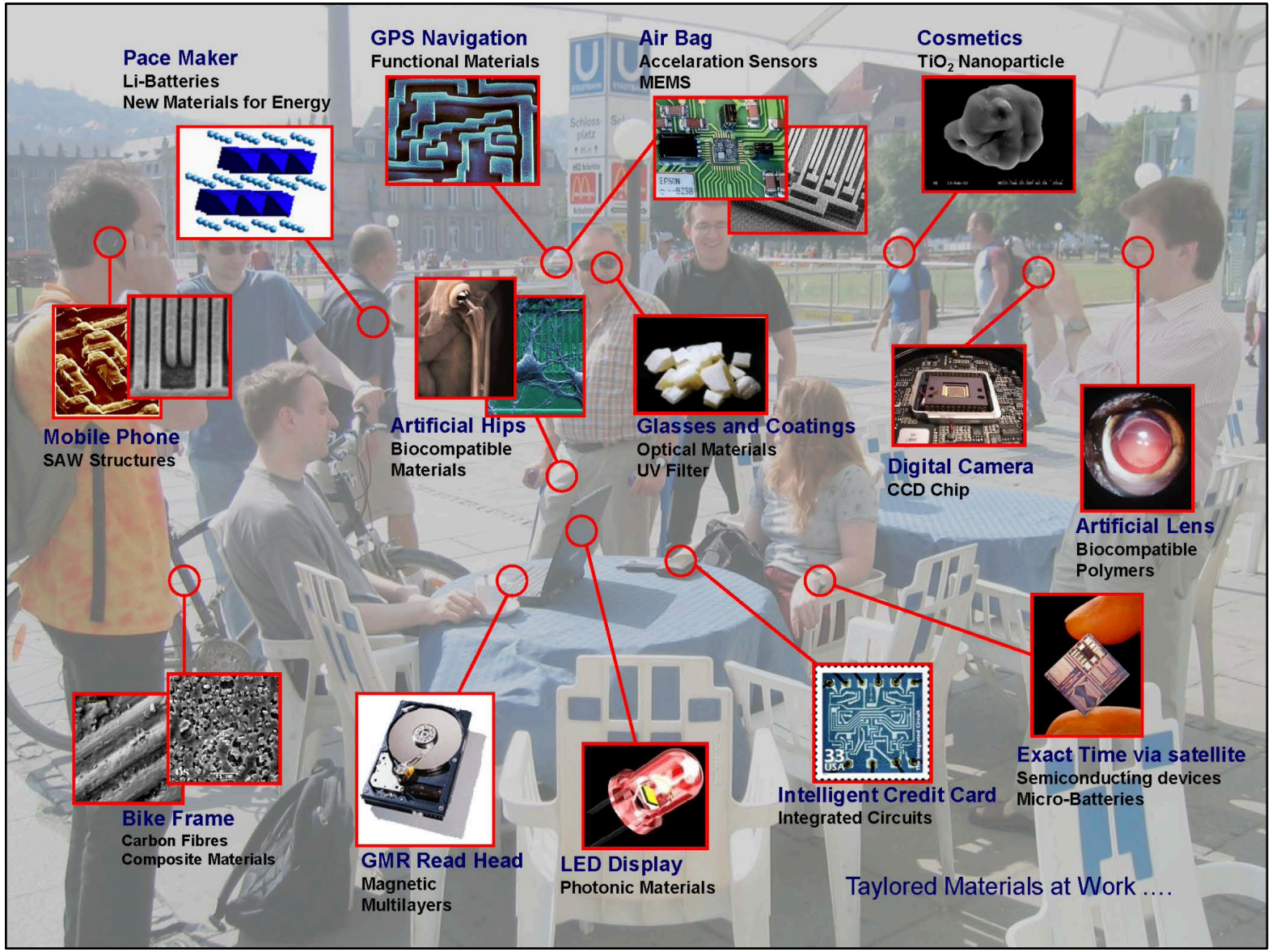
Pace Maker
Li-Batteries
New Materials for Energy
GPS Navigation
Functional Materials
Air Bag
Accelaration Sensors
MEMS
Cosmetics
TiO_2 Nanoparticle
Mobile Phone
SAW Structures
Artificial Hips
Biocompatible
Materials
Glasses and Coatings
Optical Materials
UV Filter
Digital Camera
CCD Chip
Artificial Lens
Biocompatible
Polymers
Bike Frame
Carbon Fibres
Composite Materials
GMR Read Head
Magnetic
Multilayers
LED Display
Photonic Materials
Intelligent Credit Card
Integrated Circuits
Exact Time via satellite
Semiconducting devices
Micro-Batteries
Taylored Materials at Work ….

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Quote from 'Accelerators for Americas Future' Report, pp. 4, DoE, USA, 2011

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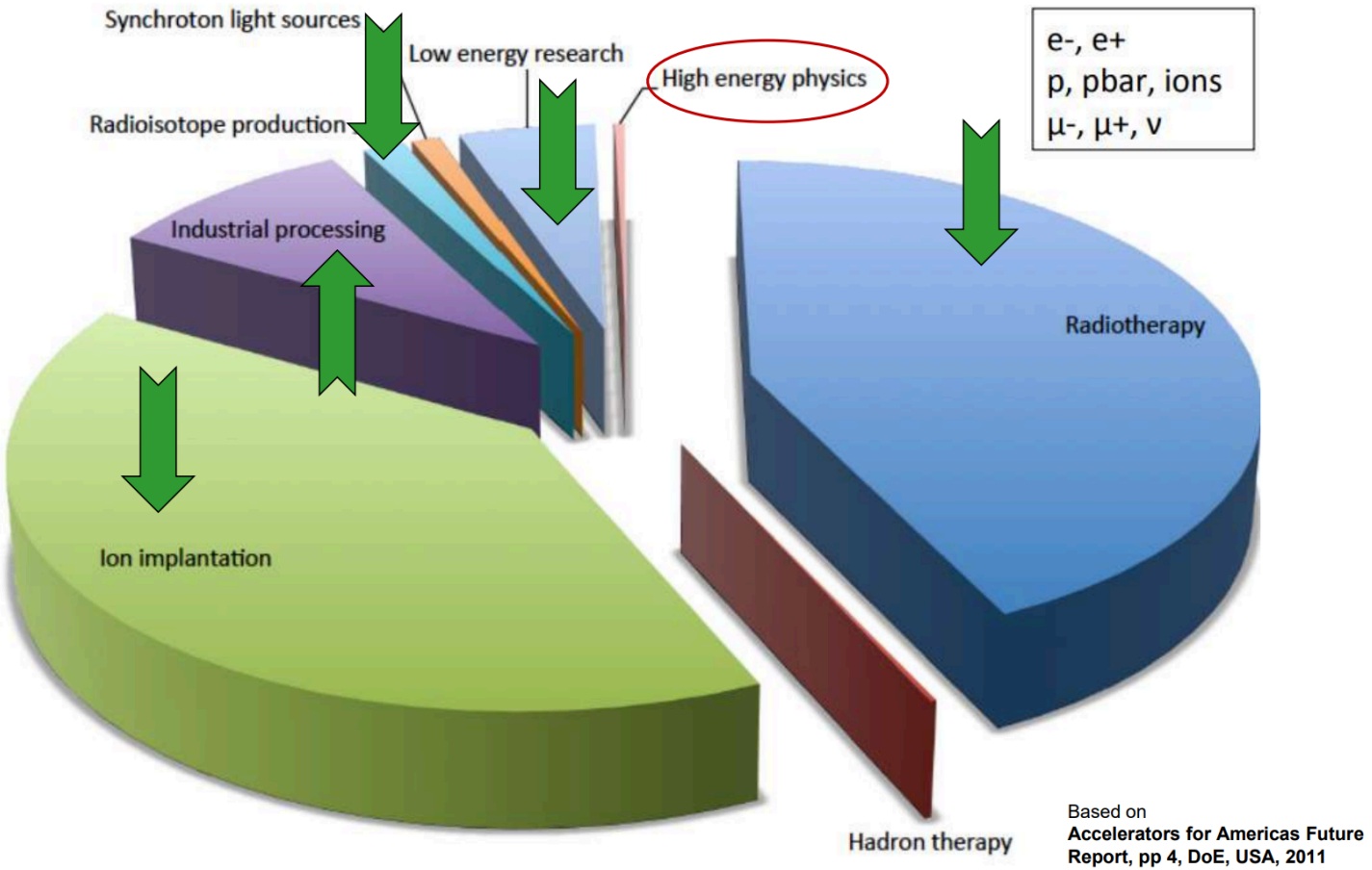
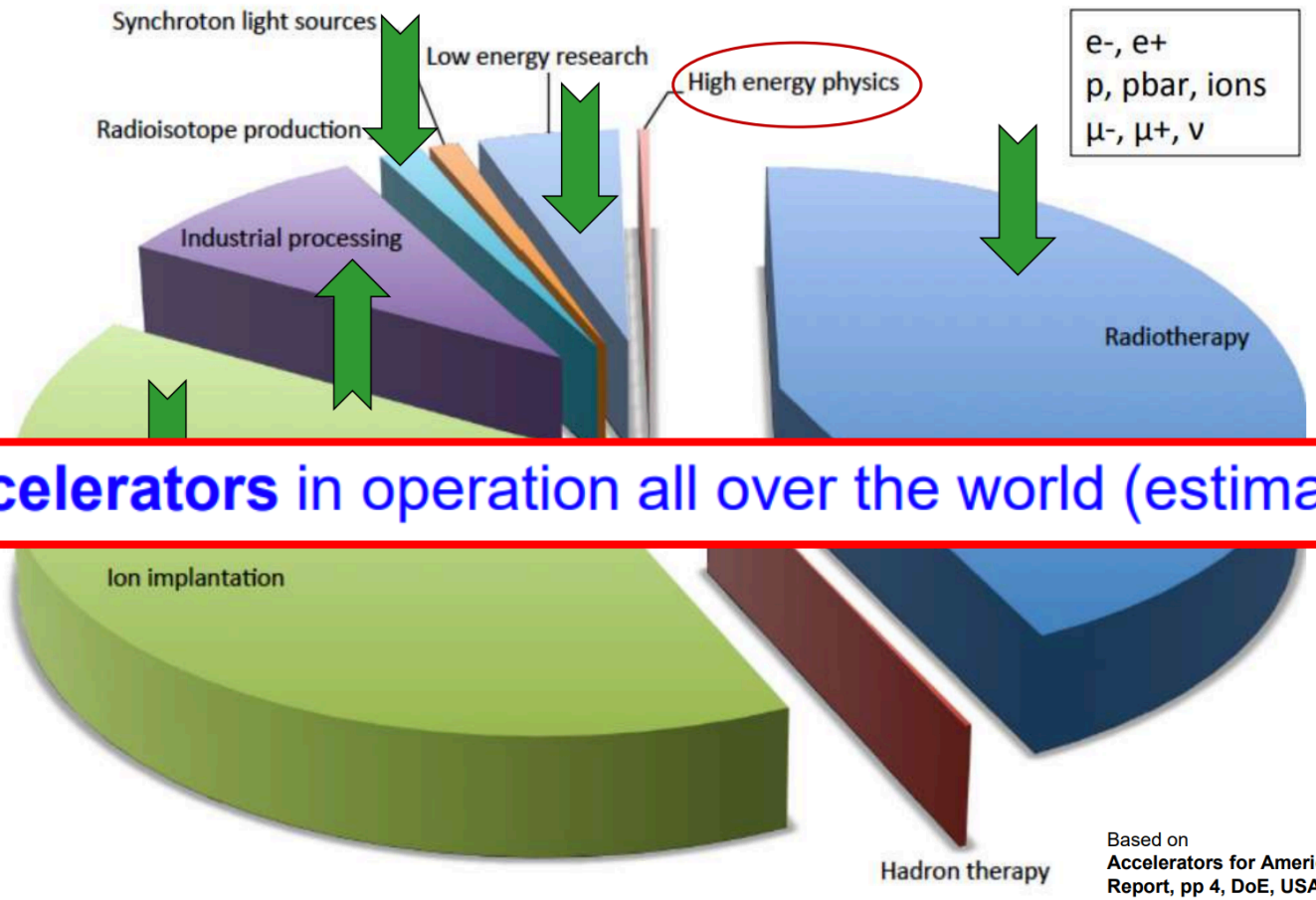


All different accelerator types are **spin offs** of accelerators for nuclear and particle physics



Based on
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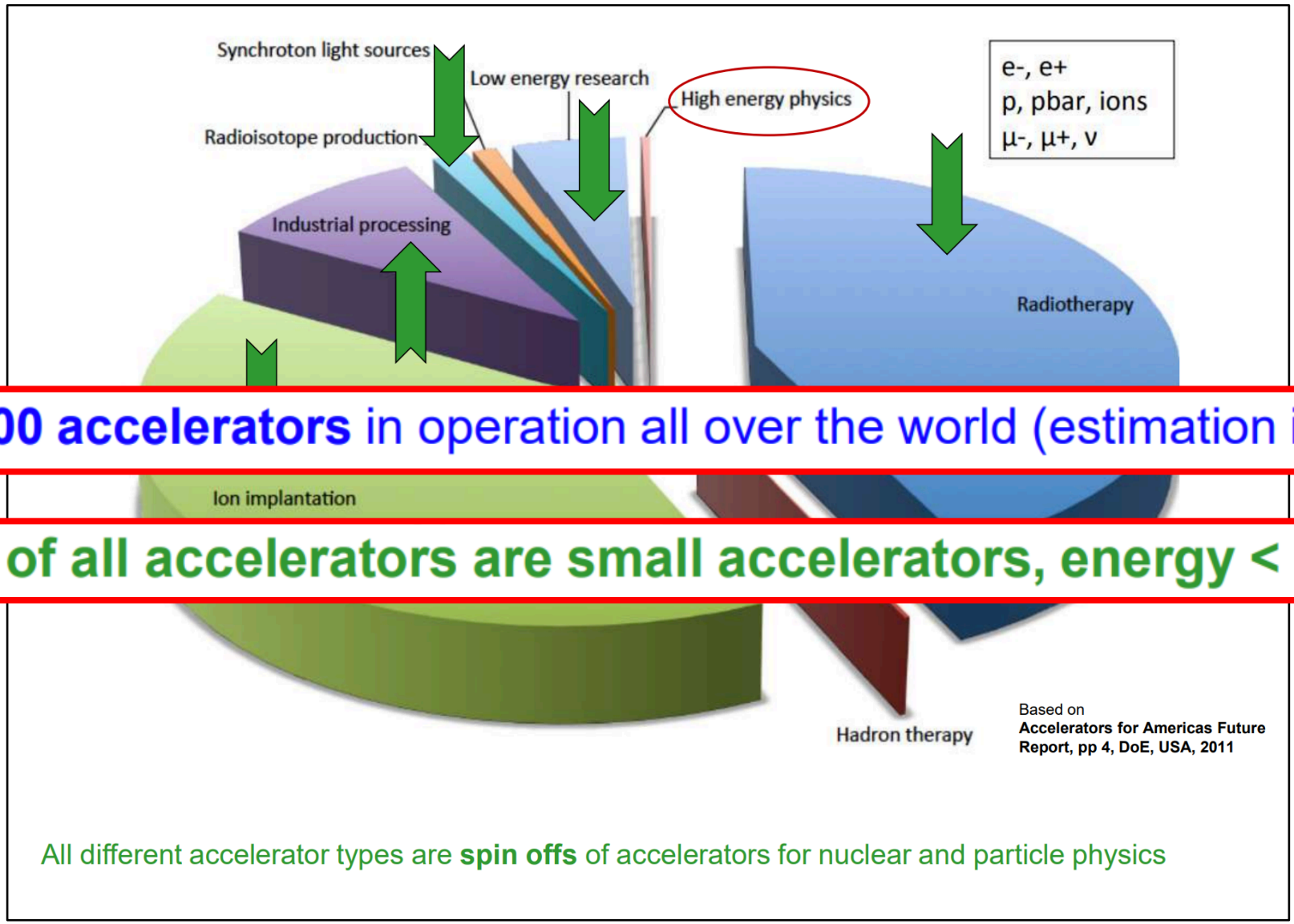

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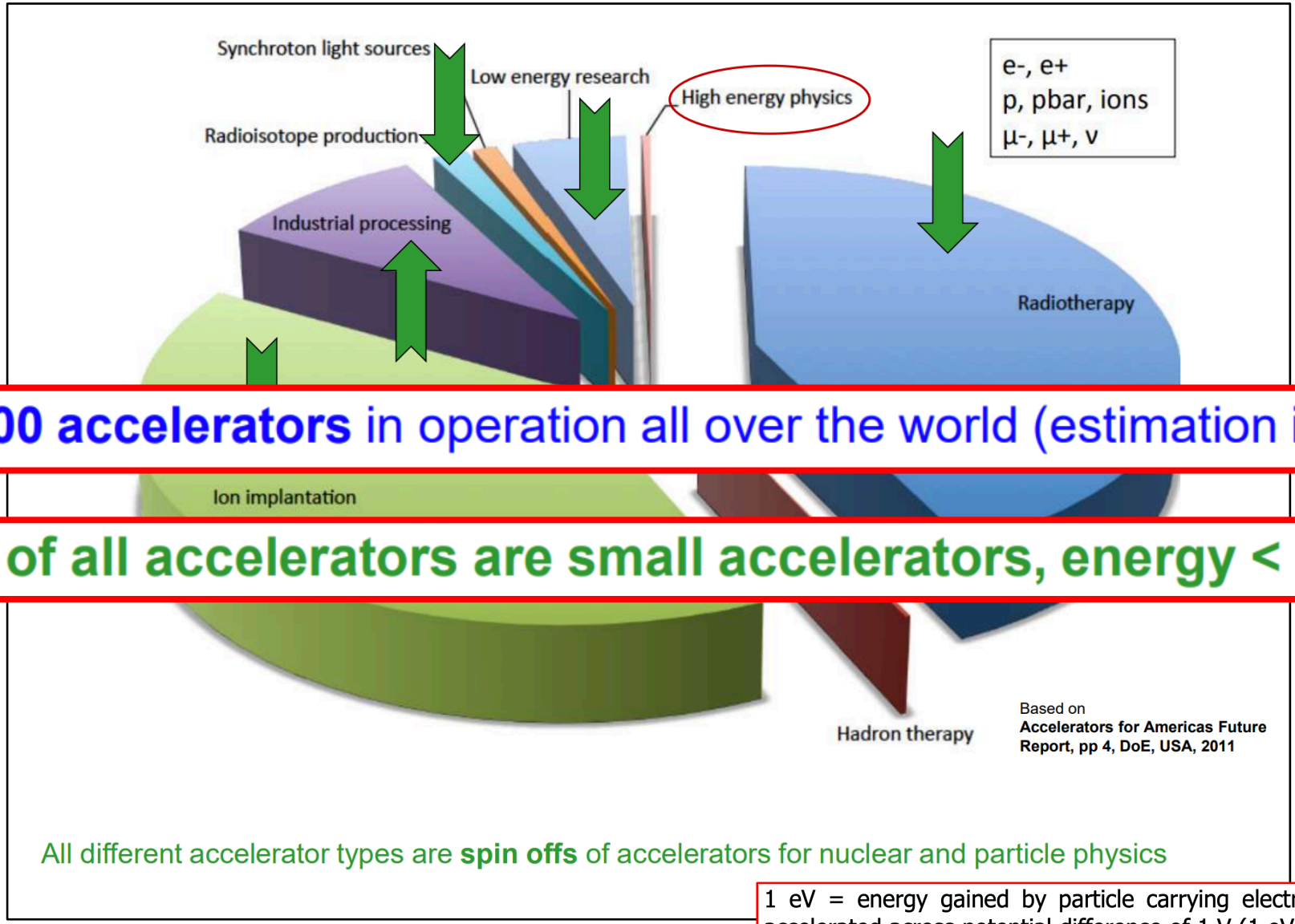

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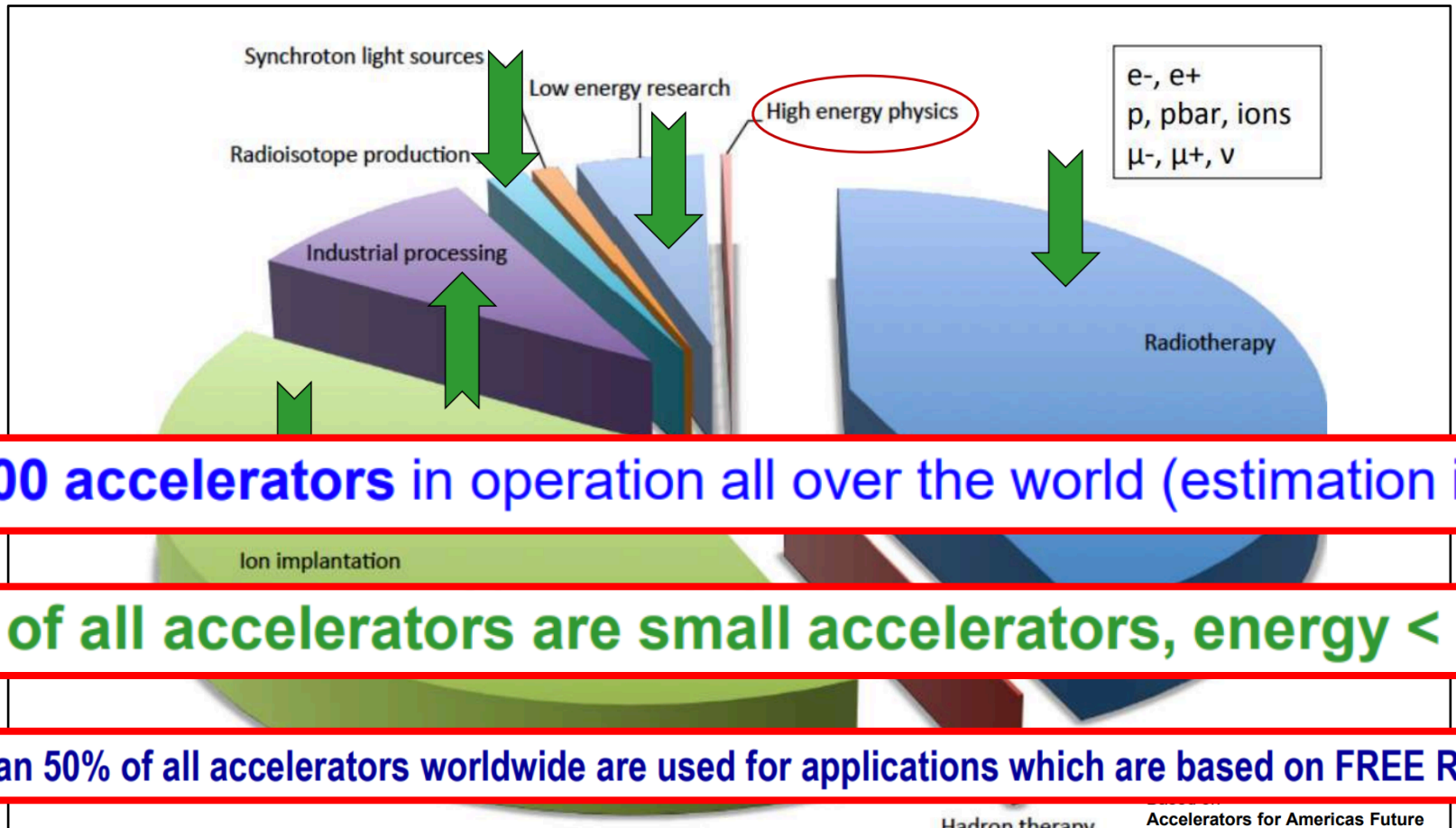
1 eV = energy gained by particle carrying electron charge when accelerated across potential difference of 1 V (1 eV = 1.6 E-19 J)



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!!! More than 50% of all accelerators worldwide are used for applications which are based on FREE RADICALS !!!

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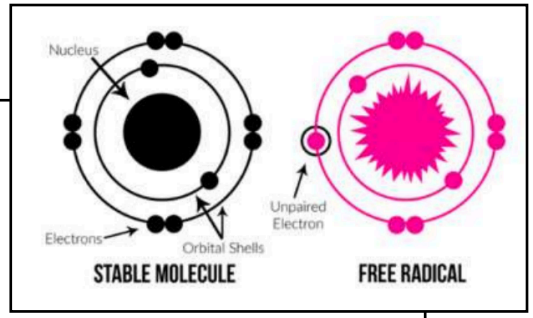

W. Mondelaers

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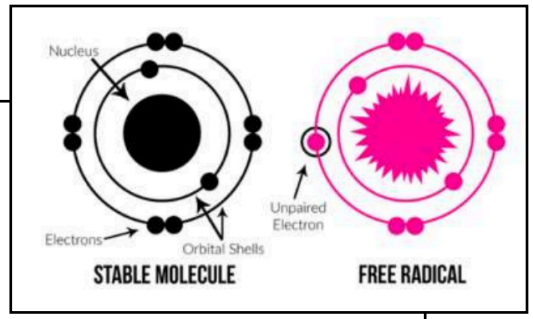

high chemical reactivity

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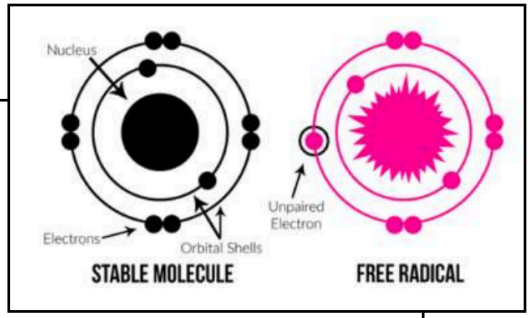


high chemical reactivity

- **damage DNA** — *radiotherapy, food irradiation, sterilisation*
- **chain reaction** — $R^\circ + AB \rightarrow R\text{-}AB^\circ$; $R\text{-}AB^\circ + AB \rightarrow R\text{-}AB\text{-}AB^\circ$ — *polymer chemistry*
- **special chemical reactions** — *radiation synthesis*
- **graft a second polymer** — *curing biomaterials*

W. Mondelaers

Myself

Former Section Leader (2010-20) on collective effects and beam instabilities: ~ 20-30 people

i.e. in particular when the Higgs Boson was discovered on July 4, 2012

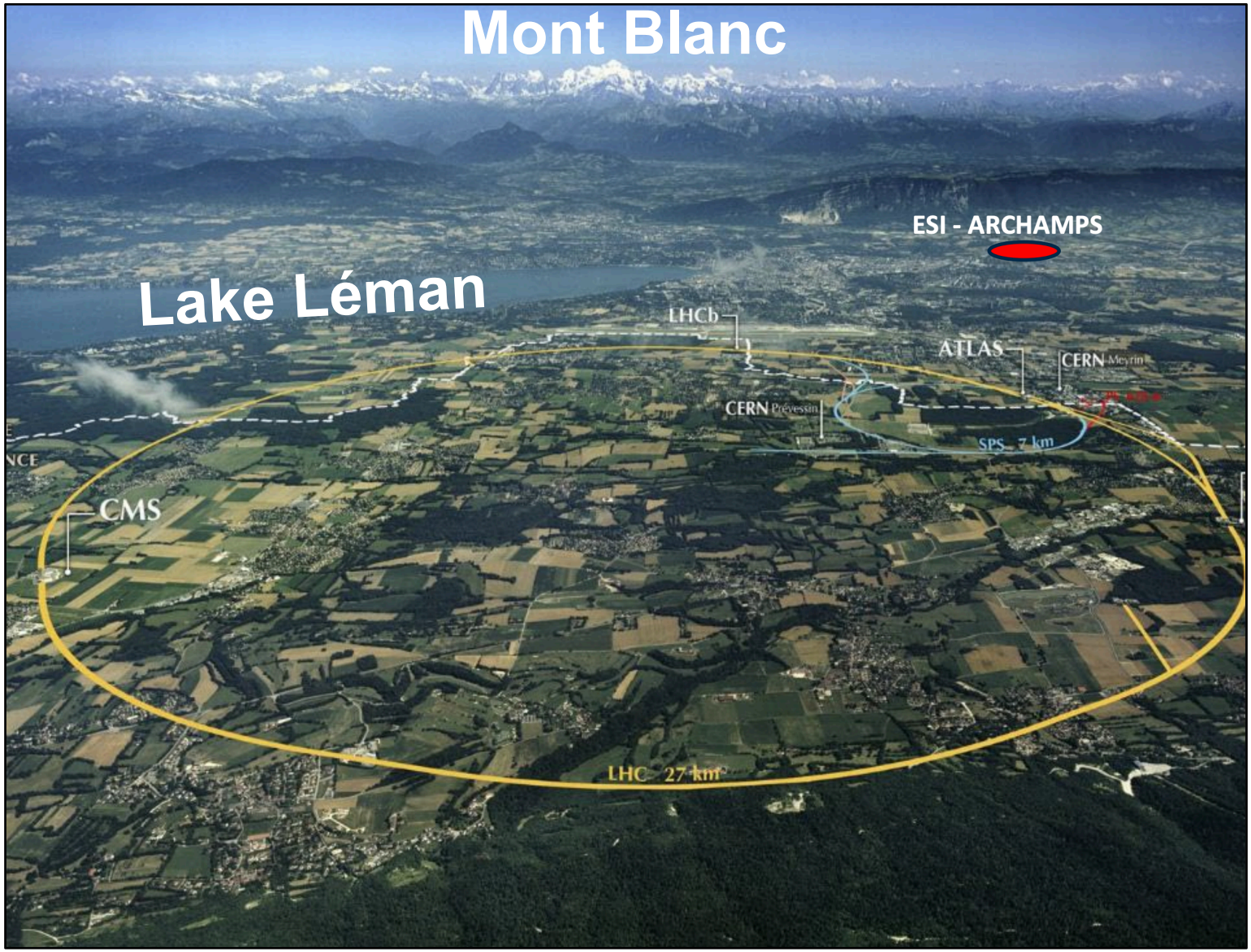
Former coordinator of the CERN PS, SPS, LHC Injectors Machine Studies, and finally LHC

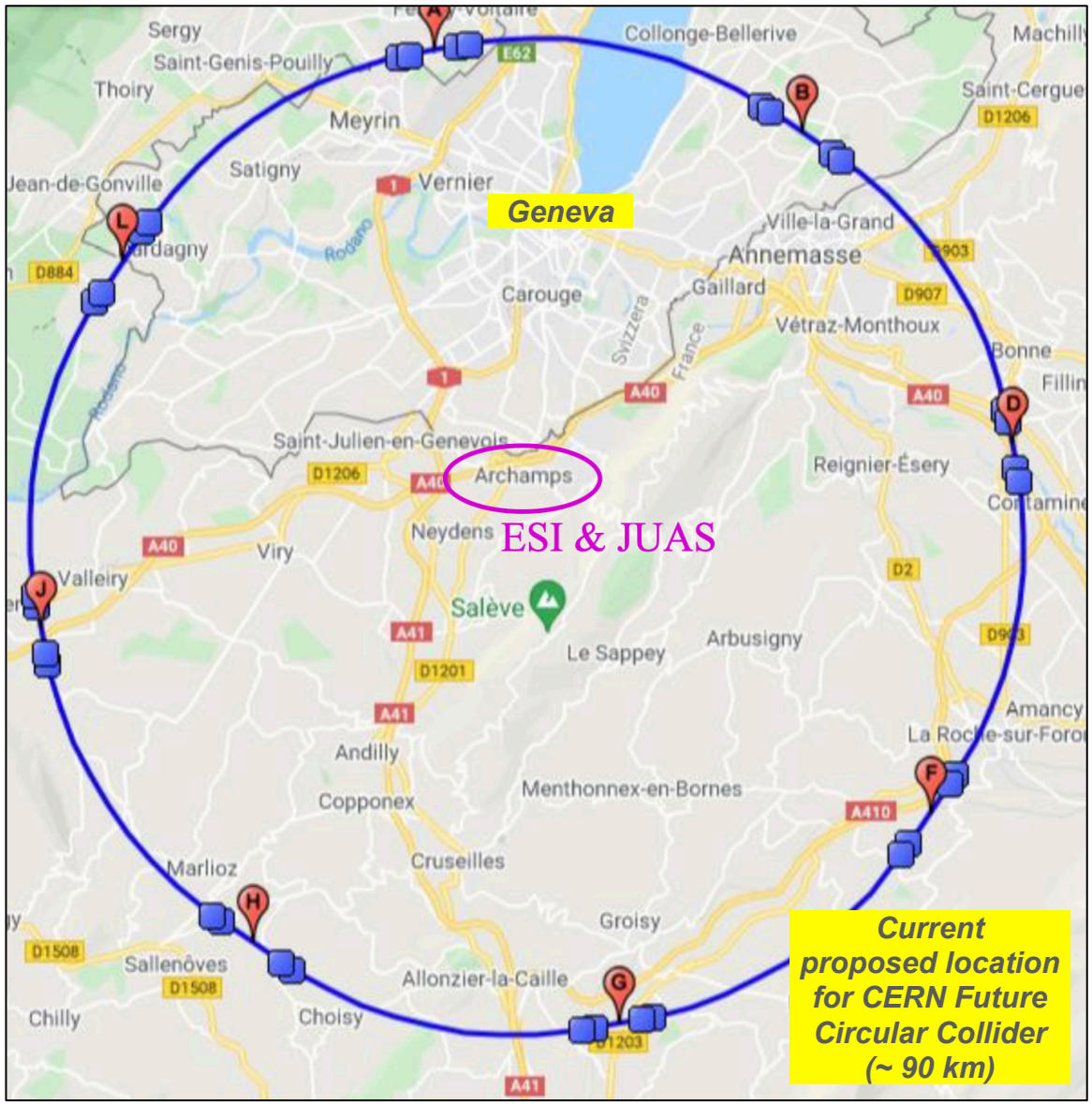
HiLumi HL-LHC PROJECT

Task Leader on collective effects since the beginning (2011) until 2023

International MUON Collider Collaboration

Since 2021


Mont Blanc
ESI - ARCHAMPS
Lake Léman
LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
CMS
LHC 27 km


Geneva
ESI & JUAS
Current proposed location for CERN Future Circular Collider (~ 90 km)
Sergy
Saint-Genis-Pouilly
Thoiry
Meyrin
Satigny
Vernier
Collonge-Bellerive
Saint-Cergue
Ville-la-Grand
Annemasse
Gaillard
Vétraz-Monthoux
Carouge
Saint-Julien-en-Genevois
Archamps
Reignier-Ésery
Neydens
Viry
Valleiry
Salève
Le Sappey
Arbusigny
Andilly
Copponex
Menthonnex-en-Bornes
Cruseilles
Marlioz
Groisy
Sallenôves
Allonzier-la-Caille
Chilly
Choisy
Amancy
Bonne
D1206
D884
D907
A40
A41
D1201
D1508
D2
A410
D1203
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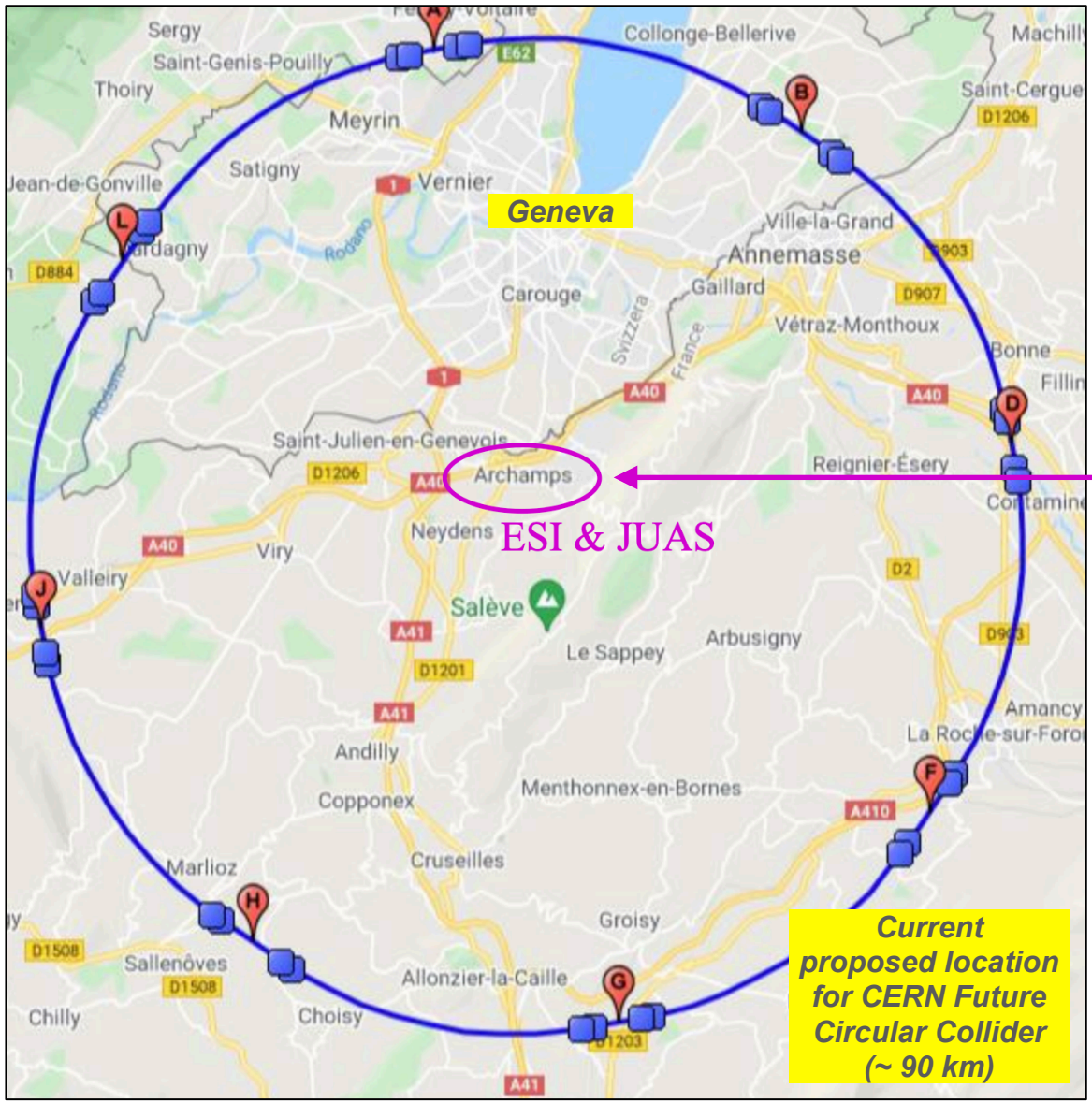
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juas 30 years anniversary and JUAS book

Celebration of the 30th anniversary of JUAS and presentation of the JUAS book

27 November 2024
CERN
Europe/Zurich timezone

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- Overview
- Timetable
- Registration
- Dates and deadlines
- Practical Information
  - How to get to CERN Science Gateway
  - Accommodation
  - How to get your badge
  - How to get WIFI
- Surveys

ESI team
juas@esi-archamps.eu

The Joint Universities Accelerator School (JUAS) has provided postgraduate-level education in the science and technology of particle accelerators to more than 1400 students since 1994. Most have earned credits towards Masters or Doctoral degrees at our Partner Universities in Europe, while students at other universities around the world and early-career professionals have sought to enhance their applicable knowledge and skills. Many have gone on to pursue successful careers in large accelerator laboratories such as CERN, in industry or in universities.

The JUAS is turning 30 this year: Let's celebrate together this important milestone during a full day at CERN on 27th November 2024!

The main goal of this event is of course to get together and it will be also the occasion to present to all of you the JUAS-2024 book, which has been written for this occasion and which will be released on 15/11/2024.

We do hope that you will be able to join to share a great moment together!

Group photo of the participants taken with the Globe of Science and Innovation in the background. More photos from the event are available from CDS and in CERN BOX.

A video showcasing 30 years of memories through photos was created for the anniversary and presented at the event (see below or in this LINK).

Starts 27 Nov 2024, 09:15
Ends 27 Nov 2024, 18:30
Europe/Zurich

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81/R-003A - Science Gateway Auditorium A
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1217 Meyrin
Switzerland
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Elias Metral

JUAS-30event_GroupPhoto.jpg
JUAS-30event.mp4
JUAS Video 30 years in photos.mp4

https://indico.cern.ch/event/1372615/timetable/?view=standard

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https://e-publishing.cern.ch/index.php/CYRSP/issue/view/168

CERN Yellow Reports:
School Proceedings

CERN-2024-003

- 19 Editorial Board members
- 62 authors
- 4 volumes
- 2371 pages

Proceedings of the Joint Universities Accelerator School (JUAS)

Courses and exercises

Editorial committee:
Elias Métral (Chair), Frédérick Bordry, Marco Bozzo, Phil Burrows, Joachim Enders, Angeles Faus-Golfe, Terry Garvey, Sophie Kazamias, Yuri Kubyshin, Philippe Lebrun, Joël Le Duff, François Méot, Luigi Palumbo, Marcelle Rey-Campagnolle, Louis Rinolfi, Vittorio Vaccaro†, Ursula van Rienen, Jens Vigen, Carsten Welsch

† Deceased 11 February 2023

4 EU-funded challenges (2022-25)

=> Potential new applications

Particle accelerators

- Particle accelerators are devices that handle the motion of particles by means of **EM fields**

Particle accelerators

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"The Electricity Fairy" (600 m^2) from Raoul Dufy, in Paris's Museum of Modern Art, for the 1937 International Exposition in Paris

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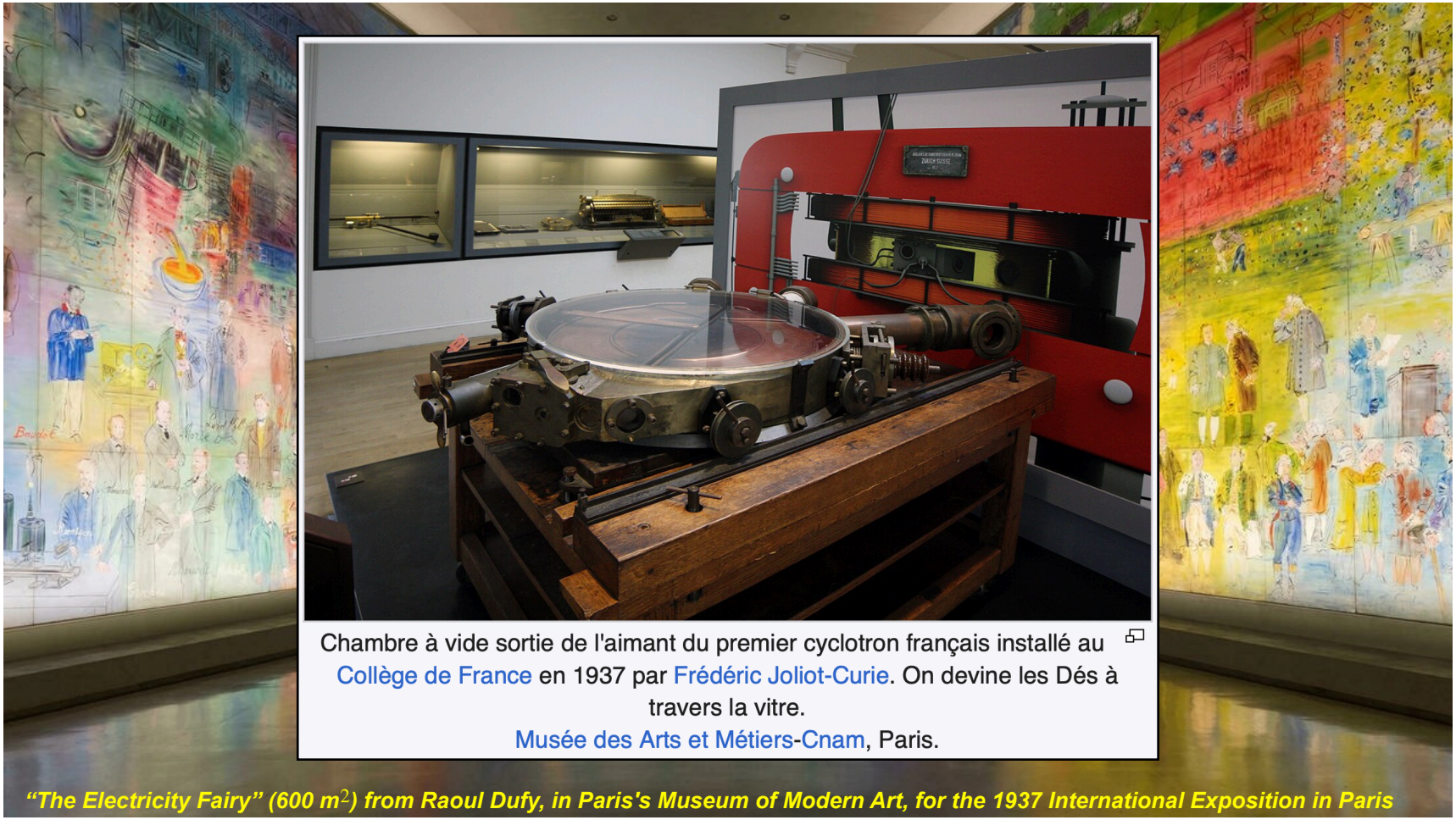

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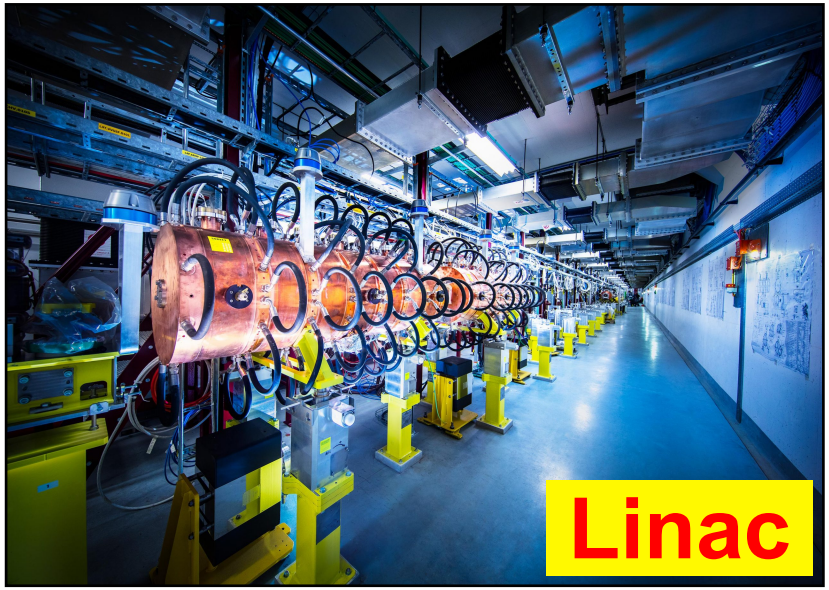
- **Classical relativistic mechanics** (i.e. Newton's second law of motion, including special relativity) is what is most often used => **Quantum mechanics** needed for instance for radiations emitted by particles, scattering, superconductivity and e- microscopes

Different types of PA

Different types of PA



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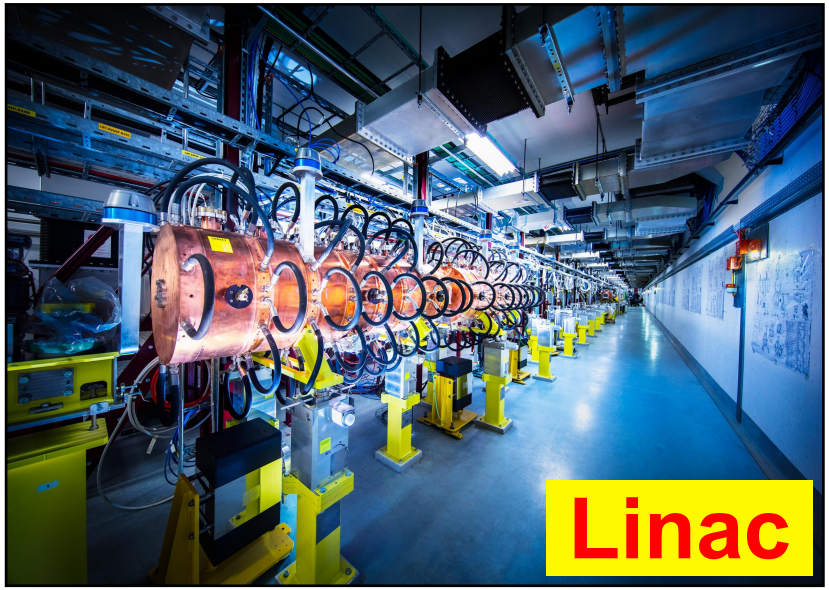

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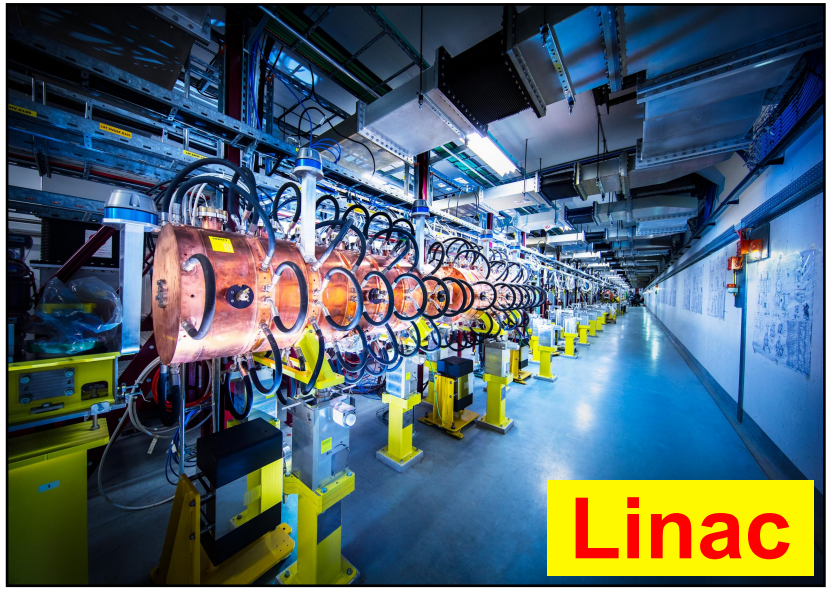

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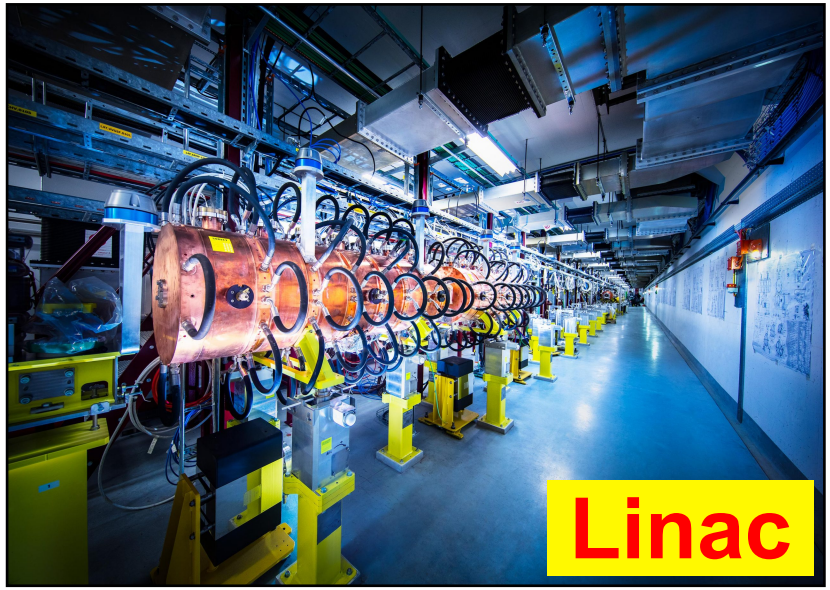
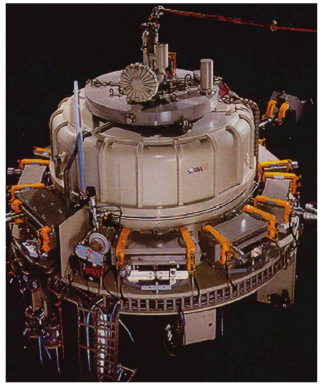
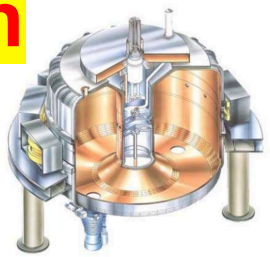
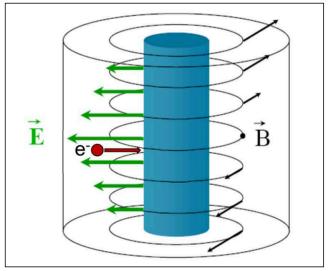


Rhodotron

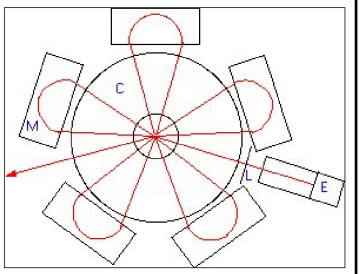
Only accelerator not designed for science, but developed as high-power accelerator for industrial applications



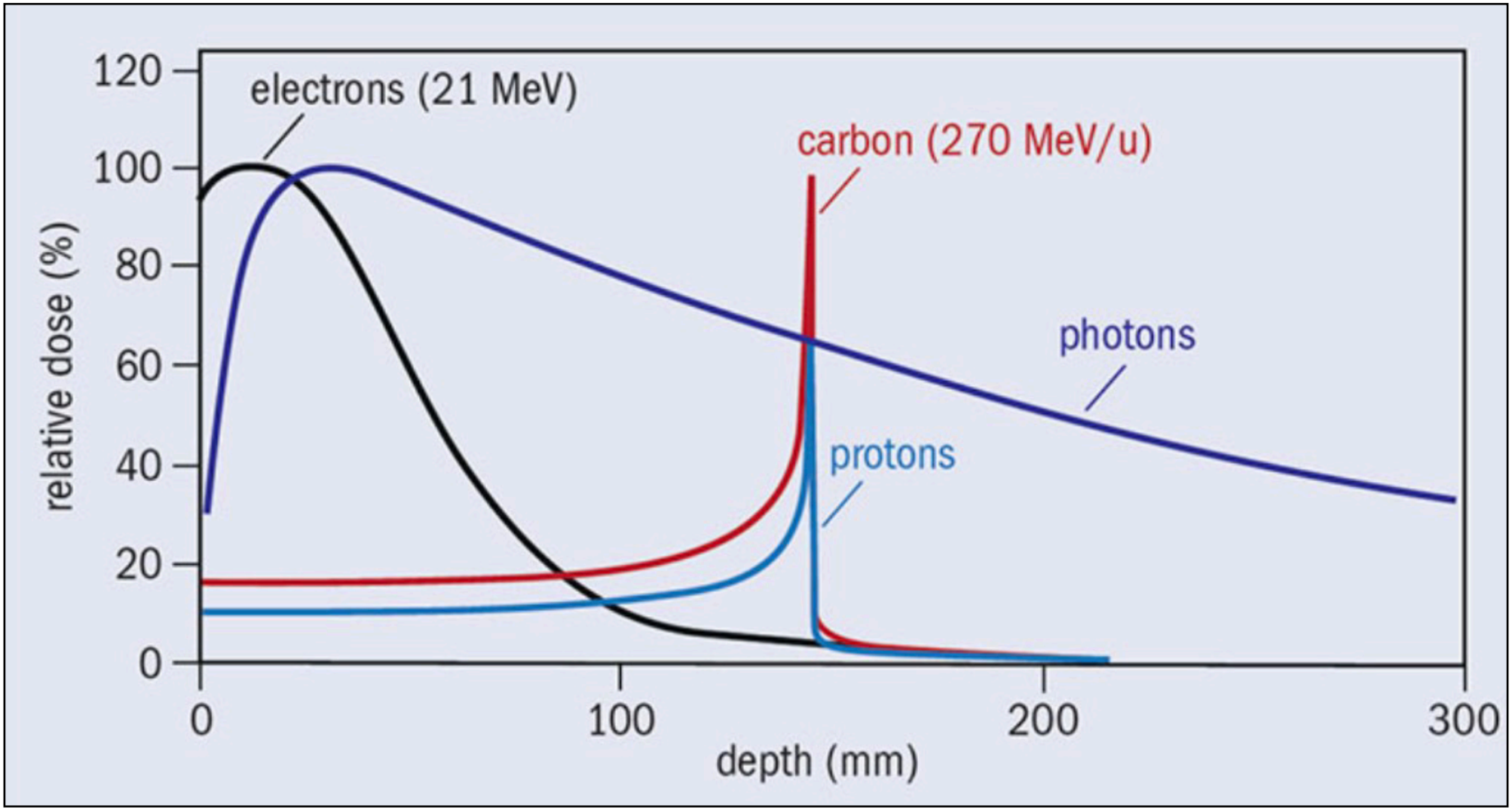




W. Mondelaers

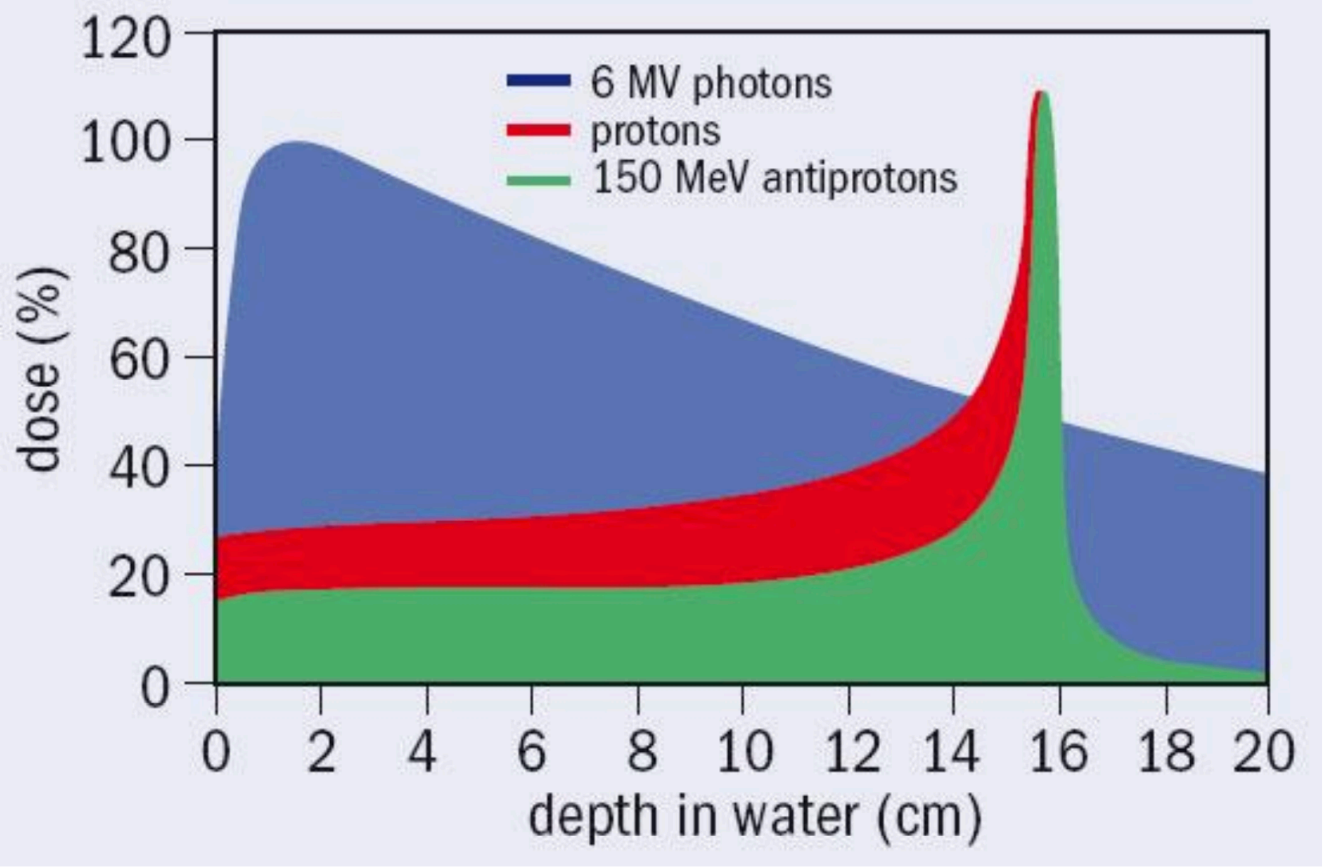


2 to 10 MeV (50 MeV)



W. Mondelaers

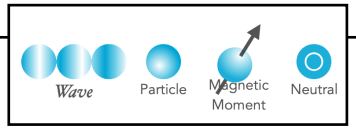
Antimatter?

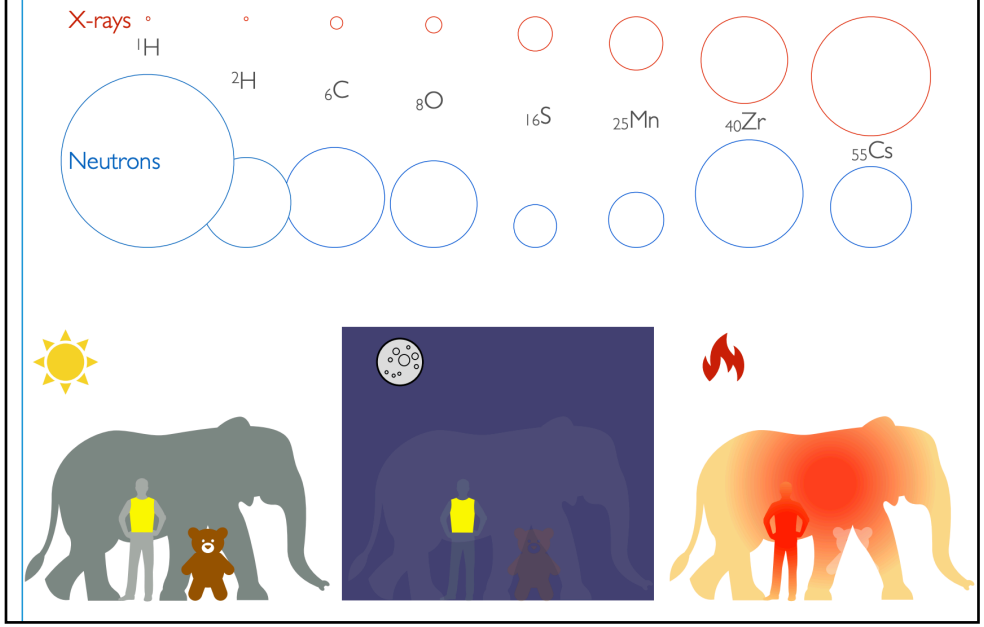


A. Durham

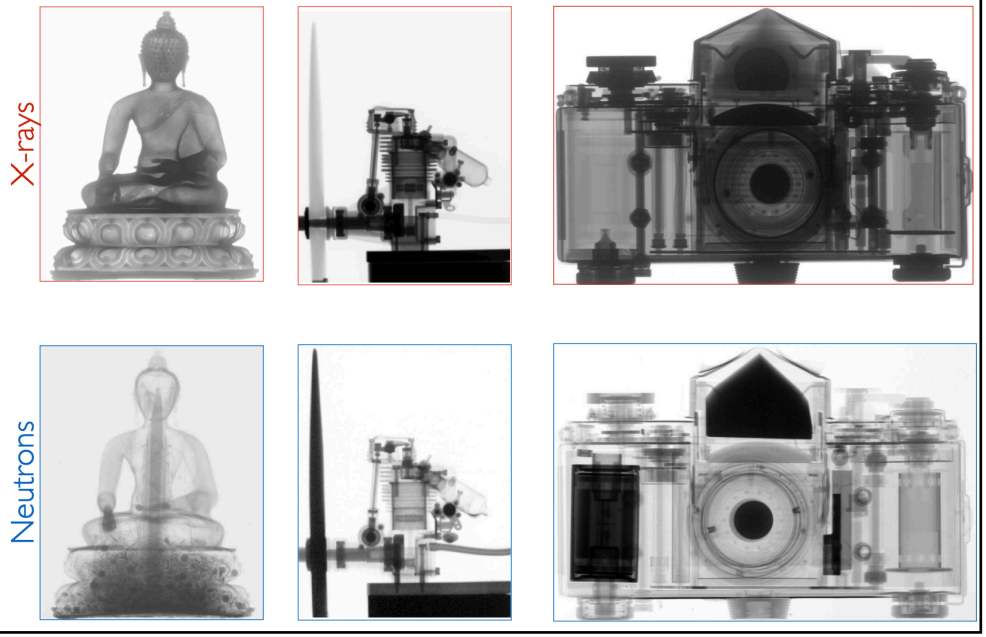
Photon vs. neutron sources

Photons vs. Neutrons





Neutron vs. X-ray Imaging



M. Eshraqi

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1994 - 2026: >30 YEARS OF SCIENCE

Construction:1988-1994
Operation: 1994-2018

ESRF, the first 3rd-generation synchrotron: 11 European countries joining forces to open new vistas in synchrotron science

Upgrade Programme: 2009-2022

ESRF UPGRADE PROGRAMME (2009-2022) launched by the ESRF's 21 partner countries. UP PHASE-I delivered in 2015 on time and within the budget

Operation with ESRF-EBS: 25 AUGUST 2020

Delivery of **ESRF-Extremely Brilliant Source** (EBS), a game changer: the first of a new generation of high-brilliance X-ray sources

January 2026

32 years of operation
5.5 years of successful operation of ESRF-EBS

BRINGING NATIONS TOGETHER TO ENABLE SCIENTIFIC EXCELLENCE AND TO ADDRESS GLOBAL CHALLENGES

Q. Qin

The European Synchrotron | ESRF

Q. Qin

We accelerate an electron beam from the linac, then a booster, and finally store it in the storage ring, ……

844 m

Particle	Electrons
Energy	6 GeV
Intensity	200 mA
Hours/year	~5500

34 + 12
Beamlines
(public + CRG)

The European Synchrotron | ESRF

Collaborative Research Group

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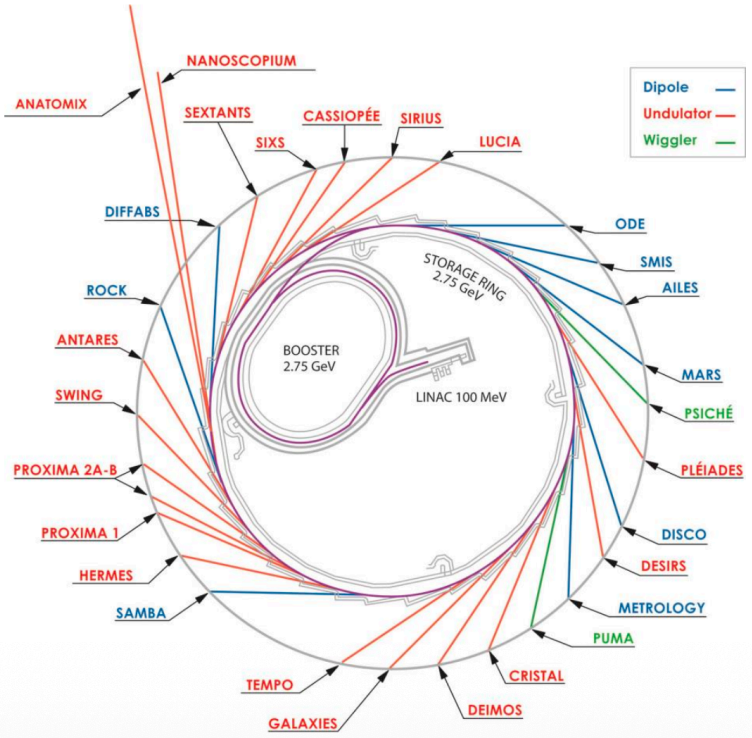
SOLEIL in a Nutshell

72% 28%

- Storage ring 354m, 2.75GeV
- 29 beamlines
- Open to external users in 2008



J. Daillant

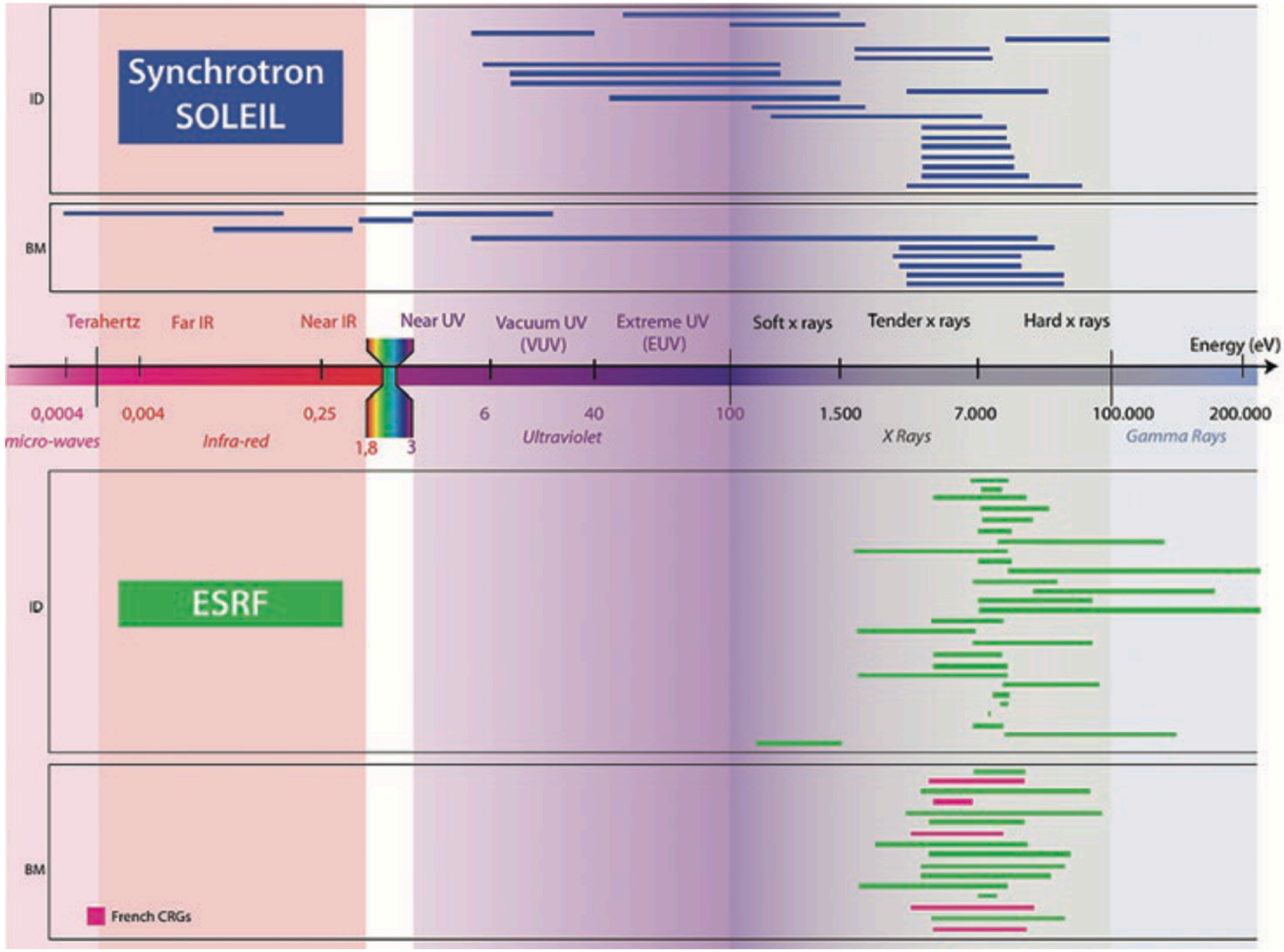
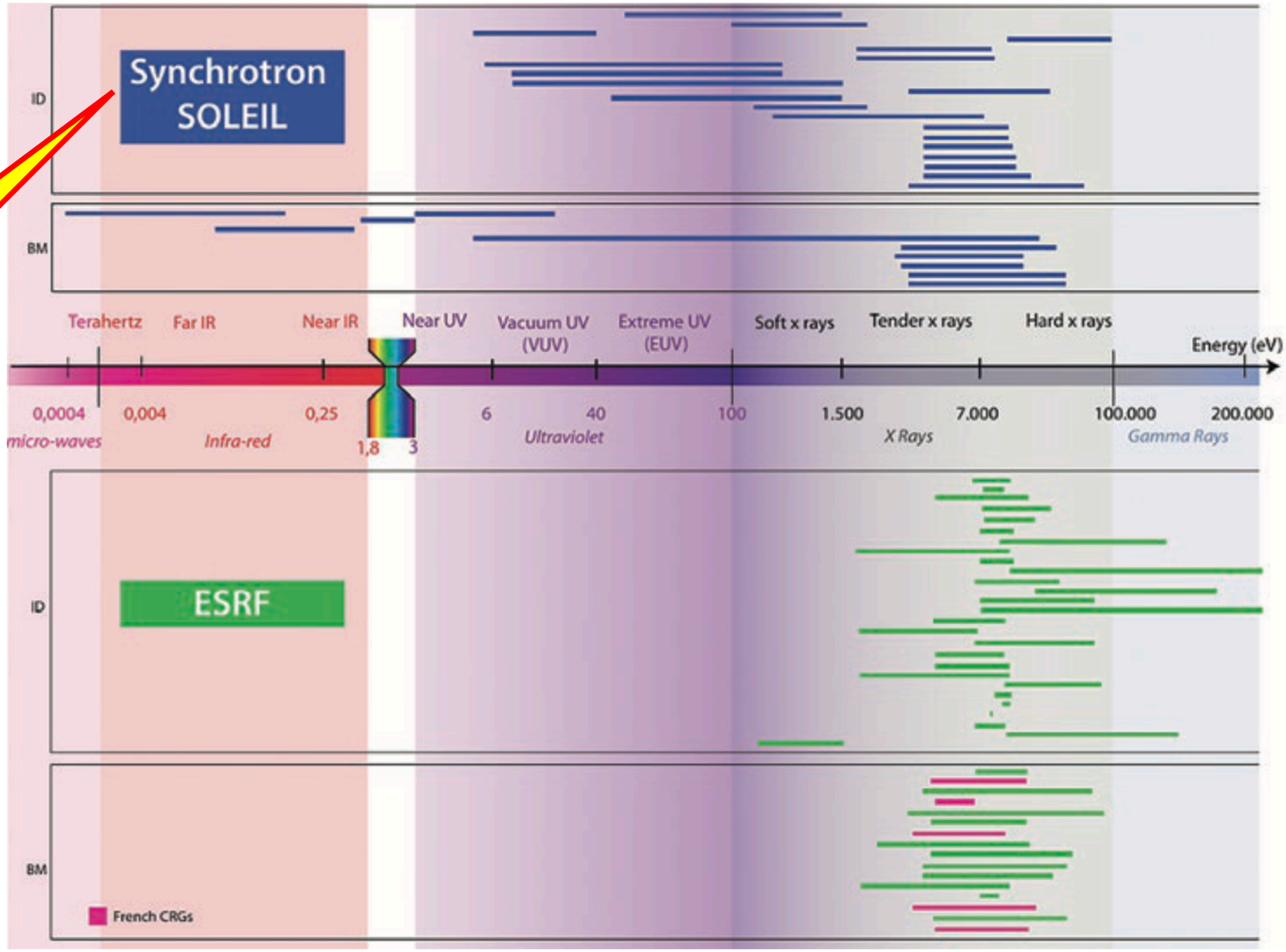


Figure 1: complementarity between SOLEIL (in blue) and ESRF (in green). French CRGs at the ESRF are marked in red.

SOLEIL II upgrade project (towards 4th generation) => 2025-2030: construction phase



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une source de lumière compacte

Thom X : a high intensity Inverse Compton X-source

Demonstrator for a compact X-source

Baseline initial Design Parameters

- Equipements area : 300 m²
- Photon Energy : 30 to 90 keV
- Flux: 10^{12} à 10^{13} γ/s
- Brillance: 10^{11} ph/s/mrad²/mm²/

ThomX
Light Source & Laser Plasma Acceleration

Status of the project

Installation completed and operationnal

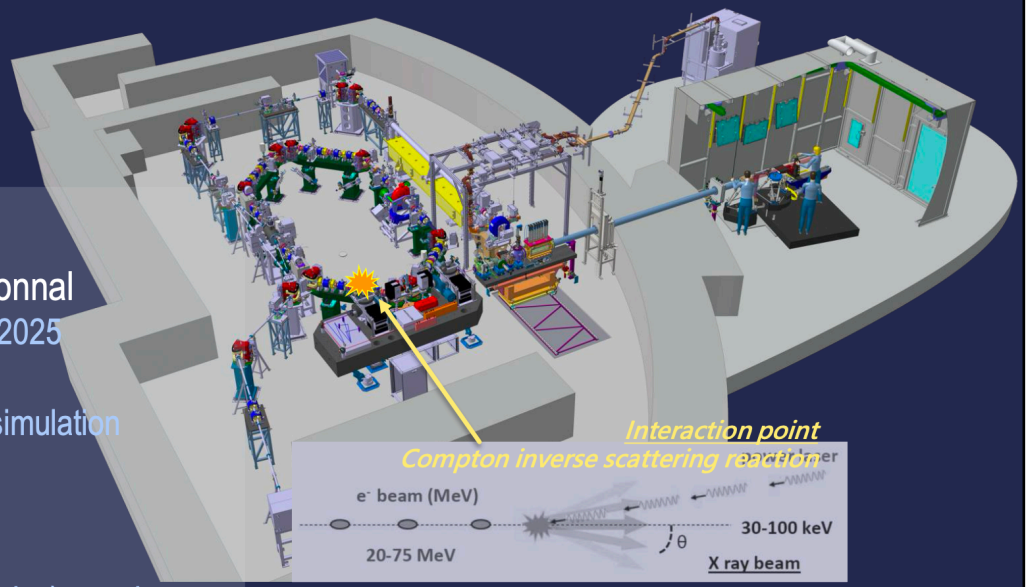
- Commissioning phase : 2024 and 2025

Recent news

- Correction of the orbit length and simulation
- Stabilization of the beam transport
- Presently flux of a few x 10^{11} ph/s

Objectives

- Optimization (flux/spectrum/beam-size) ongoing
- Commissioning of the X-ray beam analysis devices
- Design flux targetted w/in the next months



A. Faus Golfe

Contents

SPIRAL2 = Système de production d'Ions Radioactifs en Ligne de 2e génération

An ion accelerator facility: From science to industry

GANIL

Facility :

5 cyclotrons

1 superconducting linac

Large Spectrometers, traps, lasers

Beams :

Stable ions beams
from proton to uranium
up 95 MeV/nucleon
Radioactive ion beams

1 Neutron beam (40 MeV)

B. Jacquot

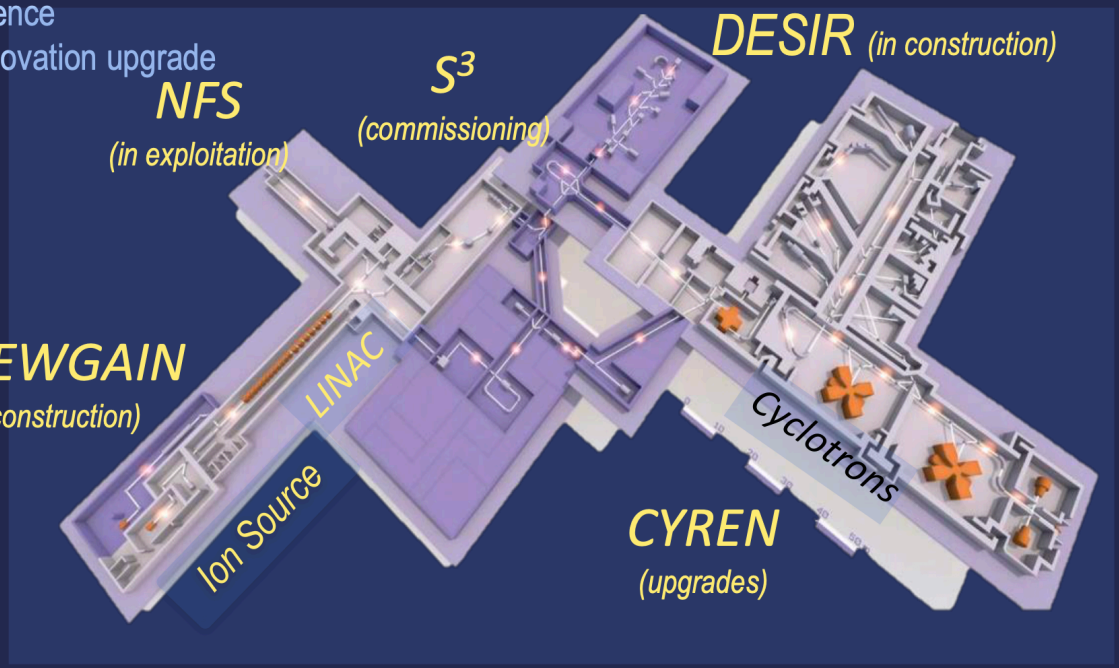
GANIL facility

GANIL : a pilar at the heart of the national priority

A major program of upgrades is underway supported by the ministry

- S^3 experiment– *Superconducting Spectrometer Separatror* –
- DESIR experiment – *Decay, Excitation, and Storage of Radioactive Ions* –
- NEWGAIN injector – a New GANIL INjector –
- NFS : Neutrons For Science
- CYREN : Cyclotron Renovation upgrade

GANIL
ESFRI Landmark Infrastructure



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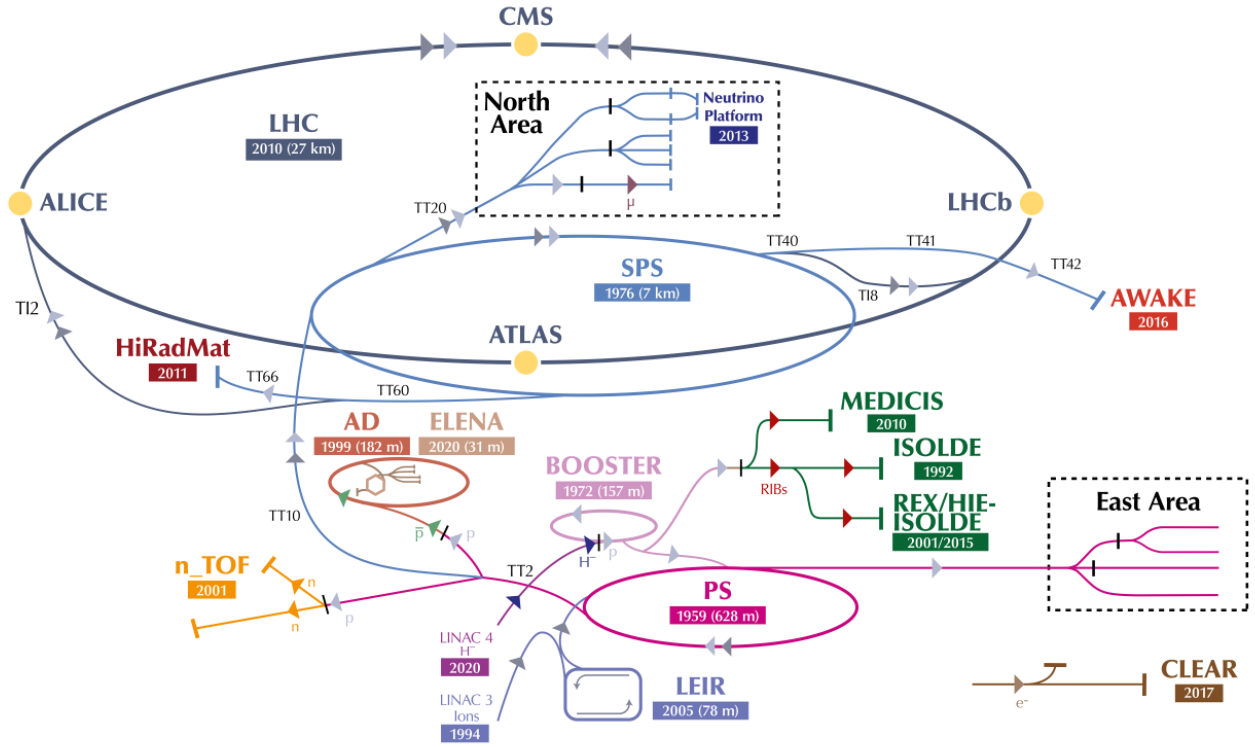
The CERN accelerator complex
Complexe des accélérateurs du CERN



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- n-TOF: n-induced cross-sections
- CLOUD: impact of cosmic rays on aeorosols and clouds
- AD / ELENA: Antiproton Decelerator for antimatter studies
- COMPASS → AMBER: hadron structure and spectroscopy
- NA61/SHINE: ions and neutrino targets
- NA62: rare kaon decays
- NA64: search for dark photons
- NA65: study of tau neutrino production
- Neutrino Platform: ν detector R&D for experiments in the US and Japan
- Etc. etc.

▸ H^- (hydrogen anions) ▸ p (protons) ▸ ions ▸ RIBs (Radioactive Ion Beams) ▸ n (neutrons) ▸ $\bar{p}$ (antiprotons) ▸ e^- (electrons) ▸ μ (muons)

LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKefield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE-ISOLDE - Radioactive EXperiment/High Intensity and Energy ISOLDE // MEDICIS // LEIR - Low Energy Ion Ring // LINAC - LINear ACcelerator // n_TOF - Neutrons Time Of Flight // HiRadMat - High-Radiation to Materials // Neutrino Platform

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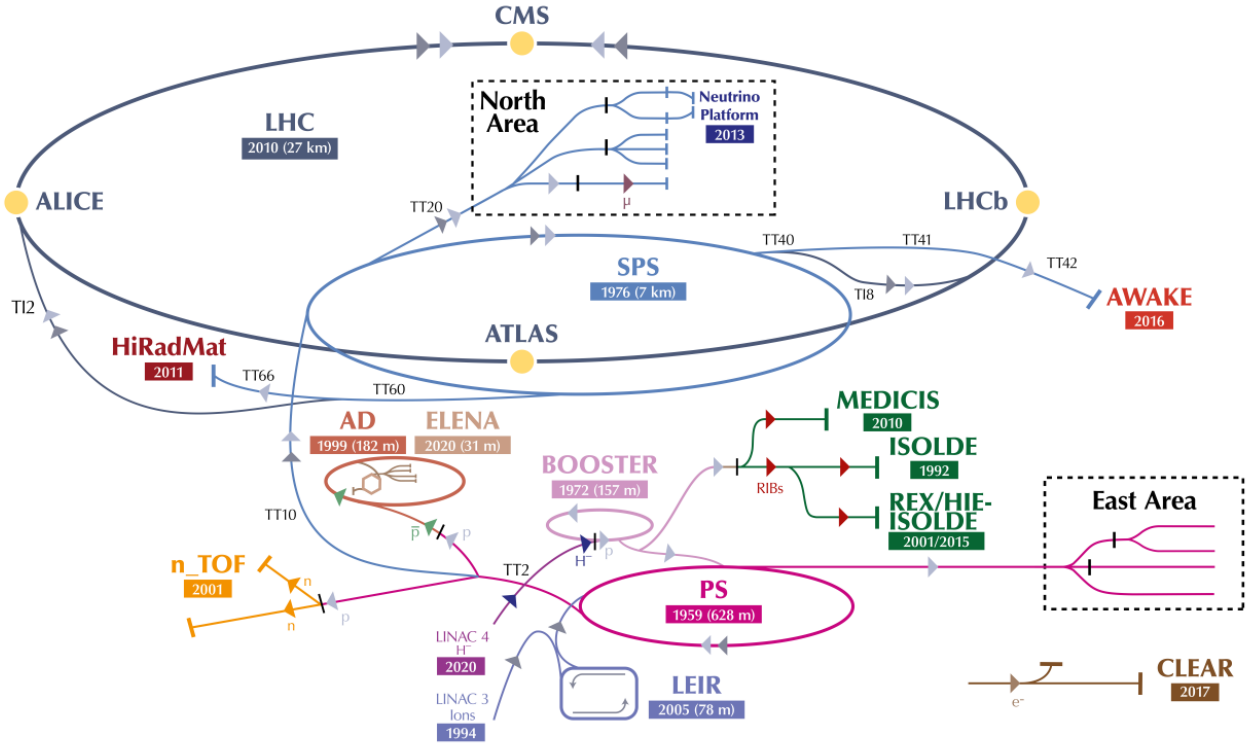

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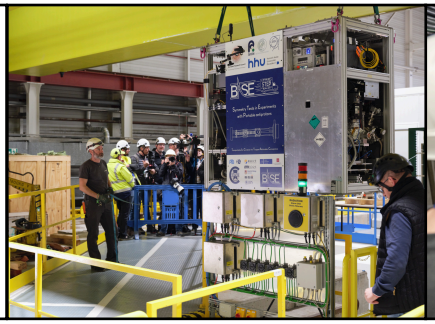
BASE experiment at CERN succeeds in transporting antimatter

Geneva, 24 March 2026. Today, in a world first, a team of scientists from the BASE experiment at CERN successfully transported a trap filled with antiprotons in a truck across the Laboratory's main site. The team managed to accumulate a cloud of 92 antiprotons in an innovative portable cryogenic Penning trap, then disconnect it from the experimental facility, load it onto a truck and continue experiment operation after transport. This is a remarkable achievement, given that antimatter is very difficult to preserve, as it annihilates upon contact with matter. This world premiere is a test, the ultimate aim being to transport antiprotons to other European laboratories, such as Heinrich Heine University Düsseldorf (HHU), where very-high-precision measurements of the antiproton properties could be performed.



1987: LIL : LEP Injector Linac

Réalisé par le LAL / Orsay

Ce linac produisait et accélérait des électrons et des positons à 500 MeV

100 m long

f = 2.99855 GHz

LEP operation: 1989- 2000

LEP = Large Electron Positron collider

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Conférence SFP 6 juillet 2023 Louis Rinolfi 14

=> See "Histoire française des accélérateurs de particules" (Conférence: 150 ans SFP, Louis Rinolfi)

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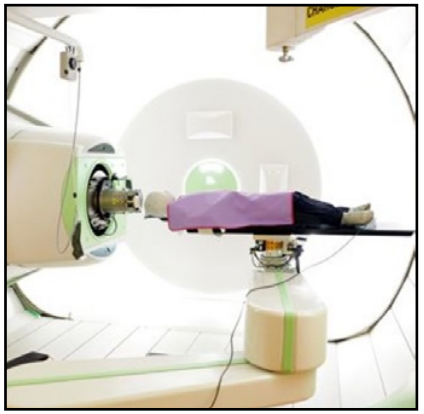

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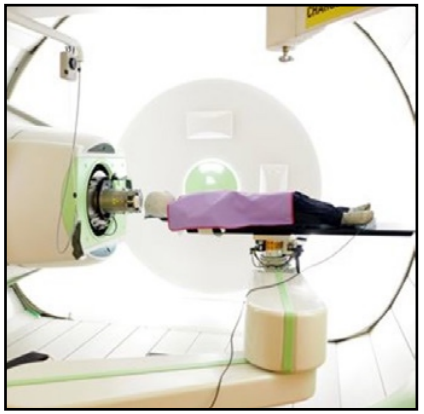
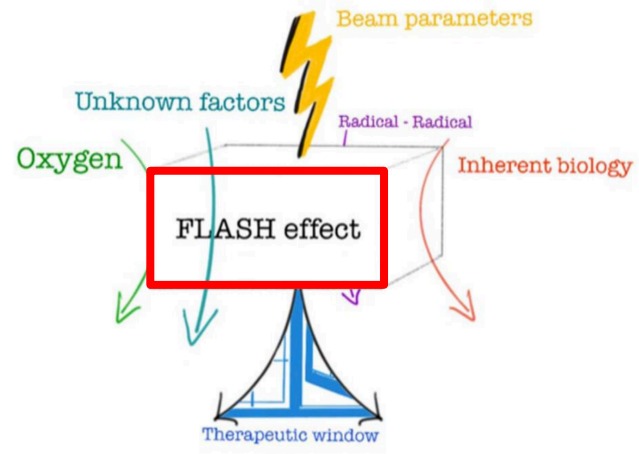
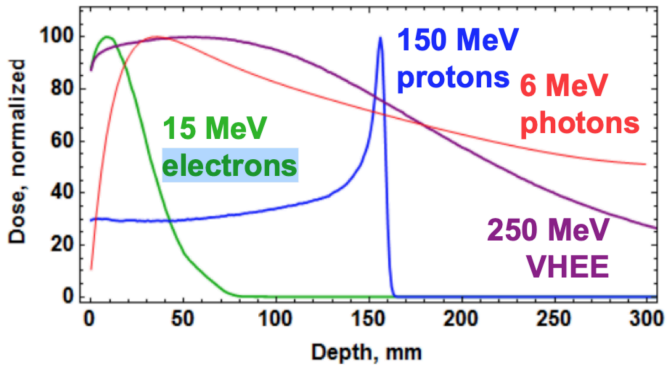
- Production of radioisotopes with Cyclotrons
  - ARRONAX (Nantes)
  - CYRCé (Strasbourg)
  - CEMHTI (Orléans)
  - …



FLASH radiation (>100 Gy/sec)



FLASH - VHEE



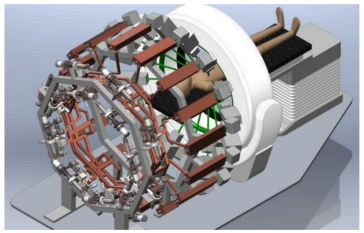
Deep dose-penetration in tissue (~30cm)

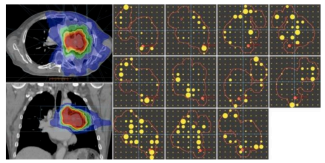
Superior dose deposition properties compared to MV photons

FLASH - Electrons

FLASH - photons

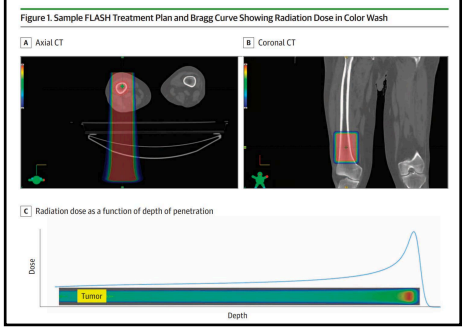
Phaser (Stanford) : Pluridirectional High-Energy Agile Scanning Electron Radiotherapy





Simulated SPHINX-based IMRT treatment plan for a locally advanced lung cancer. (Radiother. Oncol. 10.1016/j.radonc.2019.05.005)

FLASH - Protons



A. Durham

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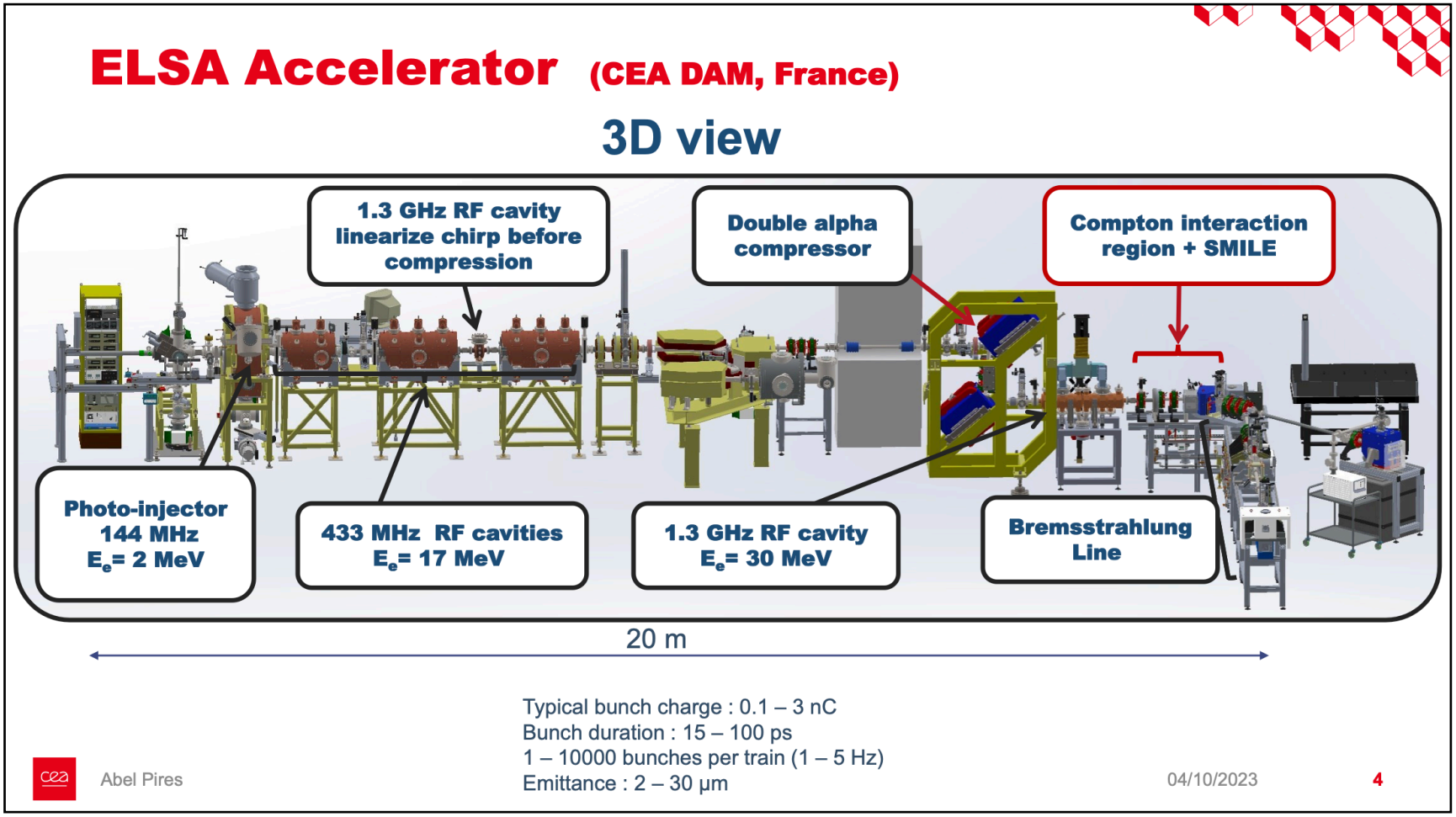
- In France, industrial accelerators are everywhere (factories, hospitals, laboratories, ports, customs, etc.) often small and specialized, essential but invisible

- ELSA (Electrons, Lasers, Source X et Applications) from CEA => Direction des Applications Militaires (DAM)



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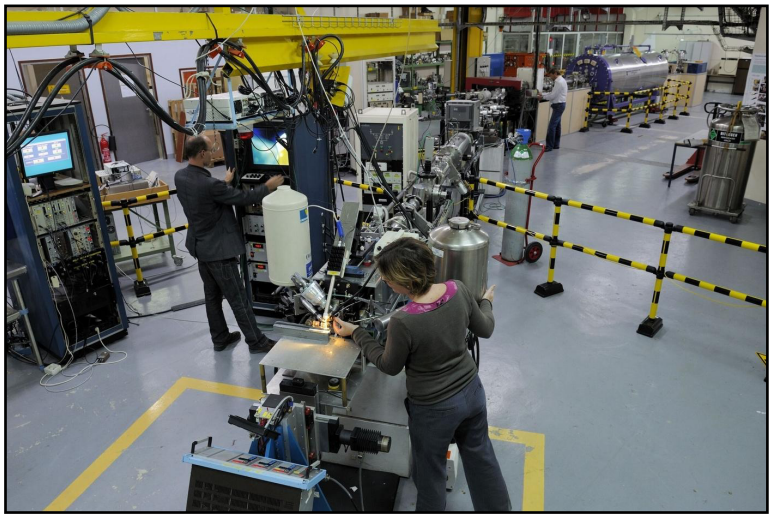
- AGLAE = Accélérateur Grand Louvre d'Analyse Elémentaire (Louvre Museum, Paris)
  - 4 MeV p+ (with also alpha particles)
  - 26 m (10 tons)

PIXE (Particle-Induced X-ray Emission)
RBS (Rutherford BackScattering)
PIGE (Particle-Induced Gamma-ray Emission)



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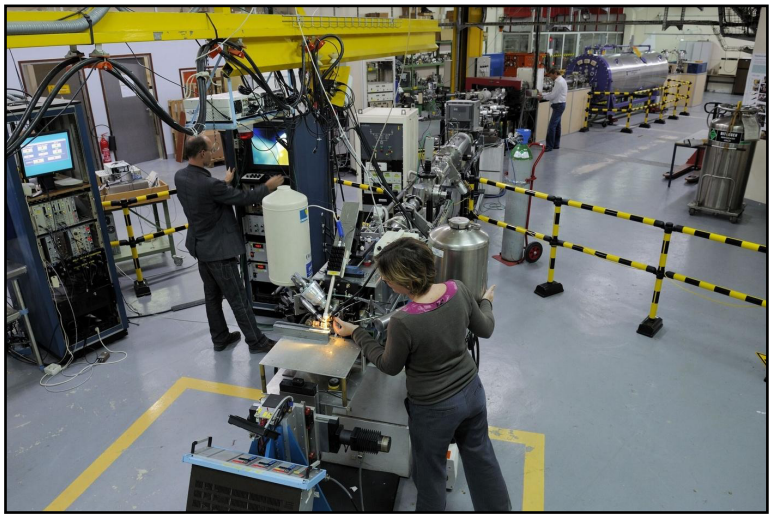
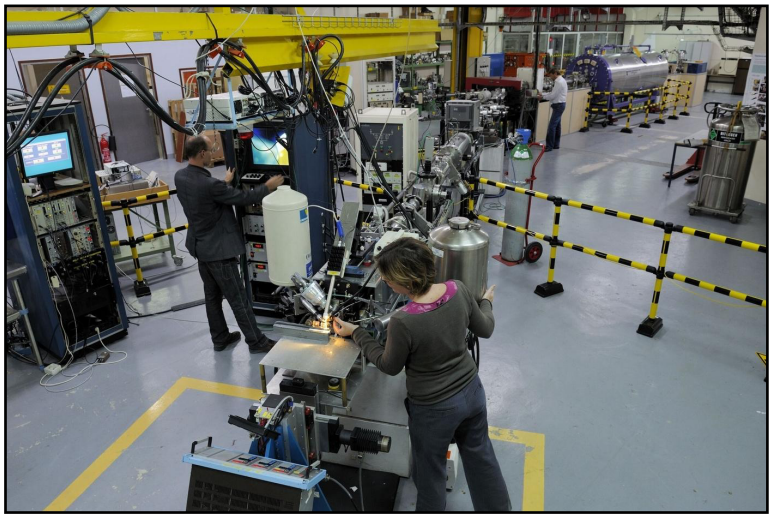


- AIFIRA (Bordeaux), etc.

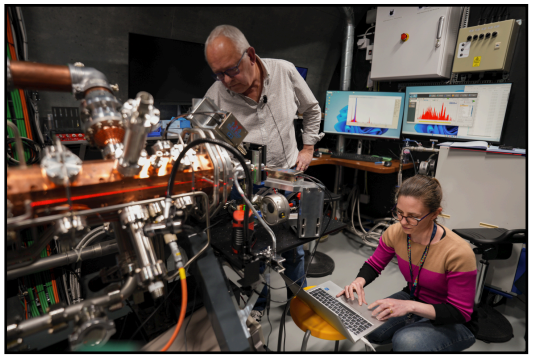
- AGLAE = Accélérateur Grand Louvre d'Analyse Elémentaire (Louvre Museum, Paris)
  - 4 MeV p+ (with also alpha particles)
  - 26 m (10 tons)

PIXE (Particle-Induced X-ray Emission)
RBS (Rutherford BackScattering)
PIGE (Particle-Induced Gamma-ray Emission)



- AIFIRA (Bordeaux), etc.

- ELISA = Experimental LInac for Surface Analysis (Science Gateway, CERN)
  - 2 MeV p+
  - 1-m long RFQ @ 750 MHz



Conclusions

- France has a diverse ecosystem of particle accelerators, including:
  - Large research facilities (synchrotrons such as SOLEIL and ESRF; heavy-ion laboratory like GANIL)
  - Facilities for healthcare and isotope production (medical cyclotrons)
  - As well as specialized research platforms and cultural applications (such as AGLAE)

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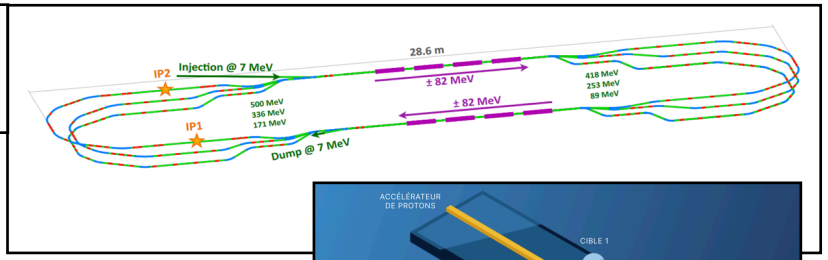
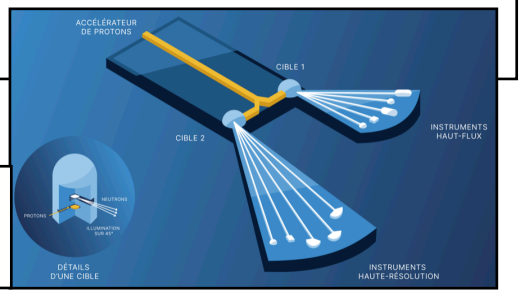
- These infrastructures support fundamental research programs, industrial and biomedical needs, and a wide range of societal applications
- Ongoing / future accelerators
  - Laser plasma acceleration
  - PERLE (e- Energy Recovery Linac)
  - ICONE: a new French neutron scattering source
  - Etc.

PERLE



ICONE
Neutrons for Materials Sciences



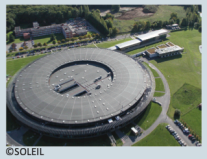
Summary from SFP in 2019

“Les activités Accélérateurs en France”

La France accueille quatre grands accélérateurs

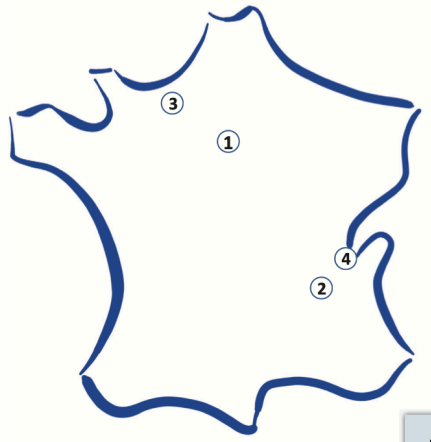
① SOLEIL (Saint-Aubin)

Source de lumière synchrotron de 3ème génération (depuis 2006)


©SOLEIL

- Linac 100 MeV
- Booster 3 Hz
- Anneau de stockage 2,75 GeV
- Circonférence 354 m
- Basse émittance 3,7 nm.rad

29 lignes de lumière



② ESRF (Grenoble)

Source de lumière synchrotron de 3ème génération (depuis 1994)
Soutenue et partagée par 22 pays


©ESRF

- Linac 200 MeV
- Booster 4 Hz
- Anneau de stockage 6 GeV
- Circonférence 844 m
- Emittance horizontale 4 nm.rad

49 lignes de lumière

Programme d’évolution :
Phase 1 (2009 à 2015) Remise à niveau des lignes de lumière
Phase 2 (2015 à 2022) Reconstruction de l’anneau de stockage avec une émittance horizontale de 130 pm.rad
Arrêt décembre 2018 – retour utilisateur août 2020

2 GRANDES INSTALLATIONS EUROPÉENNES

③ GANIL (Caen)

Installation dédiée à la recherche et aux applications industrielles utilisant des faisceaux d’ions.

Cinq cyclotrons
5000 heures de faisceau par an
3 faisceaux en parallèle, de 1 à 95 MeV/nucléon


©GANIL

SPIRAL 2 :
Phase 1 (LINAC): accélération H+, D+ et ions
Phase 2 : production d’ions radioactifs en projet
Implication CEA - CNRS - Industrie

④ CERN (Genève)

Un complexe unique au monde d’accélérateurs de particules pour repousser les limites de la connaissance de l’univers (fondé en 1954).

LHC : Large Hadron Collider
6,5 TeV par faisceau
Circonférence 27 km
Température -271°C


©CERN

Complexe accélérateurs :
une chaîne de machines qui accélèrent les particules à des énergies croissantes :
- Linac 2
- PSB : PS Booster
- PS : Proton Synchrotron
- Quatre détecteurs : ALICE, ATLAS, CMS et LHCb
- AD : Décélérateur d’antiprotons
- ISOLDE : Séparateur d’isotopes
- CLIC : Collisionneur linéaire compact

Contribution CEA - CNRS :
Quadrupôles magnétiques supraconducteurs et partie du système cryogénique de l’accélérateur.
Aimants géants de ATLAS & CMS.
Participation aux études pour le FCC (Future Circular Collider) pour prendre le relais du LHC jusqu’à 100 TeV.

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Summary from SFP in 2019

“Les activités Accélérateurs en France”

Une recherche française riche et variée

Accélérateurs pour la santé

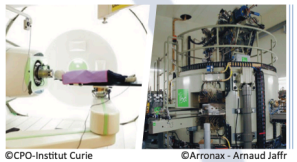
5 **ARCHADE** (Caen) Projet Hadronthérapie

6 **ARRONAX** (Nantes) Cyclotron haute intensité 70 MeV pour la recherche en médecine nucléaire et en radiochimie

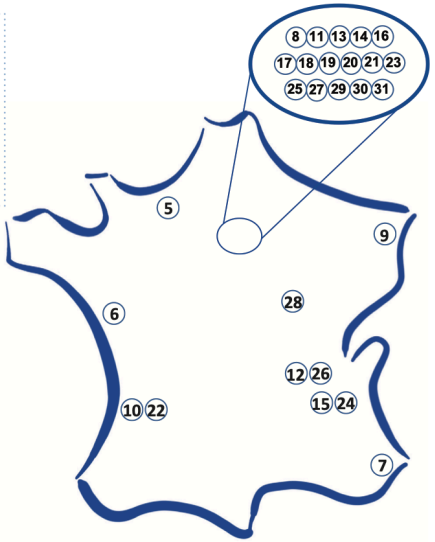
7 **CAL** (Nice) Cyclotron 65 MeV pour la protonthérapie

8 **CPO** – Institut Curie (Orsay) Centre de protonthérapie
Nouveau cyclotron 230 MeV avec une gantry isocentrique

9 **CYRCE** (Strasbourg) Production de radio-isotopes pour le diagnostic ou le traitement médical



©CPO-Institut Curie ©Arronax - Arnaud Jaffr



Laboratoires de pointe

Nouveaux concepts d’accélération

21 **APOLLON** (Saclay) Impulsions laser 10 PW pour l’étude d’accélération d’électrons dans le domaine multi-GeV

22 **CELIA** (Bordeaux) Centre Lasers Intenses et Applications, CENBG Centre d’Etudes Nucléaires de Bordeaux Gradignan

23 **LULI, LOA, LPGP, LLR, LIDYL, DACM, LAL** (Ile de France) Techniques d’accélération par interaction laser-plasma

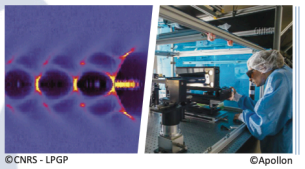
24 **LNCMI** (Grenoble) Laboratoire National des Champs Magnétiques Intenses

Physique nucléaire

25 **CSNSM** (Orsay) Centre de Sciences Nucléaires et de Sciences de la Matière

26 **IPNL** (Lyon) Institut de Physique Nucléaire de Lyon

27 **IPNO** (Orsay) Production de faisceaux d’ions légers



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Accélérateurs pour la recherche

10 **AIFIRA** (Bordeaux) CENBG - Production de faisceaux d’ions légers

11 **ALTO** (Orsay) Linac électron 50 MeV pour la physique nucléaire

12 **ANAFIRE** (Lyon) ANAlyses et Faisceaux d’Ions pour la Radiobiologie et l’Environnement

13 **CLIO** (Orsay) Laser à électrons libres 50 MeV

14 **ELYSE** (Orsay) Accélérateur d’électrons picoseconde

15 **GENESIS** (Grenoble) LPSC - Générateur neutrons 14 MeV

16 **IPHI** (Saclay) Injecteur Protons Haute Intensité

17 **JANNUS** (Orsay-Saclay) Jumelage d’Accélérateurs pour les Nanosciences, le Nucléaire et la Simulation

18 **PHIL** (Orsay) Banc de test photo-injecteur pour R&D

19 **SCALP** (Orsay) Synthèse et Caractérisation par des ions AccéLérés pour la recherche Pluridisciplinaire

20 **ThomX** (Orsay) Source X Compton – Accélérateur et circulateur 50 MeV

Autres applications

Défense

28 **EPURE** (CEA Valduc) Installation pour la radiographie de matériaux de densité très élevée en mouvement très rapide dans le cadre du traité franco-britannique Teutatès

29 **ELSA** (CEA Bruyères le Châtel) Source X Compton – Linac électrons 30 MeV

30 **NENUPHAR** et **4 MeV** (CEA Bruyères le Châtel) : accélérateurs d’ions

Patrimoine culturel

31 **New AGLAE** (Paris) Accélérateur électrostatique du Musée du Louvre Laboratoire C2RMF

©CEA DAM Valduc

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